Investigation on the exclusive photoproduction of quarkonia at the LHC

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Outline

- Short motivation
- Ultra-Peripheral Collisions (UPCs) of relativistic heavy ions and nucleons
- Quarkonium production in UPCs
- Model for photoproduction cross sections - color dipole approach
- Results: exclusive J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ 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 are strongly increased at the LHC and the equivalent luminosities are higher than at existing electron colliders.
  (2) Using nuclear beams effects of very strong fields can be studied (small-x physics, nuclear shadowing, $\ldots$).

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 are reached away from mid-rapidity.
- In Pbp mode, for J/ψ at $y \simeq -3$ corresponds to a gluon x-value $x_A \simeq 5 \times 10^{-4}$ and $x_p \simeq 10^{-2}$.
- Experimental feasibility of studying exclusive meson production in UPCs has been demonstrated at LHC and supported by previous experience at RHIC.
- Large theoretical uncertainties, mainly for the photonuclear cross section.

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:

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

- The photon energy is k and $\xi = 2kR_A/\gamma_L$.

Photoproduction in pp collisions

- In pp case, the photon energy spectrum is given by a modified version of Weizsäcker-Williams approximation:

$$\frac{dn_\gamma}{dk} = \frac{\alpha_{em}}{2\pi\, k}\left[1 + \left(1 - \frac{2k}{\sqrt{s}}\right)^2\right]\left(\ln\xi - \frac{11}{6} + \frac{3}{\xi} - \frac{3}{2\xi^2} + \frac{1}{3\xi^3}\right)$$

- Photon energy is k and $\sqrt{s}$ is the hadron-hadron centre-of-mass energy.
- Given the Lorentz factor of a single beam, $\gamma_L = \sqrt{s}/(2m_p)$, one has that $\xi = 1 + (Q_0^2/Q_{\min}^2)$ with $Q_0^2 = 0.71$ GeV^2 and $Q_{\min}^2 = k^2/\gamma_L^2$.

Quarkonium photoproduction in pp

- 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

$$\frac{d\sigma(pp \to pp + V)}{dy} = S^2_{\mathrm{gap}} \left[k_1 \frac{dn_\gamma}{dk_1} \sigma_{\gamma p \to V p}(k_1) + k_2 \frac{dn_\gamma}{dk_2} \sigma_{\gamma p \to V p}(k_2) \right]$$

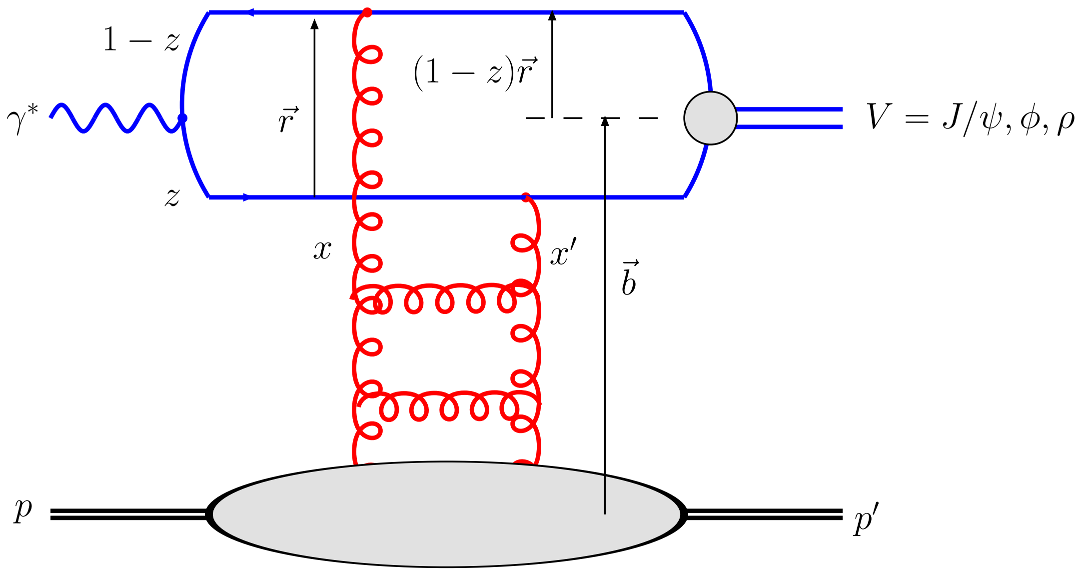
- Here, $k_{1,2} = (M_V/2)\exp(\pm y)$. At mid-rapidity, $k_1 = k_2$ and the contributions from the two terms are equal.
- The square of the γp centre-of-mass energy is given by $W^2_{\gamma p} \simeq 2k\sqrt{s}$.
- The absorptive corrections due to spectator interactions between the two hadrons are represented by the factor S_{gap}.

