

Quarkonium Photoproduction in pp and AA at the LHC

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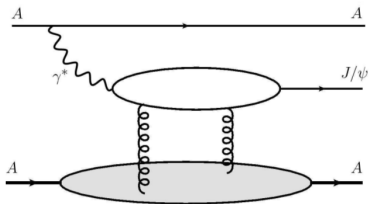
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- Introduction
 - Exclusive vector meson photoproduction
 - Pomeron exchange
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 - Node effect
- Vector mesons production in pp and PbPb collisions
 - Differential cross section calculation
 - Vector mesons wave function
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- Summary

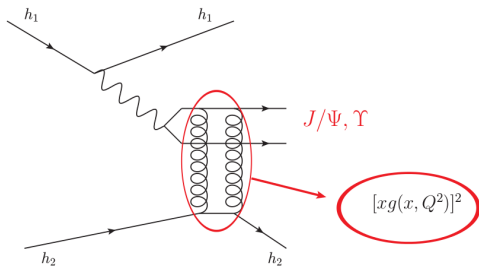
Exclusive vector meson photoproduction

- $\gamma + p \rightarrow V + p \rightarrow$ has been investigated experimentally and theoretically as it allows to test perturbative Quantum Chromodynamics
- The quarkonium masses (m_c, m_b), give a perturbative scale for the problem even at $Q^2 = 0$



Pomeron Exchange

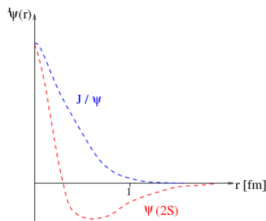
- An outstanding feature of diffractive photoproduction of mesons in the high energy regime is the possibility to investigate the Pomeron exchange



Pomeron \rightarrow two gluons (vacuum quantum numbers)

- The diffractive production of the 2S radially excited vector mesons, like $\Psi(2S)$, is specially interesting due to the node effect ¹

Node Effect: Strong cancellation of dipole size contributions to the production amplitude from the region above and below the node position in the 2S radial wavefunction.

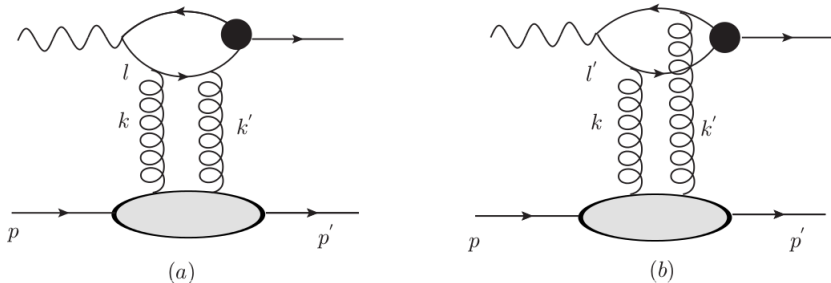


→ This is the origin of the large suppression of the photoproduction of radially excited vector mesons 2S versus 1S

¹J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Phys. Lett. B 374, 199, 1996

Diffractive production of meson at $t = 0$

An important class of diffractive reactions where we can use a perturbative treatment is the vector meson production in DDIS: $\gamma^* p \rightarrow V p$. Two gluons exchange diagrams that contribute to the amplitude of the vector meson leptonproduction are shown in the figure below:



In the color dipole formalism, the amplitude can be written as:

$$A \propto \Psi^\gamma \otimes \sigma^{q\bar{q}} \otimes \Psi^V, \quad (1)$$

Amplitude ²:

$$A_T(W^2, t = 0) = -4\pi^2 i\alpha_s W^2 \int \frac{dk^2}{k^4} \left(\frac{1}{l^2 - m_c^2} - \frac{1}{l'^2 - m_c^2} \right) \times f(x, k^2) e_c g_\Psi M_\Psi \quad (2)$$

$l(l')$ \rightarrow quark (antiquark) momentum

k \rightarrow gluons transverse momentum

$f(x, k^2)$ \rightarrow unintegrated gluons distribution.

