Physikzentrum Bad Honnef

Probing the QCD Dynamics in Photon Induced interactions at the LHC

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Theory High Energy Physics – Lund University - Sweden

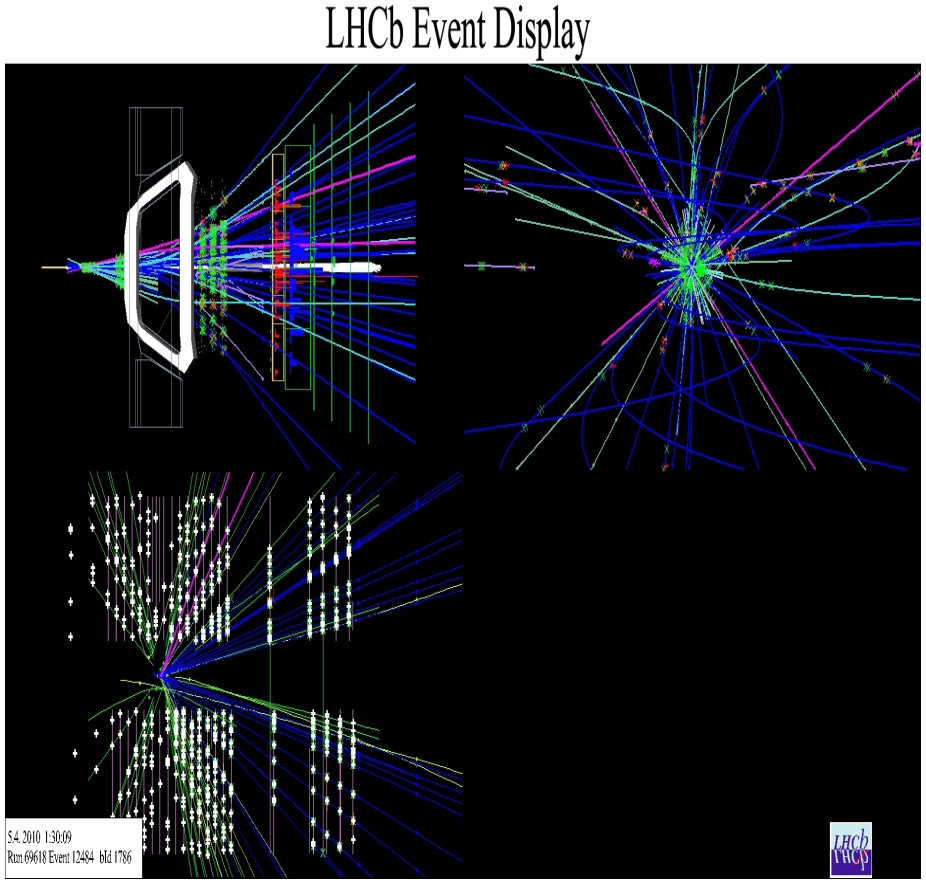
and

High and Medium Energy Group – UFPel - Brazil

WE – Heraus Physics School – Bad Honnef
18 Aug 2015

Motivation

Typical *pp* events:



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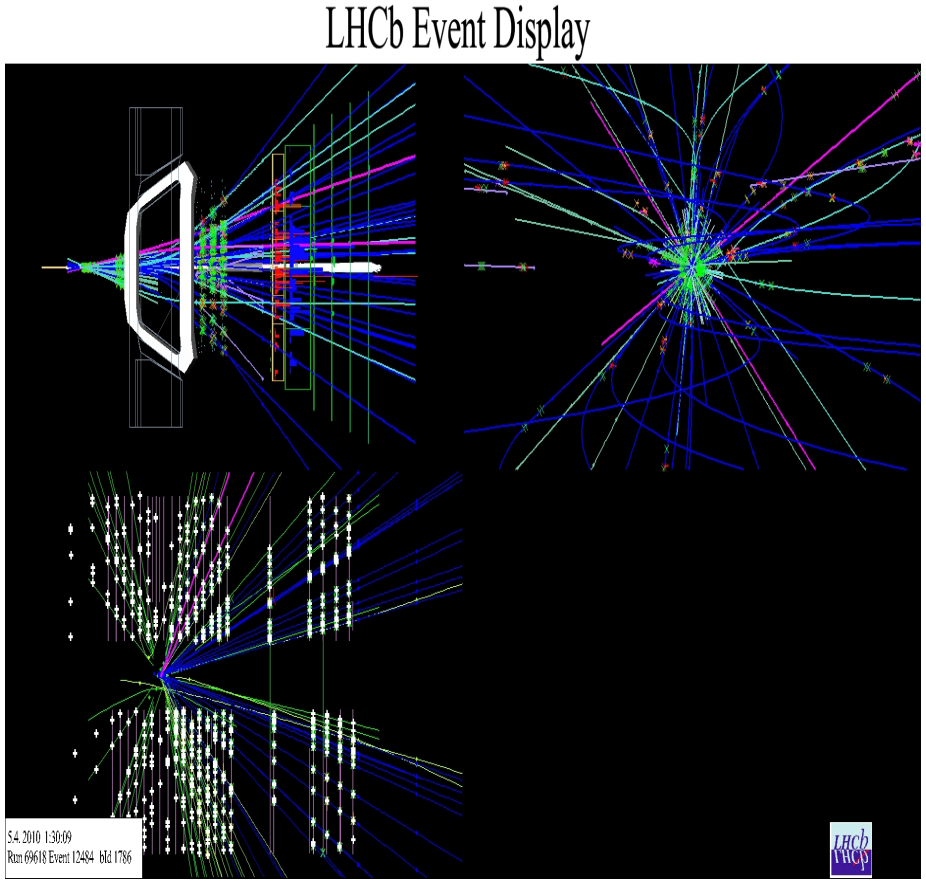

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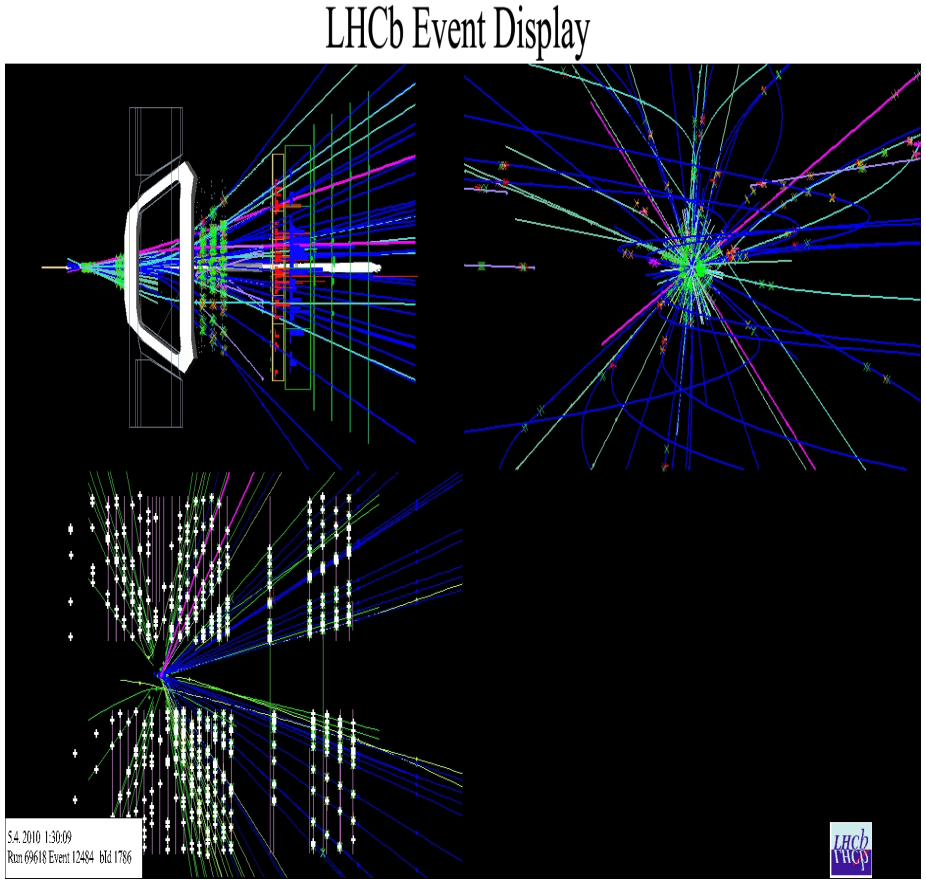

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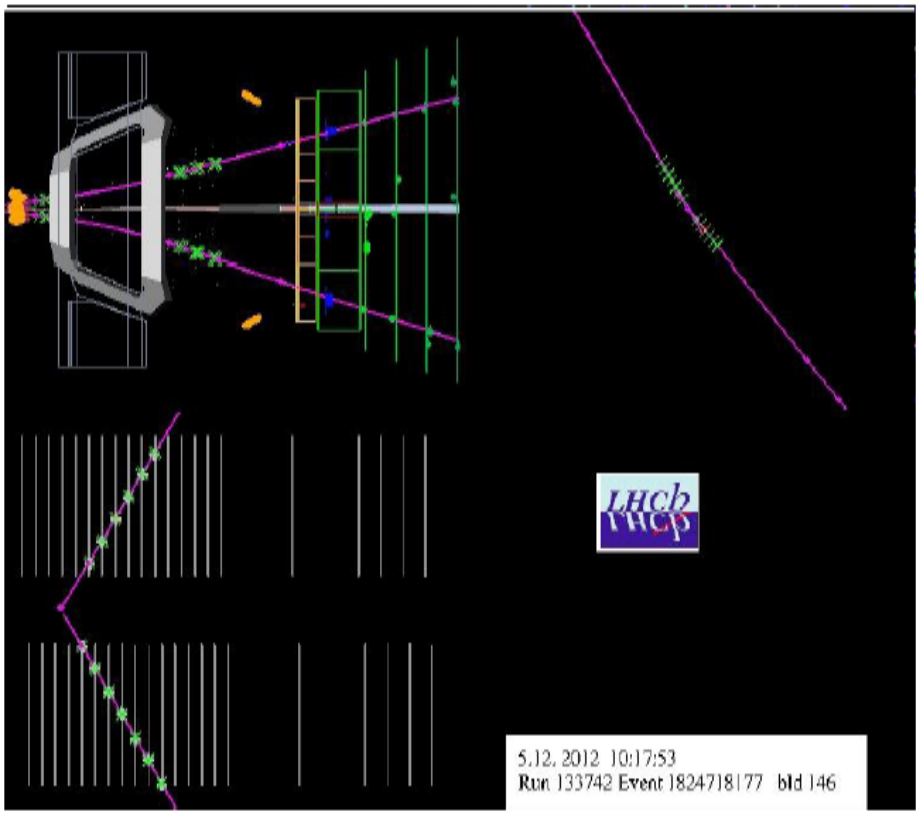

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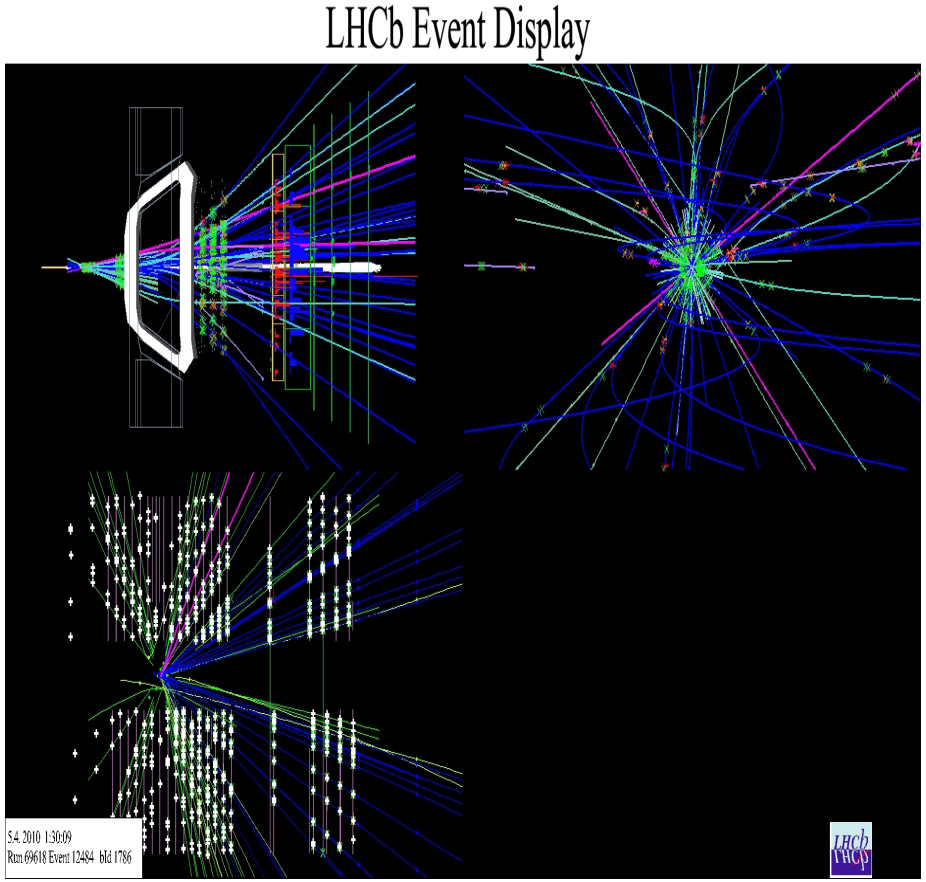

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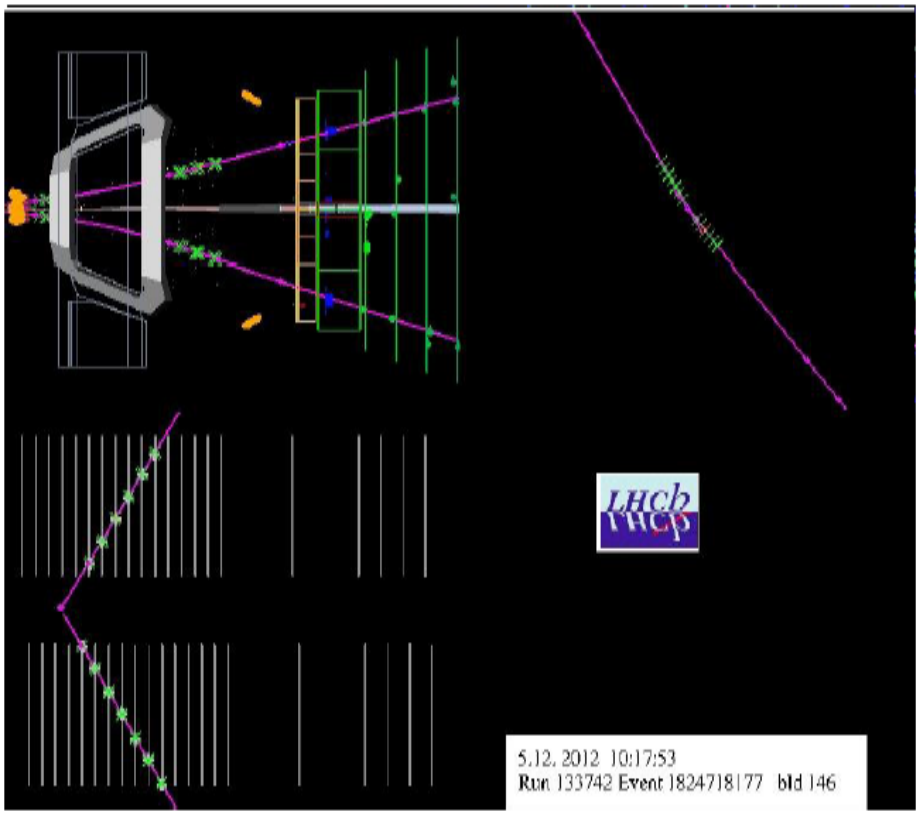

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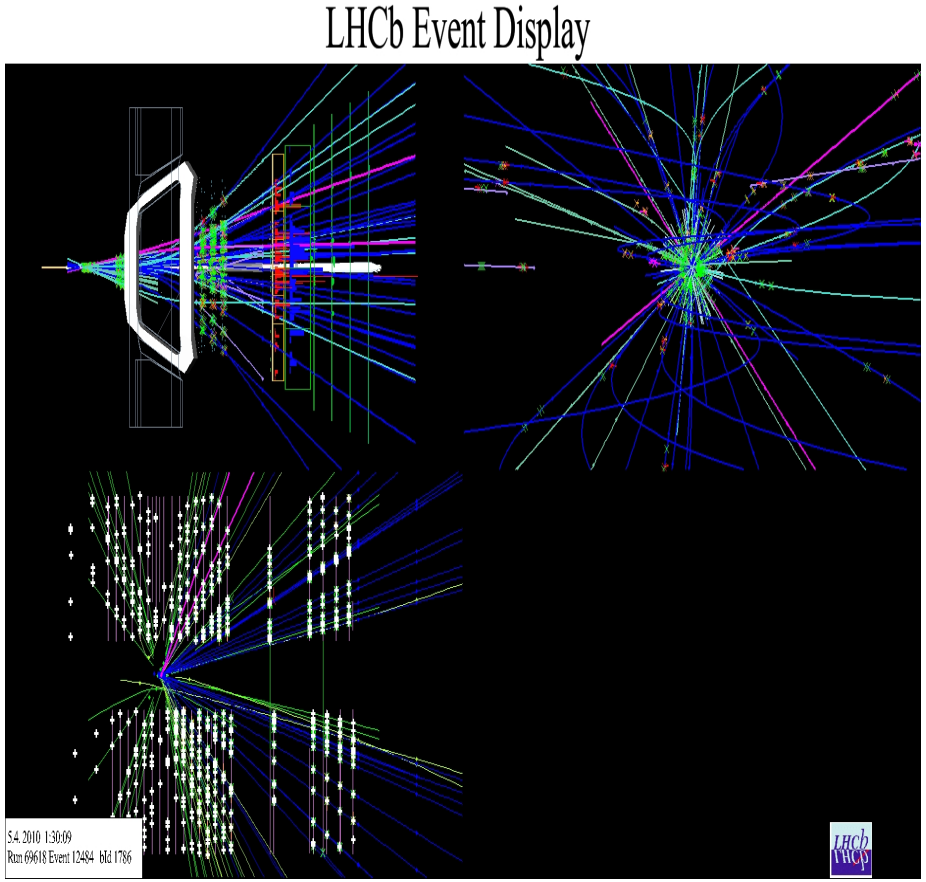

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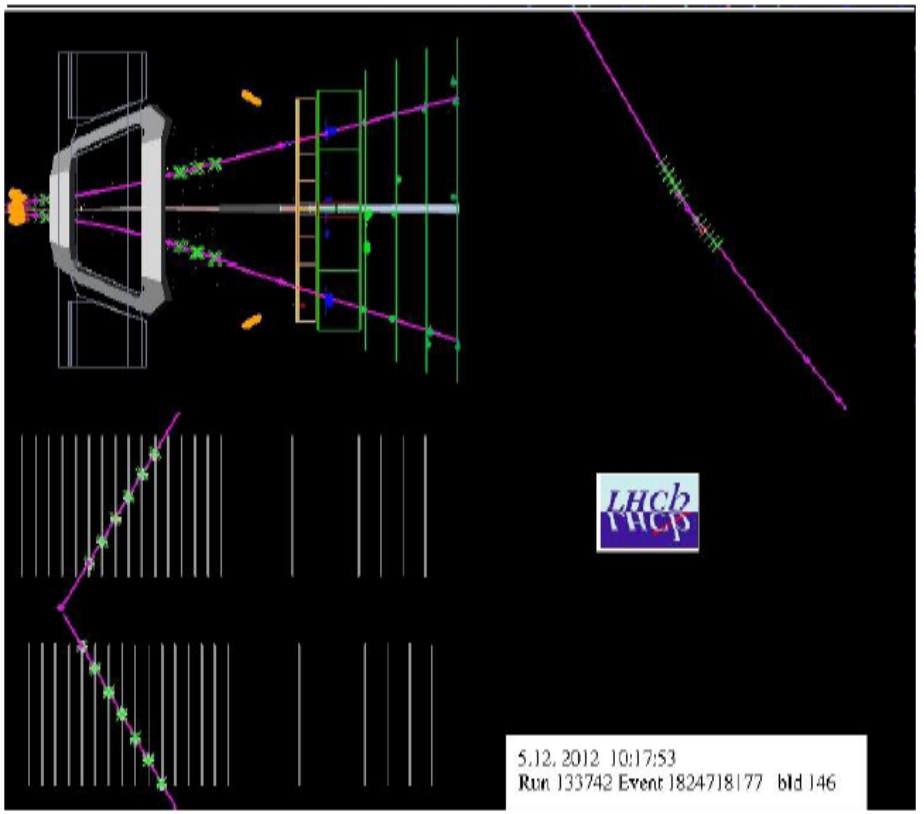

Central Exclusive Process (CEP)

Central Exclusive Processes

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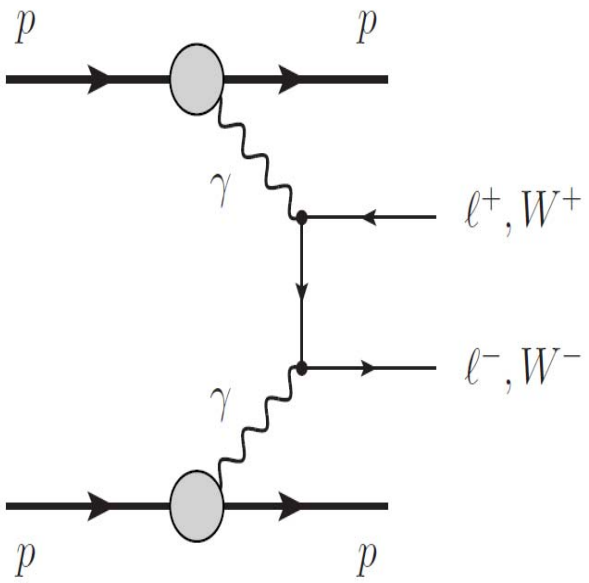

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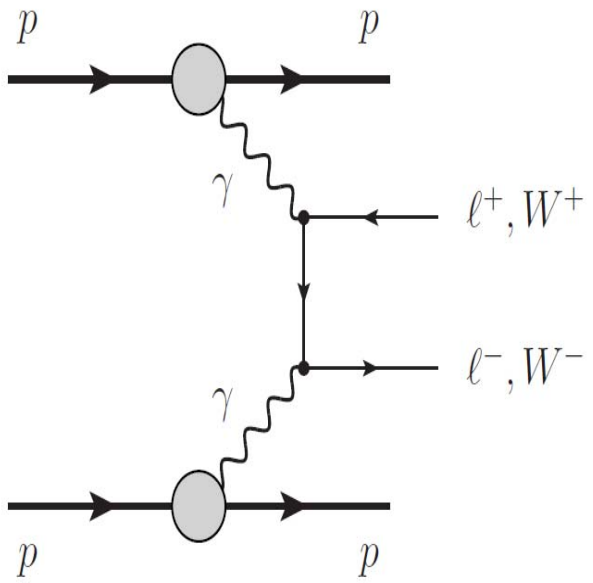

- Very clean processes: Central production with forward hadrons
- Accessible measurements:

1. Luminosity via dilepton production ($\gamma\gamma \to \mu^+\mu^-$);
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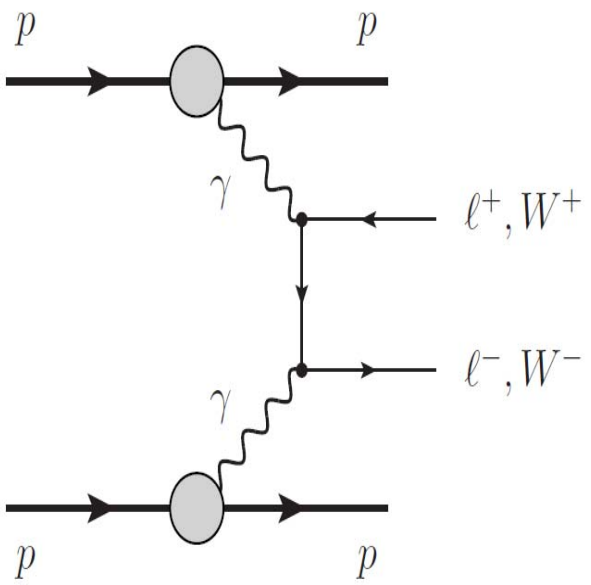

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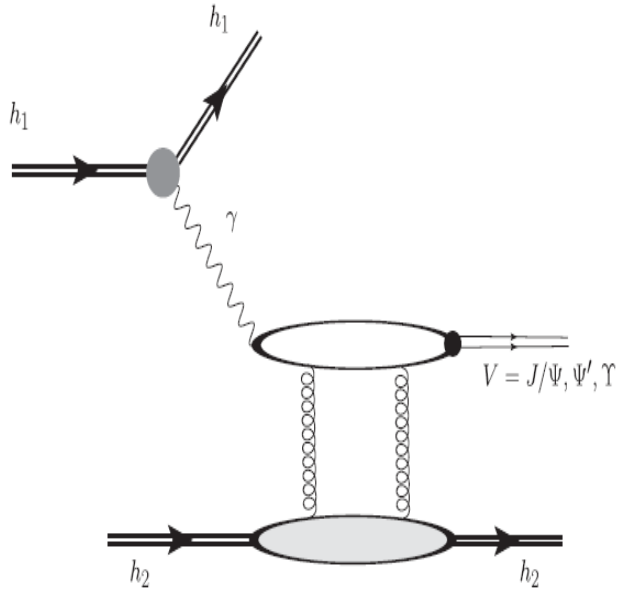

