Coherent and incoherent Upsilon production in ultraperipheral collisions at the Large Hadron Collider

M.B. Gay Ducati, F. Kopp, M.V.T. Machado
High Energy Physics Phenomenology Group, GFPAE IF-UFRGS
Caixa Postal 15051, CEP 91501-970, Porto Alegre, RS, Brazil

The exclusive photoproduction of Υ(nS) states were calculated in ultra peripheral collisions for coherent and incoherent process in PbPb at $\sqrt{s_{NN}} = 5.5$ TeV. Different dipole models were compared in the theoretical framework of light-cone color dipole formalism. Moreover, it was calculated the differential cross section for the Upsilon states and their total cross section for two intervals of rapidity: $|y| \leq 4.4$ and $2 \leq y \leq 4.5$. A systematic study is done on the theoretical uncertainties associated to the production and predictions are presented for the first time for the incoherent cross section of the radially excited states.

PACS numbers: 12.38.Bx; 13.60.Hb

I. INTRODUCTION

The study of exclusive meson photoproduction in UPC [1] is an essential tool to understand the low-x physics and also to investigate the gluon density in this regime. In the UPC case, the exclusive photoproduction dominates the process through the emission of quasi-virtual photons which interact with the target. The photon-target interaction amplitude, when considering the light-cone approach for meson production and computing predictions on dynamics beyond the leading logarithmic QCD approach for meson photoproduction in $pp$ collisions. Those calculations were carried out in the theoretical framework of the color light-cone dipole formalism [2] and focused only on the coherent channel where the initial state particles remain intact after interaction. It was shown that the corresponding predictions describe correctly the experimental results from LHCb Collaboration [7] for $\Upsilon$ photoproduction in $pp$ collisions. Those data were obtained for typically large rapidities and the x-values to be covered are increasingly smaller for forward rapidities. We roughly get $x = \frac{m}{\sqrt{s_{NN}}} e^{-y} \approx 8 \times 10^{-5}$ at $y = 3$ and it is clear that gluon dynamics is being probed at extremely low-x and low perturbative scales $\mu^2 \approx 20$ GeV$^2$. This kinematical range is in the limit of application of usual pQCD and saturation approach should be relevant. For nuclear targets, the nuclear saturation scale $Q_{sat,A}^2 \simeq cA^{1/3}Q_{sat,p}^2$ (with $c \simeq 0.3$) reaches 2 GeV$^2$ in those cases [8]. The main novelty in current work is the detailed study of the incoherent cross section for the upsilon states. This is quite important, as it was pointed out that incoherent diffraction probes the fluctuations in the interactions strengths of multiparton Fock states in the nuclear wavefunctions [9]. The connection between incoherent diffraction and fluctuations is a quite rich subject and the pioneering works are found in Refs. [10]. Recently, the topic is very active and we call attention to the following works [11,12].

In this work, we investigate the exclusive (coherent and incoherent) production of $\Upsilon(1S)$ and its radially excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ in PbPb collisions for LHC energy. In a previous work [6] the coherent photoproduction of $\Upsilon$ states at various energies in $pp$, pPb PbPb collisions at the LHC has been considered. Those calculations were carried out in the theoretical framework of the color light-cone dipole formalism [2] and focused only on the coherent channel where the initial state particles remain intact after interaction. It was shown that the corresponding predictions describe correctly the experimental results from LHCb Collaboration [7] for $\Upsilon$ photoproduction in $pp$ collisions. Those data were obtained for typically large rapidities and the x-values to be covered are increasingly smaller for forward rapidities. We roughly get $x = \frac{m}{\sqrt{s_{NN}}} e^{-y} \approx 8 \times 10^{-5}$ at $y = 3$ and it is clear that gluon dynamics is being probed at extremely low-x and low perturbative scales $\mu^2 \approx 20$ GeV$^2$. This kinematical range is in the limit of application of usual pQCD and saturation approach should be relevant. For nuclear targets, the nuclear saturation scale $Q_{sat,A}^2 \simeq cA^{1/3}Q_{sat,p}^2$ (with $c \simeq 0.3$) reaches 2 GeV$^2$ in those cases [8]. The main novelty in current work is the detailed study of the incoherent cross section for the upsilon states. This is quite important, as it was pointed out that incoherent diffraction probes the fluctuations in the interactions strengths of multiparton Fock states in the nuclear wavefunctions [9]. The connection between incoherent diffraction and fluctuations is a quite rich subject and the pioneering works are found in Refs. [10]. Recently, the topic is very active and we call attention to the following works [11,12].

