24th Low-x Meeting
KRF, Gyöngyös, Hungary, June 6-11 2016

Photon – induced interactions in the run II at the LHC

Victor P. Goncalves

Theory High Energy Physics – Lund University - Sweden

and

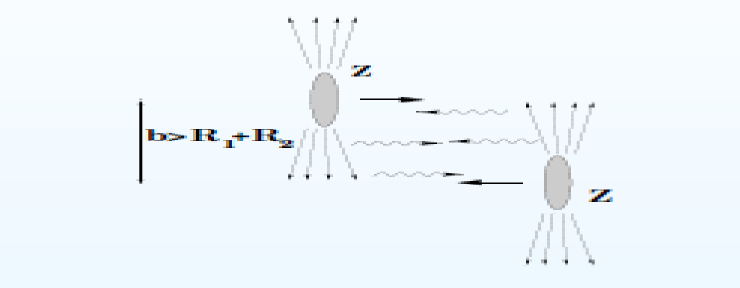
High and Medium Energy Group – UFPel – Brazil

Based on arXiv:1605.05840, arXiv:1605.08186 and paper in preparation

In collaboration with B. Moreira, F. Navarra, M. Machado, G. S. dos Santos and D. Spiering.

**Gyöngyös
07 June
2016**

Motivation



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2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

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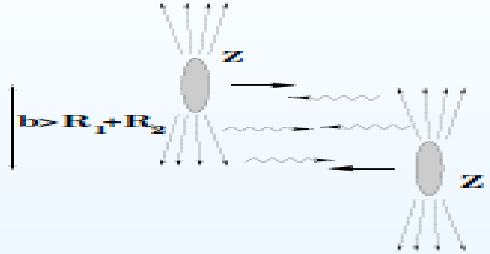

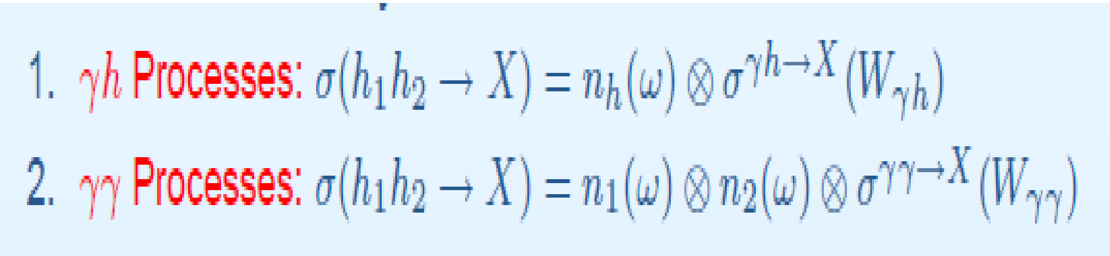

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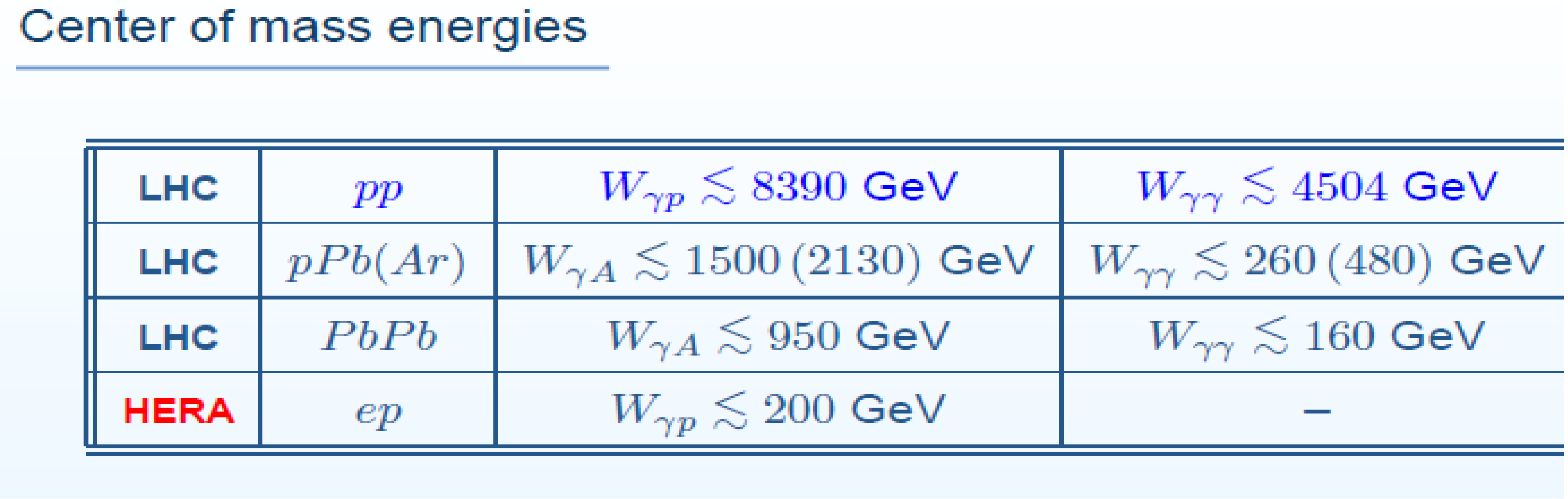

Center of mass energies

LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$W_{\gamma\gamma} \lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

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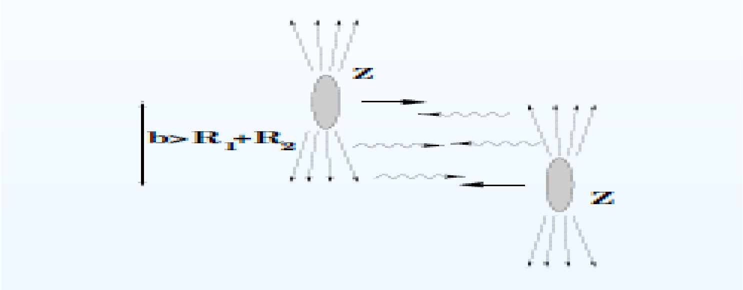

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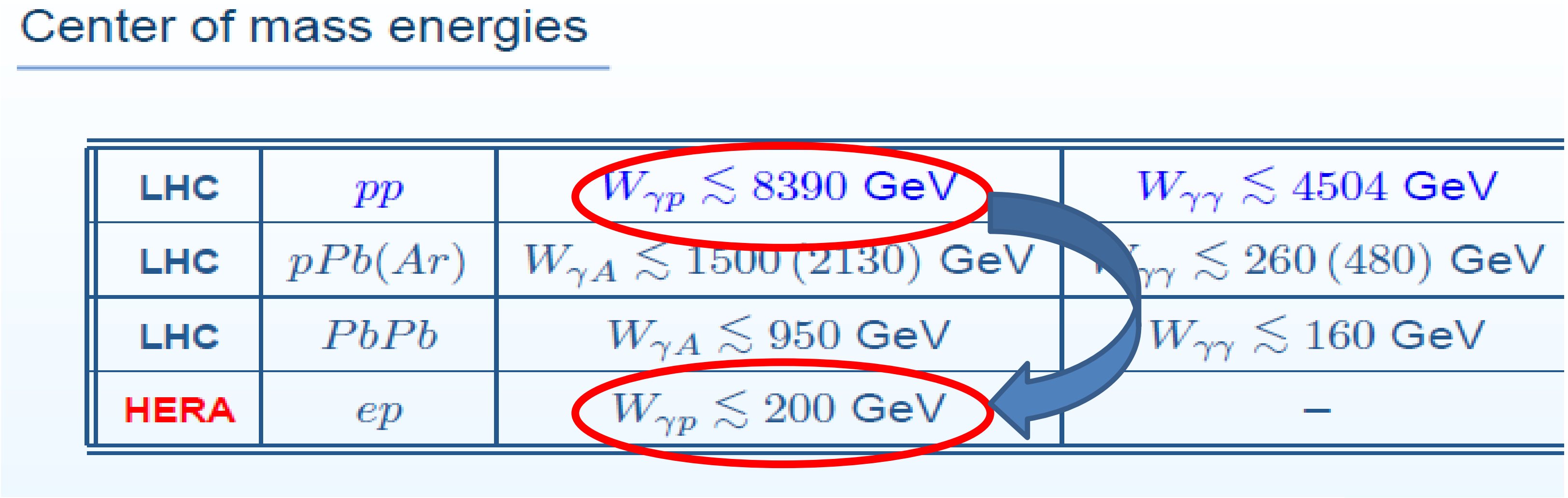

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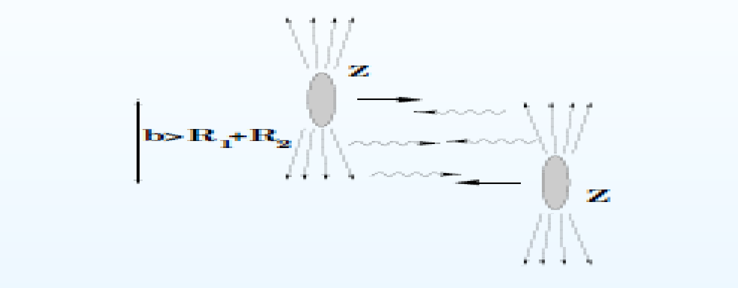
- Photoproduction in pp collisions at LHC probes energies one order of magnitude larger than HERA.

Motivation



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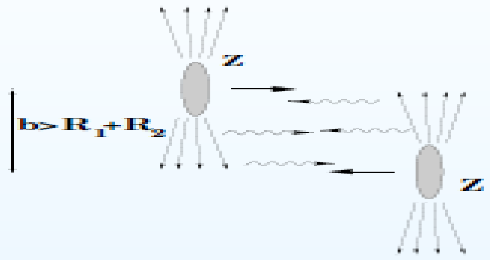
- Photoproduction in pA and AA collisions probes an unexplored regime of center of mass energies.

Motivation



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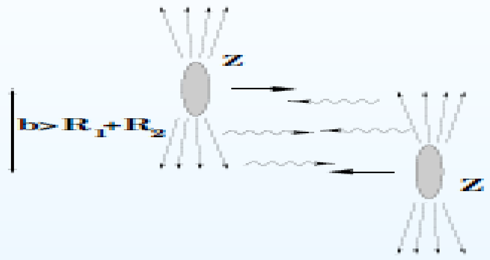
- The LHC is the world's most powerful collider not only for protons and lead ions but also for $\gamma\gamma$ and γh collisions.

Motivation



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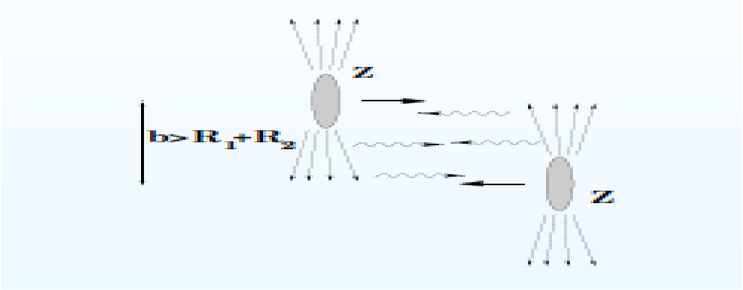
- Photon - induced interactions at LHC allows to study Quantum Chromodynamics in an unexplored regime of center of mass energies.

Photon - Hadron Interactions:
Inclusive and exclusive processes



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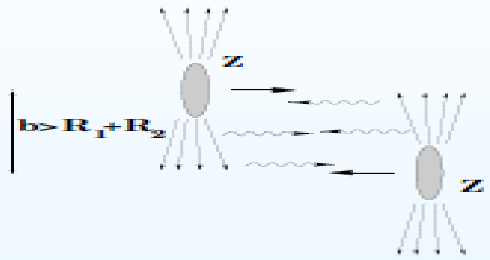

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- Inclusive processes: $\gamma p \longrightarrow XY$

$\Rightarrow$ Heavy quark photoproduction ($X = c\bar{c}$, $b\bar{b}$)

The final state is characterized by one rapidity gap due to the dissociation of the hadron target ($pp \longrightarrow p \otimes XY$).

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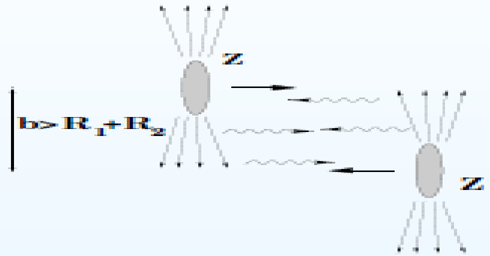

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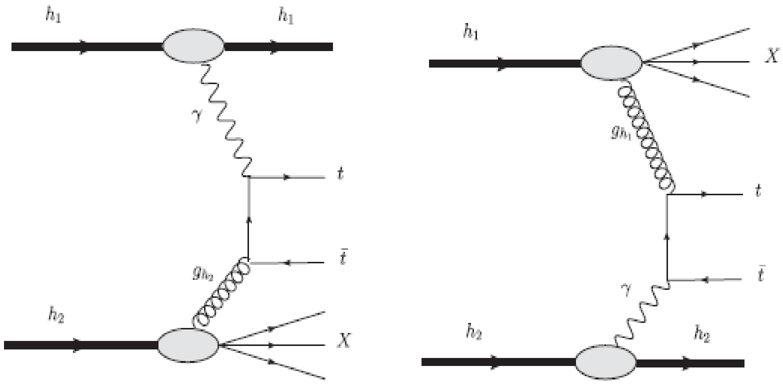

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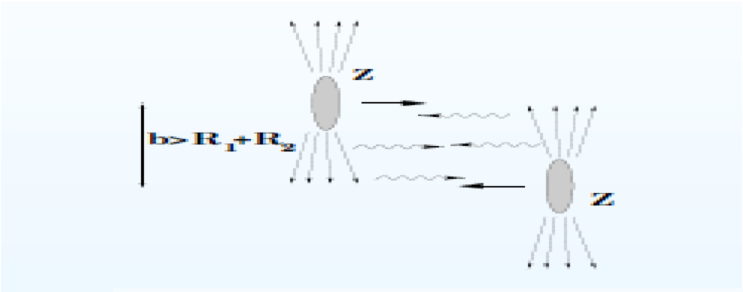

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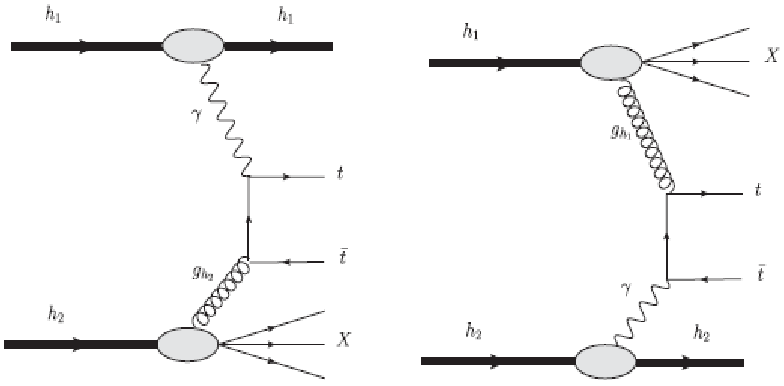

