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Signals for black body limit in coherent ultraperipheral heavy ion collisions

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Abstract

We argue that study of total cross section of photoabsorption and coherent photoproduction of ρ, ρ'-mesons in ultraperipheral heavy ion collisions (UPC) is effective method to probe onset of black body limit (BBL) in the soft and hard QCD interactions. We illustrate the expected features of the onset of BBL using generalized vector dominance model. We show that this model describes very well ρ-meson coherent photoproduction at $6 \leqslant E_\gamma \leqslant 10$ GeV. In the case of ρ-meson production we find a UPC cross section which is a factor ~ 1.5 larger than the one found by Klein and Nystrand. The advantages of the process of coherent dijet production to probe onset of BBL in hard scattering regime where decomposition over the twists becomes inapplicable are explained and relative importance of the γ + pomeron and $\gamma + \gamma$ mechanisms is estimated. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

Studies of the coherent interactions of photons with nucleons and nuclei were one of the highlights of the strong interaction studies of the seventies, for the excellent summaries see [1,2].

The fundamental question which one can investigate in the coherent processes is how interactions change for different types of projectiles with increase of the size/thickness of the target. Several regimes appear possible. In the case of a hadronic projectile (proton, pion, etc.) high-energy interactions with the nucleus rather rapidly approach a black body limit (BBL) in which the total cross section of the interaction is equal to $2\pi R_A^2$. Another extreme limit is the interaction of small size projectiles (or wave packages). In this case at sufficiently high energies the system remains frozen during the passage through the nucleus and the regime of color transparency is reached in which the amplitude of interactions is proportional to the gluon density of the nucleus which is somewhat smaller than the sum of the nucleon gluon densities due to the leading twist nuclear shadowing. In this regime the cross section of interaction rapidly grows with energy reflecting the fast increase of the gluon densities at small x and large Q^2 and it may reach ultimately the black limit of interaction from the perturbative domain. (This limit can correspond to quite differ-

ent perturbative QCD dynamics, in particular, it could be reached already at $x \geqslant 10^{-3}$ where $\ln x$ effects are a small correction.) The BBL for the interaction of the small size dipoles with heavy nuclei represents a new regime of interactions when the leading twist approximation and therefore the whole notion of the parton distributions becomes inapplicable for the description of hard QCD processes in the small x regime. Obviously there should exist also many cases when the projectile represents a superposition of configurations of different sizes (leading to fluctuations of the strength of interaction).

In this respect interactions of photons with heavy nuclei provide unique opportunities since the photon wave function contains both the hadron-like configurations (vector meson dominance) and the direct photon configurations (small $q\bar{q}$ components). The important advantage of the photon is that at high energies the BBL is manifested in diffraction into a multitude of the hadronic final states (elastic diffraction $\gamma \rightarrow \gamma$ is negligible) while in the hadron case only elastic diffraction survives in the BBL and details of the dynamics leading to this regime remain hidden. Spectacular manifestations of BBL in (virtual) photon diffraction include strong enhancement of the large mass tail of the diffractive spectrum as compared to the expectations of the triple pomeron limit, large cross section of the high p_t dijet production [3].

In preQCD time V. Gribov explored the complete absorption of hadrons by heavy nucleus to calculate the total cross section of photo(electro)production processes off heavy nuclei through the hadron polarization operator for the photon $\rho(M^2)$:

$$F_T\left(x, Q^2\right) = \int\limits_{m_0^2}^{2q_0/R_A} dM^2 \frac{2\pi R_A^2}{12\pi^3} \frac{Q^2 M^2 \rho(M^2)}{(M^2 + Q^2)^2}, \quad (1)$$

where $q_0 = \omega_\gamma$ is the photon energy, $m_0^2 \approx m_\rho^2$. The upper cutoff in the integral in the black body limit formulae (the Gribov approximation) comes from the nucleus form factor

$$-t_{\min} R_A^2/3 \approx \left(\frac{M^2 + Q^2}{2q_0}\right)^2 R_A^2/3 \ll 1. \quad (2)$$

The distinctive feature of Eq. (1) is that the contribution of large masses in the wave function of projectile photon (a direct photon contribution) is not suppressed. Consequently, Eq. (1) leads to $\sigma_{\gamma A}^{\text{tot}} \propto 2\pi R_A^2 \alpha_{\text{em}} \ln(2q_0/R_A m_\rho^2)$ for $A \gg 1$ (this is qualitatively different from the hadron case where $\sigma_{hA}^{\text{tot}} \approx 2\pi R_A^2$), and grossly violates expectations of the Bjorken scaling for the Q^2 dependence of $\sigma_{\gamma A}^{\text{tot}}$.

To overcome this puzzle J. Bjorken suggested a long time ago the aligned jet model in which only $q\bar{q}$ pairs with small p_t can interact while high p_t configurations in the photon wave function remain sterile [9]. Existence of sterile states has been explained later as due to the color transparency phenomenon [10]. More recently it was understood that states which behave as sterile at moderate energies, may interact at high enough energies with a hadron target with cross sections comparable to that for soft QCD phenomena.

Thus the Gribov's assumptions are justified in QCD for the interaction of a range of hadronic components of the photon wave function with heavy nucleus target. At the same time even at small x some components are still small enough, so that they interact with a small cross section—for these components the color transparency still survives. Hence one needs smaller x to reach the BBL than allowed by the cutoff in the integral in Eq. (1). This x-range was not reached so far experimentally in ep collisions.

It is worth emphasizing that the hypothesis of BBL corresponds to the assumption that at sufficiently small x partons with large virtuality interact with heavy nuclei without any suppression with a cross sections $\approx 2\pi R_A^2$. It is this feature of the BBL which is responsible for the gross violation of the Bjorken scaling and for the above mentioned qualitative difference of the energy dependence of $\sigma_{\text{tot}}^{\gamma A}$ and σ_{tot}^{hA}.

