QCD Challenges in pp, pA and AA collisions at high energies

Double Vector Meson Production in Photon - Induced Interactions at Hadronic Colliders

Bruno Duarte da Silva Moreira

V.P. Gonçalves, B.D. Moreira, F.S. Navarra - Eur.Phys.J. C 76 (2016).

ECT* - Trento, 27^{th} February – 3^{rd} March 2017

Outline

- Introduction
- Photon-induced processes
- Ultra-peripheral collisions
- Color dipole formalism
- Double vector meson production in double photon-nucleus interactions
- Results
- Conclusions

Introduction

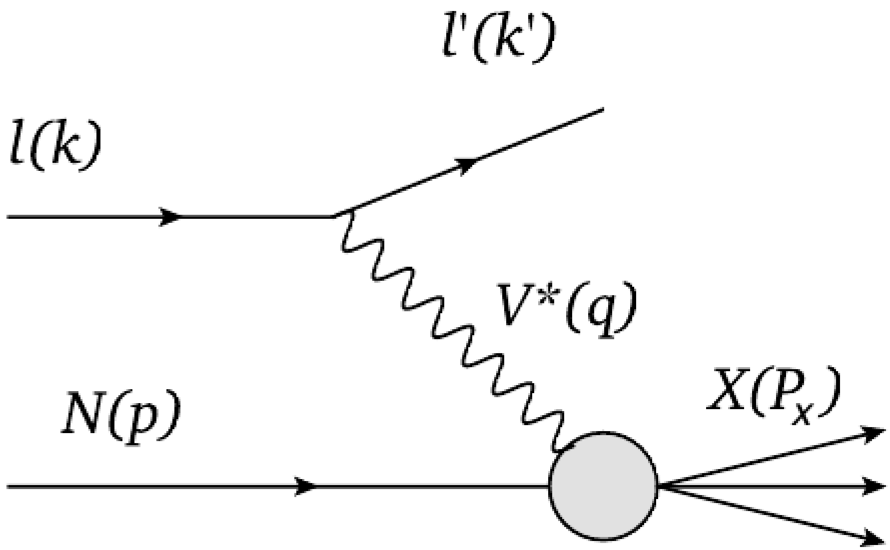
- The advent of high energy colliders has motivated:
  - Search for new physics.
  - Study and detection of new particles.
  - Study of high energy particle physics.

Introduction

- The advent of high energy colliders has motivated:
  - Search for new physics.
  - Study and detection of new particles.
  - Study of high energy particle physics.
    - Study of the high energy QCD dynamics.

Introduction

- DIS - a suitable way to study the QCD dynamics and the hadron structure in photon-nucleon interactions.



- DIS and DDIS were studied at HERA.

Introduction

- In collisions at high energies and moderate virtualities, the hadron becomes a dense system filled, mainly, by gluons.

- If gluon density is very large, is expected that gluon recombination effects must be important. - saturation

- Some evidences of saturation at HERA, RHIC and LHC.
  - Although this, the saturation is still an open question.

Photon-induced processes

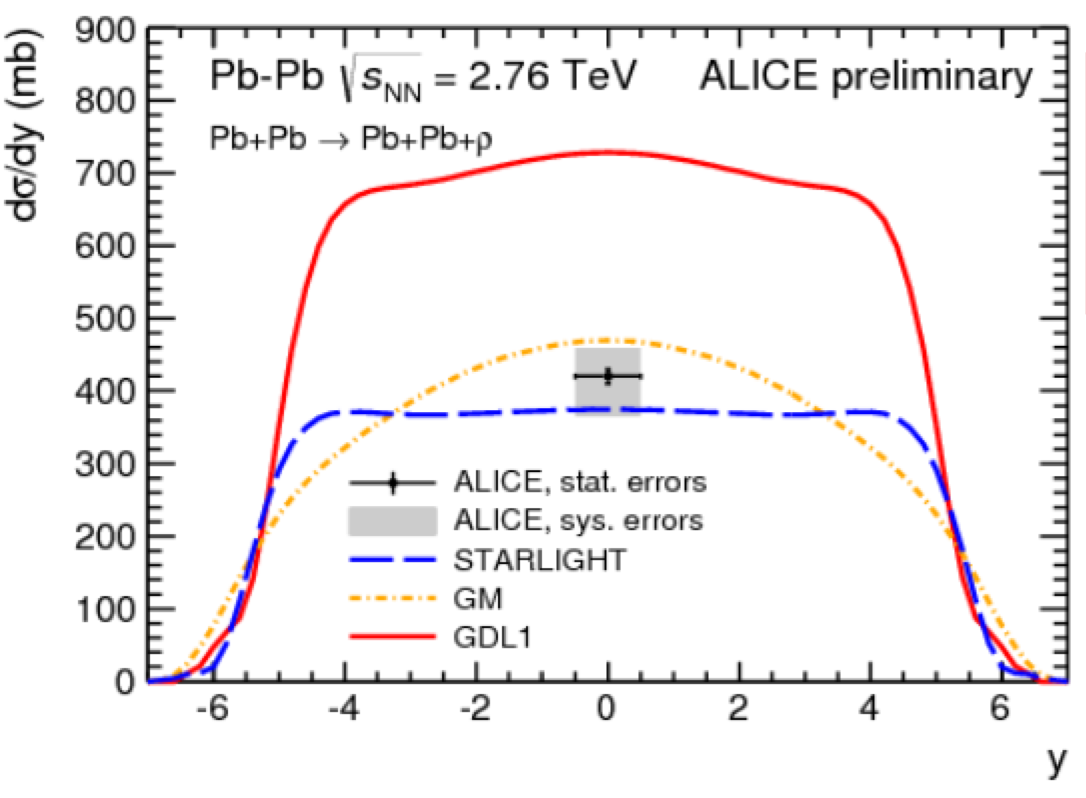
- Future EIC – study of photon-hadron interaction through DIS and DDIS in larger energies compared to the HERA.
- Alternative for the study of photon-hadron interactions – LHC as a photon collider in ultra-peripheral hadronic collisions (UPCs) - exclusive vector meson photoproduction
  - First experimental studies - RHIC for ρ production in AuAu collisions.
  - LHC – larger energies compared with RHIC.

Photon-induced processes

- What has been done about this subject?

Photon-induced processes

- What has been done about this subject?
- LHC data about diffractive vector meson production in pp, pA and AA ultra-peripheral collisions.

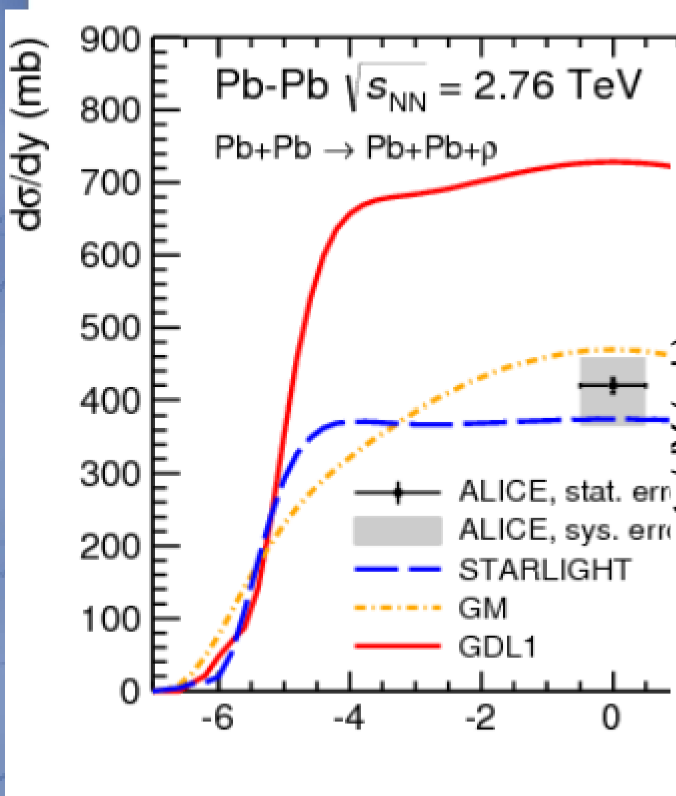


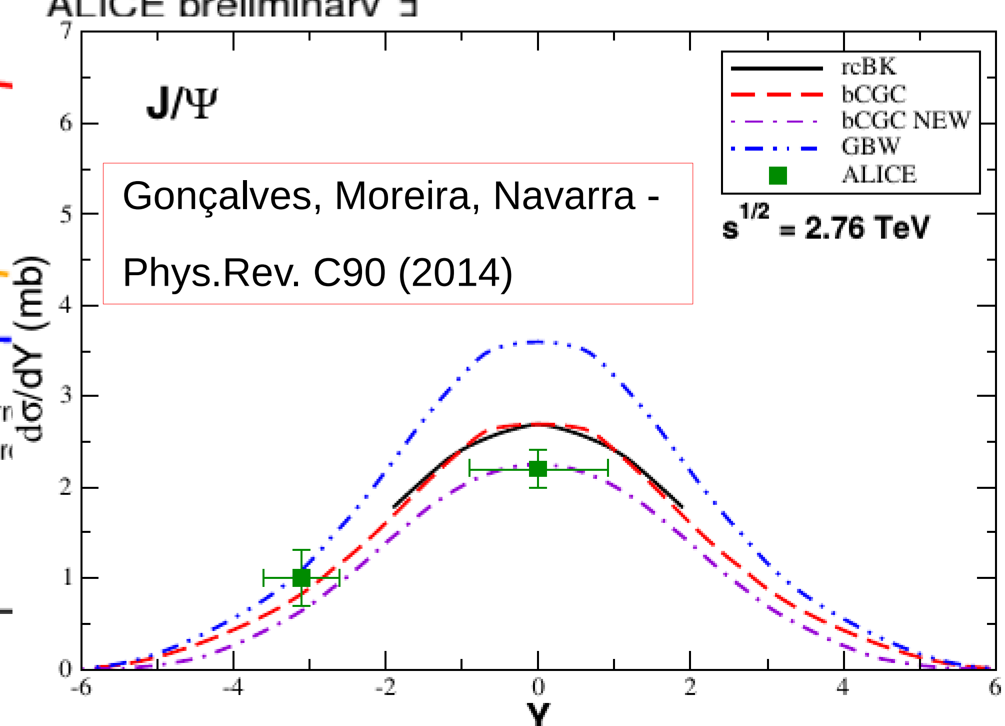
Review with graphics, model references and detailed discussion:

J.Phys. G43 (2016)

Photon-induced processes

- What has been done about this subject?
- LHC data about diffractive vector meson production in pp, pA and AA ultra-peripheral collisions.





