Published by Institute of Physics Publishing for SISSA/ISAS
Received: *May 18, 2003*
Accepted: *August 25, 2003*

Onset of perturbative color opacity at small x and Υ coherent photoproduction off heavy nuclei at LHC

Leonid Frankfurt
Nuclear Physics Dept., School of Physics and Astronomy, Tel Aviv University
69978 Tel Aviv, Israel
E-mail: frankfur@lev.tau.ac.il

Vadim Guzey
Institut für Theoretische Physik II, Ruhr-Universität Bochum
D-44780 Bochum, Germany
E-mail: vadim.guzey@tp2.ruhr-uni-bochum.de

Mark Strikman
Department of Physics, the Pennsylvania State University, State College
PA 16802, USA
E-mail: strikman@phys.psu.edu

Michael Zhalov
Petersburg Nuclear Physics Institute
Gatchina 188350, Russia
E-mail: zhalov@mail.pnpi.spb.ru

Abstract: We study photon-induced coherent production of Υ in ultraperipheral heavy ion collisions at the LHC and demonstrate that the counting rates will be sufficient to measure nuclear shadowing of generalized gluon distributions. This will establish the transition from the regime of color transparency to the regime of perturbative color opacity in an unambiguous way. We argue that such measurements will provide the possibility to investigate the interaction of ultra-small color dipoles with nuclei in QCD at large energies, which is beyond the reach of electron-nucleon (nucleus) colliders, and which will unambiguously discriminate between the leading twist and higher twist scenarios of gluon nuclear shadowing.

Keywords: QCD, Deep Inelastic Scattering, Phenomenological Models.

Contents

1. Introduction

High energy coherent vector meson photo- and electroproduction provides new tools for understanding of many exciting phenomena in the QCD physics of hadron-nucleus interactions [1]. The photon wave function comprises a variety of hadronic components as well as a direct contribution of quark-antiquark pairs. In the high energy regime, the photon transforms into a $q\bar{q}$ pair long before the nuclear target. The transverse size of the produced $q\bar{q}$ pair is controlled by the mass of the quark ($r \propto m_q^{-1}$, provided $m_q \gg \Lambda_{QCD}$, which is certainly the case for the bottom quark with $m_b \approx 5\,\mathrm{GeV}$). Correspondingly, the scale of virtuality in the considered processes is $Q^2 \geq m_q^2$.

The strength of the high-energy interaction of small dipoles in QCD depends on the size of the area occupied by the color field within the interacting objects: the smaller the size, the weaker the interaction [2, 3]. Probably the most sensitive indicator of the size of the interacting objects is the t-dependence of exclusive vector meson electro- and photoproduction. The current HERA data on vector meson electroproduction on the proton target, see e.g. [4], are consistent with the prediction of [5] that the t-slopes of the ρ and J/ψ production cross sections should converge to the same value with the rate of convergence consistent with the estimate of [6]. This indicates that at small x, $x = (M_V^2 + Q^2)/s$ (x is related to the momentum fractions of the exchanged gluons — see the discussion of eq. (2.4) below; s is the invariant energy for $\gamma - N$ scattering), the configurations of much smaller size than the average light meson size dominate J/ψ production for all Q^2 and ρ production for $Q^2 \geq 5\,\mathrm{GeV}^2$.

The main theoretical tool in considering various hard DIS processes has been QCD factorization theorems. In the kinematics of small x and sufficiently large Q^2, the QCD factorization theorem predicts that the cross section of coherent (nucleus remains intact) production of vector mesons off any hadronic target, including a nucleus, is proportional to the square of the gluon parton density[1] of the target, $G_T(x, Q^2)$ [5, 7, 8]. In this

[1] Note that the corrections due to the skewedness effects at large Q^2 and small x are calculable in terms of the QCD evolution equation for the generalized parton distributions.

work, we consider nuclei of Ca and Pb as our targets. Note that the phenomenon of color transparency in electro- and photoproduction of vector mesons, including Υ, was also considered in ref. [9] within the framework of the eikonal approximation and the two-gluon exchange model of F. Low [2]. This analysis contradicts QCD factorization theorems and predict color transparency at small x, while QCD predicts color opacity. A concise discussion of the differences between our approach, based on the QCD factorization theorem, and the eikonal approximation is presented in section 2.

As dictated by the QCD factorization theorem, the knowledge of nuclear gluon distributions is crucial for reliable predictions for coherent processes with nuclei and many other aspects of small-x nuclear dynamics. The nuclear parton distributions have been analyzed both phenomenologically, by fitting to the available data [10, 11] (which for $Q^2 \geq 2\,\mathrm{GeV}^2$ correspond to $x \geq 10^{-2}$), and theoretically, by using various models, see ref. [12] for the review. In spite of sizable deviations between predictions for the nuclear gluon distributions by the aforementioned groups, these analyses suggest rather significant nuclear shadowing assuming that the leading twist effects in DIS on nuclear targets dominate. However, the situation is complicated by the fact that when the nuclear gluon distribution is inferred from the scaling violations of the nuclear structure function F_{2A}, low values of Bjorken x correspond to rather moderate Q^2, where higher twist effects, such as e.g. diffractive vector meson production, are not negligible.

Among multiple theoretical models of small-x nuclear gluon distributions we would like to single out the following two, rather distinct approaches. The first one focuses on sufficiently large virtualities, $Q^2 \geq 4\,\mathrm{GeV}^2$, where leading twist is expected to dominate. It is assumed that soft physics (in the spirit of the aligned jet model of Bjorken), which dominates at the starting scale of QCD evolution for quark parton distributions, should be present in the gluon sector as well, so that the gluon shadowing effects at the initial evolution scale of a few GeV^2 should be comparable to that of quarks [10, 13]. Recently a more quantitative approach became possible. It is based on the combination of the Gribov theorem connecting diffraction and shadowing [14] and the Collins factorization theorem for hard diffraction in DIS [15]. As a result, this approach effectively takes into account the non-conservation of the number of particles during QCD evolution and the restoration of the gluon fields by small color singlets. When combined with the HERA hard diffractive data and quasi-eikonal modeling of multiple rescattering terms, it leads to the prediction that the gluon shadowing is significantly larger than that for quarks at the starting scale of QCD evolution of $Q^2 \sim 4\,\mathrm{GeV}^2$.

