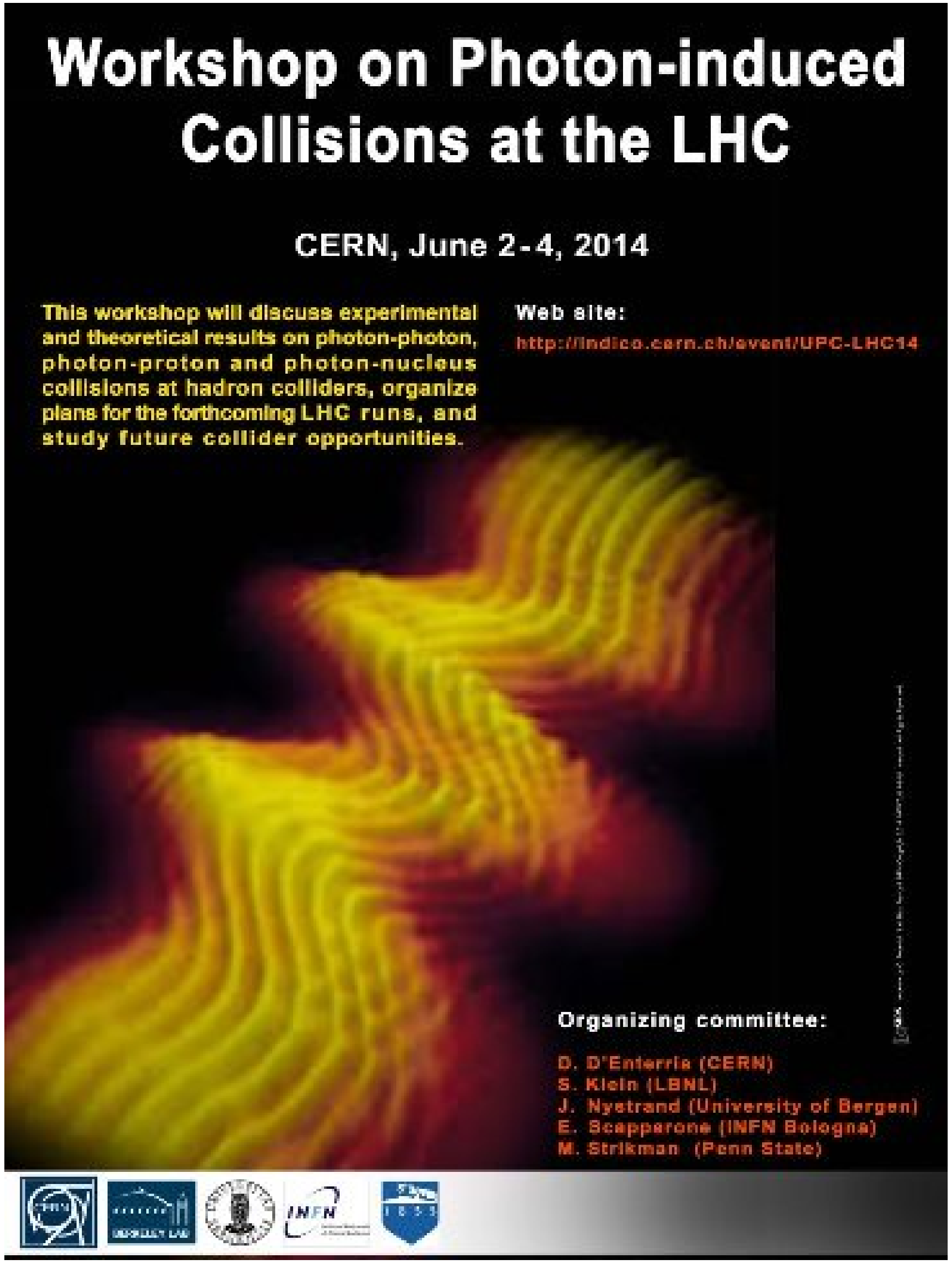

Probing QCD at low and high energies in photon – hadron interactions at LHC

Victor P. Gonçalves

Instituto de Física e Matemática

UFPel - Brazil

Outline

Photon – hadron interactions at LHC as a probe of the:

- QCD dynamics at high energies
- Odderon
- Charmoniumlike exotic states

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Photon – hadron interactions at LHC as a probe of the:

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Main goal: *Demonstrate that photon - hadron interactions at LHC are an important laboratory to study several aspects of the strong interactions.*

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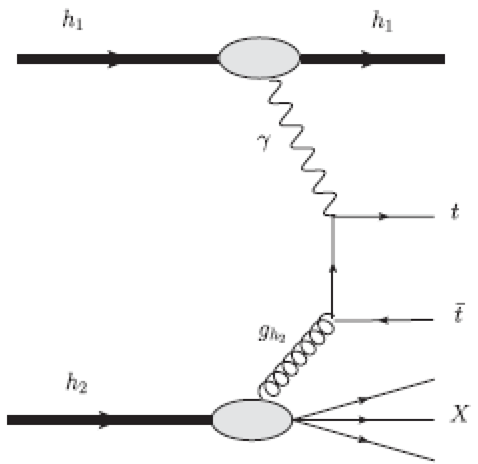
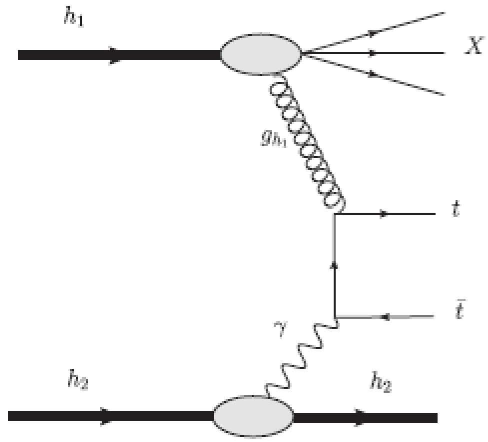
<u>First alternative</u>: Heavy quark production





Baur, Baron 91
Greiner et al. 91
VPG, Bertulani 02
Klein, Nystrand, Vogt 01, 02
VPG, Machado 03, 05, 07, 09
Adeluyi, Bertulani 11, 12
VPG 13

Probing QCD dynamics at high energies in UPHIC

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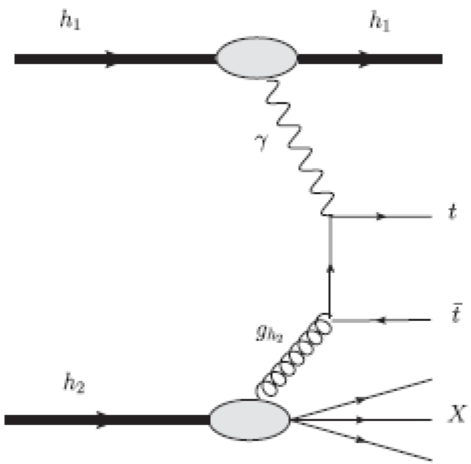

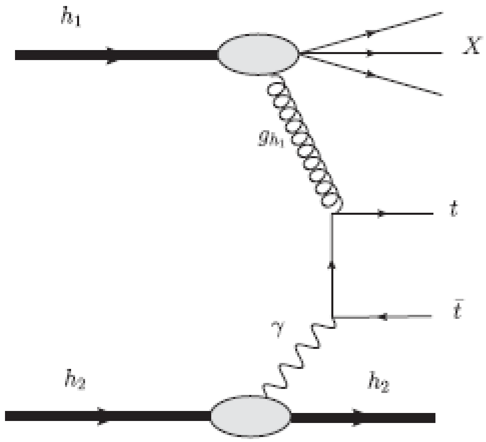

- Cross section proportional to the gluon distribution.
- Final state characterized by one rapidity gap.
- So far we haven't experimental data for this observable.

Probing QCD dynamics at high energies in UPHIC

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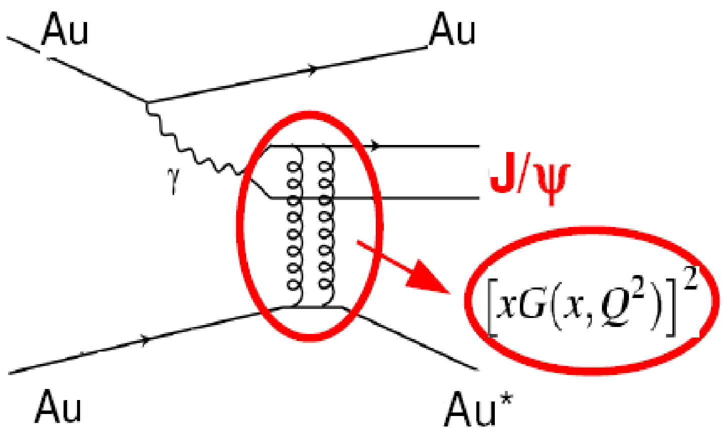
It is possible to constrain the gluon distribution in UPHIC?

