Photoproduction and Small-x

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Motivation

- The knowledge of QCD dynamics at very high energies is essential in order to understand the hadronic interactions at current and future accelerators.
- Parton distributions extracted from HERA ep collider are used in the description of hadronic interactions studied at Tevatron (LHC).
- LHC will probe pdf's (gluons) at very low-x, which are not constrained by current accelerators data (information gap!).
- Is a simple extrapolation of DGLAP/BFKL evolution enough ?
- How do we treat processes characterized by low momentum scale ?
- Are the current estimations for small-x nuclear shadowing reliable ?
- Does the gluon distribution saturate at small-x ?
- The high energy HERA data are reasonably described by saturation models (within the color dipole approach), but several open questions remain ...

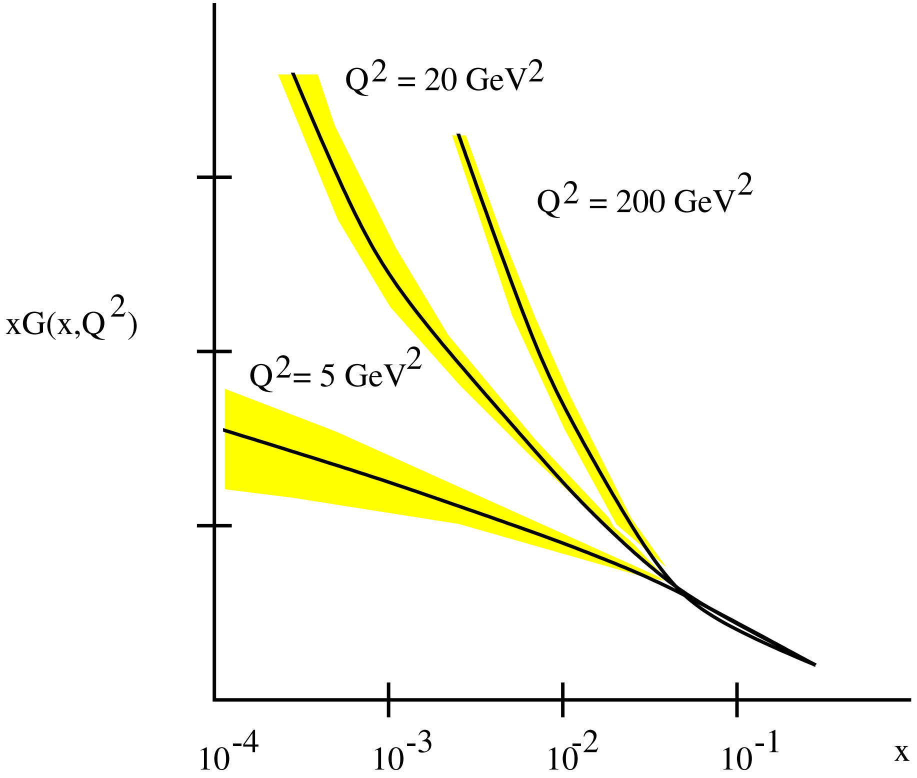
Our goal: use photoproduction of heavy quarks and vector mesons to perform phenomenology with saturation physics. Coherent $pp/pA/AA$ interactions at LHC energies are a good place for an alternative search.

Outline

- Small-x Physics;
- Parton Saturation;
- Color dipole results for charm/bottom photoproduction;
- Some aplications for $Q\bar{Q}$ photoproduction at UPCs;
- Color dipole results for meson photoproduction;
- Some aplications for V_M photoproduction at UPCs;
- Summary.

Small-x Physics

- From HERA data:



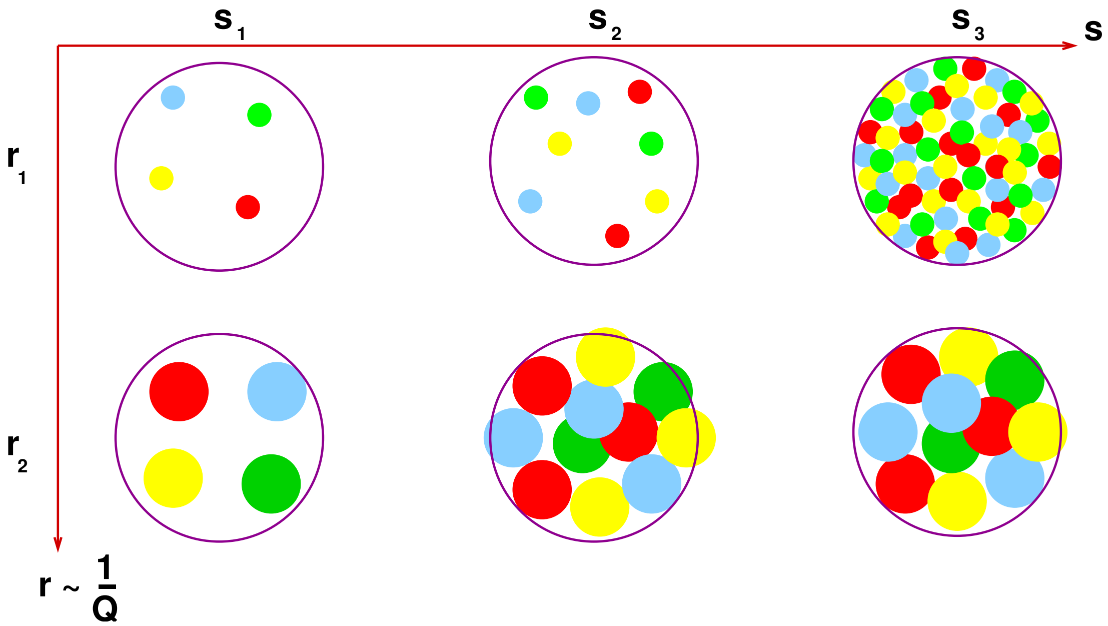
Bjorken x variable: $x = \frac{Q^2}{s}$.

- For high energies (small x) the hadrons are characterized by a high density of gluons.
- In this regime, the recombination process $gg \longrightarrow g$ cannot be disregarded.
  $\Rightarrow$ Modification of the evolution equations with the inclusion of non-linear terms.

  $\Rightarrow$ Parton saturation effects.

Theoretical Expectations

- In usual pQCD approach, pdfs evolve via linear evolution equation (DGLAP), which considers emission diagrams in its construction.
- Power-like bahavior for gluon pdf, $xg(x, Q^2) \propto x^{-\lambda}$, $\lambda = \lambda(Q^2)$.
- At very low-x, recombination process $gg \rightarrow g$ can be considered.
  $\Rightarrow$ Modification of the evolution equations by including non-linear terms (tames the growth of gluon density!).



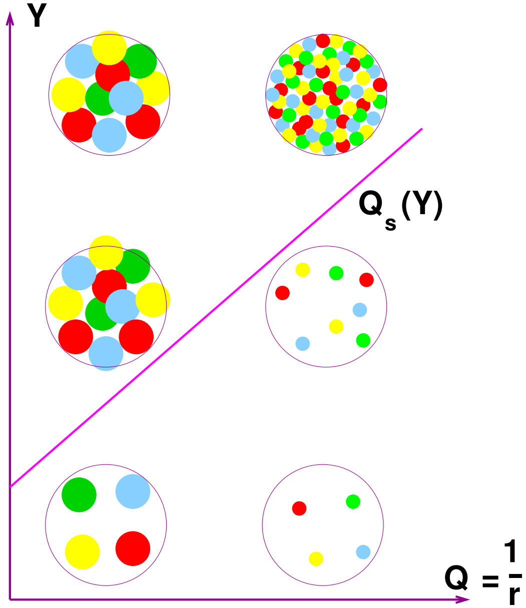
High energy evolution equations

- A promising evolution equation (it allows assymptotic analytical solutions) is the Balitsky-Kovchegov (BK 1996/1999) and its corresponding extentions.
- Projectile can be described as a quark-antiquark dipole and the target described in terms of its color field.
- BK gives QCD evolution equation on rapidity variable $Y = \ln(1/x)$ for the dipole-target amplitude, $\mathcal{N}(r,\, b,\, Y)$, including single and multiple scatterings.
- The dipole transverse size is r and b is the impact parameter.
- Several numerical calculations for the solution are available (small depedence on the initial conditions).
- In the toy model for $(0+1)$ dimensions, where $N = N(Y)$:

$$\frac{dN}{dY} = k(N - N^2)\,, \qquad N(Y) = \frac{e^{kY}}{e^{kY} + c}, \quad (k > 0)$$

- Solution is logistic curve. Important property: amplitude saturates at high energies $N(Y \to \infty) = 1$.