Another group of the models [16] aims to model the effects of the modification of the nuclear gluon field both in the regime of high gluon densities, where the decomposition over twists is not applicable, and at large Q^2, where leading twist dominates. It assumes that parton densities are saturated at $Q^2 \leq Q_s^2$ ($Q_s^2(x)$ is the saturation scale). An important feature of these models is that they do not lead to leading twist shadowing at $Q^2 \gg Q_s^2$, see e.g. discussion in [17, 18]. In particular, the effect of nuclear shadowing for the interaction of a small dipole is modeled in the frozen impact parameter eikonal approximation with the dipole coupled to the unscreened (unshadowed) nucleon gluon fields, which leads to the shadowing correction $\propto xG_N(x,Q^2)/Q^2$.

The pattern of the nuclear gluon parton distribution as a function of decreasing x and $Q^2 \sim$ few GeV^2 looks as follows. In the x-range, where nuclear gluons are not shadowed, $x \sim 0.05 - 0.1$, one expects the regime of color transparency ($G_A(x,Q^2) = AG_N(x,Q^2)$) for coherent production of onium (heavy quark-antiquark) states. At lower x, leading twist shadowing would lead to the onset of the perturbative color opacity ($G_A(x,Q^2) < AG_N(x,Q^2)$). However, this shadowing merely slows down the increase of the gluon density with the decrease of x. Hence, at sufficiently small x, the perturbative color opacity regime will be also violated. Eventually, this will lead to the onset of the black body limit (BBL) [19] or another nonlinear regime of QCD.

The crucial questions for understanding the interplay among the above mentioned phenomena and regimes are the following. What is the kinematical region where the squeezing of the $q\bar{q}$ dipole takes place, which justifies the application of perturbative QCD? What are the leading mechanisms of nuclear shadowing at very small x, where the small size dipole-nucleon interaction become large? Can the gluon saturation effect at small x stop the increase of the cross section before reaching the BBL?

In order to establish the effect of nuclear opacity and clarify the role of the leading and higher twist mechanisms of nuclear shadowing in an unambiguous way, it is necessary to investigate the interaction of a small quark-antiquark dipole with the nuclear medium and check whether the amplitude of the interaction is reduced as compared to the color transparency expectation of the amplitude being proportional to the atomic number. Production of light vector mesons in DIS at small x by longitudinally polarized photons and photoproduction of onium states seem to be optimal for these purposes. The studies within the framework of the dipole model in ref. [20] suggest that one is safely into the perturbative domain for $x \leq 10^{-3}$ only if the transverse distances (transverse sizes of the dipole) are rather low, $d_t \sim 0.3$ fm. For light mesons this requires $Q^2 \geq 15\,\mathrm{GeV}^2$ and, hence, an eA collider with energies of HERA and large luminosity. Increasing the mass of the produced vector mesons, photoproduction of J/ψ appears to be the borderline case — the amplitude seems to be receiving a significant contribution from the transitional region between perturbative and nonperturbative QCD. Although J/ψ photoproduction suits well the studies of the onset of color opacity, in general it may be rather problematic to distinguish the perturbative regime, where the amplitude is proportional to the gluon density, from the regime, where the fast increase of the gluon density results in the violation of the leading twist approximation and the transition to the black body limit takes place.

In ref. [21] it was suggested to study the onset of BBL in coherent photoproduction of dijets from heavy nuclei since in this case the role of the leading twist shadowing is negligible. On the contrary, coherent Υ photoproduction off heavy nuclei seems to be essentially unique for the investigation of the onset of the perturbative color opacity in the leading twist (LT) shadowing regime. In this case, the interaction is dominated by such small transverse interquark distances d_t, $d_t \sim 0.1$ fm, that the physics of the interactions is definitely perturbative up to very large energies (down to very small x). For example, the cross section of the interaction of a dipole with $d_t \sim 0.1$ fm is $\sigma(d_t = 0.1\,\mathrm{fm}, x = 10^{-4}) = 3.5$ mb and it is even smaller for larger x.

In order to probe the onset of perturbative color opacity in the Υ production, one would need to reach $x \ll 10^{-2}$. This would require an electron-nucleus collider in the HERA energy range with a luminosity per nucleon comparable to the luminosity in the electron-proton collisions, which appears to be rather problematic for HERA. At the same time there are plans for studying photoproduction off nuclei at the LHC using ultraperipheral heavy ion collisions, including the studies of coherent onium photoproduction. For the review and extended list of references, see ref. [22].

Recently it was demonstrated [23] that the yield of J/ψ in coherent production in the kinematics of ultraperipheral ion collisions at the LHC is suppressed at the central rapidities by a factor of 6 compared to that in the impulse approximation. Such a significant effect of the suppression would clearly signal the revealing of the color opacity phenomenon. However, as mentioned above, the gluon virtualities in this case are on the borderline between the perturbative and nonperturbative QCD regimes, $Q^2_{eff} \sim 3 \div 4\,\mathrm{GeV}^2$, and the leading twist approximation might not be accurate enough for the evaluation of the scattering amplitude, especially since the nonperturbative region could probably give a significant correction [24].

In summary, Υ photoproduction stands out as the simplest test of the propagation of small color dipoles, $d_t = 0.1$ fm, at the LHC energies. This will allow to investigate nuclear gluon fields at the effective scale $Q^2 \sim 40\,\mathrm{GeV}^2$. In this case, the estimates of nuclear shadowing via the leading twist mechanism based on perturbative QCD used in ref. [23], will be much better justified. The main objective of this work is to present the results of a study of coherent production of Υ in ultraperipheral collisions of heavy ions in the kinematics of the LHC.