Photon-induced processes

- The data shows large cross sections for a single vector meson production in a single γ h scattering mechanism (SSM).
  - Non negligible probability for the double vector meson production due to the double γh scattering mechanism (DSM).

Double Scattering Mechanism

- Spencer Klein and Joakim Nystrand - Phys.Rev. C 60 (1999).
  - Formalism of DSM for total cross sections.
  - Total cross sections for vector meson production.

- Mariola Kłusek-Gawenda and Antoni Szczurek - Phys.Rev. C89 (2014).
  - Detailed analysis for double ρ production.
  - Differential distributions.
  - Total cross sections.
  - Smearing of ρ mass.

- Both – photon-nucleus interaction based on VDM.

Double Scattering Mechanism

- V.P. Goncalves, B.D. Moreira, F.S. Navarra - Eur.Phys.J. C 76 (2016).
  - $\rho\rho$, $J/\psi J/\psi$ and $\rho J/\psi$ production in pp, pA and AA UPCs.
  - Rapidity distributions.
  - Behavior of total cross section with CM collision energy.
  - Color dipole for the interaction photon-nucleus (saturation).

Single Scattering Mechanism for Exclusive Vector Meson Production

Ultra-Peripheral Collisions

- We are interested in hadronic collisions in which the impact parameter is larger than the sum of the two hadrons in the initial state (UPC).
- In UPCs at high energies, the nucleus acts as a source of almost real photons (small virtualities).
  - The cross section of the nucleus-nucleus collisions can be written in the factorized form.

$$\frac{d\sigma}{d^2b\,dy} = \omega_1 N_{A_1}(\omega_1, b)\, \sigma_{\gamma A_2 \to V A_2}(\omega_1) + (1 \Longleftrightarrow 2)$$

Ultra-Peripheral Collisions

For the production of a single vector meson (SSM), we have

$$\frac{d\sigma}{d^2b\,dy} = \omega_1 N_{A_1}(\omega_1, b)\, \sigma_{\gamma A_2 \to V A_2}(\omega_1) + (1 \Longleftrightarrow 2)$$

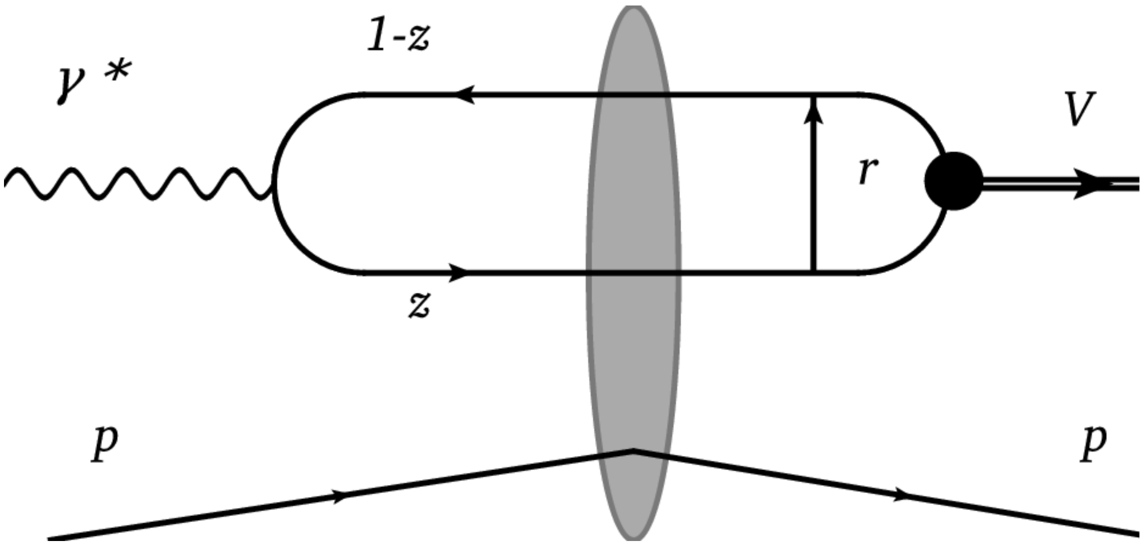
$$N_A(\omega, b) = \frac{Z^2 \alpha_{EM}}{\pi^2} \omega K_1^2 \left(\frac{\omega b}{\gamma} \right)$$

$$\omega_{1,2} = \frac{M_V}{2} e^{\pm y}$$

$$\sigma_{\gamma A \to V A} \quad ?$$

Color Dipole Formalism

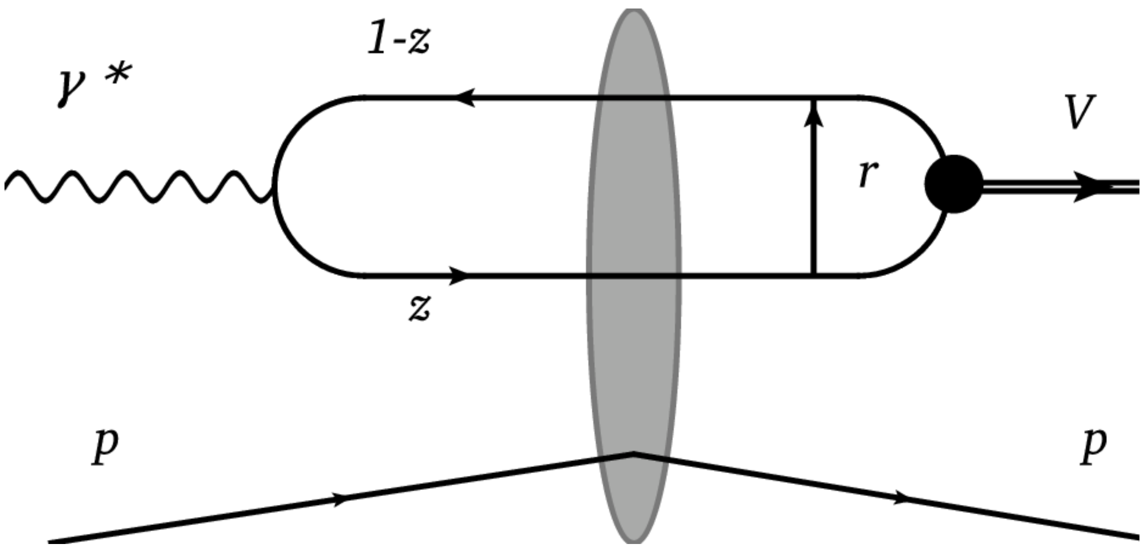
- Photon-hadron collision on a frame where most of the energy is carried by the hadron, while the photon only has enough energy to fluctuate in a color dipole.



Color Dipole Formalism

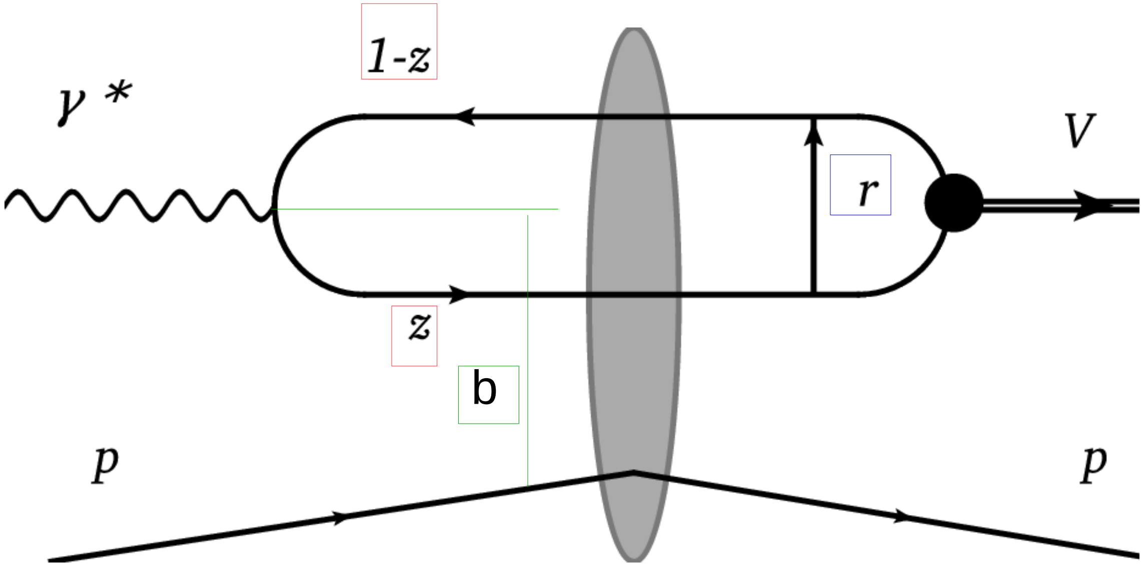
For a coherent production of a vector meson

$$\sigma\,(\gamma A \to VA) = \int d^2\mathbf{b} \left[\int d^2\mathbf{r} \int dz\, (\Psi_V^* \Psi)\, \mathcal{N}_A(x, \mathbf{r}, \mathbf{b}) \right]^2$$



Color Dipole Formalism

$$\sigma\,(\gamma A \rightarrow V A) = \int d^2\mathbf{b}\left[\int d^2\mathbf{r}\int dz\,(\Psi_V^*\Psi)\,\mathcal{N}_A(x,\mathbf{r},\mathbf{b})\right]^2$$



