Large $t$ diffractive $\rho$ meson photoproduction with target dissociation in ultraperipheral $pA$ and $AA$ collisions at LHC.

L. Frankfurt  
School of Physics and Astronomy,  
Tel Aviv University, Tel Aviv, 69978, Israel  
M. Strikman  
Department of Physics, Pennsylvania State University,  
University Park, PA 16802, USA  
M. Zhalov  
St. Petersburg Nuclear Physics Institute, Gatchina, 188300 Russia

Abstract

We demonstrate that study of large $t$ vector meson photoproduction with rapidity gaps in ultraperipheral proton-ion and ion-ion collisions at LHC would allow to investigate the energy dependence of cross section of elastic scattering of a small dipole off the parton over a wide range of energies $10^3 < s_{\text{dipole-parton}} < 10^6 \text{GeV}^2$ where this cross section is expected to change by a factor $\geq 20$. The accessible energy range exceeds the one reached at HERA by a factor of 10 both in $\gamma p$ and in $\gamma A$ scattering. In addition, study of A-dependence of this process will allow to determine the $t$ range where interaction of small dipoles gives the dominant contribution and to investigate effects of absorption for the propagation of ultrarelativistic small $q\bar{q}$ dipoles through the nuclear media and probe in a novel way onset of the black disk regime.

1 Introduction

One of the principal features of small $x$ processes is a nontrivial interplay between the evolution in $\ln(x_o/x)$ and in $\ln(Q^2/Q_o^2)$. It has been understood long ago that investigations of large $t$ processes with a large rapidity gap give principal possibility to ensure that the coupling constant is small and the evolution of the hard scale is suppressed. As a result such processes allow to investigate $\ln(x_o/x)$ physics separately from the $\ln(Q^2/Q_o^2)$ evolution. Challenging QCD phenomena include transition from the regime of nuclear color transparency to color opacity and other regimes of high energy strong interaction with a small coupling constant. Though the color transparency phenomenon is established experimentally in [1, 2] further studies are certainly necessary to establish the range of energies and virtualities for which phenomenon takes place. Also, there is a number of indirect indications for onset of the
regime of color opacity, a direct evidence is very limited, see however [3]. The rapidity gap processes we discuss in this paper will provide additional handles to address these questions.

To probe this physics a number of small x processes which originate due to elastic scattering of a parton and a small quark-antiquark (q\overline{q}) color singlet dipoles (we will refer to them in the following simply as dipoles) at large momentum transfer and at high energies were suggested. This includes hard diffraction in \( pp \to pX \) process at large \( t \), production of two jets accompanied by rapidity gap-coherent Pomeron [4], the rate of production of two back to back jets with a large rapidity gap in between [5] as compared to the rate of two jet production in the same kinematics without rapidity gaps [6, 7], photo(electro) production of vector mesons at large \( t \) with a rapidity gap [8, 9, 10]. Production of two jets with a gap in between was studied experimentally at the Tevatron, see e.g. [11]. Over the last ten years the theoretical and experimental studies were focused on the photo/electro production off a proton. Studies of these processes at HERA resulted in the measurements of the relevant cross sections [12, 13, 14, 15, 16] in a region of the photon-proton center of mass energies \( 20 \text{ GeV} \leq W_{\gamma p} \leq 200 \text{ GeV} \).

The HERA data agree well with many (though not all) predictions of the QCD motivated models (several of which use the LO BFKL approximation [17]), see for example [16] and references therein.

Clearly it would be beneficial to extend such study to higher \( W_{\gamma p} \) and over a larger range of the rapidity gap intervals to investigate \textit{how energy dependence of the small dipole - parton scattering changes with t}. Recently we demonstrated [18] that this will be possible using quasi-real photons in the ultraperipheral collisions (UPC) of protons with nuclei at LHC.

Here we perform a more detailed analysis focusing on study of \( \rho \) meson photoproduction:

\[
\gamma + p(A) \to \rho + \text{rapidity gap} + X, \tag{1}
\]

at large \( t \) and with a rapidity gap between \( \rho \)-meson and produced hadronic system \( X \) in the proton-nucleus and nucleus-nucleus UPC at LHC. We consider the kinematics where the rapidity gap interval is sufficiently large (\( \geq 4 \)) to suppress contribution of the fragmentation processes. Related physics can be investigated in the diffractive production of charm or two jets separated by large rapidity gap from the nucleon fragmentation region. For example, studies of the A-dependence of production of two jets in the processes like \( \gamma + A \to (\text{jet} + M_1) + \text{rapidity gap} + (\text{jet} + M_2) \) will allow to check presence of the color transparency effects in the gap survival in hard photon induced processes [19].

The CMS and ATLAS detectors are well suited for observing such processes since they cover large rapidity intervals.

The main variables determining the dynamics of the process are the mass \( M_X \) of system produced due to the dissociation of proton target, the square of the transferred momentum \(-t \equiv Q^2 = -(p_\gamma - p_V)^2\), and the invariant energy of the q\overline{q}- parton elastic scattering

\[
s' = xW_{\gamma p}^2, \tag{2}
\]

where

\[
x = \frac{-t}{(-t + M_X^2 - m_N^2)}, \tag{3}
\]
is a fraction of the proton momentum carried by the parton involved in the elastic scattering off the $q\bar{q}$ pair. The rapidity gap between the produced vector meson and knocked out parton (roughly corresponding to the leading edge of the rapidity range filled by the hadronic system $X$) is related to $W^2_{\gamma p}$ and $t$ (for large $t, W^2_{\gamma p}$) as

$$y_r = \ln \frac{xW^2_{\gamma p}}{\sqrt{(-t)(m^2_V - t)}}.$$  

Obviously it is rather difficult to measure the mass of diffractively produced system $M_X$ or the value of $x$ directly. However it can be determined with a good accuracy by measuring momenta of the particles in the system $X$ closest to the rapidity gap.