2. Production of Υ in ultraperipheral collisions

The cross section of coherent Υ production integrated over the transverse momentum of the nucleus, which emitted a photon, can be written using the standard Weizsacker-Williams approximation [25] in the following form:

$$\frac{d\sigma(AA \to \Upsilon AA)}{dy} = N_\gamma(y)\sigma_{\gamma A \to \Upsilon A}(y) + N_\gamma(-y)\sigma_{\gamma A \to \Upsilon A}(-y)\,. \tag{2.1}$$

Here $y = \ln \frac{2\gamma m_N M_V}{s}$ is the c.m. rapidity of the produced Υ; γ is Lorentz factor; $\sigma(y)$ is the cross section for photoproduction of Υ; $N_\gamma(y)$ is the flux of the equivalent photons [26]:

$$N(y) = \frac{Z^2\alpha}{\pi^2}\int d^2b\,\Gamma_{AA}(\vec{b})\frac{1}{b^2}X^2\left[K_1^2(X) + \frac{1}{\gamma}K_0^2(X)\right], \tag{2.2}$$

where $K_0(X)$ and $K_1(X)$ are modified Bessel functions of the argument $X = bm_V e^y/(2\gamma)$; $\vec{b}$ is the transverse distance between the centers of the colliding nuclei. The standard Glauber profile factor,

$$\Gamma_{AA}(\vec{b}) = \exp\left(-\sigma_{NN}\int\limits_{-\infty}^{\infty} dz \int d^2b_1\,\rho_A(z,\vec{b}_1)\rho_A(z,\vec{b}-\vec{b}_1)\right), \tag{2.3}$$

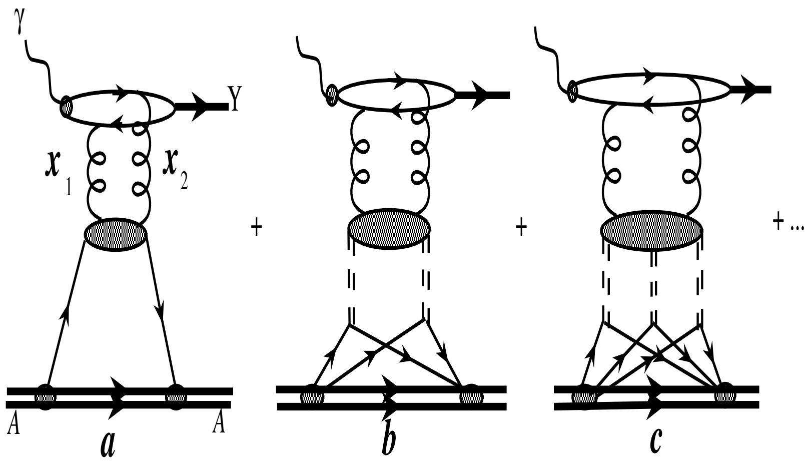

Figure 1: High energy quarkonium photoproduction in the leading twist approximation.

accounts for the inelastic strong interactions of the nuclei at impact parameters $b \leq 2R_A$ and, hence, suppresses the corresponding contribution to the Υ photoproduction. In our calculations we use the nuclear matter density $\rho_A(z, \vec{b})$ obtained from the mean field Hartree-Fock-Skyrme (HFS) model, which describes many global properties of nuclei [27] as well as many single-particle nuclear structure characteristics extracted from the high energy $A(e, e'p)$ reactions [28].

The amplitude of Υ photoproduction (necessary for the calculation of $\sigma_{\gamma A \to \Upsilon A}$ in eq. (2.1)) in the leading twist approximation is described by the series of the Feynman diagrams depicted in figure. 1. The QCD factorization theorem[2] for exclusive meson photoproduction [5, 7, 29] allows one to express the imaginary part of the forward amplitude for the production of a heavy vector meson by a photon, $\gamma + T \to V + T$, through convolution of the wave function of the meson at the zero transverse separation between the quark and antiquark, the hard interaction block and the generalized parton distribution (GPD) of the target, $G_T(x_1, x_2, Q^2, t_{min})$, evaluated at $t_{min} \approx -x^2 m_N^2$. The momentum light cone fractions x_i of the gluons attached to the quark loop satisfy the relation:

$$x_1 - x_2 = \frac{m_\Upsilon^2}{s} \equiv x\,, \tag{2.4}$$

where $s = 4E_N\omega = 4\gamma\omega m_N$ is the invariant energy for $\gamma - N$ scattering ($E_N = \gamma m_N$ is the energy per nucleon in the c.m. of the nucleus-nucleus collisions). If the quark Fermi motion and binding effects were negligible, then $x_2 \ll x_1$ as a consequence of the fact that

[2]The proof of the factorization theorem for diffractive electroproduction of vector mesons is rather straightforward [29] and, therefore, it is generally accepted in the published literature. At the same time, the proof of the factorization theorem is more delicate in the case of hadron-initiated processes such as diffraction of pions into two jets. For such processes factorization was questioned in refs. [30, 31]. However, approximations used in these papers appear to violate gauge invariance when describing hadron desintegration into jets in high-energy processes off the nucleon (nucleus) target. In particular, the same approximations lead to the formulae for the process of dijet production by the pion projectile off the Coulomb field of a nucleon (nucleus) [32], which differ from the exact answer deduced from the requirement of the conservation of the e.m. current and renormalizability of QCD [33].

the mass of the intermediate state, which approximately equals $2m_Q$, is close to the mass of the produced onium state. Numerical estimates using realistic potential model wave functions indicate that for J/ψ, $x_1 \sim 1.5x, x_2 \sim x/2$ [24], and that for Υ, $x_2/x_1 \sim 0.1$ [34]. Modeling of the GPDs at moderate Q^2 suggests that, to a good approximation, $G_T(x_1, x_2)$ can be approximated by the gluon density at $x = (x_1 + x_2)/2$ [5, 35]. For large Q^2 and small x, GPDs are dominated by QCD evolution from the region of much higher light cone fractions x_i, where the effect of skewedness is unimportant. Therefore, since QCD evolution conserves $x_1 - x_2$, the generalized parton distributions in the kinematics of our interest are determined primarily by diagonal parton distributions.

In light of the above discussion, we approximate the amplitude of Υ photoproduction off nucleus at $k_t^2 = 0$, presented by a series of diagrams in figure 1, as

$$M(\gamma + A \to \Upsilon + A) = M(\gamma + N \to \Upsilon + A)\frac{G_A(x, Q^2_{\text{eff}})}{AG_N(x, Q^2_{\text{eff}})} F_A(t_{\min}) \,, \tag{2.5}$$

where F_A is nuclear form factor normalized so that $F_A(0) = A$; $Q^2_{\text{eff}}(\Upsilon) \sim 40\,\text{GeV}^2$ according to the estimates of [6]. equation (2.5) is based on the QCD factorization theorem for photoproduction of heavy vector mesons and the reduction of the generalized parton distributions to the ordinary ones for small x and large Q^2.

