Second LHCb Heavy Ion Workshop:

Exploring matter with precision charm and bottom production measurements in Heavy Nuclei Collisions

Theory of Ultra - Peripheral Collisions

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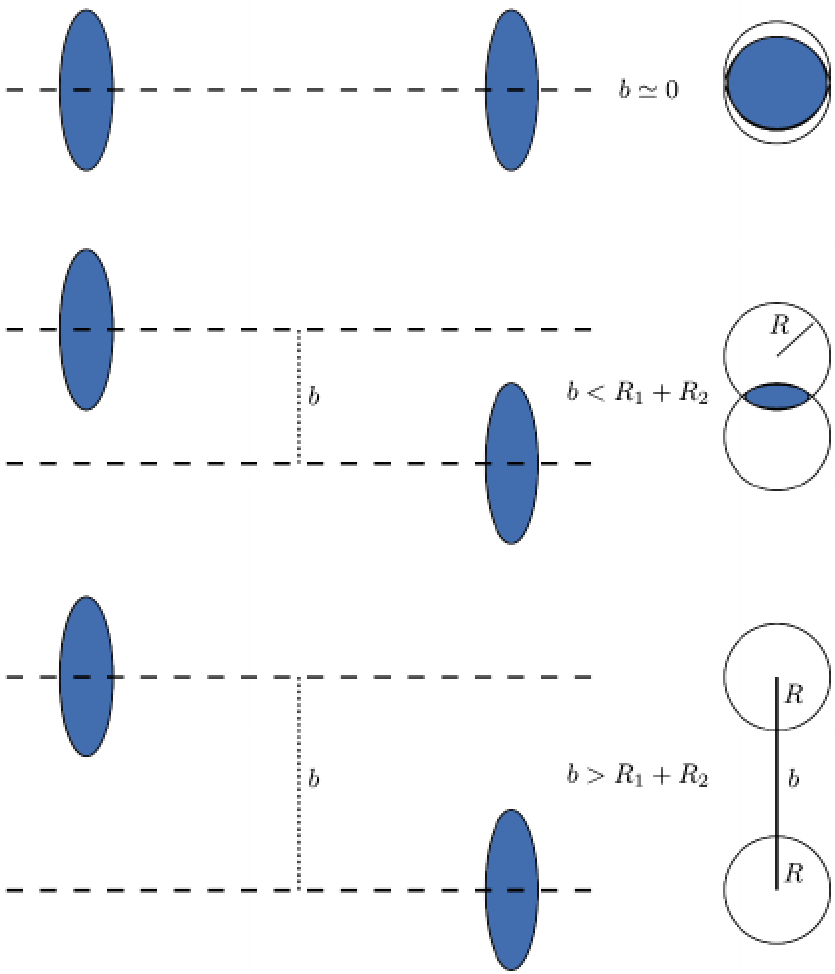
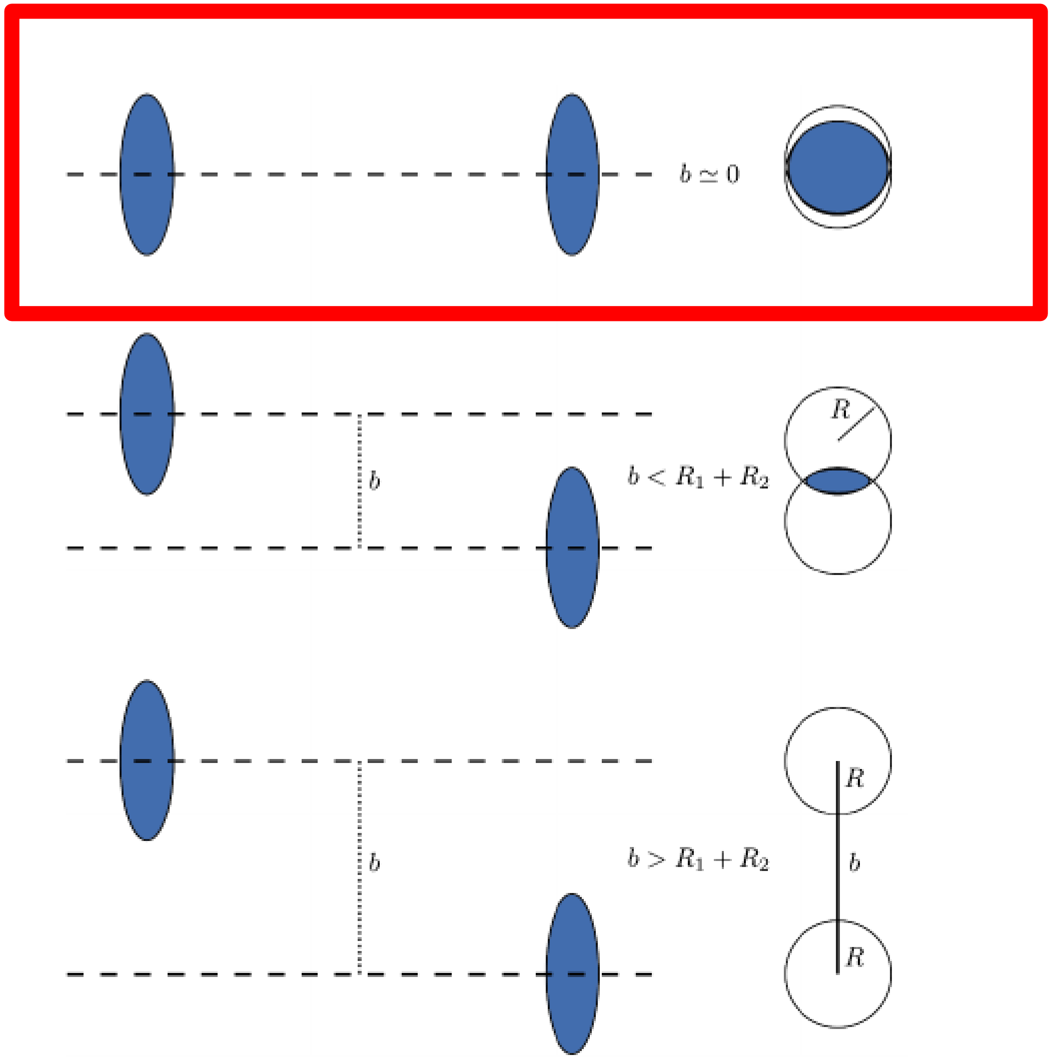
06 Sept 2019

Hadronic collisions



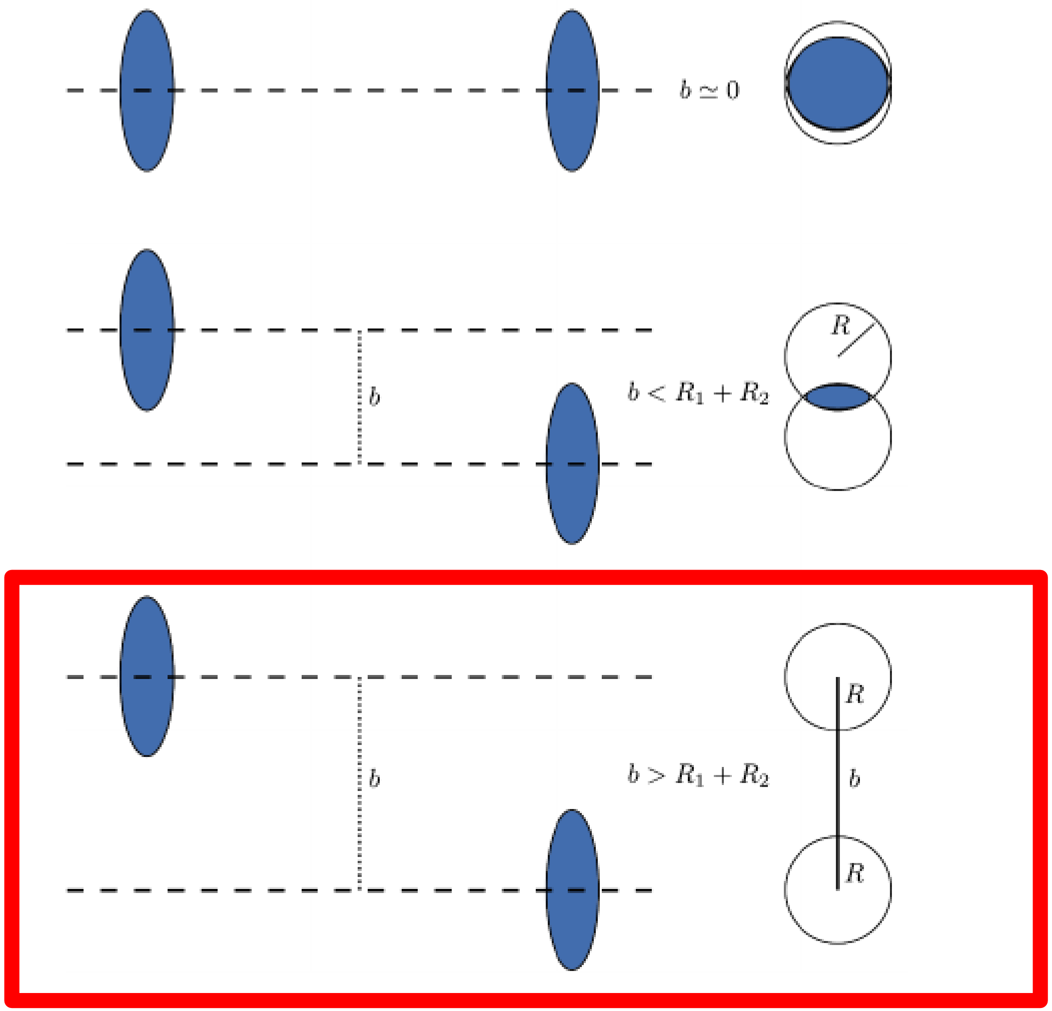
Hadronic collisions



Central collisions:

Dominated by strong interactions!

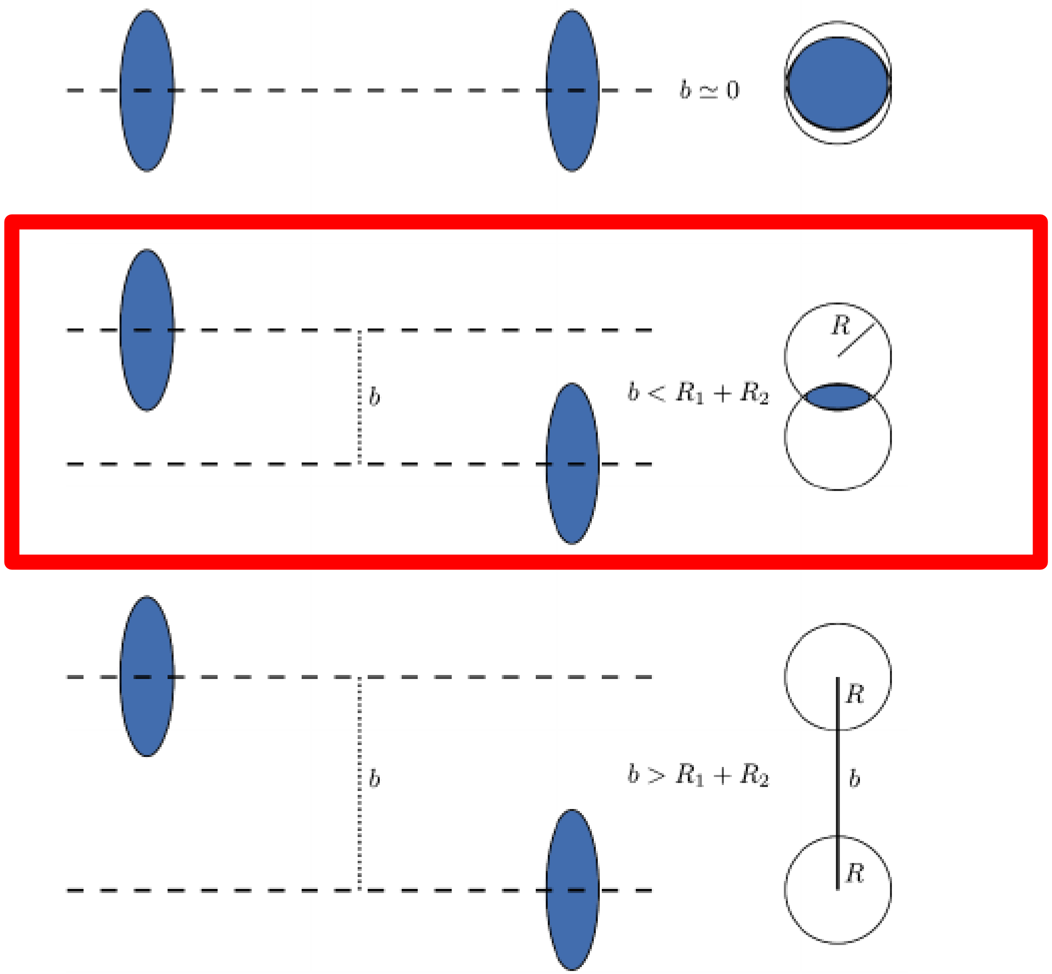
Hadronic collisions



Ultra - peripheral collisions:

Dominated by photon - induced interactions!

Hadronic collisions



Peripheral collisions:

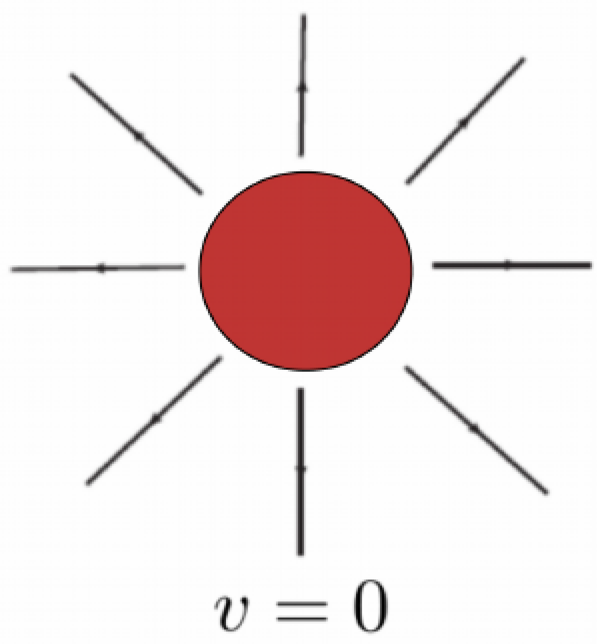
The contribution of photon – induced interactions can become dominant in the dilepton and vector meson production for some regions of phase space!

Ultra - peripheral Collisions: Basic Concepts

The equivalent photon approximation

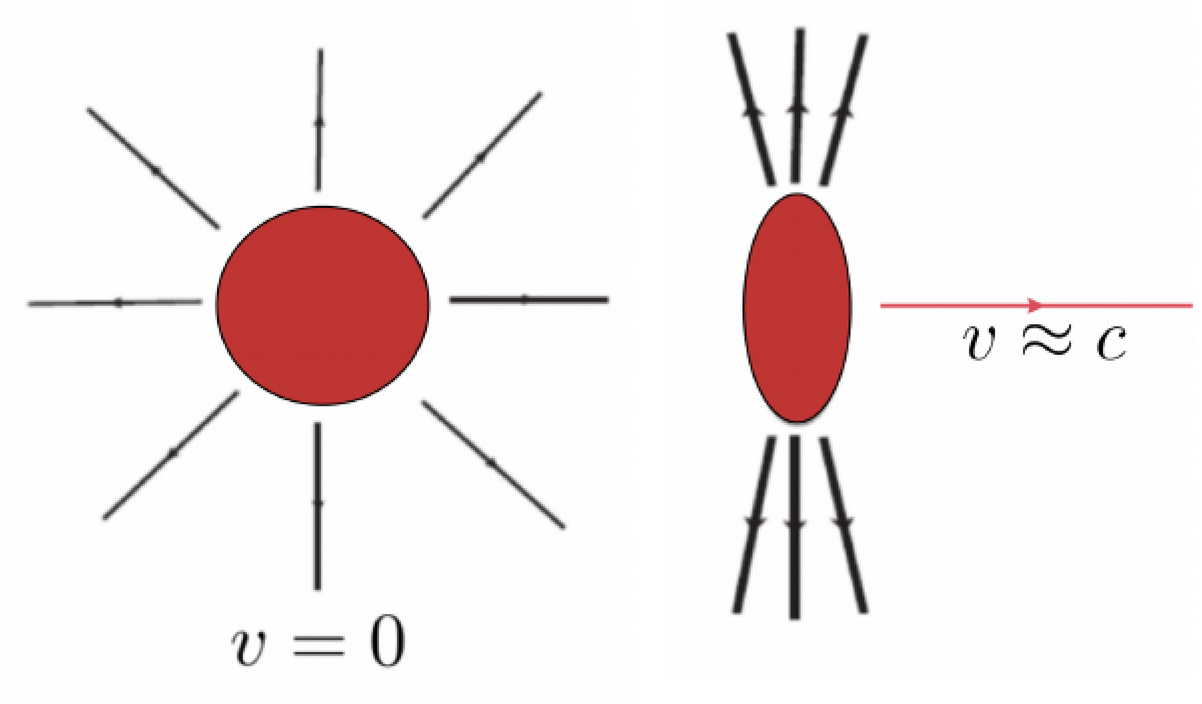
The equivalent photon approximation

Consider a charged nucleus at rest. The associated electromagnetic field can be represented by:



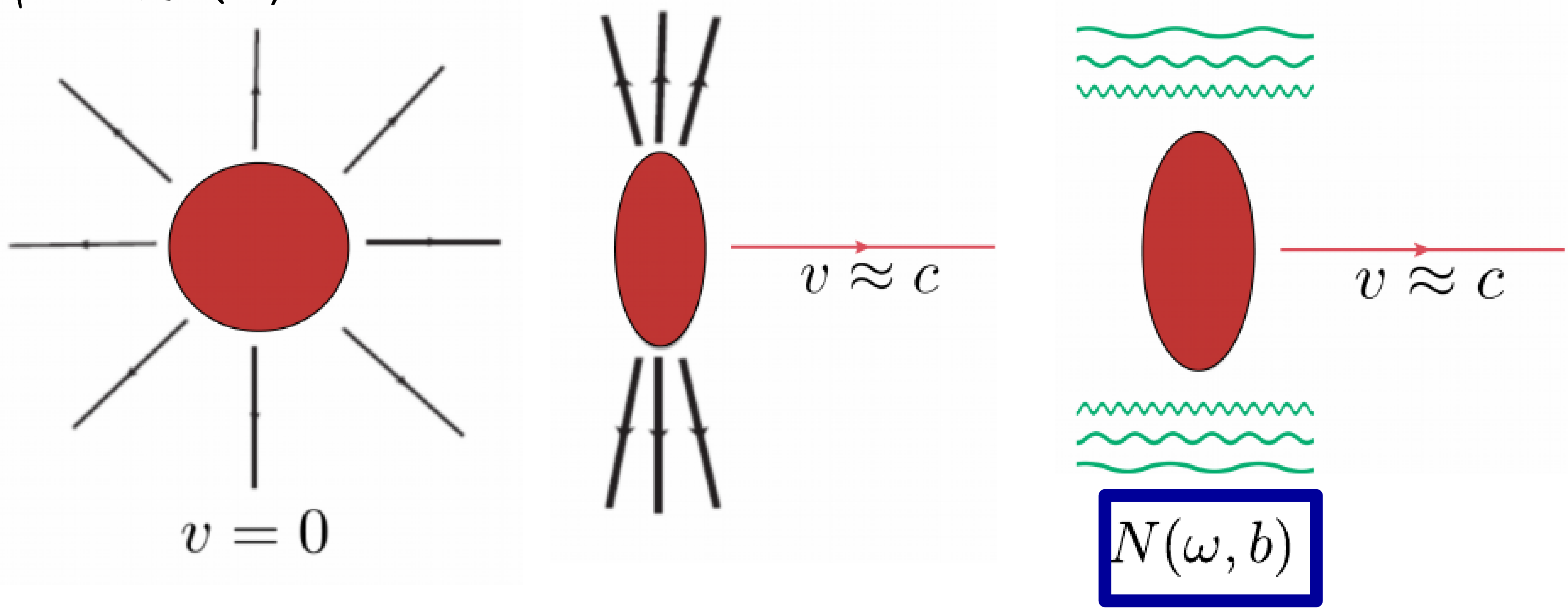
The equivalent photon approximation

As the nucleus moves with nearly the speed of light, the electromagnetic field becomes transverse to its velocity.



The equivalent photon approximation

Since the electric and magnetic field associated to the nucleus takes on the same absolute value, this transverse electromagnetic field can be simulated by an equivalent swarm of photons (*):



(*) E. Fermi (1924), E. J. Williams (1933), C. F. Von Weizsacker (1934).

The equivalent photon flux

$$N(\omega, \mathbf{r}) = \frac{Z^2 \alpha_{em}}{\pi^2 \omega} \left| \int_0^\infty dk_\perp k_\perp^2 \, \frac{F\left(\boldsymbol{k}_\perp^2 + \frac{\omega^2}{\gamma^2}\right)}{\boldsymbol{k}_\perp^2 + \frac{\omega^2}{\gamma^2}} \, J_1(r k_\perp) \right|^2$$

The equivalent photon flux

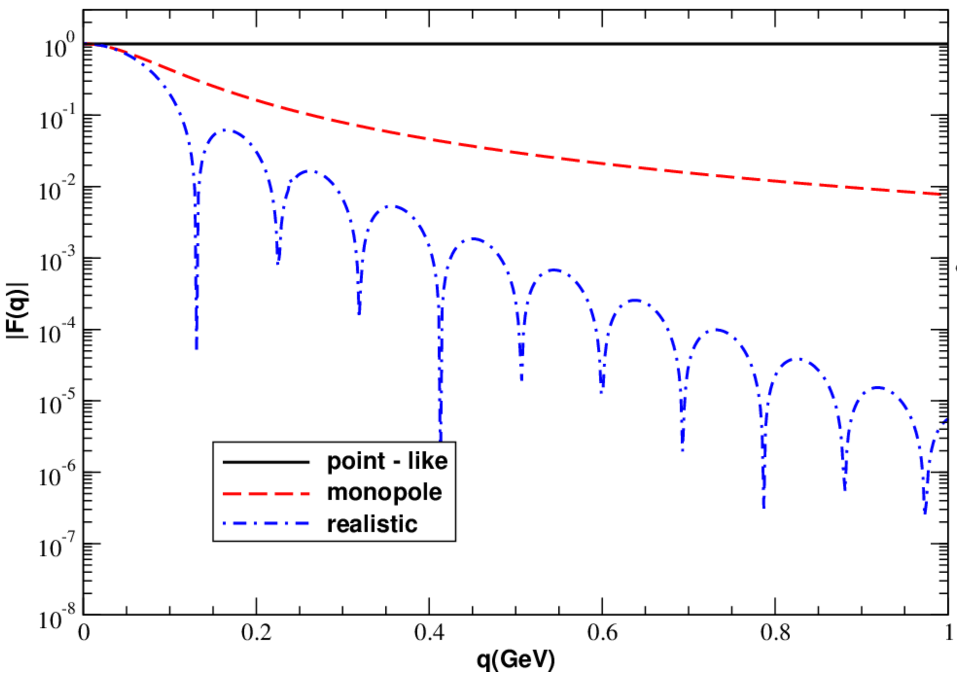
$$N(\omega, \mathbf{r}) = \frac{Z^2 \alpha_{em}}{\pi^2 \omega} \left| \int_0^\infty dk_\perp k_\perp^2 \frac{F\left(\boldsymbol{k}_\perp^2 + \frac{\omega^2}{\gamma^2}\right)}{\boldsymbol{k}_\perp^2 + \frac{\omega^2}{\gamma^2}} J_1(rk_\perp) \right|^2$$

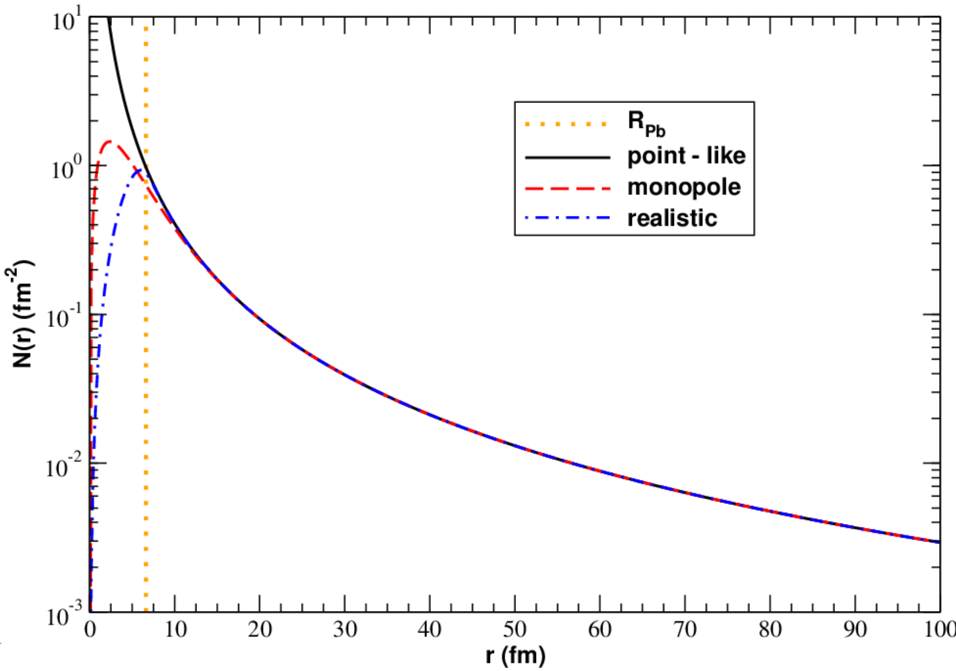
Properties:

* Enhanced for a large nuclei;

* Strongly dependent on the description of the nuclear form factor F.