Saturation scale

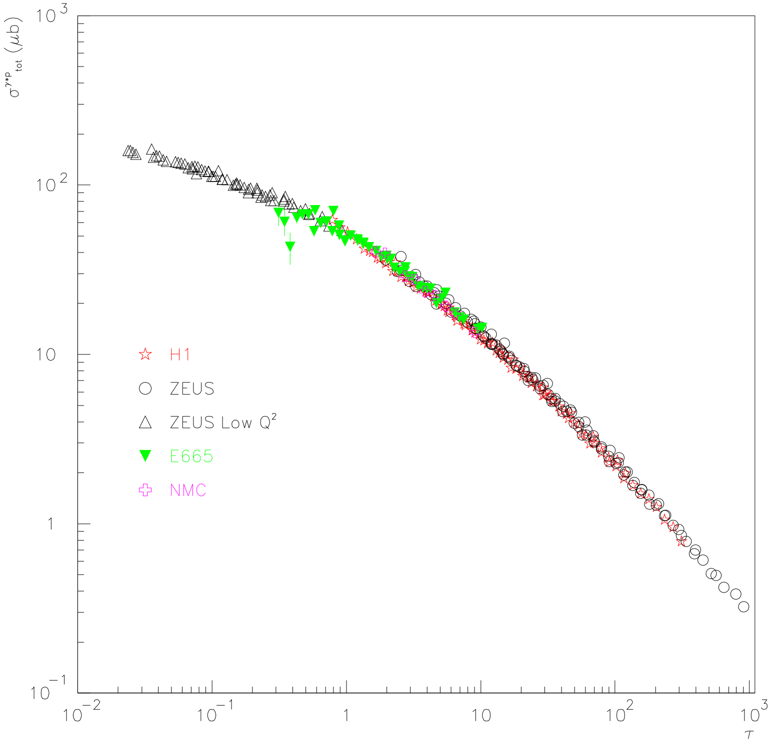


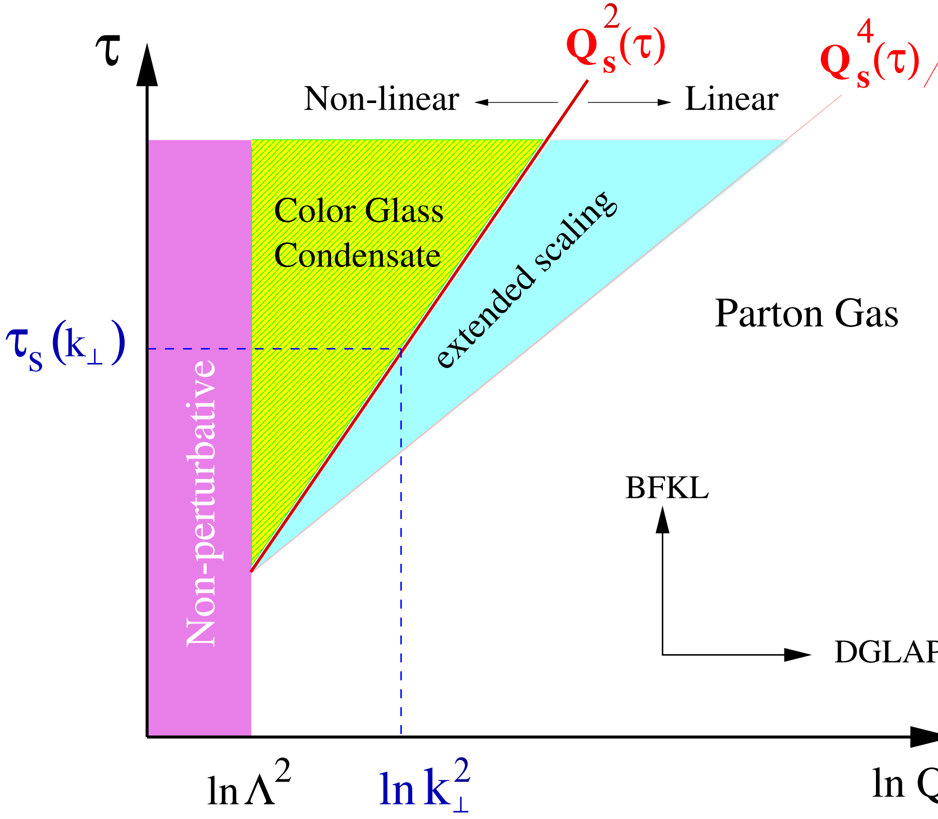
- Solution has 3 behaviors: (1) regions where amplitude is small and non-linear corrections are small; (2) transition region and (3) asymptotic region where $N \simeq 1$.
- Limit of transition region is characterized by saturation scale $Q_s(Y)$. BK leading logarithmic solution gives $Q_s \propto \exp(\bar{\alpha}_s^2 \lambda Y) \sim x^{-\alpha}$.
- For small size dipoles, $r < 1/Q_s \to N \ll 1$, and for large size dipoles, $r > 1/Q_s \to N \simeq 1$.
- Saturation physics is important for processes characterized by momentum scale near or below saturation scale.

Today: Any evidence of saturation ?

- HERA: $\sqrt{s_{ep}} = 300$ GeV.

Geometric scaling on $\tau = Q^2/Q_s^2$:



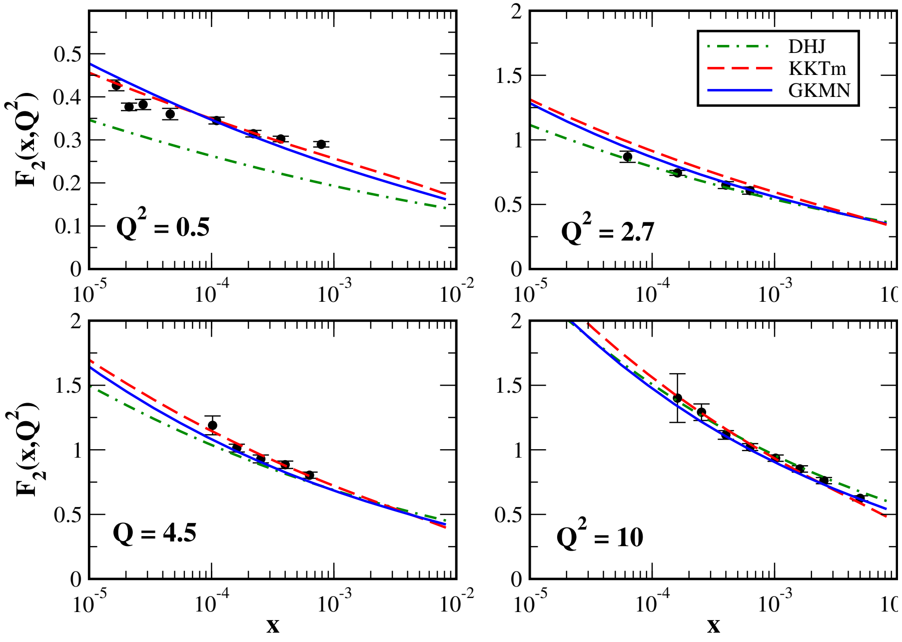


$\Rightarrow$ Evidence of the non-linear regime of the QCD dynamics.

