Theoretical Status of UPC Quarkonia Production: pp, pA and AA

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Outlook

- Introduction
  - $\rightarrow$ Quarkonium production mechanisms
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  - $\rightarrow$ Exclusive photoproduction $\rightarrow$ Pomeron exchange
- Vector mesons production in pp and PbPb collisions
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  - $\rightarrow$ Vector mesons wave function
  - $\rightarrow$ Dipole cross section model
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- Summary

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Why to Investigate the Quarkonium Production?

- In pp collision

  → Heavy-quark mass acts as a long distance cut-off

  → pQCD reliable up to low transverse momenta (p_T).

  → Test for both perturbative(partonic cross section) and non-perturbative($Q\bar{Q} \rightarrow$ meson state) aspects of QCD calculations.

- In nuclear collision

  → Open and hidden heavy-flavour production constitutes a sensitive probe of the QGP.

  → The in-medium dissociation probability of these states are expected to provide an estimate of the initial temperature reached in the collisions.

  → The nuclear modification of the PDFs can also be studied using quarkonium photoproduction in ultra-peripheral nucleus–nucleus collisions.

Quarkonium Production in pp

The cross section for quarkonium production can be written as

$$d\sigma^{Q} = f_a(x_a) f_b(x_b) \times d\hat{\sigma}_{ab}^{q\bar{q}} \times \langle O_{q\bar{q}}^{Q} \rangle \quad (1)$$

where

$f_{a/b}(x_{a/b})$ are partonic distribution functions, obtained from other experiments as DIS.

$d\hat{\sigma}_{ab}^{q\bar{q}}$ is the partonic cross section which describes how to produce the heavy quark pair (calculable with pQCD).

$\langle O_{q\bar{q}}^{Q} \rangle$ describes the evolution of the heavy quark pair into the quarkonium state Q. It is commonly represented by the models CSM, CEM or NRQCD.

Hadroproduction

- Colour Singlet Model (CSM) [1]

$$\sigma_{A+B\to H+X} = \frac{|R_H(0)|^2}{4\pi} \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a) f_{b/B}(x_b) \hat{\sigma}_{ab\to c\bar{c}_1}({}^{2S+1}L_J)X$$

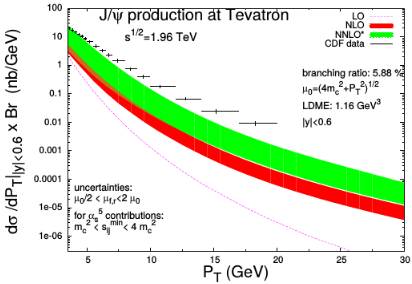

Figure extracted from **arXiv:1208.5506v3 [hep-ph].**

→ $|R_H(0)|^2$ is the square of wave function state H calculated in the origin.

→ Heavy quark pair with the same quantum numbers as the final meson.

→ Disregards the factorization → Direct production of state meson.

[1] E. Braaten, S. Fleming and T. C. Yuan, Ann. Rev. Nucl. Part. Sci. 46, 197, 1996

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Hadroproduction

- Colour Octet Model (NRQCD) [2]

$$\sigma(H) = \mathrm{Im} \sum_{n=\alpha,S,L,J} \frac{F_n}{m^{d_n-4}} \langle \mathcal{O}_\alpha^H \left({}^{2S+1}L_J\right) \rangle$$

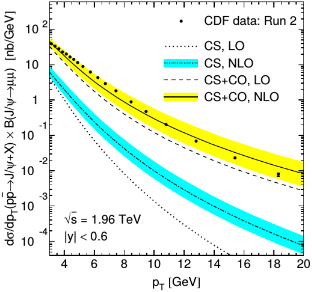

Figure extracted from **arXiv:1208.5506v3 [hep-ph].**

→ Both colorless and colored states of the heavy quark pairs are considered.

→ The relative contribution of the states is parametrized.

[2] W. E. Caswell and G. P. Lepage, Phys. Lett. B 167, 437, 1986

Hadroproduction

- Colour Evaporation Model (CEM) [3,4]

$$\sigma_{\text{charmonium}} = \frac{1}{9}\int_{2m_c}^{2m_D} dm_{c\bar{c}} \frac{d\sigma_{c\bar{c}}}{dm_{c\bar{c}}}$$

$$\sigma_{\text{open}} = \frac{8}{9}\int_{2m_c}^{2m_D} dm_{c\bar{c}} \frac{d\sigma_{c\bar{c}}}{dm_{c\bar{c}}} + \int_{2m_D}^{\sqrt{s}} dm_{c\bar{c}} \frac{d\sigma_{c\bar{c}}}{dm_{c\bar{c}}}$$

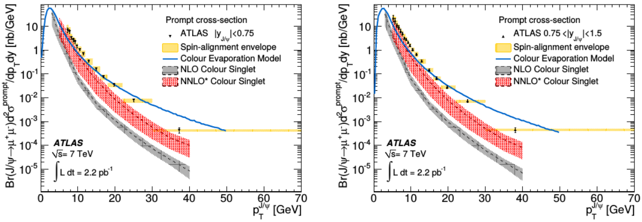

Figure extracted from **Georges Aad *et al.*, Nucl.Phys. B850, 387, 2011**

→ Cross section of a given quarkonium is proportional to the heavy quark pair cross section.