The equivalent photon flux





1th Lesson: The approximation assumed for the FF determines the behaviour of the photon flux for distances smaller than the nuclear radius!

The equivalent photon flux

Maximum photon energy:

The maximum available equivalent photon energy can be estimated from the uncertainty principle, which implies:

$$\Delta t \Delta E \approx 1 \Rightarrow (\frac{R}{\gamma v}) \times \omega \approx 1$$

Where Δt is the time of collision, R is the nuclear radius and γ is the Lorentz factor. We obtain that:

$$\boxed{\omega_{max} \approx \frac{\gamma}{R}}$$

2th Lesson: The photon spectrum is harder for smaller charges and depends on the collider energy!

$$\gamma^{Au}_{RHIC} = 108 \Rightarrow \omega_{max} \approx 3 \text{ GeV}$$

$$\gamma^{Pb}_{LHC} = 2750 \Rightarrow \omega_{max} \approx 80 \text{ GeV} \qquad \gamma^{Ca}_{LHC} = 3750 \Rightarrow \omega_{max} \approx 180 \text{ GeV}$$

The equivalent photon flux

Maximum photon transverse momentum:

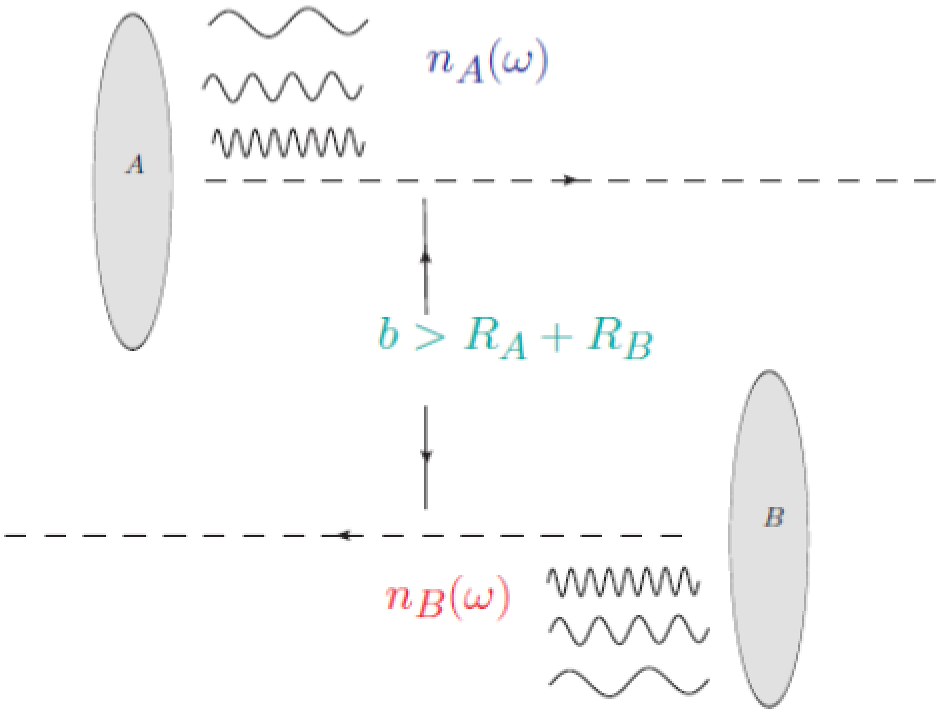
The coherence condition for the photon emission implies that the minimum wavelength of the photon is of the order of the nuclear radius. Consequently:

$$\boxed{Q^2 \lesssim 1/\lambda^2 \sim 1/R^2}$$

3th Lesson: The photon spectrum is dominated by photons with small transverse momentum!

For Pb (p) we have that Qmax = 0.06 (0.28) GeV!

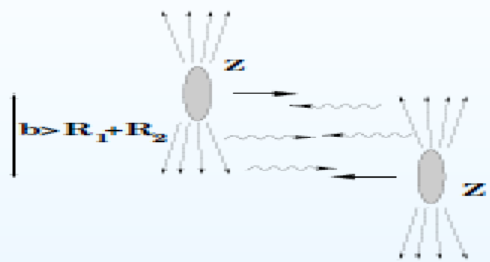
4th Lesson: LHC = Photon collider



$$\frac{n(\omega)}{\omega} = \int d^2\mathbf{r}\, N(\omega, \mathbf{r})$$

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

LHC = Photon collider



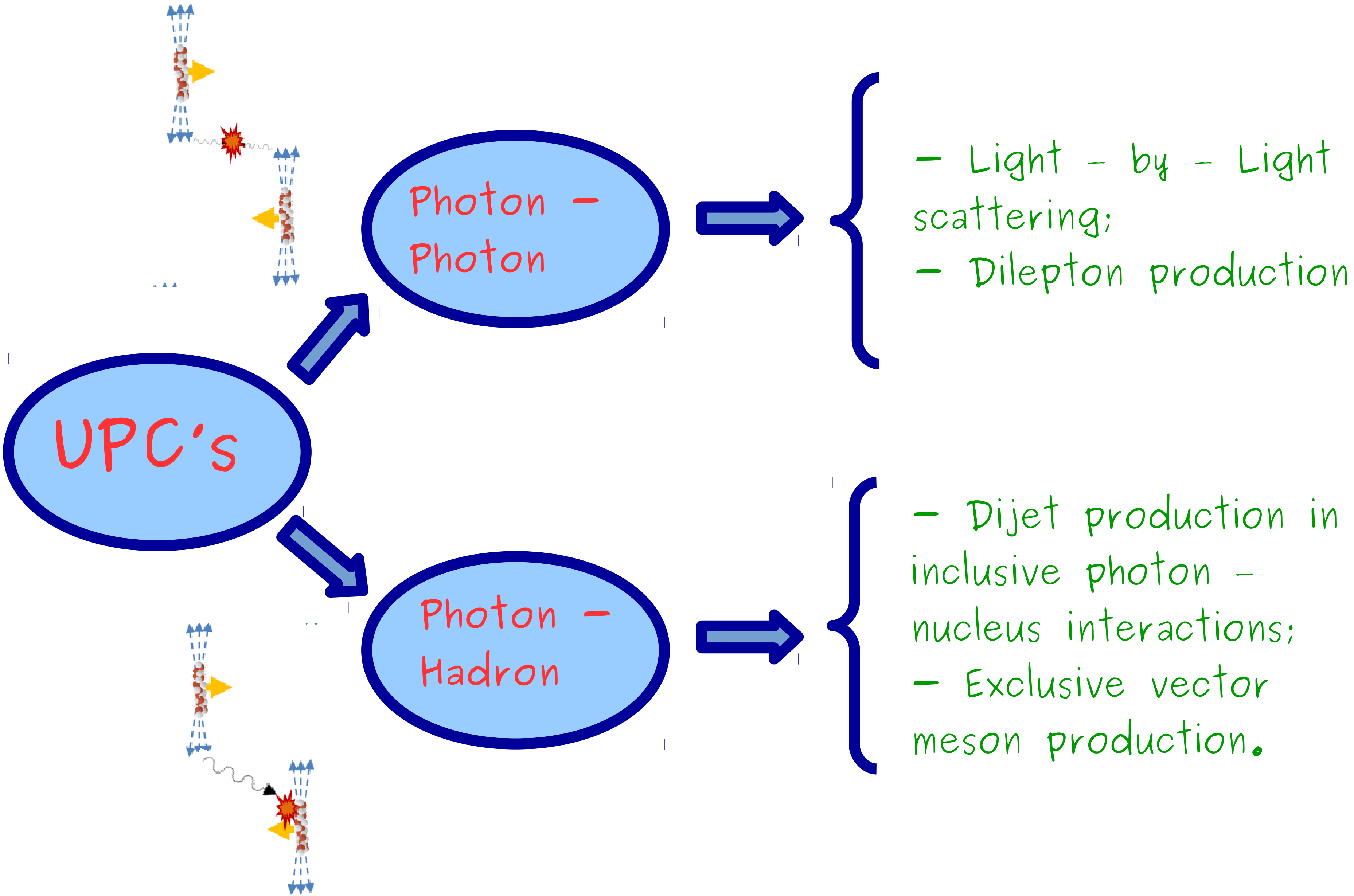
1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

Center of mass energies

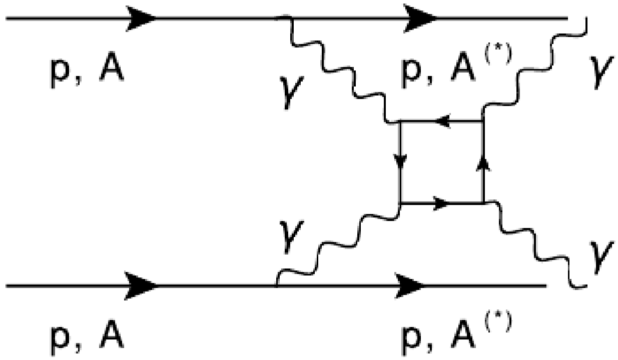
LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$W_{\gamma\gamma} \lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

LHC allow us to probe the particle production by photon – photon and photon – hadron interactions in an energy range unexplored by previous colliders.

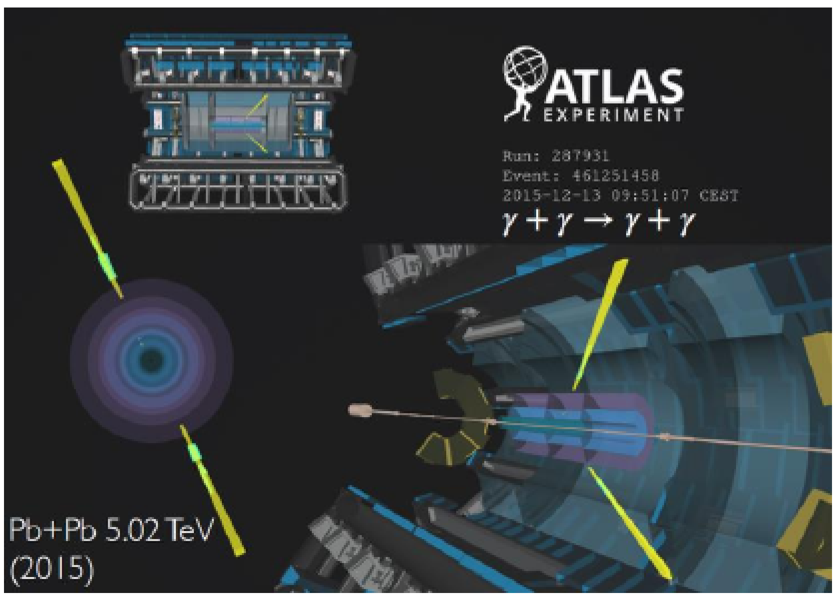
Ultra - peripheral Collisions:
Theory x Experiment


UPC's
Photon – Photon
Photon – Hadron
– Light – by – Light scattering;
– Dilepton production.
– Dijet production in inclusive photon – nucleus interactions;
– Exclusive vector meson production.

Light - by - Light Scattering

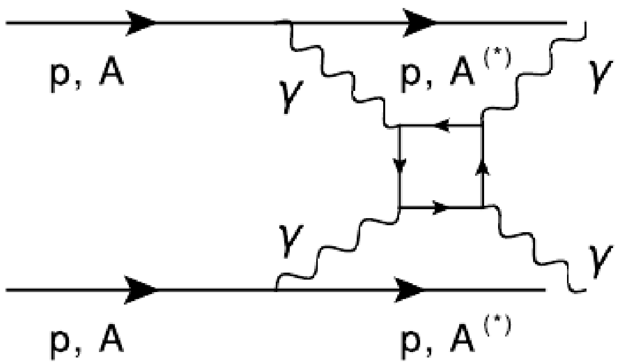


Textbook QED process that had nevertheless not been directly observed!



D'Enterria - da Silveira; Klusek-Gawenda, Szczurek, ...

Light - by - Light Scattering



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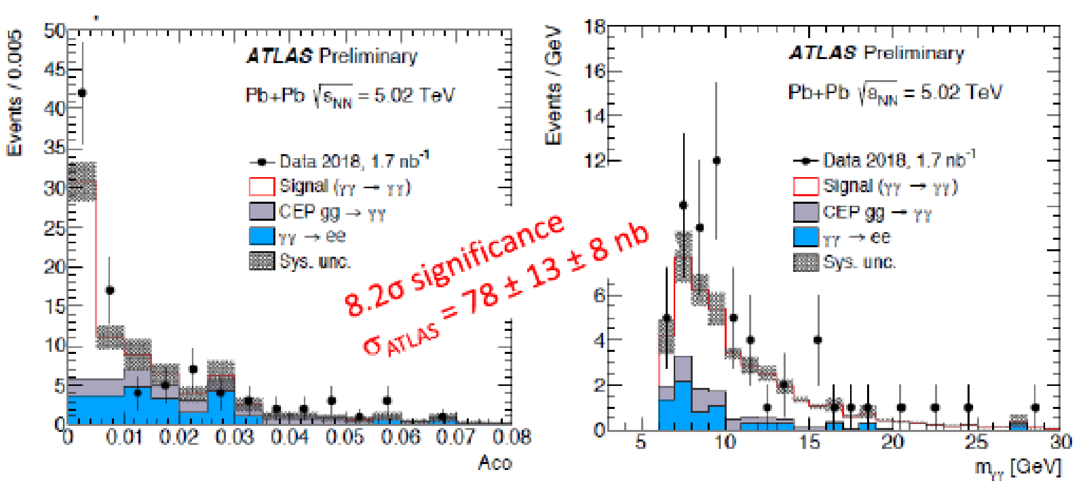
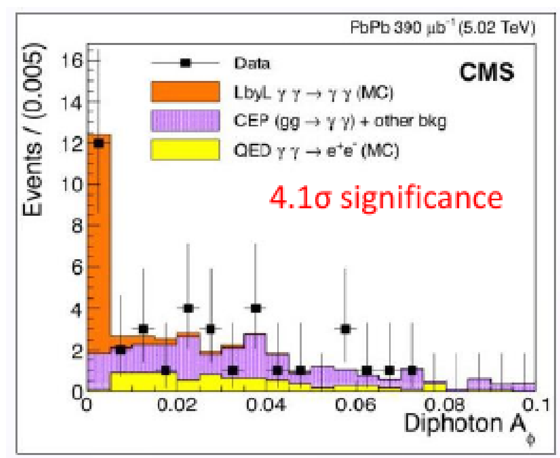


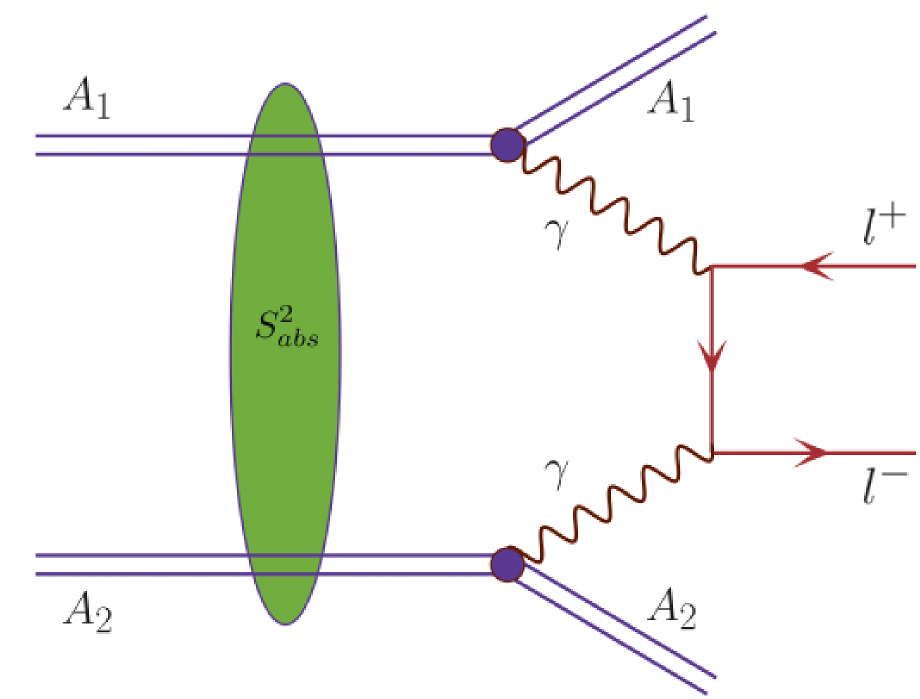


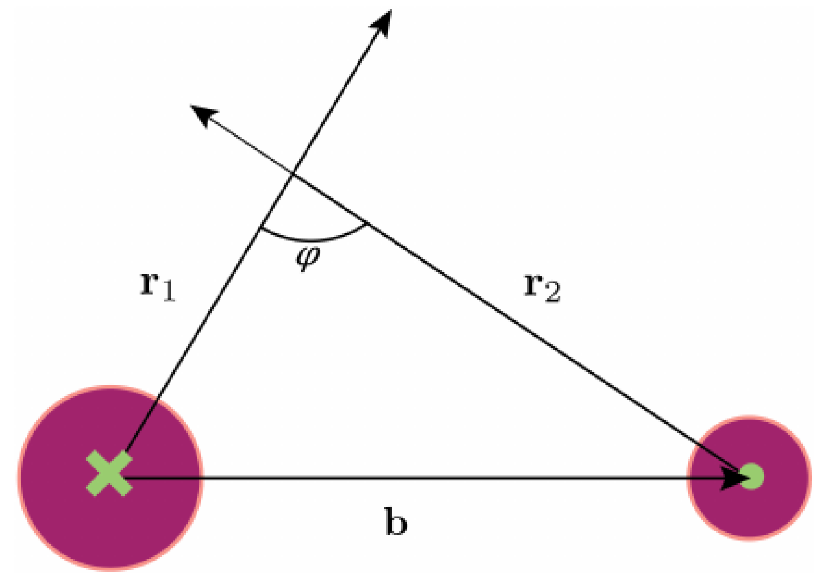
1810.04602

Cross sections and distributions consistent with SM predictions!

D'Enterria - da Silveira; Klusek-Gawenda, Szczurek, ...

Dilepton production

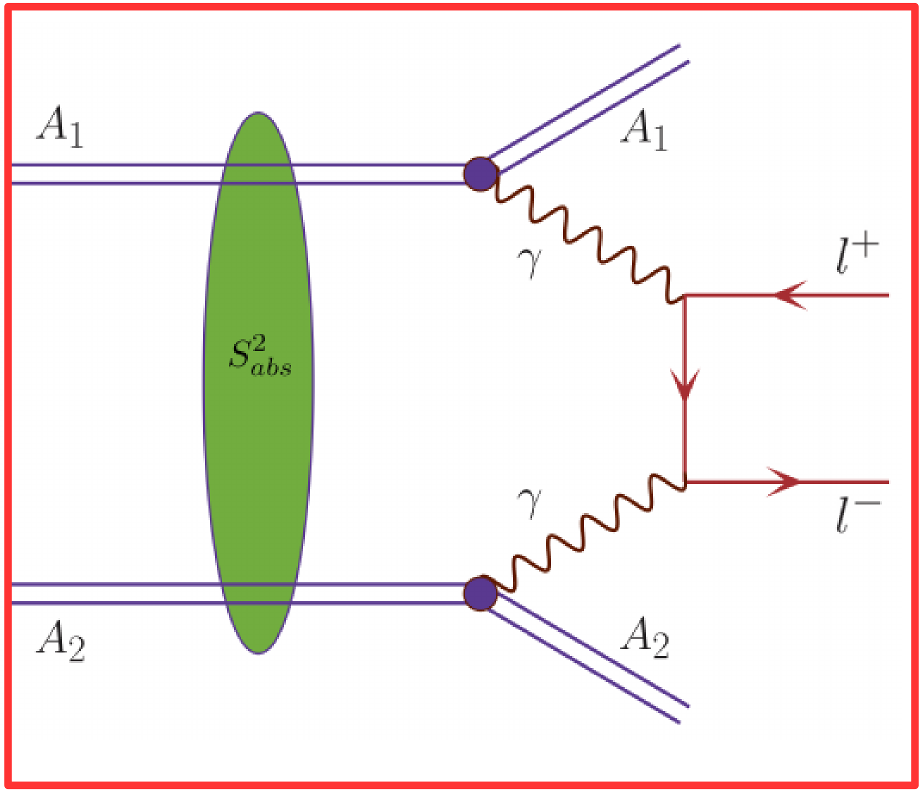


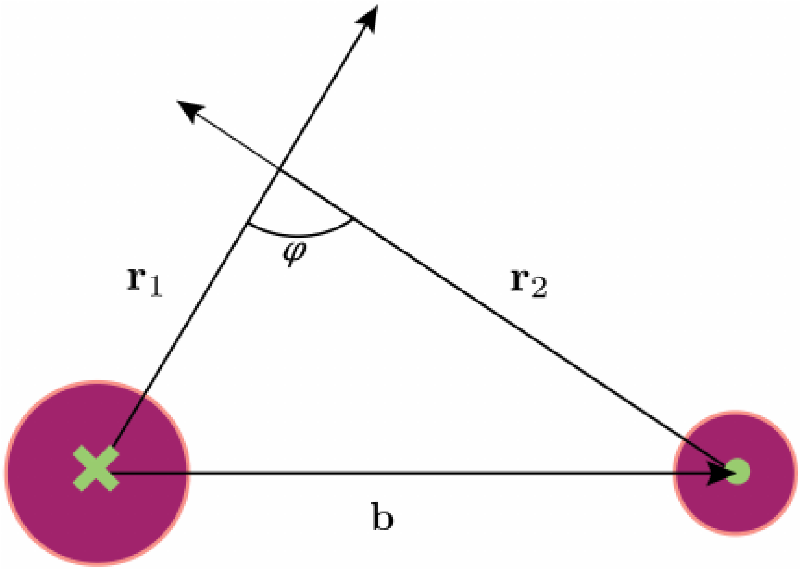


$$\sigma(AA \to l^+l^- AA; s_{AA}) = \int \hat{\sigma}(\gamma\gamma \to l^+l^-; W)\, S^2_{abs}(\mathbf{b}) N(\omega_1, \mathbf{r}_1)\, N(\omega_2, \mathbf{r}_2)\, d^2\mathbf{r}_1\, d^2\mathbf{r}_2\, d\omega_1\, d\omega_2$$

