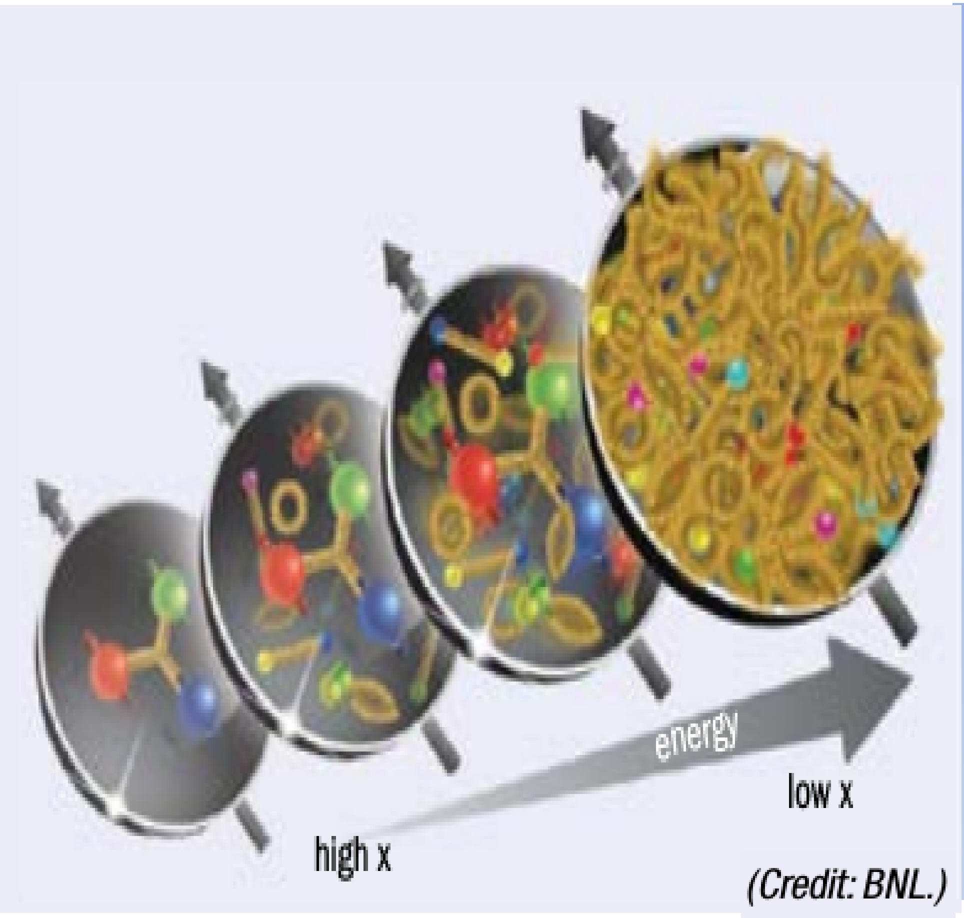
COST Workshop on Interplay of Hard and Soft QCD Probes for Collectivity in Heavy Ion Collisions



Exclusive Vector Meson Photoproduction: Recent results and Prospects

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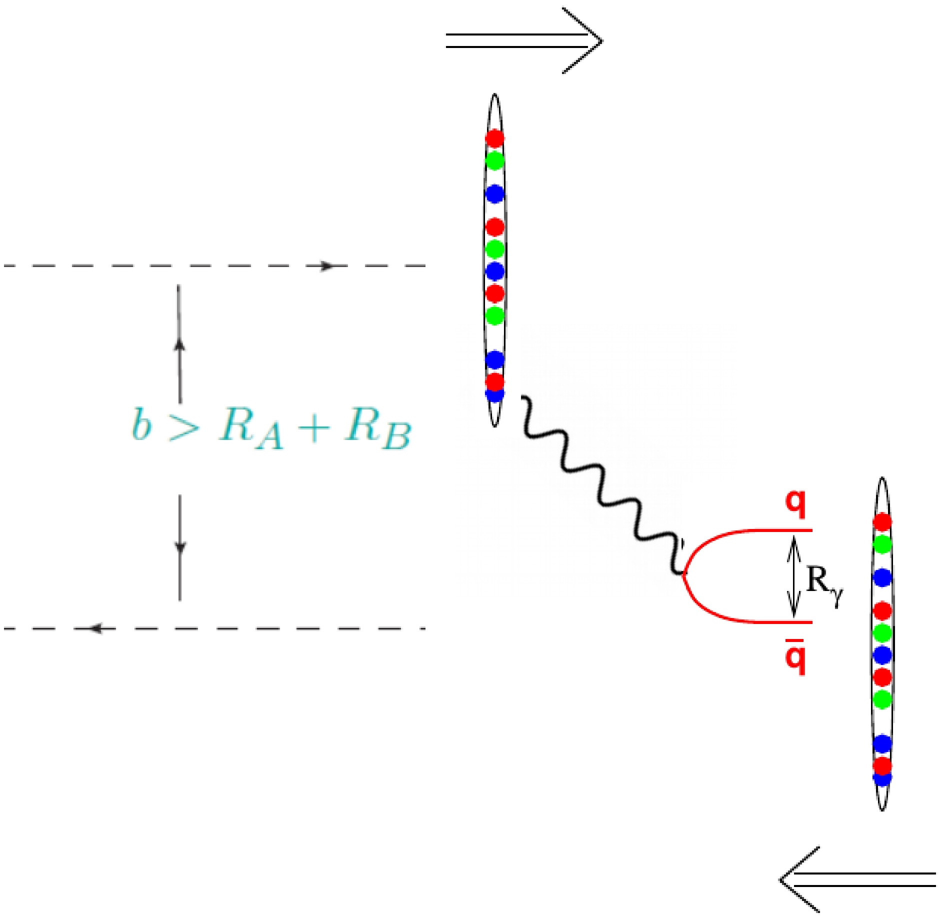
01 Mar 2019

Outline

- Motivation
- Vector meson photoproduction in hadronic colliders: Basic Concepts
- Recent results
- Prospects
- Summary

Motivation

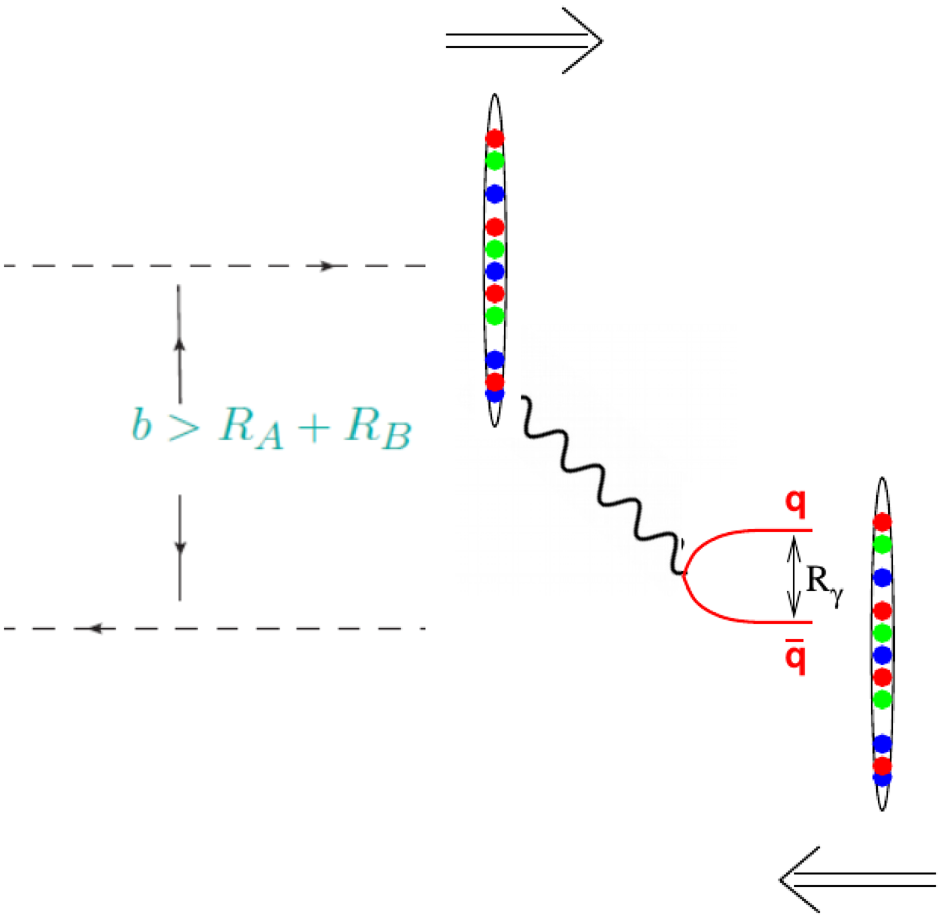
Ultraperipheral Hadronic Collisions:
Photon - induced interactions

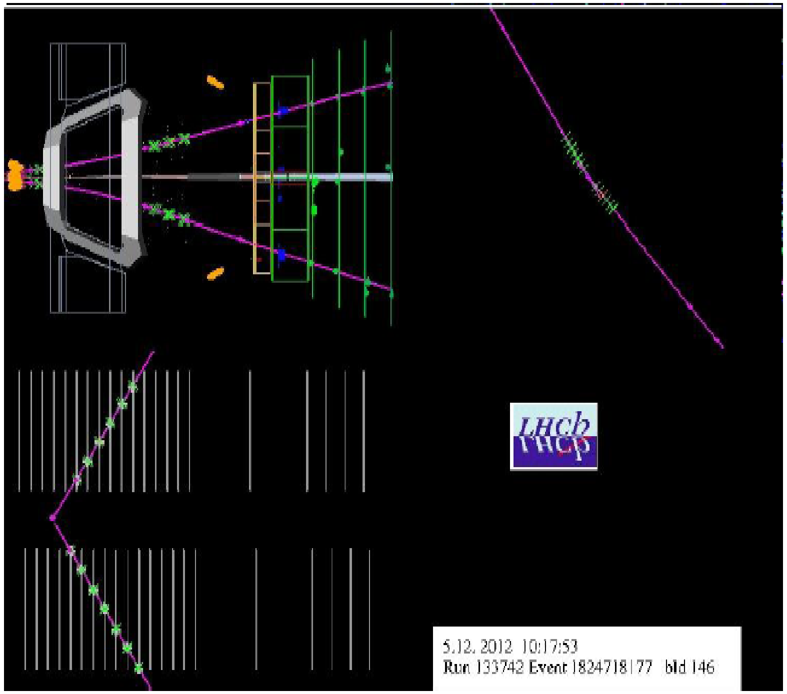


- Dominated by photon - photon and photon - hadron interactions;

- Photon emission determined by QED (Photon flux α Z^2).

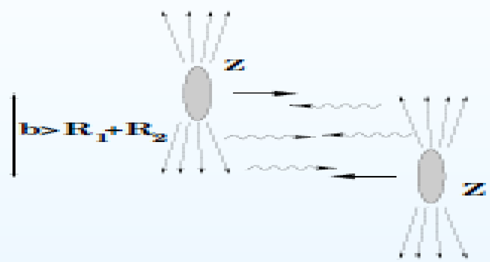
Ultraperipheral Hadronic Collisions: Photon - induced interactions





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

Ultraperipheral Hadronic Collisions: Photon - induced interactions



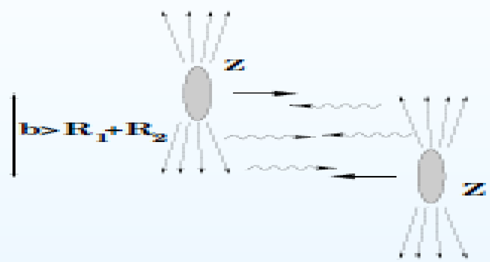
1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

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	–

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

Ultraperipheral Hadronic Collisions: Photon - induced interactions



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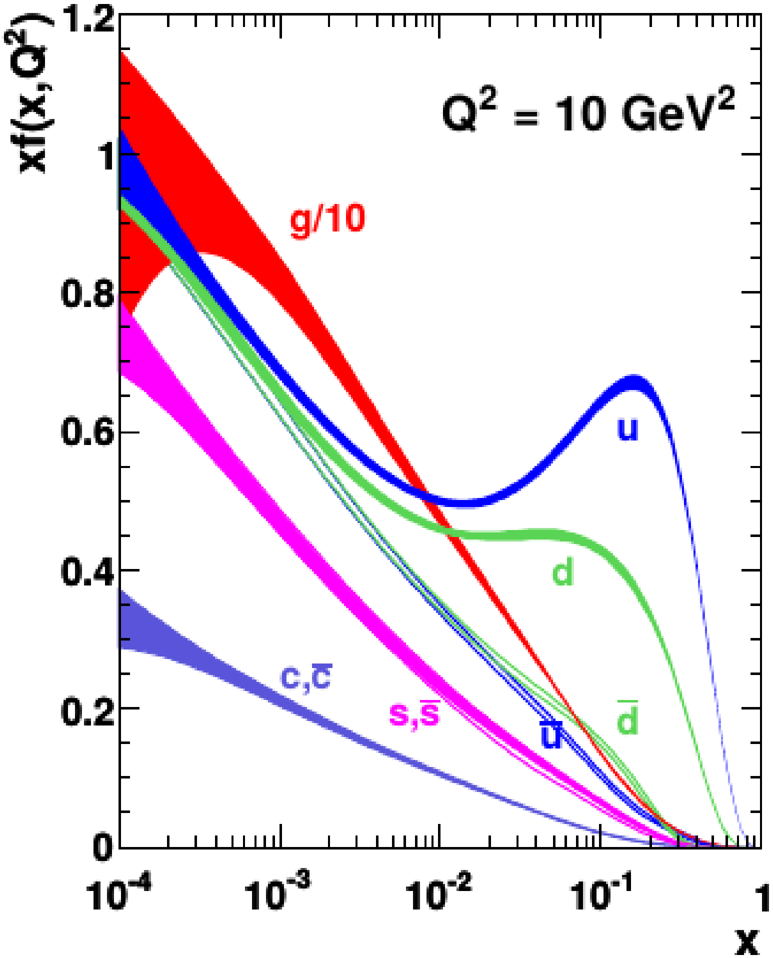
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