One of striking features of the BBL regime is the suppression of nondiagonal transitions in the photon interaction with heavy nuclei [14].[1] Indeed in the BBL the dominant contribution to the coherent diffraction originates from "a shadow" of the fully absorptive interactions at impact parameters $b \leqslant R_A$ and hence the orthogonality condition is applicable.

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[1] In Ref. [15] it was assumed that one can neglect interference effects for a nucleon target also. In this case in order to preserve the Bjorken scaling one has to make an assumption that the cross section of the interaction of heavy mass configurations with nucleons decreases $\propto 1/M^2$.

Very little is known experimentally so far about coherent photon induced diffractive phenomena due to the problems of separating events where nucleus remained intact in the fixed target experiments and absence of electron–nucleus colliders. New opportunities for the investigation of photon–nucleus interactions become available in ultraperipheral collisions (UPC) of heavy nuclei at RHIC and LHC. These studies will allow to extract the cross section of the coherent γA interactions up to $\sqrt{s} \sim 60(15)$ GeV (LHC/RHIC) due to a possibility to select the events where colliding nuclei remain intact or nearly intact, see, e.g., [4,5], see Refs. [6,7] for the recent reviews and extensive lists of references. Recently we investigated possibilities of studying color transparency and perturbative color opacity related to the leading twist gluon shadowing in J/ψ UPC and commented on the onset of BBL for J/ψ production [8].

In this Letter we will continue studies of the UPC phenomena. Our aim is to evaluate pattern of soft QCD phenomena in the proximity to black body limit, disappearance of color transparency phenomenon in the hard processes with increase of energies. We will study photoproduction of ρ-mesons and the $I = 1$ mesonic states with masses $1.5 \leqslant M^2 \leqslant 4$ GeV^2 usually generically referred to as a ρ'-meson in the processes: $\gamma + A \to V + A, A + A \to A + A + V; V = \rho, \rho'$. To visualize expected new phenomena we will use generalized vector dominance model which takes into account fluctuations of the interaction strength to show that relative yield of ρ and ρ' mesons is sensitive to the onset of BBL physics in soft regime. We will argue that the production of two jets in the process $A + A \to A + A + 2$ jets in collisions of heavy nuclei provides a new effective method of probing the onset of BBL for the hard QCD phenomena.

2. Vector meson production off nuclei in the generalized vector dominance model

In this section we will use generalized vector dominance model to describe coherent photoproduction of hadronic states of $M \leqslant 2$ GeV off nuclei.

The vector dominance model (VDM) [11] was first suggested as an explanation of the nuclear shadowing in the interactions of photons with nuclei [12] in a close connection with the Bell discussion of

the shadowing in neutrino–nucleus scattering [13]. It was also pointed out in [12] that at sufficiently high energies heavier states may become important. Importance of extending VDM to include the heavy mass states—Generalized VDM (GVDM) was further emphasized and explored in the late sixties [14,15]. In particular, one needs large mass states to explain the slope of Q^2 dependence of structure functions at small Q^2 $-1/(1 + Q^2/0.71)$ behavior instead of $1/(Q^2 + m_\rho^2)^2$ predicted by the VDM.

The main ambiguity in such an extension was the issue of nondiagonal transitions where a photon initially converts into one vector state $-V_1$ which through diffractive interactions with a nucleon converts into another state V_2. Such amplitude would interfere with the process of direct production of V_2. Such nondiagonal transitions were introduced in a number of GVD models [16,17]. Physically the importance of such transitions could be justified on the basis of the interpretation of the early Bjorken scaling for moderately small $x \sim 10^{-2}$ as due to the color transparency phenomenon—presence in the virtual photon of hadron type and point-like type configurations [10]. Presence of nondiagonal transitions is also crucial for ensuring a quantitative matching with perturbative QCD regime for $Q^2 \leqslant$ few GeV^2 [18]. Hence it is reasonable to use GVDM for the modeling of the production of the light states off nuclei.

The amplitude of the vector meson production off a nucleon can be written within the GVDM as

$$
\begin{aligned}
&A(\gamma + N \to V_j + N) \\
&= \sum_i \frac{e}{f_{V_i}} A(V_i + N \to V_j + N),
\end{aligned} \tag{3}
$$

where f_{V_i} are connected to the width of decay of the corresponding resonance in the process $e^+e^- \to$ hadrons. In the case of nuclei calculation of the amplitude of the Glauber scattering with production of a meson V requires taking into account both the nondiagonal transitions due to the transition of the photon to a different meson V' in the vertex $\gamma \to V'$ and due to change of the meson in multiple rescatterings like $\gamma \to V \to V' \to V$. This physics is equivalent to inelastic shadowing phenomenon familiar from hadron–nucleus scattering [19]. The Glauber model for the

description of these processes is well known, so, we present here only the basic formulae which we will use to calculate the photoproduction cross section[2]

$$\frac{d\sigma_{\gamma A \to V A}(t)}{dt} = \pi \left| \int_0^\infty J_0(p_t b) \Gamma(b) b\, db \right|^2. \qquad (4)$$

Here $J_0(z)$ is the Bessel function, $p_t = \sqrt{t_{\min} - t}$, $-t_{\min} = \frac{M_V^4}{4q_0^2}$ is longitudinal momentum transfer in $\gamma - V$ transition, and $\Gamma(\vec{b})$ is the nuclear profile function which is obtained in impact parameter space from the solution of the coupled multichannel Glauber equations for production of vector mesons ρ, ρ' which takes into account the finite coherence length effects due to the longitudinal momentum transfers (see, e.g., [20] for the explicit expressions).