(*) Azevedo, VPG, Moreira, EPJC79, 432 (2019)

Dilepton production





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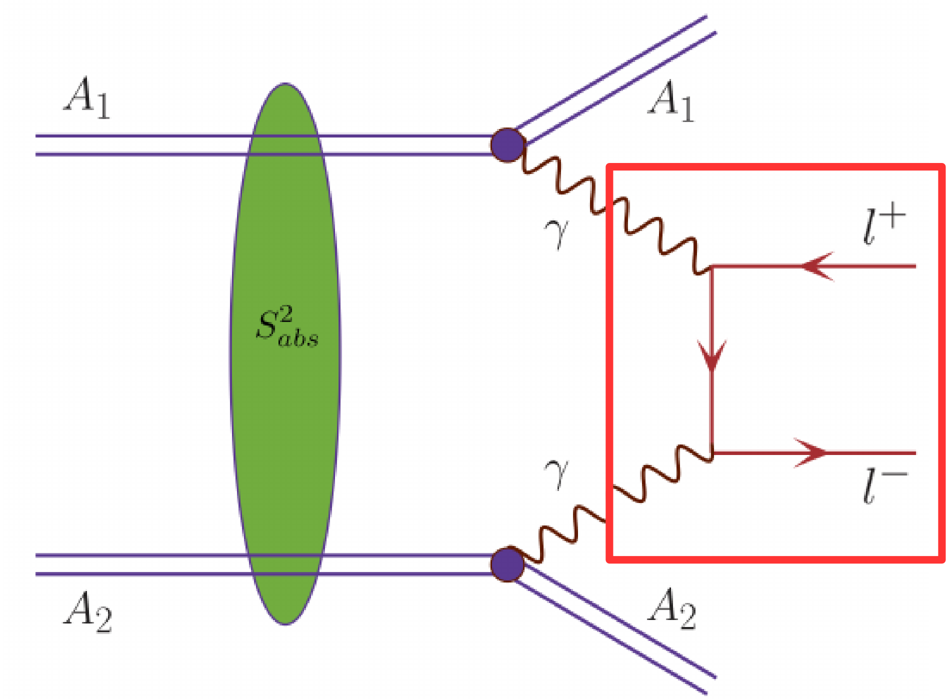
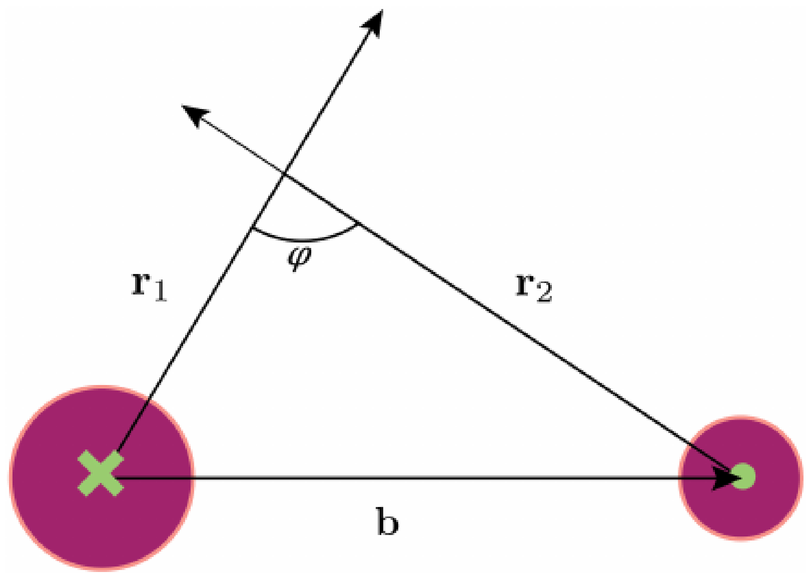
Dilepton production





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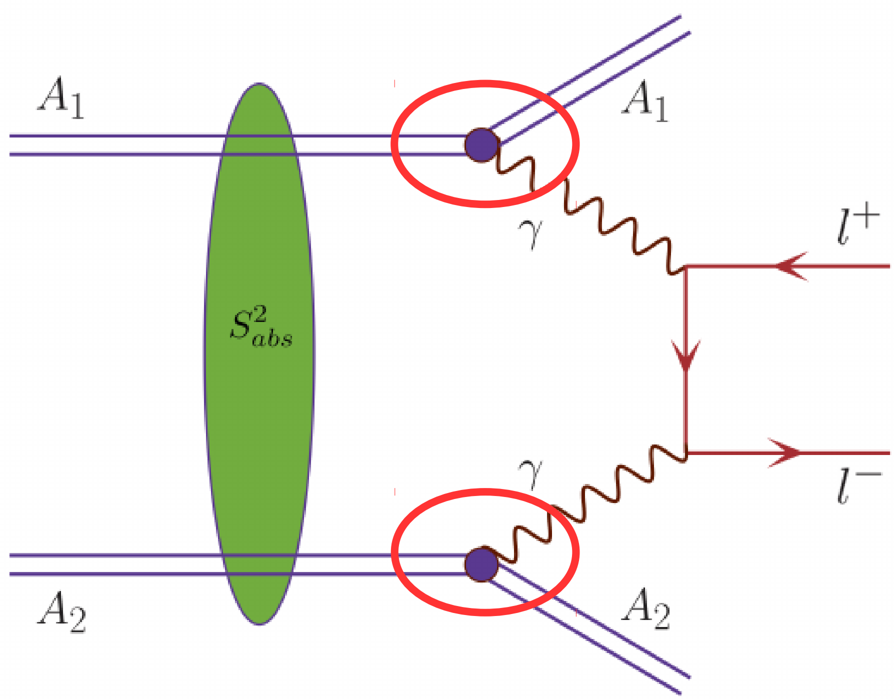
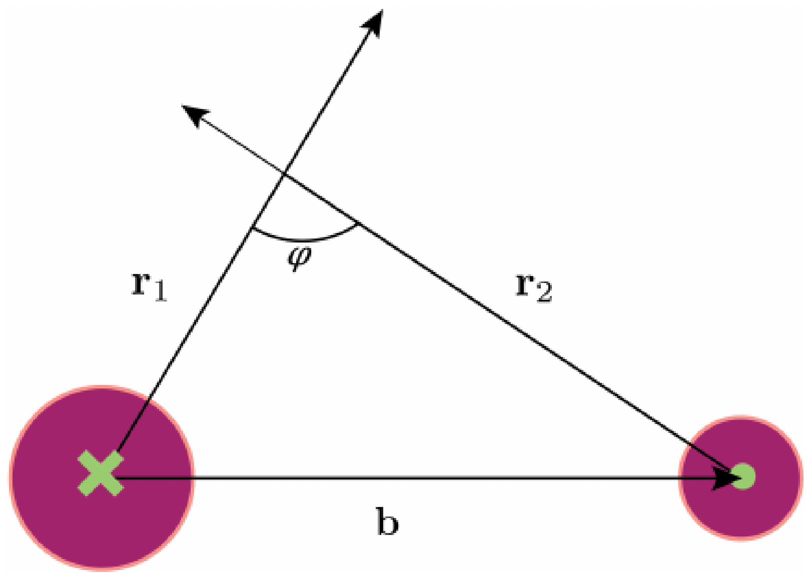
Dilepton production





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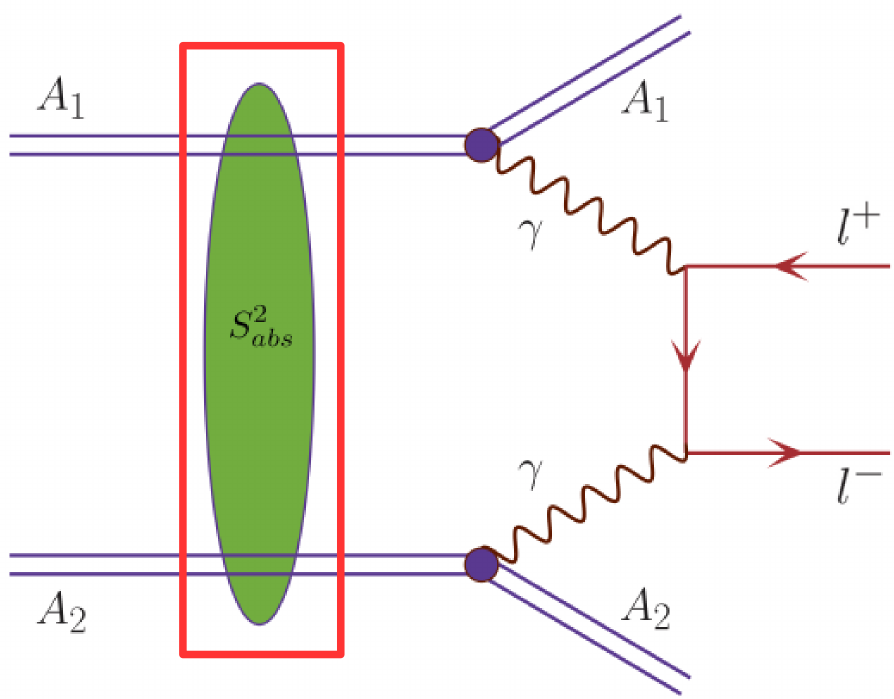
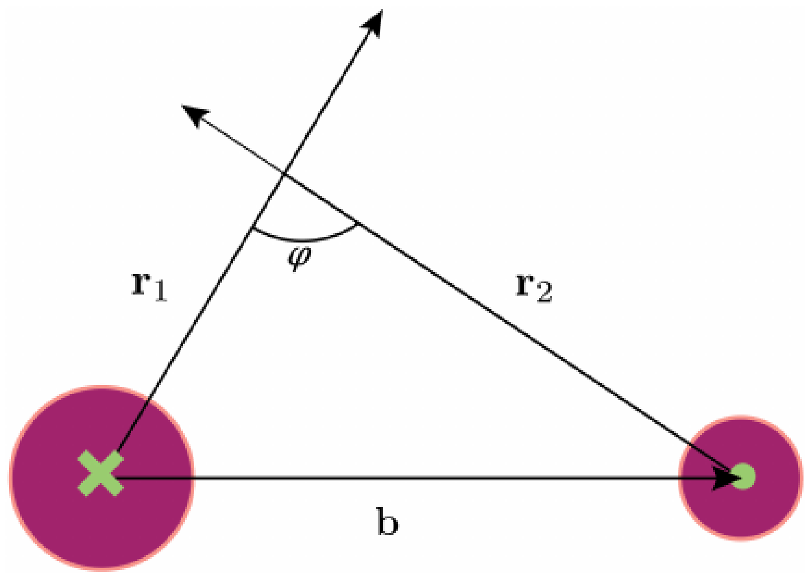
Dilepton production





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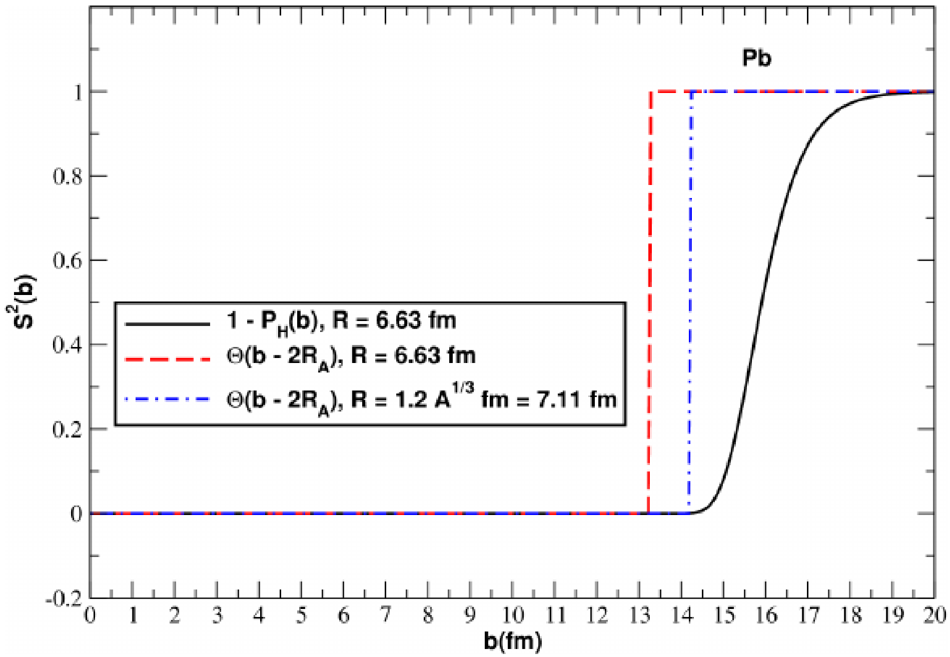
Dilepton production

Absorptive corrections:

- Geometric model: $S^2_{abs}(b) = \Theta(|\,\mathbf{b}\,| - 2R_A)$

- Glauber model: $S^2_{abs}(b) = P_{NH}(b) = exp\left[-\sigma_{nn}\int d^2\,\vec{r}\;T_A(\vec{r})\,T_A(\vec{r}-\vec{b})\right]$



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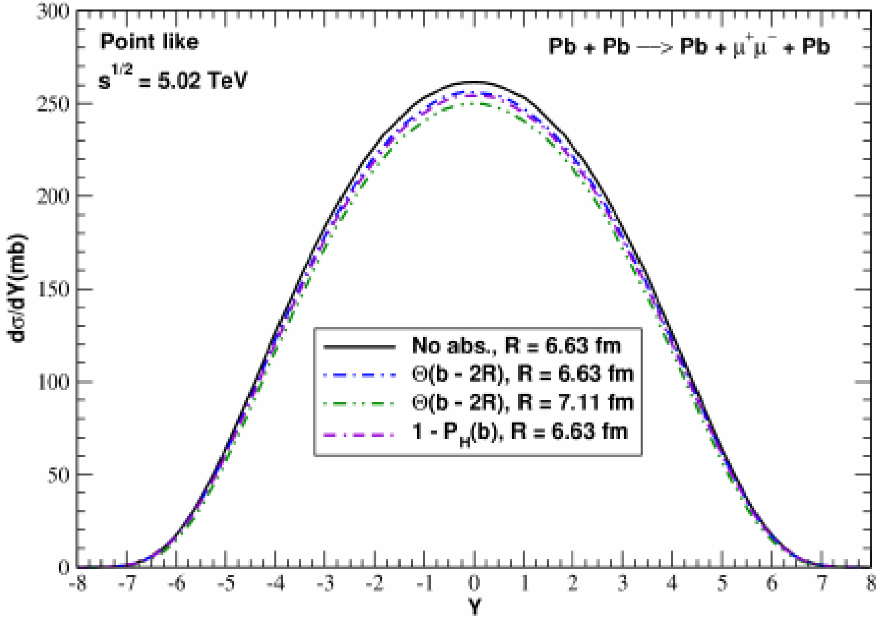
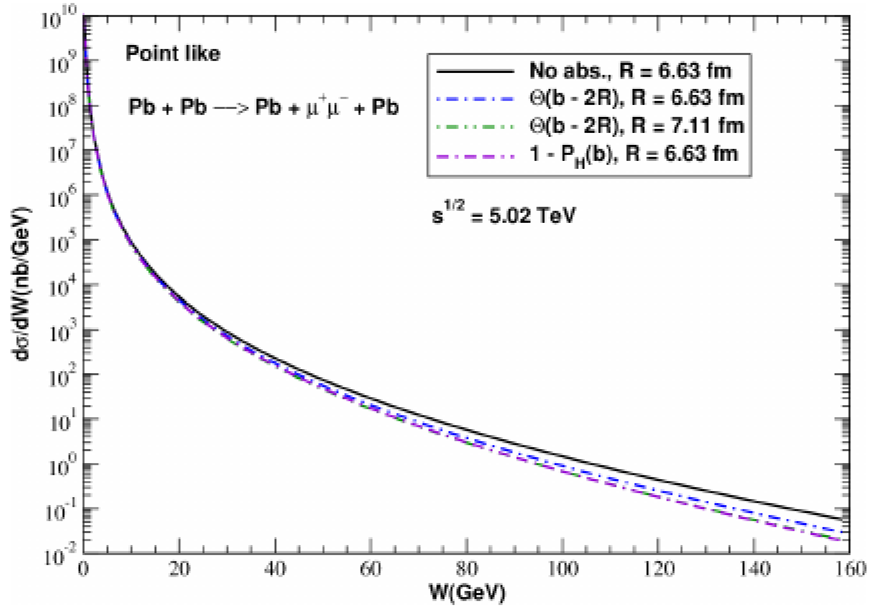
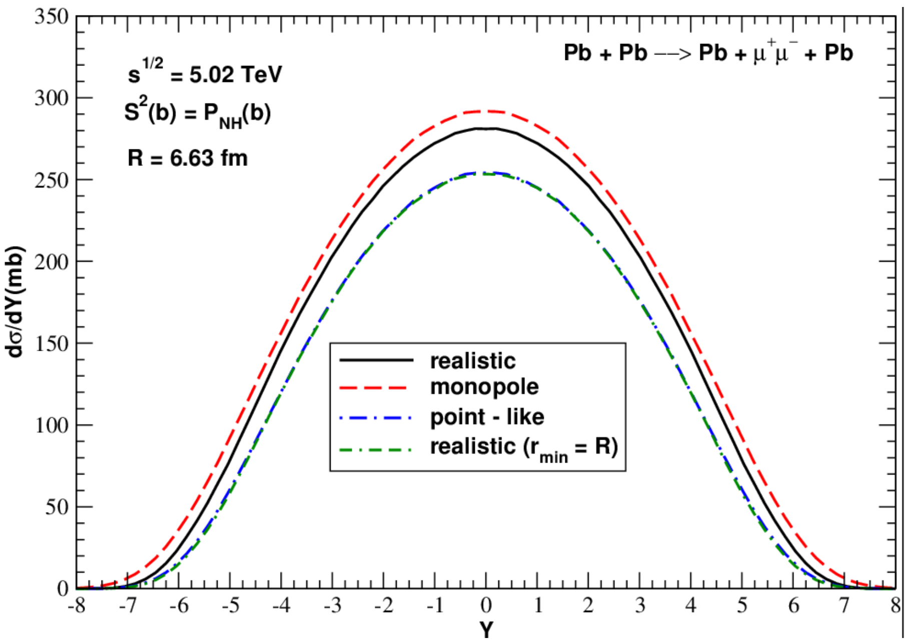
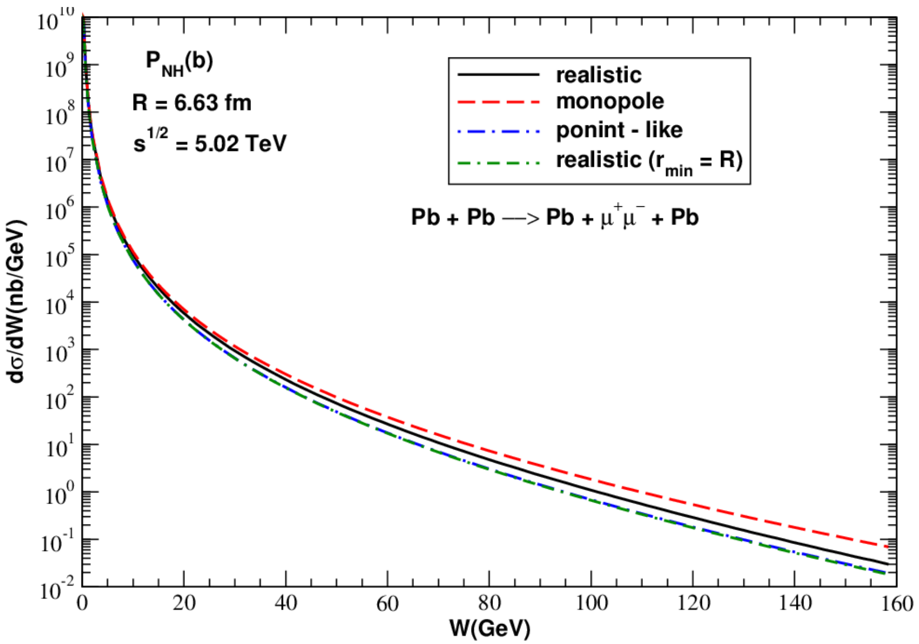




Dilepton production

Dependence on the modelling of the nuclear form factor:

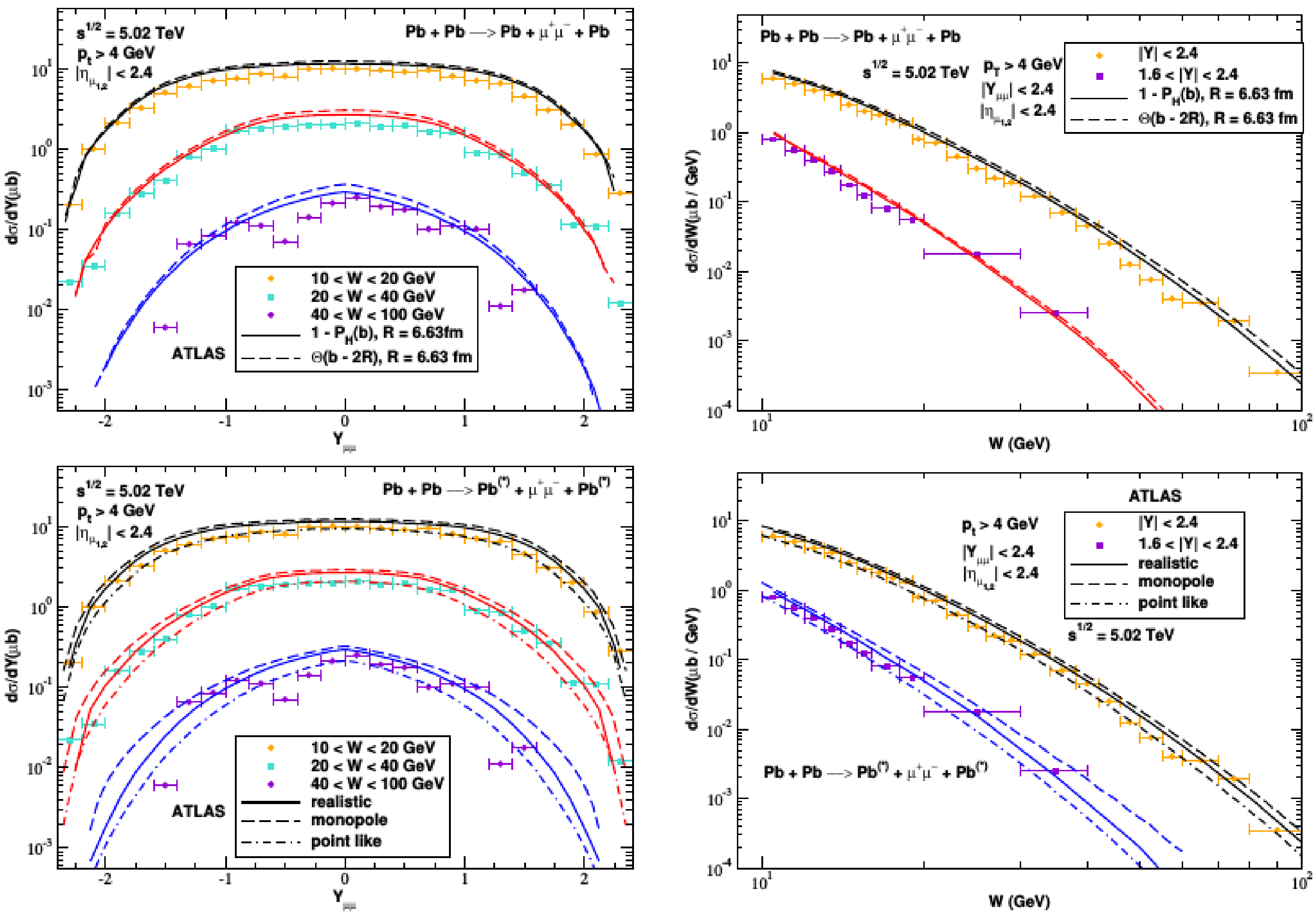




Dilepton production

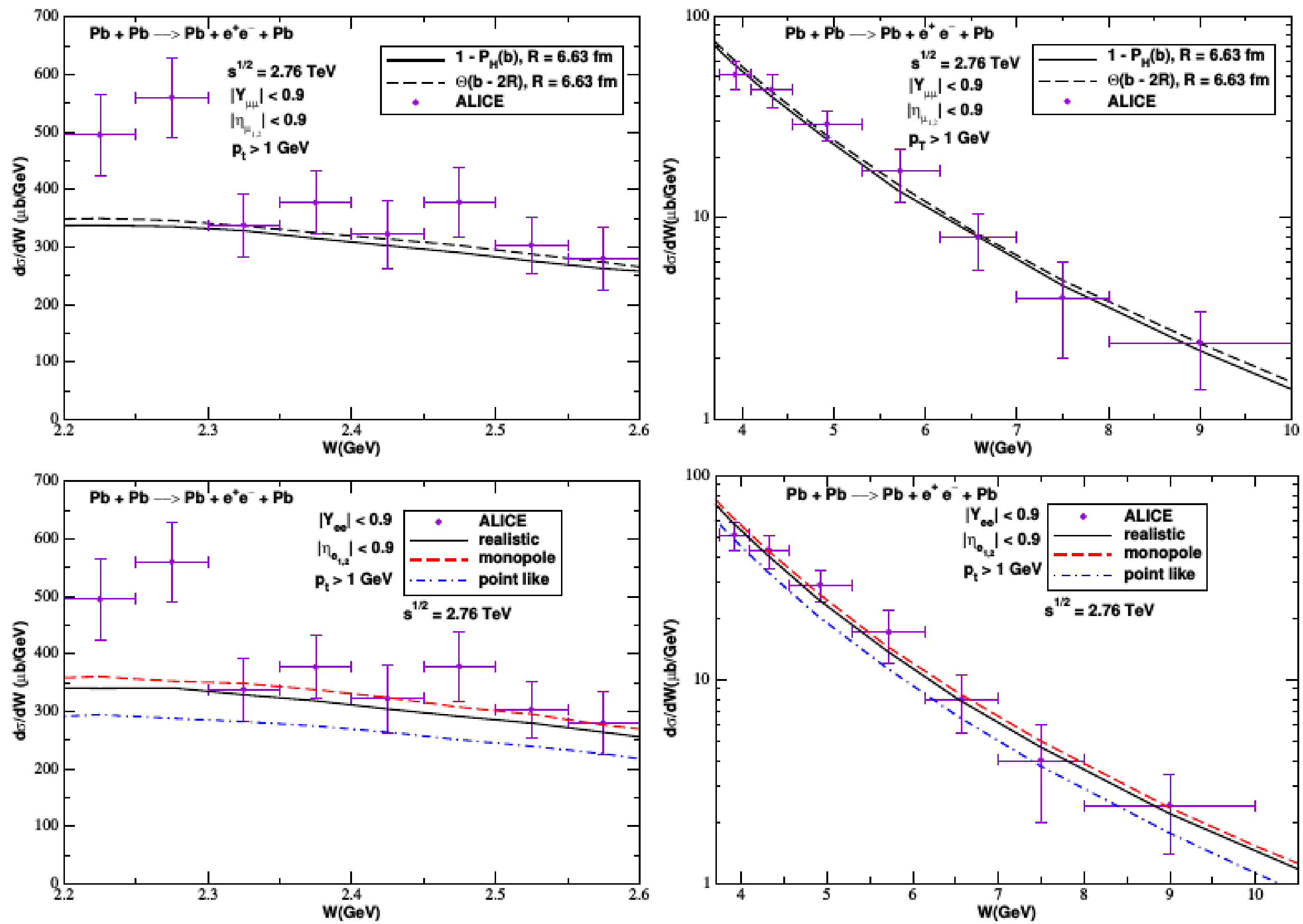
– PbPb collisions –

Including experimental cuts:



Dilepton production
- PbPb collisions -

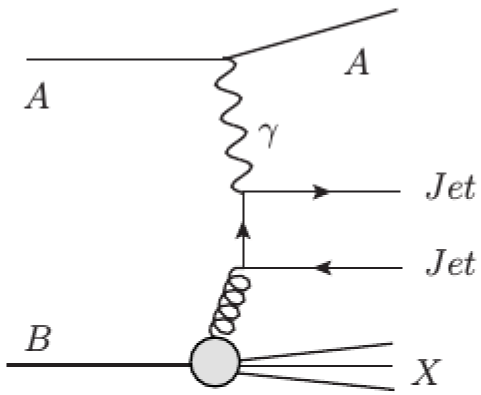
Including experimental cuts:

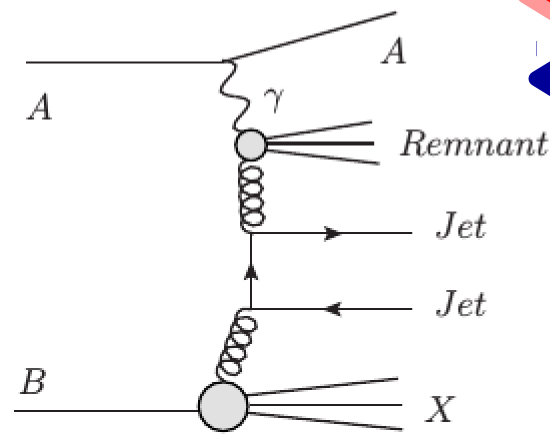


Inclusive dijet photoproduction in PbPb collisions

Intact hadron

Rapidity gap



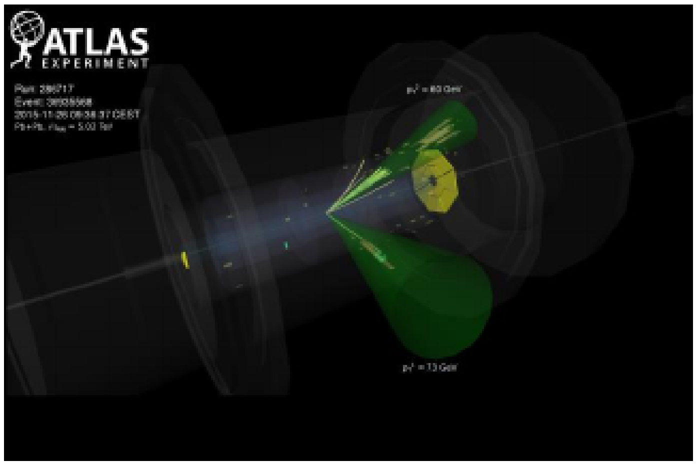


$$d\sigma(AB \to A + 2\text{jets} + X) = \sum_{a,b} \int_{y_{\min}}^{y_{\max}} dy \int_0^1 dx_\gamma \int_{x_{A,\min}}^{x_{A,\max}} dx_A f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/B}(x_A, \mu^2) d\hat{\sigma}(ab \to \text{jets})$$

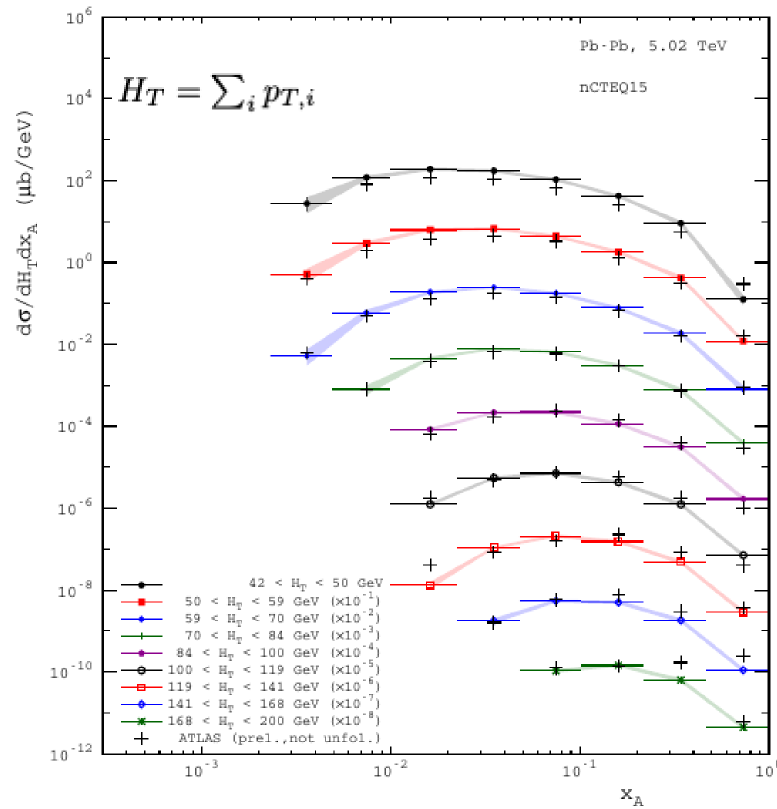
Sensitive to the nuclear effects on the gluon distribution.

VPG, Bertulani; Frankfurt, Strikman, Vogt; Guzey, Klasen; VPG et al.

Inclusive dijet photoproduction in PbPb collisions



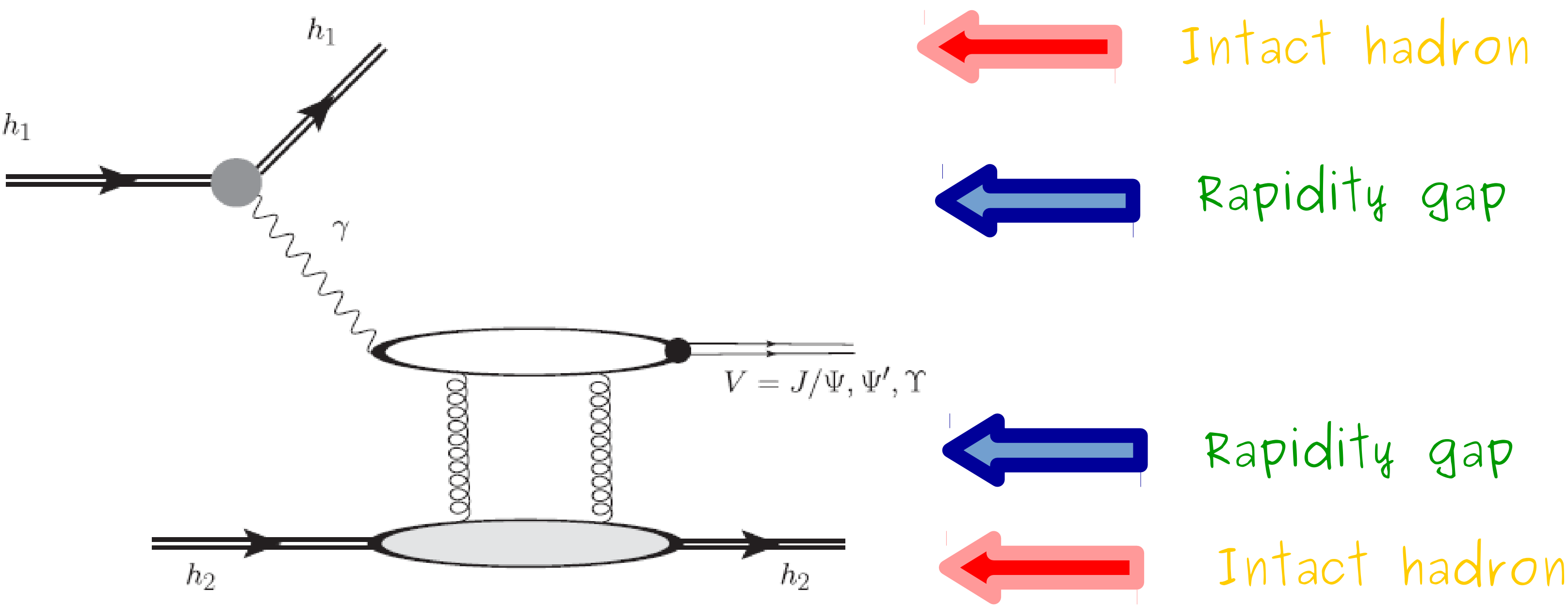
- Jet selection:
  - Anti-k_T, $R = 0.4$, $|\eta| < 4.4$
  - $p_T^{lead} > 20$ GeV, $p_T^{jets} > 15$ GeV



Such process can be used to reduce uncertainties in the determination of the nPDF's.

Guzey, Klasen: arXiv:1811.10236

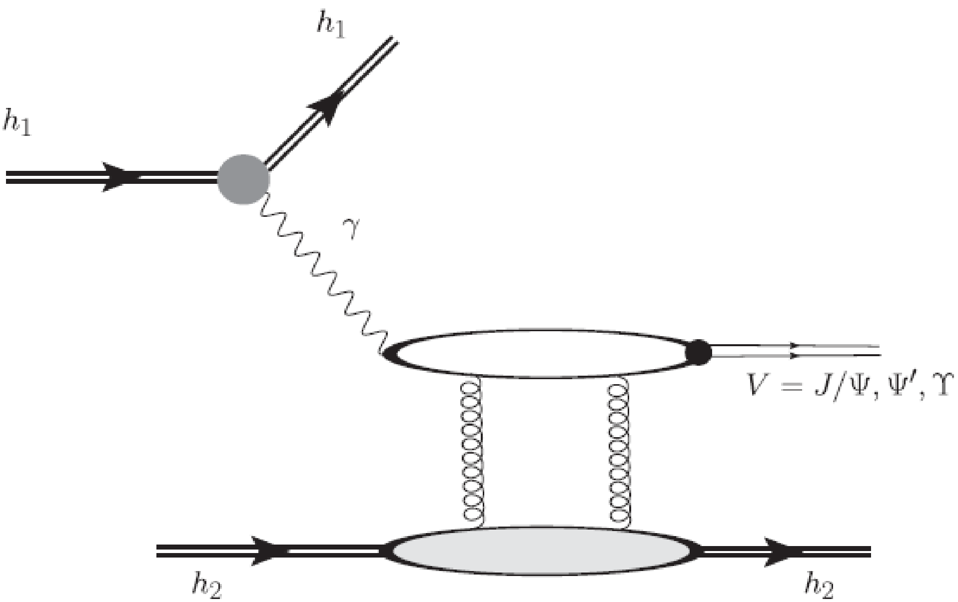
Exclusive vector meson photoproduction



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

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

Exclusive vector meson photoproduction



At leading order in LL(1/x) approx.:

$$\left.\frac{d\sigma^{\gamma h \to V h}}{dt}\right|_{t=0} = \mathcal{N}\frac{\pi^3 \Gamma_{e^+e^-} M_V^3}{48\alpha_{em}}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g_h(x, \bar{Q}^2)\right]^2$$

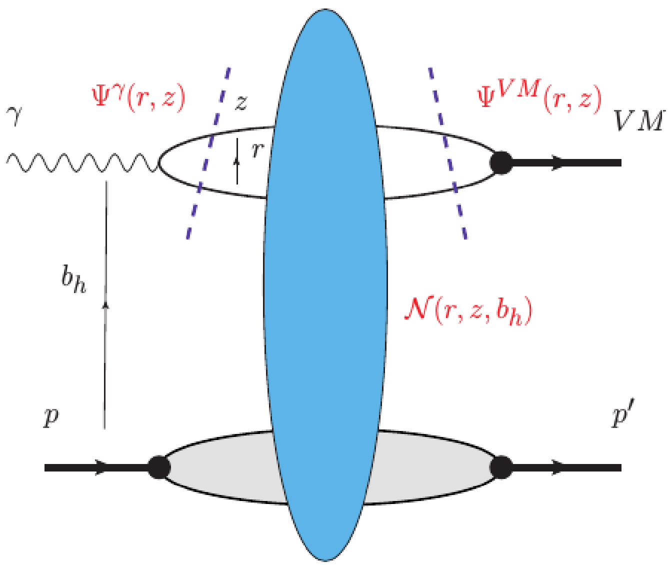
Cross section is proportional to the square of the hadron gluon distribution at small − x ($x = m_V{}^2/W^2$).

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

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

Exclusive vector meson photoproduction:
A sketch of the formalism

* In the impact parameter space:



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

Exclusive vector meson photoproduction:
A sketch of the formalism

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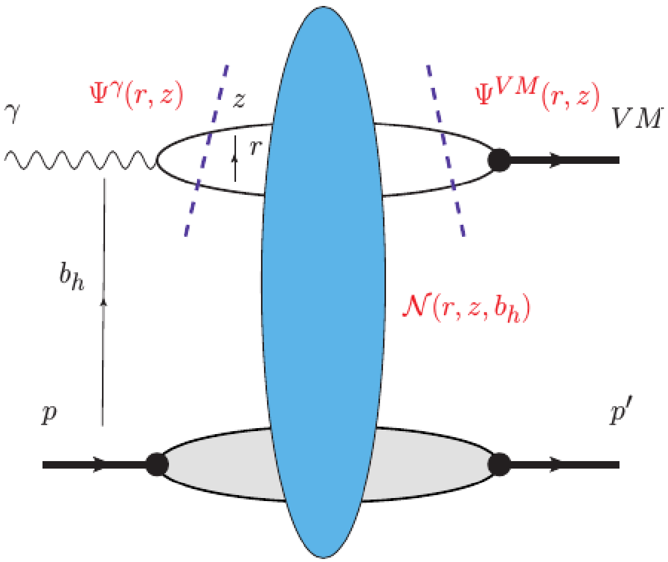

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Overlap function between the photon and vector meson wavefunctions:

– Depends on the model used to describe the VM wave functions;

Exclusive vector meson photoproduction:
A sketch of the formalism

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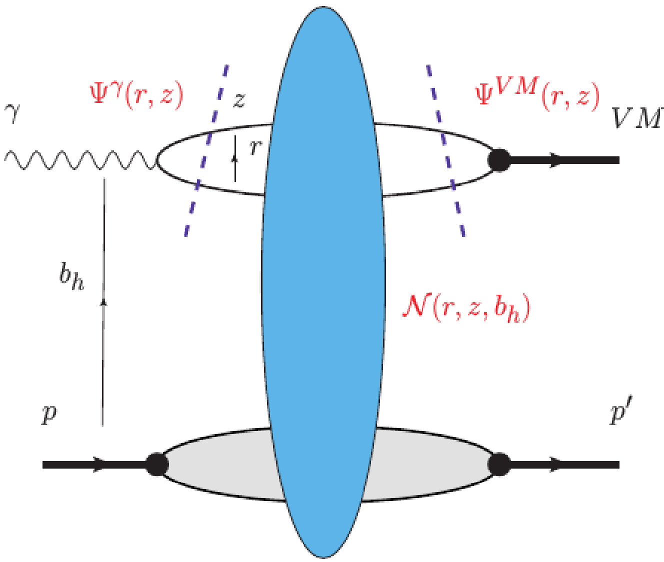

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Forward dipole – hadron scattering amplitude:

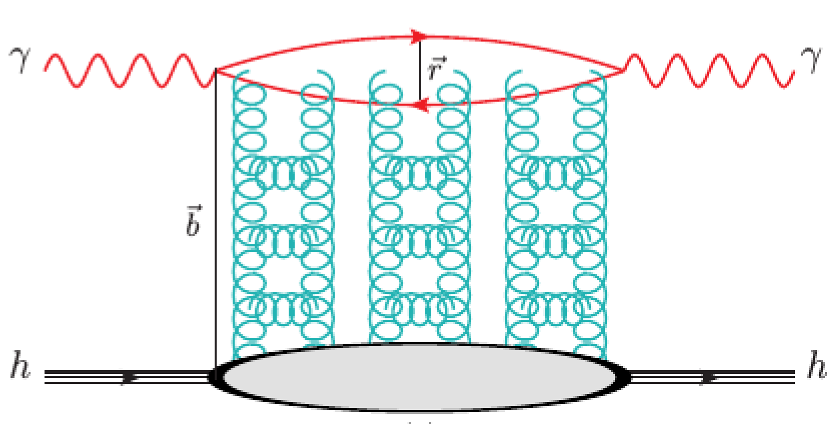
– Determined by the QCD dynamics at high energies;

– Can be modelled to take into account the non – linear effects at low – x

Dipole – proton scattering

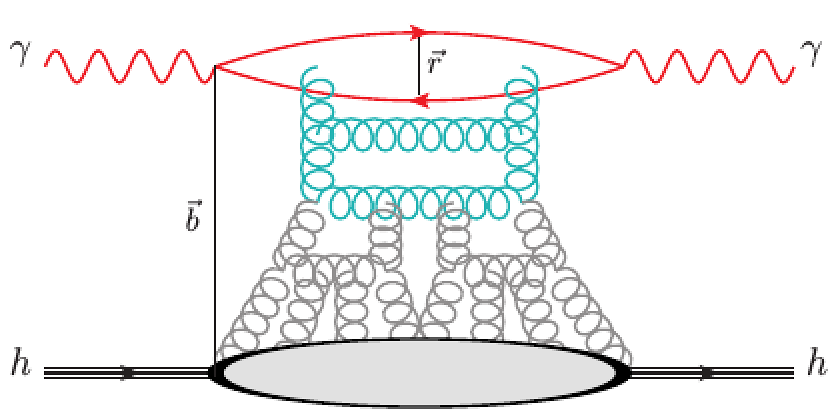
Two phenomenological models based on the CGC physics:

* IP – SAT model:



"Classical" CGC model.

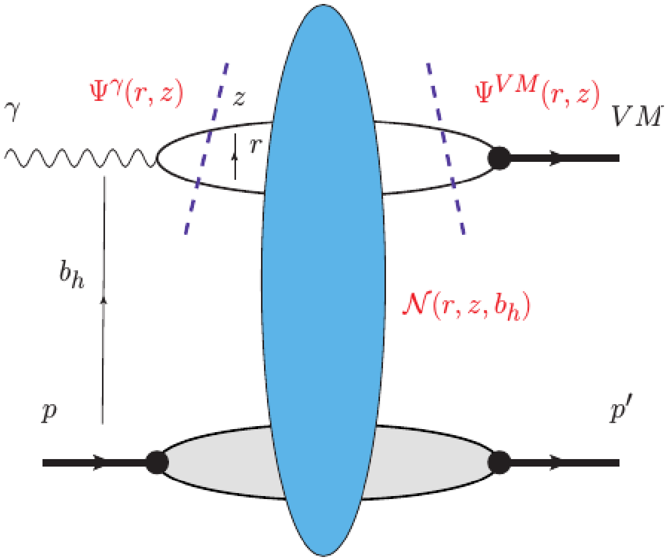
* bCGC model:



"Quantum" CGC model.