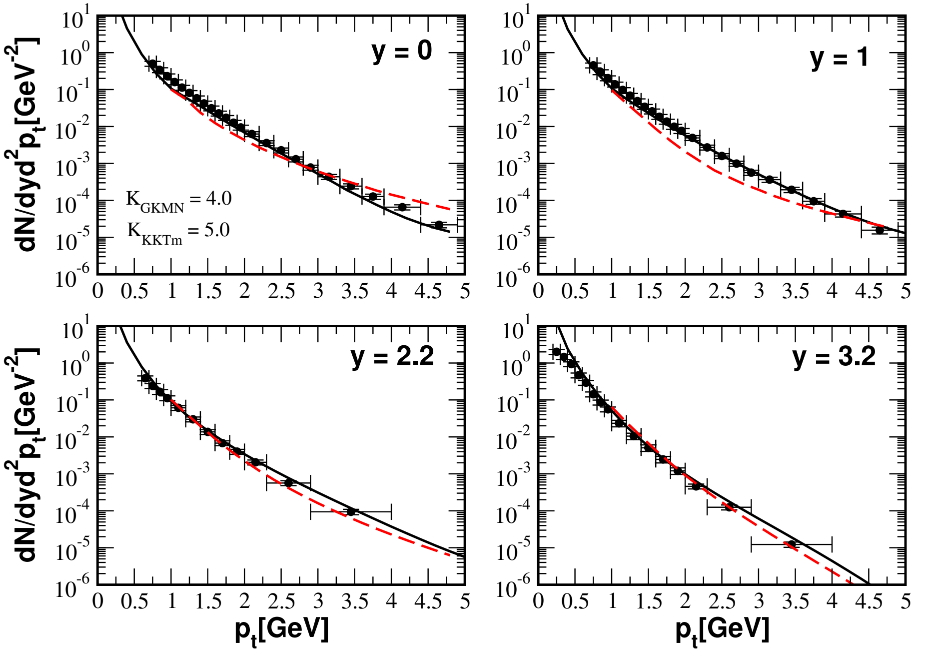
However, more definite conclusions are not possible due to the small value of Q_s in the kinematical range of HERA [$Q_s^2 = Q_0^2 (\frac{x_0}{x})^\lambda \approx 1.0$ GeV^2].

Today - any signal of saturation ?

- Saturation at HERA:



- Saturation at RHIC:



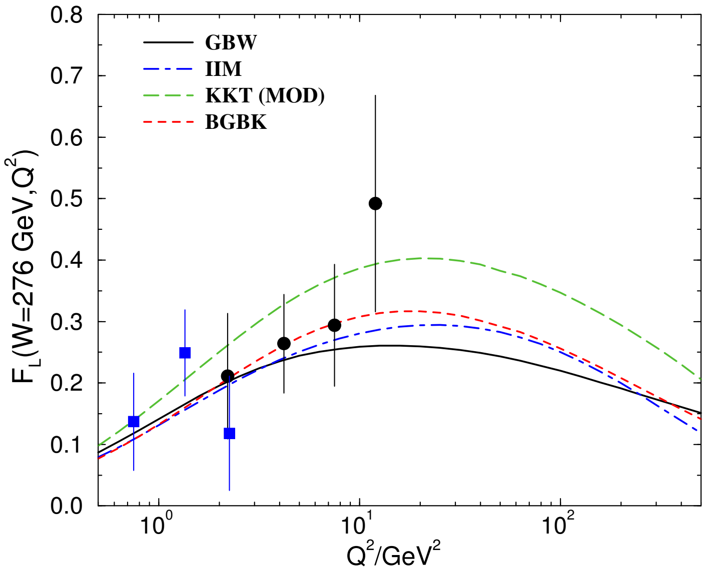
Evidence of the universality of the saturation physics!

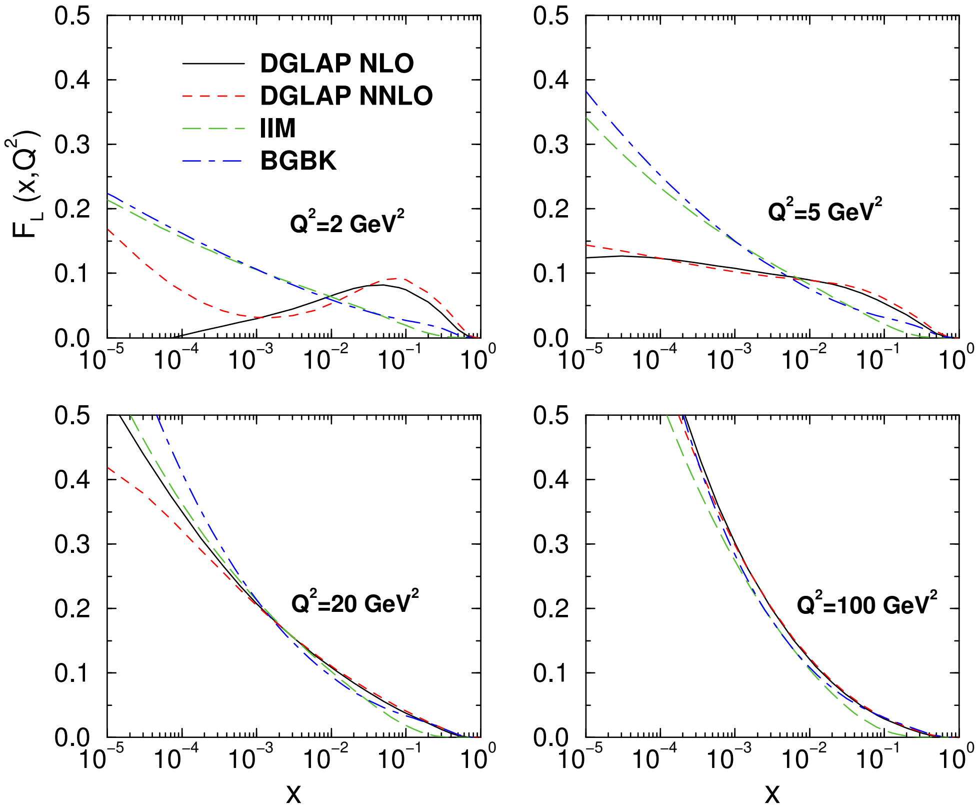
$\Rightarrow F_2$ structure function and charged particle production at RHIC computed using the same dipole cross section.

Gonçalves-Kugeratski-MVTM-Navarra **[PLB643:273 (2006)]**

Today - any signal of saturation ?

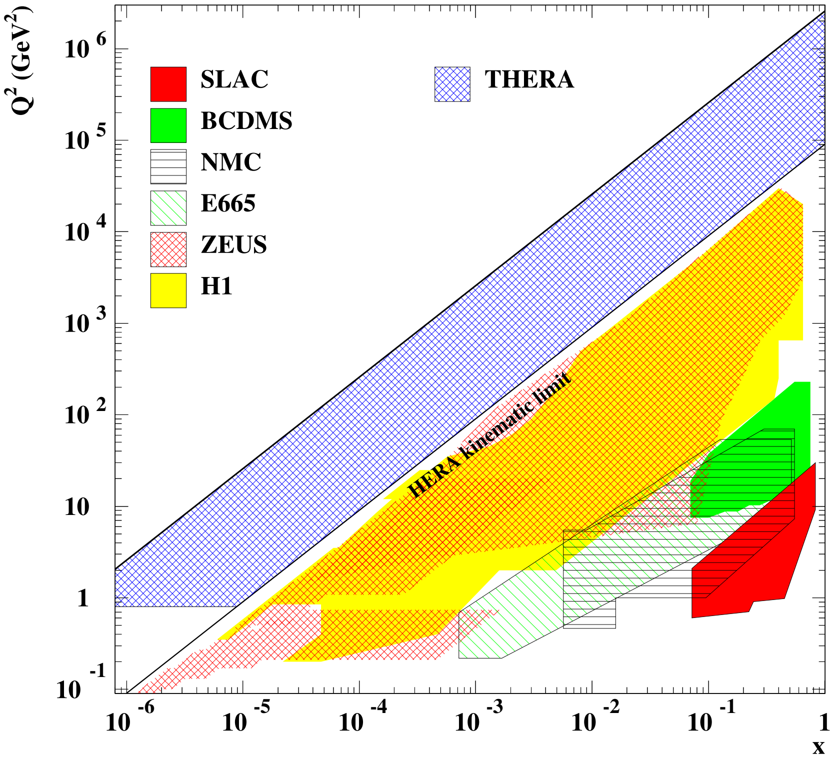
- F_2 is less sensitive to saturation corrections than F_L.
- F_L is directly dependent on the gluon pdf.
- Direct measurement of F_L would be nice!

