Small-x Physics in Coherent pA/AA interactions at LHC

Magno V.T. Machado

Universidade Federal do Pampa - UNIPAMPA

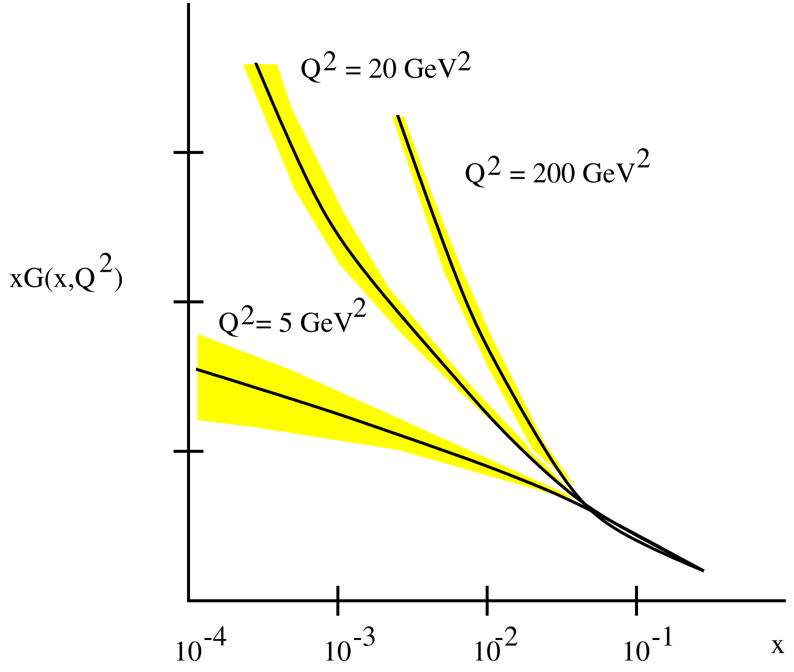
Campus de Bagé - Centro de Ciências Exatas e Tecnológicas

Outline

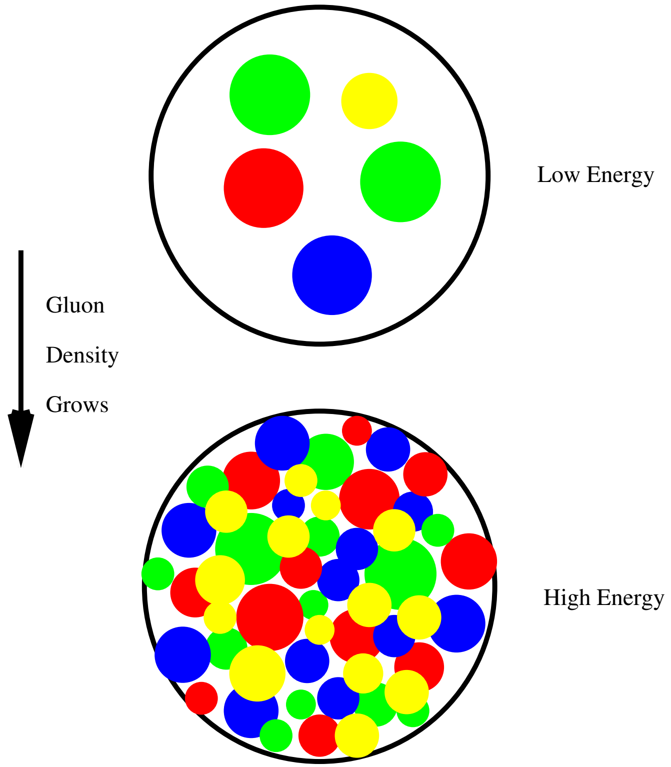
- Small-x physics (high energies);
- Parton saturation phenomenon;
- Photonuclear reactions at Ultraperipheral Heavy Ion Collisions (UPC);
- Heavy quark and vector meson production in UPC's;
- Summary.