Generally, the cross sections of the processes of large $t$ scattering with a rapidity gap are given by an incoherent sum of terms describing elastic scattering off a quark and off a gluon. Each of the terms is a product of the cross section of the quasielastic large $t$ transition $\text{projectile} + \text{parton} \to \text{final hadron} + \text{parton}$ and the corresponding parton density in the target $[4, 8, 9]$. The choice of large $t$ ensures two important simplifications. First, the parton ladder mediating quasielastic scattering is attached to the projectile via two gluons. Second is that attachment of the ladder to two partons of the target is strongly suppressed. The elastic cross section of the scattering off a gluon is enhanced by a factor of $81/16$ as compared to the scattering off a quark. Numerically, the scattering off the gluons dominates for a wide range of $x$. For example it constitutes $\sim 80\%(70\%)$ of the cross section at $x=0.1(0.3)$. The power law for the $t$-dependence of the cross section is related to the number of constituents in the hadronic vertex, hence, one can expect $1/t^6$ for three quarks $[4]$ and $1/t^4$ for the quark-antiquark system considered in $[9]$.

In the case of the photoproduction of vector mesons for the $t$ range $-t \gg \Lambda^2_{QCD}/r_V^2 > M^2_X > M^2_N$, and fixed $x < 1$, the target dissociative cross section of the vector meson photoproduction off proton can be written in the form $[9]$:

$$\frac{d\sigma_{\gamma p\to V+X}}{dt dx} = \frac{d\sigma_{\gamma+\text{quark}\to V+\text{quark}}}{dt} \left[\frac{81}{16} g_p(x, t) + \sum_i (q_{i p}(x, t) + \bar{q}_{i p}(x, t))\right].$$

(4)

Here $g_p(x, t)$ is the gluon distribution, $q_{i p}(x, t)$ and $\bar{q}_{i p}(x, t)$ - quark and antiquark distributions with flavor $i$ in the proton target. The amplitude of vector meson photoproduction off a quark $f_q(s', t)$ is dominated by a quasielastic scattering of a photon in a small quark-antiquark dipole configuration which transits to a quark-antiquark component in the vector meson.

Diffractive photoproduction of vector meson from hadron(nuclear) target is a particular case of special hard processes where evolution in $x$ is separated from the evolution in hard scale cf. discussions in $[4, 6, 8, 9]$. Really, since $t$ which guarantees smallness of the coupling constant is the same within the ladder mediating quasielastic scattering, the amplitude $f_q(s', Q^2 = -t)$ probes evolution in $\ln(1/x)$ at fixed virtuality $Q^2$. Note also, that since the the momentum transfer is shared by two gluons characteristic virtualities of the t-channel gluons in the ladder are $\approx Q^2/4$. At the same time hard scale characterizing structure function of a target is $\approx Q^2$.

In the lowest order in $\ln(1/x)$ the elastic dipole -quark amplitude, $f_q(s', t)$, is independent of $W^2_{\gamma p}$ for any fixed $t$. Account of the higher order terms in $\ln(1/x)$ was performed in the
leading and next to leading log approximation as well as modeling effects of both logs of \( Q^2 \) and \( x \). It leads to expectation\(^1\) of \( f_q \) increasing with energy as a power of \( s' / |t| \) which should weakly depend on \( t \):

\[
  f_q(s', t) \propto \left( \frac{s'}{|t|} \right)^\delta(t).
\]

The numerical results for \( \delta(0) \) are strongly modified when going from LO BFKL: \( \delta(0) \approx 0.6 \), to NLO BFKL - \( \delta(0) \approx 0.1 \), and from NLO to resummed BFKL where \( \delta(0) \approx 0.2 / 0.25 \) in a wide range of virtualities, for the recent review see [22]. Hence we will treat \( \delta(t) \) as a free parameter and assume, in most of the analysis, that \( \delta(t) \) weakly depends on \( t \).

Note that similar process for small \( t \) could be described by the triple Pomeron approximation. In this case \( f_q \propto (W_{\gamma p}^2/M_X^2)^{\alpha_P(t)-1} \) where \( \alpha_P(t) \approx 1.08 + 0.25 GeV^{-2} t \) is the Pomeron trajectory. For \(-t \geq 0.5 GeV^{-2}\) this model predicts \( f_q \) dropping with increase of energy.

The paper is organized as follows. In section 2 we analyze the current HERA data, and propose a simple parametrization of the data based on the hard mechanism of the reaction. We also estimate the rates of \( \gamma + p \rightarrow \rho + \text{gap} + X \) reaction in \( pA \) collisions at LHC and find that it will be possible to extend the HERA measurements to the energies exceeding those reached at HERA by a factor of 10. In section 3 we analyze the A-dependence of the discussed process and find it will provide a critical test of the interplay between hard and soft dynamics as well as probe onset of hard black disk regime. We also find that it will be possible to reach \( W_{\gamma p} \sim 1 TeV \) in this process and hence study hard dynamics up to \( xW_{\gamma p}^2/Q^2 \sim 10^5 \) where emission of several gluons in the ladder kinematics becomes possible.

## 2 Modeling of the elementary and rapidity gap process from HERA to LHC in ultraperipheral \( pA \) collisions

The current HERA measurements report cross sections integrated over \( M_X \) from the minimal value \( M_X = m_N \) up to some experimentally fixed upper limit of \( \hat{M} \). At fixed \( t \) this obviously corresponds to the cross section integrated over \( x \) from \( x = 1 \) to the value \( x_{\text{min}} \) determined from Eq. (3) at \( M_X = \hat{M} \).

