Quarkonium production in coherent AA collisions and small-x physics

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Outline

- Short motivation
- Ultra-Peripheral Collisions (UPCs) of heavy ions
- Quarkonium production in UPCs
- Model for photonuclear cross section - color dipole approach
- Results for exclusive J/Ψ and Υ production
- Summary.

Motivation

- UPCs are defined as collisions in which no hadronic interactions occur due to large spatial separation between projectile and target.
- Interactions are mediated by the electromagnetic field.
- One type of UPC is the photonuclear interactions, in which a photon from the projectile interacts with the hadronic component of target.
- Good reasons to study electromagnetic interactions at hadron colliders:
  (1) Range of accessible photon energies will be strongly increased at the LHC and the equivalent luminosities will be higher than at existing electron colliders.
  (2) Using nuclear beams effects of very strong fields can be studied (small-x physics, nuclear shadowing, . . .).

Motivation

- Concerning quarkonium production in UPCs, if the photon spectrum is known, $d\sigma/dy$ is a direct measure of the meson photoproduction cross section for a given photon energy.
- In the LHC (PbPb mode) the photon energies for production around mid-rapidity correspond to a gluon x-values of 6×10^{-4} for J/Ψ production and 2×10^{-3} for Υ production. Lower values of x can be reached away from mid-rapidity.
- Experimental feasibility of studying exclusive meson production in UPCs has been demonstrated at RHIC (coherent ρ production measured by STAR and J/Ψ production in PHENIX).
- The Yellow Report of Prediction for UPCs at the LHC has been recently completed.

UPCs of heavy ions

- The electromagnetic field of a relativistic particle corresponds to an equivalent flux of photons.
- In the case of interaction between two nuclei, in general the photon spectrum is computed as a function of impact parameter in a semi-classical approach.
- Thus, interactions where the nuclei interact strongly can be excluded (roughly speaking, considering $b > 2R_A$).
- We consider an analytical expression for photon spectrum:

$$\frac{dn_\gamma}{dk} = \frac{2\,Z^2\alpha_{em}}{\pi\,k}\left[\bar{\eta}\,K_0\left(\bar{\eta}\right)K_1\left(\bar{\eta}\right) + \frac{\bar{\eta}^2}{2}\,\left(K_1^2\left(\bar{\eta}\right) - K_0^2\left(\bar{\eta}\right)\right)\right],$$

- The photon energy is k and $\bar{\eta} = 2kR_A/\gamma_L$.

Quarkonium production in UPCs

- The total exclusive cross section for heavy mesons can be written as an integral over the equivalent photon energy:

$$\sigma(A+A\rightarrow A+A+V) = 2\int \sigma_{\gamma+A\rightarrow V+A}(k)\,\frac{dn_\gamma}{dk}\,dk$$

- The rapidity y of the produced vector meson is related to its mass, M_V, and the photon energy through $k=(M_V/2)\exp(y)$.
- The rapidity distribution can be obtained as

$$\frac{d\sigma(AA\rightarrow AA+V)}{dy} = k_1\frac{dn_\gamma}{dk_1}\sigma_{\gamma A\rightarrow VA}(k_1) + k_2\frac{dn_\gamma}{dk}\sigma_{\gamma A\rightarrow VA}(k_2)\,,$$

- Here, $k_{1,2}=(M_V/2)\exp(\pm y)$. At mid-rapidity, $k_1=k_2$ and the contributions from the two terms are equal.

Photonuclear cross section

- The photonuclear cross section can be written as

$$\sigma(\gamma A \to V\, A) = \left.\frac{d\sigma\,(\gamma A \to V\, A)}{dt}\right|_{t=0} \int_{t_{min}}^{\infty} d|t|\,|F_A(t)|^2$$