Gluon Distribution

- From HERA data:



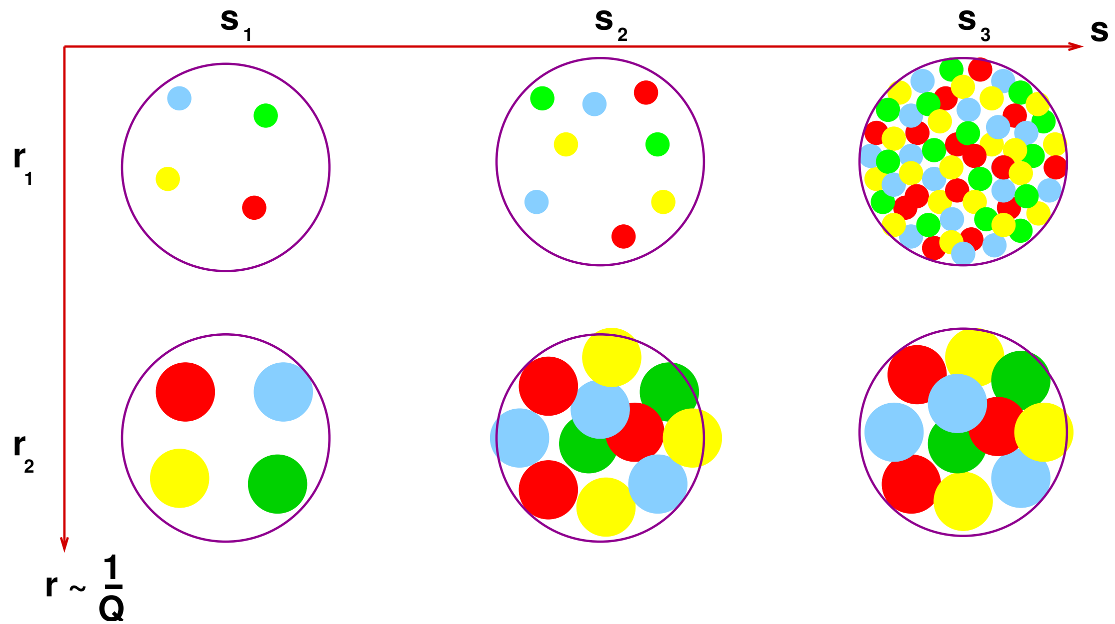
- Transverse Distribution:



- Information from deep inelastic lepton-proton scattering (DIS) at DESY-HERA.
- Bjorken variable $x \simeq Q^2/W^2_{\gamma p}$, with Q^2 photon virtuality.

Theoretical Expectations

- For high energies (small-x) the hadrons are characterized by a high density of gluons.
- In this regime, the recombination process $gg \to g$ cannot be disregarded.
  $\Rightarrow$ Modification of the evolution equations by including non-linear terms (leads to saturation of growth of gluon density!).



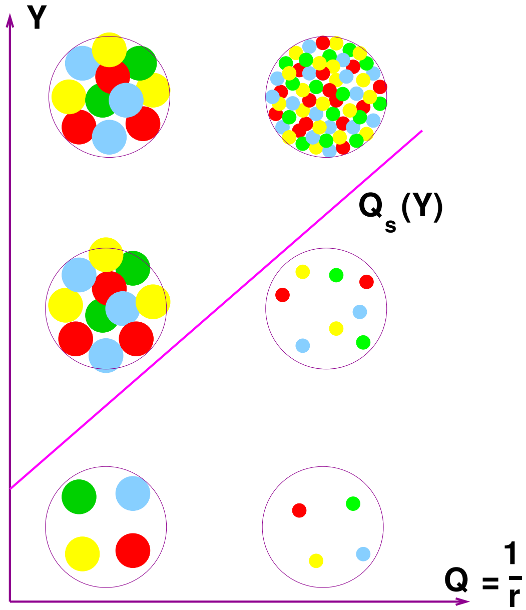
High energy evolution equations

- Recently, 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 target as a collection of dipoles (onia).
- BK obtains QCD evolution equation on rapidity variable $Y = \ln(1/x)$ for the dipole-target amplitude, $\mathcal{N}(r, b, Y)$, with single and multiple dipole-dipole scattering.
- 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 $N(Y \to \infty) = 1$.