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

Hadronic structure at high energies

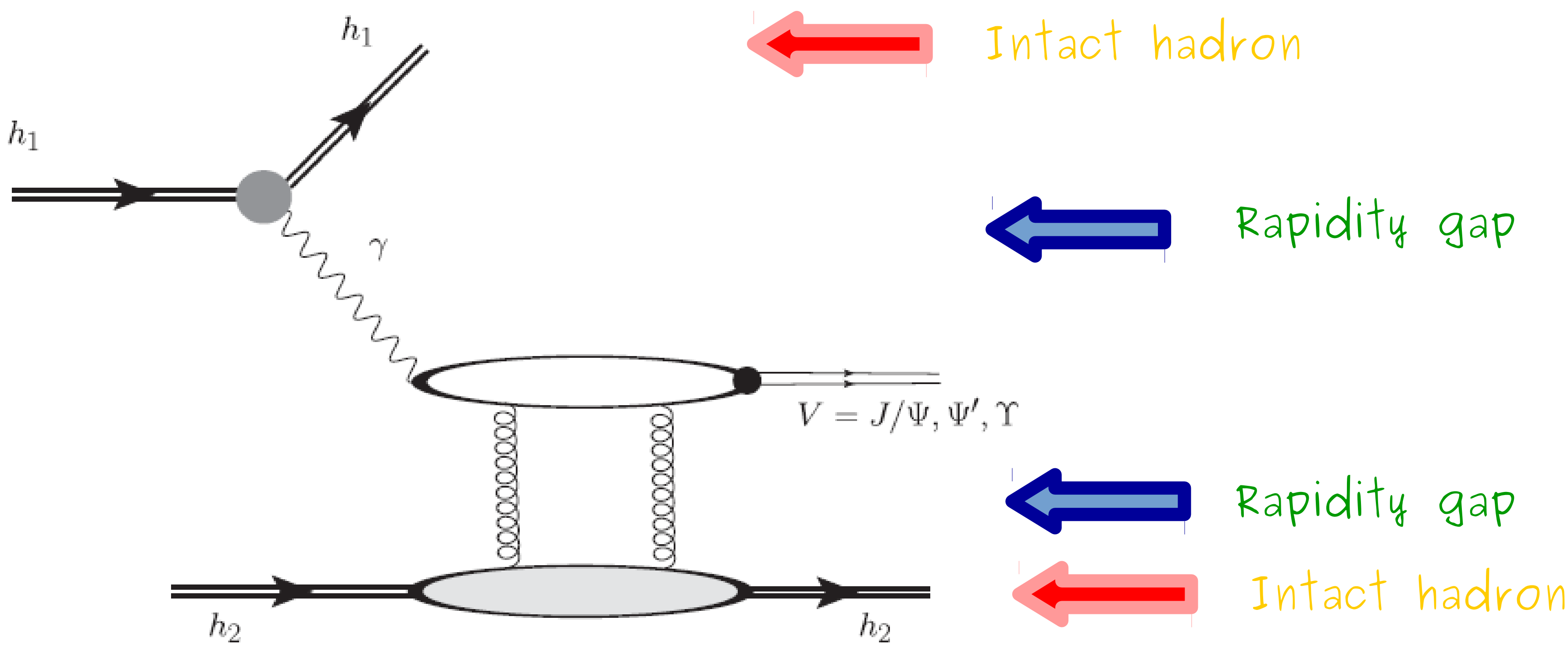


- Proton structure at high energies (small values of x) is dominated by gluons;
- Large uncertainty on the behaviour of the gluon distribution at small -x;
- Transition between the linear and non - linear regimes of the QCD dynamics is expected.

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:

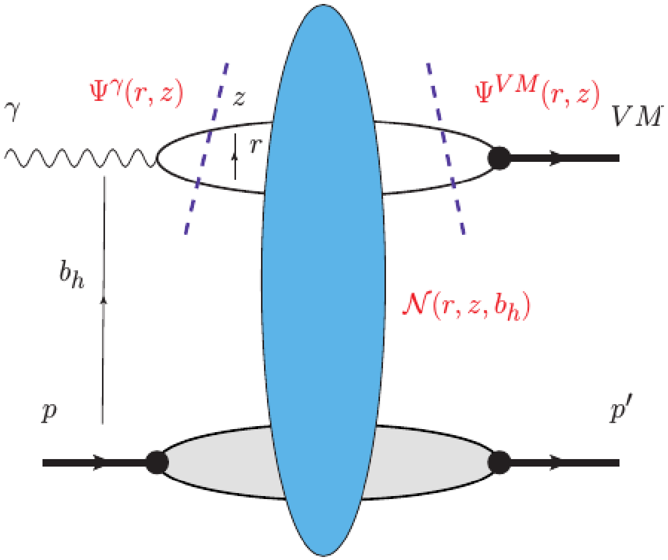


$$\frac{d\sigma\,[h_1 + h_2 \to h_1 \otimes V \otimes h_2]}{d^2b\,dy} = \left[\omega N_{h_1}(\omega, b)\, \sigma_{\gamma h_2 \to V \otimes h_2}\,(\omega)\right]_{\omega_L} + \left[\omega N_{h_2}(\omega, b)\, \sigma_{\gamma h_1 \to V \otimes h_1}\,(\omega)\right]_{\omega_R}$$

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

Exclusive vector meson photoproduction: A sketch of the formalism

* In the impact parameter space:



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

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

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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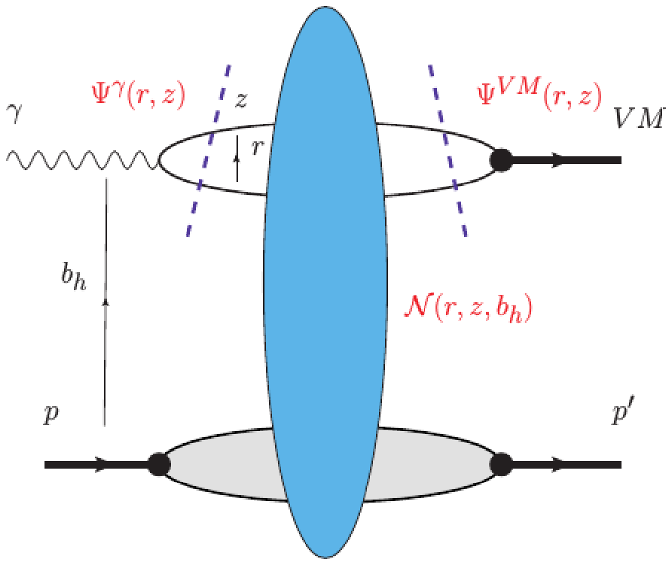

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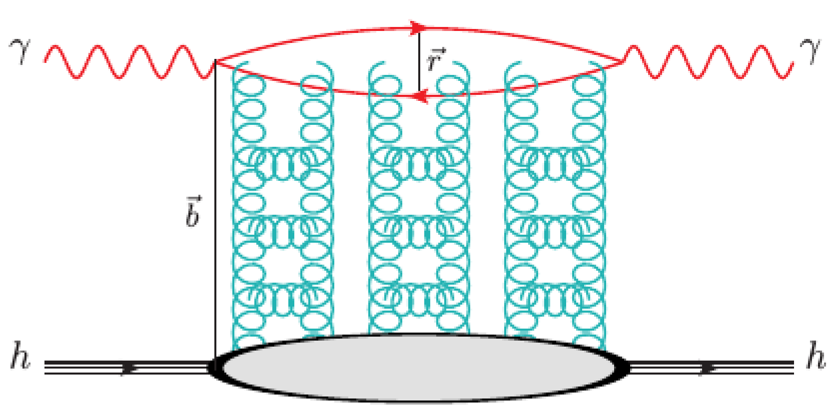
Exclusive vector meson photoproduction in hadronic collisions is strongly dependent on the description of the QCD dynamics.

Dipole – proton scattering

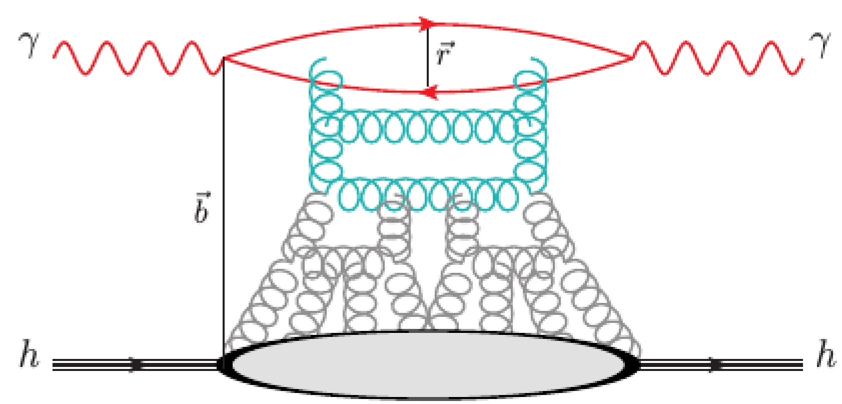
Two phenomenological models based on the CGC physics:

* IP – SAT model:



"Classical" CGC model.

* bCGC model:



"Quantum" CGC model.

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

Dipole - proton scattering

Two phenomenological models based on the CGC physics:

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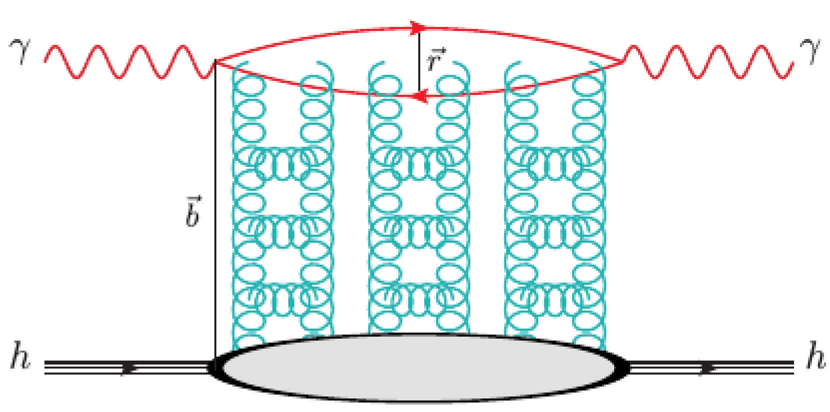

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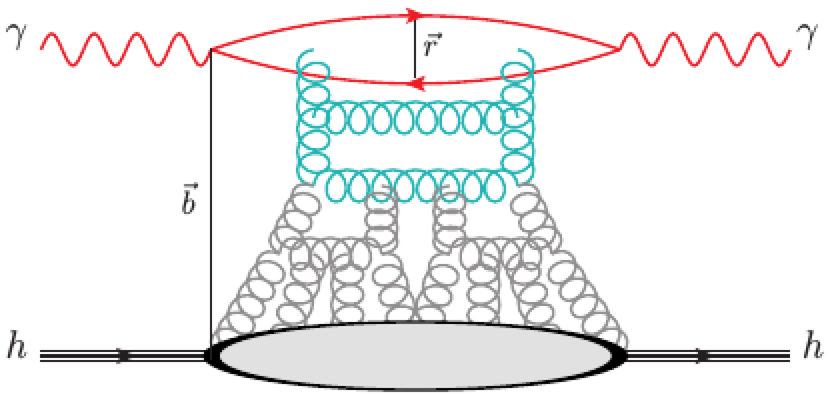


"Quantum" CGC model.

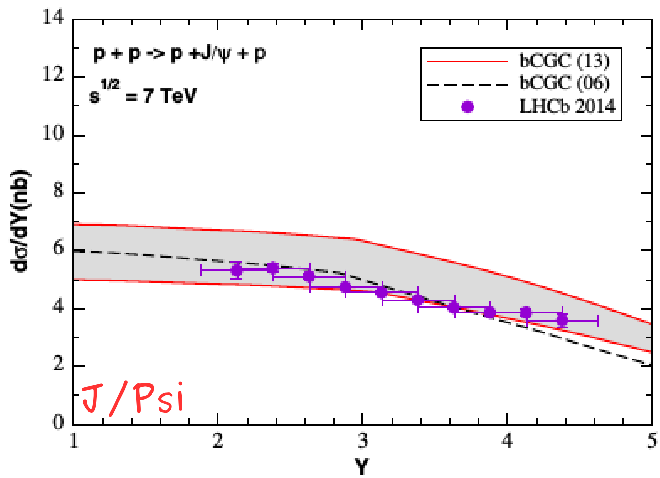
The color dipole predictions for LHC are free parameter.