Two types of cuts are considered - \( x \geq x_{\text{min}} \) and \( M_X < \hat{M} \), to reveal the dynamics of the process [1]. Most of the ZEUS and H1 measurements explored a rather narrow interval of \( W_{\gamma p} \) and were mostly focused on the \( t \) dependence of the cross section. Evaluation within pQCD of the transition \( \gamma \rightarrow \rho \) shows that at large \( t \) this cross section should be proportional to \(|t|^{-4}\). The H1 collaboration presented data on the \( t \)-dependence of the cross section in the \( t \)-range \( 1 GeV^2 \leq -t \leq 8 GeV^2 \) taken at the average value \( < W_{\gamma p} > \approx 85 GeV \). They measured also energy dependence of the cross section for values of \(-t < 2.5 GeV^2 \) in the range \( 30 GeV \leq W_{\gamma p} \leq 90 GeV \) with the cuts on the mass of produced system \( M_X \leq 0.1 W_{\gamma p} \). The \( t \)-dependence of cross section of the diffractive \( \rho, \phi \) and \( J/\psi \) photoproduction with proton dissociation was measured by ZEUS at the average value \( < W_{\gamma p} > \approx 100 GeV \) with restriction on the mass of the produced system satisfying two conditions: \( M_X < 25 \text{ GeV} \) and

\(^1\)Note however that within NLO BFKL this is not a foregone expectation as with increase of \( Q^2 \) the solution may be given by a different saddle point [20, 21].
$0.01 \leq x \leq 1$ corresponding to the selection of approximately fixed length of the rapidity gap in experiment.

Based on the structure of Eq.(4) we describe these HERA data using the following expression for the cross section

$$
\frac{d\sigma_{\gamma p \rightarrow \rho p X}}{dt} = \frac{C}{(1 - t/t_0)^4} \left( \frac{s}{m_{\rho}^2 - t} \right)^{2\delta(t)} I(x_{min}, t),
$$

where

$$
I(x_{min}, t) = \int_{x_{min}}^{1} x^{2\delta(t)} \left[ \frac{81}{16} g_p(x, t) + \sum_i \left[ q^i_p(x, t) + \bar{q}^i_p(x, t) \right] \right] dx.
$$

The gluon, quark and antiquark distributions were taken from the CTEQ6m PDF set\[^{23}\] with account for up and down quarks and antiquarks. The value of $x_{min}$ was calculated using Eq.(3) separately for each of experimental sets of the ZEUS and H1 data using reported cuts on $M_X$. The scale factor $t_0 = 1$ GeV$^2$ was fixed. The phenomenological function $\delta(t)$ which parameterizes the energy dependence of the the pQCD elastic amplitude was chosen in the form $\delta(t) = \delta_0 + \delta' t$. Values of $\delta_0$, $\delta'$ and the normalization constant $C$ were adjusted to provide a reasonable description of the available HERA data of the $\rho$ meson proton-dissociative photoproduction\[^{2}\]. The $t$-dependence of cross section was measured by H1 and ZEUS for different cuts on the produced mass $M_X$ and rather close values of the average energy $W_{\gamma p}$. As a result, these data don’t allow to fix unambiguously energy dependence of the dipole-parton amplitude (function $\delta(t)$). We obtained a reasonable description of the data assuming a relatively weak energy dependence of the amplitude $\delta(t) = 0.1$ ($C = 40$) as well as with more strong energy dependence $\delta(t) = 0.2$ ($C = 14$) expected for the hard processes (see Fig.1). We want to emphasize here that these values of $\delta(t)$ are significantly larger than the ones which would result from extrapolation of the soft Pomeron trajectory to large $t$: $\delta(t) = \alpha_p^{soft}(t) - 1 \approx 0.08 + t/4 \leq 0_{|t| > 0.4}$ GeV$^2$ even if one would introduce nonlinear term in the trajectory\[^{24}\].

Our results are consistent with a rather weak variation of the energy dependence of the elastic amplitude with $t$ - we used the value $\delta' = 0$ while the presence of very small negative value $\delta' = -0.01$ will improve agreement with H1 data at large $-t > 5$ GeV$^2$ in the case of calculations with $\delta_0 = 0.2$. In difference from the results of H1 and ZEUS analyses which found different $t$-dependence ($|t|^{-3.2}$ in the ZEUS experiment and $|t|^{-4.2}$ in the H1 experiment from their fits to the data we are able to describe both data sets with the same universal expression and the same values of parameters. This is due to the different $t$-behavior of $I(x_{min}, |t|)$ in the kinematics of ZEUS and H1 because of different cuts in experiments. In the first case the lower limit in integration over $x$ is practically constant: $x_{min} \approx 0.01$ for all range $1.5$ GeV$^2 < -t < 8$ GeV$^2$ due to the condition $0.01 < x < 1$. In the H1 kinematics ($M_X < 5$ GeV) the value of integral is decreasing with increase of $t$ because $x_{min}$ increases from $x_{min} \approx 0.06$ to $x_{min} \approx 0.25$.

As we mentioned above in the hard regime the energy dependence of the amplitude should be a weak function of $t$. In photoproduction of $\rho$ meson with rapidity gap which we consider

\[^{2}\]It is worth emphasizing here that the HERA data correspond to relatively small rapidity interval available for emission of the gluons in the color singlet ladder - $\ln(xs/Q^2) \leq 5$. This allows emission of one gluon in the ladder kinematics making it very difficult to apply a BFKL type approximation.
here one needs large $t$ to reach dominance of the hard mechanism. However in the case of exclusive onium photo/electro production or exclusive light vector meson electroproduction at large $q^2$ one expects the hard mechanism to dominate already at $t \sim 0$. Hence the parameter $\delta$ should be close to the energy dependence of the amplitude of exclusive process $\gamma^* + p \rightarrow V + p$. At HERA the highest virtualities for such amplitude are reached in the exclusive $J/\psi$ electroproduction and correspond to $\delta \sim 0.2$, for a summary see Ref. [25]. Hence our observation that similar value of $\delta$ allows to describe the rapidity gap data at large $t$ gives a support to the interpretation of the data as due to hard elastic quark-antiquark dipole - parton scattering.

Obviously, the parameter $\delta$ could be more reliably fixed analyzing the energy dependence of cross section for fixed values of $t$ in a wide range of $W_{\gamma p}$. Such preliminary data in the range $20 \ GeV < W_{\gamma p} < 100 \ GeV$ were presented at DIS06 by H1 for $-t < 2.5 \ GeV^2$ for the cut $M_X < 0.1 W_{\gamma p}$ [26]. This experimental cut leads to decrease of $x_{min}$ from $x_{min} \approx 0.3$ to $x_{min} \approx 0.02$ with increase of $W_{\gamma p}$. Under these conditions Eq. (5) leads to a strong increase of the cross section due to the strong growth of integral $I(x_{min}, |t|)$ with increase of $W_{\gamma p}$ in the range from 20 GeV to 100 GeV. This growth weakly depends on the value of $\delta$ (Fig. 2).