- $X = t\bar{t}$

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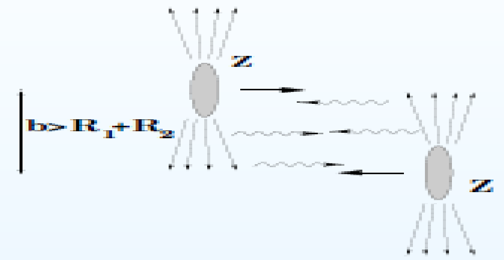
[a] VPG, PRD88, 054025 (2013)

Photon – Hadron Interactions: Inclusive and exclusive processes



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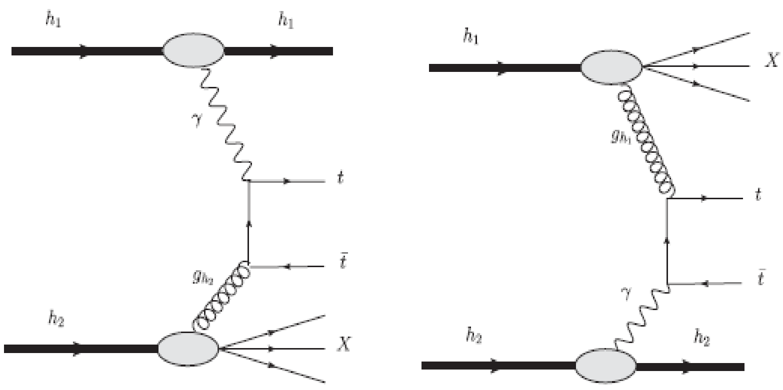

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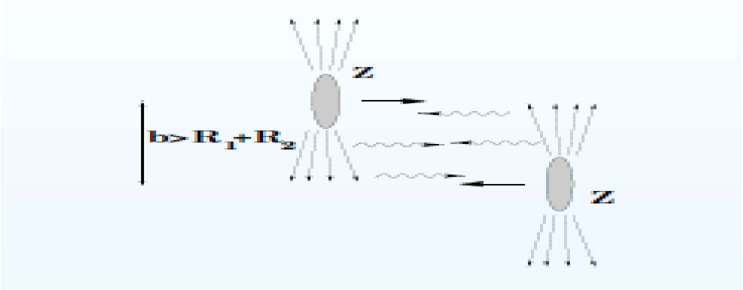
[a]VPG, PRD88, 054025 (2013)

TABLE I. The integrated cross section (events rate) for the photoproduction of top quarks in pp, pPb, and $PbPb$ collisions at LHC energies.

pp	MRST	CT10
$\sqrt{s}$ = 8 TeV	0.739 pb (73900)	0.764 pb (76400)
$\sqrt{s}$ = 14 TeV	2.50 pb (250000)	2.53 pb (253000)
pPb	**MRST**	**MRST + EPS09**
$\sqrt{s}$ = 5.5 TeV	0.036 nb (5.4/3600)	0.038 nb (5.7/3800)
$\sqrt{s}$ = 8.8 TeV	0.159 nb (23.85/15900)	0.165 nb (24.75/16500)
PbPb	**MRST**	**MRST + EPS09**
$\sqrt{s}$ = 5.5 TeV	0.42 nb (0.18)	0.40 nb (0.17)

Photon - Hadron Interactions:
Inclusive and exclusive processes



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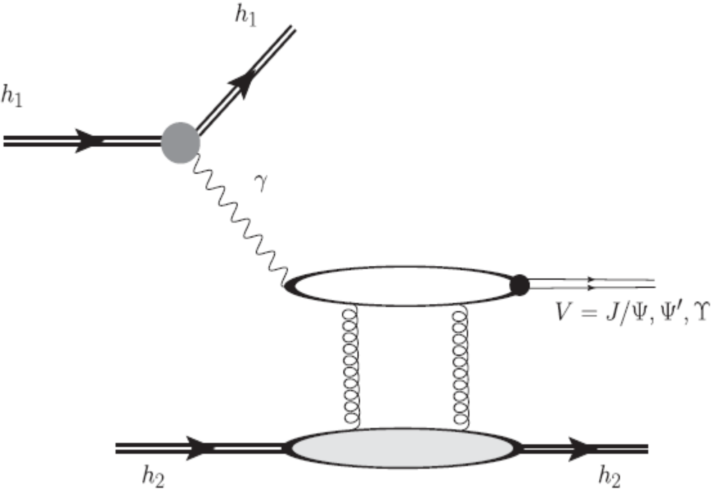

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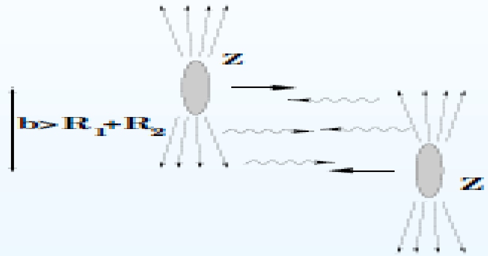

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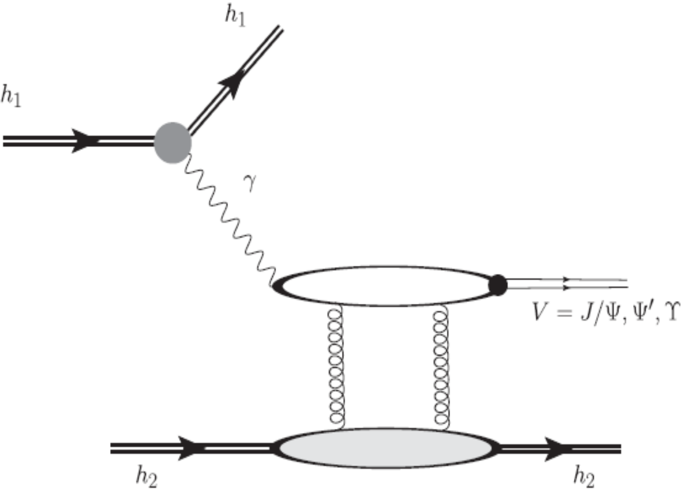
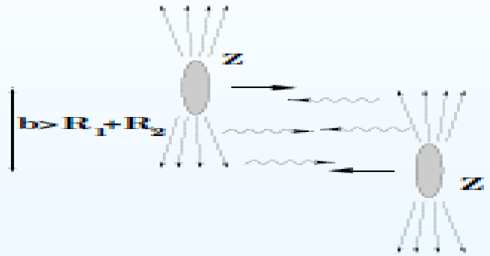


- Cross section is proportional to the square of the proton/nuclear gluon distribution.

Photon - Hadron Interactions:
Inclusive and exclusive processes



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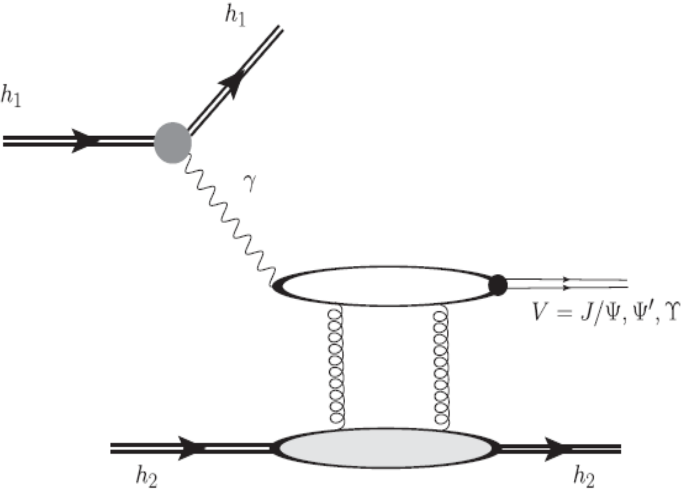

- Cross section is proportional to the square of the proton/nuclear gluon distribution.
- Diffractive vector meson photoproduction in UPHIC is a probe of the gluon distribution [a]

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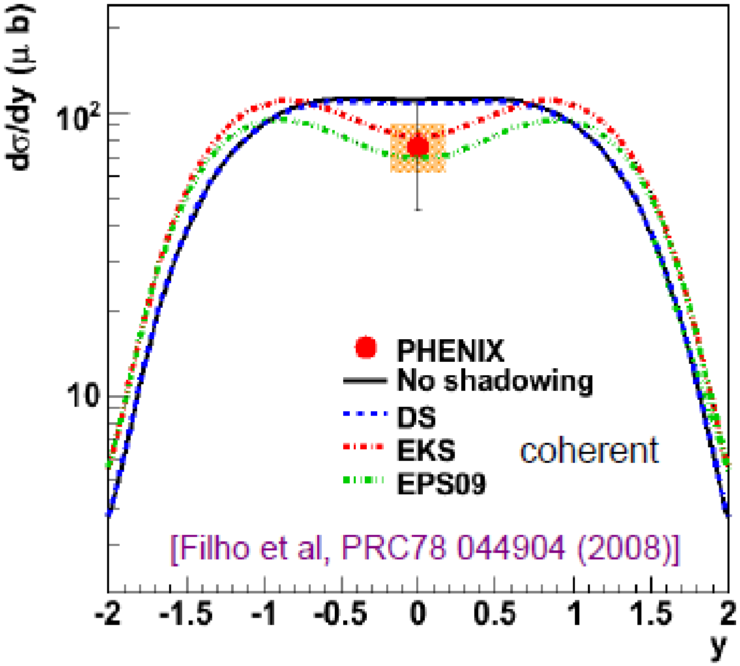
[a] VPG, Bertulani, PRC65, 054905 (2002)

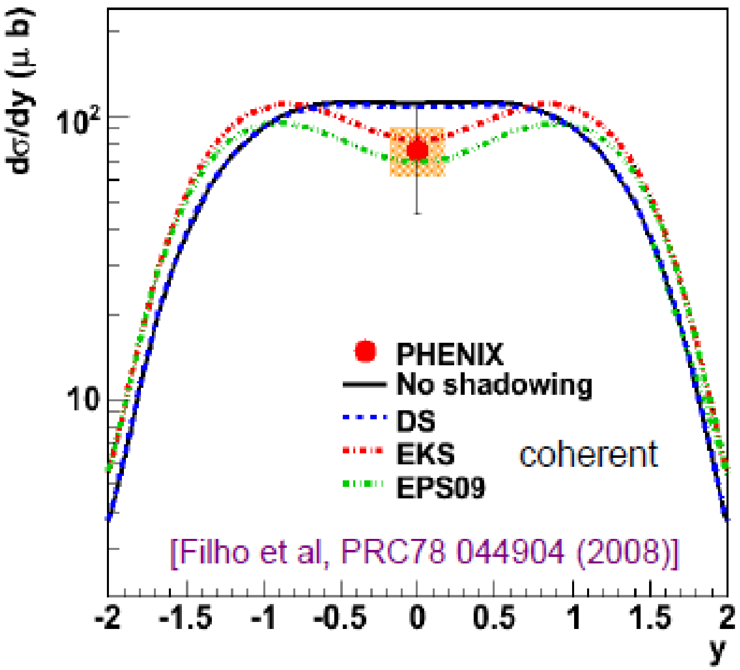
Diffractive vector meson photoproduction in UPHIC
Probing the nuclear gluon distribution



[Filho et al, PRC78 044904 (2008)]

Diffractive vector meson photoproduction in UPHIC

Probing the nuclear gluon distribution



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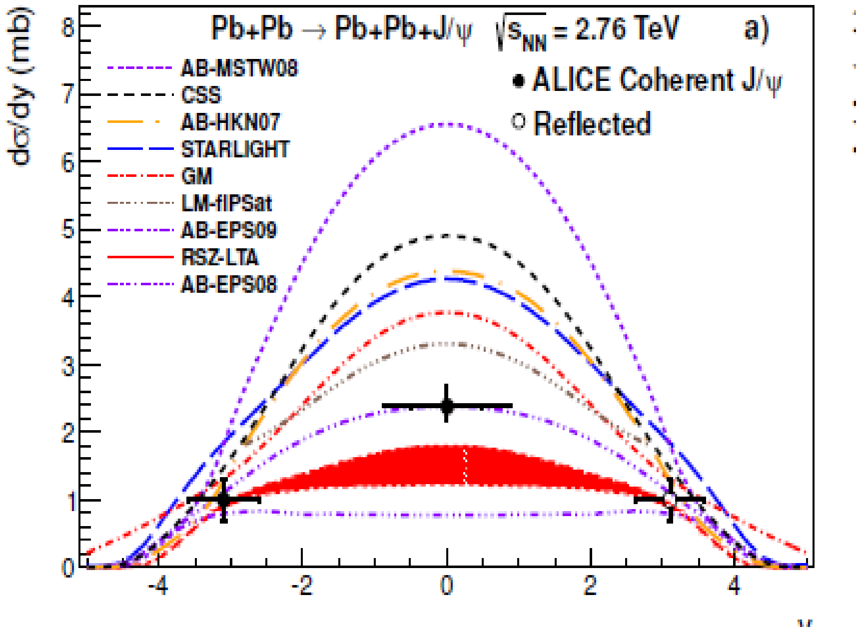
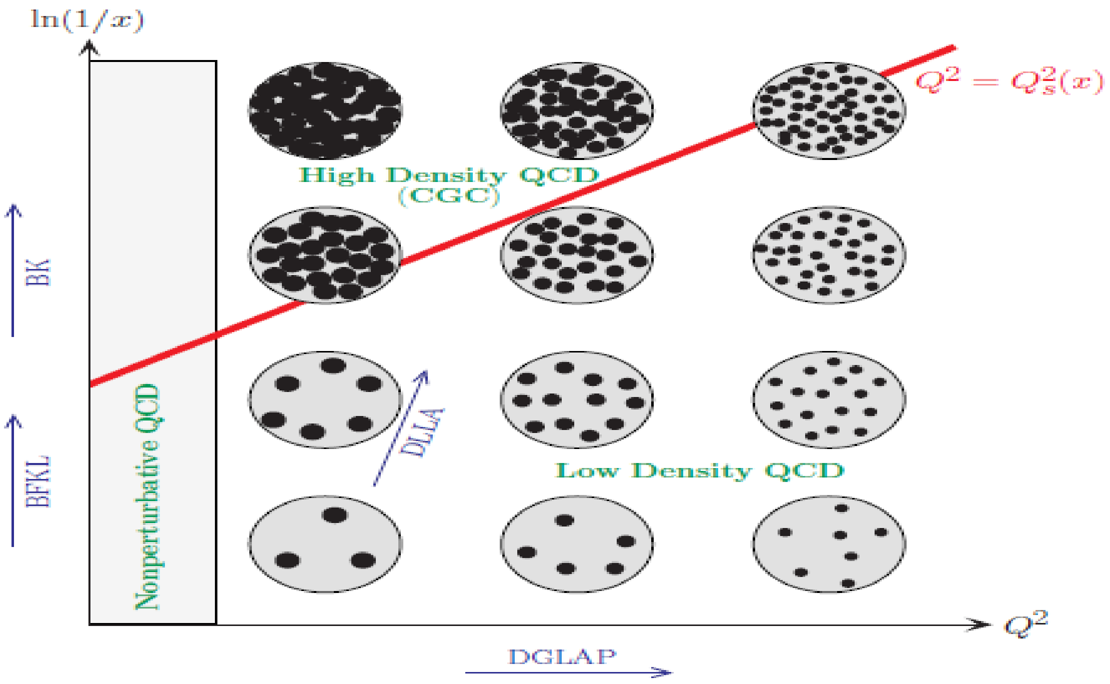


- Since $x = M_{J/\Psi}/\sqrt{s}\,\exp(-y)$ we have:

$$y = -3 \Rightarrow x = 0.02$$

$y = 0 \Rightarrow x = 0.001$ in $xg_A(x, Q^2)$.

