# QUARCONIUM PHOTOPRODUCTION IN ULTRAPERIPHERAL ION COLLISIONS WITH THE ALICE DETECTOR AT LHC

**V.N. Nikulin, V.M. Samsonov, M.B. Zhalov**

We analyze possibility to study the small Bjorken variable $x$ behavior of nuclear gluon density and other features of small $x$ QCD dynamics measuring the cross section of photoproduction of heavy quarkonia in the ultraperipheral ion collisions with the ALICE detector at LHC.

At high energies the theory of strong interactions, Quantum Chromodynamics (QCD), enters a new regime characterized by strong coherent gluon fields. The QCD cross sections are driven by gluons in the hadron wave functions carrying the very small fraction $x$ of the hadron longitudinal momentum. It was discovered at HERA that the density of soft gluons rapidly grows with a decrease of $x$ down to a value of about $10^{-4}$ at fixed momentum transfer $Q^2$ and with an increase of $Q^2$ at fixed $x$. The HERA data are obtained in the $x - Q^2$ domain where the evolution of the parton distributions can be still described within perturbative QCD (pQCD) by DGLAP (Dokshitzer-Gribov-Lipatov-Altarelly-Parisi) and by Leading Order (Balitsky-Fadin-Kuraev-Lipatov) + Next-to-Leading Order (Ciafalloni *et al.*) BFKL evolution equations. In nucleus-nucleus collisions at energies around $3A$ TeV the essential value of $x$ can be, at least, by one order smaller than those at the HERA energies. The behavior of the gluon density in this region of $x$ is still not well understood theoretically and is not studied, in particular for nuclear target, experimentally. Asymptotically ($x \to 0$) the growth of gluon density is limited by the unitarity of the $S$ matrix but already at LHC one can expect revealing of strong gluon shadowing, parton recombination and gradual onset of the gluon density saturation which could be responsible for the probability conservation within the regime of strong gluon fields. Understanding of these phenomena is very important for successful realization of the high energy nuclear physics program with ALICE detector at the LHC focused on creation and characterization of new extreme forms of a quark-gluon matter where the chiral symmetry is restored and color is not confined within hadrons.

Our goal is to demonstrate that the detector ALICE can be used without significant modifications to study the photoproduction of heavy quarkonia in the ultraperipheral ion collisions and, hence, to investigate the small $x$ QCD dynamics of high energy interactions. The ultrarelativistic heavy ions produce a significant flux of quasireal photons. The photon wave function contains the hadron components (vector dominance) as well as the direct quark-antiquark components with sizes which are controlled by the quark mass, $r \propto m_q^{-1}$. Hence, the coherent photoproduction of heavy flavor vector mesons by quasireal photons off nuclei provides unique opportunities. Selecting a particular final state which contains, for example, $c\bar{c}$ or $b\bar{b}$ pairs, one can *postselect* a small size initial state thus justifying analysis of the process within the framework of perturbative QCD. The QCD factorization theorem for the hard exclusive coherent heavy flavor vector meson ($V$) photoproduction off particular target ($T$) implies that the cross section is proportional to the square of the corresponding gluon density $G_T(x, Q^2)$:

$$\sigma_{\gamma T \to VT}(s_{\gamma T}) \propto \left| x G_T(x, M_V^2/4) \right|^2, \tag{1}$$

where $x = \frac{M_V^2}{s_{\gamma T}}$. Our analysis of the ALICE capability to study the coherent photoinduced processes in ultrarelativistic peripheral $AA$ collisions at LHC is based on the predictions of Refs. [1-3] where the cross section was calculated using the Weizsacker-Williams approximation:

$$\frac{d\sigma(AA \to VAA)}{dy} = N_\gamma(y)\sigma_{\gamma A \to VA}(y) + N_\gamma(-y)\sigma_{\gamma A \to VA}(-y). \tag{2}$$

Here $y = \ln(\frac{1}{x}\frac{M_V}{2\gamma_L m_N})$ is the rapidity, $\gamma_L$ is the Lorentz factor and $N_\gamma(y)$ is the flux of the equivalent photons emitted by nucleus which can be calculated with a reasonable accuracy. The cross section of the process $\gamma A \to VA$ was considered in the Leading Twist Approximation (LTA) for the nuclear gluon shadowing:

$$\sigma_{\gamma A\to VA}(y) = \frac{d\sigma_{\gamma N\to VN}(\omega, t_{min})}{dt}\left[\frac{G_A(x, \frac{M_V^2}{4})}{G_N(x, \frac{M_V^2}{4})}\right]^2 \int\limits_{-\infty}^{t_{min}} dt \left| \int d^2b dz e^{i\vec{q}_t\cdot\vec{b}} e^{-q_l z} \rho(\vec{b}, z)\right|^2. \qquad (3)$$

Here $-t = |\vec{q}_t|^2 + |q_l|^2$ is the square of the vector meson transverse momentum and $\sqrt{-t_{min}} = q_l = \frac{M_V^2}{2\omega}$ is the minimal longitudinal momentum transfer in the photoproduction vertex, $\rho(\vec{b}, z)$ is the nuclear density normalized by the condition $\int d^2bdz\rho(\vec{b}, z) = A$.

