Exclusive photoproduction of J/Ψ and $\Psi(2S)$ states in proton-proton collisions at the CERN LHC

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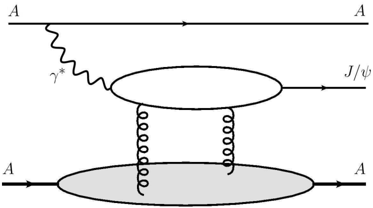
Outlook

- Introduction
  - → Exclusive vector meson photoproduction
  - → Pomeron exchange
  - → Dipole formalism
  - → Node effect
- Vector mesons production in pp and PbPb collisions
  - → Differential cross section calculation
  - → Vector mesons wave function
  - → Dipole cross section model
- Results for J/Ψ, Ψ' and Υ production
  - → Rapidity distribution of J/Ψ and Ψ'
  - → Rapidity distribution of Υ production
- Summary

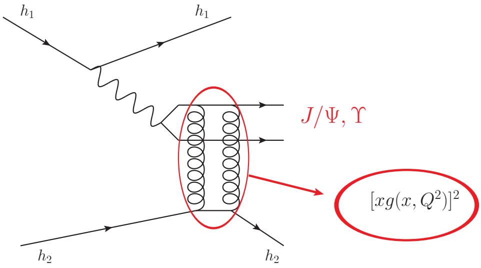
Exclusive vector meson photoproduction

- $\gamma + p \rightarrow V + p \rightarrow$ 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 $Q^2 = 0$



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

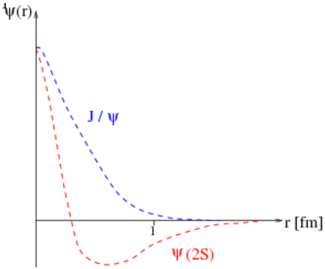


Pomeron $\rightarrow$ two gluons (vacuum quantum numbers)

Node Effect

• 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.

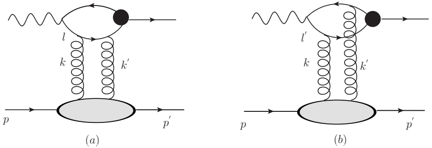


→ This is the origin of the large suppression of the photoproduction of radially excited vector mesons 2S versus 1S

[1] J. 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: $\gamma^* p \to Vp$. Two gluons exchange diagrams that contribute to the amplitude of the vector meson leptoproduction are shown in the figure below:



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

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

Diffractive production of meson at $t = 0$

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 $\Gamma^\Psi_{e^+e^-}$: $e_c^2 g_\Psi^2 = \frac{\Gamma^\Psi_{e^+e^-} M_\Psi}{12\alpha_{em}}$

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

Diffractive production of meson at $t = 0$

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

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

and the transverse cross section is:

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

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

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

Diffractive production of meson at $t = 0$

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

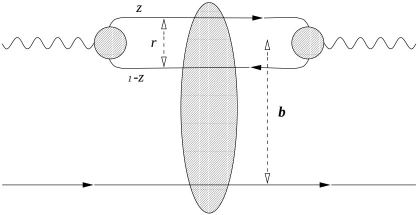
$$\left.\frac{d\sigma^{\gamma^{(*)}p\to Vp}}{dt}\right|_{t=0} = \frac{16\Gamma^{V}_{e^+e^-} M_\Psi^3 \pi^3}{3\alpha_{em}(Q^2+M_V^2)^4}\left[\alpha_s(\tilde{Q}^2)xg(x,\tilde{Q}^2)\right]^2\left(1+\frac{Q^2}{M_V^2}\right)$$

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

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

• 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

Quarkonium production in pp collisions

The rapidity distribution for quarkonium photoproduction is given by

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

where [4]

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

$S^2_{gap} = 0.8$ [5] $\to$ represents the absorptive corrections due to spectator interactions between the two hadrons [6]

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

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

[6] A. D. Martin, M. G. Ryskin and V. A. Khoze, Phys. Rev. D56, 5867, 1997. E. Gotsman, E. M. Levin and U. Maor, Phys. Lett. B309, 199, 1993.