Diffractive vector meson photoproduction in UPHIC
Probing the QCD dynamics at high energies



- Linear QCD evolution equations predict a power growth of gluon distribution as $x \to 0$ (violates unitarity).
- Number of gluons in the nucleon becomes so large that gluon recombine ⇒ Nonlinear effects
- Saturation scale Q_s (energy and atomic number dependent) defines the onset of nonlinear QCD dynamics.

Diffractive vector meson photoproduction in UPHIC
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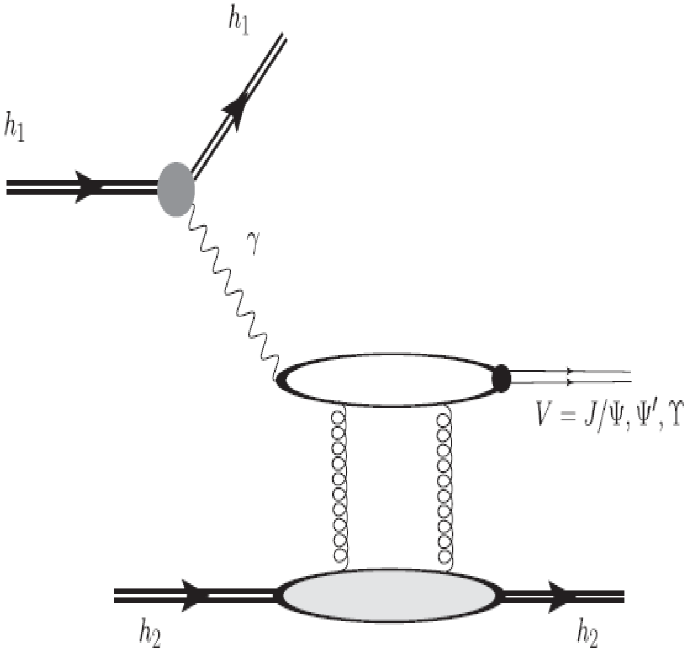

- Diffractive vector meson photoproduction in photon - induced interactions is a probe of the **nonlinear effects** in the QCD dynamics at high energies and the **vector meson wave function** [a].

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[a] VPG, Machado, EPJC 40, 519 (2005)

Diffractive vector meson photoproduction in UPHIC
Color Dipole Formalism

$$\frac{d\sigma\,[h_1+h_2\to h_1\otimes V\otimes h_2]}{d^2b\,dy} = \left[\omega N_{h_1}(\omega,b)\,\sigma_{\gamma h_2\to V\otimes h_2}(\omega)\right]_{\omega_L} + \left[\omega N_{h_2}(\omega,b)\,\sigma_{\gamma h_1\to V\otimes h_1}(\omega)\right]_{\omega_R}$$

$$\sigma(\gamma h\to Vh) = \int_{-\infty}^{0}\frac{d\sigma}{dt}\,dt = \frac{1}{16\pi}\int_{-\infty}^{0}|\mathcal{A}_T^{\gamma h\to Vh}(x,\Delta)|^2\,dt$$

$$\mathcal{A}_T^{\gamma h\to Vh}(x,\Delta) = i\int dz\,d^2\boldsymbol{r}\,d^2\boldsymbol{b}_h e^{-i[\boldsymbol{b}_h-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}}\;\underbrace{(\Psi^{V*}\Psi)_T}\;2\mathcal{N}_h(x,\boldsymbol{r},\boldsymbol{b}_h$$

Overlap functions for Vector Mesons:

$$(\Psi_V^*\Psi)_T = \frac{\hat{e}_f e}{4\pi}\frac{N_c}{\pi z(1-z)}\{m_f^2K_0(\epsilon r)\phi_T(r,z) - [z^2+(1-z)^2]\epsilon K_1(\epsilon r)\partial_r\phi_T(r,z)\}$$

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Forward dipole – hadron scattering amplitude: Determined by the QCD dynamics

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Forward dipole – hadron scattering amplitude: Determined by the QCD dynamics

- Proton: Constrained by Hera data for inclusive and exclusive processes

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Forward dipole – hadron scattering amplitude: Determined by the QCD dynamics

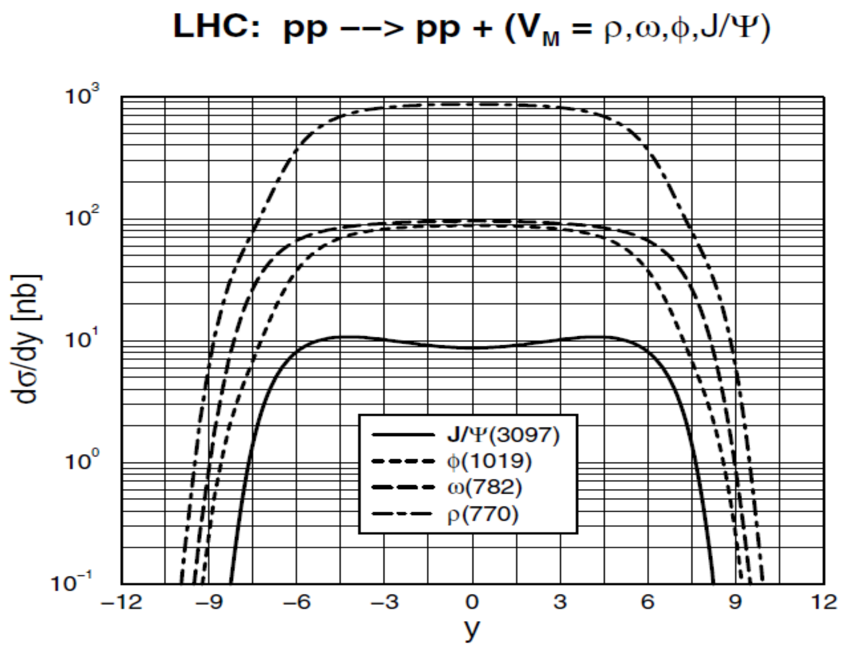
- Proton: Constrained by Hera data for inclusive and exclusive processes
- Nucleus: $$\mathcal{N}_A(x, \boldsymbol{r}, \boldsymbol{b}_A) = 1 - \exp\left[-\frac{1}{2}\sigma_{dp}(x, \boldsymbol{r}^2)\,T_A(\boldsymbol{b}_A)\right]$$

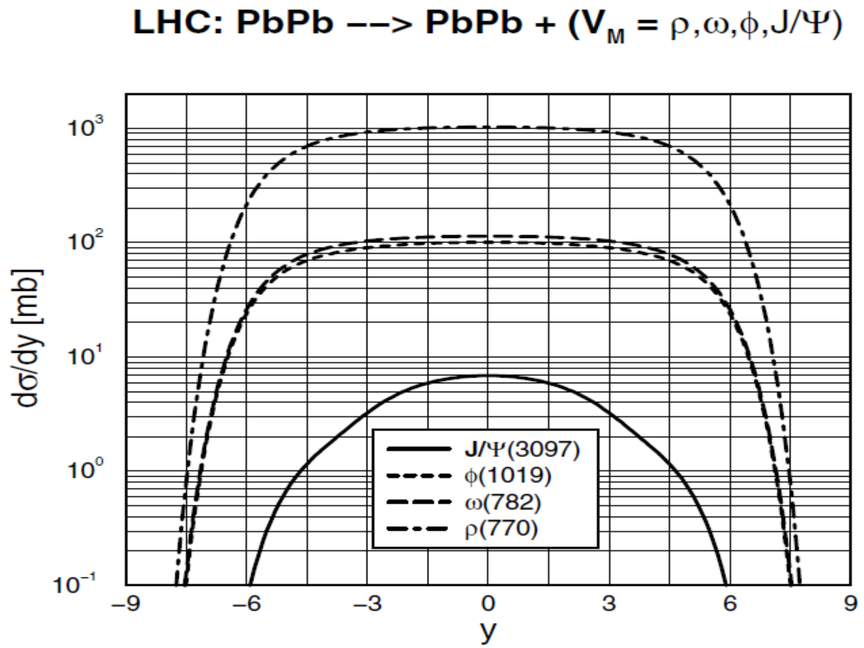
Sums all multiple elastic rescatterings of the dipole.

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

Diffractive vector meson photoproduction in UPHIC

First predictions using the Color Dipole Formalism


LHC: pp --> pp + ($V_M = \rho,\omega,\phi,J/\Psi$)


LHC: PbPb --> PbPb + ($V_M = \rho,\omega,\phi,J/\Psi$)

- Golec- Biernat – Wusthoff (GBW) :

$$\mathcal{N}^p(\hat{x},\boldsymbol{r},\boldsymbol{b}) = \mathcal{N}^p(\hat{x},\boldsymbol{r})S(\boldsymbol{b})$$

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

- DGKP model for the vector meson WF

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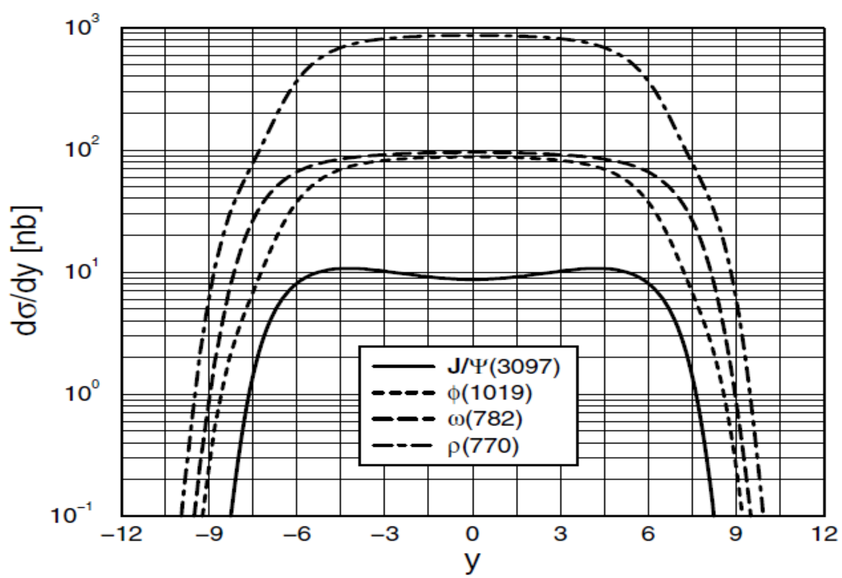
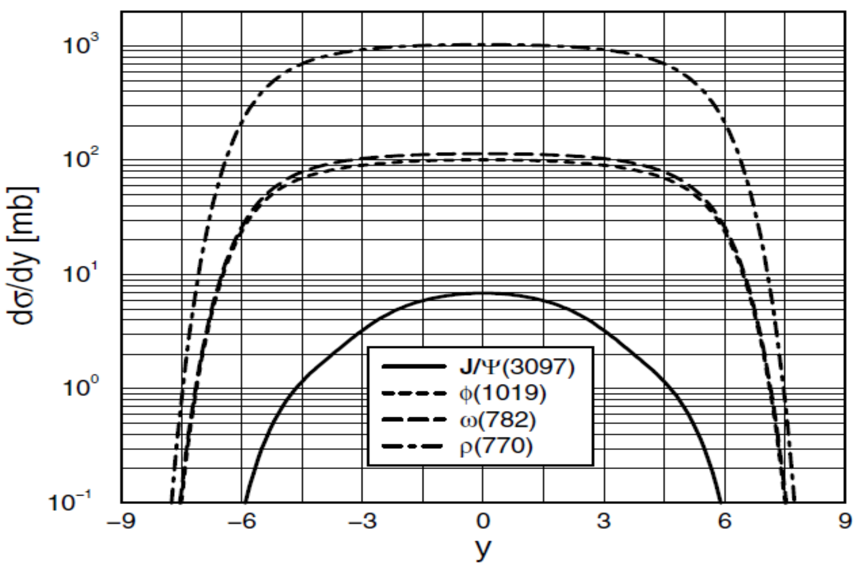
[a] VPG, Machado, EPJC 40, 519 (2005)

Diffractive vector meson photoproduction in UPHIC

First predictions using the Color Dipole Formalism


LHC: pp --> pp + ($V_M = \rho,\omega,\phi,J/\Psi$)


LHC: PbPb --> PbPb + ($V_M = \rho,\omega,\phi,J/\Psi$)

During the last 11 years, several authors have updated these predictions taking into account the improvements in our understanding of the QCD dynamics and for the description of exclusive processes in electron – proton scattering (e.g. impact parameter dependence, skewness, vector meson W. F., …)

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[a] VPG, Machado, EPJC 40, 519 (2005)

Diffractive vector meson photoproduction in UPHIC

Diffractive vector meson photoproduction in UPHIC

Overlap functions for Vector Mesons:

$$(\Psi_V^*\Psi)_T = \frac{\hat{e}_f e}{4\pi}\frac{N_c}{\pi z(1-z)}\{m_f^2 K_0(\epsilon r)\phi_T(r,z) - [z^2+(1-z)^2]\epsilon K_1(\epsilon r)\partial_r\phi_T(r,z)\}$$

- Gaus - LC :

$$\phi_T(r,z) \;=\; N_T\left[z(1-z)\right]^2\exp\left(-r^2/2R_T^2\right)$$

- Boosted Gaussian :

$$\phi_{T,L}(r,z) = N_{T,L}\, z(1-z)\exp\left[-\frac{m_f^2R^2}{8z(1-z)} - \frac{2z(1-z)r^2}{R^2} + \frac{m_f^2R^2}{2}\right]$$