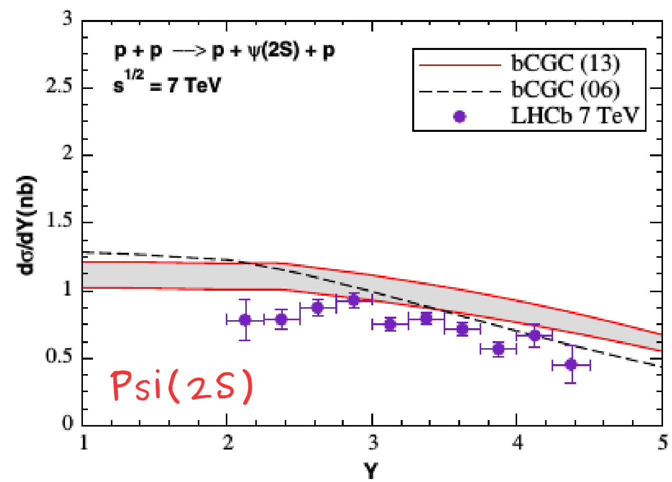
All parameters have been constrained by HERA data.

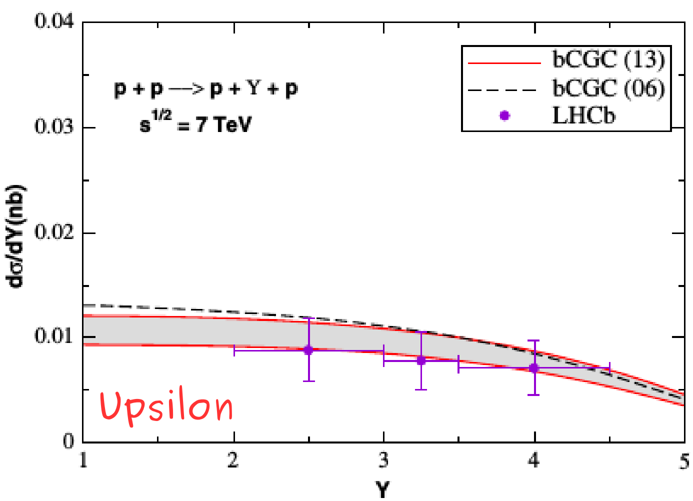
Recent results

Comparison with the LHCb Run I data

Exclusive VM photoproduction in pp collisions:



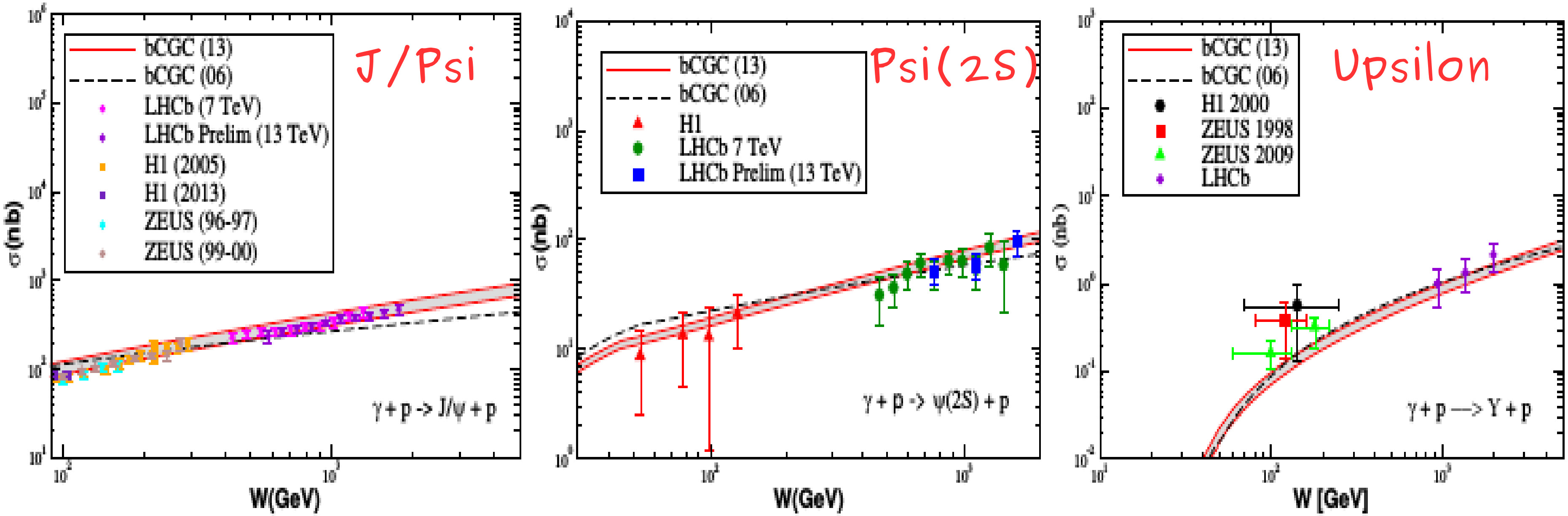




VPG, Moreira, Navarra, PRD95, 094024 (2016)

Energy dependence of the photon - proton cross sections

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

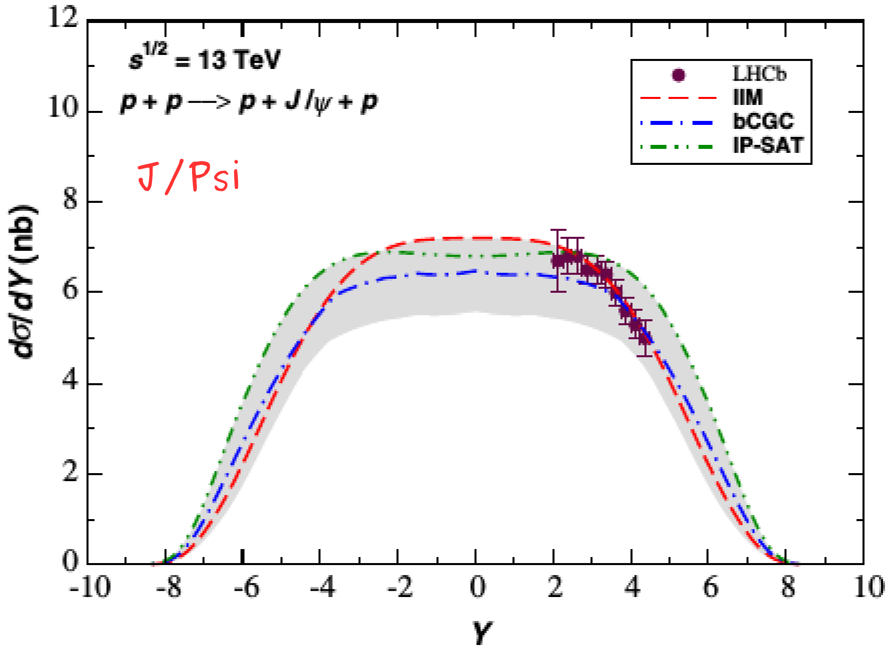


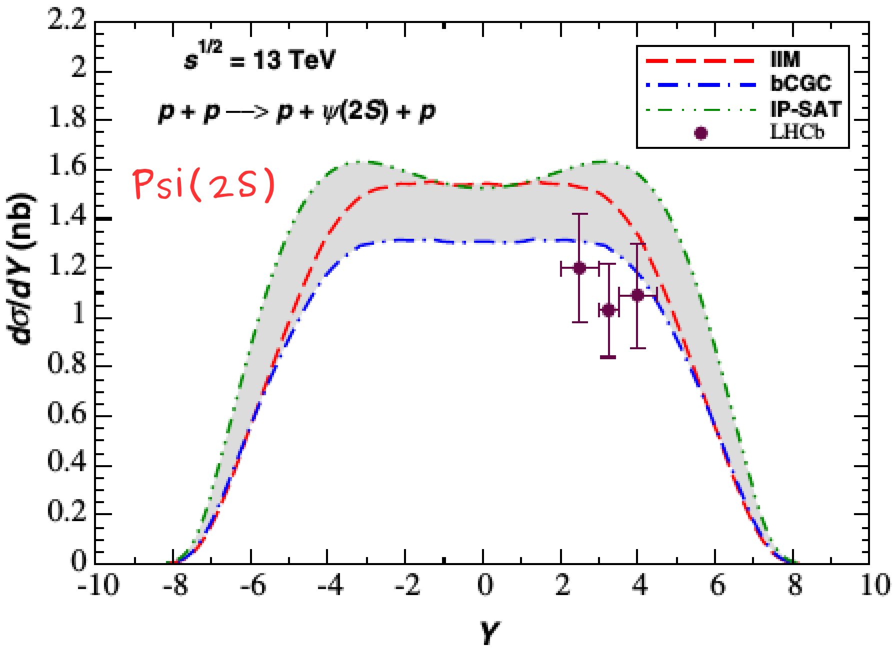
- LHC data is constraining the high - energy behavior of the photon - hadron cross sections!

VPG, Moreira, Navarra, PRD95, 094024 (2016)

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.

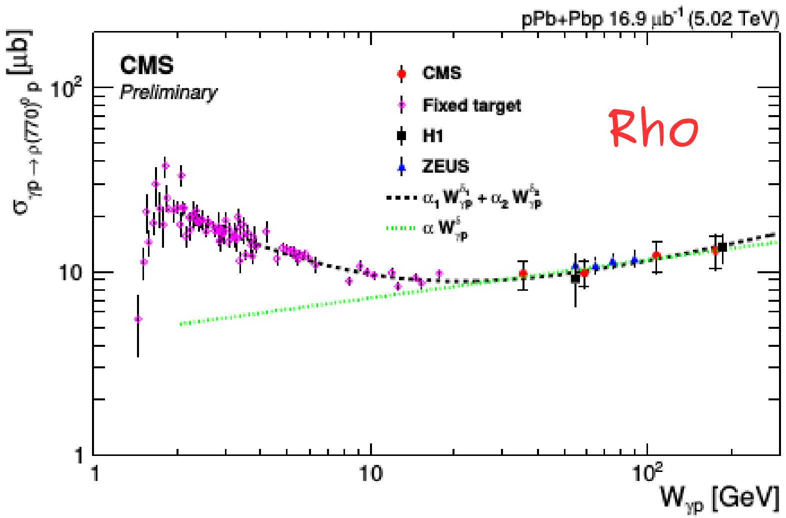
(*) VPG et al., PRD96, 094027 (2017)

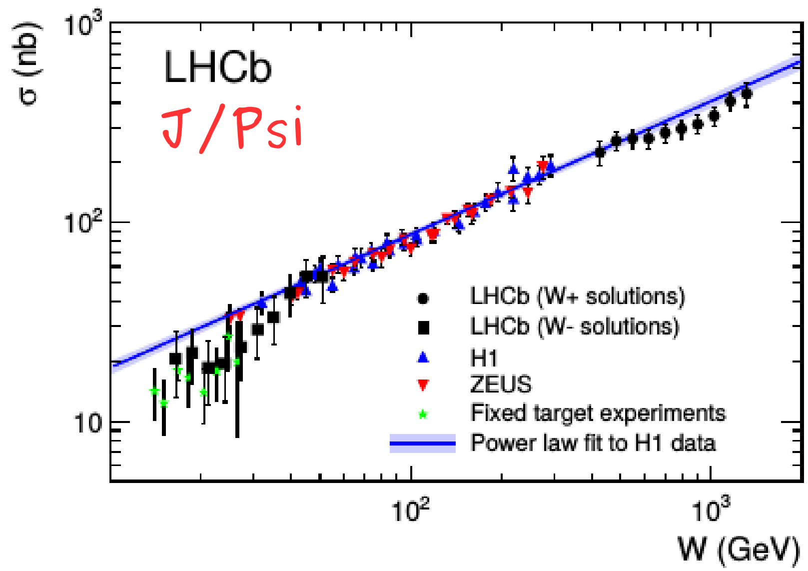
Prospects

(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.