γp cross section

$$\sigma_{\gamma^* p \to Vp}(s, Q^2) = \frac{1}{16\pi B_V} \left|\mathcal{A}\,(x, Q^2, \Delta = 0)\right|^2 , \qquad (8)$$

where the amplitude is [7]

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

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

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

$W_0 = 95$ GeV

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

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

Light cone wave functions

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

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

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

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

Light cone wave functions

$\Psi(1S)$: [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)

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

Dipole cross section

For the dipole cross section, we use the Color Glass Condensate parametrization (CGC): [9]

$$\sigma_{dip} = 2\pi R^2 N_0 \left(\frac{rQ_s}{2}\right)^{2\{\gamma_s + [\ln(2/rQ_s)/\kappa\lambda \ln(1/x)]\}} \quad , \quad rQ_s \leq 2$$

$$= 2\pi R^2 \{1 - \exp[-a \ln^2(brQ_s)]\} \quad , \quad rQ_s > 2$$

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

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

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

[9] E. Iancu, K. Itakura and S. Munier, Phys. Lett. B 590, 199, 2004

$\Psi(1S)$ rapidity distribution

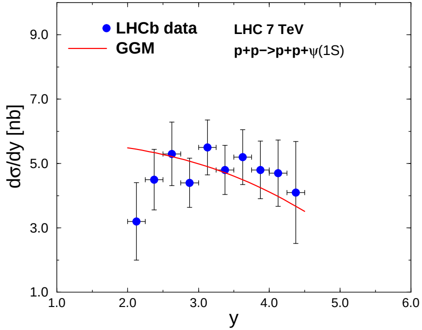
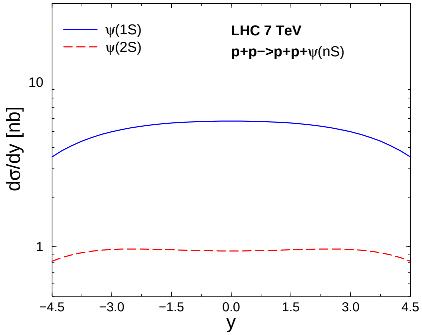


Figure: The rapidity distribution of $\Psi(1S)$ photoproduction at $\sqrt{s} = 7\,TeV$ *

- 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);

* 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;
- $\Psi(1S) \rightarrow y = 0$: $d\sigma/dy \approx 5.8nb$;
- $\Psi(2S) \rightarrow y = 0$: $d\sigma/dy \approx 0.94nb$.

Figure: The rapidity distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction at $\sqrt{s} = 7\,TeV$ *

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

Total cross section for forward region

Our prediction:

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

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

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

$\Psi(2S)/\Psi(1S)$ ratio

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):

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

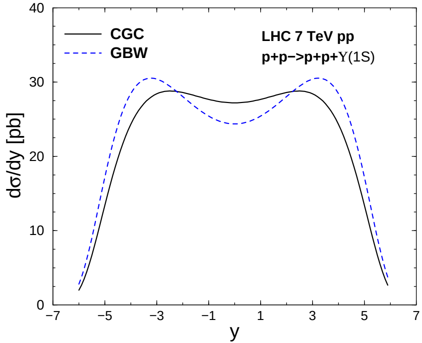


Figure: The rapidity distribution of Υ photoproduction at $\sqrt{s} = 7\,TeV$.

- Predictions for LHC $7\,TeV$, pp ;
- The models CGC and GBW were considered for the dipole cross section;
- Work in progress.

Coherent process:

$$AA \rightarrow AA + J/\Psi(\Psi').$$

$\Rightarrow$ nuclei remain intact.

Incoherent process:

$$AA \rightarrow X + J/\Psi(\Psi').$$

$\Rightarrow$ nuclei are fragmented.

Coherent cross section: [10]

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

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

$\Psi_V \to$ vector meson wave function.

$\Psi_\gamma \to$ photon wave function.

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

$b \to$ impact parameter.

[10] B. Z. Kopeliovich and B. G. Zakharov, Phys. Rev. D 44, 3466, 1991

Incoherent cross section

Incoherent case: [9]

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

where

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

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

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

Photon Flux: [11]

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

$\omega \to$ photon energy

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

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

[11] C. 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 supressed compared to a free nucleon due to interferences.

Ratio of the gluon density: $R_G(x, Q^2 = m_V^2/4)$, [12]

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.

