



Tranverse Momentum Distribution in Quarkonium Photoproduction in pp and AA Collisions at the LHC

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- Introduction
 - Ultraperipheral Collisions
 - The photon flux and the cross section photoproduction
 - Exclusive photoproduction → Pomeron exchange
- Vector mesons production in pp and PbPb collisions
 - Differential cross section calculation in the dipole formalism
 - Vector mesons wave function
 - Dipole cross section model
- Results for $V = (J/\Psi, \Psi', Y(1S) \text{ and } Y(2S))$ production
 - Rapidity distribution of V photoproduction
 - Transverse momentum distribution of V photoproduction
 - Proton-Proton collisions
 - Pb-Pb collisions
- Summary

Theoretical Motivation

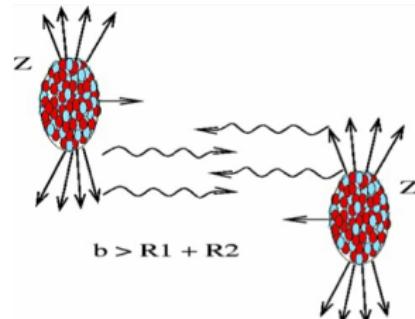
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The photoproduction is dominant in ultra-peripheral scattering ($b_{\text{impact}} > 2R_A$).



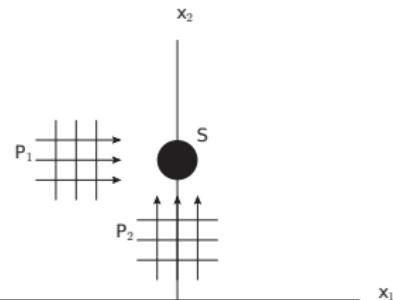
From Weizsäcker-Williams method, the total cross section can be given by

$$\sigma_X = \int d\omega \frac{dN(\omega)}{d\omega} \sigma_X^\gamma(\omega)$$

where,

$\frac{dN(\omega)}{d\omega}$ → Photon Flux

$\sigma_X^\gamma(\omega)$ → Photoproduction Cross Section



Exclusive vector meson photoproduction

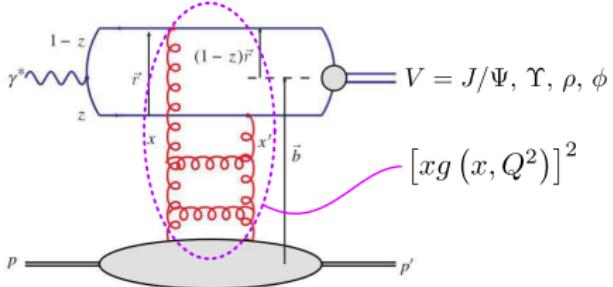
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- $\gamma + p \rightarrow V + p \rightarrow$ has been investigated experimentally and theoretically as it allows to test perturbative Quantum Chromodynamics.
- The quarkonium masses (m_c , m_b), give a perturbative scale for the problem even at $Q^2 = 0$.
- The photoproduction of mesons in the high energy regime is a possibility to investigate the Pomeron exchange.



Pomeron → two gluons (vacuum quantum numbers)

$x(x')$ → gluon momentum fraction;

z → quark momentum fraction;