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

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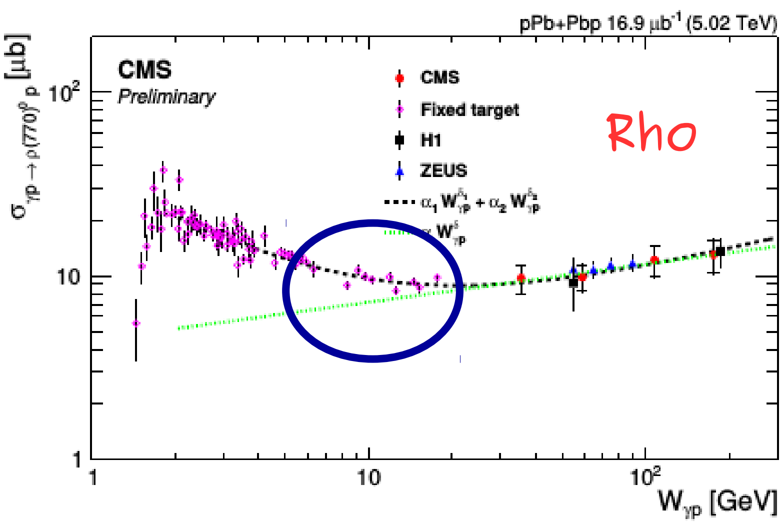
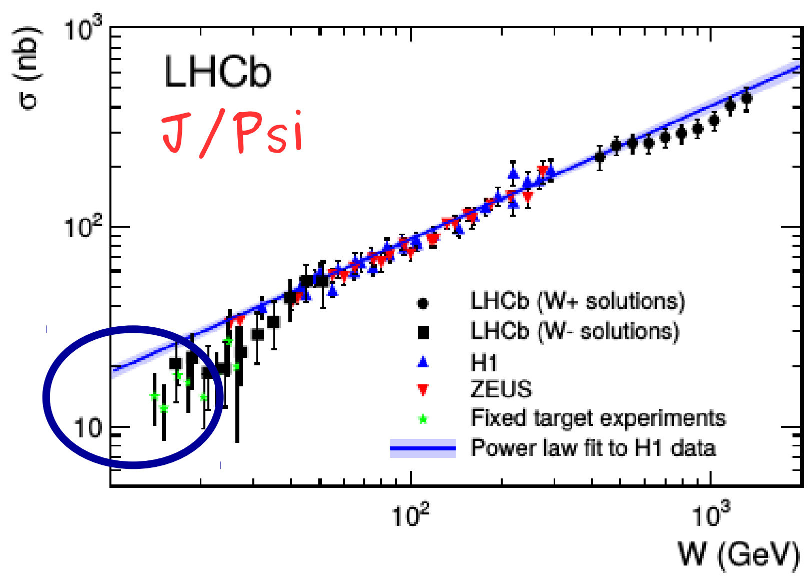
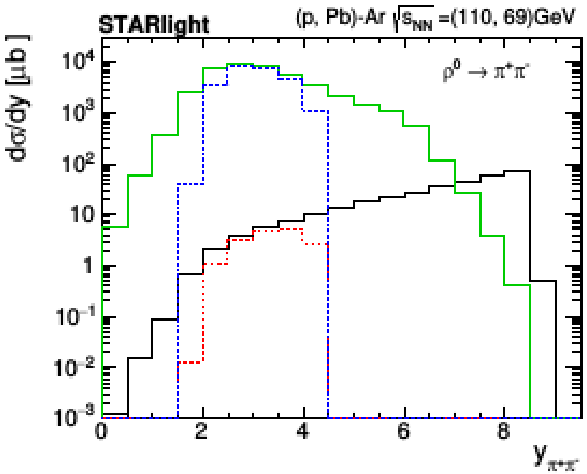




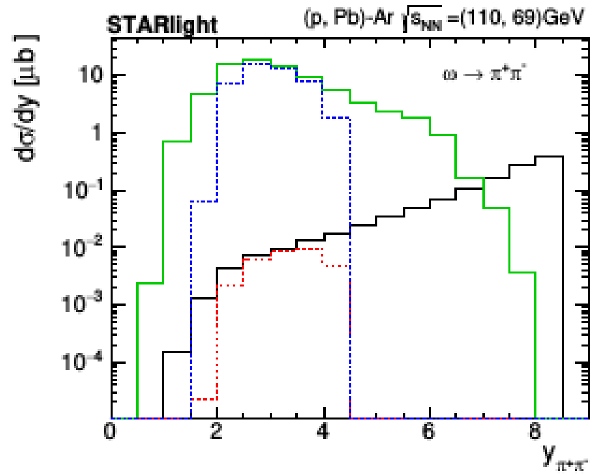
(*) VPG, Medina EPJC78, 693 (2018)

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

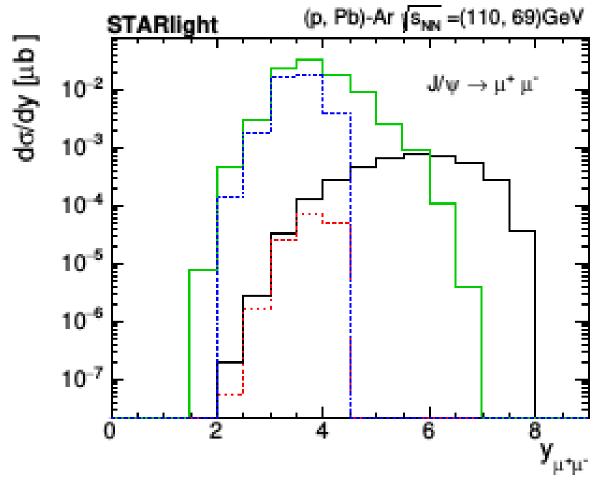
Rho



Omega



J/Psi

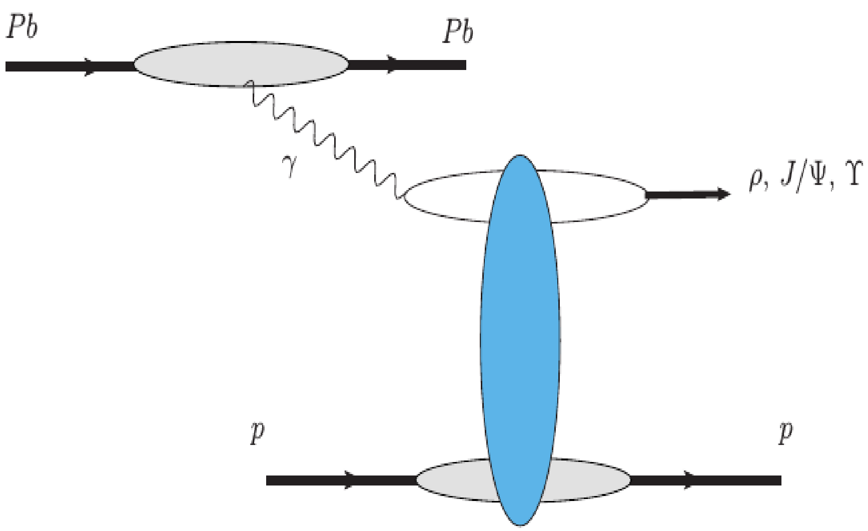


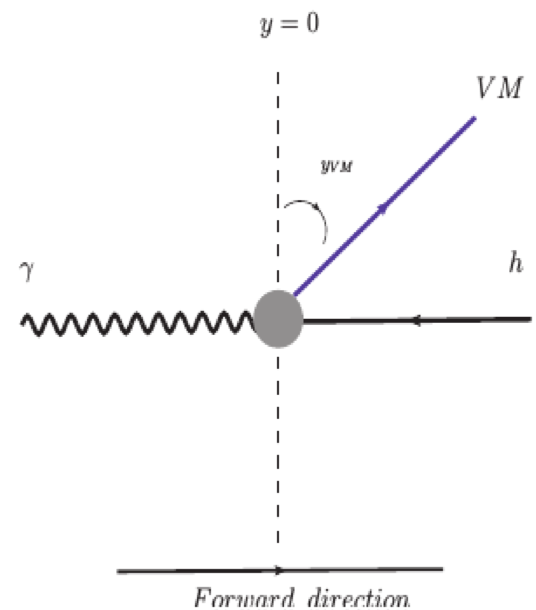
—p-Ar
---p-Ar LHCb
—Pb-Ar
.....Pb-Ar LHCb

Final State	p-Ar	p-He	Pb-Ar	Pb-He
$\rho^0 \to \pi^+\pi^-$	318.60 (16.50) μb	6.97 (1.09) μb	42.50 (24.50) mb	5.60 (2.44) mb
$\omega \to \pi^+\pi^-$	1160.12 (30.71) nb	21.86 (2.29) nb	76.32 (46.21) μb	12.81 (5.35) μb
$J/\psi \to \mu^+\mu^-$	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;

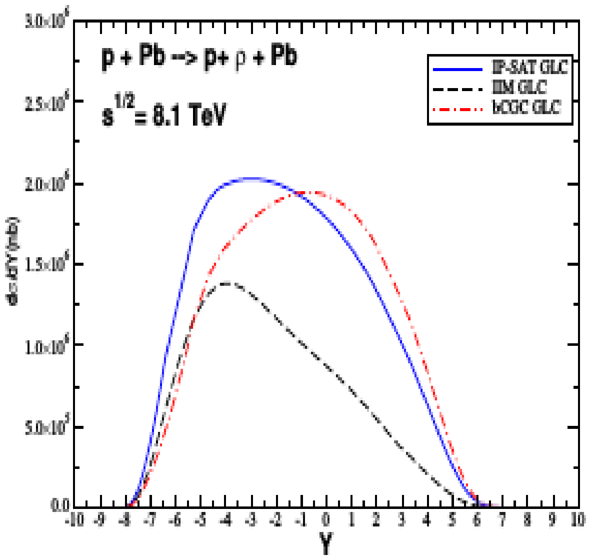
- Photon energy: $\boxed{\omega = \frac{m_V}{2} e^Y}$

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

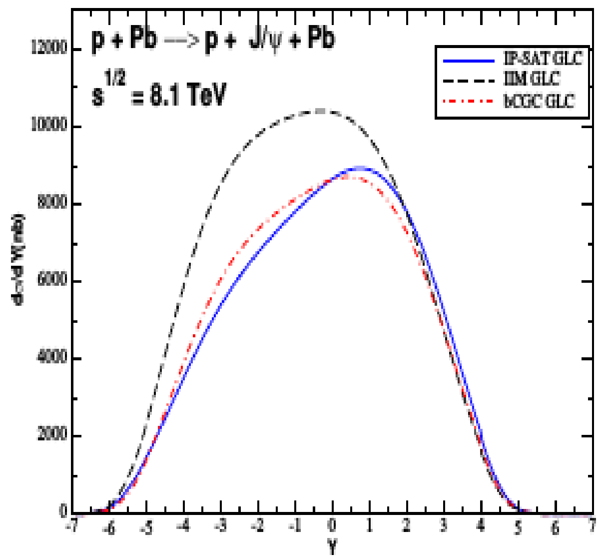
- Soft hadronic interactions are suppressed in comparison to pp collisions.

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

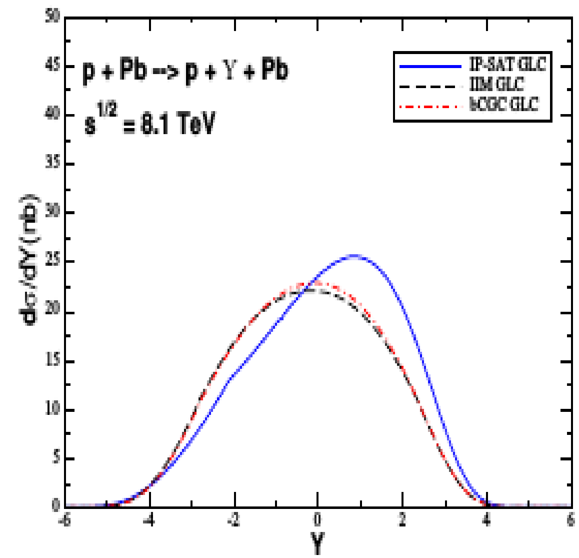
Rho



J/Psi



Upsilon

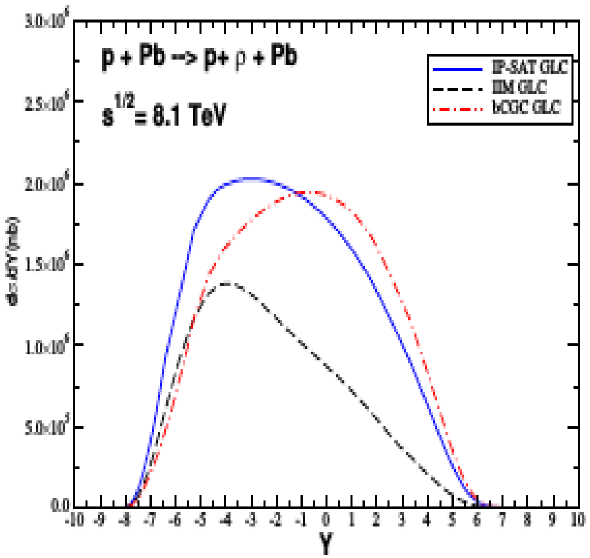


Rapidity distributions are sensitive to the different descriptions of the transition between the linear and non-linear regimes present in the distinct models.