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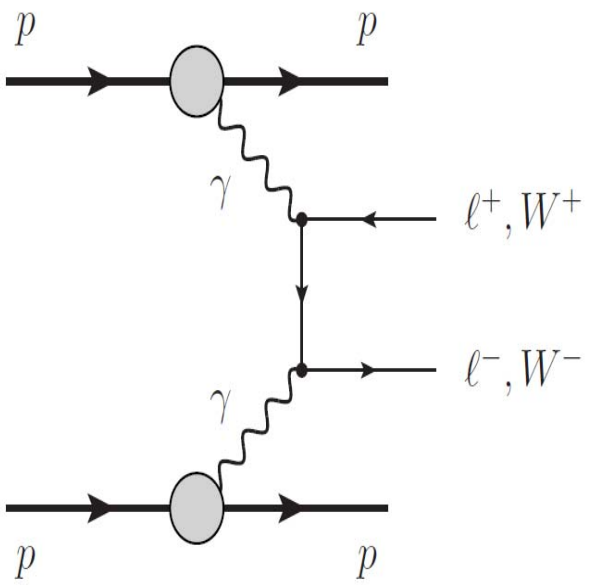

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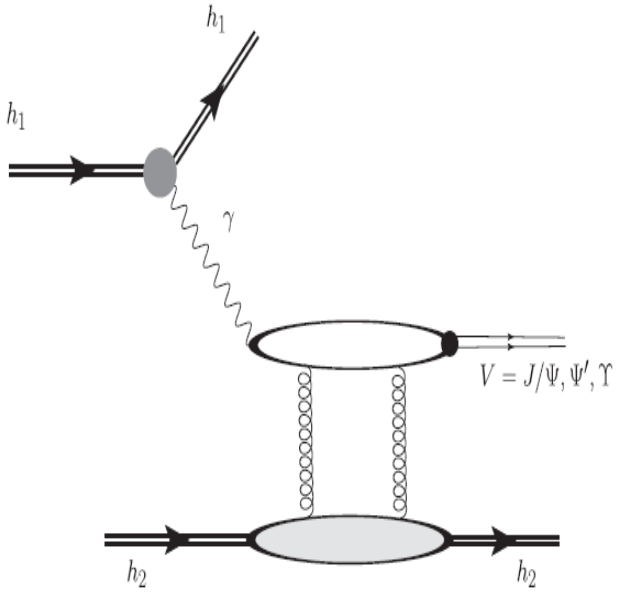

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- Sensitive to the description of diffraction.
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- Search for saturation effects.
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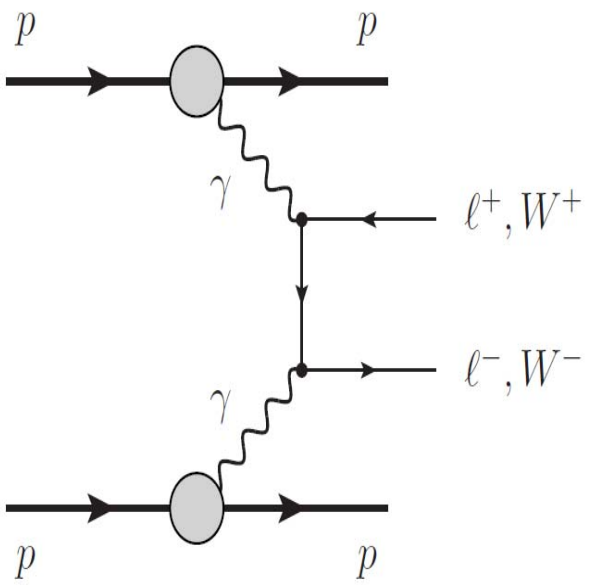

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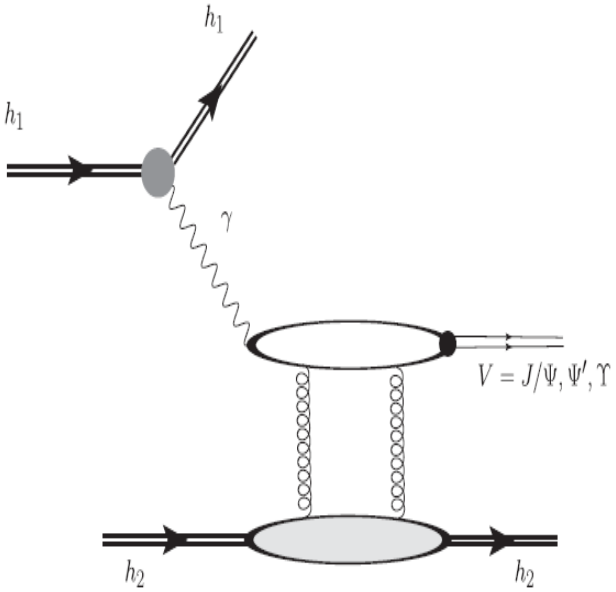

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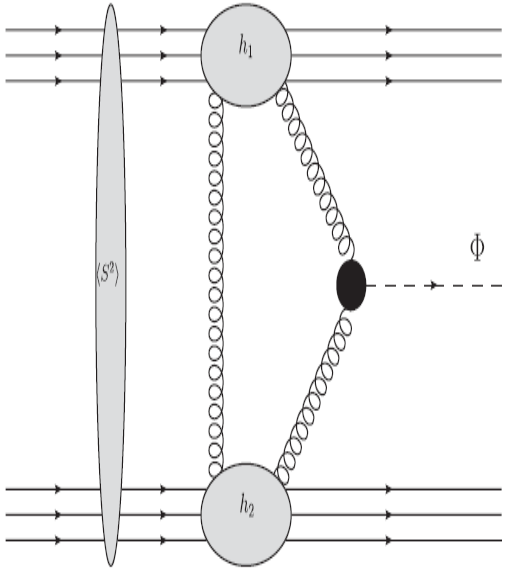

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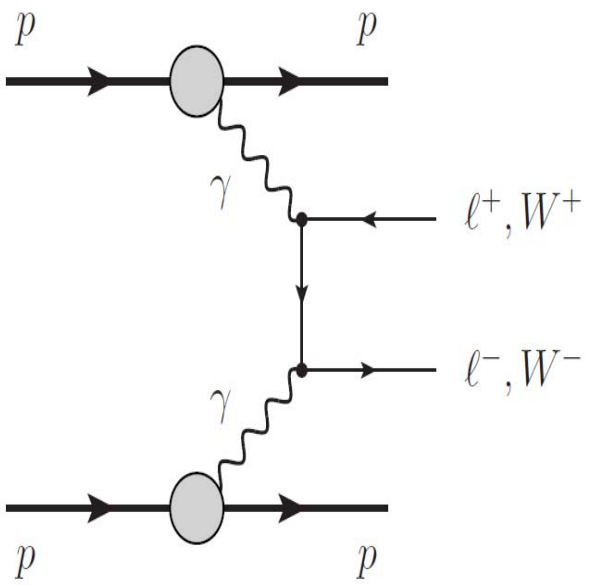

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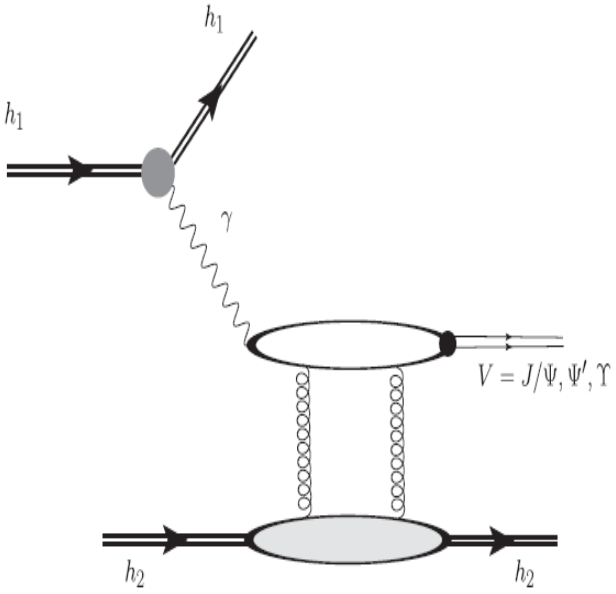

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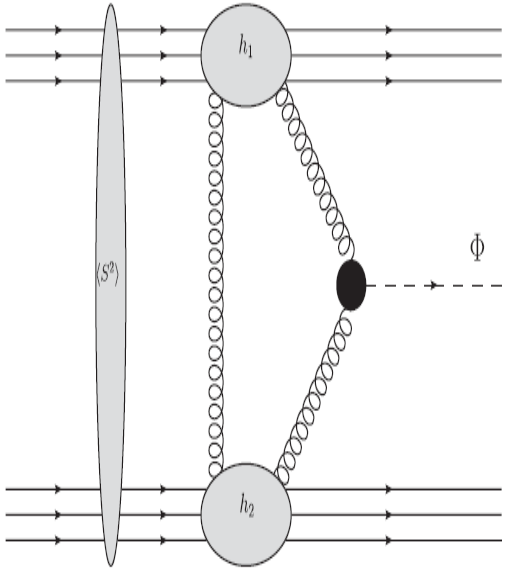

- Spin - parity analyser: only a subset of resonant states can be produced. In particular 0^{++} but not, for example, 1^{++}.
- Sensitive to the description of diffraction.
- Very sensitive to beyond Standard Model Physics.

Central Exclusive Processes

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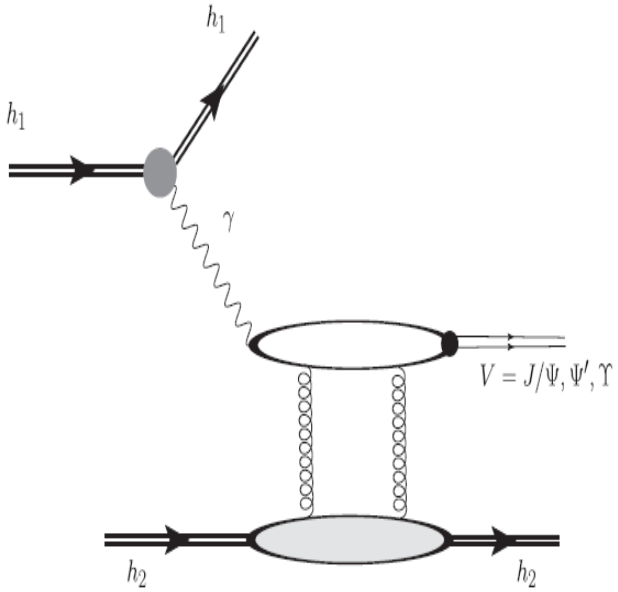

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Photon – Induced Interactions:

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The Equivalent Photon Approximation

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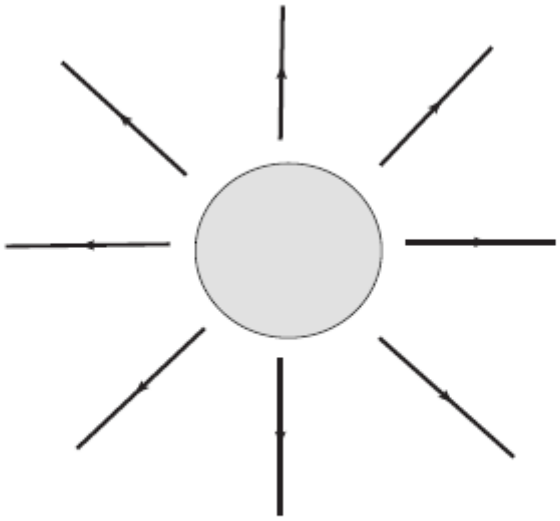
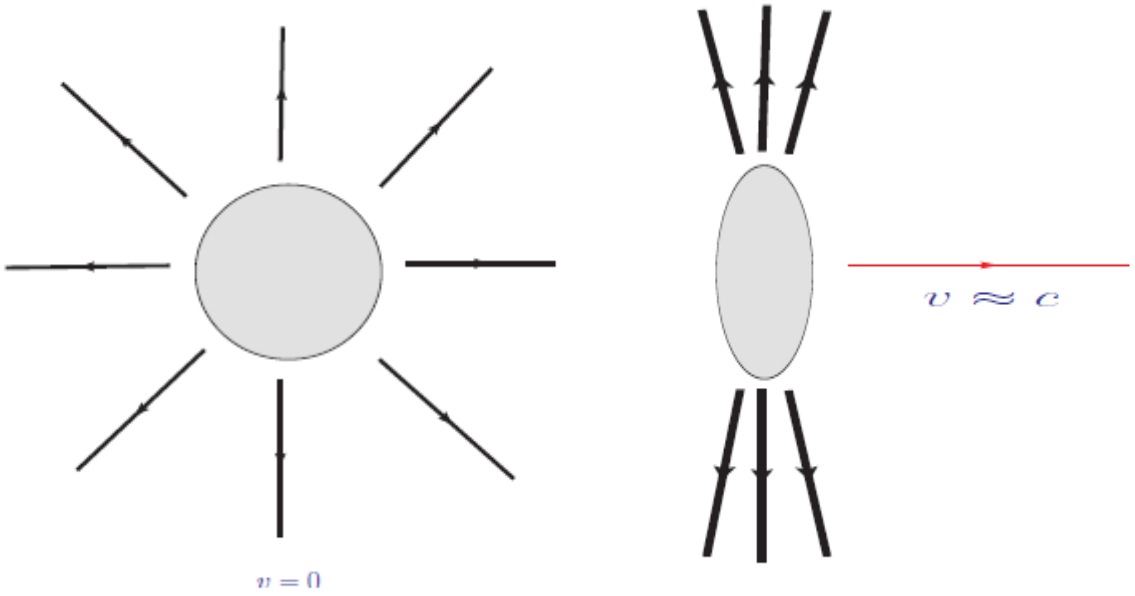
- Consider a charged nucleus at rest. The associated electromagnetic field can be represented by:



$v = 0$

Photon – Induced Interactions:
The Equivalent Photon Approximation

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



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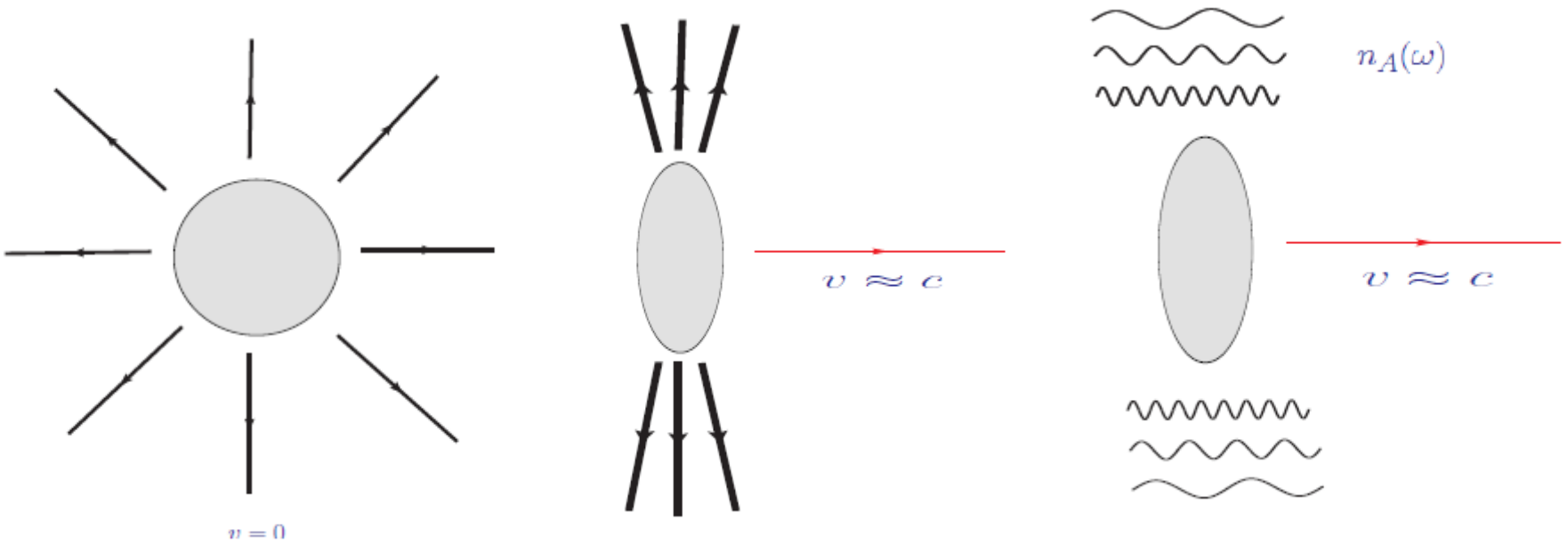
- Since the electric and magnetic field associated to the nucleus take on the same absolute value, this transverse electromagnetic field can be simulated by an equivalent swarm of photons [a].



[a] E. Fermi (1924), E. J. Williams (1933), C. F. Von Weizacker (1934)

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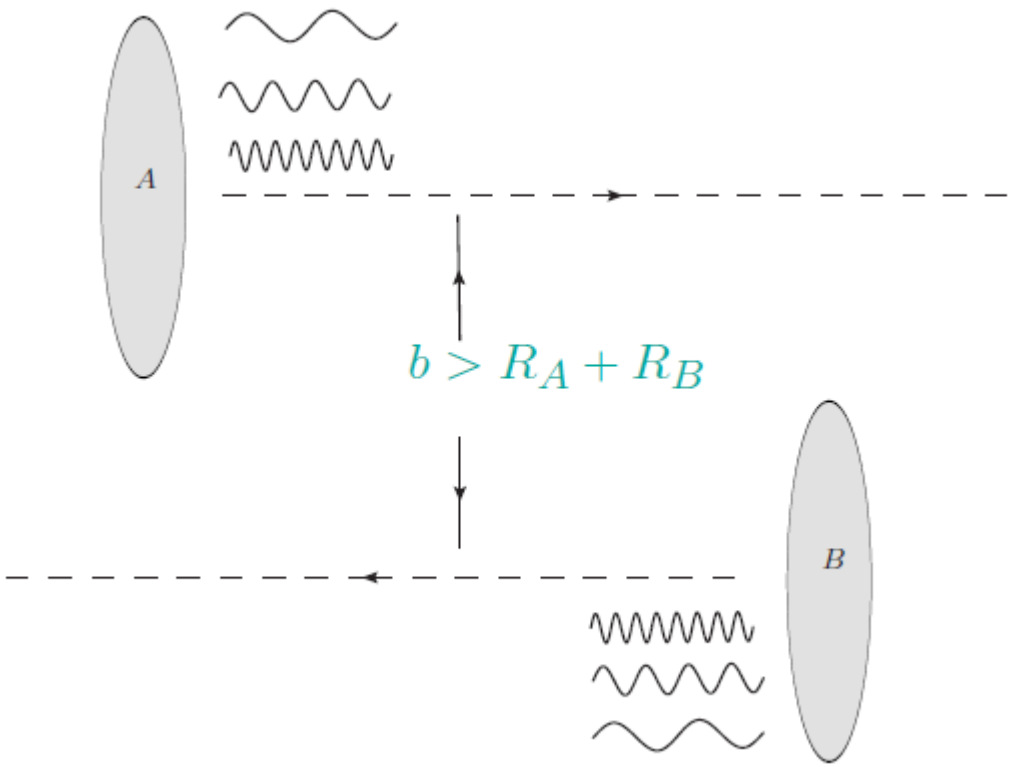
- Thus the collision of two charged nuclei at large impact parameter can be described as the collision of two equivalent swarms of photons.



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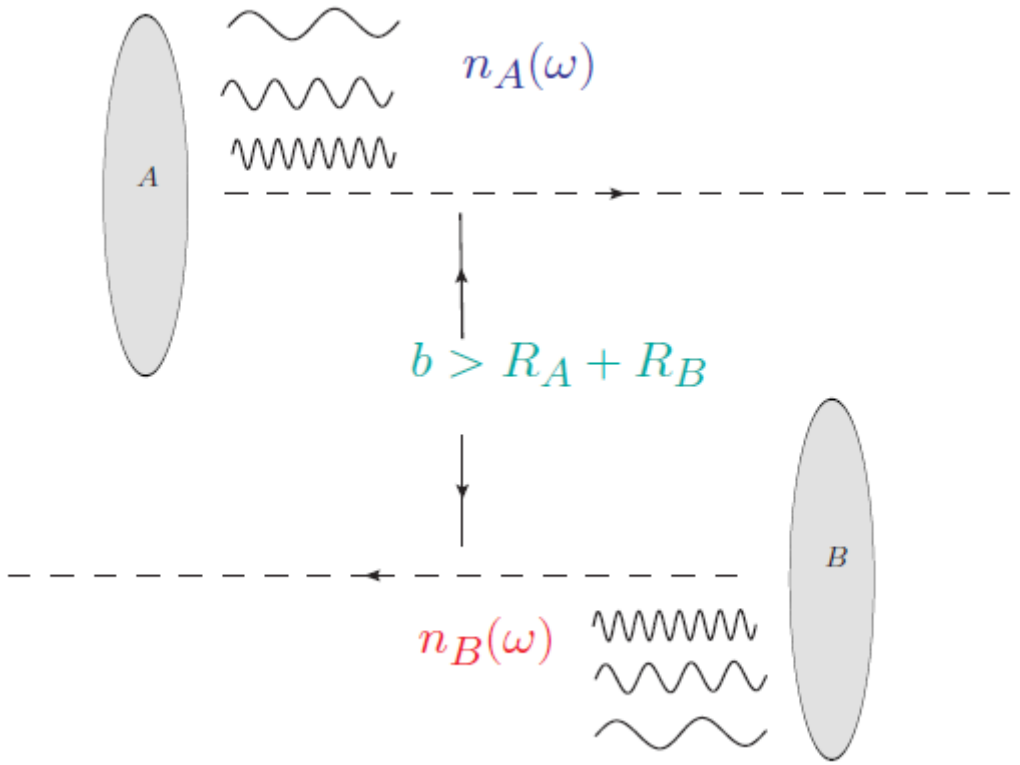

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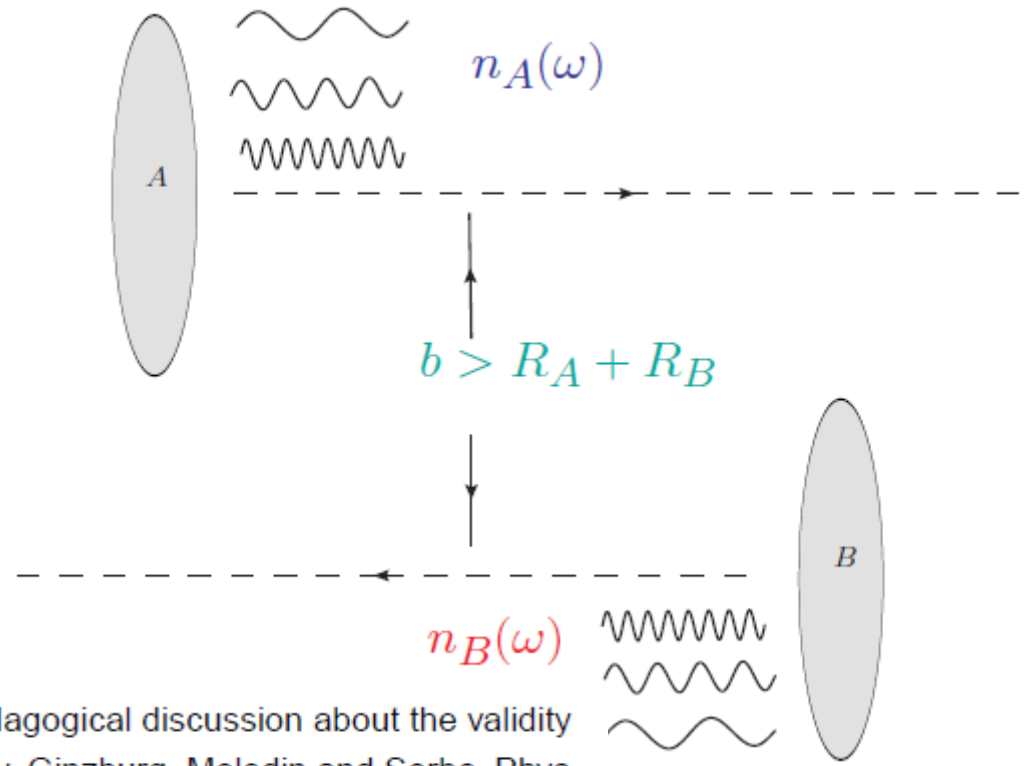
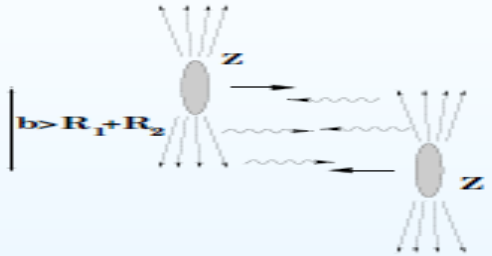


- For a detailed and pedagogical discussion about the validity of the EPA see Budnev, Ginzburg, Meledin and Serbo, Phys. Rep. 15, 181 (1975).

