Elastic and large $t$ rapidity gap vector meson production in ultraperipheral proton–ion collisions

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Abstract

We evaluate the cross sections for the production of vector mesons in exclusive ultraperipheral proton–ion collisions at LHC. We find that the rates are high enough to study the energy and momentum transfer dependence of vector meson ($\rho, \phi, J/\psi, \Upsilon$) photoproduction in $\gamma p$ scattering in a wide energy range. This would extend the measurements which were performed at HERA providing new information about interplay of soft and hard physics in diffraction. Also, we calculate the contributions to the vector meson yield due to production of vector mesons off nuclear target by photons emitted by proton. We find, that at least in the case of $\Upsilon$ production it is feasible to observe simultaneously both these processes. Such measurements would increase the precision with which the $A$-dependence of exclusive onium production can be determined. This would also enable one to estimate the amount of nuclear shadowing of generalized gluon distributions at much smaller $x$ than that is possible in $AA$ collisions and to measure the cross sections for photoproduction processes in a significantly wider energy range than that achieved in experiments with fixed nuclear targets. We also present the cross section for vector meson production in $pA$ collisions at RHIC. In addition, we consider production of vector mesons off protons with large rapidity gaps and large $t$. These processes probe small $x$ dynamics of the elastic interaction of small dipoles at high energies and large but finite $t$, that is in the kinematics where DGLAP evolution is strongly suppressed. We estimate that this process could be studied at LHC up to $W \sim 1$ TeV with detectors which will be available at LHC.

1. Introduction

Photoproduction of vector mesons provides important information about strong interaction dynamics. In the case of light mesons it probes soft pomeron dynamics, while production of heavy states probes the gluon distributions in nucleons and in nuclei as well as color transparency and color opacity phenomena. In particular, it provides a sensitive tool to look for the transverse distribution of color in nucleons, gluon shadowing effects, and the onset of the black disk limit.

It is now widely recognized that the only possibility to study such processes during the next decade after the shutdown of the operation of HERA will be ultraperipheral collisions (UPC) at LHC and RHIC (for the recent reviews see [1,2]). So far the main focus of theoretical studies has been on the production of vector meson in collisions of heavy ions.

It is expected that LHC will also run in the $pA$ mode [4]. One may expect high luminosity runs of RHIC in the $dA$ or $pA$ mode as well.\footnote{Note that the first data on production of $\rho$-mesons in ultraperipheral deuteron–gold collisions were reported in [3].} So, it is appropriate to analyze the physics potential of such runs for studies of QCD dynamics via vector meson production.

Intensive studies of onium photoproduction performed at HERA left a number of open questions. The data on $\Upsilon$ photoproduction are very limited. Statistics are not sufficient to study the energy dependence of the process which is predicted to be very strong ($\sigma(\gamma + p \rightarrow \Upsilon + p) \propto W^{1.7}$ [5,6], where $W$
is the invariant energy of collision) or the $t$-dependence of the cross section. The latter is especially interesting since it would provide a very clean measurement of gluon generalized parton distributions and, hence, of the transverse distribution of gluons in the nucleons. This is because the $\gamma$ transverse size is very small and will give a negligible contribution to the $t$ dependence (for the $J/\psi$ photoproduction the size contribution to the slope was estimated to be about 10% [7]). Moreover, it will probe the transverse spread of gluons at virtualities relevant for the studies of the exclusive Higgs production in the double pomeron kinematics, and for inclusive production of the SUSY particles, etc. Hence, it would significantly reduce uncertainties in the modeling of the impact parameter dependence of hard collisions at the LHC [8]. In the case of $J/\psi$ production, the HERA energies were close, but not high enough to reach the energy range where taming of a small ($d \sim 0.3$ fm) dipole–nucleus cross section is significant. The $W$-range was not sufficient to get an accurate measurement of the energy dependence of the $t$-slope, of universality of the trajectory describing pomeron-$d\rho_{pA}(t)$. Clearly, the taming and screening effects should be much more strongly manifested in the case of scattering off nuclei which could be studied via UPC in heavy ion collisions. Unfortunately, there are two problems. One is that in the heavy ion collisions, a photon can be emitted by either of the colliding nuclei. As a result, it is very difficult to get information about coherent onium production at $x < m_{onium}/2E_N$ where $E_N$ is the energy per nucleon for the colliding ions. The only effective way to overcome this problem appears to be to use incoherent onium production which is also sensitive to the presence of taming and screening effects [14]. Another potential problem is systematic errors due to comparison of the data taken at different machines ($\gamma p$ data at HERA and $\gamma A$ data at LHC).