It is worth noting that the precise value of Q^2_{eff} is not essential since for large Q^2, the gluon shadowing decreases slowly (logarithmically) with Q^2.

Note that the skewedness effects, which are expected to be small at $Q^2 \sim$ a few GeV^2, become important in the Υ case. They appear to increase the cross section of the reaction $\gamma + p \to \Upsilon + p$ by a factor ~ 2, see refs. [34, 36]. Potentially, this could obscure the connection between the perturbative color opacity effect and shadowing of the nuclear gluon densities. However, the analysis of [37] shows that the ratio of GPD on nucleus and on a nucleon for $t = t_{\min}$ is a weak function of x_2, slowly dropping from its diagonal value ($x_2 = x_1$) with the decrease of x_2. Overall this observation is in a agreement with the general trend mentioned above that it is more appropriate to do a comparison of the diagonal and non-diagonal cases at $x = (x_1 + x_2)/2$.

The effect of leading twist nuclear shadowing can be quantified by considering the diagram (b) in figure 1. All possible unitary cuts of the diagram lead to inelastic shadowing in hadron-nucleus total cross sections [14]. Applying these ideas to DIS on nuclei and using the factorization theorem for hard diffraction [8], coupled with the QCD analysis of the HERA data on diffractive DIS [38], nuclear parton distributions can be predicted [12, 15]. In general, the theory of leading twist nuclear shadowing should be applied in two steps. First, the nuclear gluon distribution is calculated at the starting evolution scale $Q_0^2 = 4\,\text{GeV}^2$

$$\begin{aligned} G_A(x, Q_0^2) &= AG_N(x, Q_0^2) - 8\pi \,\text{Re}\, e \,\times \\ &\times \left[\frac{(1-i\eta)^2}{1+\eta^2} \int d^2 b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_{x}^{x_{I\!P}^0} dx_{I\!P}\, g_N^D\left(\frac{x}{x_{I\!P}}, x_{I\!P}, Q_0^2, t_{\min}\right) \times \right. \\ &\left. \times\, \rho_A(\vec{b}, z_1)\rho_A(\vec{b}, z_2) e^{ix_{I\!P} m_N (z_1 - z_2)}\, e^{-\frac{1}{2}\sigma_{\text{eff}}(x, Q_0^2)(1-i\eta)\int_{z_1}^{z_2} dz \rho_A(\vec{b}, z)}\right] . \end{aligned} \tag{2.6}$$

Here $g_N^D(\frac{x}{x_{I\!P}}, x_{I\!P}, Q_0^2, t_{\min})$ is the diffractive gluon parton distribution of the nucleon; $x_{I\!P}$ is the Pomeron momentum fraction; η is the ratio of the real to imaginary parts of the elementary diffractive amplitude; $x_{I\!P}^0 = 0.03$ is the cut-off parameter of the theory. As an input, we used the H1 parameterization [38] of $g_N^D(\frac{x}{x_{I\!P}}, x_{I\!P}, Q_0^2, t_{\min})$. The effect of the interactions with three and more nucleons of the target (graph (c) in figure 1) is included in the attenuation factor $T = \exp(-\sigma_{\rm eff}(x, Q_0^2)(1-i\eta)/2 \int_{z_1}^{z_2} dz \rho_A(\vec{b}, z))$. The effective cross section $\sigma_{\rm eff}(x, Q_0^2)$ accounts for the elastic rescattering of the produced diffractive state off the nucleons in a series of the rescattering diagram (graphs (b) and (c) in figure 1) and is defined by the equation

$$\sigma_{\rm eff}(x, Q_0^2) = \frac{16\pi}{(1+\eta^2) G_N(x, Q_0^2)} \int_x^{x_{I\!P}^0} dx_{I\!P}\, g_N^D\left(\frac{x}{x_{I\!P}}, x_{I\!P}, Q_0^2, t_{\min}\right). \tag{2.7}$$

Second, since photoproduction of Υ corresponds to larger Q^2 scales, $Q^2 \approx 40\,{\rm GeV}^2$, the gluon parton distribution should be evolved up to this scale using the NLO QCD evolution equations.

In the limit of low nuclear density, when the effect of the attenuation factor T can be neglected, the leading twist nuclear shadowing theory contains no theoretical uncertainties. eq. (2.6) can be applied to evaluate $G_A(x, Q^2)$ at any scale Q^2 and not only at Q_0^2. A simple estimate of Bjorken x typical for photoproduction of Υ using eq. (2.4) gives $x \approx 2 \times 10^{-3}$. We have checked that the attenuation factor can be neglected for $x \geq 10^{-3}$ for Ca and for $x \geq 10^{-2}$ for Pb.

In the general case, eq. (2.6) should be used only at rather moderate Q_0^2 and should serve as an input for QCD evolution: The modeling of multiple rescattering by the attenuation factor T ignores the fluctuations in the strength of the interaction around the average value $\sigma_{\rm eff}$, which is a good approximation only at moderate Q_0^2. Indeed, at $Q_0^2 \approx 3 \div 4\,{\rm GeV}^2$, the interactions are predominantly soft with small cross section fluctuations. The effect of cross section fluctuations is automatically included in QCD evolution, which leads to violation of the Glauber-like structure of the expression for the shadowing for $Q^2 > Q_0^2$. In this respect, our approach is very different from the models, where the interaction with nuclear targets is modeled through eikonalization of the color dipole-nucleon cross section, see refs. [39, 40] for typical applications. Since the eikonalization procedure has no sound grounds in QCD, the resulting expressions suffer from such serious deficiencies as the incomparability with QCD evolution and the inability to consistently predict nuclear shadowing for various parton flavors.