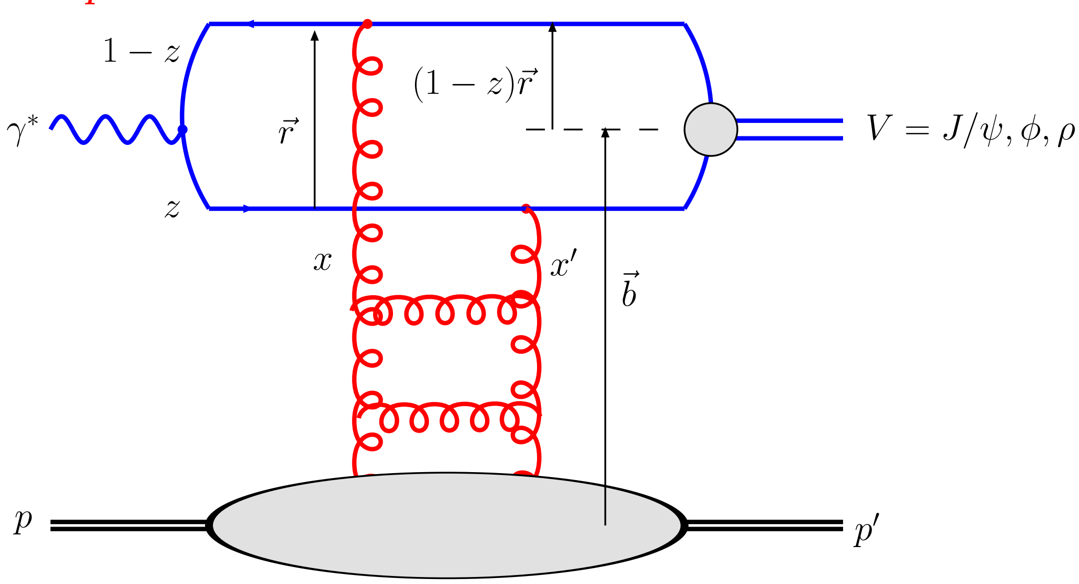
- $F_A(t)$ is the nuclear form factor and $t_{min} = (M_V^2/4k\gamma_L)^2$.
- Different implementations of $\frac{d\sigma(\gamma A \to V\, A)}{dt}|_{t=0}$ in literature.
- Klein and Nystrand: consider hadronic shadowing negligible for J/Ψ and Υ, $\frac{d\sigma(\gamma A \to V\, A)}{dt}|_{t=0} = A^2 \frac{d\sigma(\gamma p \to V\, p)}{dt}|_{t=0}$. Last quantity is taken from a fit to HERA data for vector mesons (and its corresponding extrapolation).
- M. Strikman and collaborators: consider leading twist shadowing $\frac{d\sigma(\gamma A \to V\, A)}{dt}|_{t=0} = \frac{[x g_A(x,\bar{Q})]^2}{[x g_N(x,\bar{Q})]^2} \frac{d\sigma(\gamma p \to V\, p)}{dt}|_{t=0}$. Last quantity also taken from fits to HERA data.

Model for photonuclear reaction

- We consider the color dipole approach to compute the photonuclear cross section (valid for $x \lesssim 10^{-2}$).

$$\mathcal{A}(\gamma A \to V\,A) = -i \int dz\, d^2\boldsymbol{r}\, \Psi_V^*(z,r)\, \sigma_{dip}^{\mathrm{nuc}}(x, \boldsymbol{r}; A)\, \Psi_\gamma(z,r,Q^2)$$

- The basic quantities are the photon and vector meson wavefunction (Ψ_γ and Ψ_V) as well as the dipole-target cross section, $\sigma_{dip}^{\mathrm{nuc}}(x, r;\ A)$.



Meson wave function

- We consider the simple Gaus-LC wave functions, which are shown to reproduce DESY-HERA data for vector meson photoproduction and electroproduction.
- Small sensitivity to a different choice for the meson wave function (for instance, boosted Gaussian) in photoproduction.
- The parameters of meson wave functions are determined by requiring the normalization condition and decay width.
- Photon wave functions are known.