Color Dipole Formalism

$$\sigma\left(\gamma A \to VA\right) = \int d^2\mathbf{b} \left[\int d^2\mathbf{r} \int dz \left(\Psi_V^* \Psi\right) \mathcal{N}_A(x, \mathbf{r}, \mathbf{b}) \right]^2$$

Overlap

Amplitude
dipole-nucleus

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

Armesto, N. - Eur. Phys. J. C26 (2002).

dipole - nucleon

Model to σ_{dip}

- bCGC: Kowalski, Motyka and Watt – Phys. Rev. D **74** (2006)

$$\mathcal{N}(x,\mathbf{r},\mathbf{b}) = \begin{cases} \mathcal{N}_0\left(\frac{rQ_s}{2}\right)^{2[\gamma_s+(1/(\kappa\lambda Y))\ln(2/(rQ_s))]} & , rQ_s \le 2 \\ 1-\exp\left[-A\ln^2(BrQ_s)\right] & , rQ_s > 2 \end{cases}$$

$$\sigma_{dip} = 2\int \mathrm{d}^2 b\mathcal{N}(x,r,b)$$

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

- Update of the parameters: Rezaeian e Schmidt – Phys. Rev. D **88** (2013)

Model to ψ_V

- The overlap between the wave functions of the photon and the vector meson is given by

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

where

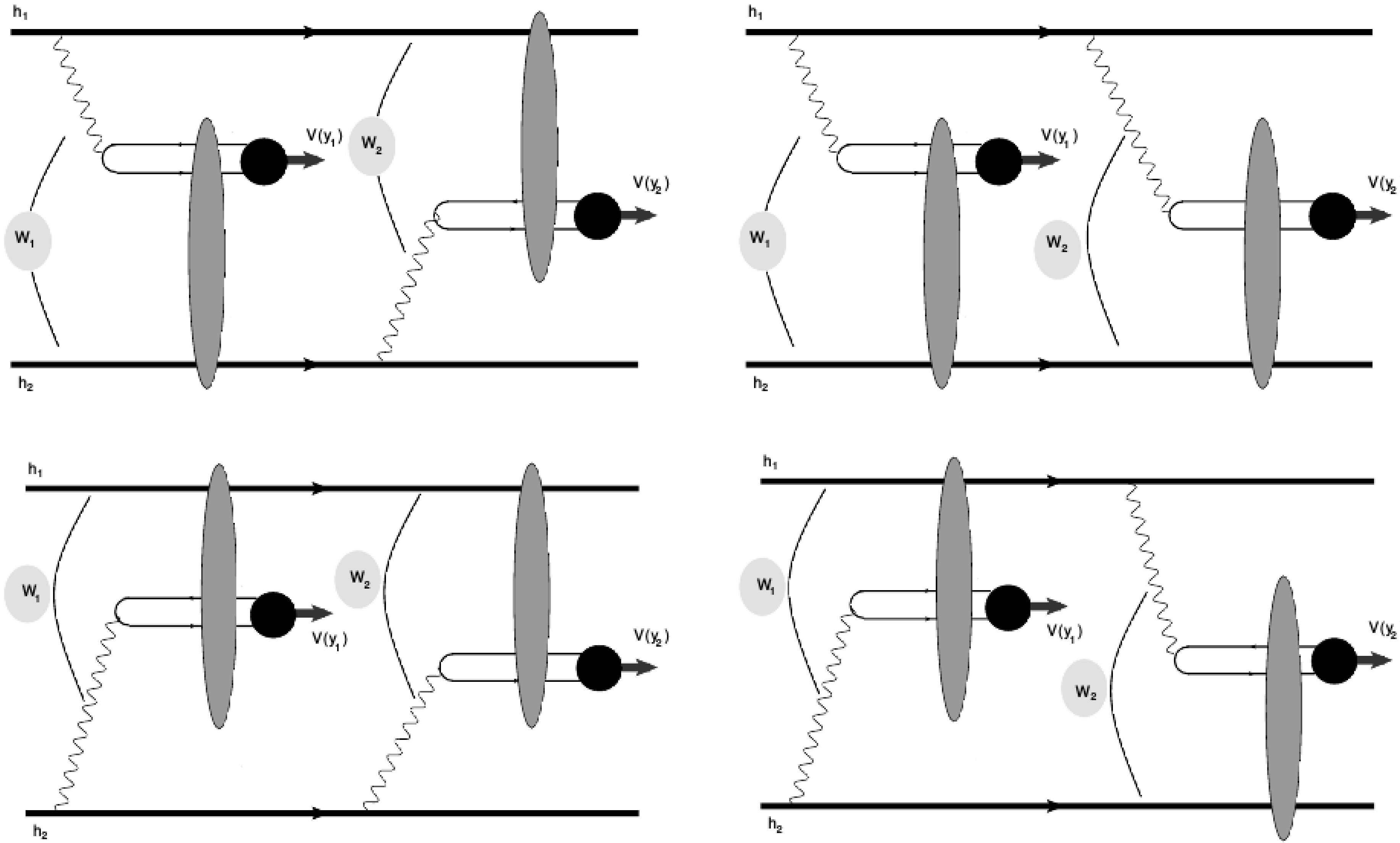
$$\varepsilon^2 = z(1-z)Q^2 + m_f^2 \;\; \mathrm{e} \;\; \nabla_r^2 \equiv (1/r)\partial_r + \partial_r^2$$

- Gaus – LC – Phys. Rev. D **74**, 074016 (2006)

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

Double Scattering Mechanism

Double vector meson production



Double vector meson production

- We have considered the following expression

$$\frac{d\sigma_{A_1 A_2 \to A_1 V_1 V_2 A_2}}{dy_1 dy_2} = C \int_{b_{min}} \frac{d\sigma_{A_1 A_2 \to A_1 V_1 A_2}}{d^2 b dy_1} \times \frac{d\sigma_{A_1 A_2 \to A_1 V_2 A_2}}{d^2 b dy_2} d^2 b$$

$$b_{min} = R_1 + R_2$$

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SSM   SSM

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$$\frac{1}{2}, \text{ if } V_1 = V_2$$

$$1, \text{ if } V_1 \neq V_2$$

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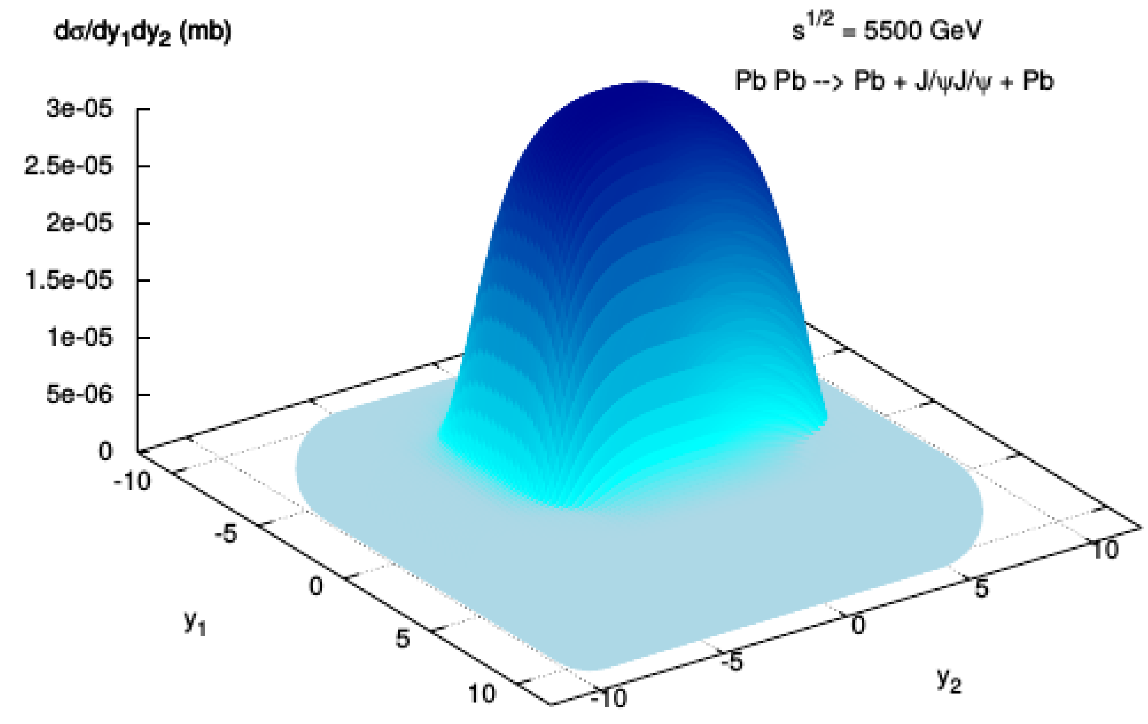
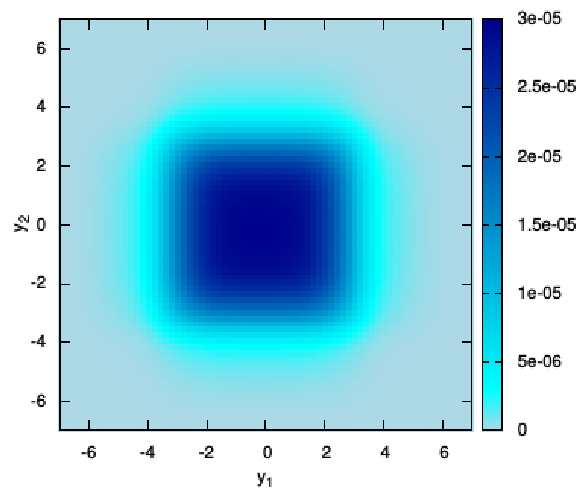
$$b_{min} = R_1 + R_2$$

Only UPCs !

