

Exclusive Vector Meson Photoproduction: Recent results and Prospects

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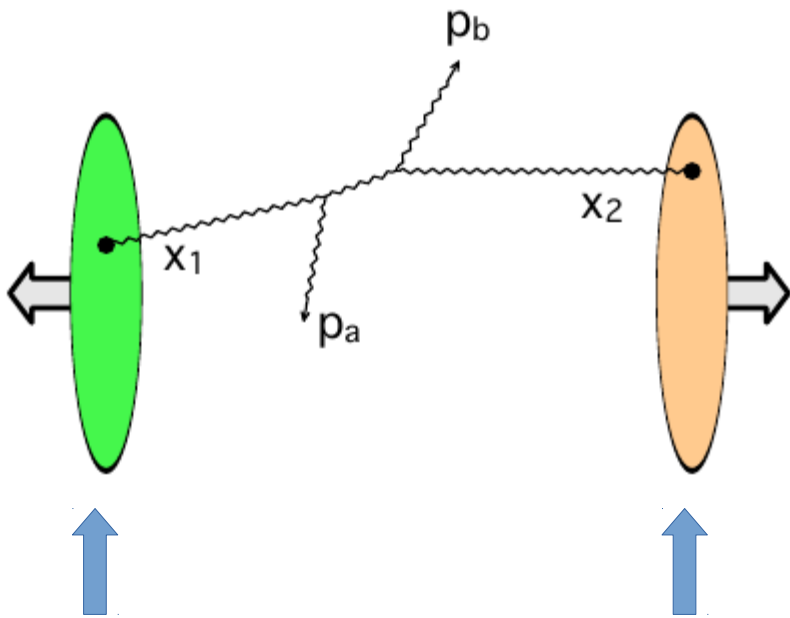
Outline

- ✓ Motivation for the study of photon - induced interactions at the LHC
- ✓ Vector meson photoproduction in hadronic colliders: Basic Concepts
- ✓ Recent results
- ✓ Prospects
- ✓ Summary

Motivation for the study of
Photon - induced
interactions at the LHC

Central Hadronic Collisions

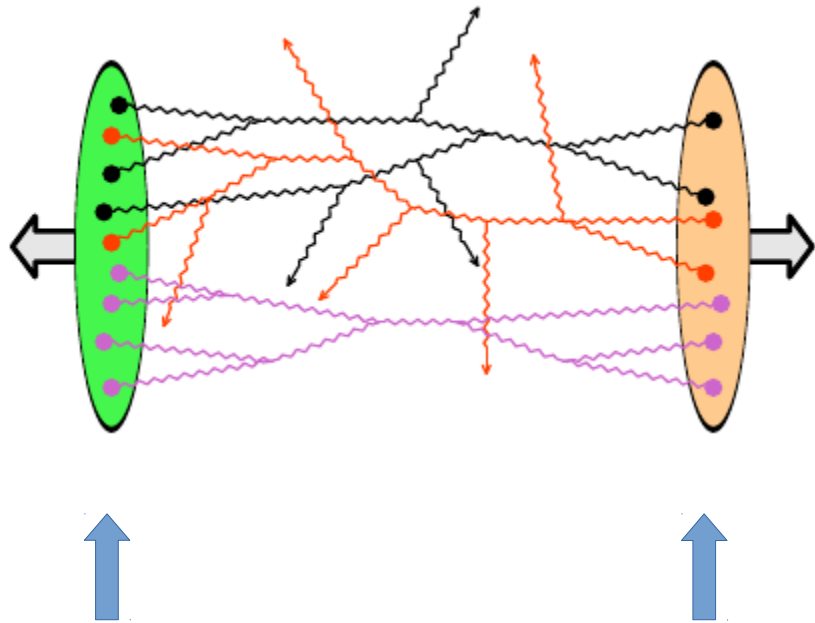
* Small Energy Regime (pre-LHC):



Low partonic density in the incident particles

Central Hadronic Collisions

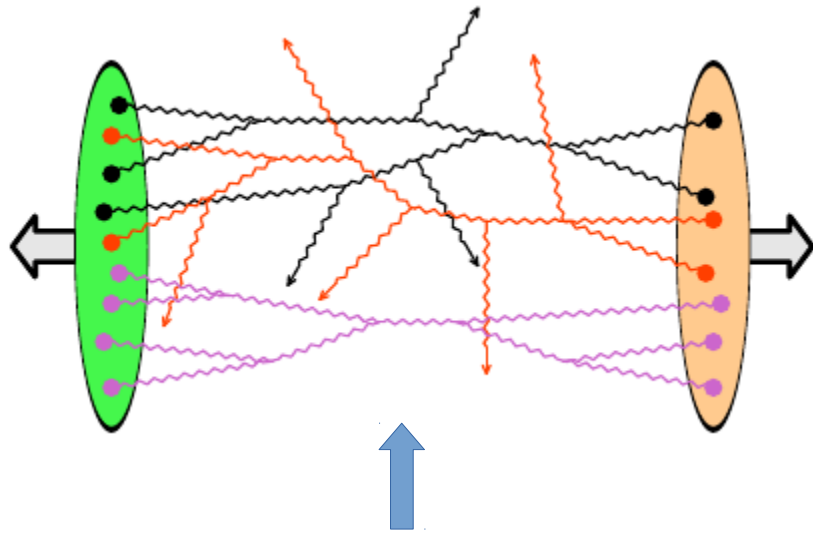
* High Energy Regime (LHC):



High partonic density in the incident particles!

Central Hadronic Collisions

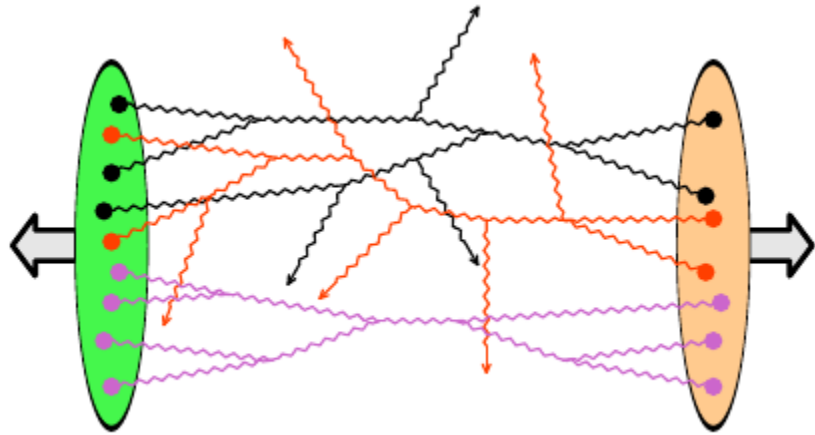
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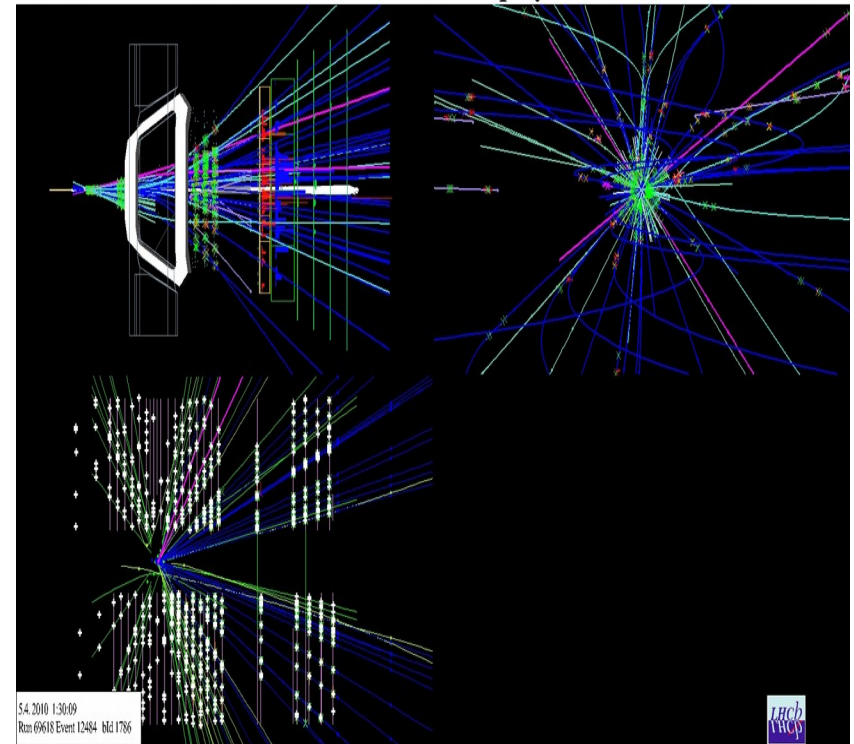
Multiple parton interactions

Central Hadronic Collisions

* High Energy Regime (LHC):

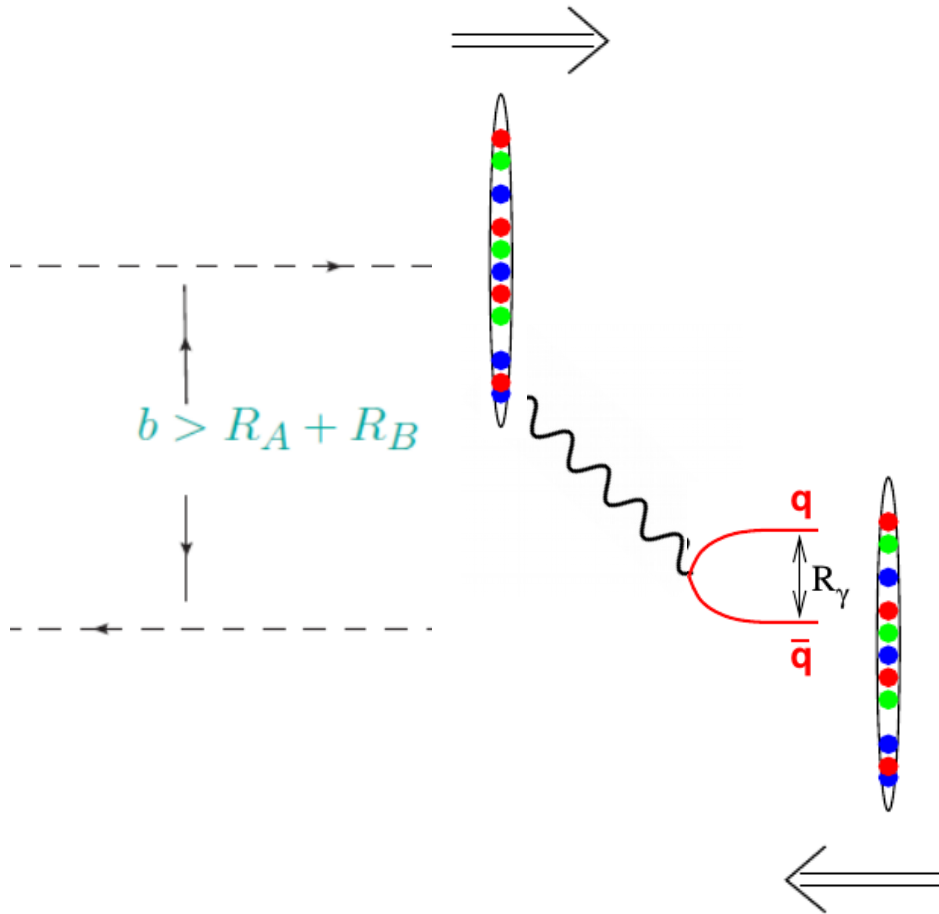


LHCb Event Display



➡ Events characterized by many tracks and the production of particles with high p_T .

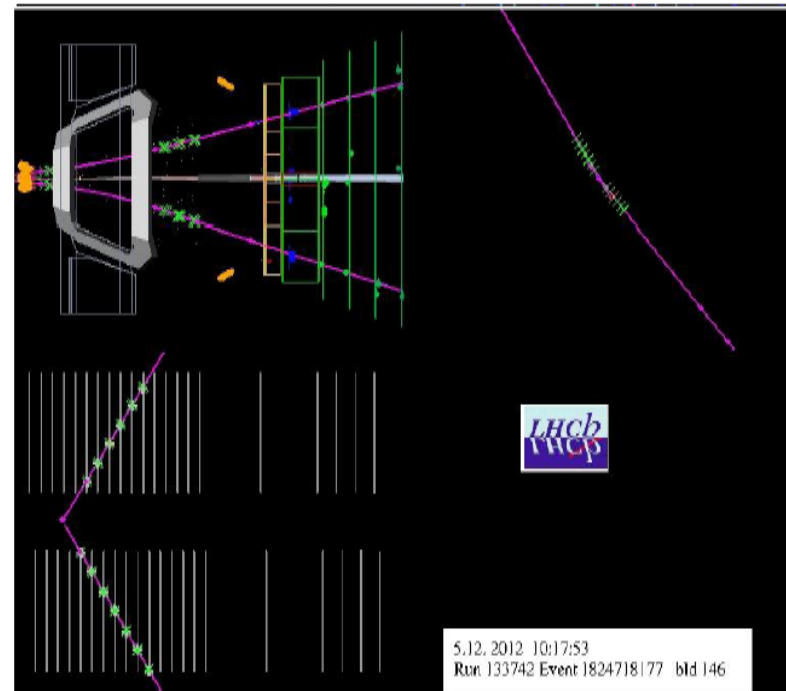
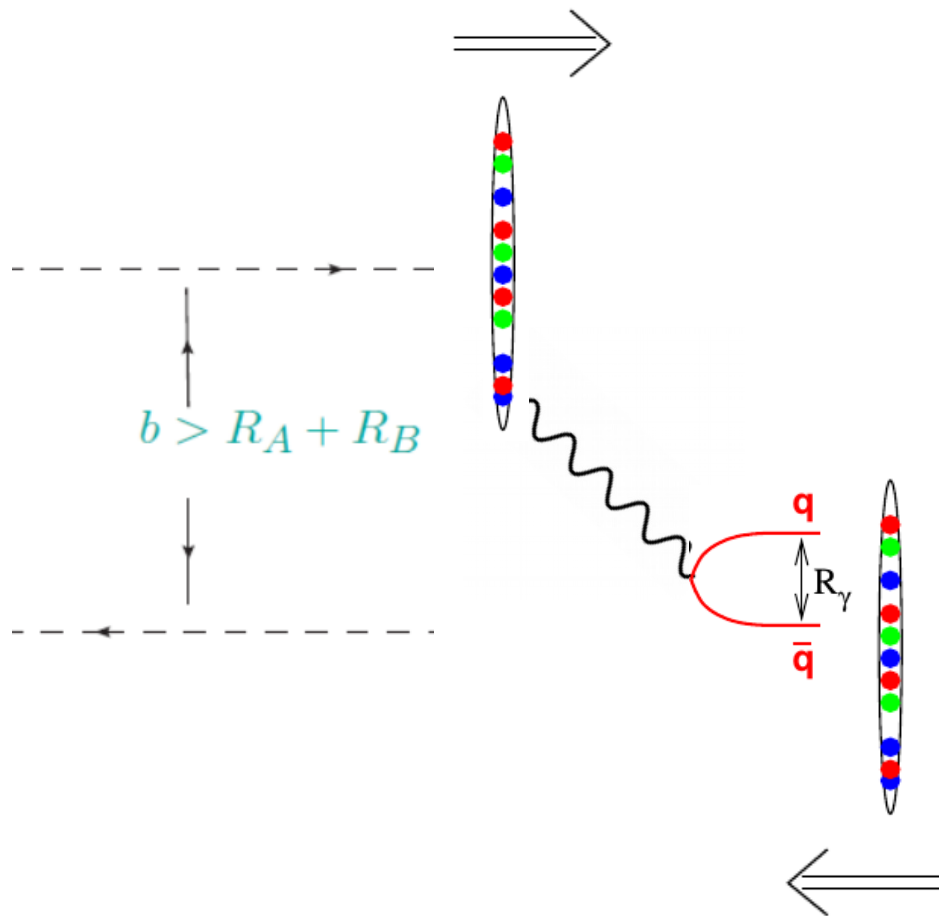
Ultraperipheral Hadronic Collisions: Photon - induced interactions