Photon – Induced Interactions:
Center of mass energies



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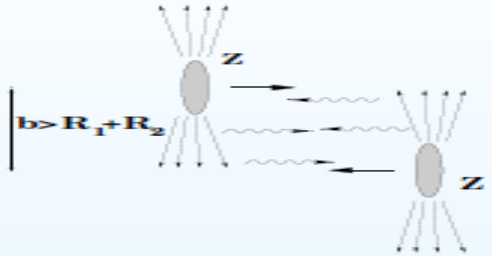

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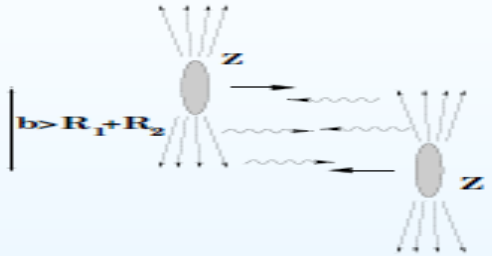

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- Photoproduction in pp collisions at LHC probes energies one order of magnitude larger than HERA.

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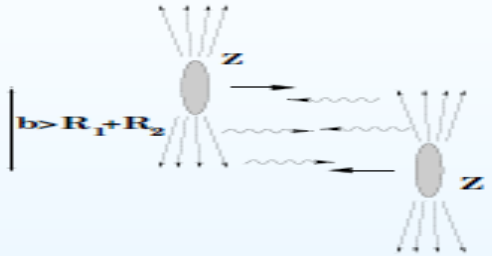

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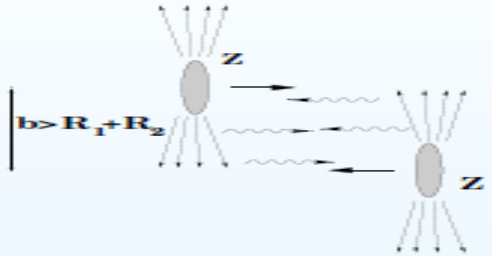

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- Photoproduction in pA and AA collisions probes an unexplored regime of center of mass energies.

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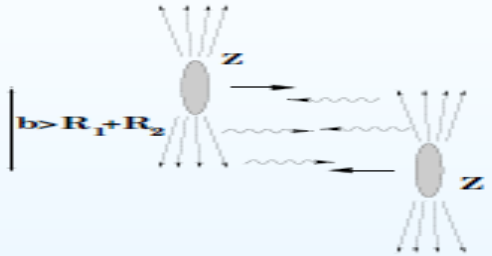

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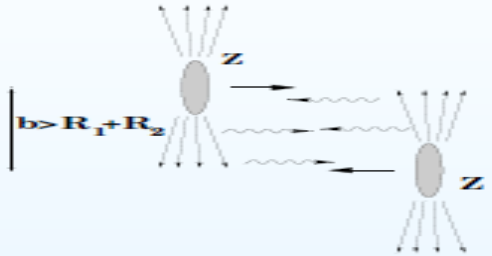

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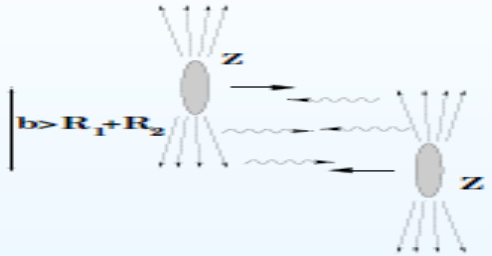

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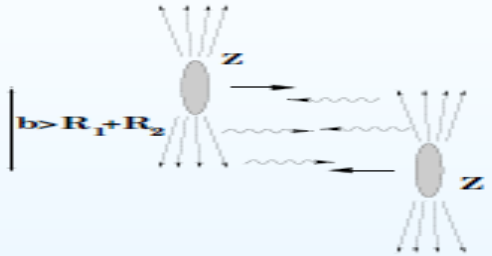
- The LHC is the world's most powerful collider not only for protons and lead ions but also for $\gamma\gamma$ and γh collisions.

Photon – Induced Interactions: Center of mass energies



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

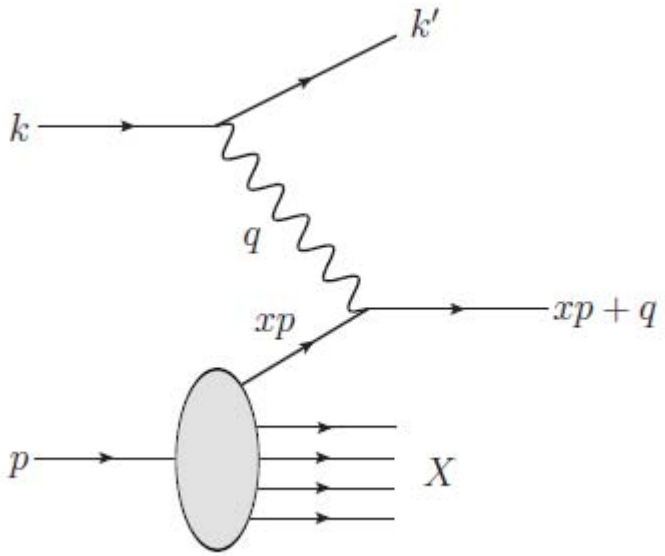
LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$W_{\gamma\gamma} \lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

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

Open questions in the QCD dynamics at high energies

(I) The proton gluon distribution

Deep inelastic ep scattering



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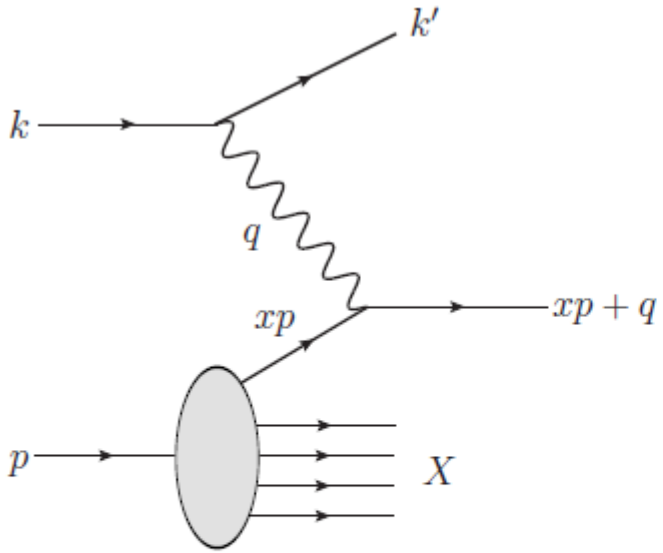

$$\sigma = \frac{4\pi\alpha_{em}}{Q^2} F_2(x, Q^2)$$

$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2p \cdot q}$$

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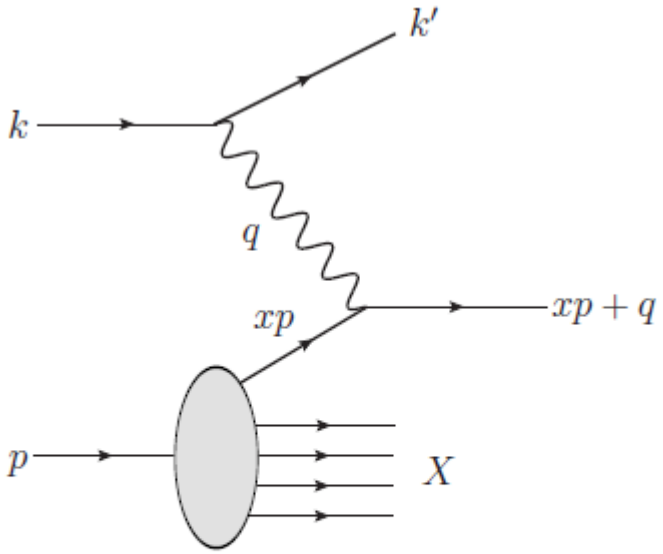

$$\sigma = \frac{4\pi\alpha_{em}}{Q^2} F_2(x, Q^2)$$

$$F_2(x, Q^2) = x \sum_i e_i^2 f_i(x, Q^2)$$

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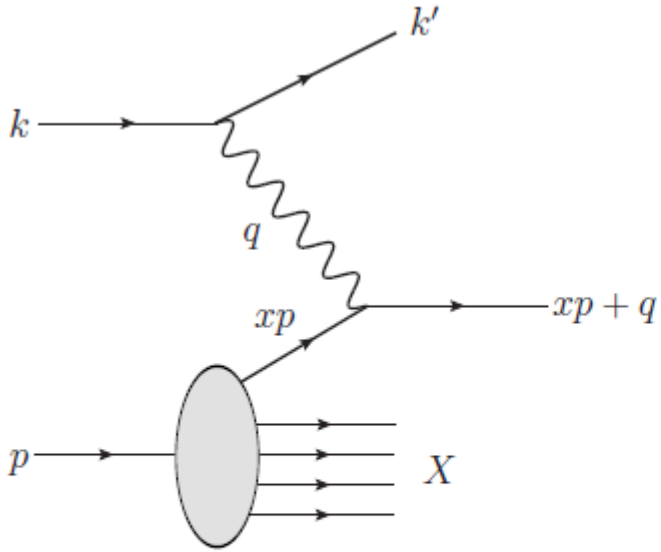

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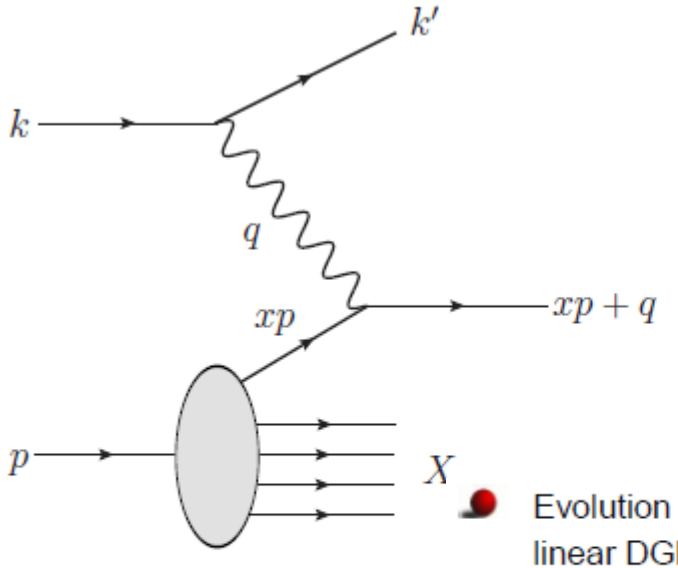

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Evolution of the parton distributions in the hard scale $\mu^2 = Q^2$ described by the linear DGLAP equations. Resum Q^2 logs: $\sum_n [\alpha_s \ln(Q^2/Q_0^2)]^n$.

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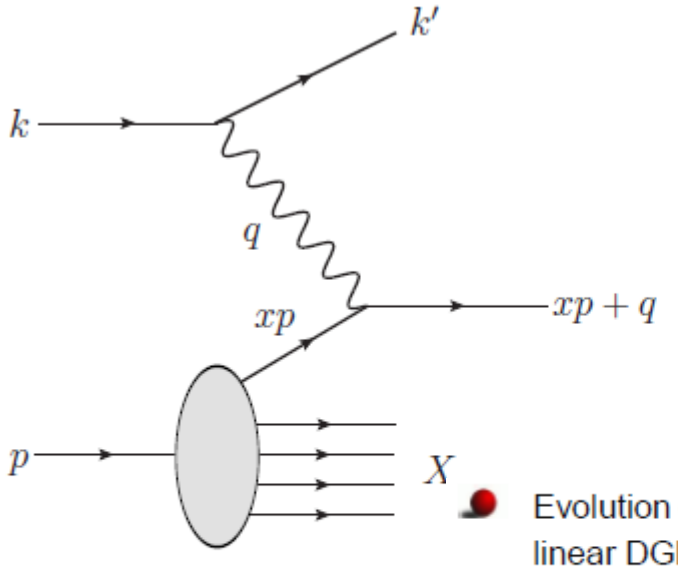

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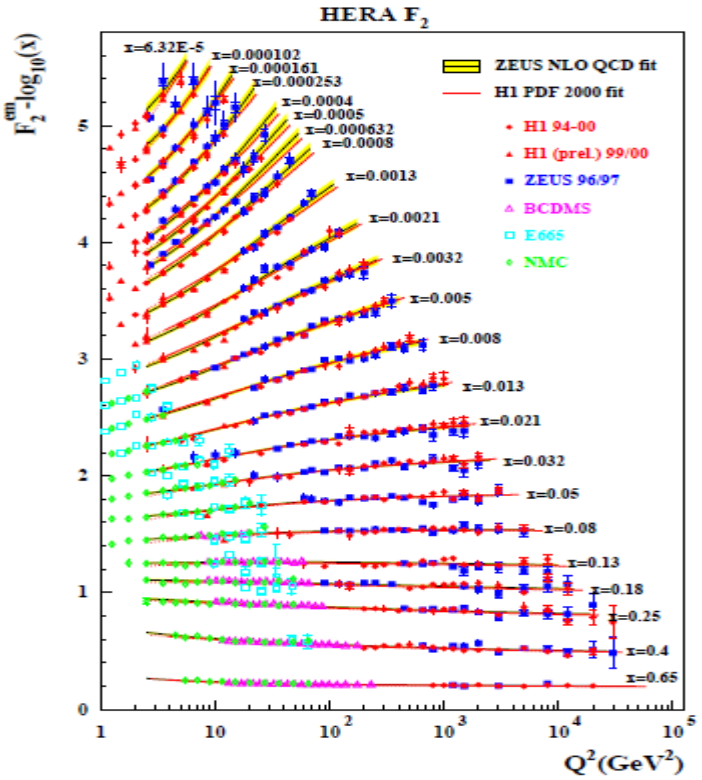
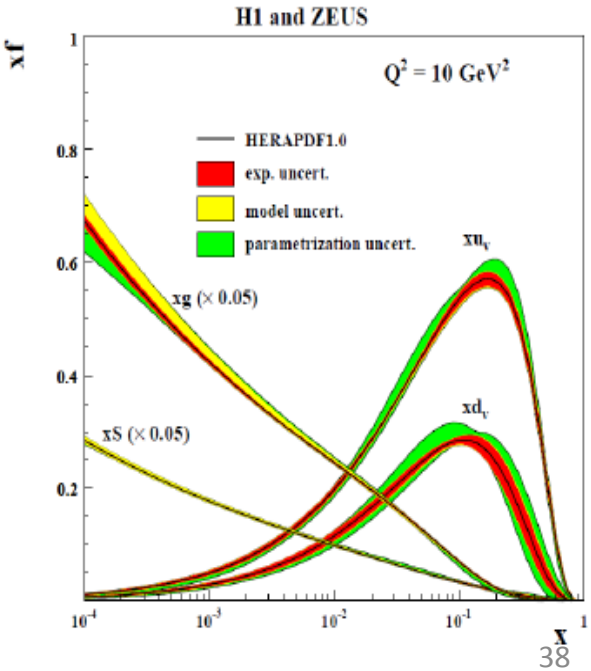
High energies $\Longleftrightarrow$ Small-x

(I) The proton gluon distribution

- Proton structure determined by the HERA measurements in ep collisions in a large kinematical range;





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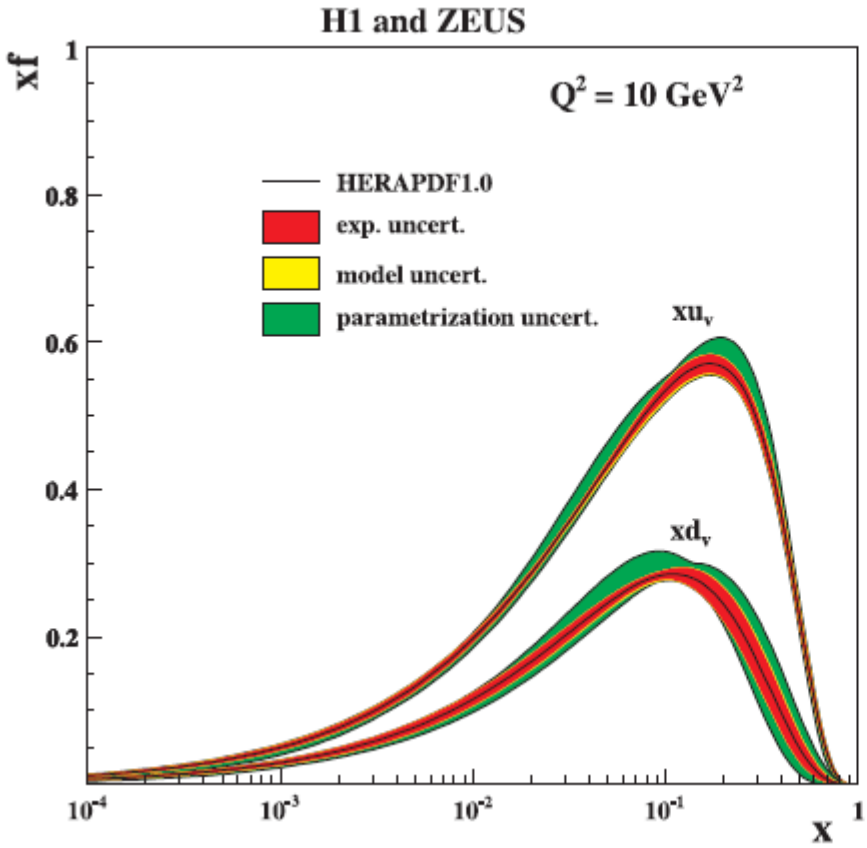

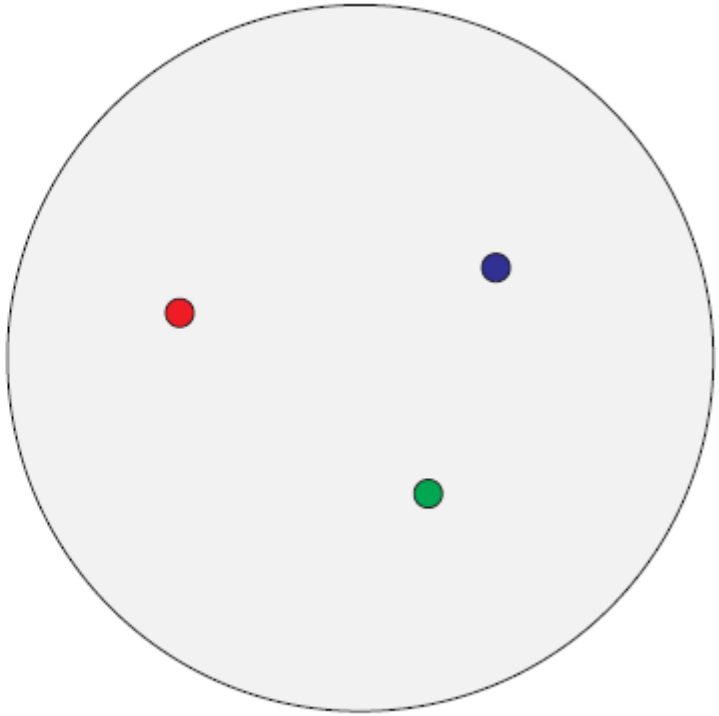

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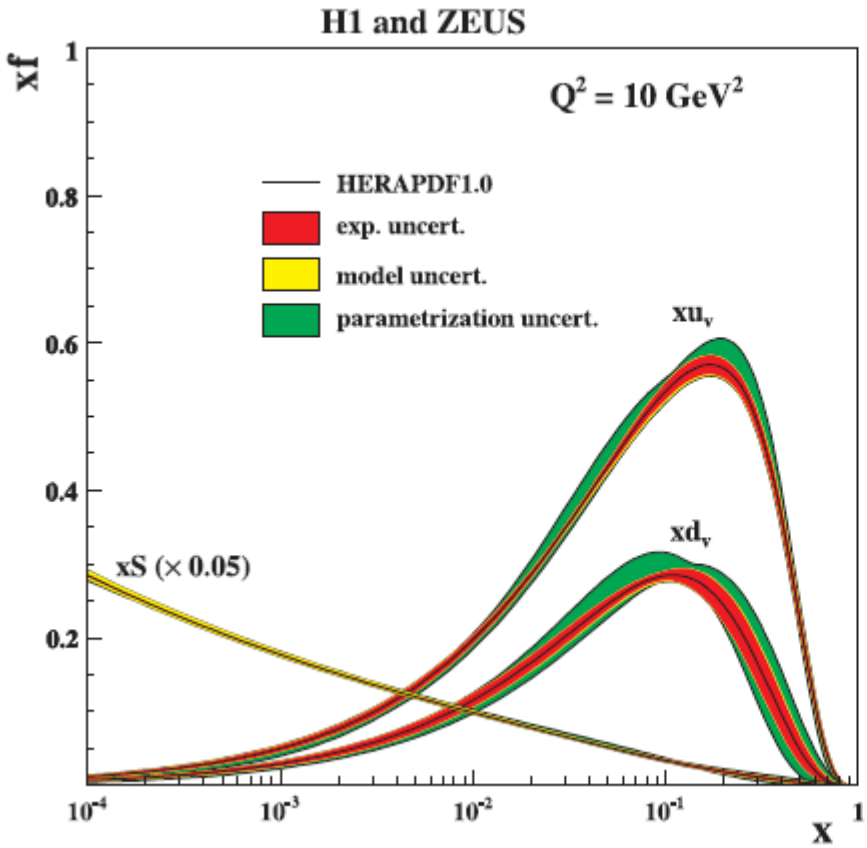