Next we address the issue of the accuracy of the substitution of the ratio of the generalized gluon densities by the ratio of the diagonal parton densities at the normalization scale. In the case of scattering off two nucleons (only graph (b) in figure 1), one can express the leading twist screening through the nondiagonal matrix element of the diffractive distribution function, $\tilde{g}^D$ (an analog of generalized PDF). It depends on the light-cone fraction, which the nucleon lost in the $|in\rangle$ and $\langle out|$ states, $x_{I\!P}$ and $x_{I\!P} - x$, respectively, as well as

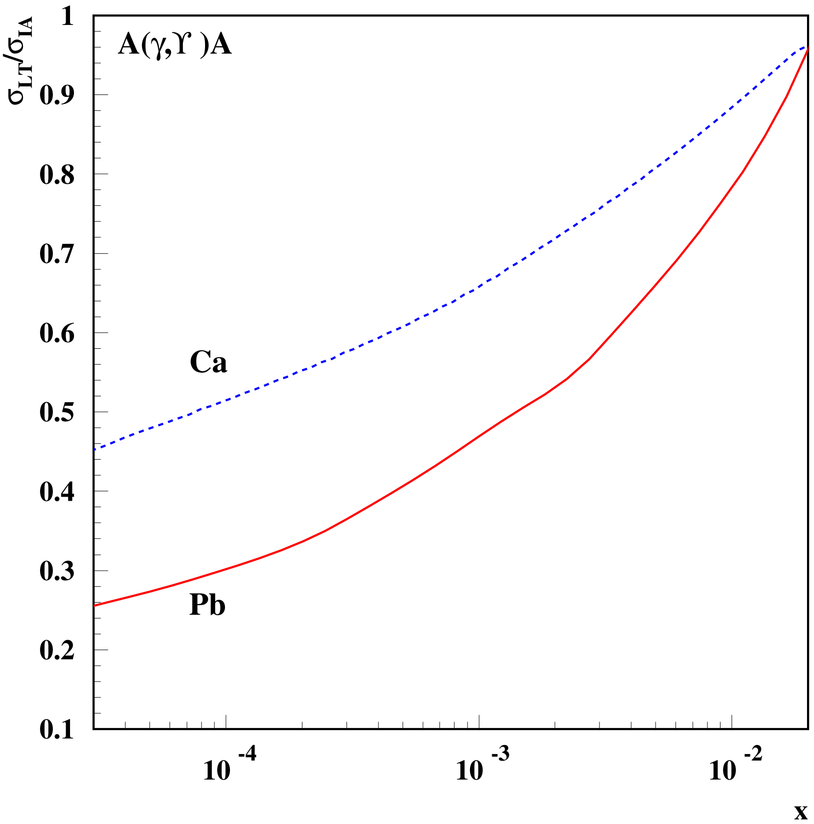

Figure 2: The shadowing effect in Υ photoproduction off Pb and Ca.

on $\beta_{in} = x_1/x_{I\!P}, \beta_{out} = (x_1 - x)/(x_{I\!P} - x)$ and t, Q^2. If we make a natural assumption that

$$\tilde{g}^D(x_1, x, x_{I\!P}, Q_0^2, t) = \sqrt{g^D(\beta_{in}, Q_0^2, x_{I\!P}, t) g^D(\beta_{out}, Q_0^2, x_{I\!P} - x, t)}\,, \tag{2.8}$$

we find that in the kinematics we discuss, the resulting skewedness effects are numerically small. They are smaller than the uncertainties in the input gluon diagonal diffractive PDFs.

The discussion of the nuclear gluon distribution culminates in the fact that the cross section of the process $\gamma A \to \Upsilon A$ can be readily obtained by squaring the amplitude in eq. (2.5)

$$\sigma_{\gamma A\to \Upsilon A}(s) = \frac{d\sigma_{\gamma N\to \Upsilon N}(s, t_{\rm min})}{dt} \left[\frac{G_A(\frac{M_\Upsilon^2}{s}, Q_{\rm eff}^2)}{AG_N(\frac{M_\Upsilon^2}{s}, Q_{\rm eff}^2)}\right]^2 \int\limits_{-\infty}^{t_{\rm min}} dt \left| \int d^2b dz e^{i\vec{q}_t\cdot\vec{b}} e^{-iq_l z} \rho_A(\vec{b}, z)\right|^2 , \tag{2.9}$$

where $-t = |\vec{q}_t|^2 + |q_l|^2$ is the square of the vector meson transverse momentum and $q_l = m_N M_\Upsilon^2/s$ is the minimal longitudinal momentum transfer in the photoproduction vertex.

The elementary cross section of forward Υ photoproduction in the energy range of interest is not known well experimentally. In our calculation, we used a simple parametrized

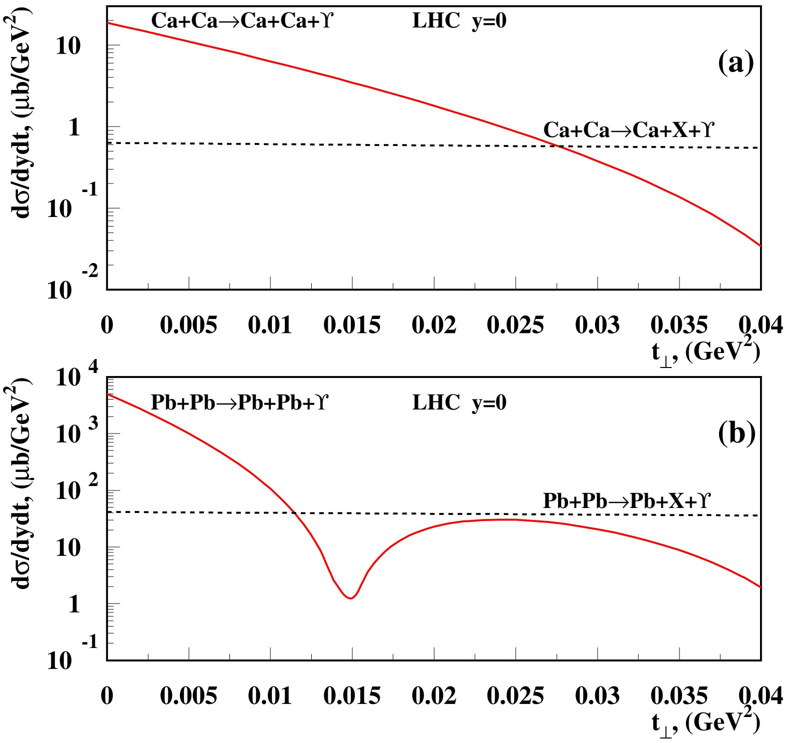

Figure 3: The momentum transfer dependence in coherent Υ production in ultraperipheral collisions at the LHC. The solid curve corresponds to the coherent cross section including the effect of nuclear shadowing; the dashed curve corresponds to incoherent Υ production.