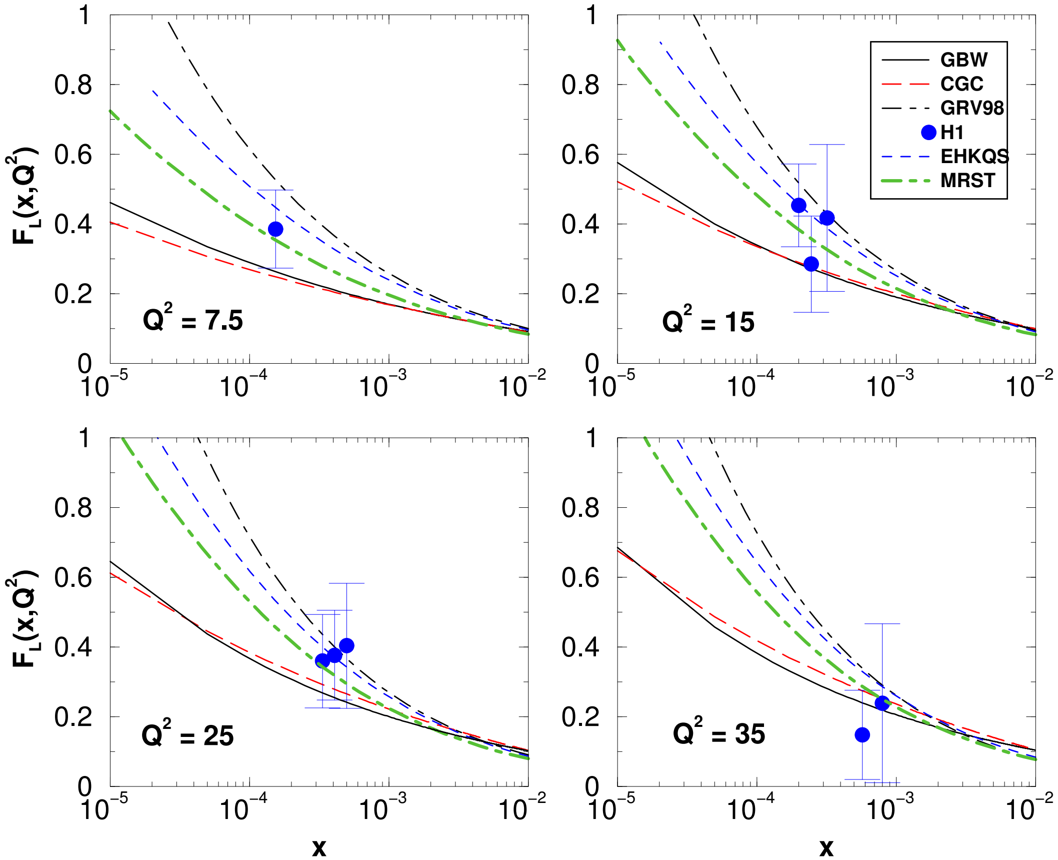
Saturation scale



- Solution has 3 behaviors: (1) regions where amplitude is small non-linear corrections are small; (2) transition region and (3) assymptotic region where $N \simeq 1$.
- Limit of transition region is characterized by saturation scale $Q_s(Y)$. BK solution, $Q_s \propto \exp(\bar{\alpha}_s^2 \lambda Y) \sim x^{-\lambda}$.
- For $r < 1/Q_s \rightarrow N \ll 1$ and for $r > 1/Q_s \rightarrow N \simeq 1$.

Today - any signal of saturation ?

- HERA: $\sqrt{s_{ep}} = 300$ GeV, $Q_s \simeq 1$ GeV (hard to disentangle!).



- FUTURE: 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.