Results

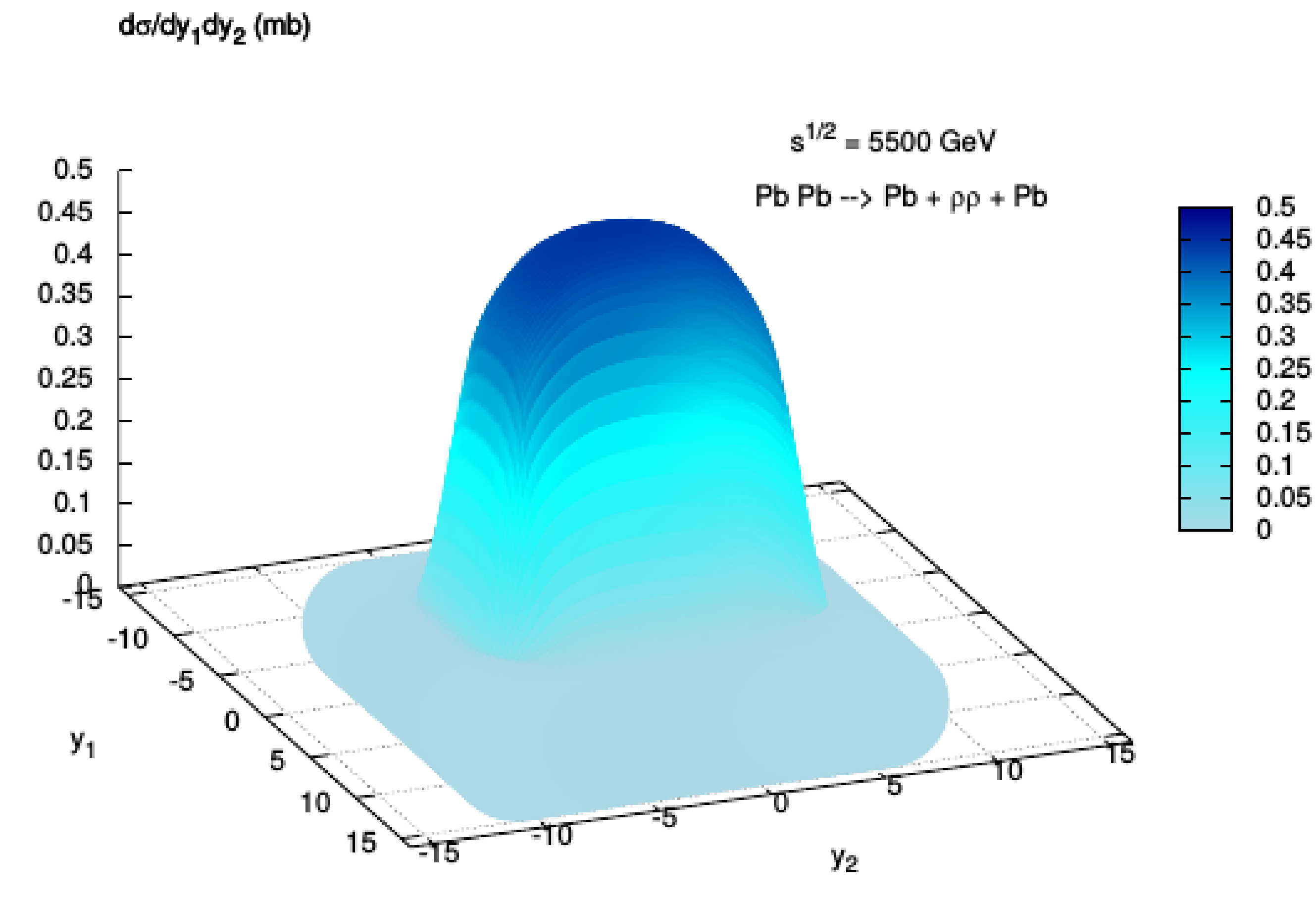


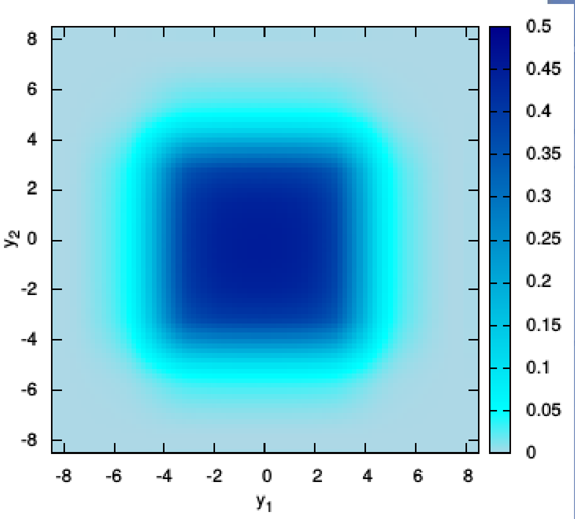
dσ/dy1dy2 (mb)
s^1/2 = 5500 GeV
Pb Pb --> Pb + J/ψJ/ψ + Pb
3e-05
2.5e-05
2e-05
1.5e-05
1e-05
5e-06
0
-10
-5
0
5
10
y1
y2



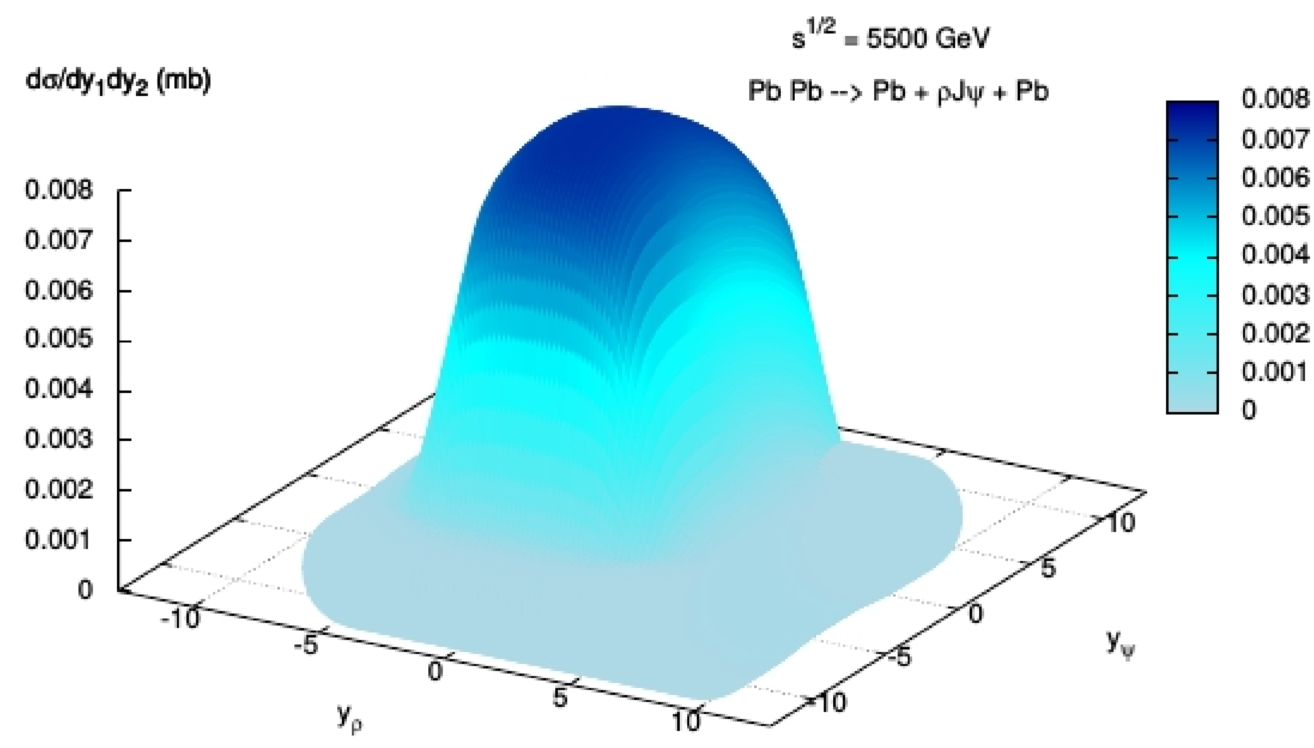
3e-05
2.5e-05
2e-05
1.5e-05
1e-05
5e-06
0
6
4
2
0
-2
-4
-6
y2
y1