The cross section is given by:

$$\frac{d\sigma_T^{\gamma^{(*)}p \rightarrow \Psi p}}{dt} = \frac{1}{16\pi W^4} |A_T|^2. \quad (3)$$

The constant g_Ψ can be determined from the decay $\Gamma_{e^+e^-}^\Psi$: $e_c^2 g_\Psi^2 = \frac{\Gamma_{e^+e^-}^\Psi M_\Psi}{12\alpha_{em}}$

²M. G. Ryskin, Z. Phys. C 57, 89, 1993

In the $\ln \tilde{Q}^2$ dominant approach, the amplitude is written as ²:

$$A_T \simeq 2\pi^2 i e_c g_\Psi M_\Psi \alpha_s(\tilde{Q}^2) W^2 \frac{xg(x, \tilde{Q}^2)}{\tilde{Q}^4} \quad (4)$$

and the transverse cross section is:

$$\left. \frac{d\sigma_T^{\gamma^{(*)}p \rightarrow \Psi p}}{dt} \right|_{t=0} = \frac{16\Gamma_{e^+e^-}^\Psi M_\Psi^3 \pi^3}{3\alpha_{em}(Q^2 + M_\Psi^2)^4} \left[\alpha_s(\tilde{Q}^2) xg(x, \tilde{Q}^2) \right]^2. \quad (5)$$

In \tilde{Q}^2 approach \rightarrow the amplitude is driven by two gluons exchange diagrams

$xg(x, \tilde{Q}^2) \rightarrow$ gluons distribution

The complete differential cross section (T+L) in the $\ln \tilde{Q}^2$ dominant is ²:

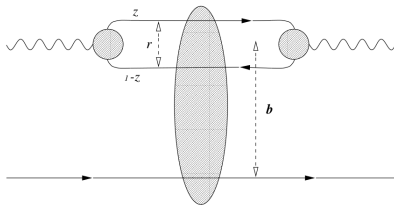
$$\left. \frac{d\sigma^{\gamma^{(*)}p \rightarrow Vp}}{dt} \right|_{t=0} = \frac{16\Gamma_{e^+e^-}^V M_\Psi^3 \pi^3}{3\alpha_{em}(Q^2 + M_V^2)^4} \left[\alpha_s(\tilde{Q}^2) xg(x, \tilde{Q}^2) \right]^2 \left(1 + \frac{Q^2}{M_V^2} \right)$$

$xg(x, \tilde{Q}^2) \rightarrow$ grows in small- $x \rightarrow$ undetermined

Dipole formalism \rightarrow can restrict $xg(x, \tilde{Q}^2) \rightarrow$ includes gluon saturation

Dipole Formalism

- In the LHC energy domain hadrons and photons can be considered as color dipoles in the light cone representation ³.
- The scattering process is characterized by the color dipole cross section representing the interaction of those color dipoles with the target.



$r \rightarrow$ dipole separation.

$z(1 - z) \rightarrow$ quark(antiquark) momentum fraction.

$b \rightarrow$ impact parameter.

³ Nikolaev and Zakharov, Z. Phys. C 49, 607, 1991

The rapidity distribution for quarkonium photoproduction is given by

$$\frac{d\sigma}{dy}(pp \rightarrow p \otimes \psi \otimes p) = S_{\text{gap}}^2 \left[\omega \frac{dN_\gamma}{d\omega} \sigma(\gamma p \rightarrow \psi(nS) + p) + (y \rightarrow -y) \right], \quad (6)$$

Photon flux: ⁴

$$\frac{dN_\gamma(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega} \left[1 + \left(1 - \frac{2\omega}{\sqrt{s}} \right)^2 \right] \times \left(\ln \xi - \frac{11}{6} + \frac{3}{\xi} - \frac{3}{2\xi^2} + \frac{1}{3\xi^3} \right), \quad (7)$$

$\omega \rightarrow$ photon energy

$S_{\text{gap}}^2 = 0.8^5 \rightarrow$ represents the absorptive corrections due to spectator interactions between the two hadrons ⁶

⁴C. A. Bertulani, S. R. Klein and J. Nystrand, *Ann. Rev. Nucl. Part. Sci.* 55, 271, 2005

⁵W. Schafer and A. Szczurek, *Phys. Rev. D* 76, 094014, 2007

⁶A. D. Martin, M. G. Ryskin and V. A. Khoze, *Phys. Rev. D* 56, 5867, 1997. E. Gotsman, E. M. Levin and U. Maor, *Phys. Lett.* B309, 199, 1993.