→ Soft interactions randomise the colour charges → quakonium production is independent of the color.

[3] H. Fritzsch, Phys. Lett. B 67, 217, 1977

[4] C. B. Mariotto, M. B. Gay Ducati and G. Ingelman, Eur.Phys.J. C 23, 527, 2002

Photoproduction

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- Colour Dipole Model [5]

$\rightarrow$ The deep-inelastic scaterring is viewed as the interaction of a color dipole with the target.

$\rightarrow$ Dipole lifetime is much longer than the lifetime of its interaction with the target.

$\rightarrow$ Photoproduction cross section is the factorized in photon-meson wave function and dipole cross section.

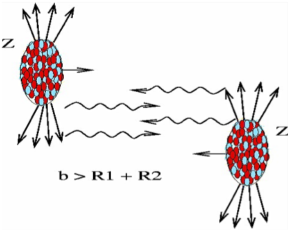
$$A \propto \Psi^{\gamma} \otimes \sigma^{q\bar{q}} \otimes \Psi^{V}$$

$\rightarrow$ Enables to include nuclear effects and the parton saturation phenomenon.

[5] M. B. Gay Ducati, F. Kopp, M. V. T. Machado and S. Martins, Phys.Rev. D 94, 094023, 2016

Photoproduction in UPC - Theoretical Motivation

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



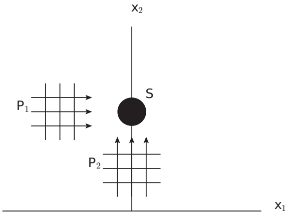
From Weizsäcker-Williams method, the total cross section can be given by

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

where,

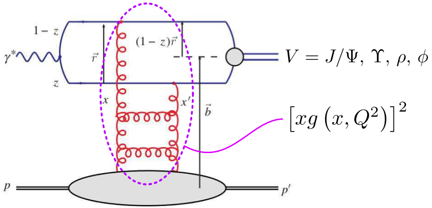
$\frac{dN(\omega)}{d\omega}$ →Photon Flux

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



Exclusive vector meson photoproduction

- $\gamma + p \to V + p \to$ 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 $\to$ two gluons (vacuum quantum numbers)

$x(x')$ $\to$ gluon momentum fraction;

z $\to$ quark momentum fraction;

Diffractive production of meson at $t = 0$

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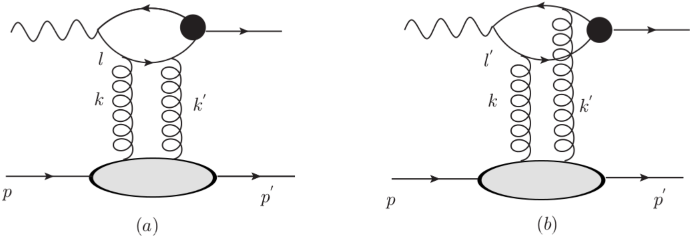
- An important class of diffractive reactions where we can use a perturbative treatment is the vector meson production in DDIS: $\gamma^* p \to Vp$.
- Two gluons exchange diagrams that contribute to the amplitude of the vector meson leptoproduction are shown in the figure below:



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

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

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Diffractive production of meson at $t = 0$

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Amplitude [6]:

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

$g_V^2 = 3\Gamma_{ee} M_V / 64\pi\alpha^2 \rightarrow$ specifies the $q\bar{q}$ coupling to the vector meson

$\Gamma_{ee} \rightarrow$ width decay $V \rightarrow e^+e^-$

$e_c \rightarrow \frac{2}{3}$ 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:

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

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

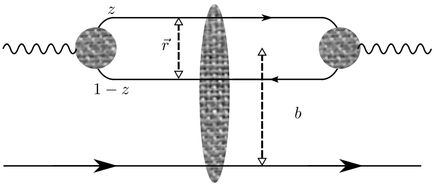
Dipole formalism $\rightarrow$ can restrict $xg(x,\tilde{Q}^2)$ $\rightarrow$ includes gluon saturation

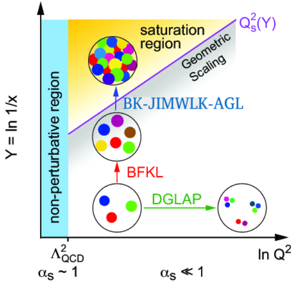
[6] M. G. Ryskin, Z. Phys. C 57, 89, 1993

Dipole Formalism

- In the LHC energy domain hadrons and photons can be considered as color dipoles in the light cone representation [7].