Results

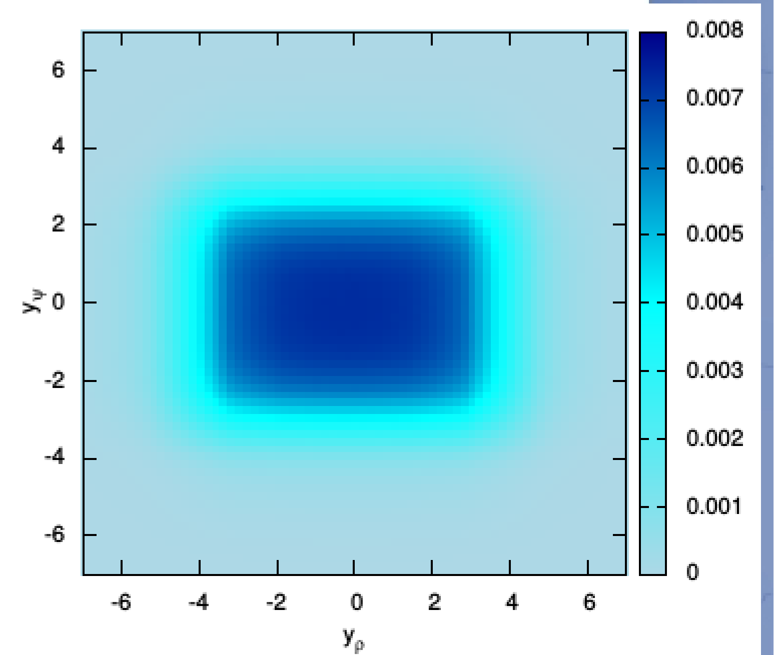




Results



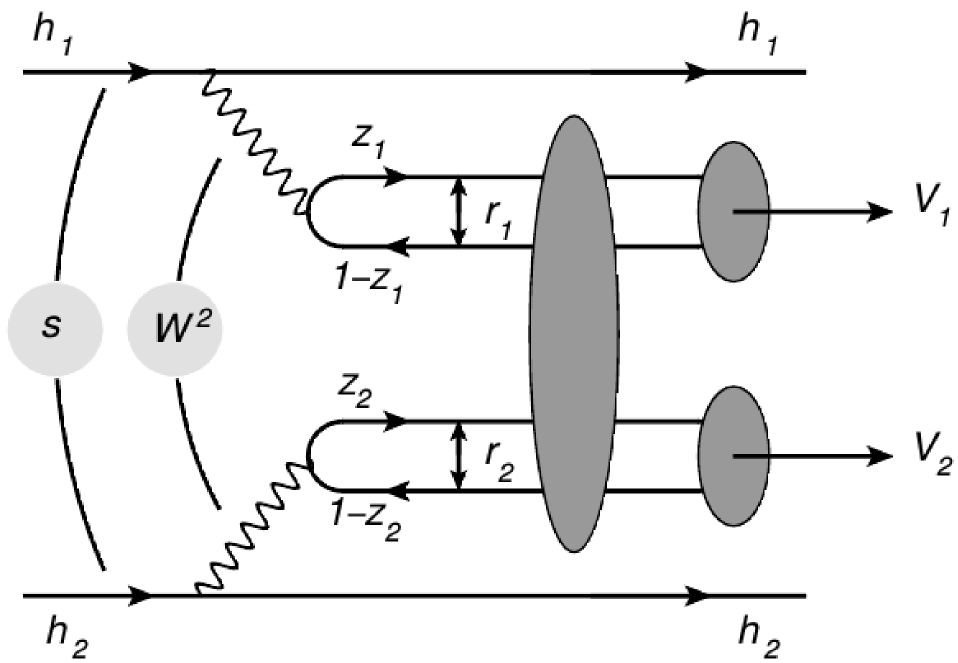
$s^{1/2}$ = 5500 GeV
Pb Pb --> Pb + ρJψ + Pb
dσ/dy₁dy₂ (mb)
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-10
-5
0
5
10
y_ρ
y_ψ



6
4
2
0
-2
-4
-6
y_ψ
y_ρ
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0

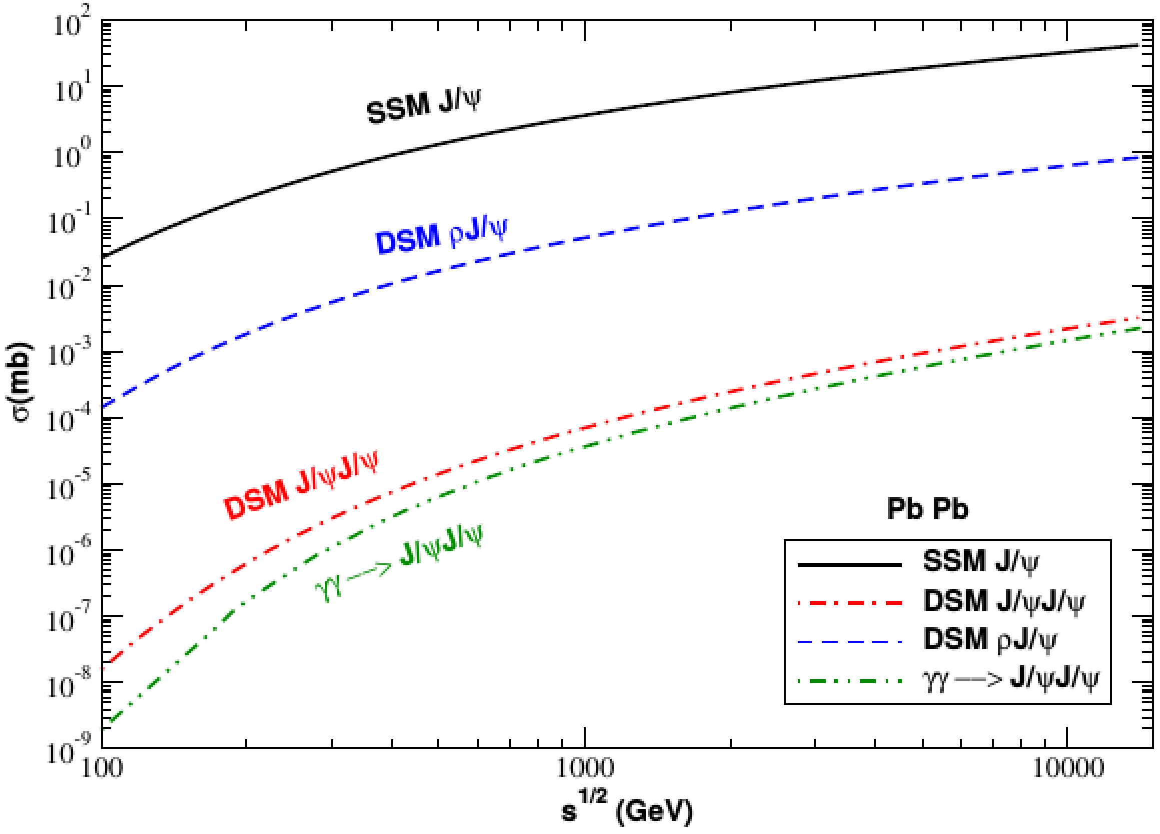
Double vector meson production

- Comparison: Double vector meson production in UPC due to $\gamma\gamma$ interactions.

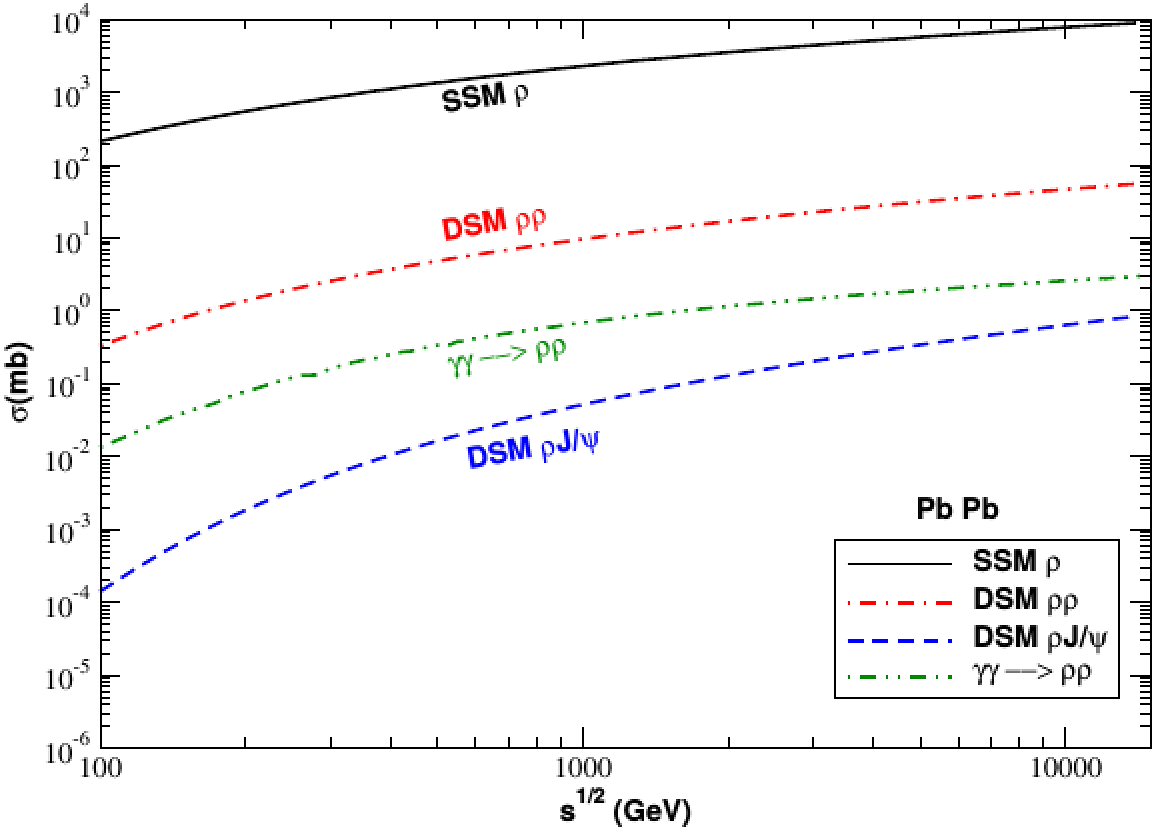


Gonçalves, V.P., Moreira, B.D. and Navarra, F.S. – Eur.Phys.J. C 76 (2016).