Model for photoproduction cross section

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

$$\mathcal{A}(\gamma p \to V\, p) = -i \int dz\, d^2\boldsymbol{r}\, \Psi^*_V(z,r)\, \sigma_{dip}(x,x',\boldsymbol{r})\, \Psi_\gamma(z,r,Q^2)$$

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



Model for photoproduction cross section

- The cross section for exclusive production of quarkonia off a nucleon target is given by:

$$\sigma_{\gamma^* p\to Vp}(s,Q^2) = \frac{1}{16\pi B_V}\left|\mathcal{A}\left(x,Q^2,\Delta=0\right)\right|^2$$

- B_V is the diffractive slope parameter in the reaction $\gamma^* p \to Vp$. Here, we consider the energy dependence of the slope using the Regge motivated expression:

$$\begin{aligned} B_V(W_{\gamma p}) &= b_{el}^V + 2\alpha' \log\left(\frac{W_{\gamma p}}{W_0}\right)^2 \\ \alpha' &= 0.25\, GeV^{-2} \;\; \text{and} \; W_0 = 90\, GeV \end{aligned}$$

- For instance, we used measured slopes at $W_{\gamma p} = 90$ GeV, i.e. $b_{el}^{\psi(1S)} = 4.99 \pm 0.41$ GeV^{-2} and $b_{el}^{\psi(2S)} = 4.31 \pm 0.73$ GeV^{-2} (H1@HERA).

Models for the meson wavefunction

- One example is the boosted gaussian wavefunction:

$$\psi^{nS}_{\lambda,h\bar{h}} = \sqrt{\frac{N_c}{4\pi}}\frac{\sqrt{2}}{z(1-z)}\Big\{\delta_{h,\bar{h}}\delta_{\lambda,2h}m_c + i(2h)\delta_{h,-\bar{h}}e^{i\lambda\phi} \times \left[(1-z)\delta_{\lambda,-2h} + z\delta_{\lambda,2h}\right]\partial_r\Big\}\,\phi_{nS}(z,r)$$

- For the $1S$ state one has explicitly (T contribution):

$$\phi_{1S}(r,z) = N_T^{(1S)}\left\{4z(1-z)\sqrt{2\pi R^2_{1S}}\exp\left[-\frac{m_q^2 R^2_{1S}}{8z(1-z)}\right] \times \exp\left[-\frac{2z(1-z)r^2}{R^2_{1S}}\right]\exp\left[\frac{m_q^2R^2_{1S}}{2}\right]\right\}$$

- Parameters (R^2_{1S}, N_T) obtained using the normalization property of wavefunctions and the predicted decay widths.

Model for the meson wavefunction

- The radial wavefunction of the $2S$ state is obtained by the following modification of the $1S$ state:

$$\phi_{2S}(r,z) = N_T^{(2S)}\left\{4z(1-z)\sqrt{2\pi R_{2S}^2}\,\exp\left[-\frac{m_q^2 R_{2S}^2}{8z(1-z)}\right]\right.$$

$$\times \quad \exp\left[-\frac{2z(1-z)r^2}{R_{2S}^2}\right]\exp\left[\frac{m_q^2 R_{2S}^2}{2}\right]$$

$$\times \quad \left.\left[1-\alpha\left(1+m_q^2 R_{2S}^2-\frac{m_q^2 R_{2S}^2}{4z(1-z)}+\frac{4z(1-z)}{R_{2S}^2}r^2\right)\right]\right\}$$

- Parameters α and R_{2S} are constrained from the orthogonality conditions for the meson wavefunction.
- Note: for Light Cone Gaussian (LCG) wavefunction, in $1S$ state, one has $\phi_T = N_T\, z(1-z)\,\exp\left[-r^2/(2R_T^2)\right]$.