$$\sigma_{\gamma^* p \rightarrow V p}(s, Q^2) = \frac{1}{16\pi B_V} |\mathcal{A}(x, Q^2, \Delta = 0)|^2, \quad (8)$$

where the amplitude is ⁷

$$\mathcal{A}(x, Q^2, \Delta) = \sum_{h, \bar{h}} \int dz d^2 \Psi_{h, \bar{h}}^\gamma \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h, \bar{h}}^{V*}, \quad (9)$$

$B_V(W_{\gamma p}) = b_{el}^V + 2\alpha' \log\left(\frac{W_{\gamma p}}{W_0}\right)^2 \rightarrow$ diffractive slope parameter

$$\alpha' = 0.25 \text{ GeV}^{-2}$$

$$W_0 = 95 \text{ GeV}$$

$$b_{el}^{\psi(1S)} = 4.99 \pm 0.41 \text{ GeV}^{-2} \text{ and } b_{el}^{\psi(2S)} = 4.31 \pm 0.73 \text{ GeV}^{-2}$$

⁷ N. N. Nikolaev, B. G. Zakharov, Phys. Lett. B 332, 184, 1994

The light cone wave functions of the meson are written as:

$$\Psi_{h,\bar{h}}^{V,L}(r,z) = \sqrt{\frac{N_c}{4\pi}} \delta_{h,-\bar{h}} \frac{1}{M_V z(1-z)} \times [z(1-z)M_V^2 + \delta(m_f^2 - \nabla_r^2)] \phi_L(r,z)$$

$$\nabla_r^2 = (1/r)\partial_r + \partial_r^2$$

$$\begin{aligned} \Psi_{h,\bar{h}}^{V,T(\gamma=\pm)}(r,z) &= \pm \sqrt{\frac{N_c}{4\pi}} \frac{\sqrt{2}}{z(1-z)} \{ie^{\pm i\theta_r} [z\delta_{h\pm,\bar{h}\mp} - (1-z)\delta_{h\mp,\bar{h}\pm}] \partial_r \\ &\quad + m_f \delta_{h\pm,\bar{h}\mp} \} \phi_T(r,z) \end{aligned}$$

$\Psi(1S)$: ⁸

$$\phi_\lambda(r, z) = N_\lambda \left[4z(1-z)\sqrt{2\pi R^2} \exp\left(-\frac{m_f^2 R^2}{8z(1-z)}\right) \exp\left(-\frac{2z(1-z)r^2}{R^2}\right) \times \exp\left(\frac{m_f^2 R^2}{2}\right) \right]$$

$\Psi(2S)$: ¹

$$\phi_{2S}(r, z) = \phi_{1S}(r, z)[1 + \alpha_{2S}g_{2S}(r, z)]$$

$$g_{2S}(r, z) = 2 - m_f^2 R_{2S}^2 + \frac{m_f^2 R_{2S}^2}{4z(1-z)} - \frac{4z(1-z)r^2}{R_{2S}^2}$$

→ Boosted Gaussian Wavefunction (BG)

$N_\lambda, R, \alpha_{2S}$ → parameters from the orthogonality condition of wave functions

⁸ J. R. Forshaw, R. Sandapen and G. Shaw, JHEP 0611, 025, 2006

The GBW (Golec-Biernat and Wusthoff) parametrization is given by: ⁹

$$\sigma_{dip}(x, \vec{r}; \gamma) = \sigma_0 \left[1 - \exp \left(-\frac{r^2 Q_{sat}^2}{4} \right)^{\gamma_{eff}} \right],$$

$$\gamma_{eff} = 1$$

Saturation scale $\rightarrow Q_{sat}^2(x) = \left(\frac{x_0}{x}\right)^\lambda$

$x_0, \sigma_0, \lambda \rightarrow$ fitted to DIS HERA data

⁹K. Golec-Biernat and M. Wusthoff, Phys. Rev. D 59, 014017, 1999

Color Glass Condensate parametrization (CGC):¹⁰

$$\begin{aligned}\sigma_{dip} &= 2\pi R^2 N_0 \left(\frac{rQ_s}{2}\right)^{2\{\gamma_s + [\ln(2/rQ_s)/\kappa\lambda \ln(1/x)]\}} & , rQ_s \leq 2 \\ &= 2\pi R^2 \{1 - \exp[-a \ln^2(brQ_s)]\} & , rQ_s > 2\end{aligned}$$