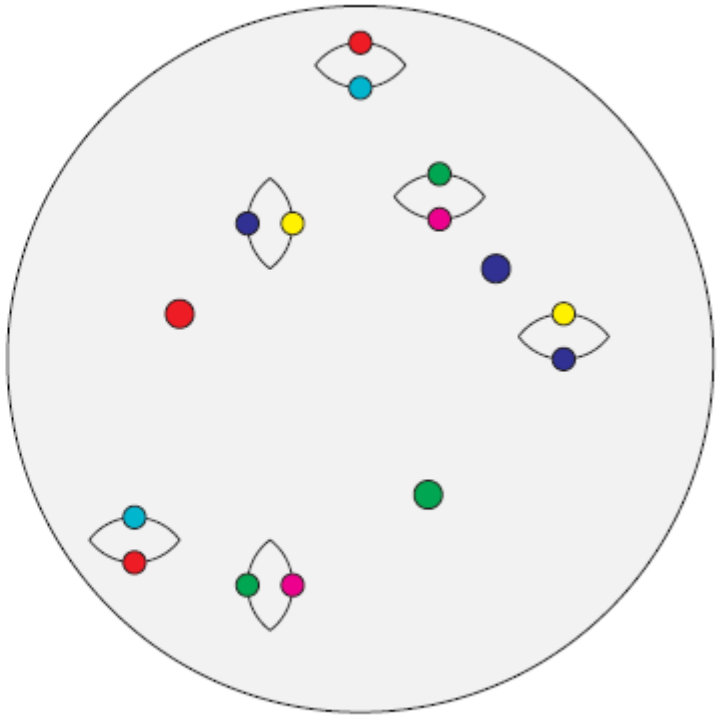

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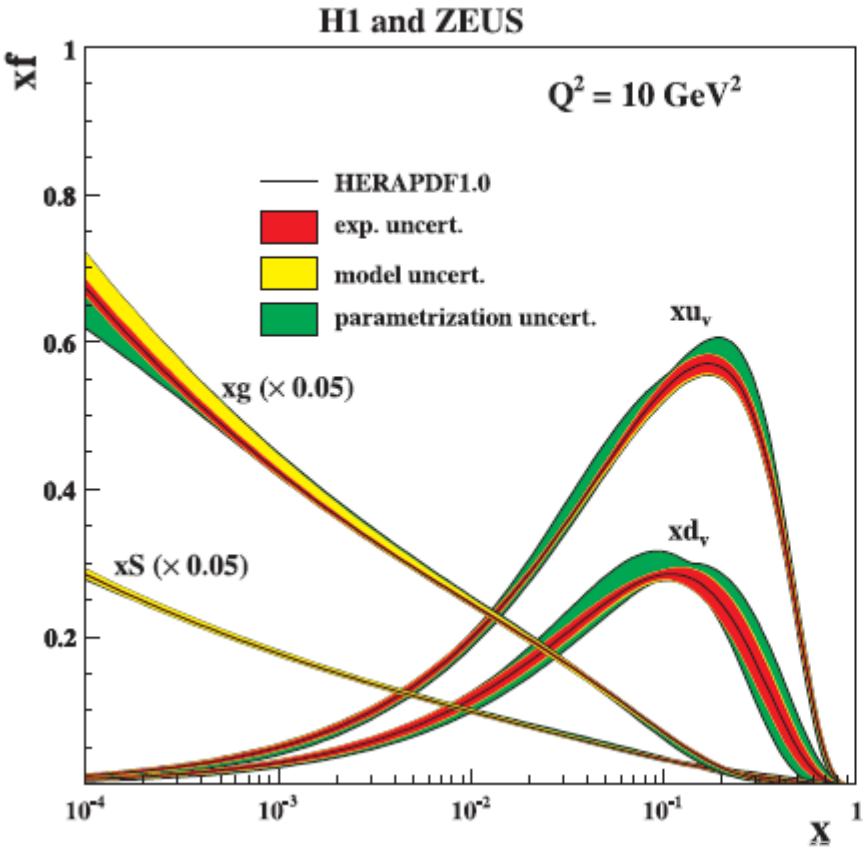
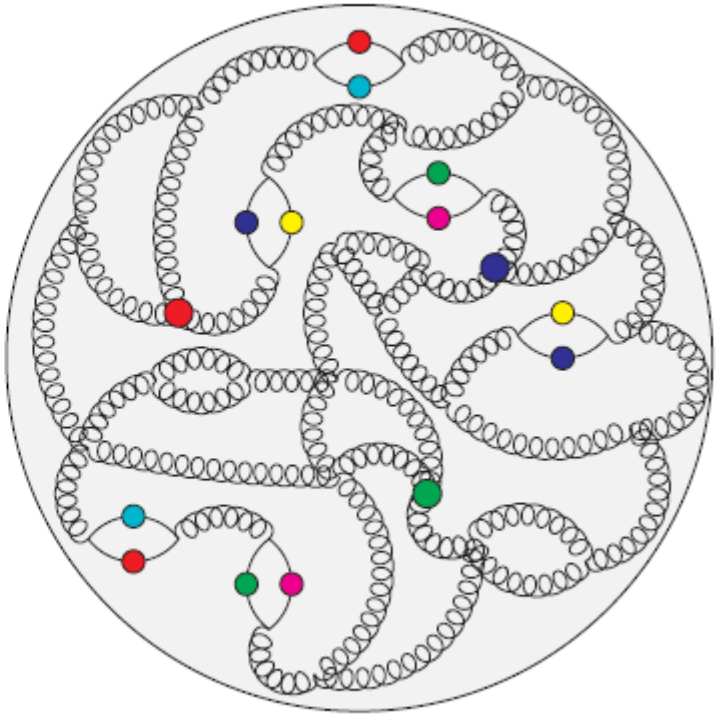
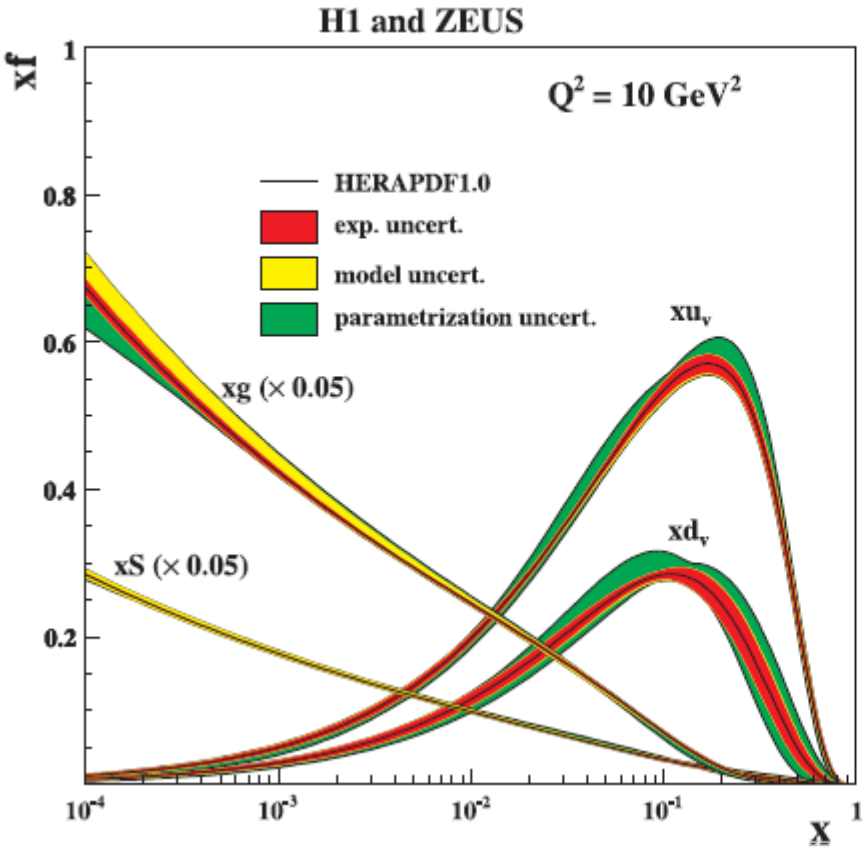
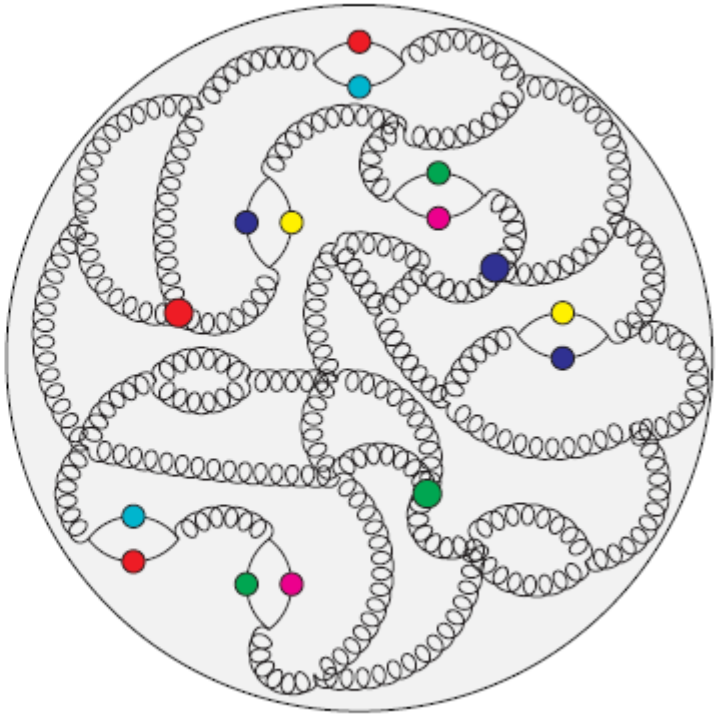




- Gluon dominates the proton structure at high energies (low momentum fractions x).

(I) The proton gluon distribution

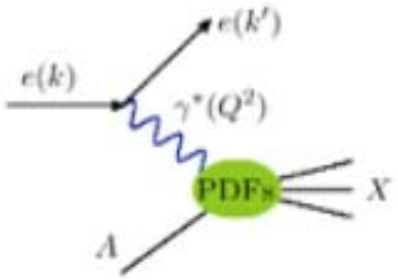




- Gluon distribution poorly known at small-x.

(II) The nuclear gluon distribution

- **Deep inelastic scattering with nuclear targets**



$$(k' - k)^2 = q^2 = -Q^2$$

$$x = A\frac{Q^2}{2(p_A \cdot q)}$$

$$F_{2A}(x) \neq AF_{2N}(x)$$

Partons distributions in the nuclei are different from the scaled proton parton distributions

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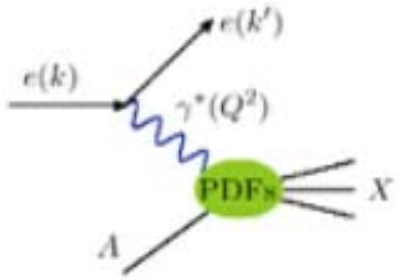

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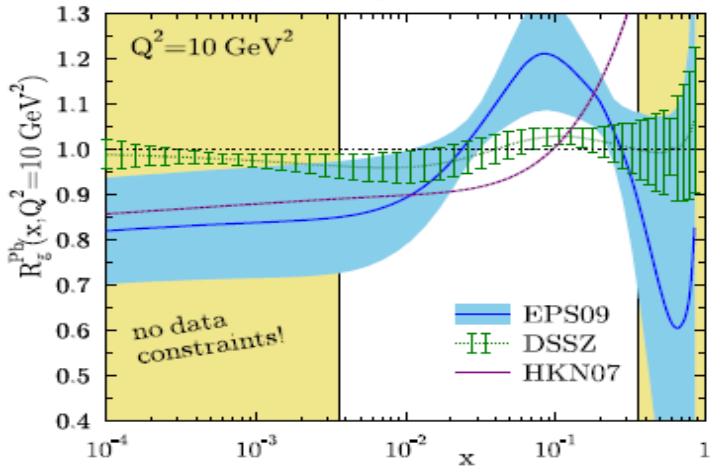
Partons distributions in the nuclei are different from the scaled proton parton distributions

$$R_g \equiv \frac{xg_A(x,Q^2)}{A \cdot xg_p(x,Q^2)}$$

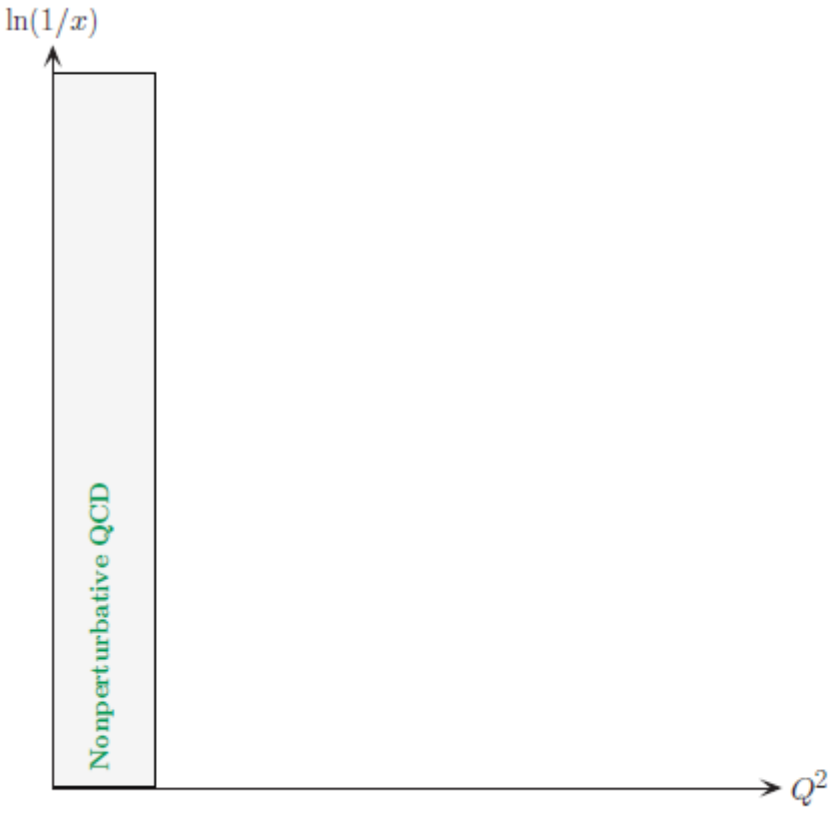
- No nuclear effects $\Rightarrow R_g = 1.$



Eskola, Puukkunen, arXiv:1401.2345

- The current eA experimental data does not constrain the small-x behaviour.
- Large theoretical uncertainty present in the kinematical range probed by LHC.

(III) The transition between the linear and nonlinear regime of QCD dynamics



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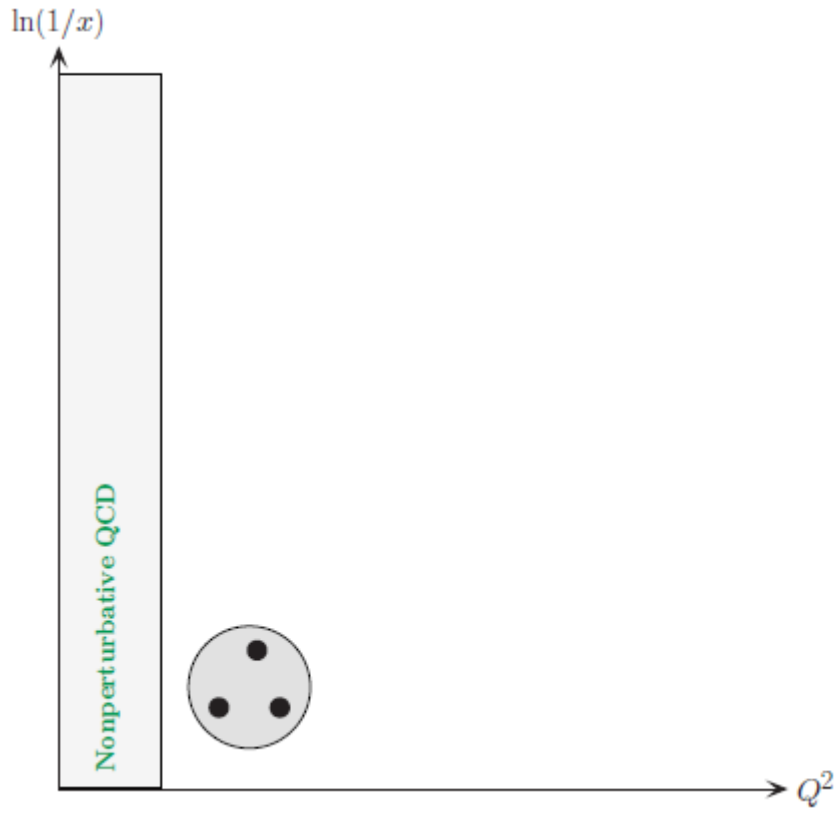

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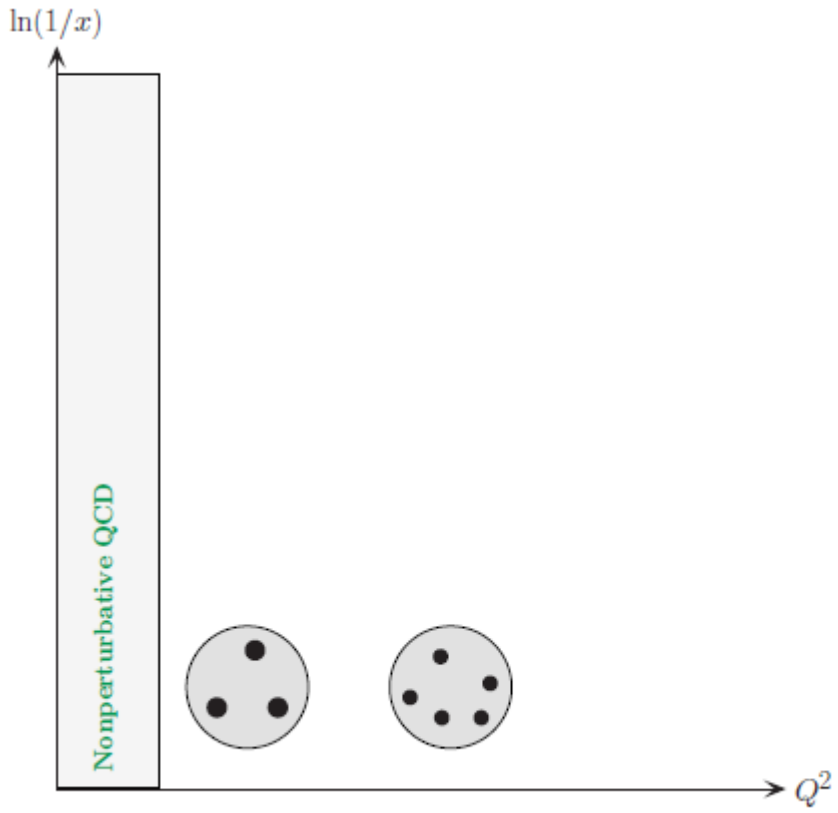

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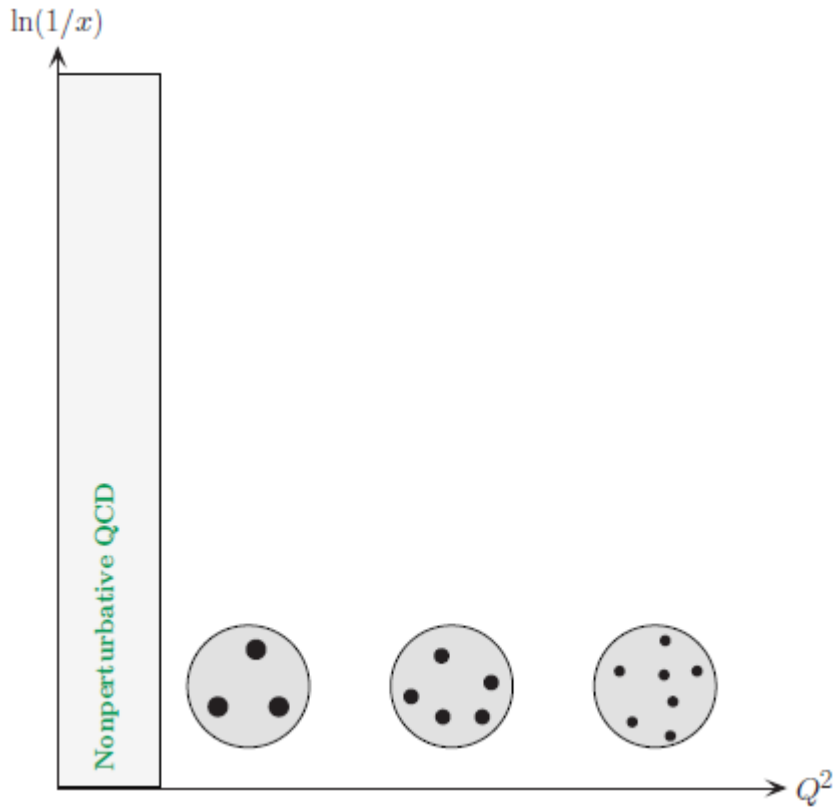

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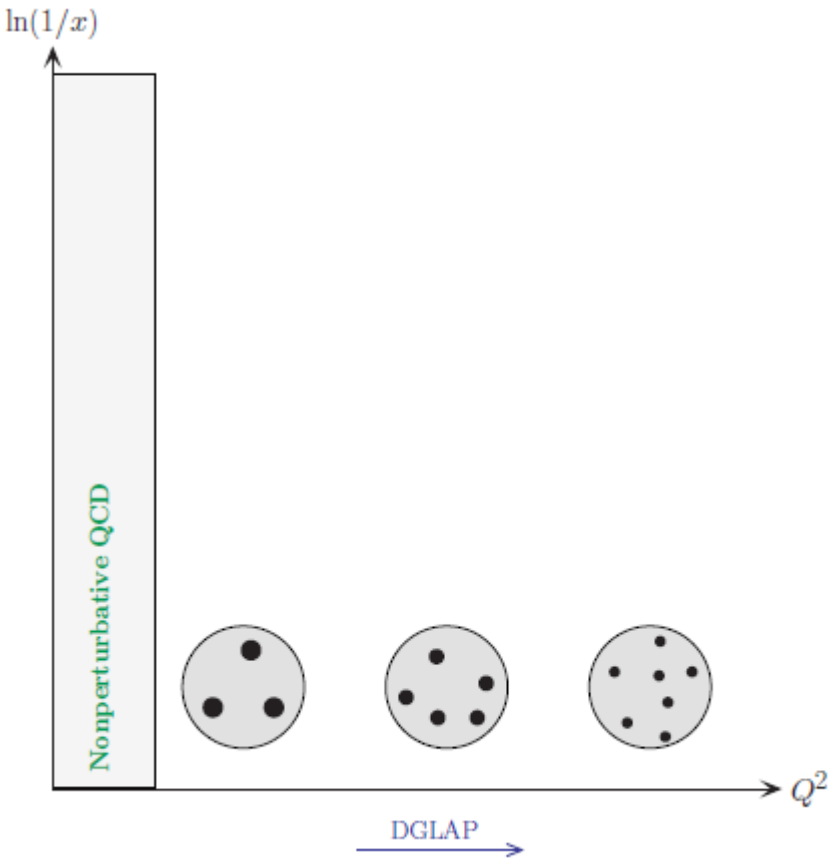

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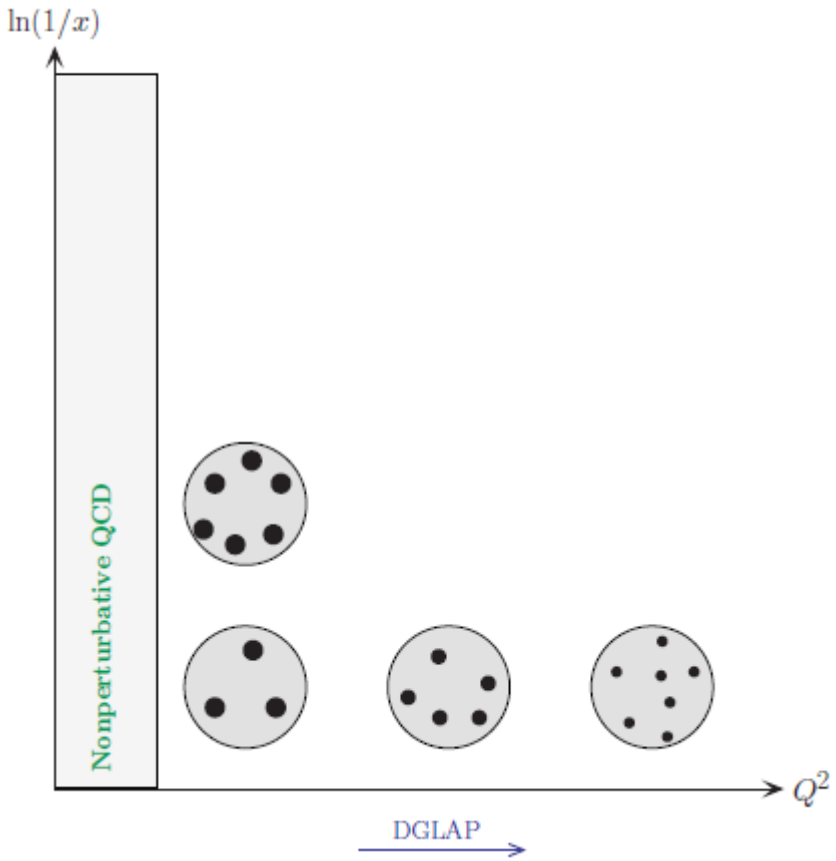

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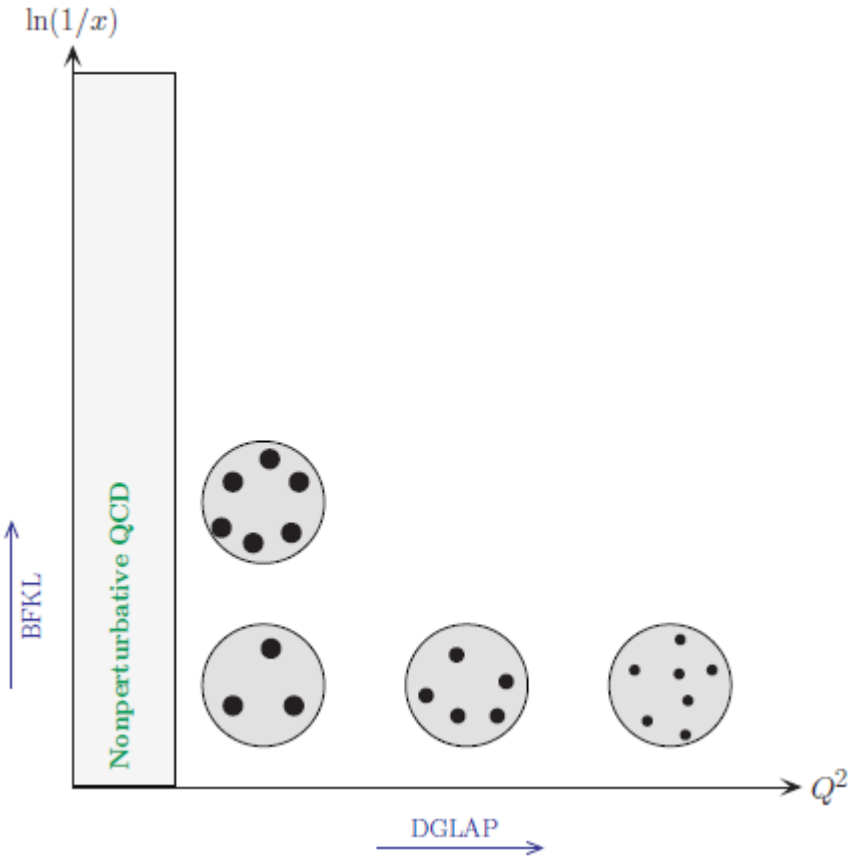

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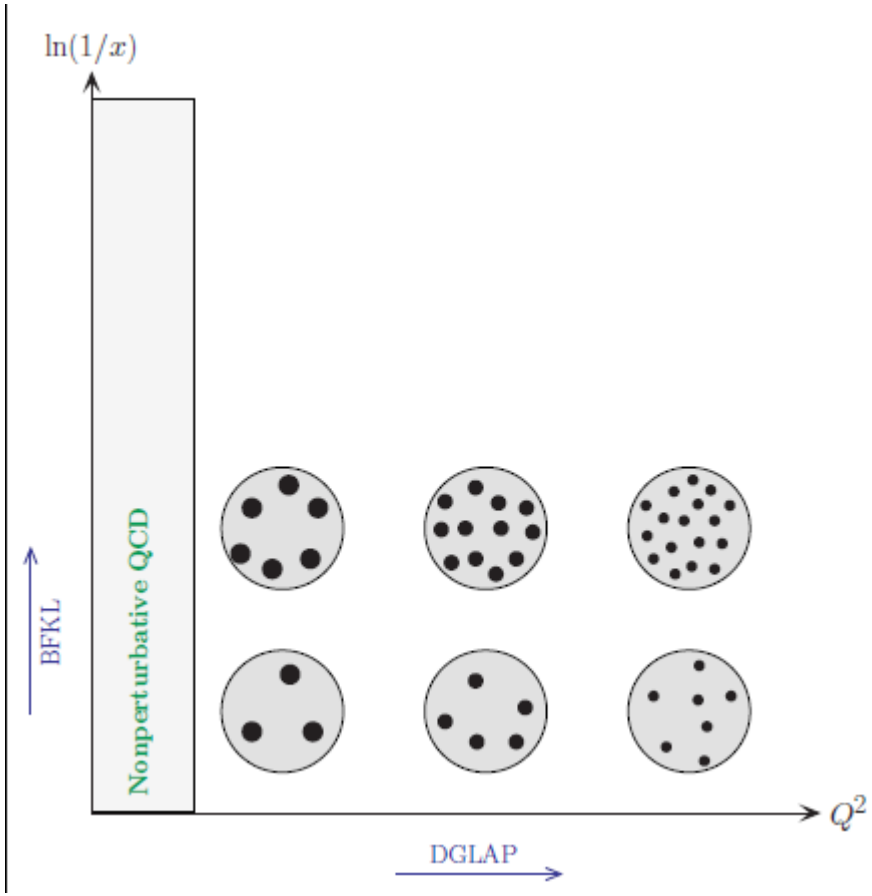

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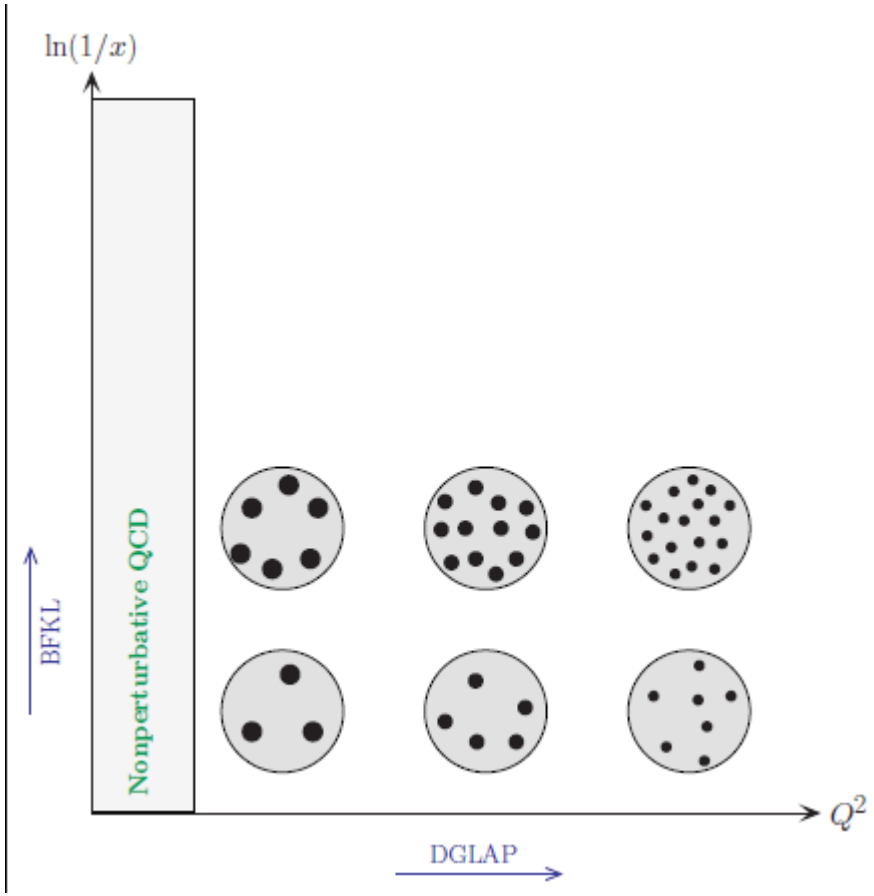

- Linear QCD evolution equations predict a power growth of gluon distribution as $x \to 0$ (violates unitarity).