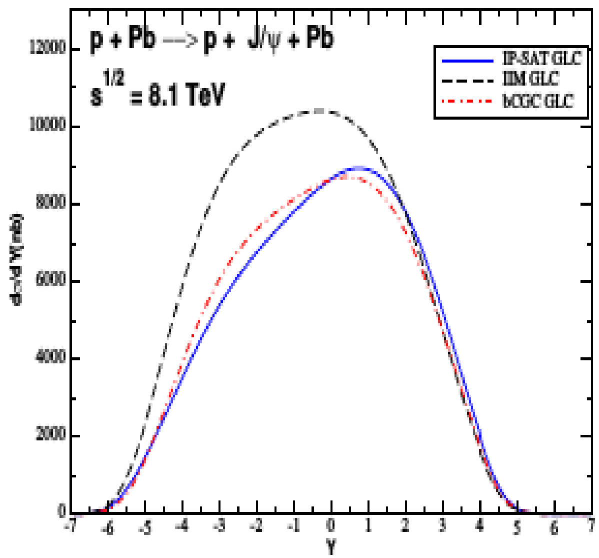
(*) VPG et al., PRD96, 094027 (2017)

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

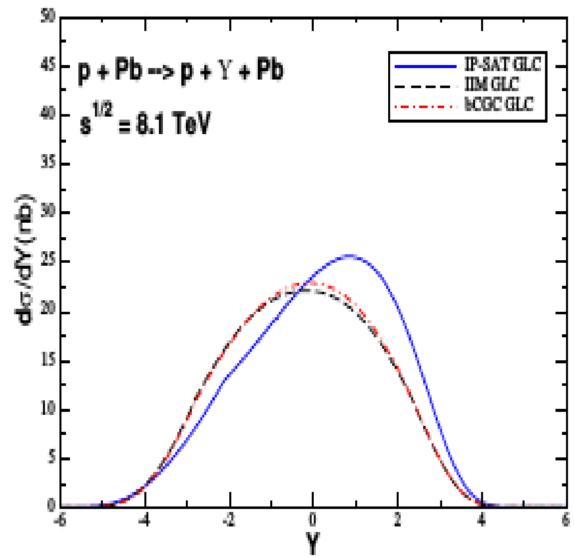
Rho



J/Psi



Upsilon

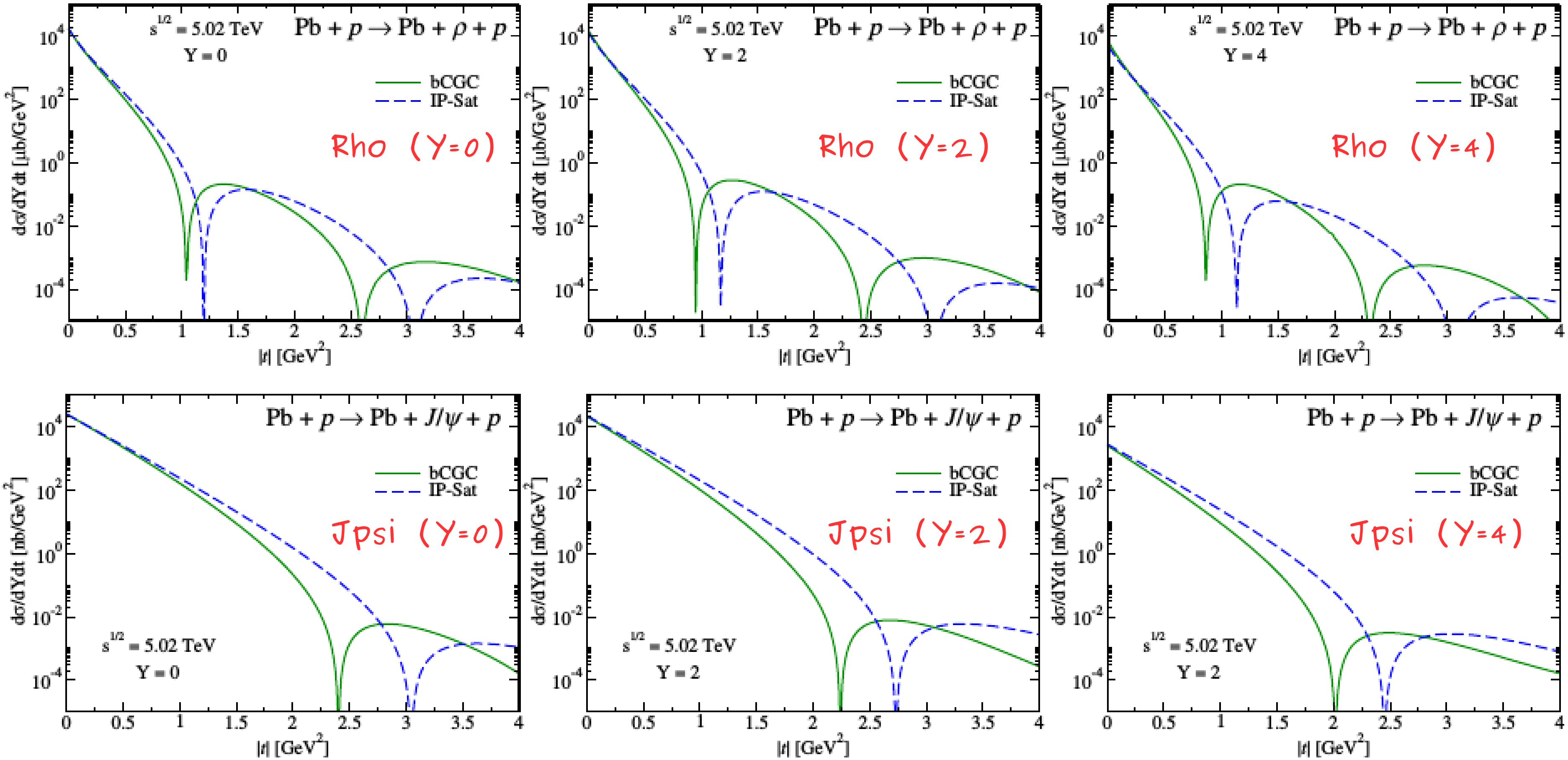


In order to discriminate/constrain the modelling of the QCD dynamics using the data for the rapidity distribution we should to have data for more than one VM.

(*) VPG et al., PRD96, 094027 (2017)

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

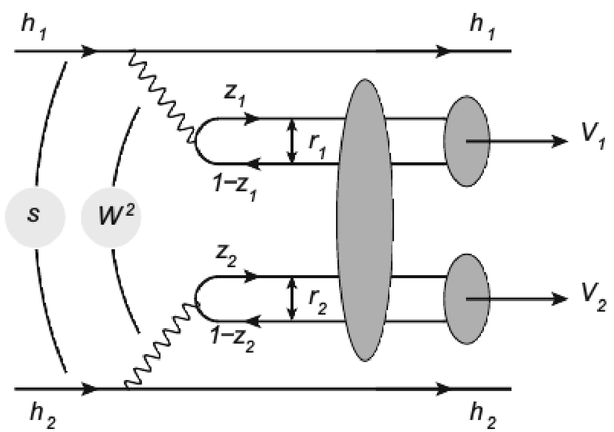
Alternative: Transverse momentum distributions (*)



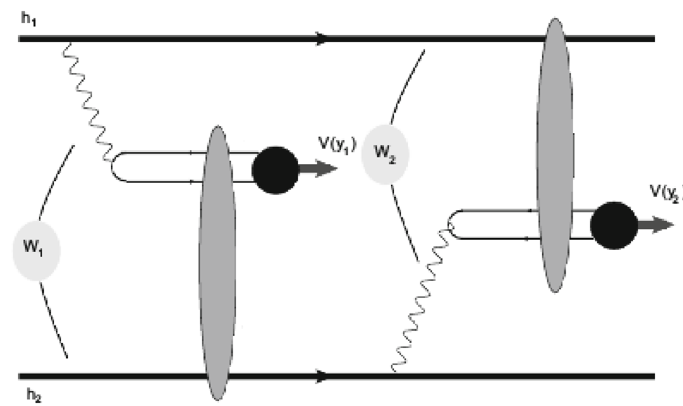
(*) VPG, Spiering, Navarra, arXiv:1811.09124 [hep-ph]

(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

VPG, Moreira, Navarra, EPJC 76, 388 (2016).

See also Szczurek, Kluzek, Schafer, PLB674, 92 (2009) and PRC89, 024912 (2014)

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

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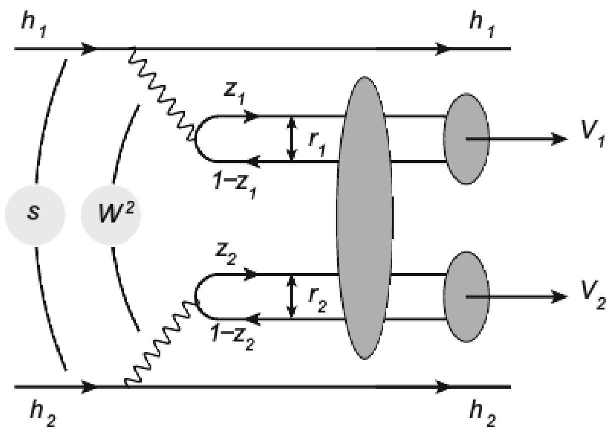

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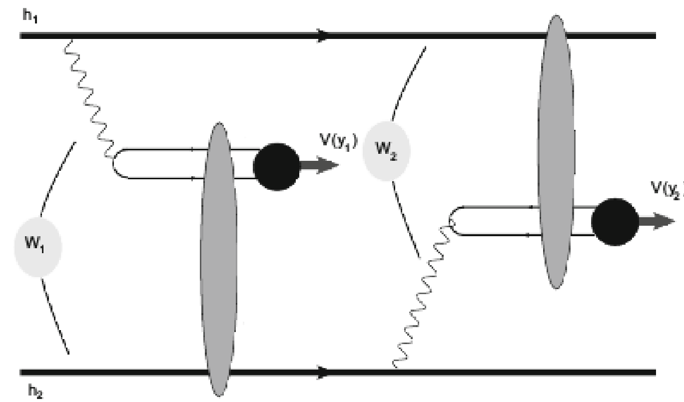

Final state	Mechanism	pPb $\sqrt{s} = 5$ TeV
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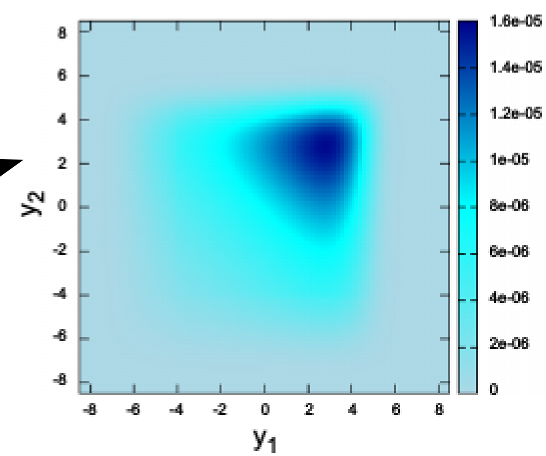
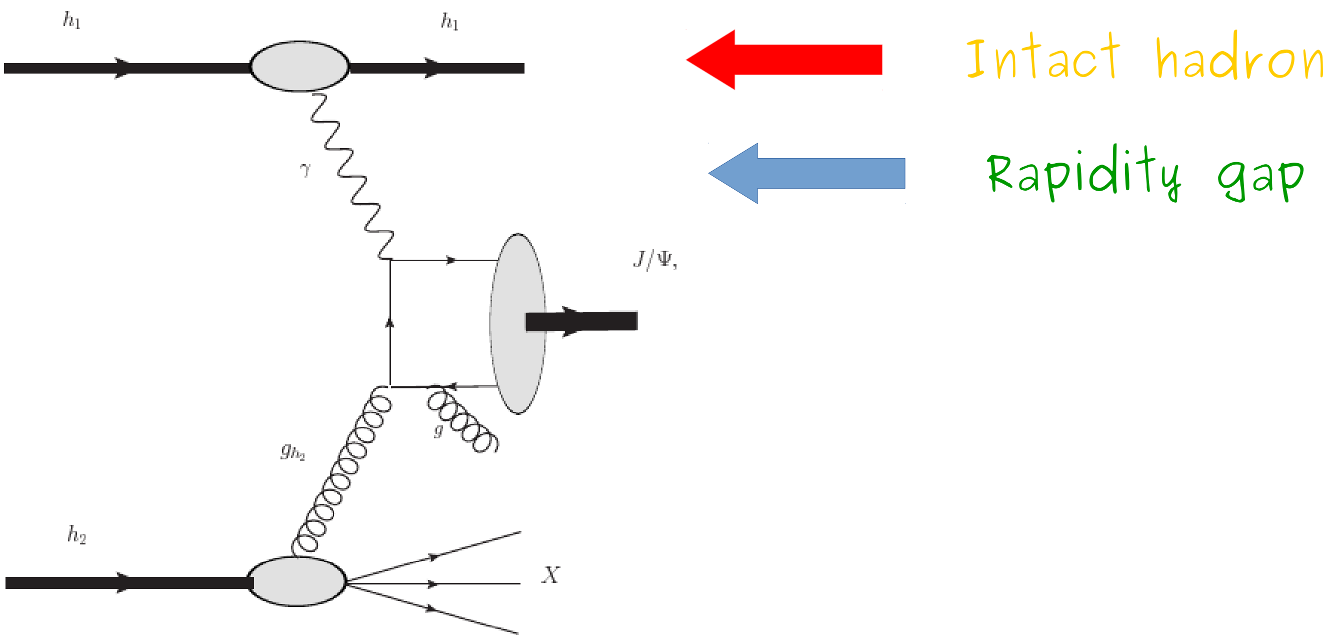


VPG, Moreira, Navarra, EPJC 76, 388 (2016).

See also Szczurek, Kluzek, Schafer, PLB674, 92 (2009) and PRC89, 024912 (2014)

(IV) Inclusive VM photoproduction in $p^{\uparrow}p$ and $p^{\uparrow}Au$ as a probe of the Gluon Sivers function (**).