$\Rightarrow$ Main motivation:

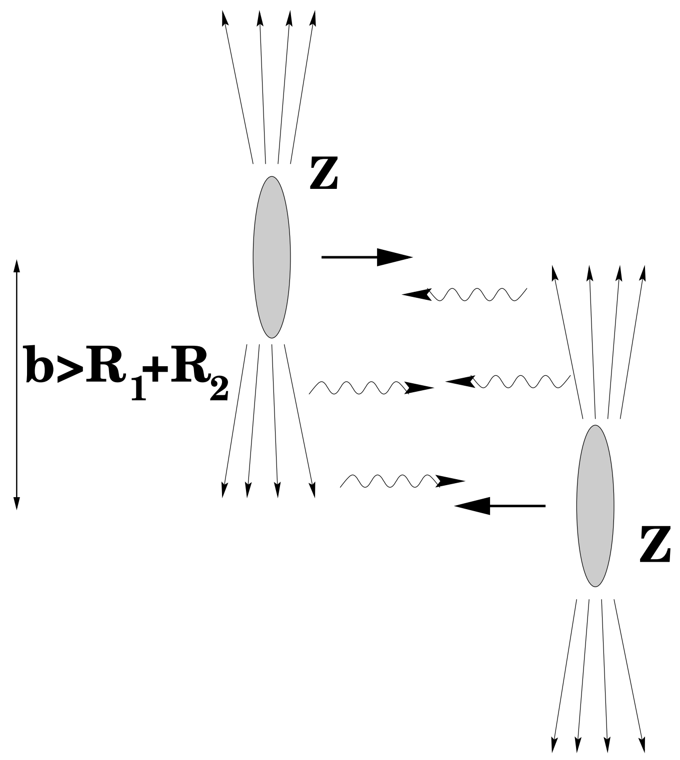
- Nuclear saturation scale:

$$\boxed{Q_s^2(x;A) = \frac{3\pi^2\alpha_s}{2}\,\frac{xG_A(x,Q_s^2(x;A))}{\pi R_A^2}}$$

- The nucleus amplifies the dynamical effects associated to the high parton density.
- Relation between proton saturation scale and nuclear saturation scale, $Q_{s,A} \propto A^{\alpha}\, Q_{s,p}$ ($\alpha = 1/3$?).
- Intense theoretical investigations on saturation effects in nucleus collisions (Color Glass Condensate, etc...)

An alternative:

Ultraperipheral Heavy Ion Collisions (UPC's):



- γp Processes: $\sigma(pA \rightarrow pAX) = n_A(\omega) \otimes \sigma^{\gamma p}(W_{\gamma p})$
- γA Processes: $\sigma(AA \rightarrow AAX) = n_A(\omega) \otimes \sigma^{\gamma A}(W_{\gamma A})$
- $\gamma\gamma$ Processes: $\sigma(AA \rightarrow AAX) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma}(W_{\gamma\gamma})$
- The number of equivalent photons: $n_A\,(\omega) = \int d^2b\, N(\omega, b)$

Photoproduction reactions at UPC's

- The photoproduction cross section is given by,

$$\sigma_{AA\to f\,AA}(\sqrt{s}) = \int \frac{d\,\omega}{\omega}\, n_A\,(\omega)\,\sigma_{\gamma A\to f\,X}\,(\omega)$$

$$\sigma_{pA\to f\,pA}(\sqrt{s}) = \int \frac{d\,\omega}{\omega}\, n_A\,(\omega)\,\sigma_{\gamma p\to f\,X}\,(\omega)$$

$$n_A\,(\omega) = \frac{2Z^2\alpha}{\pi\,\omega}\left[\bar{\eta}\,K_0\,(\bar{\eta})\,K_1\,(\bar{\eta}) + \frac{\bar{\eta}^2}{2}\,\left(K_1^2\,(\bar{\eta}) - K_0^2\,(\bar{\eta})\right)\right]\,, \qquad \bar{\eta} = \frac{2\omega R}{\gamma}$$

- For PbPb at LHC, $\gamma = 2930$ and $\sqrt{S_{\rm NN}} = 5500$ GeV , giving the maximum energy $W_{\gamma A} \lesssim 950$ GeV.
- For p Pb at LHC, $\gamma = 4690$, giving the maximum c.m.s. γp energy $W_{\gamma p} \approx 1500$ GeV ($5\times$ DESY-HERA energy).