We will demonstrate here that the study of UPC of protons with nuclei allows one to circumvent these problems by measuring production of vector mesons in the energy and $t$ range which is much larger than at HERA. In the case of light vector mesons such study would provide an opportunity to compare effective pomeron trajectories for vector meson production and proton-proton elastic scattering at similar energies hence complementing the planned studied of $pp$ elastic scattering by TOTEM and, probably, by ATLAS.

2. Summary of the formalism

Currently, the theory of photoproduced processes in $AA$ and $pA$ collisions is well developed (for the recent review see [10]). The production of vector mesons (VM) is described in the standard Weizsacker–Williams (WW) approximation with inclusion of quasirole photon emission by both the colliding partners. The expression for the cross section in the WW approximation takes the form

$$
\frac{d\sigma(pA \rightarrow VpA)}{dy \, dt} = N^Z_{\gamma}(y)^A \frac{\sigma_{p+Vp}^A(y)}{dt} + N^A_{\gamma}(y) \frac{\sigma_{VpA \rightarrow VpA}^A(-y)}{dt}.
$$

(1)

Here, $t$ is the momentum transferred squared and $y$ is the rapidity of produced vector meson,

$$
y = \frac{1}{2} \ln \frac{E_V - p_V^+}{E_V + p_V^-}.
$$

(2)

The flux of the equivalent photons $N^Z_{\gamma}(y)$ corrected for suppression of the strong $pA$ interactions at small impact parameters is given by the expression [10]:

$$
N^Z_{\gamma}(y) = \frac{Z^2 \alpha}{\pi^2} \int d^2b \Gamma_{pA}(\vec{b}) \frac{1}{b^2} X^2 \left[ K^2_0(X) + \frac{1}{y} K^2_1(X) \right].
$$

(3)

Here, $K_0(X)$ and $K_1(X)$ are modified Bessel functions with arguments $X = \frac{bm_{VM}}{2p}$, $\gamma$ is the Lorentz factor for the nucleus and $\vec{b}$ is the impact parameter. This expression neglects the nuclear electric form factor which is a good approximation for the essential range of impact parameters ($b$ much larger than $R_A$). It also neglects small effects of interference between emission from two colliding particles, see, e.g., discussion in [11]. The condition that the nucleus does not break up imposes a condition that scattering happens at large impact parameters, $b \geq R_A + r_N$. This can be quantified by the introduction of the thickness function for the strong proton-nucleus interaction:

$$
T_A(\vec{b}) = \int dz \rho_A(z, \vec{b}).
$$

(4)

Here, $\rho(z, b)$ is the density of nuclear matter which is well known from detailed studies of the elastic and quasielastic scattering of protons on nuclei at $E_p \geq 1$ GeV, see review in [12]. The probability that an interaction does not occur at a given impact parameter is given by

$$
\Gamma_{pA}(b) = \exp(-\sigma_{NN} T_A(b)).
$$

(5)

In our numerical studies we used the Hartree–Fock–Skyrme model for $\rho_A(r)$ which gives a good description of the elastic and quasielastic data mentioned above. At LHC energies the elementary nucleon–nucleon cross section is of the order of 100 mb. Therefore, interactions at small impact parameters $b < R_A + r_N$ do not contribute to the discussed processes. The contribution from the transition region $b \sim R_A + r_N$ where absorption is not complete but still significant gives a very small contribution. So, one can safely neglect the inelastic screening corrections which are, in any case, small for the LHC energies. The simple but reasonably justified expression for the photon flux produced by the Coulomb field of the accelerated proton

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2 A brief account of the part of this study dealing with coherent photoproduction off protons was presented a year ago at the $pA$ workshop at CERN [9].