Second alternative: Diffractive photoproduction of vector mesons



Klein, Nystrand, 99
VPG, Bertulani, 02
Frankfurt, Strikman, Zhalov 02
Ayala, VPG, Griep 08
Adeluyi, Bertulani 11, 12
Jones, Martin, Ryskin, Teubner 13, 14
Guzey, Zhalov 13, 14

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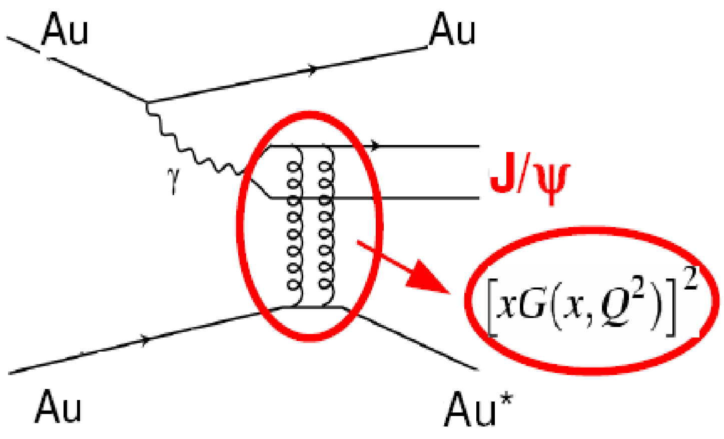
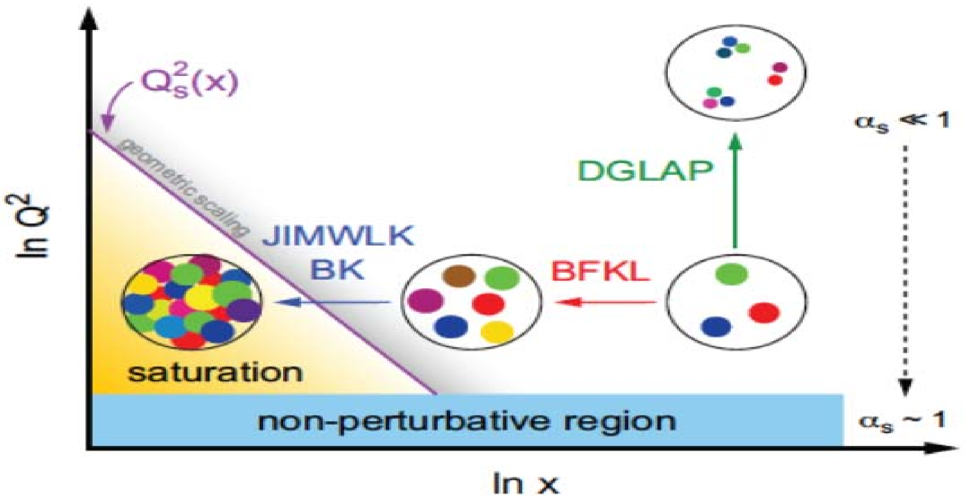


- Cross section proportional to the squared gluon distribution.
- Final state characterized by two rapidity gaps.

Probing QCD dynamics at high energies in UPHIC

<u>Diffractive photoproduction of vector mesons in UPHIC also allows to test some theoretical expectations for the QCD at high energies</u>:

- Onset of non-linear QCD effects when the gluon density is high (small – x);
- Breakdown of the linear DGLAP dynamics for the gluon distribution and the factorization of the cross sections.



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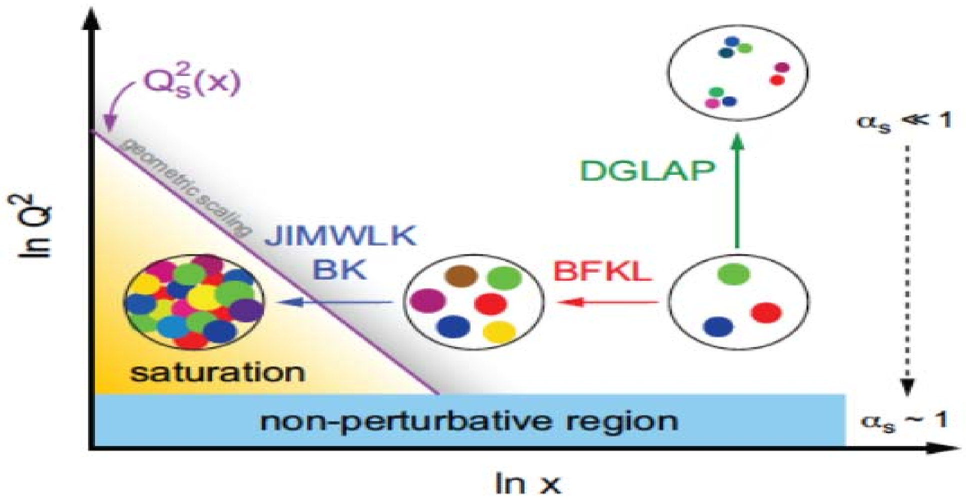

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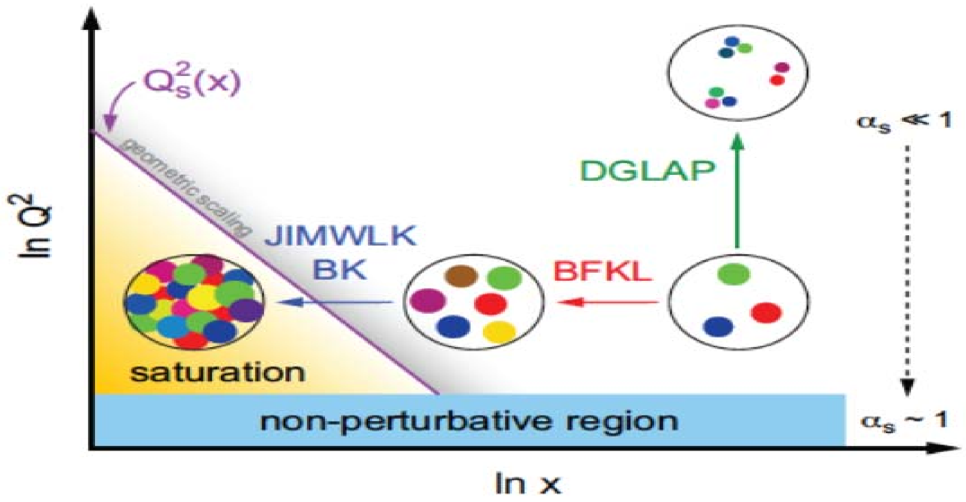

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VPG, Machado 04, 06, 08, 13
Motyka – Watt 08
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VPG, Moreira, Navarra 14

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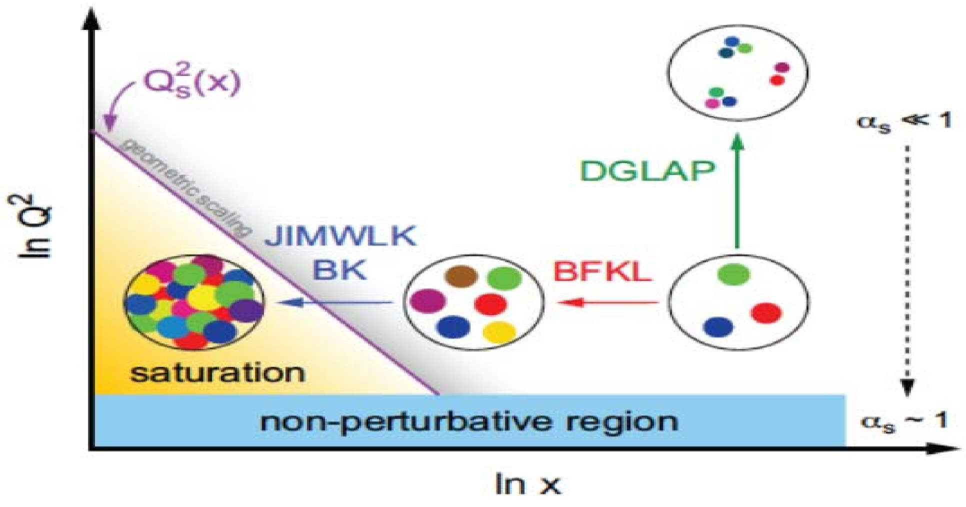

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Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

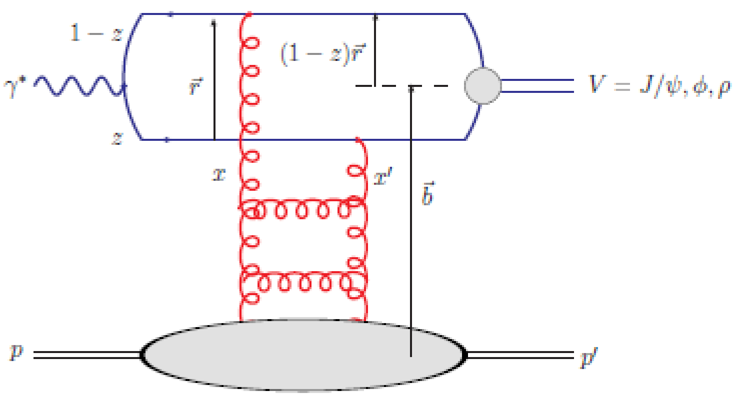
- Study of the diffractive photoproduction of J/Psi in pp, pA and AA collisions at LHC energies using the *color dipole formalism* and *different parameterizations for the dipole – target scattering amplitude*.
- ***Main goal:*** Estimate the theoretical uncertainty present in the current predictions in the literature.