Diffractive vector meson photoproduction in UPHIC

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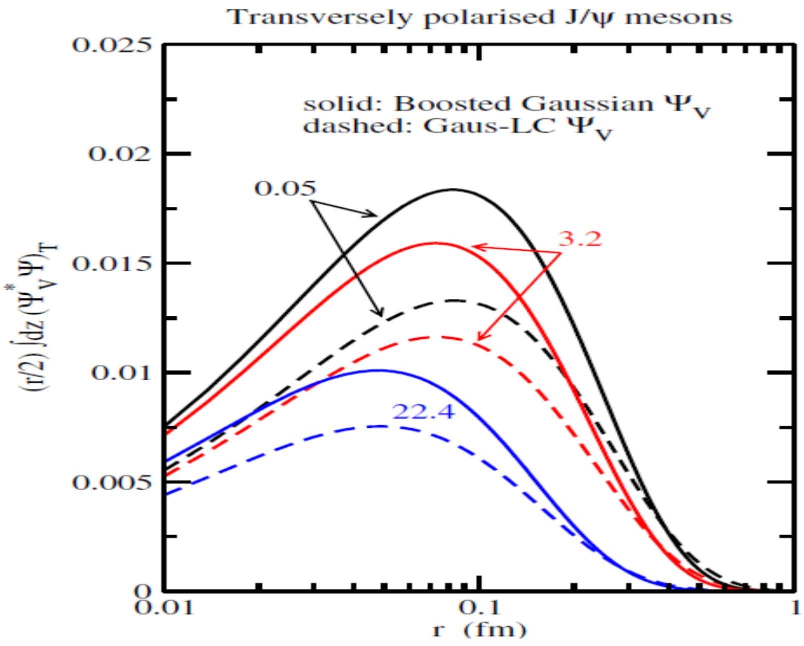
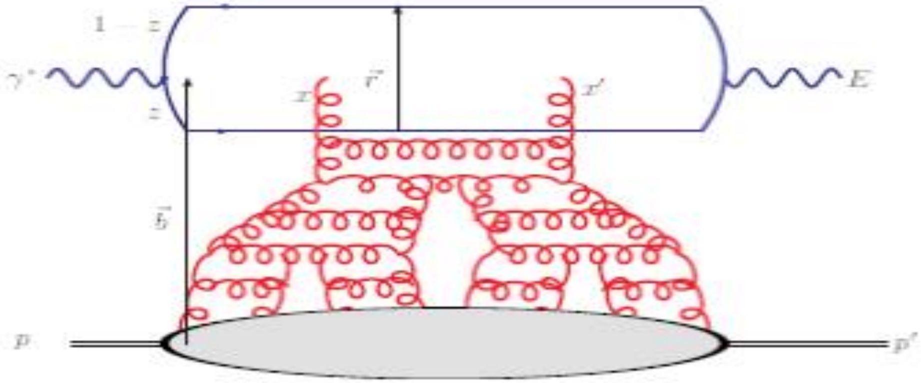


Kowalski, Motyka and Watt (06)

Diffractive vector meson photoproduction in UPHIC

Dipole – proton scattering amplitude:



- **bCGC :** $$\mathcal{N}^p(\hat{x},\boldsymbol{r},\boldsymbol{b}) = \begin{cases} \mathcal{N}_0\left(\frac{rQ_s(b)}{2}\right)^{2\left(\gamma_s+\frac{\ln(2/rQ_s(b))}{\kappa\lambda Y}\right)} & rQ_s(b) \leq 2 \\ 1 - e^{-A\ln^2(BrQ_s(b))} & rQ_s(b) > 2 \end{cases}$$

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

Diffractive vector meson photoproduction in UPHIC

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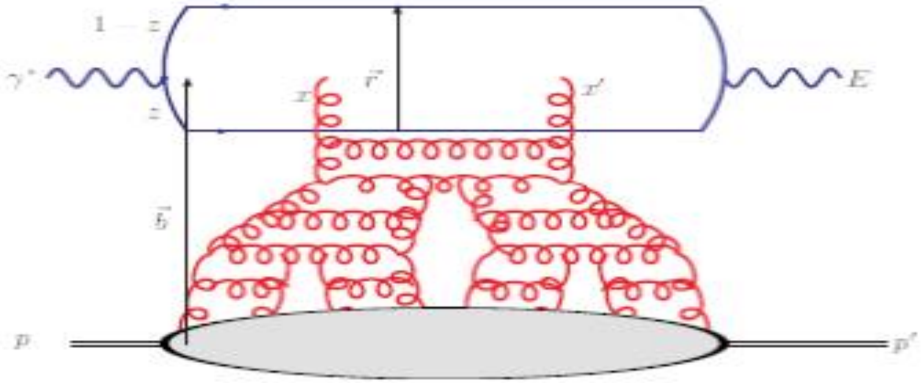

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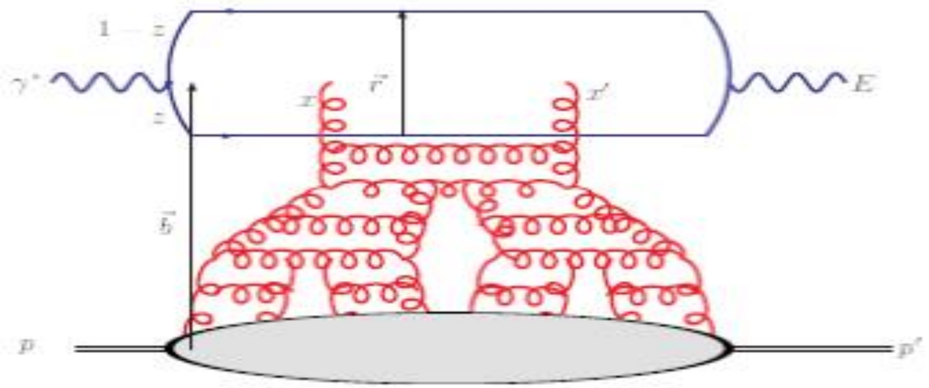
  - Proposed originally by Kowalski, Motyka and Watt (06)
  - Parameters of the model updated considering the high precision combined HERA data (Rezaeian, Schmidt, 13)

Diffractive vector meson photoproduction in UPHIC

Dipole – proton scattering amplitude:



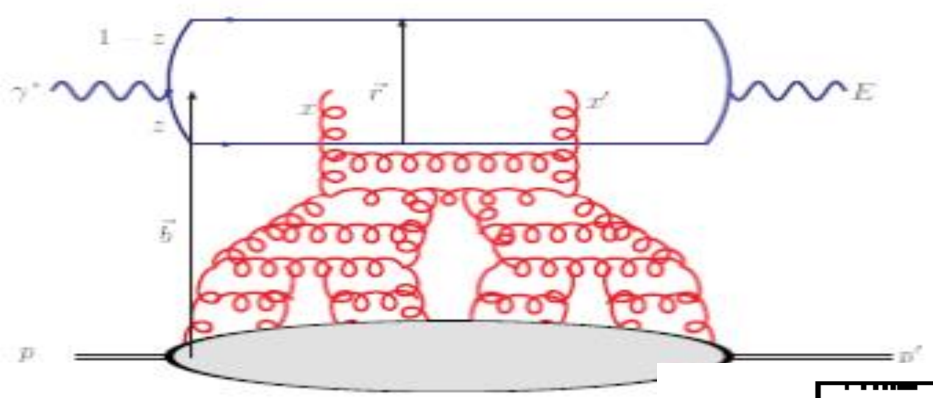
- Iancu – Itakura – Munier (IIM/CGC):

$$\mathcal{N}^p(\hat{x},\boldsymbol{r},\boldsymbol{b}) = \mathcal{N}^p(\hat{x},\boldsymbol{r})S(\boldsymbol{b})$$

$$\mathcal{N}^p(x,\mathbf{r}) = \begin{cases} \mathcal{N}_0\left(\frac{r\,Q_s}{2}\right)^{2\left(\gamma_s+\frac{\ln(2/r\,Q_s)}{\kappa\,\lambda\,Y}\right)}, & \text{for } rQ_s(x) \le 2\,, \\ 1-\mathrm{e}^{-a\,\ln^2(b\,r\,Q_s)}, & \text{for } rQ_s(x) > 2\,, \end{cases}$$

Diffractive vector meson photoproduction in UPHIC

Dipole – proton scattering amplitude:



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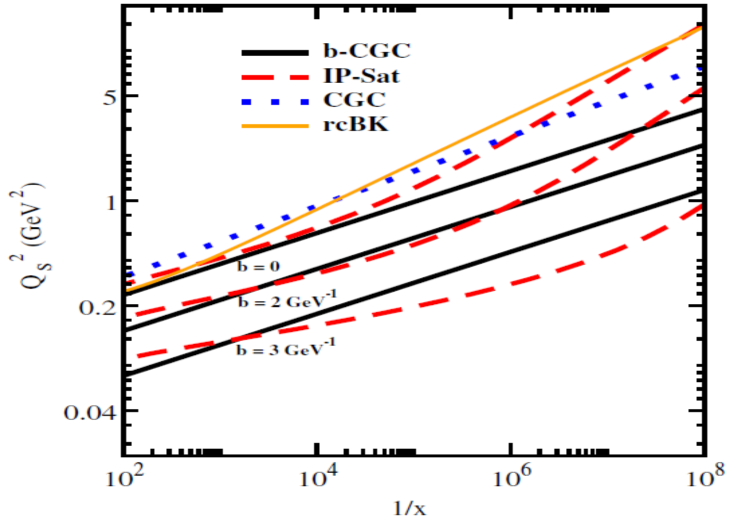

Rezaeian, Schmidt (13)

Comparison with the Run I data

- Diffractive J/Ψ photoproduction in hadronic collisions [a]

[a] VPG, Moreira, Navarra, PRD90, 15203 (2014)

Comparison with the Run I data

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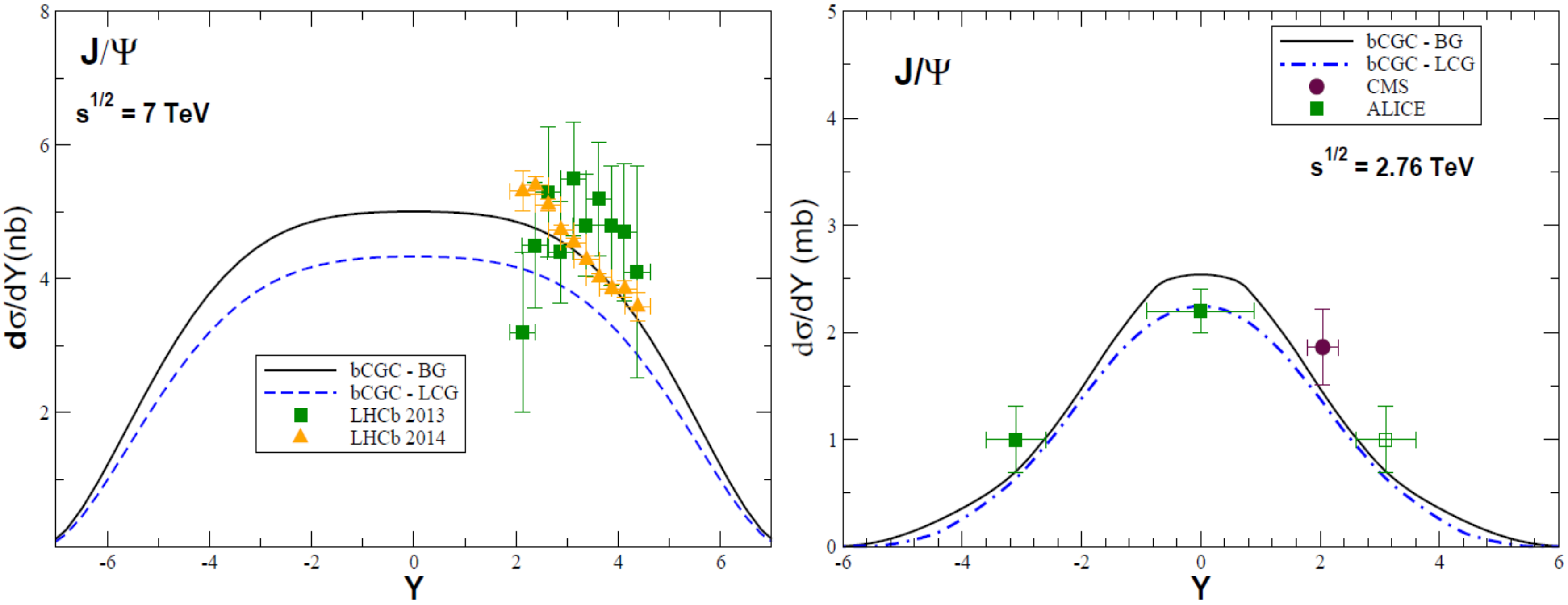

(a) VPG, Moreira, Navarra, PRD90, 15203 (2014)

Comparison with the Run I data

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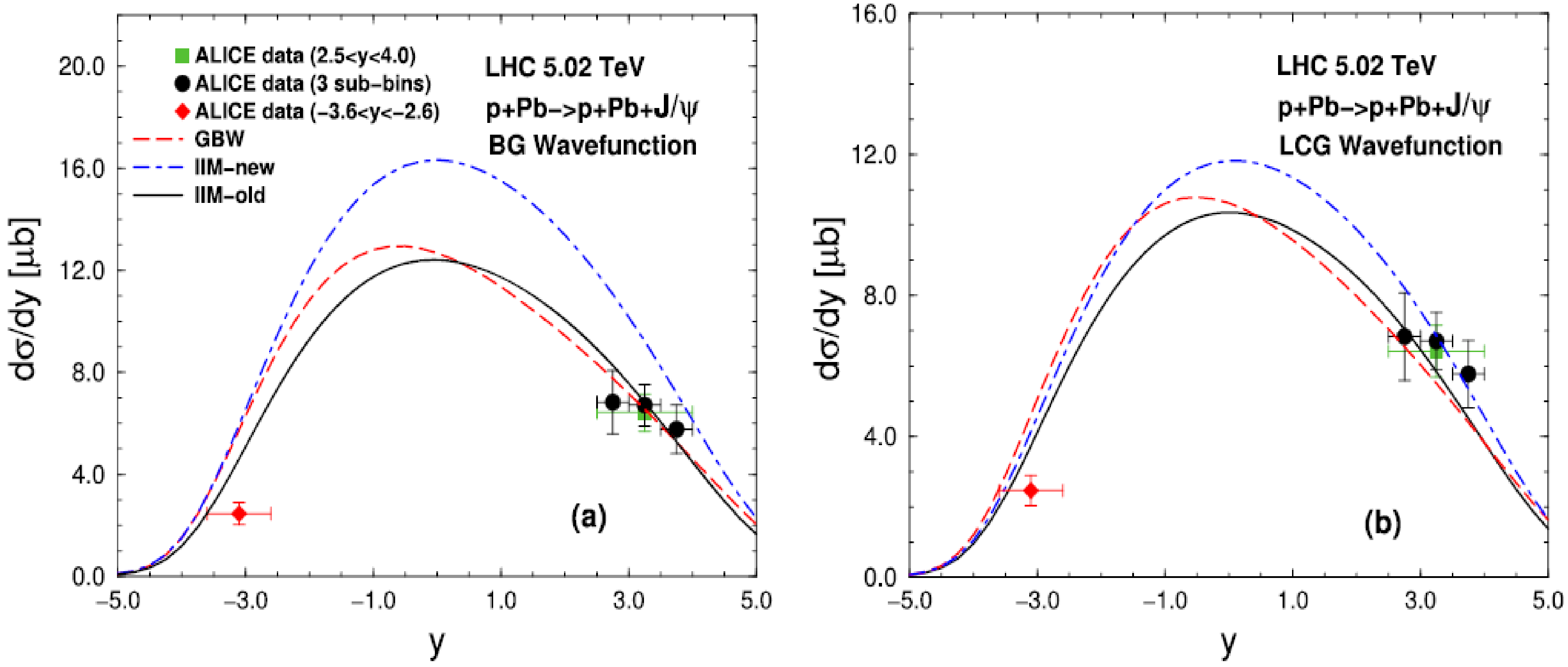