Diffractive production of meson at $t = 0$

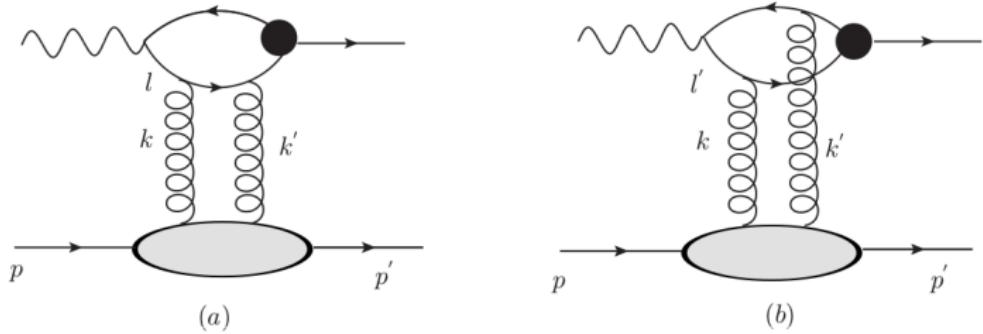
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- An important class of diffractive reactions where we can use a perturbative treatment is the vector meson production in DDIS: $\gamma^* p \rightarrow V p$.
- Two gluons exchange diagrams that contribute to the amplitude of the vector meson leptoproduction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



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

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



Diffractive production of meson at $t = 0$

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Amplitude¹:

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

$e_c \rightarrow \frac{2}{3}$ for $\psi_{(1S),(2S)}$ and $\frac{1}{3}$ for $Y_{(1S),(2S)}$

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

$k, l(l') \rightarrow$ gluons transverse momentum and quark (antiquark) momentum

$m_f, M_V \rightarrow$ quark mass (m_c or m_b) and vector meson mass, respectively.

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

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

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

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

¹ M. G. Ryskin, Z. Phys. C 57, 89, 1993

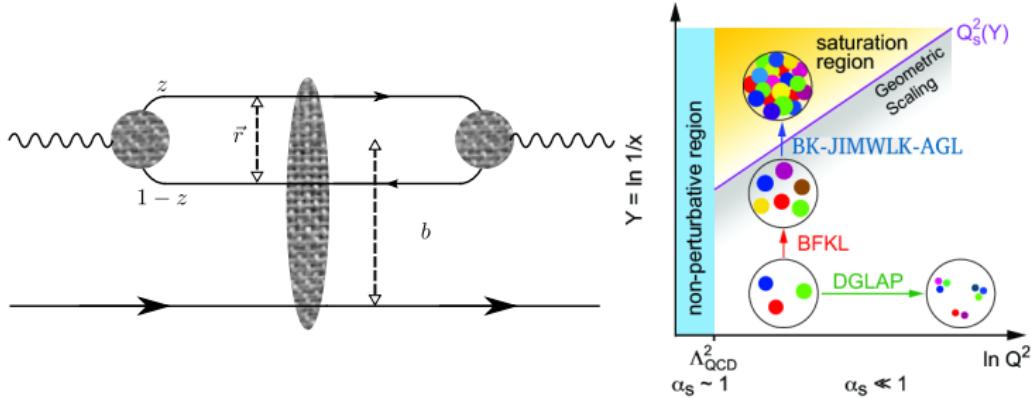
Dipole Formalism

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- In the LHC energy domain hadrons and photons can be considered as color dipoles in the light cone representation ².
- The scattering process is characterized by the color dipole cross section representing the interaction their with the target.



r' → dipole separation.

$z(1-z)$ → quark(antiquark) momentum fraction.

b → impact parameter.

²N. N. Nikolaev, B. G. Zakharov, Z. Phys. C 49, 607, 1991



Quarkonium production in pp collisions

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The rapidity distribution for quarkonium photoproduction is given by

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

Photon flux:³

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

$\omega \rightarrow$ photon energy

$S_{gap}^2 = 0.8$ ⁴ → represents the absorptive corrections due to spectator interactions between the two hadrons⁵ - Average

³ C. A. Bertulani, S. R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55, 271, 2005

⁴ W. Schafer and A. Szczurek, Phys. Rev. D 76, 094014, 2007

⁵ 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

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$$\sigma_{\gamma^* p \rightarrow Vp}(s, Q^2) = \frac{1}{16\pi B_V} \left| \mathcal{A}(x, Q^2, \Delta = 0) \right|^2, \quad (4)$$

where the amplitude is ⁶

$$\mathcal{A}(x, Q^2, \Delta) = \sum_{h,\bar{h}} \int dz d^2r \Psi_{h,\bar{h}}^\gamma \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h,\bar{h}}^{V*}, \quad (5)$$

$$B_V(W_{\gamma p}) = b_{el}^V + 2\alpha' \log \left(\frac{W_{\gamma p}}{W_0} \right)^2 \rightarrow \text{diffractive slope parameter}$$
$$\alpha' = 0.25 \text{ GeV}^{-2}$$

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

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

⁶

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



Light cone wave functions

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

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

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

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

N_c → color number.