Dipole-proton cross section

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

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

  where $\bar{\tau} = \boldsymbol{r} Q_{\rm sat}$ and $\gamma_{\rm eff}(x,\, r) = \gamma_{\rm sat} + \frac{\ln(2/\tilde{\tau})}{\kappa\,\lambda\,Y}$, where $\gamma_{\rm sat} = 0.63$, $\kappa = 9$ and $Y = \ln(1/x)$.
- Saturation scale is given by $Q_{\rm sat} = (x_0/x)^{\lambda/2}$.
- Fit to small-x HERA data: $x_0 = 2.7 \times 10^{-7}$, $\lambda = 0.177$ and $\sigma_0 = 35.7$ mb ($\chi^2/{\rm dof} = 0.9$ for $Q^2 =$ [0.5,45]). Ref.: e.g. Kowalski, Motyka and Watt, PRD74: 074016 (2006).
- Updated: Rezaeian and Schmidt, PRD88: 074016 (2013).
- Fixed masses: e.g. $m_q = 0.14$ 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:

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

- 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

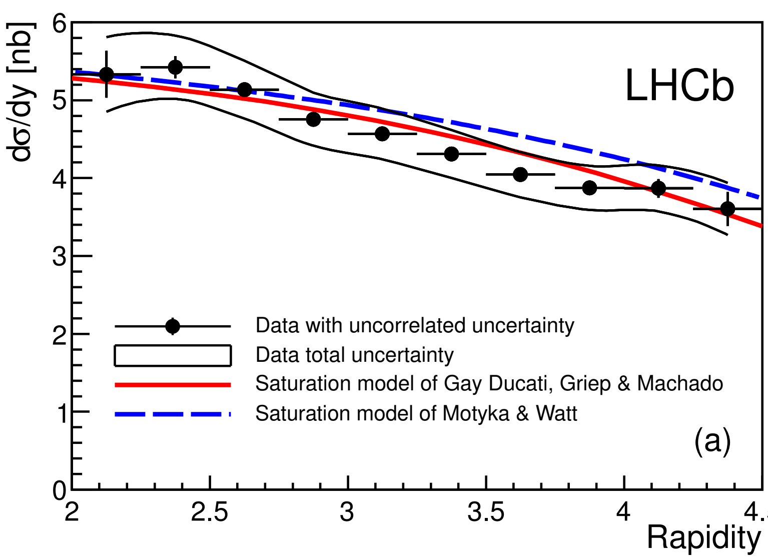
$$R_g = \frac{2^{2\alpha+3}}{\sqrt{\pi}} \frac{\Gamma\left(\alpha+\frac{5}{2}\right)}{\Gamma\left(\alpha+4\right)}$$