- The scattering process is characterized by the color dipole cross section representing the interaction their with the target.





$r \rightarrow$ dipole separation.
$z(1-z) \rightarrow$ quark(antiquark) momentum fraction.
$b \rightarrow$ impact parameter.

[7] N. N. Nikolaev, B. G. Zakharov, Z. Phys. C 49, 607, 1991

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Quarkonium production in pp collisions

The rapidity distribution for quarkonium photoproduction is given by

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

Photon flux: [8]

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

$\omega \to$ photon energy

$S^2_{gap} = 0.8$ [9] $\to$ represents the absorptive corrections due to spectator interactions between the two hadrons [10] - Average

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

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

[10] 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.

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γp cross section

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

where the amplitude is [11]

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

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

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

$W_0 = 95\ \mathrm{GeV}$

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

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

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Light cone wave functions

The light cone wave functions of the meson are written as [12]

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

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

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

$N_c \rightarrow$ color number.

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

[12] H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D 74, 074016, 2006

Light cone wave functions

Boosted Gaussian Wavefunction

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

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

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

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

$\Upsilon(3S)$:

$$\phi_{T,L}^{3S}(r,z) = \mathcal{N}_{T,L} z(1-z) \exp\left\{-\frac{m_f^2 \mathcal{R}_{3S}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}_{3S}^2} + \frac{m_f^2 \mathcal{R}_{3S}^2}{2}\right\} \times \left\{1 + \alpha_{3S,1} g_{3S}(r,z) + \alpha_{3S,2}\left[g_{3S}^2(r,z) + 4\left(1 - \frac{4z(1-z)r^2}{R_{3S}^2}\right)\right]\right\}$$

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

Light cone wave functions

$\mathcal{N}_{T,L}, \mathcal{R}^2_{nS}, \alpha_{2S} \rightarrow$ parameters from the wave functions orthogonality condition [13, 14]

Meson	m_f (GeV)	$\mathcal{N}_L$	$\mathcal{N}_T$ GeV	$\mathcal{R}^2$ (GeV^{-2})	$\alpha_{nS,1}$	$\alpha_{nS,2}$	M_V (GeV)	$\Gamma^{exp}_{e^+e^-}$ (KeV)	$\Gamma_{e^+e^-}$ (KeV)
J/ψ	1.4	0.57	0.57	2.45	0	0	3.097	5.55±0.14	5.54
$\psi(2S)$	1.4	0.67	0.67	3.72	-0.61	0	3.686	2.37±0.04	2.39
$\Upsilon(1S)$	4.2	–	0.481	0.567	0	0	9.46	1.34±0.018	1.34
$\Upsilon(2S)$	4.2	–	0.624	0.831	-0.555	0	10.023	0.612±0.011	0.611
$\Upsilon(3S)$	4.2	–	0.668	1.028	-1.219	0.217	10.355	0.443±0.011	0.443

[13] N. Armesto and Amir H. Rezaeian, Phys. Rev. D90, 054003, 2014

[14] B. E. Cox, J. R. Forshaw and R.Sandapen, JHEP06, 034, 2009

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Dipole Cross Section - GBW

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The GBW (Golec-Biernat and Wusthoff) parametrization is given by: [15]

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

$\gamma_{\text{eff}} = 1$

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

GBW_{old} [9] $\rightarrow Q_{sat}^2(x) = \left(\frac{x_0}{x}\right)^{\lambda}$ $\sigma_0 = 29.12$, $x_0 = 0.41 \times 10^{-4}$ and $\lambda = 0.277$

GBW_{new} [16] (consider the effect of the gluon number fluctuations) $\rightarrow$ $\sigma_0 = 31.85$, $x_0 = 0.0546 \times 10^{-4}$ and $\lambda = 0.225$

[15] K. Golec-Biernat and M. Wusthoff, Phys. Rev. D 59, 014017, 1999

[16] M. Kozlov, A. Shoshi and W. Xiang, JHEP 0710, 020, 2007

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Dipole cross section - CGC

Color Glass Condensate parametrization (CGC): [17]

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

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

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

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

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

CGC_{old}[18] $\rightarrow$ $\sigma_0 = 27.33$, $x_0 = 0.1632 \times 10^{-4}$, $\lambda = 0.2197$ and $\gamma_s = 0.7376$

CGC_{new}[19] $\rightarrow$ $\sigma_0 = 21.85$, $x_0 = 0.6266 \times 10^{-4}$, $\lambda = 0.2319$ and $\gamma_s = 0.762$

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

[18] G. Soyez, Phys. Lett. B 655,32, 2007

[19] A.H. Rezaeain and I. Schmidt, Phys. Rev. D 88, 074016, 2013

Dipole cross section - BCGC

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Color Glass Condensate parametrization (b-CGC): [20]

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

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

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

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

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

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

$b - CGC_{old}^{14} \rightarrow$ $x_0 = 0.0184 \times 10^{-4}$, $\lambda = 0.119$ and $\gamma_s = 0.46$

[20] G. Watt and H. Kowalski, Phys. Rev. D 78, 014016, 2008

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

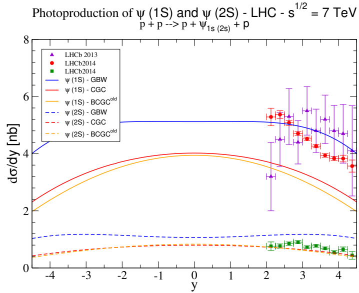

Figure: The rapidity distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction at $\sqrt{s} = 7\,TeV$.