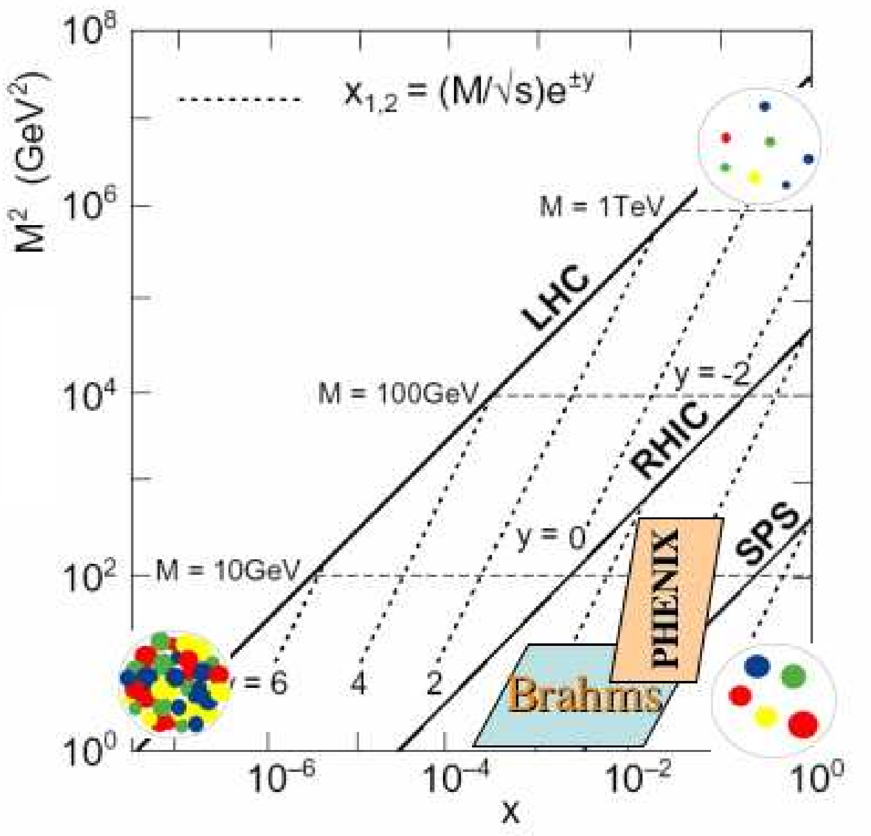




Future: *ep* and *pp* collisions

- THERA: $\sqrt{s_{ep}} = 1$ TeV and LHC: $\sqrt{s_{pp}} = 14$ TeV.





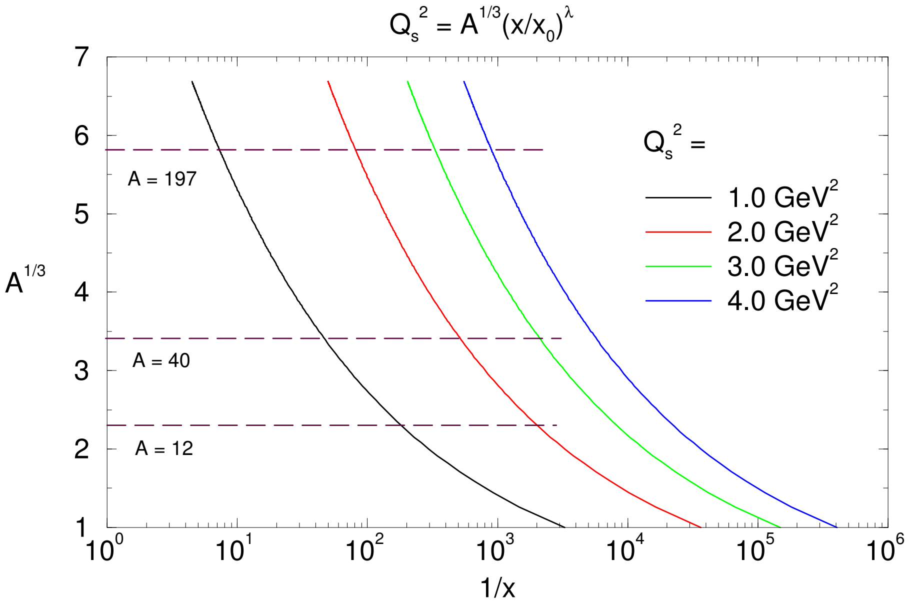
Future: eA collisions

- eRHIC: $\sqrt{s_{eA}} = 100$ GeV and THERA: $\sqrt{s_{eA}} = 1$ TeV.

Main motivation:

Saturation scale:

$$\boxed{Q_s^2(x;A) = A^\alpha Q_s^2(x;p) = A^\alpha \times Q_0^2(\frac{x_0}{x})^\lambda}$$

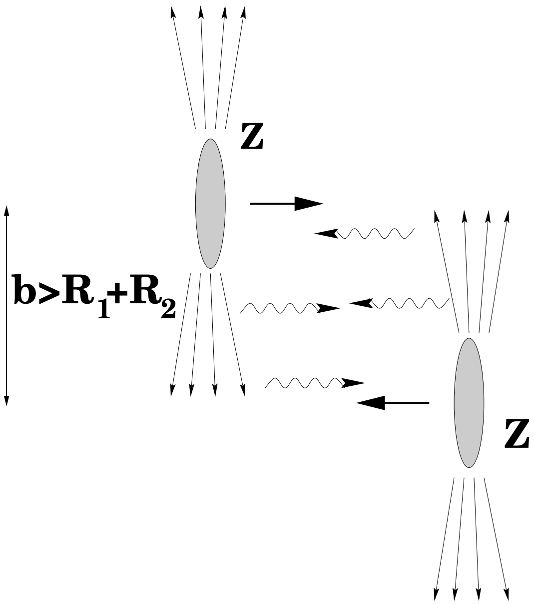


$\Rightarrow$ The nucleus amplifies the dynamical effects associated to the high parton density.

$\Rightarrow$ Saturation scale can grow up to $Q_s^2 \sim 5$ GeV^2 at LHC.

A good alternative beyond HERA:

Photoproduction in pp (pA) or AA collisions:



- γp Processes:
  $\sigma(pp \to X) = n_p(\omega) \otimes \sigma^{\gamma p}(W_{\gamma p})$
  $\sigma(pA \to X) = n_A(\omega) \otimes \sigma^{\gamma p}(W_{\gamma p})$
- γA Processes: $\sigma(AA \to X) = n_A(\omega) \otimes \sigma^{\gamma A}(W_{\gamma A})$
- $\gamma\gamma$ Processes: $\sigma(AA \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma}(W_{\gamma\gamma})$

Photoproduction calculation

- The photoproduction cross section is given by,

$$\sigma(h_1 h_2 \to X)(\sqrt{s}) = \int \frac{d\,\omega}{\omega}\, n_h\,(\omega)\, \sigma_{\gamma\,h}\,(W_{\gamma h}^2 = 2\,\omega\sqrt{s})$$

- The number of equivalent photons:

$$n_A\,(\omega) \quad = \quad \frac{2\,Z^2\alpha_{em}}{\pi\,\omega}\left[\bar{\eta}\,K_0\,(\bar{\eta})\,K_1\,(\bar{\eta}) + \frac{\bar{\eta}^2}{2}\,\left(K_1^2\,(\bar{\eta}) - K_0^2\,(\bar{\eta})\right)\right]\,,$$

where $\bar{\eta} = \omega\,R_{eff}/\gamma_L$, with $R_{eff} = R_p + R_A$ ($R_{eff} = 2R_A$) for pA (AA) collisions.

$$n_p\,(\omega) \quad = \quad \frac{\alpha_{\rm em}}{2\pi\,\omega}\left[1 + \left(1 - \frac{2\,\omega}{\sqrt{S_{NN}}}\right)^2\right]\left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\,\Omega^2} + \frac{1}{3\,\Omega^3}\right)\,,$$

where $\Omega = 1 + [\,(0.71\,\mathrm{GeV}^2)/Q^2_{\rm min}\,]$ and $Q^2_{\rm min} = \omega^2/[\,\gamma_L^2\,(1 - 2\,\omega/\sqrt{s})\,]$.

Advantages of photoproduction

Center of mass energy:

LHC	$pPb(Ar)$	$W_{\gamma p} \lesssim 1500\,(2130)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV

- Photoproduction can help us to gain information on the dynamics of γp and γA reactions for energies higher than HERA.