$Q_s = (x_0/x)^{\lambda/2} \text{ GeV} \rightarrow$ saturation scale

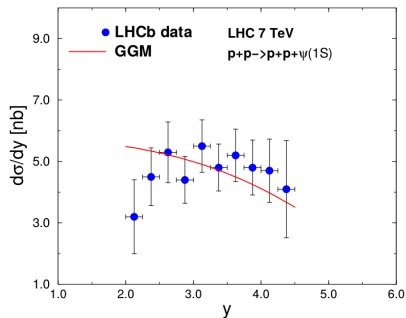
$\gamma_s = 0.63, \kappa = 9.9 \rightarrow$ fixed to their LO BFKL values

$R, x_0, \lambda, N_0 \rightarrow$ free parameters of the fit

$$a = \frac{-N_0\gamma_s^2}{(1-N_0)^2 \ln(1-N_0)}, \quad b = \frac{1}{2}(1-N_0)^{-(1-N_0)/N_0\gamma_s}$$

¹⁰ E. Iancu, K. Itakura and S. Munier, Phys. Lett. B 590, 199, 2004

$\Psi(1S)$ rapidity distribution



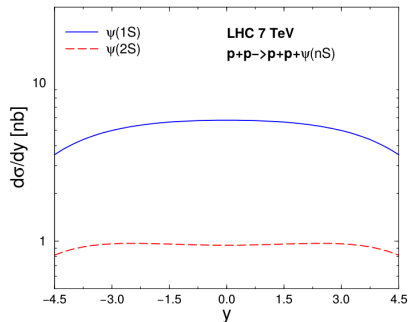
- Predictions to LHC 7 TeV, for pp at forward region ;
- The model CGC was considered for the dipole cross section;
- The relative normalization and overall behavior on rapidity is quite well reproduced in forward regime;
- LHCb data (J. Phys. G 40, 045001, 2013);

Figure : The rapidity distribution of $\Psi(1S)$

photoproduction at $\sqrt{s} = 7 \text{ TeV}$ *

* MBGD, M. T. Griep and M. V. T. Machado, Phys. Rev. D 88, 017504, 2013

$\Psi(1S)$ and $\Psi(2S)$ rapidity distribution



- Predictions to LHC 7 TeV, pp, including mid-rapidity and backward regions ;
- The model CGC was considered for the dipole cross section;
- $\Psi(1S) \rightarrow y = 0: d\sigma/dy \approx 5.8 \text{ nb}$;
- $\Psi(2S) \rightarrow y = 0: d\sigma/dy \approx 0.94 \text{ nb}$.

Figure : The rapidity distribution of $\Psi(1S)$ and

$\Psi(2S)$ photoproduction at $\sqrt{s} = 7 \text{ TeV}$ *

* MBGD, M. T. Griep and M. V. T. Machado, Phys. Rev. D 88, 017504, 2013

Our prediction:

$$\sigma_{pp \rightarrow \psi(2S)(\rightarrow \mu^+ \mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.7 \text{ pb}$$

LHC measure (J. Phys. G 40, 045001, 2013):

$$\sigma_{pp \rightarrow \psi(2S)(\rightarrow \mu^+ \mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.8 \pm 1.6 \text{ pb}$$

Our prediction:

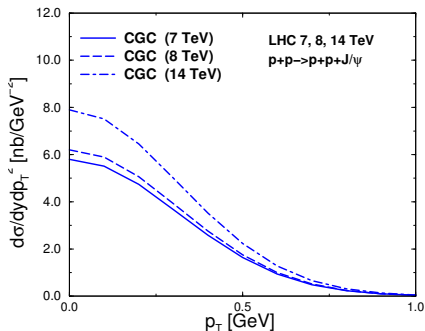
$$[\psi(2S)/\psi(1S)]_{y=0} = 0.16$$

$$[\psi(2S)/\psi(1S)]_{2 < y < 4.5} = 0.18$$

LHCb determination (J. Phys. G 40, 045001, 2013):

$$[\psi(2S)/\psi(1S)](2.0 < \eta_{\mu^\pm} < 4.5) = 0.19 \pm 0.04$$

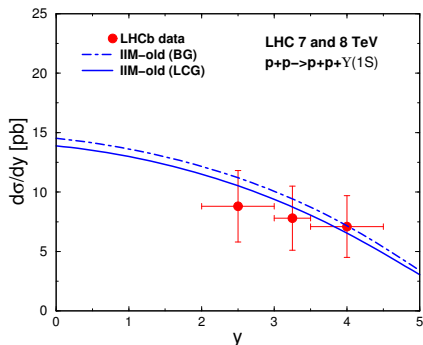
Transverse momentum distribution for J/ψ production.