Numerical results for pp@LHC

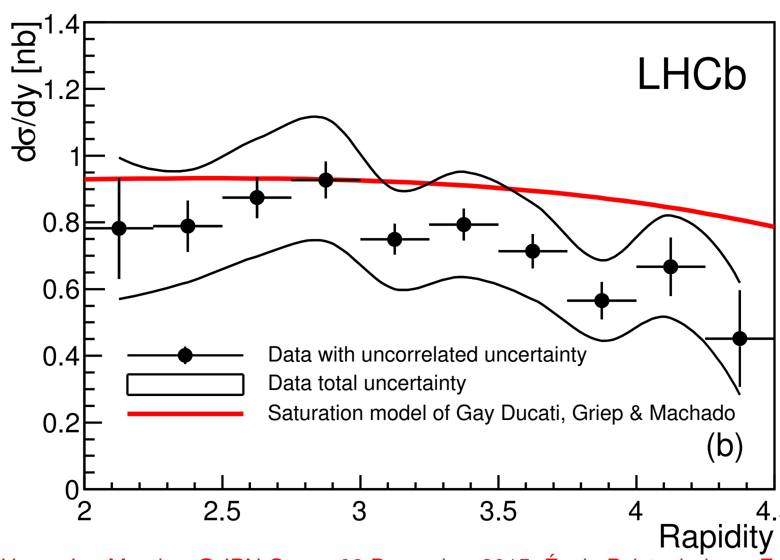
Photoproduction of $V = J/\psi,\ \psi(2S)$ at 7 TeV: M.B. Gay Ducati, M.T. Griep, MVTM, PRD88, 017504 (2013).

- Fairly describes the measured forward rapidity region.
- With $S^2_{\rm gap} = 0.8$ we find in the interval $2 \leq y \leq 4.5$ (LHCb data) $\sigma(pp \to p + J/\psi + p) \times {\rm Br}(J/\psi \to \mu^+\mu^-) = 698$ pb and $\sigma(pp \to p + \psi(2S) + p) \times {\rm Br}(\psi(2S) \to \mu^+\mu^-) = 18$ pb.

J/ψ



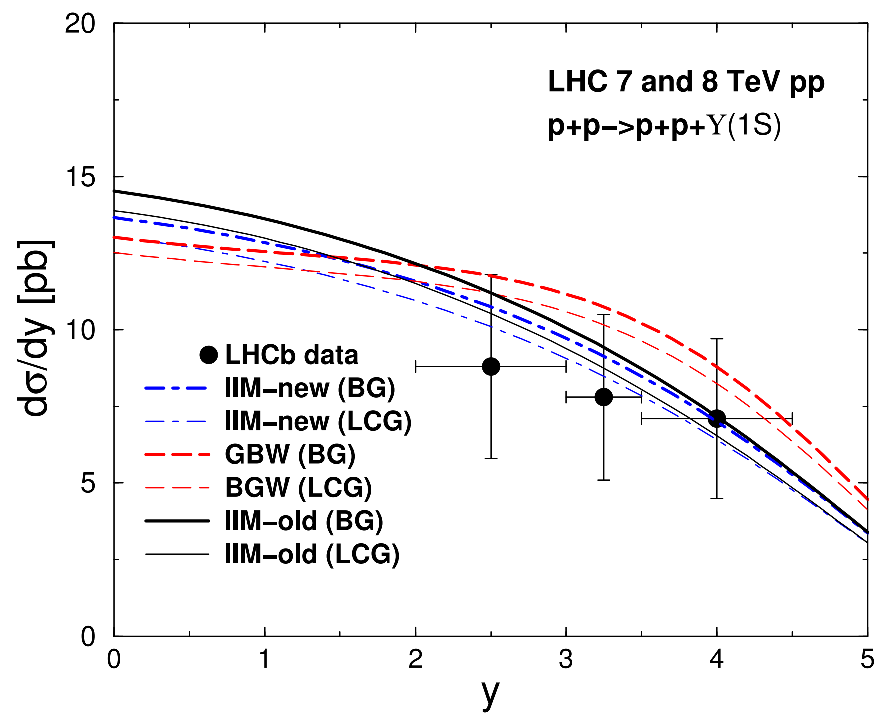
$\psi(2S)$



Numerical results for pp@LHC

Photoproduction of $V = \Upsilon(1S)$ at 7-8 TeV: G. Sampaio dos Santos, MVTM, J. Phys. G 42, 105001 (2015)

- Fairly describes the measured forward rapidity region.
- We take $\langle S^2_{\rm gap}\rangle = 0.8$ and $b_{el}^{\Upsilon} = 3.68$ GeV^{-2}, $\alpha' = 0.164$ GeV^{-2} and $W_0 = 95$ GeV, where $B_V = b_{el}^V + 2\alpha' \log\left(\frac{W_{\gamma p}}{W_0}\right)^2$.