(*) VPG, B. D. Moreira, F. S. Navarra, arXiv: 1405.6977 [hep-ph]

Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

- **Formalism**:

- For photon – proton interactions:



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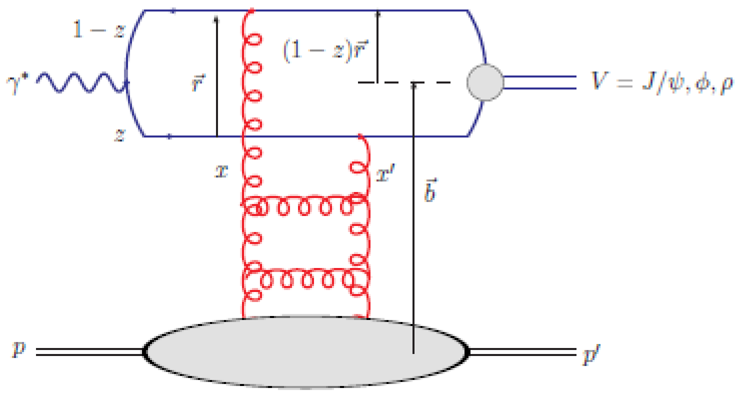

$$\sigma(\gamma p \to J/\Psi p) = \frac{1}{16\pi}\int dt\,|\mathcal{A}^{\gamma p\to J/\Psi p}(x,\Delta)|^2\,R_g^2(1+\beta^2)$$

$$\mathcal{A}^{\gamma p\to J/\Psi p}(x,\Delta) = i\int dz\,d^2r\,d^2b\,e^{-i[b-(1-z)r].\mathbf{\Delta}}\,(\Psi^*_{J/\Psi}\Psi)\,2\mathcal{N}_p(x,r,b)$$

$$R_g(\lambda_e) = \frac{2^{2\lambda_e+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda_e+5/2)}{\Gamma(\lambda_e+4)}, \quad \text{with} \quad \lambda_e \equiv \frac{\partial \ln[\mathcal{A}(x,\Delta)]}{\partial \ln(1/x)}$$

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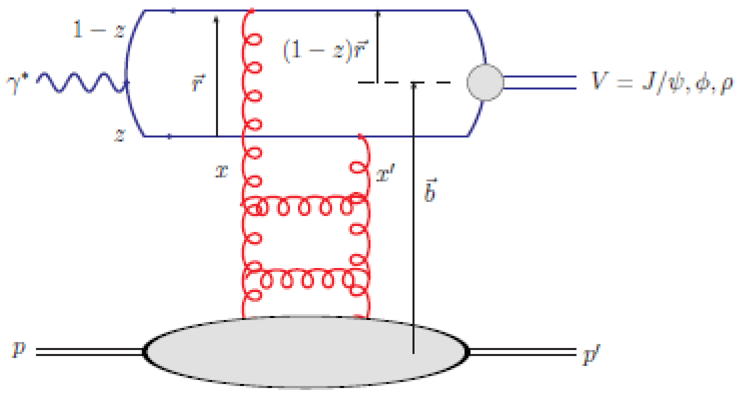

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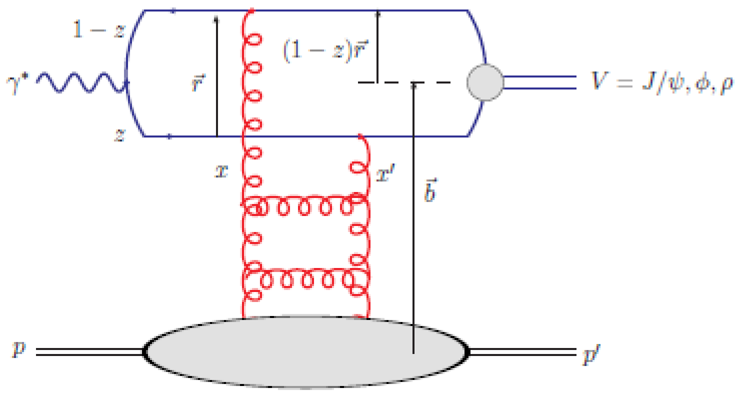

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Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

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- For photon – nucleus interactions:

$$\sigma^{coh}\left(\gamma A \rightarrow J/\Psi A\right) = \int d^2\boldsymbol{b} \left[\int d^2\boldsymbol{r} \int dz (\Psi^*_{J/\Psi}\Psi)\mathcal{N}_A(x, \boldsymbol{r}, \boldsymbol{b})\right]^2$$

We assume a coherent interaction in that the nuclei remains intact.

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- ***<u>Main inputs in the calculations</u>***:

1. Vector Meson Wave Functions: LC – Gaus Model
2. Dipole – target scattering amplitude:

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- GBW Model

Golec-Biernat-Wustoff:

$$\mathcal{N}^{GBW}(x,b,r) = \theta(R_p - b)\left(1 - \exp\left[-\frac{r^2\, Q_s^2(x)}{4}\right]\right)$$

$$Q_s^2(x) = Q_{s0}^2\left(\frac{x_0}{x}\right)^{\lambda} \quad \text{with} \quad \lambda \sim 0.2 \div 0.3$$

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   - Impact parameter CGC model

$$\mathcal{N}_p(x,r,b) = \begin{cases} \mathcal{N}_0 \left(\frac{r\,Q_{s,p}}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/rQ_{s,p})}{\kappa\,\lambda\,Y}\right)} & rQ_{s,p} \le 2 \\ 1 - \exp^{-A\,\ln^2(B\,r\,Q_{s,p})} & rQ_{s,p} > 2 \end{cases}$$

$$Q_{s,p} \equiv Q_{s,p}(x,b) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}} \left[\exp\left(-\frac{b^2}{2B_{\rm CGC}}\right)\right]^{\frac{1}{2\gamma_s}} .$$

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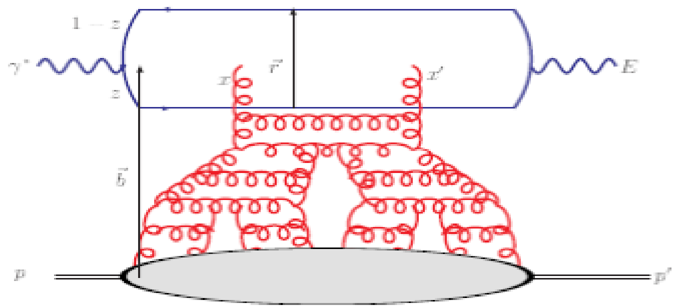

- Proposed originally by Kowalski, Motyka and Watt (06) – bCGC
- Parameters of the model were recently updated considering the high precision combined HERA data (Rezaeian, Schmidt, 13) – bCGC NEW

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Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

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$$\mathcal{N}_A(x, \boldsymbol{r}, \boldsymbol{b}) = 1 - \exp\left[-\frac{1}{2}\,\sigma_{dp}(x, \boldsymbol{r}^2)\,T_A(\boldsymbol{b})\right]$$

$$\sigma_{dp}(x, \boldsymbol{r}^2) = 2\int d^2b\,\mathcal{N}_p(x, \boldsymbol{r}, \boldsymbol{b})$$

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Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

- **Results for photon – hadron collisions**

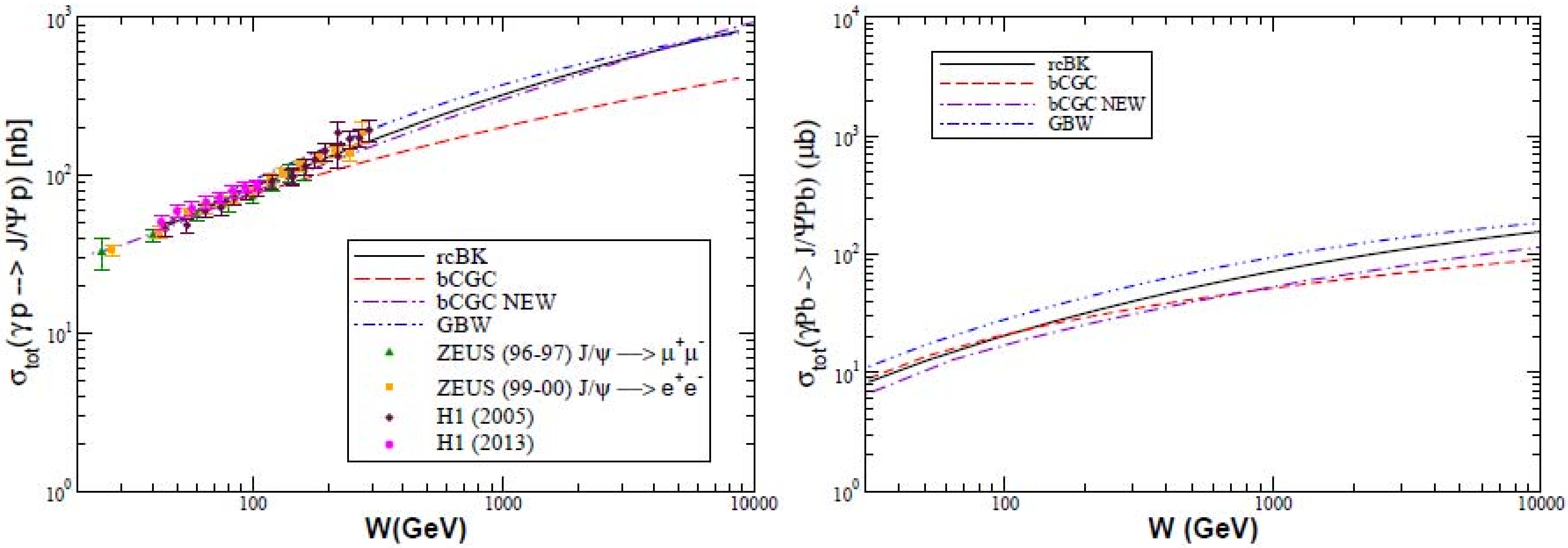

FIG. 1: Diffractive photoproduction of J/Ψ in γp (left panel) and γPb (right panel) collisions. Data from HERA [57].