The paper is organized as follows. In the next section we give the main theoretical information to obtain the rapidity distribution of coherent and incoherent production of $\Upsilon(1S, 2S, 3S)$ states in PbPb collisions for the future LHC run and energies close to the run2. The main motivation is the successful description of experimental results measured by LHCb Collaboration [7] for $\Upsilon(1S)$ in $pp$ collisions. In the section III we present the phenomenological calculations, discuss the main theoretical

arXiv:1708.08546v1 [hep-ph] 28 Aug 2017
The dipole-proton cross section is denoted by \( \sigma \) and incoherent processes can be simply computed in high factorizes out from the dipole-nucleon scattering amplitude \( \Psi(z) \) is Gaussian and that the impact parameter dependence is ultra-relativistic and purely electromagnetic, one can use the Weizsäcker-Williams approximation [1].

The exclusive photoproduction of \( \Upsilon \) states off a nucleon target is given by, 

\[
\sigma(\gamma A \rightarrow \Upsilon A) = \int d^2b \left| \sum_{h,h} \int dz d^2r \Psi^*_{h,h} \Psi_{h,h}(x,r) T_A(b) \right|^2, 
\]

where \( T_A(b) \) is the nuclear thickness function. In the numerical evaluations, we have considered the boosted Gaussian wavefunction and several phenomenological saturation models, which encode the main properties of the saturation approaches. Accordingly, the cross sections above include both the skewedness and real part of amplitude corrections. Namely, we multiply the result above by \( K^2 = R_g^2(1 + \beta^2) \), where \( \beta = \tan(\pi \lambda_{f} / 2) \) is the ratio of real to imaginary parts of the scattering amplitude and \( R_g \) incorporates the off-forward correction (see [6] for details). The effective power on energy, \( \lambda_{f} \), is determined for each case. In order to take into account the threshold correction for the dipole cross section, we have multiplied them by a factor \((1 - x)^7\).

Finally, we set the parameters and phenomenological models to be considered in next section. For the slope parameter it was considered the energy dependency from the Regge phenomenology [6].

\[
B_{\Upsilon} = b_{el}^{\Upsilon} + 2 \alpha’ \log \left( \frac{W_{\gamma A}^2}{W_0^2} \right),
\]

with \( \alpha’ = 0.164 \text{ GeV}^{-2} \), \( W_0 = 95 \text{ GeV} \), \( b_{el}^{\Upsilon(1S)} = 3.68 \text{ GeV}^{-2} \), \( b_{el}^{\Upsilon(2S)} = 3.61 \text{ GeV}^{-2} \) and \( b_{el}^{\Upsilon(3S)} = 3.57 \text{ GeV}^{-2} \). It will be taken into account only for the incoherent cross section.

For the meson wavefunction, we will use the Boosted-Gaussian model [10] because it can be applied in a systematic way for excited states. The corresponding function is given by [17],

\[
\phi_{nS}(r,z) = \sum_{k=0}^{n-1} \alpha_{nS,k} R_{nS}^2 \tilde{D}^2(k,r,z) G_{nS}(r,z),
\]

with \( \alpha_{nS,0} = 1 \). The operator \( \tilde{D}^2(r,z) \) is defined by

\[
\tilde{D}^2(r,z) = m_f^2 - \left( \frac{1}{2} \partial_r + \partial_z^2 \right) - m_f^2, 
\]

and it acts on the following general integrand function

\[
G_{nS}(r,z) = N_{nS} z(1 - z) \exp \left( - \frac{m_f^2 R_{nS}^2}{8z(1 - z)} - \frac{2z(1 - z)^2}{R_{nS}^2} + \frac{m_f^2 R_{nS}^2}{2} \right). 
\]
The main physical quantity is the dipole scattering cross section. We consider the following phenomenological models in our analysis: GBW [18], CGC [19] and BCGC [20]. The GBW model is defined by the eikonal shape for the dipole cross section,

$$\sigma_{qg}^{GBW}(x,r) = \sigma_0 \left(1 - e^{-r^2 Q_s^2(x)/4}\right), \tag{7}$$