Dipole-nucleus cross section

- Dipole-target cross section can be extended for nuclear case using the Glauber-Gribov picture:

$$\sigma_{dip}^{\rm nuc}(x,\, r;\, A) = 2\int d^2b\, \left\{ 1 - \exp\left[-\frac{1}{2}\, A\, T_A(b)\, \sigma_{dip}(x,\, \boldsymbol{r}) \right] \right\}$$

- Nuclear profile function $T_A(b)$ (from Wood-Saxon), where b is the impact parameter of the center of the dipole relative to the center of the nucleus.
- It sums up all the multiple elastic rescattering diagrams of the $q\bar{q}$ pair and is justified for large coherence length.
- Approach describes (scarce) data for the nuclear ratios for $x \leq 10^{-2}$ (for instance, see Armesto, EPJC26 (2002) 35).
- The main input is the dipole-proton cross section, $\sigma_{dip}(x, r)$.

Dipole-proton cross section

- We take recent parameterization based on the saturation physics [Iancu-Itakura-Munier, PLB590:199, 2004]:

$$\sigma_{dip}^{CGC}(x, \boldsymbol{r}) = \sigma_0 \begin{cases} \mathcal{N}_0 \left(\frac{\bar{\tau}^2}{4}\right)^{\gamma_{\text{eff}}(x,r)}, & \text{for } \bar{\tau} \leq 2\,, \\ 1 - \exp\left[-a \ln^2(b\,\bar{\tau})\right], & \text{for } \bar{\tau} > 2\,, \end{cases}$$

  where $\bar{\tau} = \boldsymbol{r} Q_{\text{sat}}$ and $\gamma_{\text{eff}}(x,\, r) = \gamma_{\text{sat}} + \frac{\ln(2/\tilde{\tau})}{\kappa\,\lambda\,Y}$, where $\gamma_{\text{sat}} = 0.63$, $\kappa = 9$ and $Y = \ln(1/x)$.
- Saturation scale is given by $Q_{\text{sat}} = (x_0/x)^{\lambda/2}$.
- Most recent fit to small-x HERA data: $x_0 = 2.7 \times 10^{-7}$, $\lambda = 0.177$ and $\sigma_0 = 35.7$ mb ($\chi^2/\text{dof} = 0.9$ for $Q^2 =$ [0.5,45]).
- Ref.: Kowalski, Motyka and Watt, PRD74: 074016 (2006).
- Quark masses are $m_q = 0.14$ GeV and $m_c = 1.4$ GeV.

Corrections for exclusive processes

- The real part of amplitude can be accounted for by multiplying the differential cross section by a factor $(1+\beta^2)$.
- The ratio of real to imaginary parts is given by:

$$\beta = \tan\left(\frac{\pi\alpha}{2}\right), \qquad \text{where} \;\; \alpha \equiv \frac{\partial \ln\left[\mathcal{A}\left(\gamma A \to V\,A\right)\right]}{\partial \ln(W^2)}$$

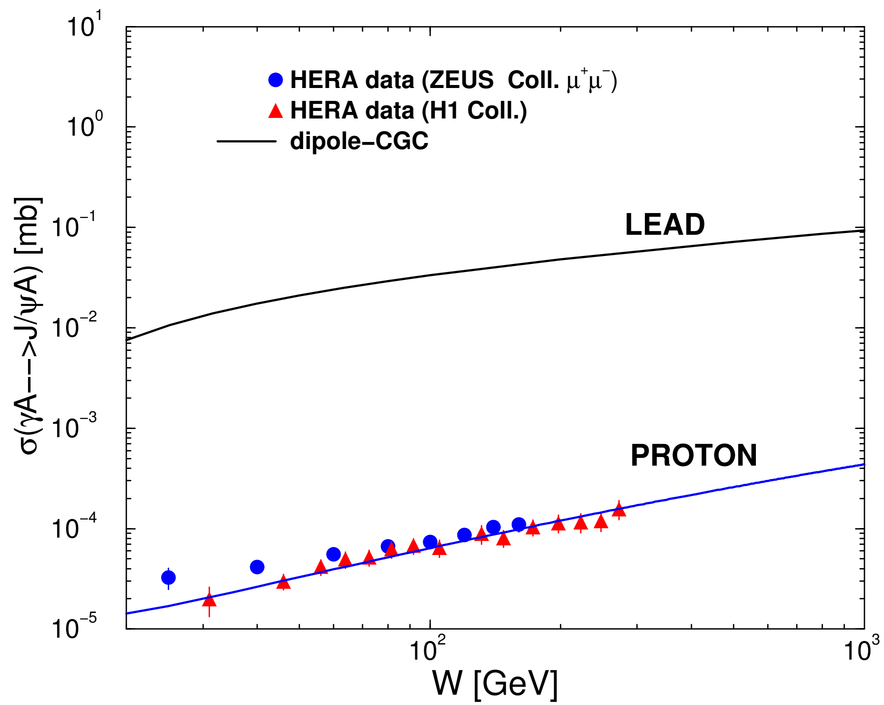
- For exclusive production, off-diagonal gluon distribution should be used, since the two exchanged gluons carry different fractions x and x' of the proton's momentum.
- Off-forward effects can be (phenomenologically) accounted for by multiplying the differential cross section by a factor R_g^2 [Shuvaev at al., **Phys. Rev D60 014015 (1999)**], where