Final state:

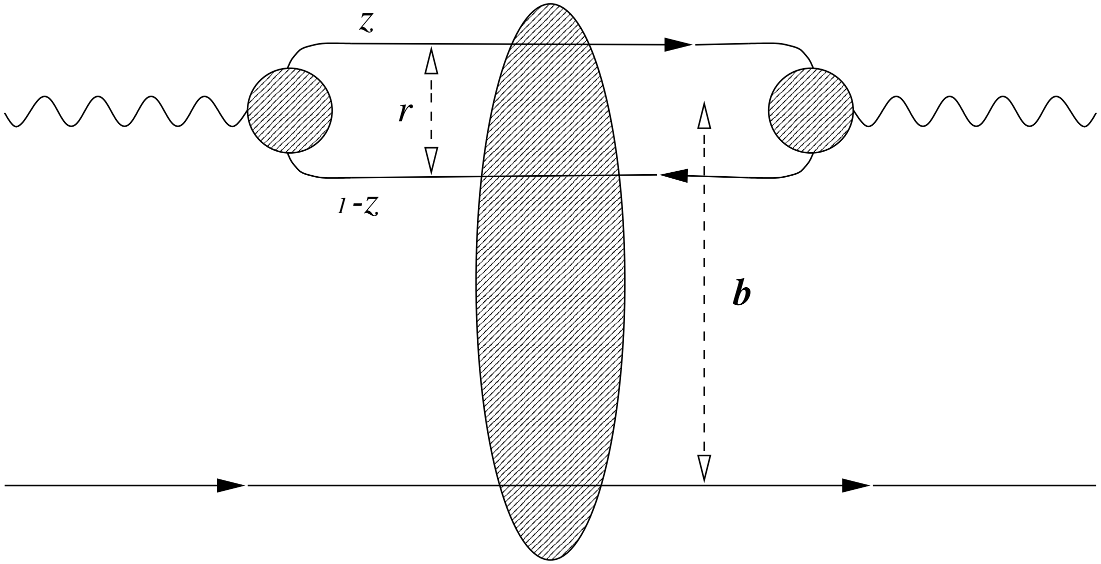
- In the inclusive heavy quark photon-hadron production the final state is characterized by one rapidity gap due to the dissociation of the hadron target.
- In contrast, in the vector meson production the final state is, in general, characterized by two rapidity gaps.

Heavy Quark Photoproduction

Considering γh scattering in the dipole model, the probing projectile fluctuates into a quark-antiquark pair (a dipole) with transverse separation $\boldsymbol{r}$ long after the interaction, which then scatters off the proton. The $Q\bar{Q}$ production cross section reads as,

$$\sigma\left(\gamma h \to Q\overline{Q}X\right) = \sum_{i=T,L} \int dz\, d^2\boldsymbol{r}\, \Psi_i^{\gamma}(z,r,Q^2)\, \sigma_{dip}(x,\boldsymbol{r})\, \Psi_i^{\gamma *}(z,r,Q^2)$$

- The basic blocks are the photon wavefunction, Ψ^{γ} and the dipole-target cross section, σ_{dip}.



Dipole cross section

The dipole cross section σ_{dip} can be put in the following way,

$$\sigma_{dip}(x, \boldsymbol{r}) = 2 \int d^2 b_\perp \; [1 - \mathrm{S}\,(x, \boldsymbol{r}, b_\perp)] \;\; ,$$

where S is the S-matrix element which encodes all the information about the hadronic scattering, and thus about the non-linear and quantum effects in the hadron wave function.

- $S \rightarrow 0$: Black disc limit
  $S \rightarrow 1$: Color transparency
- Typical solution:

$$\boxed{S(x, \boldsymbol{r}, b_\perp) = \exp\left(-\boldsymbol{r}^2 \frac{Q_s^2(x, b_\perp)}{4}\right)^{\gamma_{eff}}}$$

where Q^2_{sat} defines the onset of the saturation phenomenon, which depends on energy.

Dipole-proton cross section

- Saturation model [Golec Biernat - Wusthoff, PRD60:114023, 1999]

$$\sigma_{dip}^{\mathrm{SAT}}(\tilde{x},\, \boldsymbol{r}^2) = \sigma_0 \left[1 - \exp\left(- \frac{Q_{\mathrm{sat}}^2(x)\, \boldsymbol{r}^2}{4} \right) \right]$$

$$Q_{\mathrm{sat}}^2(x) = \left(\frac{x_0}{\tilde{x}} \right)^{\lambda} \mathrm{GeV}^2; \quad \tilde{x} = x_{Bj} \left(1 + \frac{4\, m_f^2}{Q^2} \right)$$

- CGC phenomenological model [Iancu-Itakura-Munier, PLB590:199, 2004]:

$$\sigma_{dip}^{\mathrm{CGC}}(\tilde{x}, \boldsymbol{r}) = \sigma_0 \begin{cases} \mathcal{N}_0 \left(\frac{\bar{\tau}^2}{4} \right)^{\gamma_{\mathrm{eff}}\,(\tilde{x},\, r)}, & \text{for } \bar{\tau} \leq 2\,, \\ 1 - \exp\left[-a\, \ln^2(b\, \bar{\tau}) \right], & \text{for } \bar{\tau} > 2\,, \end{cases}$$

  where $\bar{\tau} = \boldsymbol{r} Q_{\mathrm{sat}}(\tilde{x})$ and $\gamma_{\mathrm{eff}}\,(\tilde{x},\, r) = \gamma_{\mathrm{sat}} + \frac{\ln(2/\tilde{\tau})}{\kappa\, \lambda\, y}$, where $\gamma_{\mathrm{sat}} = 0.63$ is the LO BFKL anomalous dimension at saturation limit.

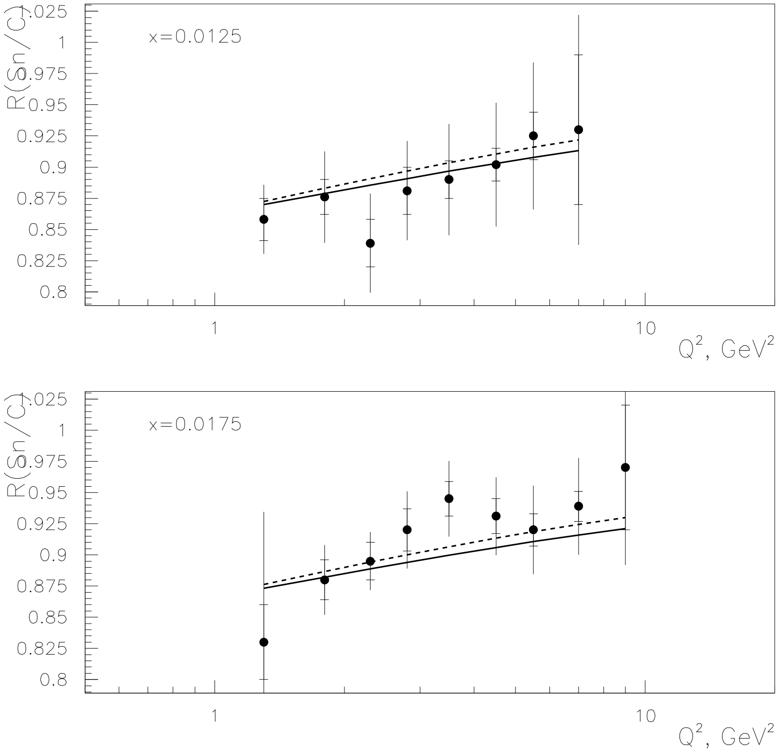
- Parameters $(x_0,\, \lambda,\, \sigma_0)$ fitted from small-x DESY-HERA data.
- Good quality of fit using the more recent F_2 data.
- Mass of quarks are input of the model ($m_q = 0.14$ GeV/$m_c = 1.5$ GeV for GBW and $m_q = 0.14$ GeV/$m_c = 1.3$ GeV for CGC).

Dipole-nucleus cross section

- Model can be extended for nucleus scattering using the Glauber-Gribov picture [Armesto, EPJC26:35, 2002].

$$\sigma^{A}_{dip}(\tilde{x},\, \boldsymbol{r}^2,\, A) = 2\int d^2b\,\left\{1-\exp\left[-\frac{1}{2}\,A\,T_A(b)\,\sigma^{SAT}_{dip}(\tilde{x},\, \boldsymbol{r}^2)\right]\right\}$$