[12] L. Frankfurt, V. Guzey and M. Strikman, Phys. Rept. 512, 255, 2012

Differential cross section for J/Ψ production

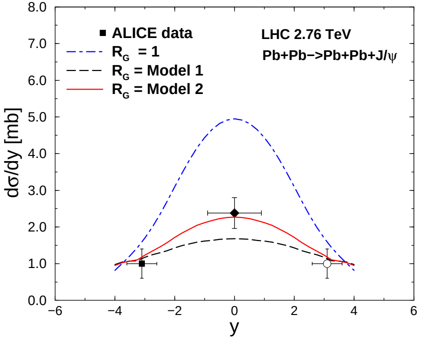


Figure: The rapidity distribution of coherent $\Psi(1S)$ meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC *

- $\sigma_{dip} \to R_G(x, Q^2)\sigma_{dip}$;
- R_G Model 1 $\to$ higher nuclear shadowing;
- R_G Model 2 $\to$ 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 $x \to 1$ was not included in the present calculation.
- R_G Model 2 is preferred in this analysis.
- ALICE data: Phys. Lett. B718 (2013) 1273 .

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

Results

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.

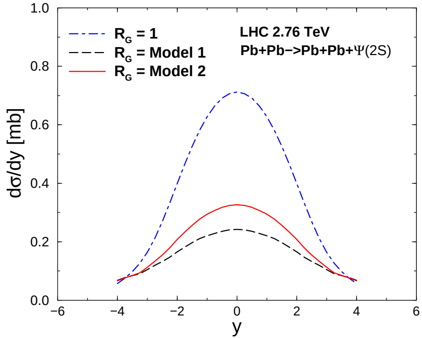
→ The prediction using Model 2 for R_G describes the ALICE data

→ $R_G = 1$ - 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
$y = 0$	$d\sigma/dy = 0.71 mb$	$d\sigma/dy = 0.24 mb$	$d\sigma/dy = 0.33 mb$

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

Analyzing the ratio $\Psi(2S)/\Psi(1S)$

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 CDF [13]: 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

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

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

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

Coherent:

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

Incoherent:

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

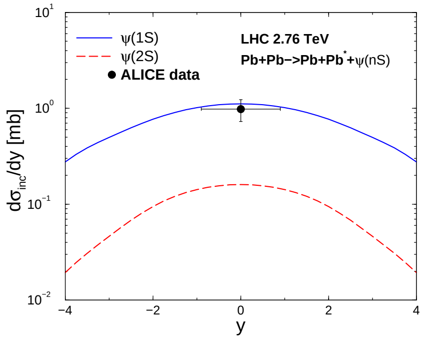


Figure: The rapidity distribution of incoherent $\Psi(1S)$ (solid line) and $\Psi(2S)$ (dashed line) meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC *

- 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.

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

Results

$\Psi(1S)$:

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

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

$\longrightarrow$ the prediction describes the recent ALICE data

$\Psi(2S)$:

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

$\longrightarrow$ 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.

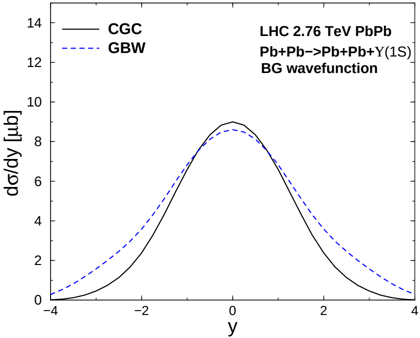


Figure: The rapidity distribution of Υ photoproduction at $\sqrt{s} = 2.76\,TeV$.

- Predictions to LHC $2.76\,TeV$, PbPb ;
- The parametrizations CGC and GBW were considered for the dipole cross section;
- The BG wavefunction was used;
- $y = 0$: $d\sigma/dy \approx 9\mu b \rightarrow$ 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.

Summary 1

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

Summary 2

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!

Light Cone Variables

$$a_+ = a_0 + a_3$$

$$a_- = a_0 - a_3$$

$$\vec{a_t} = (a_1, a_2)$$

$$a \cdot b = \frac{1}{2}(a_+ b_- + a_- b_+) - \vec{a_t} \cdot \vec{b_t}$$

$$p_- = \frac{|\vec{p}|^2 + m^2}{p_+}$$ $\rightarrow$ momentum