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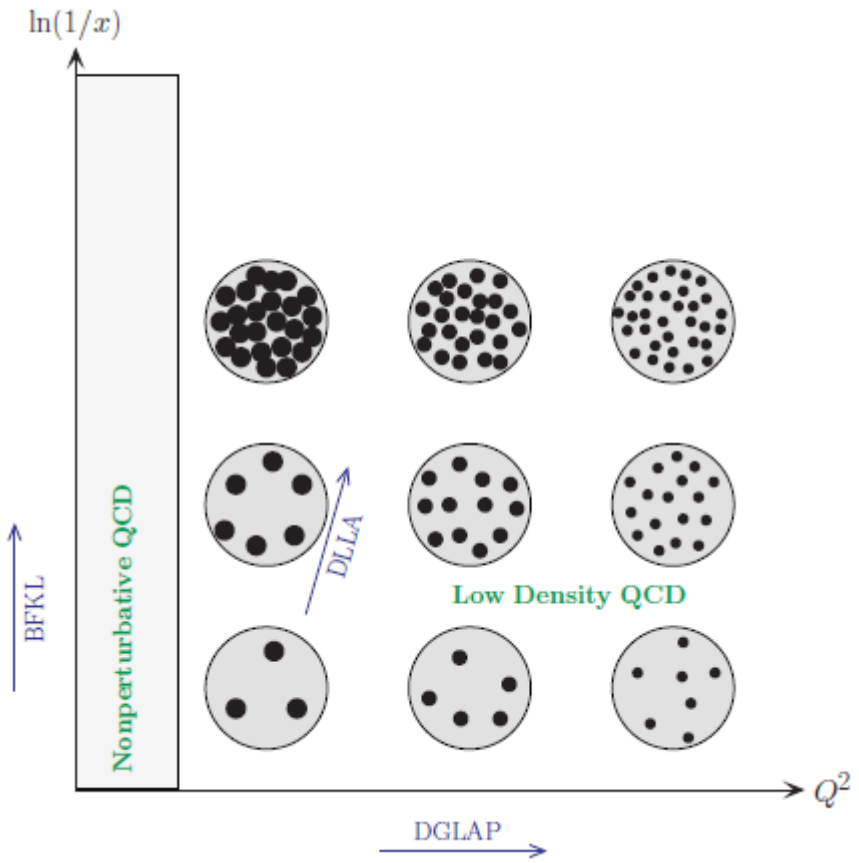

- Linear QCD evolution equations predict a power growth of gluon distribution as $x \to 0$ (violates unitarity).
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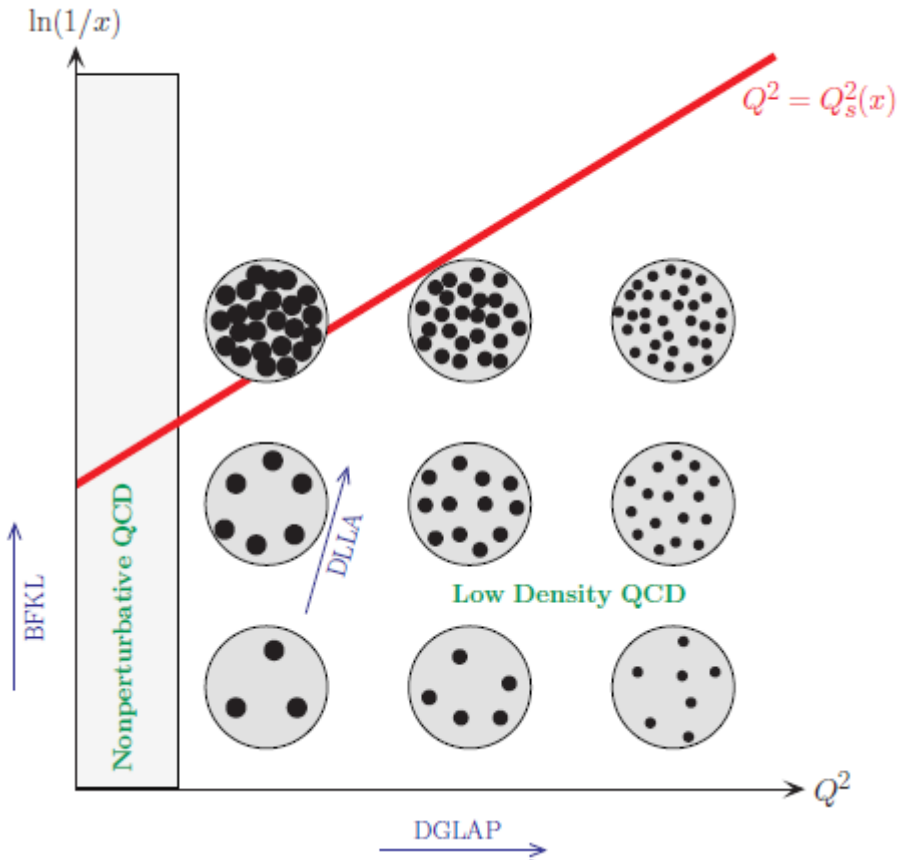

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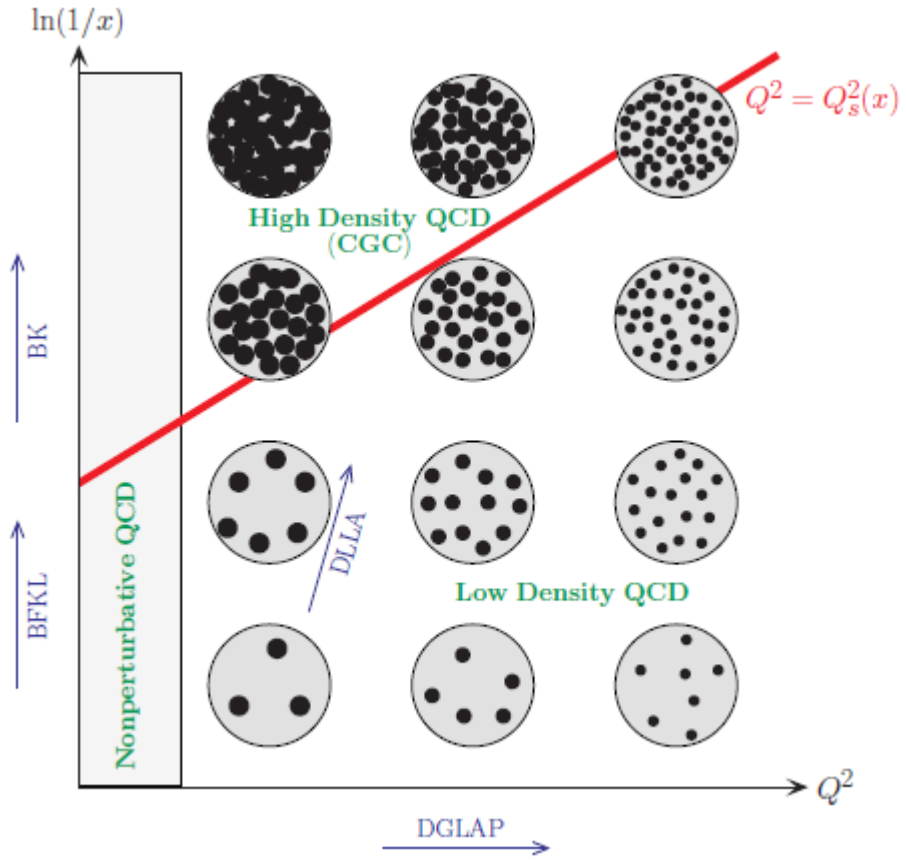

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- Saturation scale Q_s (energy and atomic number dependent) defines the onset of nonlinear QCD dynamics.
- CGC: Effective theory which describes the evolution of a hadronic wavefunction with increasing energy in the presence of non-linear effects associated with the high gluon density.
- Evolution described by an infinite hierarchy of equations, the B-JIMWLK equations, which reduces to the Balitsky - Kovchegov (BK) equation in the mean field approximation.
- Running coupling BK solution largely used to estimate saturation in $ep/\nu p/pp/pA$ collisions.
- Very good description of the HERA, RHIC and LHC data.

Photon – Hadron Interactions:
Typical processes

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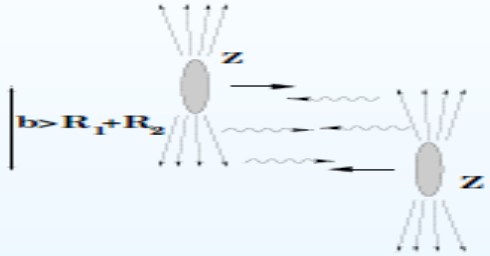

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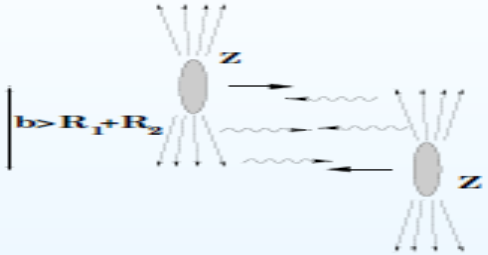
Photon – Hadron Interactions: Typical processes



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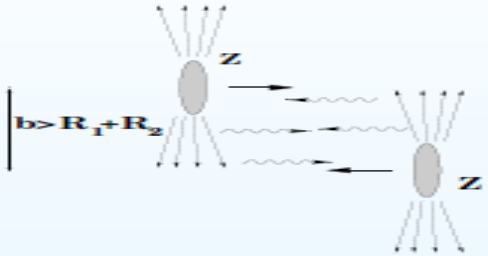
- Inclusive processes: $\gamma p \to XY$

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

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

Photon – Hadron Interactions: Typical processes



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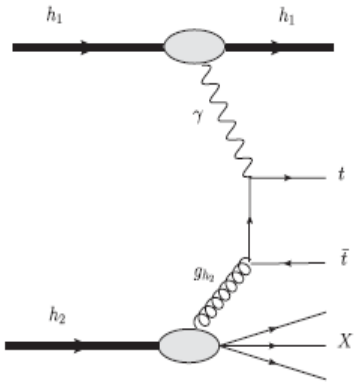

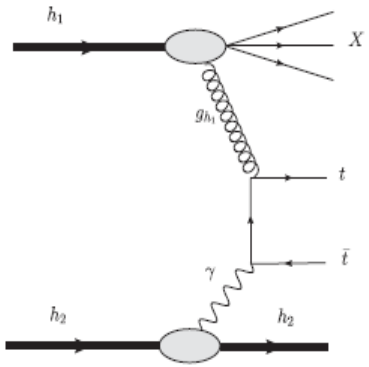

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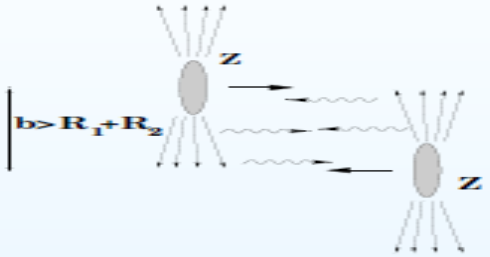

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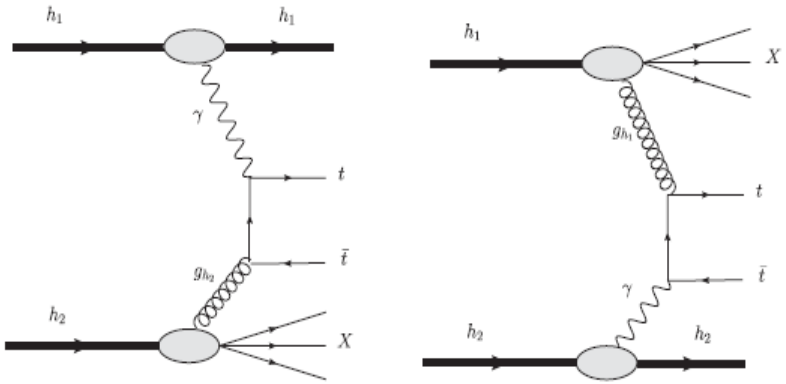

- $X = t\bar{t}$ [a]VPG, PRD88, 054025 (2013)

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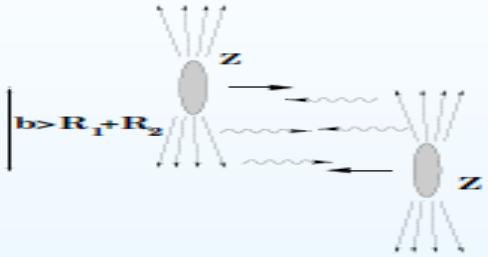

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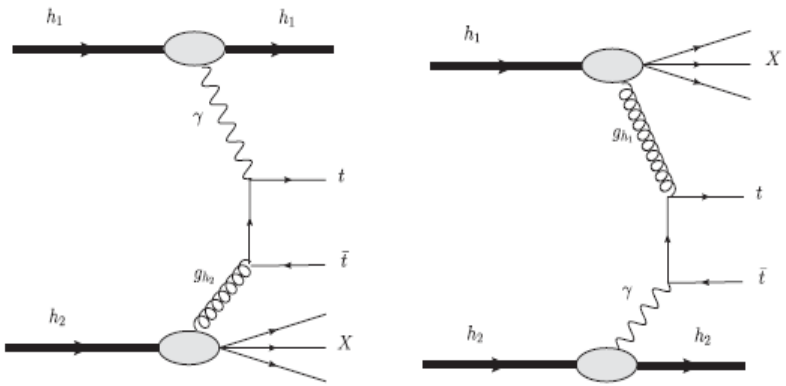

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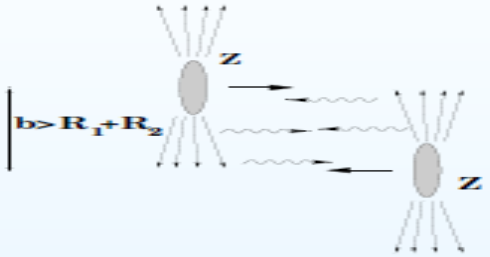
TABLE I. The integrated cross section (events rate) for the photoproduction of top quarks in pp, pPb, and $PbPb$ collisions at LHC energies.

pp	MRST	CT10
$\sqrt{s} = 8$ TeV	0.739 pb (73900)	0.764 pb (76400)
$\sqrt{s} = 14$ TeV	2.50 pb (250000)	2.53 pb (253000)

pPb	MRST	MRST + EPS09
$\sqrt{s} = 5.5$ TeV	0.036 nb (5.4/3600)	0.038 nb (5.7/3800)
$\sqrt{s} = 8.8$ TeV	0.159 nb (23.85/15900)	0.165 nb (24.75/16500)

PbPb	MRST	MRST + EPS09
$\sqrt{s} = 5.5$ TeV	0.42 nb (0.18)	0.40 nb (0.17)

Photon – Hadron Interactions: Typical processes



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

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The final state is characterized by two rapidity gaps

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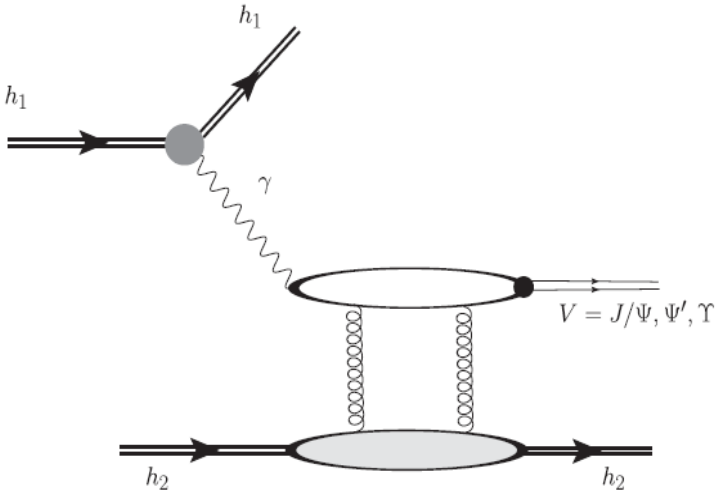

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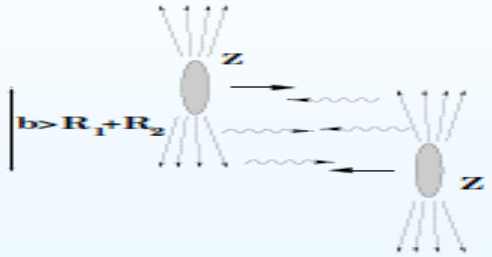

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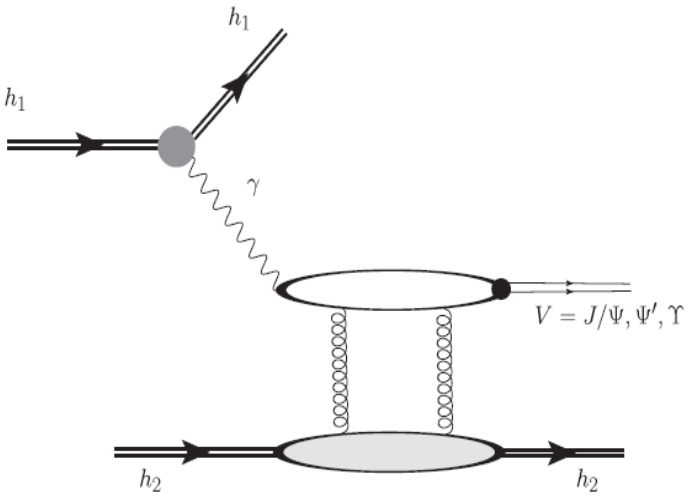

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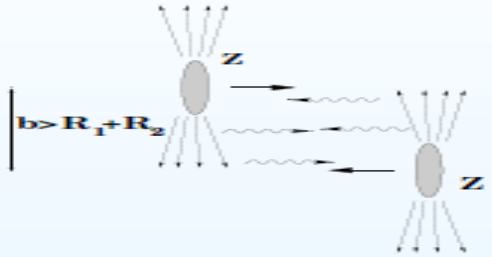

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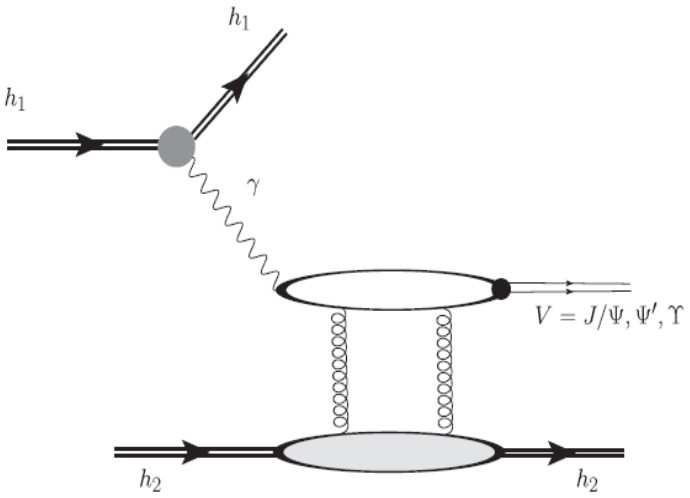

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[a] VPG, Bertulani, PRC65, 054905 (2002)

Photon – Hadron Interactions:
Constraining the nuclear gluon distribution

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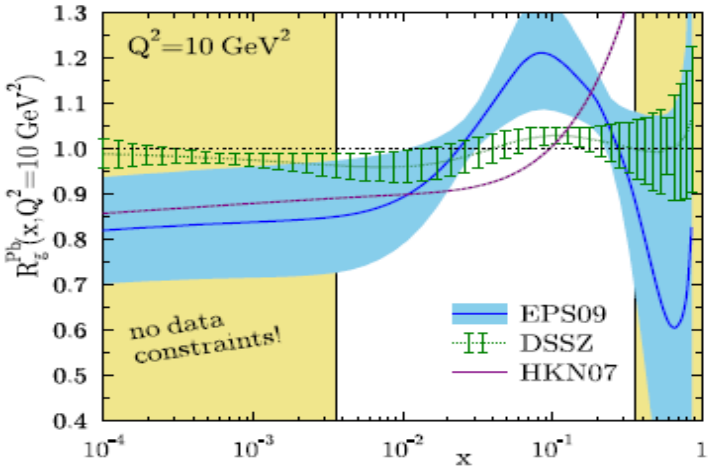

Eskola, Puukkunen, arXiv:1401.2345

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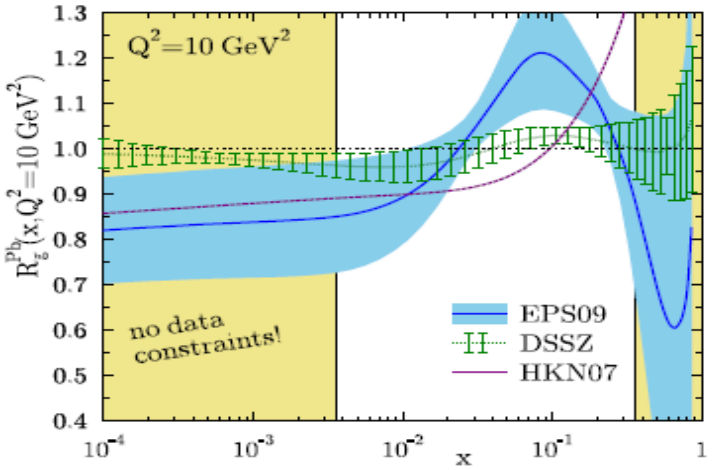