In Ref. [20] the simplest nondiagonal model (which is a truncation of a more general model [16,17]) was considered with two states ρ and ρ' which have the same diagonal amplitudes of scattering off a nucleon and the fixed ratio of coupling constants

$$f_{\rho'}/f_\rho = \sqrt{3}, \qquad (5)$$

while the ratio of the nondiagonal and diagonal amplitudes

$$\frac{A(\rho + N \to \rho' + N)}{A(\rho + N \to \rho + N)} = -\epsilon, \qquad (6)$$

and the value $\sigma_{\rho N}^{\rm tot}$ were found from the fit to the forward $\gamma + A \to \rho + A$ cross sections measured at $\omega_\gamma = 6.1$, 6.6 and 8.8 GeV [21]. It was pointed out that this model with reasonable values of $\sigma_{\rho N}$ and ϵ allows to bring the value of f_ρ determined from the photoproduction of ρ-mesons off protons assuming approximate equality of the cross sections of $\rho - N$ and $\pi - N$ interactions into a good agreement with the e^+e^- data thus removing a long standing 20% discrepancy between two determinations. One should emphasize here that in the logic of GVDM ρ'-meson approximates the hadron production in the interval of hadron

masses $\Delta M^2 \sim 2$ GeV^2, so the values of the production cross section refer to the corresponding mass interval.

As a first step we shall refine the model and then compare it with more detailed experimental data. First of all we diminish the dependence on the nuclear structure parameters by calculating the nuclear densities in the Hartree–Fock–Skyrme (HFS) approach. This model not only provided an excellent description (with an accuracy $\approx 2\%$) of the nuclear root mean square radii and the binding energies of spherical nuclei along the periodical table from carbon to uranium [22] but also was successfully used to describe in the Glauber approximation such detailed characteristics of the nuclear structure as the shell model momentum distributions in the high energy $(p, 2p)$ [23] and $(e, e'p)$ [24] reactions. Next, we fixed the values of the total cross section of the ρN interaction and $\eta_{\rho N} = \frac{\mathrm{Re}\, A_{\rho N}}{\mathrm{Im}\, A_{\rho N}}$ using the corresponding parameterizations suggested in the Landshoff–Donnachie model [25]. Accounting for the nondiagonal $\rho - \rho'$ transitions the value of ϵ was looked for to provide a best fit to the differential cross section of the ρ-meson photoproduction off lead at $\omega_\gamma = 6.2$ GeV and $p_t^2 = 0.001$ GeV^2. As a result (Fig. 1(a)) we found $\epsilon = 0.18$ which is indeed very close to the lower end of the range $\epsilon = 0.2$–0.28 suggested in [20]. Note that this value leads to a suppression of the differential cross section of the ρ-photoproduction in $\gamma + p \to \rho + p$ by a factor of $(1 - \epsilon/\sqrt{3})^2 \approx 0.80$ practically coinciding with phenomenological renormalization factor $R = 0.84$ introduced in [25] to achieve the best fit of the elementary ρ-meson photoproduction forward cross section in the VDM which neglects mixing effects.

With all parameters fixed we calculated the differential cross sections of ρ-production off nuclei and found a good agreement (Figs. 1(b)–(f)) with available data [21].

A rather small systematic discrepancy with the data at $p_t^2 \approx 0.01$ GeV^2 appears to be due to the incoherent ρ photoproduction which is strongly suppressed for the very small p_t but gives a contribution comparable to the coherent one for $p_t^2 \approx 0.01$ GeV^2.

We have also checked the description of the A-dependence for the forward ρ photoproduction cross section (Fig. 2). In difference from Ref. [25] we

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[2] In this calculation we neglect the triple pomeron contribution which is present at high energies. This contribution though noticeable for the scattering off the lightest nuclei becomes a very small correction for the scattering of heavy nuclei due the strongly absorptive nature of interaction at the central impact parameters.
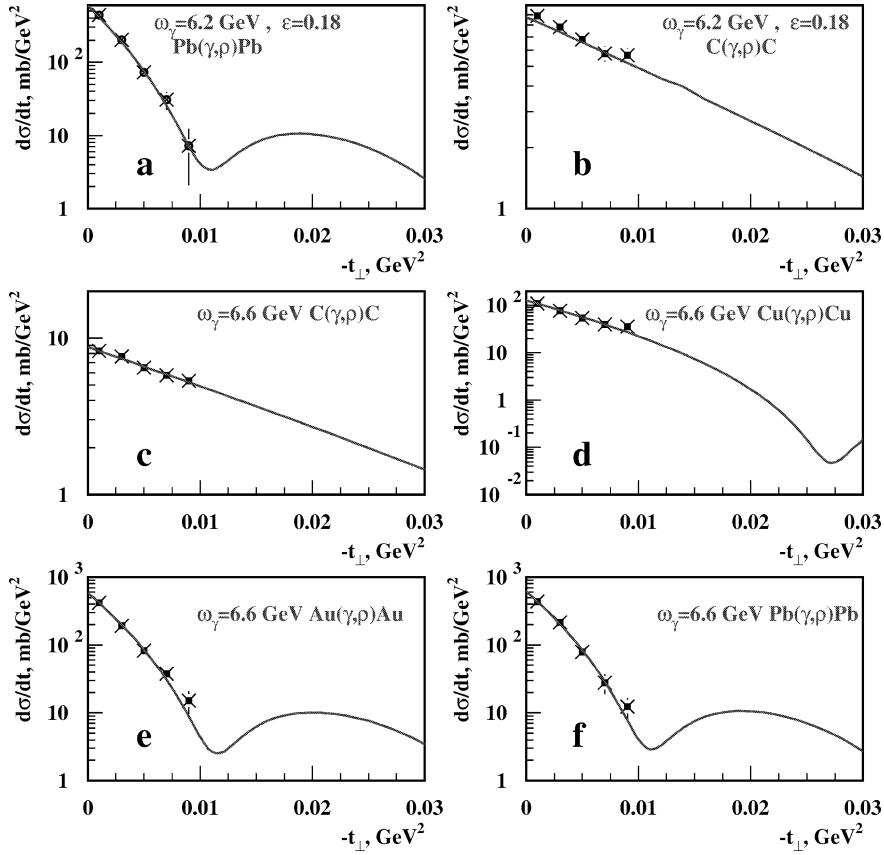
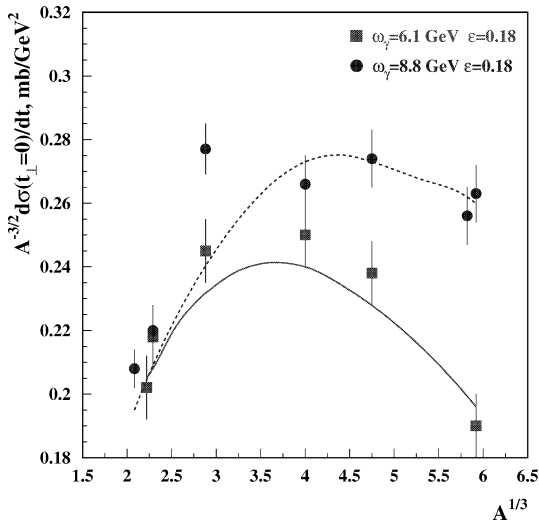Fig. 1. Description of the ρ-production data [21] by the GVDM Glauber model with the value $\epsilon = 0.18$.