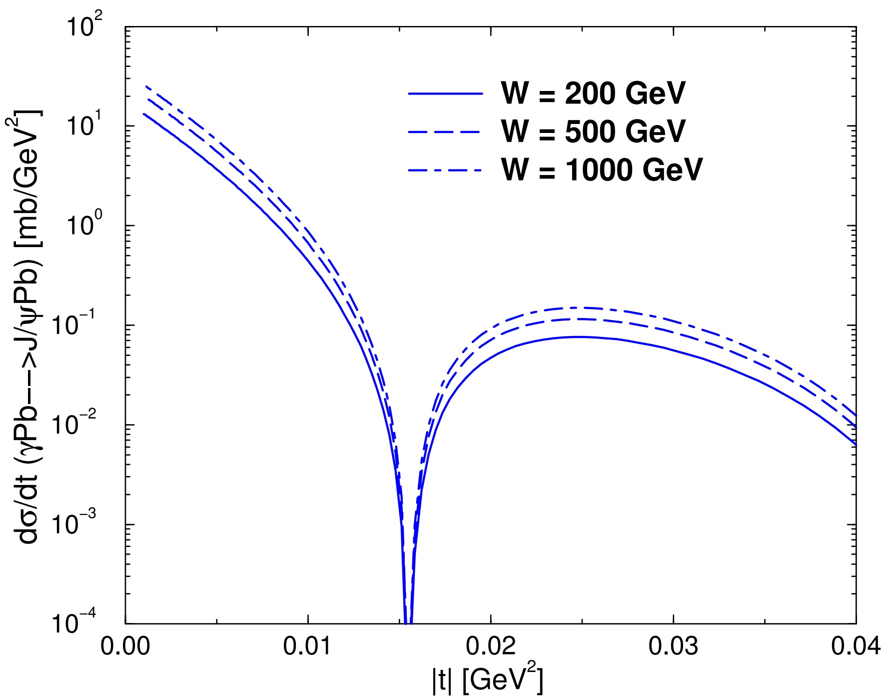
$$R_g = \frac{2^{2\alpha+3}}{\sqrt{\pi}}\,\frac{\Gamma\left(\alpha+\frac{5}{2}\right)}{\Gamma\left(\alpha+4\right)}$$

Numerical results - $J/\Psi(1S)$

Photoproduction of $V = J/\Psi(3097)$:

- Photonuclear cross section as a function of $W_{\gamma A}$.
- Extrapolation to $W_{\gamma A} = 1$ TeV.
- Differential cross section as a function of $|t|$.