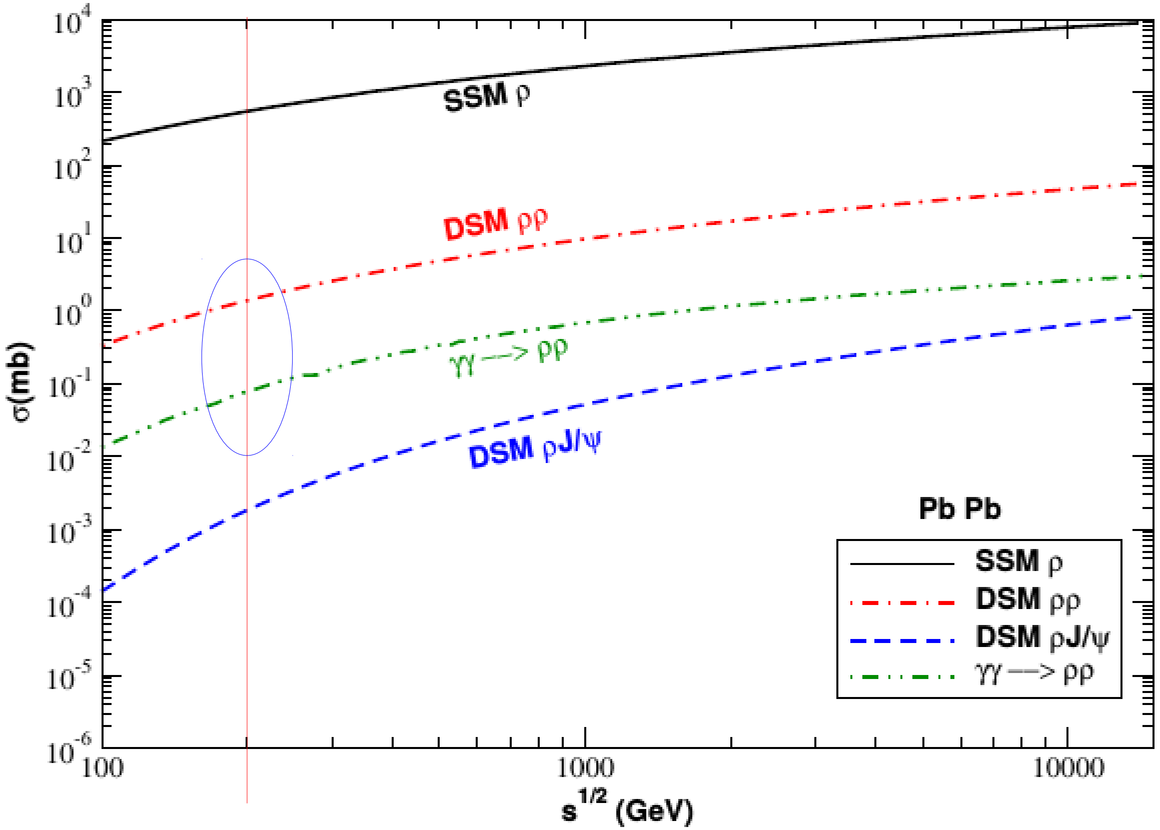
Double vector meson production



Double vector meson production



Double vector meson production



RHIC energy

In agreement with: Kłusek-Gawenda and Szczurek - Phys.Rev. C89 (2014).

Double vector meson production

LHC energies

Final state	$PbPb$ $\sqrt{s} = 2.76\,\mathrm{TeV}$	$PbPb$ $\sqrt{s} = 5.5\,\mathrm{TeV}$
$J/\Psi J/\Psi$	402.301 nb	1054.951 nb
$\rho\rho$	21.150 mb	29.421 mb
$\rho J/\Psi$	0.18 mb	0.35 mb

Double vector meson production

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$\rho\rho$	21.150 mb	29.421 mb
$\rho J/\Psi$	0.18 mb	0.35 mb

SSM:

J/ψ	11.0 mb	20.3 mb
ρ	4.43 b	6.2 b

Double vector meson production

Final state		LHCb $2 < y_{1,2} < 4.5$	ATLAS/CMS $-2 < y_{1,2} < 2$	ALICE $-1 < y_{1,2} < 1$
$J/\Psi J/\Psi$	$PbPb$ ($\sqrt{s} = 2.76\,\mathrm{TeV}$)	5.51 nb	234.94 nb	69.91 nb
	$PbPb$ ($\sqrt{s} = 5.5\,\mathrm{TeV}$)	30.85 nb	446.11 nb	118.03 nb
$\rho\rho$	$PbPb$ ($\sqrt{s} = 2.76\,\mathrm{TeV}$)	0.93 mb	6.08 mb	1.58 mb
	$PbPb$ ($\sqrt{s} = 5.5\,\mathrm{TeV}$)	1.50 mb	7.06 mb	1.79 mb
$\rho J/\Psi$	$PbPb$ ($\sqrt{s} = 2.76\,\mathrm{TeV}$)	4.48 μb	75.17 μb	20.94 μb
	$PbPb$ ($\sqrt{s} = 5.5\,\mathrm{TeV}$)	13.42 μb	112.00 μb	29.06 μb

Conclusions

- We have estimated the double production of vector mesons in photon-nucleus interactions.
- This kind of process can be used to increase our knowledge about the diffractive photoproduction of vector mesons and the QCD dynamics at high energies.
- Our results show that the double production of vector mesons are relevant at kinematic range of LHC.
  - Experimental study is feasible.
- The experimental study of this process can be important to fix the QCD dynamics and the DSM.

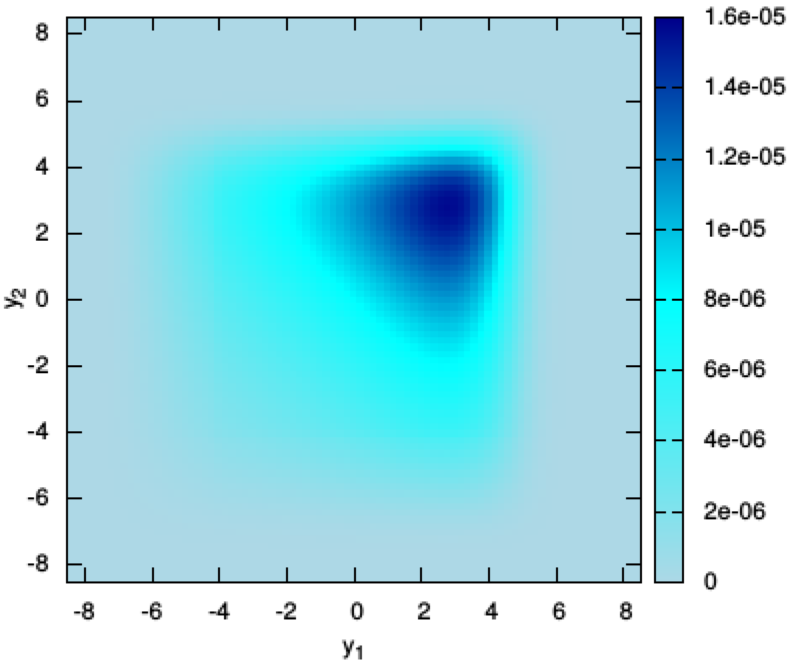
Thank You!

Extras

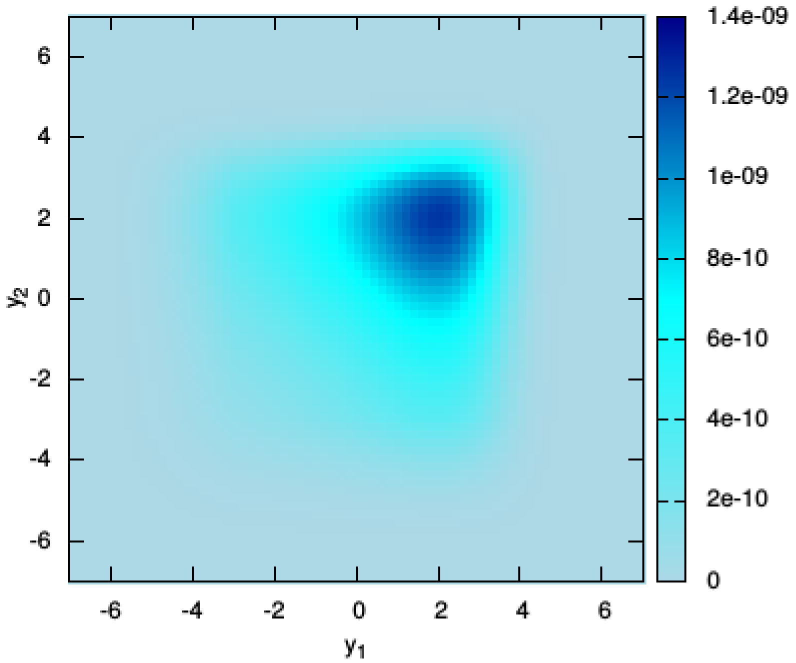
More results

- pPb → p + VV + Pb (5 TeV)

ρρ



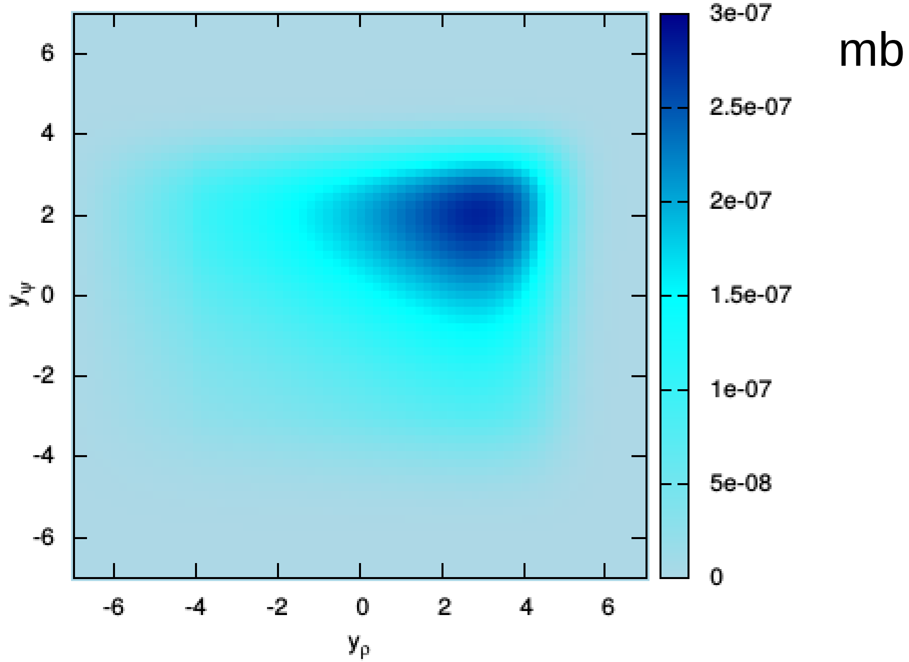
J/ψJ/ψ



Unit of the rapidity distribution: mb

More results

- pPb → p + VV + Pb (5 TeV) – mixed final states.