No results for the energy dependence of the process in the kinematics where $M_X$ is restricted from above by some value $M$ were reported by the HERA experiments so far. The reported energy dependence is substantially weaker than the one given by Eq. (5) (Fig. 3). For moderate $t$ the energy dependence of the cross section is sensitive to the scale of the gluon pdf’s in Eq (I). To illustrate this point we present in Fig. 3 the result of calculations for two choices of scale in Eq. 4: $Q^2$ and $Q^2/4$. It appears that the energy dependence of the data is described better if the scale is $\leq Q^2/4$.

It is not likely that further studies at HERA will be able to cover a sufficiently wide range of $W_{\gamma p}$ and rapidity gaps necessary to study the energy dependence of the large $t$ elastic amplitude of ”small size dipole” - parton scattering. On the other hand at LHC CMS and ATLAS would have large enough rapidity coverage to observe reaction (1) in a wide range of $W_{\gamma p}$ and rapidity gaps in the ultraperipheral proton - nucleus collisions. Hence, we use parametrization of $\gamma + p \rightarrow X + \rho$ cross section given by Eqs. (5) to estimate the large $t$ rapidity gap cross section of the $\rho$ meson photoproduction in the ultraperipheral proton-nucleus and (in the next section) in nucleus-nucleus collisions at LHC. For the case of proton-ion UPC we do not address here a small contribution generated by $\gamma + A \rightarrow \rho + X$ reaction since it is much smaller and can be easily separated experimentally. Hence, the large $t$ nucleon dissociative cross section for this process will be given by expression

$$
\frac{d\sigma_{pA\rightarrow pXA}}{dydt} = N^Z_{\gamma}(y) \frac{d\sigma_{\gamma N\rightarrow \rho X}(y)}{dt},
$$

(7)

where $N^Z_{\gamma}(y)$ is the flux of photons with energy $\omega = \frac{m_\rho}{2} e^y$ generated by fast moving ion with charge $Z$ and the rapidity of vector meson is determined by expression $y = \frac{1}{2} \ln \frac{E^V + p^V}{E^V - p^V}$.

We considered two regimes for the $\rho$-meson photoproduction with large rapidity gap at intermediate and large momentum transfer in UPC at the LHC analogous to the ones studied at HERA:

- The cross section can be studied at fixed $t$ as a function of rapidity of the produced $\rho$ meson imposing the restriction $M_X \leq 5 GeV$. In this case the lower limit $x_{min}$ of
Figure 1: Description of ZEUS and H1 data for $t$-dependence of the large $t$ and rapidity gap cross section. ZEUS data were taken at average $W_{\gamma p}=100$ GeV with fixed cut $M_X \leq 25$ GeV and additional restriction $0.01 < x < 1$. The H1 data were taken at average $W_{\gamma p}=85$ GeV and cut $M_X \leq 5$ GeV.
\[ \gamma + p \rightarrow X + \rho, \ -t = 2.23 \text{ GeV}^2 \]

\[ \frac{M_X}{W_{\gamma p}} < 0.1 \]

\[ M_X \leq 5 \text{ GeV} \]

Figure 2: Energy dependence of cross section given by Eqs. (5,6) at \(-t = 2.23 \text{ GeV}^2\). Solid and long dash lines - calculations with \(\delta = 0.2\) and \(C = 14\); dot-dashed and short dash lines - calculations with \(\delta = 0.1\) and \(C = 40\).
Figure 3: Comparison of the preliminary H1 data [26] with energy dependence of cross section given by Eqs. (5,6). Solid and long dash lines - calculations with $\delta = 0.2$ and virtuality of parton $Q^2_{\text{eff}} = -t$ and $Q^2_{\text{eff}} = -t/4$ correspondingly, short dash and dot-dashed lines - with $\delta = 0.1$ and virtuality $Q^2_{\text{eff}} = -t$ and $Q^2_{\text{eff}} = -t/4$ correspondingly.
Figure 4: Rapidity distribution for the large $t$ and rapidity gap cross section of $\rho$ meson photoproduction in ultraperipheral proton-argon collisions in kinematics of LHC. Solid and dashed lines - calculations with $\delta = 0.2$, dot-dashed and short dash - with $\delta = 0.1$. The counting rates for pAr collisions can be estimated using the value of luminosity $L = 6 \mu b^{-1} sec^{-1}$ expected at LHC.
Figure 5: Rapidity distribution for the large $t$ and rapidity gap cross section of $\rho$ meson photoproduction in ultraperipheral proton-lead collisions in kinematics of LHC. Notation is the same as in previous figure. The corresponding counting rates can be easy estimated using the value of luminosity of pPb collisions $L = 10^{-1} \mu b^{-1} sec^{-1}$.
integration over $x$ does not depend on $W_{\gamma p}$ and the amplitude of dipole - parton elastic scattering varies with $W_{\gamma p}$ due to the increase of the rapidity gap due to the increase of the rapidity of the produced vector meson. Such approach could allow one to study energy dependence of the dipole-parton amplitude and determine parameter $\delta$.

- Cross section is studied for $M_X = 0.1 \cdot W_{\gamma p}$. This type of cut is interesting since it corresponds to keeping the rapidity gap fixed and changing the value of $x_{\text{min}}$. Such study could be useful for testing the parton distribution functions and the reaction mechanism by extracting from the data the integral $I(x_{\text{min}}, t)$ at different values of $x_{\text{min}}$ and $t$.

Note, that we do not consider here the photoproduction cross section at $W_{\gamma p} < 20 GeV$ where our parametrization (Eqs. 5, 6) based on the HERA data will be hardly reliable, in particular, for a case when the produced mass is fixed by the condition $M_X \leq 5 GeV$. On the other hand, one can see from Fig.2 that the cross section is very small if $M_X \leq 2 GeV$.