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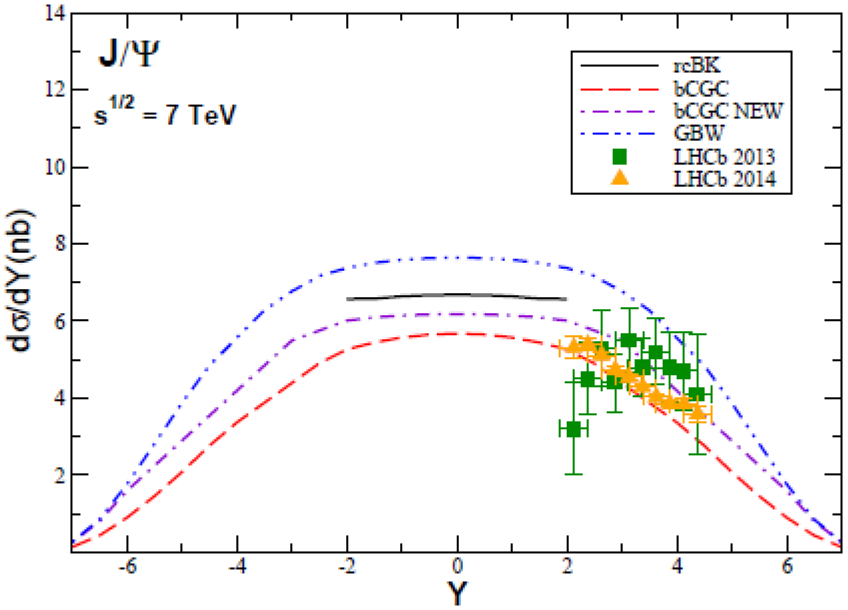
Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

- **Results for pp collisions**



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Diffractive photoproduction of J/Psi in hadronic collisions at LHC (*)

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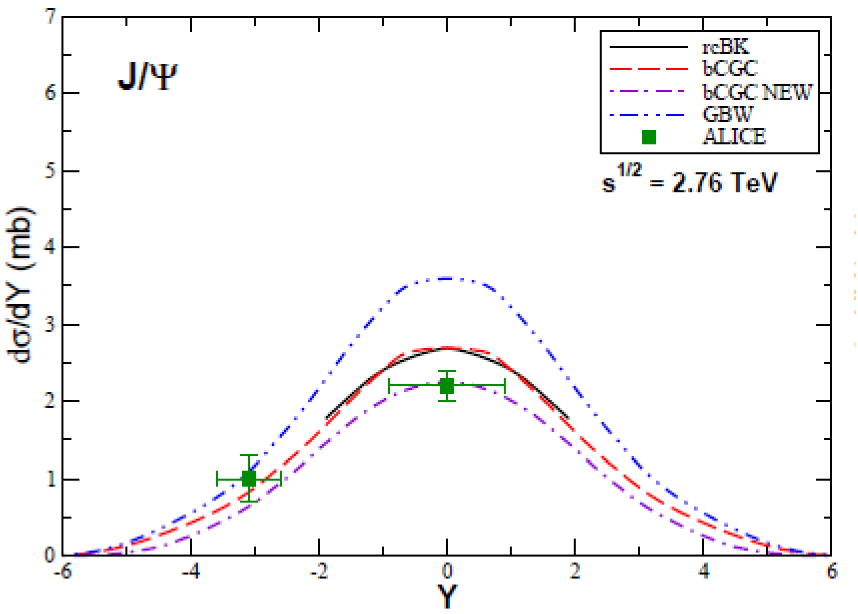

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Probing the Odderon in UPHIC

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In perturbative QCD the **Pomeron** corresponds to a C-even parity (C being the charge conjugation) compound state of two t-channel reggeized gluons;

(*) VPG, Nuc. Phys. A902 (2013) 32

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A natural prediction of the QCD is the presence of a C-odd compound state of three reggeized gluons, the so-called **Odderon**, which dominates the hadronic cross section difference between the direct and crossed channel processes at very high energies.

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Open question: Does the Odderon exist?

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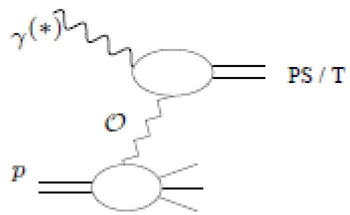
Experimental evidence for Odderon still is weak. Recent studies of the data on the differential elastic pp scattering shows that one needs the Odderon to describe the cross sections in the dip region.

(*) VPG, Nuc. Phys. A902 (2013) 32

Probing the Odderon in UPHIC (*)

Alternative: Consider exclusive processes in which the Odderon is the only contribution!

diffractive pseudoscalar and tensor meson production $\gamma^{(*)} p \to M_{PS/T}\, p$



Basic idea: As the photon carries negative C parity, its transformation into a diffractive final state system of positive C parity requires the t-channel exchange of an object of negative C parity.

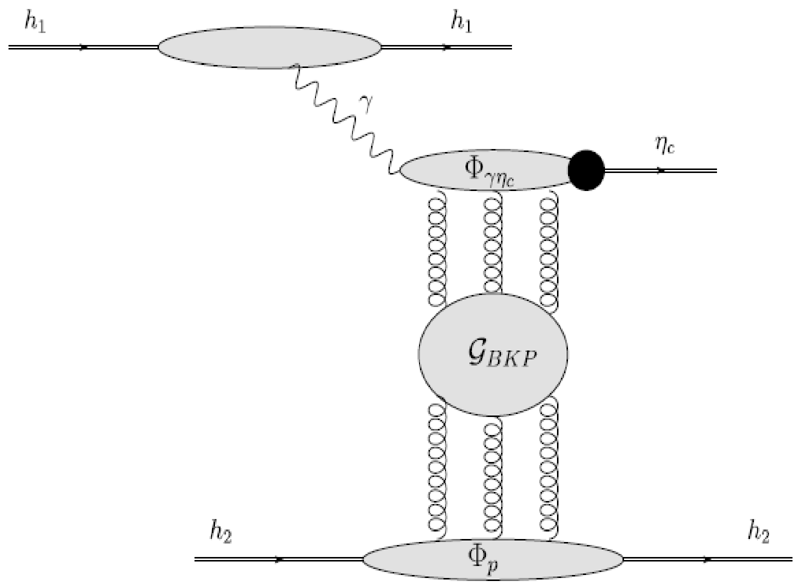
Pomeron exchange cannot contribute to this process.

Particular promising process: Diffractive η_c photoproduction, since the meson mass provides a hard scale that makes a perturbative calculation possible.

(*) VPG, Nuc. Phys. A902 (2013) 32

Probing the Odderon in UPHIC (*)

Photoproduction of η_c in UPHIC



$$\frac{d\sigma}{dt} = \frac{1}{32\pi} \sum_{i=1,2} |\mathcal{A}^i|^2$$

$$\mathcal{A}^i = \frac{5}{1152} \frac{1}{(2\pi)^8} \langle \Phi^i_{\gamma\eta_c} | \mathcal{G}_{BKP} | \Phi_p \rangle .$$

The Odderon Green function G is described in terms of the solution of the BKP equation, which resums terms of the order $\alpha_s(\alpha_s \log s)^n$ With arbitrary n in which three gluons in a C = -1 state are exchange in the t-channel.

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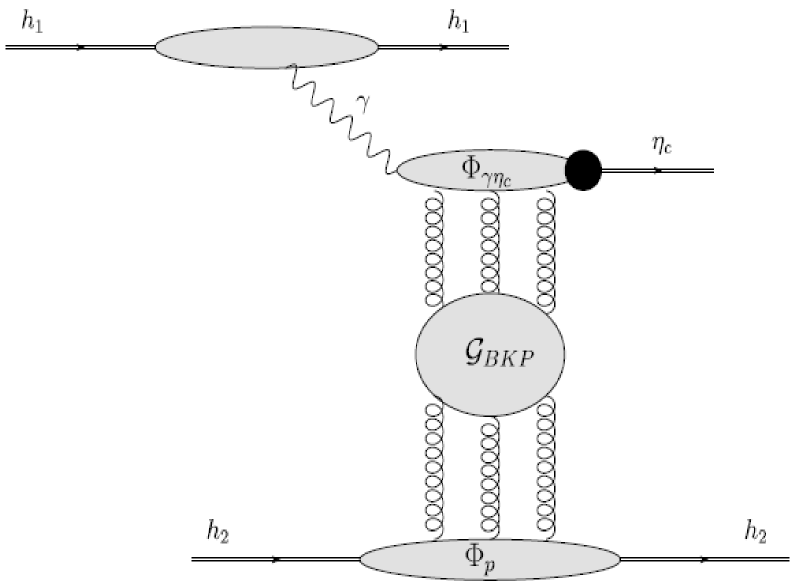
Photoproduction of η_c in UPHIC



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We have used two models for the Odderon exchange:

- CKMS: simplified three gluon model
- BBCV: takes into account the interaction between the three gluons.

CKMS: Czyzewski, Kwiecinski, Motyka, Sadzikowski
BBCV: Bartels, Braun, Colferai, Vacca.