- 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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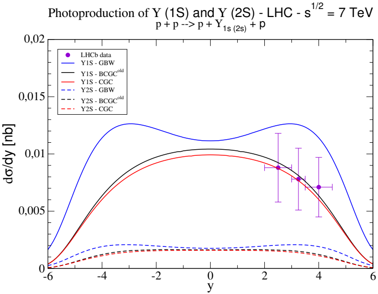


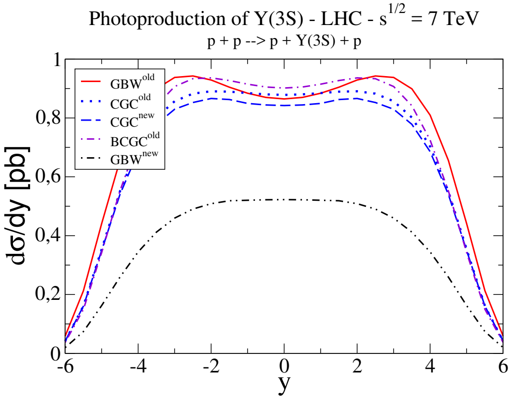
Figure: The rapidity distribution of $Y(1S)$ and $Y(2S)$ photoproduction at $\sqrt{s} = 7TeV$

- Predictions to rapidity distribution at LHC ($7TeV$) for $Y(1S,2S)$, for pp collisions; [a]
- The models GBW, CGC and b-CGC were considered for the dipole cross section;

[a] M. B. Gay Ducati, F. Kopp, M. V. T. Machado and S. Martins, Phys.Rev. D 94, 094023, 2016

$Y(3S)$ rapidity distribution

- The rapidity distribution of $Y(3S)$ photoproduction at $\sqrt{s} = 7\,TeV$



Total cross section for forward region

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Our prediction:

Table: Total cross section in the rapidity region $2.0 < \eta < 4.5$ (in units of *pb*) for photoproduction of the $\psi(1S,2S)$ (corrected for acceptance) and $\Upsilon(1S,2S,3S)$ states in *pp* collisions at $\sqrt{s} = 7$ TeV compared to the LHCb data [21,22] (errors are summed into quadrature).

$\sigma_{pp\to J/\psi\to\mu^+\mu^-}$	*GBW*	CGC^{old}	CGC^{new}	$BCGC^{old}$	GBW^{ksx}	LHCb measure
$\psi(1s)$	277.60	213.69	199.58	154.57	170.81	291 ± 20.24
$\psi(2s)$	8.40	5.94	5.98	4.13	4.39	6.5 ± 0.98
$\Upsilon(1s)$	25.05	20.45	20.02	19.12	12.5	9.0 ± 2.7
$\Upsilon(2s)$	4.32	3.8	3.70	3.9	2.05	1.3 ± 0.85
$\Upsilon(3s)$	0.35	0.32	0.31	0.33	0.17	–

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

22 (JHEP 1509, 084, 2015)

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

Our prediction:

$$[\psi(2S)/\psi(1S)]_{2<y<4.5} = \overset{\text{gbw}}{0.03},\ \overset{cgc^{old}}{0.027},\ \overset{cgc^{new}}{0.03},\ \overset{bcgc^{old}}{0.027},\ \overset{gbw^{ksx}}{0.026}$$

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

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

Rapidity Distribution in pA Collisions

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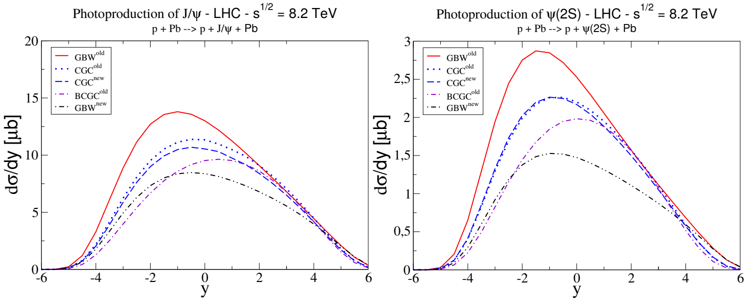
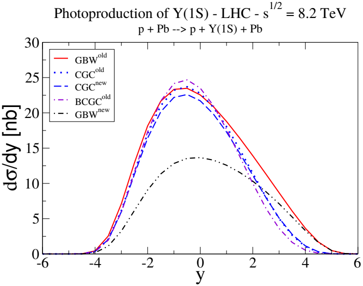
Summary