form

$$\frac{d\sigma_{\gamma N\to\Upsilon N}(s,t)}{dt} = 10^{-4} B_\Upsilon \left[\frac{s}{s_0}\right]^{0.85} \exp(B_\Upsilon t) \tag{2.10}$$

with the reference scale $s_0 = 6400\,\mathrm{GeV}^2$; the slope parameter $B_\Upsilon = 3.5\,\mathrm{GeV}^{-2}$ and the energy dependence, which follows from the calculations [34] of photoproduction of Υ in the leading $\log Q^2$ approximation with an account for the skewedness of the partonic density distributions. The cross section is normalized so that the total cross section is in μb.

The results of the calculations using eq. (2.9) are presented in figure 2. The figure depicts the ratio of $\sigma_{\gamma A\to\Upsilon A}$ calculated with eq. (2.9) to that calculated ignoring the effect of nuclear shadowing (setting $G_A = AG_N$). We find a rather strong suppression of the coherent Υ photoproduction cross section off nuclei. Note that ultraperipheral collisions at the LHC are sensitive to the x-range of $3\times10^{-4} \le x \le 5\times10^{-3}$.

Since the significant effect of shadowing is far beyond the energies available in the fixed target experiments with the photon beams, the only opportunity to study this phenomenon is coherent production in ultraperipheral at the LHC.[3] In this kinematics, coherent events can be selected by the requirement of anticoincidence with the signal in a zero degree

[3]In principle, HERA can reach into the necessary kinematics. However, this would require both the approval of HERA III program and development of the system necessary for high luminosity runs with heavy nuclei.

JHEP08(2003)043

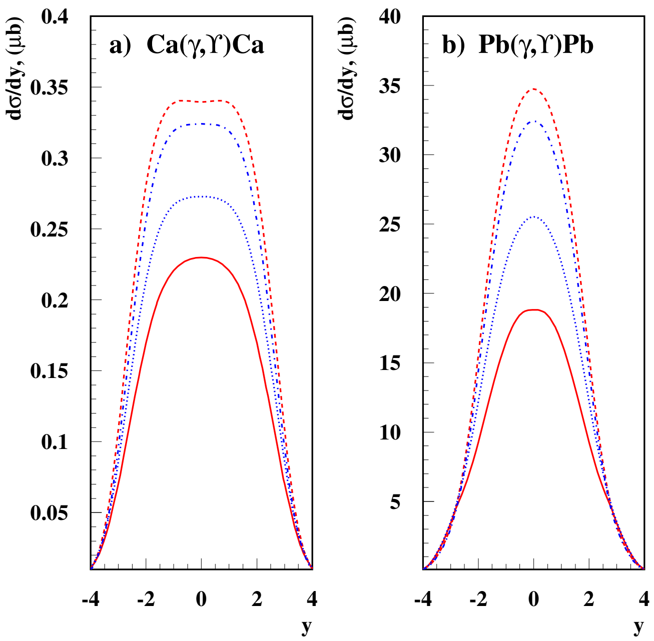

Figure 4: The rapidity distribution for coherent Υ production in Ca-Ca and Pb-Pb ultraperipheral collisions at the LHC. The solid curve corresponds to the calculation including leading twist nuclear shadowing; the dotted curve corresponds to the calculation with the model of shadowing of Eskola et al.; the dot-dashed curve is the calculation in the eikonal dipole rescattering model; the dashed curve corresponds to the impulse approximation.

calorimeter (the requirement is that there are no neutrons in the final state) and by selecting the produced Υ with small transverse momenta, which strongly suppresses the contribution of incoherent diffraction. The specific transverse momentum distributions for both coherent and incoherent production are shown in figure 3. The cross section of incoherent Υ photoproduction was estimated in the impulse approximation as

$$\frac{d\sigma_{\gamma A\to\Upsilon X}(s,t)}{dt} = A\frac{d\sigma_{\gamma N\to\Upsilon N}(s,t)}{dt}\,. \tag{2.11}$$

This constitutes the upper limit for the incoherent contribution.

The rapidity distributions for coherent Υ production in ultraperipheral collisions with Ca and Pb beams are shown in figure 4 and the corresponding total cross sections are given in table 1. For comparison, in figure 4 we also present results (the dotted curve) of the calculation using the model of Eskola *et al.* [10] for the gluon shadowing, which predicts somewhat smaller suppression of the Υ yield. In order to illustrate that that eikonal dipole models of rescatterings give a much smaller suppression, we present also the result of the eikonal calculation (the dot-dashed curve) using the analysis of the value of $\sigma(d,x)$ from [20] (the results of [41] for $d \sim 0.1$ fm are very similar, see comparison in [20]).

It appears that a detector with good acceptance for Υ production for the currently discussed luminosities for heavy ion runs at the LHC will collect enough statistics to measure the cross section of the discussed process with good precision. As seen from the comparison

Approximation	CaCa at LHC($\gamma = 3500$)	PbPb at LHC($\gamma = 2760$)
Impulse	1.8 μb	133 μb
Glauber+Leading twist shadowing	1.2 μb	78 μb

Table 1: Total cross sections of Υ production in UPC at LHC.

to the calculations in the impulse approximation (figure 4), the yield of Υ is expected to be suppressed by a factor of two at central rapidities due to leading twist shadowing. Practically, the only opportunity to draw the conclusion about the onset of the color opacity from the measurement of the Υ yield in the ultraperipheral ion collisions at the LHC, which we see at the moment, is the comparison of the calculations with the data. Obviously until the rather large uncertainty in the absolute value of the $\gamma + N \to \Upsilon + N$ cross section exists, such a conclusion cannot be considered as decisive. However, in the coming couple of years it is expected that this elementary cross section will be measured at HERA with much better accuracy. Besides, the energy dependence of the elementary cross section can be considered as well established theoretically. Hence, a measurement of the Υ yield at the edge of the rapidity distribution, where the effect of shadowing is still insignificant, could help to eliminate the uncertainty and verify the calculation of the cross section in the impulse approximation in all ranges of rapidities. Therefore, a comparison with the data at the central rapidities would provides us with an estimate of the shadowing effect. Note that there exists a procedure [42] to separate the production of mesons at small and large impact parameters through the study of the nucleus break up, which would allow to determine the ratio of the cross section of Υ production by left and right moving photons for a given rapidity. Another possibility will be to measure the elementary cross section at the LHC in ultraperipheral collisions of protons with nuclei. Though this cross section is a factor of $\propto A^{4/3}$ smaller, the expected luminosity in pA collisions is a factor of 100 larger than in AA collisions.