Quarkonium production in UPCs

- The total exclusive (coherent) cross section can be written as an integral over the equivalent photon energy:

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

- The rapidity distribution reads now as:

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

- Once again, one has $k_{1,2} = (M_V/2)\exp(\pm y)$.
- Now, a model for the photonuclear cross section is in order.
- Information on nuclear effects should be included.

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 $\frac{d\sigma(\gamma A\to V\,A)}{dt}|_{t=0} = \frac{[xg_A(x,\bar{Q})]^2}{[xg_N(x,\bar{Q})]^2}\frac{d\sigma(\gamma p\to V\,p)}{dt}|_{t=0}$. 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.

$$\sigma(\gamma A \to V\, A) = \int d^2b \left| \int dz\, d^2\boldsymbol{r}\, \Psi_V^*(z,r)\, \mathcal{N}^{\rm nuc}(x,\boldsymbol{r};b)\, \Psi_\gamma(z,r,Q^2)\right.$$

- Dipole amplitude can be extended for nuclear case, with simple expression at large coherent length:

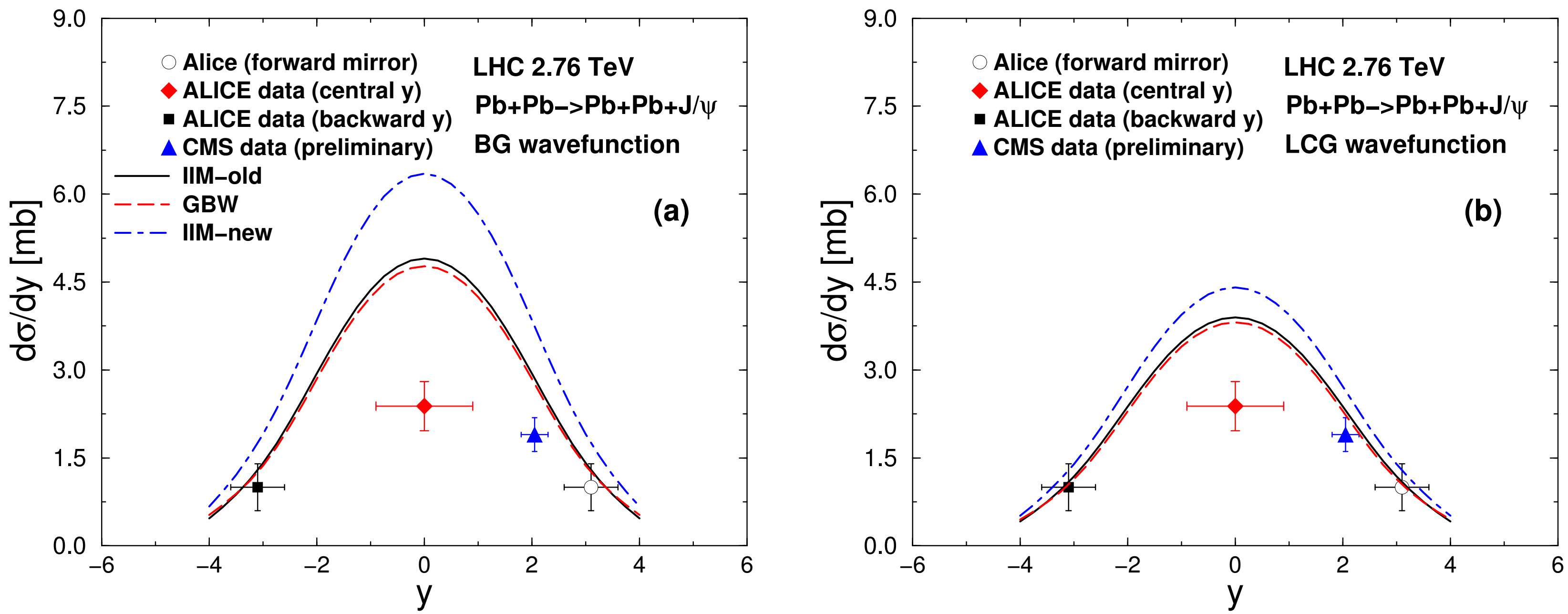
$$\mathcal{N}^{\rm nuc}(x,\, r;\, b) = \left\{ 1 - \exp\left[-\frac{1}{2}\, A\, T_A(b)\, \sigma_{dip}(x,\, \boldsymbol{r}) \right] \right\}$$