- Dominated by photon - photon and photon - hadron interactions;

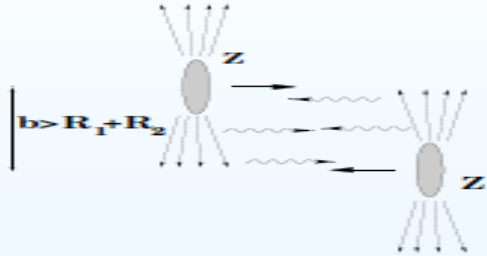
- Photon emission determined by QED (Photon flux $\propto Z^2$).

Ultrapерipheral Hadronic Collisions: Photon - induced interactions



Events characterized by few tracks and the production of particles with low p_T .

Ultraperipheral Hadronic Collisions: Photon - induced interactions



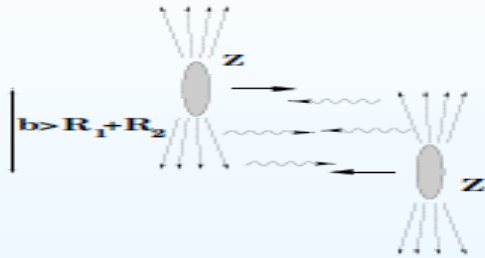
Center of mass energies

1. γh Processes: $\sigma(h_1 h_2 \rightarrow X) = n_h(\omega) \otimes \sigma^{\gamma h \rightarrow X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \rightarrow X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \rightarrow X}(W_{\gamma\gamma})$

LHC	<u>pp</u>	$W_{\gamma p} \lesssim 8390 \text{ GeV}$	$W_{\gamma\gamma} \lesssim 4504 \text{ GeV}$
LHC	<u>pPb(Ar)</u>	$W_{\gamma A} \lesssim 1500 (2130) \text{ GeV}$	$W_{\gamma\gamma} \lesssim 260 (480) \text{ GeV}$
LHC	<u>PbPb</u>	$W_{\gamma A} \lesssim 950 \text{ GeV}$	$W_{\gamma\gamma} \lesssim 160 \text{ GeV}$
HERA	ep	$W_{\gamma p} \lesssim 200 \text{ GeV}$	-

Photoproduction in hadronic collisions at the LHC probes the hadronic wave function in a unexplored regime of CM energies.

Ultraperipheral Hadronic Collisions: Photon - induced interactions



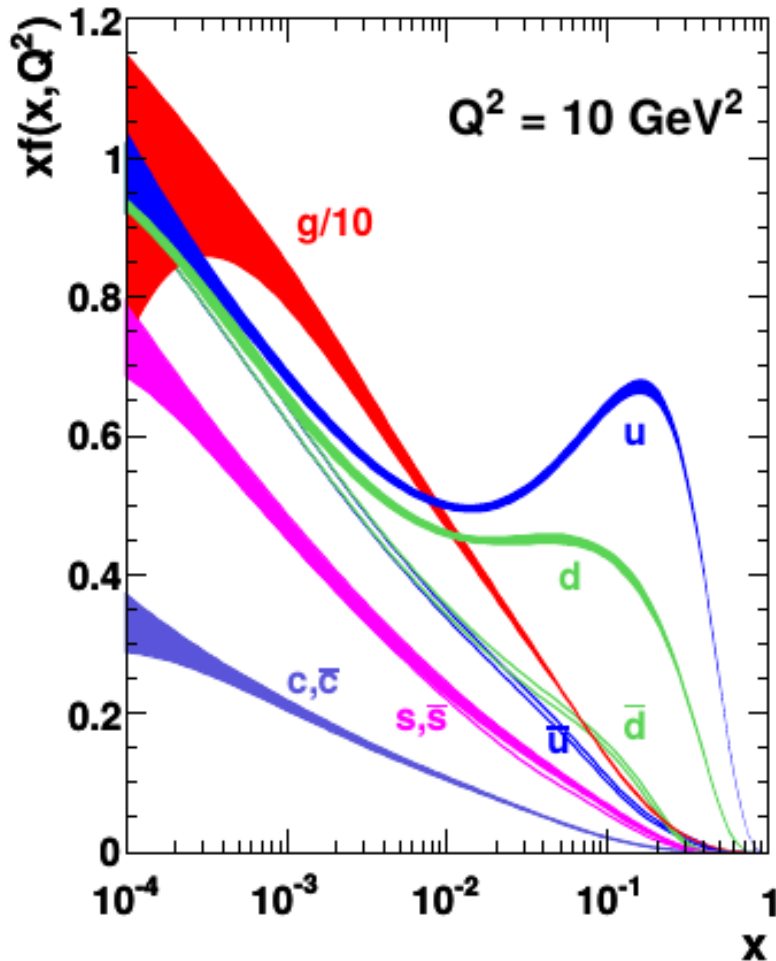
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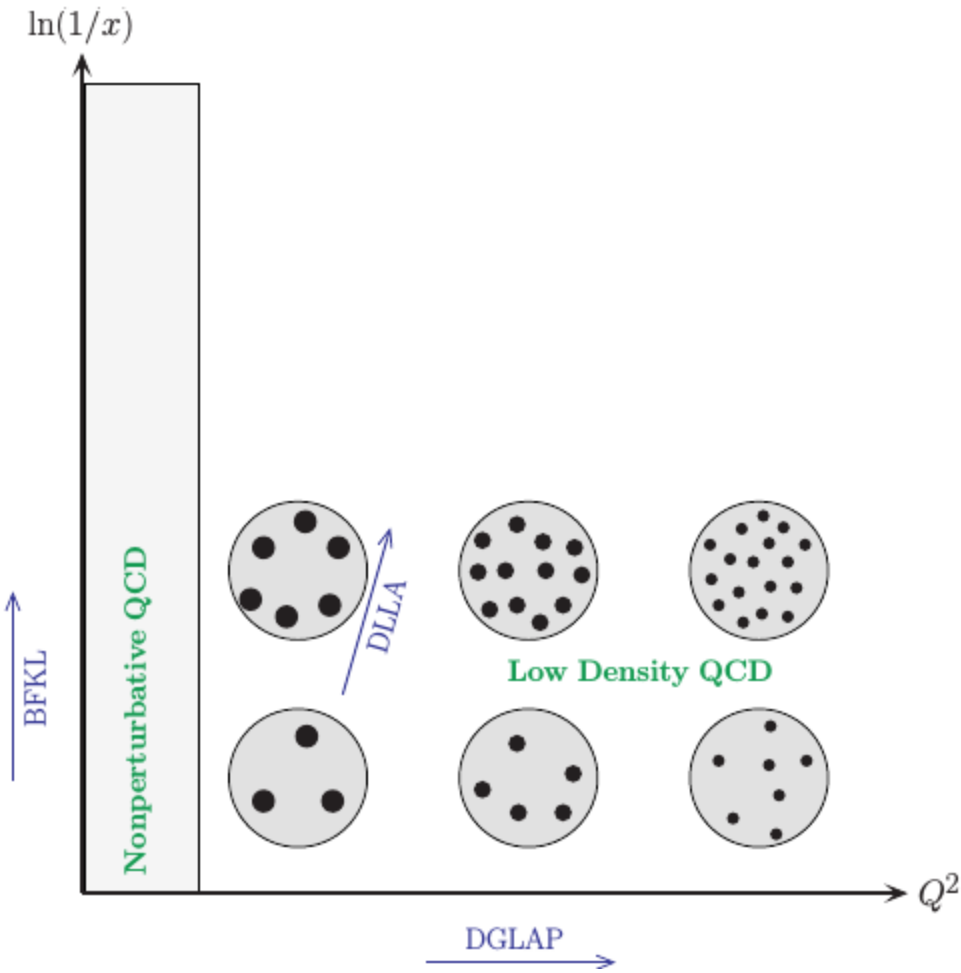
Photon - induced interactions at the LHC allows to study the high energy regime of QCD (Small - x Physics).

Hadronic structure at high energies

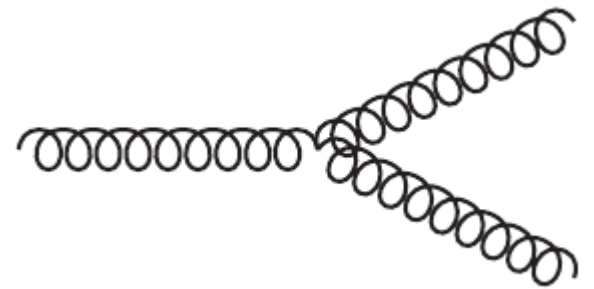


- ✓ Proton structure at high energies (small values of x) is dominated by **gluons**;
- ✓ Large uncertainty on the behaviour of the gluon distribution at small $-x$;
- ✓ Transition between the linear and non - linear regimes of the QCD dynamics is expected.

Hadronic structure at high energies

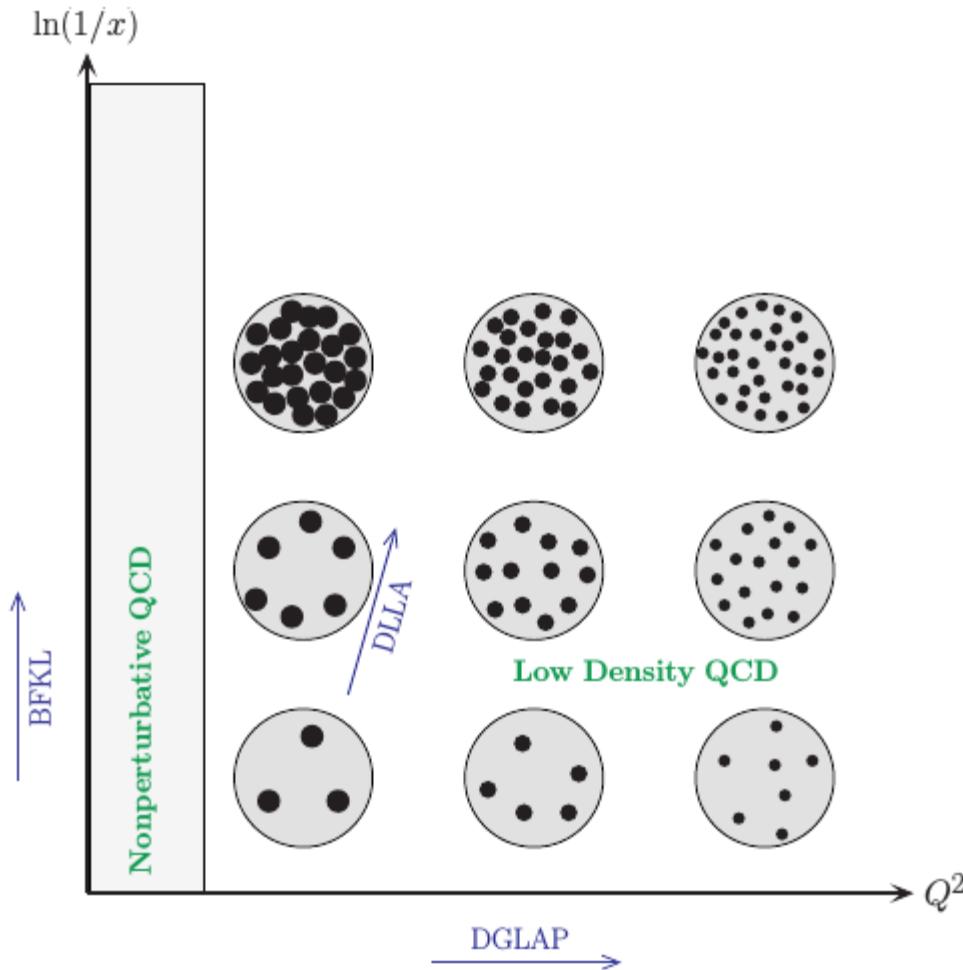


- At low energies, the partonic density is small, and the evolution is determined by the emission process:

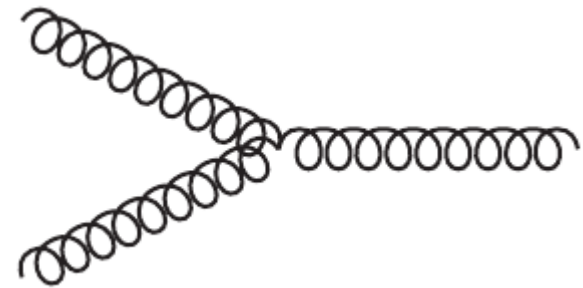


➡ The dynamics is described by linear evolution equations (DGLAP/BFKL).