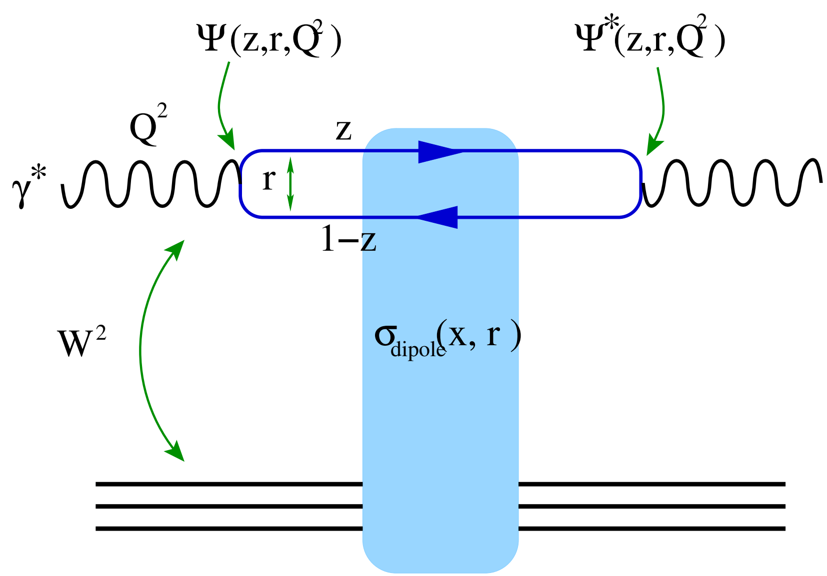
Heavy Quark Photoproduction

- Phenomenological model using parton saturation at small-x:

- Dipole frame for γp scattering: probing projectile fluctuates into a quark-antiquark pair (a dipole) with transverse separation $\boldsymbol{r}$ long after the interaction.

$$\sigma\,(\gamma p \to Q\overline{Q}X) = \sum_{h,\bar{h}} \int\int dz\, d^2\boldsymbol{r}\; \Psi^{\gamma}_{h,\bar{h}}\; \sigma_{dip}(x,\boldsymbol{r})\; \Psi^{\gamma *}_{h,\bar{h}}$$

- Basic blocks: photon wavefunction, Ψ^{γ} and dipole-target cross section, σ_{dip}.



Vector Meson Photoproduction

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

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

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

- Total cross section:

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

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

Dipole cross section

In the Color Glass Condensate (CGC) formalism, σ_{dip} can be computed in the eikonal approximation,

$$\sigma_{dip}(x,\boldsymbol{r}) = 2\int d^2b\,[1-\mathrm{S}\,(x,\boldsymbol{r},b)]\ ,\qquad \mathcal{N}(x,\boldsymbol{r},b) = 1-\mathrm{S}\,(x,\boldsymbol{r},b)$$