$h, \bar{h} = \pm \frac{1}{2}$ → quarks helicity.

Light cone wave functions

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Boosted Gaussian Wavefunction

$\Psi(1S)$ and $Y(1S)$:

$$\phi_{T,L}^{1S}(r,z) = \mathcal{N}_{T,L} z(1-z) \exp\left\{-\frac{m_f^2 \mathcal{R}_{1S}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}_{1S}^2} + \frac{m_f^2 \mathcal{R}_{1S}^2}{2}\right\}$$

$\Psi(2S)$ and $Y(2S)$:

$$\phi_{T,L}^{2S}(r,z) = \mathcal{N}_{T,L} z(1-z) \exp\left\{-\frac{m_f^2 \mathcal{R}_{2S}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}_{2S}^2} + \frac{m_f^2 \mathcal{R}_{2S}^2}{2}\right\} [1 + \alpha_{2S} g_{2S}(r,z)]$$

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

$\mathcal{N}_{T,L}, \mathcal{R}_{nS}^2, \alpha_{2S} \rightarrow$ parameters from the wave functions orthogonality condition ^{7, 8}

Meson	m_f (GeV)	\mathcal{N}_L	\mathcal{N}_T GeV	\mathcal{R}^2 (GeV $^{-2}$)	α_{2S}	M_V (GeV)	$\Gamma_{e^+e^-}^{\text{exp}}$ (KeV)	$\Gamma_{e^+e^-}$ (KeV)
J/ψ	1.4	0.57	0.57	2.45	0	3.097	5.55 ± 0.14	5.54
$\psi(2S)$	1.4	0.67	0.67	3.72	-0.61	3.686	2.37 ± 0.04	2.39
$Y(1S)$	4.2	–	0.481	0.567	0	9.46	1.34 ± 0.018	1.34
$Y(2S)$	4.2	–	0.624	0.831	-0.555	10.023	0.612 ± 0.011	0.611

⁷ N. Armesto and Amir H. Rezaeian, Phys. Rev. D90, 054003, 2014

⁸ B. E. Cox, J. R. Forshaw and R. Sandapen, JHEP06, 034, 2009



Dipole Cross Section - GBW

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

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

$$\gamma_{eff} = 1$$

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

$$x_0 = 3 \times 10^{-4}, \sigma_0 = 23 \text{ mb}, \lambda = 0.29 \rightarrow \text{fitted to DIS HERA data}$$

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



Dipole cross section - CGC

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Color Glass Condensate parametrization (CGC):¹⁰

$$\sigma_{q\bar{q}}^{CGC}(x, r) = \sigma_0 \times \begin{cases} N_0 \left(\frac{rQ_s}{2}\right)^{2(\gamma_s + (1/\kappa\lambda Y)\ln(2/rQ_s))}, & rQ_s \leq 2 \\ 1 - e^{-A\ln^2(BrQ_s)}, & rQ_s > 2 \end{cases}$$