- Predictions for LHC 7, 8, 14 TeV, pp ;
- The models CGC and Boosted Gaussian wavefunction were considered;
- Connected to the t dependence.

Figure : The p_T distribution of J/ψ photoproduction at $\sqrt{s} = 7, 8, 14$ TeV.

Differential cross section for Υ production.



- Predictions for LHC 7, 8 TeV pp ;
- The model CGC (updated IIM dipole cross section) is considered. LHCb data included;
- Uncertainty on meson wavefunction (LCG or BG) has been introduced.

Figure : The rapidity distribution of Υ photoproduction at $\sqrt{s} = 7, 8 \text{ TeV}$.

Coherent process:



\Rightarrow nuclei remain intact.

Incoherent process:



\Rightarrow nuclei are fragmented.

Coherent cross section: ¹¹

$$\sigma^{cohe}(\gamma A \rightarrow J/\psi A) = \int d^2b \left\{ \left| \int d^2r \int dz \Psi_V^*(r, z) \left(1 - \exp \left[-\frac{1}{2} \sigma_{dip}(x, r) T_A(b) \right] \right) \Psi_{\gamma^*}(r, z, Q^2) \right|^2 \right\}$$

$\sigma_{dip} \rightarrow$ dipole cross section.

$\Psi_V \rightarrow$ vector meson wave function.

$\Psi_{\gamma} \rightarrow$ photon wave function.

$T_A(b) = \int dz \rho_A(b, z)$, $\rho_A(b, z) \rightarrow$ nuclear thickness function.

$b \rightarrow$ impact parameter.

¹¹B. Z. Kopeliovich and B. G. Zakharov, Phys. Rev. D 44, 3466, 1991

Incoherent case: ⁹

$$\sigma^{inc}(\gamma A \rightarrow J/\psi X) = \frac{|Im\mathcal{A}(s, t=0)|^2}{16\pi B_V}$$

where

$$|Im\mathcal{A}(s, t=0)|^2 = \int d^2b T_A(b) \left[\left| \int d^2r \int dz \Psi_V^*(r, z) \sigma_{dip} \right. \right. \\ \left. \left. \times \exp \left[-\frac{1}{2} \sigma_{dip} T_A(b) \right] \Psi_{\gamma^*}(r, z, Q^2) \right|^2 \right]$$

$$B_V = 0.6 \times \left(\frac{14}{(Q^2 + M_V^2)^{0.26}} + 1 \right) \rightarrow \text{diffractive slope parameter, } \gamma^* p \rightarrow \Psi p$$

$$\frac{d\sigma}{dy}(AA \rightarrow AAV) = \sigma_{\gamma A} \otimes \frac{dN_{\gamma}(\omega)}{d\omega} \quad (10)$$

Photon Flux: ¹²

$$\frac{dN_{\gamma}(\omega)}{d\omega} = \frac{2Z^2\alpha_{em}}{\pi\omega} \left[\xi_R^{AA} K_0(\xi_R^{AA}) K_1(\xi_R^{AA}) \frac{(\xi_R^{AA})^2}{2} K_1^2(\xi_R^{AA}) - K_0^2(\xi_R^{AA}) \right]. \quad (11)$$

$\omega \rightarrow$ photon energy

$K_0(\xi), K_1(\xi) \rightarrow$ modified Bessel functions.

$\xi_R^{AA} = 2R_A\omega/\gamma_L$, $R_A \rightarrow$ nuclei radius.

¹²C. A. Bertulani, S. R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55, 271, 2005

Nuclear shadowing renormalizing the dipole cross section \rightarrow gluon density in nuclei at small Bjorken- x is expected to be suppressed compared to a free nucleon due to interferences.

Ratio of the gluon density: $R_G(x, Q^2 = m_V^2/4)$,¹³

Small- x photon scatters off a large- x gluon or vice-versa.