where $\sigma_0 = 2\pi R^2$ is a constant and $Q_s^2(x) = (x_0/x)^\lambda GeV^2$ denotes the saturation scale. We also consider the CGC model [19], based in the Color Glass Condensate framework, in which gluon saturation effects are incorporated via an approximate solution of the Balitsky-Kovchegov equation [4]. The expression for the CGC model is given by,

$$\sigma_{qg}^{CGC}(x,r) = \sigma_0 \left\{ \begin{array}{ll}
N_0 \left(\frac{rQ_s}{x}\right)^{\gamma_{eff}(x,r)} & : rQ_s \leq 2 \\
1 - e^{-Ah r^2(B r Q_s)} & : rQ_s > 2
\end{array} \right. \tag{8},$$

where $\gamma_{eff}(x,r) = 2(\gamma_s + (1/\kappa\lambda) \ln(1/x))ln(2/rQ_s)$ is the effective dimensional and one has the constant $\kappa = 9$.

In order to investigate the theoretical uncertainty associated to the models for the dipole cross section, we use the original values (OLD label) of parameters for the fits including the charm contribution. That is, for GBW-OLD we follow Ref. [18], for CGC-OLD Ref. [21] is considered and bCGC-OLD refers to Ref. [20]. The bCGC model uses the same functional form of Eq. (8) and replaces the saturation scale in the following way: $Q_s^2(x) \rightarrow Q_s^2(x,b)^2 = (x_0/x)^\lambda \exp[-b^2/(2\gamma_s BCGC)]$. Moreover, we consider the updated version of those models, GBW-NEW [22], CGC-NEW [22] and bCGC-NEW [22], respectively. A comment is in order here: the GBW-NEW parametrization is very different from other color dipole fits, as it includes energy evolution of the subnucleonic shape of the proton and it can potentially significantly affect the incoherent cross section. In particular, GBW-OLD and GBW-NEW are qualitatively very different and GBW-NEW is not fitted to all $F_2$ small-$x$ data (DESY-HERA) as discussed in details in Ref. [12].

III. RESULTS AND DISCUSSIONS

Let us start the analysis by computing the theoretical predictions for the coherent process for PbPb collisions at $5.5$ TeV. Here, we disregard any absorptive corrections. In Figure 1 it is presented the results for photoproduction of $\Upsilon$ states, including its radial excitations, taking into account the different models presented in the last section. The theoretical uncertainty is relatively large, being of order 15% for the 1S state (similar for the remaining 2S and 3S states). We could have an additional uncertainty related to the vector meson wave function, however in Ref. [23] it was shown that this is not the case for $\Upsilon$ states (the overall theoretical uncertainty is within the experimental error bars in pp case [7]). For the main contribution, we have $d\sigma_{coh}/dy(y=0) = 18.5 \pm 3.5 \mu b$ for $\Upsilon(1S)$. The relative contribution of the excited states compared to the bound states is $\Upsilon(1S)/\Upsilon(2S)/\Upsilon(3S) = 1/0.17/0.09$. We see that the relative normalization and the overall behavior is changed mostly at mid-rapidity when comparing the old and updated versions of the dipole cross sections (the deviation at large rapidities is less evident). Notice that the LHCb data for upsilon production in $pp$ collisions is reproduced by all the models in the forward region [7] as shown in Ref. [8]. Therefore, the current level of the experimental uncertainties does not allow us to make definitive statements about the precision of the models considered. For sake of completeness, we present the integrated cross sections considering distinct cuts on rapidity. In Table I we present the results for the full rapidity coverage, $-4 < y < 4$, and forward rapidities, $2 \leq y \leq 4.5$. In both tables I and II we present only the updated versions of the dipole cross sections. For sake of completeness, we present the ratio of the cross sections, $\sigma(\gamma A \rightarrow \Upsilon(nS)A)/\sigma(\gamma A \rightarrow \Upsilon(1S)A)$, as a function of the photon-nucleus centre-of-mass energy, $W_{\gamma A}$. We present in Fig. 2 the result using the bCGC-NEW and GBW-NEW dipole cross sections. It was verified that the CGC-NEW result is quite similar to the bCGC-NEW one. We see a relative energy dependence, following the same trend as for the $\psi(nS)$ states [24].