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

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

R , x_0 , λ , N_0 → 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



Dipole cross section - BCGC

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Color Glass Condensate parametrization (b-CGC):¹¹

$$\sigma_{q\bar{q}}^{bCGC}(x, r) = 2 \times \begin{cases} N_0 \left(\frac{rQ_s}{2} \right)^{2(\gamma_s + (1/\kappa\lambda Y)\ln(2/rQ_s))}, & rQ_s \leq 2 \\ 1 - e^{-A\ln^2(BrQ_s)}, & rQ_s > 2 \end{cases}$$

$$Q_s^{bCGC} = (x_0/x)^{\lambda/2} \left[\exp \left(-\frac{b^2}{2B_{CGC}} \right) \right]^{1/2\gamma_s} \text{GeV} \rightarrow \text{saturation scale}$$

$$B_{CGC} = 7.5 \text{ GeV}^{-2}$$

$\gamma_s = 0.46$, $\kappa = 9.9$ → fixed to their LO BFKL values

R , x_0 , λ , N_0 → free parameters of the fit

$$A = \frac{-N_0 \gamma_s^2}{(1-N_0)^2 \ln(1-N_0)}, B = \frac{1}{2} (1-N_0)^{-(1-N_0)/N_0 \gamma_s}$$

¹¹ G. Watt and H. Kowalski, Phys. Rev. D 78, 014016, 2008

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

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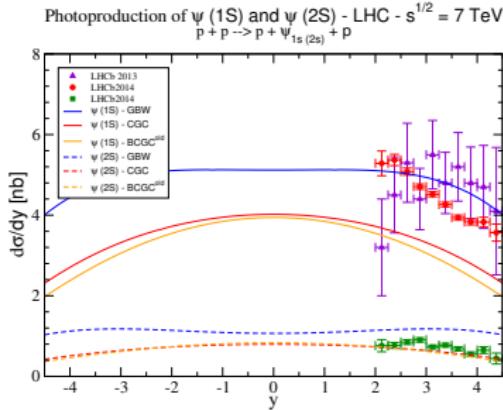


Figure: The rapidity distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction at $\sqrt{s} = 7 \text{ TeV}$.

- Predictions to rapidity distribution at LHC (7 TeV), for pp collisions;
- The models GBW, CGC and b-CGC were considered for the dipole cross section;
- The relative normalization and overall behavior on rapidity is quite well reproduced in the forward regime;
- LHCb data:

(J. Phys. G 40, 045001, 2013);

(J. Phys. G 41, 055002, 2014).

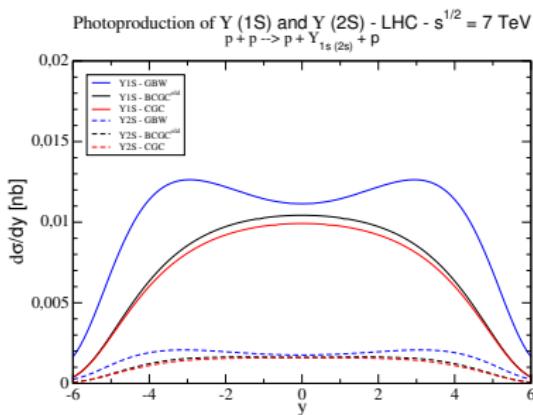
Y(1S) and Y(2S) rapidity distribution

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- Predictions to rapidity distribution at LHC (7 TeV), for pp collisions;
- The models GBW, CGC and b-CGC were considered for the dipole cross section;

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



Total cross section for forward region

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Our prediction:

Table: Total cross section in the rapidity region $2.0 < \eta < 4.5$ for the vector mesons J/ψ , $\Psi(2S)$, $Y(1S)$ and $Y(2S)$.

$\sigma_{pp \rightarrow J/\psi \rightarrow \mu^+ \mu^-}$	<i>GBW</i>	<i>CGC</i>	<i>BCGC</i>	<i>LHCb measure</i> ^{12,13}
J/ψ	283.28	186.59	170.25	$291 \pm 7 \pm 19$ pb
$\Psi(2S)$	9.05	4.74	4.52	$6.5 \pm 0.9 \pm 0.4$ pb
$Y(1S)$	12.0	7.4	7.81	$9 \pm 2.1 \pm 1.7$ pb
$Y(2S)$	1.97	1.31	1.41	$1.3 \pm 0.8 \pm 0.3$ pb

¹²(J. Phys. G 41, 055002, 2014)