The key characteristics of the nuclear shadowing in the photoproduction of the hidden heavy flavor vector mesons is the ratio of the gluon density distribution in nucleus, $G_A(x, Q^2)$, to that in proton, $G_N(x, Q^2)$. At $x \geq 0.01$ the nuclear gluon density $G_A(x, Q^2) \approx AG_N(x, Q^2)$, and a distance on which the squeezed $q\bar{q}$ pair transforms into the "ordinary" meson is large at high energies. Hence, one should expect the revealing of the Color Transparency (CT) effect when small colour singlet dipole $q\bar{q}$ passes through the nuclear medium. With a decrease of $x$ ($x < 0.01$) the nuclear gluon shadowing ($G_A(x, Q^2)/AG_N(x, Q^2) < 1$) should lead to a gradual disappearance of color transparency and to the onset of a new regime – *the perturbative color opacity* in photoproduction of heavy quarkonium off nuclei.

The total cross sections for the coherent $J/\psi$ and $\Upsilon$ production in the ultraperipheral ion collisions calculated in Refs. [1-3] are given in Table 1. From comparison of calculations performed in the LTA with estimates in the Impulse Approximation it follows that the $\Upsilon$ yield is expected to be suppressed by a factor of 2 at central rapidities due to the leading twist shadowing. The suppression of the $J/\psi$ cross section is much stronger, by a factor of 4–6. In principle, the multiple eikonal type rescatterings of the small color singlet dipole (squeezed $q\bar{q}$ pair) off nucleus could also result in suppression of the heavy quarkonium photoproduction. This mechanism predicts significantly smaller suppression than the leading twist gluon shadowing, at least for $x \leq 0.001$.

Experimentally, the coherent quarkonium photoproduction in the ultraperipheral ion collisions has clearly distinguishable signature. The dimuon decay mode could be used to tag effectively the reaction of interest. The ALICE muon arm provides the Level 0 triggers in the situations when one or two fast ($p > 5$ GeV/c) muons are within its acceptance ($2^\circ < \Theta < 8^\circ$). The reconstructed equivalent mass of the muon pair identifies the parent particle (the dimuon arm mass resolution is about 100 MeV at $\Upsilon$ mass). Since the ions in the coherent photoproduction remain intact, only muon pair should be detected and nothing else. The photon spectrometer PHOS covers approximately 10% of the barrel solid angle. The grazing ion collision results in strong nucleon-nucleon interactions with production of some number of hadrons that hit the PHOS with a large probability. That is why a veto from the PHOS subsystem could be used to preselect very peripheral events. This signal is implemented in the PHOS Level 0 trigger electronics on our request. We expect that the PHOS veto will reduce the single muon trigger rate to affordable level. The inefficiency estimated for such kind of trigger (the muon hit in the PHOS) is expected to be at a level of 3%.

*Table 1*

Total cross sections of $J/\psi$ and $\Upsilon$ production
in ultraperipheral collisions at LHC

| Colliding ions | CaCa, $\gamma = 3500$ | | PbPb, $\gamma = 2700$ | |
|---|---|---|---|---|
| Quarkonium | $J/\psi$ | $\Upsilon$ | $J/\psi$ | $\Upsilon$ |
| Impulse | 0.6 mb | 1.8 $\mu$b | 70 mb | 133 $\mu$b |
| Leading Twist | 0.2 mb | 1.2 $\mu$b | 15 mb | 78 $\mu$b |

Further improvement could be achieved at trigger level 1 applying the decision of the Zero Degree Calorimeters (ZDC). The coherent photoproduction of vector mesons in the ultraperipheral collisions can be accompanied by some number of neutrons emitted due to decays of one or both nuclei excited by additional photon exchanges. These neutrons with high efficiency will be detected by the ZDC placed on the axis of the ALICE detector at large distances from the interaction point. Detecting of the dimuon pair in combination with the vetoes of hadron detector systems and ZDCs will effectively select the coherent photoproduction events.