We now focus on the incoherent reaction, $PbPb \rightarrow Pb \Upsilon Pb^*$. This is a new contribution to the literature concerning the upsilon production. The rapidity distribution is shown in Fig. 3 using the same notation as the previous figure. As already known, the incoherent cross section is smaller than the coherent one. The typical ratio is $(d\sigma_{inc}/dy)/(d\sigma_{coh}/dy) \simeq 0.2$. For instance, we obtain $d\sigma_{inc}/dy(y=0) = 3.75 \pm 1.25 \mu b$ for $\Upsilon(1S)$. The theoretical uncertainty seems to be larger than in the coherent case. The integrated cross sections are shown in Table II in the rapidity ranges $|y| \leq 4$ and $2 \leq y \leq 4.5$.

The calculations performed above can be compared to another theoretical approaches available in the literature. Let start comparing them to the STARlight Monte Carlo [12]. For the coherent production, the predictions for the $\Upsilon$ state ratios are lower that STARlight results. As discussed in Ref. [8], the possible origin comes from the extrapolation of HERA-DATA and taking a fixed ratio

| TABLE I: Integrated cross section (in units of $\mu b$) for coherent reactions, $PbPb \rightarrow Pb \Upsilon Pb^*$, for full rapidity coverage and forward rapidities. Here, we consider the updated versions of dipole cross sections. |
|---------------------------------|---------|----------|---------|
| Process: $PbPb$ $\sqrt{s} = 5.5$ TeV | $|y| \leq 4$ | $2 \leq y \leq 4.5$ |
| $\Upsilon(nS)$ | GBW | CGC | b-CGC |
| $\Upsilon(1S)$ | 163.7 (60.8) | 171.9 (63.8) | 143 (53.1) |
| $\Upsilon(2S)$ | 20.3 (7.8) | 22.0 (8.2) | 20.5 (7.7) |
| $\Upsilon(3S)$ | 10.3 (3.9) | 11.9 (4.3) | 10.9 (4.1) |
Glauber-Gribov approach. We verified that our results are also smaller that in Ref. [13], which can be related to more shadowing in color dipole models compared to the VDM+Glauber approach. In Ref. [25] only the coherent contribution was computed and the theoretical uncertainty we have found in the color dipole approach is comparable to perturbative QCD formalism. Concerning similar dipole calculations, more recent investigations are available in Refs. [23, 26]. In Ref. [26] only the coherent \( \Upsilon(1S) \) production has been considered at 5.02 TeV. The results are smaller than ours and the main reason is the wavefunction chosen (Light Cone Gaussian wavefunction which gives smaller overall normalization compared to Boosted Gaussian one). The authors in [26] did not investigate the theoretical uncertainty associated to the wavefunction and dipole cross sections as well (only the uncertainty coming from one model for dipole cross section was addressed). In Ref. [23] the theoretical uncertainty for the coherent and incoherent cross section was investigated. However, predictions for higher energies in PbPb collisions were not presented and only the \( \Upsilon(1S) \) state was considered (the results are consistent with ours in that case). Finally, we did not consider photonuclear breakup in the present study. We will consider them in future analysis as they are important and the distinct channels have been measured for \( p \) and \( J/\psi \) photoproduction in UPCs [27, 28]. This sort of analysis was recently done in Ref. [29], where the coherent \( \Upsilon(1S) \) production was considered using a pQCD model with NLO accuracy. An important point discussed in [20] is that the large \( y \) region gives the dominant contribution for 0nXn and XnXn channel and they probe larger photon-target centre-of-mass energy than the case without neutron tagging.

### IV. SUMMARY

We presented the predictions of rapidity distribution and integrated cross sections for the \( \Upsilon(1S, 2S, 3S) \) states for the LHC run 2 energies. The rapidity intervals used in total cross section were selected to match with the rapidity coverage of LHCb and ALICE detectors both
covering $2 \leq y \leq 4.5$. The main contribution is the computation of the incoherent cross section within the color dipole approach and Glauber-Gribov treatment of nuclear shadowing. The cross section for the excited states are also calculated in a consistent formalism where the wavefunction of $2S$ and $3S$ states are theoretically well constrained. The usual procedure in the literature involves only an extrapolation of DESY-HERA production ratios to the LHC energies. Our calculations are directly comparable to the STARLight calculation, where distinct procedures are involved in the computation of nuclear shadowing (VDM plus Glauber model versus color dipole plus Glauber-Gribov approach) and how to obtain the incoherent cross section.