Exclusive vector meson photoproduction: A sketch of the formalism

* In the impact parameter space:



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

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

Exclusive vector meson photoproduction:
A sketch of the formalism

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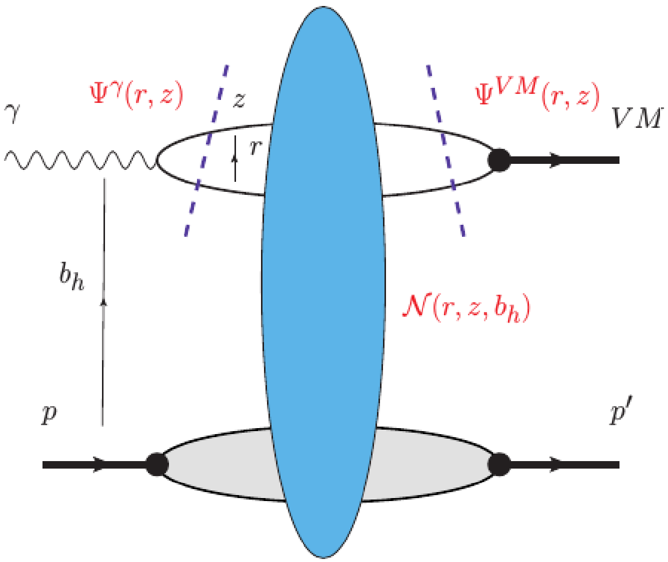

$$\mathcal{A}_T^{\gamma h \to Vh}(x,\Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b}_h e^{-i[\boldsymbol{b}_h-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}}\, (\Psi^{V*}\Psi)_T\; 2\mathcal{N}_h(x,\boldsymbol{r},\boldsymbol{b}_h)$$

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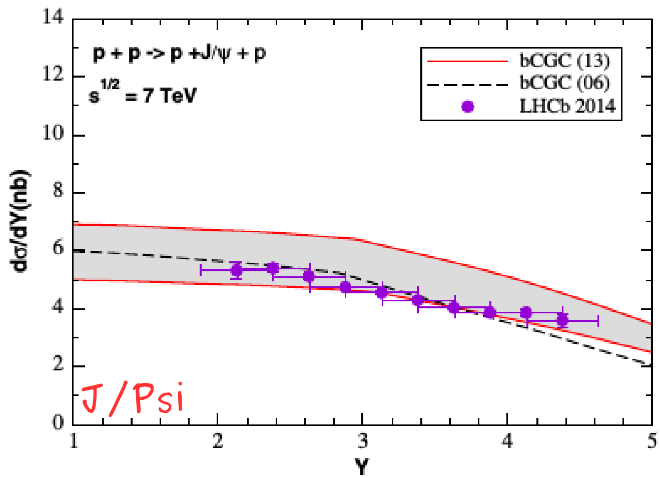
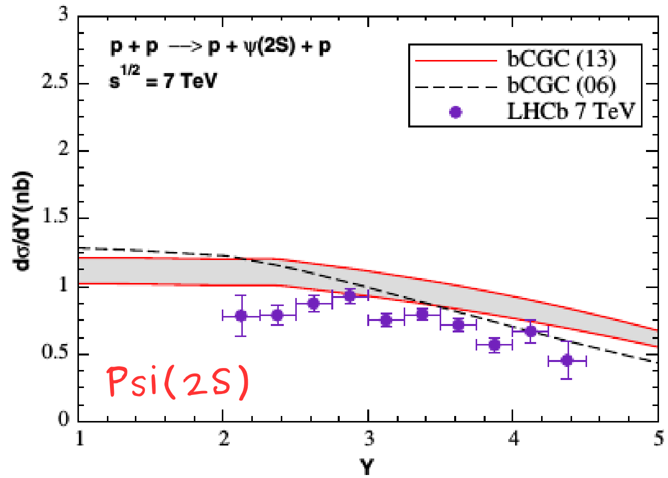
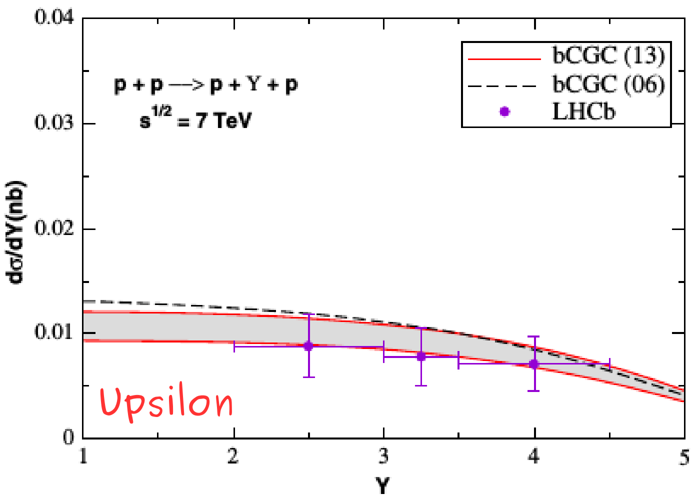
⇨ Exclusive vector meson photoproduction in hadronic collisions is strongly dependent on the description of the QCD dynamics.

Exclusive vector meson photoproduction in pp collisions

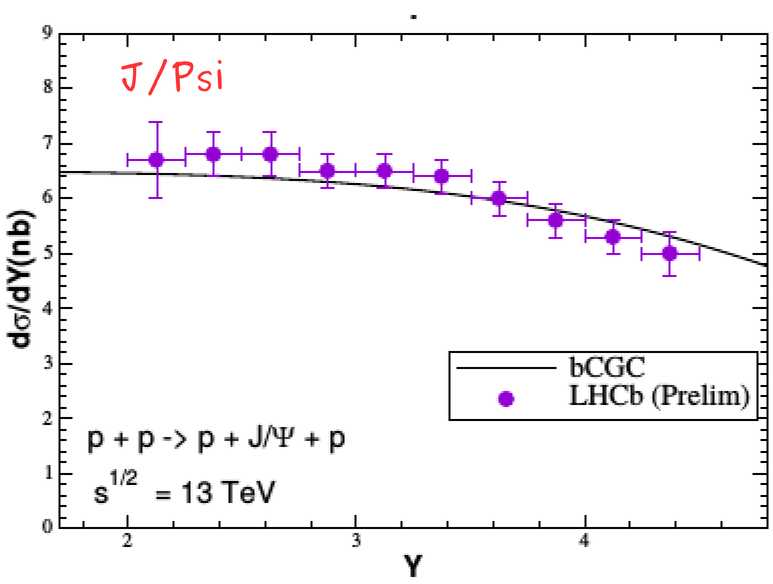


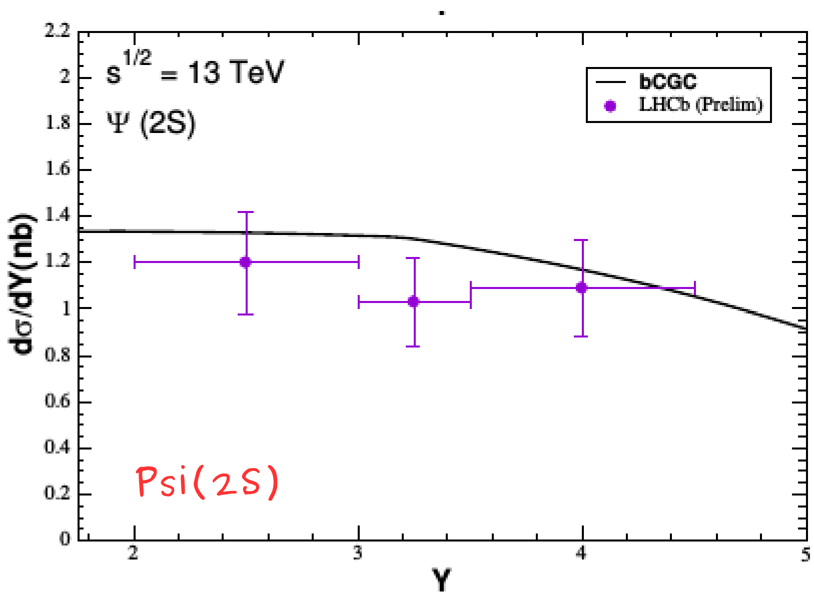




VPG, Moreira, Navarra, PRD95, 094024 (2016)

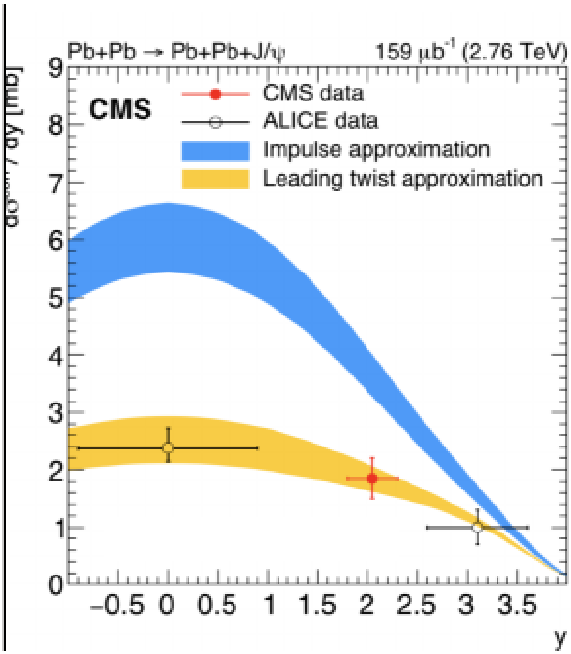
Exclusive vector meson photoproduction in pp collisions

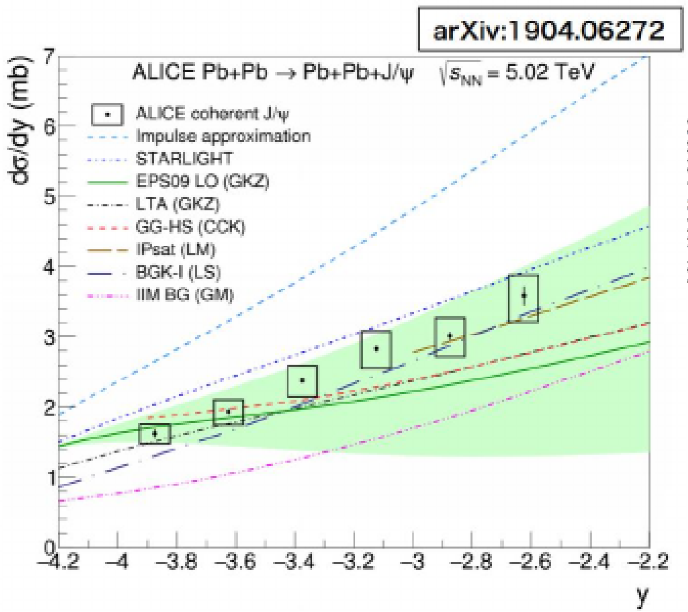


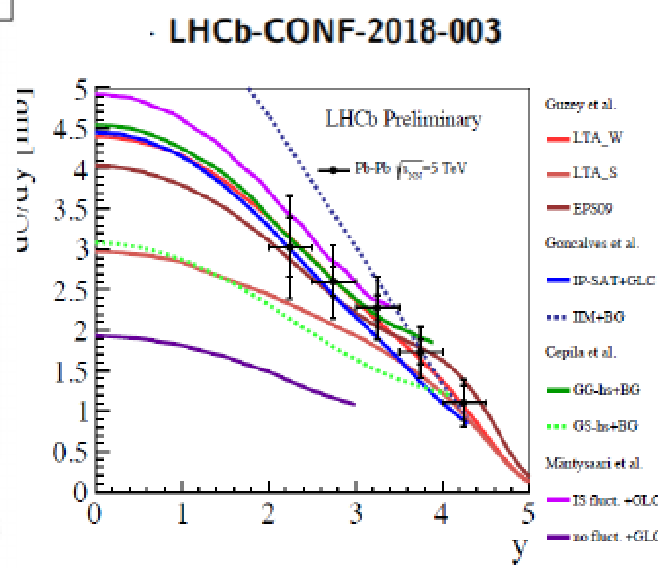


VPG, Moreira, Navarra, PRD95, 094024 (2016)

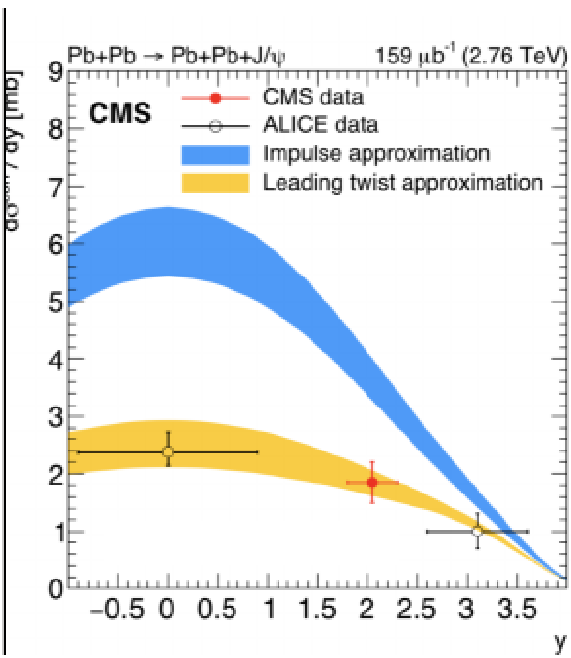
Exclusive vector meson photoproduction in PbPb collisions



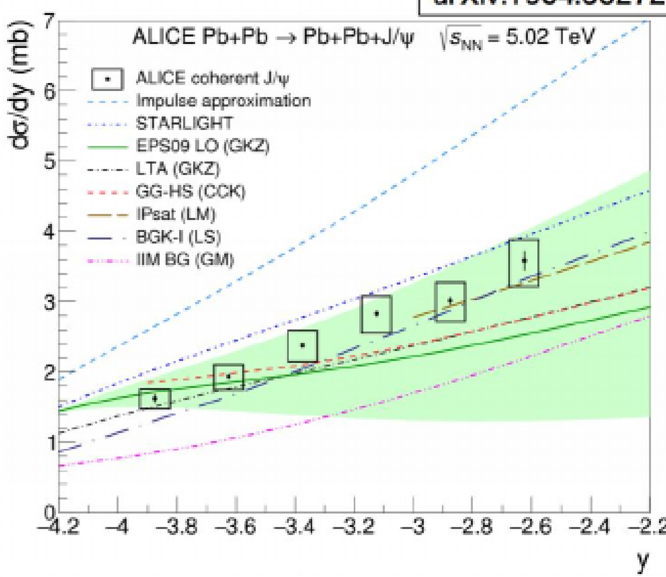




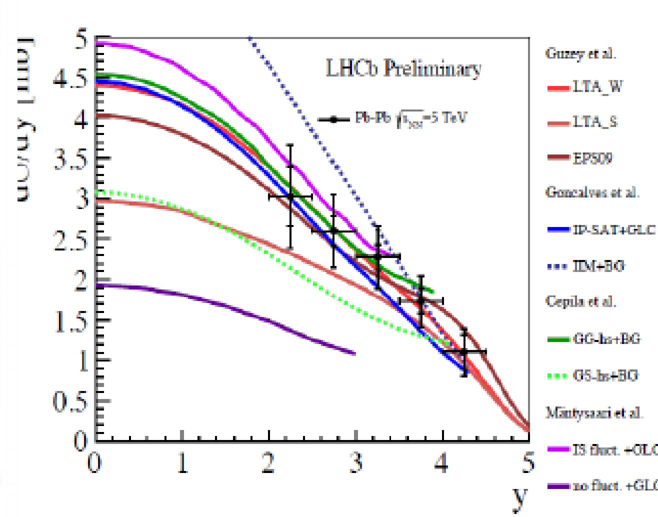
Exclusive vector meson photoproduction in PbPb collisions



arXiv:1904.06272



LHCb-CONF-2018-003

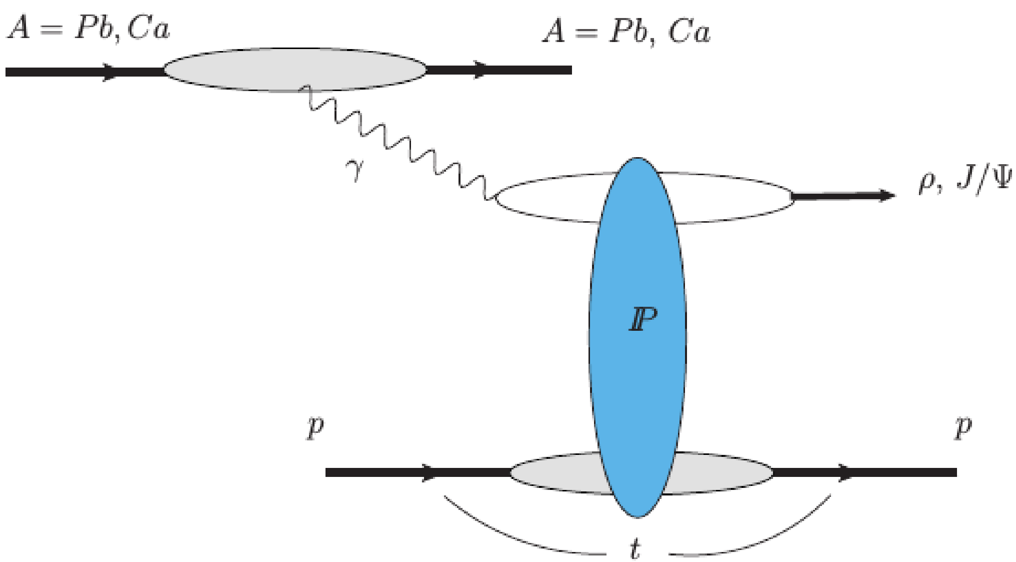


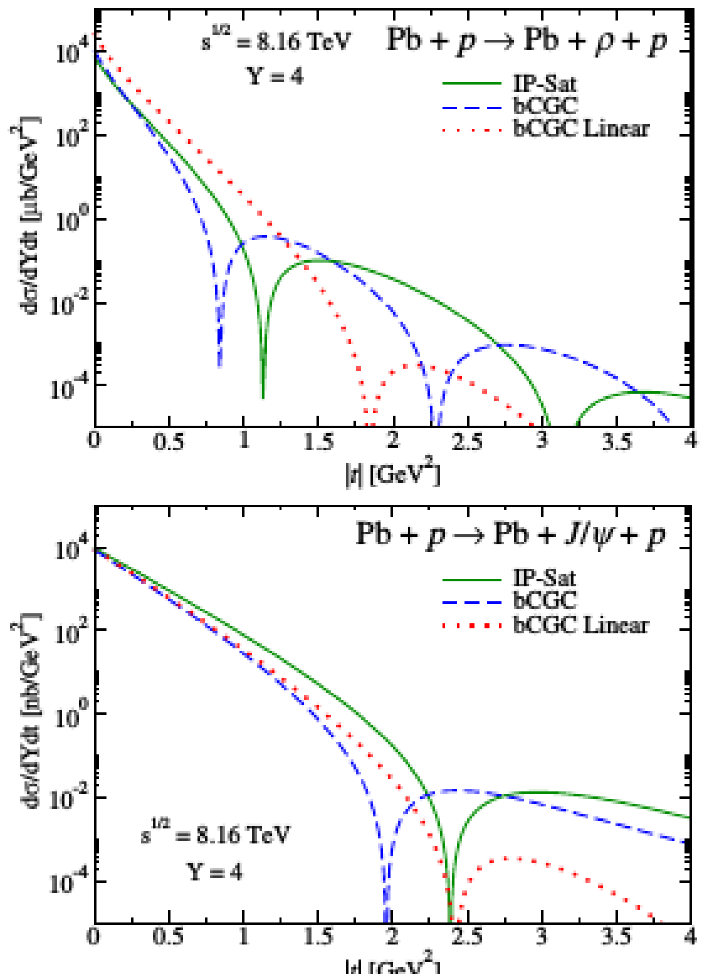
In order to discriminate/constrain the modelling of the QCD dynamics using the data for the rapidity distribution we should to have data for more than one VM.

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

Exclusive vector meson photoproduction

pA Collisions:



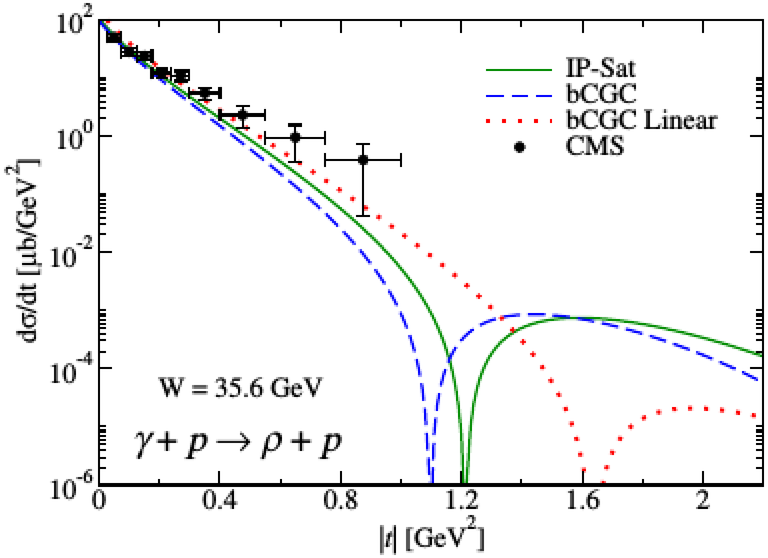


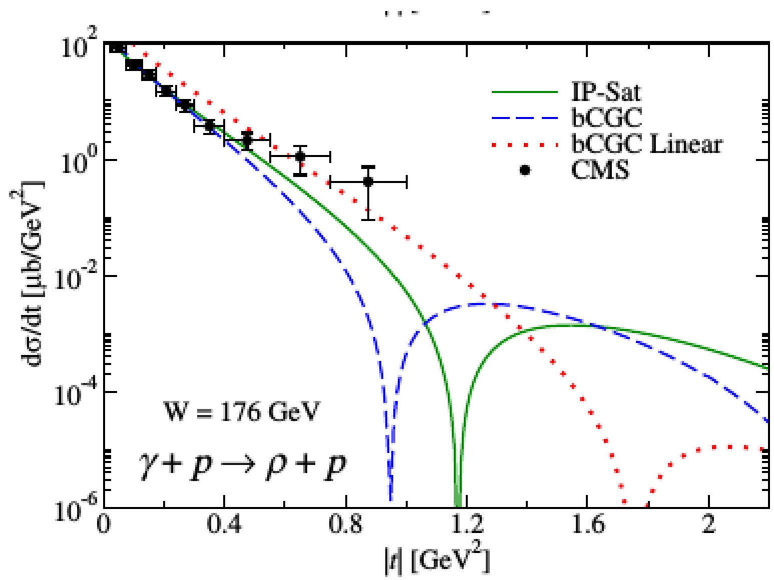
VPG, Spiering, Navarra, PLB 791, 299 (2019)

Exclusive vector meson photoproduction

pA Collisions:

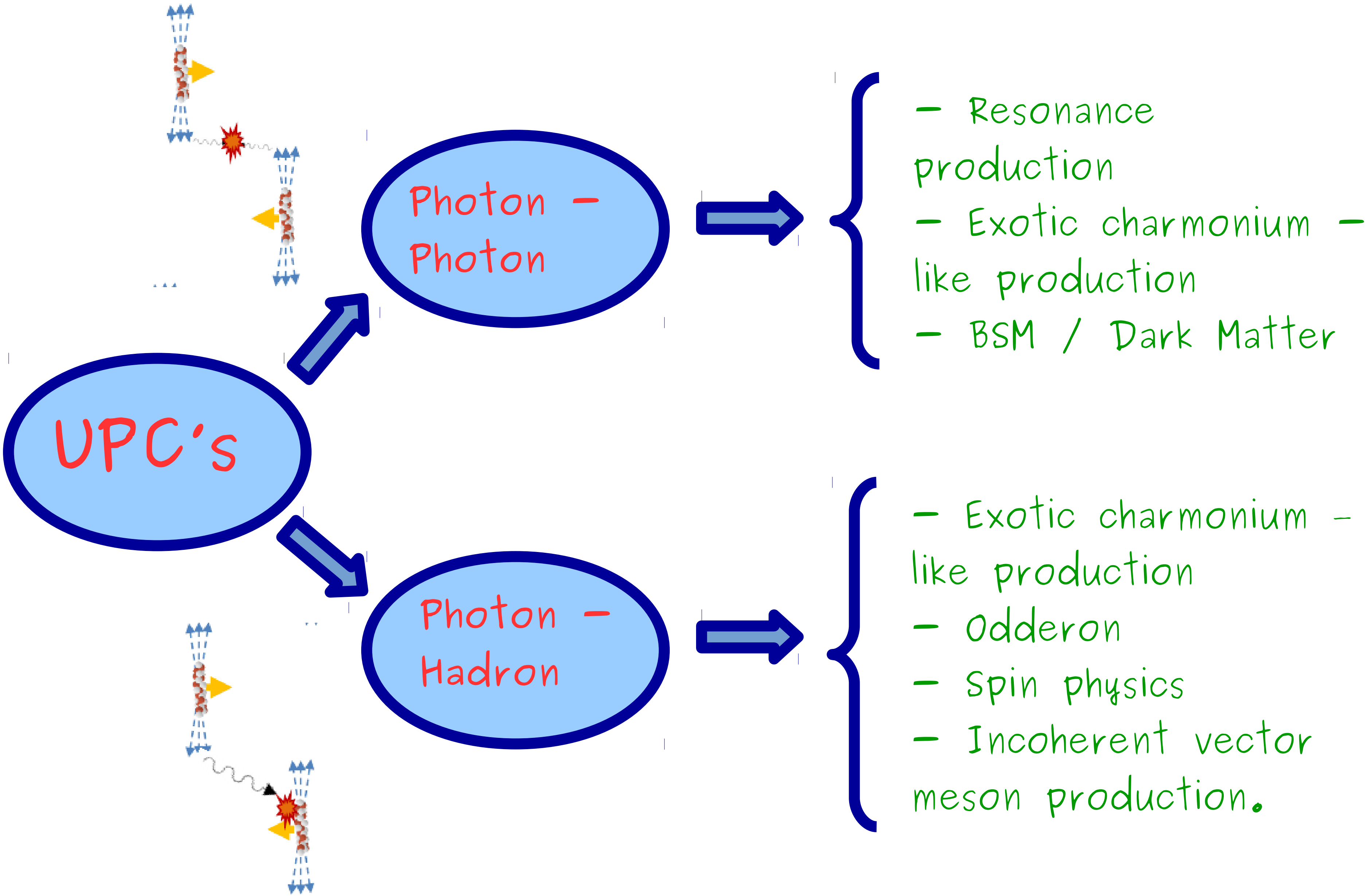
CMS: arXiv:1902.01339

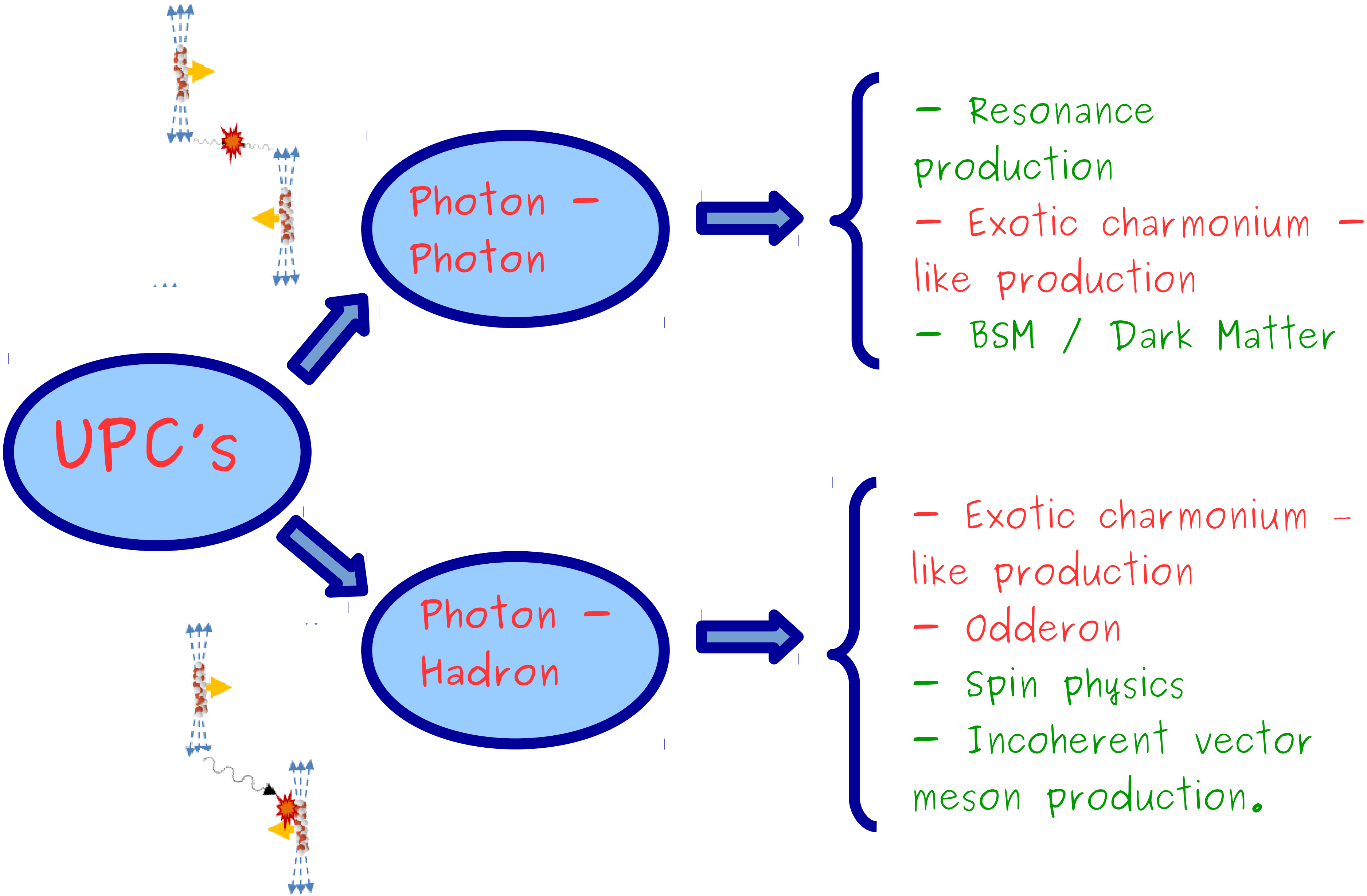




VPG, Spiering, Navarra, PLB 791, 299 (2019)

Ultra - peripheral Collisions:
Prospects


UPC's
Photon - Photon
- Resonance production
- Exotic charmonium - like production
- BSM / Dark Matter
Photon - Hadron
- Exotic charmonium - like production
- Odderon
- Spin physics
- Incoherent vector meson production.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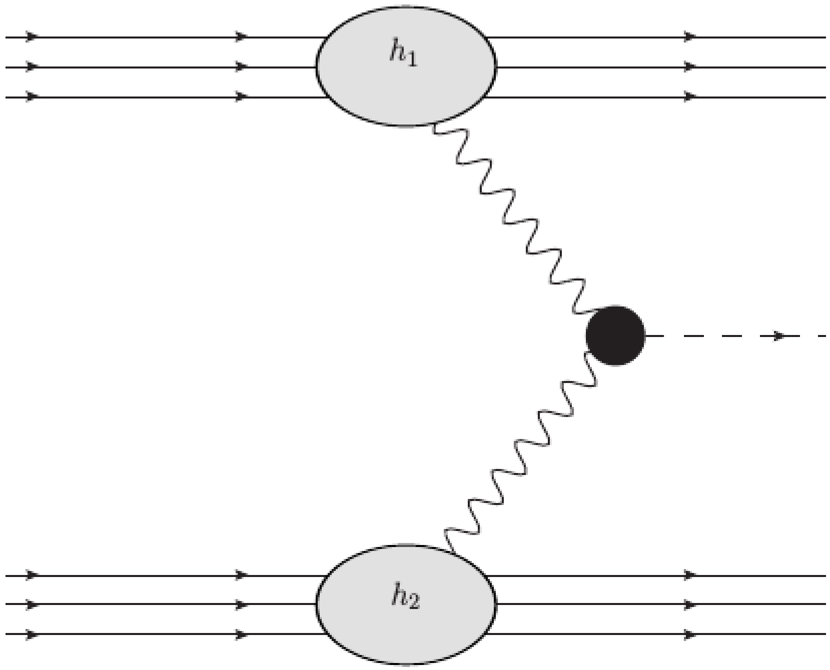
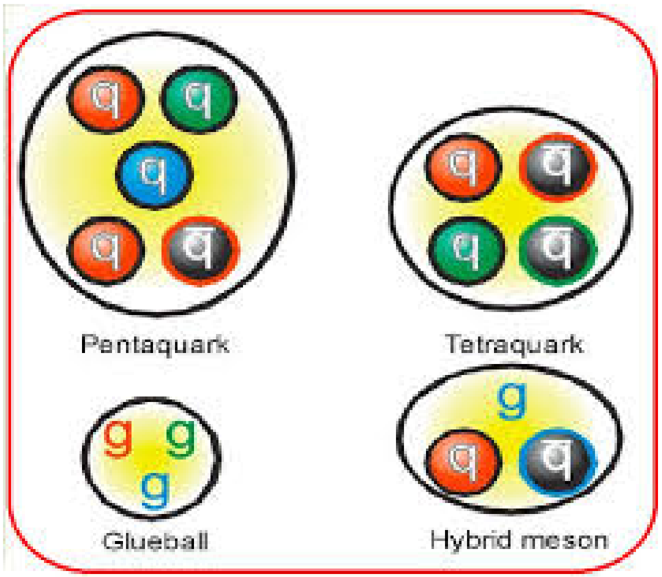
Resonance production



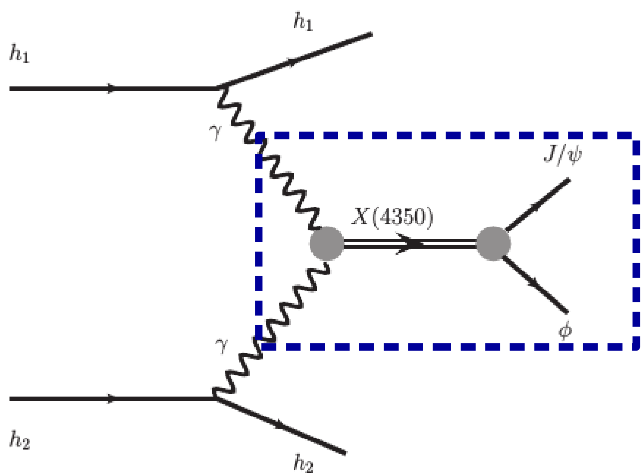


$$\sigma\left(h_1 h_2 \to h_1 \otimes R \otimes h_2; s\right) = \int \hat{\sigma}\left(\gamma\gamma \to R; W\right) N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_2\right) S^2_{abs}(\mathbf{b}) \mathrm{d}^2\mathbf{b}_1 \mathrm{d}^2\mathbf{b}_2 \mathrm{d}\omega_1 \mathrm{d}\omega_2$$

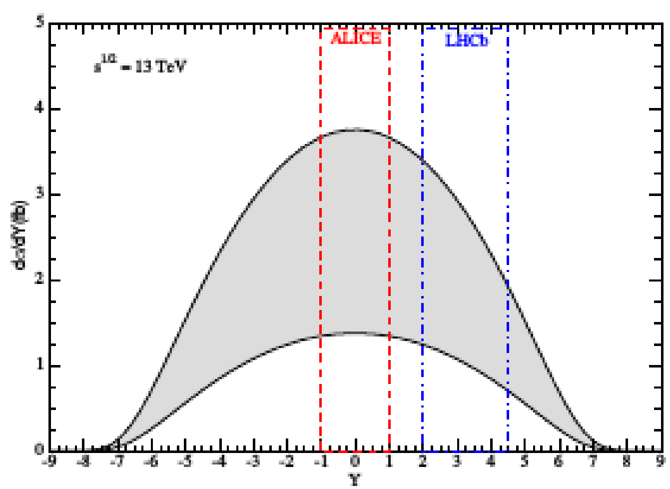
$$\sigma_{\gamma\gamma\to R}(\omega_1,\omega_2) = 8\pi^2(2J+1)\frac{\Gamma_{R\to\gamma\gamma}}{M_R}\delta(4\omega_1\omega_2 - M_R^2)$$

Probing Exotic Charmoniumlike states in photon - photon interactions

Photoproduction of X(4350):



Constrained by Belle Collaboration.



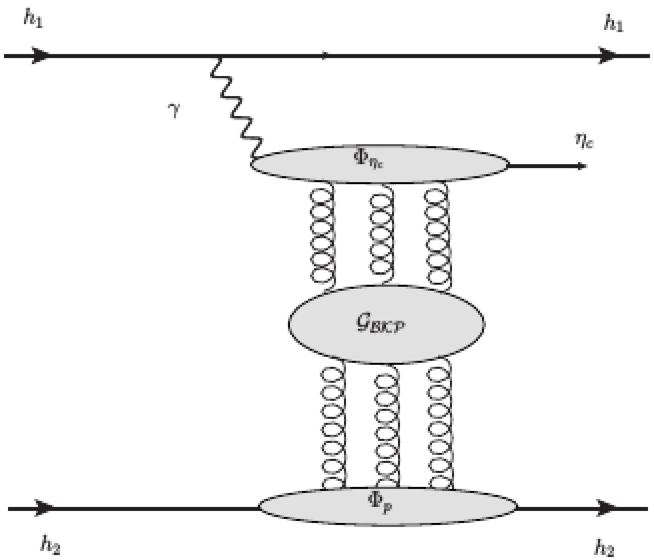
Collision	Resonance	LHCb $2 < Y < 4.5$
pp ($\sqrt{s}$ =13 TeV)	$X(4350)$, 0^{++}	(2.47 – 6.13) fb
	$X(4350)$, 2^{++}	(2.52 – 6.88) fb
pPb ($\sqrt{s}$ =8.1 TeV)	$X(4350)$, 0^{++}	(10.20 – 25.30) pb
	$X(4350)$, 2^{++}	(10.30 – 28.30) pb
$PbPb$ ($\sqrt{s}$ =5.02 TeV)	$X(4350)$, 0^{++}	(14.60 – 36.20) nb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

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

Probing the Odderon

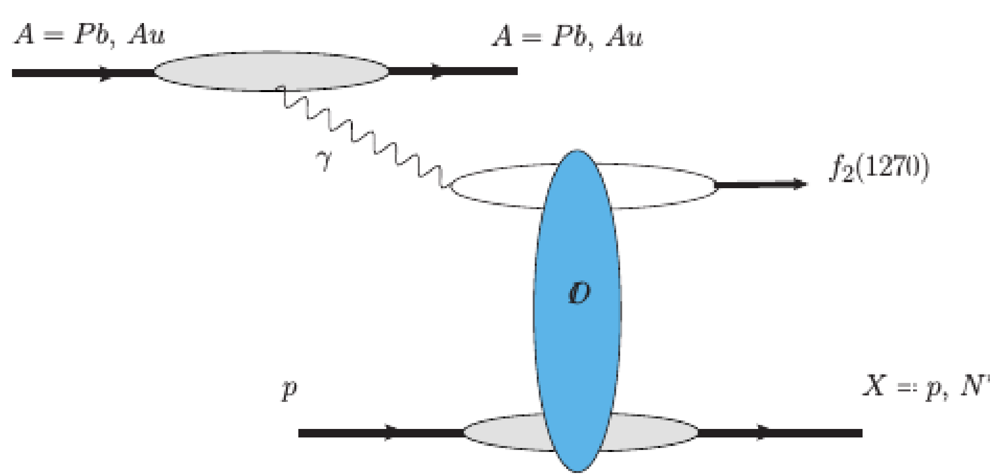
Odderon: Natural prediction of pQCD. C-Odd compound state of three reggeized gluons.

Photoproduction of pseudoscalar mesons: As the photon carries negative C parity, its transformation into a diffractive final state of positive C parity requires the t-channel exchange of an object with negative parity. Pomeron cannot contribute to this process!



	$\gamma\gamma$ interactions	Exclusive $\gamma\mathbb{O}$ interactions
pp ($\sqrt{s} = 13$ TeV)	0.059 nb	0.013 nb
pPb ($\sqrt{s} = 8.1$ TeV)	0.182 μb	0.032 μb

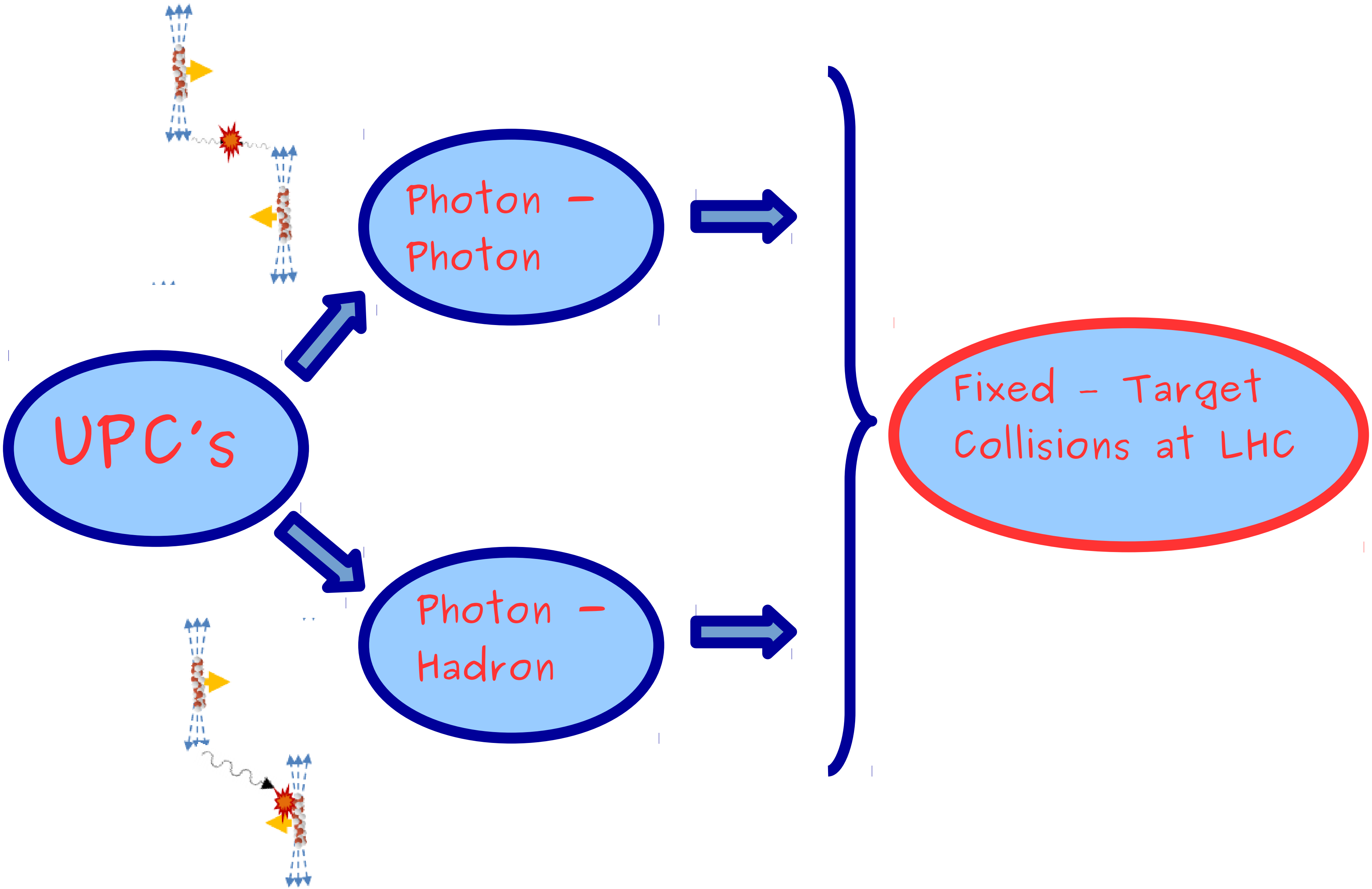
VPG, NPA 902, 32 (2013); VPG, Sauter, PRD 91, 094014 (2015); VPG, Moreira, PRD97 (2018) 014001



Cross sections in μb

	ALICE/CMS ($-2.0 \leq Y \leq +2.0$)	LHCb ($2.0 \leq Y \leq 4.6$)
$\gamma\mathbb{O}$	8.37	0.85
$\gamma\gamma$	3.34	5.32

VPG, EPJC 79, 408 (2019)

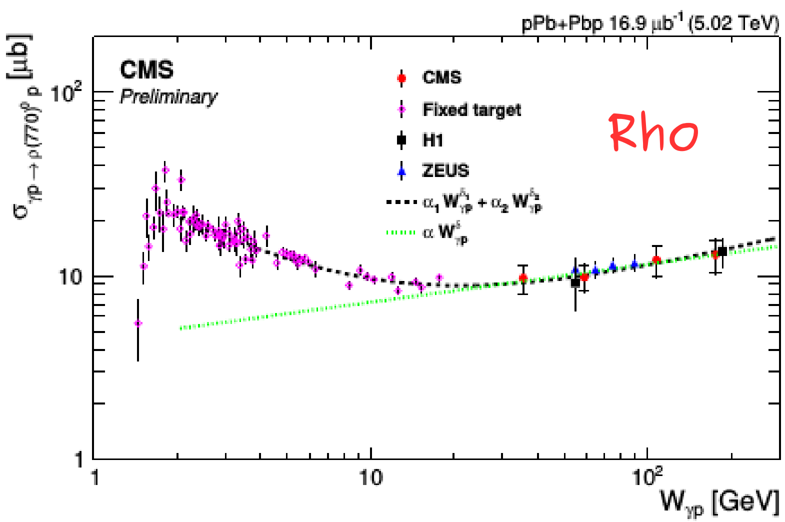


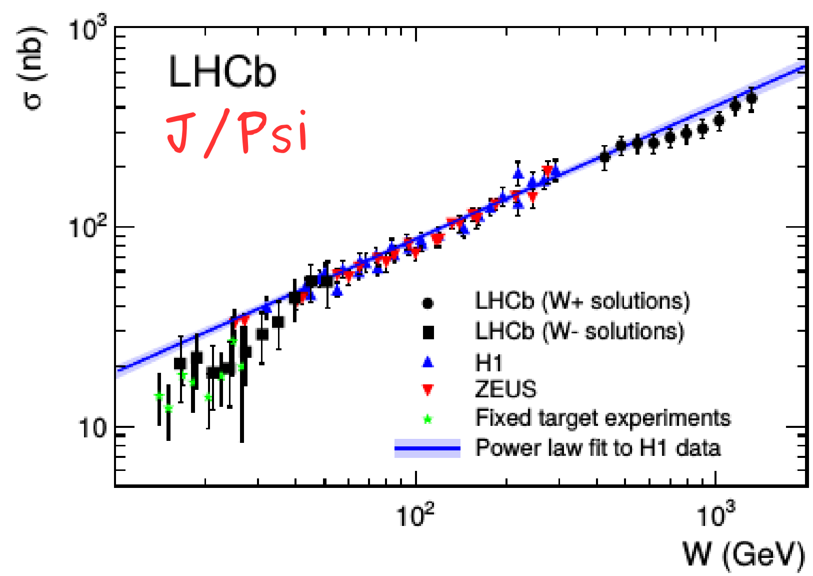
UPC's
Photon - Photon
Photon - Hadron
Fixed - Target Collisions at LHC

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); Lansberg, Massacrier, et al.