The results of calculations for $\rho$ meson nucleon dissociative photoproduction in proton-argon and proton-lead ultraperipheral collisions at $-t = 2.5 GeV^2$ and $-t = 5.0 GeV^2$ in the kinematics of the LHC are presented in Figs.11,5. Note here, that the cross section should drop rather slowly with $t$ - the integrated rate for $-t > t_{\text{min}}$ drops approximately as $1/t_{\text{min}}^3$. One can see that with expected at the LHC luminosity of the proton-ion collisions the rates remain high up to sufficiently large $t$. In particular, the rates for $-t > 10 GeV^2$ are only a factor of 10 smaller than for $-t > 5 GeV^2$. It is also worth noticing that the rates for $J/\psi$ production would be also significant since though these rates for a fixed $t$ are smaller than for $\rho$ production, one would be able to use for the analysis $-t \geq 1 GeV^2$ where the discussed process gives much larger contribution than the exclusive diffractive process $\gamma + p \rightarrow J/\psi + p$.

The most of the events detected in the considered kinematics would correspond to $x \geq 0.01$, so the main information which will be possible to infer from the data would be on the energy dependence of the elastic “quark – antiquark dipole” – parton amplitude for different virtualities. Some number of the events can also be collected for $x$ as low as $x \sim 10^{-3}$. On the other hand it will be probably very difficult to reach the $x \geq 0.4$-range where scattering off quarks gives a larger contribution than scattering off gluons. Overall it is clear that the energy range for the dipole - parton interactions will be large enough: $s_{\text{max}}/s_{\text{min}} \geq 4 \cdot 10^3$ to provide a precision measurement of the energy dependence of the amplitude. If $\delta \approx 0.2$, the elastic cross section should increase in this interval by a factor $\sim 30$.

3 A-dependence of the cross section and estimates for the photoproduction in the heavy ion UPC.

Since the large $t$ rapidity gap processes $\gamma(\gamma^*) + N \rightarrow V + X$ are dominated by elastic scattering of small $q\bar{q}$ pairs off partons in a target one can use these processes imbedded in nuclei to investigate in a novel way interaction of small dipoles with the nuclear medium.

The ultraperipheral nucleus-nucleus collisions at LHC will provide the first opportunity to investigate physics of new QCD regime of high energy strong interaction with small coupling constant and large target thickness (further studies will be possible at an electron-ion collider). The specific of nucleus-nucleus ultraperipheral collisions which differs them
from the proton-nucleus collisions is that vector mesons are produced by photons emitted by both colliding nuclei. Hence, the cross section is given by the sum of two contributions

$$\frac{d\sigma_{AA\rightarrow\rho XAA'}}{dydt} = N_\gamma Z(y)\frac{d\sigma_{\gamma A\rightarrow\rho XA'}}{dt} + N_\gamma Z(-y)\frac{d\sigma_{\gamma A\rightarrow\rho XA'}}{dt}. \quad (8)$$

Here $\sigma_{\gamma A\rightarrow\rho XA'}$ is cross section of $\rho$ photoproduction off nucleus with mass number $A$, $X$ is a product of the target nucleon diffractive dissociation and $A'$ denotes a residual nucleus. Several neutrons will be produced due to electromagnetic excitation of $A'$ by the nucleus $A$ which emitted a photon involved in the reaction $\gamma A$. The system $X$ should resemble the one produced in the deep inelastic scattering off a nucleus $A$ at similar $x$ and $Q^2 \sim -t$ (except that the proportion of the scattering off gluons and quarks is different). The spectrum of the hadrons is given by a superposition of the processes of the fragmentation of gluons and quarks in proportion given by Eq.(11). Also, these hadrons should be balancing the transverse momentum of the vector meson. Note here that the momenta of the leading hadrons in the rest frame of the nucleus are of the order $-t/(2m_Nx)$. Hence, based on the measurements of the EMC [27] we can expect that for large $t$ and for $x \leq 5 \cdot 10^{-2}$ absorption effects for the leading hadrons are small. Nevertheless, a few neutrons will be produced in the fragmentation region of the nucleus due to the final state interactions of produced hadrons[28]. Therefore in the discussed process either one or both Zero Degree Calorimeters would detect several neutrons. Detection of hadrons in the system $X$ allows to determine which of the nuclei generated a photon, and hence determine invariant energy of the $\gamma A$ collision.

We already mentioned that study of A-dependence of the process $\gamma + A \rightarrow \rho + X + A'$ at large $t$ allows to reveal the dynamics of the small dipole - nucleus interaction. Before discussing the expectations for A-dependence in this kinematics let us estimate what one can expect for A-dependence in the high energy nucleon dissociative $\rho$-meson photoproduction off nuclei at small $t$. At high energies the process originates from the interaction of the photon in an average configuration which interacts inelastically with the strength comparable to that of $\rho$-meson. The fluctuations of the interaction strength in this case are rather small and the photoproduction cross section can be calculated using the Gribov-Glauber approximation for high energy incoherent processes (note, that in quantum field theory the process is described by non-planar diagrams, see discussion below):

$$\frac{d\sigma_{\gamma A\rightarrow\rho XA}}{dt} = A_{eff} \frac{d\sigma_{\gamma p\rightarrow\rho + X}}{dt}, \quad (9)$$

where

$$A_{eff} = 2\pi \int_0^\infty db \int_{-\infty}^\infty dz \rho_A(b, z) \exp \left[ -\sigma_{in}^\rho N \int_{-\infty}^\infty \rho_A(b, z) dz \right]. \quad (10)$$

Here $\rho_A(b, z)$ is the nuclear density ($\int d^3r \rho_A(r) = A$). The effective number of nucleons $A_{eff}$ involved in the the process of the vector meson photoproduction off nucleus determines so called rapidity gap survival probability which can be estimated as

$$\frac{A_{eff}}{A} = \frac{1}{A} \int d^2b T(b) \exp(-\sigma_{in}^\rho N T(b)). \quad (11)$$
where \( T(b) = \int_{-\infty}^{\infty} dz \rho_A(z,b) \) is the optical thickness. In the range of high energies which could be reached in \( \rho \) meson photoproduction off lead at LHC growth of the cross section \( \sigma_{IN}^\rho \) is significant and the resulting suppression becomes very large - \( A_{eff}/A \sim A^{-\frac{3}{2}} \), emphasizing peripheral character of the process.