(**) VPG, PRD97 (2018) 014001

Inclusive vector meson photoproduction at hadronic colliders: Polarized target

$$\sigma_{hp^\uparrow \to hJ/\Psi X}(\sqrt{s}) = \int dx_\gamma d^2\boldsymbol{k}_{\perp\gamma}\; f_{\gamma/h}(x_\gamma, \boldsymbol{k}_{\perp\gamma}) \cdot \sigma_{\gamma p^\uparrow \to J/\Psi X}(W^2_{\gamma p})$$

Quarkonium photoproduction: Color Evaporation Model

$$\sigma_{\gamma p^\uparrow \to J/\Psi X} = F_{J/\Psi}\; \overline{\sigma}_{\gamma p^\uparrow \to c\bar{c}X}$$

With:

$$\overline{\sigma}_{\gamma p^\uparrow \to c\bar{c}X} = \int_{4m_c^2}^{4m_D^2} dM^2_{c\bar{c}}\, dx_g\, d^2\boldsymbol{k}_{\perp g}\, f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g})\, \frac{d\sigma[\gamma g \to c\bar{c}]}{dM^2_{c\bar{c}}}$$

The cross section is proportional to the number density of gluons in the proton with transverse polarization S and momentum P, which is usually parametrized as:

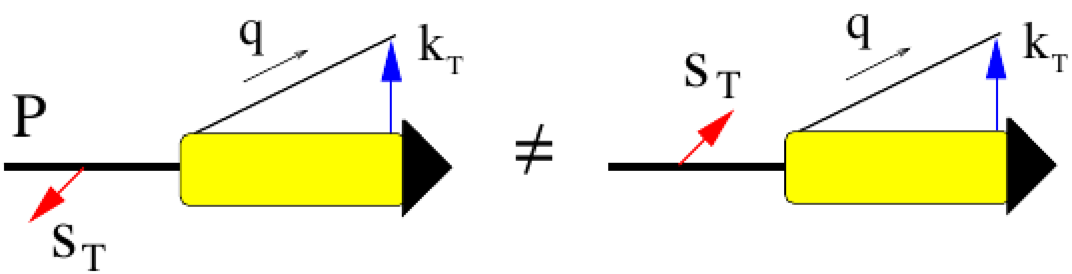
$$f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}, \boldsymbol{S}) \equiv f_{g/p}(x_g, k_{\perp g}) + \frac{1}{2}\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g})\hat{\boldsymbol{S}} \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}_{\perp g}})$$

Unpolarized gluon TMD

Gluon Sivers function

Sivers effect

Sivers (90's) have proposed that the transverse momentum of the partons inside of hadrons can be correlated with the spin.



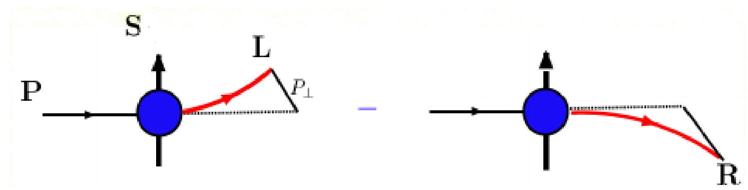
Gluon Sivers function: Unpolarized gluon in a polarized nucleon. Parametrizes the correlation between the azimuthal distribution of an unpolarized parton and the spin of its parent nucleon.

- While the quark Sivers function have been measured directly in many processes (e.g. SIDIS and DY), no direct clear measurements of the gluon Sivers function have been done.
- Potential probes: Quarkonium Electroproduction, J/Psi and D meson production in hadronic collisions, …

Single Spin Asymmetry

In order to probe the gluon Sivers function, in what follows we will investigate the impact of different models for $\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g})$ in the rapidity dependence of the single spin asymmetry, defined as:

$$\boxed{A_N(Y) = \frac{\frac{d\sigma^\uparrow}{dY} - \frac{d\sigma^\downarrow}{dY}}{\frac{d\sigma^\uparrow}{dY} + \frac{d\sigma^\downarrow}{dY}}}$$



Where $\frac{d\sigma^\uparrow}{dY}$ and $\frac{d\sigma^\downarrow}{dY}$ are respectively the differential cross sections measured when the proton is transversely polarized up (↑) and down (↓) with respect to the scattering plane. One have that:

$$\frac{d\sigma^\uparrow}{dY} - \frac{d\sigma^\downarrow}{dY} = F_{J/\Psi} \int d\phi_{q_T} \int q_T dq_T \int_{4m_c^2}^{4m_D^2} dM_{c\bar{c}}^2 \int d^2\boldsymbol{k}_{\perp g}\, f_{\gamma/h}(x_\gamma, \boldsymbol{q}_T - \boldsymbol{k}_{\perp g})$$
$$\times \; [f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}) - f_{g/p^\downarrow}(x_g, \boldsymbol{k}_{\perp g})]\, \hat{\sigma}_0(M_{c\bar{c}}^2)\, \sin(\phi_{q_T} - \phi_S)$$

$$\frac{d\sigma^\uparrow}{dY} + \frac{d\sigma^\downarrow}{dY} = 2\, F_{J/\Psi} \int d\phi_{q_T} \int q_T dq_T \int_{4m_c^2}^{4m_D^2} dM_{c\bar{c}}^2 \int d^2\boldsymbol{k}_{\perp g}\, f_{\gamma/h}(x_\gamma, \boldsymbol{q}_T - \boldsymbol{k}_{\perp g})\, f_{g/p}(x_g, \boldsymbol{k}_{\perp g}) \hat{\sigma}_0(M_{c\bar{c}}^2)$$

Single Spin Asymmetry

In our calculations we will assume that:

- Unpolarized gluon TMD: Gaussian form

$$\boxed{f_{g/p}(x_g, \boldsymbol{k}_{\perp g}) = f_{g/p}(x_g, \mu^2)\frac{1}{\pi\langle\, k_{\perp g}^2\rangle}e^{-\, k_{\perp g}^2/\langle\, k_{\perp g}^2\rangle}}$$

- Proton is moving along z – axis with momentum P and transversely polarized along y – axis;

- The gluon Sivers function can be parametrized as follows:

$$\boxed{\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g}) = 2N_g(x_g) f_{g/p}(x_g, \mu^2) h(k_{\perp g})\frac{e^{-\, k_{\perp g}^2/\langle\, k_{\perp g}^2\rangle}}{\pi\langle\, k_{\perp g}^2\rangle}}$$

Where:

$$N_g(x_g) = N_g x_g^\alpha (1-x_g)^\beta \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta} \quad \text{and} \quad h(k_{\perp g})\frac{e^{-\, k_{\perp g}^2/\langle\, k_{\perp g}^2\rangle}}{\pi\langle\, k_{\perp g}^2\rangle} = \frac{\sqrt{2e}}{\pi}\sqrt{\frac{1-\rho}{\rho}}\, k_{\perp g}\frac{e^{-\, k_{\perp g}^2/\rho\langle\, k_{\perp g}^2\rangle}}{\langle\, k_{\perp g}^2\rangle^{3/2}}$$

Single Spin Asymmetry

Possible parametrizations:

D'Alesio et al. [JHEP1509,119 (2015)]: Obtained by fitting the PHENIX data and using the quark Sivers parameters extracted earlier from the SIDIS data.

SIDIS1	$N_g = 0.65$	$\alpha_g = 2.8$	$\beta_g = 2.8$	$\rho = 0.687$	$\langle k_\perp^2 \rangle = 0.25\, GeV^2$
SIDIS2	$N_g = 0.05$	$\alpha_g = 0.8$	$\beta_g = 1.4$	$\rho = 0.576$	

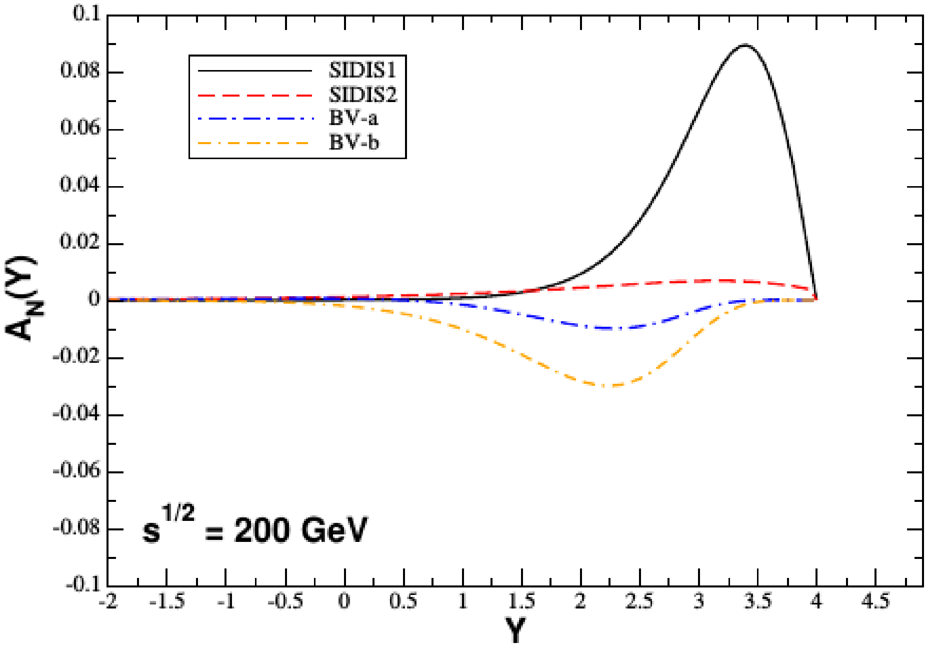
Boer and Vogelsang [PRD69, 094025 (2004)]: Proposed to express the gluon Sivers function in terms of the quark Sivers one.

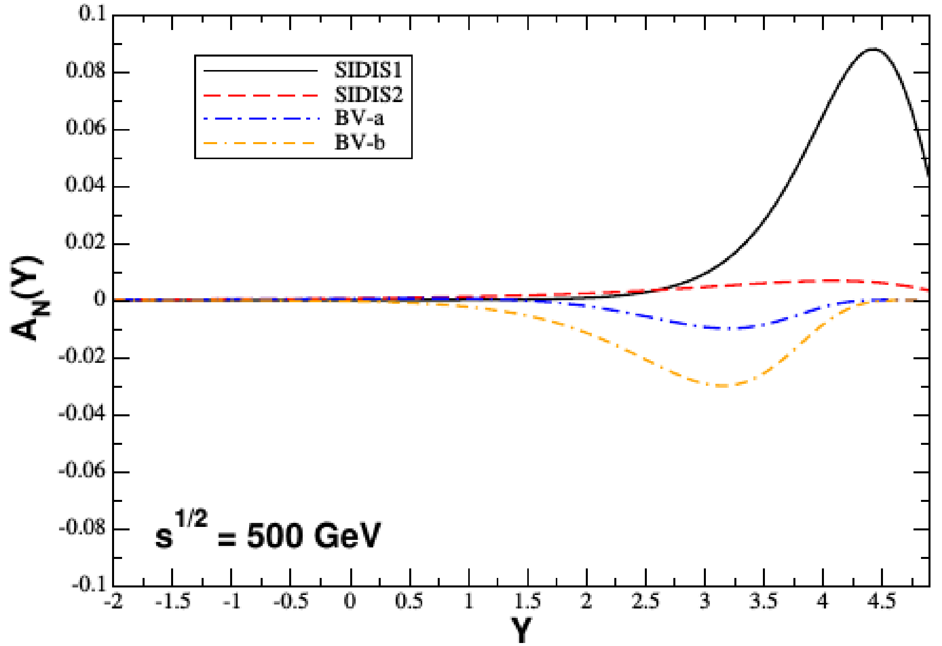
$$\mathcal{N}_g(x) = (\mathcal{N}_u(x) + \mathcal{N}_d(x))/2 \text{ (BV (A))}$$

$$\mathcal{N}_g(x) = \mathcal{N}_d(x) \text{ (BV (B))}$$

Results:

$$A_N(Y) = \frac{\frac{d\sigma^\uparrow}{dY} - \frac{d\sigma^\downarrow}{dY}}{\frac{d\sigma^\uparrow}{dY} + \frac{d\sigma^\downarrow}{dY}}$$





(*) VPG, PRD97 (2018) 014001

Summary

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- ✓ The vector meson photoproduction in photon – induced interactions is an important probe of the QCD and hadronic structure at high energies.
- ✓ In order to improve our understanding in these topics we should to advance in the theoretical description of the Vector Meson WF, dipole – proton scattering amplitude, Skeweness correction, …
- ✓ The Run II data for the photoproduction of different VM will be fundamental to constrain and/or discriminate between different models.
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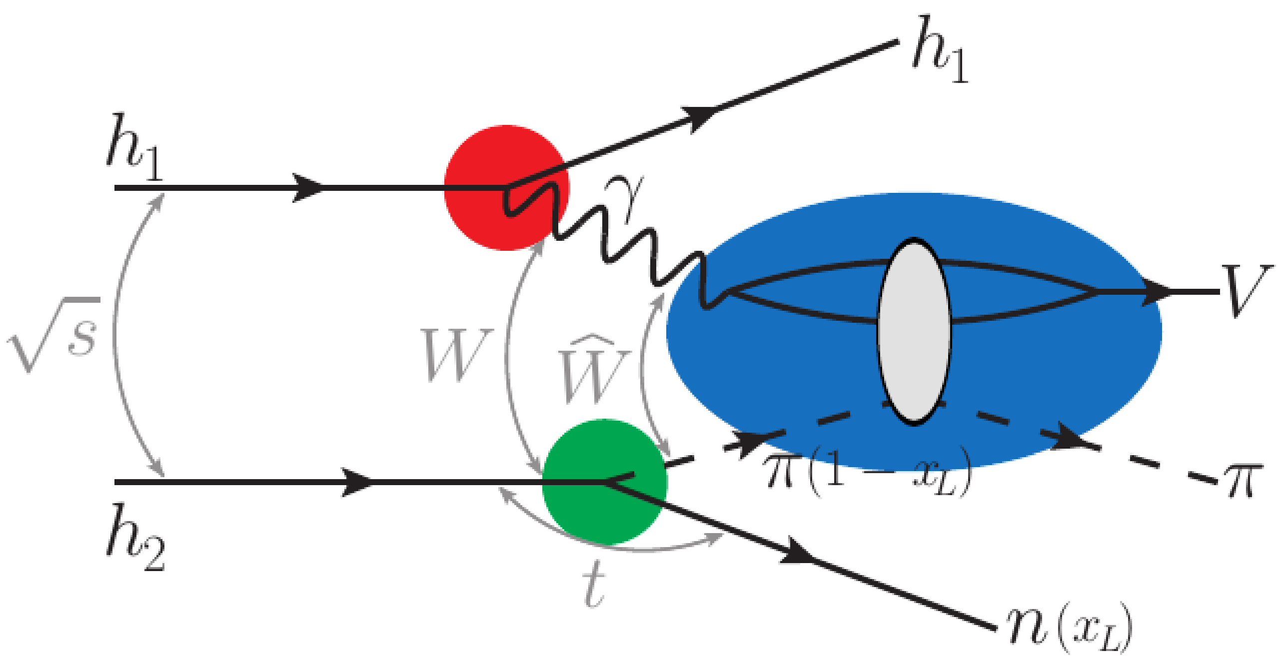
Thank you for your attention!