(a) Machado, dos Santos, JPG 42, 155001 (2015)

Comparison with the Run I data

- Diffractive Υ photoproduction in hadronic collisions [b]

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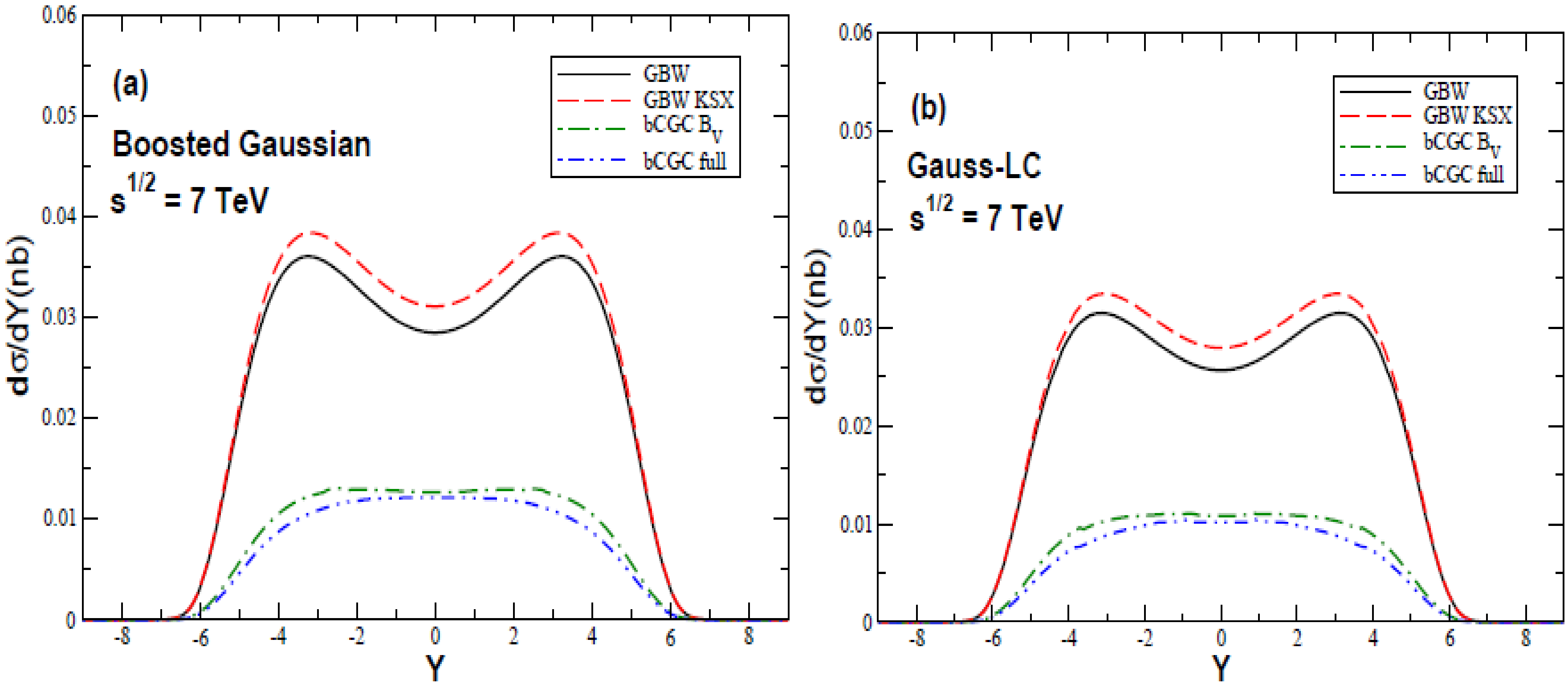
[b] VPG, Moreira, Navarra, PLB 472, 172 (2015)

Comparison with the Run I data

- Diffractive Υ photoproduction in hadronic collisions [b]



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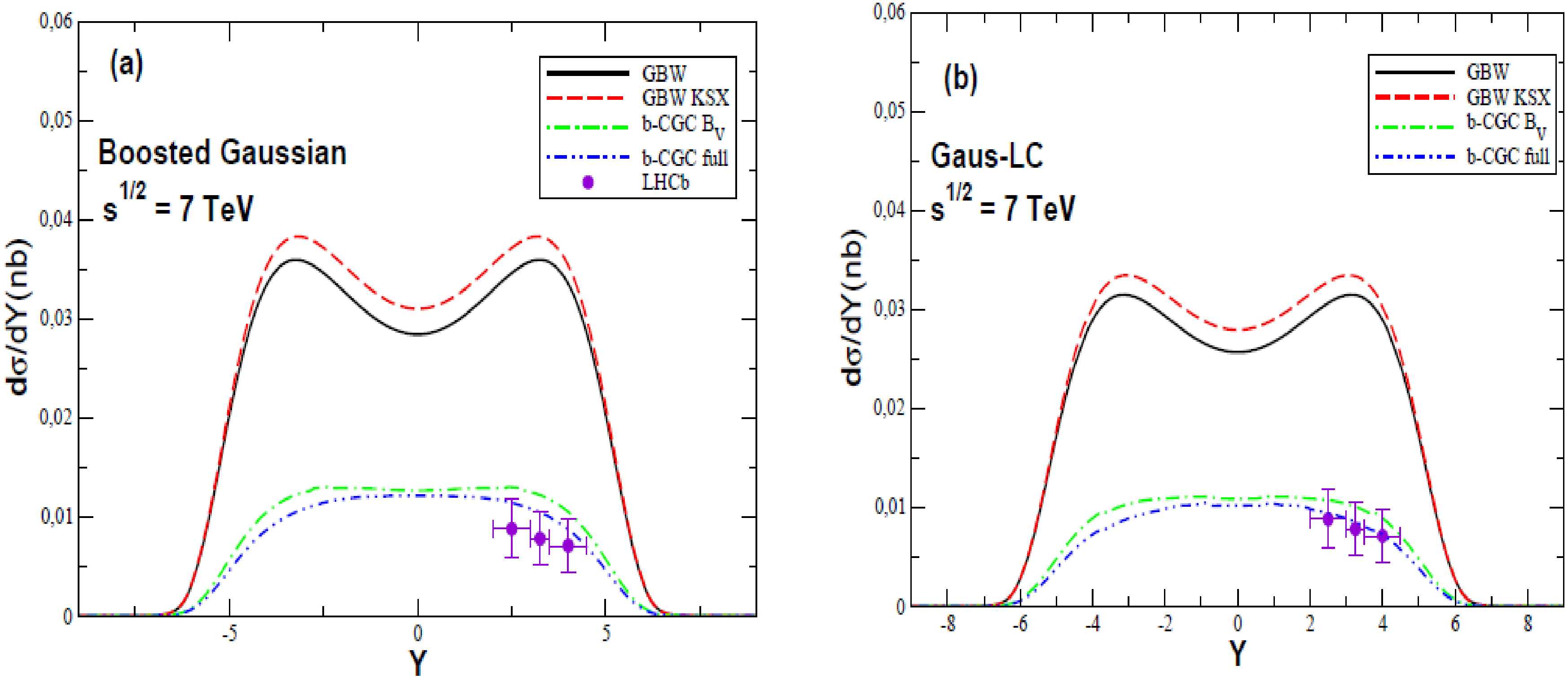
[b] VPG, Moreira, Navarra, PLB 472, 172 (2015)

Comparison with the Run I data

- Diffractive Υ photoproduction in hadronic collisions [b]



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[b] VPG, Moreira, Navarra, PLB 472, 172 (2015)

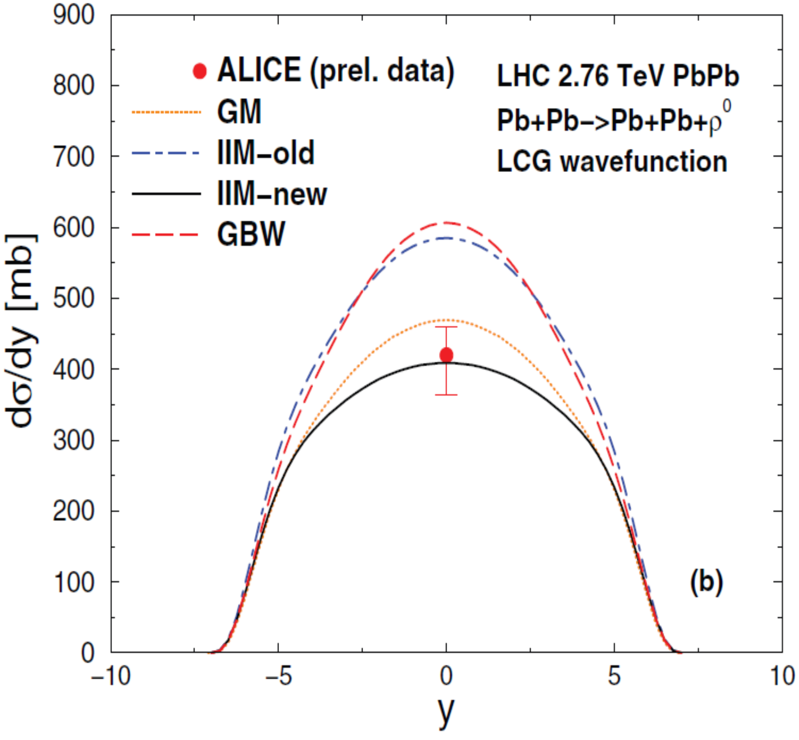
Comparison with the Run I data

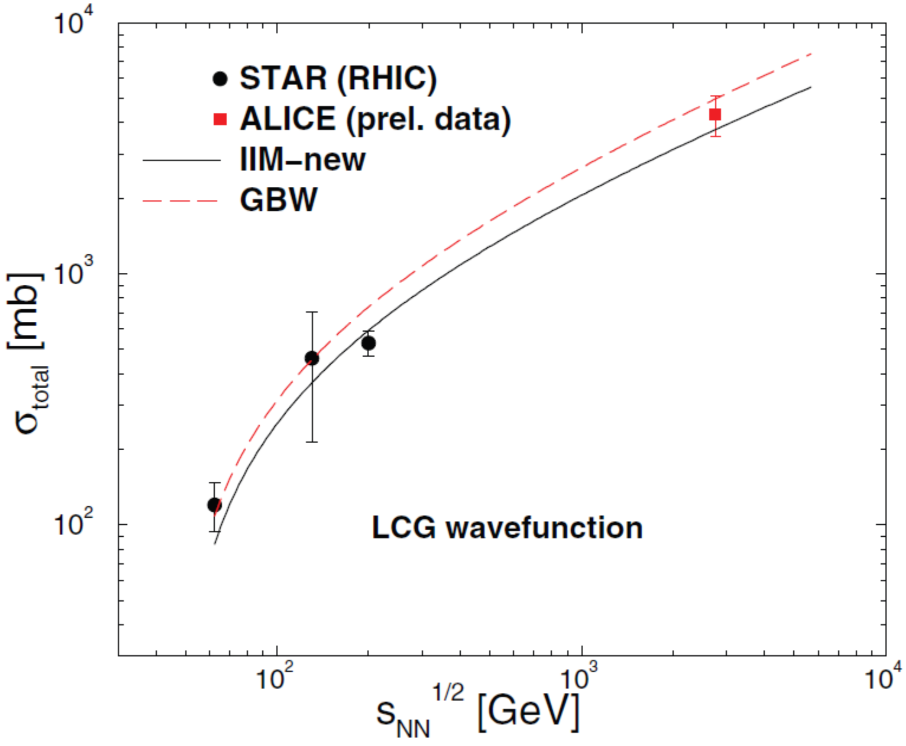
- Diffractive ρ photoproduction in hadronic collisions [c]

(c) VPG, Machado, EPJC 40, 519 (2005); PRC80, 054901 (2009); PRC84, 011902 (2011)
Machado, dos Santos, PRC91, 025203 (2015)

Comparison with the Run I data

- Diffractive ρ photoproduction in hadronic collisions [c]





[c] VPG, Machado, EPJC 40, 519 (2005); PRC80, 054901 (2009); PRC84, 011902 (2011)
Machado, dos Santos, PRC91, 025203 (2015)

Predictions for the Run II

(*) VPG, Machado, Moreira, Navarra, dos Santos (paper in preparation)