Fig. 2. Description of the A-dependence of forward ρ-production data [21] by the GVDM Glauber model with $\epsilon = 0.18$.

did not find any evidence for an increase of ϵ by almost 50% (from 0.2 to 0.28) when the energy of photons is increased from 6.2 GeV up to 8.8 GeV.

As far as we know previously this important check of the Glauber model predictions in the vector meson production off $A > 2$ nuclei has never been performed in such self-consistent way. In view of a good agreement of the model with the data on ρ-meson production in the low energy domain we will use this model to consider the ρ meson photoproduction at higher energies of photons. The increase of the coherence length with the photon energy leads to a qualitative difference in the energy dependence of the coherent vector meson production off light and heavy nuclei (Fig. 3) and to a change of the A-dependence for the ratio of the forward ρ' and ρ-meson production cross sections between $\omega_\gamma \sim 10$ GeV and $\omega_\gamma \sim 50$ GeV (Fig. 4). The observed pattern reflects the difference of the coher-

ence lengths of the ρ-meson and a heavier ρ'-meson which is important for the intermediate photon energies $\leqslant 30$ GeV.

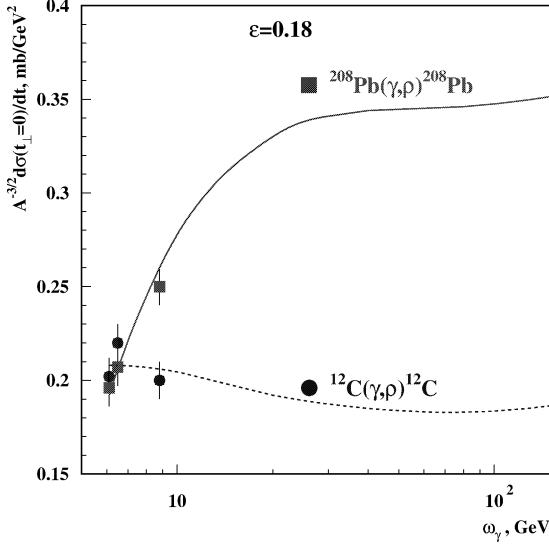Unfortunately no experimental data are available at the moment on the coherent ρ' photoproduction and

Fig. 3. The energy dependence of the ρ-photoproduction cross section calculated in the GVDM + Glauber model.
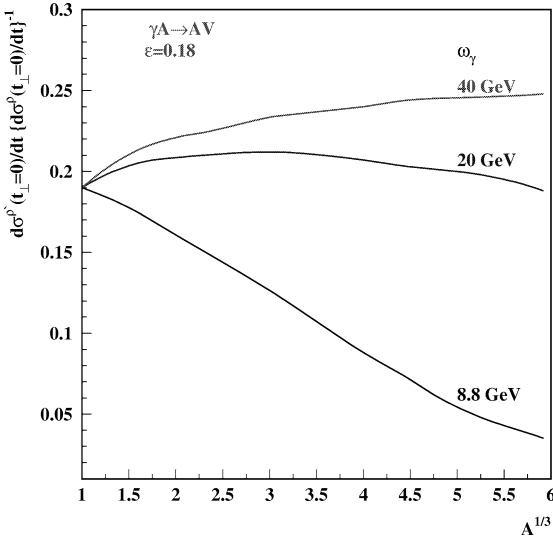

Fig. 4. The A-dependence of the ratio of ρ'/ρ forward photoproduction cross sections calculated in the GVDM + Glauber model.

on the ρ photoproduction at energies $\geqslant 10$ GeV. Such studies maybe possible with the HERMES detector at DESY and in the E-160 experiment at SLAC. On the other hand, a very promising way to collect such data would be a study of the coherent light vector meson production in the ultraperipheral ion collisions (UPC) at RHIC and LHC where one can explore the wide range of the quasi-real photon energies.