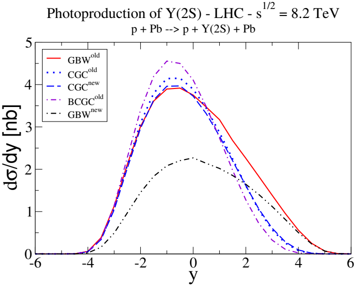
- We also estimates the rapidity distribution for $\Psi(1S, 2S)$ in pA collisions at $\sqrt{s} = 8.2 TeV$,



Rapidity Distribution in pA Collisions

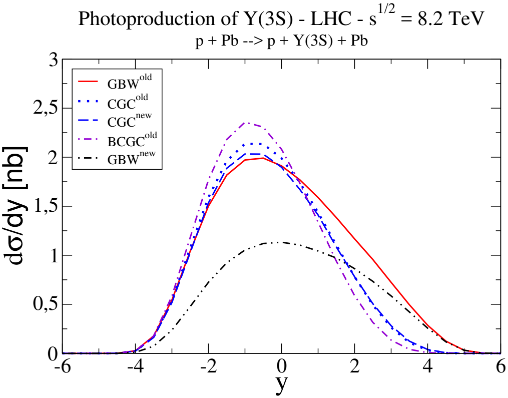
- For $\Upsilon(1S, 2S)$, were obtained the results





Rapidity Distribution in pA Collisions

- For $Y(3S)$, we obtained



Transverse momentum distribution in pp collisions

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Summary

- 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

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

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

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

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

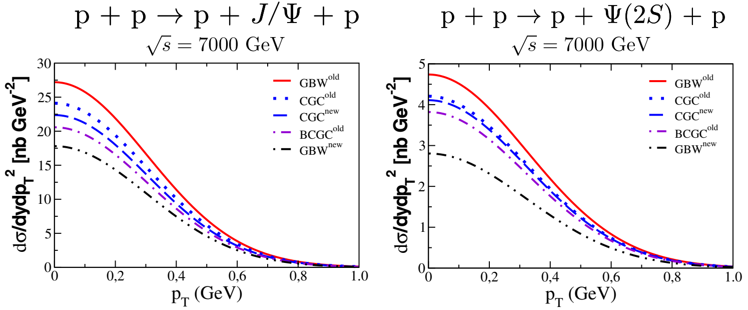
with $\alpha' = 0.25$ GeV^{-2}, $W_0 = 90$ GeV, $b_{el}^{J/\psi} = 4.99 \pm 0.41$ GeV^{-2} and $b_{el}^{\psi(2S)} = 4.31 \pm 0.73$ GeV^{-2} for Ψ's, and $\alpha' = 0.164$ GeV^{-2}, $W_0 = 95$ GeV and $b_{el}^{\Upsilon(1S),(2S)} = 3.68$ GeV^{-2} for Υ's, from J. Phys. G42 105001, (2015).

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

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

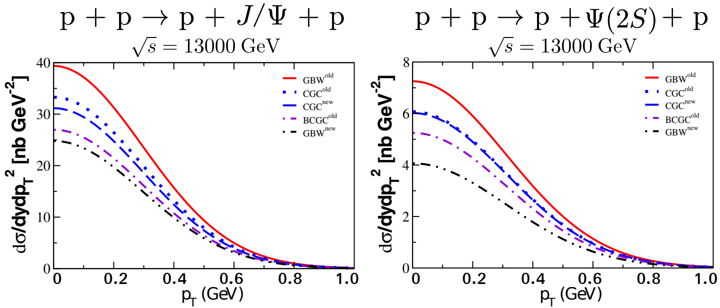
$$\left.\frac{d^2\sigma}{dy dp_T^2}\right|_{y=0} \approx \left.\frac{d\sigma}{dy}\right|_{y=0} B_V(y=0)e^{-B_V p_T^2} \quad (6)$$

Our estimates:



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

To $\sqrt{s} = 13$ TeV, were obtained the results



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

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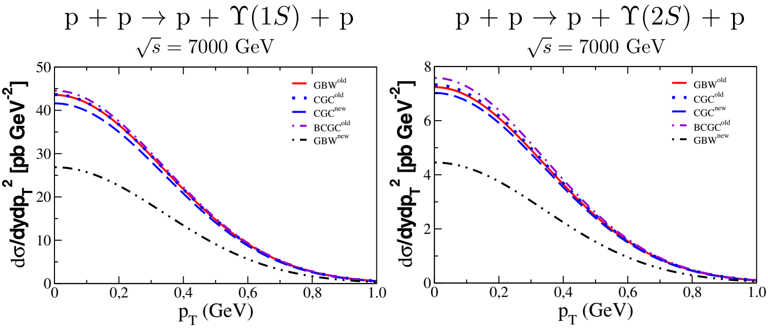
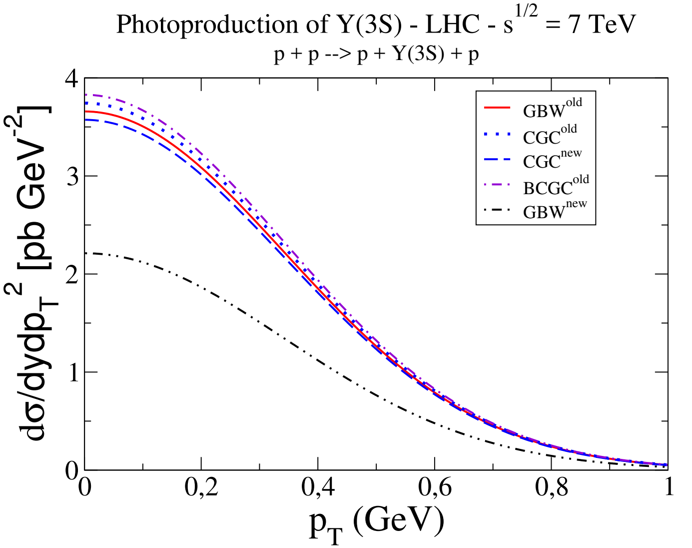
For Y(1S) and Y(2S), we obtain

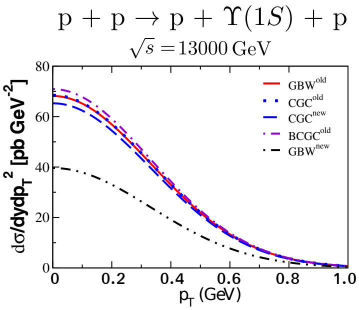


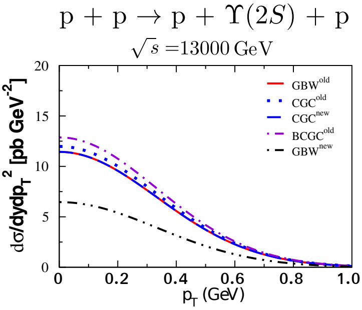
p_T^2 - distribution in pp collisions for $Y(3S)$



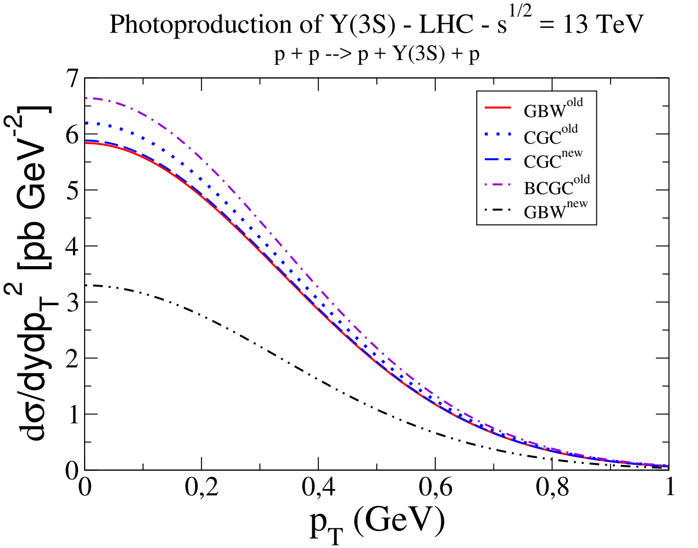
p_T^2 - distribution in pp collisions for $Y(1S)$ and $Y(2S)$

To $\sqrt{s} = 13$ TeV, we estimate





p_T^2 - distribution in pp collisions for $Y(3S)$



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

Coherent process:

$$AA \rightarrow AA + V.$$

$\Rightarrow$ nuclei remain intact.

Incoherent process:

$$AA \rightarrow X + V.$$

$\Rightarrow$ nuclei are fragmented.

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

Coherent cross section: [23,24]

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

$\sigma_{dip} \to$ 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.

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

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

Transverse momentum distribution in AA collisions

The p_T^2-distribution for quarkonium photoproduction in AA collisions is given by

$$\left.\frac{d^2\sigma}{dydp_T^2}\right|_{y=0} = \frac{\left.\frac{d\sigma}{dy}\right|_{y=0}\left|F(|t|=p_T^2)\right|^2}{\int_{-\infty}^{t_{min}}\left|F(|t|=p_T^2)\right|^2 dt} \qquad \text{with} \qquad t_{min} = \left(\frac{m_V^2}{4\omega}\right)^2 \qquad (7)$$

where

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

with [25]

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

$A_{Pb} = 207$

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

$a = 0.7\ fm$.