- Nuclear thickness 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.
- The nuclear effect included via eikonalization above corresponds to the lowest $Q\bar{Q}$ Fock component of photon.

Numerical results - rapidity distribution

Photoproduction of $V = J/\psi, \psi(2S)$ at 2.76 TeV [a]:

- Overestimation of ALICE data for central rapidity (for BG+IIM). Message is that nuclear effects in model are weaker than expected from data.
- Large uncertainties concerning the theoretical modeling.



[a] G. Sampaio dos Santos, MVTM, J. Phys. G 42, 105001 (2015)

Incoherent cross section

- The incoherent processes can also be computed in high energies where the large coherence length $l_c \gg R_A$ is fairly valid.
- In such case the transverse size of $Q\bar{Q}$ dipole is frozen by Lorentz effects.
- The expression for the incoherent cross section can be written as:

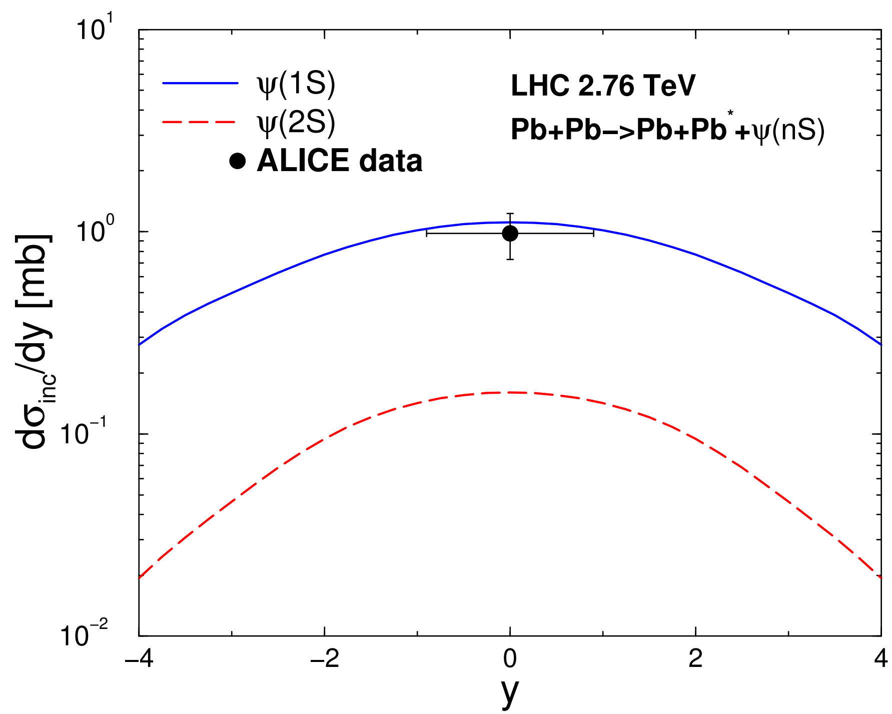
$$\sigma(\gamma A \to V A^*) = \frac{1}{16\pi \, B_V(s)} \int d^2b \, T_A(b) \times \left| \langle \Psi^V | \sigma_{dip}(x, \boldsymbol{r}) \exp\left[-\frac{1}{2} \sigma_{dip}(x, \boldsymbol{r}) T_A(b) \right] | \Psi^\gamma \rangle \right|^2$$

- The bracket means overlaping on the photon/meson wavefunctions.