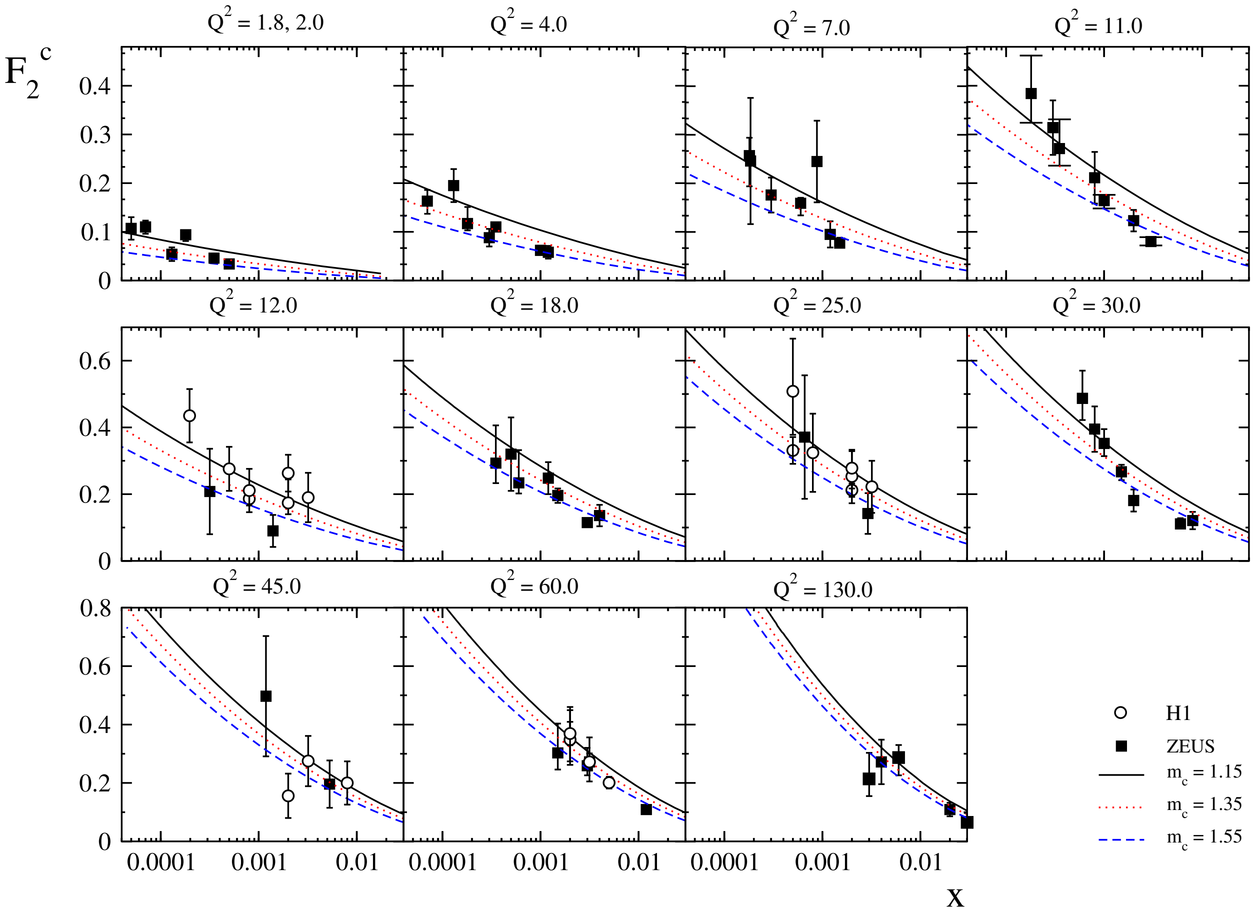
- Describes data for the nuclear ratios at small-x.



The charm structure function

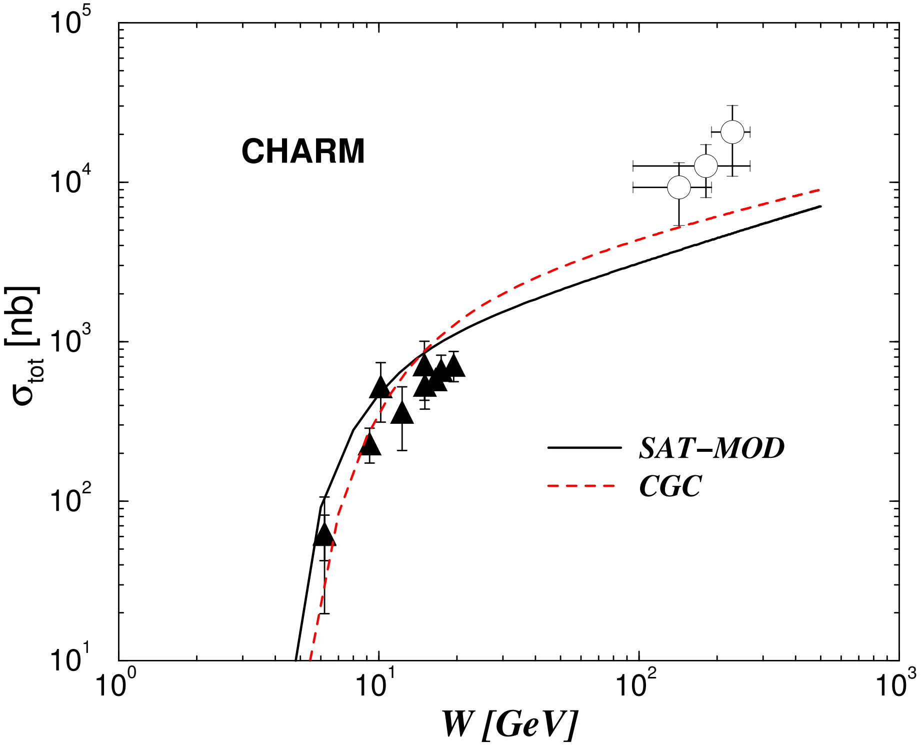
- Saturation models give good results for charm SF.

$$F_2^{c\bar{c}}(x,Q^2) = \frac{Q^2}{4\pi\alpha}\,\sigma_{tot}(\gamma p \to c\bar{c}X)$$



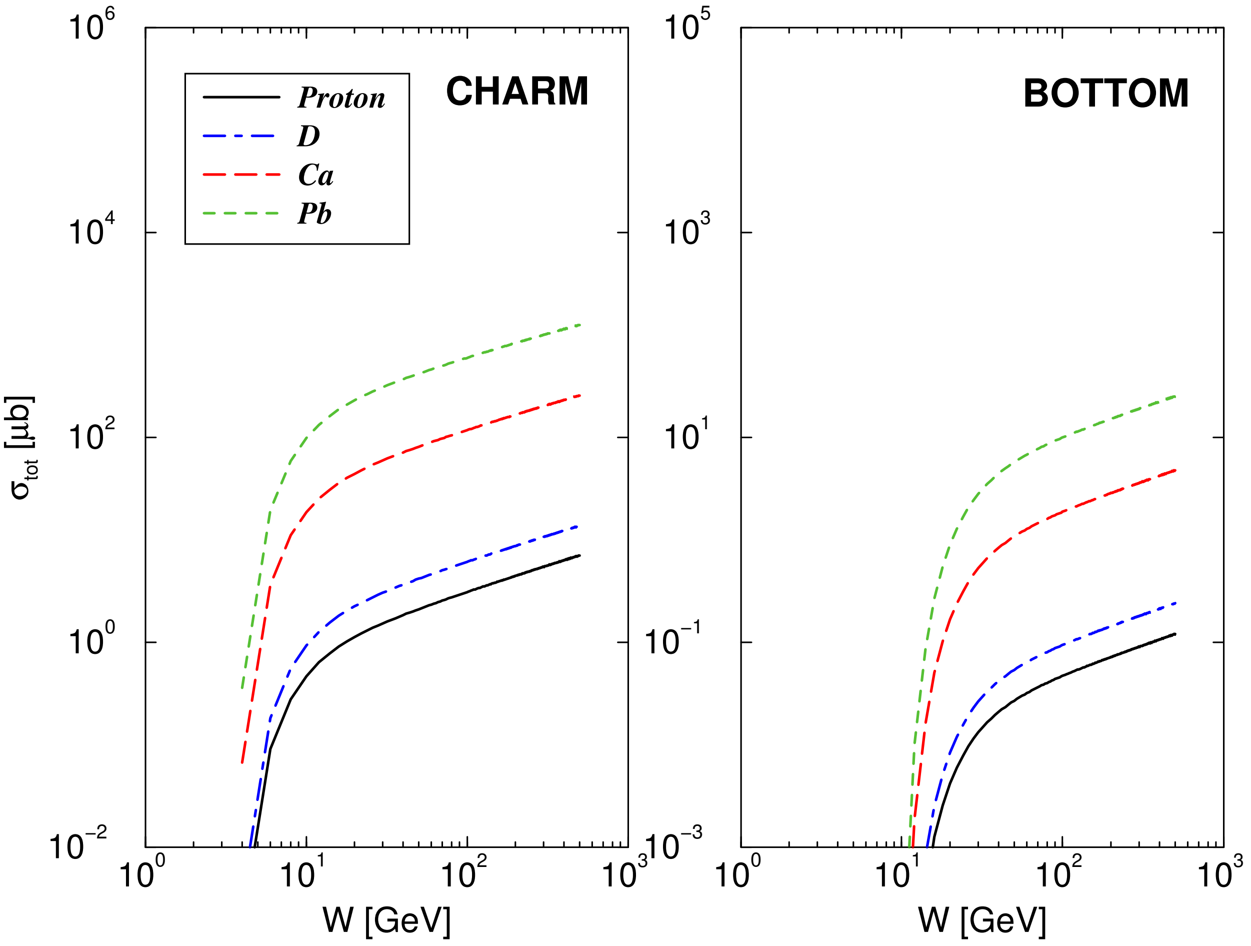
$Q\bar{Q}$ photoproduction in γp

- Problems ?! Saturation models overestimate high energy HERA data.
- Some room for resolved photon contribution.
- Threshold factor has been included.
- Gonçalves, MVTM, **[Eur. Phys. J. C30 (2003)]**



$Q\bar{Q}$ photoproduction in γA

- Calculation using saturation model + shadowing.
- Saturation models give a lower bound for nuclear cross sections.
- No evidence for very strong nuclear shadowing at $W_{\gamma A} < 1$ TeV.