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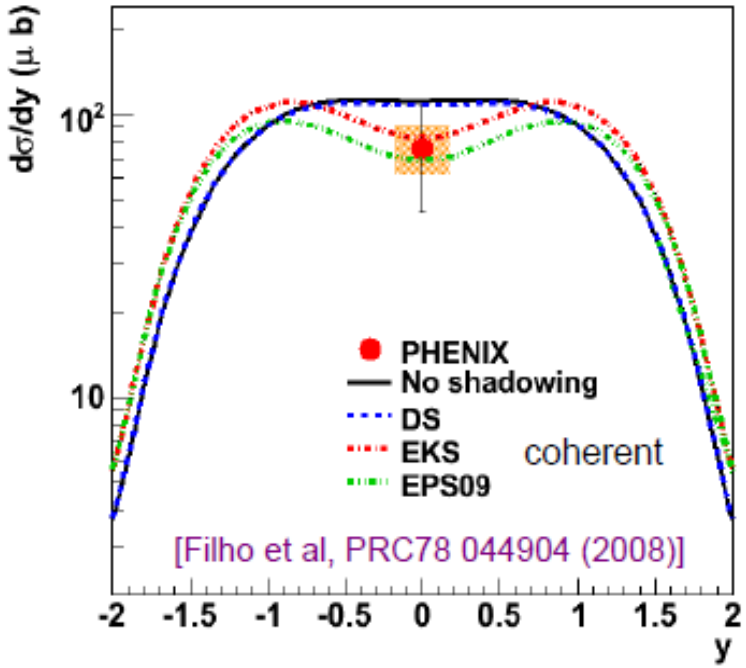

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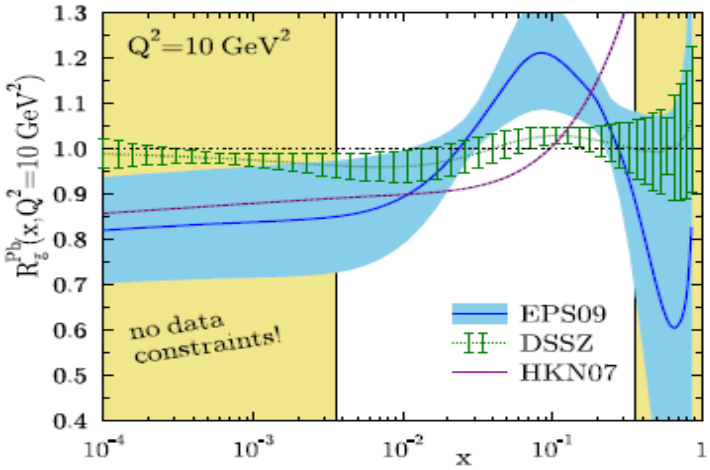

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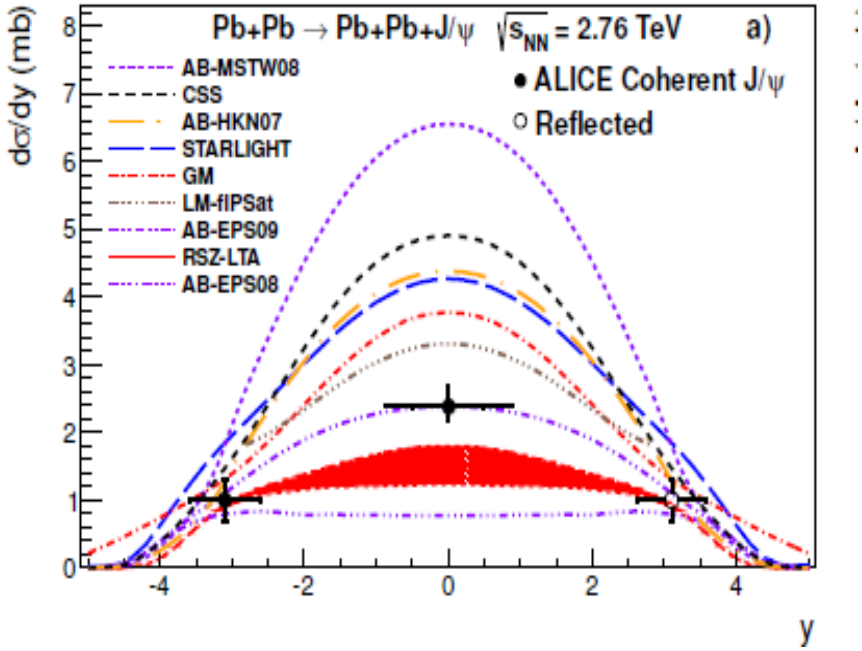

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$$y = -3 \Rightarrow x = 0.02$$

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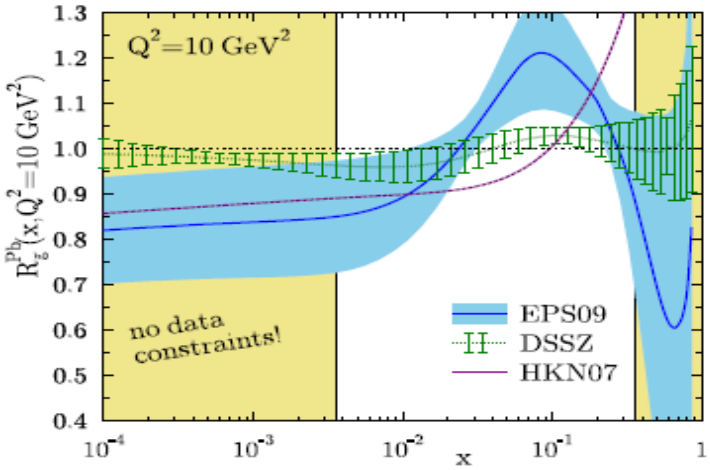

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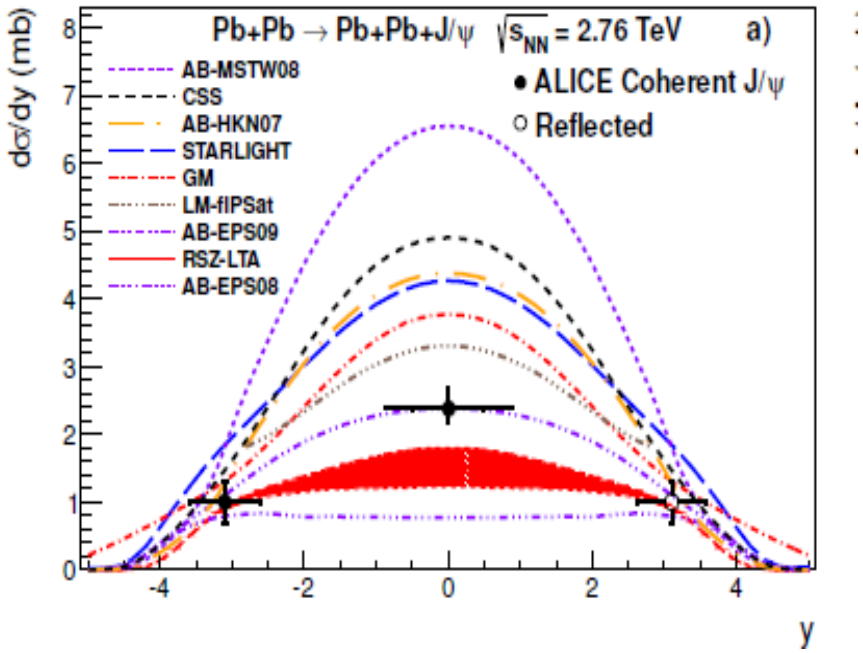

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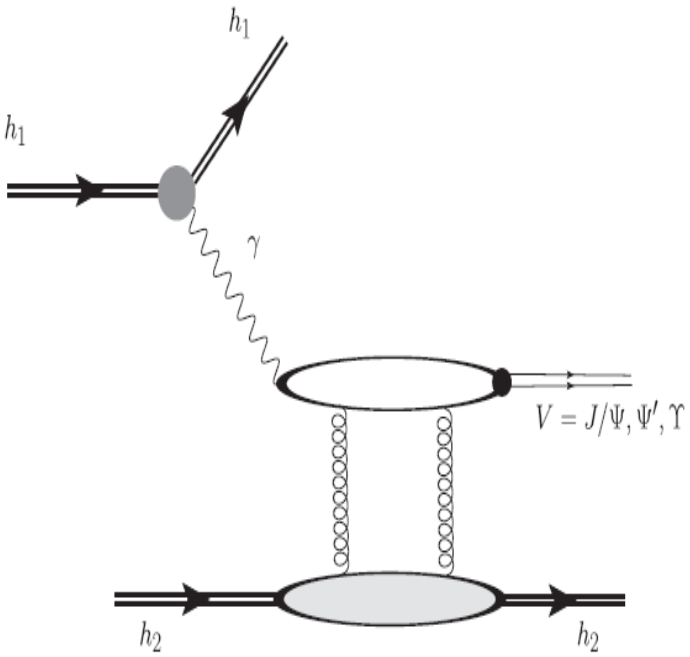
Photon – Hadron Interactions:
Probing the QCD dynamics



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

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

Photon – Hadron Interactions:
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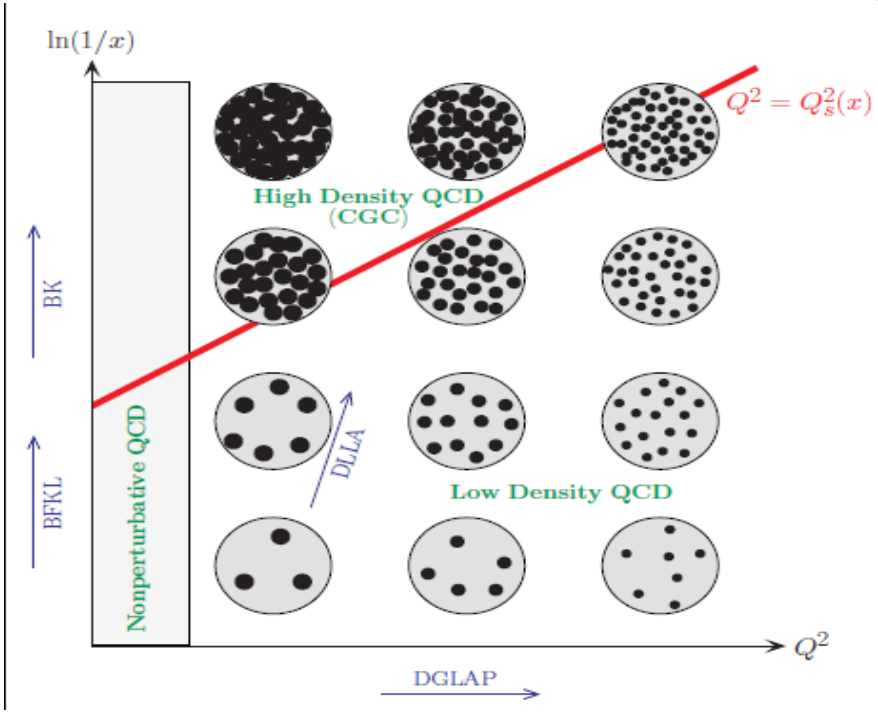

- Linear QCD evolution equations predict a power growth of gluon distribution as $x \to 0$ (violates unitarity).
- Number of gluons in the nucleon becomes so large that gluon recombine ⇒ Nonlinear effects
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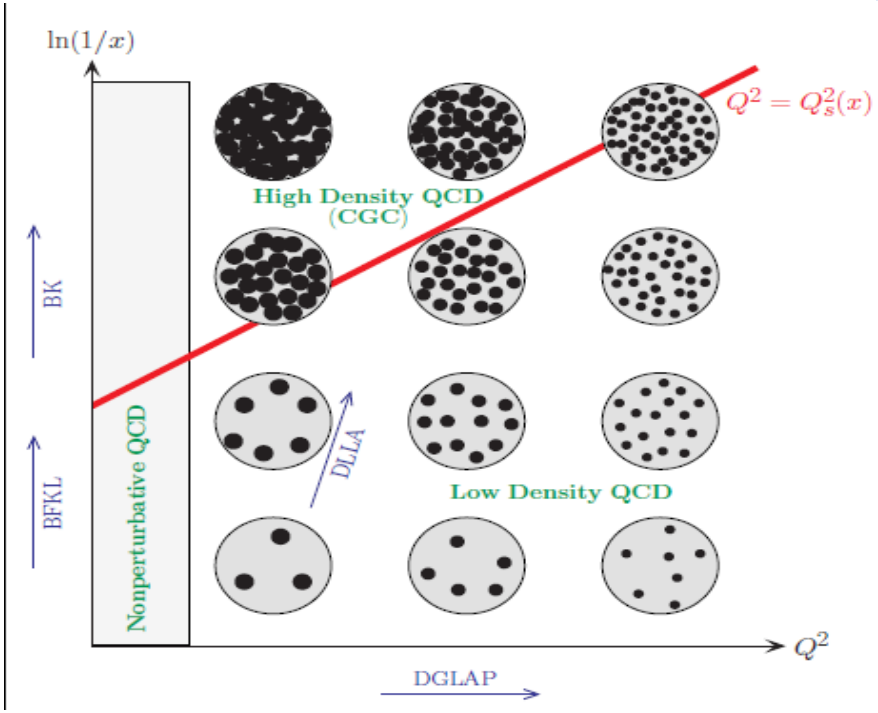

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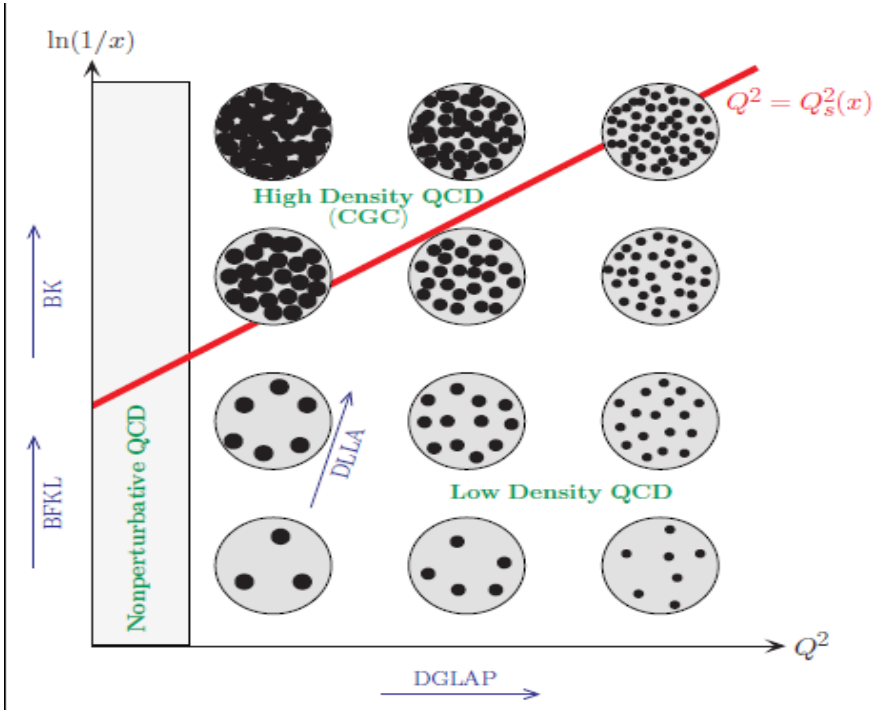

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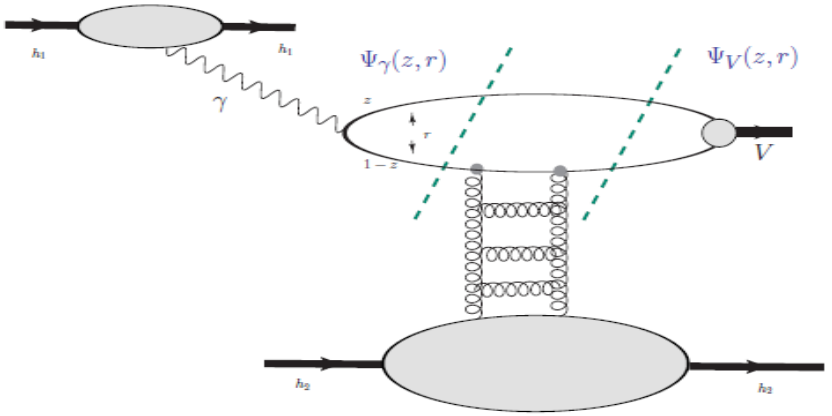

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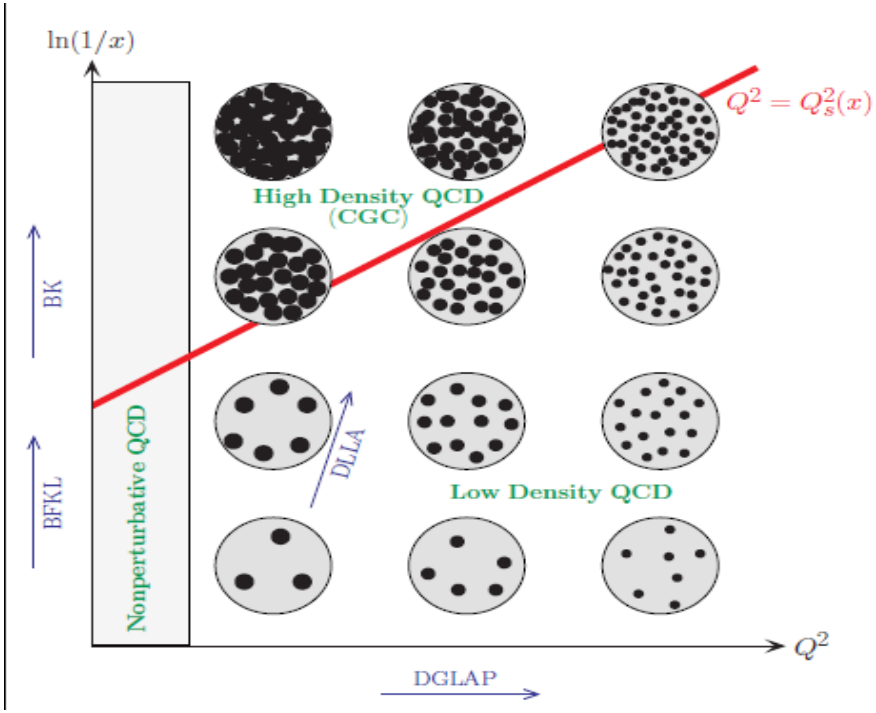

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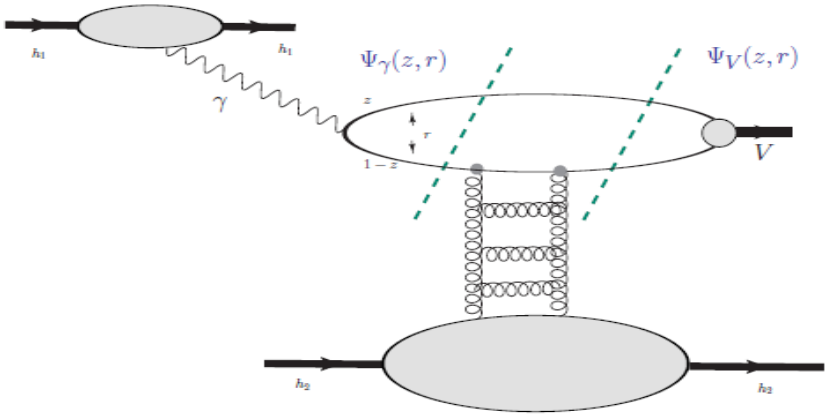

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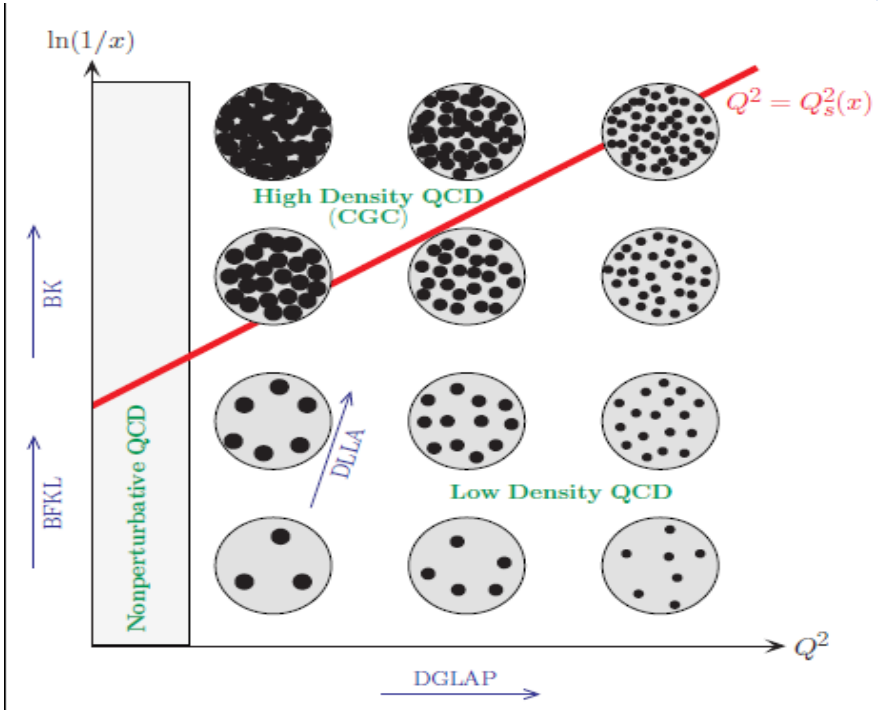

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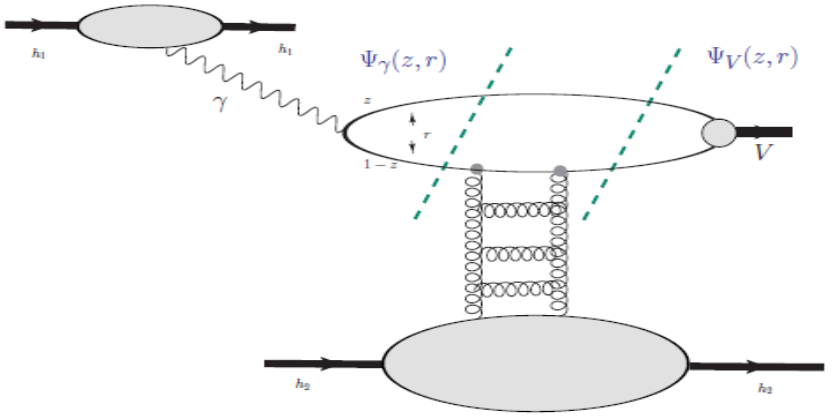

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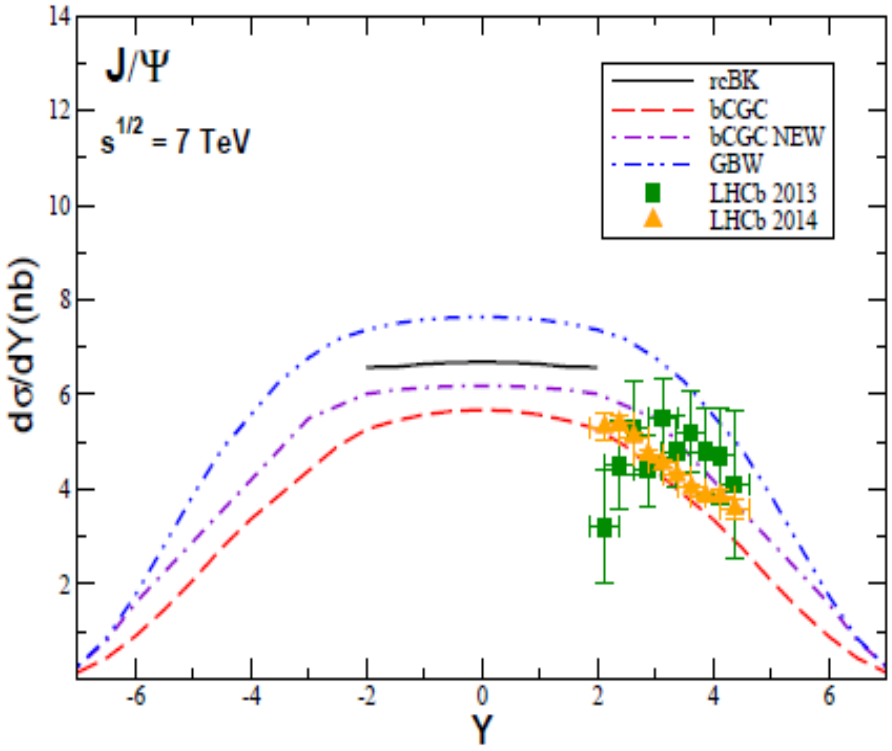