¹³(JHEP 1509, 084, 2015)



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

Our prediction:

$$[\psi(2S)/\psi(1S)]_{y=0} = \begin{matrix} \text{gbw} \\ \text{cgc} \\ \text{bcgc} \end{matrix} 0.207, 0.196, 0.21$$

$$[\psi(2S)/\psi(1S)]_{2 < y < 4.5} = \begin{matrix} \text{gbw} \\ \text{cgc} \\ \text{bcgc} \end{matrix} 0.031, 0.025, 0.027$$

LHCb determination (J. Phys. G 41, 055002, 2014):

$$[\psi(2S)/\psi(1S)](2.0 < \eta_\mu < 4.5) = 0.022$$

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Transverse momentum distribution in pp collisions

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- p_T^2 -distributions of the vector meson processes are an important source of information on the proton in the low- x region.
- It is common to parameterize this distribution as

$$\frac{d\sigma}{dt} \propto \exp(-B_D|t|)$$

B_D (effective slope) is a parameter that characterizes the area size of the interaction region.

- For J/ψ , $\psi(2S)$, $\Upsilon(1S)$ and $\Upsilon(2S)$ we use the Regge expression

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

with $\alpha' = 0.25 \text{ GeV}^{-2}$, $W_0 = 90 \text{ GeV}$, $b_{el}^{J/\psi} = 4.99 \pm 0.41 \text{ GeV}^{-2}$ and $b_{el}^{\psi(2S)} = 4.31 \pm 0.73 \text{ GeV}^{-2}$ for Ψ 's, and $\alpha' = 0.164 \text{ GeV}^{-2}$, $W_0 = 95 \text{ GeV}$ and $b_{el}^{\Upsilon(1S),(2S)} = 3.68 \text{ GeV}^{-2}$ for Υ 's, from [J. Phys. G42 105001, \(2015\)](#).

p_T - distribution in pp collisions for J/ψ and $\psi(2S)$

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The p_T -distribution for quarkonium photoproduction in central rapidity in pp collisions is given by

$$\left. \frac{d^2\sigma}{dydp_T} \right|_{y=0} \approx 2p_T \left. \frac{d\sigma}{dy} \right|_{y=0} B_V(y=0) e^{-B_V p_T^2} \quad (6)$$

Our estimates:

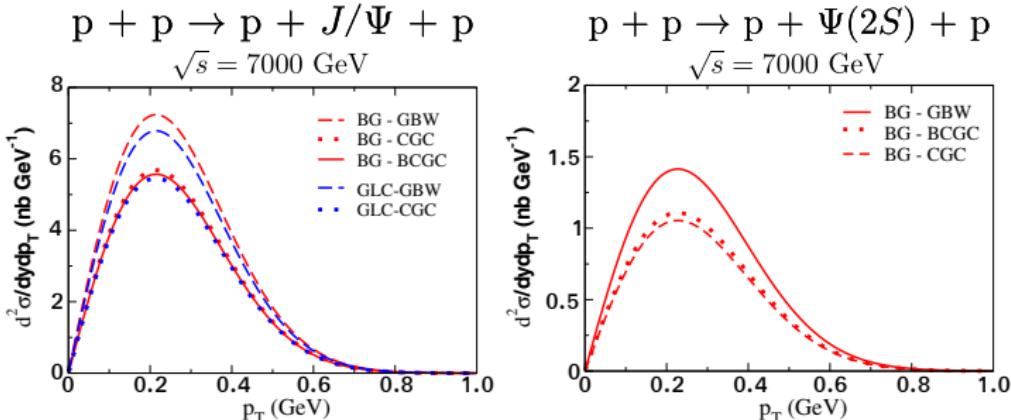


Figure: The transverse momentum distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction at $\sqrt{s} = 7\text{TeV}$