Photoproduction in pp collisions

Heavy Quark Photoproduction in pp collisions

- The γp cross section enters as input in pp coherent process.
- Gonçalves, MVTM, **Phys.Rev.D71 (2005)**

$$\sigma(pp \to Q\bar{Q}\,pp) = 2\int \frac{dn_\gamma^p\,(\omega)}{d\omega}\,\sigma_{\gamma\,p\to Q\bar{Q}}\,(\omega)\,d\,\omega$$

	$Q\overline{Q}$	**COLLINEAR pQCD**	**CGC model**
LHC	$c\bar{c}$	16 μb	5 μb
	$b\bar{b}$	230 nb	110 nb

Photoproduction in pA collisions

Heavy Quark Photoproduction in pA collisions

- The γp cross section also enters as input in pA coherent process.
- Gonçalves, MVTM, **Phys.Rev.C73 (2006)]**

$$\sigma(pA \to Q\bar{Q}\,pA) = \int \frac{dn_\gamma^A\,(\omega)}{d\omega}\,\sigma_{\gamma\,p\to Q\bar{Q}}\,(\omega)\,d\,\omega$$

- Integrated cross section (event rates/month) for the photoproduction of heavy quarks in pA collisions at LHC:

	X	**COLLINEAR pQCD**	**CGC model**
LHC	$c\bar{c}$	8 mb (10^8)	5 mb $(1 \cdot 10^9)$
	$b\bar{b}$	40 μb (10^7)	80 μb $(6 \cdot 10^7)$

Photoproduction in AA collisions

Heavy Quark photoproduction in AA collisions

- Photonuclear cross section enters as input in AA coherent process.
- Gonçalves, MVTM, **EPJC 31 (2003)**
- PbPb at LHC.

$Q\overline{Q}$	Collinear pQCD	CGC model
$c\bar{c}$	1200 mb	633 mb
$b\bar{b}$	5.0 mb	8.0 mb

$\Rightarrow$ A lower value for charm but near value for bottom.

Diffractive $Q\bar{Q}$ production

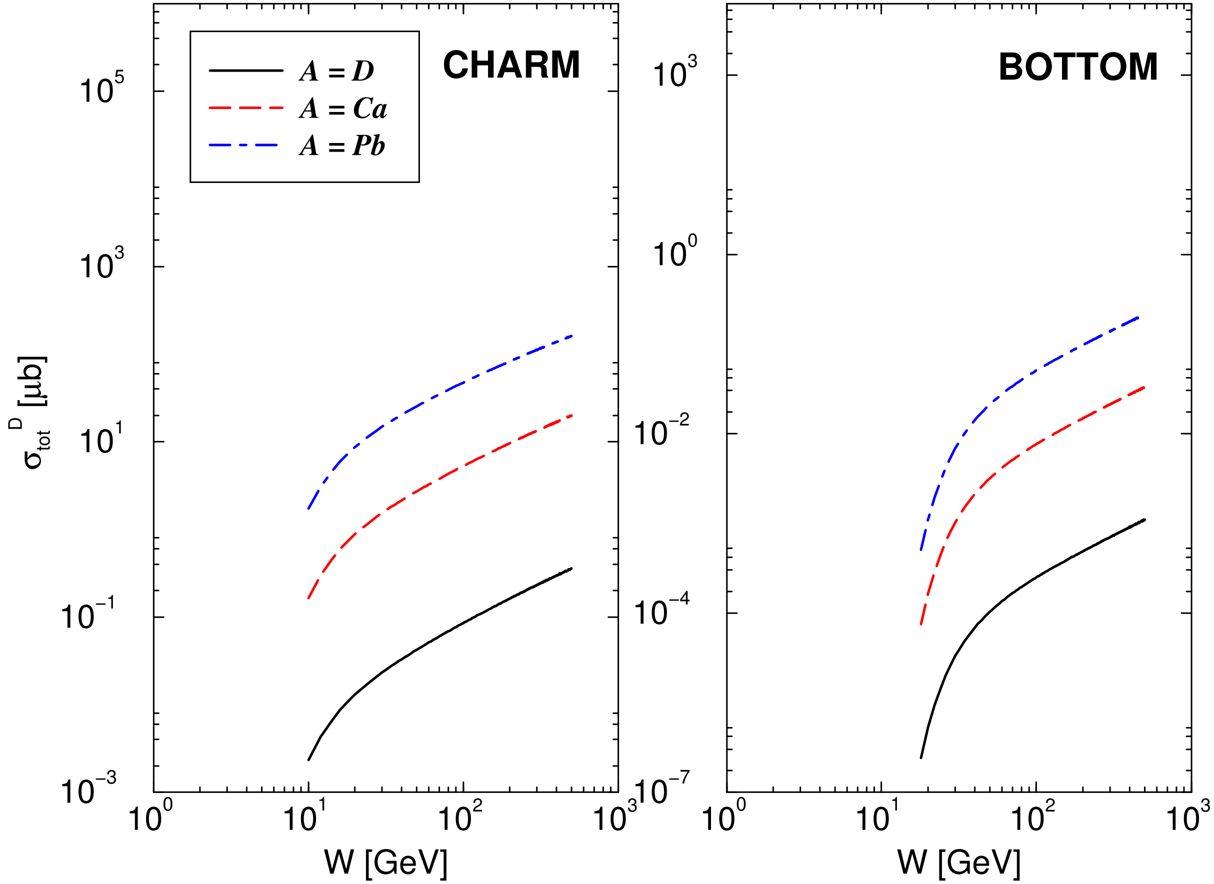
- It is possible to study the QCD dynamics considering the diffractive heavy quark photoproduction, which is much more sensitive to large-size dipoles than the inclusive one.
- In the dipole approach, the total diffractive cross section is

$$\sigma^D_{T,L} = \int dt \left. \frac{d\sigma^D}{dt} \right|_{t=0} e^{-B_D|t|} = \frac{1}{16\pi B_D} \int dz\, d^2\boldsymbol{r}\, |\Psi^\gamma_{T,L}(z,\boldsymbol{r},Q^2)|^2\, \sigma^2_{dip}(\tilde{x},\boldsymbol{r})$$

- B_D is the diffractive slope parameter.
- The diffractive contribution grows when considering higher energies and nuclear targets.
- In the black disk regime the contribution approaches 50%.

Diffractive HQ photoproduction

- Calculations for Ca and Pb.
- Diffractive contribution is at least 10% of total cross section.



Vector Meson Photoproduction

- Photoproduction of vector mesons ($V = \rho, J/\Psi$):

$$\mathcal{I}m\, \mathcal{A}\,(\gamma h \to V h) = \int dz\, d^2\boldsymbol{r}\, \Psi^{\gamma}(z,r)\, \sigma_{dip}(\tilde{x},\boldsymbol{r})\, \Psi^{V*}(z,r)\,,$$

  where $\Psi^{\gamma}_{n,\bar{n}}(z,\,\boldsymbol{r})$ and $\Psi^{V}_{n,\bar{n}}(z,\,\boldsymbol{r})$ are the light-cone wavefunctions of the photon and vector meson, respectively.