Numerical result - incoherent case

Incoherent J/ψ, $\psi(2S)$ photoproduction in AA collisions @ LHC

- Fairly description of J/ψ ALICE data at central rapidity.
- Some space for further suppression. Not compared to coherent case (Here, we use BG wavefunction).



Quarkonium in pA collisions

- 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

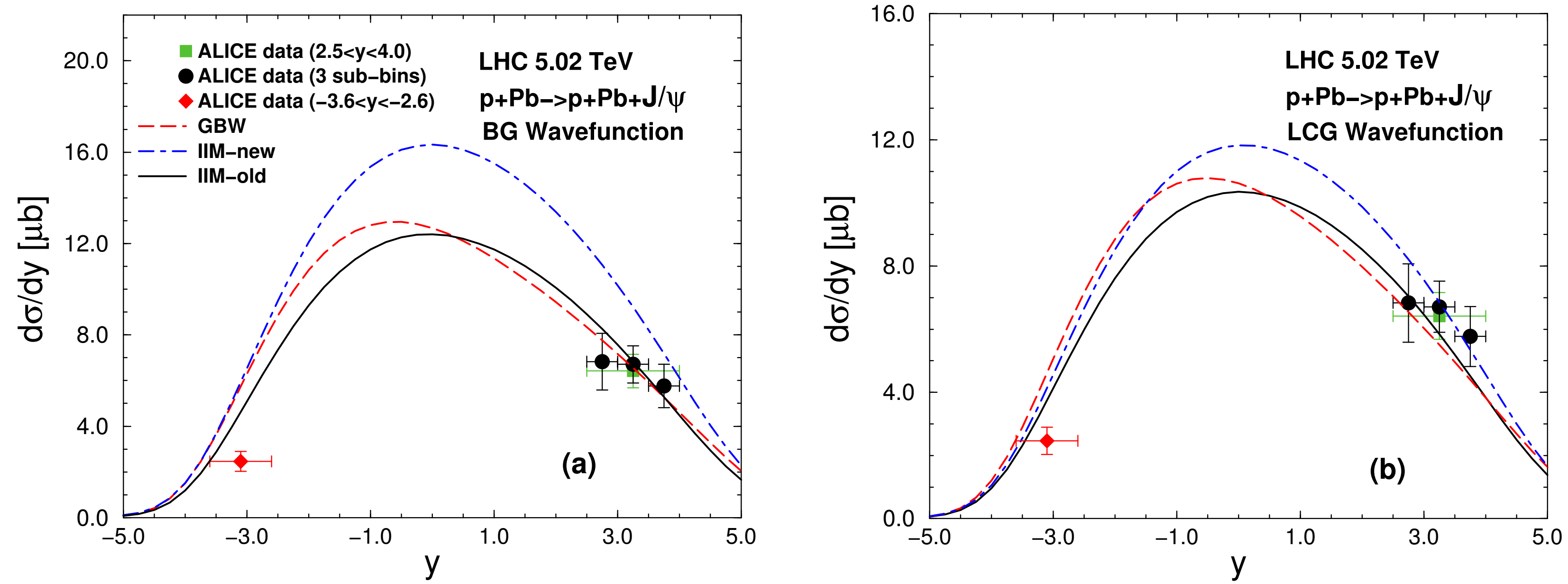
$$\frac{d\sigma(pA \to pA + V)}{dy} = \frac{dn_\gamma^A}{dk_1}\sigma_{\gamma p \to V p}(y) + \frac{dn_\gamma^p}{dk_2}\sigma_{\gamma A \to V A}(-y)\,,$$

- $\frac{dn_\gamma^p}{dk_2}$ is the photon flux of the accelerated proton.
- $\frac{dn_\gamma^A}{dk_2}$ is the photon flux of the accelerated nucleus.
- Allow to do phenomenology for γp and γA interactions.
- Photon-proton contribution is dominant due to large photon flux from nucleus.

Numerical result - pA @ LHC

Analysing the theoretical uncertainty on meson wavefunction and dipole cross section fo J/ψ photoproduction in pA collisions @ LHC

- Here, using GB and LCG wavefunctions and updated IIM [a].