[25] V.P. Gonçalves, M.V.T. Machado, Eur. Phys. J. C 40, 519, 2005

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

We calculate the $p_T^2 - \textit{distribution}$ using the same models that the case pp and obtain

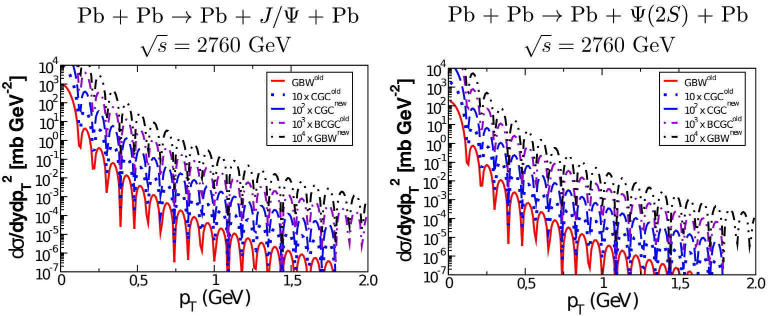


Figure: The square transverse momentum distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction in Pb-Pb collisions at $\sqrt{s} = 2.76\,TeV$

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

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To $\sqrt{s} = 5.5$ TeV, we obtain

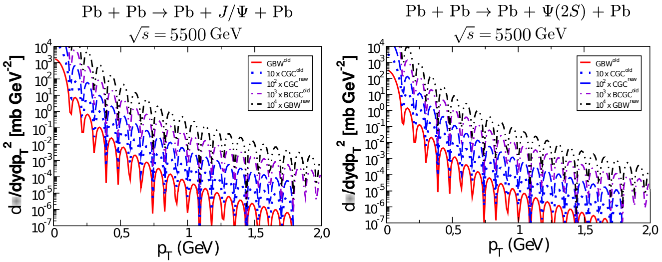

Figure: The square transverse momentum distribution of $\Psi(1S)$ and $\Psi(2S)$ photoproduction in Pb-Pb collisions at $\sqrt{s} = 5.5 TeV$

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

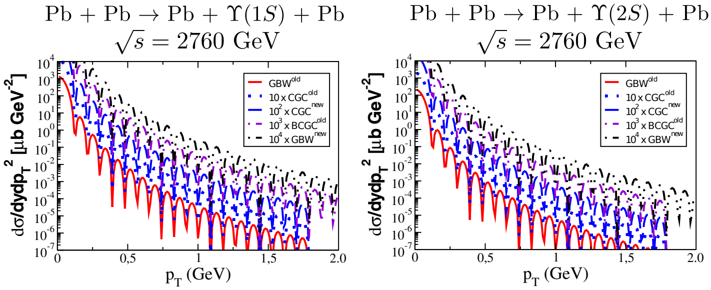

Figure: The square transverse momentum distribution of $Y(1S)$ and $Y(2S)$ photoproduction in Pb-Pb collisions at $\sqrt{s} = 2.76\,TeV$

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

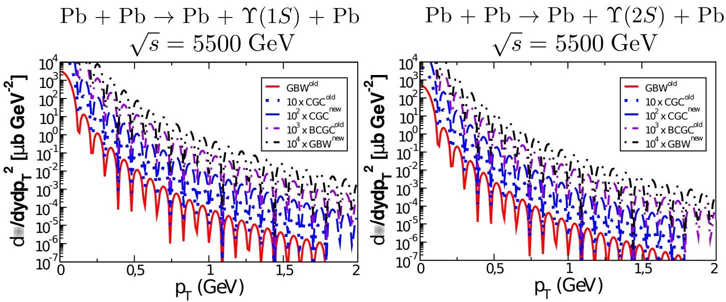

Figure: The square transverse momentum distribution of $Y(1S)$ and $Y(2S)$ photoproduction in Pb-Pb collisions at $\sqrt{s} = 5.5 TeV$ [26]

[26] M. B. Gay Ducati, F. Kopp, M. V. T. Machado and S. Martins, Phys.Rev. D 94, 094023, 2016

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Ultraperipheral to Peripheral

- Based on the good results of UPC, we extend the theoretical framework to peripheral collisions $\rightarrow$ to test the robustness of the formulation.

- Modifications: change in the photon flux [27]

$$\frac{d\sigma}{dy} = \int_{bmin}^{bmax} d^2b\, \omega N^{(2)}(\omega, b)\sigma_{\gamma A \rightarrow \gamma V}$$

where $N^{(2)}(\omega, b)$ is the effective photon flux.