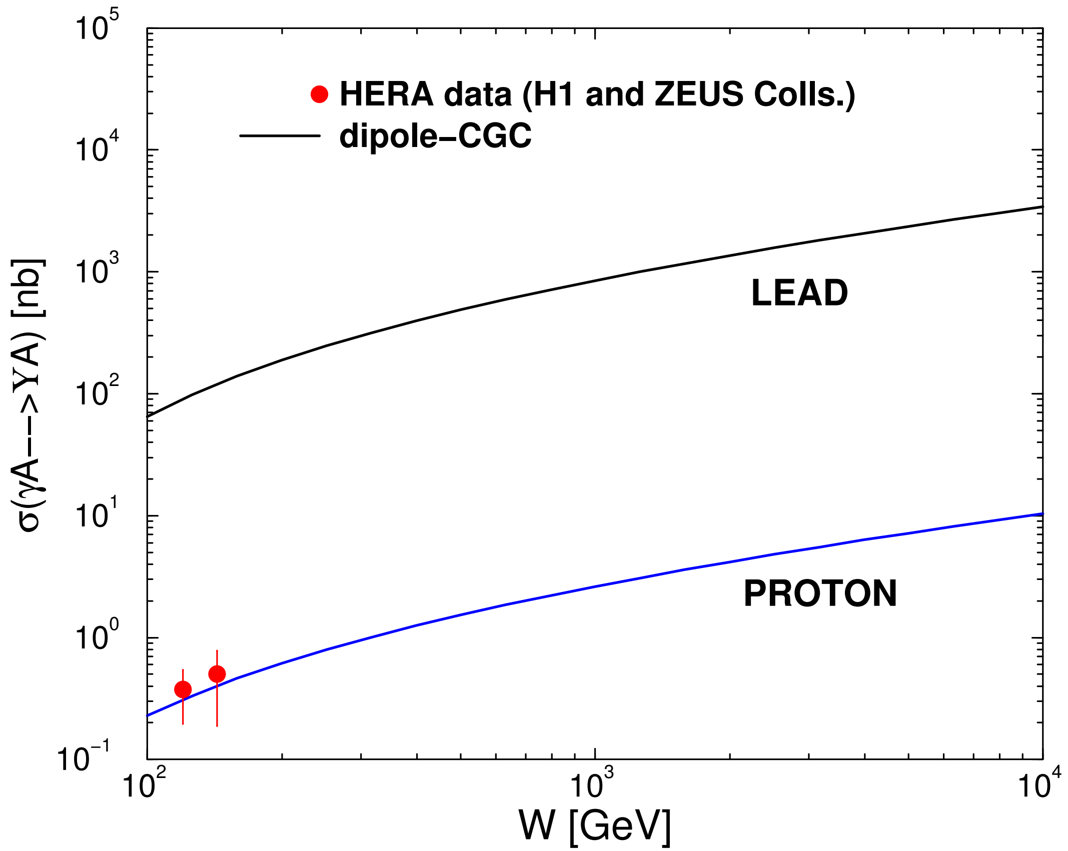




Numerical results - $\Upsilon(1S)$

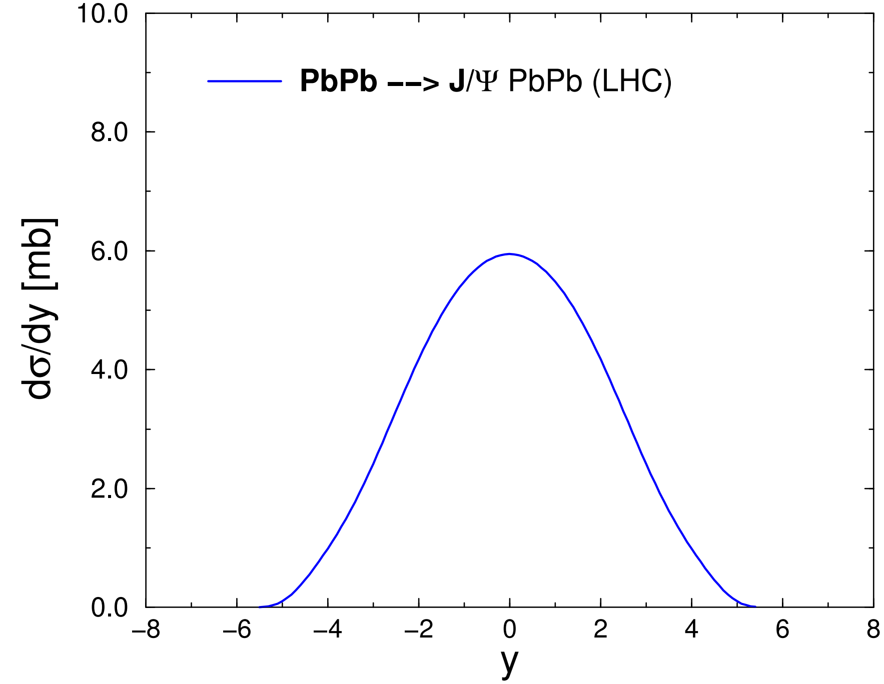
Photoproduction of $V = \Upsilon(1S)$:

- Photonuclear cross section as a function of $W_{\gamma A}$.
- Comparison with the (scarse) DESY-HERA data.
- We use bottom mass $m_b = 4.2$ GeV.