Predictions for the Run II

- Diffractive vector meson photoproduction in proton - proton collisions

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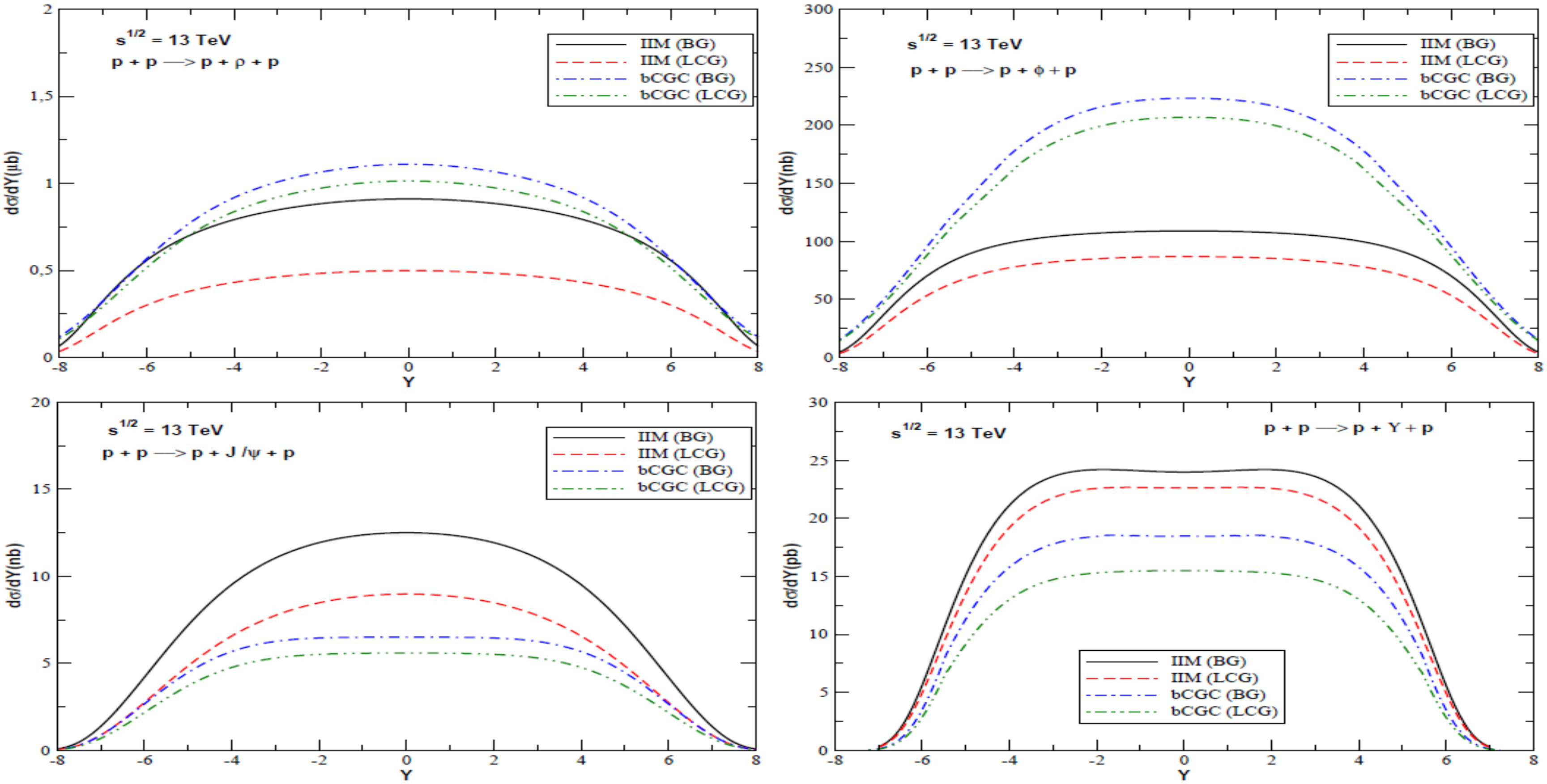
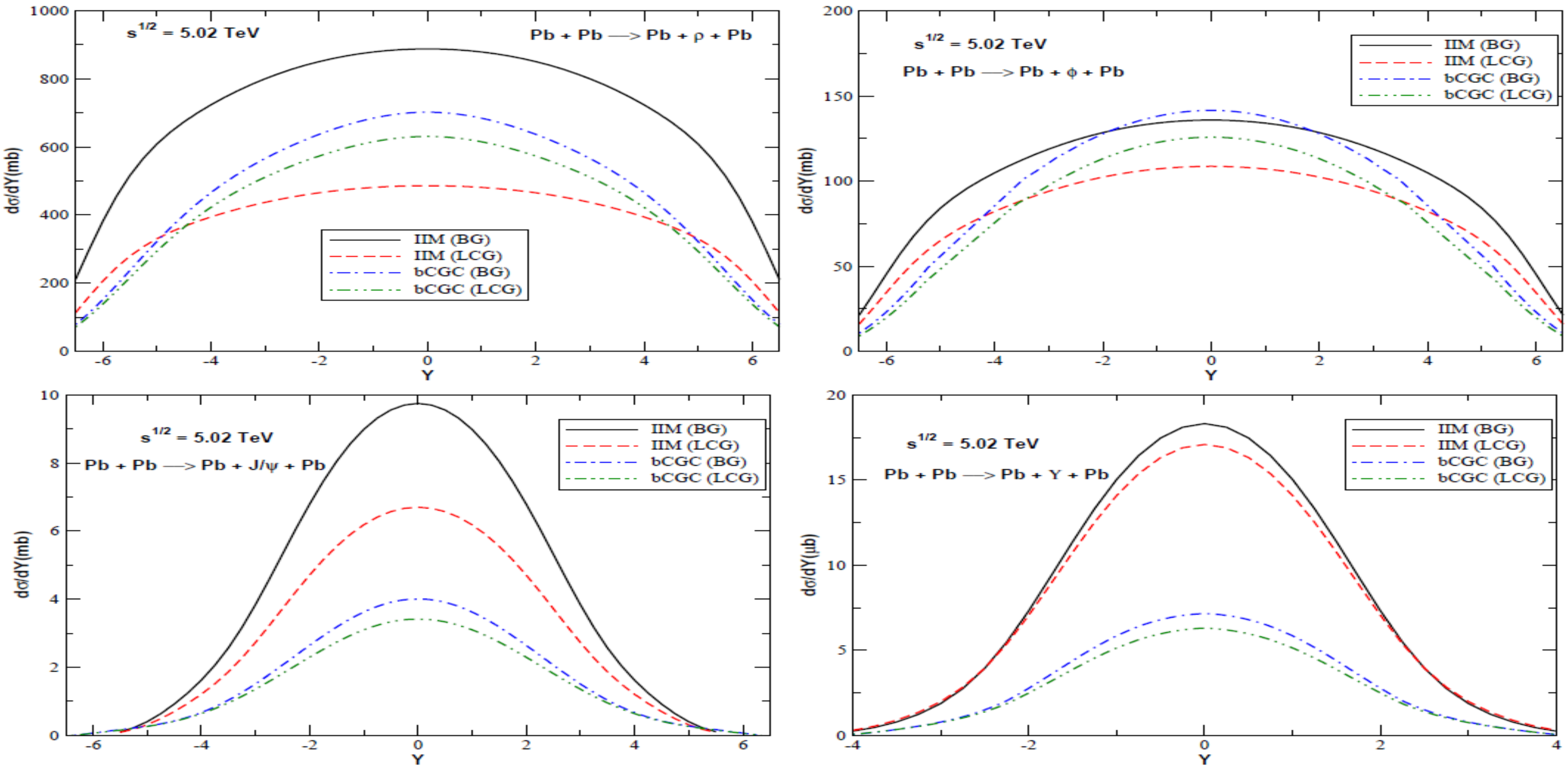


(*) VPG, Machado, Moreira, Navarra, dos Santos (paper in preparation)

Predictions for the Run II

- Diffractive vector meson photoproduction in heavy ion collisions



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Predictions for the Run II

- Double Vector Meson production

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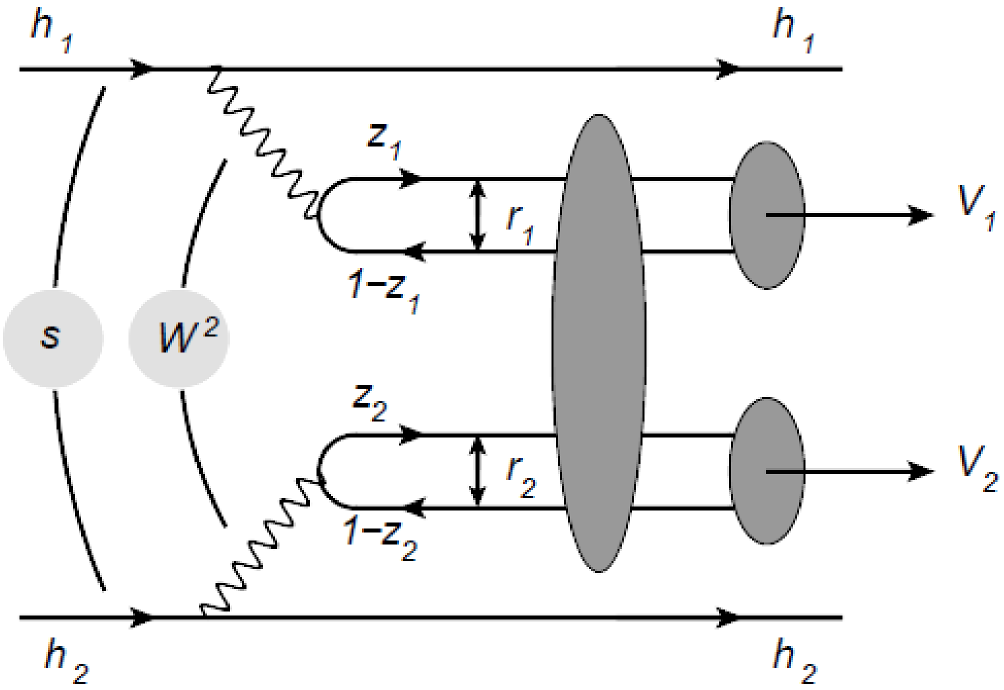
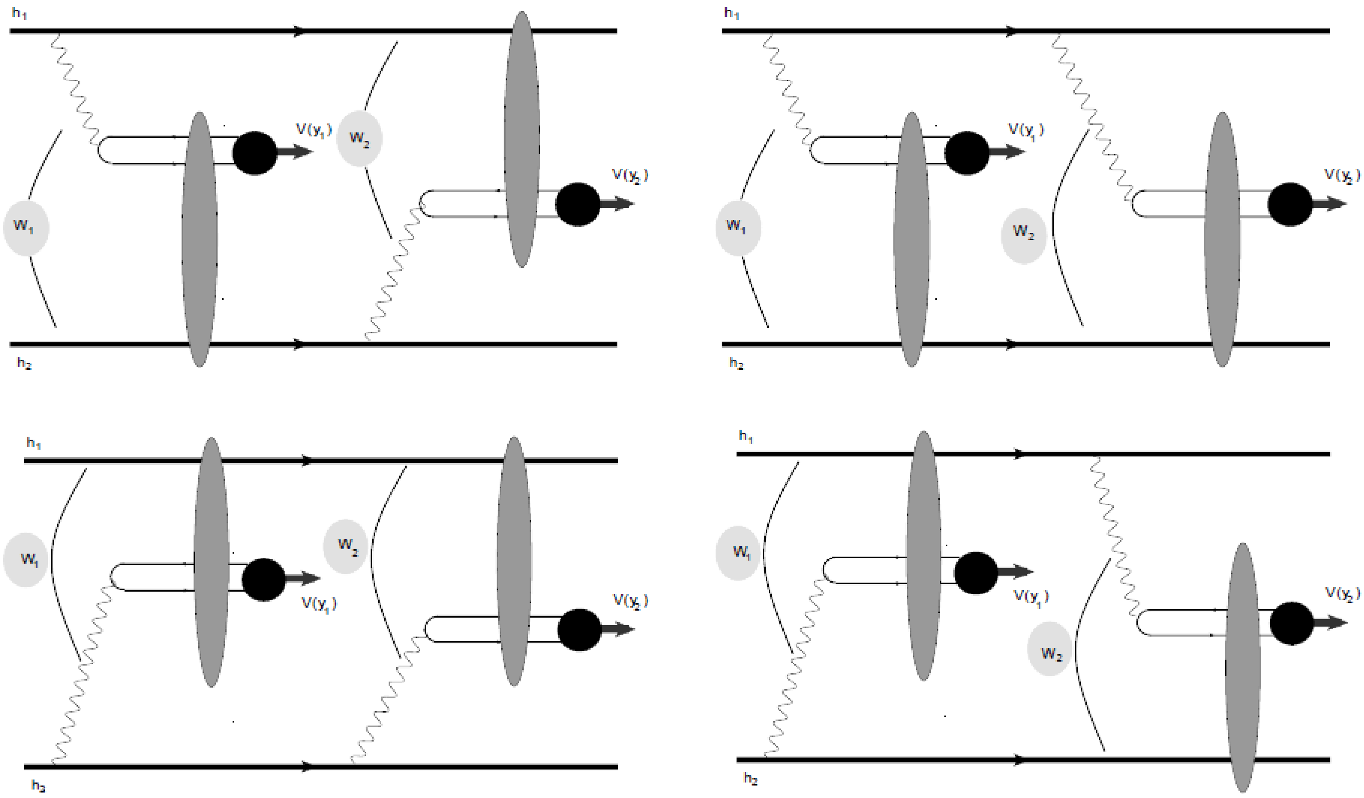


VPG, Moreira, Navarra, EPJC 76, 103 (2016)

Predictions for the Run II

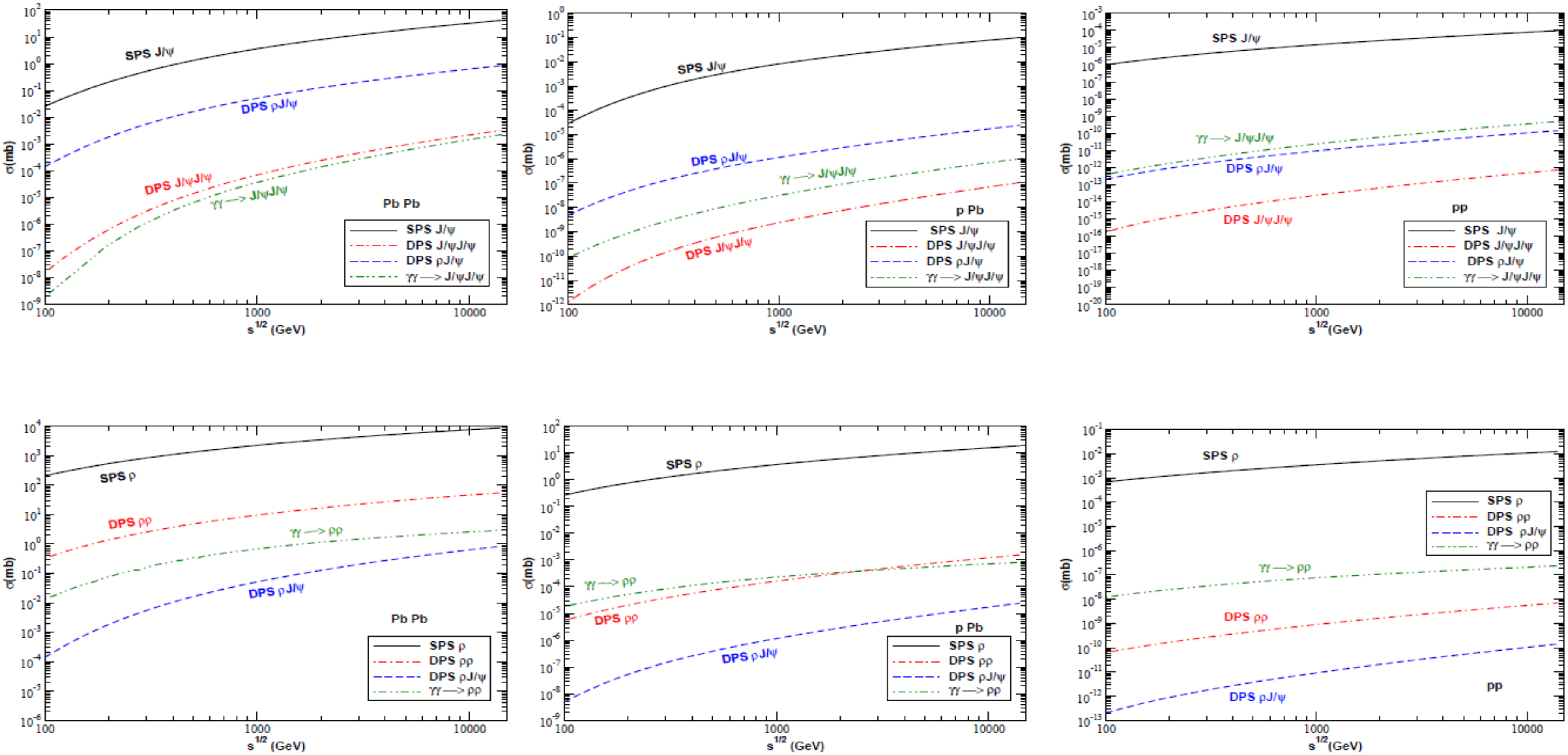
- Double Vector Meson production



(*) VPG, Moreira, Navarra, arXiv:1605.05840[hep-ph]