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

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

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

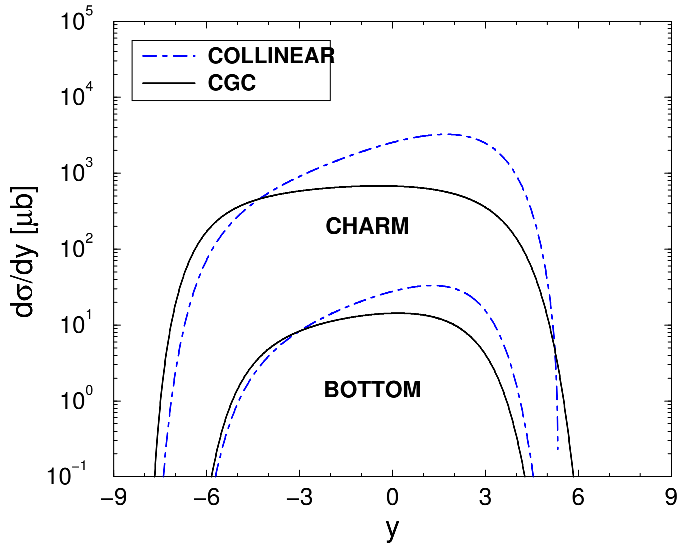
- Saturation scale $Q^2_{\mathrm{sat}}(x) = \left(\frac{x_0}{x}\right)^{\lambda} \simeq \left(\frac{10^{-4}}{x}\right)^{0.3}\ \mathrm{GeV}^2$
- Extension for nuclei using the Glauber-Gribov formalism.

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

Results (I)

Heavy Quark Photoproduction in pA collisions

- Gonçalves-Machado **[Phys.Rev.C73:044902,2006]**
- Rapidity distribution:



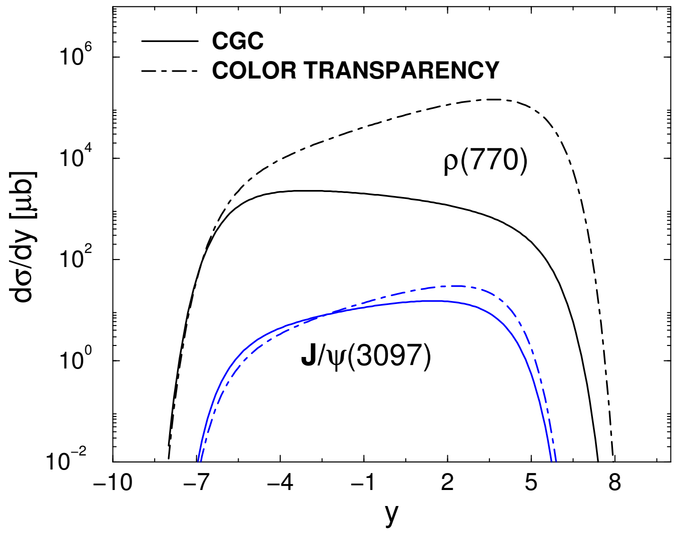
- Integrated cross section for the photoproduction of heavy quarks in pA collisions at LHC:

	X	**COLLINEAR**	**CGC**
LHC	$c\bar{c}$	17 mb	5 mb
	$b\bar{b}$	155 μb	81 μb

Results (II)

Vector Meson Photoproduction in pA collisions

- Gonçalves-Machado **[Phys.Rev.C73:044902,2006]**
- Rapidity distribution:



- Integrated cross section for the photoproduction of vector mesons in pA collisions at LHC:

	X	**CGC**
LHC	ρ	14 mb
	J/Ψ	95 μb

Results (III)

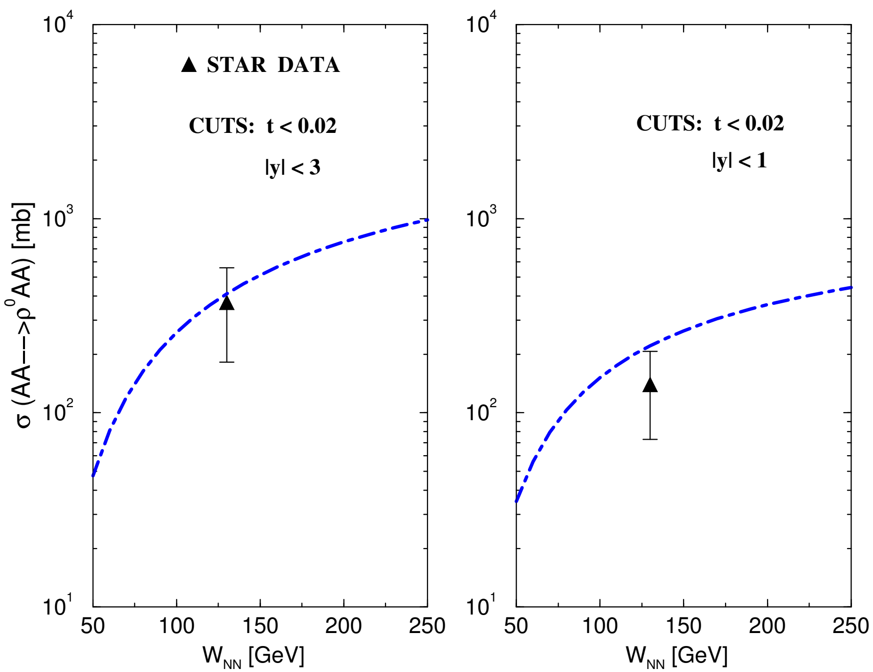
Heavy Quark Photoproduction in AA collisions