Hadronic structure at high energies

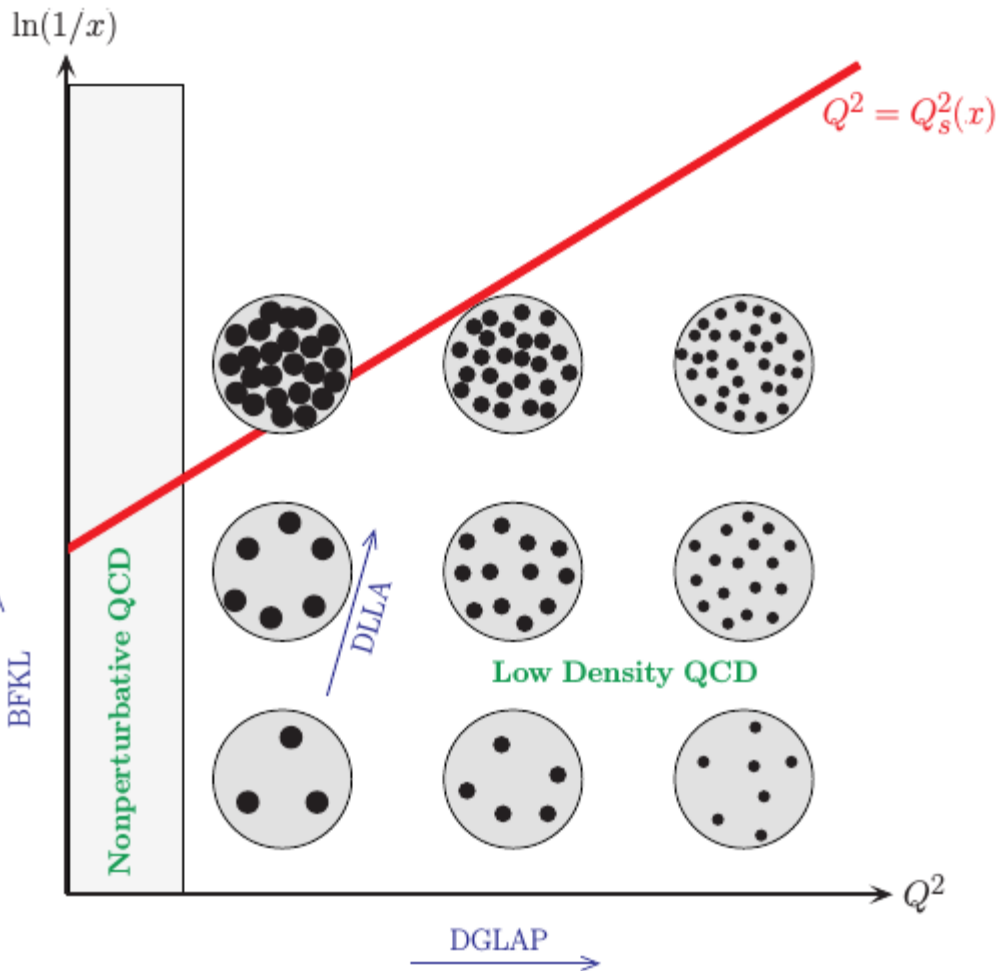


- At higher energies, the partonic density increases and the contribution of the recombination processes become non-negligible:



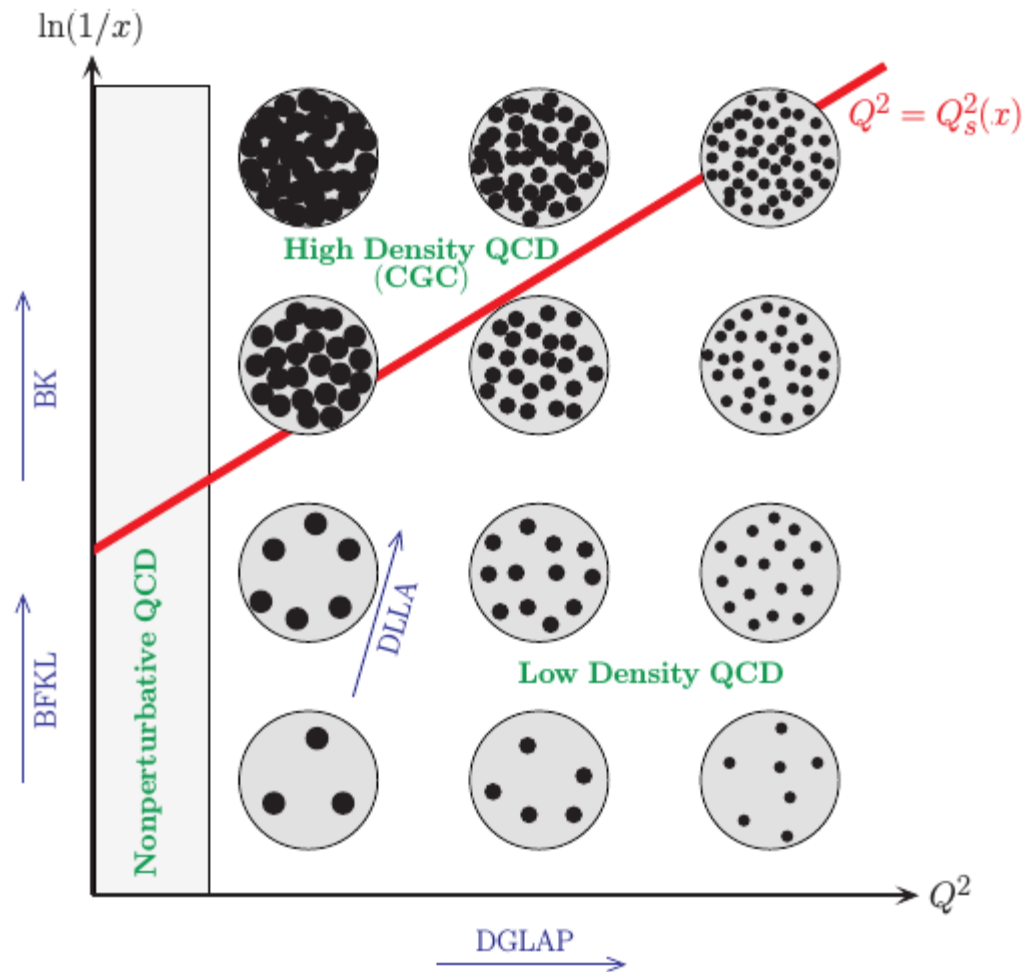
➡ Non-linear effects in the description of the QCD dynamics.

Hadronic structure at high energies



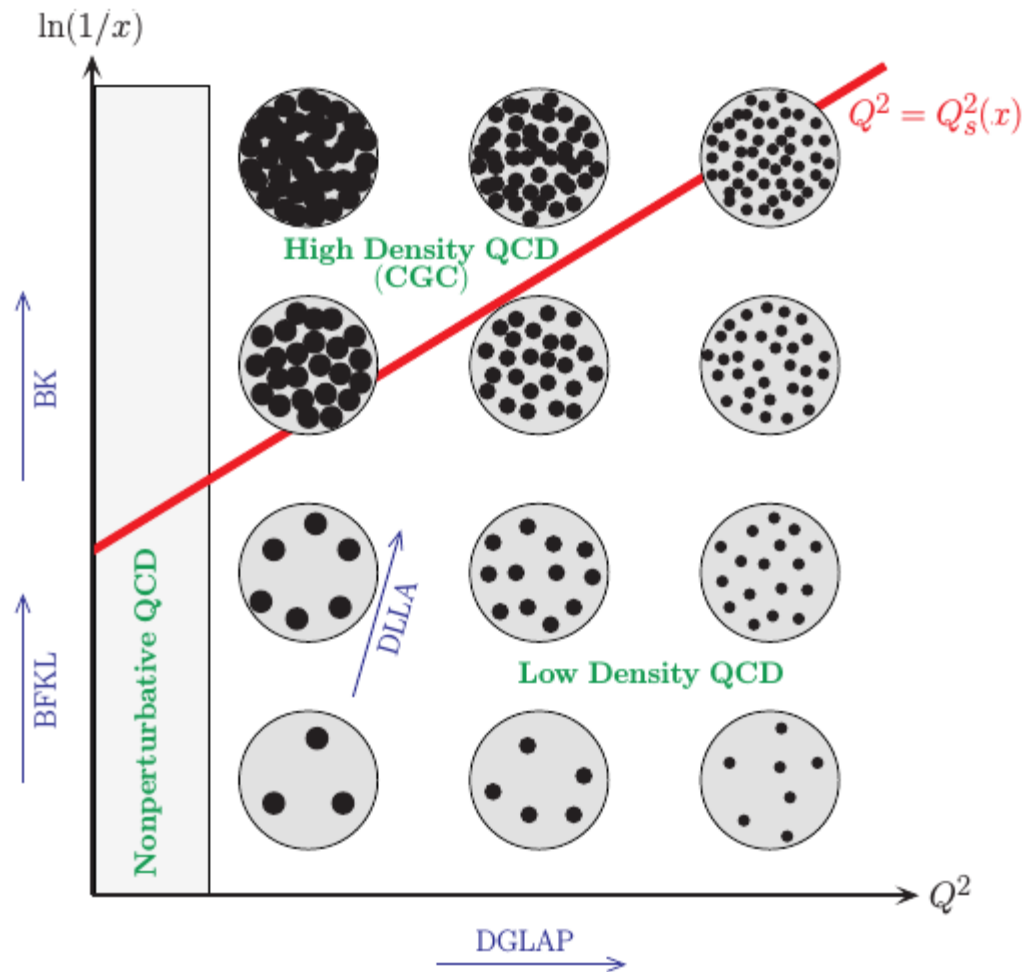
- ✓ The transition between the linear and non-linear regimes of the QCD dynamics is described by the saturation scale, which is energy and atomic number dependent;

Hadronic structure at high energies



- ✓ The transition between the linear and non-linear regimes of the QCD dynamics is described by the saturation scale, which is energy and atomic number dependent;
- ✓ High density regime of QCD described by the Color Glass Condensate (CGC) formalism.

Hadronic structure at high energies



Open questions:

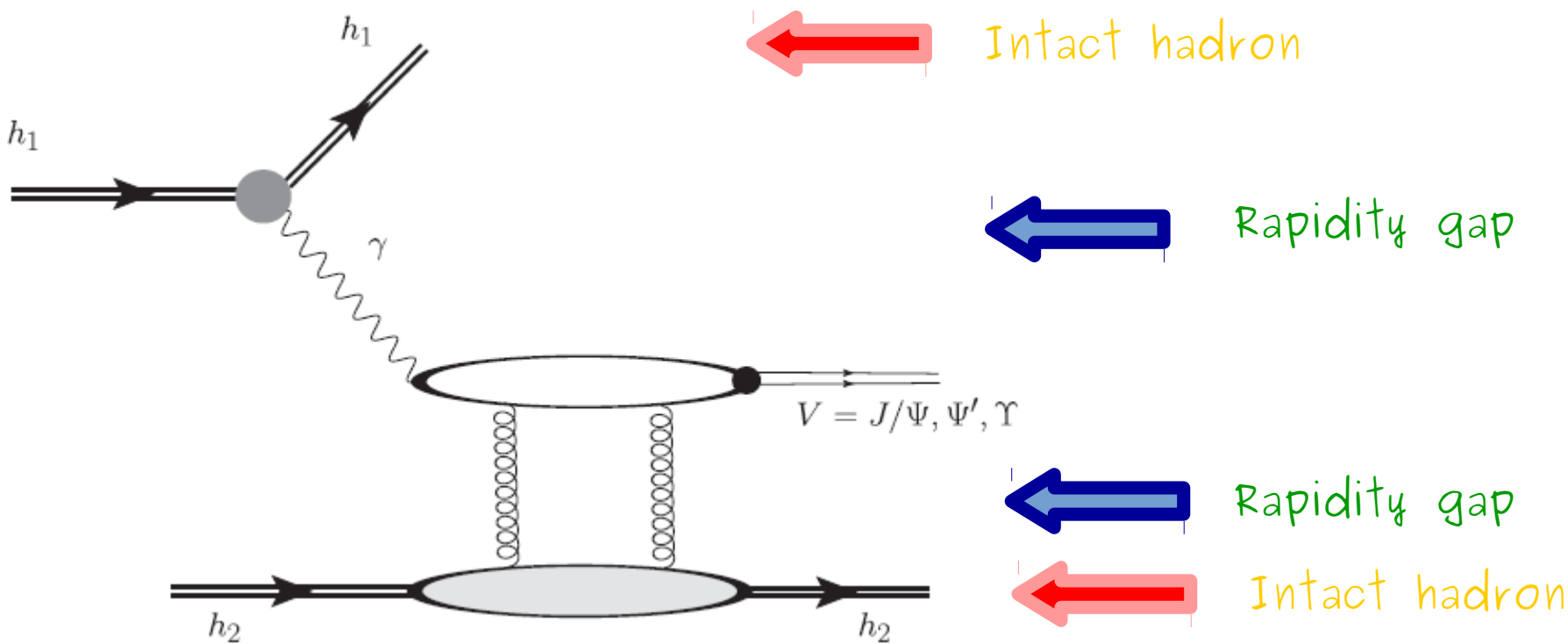
- Where (x, Q^2) the non-linear effects become non-negligible?
Run 1, 2, 3 ...??
- What is the limit of validity of a model based on the linear (e.g. DGLAP) dynamics?
- What is the impact of the non-linear effects in the description of the LHC observables?
- What is the correct description of the hadron WF at high energies?