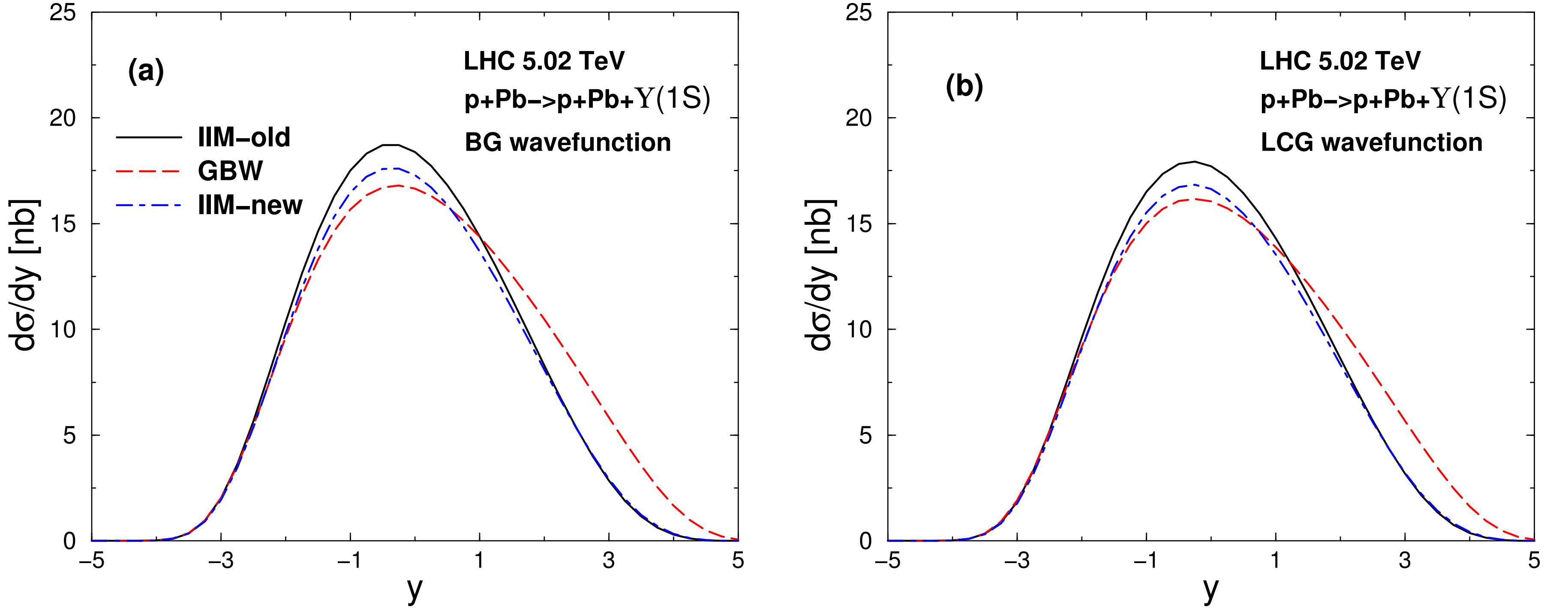


[a] IIM-new: A.H. Rezaeain and I. Schmidt, Phys. Rev. D88, 074016 (2013).

Numerical result - pA @ LHC

Result for $\Upsilon(1S)$ photoproduction in pA collisions @ LHC

- Nuclear effects less important than for charmonia.
- Photon-nucleus contribution is non-negligible in some rapidity regions.



Summary

- We compute the quarkonium photoproduction production in pp, PbPb and Pbp collisions at the LHC.
- For the photonuclear cross section we consider the color dipole approach, with a particular phenomenological model for the dipole amplitude.
- The theoretical prediction for pp case is consistent with LHCb data on forward rapidity.
- In PbPb the predicted coherent cross section has weaker nuclear effect than expected from ALICE data at central rapidity. Incoherent case is somehow consistent with ALICE.
- Predictions for pA mode are presented, including $\Upsilon(1S)$ production (theoretical uncertainties analysed).