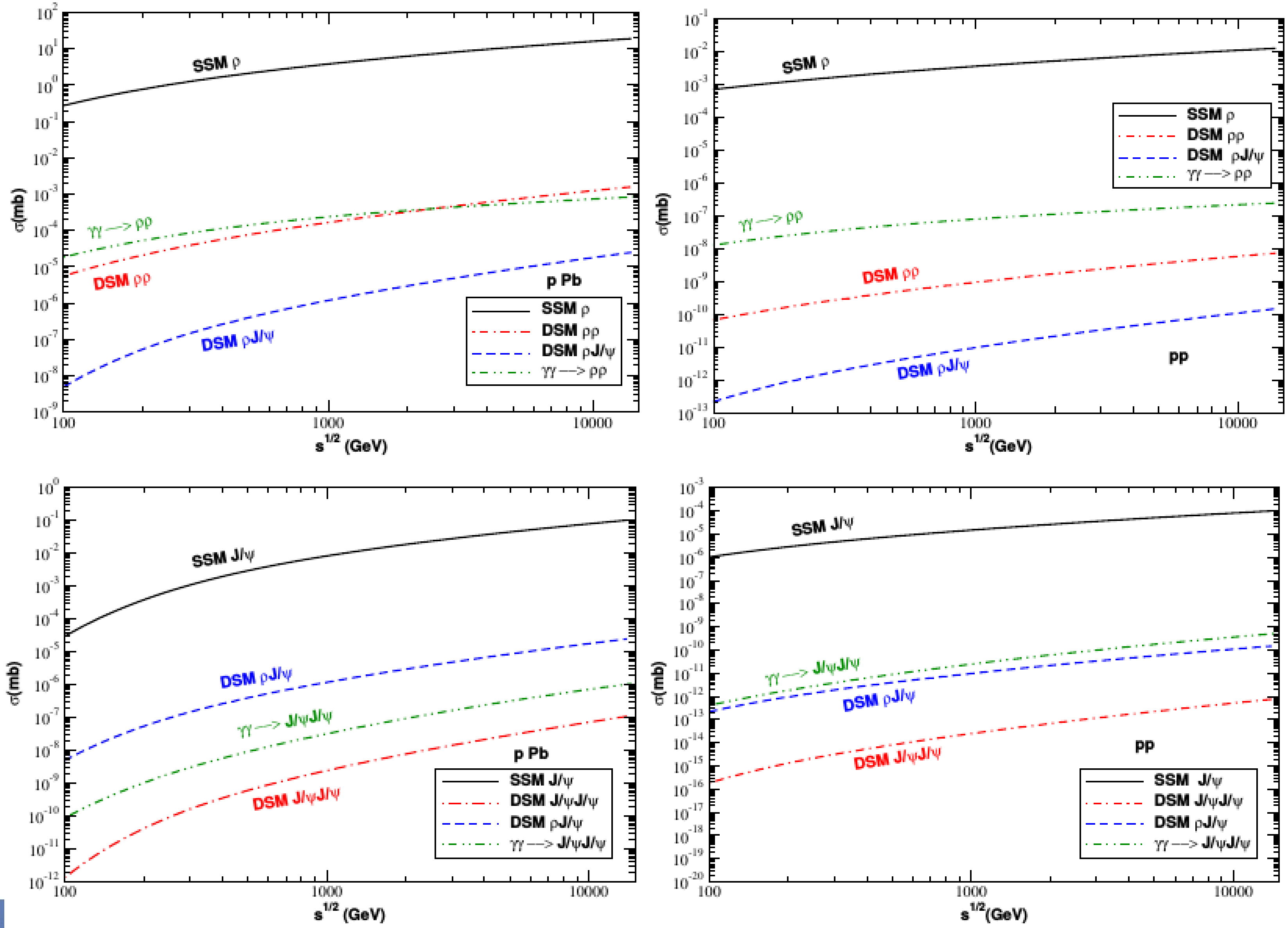
More results

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
$J/\Psi J/\Psi$	DSM	402.301 nb	1054.951 nb	28.473 pb	3.223×10^{-4} pb	7.256×10^{-4} pb
	$\gamma\gamma$	235.565 nb	658.589 nb	310.194 pb	0.2412 pb	0.4793 pb
$\rho\rho$	DSM	21.150 mb	29.421 mb	702.595 nb	4.354 pb	7.083 pb
	$\gamma\gamma$	1.389 mb	1.973 mb	536.432 nb	182.442 pb	237.006 pb
$\rho J/\Psi$	DSM	0.18 mb	0.35 mb	8.929 nb	7.469×10^{-2} pb	14.288×10^{-2} pb

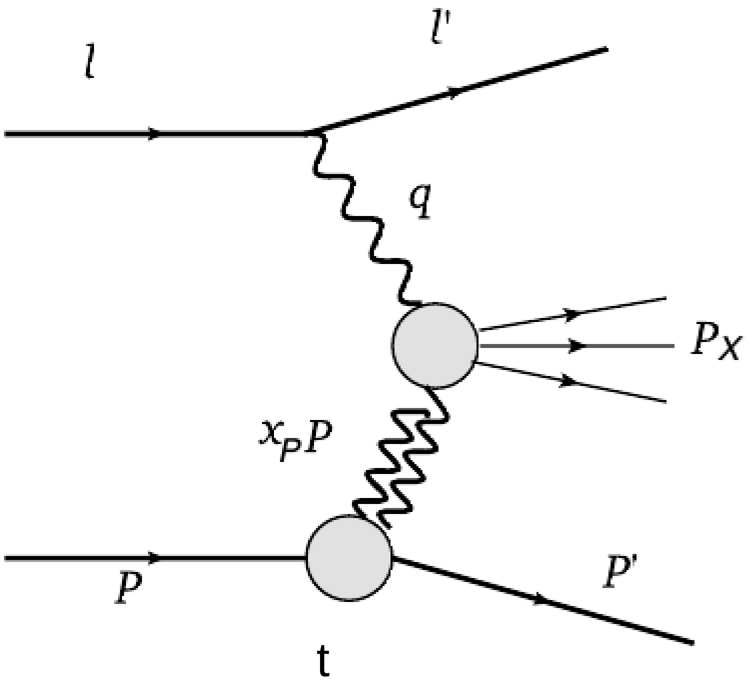
More results

Final state		LHCb $2 < y_{1,2} < 4.5$	ATLAS/CMS $-2 < y_{1,2} < 2$	ALICE1 $-1 < y_{1,2} < 1$
$J/\Psi J/\Psi$	$PbPb$ ($\sqrt{s} = 2.76$ TeV)	5.51 nb	234.94 nb	69.91 nb
	$PbPb$ ($\sqrt{s} = 5.5$ TeV)	30.85 nb	446.11 nb	118.03 nb
	pPb ($\sqrt{s} = 5$ TeV)	3.25 pb	8.87 pb	2.16 pb
$\rho\rho$	$PbPb$ ($\sqrt{s} = 2.76$ TeV)	0.93 mb	6.08 mb	1.58 mb
	$PbPb$ ($\sqrt{s} = 5.5$ TeV)	1.50 mb	7.06 mb	1.79 mb
	pPb ($\sqrt{s} = 5$ TeV)	84.09 nb	122.03 nb	30.11 nb
$\rho J/\Psi$	$PbPb$ ($\sqrt{s} = 2.76$ TeV)	4.48 μb	75.17 μb	20.94 μb
	$PbPb$ ($\sqrt{s} = 5.5$ TeV)	13.42 μb	112.00 μb	29.06 μb
	pPb ($\sqrt{s} = 5$ TeV)	1.02 nb	2.08 nb	0.51 nb