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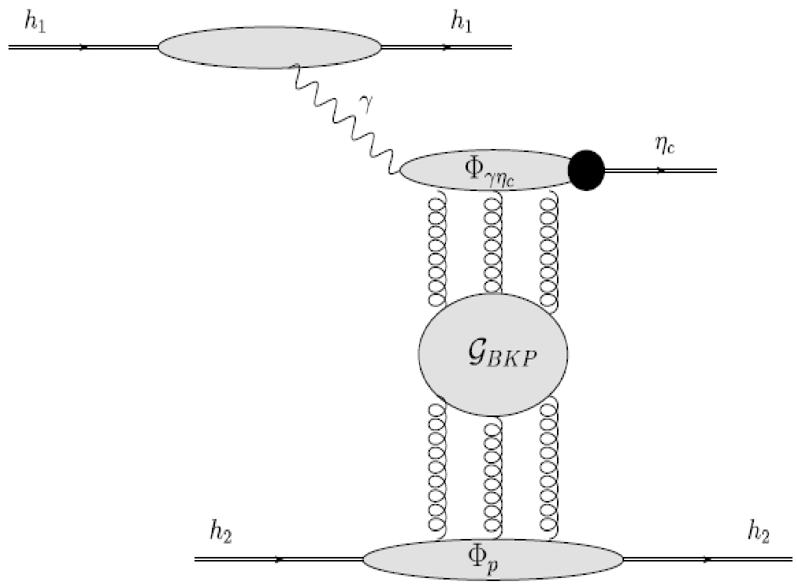

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Probing the Odderon in UPHIC (*)

Results for the diffractive η_c photoproduction in UPHIC

Table 1
Cross sections (event rates/year) for the diffractive η_c photoproduction in pp collisions at LHC energies.

$\sqrt{s_{NN}}$	CKMS	BBCV
8 TeV	0.55 pb (55 000)	10.10 pb (1×10^6)
14 TeV	0.65 pb (65 000)	13.90 pb (1.4×10^6)

Table 2
Cross sections (event rates/year) for the diffractive η_c photoproduction in PbPb collisions at LHC energies.

$\sqrt{s_{NN}}$	CKMS	BBCV
2.76 TeV	0.30 μb (126)	14.25 μb (5985)
5.5 TeV	0.40 μb (168)	23.59 μb (9912)

Caveat: The cross sections for the production of η_c in photon – photon interactions is a factor 6 larger (**) . Experimental separation between photon – hadron and photon – photon interactions is necessary in order to probe the Odderon.

(*) VPG, Nuc. Phys. A902 (2013) 32;
(**) See, e.g., Bertulani, PRC79, 047901 (2009) and VPG, da Silva and Sauter, PRC87, 028201 (2013).

Probing Charmoniumlike Exotic States in UPHIC

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- ***Our goal:*** Estimate the production of charmoniumlike exotic states Z(4430), Zc(3900), X(3915) and Y(3940) in photon – hadron interactions at LHC.

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- For similar studies in photon – photon interactions see, e.g., Bertulani, PRC79, 047901 (2009) and VPG, da Silva and Sauter, PRC87, 028201 (2013).

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Probing Charmoniumlike Exotic States in UPHIC (*)

Main input: photon – hadron cross section for the production of the exotic charmoniumlike state.

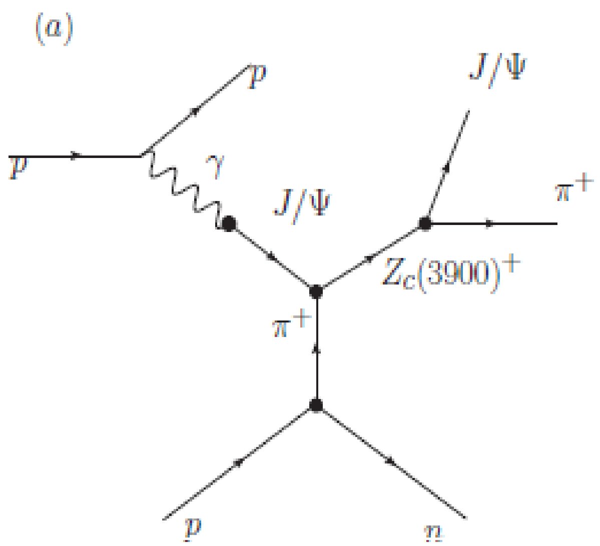
In our calculations we use the formalism proposed by Close, He, Liu, Lin, Zhao and Xu in a series of papers, which combines an effective Lagrangian approach with Vector Meson Dominance.

The interaction is described in terms of a meson exchange, which is neutral/charged for the production of a neutral/charged exotic charmoniumlike state.

(*) VPG, M. L. L. da Silva, arXiv:1405.6640 [PRD (in press)]

Probing Charmoniumlike Exotic States in UPHIC (*)

Probing Zc(3900) in UPHIC:



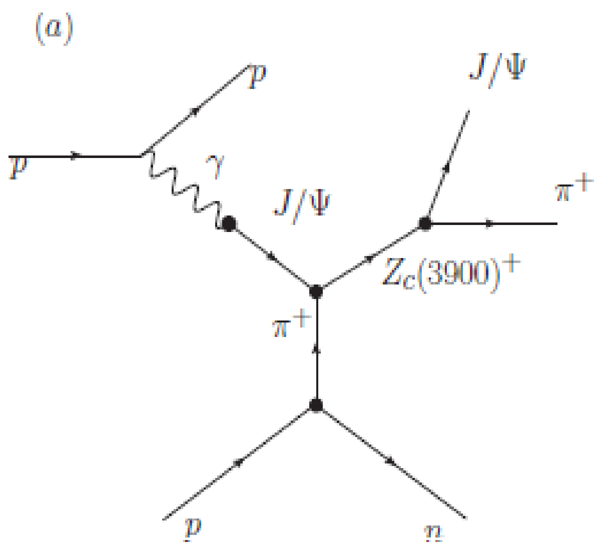
Basic idea: the photon stemming from one of the incident protons fluctuates into a J/Psi which interacts with the other proton through the pion exchange producing a neutron n and a Zc(3900)+ state which decays in the J/Psi + pion system.

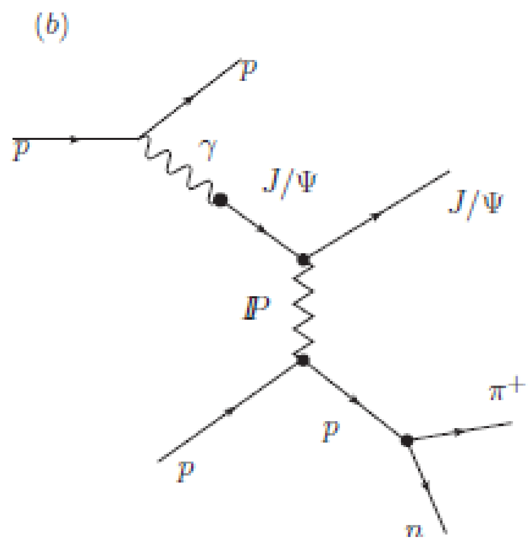
(*) VPG, M. L. L. da Silva, arXiv:1405.6640 [PRD (in press)]

Probing Charmoniumlike Exotic States in UPHIC (*)

Probing Zc(3900) in UPHIC:

Main background:





(*) VPG, M. L. L. da Silva, arXiv:1405.6640 [PRD (in press)]

Probing Charmoniumlike Exotic States in UPHIC (*)

Results for the photon – hadron cross sections:

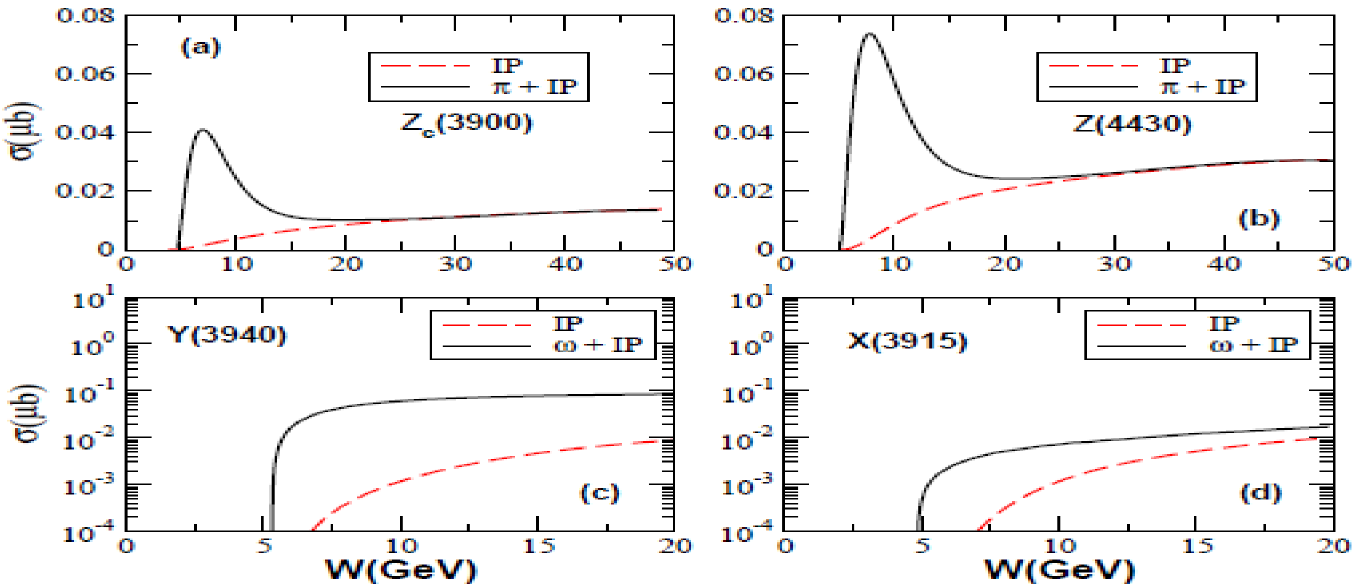


FIG. 2. (Color online) Energy dependence of the photoproduction cross sections. The signal (Meson + IP) and background (IP) contributions are presented separately.