Extras

(V) Exclusive VM photoproduction associated to a leading baryon at the LHC



$$W^2 = m_V e^Y \sqrt{s}$$

$$\hat{W}^2 = (1-x_L)W^2$$

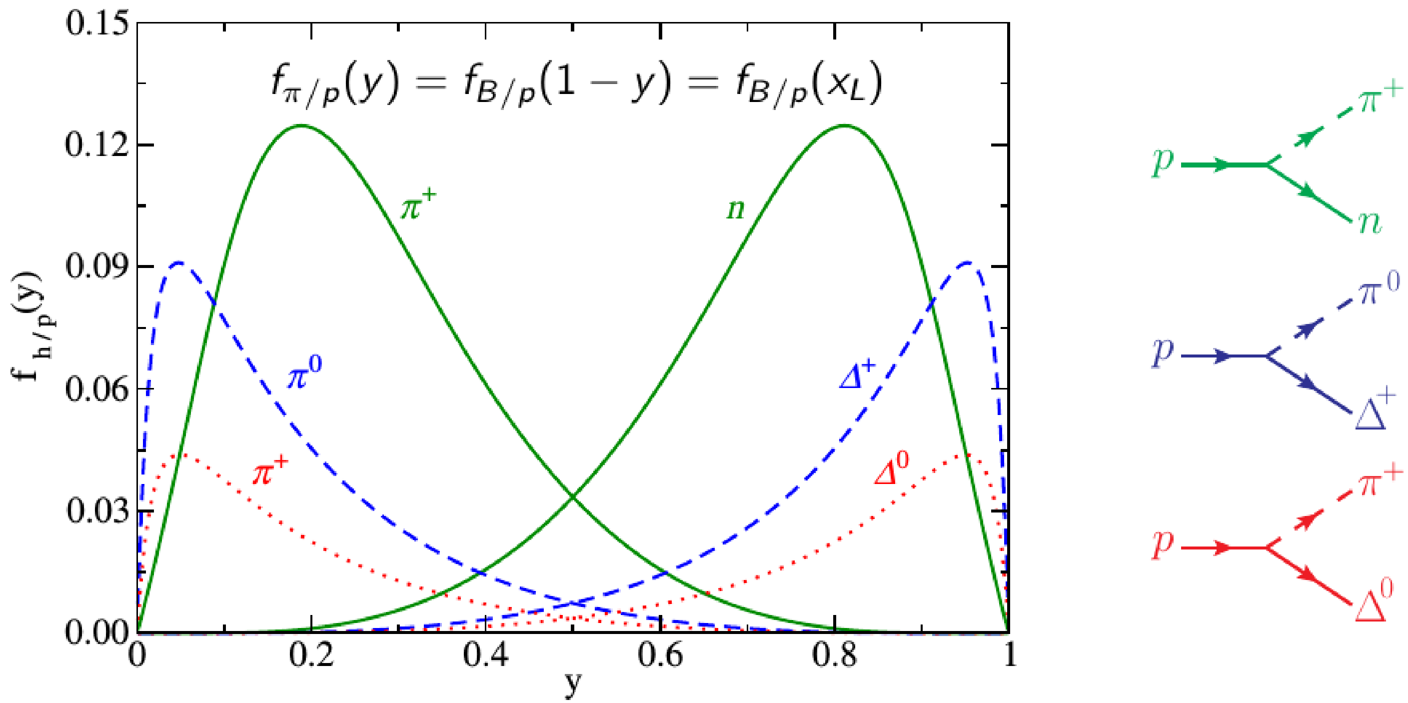
$$\frac{d\sigma(h_1+h_2 \rightarrow h_1+V+\pi+n)}{dY dx_L dt} = N_{\gamma/h_1}(Y) \otimes f_{\pi/p}(x_L,t) \otimes \sigma_{\gamma\pi}(\hat{W})$$

VPG, Spiering, Navarra et al, PRD94, 014009 (2016); PRD97, 074002 (2018).

(V) Exclusive VM photoproduction associated to a leading baryon at the LHC

Flux of pions / Pion Splitting function:

$$\boxed{f_{\pi/p}(y) = \frac{1}{4\pi}\frac{g_{p\pi B}^2}{4\pi}\int_{-\infty}^{t_{min}} dt \frac{\mathcal{B}(t, m_p, m_B)}{(t-m_\pi^2)^2} y^{1-2t}[F(t)]^2}$$



VPG, Spiering, Navarra et al, PRD94, 014009 (2016); PRD97, 074002 (2018).

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Photon – pion cross section:

$$\sigma(\gamma^* \pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{L,T} \int_{-\infty}^{0} \left| \mathcal{A}_{L,T}^{\gamma^* \pi \to E\pi}(\hat{x}, \Delta) \right|^2 d\hat{t}$$

$$\hat{t} = -\Delta^2 \qquad \hat{x} = \frac{Q^2+m_f^2}{\hat{W}^2+Q^2} = \frac{Q^2+m_f^2}{(1-x_L)W^2+Q^2}$$

$$\mathcal{A}_{L,T}^{\gamma^* \pi \to E\pi} = i \int dz\, d^2\vec{r}\, d^2\vec{b}\, e^{-i[\vec{b}-(1-z)\vec{r}]\cdot\vec{\Delta}} \left[\Psi_E^* \Psi(z, \vec{r}, Q^2)\right]_{L,T} 2\mathcal{N}^{\pi}(\hat{x}, \vec{r}, \vec{b})$$

Main assumption $\Longrightarrow$ $\mathcal{N}^{\pi}(\hat{x}, \vec{r}, \vec{b}) = R_q \cdot \mathcal{N}^{p}(\hat{x}, \vec{r}, \vec{b})$

$R_q = \text{cte} \quad \rightsquigarrow \quad 1/3 \leq R_q \leq 2/3$

VPG, Spiering, Navarra et al, PRD94, 014009 (2016); PRD97, 074002 (2018).

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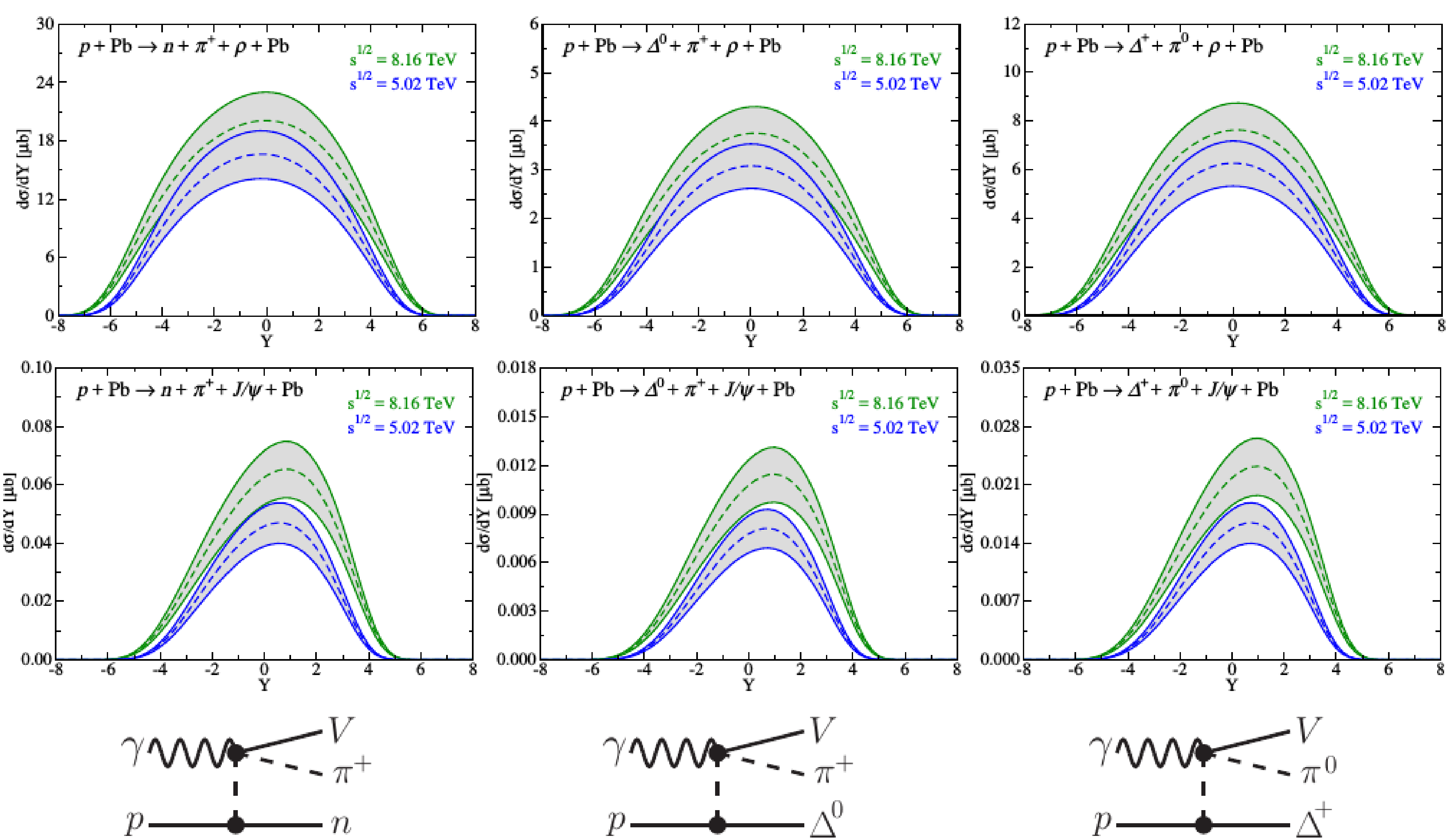

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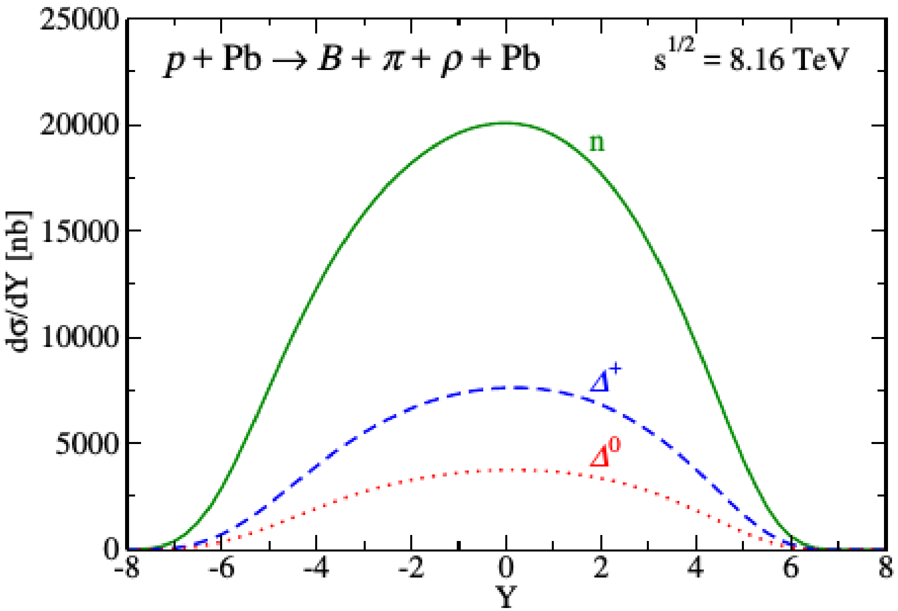
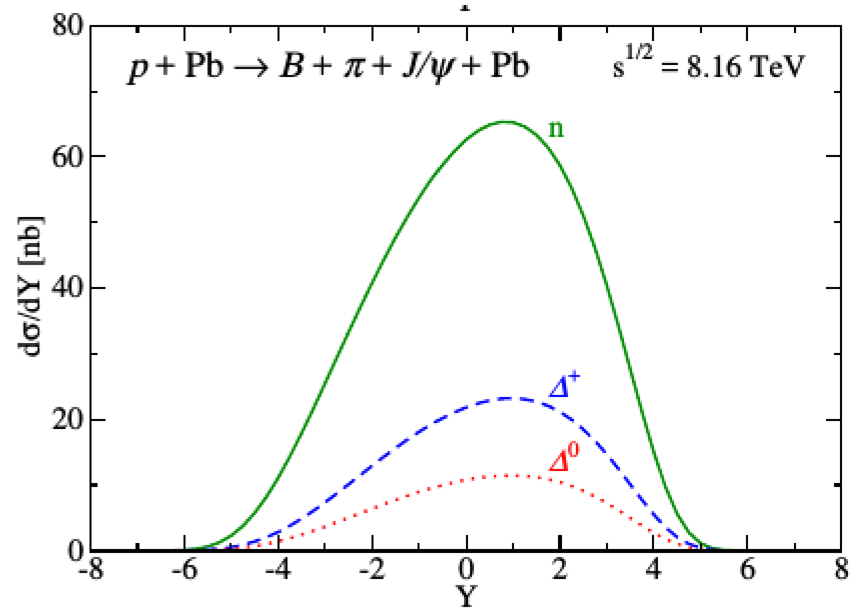




VPG, Spiering, Navarra et al, PRD94, 014009 (2016); PRD97, 074002 (2018).