Photoproduction in AA collisions

J/Ψ photoproduction in AA collisions

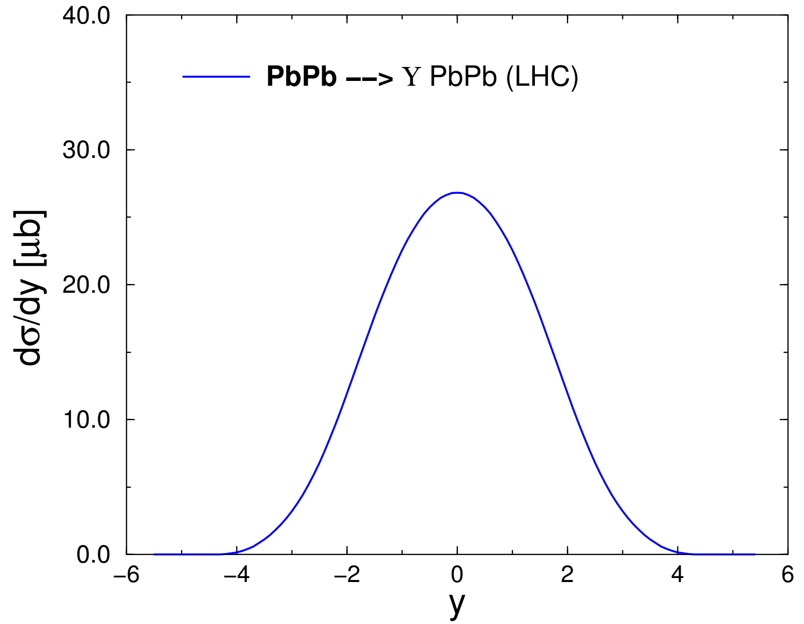


- Integrated cross section at the LHC: $\frac{d\sigma\,(y{=}0)}{dy} = 6$ mb.

y-cut	this work	FS	KN	hadropr. $[A^2 \times \sigma(pp)]$
total	32 mb	15 mb	32 mb	820 mb
$\|y\| < 1$	11 mb	—	—	—

Photoproduction in AA collisions

Υ photoproduction in AA collisions



- Integrated cross section at the LHC: $\frac{d\sigma\ (y{=}0)}{dy} = 27\ \mu$b.

y-cut	this work	FS	KN	hadropr. $[A^2 \times \sigma(pp)]$
total	96 μb	78 μb	170 μb	8 mb
$\lvert y\rvert < 1$	48 μb	—	—	—

Comments and remarks

- In the pA collisions the quasireal photons can be emmited by both the nucleus and the proton.
- The expression for the cross section takes the form

$$\frac{d\sigma(pA \to pA + V)}{dydt} = \frac{dn_\gamma^A}{dk_1}\frac{\sigma_{\gamma p \to V p}(y)}{dt} + \frac{dn_\gamma^p}{dk_2}\frac{\sigma_{\gamma A \to V A}(-y)}{dt},$$

- $\frac{dn_\gamma^p}{dk_2}$ is the photon flux of the accelerated proton.
- Allow to do phenomenology for γp and γA interactions.
- Finally, a background to the coherent production is the incoherent interaction, where the final state nucleus is excited, $\gamma A \to V\,A'$.

Summary

- We compute the coherent quarkonium (J/Ψ and Υ) production in UPCs for PbPb scattering at the LHC.
- For the photonuclear cross section we consider the color dipole approach, with a phenomenological model for the dipole cross section.
- The results are compatible with other phenomenological approaches in literature.
- An extension for pA collisions and an estimation of incoherent production remain to be done.