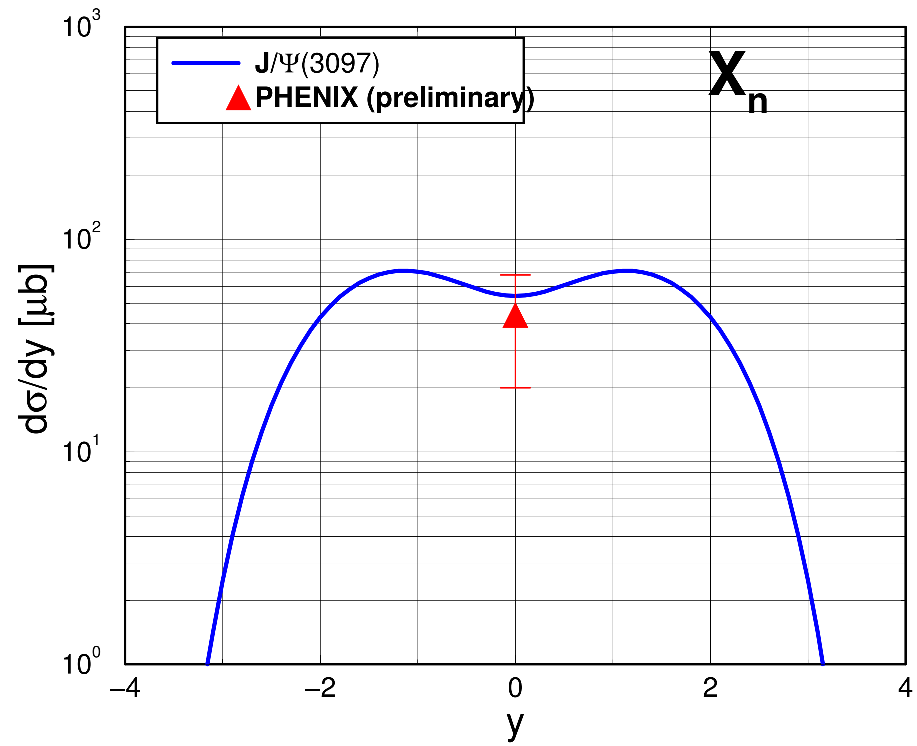
- Gonçalves-Machado, **[EPJC 31, 371-378 (2003)]**

$Q\overline{Q}$	Collinear	SAT-MOD	SEMIHARD	CGC
$c\bar{c}$	2056 mb	862 mb	2079 mb	633 mb
$b\bar{b}$	20.1 mb	10.75 mb	18 mb	8.9 mb

Results (IV)

- Comparison with RHIC and predictions to LHC:





	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

Summary

- The QCD dynamics at high energies is of utmost importance for building a realistic description of $pp/pA/AA$ collisions at LHC.
- We propose two specific final states (heavy quarks and mesons) where the experimental identification could be feasible in UPC's as an alternative to eA colliders.
- Photoproduction of heavy quarks should provide a feasible and clear measurement of the underlying QCD dynamics at high energies.
- The photoproduction of ρ mesons is dominated by physics below saturation scale and good place to see saturation effects.