At the same time, it was recently shown [3] that the ultraperipheral heavy ion collisions can be used to measure not only the nuclear gluon densities but also the nucleon gluon density almost in the same kinematical conditions. To achieve these aims, one has to study quasielastic quarkonium photoproduction off the nuclear nucleon at momentum transfer more than a few hundreds MeV. In this case one of the colliding nuclei which emits the photon remains intact. The nucleon of another nucleus, participating in the process of photoproduction, will interact with other nucleons of target nucleus. As a result, the nucleus becomes excited and decays emitting a few neutrons [3] which will be registered by ZDC. The cross section of this incoherent process is proportional to the squared nucleon gluon density and the mass number of the target nucleus. The experimental signature of such events is signal from one side ZDC detecting a few neutrons in direction opposite to the direction of quarkonium produced with transverse momentum $p_t \geq 200$ MeV. Similar type of events can be due to the physical background – coherent production of heavy quarkonia in strong interactions, however the probability to keep, at least, one of the colliding ions intact in such processes is expected to be very small.

An estimate of the total yields is not sufficient to prove the feasibility of the experimental studies. The sub-detectors, capable to detect heavy quarkonia through their dimuon decay, should be able to produce trigger for the coherent $J/\psi$ and $\Upsilon$ production in the ultraperipheral collisions ; also the acceptances of these sub-detectors may cut significantly the phase space of the reaction. The acceptances were estimated using the approximative method and with the detailed `AliRoot` simulation code – both approaches give similar results. No detailed event reconstruction was done. In the approximate simulation we *assume* that the muon in angular range $2^\circ < \Theta < 8^\circ$ and $p > 5$ GeV/c is detected by the muon arm and the muon in the range of $45^\circ < \Theta < 135^\circ$ is detected in the barrel detectors (ITS + TPC). In the `AliRoot` simulation we assume that once the muon passed through the detector (10 Tracking chambers + 4 Trigger chambers of the dimuon arm and/or has hits both in ITS and TPC), the detector response could be successfully analyzed. The muon trigger efficiencies were taken into account.

The machine-induced background (beam-gas interactions) is expected to be negligible.

Another source of physical background is the muon pair production in $\gamma\gamma$ interactions. The total number of these triggers could be significant. The studies of the muon pair production in $\gamma\gamma$ interactions have a special interest, this well understandable process could be used for the calibrations of the detector.

The signal-to-background ratio in the mass range of interest (in the vicinity of the $J/\psi$ peak) is expected to be of the order of one. The significance (signal/$\sqrt{\text{signal} + \text{background}}$) of the data collected during standard LHC heavy ion year (running time of $10^6$ sec at mean luminosity of $\mathcal{L}_{mean} = 0.5 \times 10^{27}\text{sec}^{-1}\text{cm}^{-2}$) is estimated to be about 100 in a case of $J/\psi$ and of the order of 1 in a case of $\Upsilon$. The mass ranges of interest have been chosen depending on the estimated mass resolution: the resolution is better in case when second muon is detected in the barrel part because the vertex position can be reconstructed.

The acceptances for the heavy quarkonia photoproduction in the ultraperipheral lead-lead collisions are presented in Figs. 1, 2.

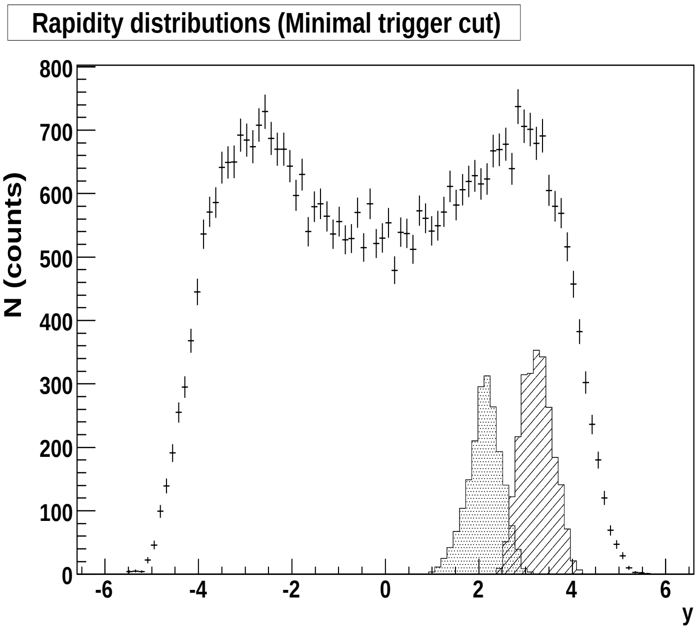

**Fig. 1.** The $J/\psi$ coherent photoproduction acceptance, the `AliRoot` estimation within *Minimal* trigger $p_T$ cut. The left (grey) peak corresponds to the case when one muon is triggered by the dimuon spectrometer, the other one is detected by the barrel. The right (hatched) peak is formed of the muon pair detected by the dimuon arm. Pb-Pb collision case