At large \( t \) the dominant component of the photon responsible for the nucleon dissociative photoproduction of vector mesons off nucleus is the quark-antiquark pair characterized by the small transverse size \( (d \propto 1/\sqrt{|t|}) \) - the \( q\bar{q} \) dipole. So, with increase of \( t \) leading and higher twist nuclear shadowing effects should decrease due to color transparency phenomenon. It has been understood long ago \( 29, 30 \) that the contribution of planar (eikonal/Glauber rescattering) diagrams to the amplitude for high energy collisions is cancelled in a quantum field theory. Recently this result has been generalized to pQCD for the interaction of spatially small dipole with a large size color singlet dipole via exchange by two color octet amplitudes see \( 31 \) or via exchanges by several color singlet amplitudes\( 32 \). Principal difference between description of scattering process within quantum mechanics and QCD as the quantum field theory is that with increase of the incident energy the dipole with an increasing probability fluctuates into configurations with a larger and larger number of constituents before the collision \( 33, 32 \). Each of these constituents can interact only once with a parton (dipole) of a target through an amplitude with vacuum quantum numbers in the crossed channel. Thus account of causality and/or energy-momentum conservation leads to Gribov-Glauber picture but for the interaction of projectile and target described as a collection of partons - bare particles of QCD.

In the case of a small dipole - nucleus scattering the first rescattering is given by pQCD cross section for the interaction of the \( q\bar{q} \) dipole of the transverse size \( d \) with the nucleon which in the leading order approximation can be written as \( 34 \)

\[
\sigma_{inel}^{q\bar{q}N}(\bar{x}, d^2) = \frac{\pi^2}{4} F^2 \frac{d^2}{d^2 b} g_T^2(\bar{x}, Q_{eff}^2). \tag{12}
\]

Here \( F^2 = 4/3 \) is the Casimir operator of the fundamental representation of the \( SU(3) \) gauge group, \( Q_{eff}^2 \) is the effective virtuality and \( \bar{x} = Q_{eff}^2/W_{\gamma p}^2 \). Since the size of the dipole scales as \( 1/\sqrt{|t|} \), at sufficiently large \( t \) and fixed \( W_{\gamma p} \) the cross section \( \sigma_{inel}^{q\bar{q}-N} \) become so small that one can neglect interactions with \( N \geq 3 \) nucleons. Then the rapidity gap survival probability can be estimated using simple expression:

\[
A_{eff}/A = 1 - \sigma_{inel}^{q\bar{q}-N} \frac{1}{A} \int d^2 b T^2(b). \tag{13}
\]

With increase of \( W_{\gamma p} \) at fixed \( t \) the dipole-nucleon cross section \( \sigma(q\bar{q} - N) \) rapidly increases due to the growth of the small \( \gamma \) gluon density \( (\propto (W_{\gamma p}^2/Q_{eff}^2)^n, n \geq 0.2) \). This results in breakdown of the Eq.13 and one has to take into account higher order rescatterings involving \( N \geq 3 \) nucleons which interact with configurations containing three \( (q\bar{q}g) \) and more partons. The cross sections of interaction with such configurations should be larger than \( \sigma_{inel}^{q\bar{q}-N} \) given by Eq.12 because the projectile with a significant probability effectively consists of several dipoles of sizes comparable to the size of the initial dipole. Hence the eikonal type expansion of the amplitude over the number of rescatterings based on the averaged strength of interaction will obviously somewhat overestimate the the absorption.
Still it appears reasonable to use the eikonal approximation for the rough estimate of the magnitude of the suppression. In particular, in Fig. 6 we show calculation of $A_{eff}/A$ as a function of $\sigma_{eff}$ which one can consider as a parameter modeling the averaged strength of dipole-nucleon interaction in nuclear medium. The accuracy of such estimates of $A_{eff}/A$ should be better both in the limit of small $\sigma_{eff}$ when $N > 2$ terms give a small correction ($\sigma_{eff} \leq 3 \text{mb}$ for $A \sim 200$) and for large $\sigma_{eff}$ where interaction is close to the BDR.

Clearly, increase of $t$ at fixed energy leads to $A_{eff}/A \rightarrow 1$ revealing the onset of color transparency. However for $W_{\gamma p} \approx 100 \text{GeV}$ typical for UPC collisions at LHC and for upper range of HERA a dipole of transverse size $d=0.2 \text{fm}$ (which may correspond to $-t \sim 10 \text{GeV}^2$) interacts with a cross section $\sigma_{in}^{qq} \approx 5 \text{mb}$ leading to $A_{eff}/A$ substantially smaller than one (see Fig. 6). Hence one probably would need a larger $t$, or smaller $W_{\gamma p}$ to reach the regime of complete color transparency given by Eq. (14) below.

Overall, we expect that at fixed $t$ increase of energy will gradually lead to the onset of the regime of color opacity. At sufficiently high energies one is likely to reach a black disk regime (BDR) for interaction of the dipole with the nuclear medium and the vector meson photoproduction would be strongly suppressed for central impact parameters, leading to dominance of the peripheral process with the cross section proportional to $A^{1/3}$. It is reasonable to assume that suppression of the $\rho$-meson yield in this case would be comparable to the one in the soft regime which we discussed above and could be estimated using Eq. (11).

Higher twist effects in this kinematics would be manifested also in the structure of the final state. Due to a more peripheral nature of the higher twist mechanism large suppression of the A-dependence would be combined with a smaller break up of the nucleus which could be measured via study of the multiplicity of neutrons in the ZDC.

In the leading twist approximation the cross section of vector meson photoproduction off nuclear target is given by Eq. (4) where parton distributions within a nucleon are substituted by nuclear parton density distributions $g_A$, $q_A$ and $\bar{q}_A$

$$
\frac{d\sigma_{\gamma+p\rightarrow V+X}}{dtdx} = \frac{d\sigma_{\gamma+\text{quark}
\rightarrow V+\text{quark}}}{dt}\left[\frac{81}{16} xg_A(x,t) + \sum_i(xq_A(x,t)+x\bar{q}_A(x,t))\right], \quad (14)
$$

where $g_A$, $q_A$ and $\bar{q}_A$ are the nuclear parton distributions.