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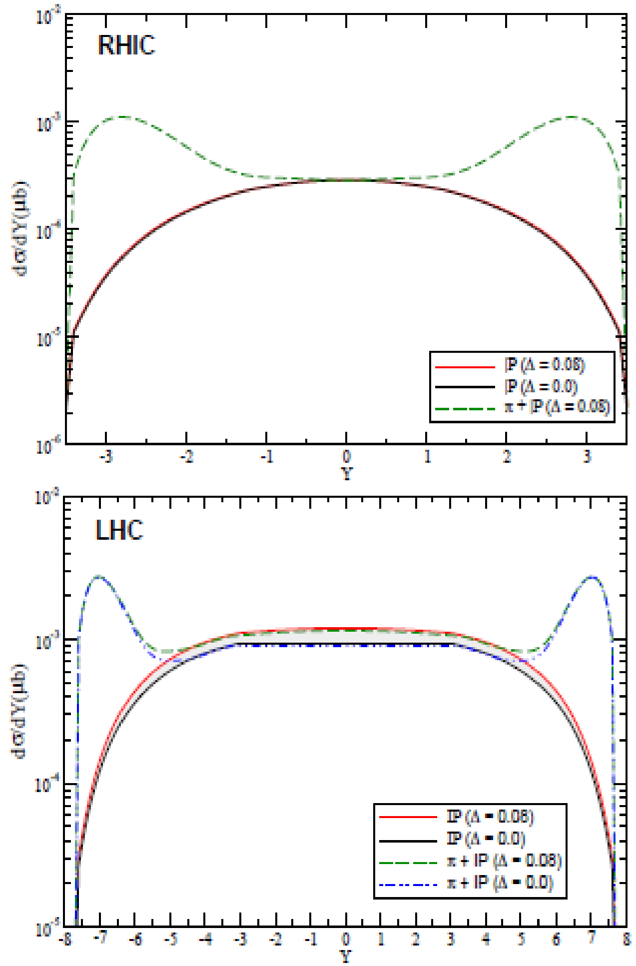
Probing Charmoniumlike Exotic States in UPHIC (*)

Results for pp collisions:

FIG. 3. (Color online) Rapidity distribution for the photoproduction of a $J/\Psi + \pi$ final state in pp collisions at RHIC ($\sqrt{s} = 0.2$ TeV) and LHC ($\sqrt{s} = 14$ TeV) energies. The solid lines represent the background associated to the Pomeron exchange for two values of the intercept Δ. The dashed lines represent the sum of the background with the signal associated to the $\gamma p \to Z_c(3900)^+ n \to J/\Psi \pi n$ interaction through π exchange.



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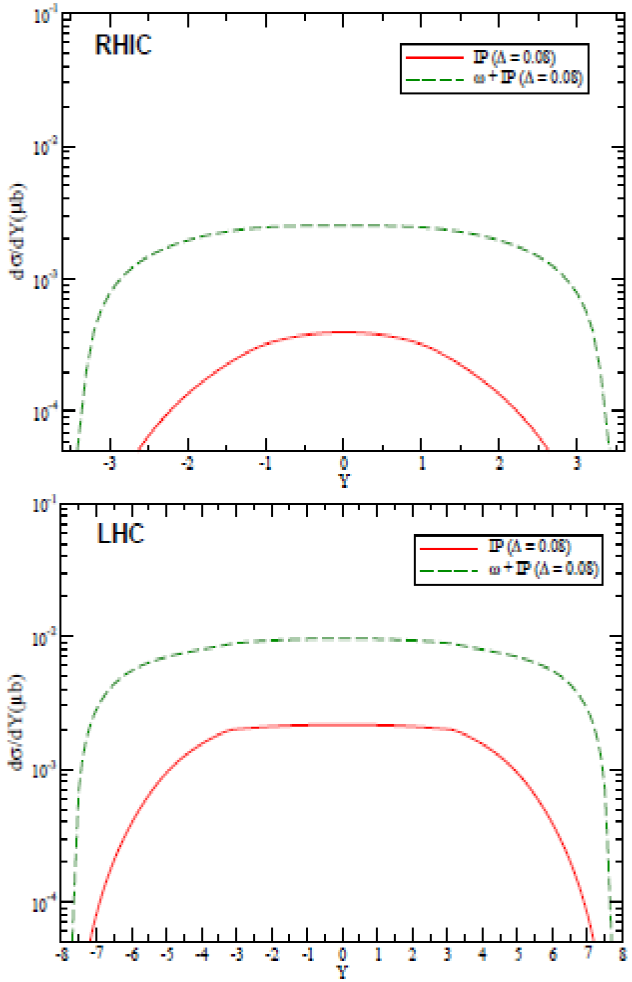
Probing Charmoniumlike Exotic States in UPHIC (*)

Results for pp collisions:

FIG. 4. (Color online) Rapidity distribution for the photoproduction of a $J/\Psi + \omega$ final state in pp collisions at RHIC ($\sqrt{s}$ = 0.2 TeV) and LHC ($\sqrt{s}$ = 14 TeV) energies. The solid lines represent the background associated to the Pomeron exchange ($\Delta = 0.08$). The dashed lines represent the sum of the background with the signal associated to the $\gamma p \rightarrow Y(3940) + p \rightarrow J/\Psi \omega p$ interaction through ω exchange.



(*) VPG, M. L. L. da Silva, arXiv:1405.6640 [PRD (in press)]

Probing Charmoniumlike Exotic States in UPHIC (*)

Total cross sections:

Reaction	Ressonance	Contribution	σ [nb] ($\sqrt{s} = 0.2$ TeV)	σ [nb] ($\sqrt{s} = 7$ TeV)	σ [nb] ($\sqrt{s} = 14$ TeV)
$\sigma(pp \to pJ/\Psi\pi n)$	–	$\mathbb{P}$	1.15	8.18 – 9.64	10.33 – 12.65
	$Z_c(3900)$	$\mathbb{P} + \pi$	3.83	14.13 – 15.52	16.89 – 19.12
$\sigma(pp \to p\Psi'\pi n)$	–	$\mathbb{P}$	2.60	18.15 – 21.32	22.87 – 27.93
	$Z(4430)$	$\mathbb{P} + \pi$	7.33	29.26 – 32.41	35.21 – 40.23
$\sigma(pp \to pJ/\Psi\omega p)$	–	$\mathbb{P}$	0.84 – 0.90	5.90 – 7.75	7.42 – 10.17
	$X(3915)$	$\mathbb{P} + \omega$	1.88 – 1.98	11.31 – 14.53	14.08 – 18.88
$\sigma(pp \to pJ/\Psi\omega p)$	–	$\mathbb{P}$	1.33	12.73 – 15.35	16.35 – 20.54
	$Y(3940)$	$\mathbb{P} + \omega$	12.62	74.28 – 85.93	92.58 – 111.19

TABLE I. Total cross sections for the photoproduction of different final states in pp collisions at RHIC and LHC energies considering the sum of the signal associated to the photoproduction of an exotic charmoniumlike state, produced by a π or ω exchange, and the background contribution associated to the Pomeron ($\mathbb{P}$) exchange. For comparison the magnitude of the background contribution is presented separately.

(*) VPG, M. L. L. da Silva, arXiv:1405.6640 [PRD (in press)]

Summary

- ✓ The LHC is the world´s most powerful collider not only for protons and lead ions but also for photon – photon and photon – hadron collisions
- ✓ The study of the inclusive and exclusive photoproduction of different final states at LHC can be useful to contrain the QCD dynamics, Odderon, Exotic states, Quarkonium production, ...;
- ✓ **Main challenge:** Experimental separation of the photon – hadron interactions.

Summary

- ✓ The LHC is the world´s most powerful collider not only for protons and lead ions but also for photon – photon and photon – hadron collisions
- ✓ The study of the inclusive and exclusive photoproduction of different final states at LHC can be useful to contrain the QCD dynamics;
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Thank you for your attention !

Extra slides

Probing the Pomeron in UPHIC

PHYSICAL REVIEW D 85, 054019 (2012)

Heavy quark production in $\gamma\mathbb{P}$ interactions at hadronic colliders

V. P. Gonçalves and M. M. Machado

$$\sigma(\gamma h \to Q\bar{Q}Xh)(W_{\gamma h}) = \int_{x_{\min}}^{1} dx \sigma^{\gamma g \to Q\bar{Q}}(W_{\gamma g}) g^D(x, \mu^2),$$

$$g^D(x, \mu^2) = \int dx_{\mathbb{P}} d\beta \delta(x - x_{\mathbb{P}}\beta) g_{\mathbb{P}}(\beta, \mu^2) f_{\mathbb{P}}(x_{\mathbb{P}}) = \int_x^1 \frac{dx_{\mathbb{P}}}{x_{\mathbb{P}}} f_{\mathbb{P}}(x_{\mathbb{P}}) g_{\mathbb{P}}\left(\frac{x}{x_{\mathbb{P}}}, \mu^2\right),$$

TABLE II. Comparison between the total cross sections for the inclusive and diffractive charm and bottom photoproduction in pp and pPb collisions at LHC.