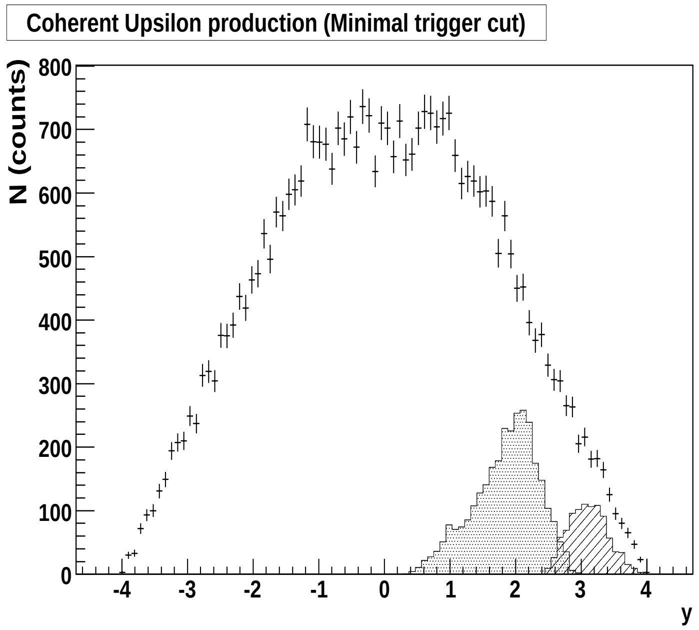

**Fig. 2.** The $\Upsilon$ coherent photoproduction acceptance, the `AliRoot` estimation within *Minimal* trigger $p_T$ cut. The left (grey) peak corresponds to the case when one muon is triggered by the dimuon spectrometer, the other one is detected by the barrel. The right (hatched) peak is formed of the muon pair detected by the dimuon arm. Pb-Pb collision case

*Table 2*

Acceptance $A$, statistics $N$, signal-to-background ratio $N/Bg$ and significance ($S = N/\sqrt{N + Bg}$) to be accumulated during heavy ion running year for the coherent $J/\psi$ photoproduction in ALICE subsystems in the Pb-Pb collisions

| | Acceptance | Statistics | $N/Bg$ | Significance |
|---|---|---|---|---|
| $\mu\mu$-channel | 5.29% | 23300 | 1.27 | 122 |
| $B\mu$-channel | 4.86% | 12200 | 0.57 | 80 |

*Table 3*

Acceptance $A$, statistics $N$, signal-to-background ratio $N/Bg$ and significance ($S = N/\sqrt{N + Bg}$) to be accumulated during heavy ion running year for the coherent $\Upsilon$ photoproduction in ALICE subsystems in the Pb-Pb collisions

| | Acceptance | Statistics | $N/Bg$ | Significance |
|---|---|---|---|---|
| $\mu\mu$-channel | 2.45% | 24 | 0.05 | 1.1 |
| $B\mu$-channel | 6.02% | 78 | 0.05 | 1.8 |

The corresponding numerical results are given in Tables 2, 3 ($\mu\mu$ stands for the case when both muons are detected in the dimuon arm; $B\mu$ denotes the case when one muon has been detected in the barrel part, while another one passed through the muon spectrometer). These results show that the ALICE detector can be used without significant modifications to study the behavior of the nucleus gluon density distributions at small $x$ and to observe the transition from the nuclear color transparency to regime of the color opacity in the ultrarelativistic peripheral ion collisions. The counting rate for the coherent $J/\psi$ photoproduction is reasonable (order of thousand of $\mu^+\mu^-$ pairs per day within the dimuon arm acceptance). In a case of $\Upsilon$ photoproduction the counting rate is about of one hundred per heavy ion running year (including those detected in dimuon trigger and in the barrel-dimuon coincidence). The information which can be obtained from studying the heavy quarkonium photoproduction in ultraperipheral ion collisions will be undoubtedly useful for the reliable interpretation of the experimental data on study of the central heavy ion collisions aimed at the investigation of the quark-gluon plasma formation at LHC.

## References

1. L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B **540**, 220 (2002).
2. L. Frankfurt, V. Guzey, M. Strikman and M. Zhalov, JHEP **0308**, 043 (2003).
3. M. Strikman, M. Tverskoy and M. Zhalov, Phys. Lett. B **626**, 72 (2005).