**Acknowledgments**

This work was partially financed by the Brazilian funding agency CNPq and Rio Grande do Sul funding agency FAPERGS.

[1] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, Y. Kharlov, Phys. Rep. 364, 359 (2002); C. A. Bertulani, S. R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55, 271 (2005).
[2] N. N. Nikolaev, B. G. Zakharov, Phys. Lett. B 332, 184 (1994); Z. Phys. C 64, 631 (1994).
[3] J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Phys. Lett. B 374, 199 (1996).
[4] F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. 60, 463 (2010); H. Weigert, Prog. Part. Nucl. Phys. 55, 461 (2005); J. Jalilian-Marian and V. Y. Kovchegov, Prog. Part. Nucl. Phys. 56, 104 (2006); A.L. Ayala, M.B. Gay Ducati and E.M. Levin, Nucl.Phys. B 493, 305 (1997).
[5] A. Dainese, in Proceedings of the 38th International Symposium of Multiparticle Dynamics (ISMD2008): Hamburg, Germany, September 15-20 2008, p.118-124, arXiv:0902.0377 [hep-ph].
[6] M. B. Gay Ducati, F. Köpp, M.V. T. Machado, and S. Martins. Phys. Rev. D 94, 094023 (2016).
[7] R. Aaij et al. [LHCb Collaboration], JHEP 1509, 084 (2015).
[8] K. Dusling , F. Gelis, T. Lappi and R. Venugopalan, Nucl. Phys. A 836, 159 (2010).
[9] T. Lappi, H. Mäntysaari, R. Venugopalan, Phys. Rev. Lett. 114, 082301 (2015). H. Mäntysaari and B. Schenke, Phys. Rev. Lett. 117, 052301 (2016).
[10] L. Frankfurt, G.A. Miller and M. Strikman, Phys. Rev. Lett. 71, 2859 (1993); A. Caldwell and H. Kowalski, Phys. Rev. C 81, 025203 (2010).
[11] Kirill Tuchin, Phys. Rev. C 79, 055206 (2009); T. Lappi and H. Mäntysaari, Phys. Rev. C 83, 065202 (2011) ; T. Toll and T. Ulrich, Phys. Rev. C 87, 024913 (2013) ; H. Mäntysaari, B. Schenke, C. Shen and P. Tribedy, Phys. Lett. B 772, 681 (2017).
[12] J. Cepila, J.G. Contreras, J. D. Tapia Takaki, Phys. Lett. B376 , 186 (2017).
[13] S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov and J. Butterworth, Comput. Phys. Commun. 212, 258 (2017).
[14] S. Klein and J. Nystrand, Phys. Rev. C 60, 014903 (1999).
[15] B. Z. Kopeliovich and B. G. Zakharov, Phys. Rev. D 44, 3466 (1991); Yu.P.Ivanov, J.Huefner, B.Z.Kopeliovich and A.V.Tarasov, AIP Conf.Proc. 660, 283 (2003).
[16] J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Phys. C 75, 71 (1997) 71.
[17] B.E. Cox, J. R. Forshaw and R. Sandapen, JHEP 0906 , 034 (2009).
[18] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D 59, 014017 (1998).
[19] E. Iancu, K. Itakura, J. Seger, Y. Gorbunov and J. Butterworth, Comput. Phys. Commun. 212, 258 (2017).
[20] H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D 74, 074016 (2006).
[21] G. Soyez, Phys. Lett. B655 , 32 (2007).
[22] A.H. Rezaeian and I. Schmidt, Phys. Rev. D88, 074016 (2013).
[23] G. Sampao dos Santos and M.V.T. Machado, J. Phys. G42, 105001 (2015).
[24] N. Armesto, A. H. Rezaeian, Phys.Rev. D90, 054003 (2014).
[25] A. Adeluyi and A. Nguyen, Phys. Rev. C 87, 027901
(2013).

[26] V.P. Gonçalves, B.D. Moreira and F.S. Navarra, Phys. Rev. D95, 054011 (2017).

[27] J. Adam et al. [ALICE Collaboration], JHEP 1509, 095 (2015).

[28] V. Khachatryan et al. [CMS Collaboration], Phys. Lett. B 396, 772 (2017).

[29] V. Guzey, E. Kryshen and M. Zhalov, Phys. Rev. C93, 055206 (2016).