- Total cross section:

$$\sigma\,(\gamma h \to V h) = R_g^2 \frac{[\mathcal{I}m\,\mathcal{A}(s,\,t=0)]^2}{16\pi\, B_V}\,(1+\beta^2)$$

  where β is the ratio of real to imaginary part of the amplitude and B_V labels the meson t-slope parameter.

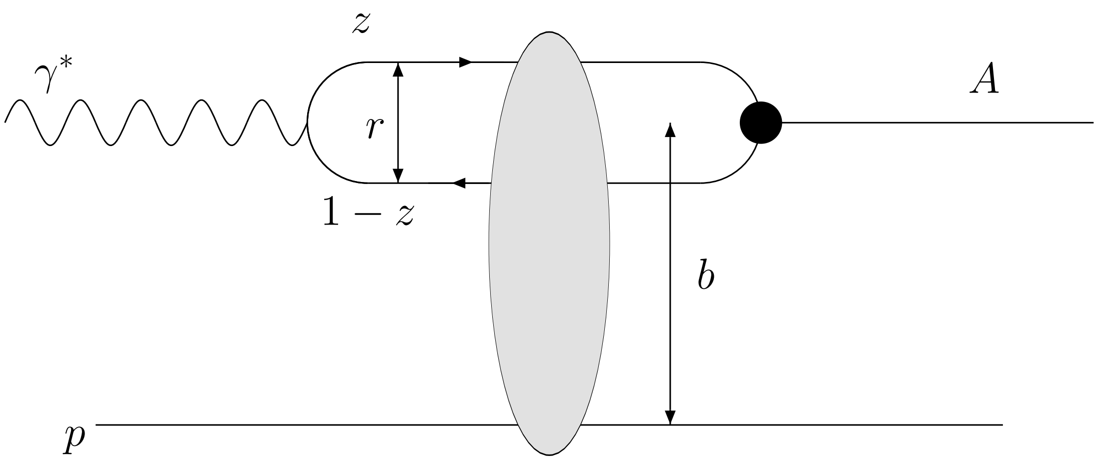
- R_g is correction for skeweness (exclusive process).
- We consider DGKP meson wavefunction (small sensitivity to the choice).

Photonuclear cross section

- The photonuclear cross section is written as

$$\sigma(\gamma A \to V\,A) = \left.\frac{d\sigma\,(\gamma A \to V\,A)}{dt}\right|_{t=0} \int_{t_{min}}^{\infty} dt\,|F(t)|^2$$

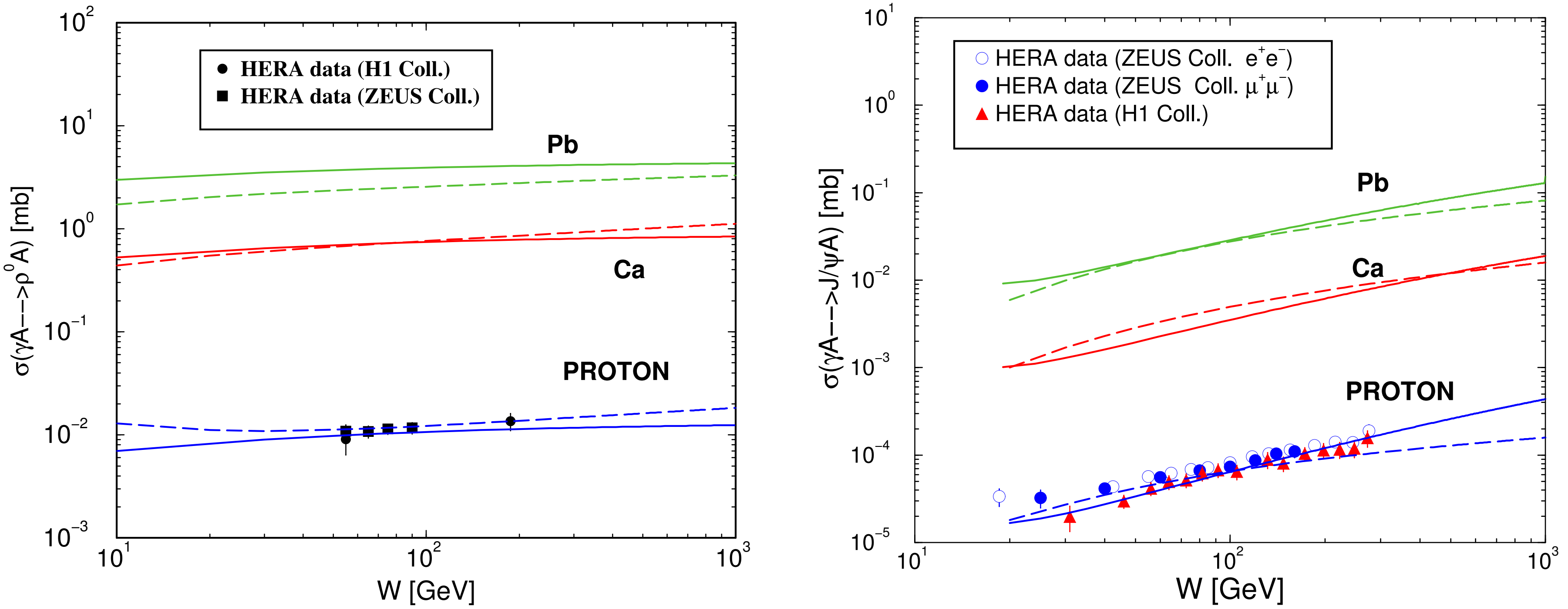
- $t_{min} = (m_V^2/4\omega)^2$.
- $F(t)$ is the nuclear form factor.
- The color dipole model allows to consider calculation of light and heavy meson in the same theoretical framework.



Comparison with HERA

Photoproduction of vector mesons ($V = \rho, J/\Psi$):

- Gonçalves, MVTM, **Eur. Phys. J. C38 (2004).**



The solid lines stand for the QCD color dipole approach and the dashed ones for the soft dipole Pomeron approach. Experimental high energy data from DESY-HERA collider on proton target are also shown.

Photoproduction in pp collisions

Vector Meson Photoproduction in pp collisions

- Gonçalves, MVTM **EPJC 40 (2005)** .
- Results consistent with J. Nystrand calculation.

$$\sigma(pp \to V\,pp) = 2 \int \frac{dn_{\gamma}^{p}\,(\omega)}{d\omega}\, \sigma_{\gamma\, p \to V}\,(\omega)\, d\,\omega$$

$\sqrt{s} = 14$ TeV	$J/\Psi\,(3097)$	$\phi\,(1019)$	$\omega\,(782)$	$\rho\,(770)$
LHC	132 nb	980 nb	1.24 μb	9.75 μb

Photoproduction in pA collisions

Vector Meson Photoproduction in pA collisions

- Gonçalves, MVTM, **Phys.Rev.C73 (2006)**

$$\sigma(pA \to V\, pA) = \int \frac{dn_\gamma^A\,(\omega)}{d\omega}\, \sigma_{\gamma\, p \to V}\,(\omega)\, d\,\omega$$

- Integrated cross section (event rates/month) for the photoproduction of vector mesons in pA collisions at LHC:

	Vector Meson	**CGC model**
LHC	ρ	14 mb $(1 \cdot 10^{10})$
	J/Ψ	95 μb $(7 \cdot 10^{7})$

Photoproduction in AA collisions

Vector Meson Photoproduction in AA collisions

- Gonçalves, MVTM, **EPJC 40 (2005)**

$$\sigma(AA \to V\,AA) = 2\int \frac{dn_{\gamma}^{A}\,(\omega)}{d\omega}\,\sigma_{\gamma\,A\to V}\,(\omega)\,d\,\omega$$

	HEAVY ION	$J/\Psi\,(3097)$	$\phi\,(1019)$	$\omega\,(782)$	$\rho\,(770)$
LHC	CaCa	436 μb	12 mb	14 mb	128 mb
	PbPb	41.5 mb	998 mb	1131 mb	10069 mb

⇒ The cross sections are large, mostly for light mesons at LHC energies.

Summary

- The high energy regime of QCD can be investigated in photoproduction at HERA and in coherent $pp/pA/AA$ collisions at LHC.
- We analyze two specific final states (heavy quarks and mesons) where the experimental identification could be feasible.
- Photoproduction of heavy quarks (inclusive and diffractive) is a good place to investigate models for parton saturation and nuclear shadowing.
- Meson photoproduction is computed using an unified framework for light and heavy mesons.
- The photoproduction of ρ mesons is dominated by physics below saturation scale, which implies that the cross section is determined by saturation region.