More results



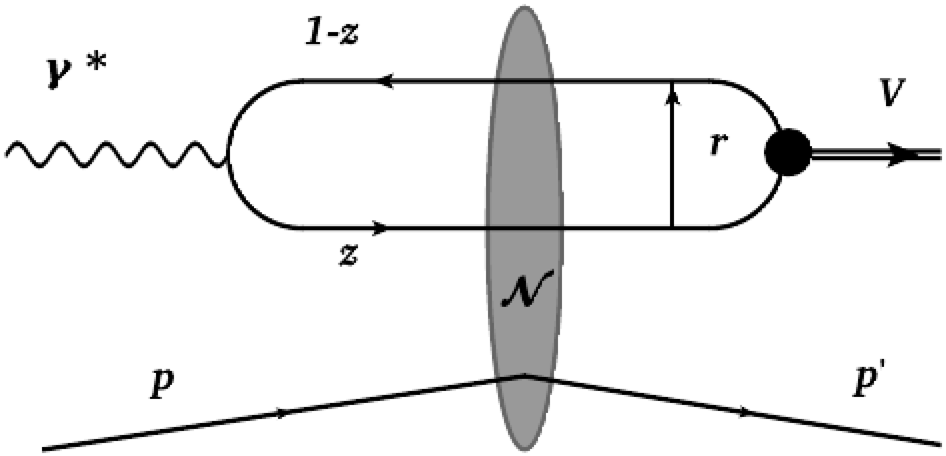
Dipole and DDIS

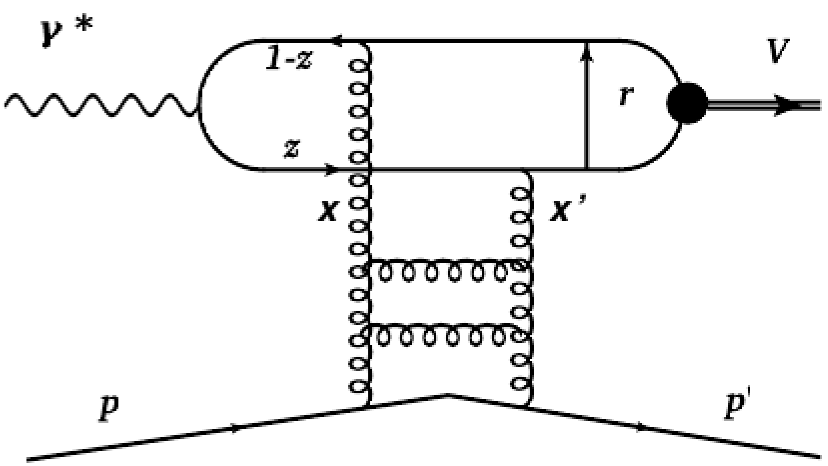


$$x_P = \frac{Q^2 + M_V^2}{W^2 + Q^2}$$

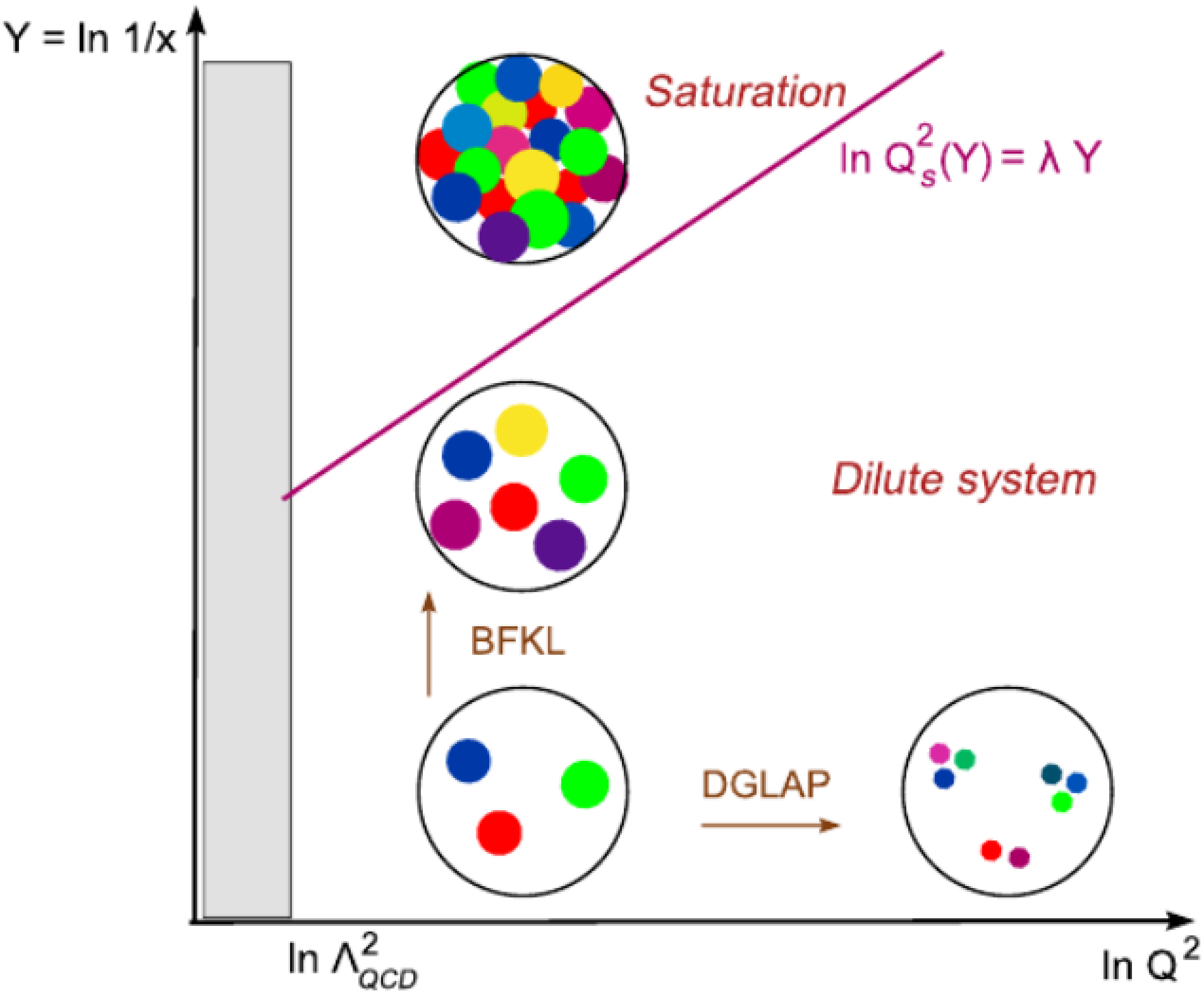
$$t = -(P' - P)^2$$

Dipole and DDIS





Saturation



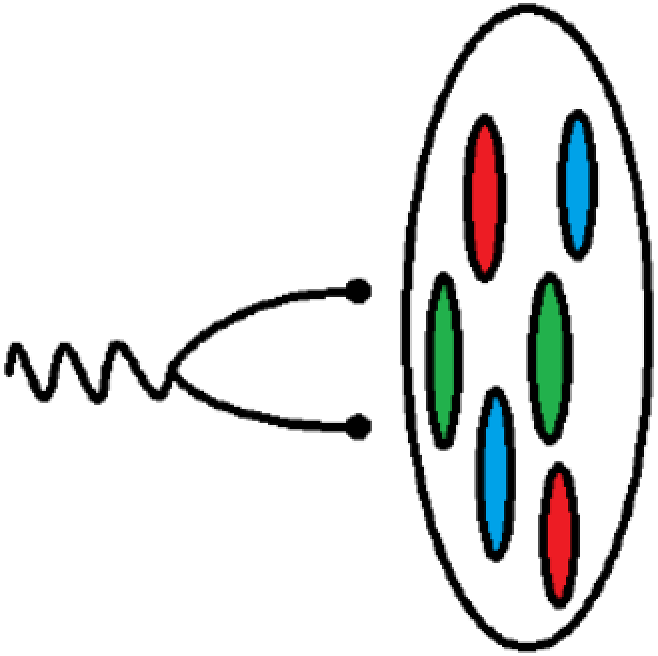
$$Q_s^2 \propto \left(\frac{1}{x}\right)^{\lambda}$$

$$x \propto \frac{1}{W^2}$$

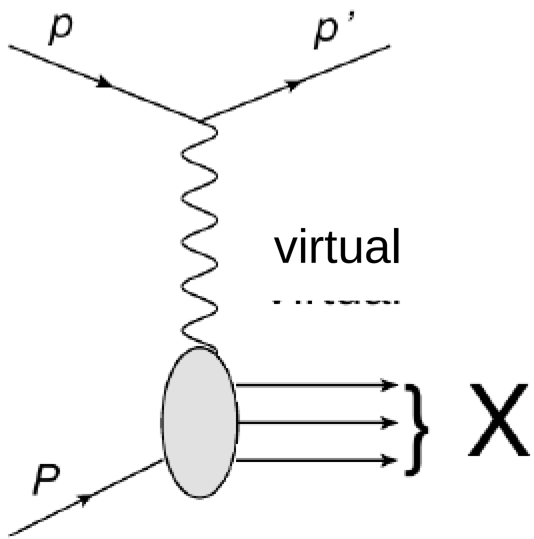
Saturation

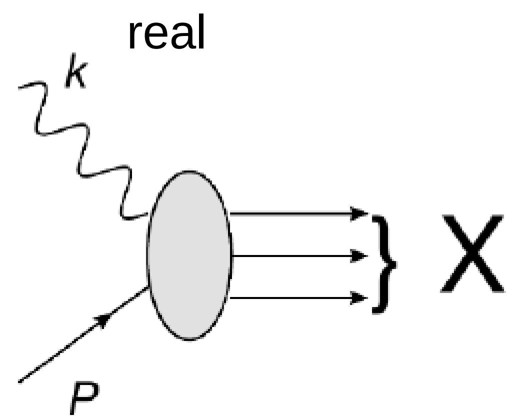
- The dipole can “see” partons with size to the order of its transverse separation.

- Non linear regime – $r > 1/Q_s$
- Linear regime – $r < 1/Q_s$



EPA





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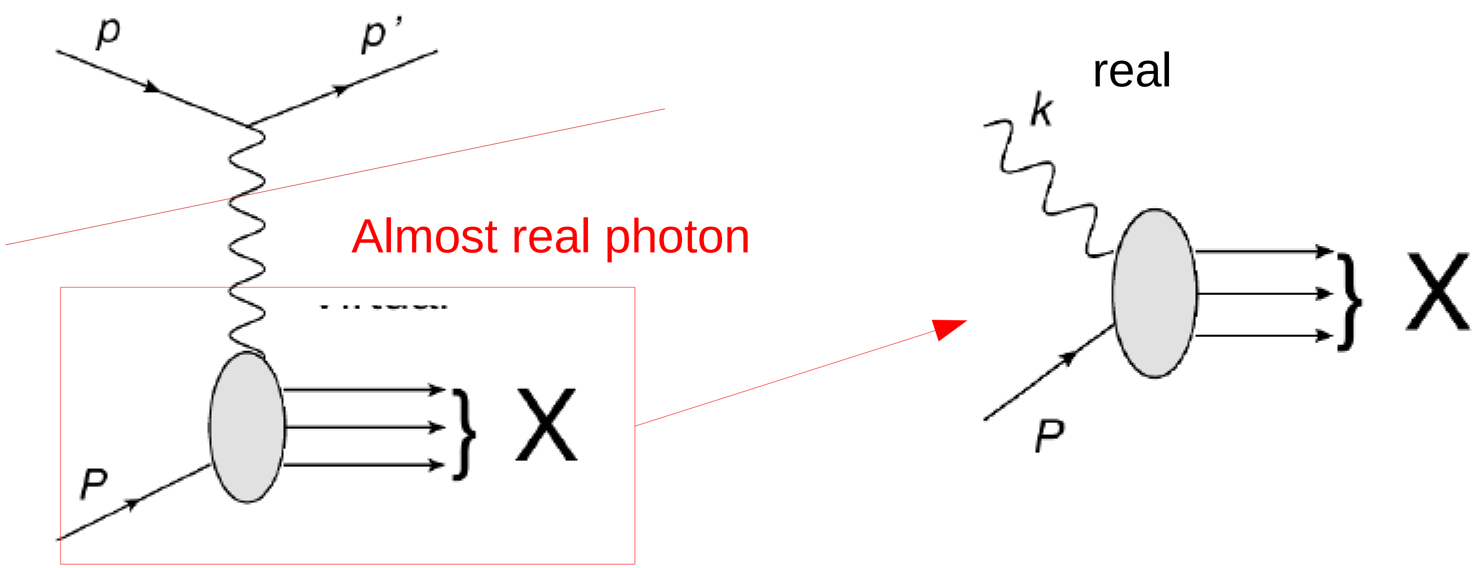

Almost real photons = small virtualities

1 - high energies
2 - large impact parameters (> R1 + R2)