Predictions for the Run II

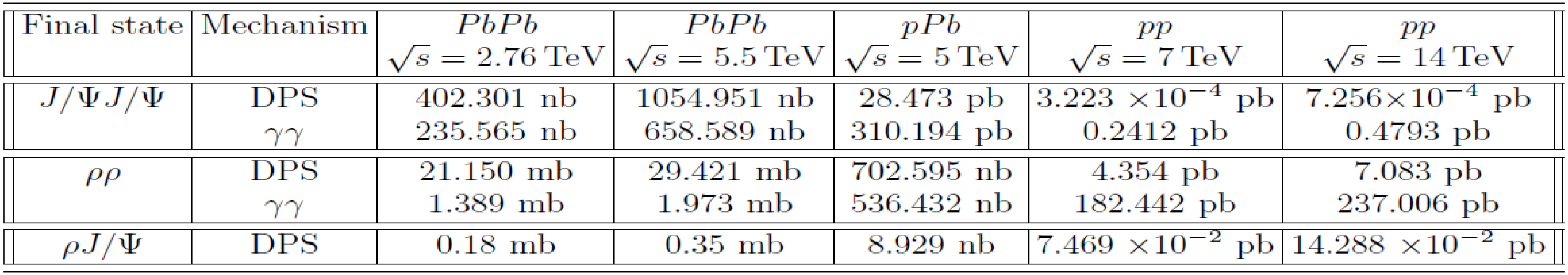
- Double Vector Meson production



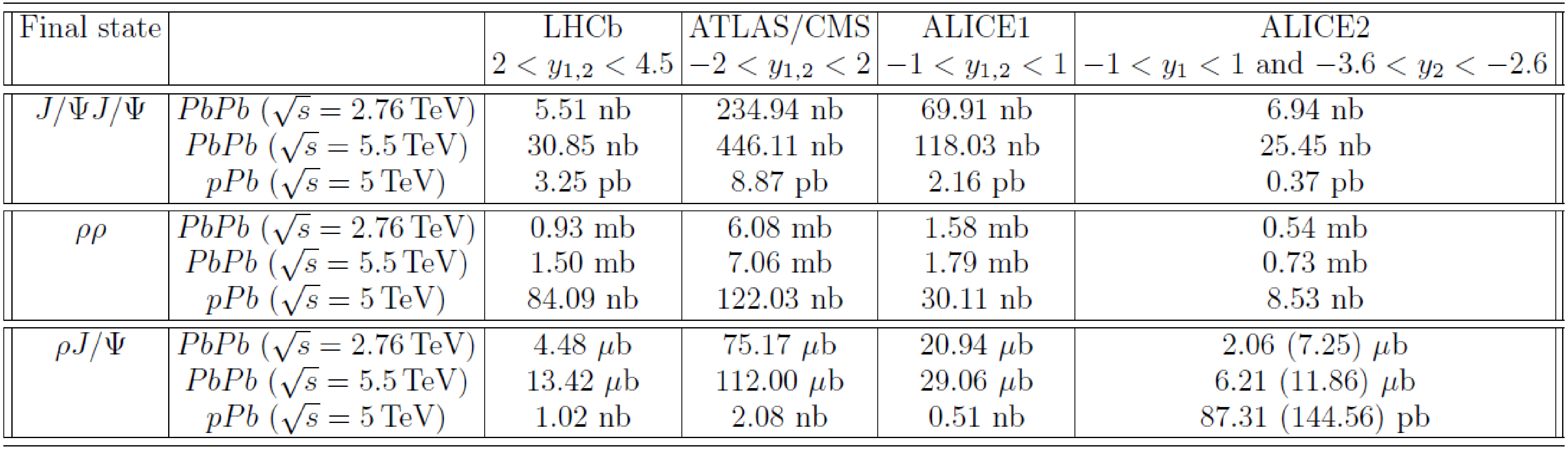
(*) VPG, Moreira, Navarra, arXiv:1605.05840[hep-ph]

Double Vector Meson Production

Predictions for the total cross sections



Final state	Mechanism	$PbPb$ $\sqrt{s} = 2.76$ TeV	$PbPb$ $\sqrt{s} = 5.5$ TeV	pPb $\sqrt{s} = 5$ TeV	pp $\sqrt{s} = 7$ TeV	pp $\sqrt{s} = 14$ TeV
$J/\Psi J/\Psi$	DPS $\gamma\gamma$	402.301 nb 235.565 nb	1054.951 nb 658.589 nb	28.473 pb 310.194 pb	3.223×10^{-4} pb 0.2412 pb	7.256×10^{-4} pb 0.4793 pb
$\rho\rho$	DPS $\gamma\gamma$	21.150 mb 1.389 mb	29.421 mb 1.973 mb	702.595 nb 536.432 nb	4.354 pb 182.442 pb	7.083 pb 237.006 pb
$\rho J/\Psi$	DPS	0.18 mb	0.35 mb	8.929 nb	7.469×10^{-2} pb	14.288×10^{-2} pb



Final state		LHCb $2 < y_{1,2} < 4.5$	ATLAS/CMS $-2 < y_{1,2} < 2$	ALICE1 $-1 < y_{1,2} < 1$	ALICE2 $-1 < y_1 < 1$ and $-3.6 < y_2 < -2.6$
$J/\Psi J/\Psi$	$PbPb$ ($\sqrt{s} = 2.76$ TeV) $PbPb$ ($\sqrt{s} = 5.5$ TeV) pPb ($\sqrt{s} = 5$ TeV)	5.51 nb 30.85 nb 3.25 pb	234.94 nb 446.11 nb 8.87 pb	69.91 nb 118.03 nb 2.16 pb	6.94 nb 25.45 nb 0.37 pb
$\rho\rho$	$PbPb$ ($\sqrt{s} = 2.76$ TeV) $PbPb$ ($\sqrt{s} = 5.5$ TeV) pPb ($\sqrt{s} = 5$ TeV)	0.93 mb 1.50 mb 84.09 nb	6.08 mb 7.06 mb 122.03 nb	1.58 mb 1.79 mb 30.11 nb	0.54 mb 0.73 mb 8.53 nb
$\rho J/\Psi$	$PbPb$ ($\sqrt{s} = 2.76$ TeV) $PbPb$ ($\sqrt{s} = 5.5$ TeV) pPb ($\sqrt{s} = 5$ TeV)	4.48 μb 13.42 μb 1.02 nb	75.17 μb 112.00 μb 2.08 nb	20.94 μb 29.06 μb 0.51 nb	2.06 (7.25) μb 6.21 (11.86) μb 87.31 (144.56) pb

(*) VPG, Moreira, Navarra, arXiv:1605.05840[hep-ph]

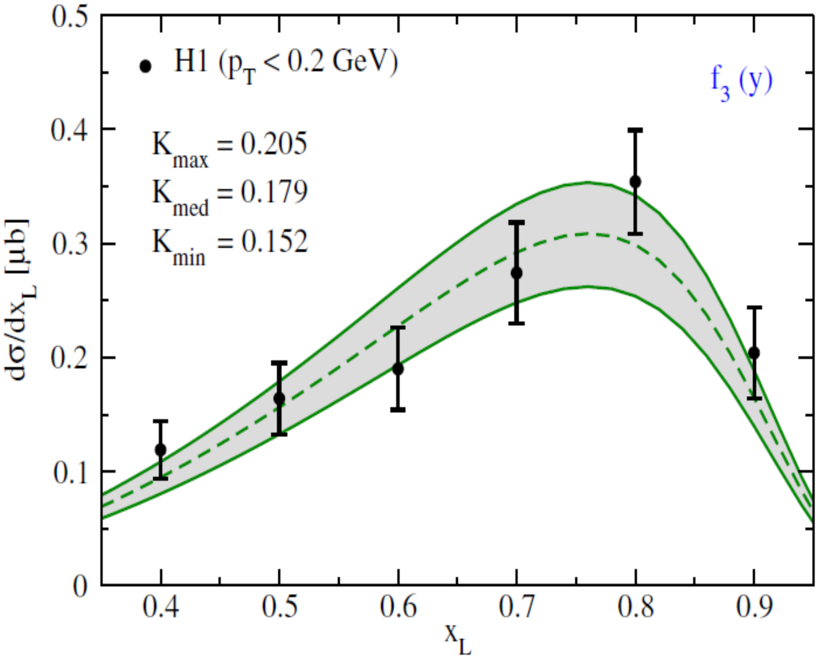
Predictions for the Run II

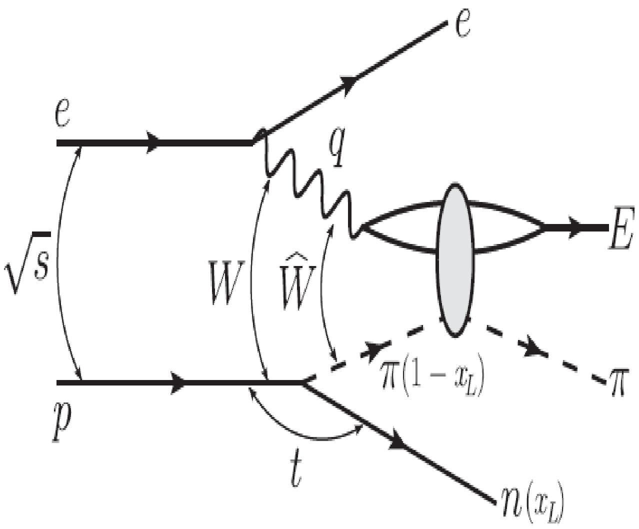
- Vector Meson photoproduction with a leading neutron

Predictions for the Run II

- Vector Meson photoproduction with a leading neutron at HERA

$$\gamma p \rightarrow \rho^0 \pi^+ n$$





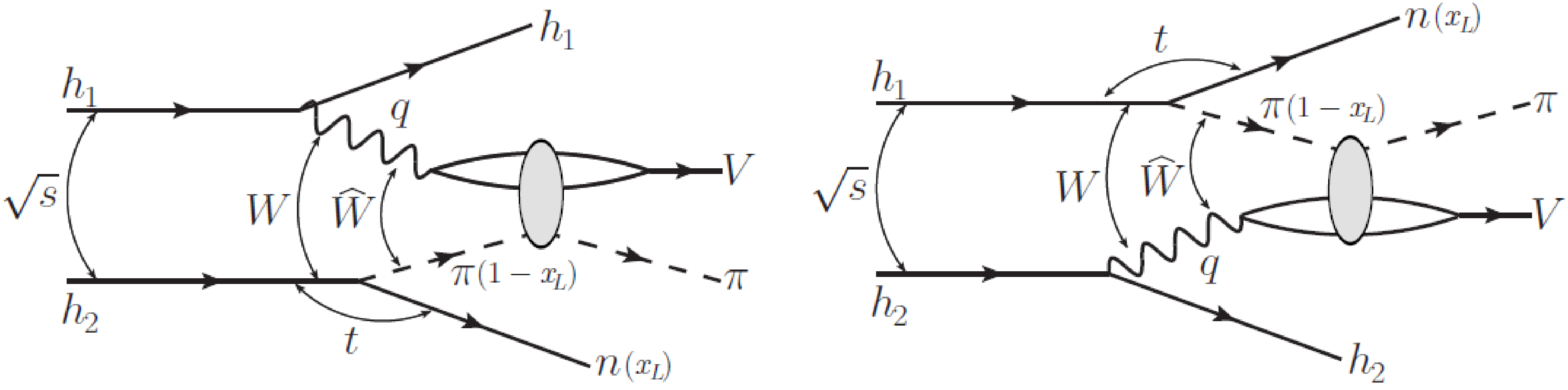
$$\sigma_{\gamma p \to V \otimes \pi + n}(W^2) = \mathcal{K} \cdot \int dx_L dt \, f_{\pi/p}(x_L, t) \cdot \sigma_{\gamma \pi \to V \otimes \pi}(\hat{W}^2)$$

VPG, Navarra, Spiering, PRD 93, 054025 *(2016)*

See talk by F. Navarra

Predictions for the Run II

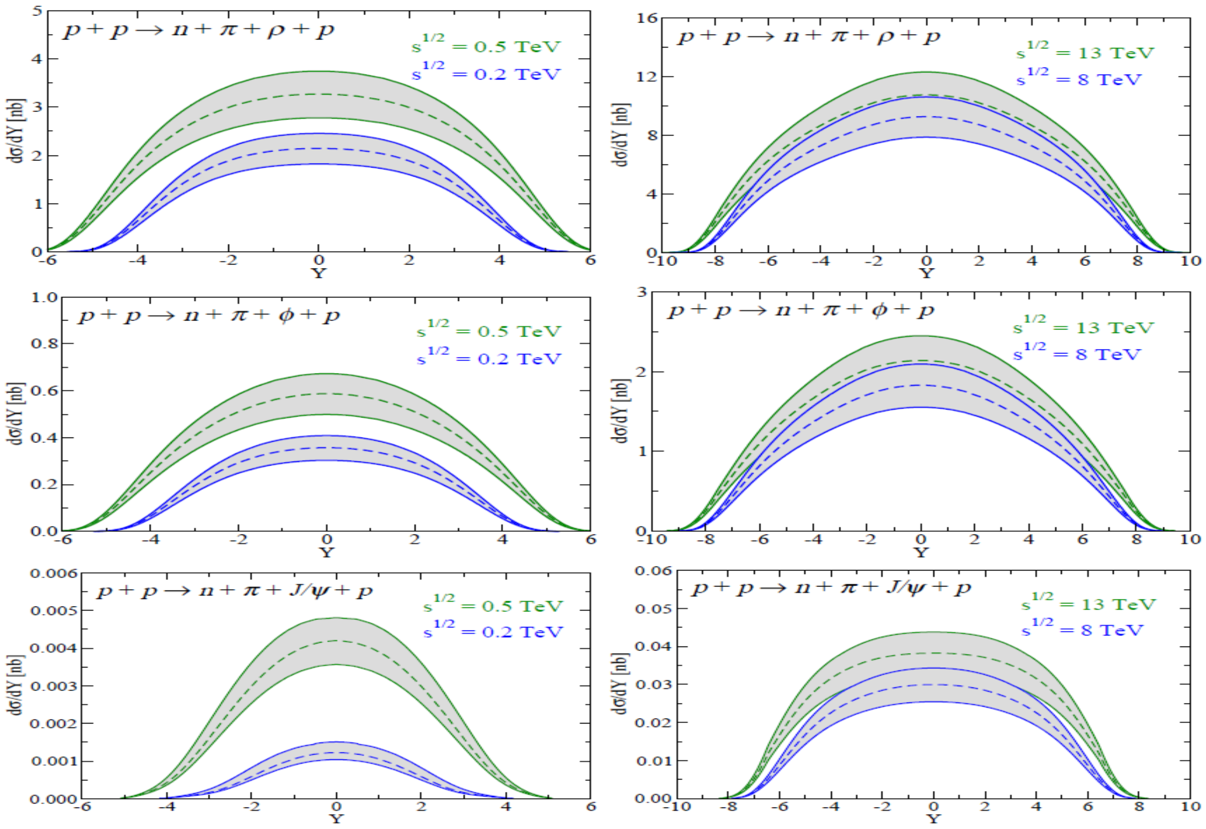
- Vector Meson photoproduction with a leading neutron in UPHIC