p_T^2 - distribution in pp collisions for J/ψ and $\psi(2S)$

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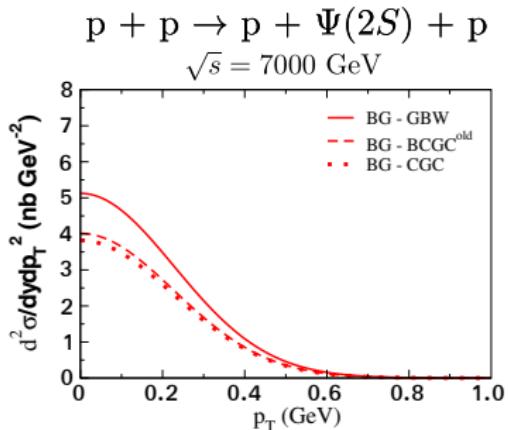
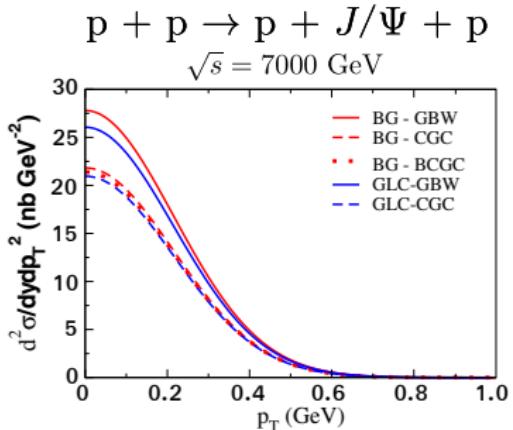
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The p_T^2 -distribution for quarkonium photoproduction in central rapidity in pp collisions is given by

$$\frac{d^2\sigma}{dydp_T^2} \Big|_{y=0} \approx \frac{d\sigma}{dy} \Big|_{y=0} B_V(y=0) e^{-B_V p_T^2} \quad (7)$$

Our estimates:



p_T^2 - distribution in pp collisions for $\Upsilon(1S)$ and $\Upsilon(2S)$

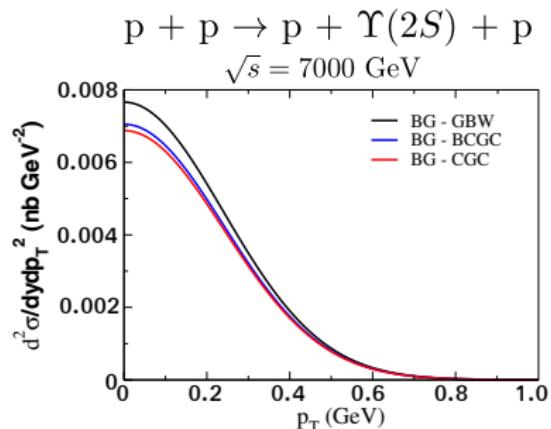
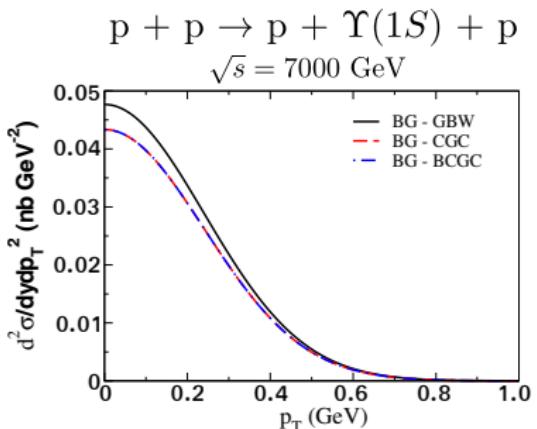
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For $\Upsilon(1S)$ and $\Upsilon(2S)$, we obtain





$V(J/\Psi, \Psi(2S), Y(1S), Y(2S))$ production in AA collisions

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Coherent process:



⇒ nuclei remain intact.

Incoherent process:



⇒ nuclei are fragmented.



V($J\Psi$, $\Psi(2S)$, $Y(1S)$, $Y(2S)$) production in AA collisions

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Coherent cross section: ^{14,15}

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

σ_{dip} → dipole cross section.