It is known experimentally that quark distributions for $0.05 < x < 0.5$ do not deviate from the linear dependence by more than 10%. For the gluons (which dominate in Eq. (14) some current models predict an enhancement of up to 20% for $x \sim 0.1$ which maybe followed by some suppression at $x \geq 0.4$. Hence the leading twist approximation of Eq. (14) leads to the prediction of the onset of color transparency regime with increase of $t$, which is characterized by a strong suppression of the interaction of small dipole with nuclear medium. Then the upper limit of the photoproduction cross section can be obtained in the Impulse Approximation (IA)

$$
\frac{d\sigma_{\gamma+p\rightarrow \rho+X}}{dt} = A \frac{d\sigma_{\gamma+p\rightarrow \rho+X}}{dt}. \quad (15)
$$

Note that studies of the discussed process at $x \geq 0.05$ allow to trigger on scattering of a high energy photon in a small $q\bar{q}$ configuration without requiring that interaction involves scattering off the small x gluon field. This is in contrast with e.g. elastic photo/electro...
Figure 6: The probability of rapidity gap survival as a function of $\sigma_{\text{eff}}$ which models the strength of dipole-nucleon interaction in nuclear medium.
production of an onium state off nuclei. Accordingly this process provides a complementary clean way to study a pattern of the interactions of a small dipole with nuclear medium in a wide range of energies.

Of separate interest is the kinematics with $M_X$ corresponding to $x \leq 0.01$ where one expects a significant leading twist gluon shadowing of structure functions (the quark contribution in this kinematics is negligible) - on the scale of a factor of $\sim 2$ for $x \sim 10^{-3}, -t \sim 10\text{GeV}^2$\cite{35}. This should result in additional decrease of $A_{eff}/A$, hence, when $x$ becomes $\ll 10^{-2}$ one would be addressing an interplay of the leading and higher twist effects in the dipole - parton interaction and the dipole - nuclear medium interactions.

For numerical estimates of the rates of the discussed process at LHC we considered two scenarios - a color transparency regime of cross section proportional to $A$ - the impulse approximation and regime of strong absorption which can be considered as a lower limit on the expected cross section. We made a natural assumption that absorption for the interaction of a small dipole for a given energy should not exceed the one for the interaction of a hadron build of same quarks. Accordingly we used Eq.(11) with $\sigma_{\rho N}$ calculated basing on the fit of \cite{36} for elastic $\rho$ meson photoproduction off proton and the vector dominance model.

Comparing to a proton-nucleus case two options of restricting the mass $M_X$ of produced system were slightly modified to take into account correctly the low energy photoproduction that is necessary because of two-side specifics of the symmetric nucleus-nucleus ultraperipheral collisions. So, we considered variation of the upper limit of $M_X$ with increase of the photon-nucleon CM energy $W_{\gamma p}$ as $M_X \leq 0.1 W_{\gamma p}$. As a second option we used combined approach: $M_X \leq 0.1 W_{\gamma p}$ until $W_{\gamma p} \leq 50\text{GeV}$ and fixed upper limit $M_X \leq 5\text{GeV}$ at higher energies (central rapidities).

We present the results of our calculations of the nucleon-dissociative $\rho$ meson photoproduction cross section in ultraperipheral heavy ion collisions at LHC for a few values of the squared momentum transfer in Figs. 7\textbf{8}9\textbf{10}.

One can see that for heavy nuclei suppression may reduce the cross section by a factor of ten and more. So the reduction depends strongly on the value of $q\bar{q}$ dipole interaction with nucleons and, hence, these processes are very sensitive to higher twist effects. Even in the case of large screening effects, the rates would be large enough up to $-t \sim 10\text{GeV}^2$ (see Fig\textbf{11}) and it would be doable to study how the screening effects are reduced with increase of $t$. This information would be complementary to the information about energy dependence of the elastic small dipole - parton amplitude which is studied in the scattering off protons.

\section{Conclusions}

To summarize, we have have found that the HERA data suggest a much faster energy dependence of the dipole - parton amplitude than in the soft dynamics. However the cuts used by the experiments make it difficult a direct determination of this energy dependence. We demonstrated that the study of the processes with rapidity gaps being feasible in UPC at LHC will allow a direct measurement of important property of the pQCD - energy dependence of the large $t$ elastic amplitude of dipole-parton scattering. In the case of $\rho$ meson production off nuclei we argued that there exist several different regimes of $A$-dependences related to the transition from a soft regime to the color transparency regime with increase of $-t$ for
Figure 7: Integrated over mass of produced system cross section of the nucleon dissociative $\rho$ meson photoproduction at $-t = 2.5 \, GeV^2$ in the ultraperipheral argon-argon collisions at LHC. The upper figure - the limit of the mass of produced system $M_X$ is proportional to the photon-nucleon center of mass energy $M_X \leq 0.1W_{\gamma p}$, in the lower figure for central rapidities the limit of $M_X$ is fixed by restriction $M_X \leq 5 \, GeV$. Solid line - calculations with Glauber-Gribov screening, dashed line - calculations in the leading twist approximation neglecting nuclear shadowing correction which is very small for discussed kinematics, dot-dashed line - one-side contribution when $\rho$ meson is produced by photons emitted by only one nucleus: large positive rapidities correspond to vector mesons produced by high energy photons. The counting rate can be estimated using expected luminosity for ArAr collisions $L = 1 \mu b^{-1} \, sec^{-1}$. 
Figure 8: The same as in Fig. 7 but at $-t = 5 \text{GeV}^2$. 