$\rightarrow y = \pm 3$: x large as 0.02

$\rightarrow y = 0$: $x = M_V e^{\pm y} \sqrt{S_{NN}}$ smaller than 10^{-3} for the nuclear gluon distribution.

¹³L. Frankfurt, V. Guzey and M. Strikman, Phys. Rept. 512, 255, 2012

Differential cross section for J/Ψ production

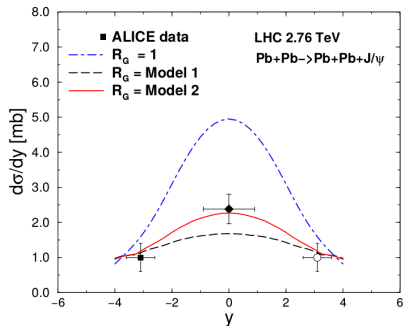


Figure : The rapidity distribution of coherent $\Psi(1S)$

meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC *

* MBGD, M. T. Griep and M. V. T. Machado, *Phys. Rev. C*88, 014910, 2013

- $\sigma_{dip} \rightarrow R_G(x, Q^2)\sigma_{dip}$;
- R_G Model 1 \rightarrow higher nuclear shadowing;
- R_G Model 2 \rightarrow small nuclear shadowing;
- $R_G = 1$: the ALICE data is overestimate by a factor 2; This prediction is consistent with previous calculations using the same formalism (V. P. Goncalves and M. V. T. Machado, *Phys. Rev. C* 84, 011902, 2011);
- In the backward/forward rapidity case, the overestimation is already expected as a proper threshold factor for $x \rightarrow 1$ was not included in the present calculation.

• **R_G Model 2 is preferred in this analysis.**

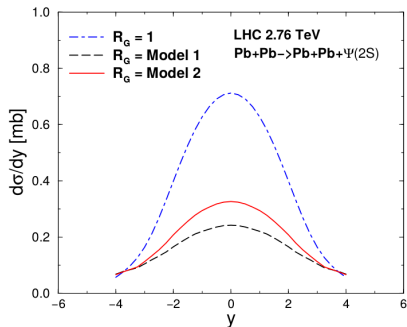
• ALICE data: *Phys. Lett. B*718 (2013) 1273 .

Rapidity	$R_G = 1$	R_G Model 1	R_G Model 2
$y = 0$	$d\sigma/dy = 4.95mb$	$d\sigma/dy = 1.68mb$	$d\sigma/dy = 2.27mb$

Table : Results.

- The prediction using Model 2 for R_G describes the ALICE data
- $R_G = 1$ - no shadowing
- R_G Model 1 - decreases 66% and R_G Model 2 - decreases 54% the rapidity distribution compared with $R_G = 1$ (for $y = 0$)
- R_G is considered independent of the impact parameter

Differential cross section for Ψ' production



- R_G Model 1 \rightarrow higher nuclear shadowing;
- R_G Model 2 \rightarrow small nuclear shadowing;
- The theoretical curves follow the same notation as in the $\Psi(1S)$ case;

Figure : The rapidity distribution of coherent $\Psi(2S)$

meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb

collisions at the LHC *

* MBGD, M. T. Griep and M. V. T. Machado, Phys. Rev. C88, 014910, 2013,

Rapidity	$R_G = 1$	R_G Model 1	R_G Model 2
$y = 0$	$d\sigma/dy = 0.71mb$	$d\sigma/dy = 0.24mb$	$d\sigma/dy = 0.33mb$

Table : Results.

- $R_G = 1$ - no shadowing
- The theoretical predictions follow the general trend as for the 1S state
- This is the first estimate in the literature for the photoproduction of 2S state in nucleus-nucleus collisions

At central rapidities, the presented predictions give the ratio

$$R_{\psi}^{y=0} = \frac{d\sigma_{\psi(2S)}}{dy} / \frac{d\sigma_{\psi(1S)}}{dy}(y=0) = 0.14$$

→ in the case $R_G = 1$ which is consistent with the ratio measured in CDF¹⁴: 0.14 ± 0.05 (exclusive charmonium production at 1.96 TeV in $p\bar{p}$ collisions)

→ a similar ratio is obtained using Model 1 and Model 2 at central rapidity

→ the ratio is not sensitive to shadowing

¹⁴T. Aaltonen et al (CDF Collaboration), Phys. Rev. Lett. 102, 242001 (2009)