3. Conclusion

We found that the ultraperipheral collisions program at the LHC will provide a practical way to search for the onset of the perturbative color opacity via the study of coherent Υ production at the LHC and will decisively discriminate between the leading twist and higher twist scenarios of gluon shadowing at large Q^2.

Acknowledgments

This work was supported by GIF, Sofia Kovalevskaya Program of the Alexander von Humboldt Foundation and DOE.

References

[1] L. Frankfurt, M. Strikman and M. Zhalov, *Coherent photoproduction from nuclei*, *Acta Phys. Polon.* **B34** (2003) 3215 [hep-ph/0304301]; *Coherent photoproduction from nuclei*, *Acta Phys. Polon.* **B34** (2003) 3215 [hep-ph/0304301].

JHEP08(2003)043

[2] F.E. Low, *A model of the bare pomeron*, *Phys. Rev.* **D 12** (1975) 163.

[3] J.F. Gunion and D.E. Soper, *Quark counting and hadron size effects for total cross-sections*, *Phys. Rev.* **D 15** (1977) 2617.

[4] H1 collaboration, C. Adloff et al., *Diffractive jet production in deep-inelastic e^+p collisions at HERA*, *Eur. Phys. J.* **C 20** (2001) 29 [hep-ex/0012051]; *Inclusive measurement of diffractive deep-inelastic ep scattering*, *Z. Physik* **C 76** (1997) 613 [hep-ex/9708016].

[5] S.J. Brodsky, L. Frankfurt, J.F. Gunion, A.H. Mueller and M. Strikman, *Diffractive leptoproduction of vector mesons in QCD*, *Phys. Rev.* **D 50** (1994) 3134 [hep-ph/9402283].

[6] L. Frankfurt, W. Koepf and M. Strikman, *Hard diffractive electroproduction of vector mesons in QCD*, *Phys. Rev.* **D 54** (1996) 3194 [hep-ph/9509311]; *Diffractive heavy quarkonium photoproduction and electroproduction in QCD*, *Phys. Rev.* **D 57** (1998) 512 [hep-ph/9702216].

[7] L. Frankfurt, G.A. Miller and M. Strikman, *Coherent nuclear diffractive production of mini-jets: illuminating color transparency*, *Phys. Lett.* **B 304** (1993) 1 [hep-ph/9305228].

[8] J.C. Collins, *Hard-scattering factorization with heavy quarks: a general treatment*, *Phys. Rev.* **D 58** (1998) 094002 [hep-ph/9806259].

[9] B.Z. Kopeliovich, J. Nemchick, N.N. Nikolaev and B.G. Zakharov, *Novel color transparency effect: scanning the wave function of vector mesons*, *Phys. Lett.* **B 309** (1993) 179 [hep-ph/9305225];
Decisive test of color transparency in exclusive electroproduction of vector mesons, *Phys. Lett.* **B 324** (1994) 469 [hep-ph/9311237].

[10] K.J. Eskola, V.J. Kolhinen and P.V. Ruuskanen, *Scale evolution of nuclear parton distributions*, *Nucl. Phys.* **B 535** (1998) 351 [hep-ph/9802350];
K.J. Eskola, V.J. Kolhinen and C.A. Salgado, *The scale dependent nuclear effects in parton distributions for practical applications*, *Eur. Phys. J.* **C 9** (1999) 61 [hep-ph/9807297].

[11] M. Hirai, S. Kumano and M. Miyama, *Determination of nuclear parton distributions*, *Phys. Rev.* **D 64** (2001) 034003 [hep-ph/0103208].

[12] L. Frankfurt, V. Guzey and M. Strikman, *Leading twist nuclear shadowing: a user's guide*, hep-ph/0303022.

[13] L.L. Frankfurt, M.I. Strikman and S. Liuti, *Evidence for enhancement of gluon and valence quark distributions in nuclei from hard lepton nucleus processes*, *Phys. Rev. Lett.* **65** (1990) 1725.

[14] V.N. Gribov, *Inelastic processes at super high-energies and the problem of nuclear cross-sections*, *Sov. J. Nucl. Phys.* **9** (1969) 369; *Glauber corrections and the interaction between high-energy hadrons and nuclei*, *Sov. Phys. JETP* **29** (1969) 483; *Interaction of gamma quanta and electrons with nuclei at high-energies*, *Sov. Phys. JETP* **30** (1970) 709.

[15] L. Frankfurt and M. Strikman, *Diffraction at HERA, color opacity and nuclear shadowing*, *Eur. Phys. J.* **A5** (1999) 293 [hep-ph/9812322].

[16] L.D. McLerran and R. Venugopalan, *Fock space distributions, structure functions, higher twists and small x*, *Phys. Rev.* **D 59** (1999) 094002 [hep-ph/9809427].

[17] A.H. Mueller, *Parton saturation: an overview*, hep-ph/0111244.

[18] Y.V. Kovchegov, *Quantum structure of the non-abelian Weizsaecker-Williams field for a very large nucleus*, *Phys. Rev.* **D 55** (1997) 5445 [hep-ph/9701229].

[19] L. Frankfurt, V. Guzey, M. McDermott and M. Strikman, *Revealing the black body regime of small x dis through final state signals*, *Phys. Rev. Lett.* **87** (2001) 192301 [hep-ph/0104154].

[20] M. McDermott, L. Frankfurt, V. Guzey and M. Strikman, *Unitarity and the QCD-improved dipole picture*, *Eur. Phys. J.* **C 16** (2000) 641 [hep-ph/9912547].