$W_{\gamma p}^{\gamma p}$, GeV

$\frac{d\sigma}{dtdy}$, $\mu$b/GeV$^2$

Ar+Ar→X+Ar+ρ LHC

$-t=5 \text{GeV}^2$, $M_X < 0.1 W_{\gamma p}$

$W_{\gamma p}^{\gamma p}$, GeV

$-t=5 \text{GeV}^2$, $M_X < 5 \text{GeV}$

$\frac{d\sigma}{dtdy}$, $\mu$b/GeV$^2$
Figure 9: The same as in Fig.7 but for PbPb UPC and \(-t = 2.5 \text{GeV}^2\). The counting rate can be estimated using expected luminosity for PbPb collisions \(L = 10^{-3} \mu \text{b}^{-1} \text{sec}^{-1}\).
Figure 10: The same as in Fig[1] but for PbPb UPC and $-t = 5 \text{GeV}^2$
Figure 11: Rapidity integrated counting rates for $\rho$ meson photoproduction with rapidity gap in the UPC Ar+Ar and Pb+Pb collisions as a function of $-t$. Lower bound of each colored space corresponds estimate in the Gribov-Glauber approach, upper - in the Impulse Approximation.
fixed $W$ and from color transparency to color opacity regimes for fixed $t$ and increase of $W_{sp}$, to an interplay of the leading and higher twist effects which is a nontrivial function of the rapidity gap interval. All together this provides a new powerful tool for studying the small dipole interaction with the media.

References

[1] E. M. Aitala et al. [E791 Collaboration], Phys. Rev. Lett. 86, 4773 (2001) [arXiv:hep-ex/0010044].

[2] M. D. Sokoloff et al. [Fermilab Tagged Photon Spectrometer Collaboration], Phys. Rev. Lett. 57, 3003 (1986).

[3] L. Frankfurt and M. Strikman, arXiv:nucl-th/0603049.

[4] L. Frankfurt and M. Strikman, Phys. Rev. Lett. 63, 1914 (1989) [Erratum-ibid. 64, 815 (1990)].

[5] J.D.Bjorken, Phys.Rev. D47 (1992)101.

[6] A.H.Mueller and W.-K.Tang, Phys.Lett.B284(1992)123.

[7] V.Del Duca and W.-K.Tang, Phys.Lett.B312(1993)225.

[8] H. Abramowicz, L. Frankfurt and M. Strikman, in SLAC Summer Inst.1994:0539-574 (QCD161:S76:1994) e-Print Archive: hep-ph/9503437, also Surv. High Energy Phys. 11, 51 (1997).

[9] J.R. Forshaw and M.G. Ryskin, Z. Phys. C 68, 137 (1995).

[10] J. Bartels et al., Phys. Lett. B 375, 301 (1996).

[11] F. Abe et al. [CDF Collaboration], Phys. Rev. Lett. 81, 5278 (1998).

[12] M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 369, 55 (1996) [arXiv:hep-ex/9510012].

[13] C. Adloff et al. [H1 Collaboration], Eur. Phys. J. C 24, 517 (2002) [arXiv:hep-ex/0203011].

[14] S. Chekanov et al. [ZEUS Collaboration], Eur. Phys. J. C 26, 389 (2003) [arXiv:hep-ex/0205081].

[15] A. Aktas et al. [H1 Collaboration], Phys. Lett. B 568, 205 (2003) [arXiv:hep-ex/0306013].

[16] A. Aktas et al. [H1 Collaboration], Phys. Lett. B 638, 422 (2006) [arXiv:hep-ex/0603038].
[17] Kuraev EA, Lipatov LN, Fadin VS, Sov. Phys. JETP 44: 443 (1976); Sov. Phys. JETP 45: 199 (1977) Balitsky II, Lipatov LN, Sov. J. Nucl. Phys. 28: 822 (1978)

[18] L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B 640, 162 (2006) [arXiv:hep-ph/0605160].

[19] L. Frankfurt and M. Strikman, [arXiv:hep-ph/9609456], Proceedings of Workshop on Future Physics at HERA (Hamburg, Germany, 25-26 Sep 1995), 949-952.

[20] L.N. Lipatov, private communication, 1989.

[21] D. Colferai, [arXiv:hep-ph/0008309]

[22] G. P. Salam, [arXiv:hep-ph/0501097].

[23] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP 0207, 012 (2002) [arXiv:hep-ph/0201195].

[24] S. Erhan and P. E. Schlein, Phys. Lett. B 481, 177 (2000) [arXiv:hep-ex/9909035].

[25] A. Levy, Nucl. Phys. Proc. Suppl. 146, 92 (2005) [arXiv:hep-ex/0501008].

[26] J.Olsson, [hep-ex/0610077] to be published in proceedings of DIS06.

[27] EMC Coll., J. Ashman et al., Z. Phys. C 52 (1991) 1.

[28] M. Strikman, M. G. Tverskoy and M. B. Zhalov, Phys. Lett. B 459, 37 (1999), [arXiv:nucl-th/9806099].

[29] S. Mandelstam, Nuovo Cim. 30, 1148 (1963).

[30] V.N. Gribov, The Theory of complex angular momenta: Gribov lectures on theoretical physics, Cambridge Univ. Press, 2003.

[31] J.Bartels, L.Lipatov and G.Vacca Nucl.Phys.B706(2005)391

[32] B. Blok and L. Frankfurt, “The casualty and/or energy-momentum conservation constraints on QCD amplitudes in small x regime,” [arXiv:hep-ph/0611062].

[33] L. Frankfurt, M. Strikman and C. Weiss, Ann. Rev. Nucl. Part. Sci. 55, 403 (2005) [arXiv:hep-ph/0507286].

[34] B. Blaettel, G. Baym, L. L. Frankfurt, H. Heiselberg and M. Strikman, Phys. Rev. D 47, 2761 (1993),
L. Frankfurt, G. A. Miller and M. Strikman, Phys. Lett. B 304, 1 (1993) [arXiv:hep-ph/9305228].
L. Frankfurt, A. Radyushkin and M. Strikman, Phys. Rev. D 55, 98 (1997) [arXiv:hep-ph/9610274].

[35] L. Frankfurt, V. Guzey and M. Strikman, Phys. Rev. D 71, 054001 (2005) [arXiv:hep-ph/0303022].
[36] A. Donnachie and P. V. Landshoff, Phys. Lett. B 478, 146 (2000) [arXiv:hep-ph/9912312].