3. Vector meson production in ultraperipheral collisions

Production of vector mesons in ultraperipheral heavy ion collisions can be expressed in the Weizsacker–Williams (WW) approximation through the cross section of the vector meson production in γA scattering

$$\frac{d\sigma_{AA \to AAV}}{dy}$$
$$= 2 \int d\vec{b} \, T_{AA}(\vec{b}) n(y, \vec{b}) \sigma_{\gamma A \to VA}(y). \qquad (7)$$

Here y is rapidity of the produced vector meson, $T_{AA}(\vec{b})$ is the thickness function of colliding nuclei on the impact parameter $\vec{b}$, $n(\vec{b}, y)$ is the flux of photon with energy

$$\omega = \frac{m_V}{2} e^y$$

emitted by one of nuclei and $\sigma_{\gamma A \to VA}(y)$ we calculated integrating the Eq. (4) over the momentum transfer in the range $t_{\min} \leqslant t \leqslant \infty$.

As we discussed in Section 2, the GVDM with the value of f_ρ fixed to the value determined from the e^+e^- annihilation gives a better description of the cross section of the coherent ρ production from nucleons. We also demonstrated that it gives a very good description of the absolute cross section and t-dependence of the cross section of the ρ-meson photoproduction off nuclei. Hence it is natural to expect that it would provide a reliable predictions for production of vector mesons in UPC. In particular, we calculated within this model coherent cross sections of both the ρ and ρ' mesons. The inelastic diffractive contribution is expected to be rejected using the veto from Zero Degree Neutron Calorimeter which is implemented in the RHIC experiments and is planned

for the LHC. This veto is the least effective for the single inelastic diffraction as this process will often result in the events where one nuclear proton is removed and the residual nucleus remains in the ground or a low excitation state. Our calculation of the single inelastic diffraction shown in Fig. 5 by dotted lines demonstrates that this background is very small for a wide range of central rapidities.

The results of our calculations for the total cross sections are given in Table 1. It should be emphasized that we have got the cross sections of the coherent ρ production considerably larger than estimates in Ref. [26] where the first quantitative study of the coherent ρ-meson production in kinematics of the peripheral ion collisions at RHIC and LHC was presented. In [26] as well as in [27] the cross section was calculated as:

$$d\sigma_{\gamma+A\rightarrow V+A} = \frac{\alpha_{em}}{4f_\rho^2}\sigma_{tot}^2(\rho A)\int_{t_{min}}^{\infty} dt\, F_A^2(t), \qquad (8)$$

where $F_A(t)$ is the nuclear form factor. Further it was assumed in [26] that $\sigma_{tot}(\rho A)$ is given by the classical mechanics formula:

$$\sigma_{tot}(\rho A) = \int d^2\vec{b}\left[1 - \exp\left(-\sigma_{tot}(\rho N)T(\vec{b})\right)\right], \qquad (9)$$

where $T(\vec{b})$ is the usual thickness function. It is easy to estimate that this formula leads to a substantially smaller value of the total cross section than the quantum mechanical Glauber expression

$$\sigma_{tot}(\rho A) = 2\int d^2\vec{b}\left[1 - \exp\left(-\frac{\sigma_{tot}^{\rho N}}{2}T(\vec{b})\right)\right]$$

a factor of two smaller for heavy enough nuclei: $\sigma_{tot}(\rho A) = \pi R_A^2$ instead of $2\pi R_A^2$. To show explicitly the difference in results we compare in Fig. 6 the rapidity distributions obtained in the VDM + Glauber model with correct accounting for the longitudinal

momentum transfer but without nondiagonal terms (solid line) and result of calculations (dashed line) with the same parameters [25] and the HFS nuclear form factor but in the model based on Eqs. (8), (9) used in [26].
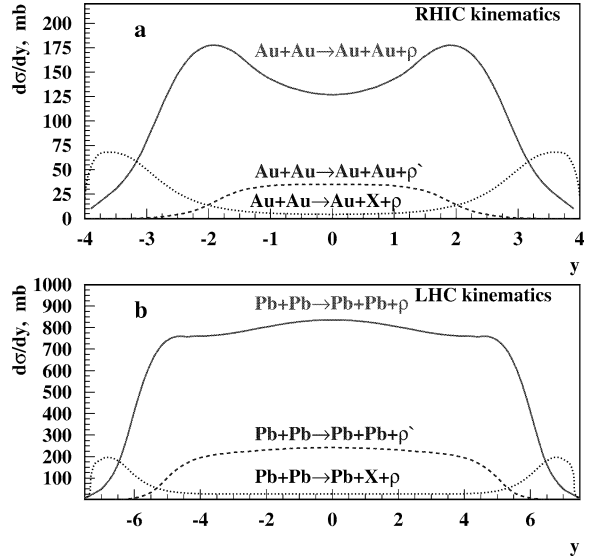

Fig. 5. Rapidity distributions for the light vector meson production at RHIC and LHC.
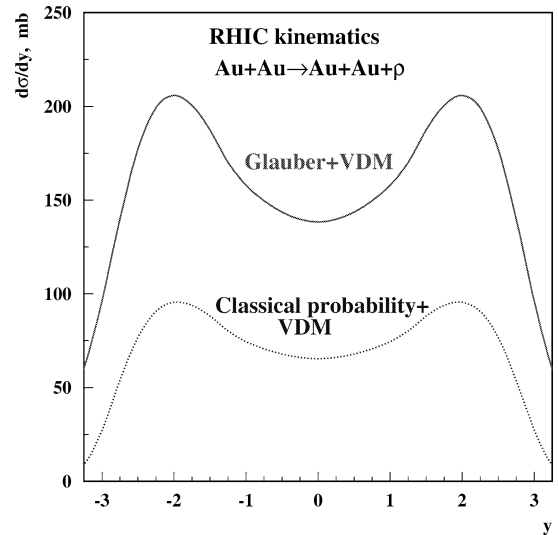

Fig. 6. Comparison of the rapidity distributions calculated in VDM + classical mechanics formula for total cross section (dotted line) with calculations within VDM + Glauber model (solid line).