3 It is worth emphasizing that these measurements are equally sensitive to the surface proton and neutron distributions.
has been obtained in [13]:

\[ N^p_{J/\psi}(y) = \frac{\alpha_{em}}{2\pi} \left[ 1 + \left( \frac{1 - \frac{M_V e^y}{\sqrt{s}}}{\frac{3}{A}} \right)^2 \right] \times \left[ \ln A - 1.83 + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3} \right], \]

where

\[ A = \left[ 1 + 0.71 \text{GeV}^2 \left( \frac{2\gamma_p e^{-y}}{M_V} \right)^2 \right], \]

and \( s = 4\gamma_L^p \gamma_L^A m_N^2 \) is the photon–nucleon center-of-mass energy (\( \gamma_L^p \) and \( \gamma_L^A \) are Lorentz factors of the colliding proton and nucleus).

3. Production of heavy quarkonia

For \( J/\psi \) photoproduction we used the fit to the existing data described in our previous paper [14]:

\[
\frac{d\sigma_{\gamma N \to J/\psi N}(s, t)}{dt} = 0.28 \left[ 1 - \left( \frac{m_{J/\psi} + m_N}{s} \right)^2 \right]^{1.5} \left( \frac{s}{10000} \right)^{0.415} \times \left[ \frac{\Theta(s_0 - s)}{1 - \frac{t}{t_0}} \right]^{-4} \Theta(s - s_0) \exp(B_{J/\psi} t),
\]

where \( B_{J/\psi} = 3.1 + 0.25 \log_{10}(s/s_0) \),

with \( s_0 = 100 \text{ GeV}^2 \).

In the case of \( \Upsilon \) production, we approximate the cross section by expression which is consistent with the limited HERA data:

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

Here, the reference scale is \( s_0 = 6400 \text{ GeV}^2 \), the slope parameter \( B_{\Upsilon} = 3.5 \text{ GeV}^{-2} \), and the energy dependence follows from the calculations [5] of the cross section for the photoproduction of \( \Upsilon \) in the leading log \( Q^2 \) approximation, taking into account the skewedness of the partonic density distributions. The cross section is normalized so that the total cross section is in microbarns.

The cross section for coherent onium photoproduction off a nuclear target is calculated with account of the leading twist nuclear shadowing (see review and references in [1]). The QCD factorization theorem for exclusive meson photoproduction [15–17] 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 the convolution of the wave function of the meson at zero transverse separation between the quark and antiquark with the hard interaction block and the generalized parton distribution (GPD) of the target, \( G_T(x_1, x_2, Q^2, t_{\text{min}}) \) \( (t_{\text{min}} \approx -x^2 m_N^2) \). To a good approximation, \( G_T(x_1, x_2, Q^2, t = 0) \) is the gluon density at \( x = (x_1 + x_2)/2 \) [17,18]. Hence, we can approximate the amplitude for the \( \Upsilon \) photoproduction off a nucleus at \( k_t^2 = 0 \) as

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

where \( F_A \) is the 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 [7].

Taking the approach similar to our previous papers on the production of onium states in nucleus–nucleus UPC [19,20], we use the theory of the leading twist nuclear shadowing (see [21] for a recent summary) to calculate the gluon shadowing effect. As input, we use the H1 parameterization [22] of diffractive gluon distribution function adjusted for preliminary results of H1 analysis reported during 2001–2002. To calculate the \( J/\psi \) photoproduction we have chosen representative values of the parameter \( \sigma_{\text{eff}} \) (see definition in [21]) allowed by the data (see Fig. 5 in [1]). Note that current uncertainties in the determination of \( \sigma_{\text{eff}} \) will be reduced soon after the new analysis of the hard diffraction data by H1 will be released [23].

In our calculations, we neglect quasielastic scattering off the nucleus since the probability of this process is relatively small and since it is easily separated from the coherent processes discussed here using information from the zero angle neutron detector (see discussion in [14]).