Ψ_V → vector meson wave function.

Ψ_γ → photon wave function.

$T_A(b) = \int dz \rho_A(b, z)$

$\rho_A(b, z)$ → nuclear thickness function.

b → impact parameter.

¹⁴ B. Z. Kopeliovich and B. G. Zakharov, Phys. Rev. D 44, 3466, 1991

¹⁵ M. B. Gay Ducati, M. T. Griep, M. V. T. Machado, Phys. Rev. C 88, 014910, 2013



Transverse momentum distribution in AA collisions

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The p_T -distribution for quarkonium photoproduction in AA collisions is given by

$$\frac{d^2\sigma}{dydp_T} \Big|_{y=0} = \frac{2p_T \frac{d\sigma}{dy} \Big|_{y=0} |F(|t|=p_T^2)|^2}{\int_{-\infty}^{t_{min}} |F(|t|=p_T^2)|^2 dt} \quad \text{with} \quad t_{min} = \left(\frac{m_V^2}{4\omega} \right)^2 \quad (8)$$

where

$$F(p_T = \sqrt{|t|}) = \frac{4\pi\rho_0}{Ap_T^3} [\sin(p_T R_A) - p_T R_A \cos(p_T R_A)] \left[\frac{1}{1+a^2p_T^2} \right]$$

with¹⁶

$$\rho_0 = 0.16 \text{ fm}^{-3}$$

$$A_{Pb} = 207$$

$$R_A = 1.2A^{1/3} \text{ fm}$$

$$a = 0.7 \text{ fm.}$$

¹⁶V.P. Gonçalves, M.V.T. Machado, Eur. Phys. J. C 40, 519, 2005

p_T - distribution in Pb-Pb collisions for J/ψ and $\psi(2S)$

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The calculation of $d\sigma/dy|_{y=0}$, uses the Boosted Gaussian wave function and the dipole cross section models (GBW, CGC and b-CGC).

Thus, we obtain

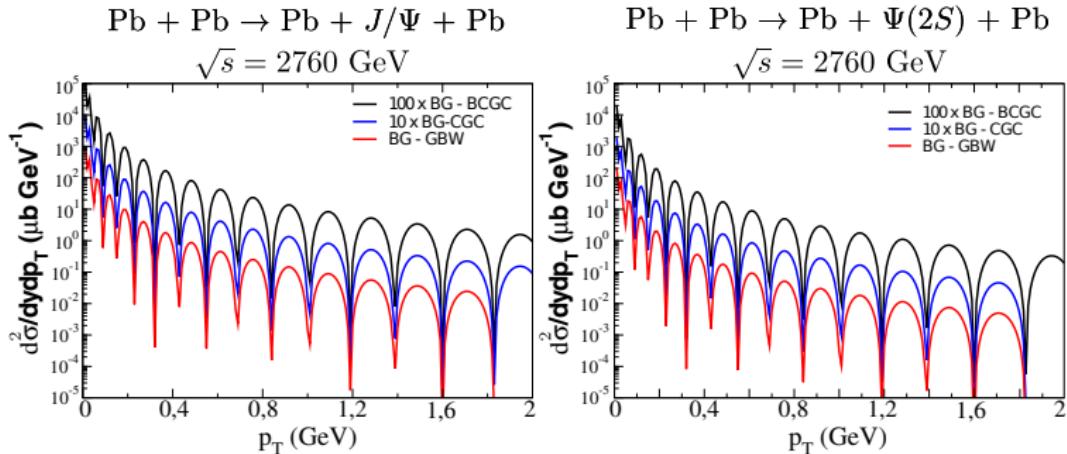


Figure: The transverse momentum distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction in Pb-Pb collisions at

$$\sqrt{s} = 2.76 \text{ TeV}$$

p_T^2 - distribution in Pb-Pb collisions for J/ψ and $\psi(2S)$

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We also calculate the p_T^2 – distribution using the same models that the last case and obtain