Vector meson
photoproduction in hadronic
colliders:

Basic concepts

Probing the QCD dynamics at high energies in photon - induced interactions at the LHC

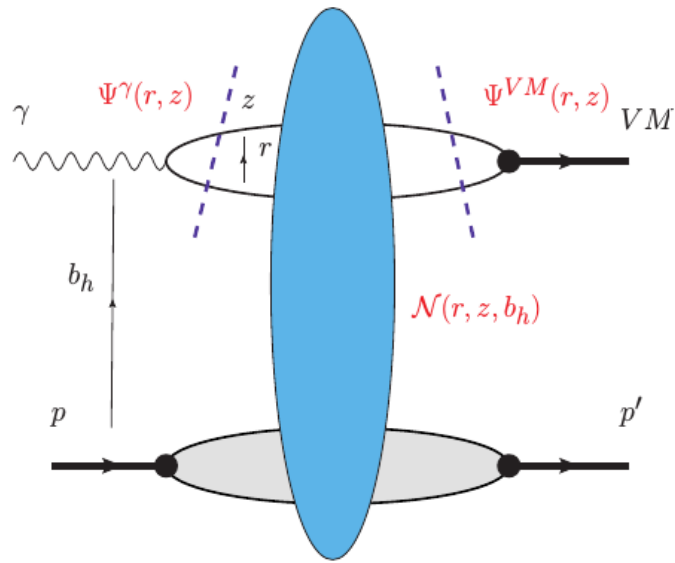
Exclusive vector meson photoproduction in hadronic collisions:



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

Exclusive vector meson photoproduction: A sketch of the formalism

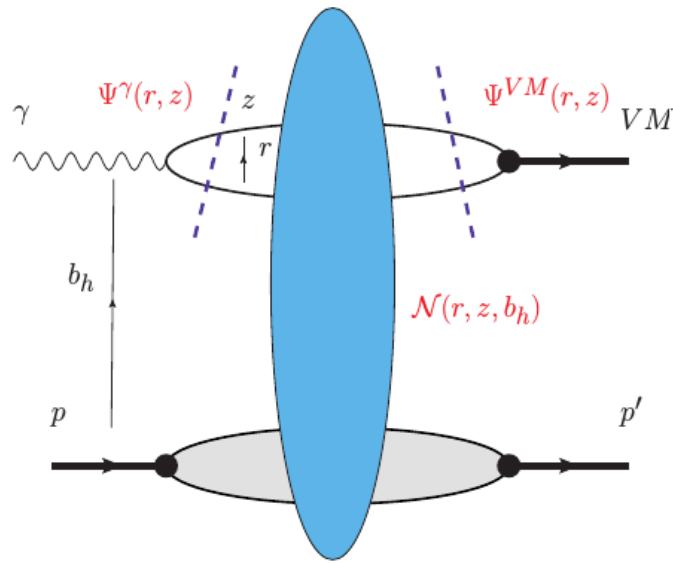
* In the impact parameter space:



$$\mathcal{A}_T^{\gamma h \rightarrow Vh}(x, \Delta) = i \int dz d^2r d^2b_h e^{-i[b_h - (1-z)r] \cdot \Delta} (\Psi^{V*} \Psi)_T 2\mathcal{N}_h(x, r, b_h)$$

Exclusive vector meson photoproduction: A sketch of the formalism

* In the impact parameter space:

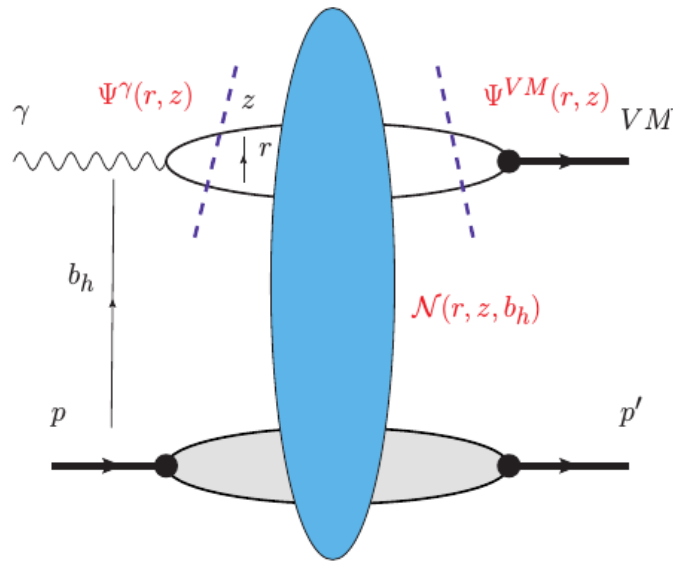


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Overlap function between the photon and vector meson wavefunctions:
- Depends of the model used to describe the VM wave functions;

Exclusive vector meson photoproduction: A sketch of the formalism

* In the impact parameter space:



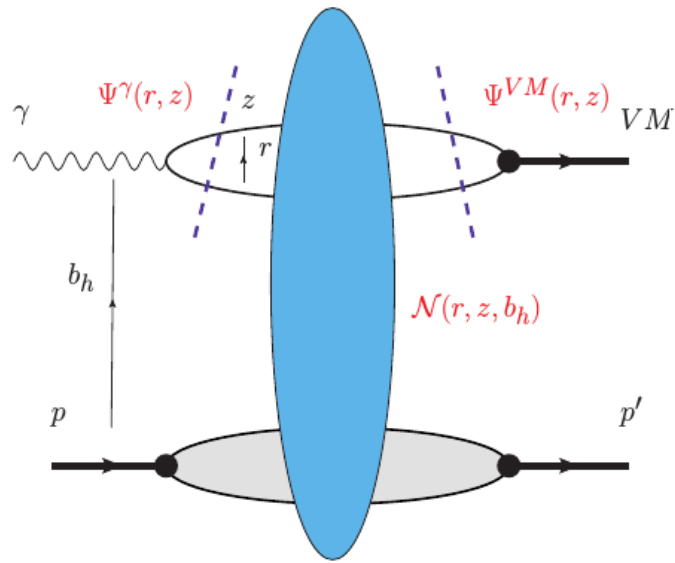
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Forward dipole - hadron scattering amplitude:

- Determined by the QCD dynamics at high energies;
- Can be modelled to take into account the non - linear effects at low - x

Exclusive vector meson photoproduction: A sketch of the formalism

* In the impact parameter space:

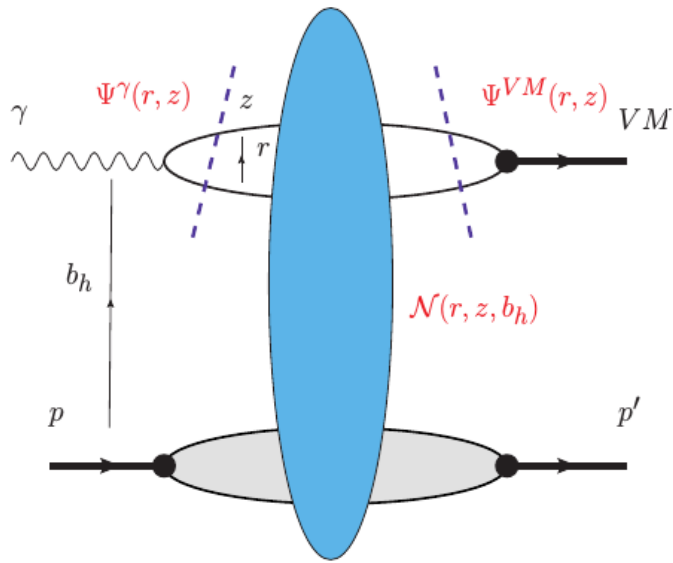


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$$\sigma(\gamma h \rightarrow Vh) = \int_{-\infty}^0 dt \frac{d\sigma}{dt} = R_g^2 (1 + \beta^2) \frac{1}{16\pi} \int_{-\infty}^0 |\mathcal{A}^{\gamma h \rightarrow Vh}(x, \Delta)|^2 dt.$$

Exclusive vector meson photoproduction: A sketch of the formalism

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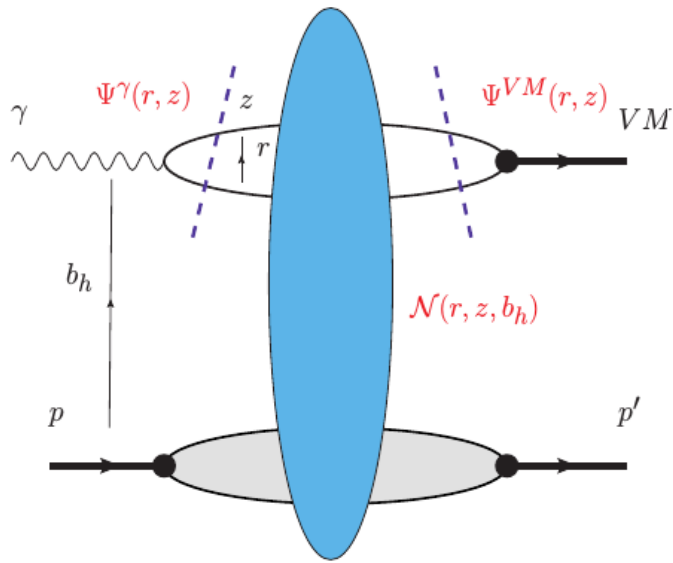
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Cross section is proportional to the **square** of the dipole - hadron scattering amplitude probed at $x = 4M_V^2/W^2$

Exclusive vector meson photoproduction: A sketch of the formalism

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$$\mathcal{A}_T^{\gamma h \rightarrow Vh}(x, \Delta) = i \int dz d^2r d^2b_h e^{-i[b_h - (1-z)r] \cdot \Delta} (\Psi^{V*} \Psi)_T 2\mathcal{N}_h(x, r, b_h)$$

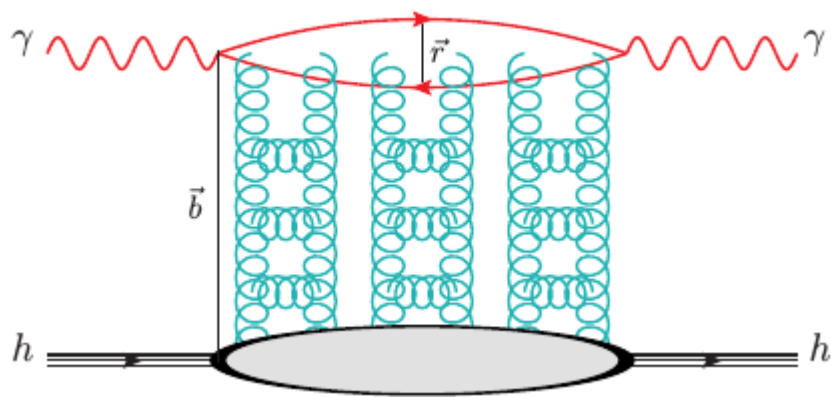
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➔ Exclusive vector meson photoproduction in hadronic collisions is strongly dependent on the description of the QCD dynamics.

Dipole - proton scattering

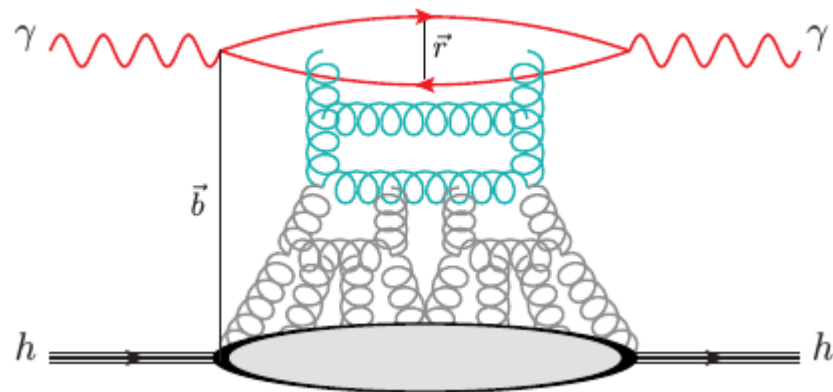
Two phenomenological models based on the CGC physics:

* IP - SAT model:



"Classical" CGC model.

* bCGC model:



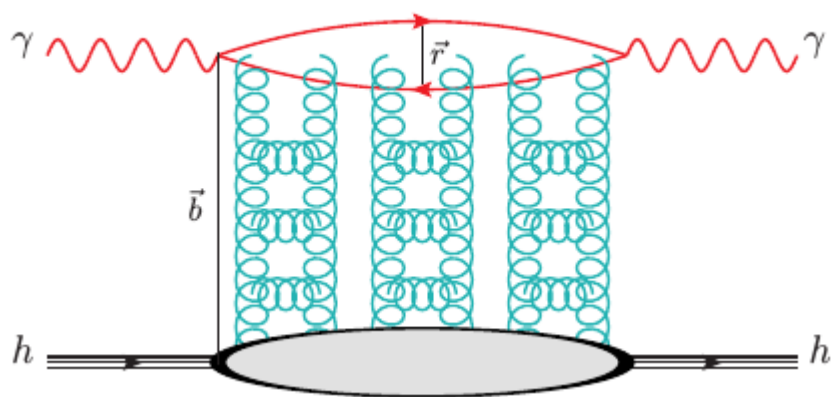
"Quantum" CGC model.

Important: Both models describe quite well the HERA ep data.