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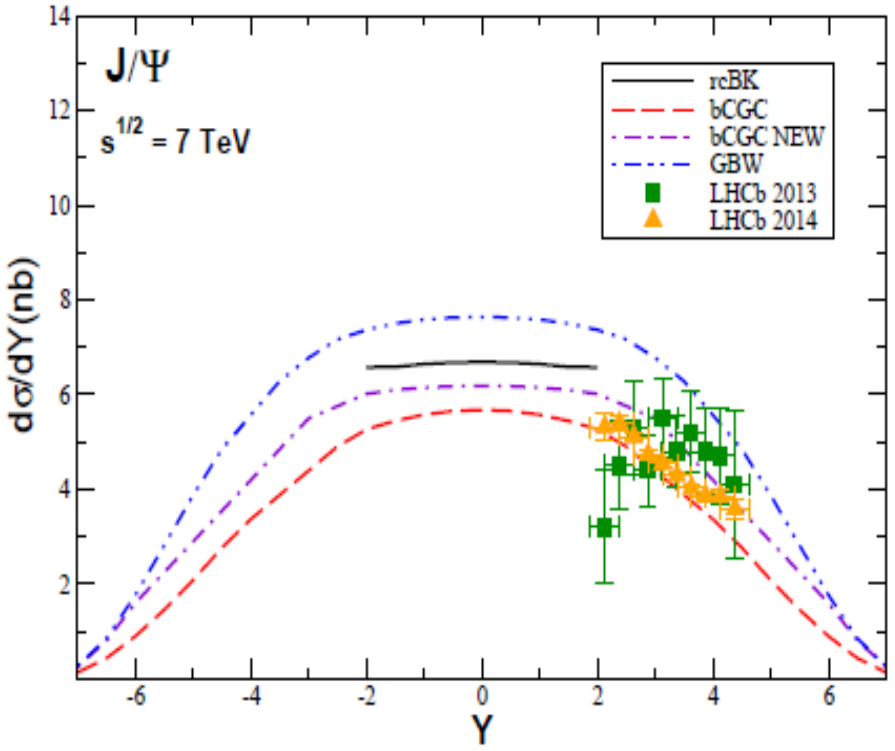

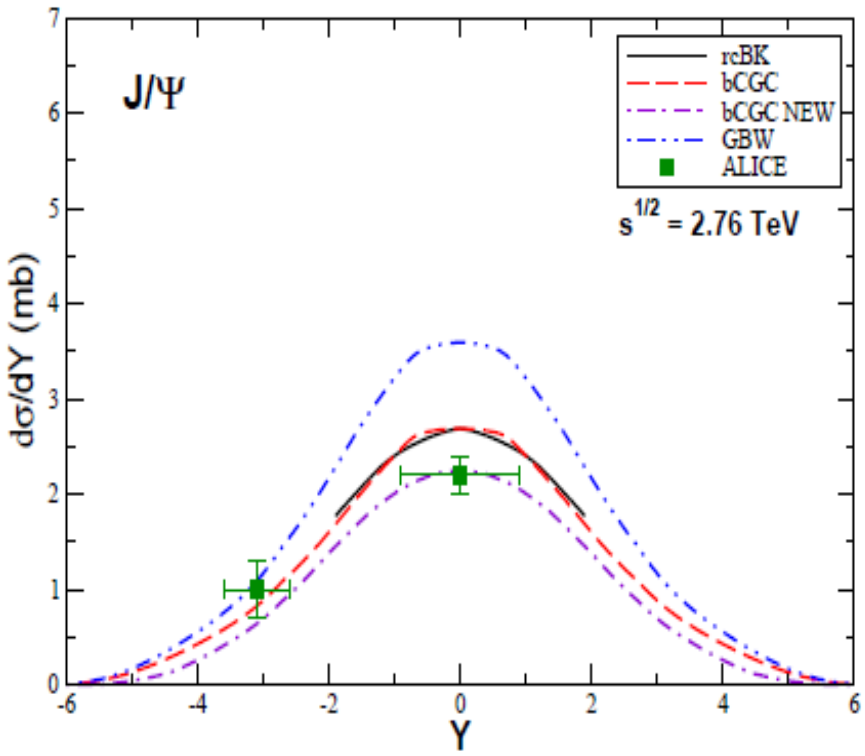

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Photon – Hadron Interactions: Probing the QCD dynamics

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

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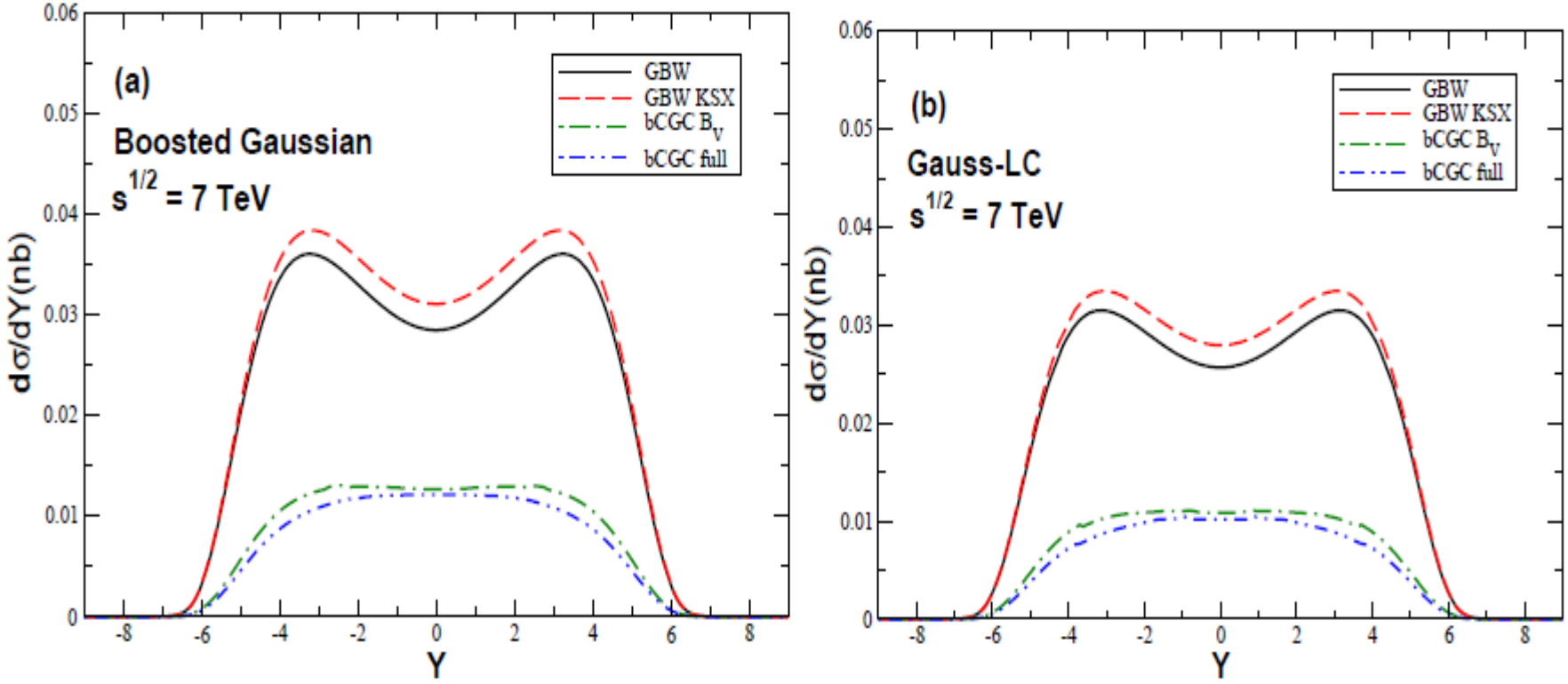

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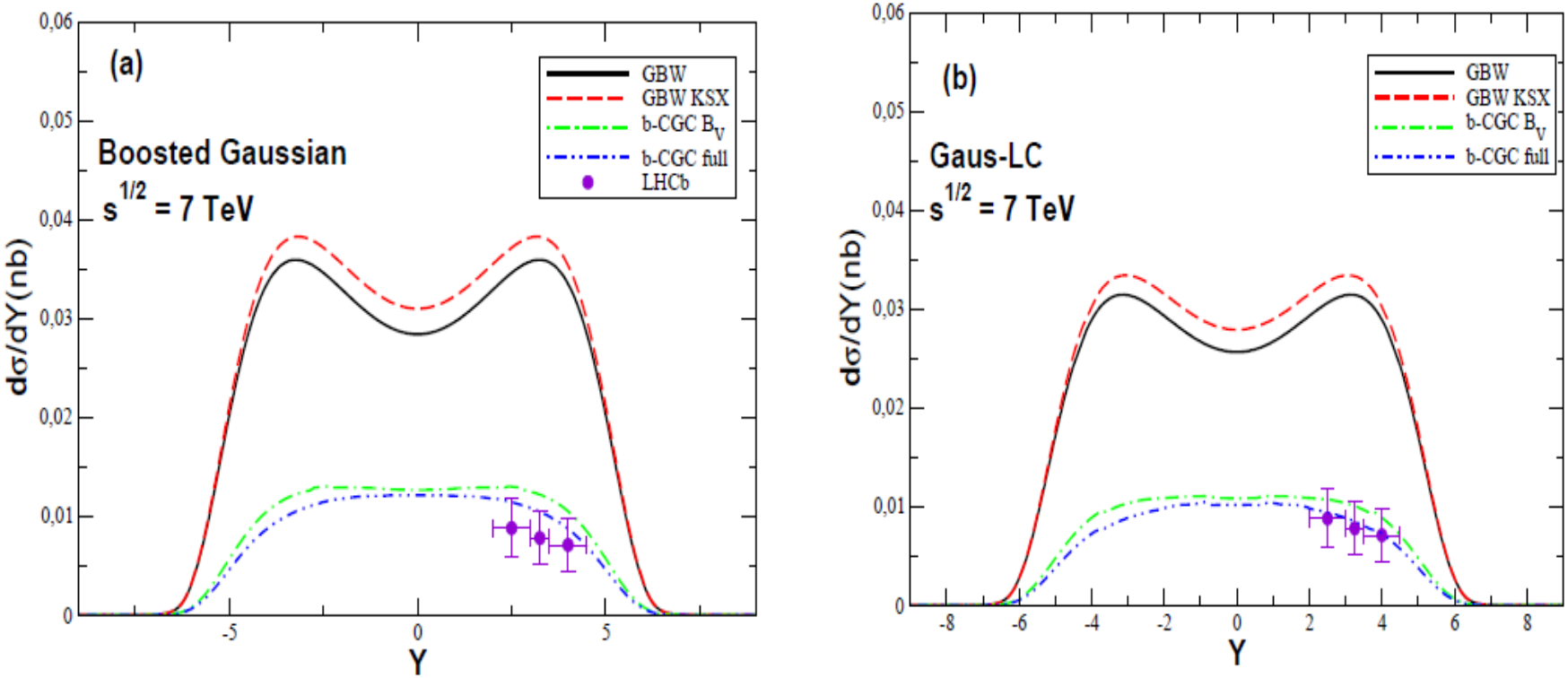

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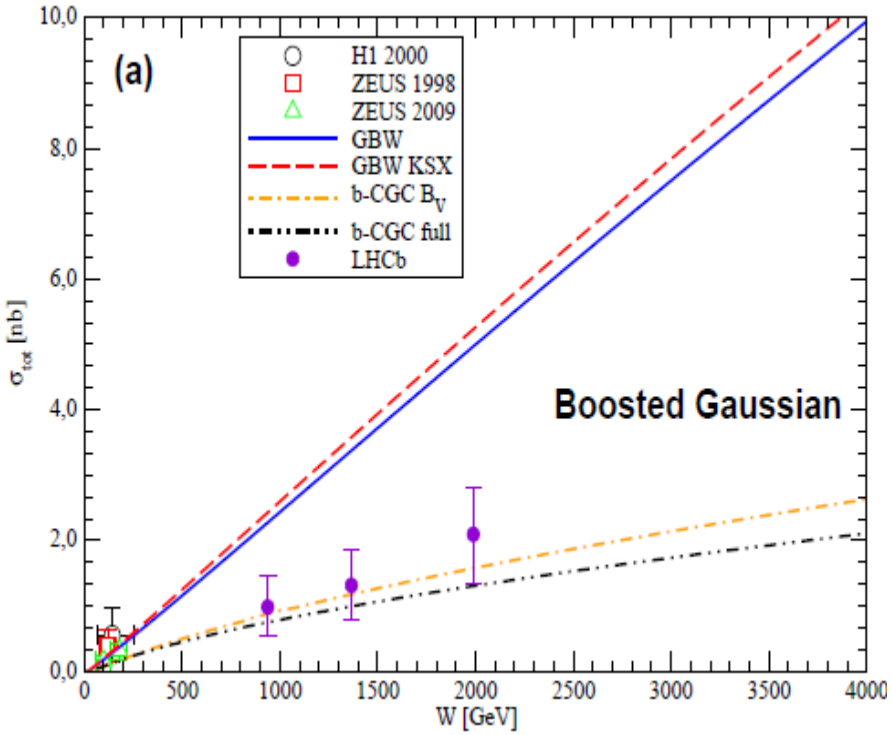

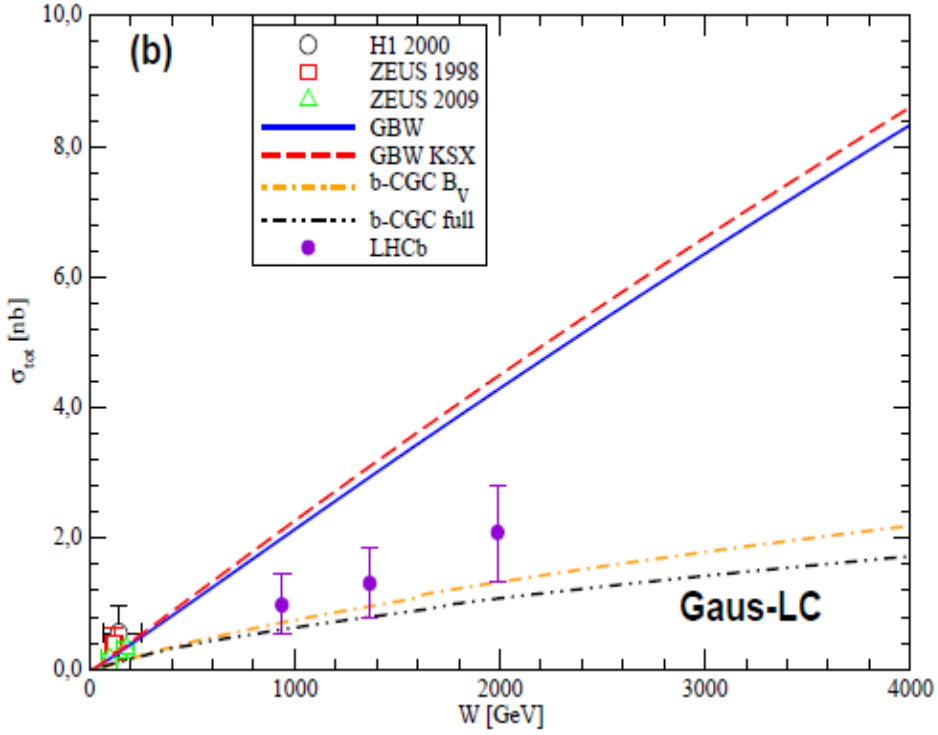

[b] VPG, Moreira, Navarra, PLB 472, 172 (2015)]

Photon – Hadron Interactions: Probing the QCD dynamics

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[c] VPG, Machado, PRC80, 054901 (2009); PRC84, 011902 (2011)

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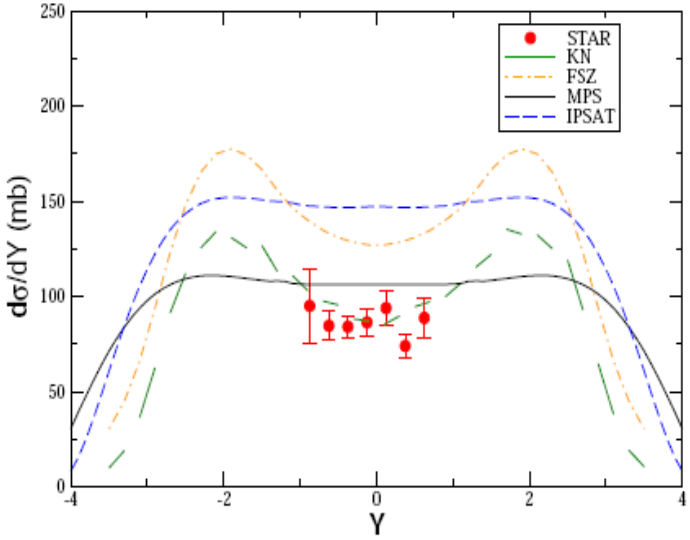

FIG. 1: (Color online) Predictions for the rapidity distribution of ρ^0 photoproduction at RHIC energy considering distinct theoretical approaches. Data from STAR Collaboration [24].

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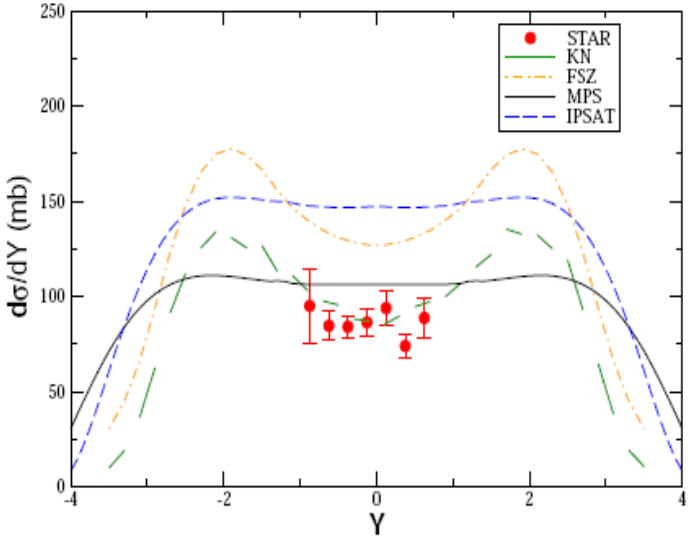

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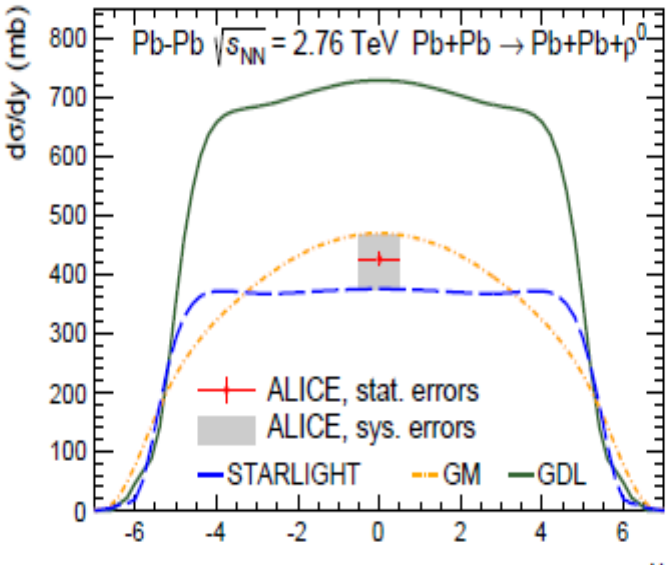

arXiv:1503.09177v1 [nucl-ex]

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Photon – Hadron Interactions:
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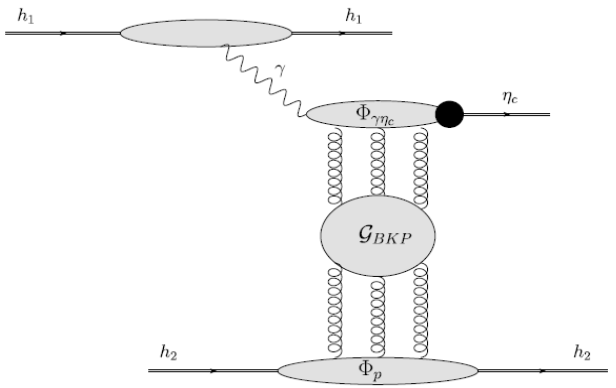

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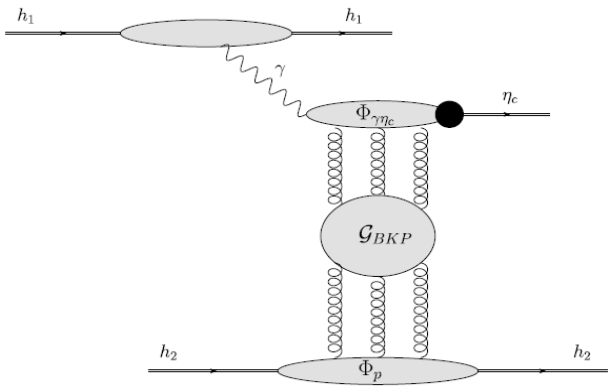


- Basic idea: As the photon carries negative C parity, its transformation into a diffractive final state system of positive C parity requires the t - channel exchange of an object of negative C parity.

[a] VPG, NPA 902, 32 (2013)

Photon – Hadron Interactions: Probing the Odderon

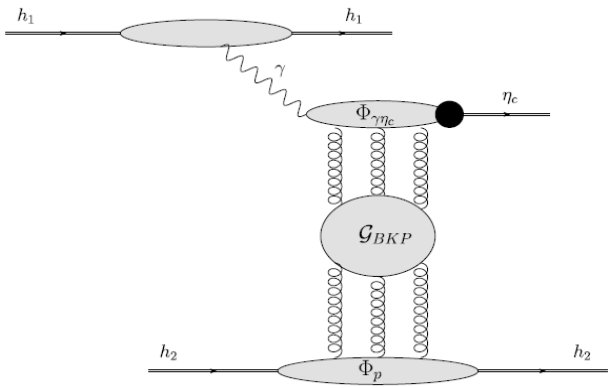
- In pQCD the Pomeron corresponds to a C - even parity (C being the charge conjugation) compound state of two t-channel reggeized gluons, which determines the high energy behaviour of the total hadronic cross sections.

- A natural prediction of the QCD is the presence of a C - odd compound state of three reggeized gluons, the so-called Odderon, which dominates the hadronic cross section difference between the direct and crossed channel processes at very high energies.

- Open question: Does the Odderon exist?

- Alternative: Consider exclusive processes in which the Odderon is the only contribution !

- Diffractive η_c photoproduction in hadronic collisions [a].



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[a] VPG, NPA 902, 32 (2013)

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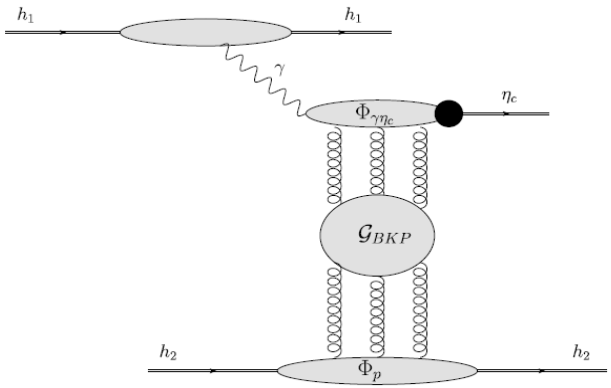

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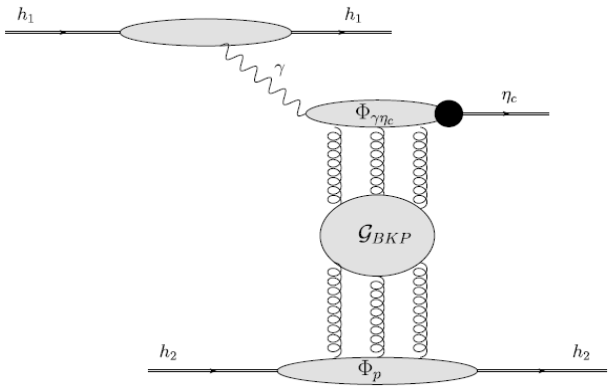

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- Predictions:

Table 1
Cross sections (event rates/year) for the diffractive η_c photoproduction in pp collisions at LHC energies.

$\sqrt{s_{NN}}$	CKMS	BBCV
8 TeV	0.55 pb (55 000)	10.10 pb (1×10^6)
14 TeV	0.65 pb (65 000)	13.90 pb (1.4×10^6)

Table 2
Cross sections (event rates/year) for the diffractive η_c photoproduction in PbPb collisions at LHC energies.

$\sqrt{s_{NN}}$	CKMS	BBCV
2.76 TeV	0.30 μb (126)	14.25 μb (5985)
5.5 TeV	0.40 μb (168)	23.59 μb (9912)

[a] VPG, NPA 902, 32 (2013)

Photon – Hadron Interactions: Probing the Odderon

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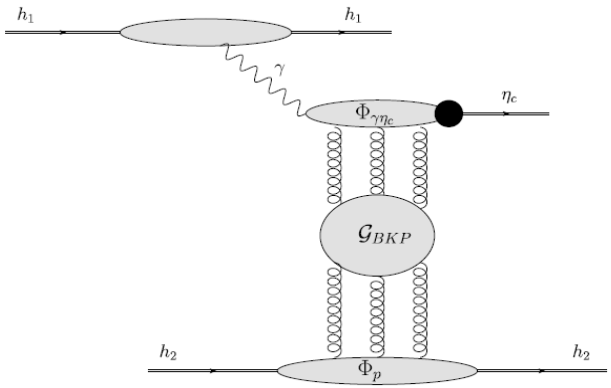

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- Predictions for the AFTER@LHC experiment [b].

h_1h_2	CKMS	BBCV
pp ($\sqrt{s} = 115$ GeV)	0.05 pb (1000.0)	0.30 pb (6000.0)
Pbp ($\sqrt{s} = 72$ GeV)	28.1 pb (31.0)	356.6 pb (393.0)
$PbPb$ ($\sqrt{s} = 72$ GeV)	5870.0 pb (41.0)	74366.0 pb (520.0)

TABLE I: Cross sections (event rates/year) for the exclusive η_c photoproduction in $pp/Pbp/PbPb$ collisions at AFTER@LHC experiment.