Table 1
Total cross sections of ρ and ρ' production in UPC at RHIC and LHC

	AuAu at RHIC	PbPb at LHC
Coherent ρ	934 mb	9538 mb
Coherent ρ'	133 mb	2216 mb
Incoherent ρ	201 mb	846 mb

In the follow up paper [27] authors considered p_t distribution of the produced vector mesons and made an interesting observation that the amplitudes of the production of a vector mesons produced when a left moving nucleus emits the photon and when right moving nucleus emits a photon should destructively interfere. Due to the condition that essential impact parameters in AA collisions are larger than $2R_A$ a significant interference occurs only for $p_t \leqslant 1/2R_A$ corresponding to $p_t \leqslant 10$ MeV [27]. This p_t range constitutes a small fraction of whole permitted phase volume and hence the interference effects can be neglected for the case of the cross sections integrated over p_t which were required to calculate the rapidity distributions presented here (Fig. 3).

In the case of ρ production corrections due to nondiagonal transitions are relatively small ($\sim 15\%$) for the case of scattering off a nuclei. As a result we find that the GVD cross section is close to the one calculated in the VD model for heavy nuclei as well.

Situation is much more interesting for ρ' production. In this case cross section of production of ρ' off a nucleon is strongly suppressed as compared to the case when the $\rho \leftrightarrow \rho'$ transitions are switched off. The extra suppression factor is ≈ 0.5.

In accordance with the general argument of Gribov the nondiagonal transitions disappear in the limit of large A (black body limit) due to the condition of orthogonality of hadronic wave functions [14]. Hence we expect that in the limit of $A \to \infty$:

$$\left.\frac{d\sigma(\gamma + A \to V_1 + A)/dt}{d\sigma(\gamma + A \to V_2 + A)/dt}\right|_{A \to \infty} = (f_2/f_1)^2. \qquad (10)$$

In reality the ρ-meson is a broad resonance which also interferes with the nonresonance $\pi^+\pi^-$ continuum, and ρ' represents a set of overlapping resonances and continuum. Also the detectors are likely to be able to detect only some of the final states. Hence it is convenient to use a more general relation for the productions of states h_1, h_2 of invariant masses M_1^2, M_2^2:

$$\left.\frac{d\sigma(\gamma + A \to h_1 + A)/dt}{d\sigma(\gamma + A \to h_2 + A)/dt}\right|_{A \to \infty} = \frac{\sigma(e^+e^- \to h_1)}{\sigma(e^+e^- \to h_2)}. \qquad (11)$$

Indeed we have found from calculations that in the case of the coherent photoproduction off lead the nondiagonal transitions becomes strongly suppressed

with increase of the photon energy. As a result the ρ'/ρ ratio increases, exceeds the ratio of the $\gamma p \to V p$ forward cross sections calculated with accounting for $\rho - \rho'$ transitions already at $\omega_\gamma \geqslant 50$ GeV and becomes close to the value of $f_\rho^2/f_{\rho'}^2$ which can be considered as the limit when one can treat the interaction with the heavy nucleus as a black one. The same trend to BBL is seen from A-dependence presented for kinematics at LHC corresponding the value of energy $W_{\gamma p} = 60$ GeV (Fig. 7).

It is worth noting here that presence of nondiagonal transitions which in terms of the formalism of the scattering eigenstates [28] corresponds to the fluctuations of the interaction cross section leads to a substantial modification of the pattern of the approach to BBL. For example, if one would neglect nondiagonal transitions one would have to reduce both $\rho - N$ and $\rho' - N$ cross sections in order to keep the values of the production cross sections in $\gamma + p \to \rho + p$ the same as in the considered GVDM. For the ρ-meson the reduction effect is a small correction $(1 - \epsilon/\sqrt{3}) \approx 0.9$, while the cross section of $\rho' - N$ interaction is reduced by a substantially larger factor $(1 - \sqrt{3}\epsilon) \approx 0.7$. This would lead to a noticeable reduction of the total cross section of the $\rho' - A$ interaction as compared to the BBL value of $2\pi R_A^2$ and reduces the ρ'/ρ ratio for $A \sim 200$
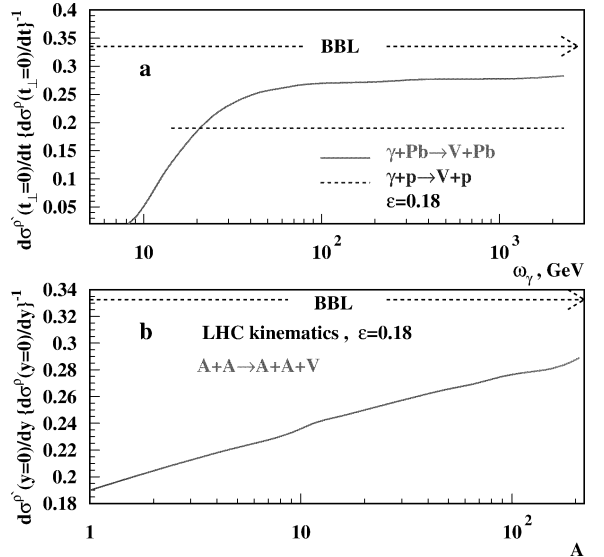

Fig. 7. (a) Energy dependence of the ratio of ρ' and ρ-meson production cross sections, (b) A-dependence of the ratio of ρ' and ρ-meson production forward cross sections in kinematics at LHC.

by $\approx 10\%$ as compared to reduction by a factor 0.9 in the original model. At the same time in a number of GVD models it is assumed that $\sigma_{\text{tot}}(VN) \propto 1/M^2$. In such a model the ρ'/ρ ratio for Pb would be reduced by a factor ~ 3.