Dipole - proton scattering

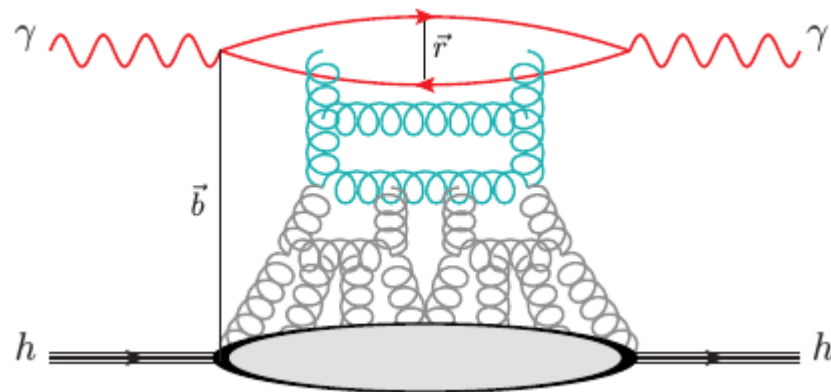
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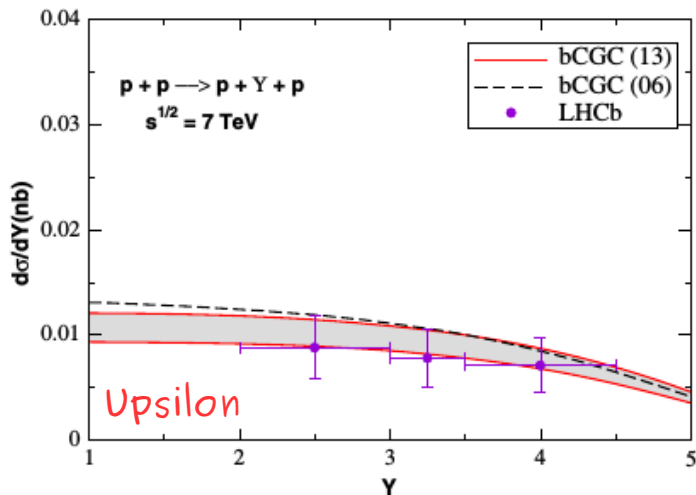
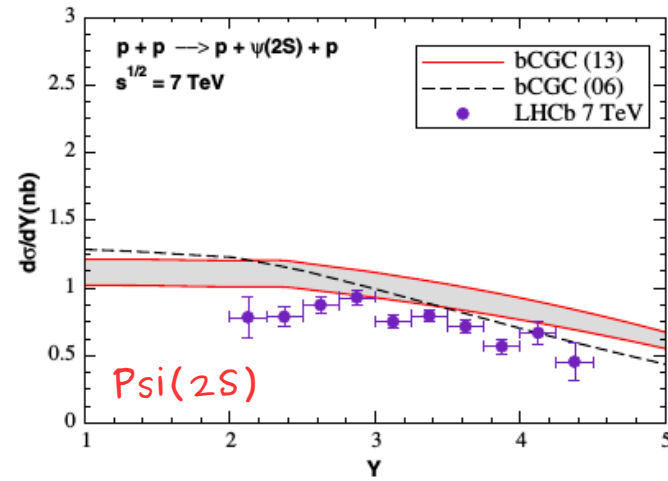
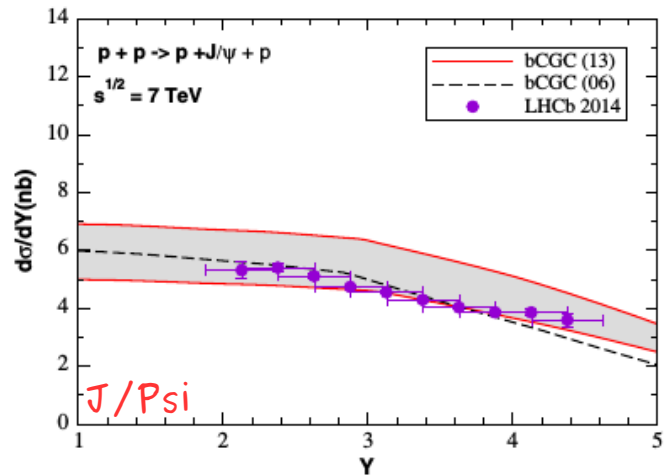
"Quantum" CGC model.

➔ The color dipole predictions for LHC are free parameter.
All parameters have been constrained by HERA data.

Recent results

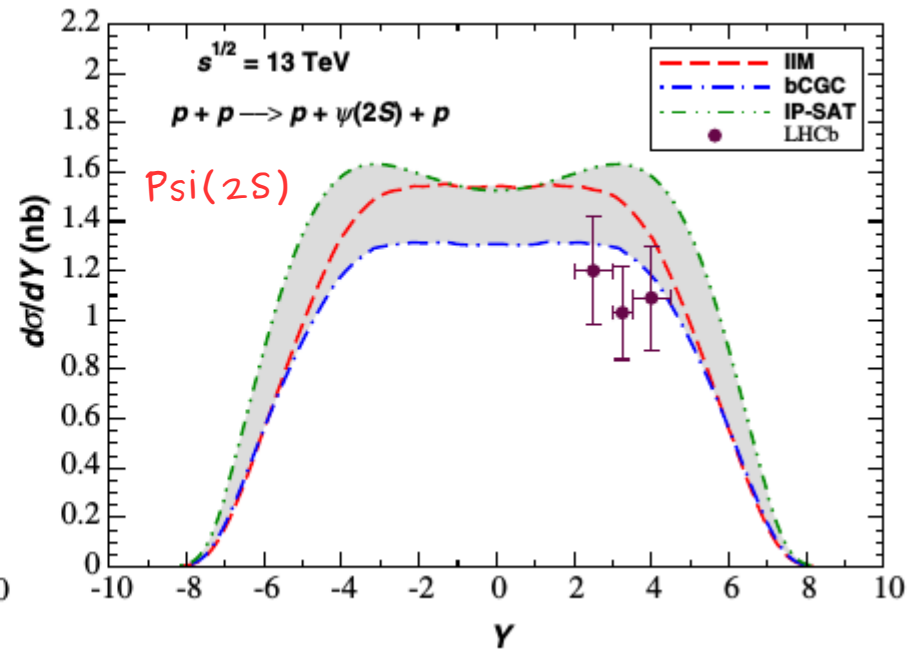
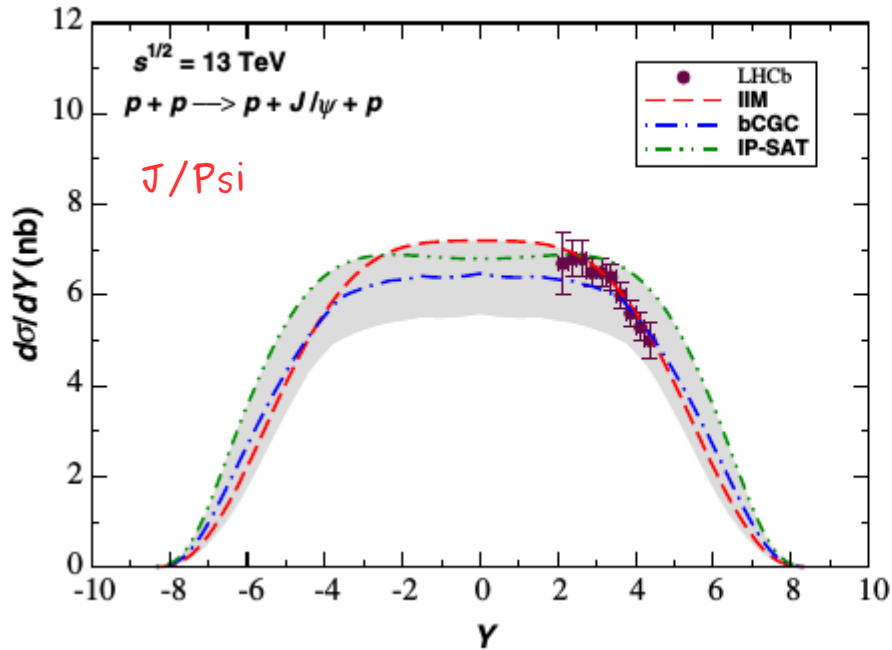
Comparison with the LHCb Run I data

Exclusive VM photoproduction in pp collisions:



Comparison with the LHCb Run II data

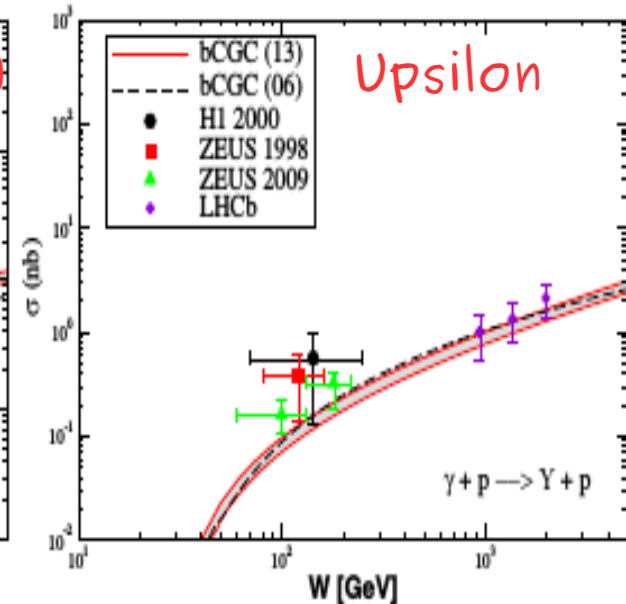
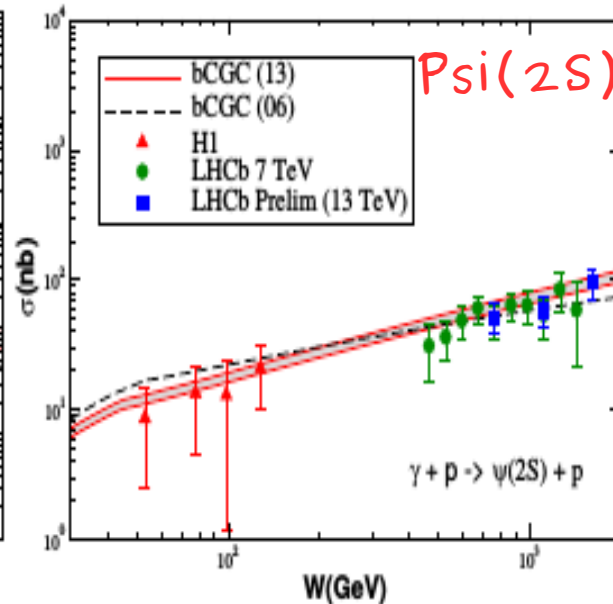
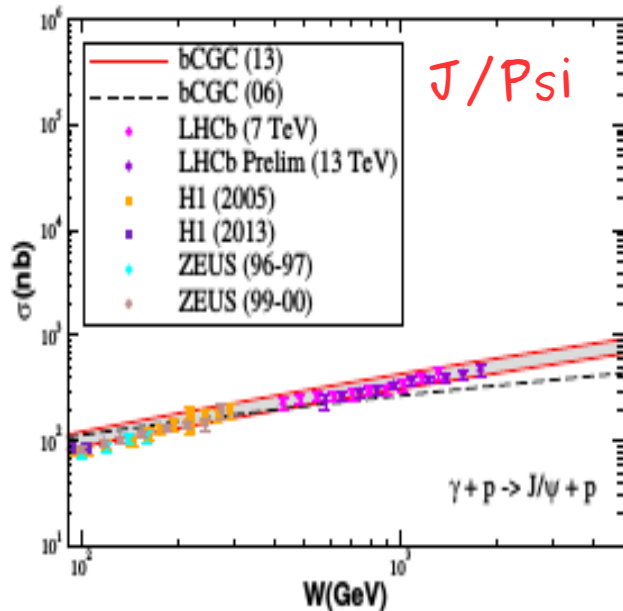
Exclusive VM photoproduction in pp collisions:



- Data is quite well describe taking into account the non - linear corrections to the QCD dynamics;
- However, it still is not able to discriminate between different approaches.

Energy dependence of the photon - proton cross sections

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



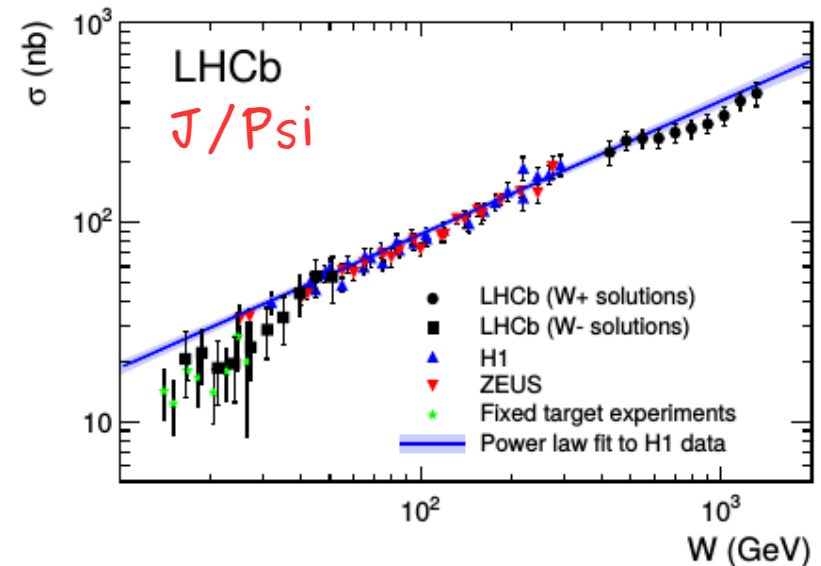
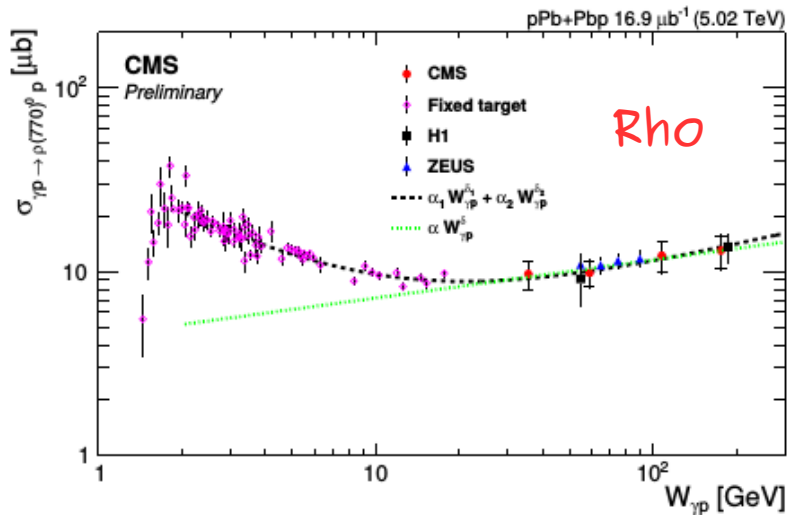
- LHCb data is constraining the high - energy behavior of the cross sections!