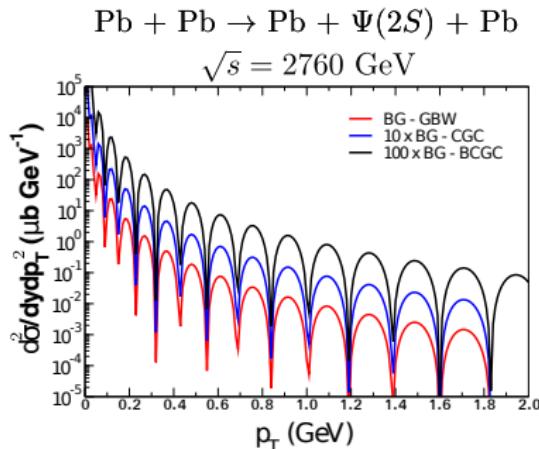
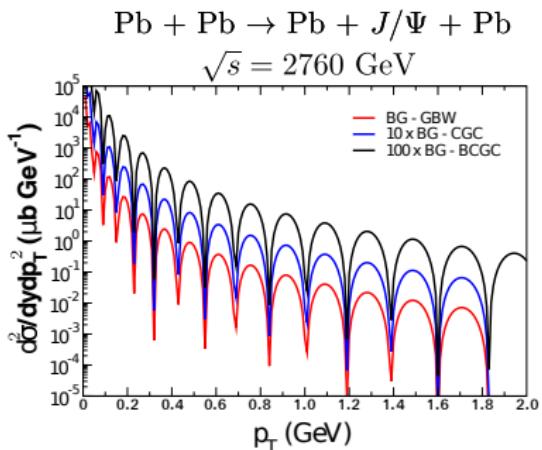


Figure: The square transverse momentum distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction in Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV

p_T^2 - distribution in Pb-Pb collisions for Y(1S) and Y(2S)

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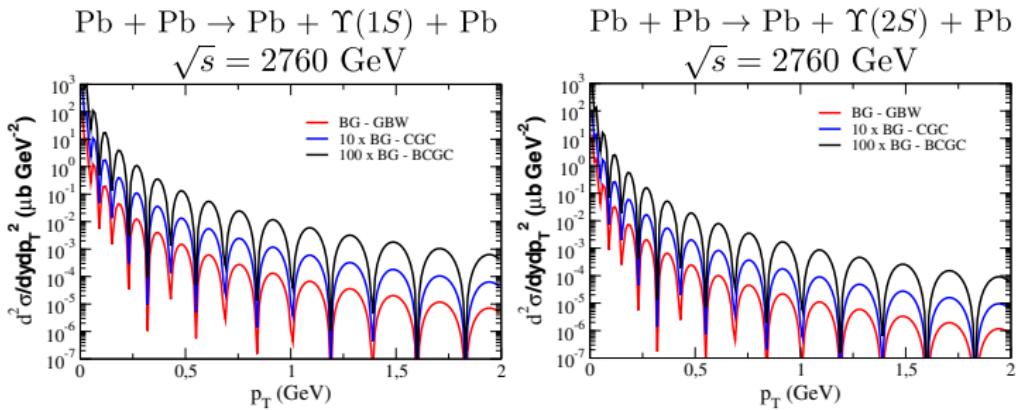


Figure: The square transverse momentum distribution of Y(1S) and Y(2S) photoproduction in Pb-Pb collisions at $\sqrt{s} = 2.76 \text{ TeV}$

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pp:

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

- The predictions for $\Psi(1S)$ and $\Psi(2S)$ 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

PbPb:

The transverse momentum distributions of coherent production of mesons $\Psi(1S)$, $\Psi(2S)$, $Y(1S)$ and $Y(2S)$ were calculated in Pb-Pb collisions using the dipole formalism.



Introduction

Cross
Section
Calculation

Results

Summary

Thank You!