The results of the calculation are presented in Figs. 1, 2 for \( J/\psi \) production in the kinematics of LHC. The direction of the incoming nucleus corresponds to positive rapidities. One can take

Fig. 1. Rapidity distribution for \( J/\psi \) meson photoproduction in \( p\text{Pb} \) and \( p\text{Ca} \) UPC at LHC. Solid line—cross section accounting for the contributions from photoproduction of both the proton and nuclear target. The long dashed curve is the contribution of the proton target and the dashed curve is the contribution of the nuclear target. In (b) and (d) effect of the nuclear shadowing was included.
see from Fig. 1 that the cross section for $J/\psi$ production off a proton target in ultraperipheral $pA$ collisions is sufficiently large to be measured in a very large energy interval $20 < W_{\gamma p} < 2 \times 10^3$ GeV. The lower limit in $W_{\gamma p}$ reflects our guess of the maximal rapidity for which $J/\psi$'s could be detected. The maximal $W_{\gamma p}$ corresponds to $x_{\text{eff}} \sim m_{J/\psi}^2 / W_{\gamma p}^2 \sim 2 \times 10^{-6}$. This is small enough to reach the domain where interaction of small dipoles contributing to the $J/\psi$ photoproduction amplitude already requires significant taming (see, e.g., [25]).

For large $W_{\gamma p}$ (positive $y$), the contribution of the coherent reaction $\gamma + A \rightarrow J/\psi + A$ to $d\sigma/dy$ is definitely negligible. Negative $y$ correspond to small $W_{\gamma p}$ and large $W_{\gamma A}$. In this case, the nuclear contribution becomes larger. Nevertheless, it remains a correction even if there is no nuclear shadowing. The nuclear contribution can be enhanced or eliminated by introducing a cut on the transverse momentum of $J/\psi$ ($p_t \lesssim 300$ MeV/c or $p_t \gtrsim 300$ MeV/c). An observation of the nuclear contribution in this range of kinematic would certainly be of great interest as it would probe the interaction of small dipoles with nuclei at $x_A \sim 10^{-5} - 10^{-6}$. In the case of large gluon shadowing, observing the nuclear contribution for such $x_A$ would require a very high resolution in $p_t$—probably less than $p_t \lesssim 150$ MeV/c. Another possible strategy would be to eliminate/estimate the contribution due to the $\gamma p$ process by studying the recoil protons which should be produced with $x_p = m_{J/\psi}^2 / W_{\gamma p}^2$. In the kinematic range discussed here $x_p \sim 10^{-1} - 10^{-3}$ so that the proton could be detected, for example, by T1, T2 trackers of TOTEM or by the Roman pot system proposed in [26].

Note also that the $J/\psi$ production cross section will be sufficiently high to measure the $t$ dependence of the $J/\psi$ production up to $-t \sim 2$ GeV$^2$ (Fig. 2), provided one will be able to suppress the contribution of the proton dissociation.

For the case of the Upsilon production (Fig. 3 left), we find that the elementary reaction can be studied for $10^2 \lesssim W_{\gamma p} \lesssim 10^3$ GeV. For $\Upsilon$ production, the available $W_{\gamma p}$ interval is smaller due to the expected strong drop of the cross section with decrease of $W_{\gamma p}$, which is not compensated by a much larger photon flux at small $W_{\gamma p}$. Still, this interval allows one to check the strong energy dependence we discussed above. That is, that the cross section is expected to increase by a factor of about 30 with increase of $W_{\gamma p}$ from 100 GeV to 1 TeV. Also, there will be enough statistics to measure the slope of the $t$-dependence. Since $\Upsilon$ is the smallest available dipole this would provide a valuable addition to the measurement of the transverse gluon distribution using $J/\psi$ exclusive production.

The relative contribution due to the scattering off the nucleus is much larger in the case of $\Upsilon$ production than for $J/\psi$. If there were no nuclear shadowing it would dominate at the rapidities corresponding to $x_A \sim 10^{-5}$. Even with inclusion of nuclear shadowing, which may reduce the nuclear cross section by a factor 3–4 (Fig. 3 right), the cross section would still be dominated by the nuclear contribution. If one would be able to apply a cut on $p_t \lesssim 300$ MeV (Fig. 4) one would be able to suppress the production off proton target effectively even further. Hence, we conclude that the $pA$ scattering would allow to study the interaction with nuclei of the dipoles of the size $\sim 0.1$ fm at very
small $x$. This is almost impossible in any other process which would be available in the next decade.