Prospects

(I) Exclusive VM photoproduction in fixed target collisions at the LHC

* Beam - gas collisions have been studied by the LHCb Collaboration and a similar programme can be developed by the **AFTER@LHC** experiment;

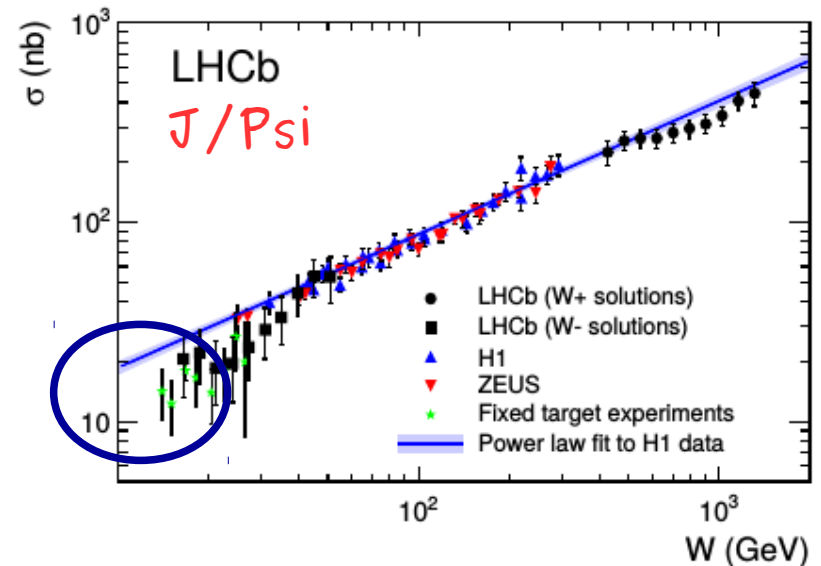
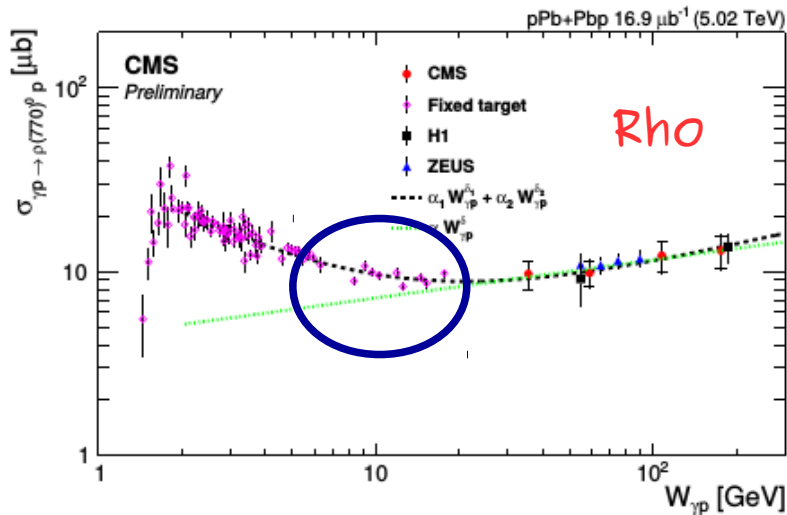
* Such collisions allows to study the vector meson photoproduction at low energies.



(I) Exclusive VM photoproduction in fixed target collisions at the LHC

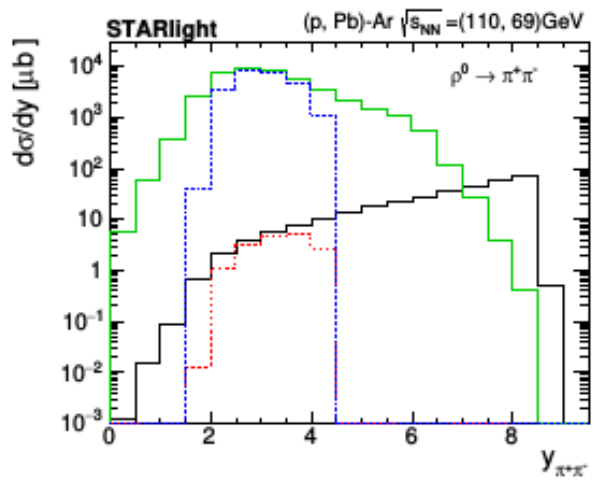
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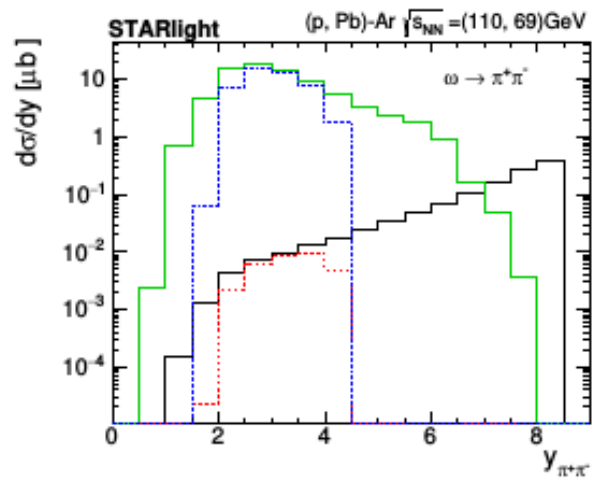


(I) Exclusive VM photoproduction in fixed target collisions at the LHC

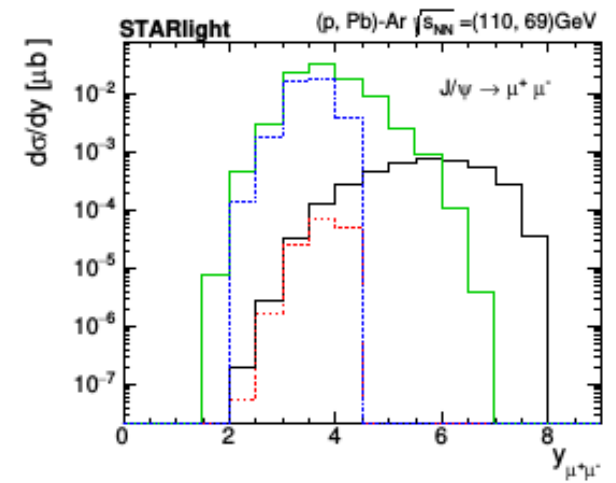
Rho



Omega



J/Psi

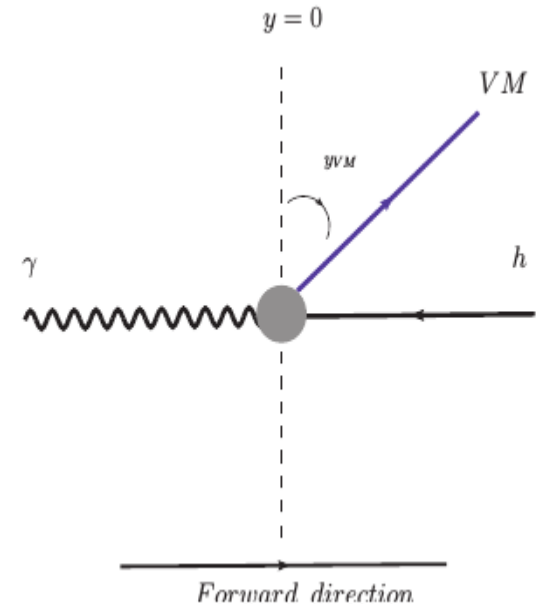
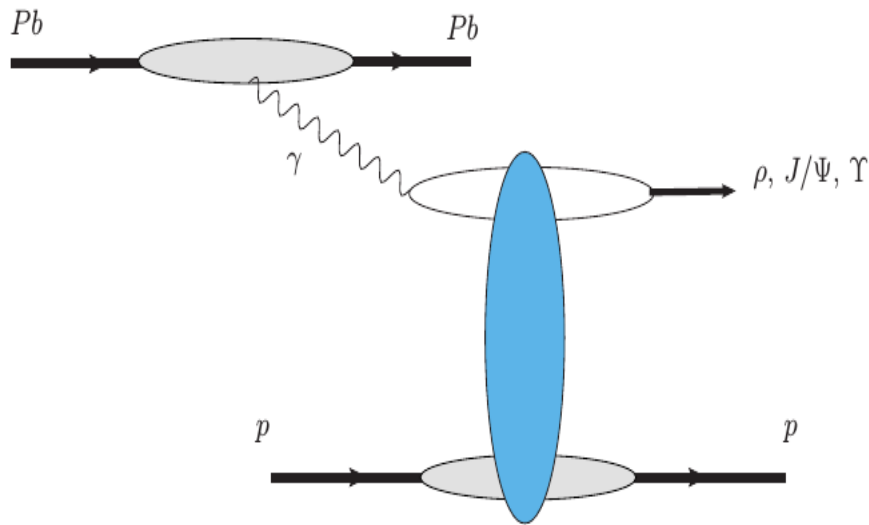


- p-Ar
- p-Ar LHCb
- Pb-Ar
- Pb-Ar LHCb

Final State	p-Ar	p-He	Pb-Ar	Pb-He
$\rho^0 \rightarrow \pi^+\pi^-$	318.60 (16.50) μb	6.97 (1.09) μb	42.50 (24.50) mb	5.60 (2.44) mb
$\omega \rightarrow \pi^+\pi^-$	1160.12 (30.71) nb	21.86 (2.29) nb	76.32 (46.21) μb	12.81 (5.35) μb
$J/\psi \rightarrow \mu^+\mu^-$	3.88 (0.14) nb	118.41 (14.29) pb	88.67 (39.68) nb	13.31 (7.15) nb

(*) VPG, Medina EPJC78, 693 (2018)

(II) Exclusive VM photoproduction in proton - nucleus collisions at the LHC



- Dominated by photon - proton interactions;

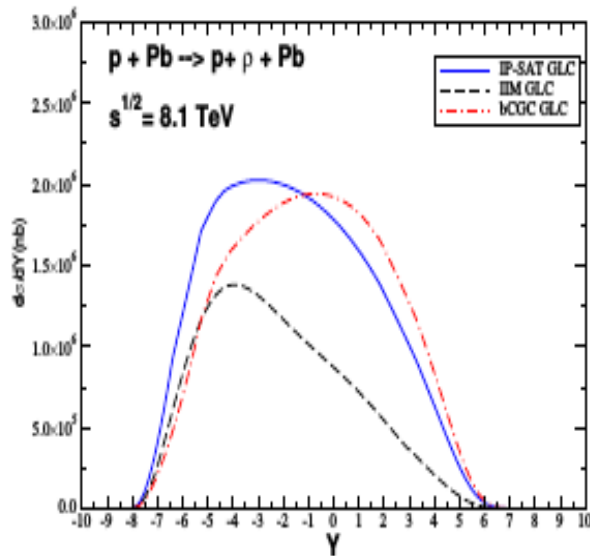
- Photon energy: $\omega = \frac{m_V}{2} e^Y$

- Photon - proton CM energy: $W^2 = m_V e^Y \sqrt{s}$

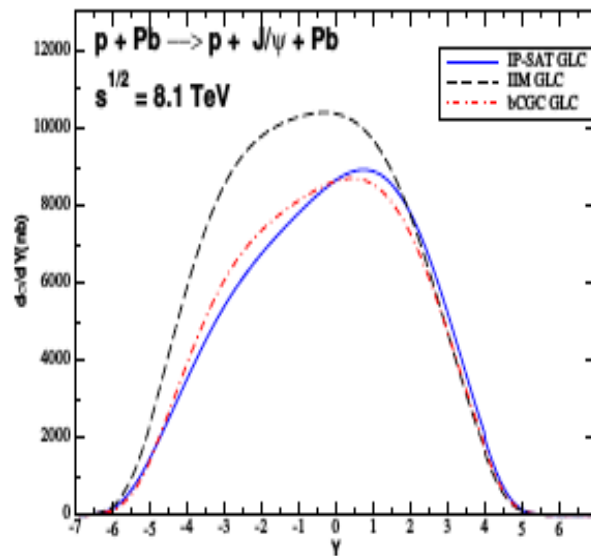
- Soft hadronic interactions are suppressed in comparison to pp collisions.