(**) VPG, Moreira, Navarra, Spiering arXiv:1605.08186[hep-ph]

Predictions for the Run II

- ➢ Vector Meson photoproduction with a leading neutron in UPHIC



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Predictions for the Run II

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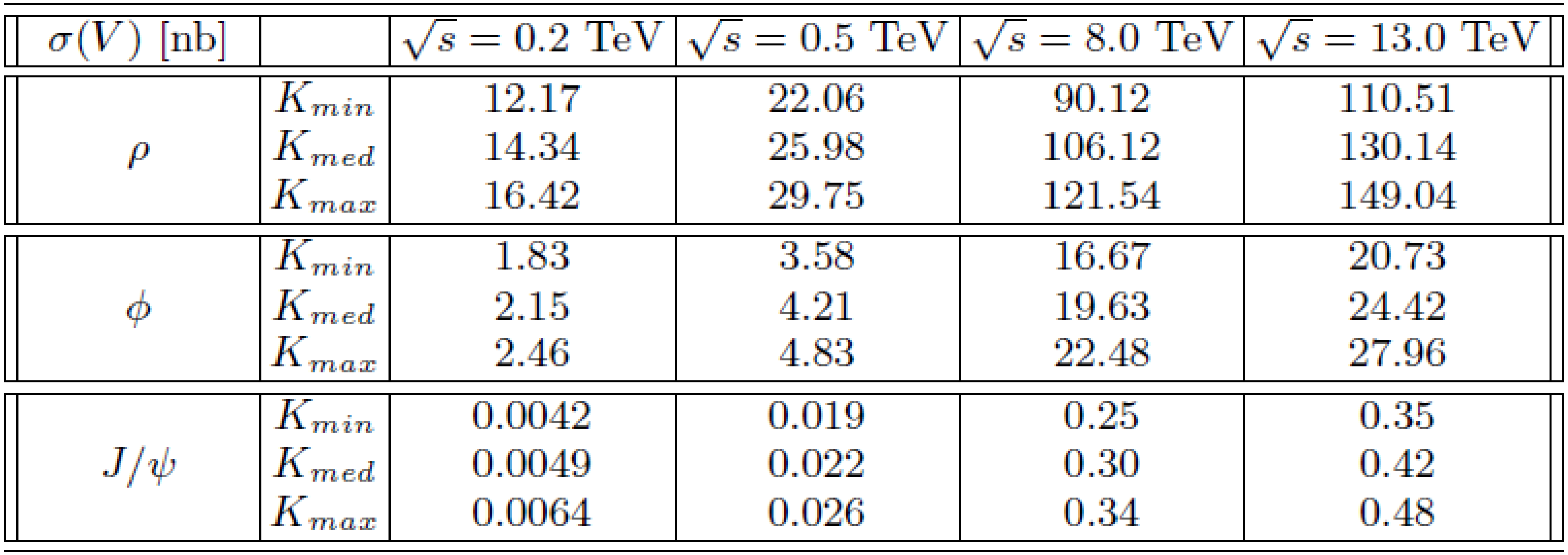

$\sigma(V)$ [nb]		$\sqrt{s} = 0.2$ TeV	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 8.0$ TeV	$\sqrt{s} = 13.0$ TeV
ρ	K_{min}	12.17	22.06	90.12	110.51
	K_{med}	14.34	25.98	106.12	130.14
	K_{max}	16.42	29.75	121.54	149.04
ϕ	K_{min}	1.83	3.58	16.67	20.73
	K_{med}	2.15	4.21	19.63	24.42
	K_{max}	2.46	4.83	22.48	27.96
J/ψ	K_{min}	0.0042	0.019	0.25	0.35
	K_{med}	0.0049	0.022	0.30	0.42
	K_{max}	0.0064	0.026	0.34	0.48

(**) VPG, Moreira, Navarra, Spiering arXiv:1605.08186[hep-ph]

Summary

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Thank you for your attention !

Extras

Double Vector Meson Production
Formalism

$$\frac{d^2\sigma_{h_1h_2\to h_1V_1V_2h_2}}{dy_1dy_2} = \mathcal{C}\int_{b_{min}} \frac{d\sigma\,\left[h_1+h_2\to h_1V_1h_2\right]}{d^2bdy_1} \times \frac{d\sigma\,\left[h_1+h_2\to h_1V_2h_2\right]}{d^2bdy_2}\, d^2b$$

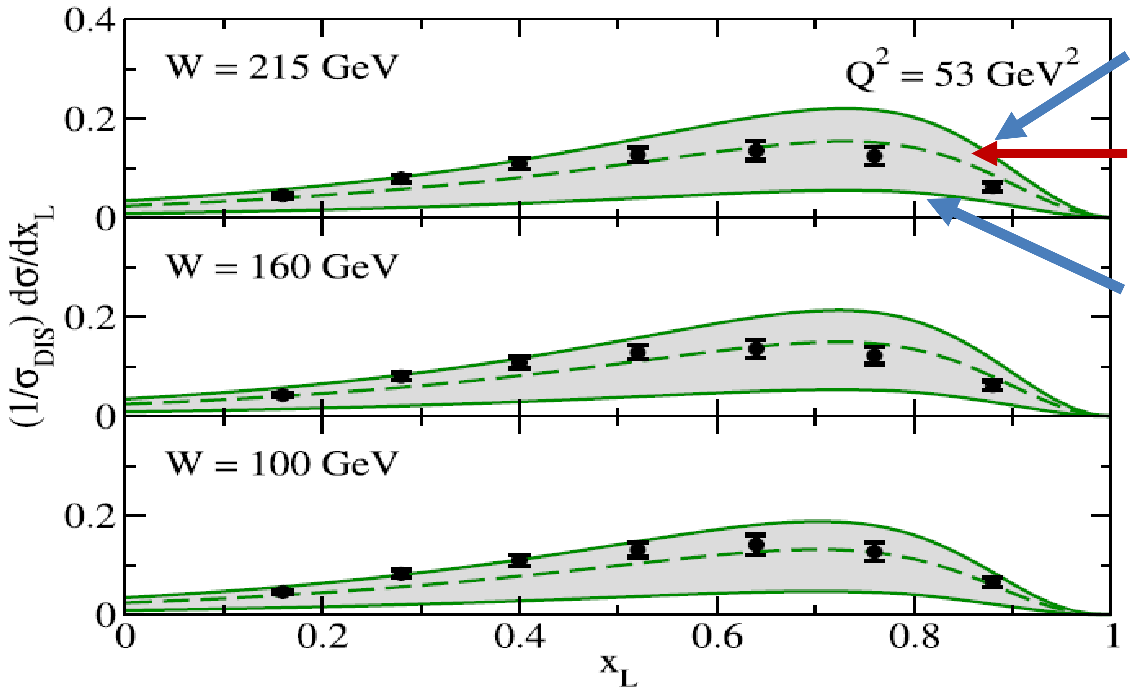
$$\frac{d\sigma\,\left[h_1+h_2\to h_1\otimes V\otimes h_2\right]}{d^2bdy} = \left[\omega N_{h_1}(\omega,b)\,\sigma_{\gamma h_2\to V\otimes h_2}\left(\omega\right)\right]_{\omega_L} + \left[\omega N_{h_2}(\omega,b)\,\sigma_{\gamma h_1\to V\otimes h_1}\left(\omega\right)\right]_{\omega_R}$$

$$N(\omega,b) = \frac{Z^2\alpha_{em}}{\pi^2}\frac{1}{b^2\omega}\cdot\left[\int u^2J_1(u)F\left(\sqrt{\frac{\left(\frac{b\omega}{\gamma_L}\right)^2+u^2}{b^2}}\right)\frac{1}{\left(\frac{b\omega}{\gamma_L}\right)^2+u^2}\mathrm{d}u\right]^2$$

(*) VPG, Moreira, Navarra, arXiv:1605.05840[hep-ph]

Leading neutron production in ep collisions
Results for Inclusive Processes

$$\frac{d^2\sigma(W,Q^2,x_L,t)}{dx_L dt} = f_{\pi/p}(x_L,t)\sigma_{\gamma^*\pi}(\hat{W}^2,Q^2)$$



Rq = 2/3; K = 1

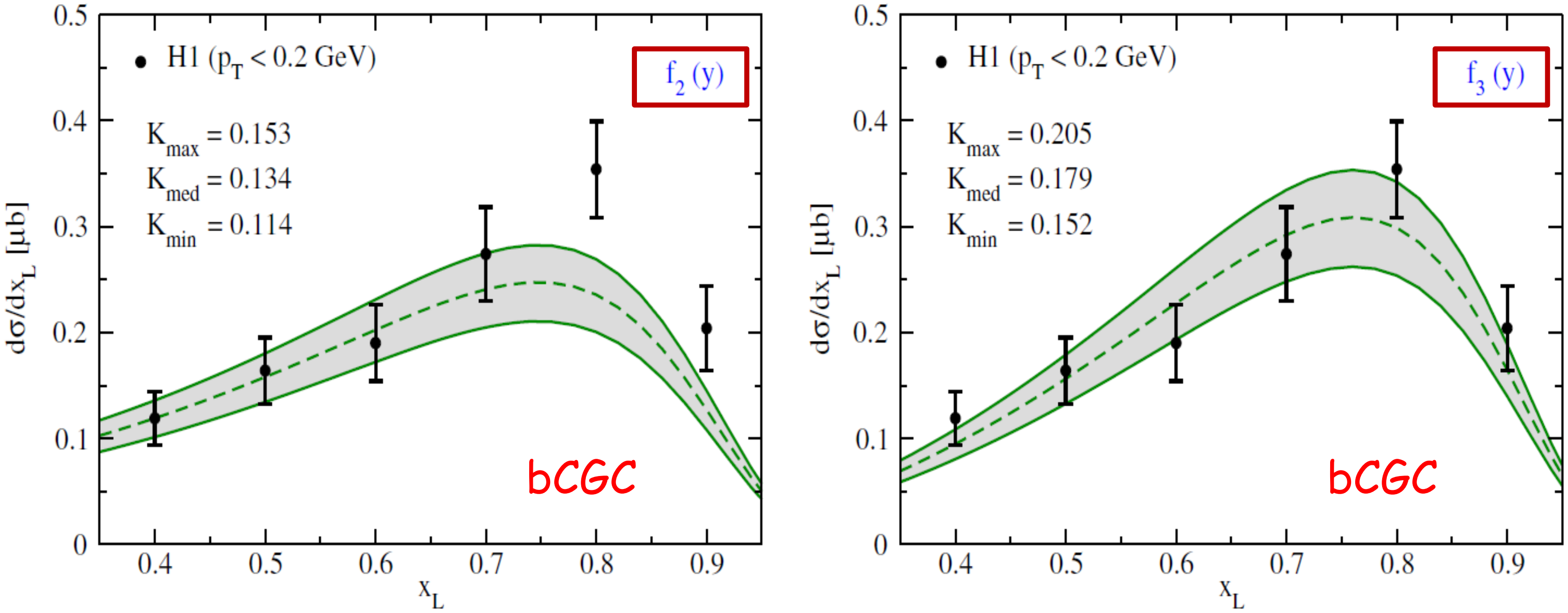
Rq . K = 0.5

Rq = 1/3; K = 0.5

Carvalho, VPG, Navarra, Spiering, PLB 572, 76(2016)

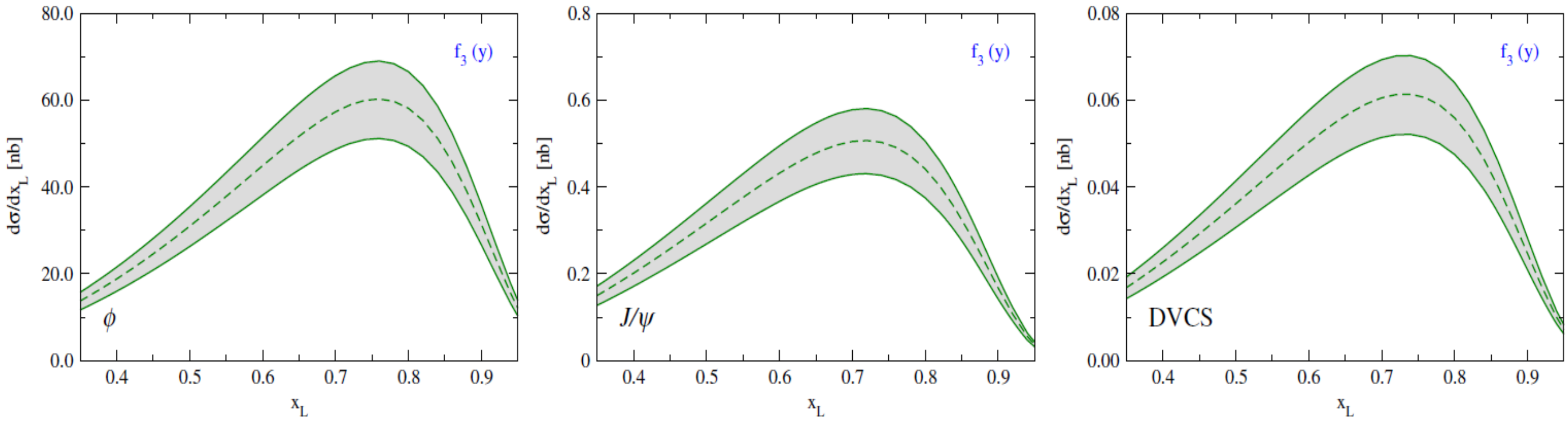
Leading neutron production in ep collisions
Results for Exclusive Processes

$$\gamma p \to \rho^0 \pi^+ n$$



VPG, Navarra, Spiering, PRD 93, 054025 *(2016)*

Predictions for Exclusive Processes with a leading neutron at HERA



$Q^2 = 0.04\ \text{GeV}^2$

$$\sigma(\gamma p \rightarrow \phi \pi n) = 25.47 \pm 3.70\ \text{nb}$$

$$\sigma(\gamma p \rightarrow J/\Psi \pi n) = 0.22 \pm 0.03\ \text{nb}$$

$Q^2 = 10\ \text{GeV}^2$

$$\sigma(\gamma^* p \rightarrow \gamma \pi n) = 0.008 \pm 0.001\ \text{nb}$$