The general BBL expression for the differential cross section of the production of the invariant mass M^2 [3] is

$$\frac{d\sigma_{(\gamma+A\to''M''+A)}}{dt\,dM^2}$$
$$= \frac{\alpha_{\text{em}}}{3\pi} \frac{(2\pi R_A^2)^2}{16\pi} \frac{\rho(M^2)}{M^2} \frac{4\left|J_1(\sqrt{-t}\,R_A)\right|^2}{-t R_A^2}. \qquad (12)$$

Hence by comparing the extracted cross section of the diffractive production of states with certain masses with the black body limit result—Eq. (12) one would be able to determine up to what masses in the photon wave function interaction remains black. Onset of BBL limit for hard processes should reveal itself also in the faster increase with energy of cross sections of photoproduction of excited states with that for ground state meson. It would be especially advantageous for these studies to use a set of nuclei—one medium range like Ca and another heavy one–one could remove the edge effects and use the length of about 10 fm of nuclear matter.

Note in passing that an interesting change of the low-mass dipion spectrum is expected in the discussed limit. It should be strongly suppressed as compared to the case of scattering off proton where nonresonance continuum is much larger than in $e^+e^- \to \pi^+\pi^-$ process.

4. Diffractive dijet production

For the γA energies which will be available at LHC one may expect that the BBL in the scattering off heavy nuclei would be a good approximation for the masses M in the photon wave function up to few GeV. This is the domain which is described by perturbative QCD for $x \sim 10^{-3}$ for the proton targets and larger x for scattering off nuclei. The condition of large longitudinal distances—small longitudinal transfer will be applicable in this case up to quite large values of the produced diffractive mass (though it will not hold for masses above 3 GeV or so at RHIC).

Really $x_{\text{eff}} = M^2/s_{\gamma N} = M/2E_N$ will be $\sim 10^{-3}$ for $M = 4$ GeV for $y = 0$. So that the condition $l_{\text{coh}} = 1/m_N x_{\text{eff}} \gg 2R_A$ is satisfied.

In the BBL the dominant channel of diffraction for large masses is production of two jets with the total cross section given by Eq. (12) and with a characteristic angular distribution $(1 + \cos^2\theta)$, where θ is the c.m. angle [3]. On the contrary in the perturbative QCD limit the diffractive dijet production except charmed jet production is strongly suppressed [29,30]. The suppression is due to the structure of the coupling of the wave function of the real photon wave to two gluons when calculated in the lowest order in α_s. As a result in the real photon case hard diffraction involving light quarks is connected to production of $q\bar{q}g$ and higher states. Thus the dijet photoproduction should be very sensitive to the onset of BBL regime.

Note that in the case of photon nucleon scattering at $\omega_\gamma \sim 100$ GeV [31] the normalized differential

$$\frac{1}{\sigma_{\text{tot}}^{\gamma N}}\,d\sigma/dM^2$$

for diffraction into large masses ($\geqslant 2$ GeV) is very similar to that for the pion–nucleon scattering and appears to be dominated by the triple Reggeon limit corresponding to the process where a photon first converts to a ρ-meson and next a large mass is produced in the $\rho - N$ diffractive scattering. Since the triple pomeron coupling constant is quite small this process should be a small correction in the BBL. Besides in this limit the triple pomeron process is screened by the multiple pomeron exchanges and originates solely from the scattering off the rim of the nucleus. Hence it is suppressed at least by a factor $\sim A^{1/3}$ as compared to the process of direct diffraction into heavy masses.

A competing process for photoproduction of dijets off heavy nuclei is production of dijets in $\gamma - \gamma$ collisions where the second photon is provided by the Coulomb field of the nucleus. Note that the dijets produced in this process have positive C-parity and hence this amplitude does not interfere with the amplitude of the dijet production in the $\gamma\mathbb{P}$ interaction which have negative C-parity.

For the calculation of the cross section of dijet production in $\gamma + \gamma$ collisions we use the lowest order perturbative QCD result which coincides up to the number of colors factor and summation over the quark

flavors with the well known QED result for the lepton pair production in $\gamma\gamma$ collisions:

$$\frac{d\sigma(\gamma + \gamma \to \text{jet} + \text{jet})}{d\Omega}$$
$$= 3 \sum_i e_{q_i}^4 \alpha_{\text{em}}^2 \frac{1}{M^2} \left[\frac{2}{\sin^2\theta} - 1 \right]. \tag{13}$$

Here the sum over the quark flavors goes over quarks with $m_q \ll M/2$ and p_t^{jet} is sufficiently large to suppress nonperturbative contribution. Using the Weizsacker–Williams approximation we evaluate the ratio of the $\gamma\gamma$ and $\gamma\mathbb{P}$ contributions to the dijet production in AA collisions in the BBL with the logarithmic accuracy:

$$R = \frac{d\sigma_{\gamma\gamma}(A + A \to \text{dijet} + A + A)}{d\sigma_{\gamma\mathbb{P}}(A + A \to \text{dijet} + A + A)}$$
$$= \frac{\sum_i e_{q_i}^4}{\sum_i e_{q_i}^2} \frac{16 Z^2 \alpha_{\text{em}}^2}{M^2 R_A^2 \sin^2\theta} \ln \frac{2q_0}{M^2 R_A}. \tag{14}$$

In the derivation of Eq. (14) we neglected a difference of the energy dependences of the processes. For the kinematics of interest (large p_t of jets and region of produced masses $M \leqslant 3$ GeV) $\theta = 90°$ in the center of mass of the produced system and we can account for three lightest flavors, hence

$$\frac{\sum_i e_{q_i}^4}{\sum_i e_{q_i}^2} = \frac{1}{3}.$$

One can easily see that $R \ll 1$ for production of high p_t jets corresponding to $\sin\theta \sim 1$, and hence the $\gamma\gamma$ contribution can be safely neglected.