(II) Exclusive VM photoproduction in **proton** - **nucleus collisions** at the LHC

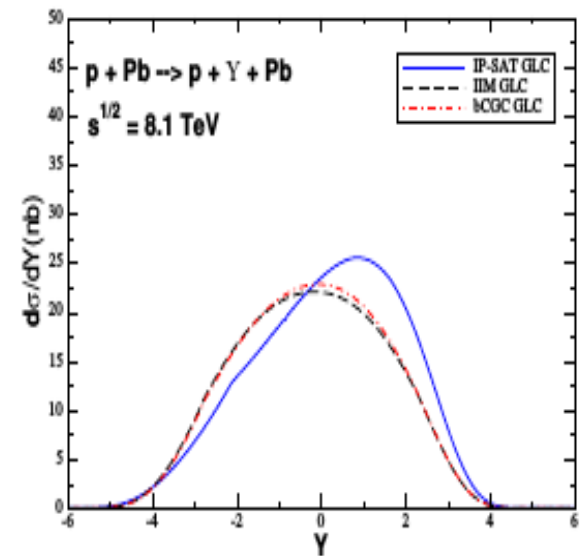
Rho



J/Psi



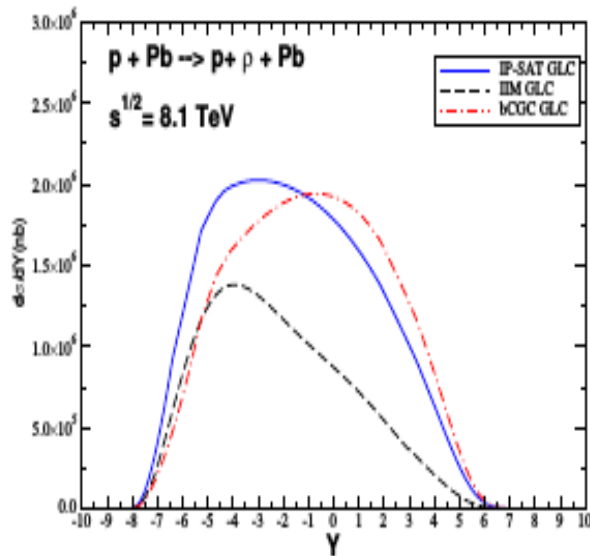
Upsilon



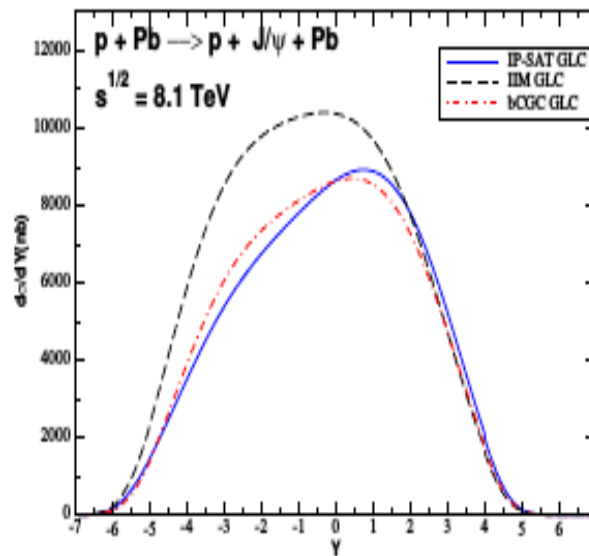
Rapidity distributions are sensitive to the different descriptions of the transition between the linear and non-linear regimes present in the distinct models.

(II) Exclusive VM photoproduction in **proton** - **nucleus collisions** at the LHC

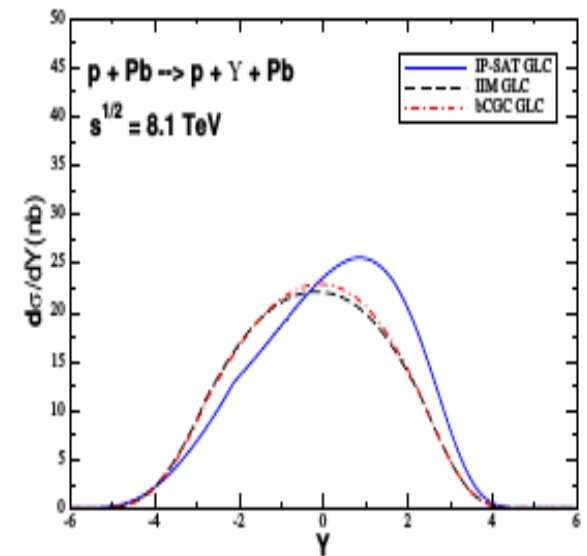
Rho



J/Psi



Upsilon

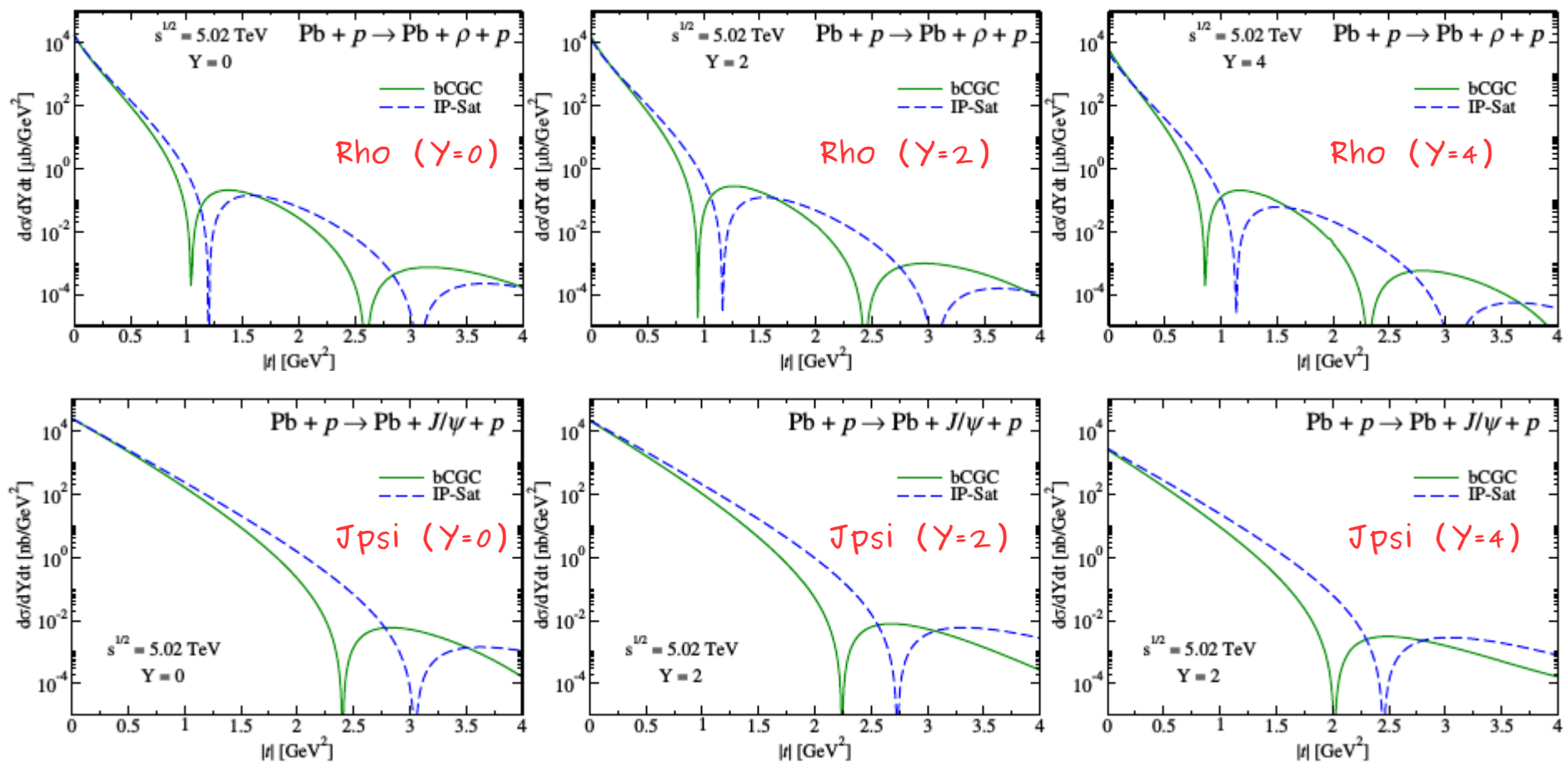


In order to discriminate/constrain the modelling of the QCD dynamics using the data for the rapidity distribution we should to have data for more than one VM.

(II) Exclusive VM photoproduction in **proton** - **nucleus collisions** at the LHC

Alternatives:

(A) Transverse momentum distributions (*)

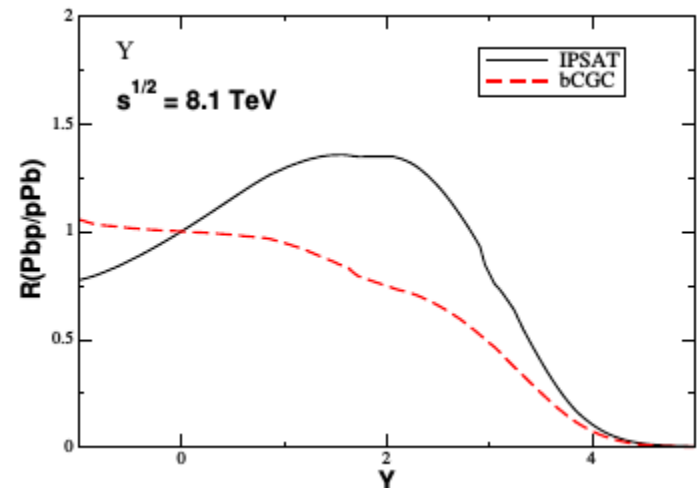
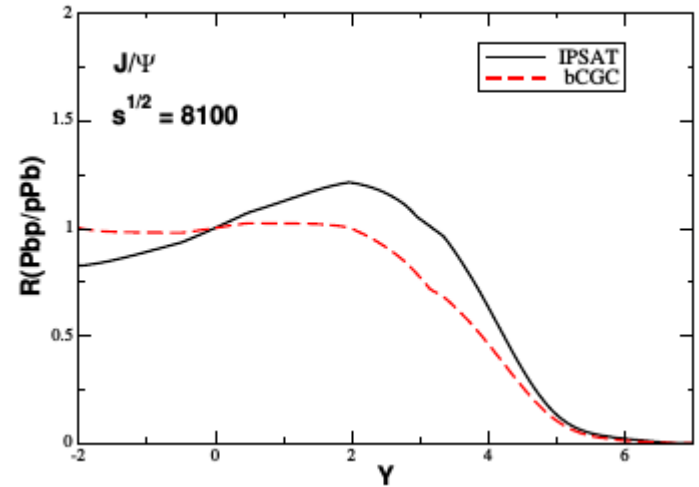
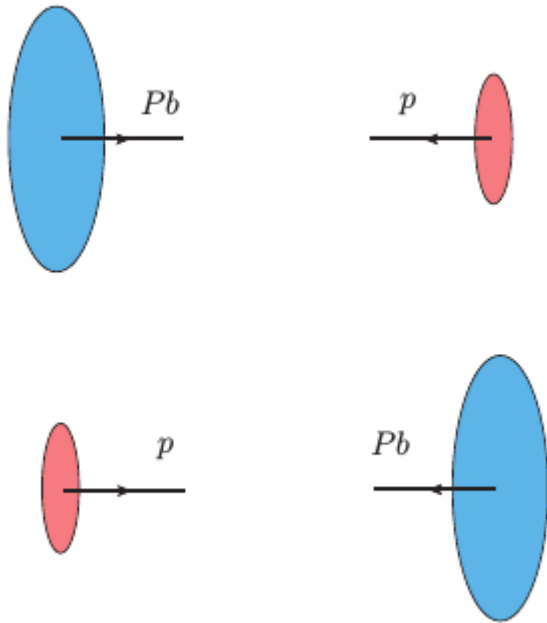


(*) VPG, Spiering, Navarra, in preparation.

(II) Exclusive VM photoproduction in **proton** - **nucleus collisions** at the LHC

Alternatives:

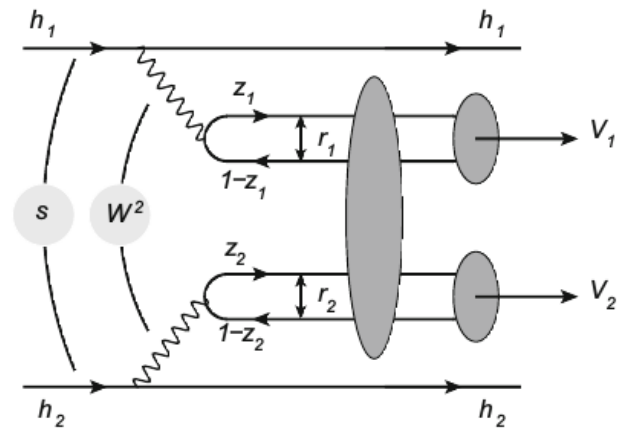
(B) Ratio Pbp / pPb (**)



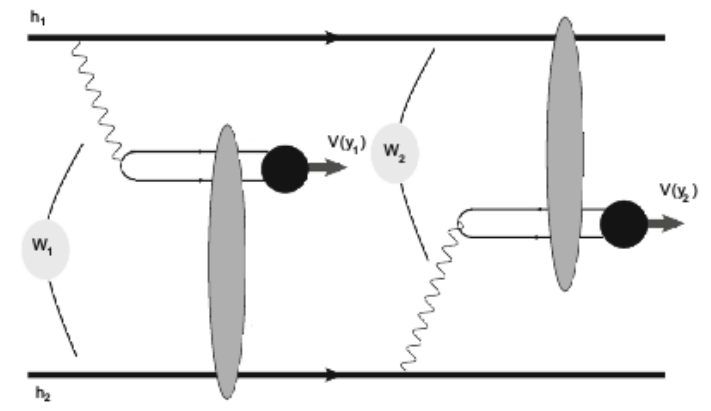
(*) VPG, Moreira, in preparation.