It is worth noting that measurements of $J/\psi$ photoproduction could be performed at RHIC in the future high luminosity proton (deuteron)–nucleus runs. Since the actual luminosity or duration of such runs are not clear now we only give differential cross sections for $J/\psi$ production in a $pA$ run at $E_p = 200$ GeV, $E_A/A = 100$ GeV in Fig. 5 without making any conclusions on the feasibility of the measurements. Similar to the LHC case we see that though the production off the proton dominates, the production of $J/\psi$ off the nucleus could give a noticeable contribution, especially, after applying a cut on the transverse momentum of $J/\psi$.

To summarize, we find that the $pA$ run at LHC will add significantly to the studies of photoproduction of oniums in the AA collisions by providing information on the onium production in the elementary reaction in the energy range exceeding substantially the energy range of HERA. In addition ultraperipheral collisions of heavy ions proton-nucleus measurements could provide an independent method of the study of the $\Upsilon$ and, probably, also $J/\psi$ photoproduction off the nuclei at very small $x_A$.

4. Production of the light vector mesons

The pomeron hypothesis of the universal strong interactions has provided a good description of $pp/\bar{p}p$ interactions at collider energies (for a recent summary see [27]). This hypothesis assumes that the total and elastic cross sections of hadron–hadron scattering are given by the single pomeron exchange, and yields the following behavior for the cross section

$$\frac{d\sigma(h_1 + h_2 \to h_1 + h_2)}{dt} = f(t) \left( \frac{s}{s_0} \right)^{2\alpha_P(t) - 2},$$

where $\alpha_P(t)$ is the pomeron trajectory which is given at small $t$ by

$$\alpha_P(t) = \alpha_0 + \alpha' t.$$  

According to the analysis of [27] the $pp$ and $\bar{p}p$ total and elastic cross sections can be well described with

$$\alpha_0 = 1.0808, \quad \alpha' = 0.25 \text{ GeV}^{-2}. \quad (13)$$

The ability to check the universality hypothesis at fixed target energies is hampered by the presence of the nonpomeron exchanges which die out at high energies. However, significant deviations from universality cannot be ruled out. For example, studies of the total cross section of $\Sigma^-N$ interaction [28] are consistent with prediction of Lipkin [29] of $\alpha_0 = 1.13$ for this reaction.

The studies of the vector meson photo/electro production play a unique role in the field of strong interactions. The photoproduction of the light vector mesons is the only practical way to check the accuracy of the universality hypothesis for the soft interactions beyond the fixed target range. This hypothesis predicts for the exclusive photoproduction,

$$\frac{d\sigma(\gamma + p \to V + p)}{dt} = f(t) \left( \frac{s}{s_0} \right)^{2\alpha_P(t) - 2}.$$  

There are several mechanisms which should lead to a breakdown of the universality. Within the soft dynamics it is due
to multi-pomeron exchanges which are not universal and are generally more important at large $t$. It was demonstrated in [30] that the data on $\rho$-meson production are consistent with Eq. (14) for the universal pomeron trajectory with parameters given by Eq. (13). At the same time the very recent results reported by H1 [31] of the measurements of cross sections integrated over $t$ for the universality of $\alpha'$. However the data seemingly contradicts to the universality of $\alpha'$.

Overall it appears that the HERA studies of the light vector meson photoproduction force us to take a fresh look at the issues of soft dynamics:

- To what accuracy the pomeron trajectory is linear?
- Is $\phi$ meson production is purely soft or in this case trends to multi-pomeron exchanges which are not universal and are generally more important at large $t$. It was demonstrated in [30] that the data on $\rho$-meson production are consistent with Eq. (14) for the universal pomeron trajectory with parameters given by Eq. (13).