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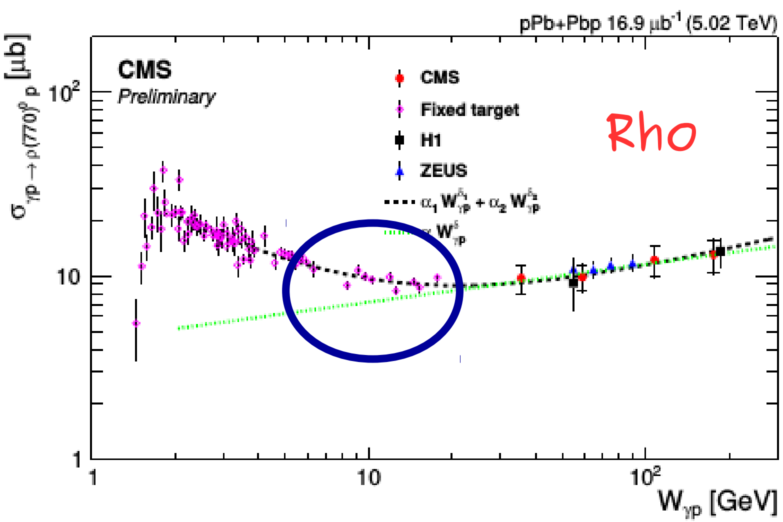
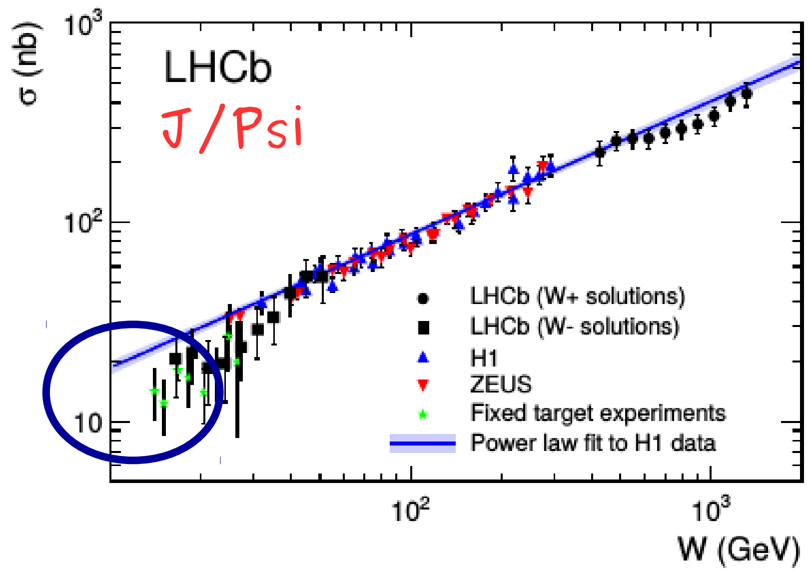
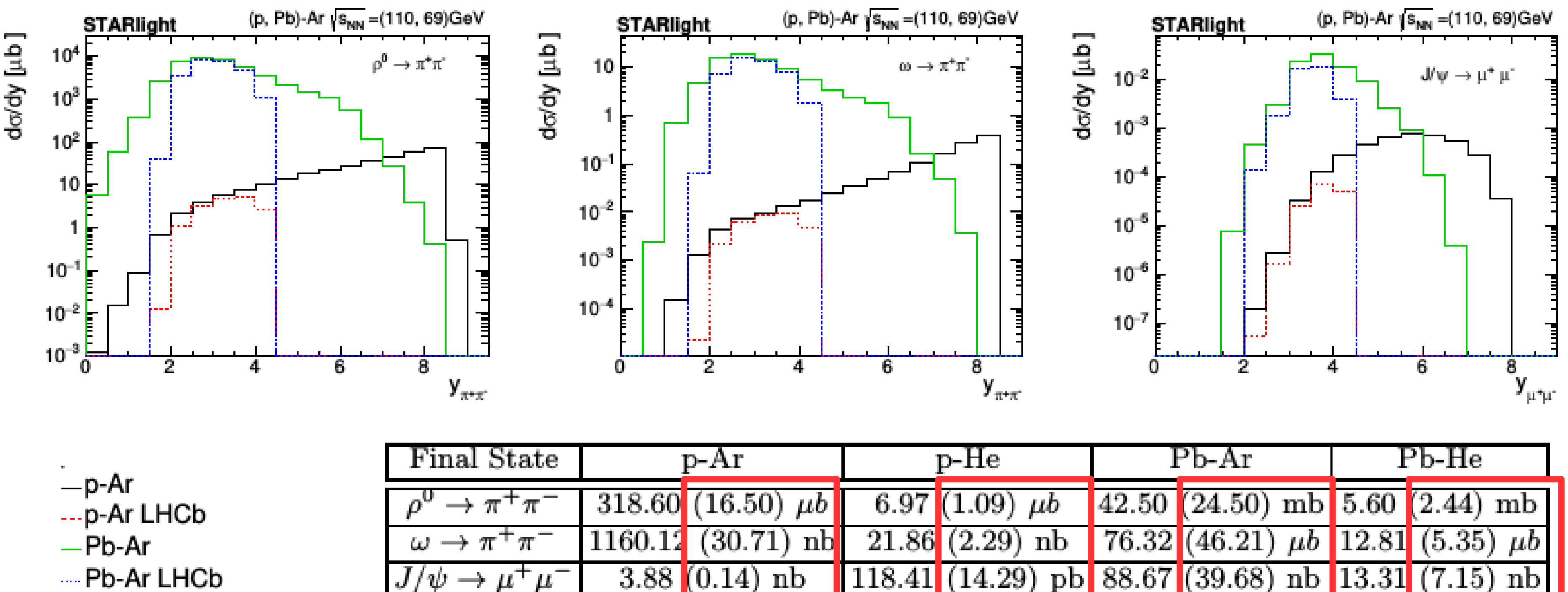




(*) VPG, Medina EPJC78, 693 (2018)

Exclusive VM photoproduction in fixed target collisions at the LHC

Rho Omega J/Psi

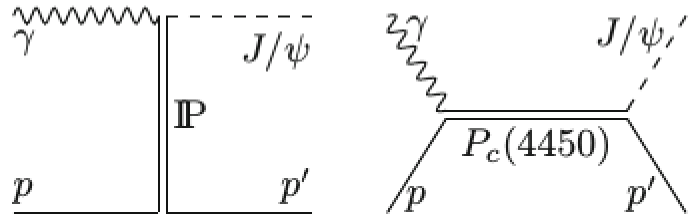


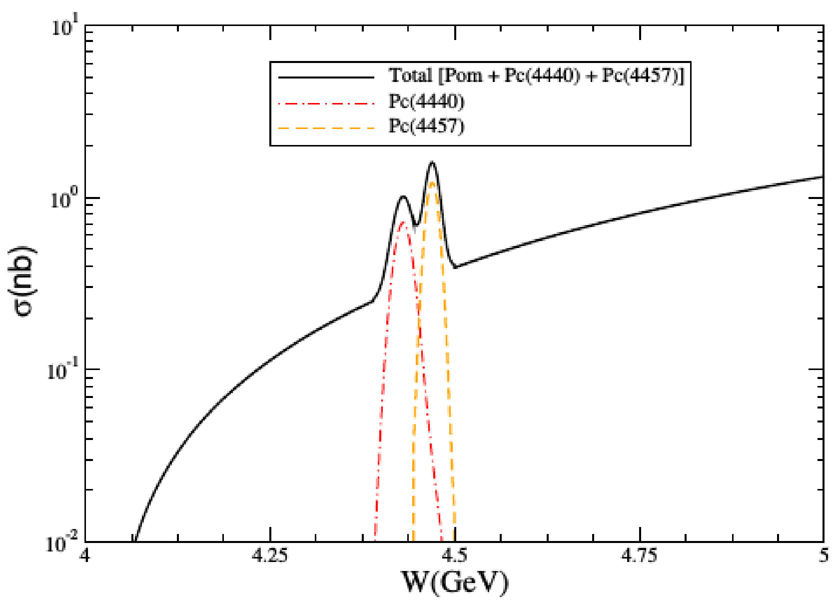
Final State	p-Ar		p-He		Pb-Ar		Pb-He	
$\rho^0 \to \pi^+\pi^-$	318.60	(16.50) μb	6.97	(1.09) μb	42.50	(24.50) mb	5.60	(2.44) mb
$\omega \to \pi^+\pi^-$	1160.12	(30.71) nb	21.86	(2.29) nb	76.32	(46.21) μb	12.81	(5.35) μb
$J/\psi \to \mu^+\mu^-$	3.88	(0.14) nb	118.41	(14.29) pb	88.67	(39.68) nb	13.31	(7.15)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

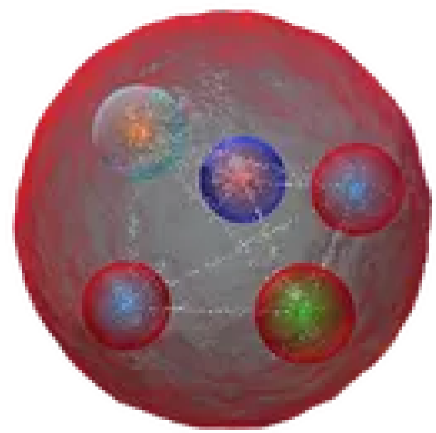
(*) VPG, Medina EPJC78, 693 (2018)

Probing Pentaquarks in photon - hadron interactions

Photoproduction of P_c:







Cao, Dai, ArXiv:1904.06015[hep-ph].

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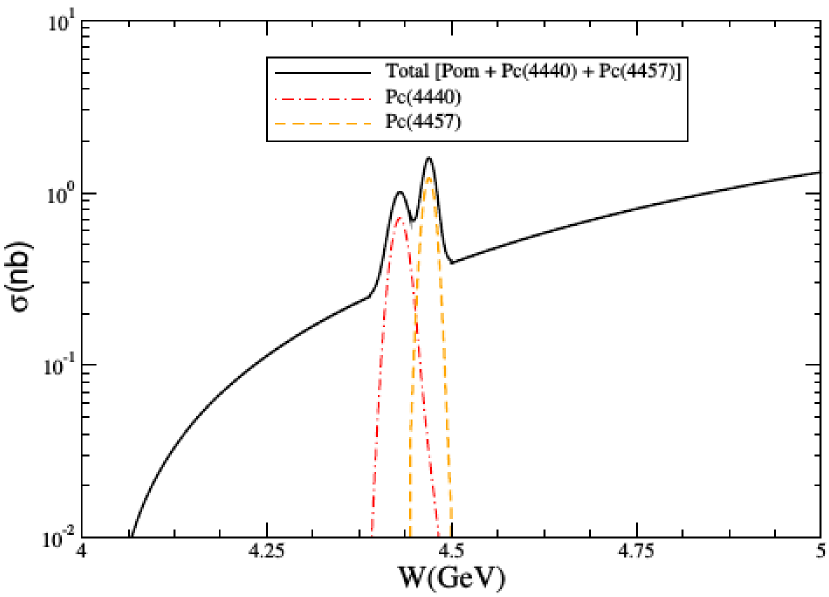
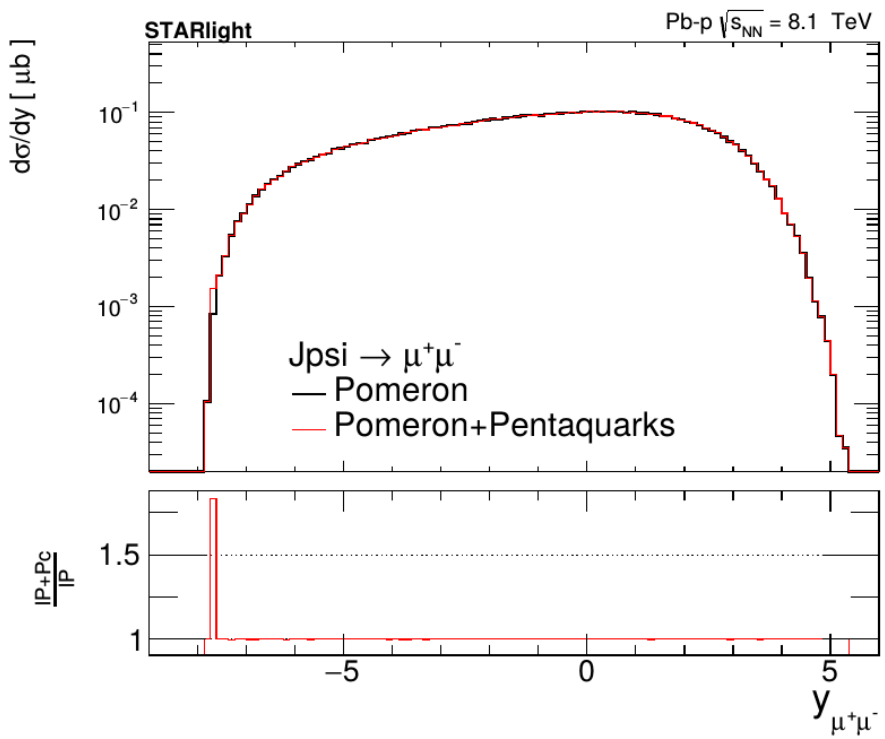


Collider mode:



VPG, Medina, work in progress.

Probing Pentaquarks in photon - hadron interactions

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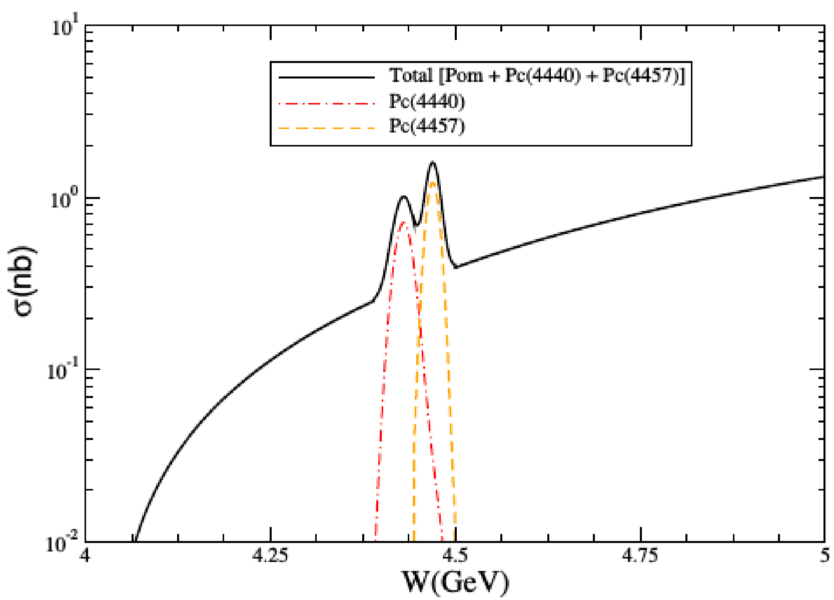
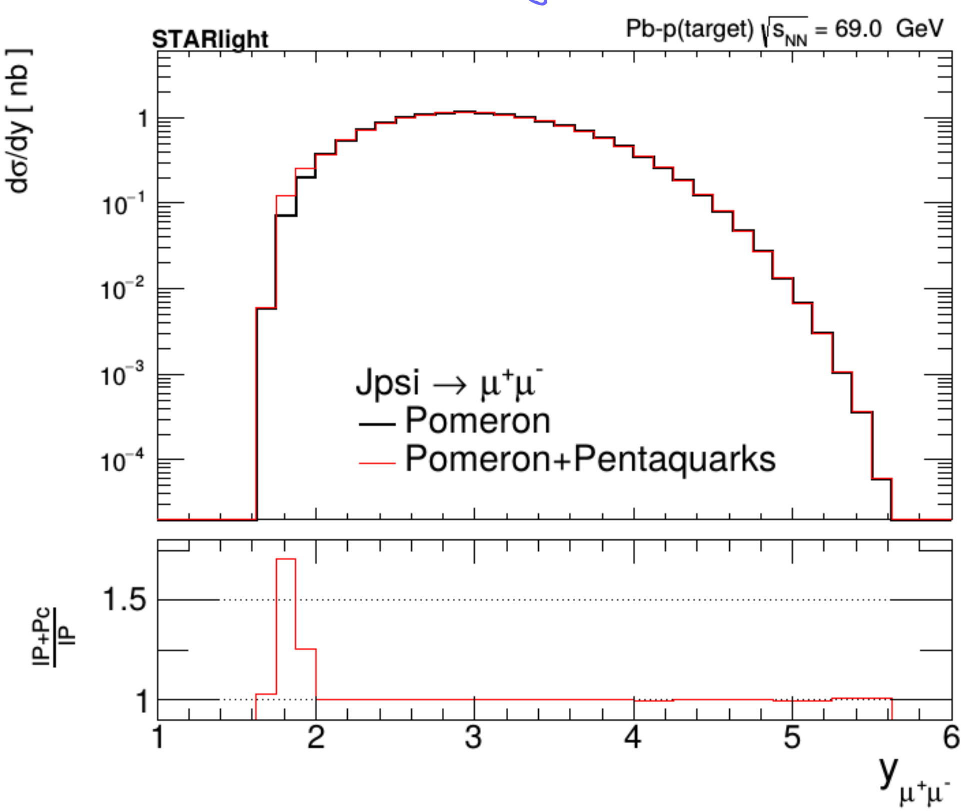


Fixed - target mode:



VPG, Medina, work in progress.

Summary

Summary

- ✓ Photon – induced interactions can be used to constrain the physics in unexplorated energy regime.
- ✓ We can learn a lot of physics studying the HE regime. However, the analysis of the low energy regime is also very important to constrain some important aspects of hadronic physics.
- ✓ The RHIC and LHC data for the photoproduction of different final states will be fundamental to constrain and/or discriminate between different models.
- ✓ Complementary studies can be performed by the analysis of the exclusive vector meson photoproduction in polarized hadronic collisions and in fixed – target collisions at the LHC.

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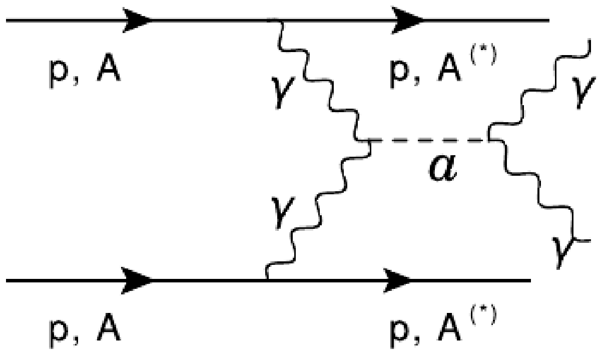
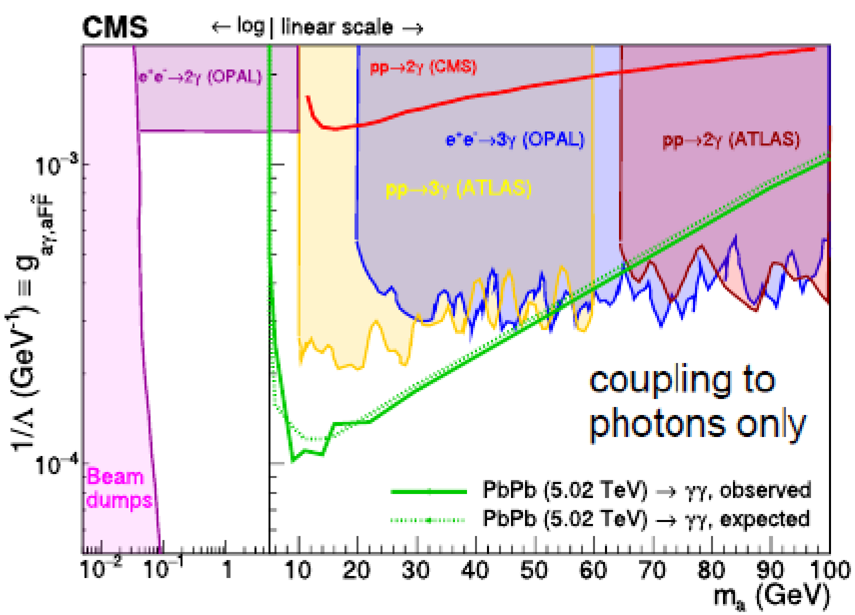
Thank you for your attention!

Axion - like particle search



- Exclusive di-photon final state from CP-odd axion - like particles.
- No evidence in this channel!

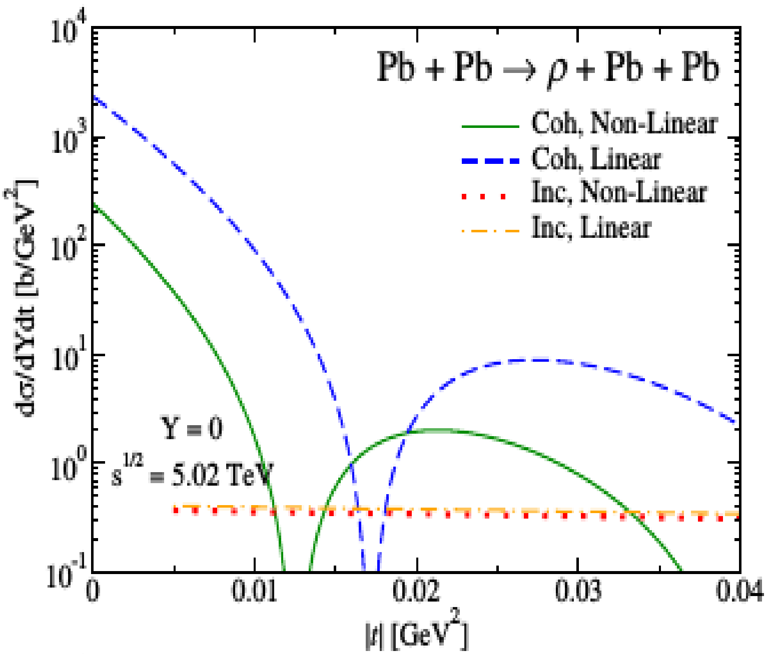


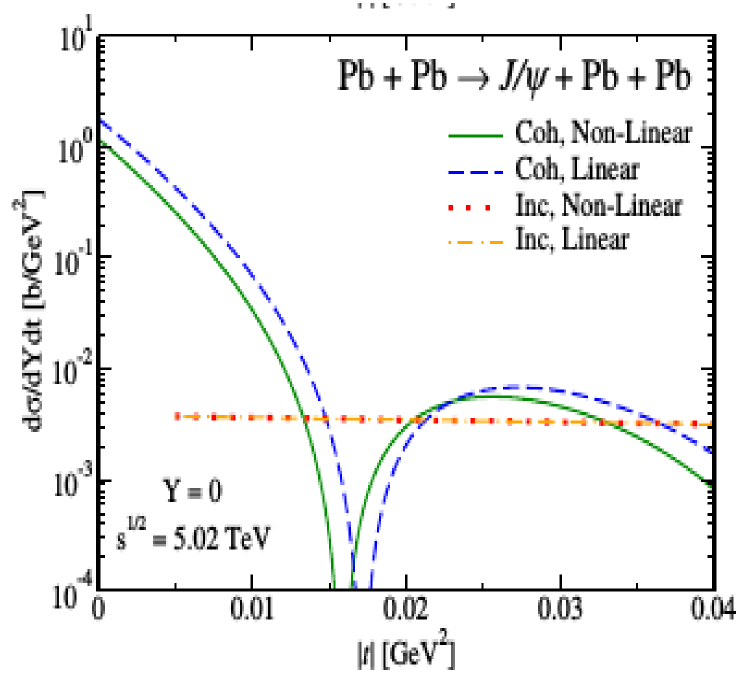
CMS 1810.04602

Royon et al; Knapen, Lin, Lou, Melia; ...