(V) Exclusive VM photoproduction associated to a leading baryon at the LHC

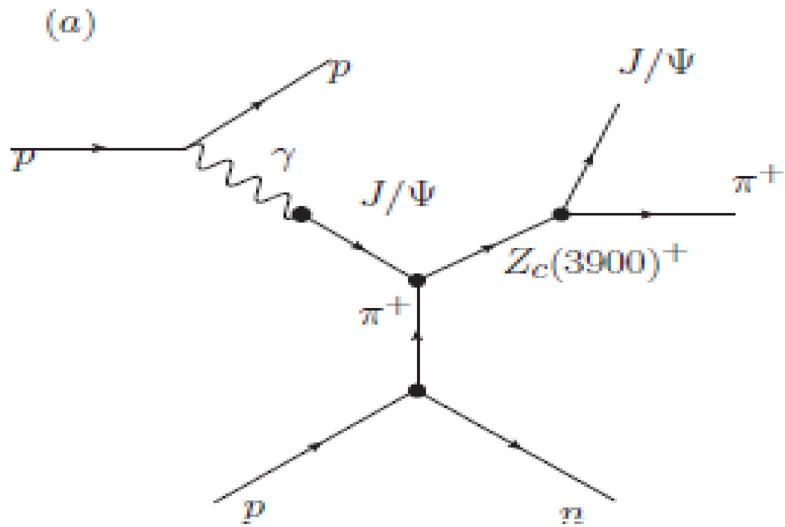
VM	ρ		J/ψ	
$\sqrt{s}$/TeV (pPb)	5.02	8.16	5.02	8.16
$\sigma(n\pi^+)/\mu$b	124.026	163.124	0.244	0.376
$\sigma(\Delta^0\pi^+)/\mu$b	22.090	29.349	0.040	0.063
$\sigma(\Delta^+\pi^0)/\mu$b	44.817	59.561	0.082	0.128

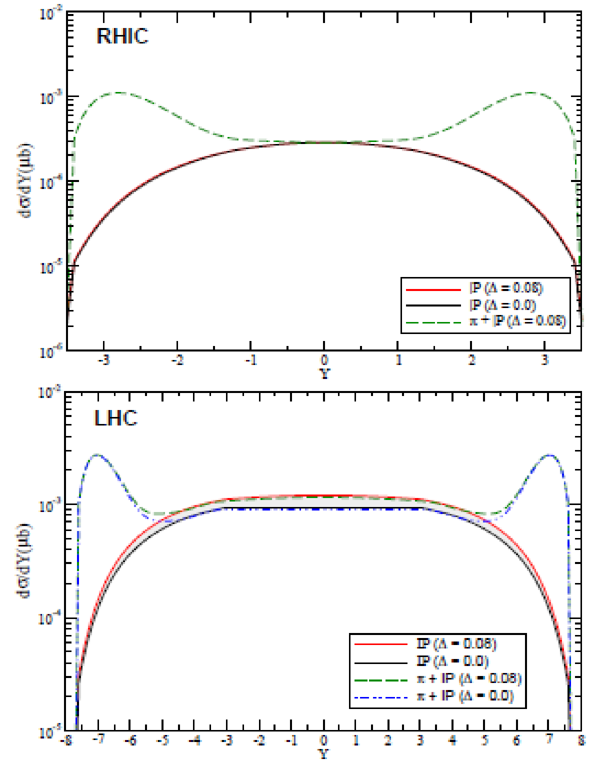
The case with a leading neutron is smaller by $\sim 10^2$ of magnitude.
The case with a leading delta is smaller by $\sim 10^3$ of magnitude.

VPG, Spiering, Navarra et al, PRD94, 014009 (2016); PRD97, 074002 (2018).

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

Photoproduction of $Z_c(3900)^+$:





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

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

VPG, Silva, PRD 89, 114005 (2014).

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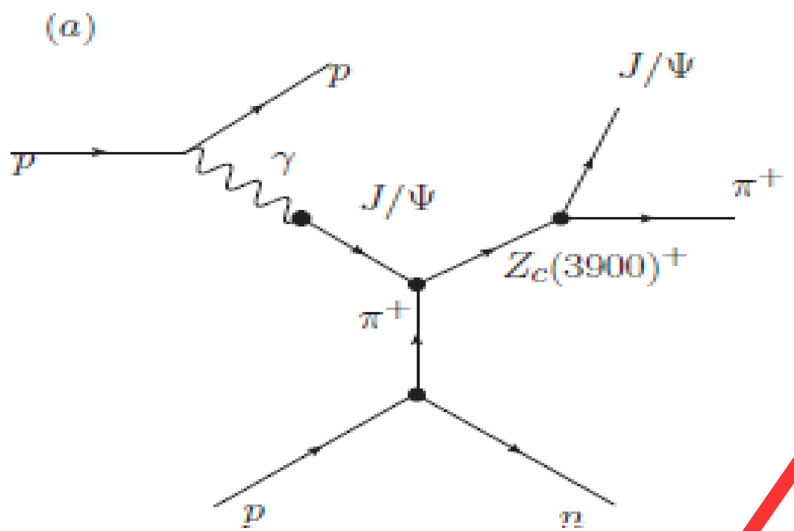
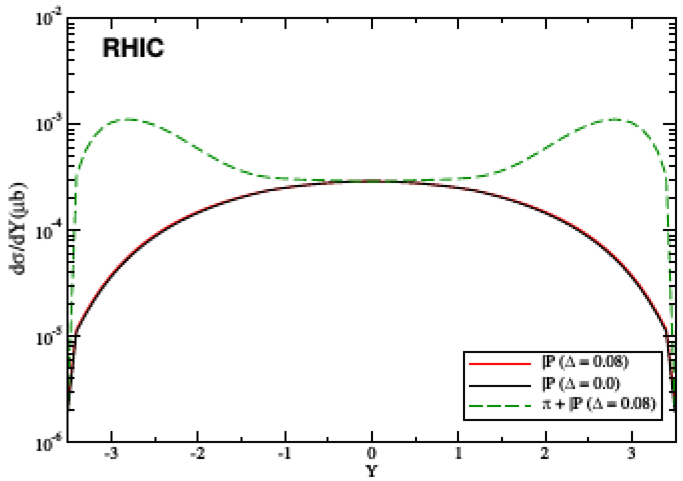
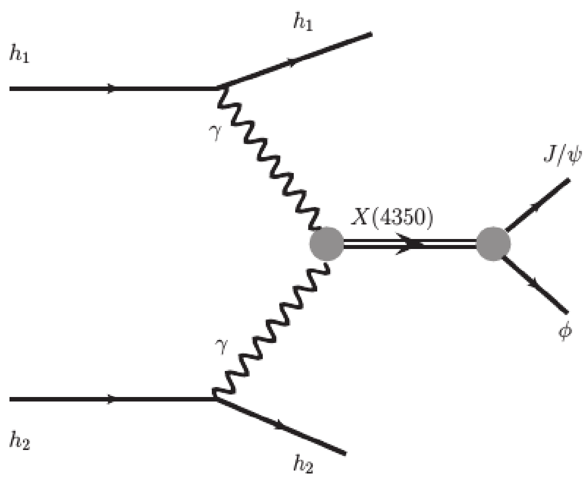




Similar enhancement is expected in fixed - target pHe collisions in the range probed by the LHCb.

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

Photoproduction of X(4350):



VPG, Moreira, EPJC 79, 7 (2019).

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

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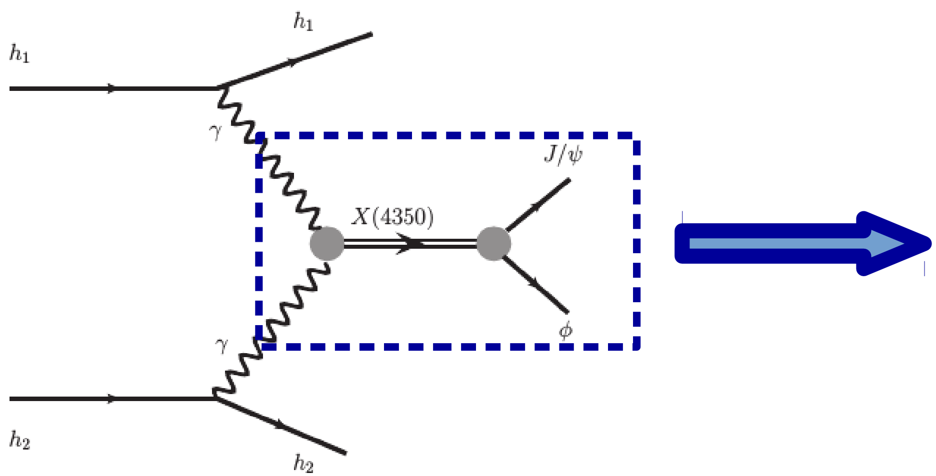

Constrained by Belle Collaboration.

VPG, Moreira, EPJC 79, 7 (2019).

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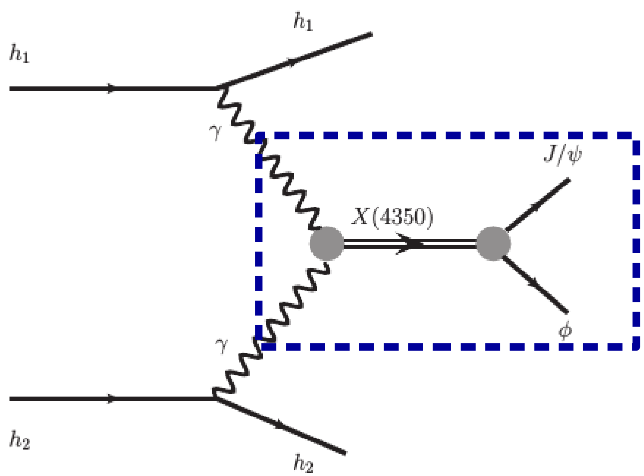

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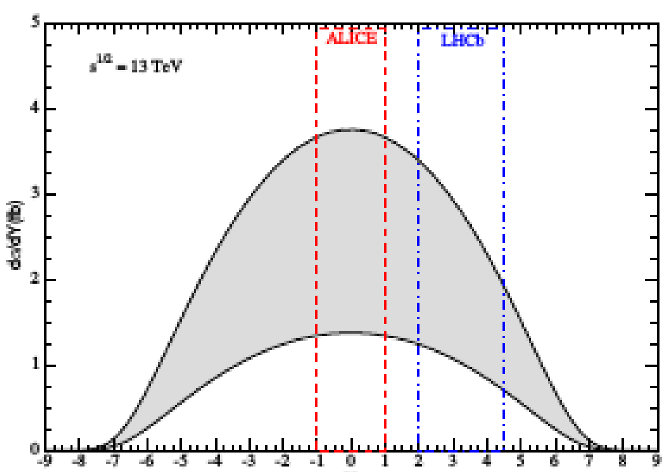

Collision	Resonance	LHCb $2 < Y < 4.5$
pp ($\sqrt{s}$ =13 TeV)	$X(4350)$, 0^{++}	(2.47 – 6.13) fb
	$X(4350)$, 2^{++}	(2.52 – 6.88) fb
pPb ($\sqrt{s}$ =8.1 TeV)	$X(4350)$, 0^{++}	(10.20 – 25.30) pb
	$X(4350)$, 2^{++}	(10.30 – 28.30) pb
$PbPb$ ($\sqrt{s}$ =5.02 TeV)	$X(4350)$, 0^{++}	(14.60 – 36.20) nb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

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