It is worth emphasizing that at the energies below the BBL where diffraction of the photon to dijets can be legitimately calculated in the lowest order in α_s (cf. calculation of a similar process of dijet production in the pion–hadron scattering in Ref. [32]) the electromagnetic mechanism is much more important. It is enhanced by a factor $1/\alpha_s^2$ and becomes much more prominent with increase of p_t of the jet. Also it enhanced for very small total momentum of the dijet system. Observation of the last effect is hardly feasible, cf. the above discussion of the vector meson production.

5. Conclusions

We demonstrated that ultraperipheral AA collisions is effective method of probing onset of BBL regime in hard processes at small x. We have demonstrated that the Glauber model predicts a significantly larger coherent ρ-meson production rates than the previous calculations. We predict a significant increase of the ratio of the yields of ρ, ρ' mesons in coherent processes off heavy nuclei due to the blackening of the soft QCD interactions in which fluctuations of the interaction strength are present. An account of nondiagonal transitions leads to a prediction of a significant enhancement of production of heavier diffractive states especially production of high p_t dijets. Study of these channels may allow to get an important information on the onset of the black body limit in the diffraction of real photons.

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References

[1] T.H. Bauer, R.D. Spital, D.R. Yennie, F.M. Pipkin, Rev. Mod. Phys. 50 (1978) 261;
T.H. Bauer, R.D. Spital, D.R. Yennie, F.M. Pipkin, Rev. Mod. Phys. 51 (1978) 407, Erratum.
[2] A. Donnachie, G. Shaw, in: A. Donnachie, G. Shaw (Eds.), Electromagnetic Interactions of Hadrons, Vol. 2, Plenum, New York, 1978, pp. 64–194.
[3] L. Frankfurt, V. Guzey, M. McDermott, M. Strikman, Phys. Rev. Lett. 87 (2001) 192301.
[4] S. Klein, E. Scannapieco, Phys. Rev. D 57 (1998) 512;
S. Klein, E. Scannapieco, nucl-th/9707008;
S. Klein, E. Scannapieco, hep-ph/9702216.
[5] E. Lippmaa et al., Felix: a full acceptance detector at the LHC: letter of intent, CERN-LHCC-97-45, LHCC-I10, August 1997, Journal of Physics to be published.
[6] G. Baur, K. Hencken, D. Trautmann, Prog. Part. Nucl. Phys. 42 (1999) 357, nucl-th/9810078.
[7] G. Baur et al., hep-ex/0201034.
[8] L. Frankfurt, M. Strikman, M. Zhalov, hep-ph/0111221.
[9] J.D. Bjorken, in: Proceedings of the International Symposium on Electron Photon Interactions at High Energies, Cornell, Ithaca, NY, 1971, pp. 281–297.
[10] L.L. Frankfurt, M. Strikman, Phys. Rep. 160 (1988) 235.

[11] J.J. Sakurai, Phys. Rev. Lett. 17 (1966) 1021.

[12] L. Stodolsky, Phys. Rev. Lett. 18 (1967) 135.

[13] J.S. Bell, Phys. Rev. Lett. 13 (1964) 57.

[14] V.N. Gribov, Zh. Eksp. Teor. Fiz. 57 (1969) 1306.

[15] S.J. Brodsky, J. Pumplin, Phys. Rev. 182 (1969) 1794.

[16] H. Fraas, B. Read, D. Schildknecht, Nucl. Phys. B 86 (1975) 346.

[17] P. Ditsas, G. Shaw, Nucl. Phys. B 113 (1976) 246;
G. Shaw, Phys. Lett. B 228 (1989) 125;
G. Shaw, Phys. Rev. D 47 (1993) 3676.

[18] L. Frankfurt, V. Guzey, M. Strikman, Phys. Rev. D 58 (1998) 094039, hep-ph/9712339.

[19] V.N. Gribov, Sov. J. Nucl. Phys. 9 (1969) 369;
V.N. Gribov, Sov. Phys. JETP 29 (1969) 483;
V.N. Gribov, Sov. Phys. JETP 30 (1970) 709.

[20] A. Pautz, G. Shaw, Phys. Rev. C 57 (1998) 2648.

[21] H. Alvensleben et al., Nucl. Phys. B 18 (1970) 333;
G. McClellan et al., Phys. Rev. D 4 (1971) 2683.

[22] M. Beiner, H. Flocard, N. Van Giai, P. Quentin, Nucl. Phys. A 238 (1975) 29.

[23] S.L. Belostotsky et al., in: Proceedings of the conference Modern developments in nuclear physics, Novosibirsk 1987, World Scientific, Singapore, 1988, p. 191.

[24] L. Lapikas, G. van der Steenhoven, L. Frankfurt, M. Strikman, M. Zhalov, Phys. Rev. C 61 (2000) 064325, nucl-ex/9905009;
L. Frankfurt, M. Strikman, M. Zhalov, Phys. Lett. B 503 (2001) 73, hep-ph/0011088.

[25] A. Donnachie, P.V. Landshoff, Phys. Lett. B 478 (2000) 146, hep-ph/9912312.

[26] S. Klein, J. Nystrand, Phys. Rev. C 60 (1999) 014903, hep-ph/9902259.

[27] S.R. Klein, J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330.

[28] M. Good, W. Walker, Phys. Rev. D 120 (1960) 1857.

[29] S.J. Brodsky, J. Gillespie, Phys. Rev. 173 (1968) 1011.

[30] M. Diehl, Z. Phys. C 66 (1995) 181, hep-ph/9407399.

[31] T.J. Chapin et al., Phys. Rev. D 31 (1985) 17.

[32] L. Frankfurt, G.A. Miller, M. Strikman, hep-ph/0010297.