		Inclusive	Diffractive dipole model	Diffractive resolved Pomeron
Charm	pp	6697 nb	161 nb	1208 nb
	pPb	5203 μb	145 μb	694 μb
Bottom	pp	123 nb	0.52 nb	15 nb
	pPb	55 μb	0.2 μb	4.5 μb

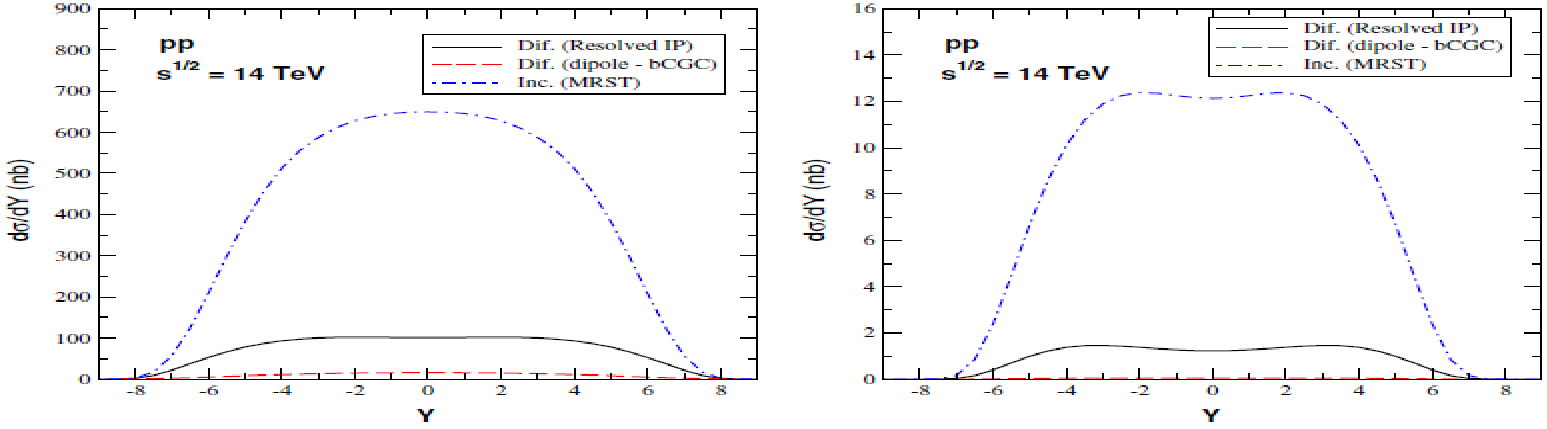


FIG. 2 (color online). Rapidity distribution for the inclusive and diffractive charm (left panel) and bottom (right panel) photoproduction in pp collisions at $\sqrt{s} = 14$ TeV.

Probing the BFKL Pomeron in UPHIC

PHYSICAL REVIEW D 81, 074028 (2010)

Diffractive J/Ψ photoproduction at large momentum transfer in coherent hadron-hadron interactions at CERN LHC

V. P. Gonçalves* and W. K. Sauter†

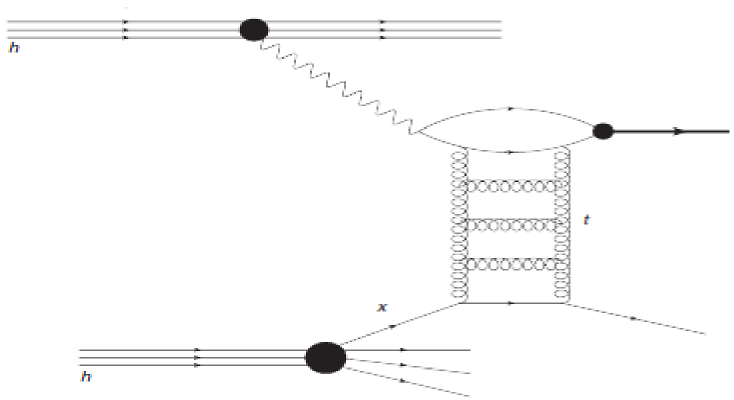


FIG. 1. High-t vector meson photoproduction in cohere[nt] hadron-hadron collisions.

$$\frac{d\sigma[h_1 + h_2 \rightarrow h_1 \otimes J/\Psi \otimes X]}{dydt} = \omega \frac{dN_\gamma(\omega)}{d\omega} \frac{d\sigma_{\gamma h \rightarrow J/\Psi X}}{dt}(\omega),$$

$$\frac{d\sigma(\gamma h \rightarrow VX)}{dtdx_j} = \left[\frac{81}{16} G(x_j, |t|) + \sum_j (q_j(x_j, |t|) + \bar{q}_j(x_j, |t|))\right] \frac{d\sigma}{dt}(\gamma q \rightarrow Vq),$$

$$\frac{d\sigma(\gamma q \rightarrow J/\Psi q)}{dt} = \frac{16\pi}{81 t^4} |\mathcal{F}(z, \tau)|^2.$$

The BFKL amplitude, in the LLA and lowest conformal spin ($n = 0$), is given by [36]

$$\mathcal{F}_{\mathrm{BFKL}}(z, \tau) = \frac{t^2}{(2\pi)^3} \int d\nu \frac{\nu^2}{(\nu^2 + 1/4)^2} e^{\chi(\nu) z} I_\nu^{\gamma J/\Psi}(Q_\perp) \times I_\nu^{qq}(Q_\perp)^*, \quad (11)$$

where $Q_\perp$ is the momentum transferred, $t = -Q_\perp^2$ (the subscript denotes two-dimensional transverse vectors), and

$$\chi(\nu) = 4\mathcal{R}e(\psi(1) - \psi(\tfrac{1}{2} + i\nu)) \quad (12)$$

is proportional to the BFKL kernel eigenvalues [39] with $\psi(x)$ being the digamma function.

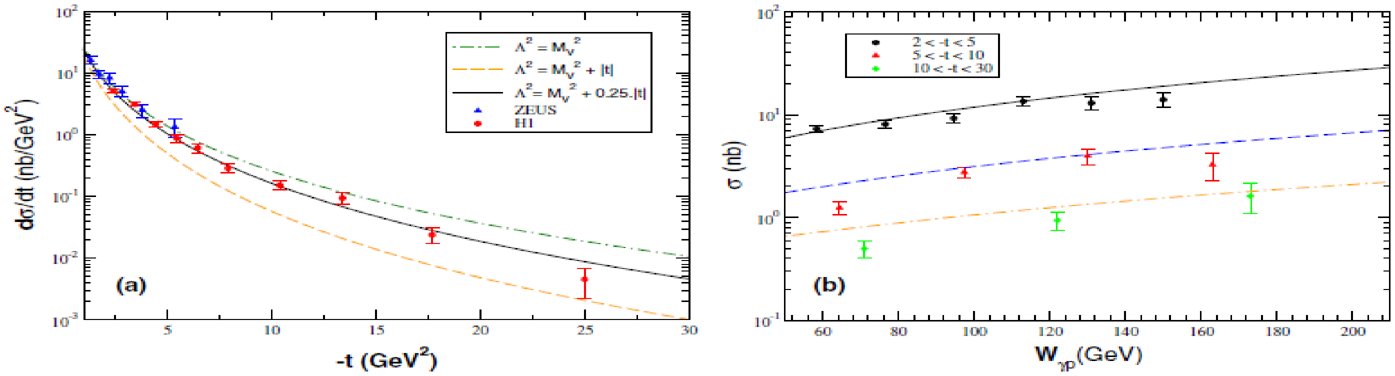


FIG. 2 (color online). (a) Differential cross section for J/Ψ production: theory compared to HERA data ($\langle W \rangle = 100$ GeV). (b) Energy dependence of the total cross section for distinct t ranges. Data are from H1 [41] and ZEUS [42] Collaborations.

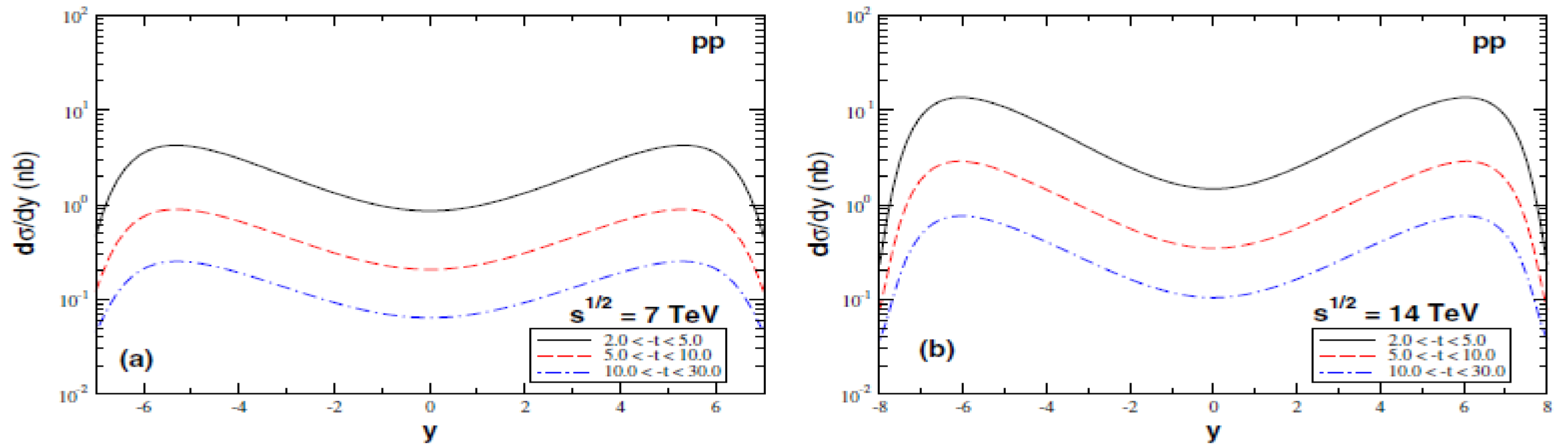


FIG. 4 (color online). Rapidity distribution for the diffractive J/Ψ photoproduction in pp collisions at LHC for distinct t ranges and different values of the center-of-mass energy: (a) $\sqrt{s} = 7.0$ TeV, and (b) $\sqrt{s} = 14.0$ TeV.