Exclusive vector meson photoproduction

PbPb Collisions:

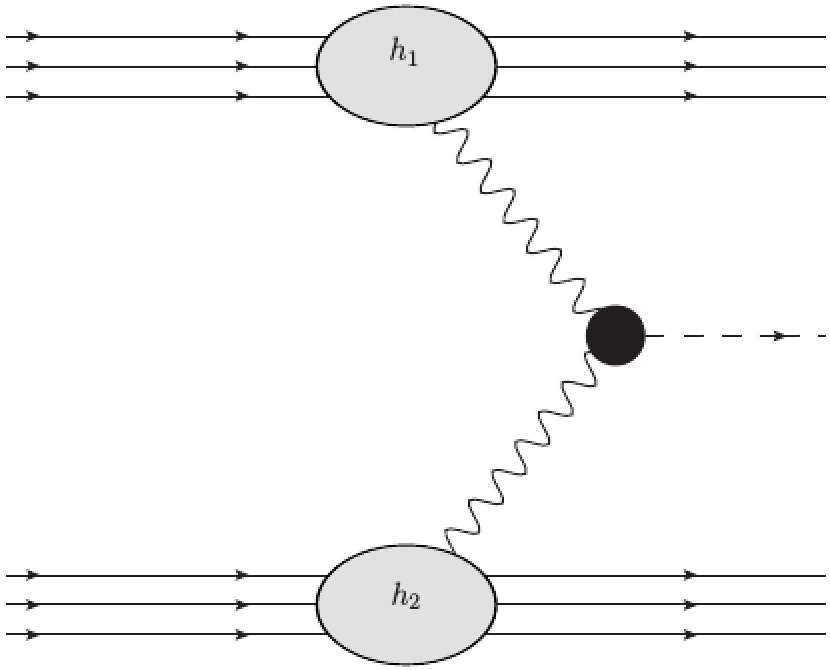


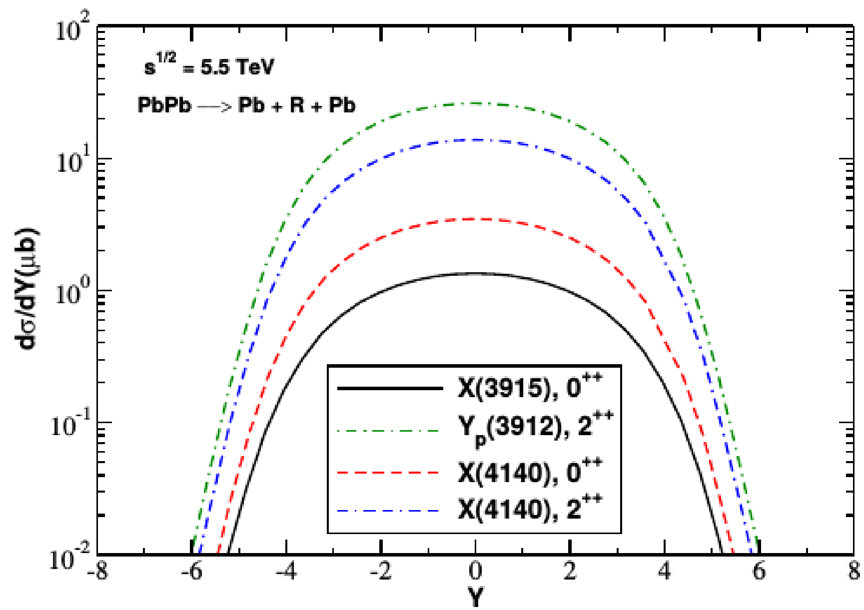


Linear model: $\mathcal{N}^A(x, r, \boldsymbol{b}_A) = \frac{1}{2}\sigma_{dp}(x, r) A T_A(\boldsymbol{b}_A)$

VPG, Spiering, Navarra, PLB 768, 299 (2017)

Probing Exotic Charmoniumlike states in photon - photon interactions





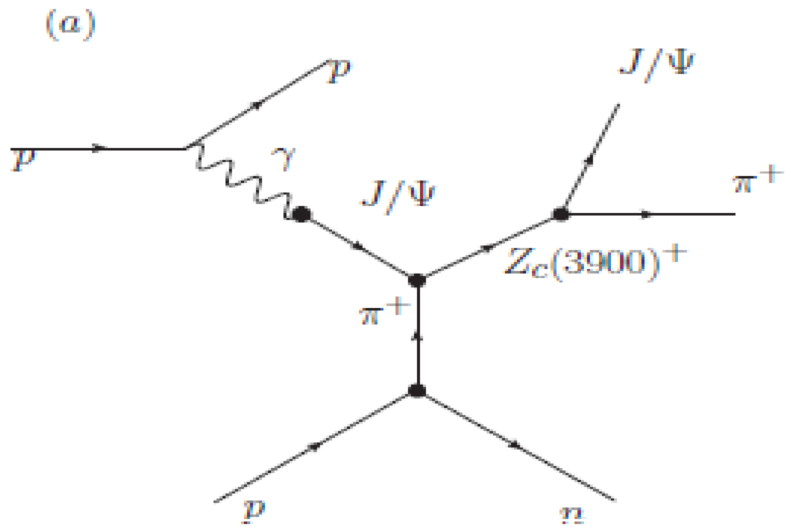
$$\sigma\left(h_1 h_2 \rightarrow h_1 \otimes R \otimes h_2; s\right) = \int \hat{\sigma}\left(\gamma\gamma \rightarrow R; W\right) N\left(\omega_1, \mathbf{b}_1\right) N\left(\omega_2, \mathbf{b}_2\right) S^2_{abs}(\mathbf{b}) \mathrm{d}^2\mathbf{b}_1 \mathrm{d}^2\mathbf{b}_2 \mathrm{d}\omega_1 \mathrm{d}\omega_2$$

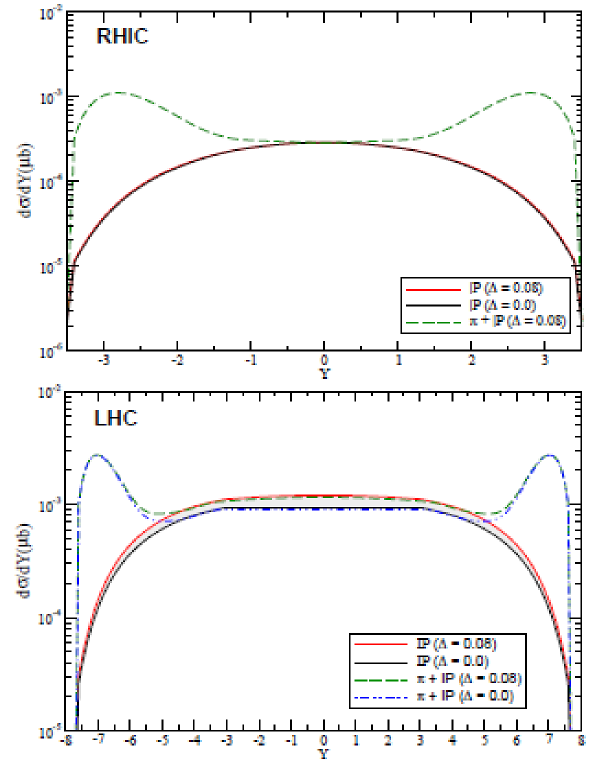
$$\sigma_{\gamma\gamma\rightarrow R}(\omega_1,\omega_2) = 8\pi^2(2J+1)\frac{\Gamma_{R\rightarrow\gamma\gamma}}{M_R}\delta(4\omega_1\omega_2 - M_R^2)$$

(*) Bertulani, VPG, Moreira, Navarra, PRD94, 094024 (2016)

Probing Exotic Charmoniumlike states in photon - hadron interactions

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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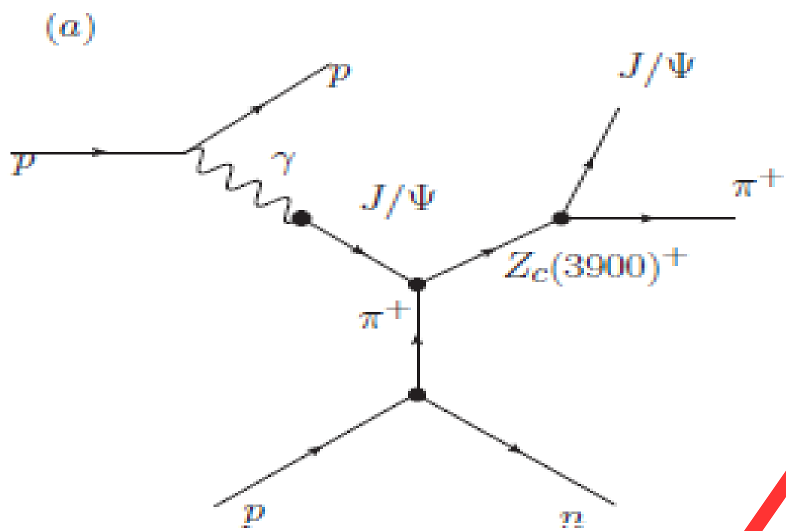
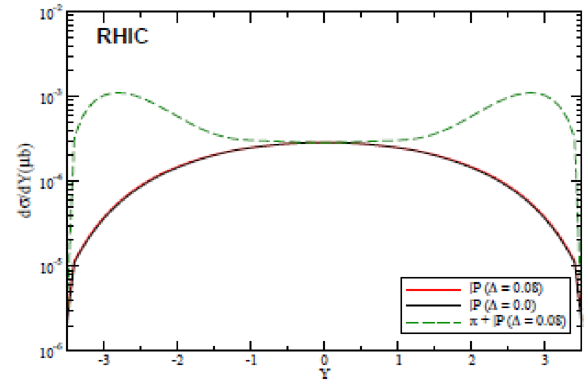
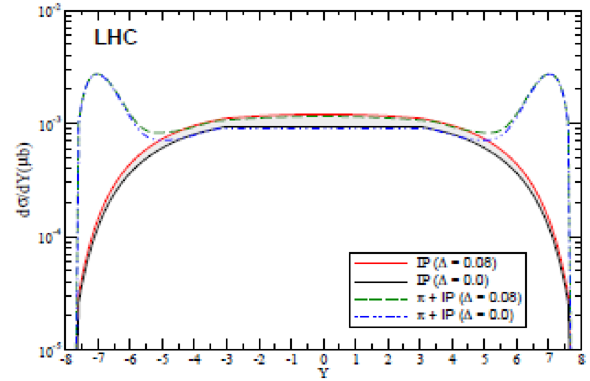


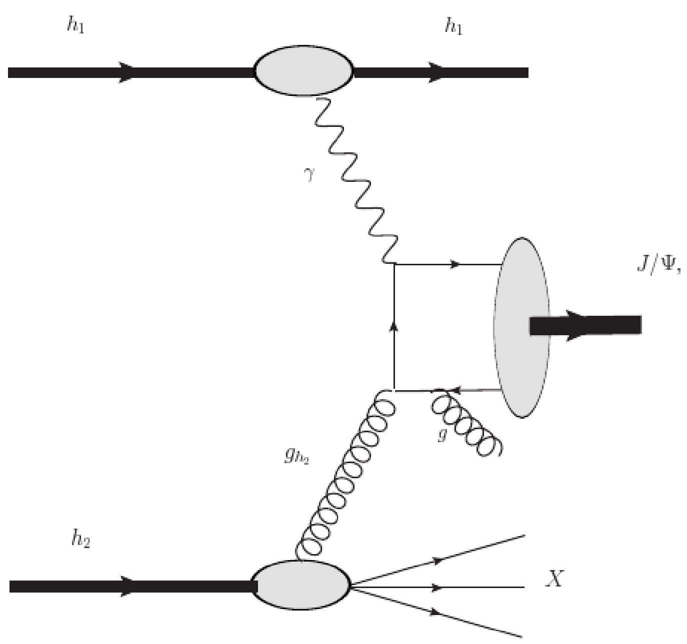




The enhancement occurs at very large rapidities (small photon - proton center - of - mass energies)!

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

Inclusive VM photoproduction in p↑p and p↑Au as a probe of the Gluon Sivers function



Intact hadron

Rapidity gap

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:

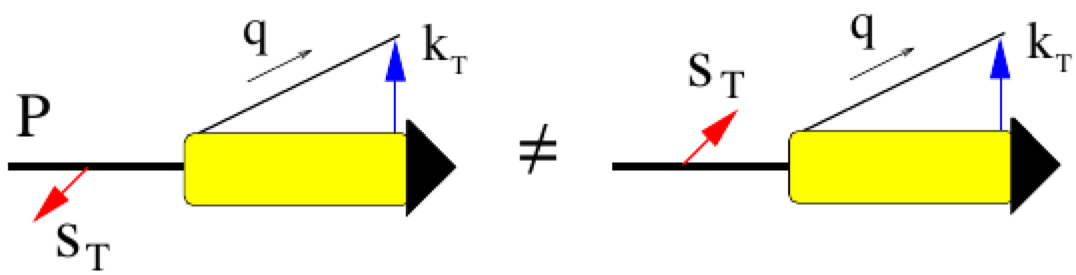
$$f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp g}, \boldsymbol{S}) \equiv f_{g/p}(x_g, k_{\perp g}) + \frac{1}{2}\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g})\hat{\boldsymbol{S}} \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}_{\perp g}})$$

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.



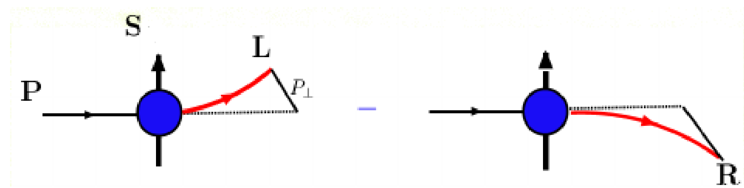
Gluon Sivers function: Unpolarized gluon in a polarized nucleon. Parametrizes the correlation between the azimuthal distribution of an unpolarized parton and the spin of its parent nucleon.

- 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:

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



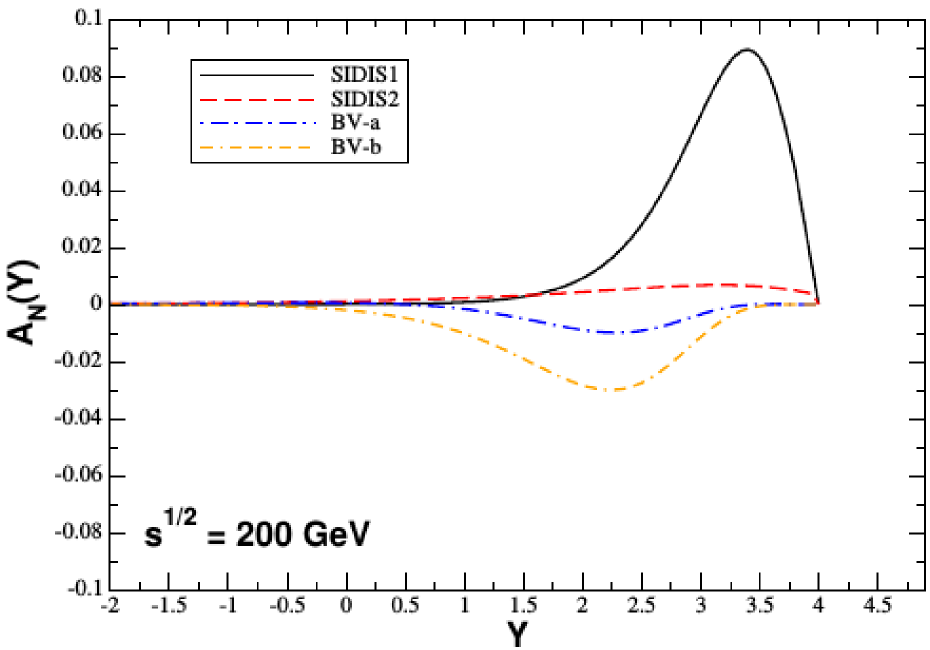
Where $\frac{d\sigma^\uparrow}{dY}$ and $\frac{d\sigma^\downarrow}{dY}$ are respectively the differential cross sections measured when the proton is transversely polarized up (↑) and down (↓) with respect to the scattering plane. One have that:

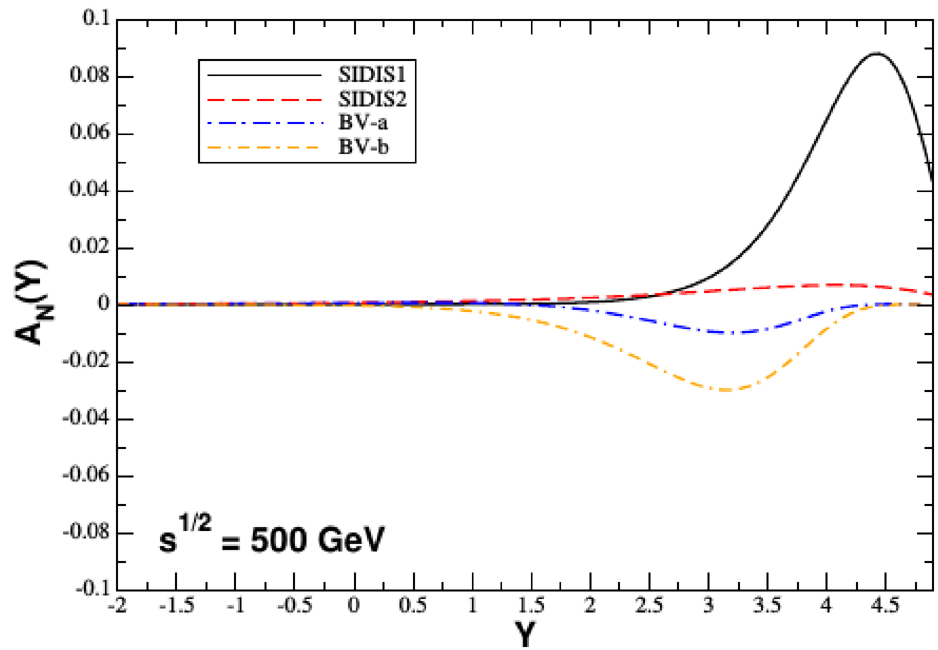
$$\frac{d\sigma^\uparrow}{dY} - \frac{d\sigma^\downarrow}{dY} = F_{J/\Psi} \int d\phi_{q_T} \int q_T dq_T \int_{4m_c^2}^{4m_D^2} dM_{c\bar{c}}^2 \int d^2\boldsymbol{k}_{\perp g}\, f_{\gamma/h}(x_\gamma, \boldsymbol{q}_T - \boldsymbol{k}_{\perp g})$$
$$\times \left[f_{g/p^\uparrow}(x_g, \boldsymbol{k}_{\perp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

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

Single Spin Asymmetry

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

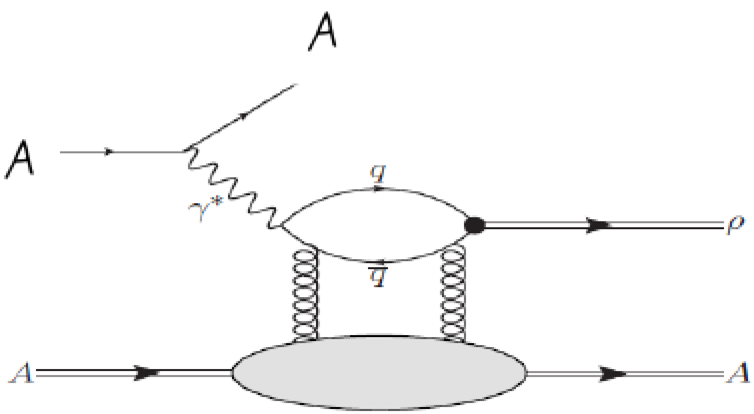




(*) VPG, PRD97 (2018) 014001

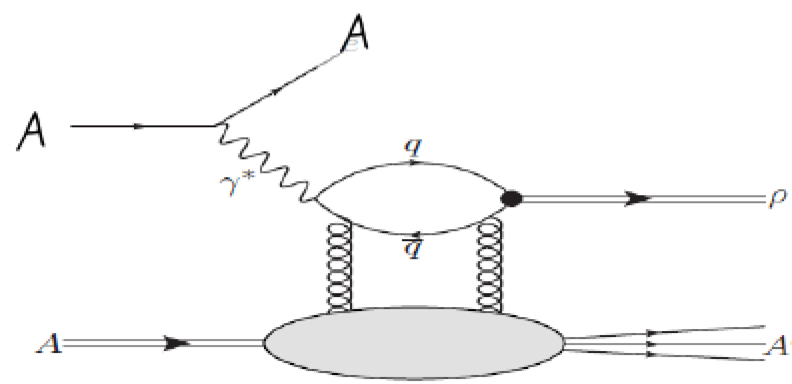
Exclusive vector meson photoproduction : Coherent x Incoherent production

Coherent production:



$$\left.\frac{d\sigma^{\gamma A\to V\,A}}{dt}\right|_{T,L} = \frac{1}{16\pi}\left|\langle\mathcal{A}(x,Q^2,\Delta)_{T,L}\rangle\right|^2 .$$

Incoherent production:



$$\left.\frac{d\sigma^{\gamma A\to V\,Y}}{dt}\right|_{T,L} = \frac{1}{16\pi}\left(\left\langle\left|\mathcal{A}(x,Q^2,\vec{\Delta})_{T,L}\right|^2\right\rangle - \left|\left\langle\mathcal{A}(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2\right)$$

Krelina, VPG, Cepila, NPA 989, 187 (2019)

Exclusive vector meson photoproduction : Coherent x Incoherent production

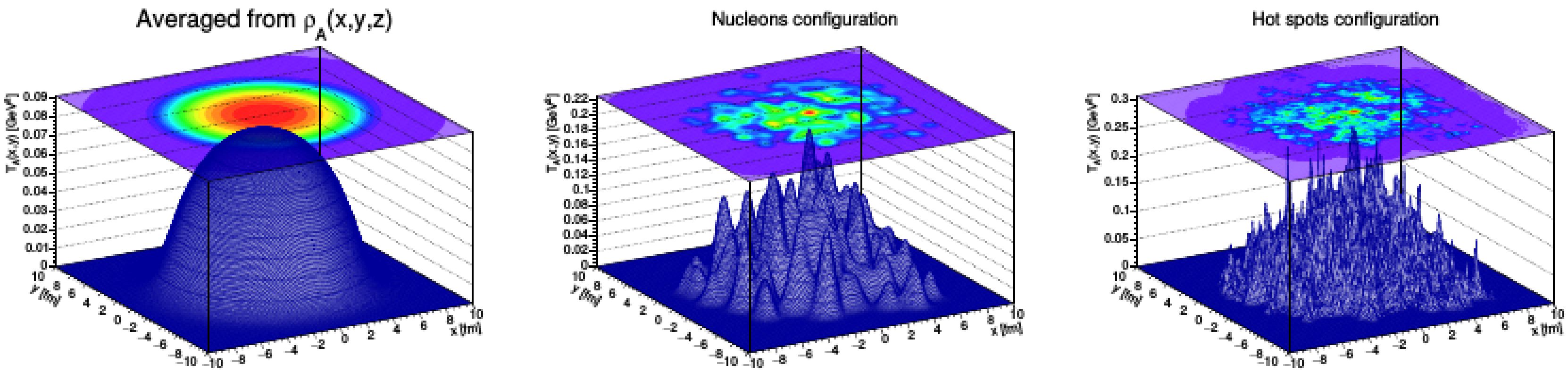


Figure 2: Comparison of nuclear profiles, $T_A(b)$, calculated from nuclear density function $\rho_A(\vec{r})$ (left), calculated using nu model where each nucleon is represented by Gaussian (center), and calculated using the hot shots model, where every nucleon from nu model is represented by a set of hot spots (right).

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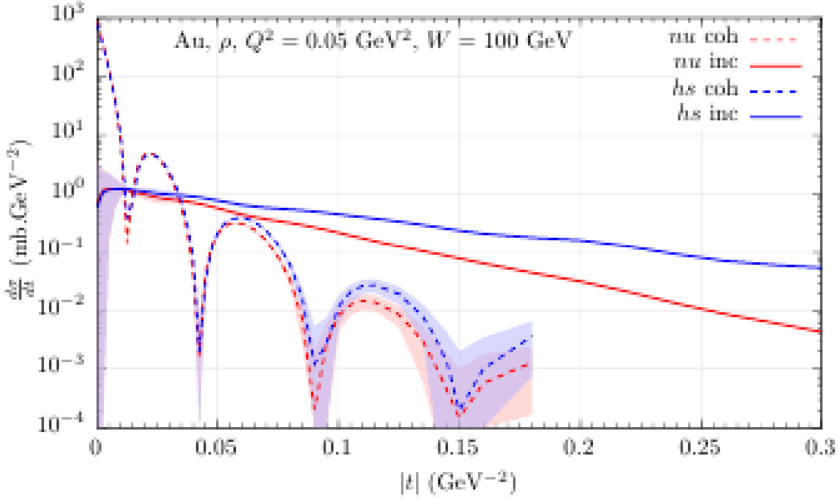
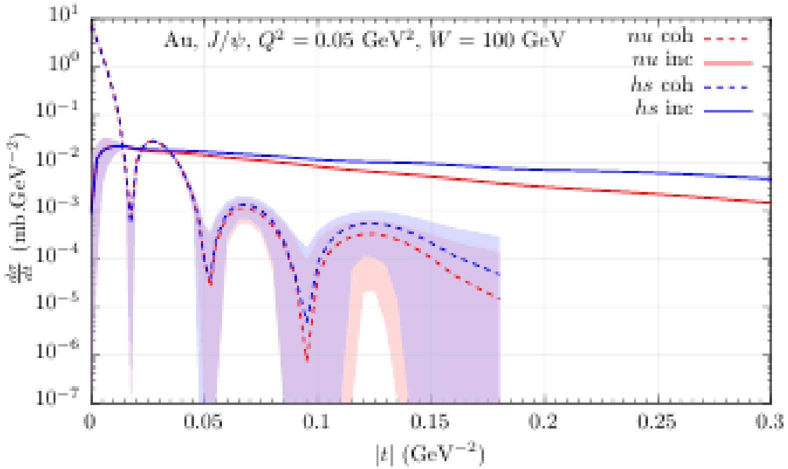
Exclusive vector meson photoproduction : Coherent x Incoherent production





Krelina,VPG,Cepila, NPA 989, 187 (2019)