[b] VPG, Sauter, PRD 91, 094014 (2015)

Photon – Hadron Interactions: Probing the Odderon

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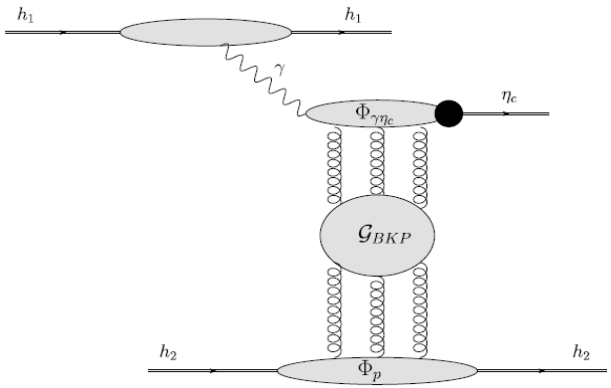

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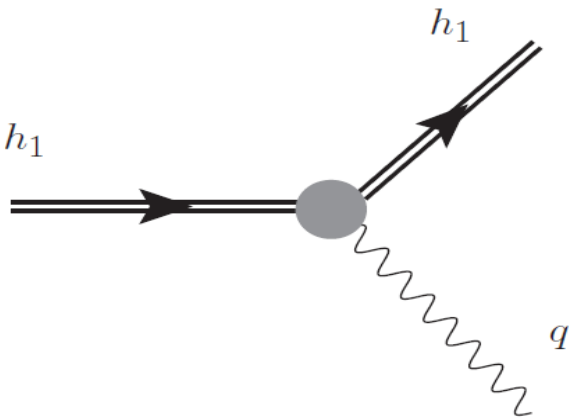
- Background is only present in pp collisions, which makes the observation of the exclusive η_c production in Pbp and $PbPb$ collisions a signature of the Odderon.

[a] VPG, NPA 902, 32 (2013)

[b] VPG, Sauter, PRD 91, 094014 (2015)

Photon – Hadron Interactions:
Probing the Photon Distribution of the Proton



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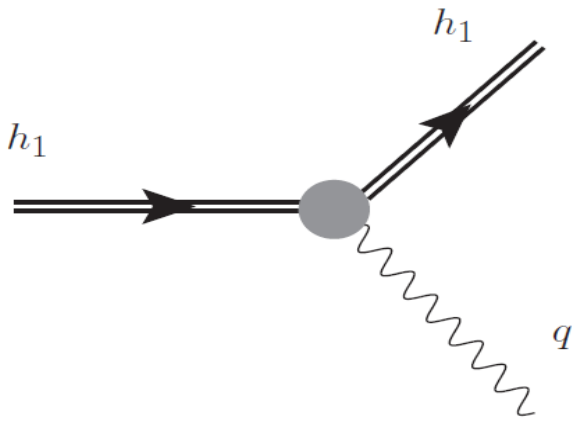

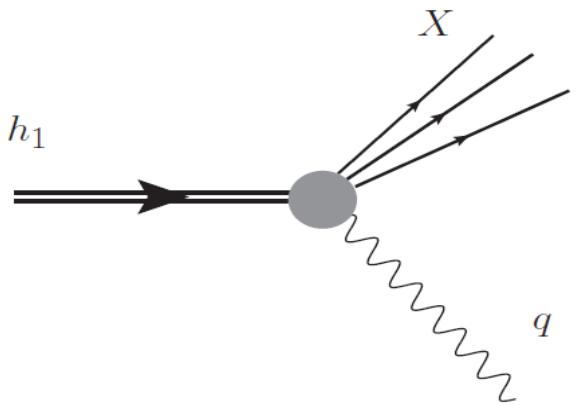

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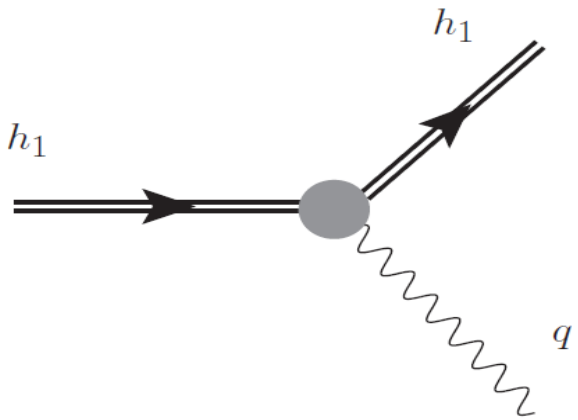

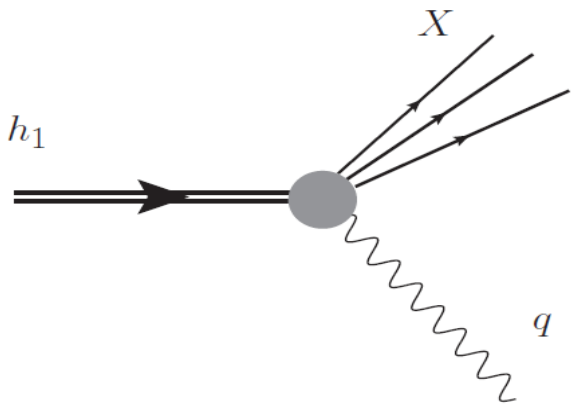

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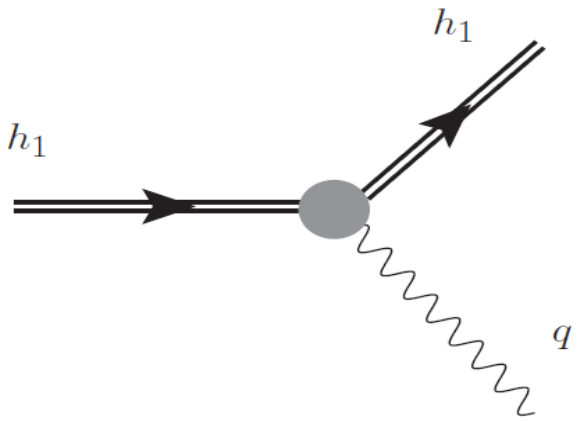

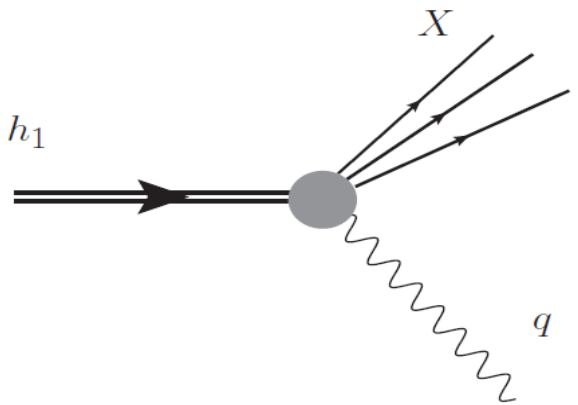

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- Several groups (MRST, NNPDF, CTEQ) have proposed to treat the photon as one of the point-like partons inside the nucleon and to account for this QED effect explicitly in the global analysis.

Photon – Hadron Interactions:
Probing the Photon Distribution of the Proton

- The inclusion of the QED effects implies that the quark, gluon and photon distributions satisfy QED-modified DGLAP equations, which are given at leading order in both α_s and α by:

$$\begin{aligned}
\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{qq}(y)\; q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\; g(\frac{x}{y},\mu^2)\Big\} \\
&+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\Big\{\tilde{P}_{qq}(y)\; e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\; e_i^2\gamma(\frac{x}{y},\mu^2)\Big\} \\
\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{gq}(y)\; \sum_j q_j(\frac{x}{y},\mu^2) + P_{gg}(y)\; g(\frac{x}{y},\mu^2)\Big\} \\
\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{\gamma q}(y)\; \sum_j e_j^2\; q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\; \gamma(\frac{x}{y},\mu^2)\Big\}\;,
\end{aligned}$$

where

$$\begin{aligned}
\tilde{P}_{qq} &= C_F^{-1}P_{qq}, \qquad & P_{\gamma q} &= C_F^{-1}P_{gq}, \\
P_{q\gamma} &= T_R^{-1}P_{qg}, \qquad & P_{\gamma\gamma} &= -\frac{2}{3}\sum_i e_i^2\;\delta(1-y)
\end{aligned}$$

and momentum is conserved:

$$\int_0^1 dx\; x\;\Big\{\sum_i q_i(x,\mu^2) + g(x,\mu^2) + \gamma(x,\mu^2)\Big\} = 1\;.$$

Photon – Hadron Interactions:
Probing the Photon Distribution of the Proton

- Initial condition $\gamma(x, Q_0^2)$:

  MRST: Naive model

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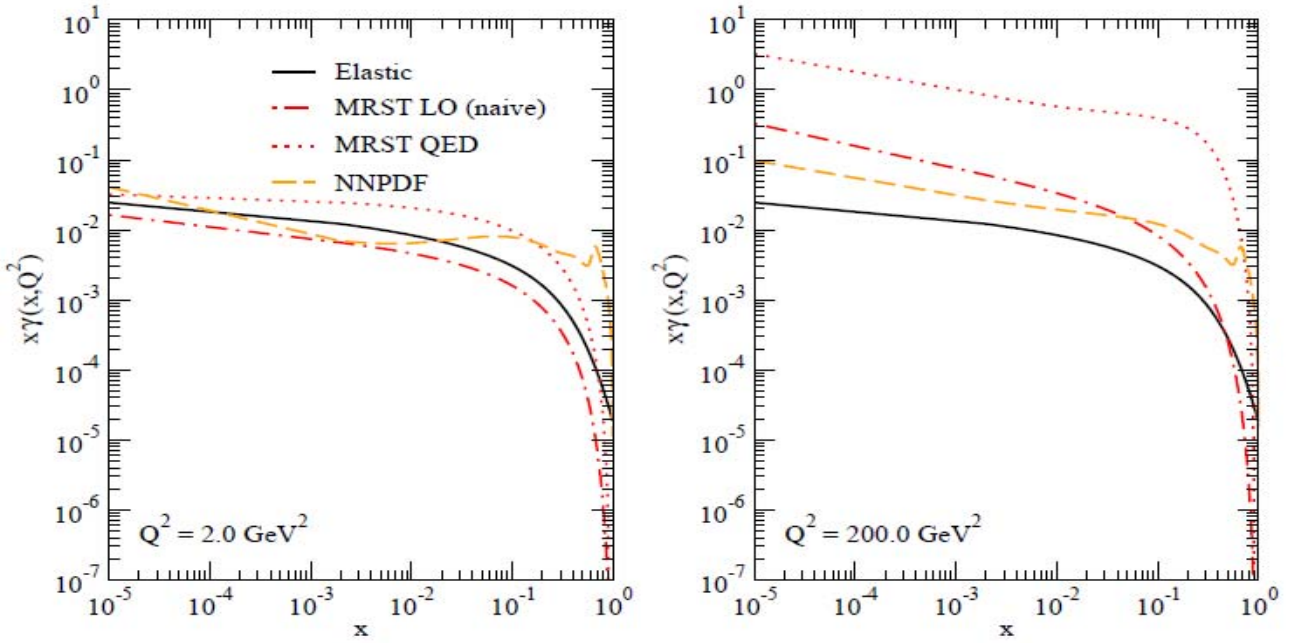
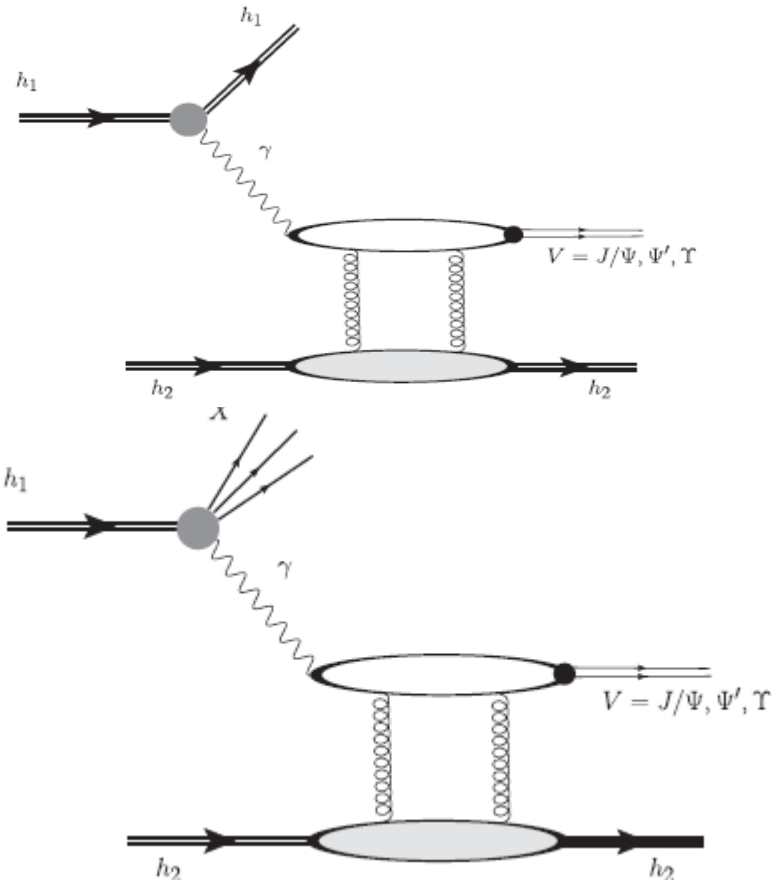


Photon – Hadron Interactions:
Probing the Photon Distribution of the Proton

- Diffractive Quarkonium Photoproduction in Hadronic Collisions as a probe of the photon flux [a].



[a] VPG, da Silveira, PRD 91, 054013 (2015)

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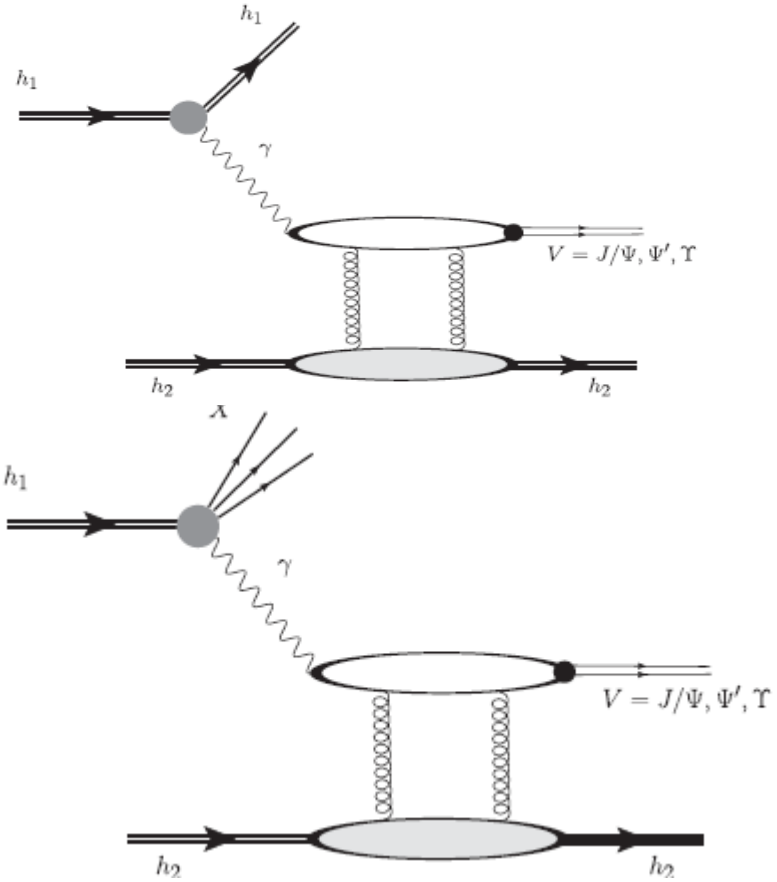

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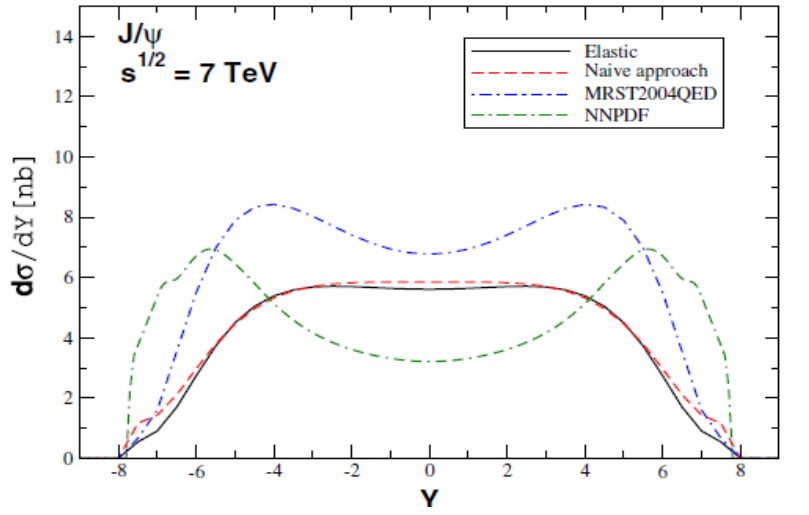

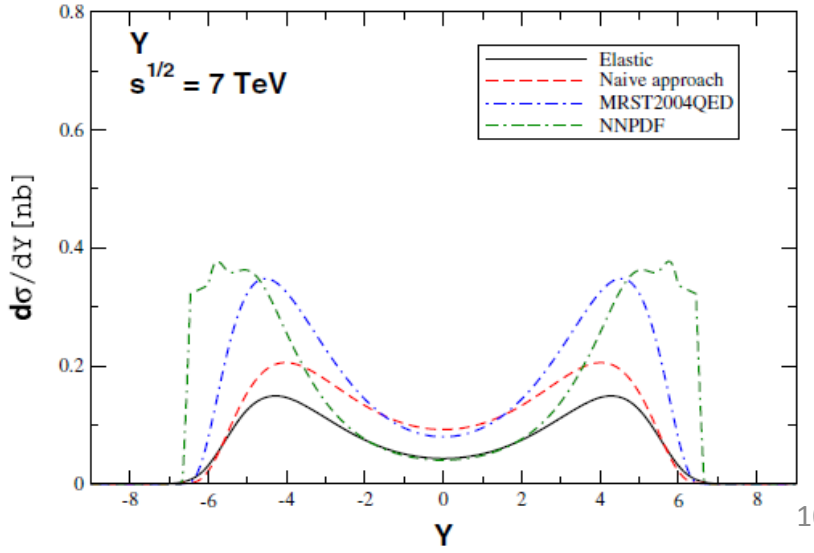

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Thank you for your attention !

Extras

Probing Quarkonium Production in photon – induced interactions

Quarkonium + Photon production in photon – induced interactions (*)

$$\frac{d\sigma[p+p\to p\otimes H+\gamma+X)]}{dY} = \omega\frac{dN_{\gamma/h_1}(\omega)}{d\omega}\sigma_{\gamma h_2\to H+\gamma+X}(\omega) + \omega\frac{dN_{\gamma/h_2}(\omega)}{d\omega}\sigma_{\gamma h_1\to H+\gamma+X}(\omega),$$

$$\sigma(\gamma+p\to H+\gamma+X) = \int dz\,dp_\perp^2\,\frac{xg(x,Q^2)}{z(1-z)}\,\frac{d\sigma}{dt}(\gamma+g\to H+\gamma)$$

$$\frac{d\sigma}{dt}(\gamma+g\to H+\gamma) = \frac{64\pi^2}{3}\,\frac{e_Q^4\alpha^2\alpha_s m_Q}{s^2}\left(\frac{s^2s_1^2+t^2t_1^2+u^2u_1^2}{s_1^2t_1^2u_1^2}\right)\langle O_8^V(^3S_1)\rangle$$

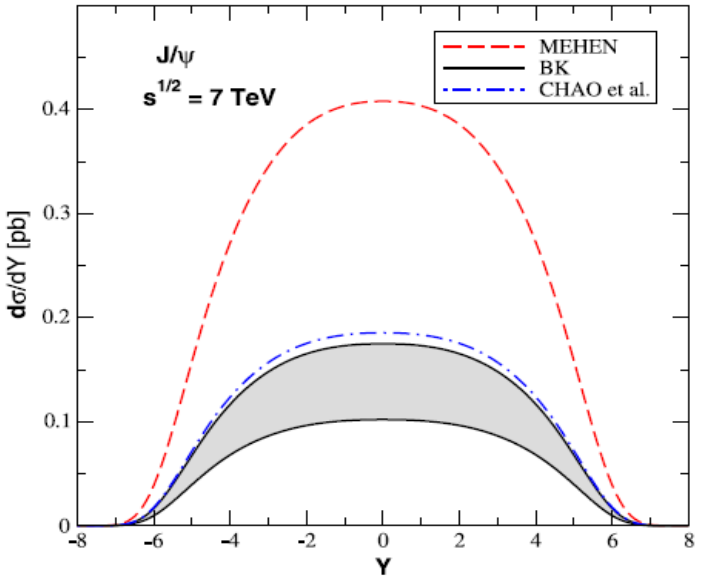
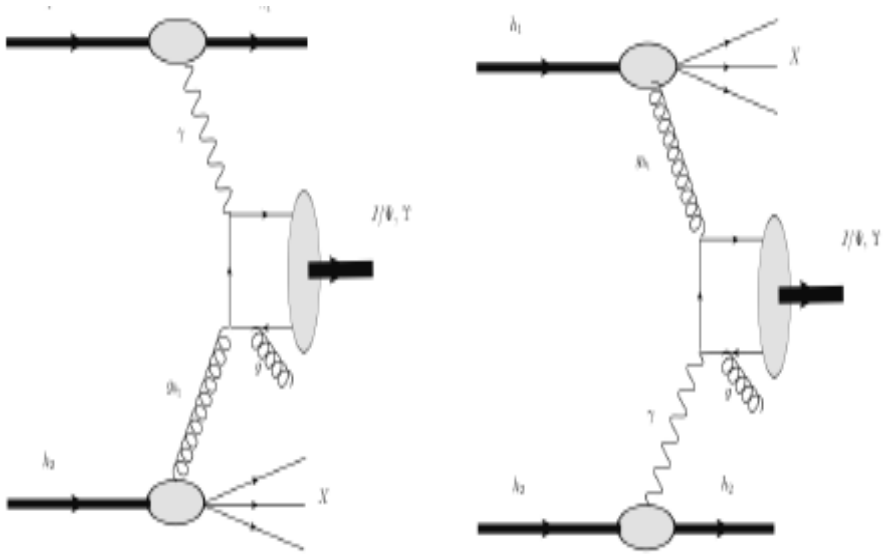


Table 1 The total cross section for the $H+\gamma$ photoproduction in coherent hadron–hadrons collisions at LHC energies

$J/\Psi+\gamma$	MEHEN	BK
LHC (7 TeV)	3.62 pb	1.23 ± 0.50 pb
LHC (14 TeV)	5.60 pb	1.90 ± 0.32 pb
$\Upsilon+\gamma$	BFL	BSV
LHC (14 TeV)	5.46 fb	1.45 ± 0.13 fb

(*) VPG, M. M. Machado, EPJC 72, 2231 (2012)

Inelastic Quarkonium production in photon – induced interactions (*)



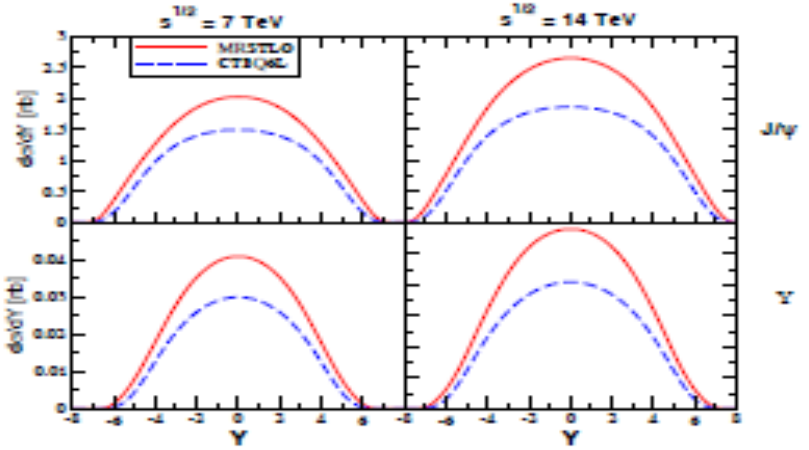


Fig. 4. Rapidity distribution for the J/Ψ and Υ production in coherent pp collisions at $\sqrt{s} = 7\,\text{TeV}$ (left panels) and 14 TeV (right panels) considering two different parametrizations for

Table 1. The total cross section (event rates) for the inelastic quarkonium photoproduction in coherent pp collisions at LHC energies.

J/Ψ	MRSTLO	CTEQ6L
$\sqrt{s} = 7\,\text{TeV}$	$18.0\,\text{nb}$ (1.8×10^9)	$13.0\,\text{nb}$ (1.3×10^9)
$\sqrt{s} = 14\,\text{TeV}$	$25.0\,\text{nb}$ (2.5×10^9)	$18.0\,\text{nb}$ (1.8×10^9)
Υ	MRSTLO	CTEQ6L
$\sqrt{s} = 7\,\text{TeV}$	$0.30\,\text{nb}$ (30×10^6)	$0.21\,\text{nb}$ (21×10^6)
$\sqrt{s} = 14\,\text{TeV}$	$0.47\,\text{nb}$ (47×10^6)	$0.33\,\text{nb}$ (33×10^6)

(*) VPG, M. M. Machado, EPJA 50, 72 (2014)