TABLE I. The integrated cross section (event rates/second) for the diffractive J/Ψ photoproduction at large momentum transfer in pp and AA collisions at LHC.

	pp ($\sqrt{s} = 7$ TeV)	pp ($\sqrt{s} = 14$ TeV)	$PbPb$ ($\sqrt{s} = 5.5$ TeV)
$2.0 < \|t\| < 5.0$	320 nb (320.0)	970 nb (970.0)	30 mb (13.0)
$5.0 < \|t\| < 10.0$	70 nb (70.0)	210 nb (210.0)	09 mb (0.38)
$10.0 < \|t\| < 30.0$	20 nb (20.0)	60 nb (60.0)	03 mb (0.12)

Eur. Phys. J. A (2011) **47**: 117
DOI 10.1140/epja/i2011-11117-1

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Diffractive vector meson production at large t in coherent hadronic interactions at CERN LHC

V.P. Gonçalves[a] and W.K. Sauter[b]

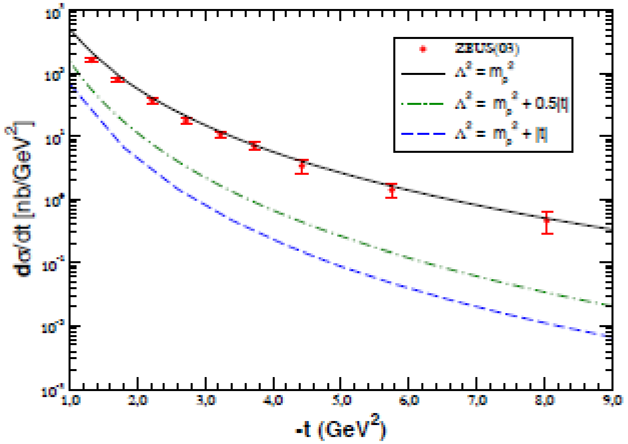
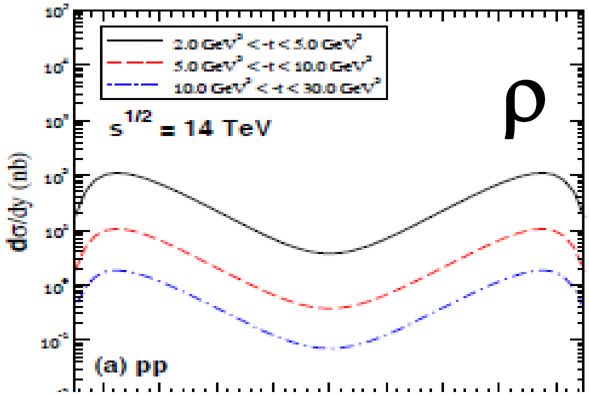
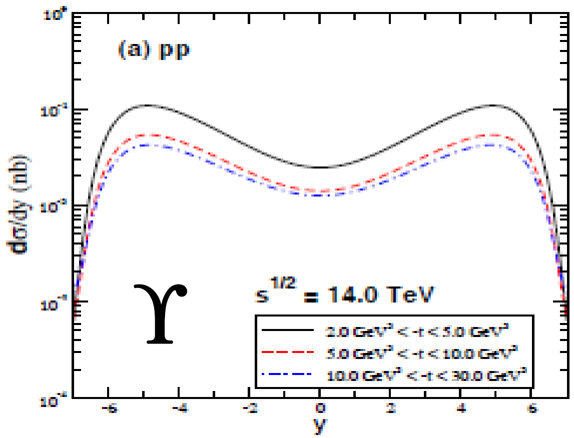


Fig. 1. (Color online) Differential cross-section for high-t diffractive ρ photoproduction. Data from ref. [27].





Probing Quarkonium Production in UPHIC

Eur. Phys. J. C (2012) 72:2231
DOI 10.1140/epjc/s10052-012-2231-7

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Quarkonium+γ production in coherent hadron–hadron interactions at LHC energies

V.P. Gonçalves[1,a], M.M. Machado[2]

$$\frac{d\sigma[p+p\to p\otimes H+\gamma+X)]}{dY} = \omega\frac{dN_{\gamma/h_1}(\omega)}{d\omega}\sigma_{\gamma h_2\to H+\gamma+X}(\omega) + \omega\frac{dN_{\gamma/h_2}(\omega)}{d\omega}\sigma_{\gamma h_1\to H+\gamma+X}(\omega),$$

$$\sigma(\gamma+p\to H+\gamma+X) = \int dz\,dp_\perp^2\frac{xg(x,Q^2)}{z(1-z)}\frac{d\sigma}{dt}(\gamma+g\to H+\gamma)$$

$$\frac{d\sigma}{dt}(\gamma+g\to H+\gamma) = \frac{64\pi^2}{3}\frac{e_Q^4\alpha^2\alpha_s m_Q}{s^2}\left(\frac{s^2s_1^2+t^2t_1^2+u^2u_1^2}{s_1^2t_1^2u_1^2}\right)\langle O_8^V(^3S_1)\rangle$$

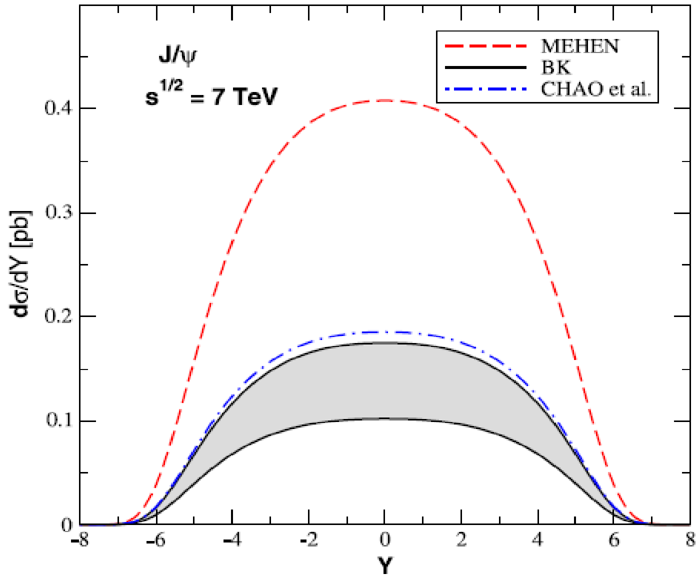


Table 1 The total cross section for the $H+\gamma$ photoproduction in coherent hadron–hadrons collisions at LHC energies

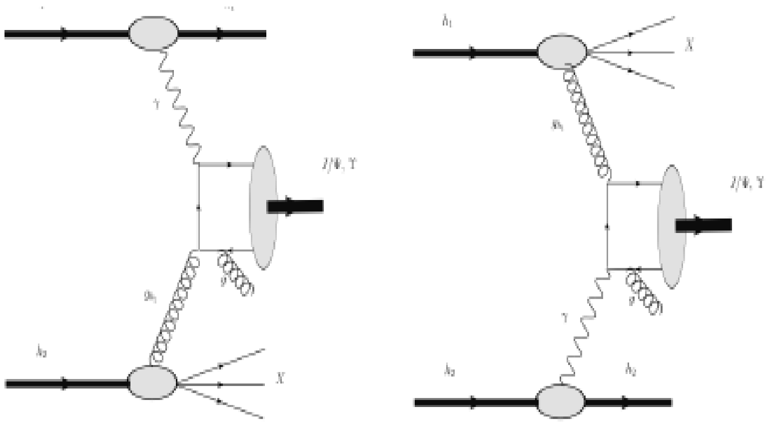
$J/\Psi+\gamma$	MEHEN	BK
LHC (7 TeV)	3.62 pb	1.23 ± 0.50 pb
LHC (14 TeV)	5.60 pb	1.90 ± 0.32 pb
$\Upsilon+\gamma$	BFL	BSV
LHC (14 TeV)	5.46 fb	1.45 ± 0.13 fb

Eur. Phys. J. A (2014) 50: 72
DOI 10.1140/epja/i2014-14072-3

Regular Article – Theoretical Physics

Inelastic quarkonium photoproduction in hadron-hadron interactions at LHC energies

V.P. Gonçalves[1,a] and M.M. Machado[2]



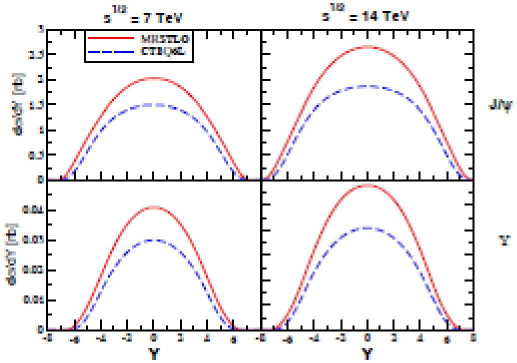


Fig. 4. Rapidity distribution for the J/Ψ and Υ production in coherent pp collisions at $\sqrt{s} = 7\,\text{TeV}$ (left panels) and 14 TeV (right panels) considering two different parametrizations for the gluon distribution.

Table 1. The total cross section (event rates) for the inelastic quarkonium photoproduction in coherent pp collisions at LHC energies.

J/Ψ	MRSTLO	CTEQ6L
$\sqrt{s} = 7\,\text{TeV}$	18.0 nb (1.8×10^9)	13.0 nb (1.3×10^9)
$\sqrt{s} = 14\,\text{TeV}$	25.0 nb (2.5×10^9)	18.0 nb (1.8×10^9)
Υ	MRSTLO	CTEQ6L
$\sqrt{s} = 7\,\text{TeV}$	0.30 nb (30×10^6)	0.21 nb (21×10^6)
$\sqrt{s} = 14\,\text{TeV}$	0.47 nb (47×10^6)	0.33 nb (33×10^6)