[21] L. Frankfurt, M. Strikman and M. Zhalov, *Signals for black body limit in coherent ultraperipheral heavy ion collisions*, *Phys. Lett.* **B 537** (2002) 51 [hep-ph/0204175]; *Coherence effects in diffractive electroproduction from nuclei*, *Nucl. Phys.* **A 711** (2002) 243 [hep-ph/0211336].

[22] A. Ageev et al., *A Full acceptance detector at the LHC (FELIX)*, *J. Phys.* **G 28** (2002) R117; G. Baur, K. Hencken, D. Trautmann, S. Sadovsky and Y. Kharlov, *Coherent $\gamma\gamma$ and γa interactions in very peripheral collisions at relativistic ion colliders*, *Phys. Rept.* **364** (2002) 359 [hep-ph/0112211].

[23] L. Frankfurt, M. Strikman and M. Zhalov, *Fading out of J/ψ color transparency in high energy heavy ion peripheral collisions*, *Phys. Lett.* **B 540** (2002) 220 [hep-ph/0111221].

[24] L. Frankfurt, M. McDermott and M. Strikman, *A fresh look at diffractive J/ψ photoproduction at HERA, with predictions for Thera*, *J. High Energy Phys.* **03** (2001) 045 [hep-ph/0009086].

[25] E. Fermi, *On the theory of the impact between atoms and electrically charged particles. (In German)*, *Z. Physik* **29** (1924) 315;
C.F. von Weizsacker, *Radiation emitted in collisions of very fast electrons. (In German)*, *Z. Physik* **88** (1934) 612;
E.J. Williams, *Nature of the high-energy particles of penetrating radiation and status of ionization and radiation formulae*, *Phys. Rev.* **45** (1934) 729.

[26] N. Baron and G. Baur, *Photon-hadron interactions in relativistic heavy ion collisions*, *Phys. Rev.* **C 48** (1993) 1999;
S. Klein and J. Nystrand, *Exclusive vector meson production in relativistic heavy ion collisions*, *Phys. Rev.* **D 60** (1999) 014903 [hep-ph/9902259].

[27] M. Beiner, H. Flocard, N. Van Giai, P. Quentin, *Nuclear ground state properties and selfconsistent calculations with the Skyrme interactions, 1. Spherical description*, *Nucl. Phys.* **A 238** (1975) 29.

[28] L. Lapikas, G. van der Steenhoven, L. Frankfurt, M. Strikman and M. Zhalov, *The transparency of C-12 for protons*, *Phys. Rev.* **C 61** (2000) 064325 [nucl-ex/9905009];
L. Frankfurt, M. Strikman and M. Zhalov, *Single particle strength restoration and nuclear transparency in high Q^2 exclusive (e, ep) reactions*, *Phys. Lett.* **B 503** (2001) 73 [hep-ph/0011088].

[29] J.C. Collins, L. Frankfurt and M. Strikman, *Factorization for hard exclusive electroproduction of mesons in QCD*, *Phys. Rev.* **D 56** (1997) 2982 [hep-ph/9611433].

[30] V.M. Braun, D.Y. Ivanov, A. Schafer and L. Szymanowski, *Towards the theory of coherent hard dijet production on hadrons and nuclei*, *Nucl. Phys.* **B 638** (2002) 111 [hep-ph/0204191].

[31] V. Chernyak, *Does the E791 experiment have measured the pion wave function profile?*, *Phys. Lett.* **B 516** (2001) 116 [hep-ph/0103295].

[32] D.Y. Ivanov and L. Szymanowski, *Coulomb dissociation of a fast pion into two jets*, *Phys. Rev.* **D 64** (2001) 097506 [hep-ph/0103184].

[33] L. Frankfurt and M. Strikman, *Coulomb induced diffraction of energetic hadrons into jets*, *Phys. Rev.* **D 67** (2003) 017502 [hep-ph/0208252].

[34] L.L. Frankfurt, M.F. McDermott and M. Strikman, *Diffractive photoproduction of upsilon at HERA*, *J. High Energy Phys.* **02** (1999) 002 [hep-ph/9812316].

[35] A.V. Radyushkin, *Generalized parton distributions*, in *At the frontier of particle physics/handbook of QCD*, M. Shifman ed., World Scientific, Singapore 2001, vol. 2, pp. 1037–1099 [hep-ph/0101225].

[36] A.D. Martin, M.G. Ryskin and T. Teubner, *Upsilon photoproduction at HERA compared to estimates of perturbative QCD*, *Phys. Lett.* **B 454** (1999) 339 [hep-ph/9901420].

[37] L. Frankfurt, V. Guzey and M. Strikman, *Color coherent phenomena on nuclei and the QCD evolution equation*, *J. Phys.* **G 27** (2001) R23 [hep-ph/0010248].

[38] H1 collaboration, C. Adloff et al., *Inclusive measurement of diffractive deep-inelastic ep scattering*, *Z. Physik* **C 76** (1997) 613 [hep-ex/9708016].

[39] N. Armesto, *A simple model for nuclear structure functions at small x in the dipole picture*, *Eur. Phys. J.* **C 26** (2002) 35 [hep-ph/0206017].

[40] B.Z. Kopeliovich and A.V. Tarasov, *Gluon shadowing and heavy flavor production off nuclei*, *Nucl. Phys.* **A 710** (2002) 180 [hep-ph/0205151];
Yu.P. Ivanov, B.Z. Kopeliovich, A.V. Tarasov and J. Huefner *Electroproduction of charmonia off nuclei*, *Phys. Rev.* **C 66** (2002) 024903 [hep-ph/0202216].

[41] K. Golec-Biernat and M. Wusthoff, *Saturation effects in deep inelastic scattering at low Q^2 and its implications on diffraction*, *Phys. Rev.* **D 59** (1999) 014017 [hep-ph/9807513];
Saturation in diffractive deep inelastic scattering, *Phys. Rev.* **D 60** (1999) 114023 [hep-ph/9903358].

[42] A.J. Baltz, S.R. Klein and J. Nystrand, *Coherent vector meson photoproduction with nuclear breakup in relativistic heavy ion collisions*, *Phys. Rev. Lett.* **89** (2002) 012301 [nucl-th/0205031].

JHEP08(2003)043