Prediction for the LHC run in PbPb mode at 5.5 TeV:

→ $\Psi(2S)$ cross section ($R_G = 1$):

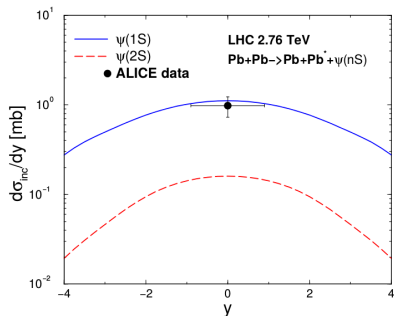
Coherent:

$$\frac{d\sigma_{coh}}{dy}(y = 0) = 1.27 \text{ mb}$$

Incoherent:

$$\frac{d\sigma_{inc}}{dy}(y = 0) = 0.27 \text{ mb}$$

Differential cross section for incoherent J/ψ and Ψ' production.



- Data from ALICE collaboration ;
- The result describes the recent ALICE data for the incoherent cross section at mid-rapidity;
- In both cases we only computed the case for $R_G = 1$;
- ALICE data: Eur. Phys. J.C (2013) 73: 2617.

Figure : The rapidity distribution of incoherent $\Psi(1S)$ (solid line) and $\Psi(2S)$ (dashed line) meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC *

* MBGD, M. T. Griep and M. V. T. Machado, Phys. Rev. C88, 014910, 2013

$\Psi(1S)$:

$$\frac{d\sigma_{\text{inc}}}{dy}(y=0) = 1.1 \text{ mb}$$

$$\frac{d\sigma_{\text{inc}}^{\text{ALICE}}}{dy}(-0.9 < y < 0.9) = 0.98 \pm 0.25 \text{ mb}$$

→ the prediction describes the recent ALICE data

$\Psi(2S)$:

$$\frac{d\sigma_{\text{inc}}}{dy} = 0.16 \text{ mb}$$

→ For the incoherent case, the gluon shadowing is weaker than the coherent case - 20% reduction compared to $R_G = 1$

Differential cross section for Υ production.

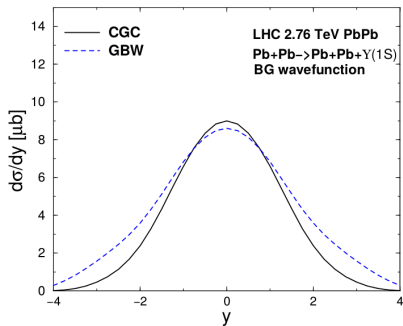


Figure : The rapidity distribution of Υ photoproduction at $\sqrt{s} = 2.76 \text{ TeV}$.

- Predictions to LHC 2.76 TeV, PbPb ;
- The parametrizations CGC and GBW were considered for the dipole cross section;
- The BG wavefunction was used;
- $y = 0$: $d\sigma/dy \approx 9 \mu\text{b} \rightarrow$ the two models have approximately equal results in the central rapidity;
- In the forward/backward region, the models presented slightly different results.
- Work in progress.

pp:

The rapidity distributions of mesons $\Psi(1S)$ and $\Psi(2S)$ production were calculated in pp collisions using the dipole formalism.

- The predictions for $\Psi(1S)$ rapidity distribution and total cross section are consistent with LHCb data
- The ratio $\Psi(2S)/\Psi(1S)$ is also consistent with LHCb determination in the forward region
- Our predictions are in agreement with the use of color dipole formalism and with the prediction from Starlight and SuperChic
- Predictions are done also for Υ photoproduction in pp collisions at LHC energies

PbPb:

The rapidity distributions of coherent and incoherent production of mesons $\Psi(1S)$ and $\Psi(2S)$ were calculated in PbPb collisions using the dipole formalism.

- The option of small shadowing is preferred in data description whereas the usual $R_G = 1$ value overestimates the central rapidity cross section by a factor 2, for the coherent case
- The prediction for the state $\Psi(2S)$ photoproduction in PbPb collisions is the first presented in the literature
- The present theoretical approach describes ALICE data for the incoherent cross section
- The central rapidity data measured by the ALICE Collaboration for the rapidity distribution of the $\Psi(1S)$ state is crucial to constrain the nuclear gluon function
- Predictions for Υ photoproduction were presented.

Thank You!