To address these questions one needs to measure photoproduction of $\rho$, $\phi$-mesons for the largest possible interval of $t$. To access the coherent cross section for the production of light vector mesons off a nucleus was calculated using the vector dominance model combined with the Glauber–Gribov multiple scattering model. The final state interaction in this model is mainly determined by the total vector meson–nucleon cross sections. For $\rho$ meson we calculated this cross section using the vector meson dominance and Donnachie–Landshoff parametrizations for the amplitude of $\gamma + p \to \rho + p$. The energy dependence of total $\rho N$ cross section $\sigma_{\rho N}$ was taken from a fit to the existing data. The results of the calculations are presented in Figs. 6, 7. We present the cross sections integrated over $t$. One can see that the rates at luminosity foreseen for $pA$ collisions at LHC are very large even for $W_{\gamma p} = 2 \times 10^3$ GeV. We also estimate $t$-dependence of these cross sections (Fig. 8) demonstrating that one would have sufficient rates at luminosity $L \approx 1.4 \times 10^{30}$ cm$^2$ s$^{-1}$ to study differential cross sections for $-t \gtrsim 2$ GeV$^2$ up to the energies at least $\sqrt{s_{NN}} \approx 1$ TeV.

Measurement of the $t$-dependence in the $W_{\gamma p}$ range extending by two orders of magnitude in the same experiment would allow to perform precision measurements of the value of the $\alpha'$ for $\rho$ and $\phi$ meson production since the expected change of the }
slope for $\alpha' = 0.25 \text{ GeV}^{-2}$ would be $\Delta B = 4.6 \text{ GeV}^{-2}$, which is $\alpha \sim 50\%$ change of the slope. The data will have enough sensitivity to check whether the nonlinear term is present in the pomeron trajectory.

Thus it appears that similar to the case of the onium production studies of this class of processes focused on production and small $t$—rapidity gaps. Two principle variables which determine the dynamics of the process are $t$, $x$, $y$, $\alpha$, and $\gamma$. Measurement of the dependence on $\ln(1/x)$ approximation [33,34]. Within the triple reggeon limit approximation, $f_{\gamma}(xW^2,t)$ is the effective pomeron trajectory. In the lowest approximation over $\ln(1/x)$ the amplitude $f_{\gamma}$ is independent of $W$ corresponding to $\alpha_{\gamma}(t) = 1$. It is often assumed (see, e.g., [33,34,36]) that the low $t$ BFKL formulae [37] which leads to $\alpha_{\gamma}(t) - 1 \approx 0.25$ could be applied for large $t$ as well. However it was recently shown [38] that another solution could also be possible for large $t$ with the BFKL approximation.

Studying the cross section at fixed $x$ gives the most direct look at the dynamics of the high-energy elastic small dipole–parton interactions for large $t$. Measurement of the dependence of the cross section on $W$ for the fixed rapidity gap (fixed $W^2/M_V^2$) gives maximal sensitivity to the dependence on the parton density. The measurements will greatly benefit from the large rapidity coverage of the LHC detectors.

Here we estimate the rate of this process for $pA$ collisions using data from the recent HERA measurements [31,39,40]. The results of the calculation are shown in Fig. 9 both for LHC and for RHIC. We find the cross sections to be large enough for the measurements in the interval of $t$ comparable to the one covered at HERA up to $W \approx 1 \text{ TeV}$ (corresponding to $y = 4.5$) as compared to $W \approx 100 \text{ GeV}$. This indicates that at LHC one could be able to do much more detailed studies of the process in Eq. (16) and explore the high energy dynamics of the small dipole interactions at large $t$ in a much broader kinematic domain. In particular, one would be able to reach $x \sim 10^{-4}$ and study the dependence of the process on the value of the rapidity gap. Similar measurements with heavy ion collisions will be feasible. They would provide one with the opportunity to study the effects of color transparency and color opacity in a number of new ways. These issues will be addressed in a separate publication.

6. Conclusions

We have demonstrated that studies of UPC in $pA$ mode at LHC will provide unique new information about diffractive $\gamma p$
collisions both in the hard regime where $x \sim 10^{-6}$ would be reachable and in the soft regime. In addition, it will be possible to investigate coherent production of $\Upsilon$ and probably $J/\psi$ in the $\gamma A$ collisions in the similar kinematics extending the kinematic domain which will be explored in UPC of heavy ions. We also found that a number of the measurements of a similar kind will be feasible at RHIC provided it will reach luminosities planned for RHIC II.

References

[38] L.N. Lipatov, private communication.