(III) Double VM photoproduction in proton - nucleus collisions at the LHC

Photon - Photon interactions:



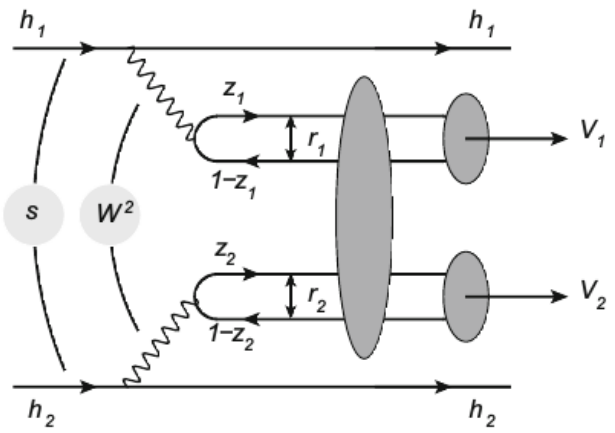
Double scattering mechanism:



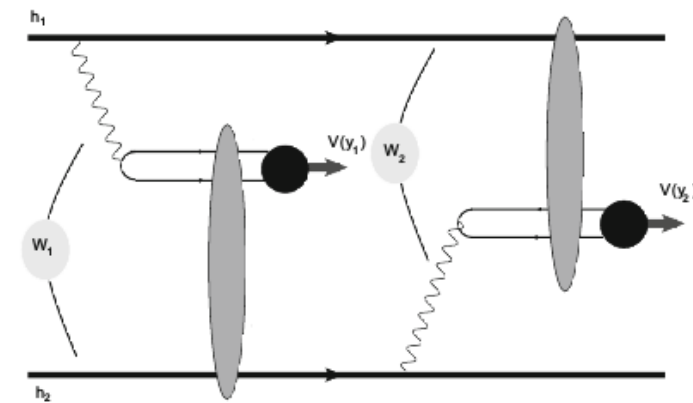
Final state	Mechanism	pPb $\sqrt{s} = 5 \text{ TeV}$
$J/\Psi J/\Psi$	DSM	28.473 pb
	$\gamma\gamma$	310.194 pb
$\rho\rho$	DSM	702.595 nb
	$\gamma\gamma$	536.432 nb

(III) Double VM photoproduction in proton - nucleus collisions at the LHC

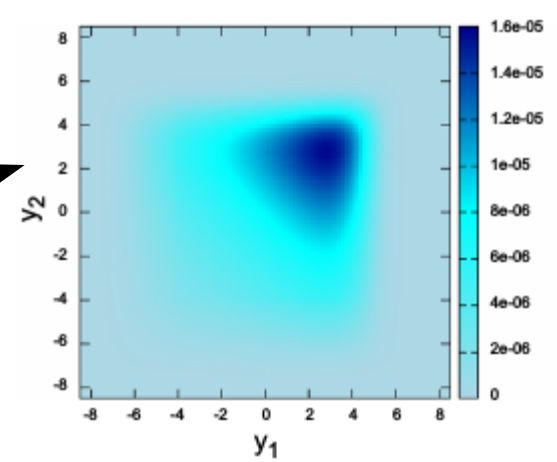
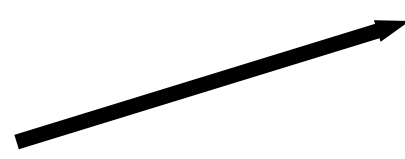
Photon - Photon interactions:



Double scattering mechanism:

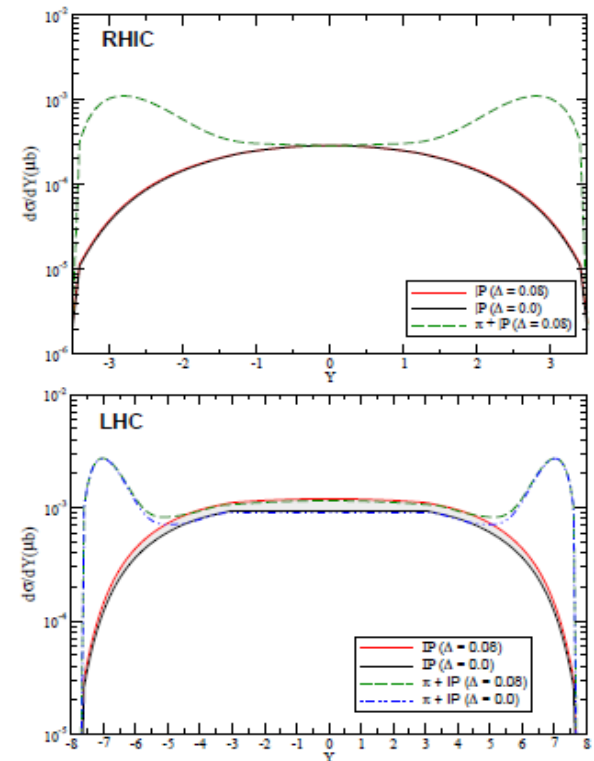
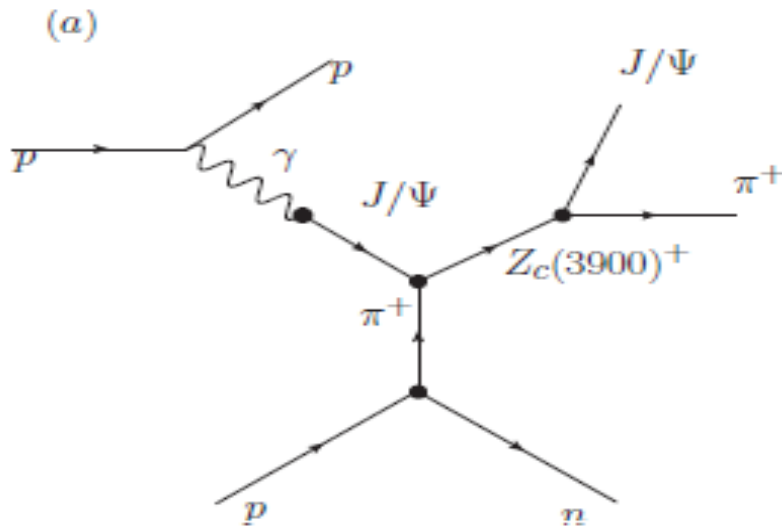


Final state	Mechanism	pPb $\sqrt{s} = 5 \text{ TeV}$
$J/\psi J/\psi$	DSM	28.473 pb
	$\gamma\gamma$	310.194 pb
$\rho\rho$	DSM	<u>702.595 nb</u>
	$\gamma\gamma$	536.432 nb



(IV) Probing Exotic Charmoniumlike states in photon - induced interactions at the LHC

Photoproduction of $Z_c(3900)^+$:

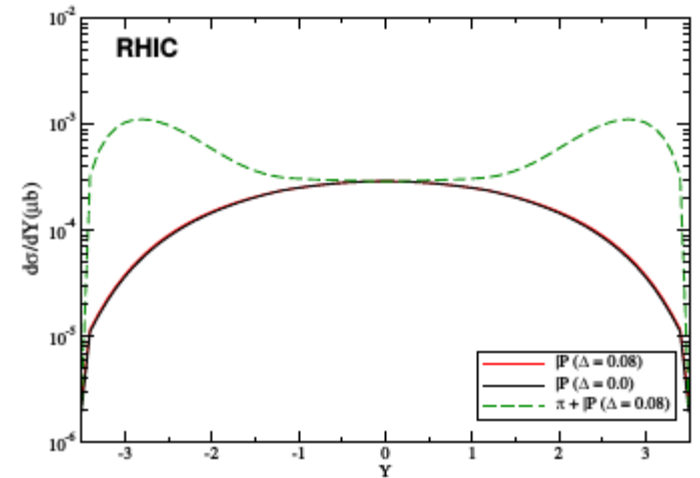
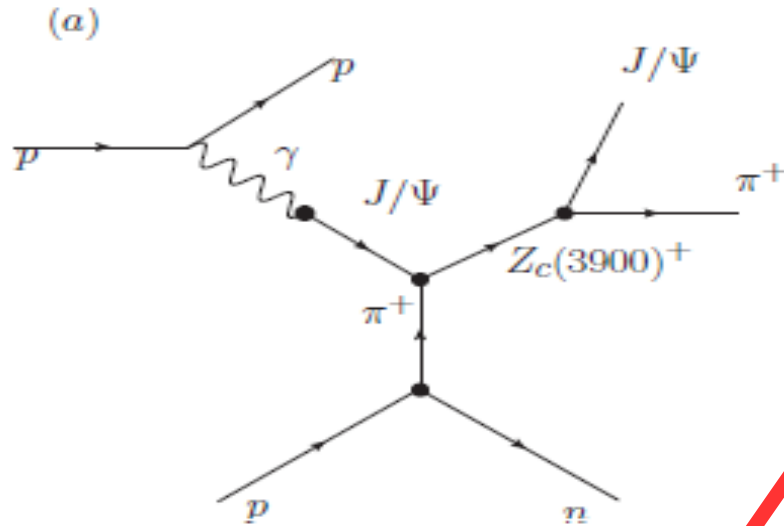


Reaction	Resonance	Contribution	σ [nb] ($\sqrt{s} = 0.2$ TeV)	σ [nb] ($\sqrt{s} = 7$ TeV)	σ [nb] ($\sqrt{s} = 14$ TeV)
$\sigma(pp \rightarrow pJ/\Psi\pi n)$	-	IP	1.15	8.18 - 9.64	10.33 - 12.65
	$Z_c(3900)$	IP + π	3.83	14.13 - 15.52	16.89 - 19.12

➡ Cross sections are enhanced by a factor Z^2 in pPb collisions.

(IV) Probing Exotic Charmoniumlike states in photon - induced interactions at the LHC

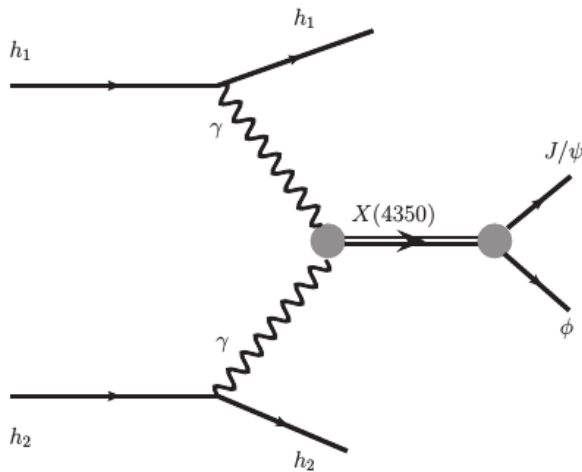
Photoproduction of $Z_c(3900)^+$:



Similar enhancement is expected in fixed - target pHe collisions in the range probed by the LHCb.

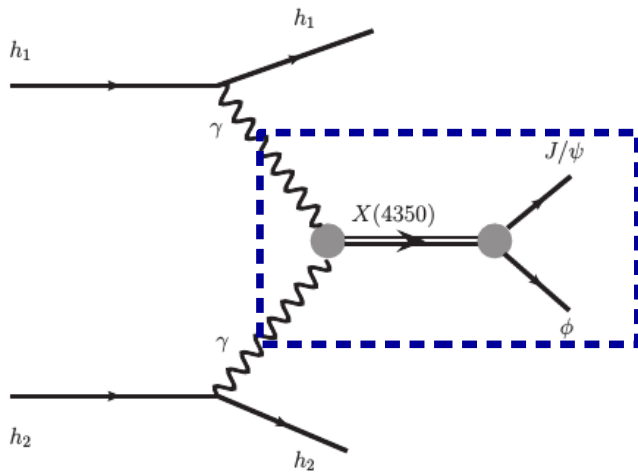
(IV) Probing Exotic Charmoniumlike states in photon - induced interactions at the LHC

Photoproduction of $X(4350)$:



(IV) Probing Exotic Charmoniumlike states in photon - induced interactions at the LHC

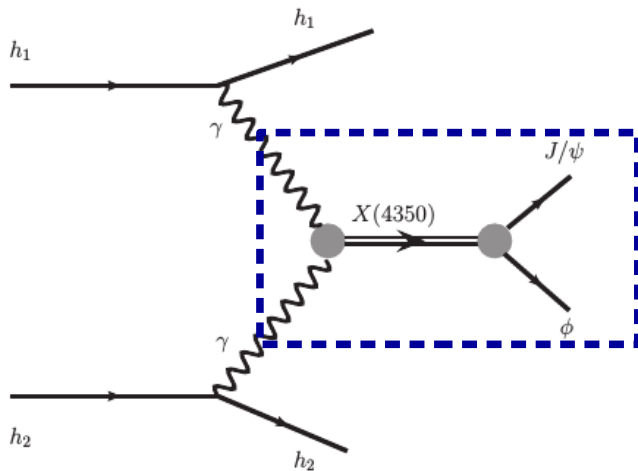
Photoproduction of $X(4350)$:



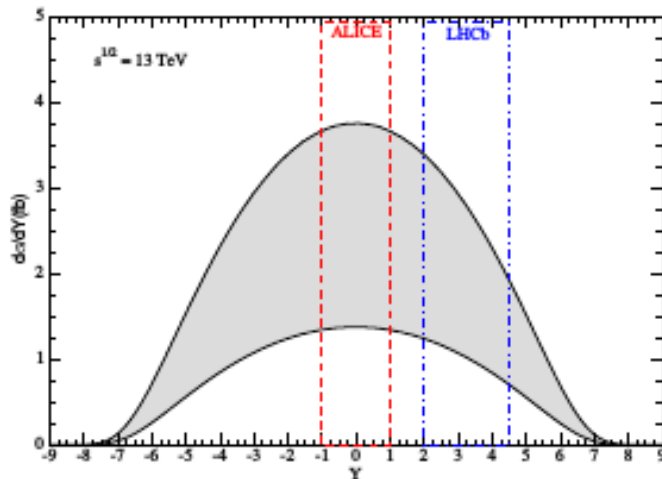
Constrained by Belle Collaboration.

(IV) Probing Exotic Charmoniumlike states in photon - induced interactions at the LHC

Photoproduction of $X(4350)$:



Constrained by Belle Collaboration.



Collision	Resonance	LHCb $2 < Y < 4.5$
pp ($\sqrt{s} = 13$ TeV)	$X(4350), 0^{++}$	(2.47 - 6.13) fb
	$X(4350), 2^{++}$	(2.52 - 6.88) fb
pPb ($\sqrt{s} = 8.1$ TeV)	$X(4350), 0^{++}$	(10.20 - 25.30) pb
	$X(4350), 2^{++}$	(10.30 - 28.30) pb
$PbPb$ ($\sqrt{s} = 5.02$ TeV)	$X(4350), 0^{++}$	(14.60 - 36.20) nb
	$X(4350), 2^{++}$	(14.90 - 40.60) nb

Such channel can be used to confirm (or not) the existence of resonances observed in e^+e^- colliders.

Summary

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MY WISH LIST

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1. Upsilon in pp at 13 TeV	QCD dynamics in the linear regime
2. Phi in pp	Transition regime between linear and nonlinear regimes
3. VM in pPb - rapidity and transverse momentum distributions	Complementary study to pp with negligible soft hadronic corrections, small uncertainty on the photon - proton CM energy, dissociate processes, ...
4. VM in PbPb	Nuclear effects, coherent and incoherent interactions, ...
5. VM production in fixed - target collisions	Description of the VM production at low energies
6. Exclusive Etac photoproduction	Odderon
7. DIFFRACTION	Exclusive, Single and Double

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Thank you for your attention!

Extras

Photoproduction of exotic charmoniumlike states