- In a purely geometrical picture, the impact parameter b is related to centrality as [28]

$$c = \frac{b^2}{4R_A^2}$$

[27] M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. C93, 044912, 2016

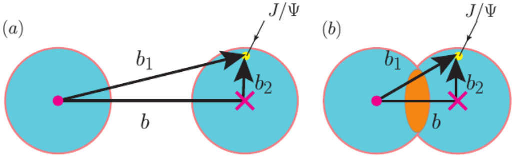
[28] W. Broniowski and W. Florkowski, Phys. Rev. C65, 024905, 2002

The Effective Photon Flux

- Restrictions

  → The photon flux must reach the target nucleus;

  → The overlap region where nuclear effects are presented was desconsidered.

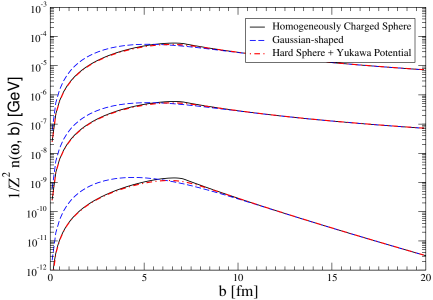


$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\Theta(R_A - b_2) \times \Theta(b_1 - R_A)}{\pi R_A^2} d^2 b_1$$

where $N(\omega_1, b_1)$ is the ordinary photon flux.

b-dependent Photon Flux

$$N(\omega, b) = \frac{z^2 \alpha_{qed}}{\pi^2 \omega} \left| \int_0^\infty dk_\perp k_\perp^2 \frac{F\left(k_\perp^2 + \left(\frac{\omega}{\gamma}\right)^2\right)}{k_\perp^2 + \left(\frac{\omega}{\gamma}\right)^2} J_1(bk_\perp) \right|^2$$



$$F_{hcs}(k^2) = 3\frac{j_1(kR)}{kR}$$

$$F_{gauss}(k^2) = \exp\left(\frac{k^2}{2Q_0^2}\right)$$

$$F_{hs+Yp}(k^2) = \frac{4\pi\rho_0}{Ak^3}\left[\frac{\sin(kR_a) - qR_a\cos(qR_a)}{1 + a^2k^2}\right]$$

with $k^2 = \vec{k}_\perp^2 + \left(\frac{\omega}{\gamma}\right)^2$ and $\gamma = \frac{\sqrt{s}}{2m_p}$

Figure: From top to bottom, the photon energies are $\omega = 10$ MeV, $\omega = 1$ GeV and $\omega = 100$ GeV.

Preliminary Results

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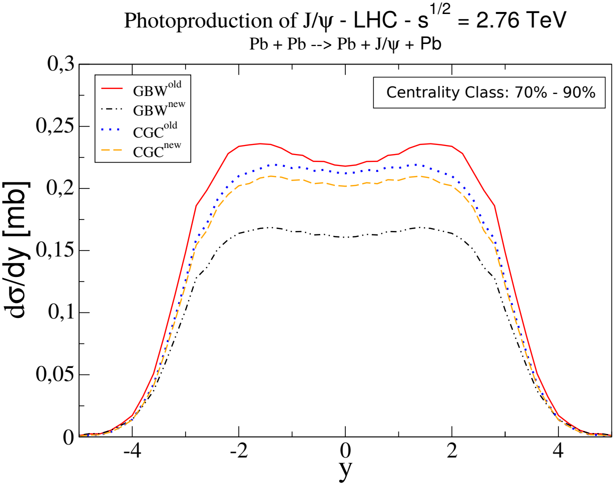
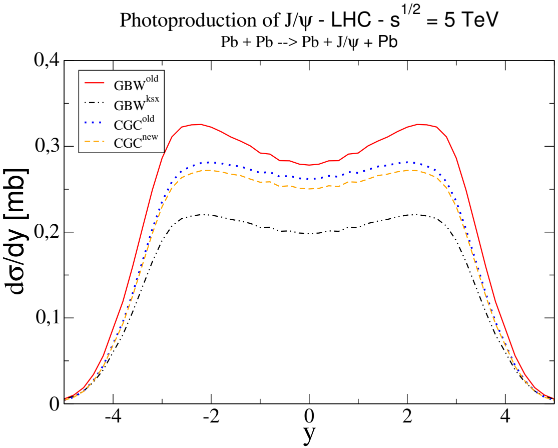
Using this approach, was calculated the rapidity distribution for the centrality class 70% to 90%,



Preliminary Results



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Summary

- The rapidity and p_T distributions of mesons $\Psi(1S,2S)$ and $Y(1S,2S,3S)$ production were calculated in pp and PbPb collisions using the dipole formalism.
- In pp, the predictions for $\Psi(1S,2S)$ and $Y(1S)$ rapidity distribution and total cross section are consistent with LHCb data.
- The transverse momentum distributions of coherent production of all mesons considered were obtained in Pb-Pb collisions at $\sqrt{s} = 7$ and $\sqrt{s} = 13$ TeV.
- Essai to peripheral: model for effective photon flux with b-dependence, providing rapidity distributions for $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.5$ TeV. (work in progress - MBGD, S. Martins.)

Thank You!