Forward particle production within pQCD

Pomeron loops vs. Running coupling

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With a little bit of help from my friends

Dionysis Triantafyllopoulos and Grégory Soyez

Summary

- On the phenomenology side:

  Nearly 'total gluon shadowing' in R_{pA} at LHC, within a rather wide window at (relatively) high $p_\perp$

$$R_{pA}(p_\perp, \eta) \approx \frac{1}{A^{1/3}}$$

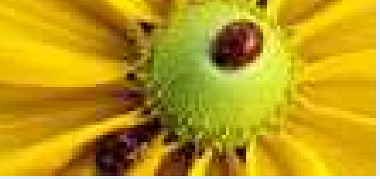
  E.I., K. Itakura, D. N. Triantafyllopoulos, hep-ph/0403103

- On the conceptual side :

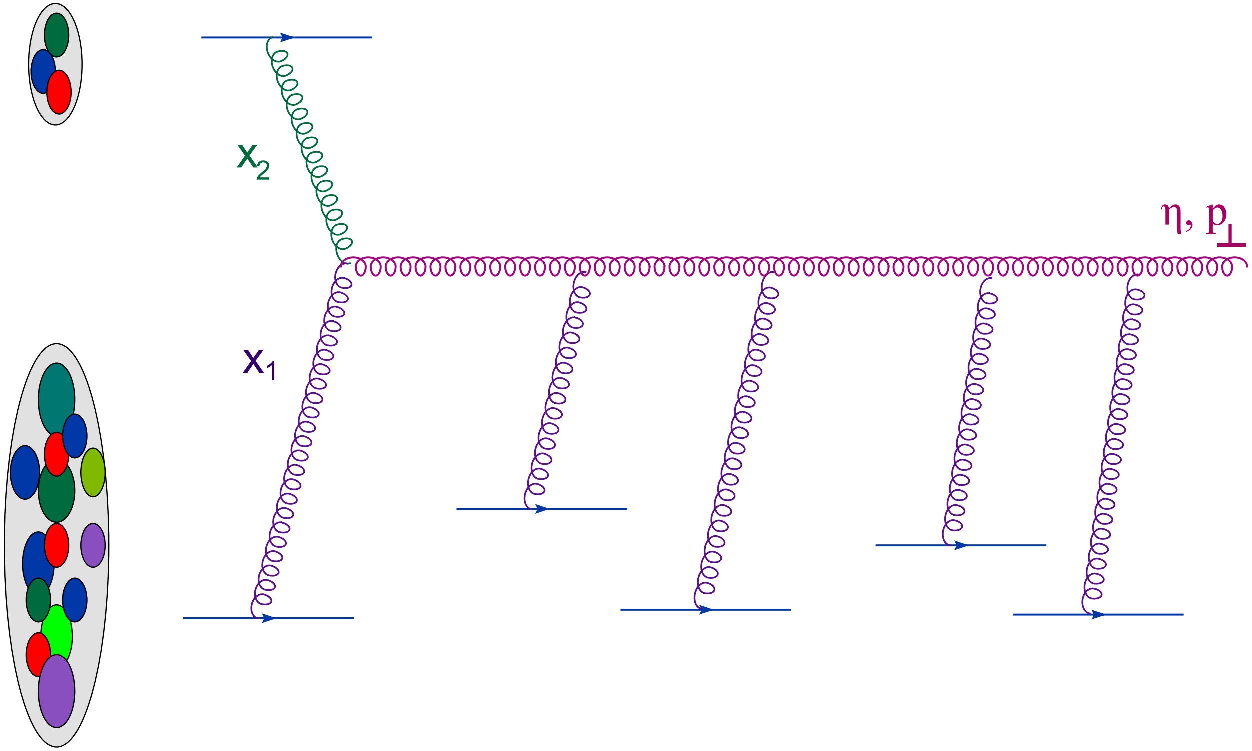
  First (numerical) results for the evolution equations with Pomeron loops and Running coupling

  A. Dumitru, E.I., L. Portugal, G. Soyez, and D.N. Triantafyllopoulos, in preparation

  These results turn out to be quite surprising !



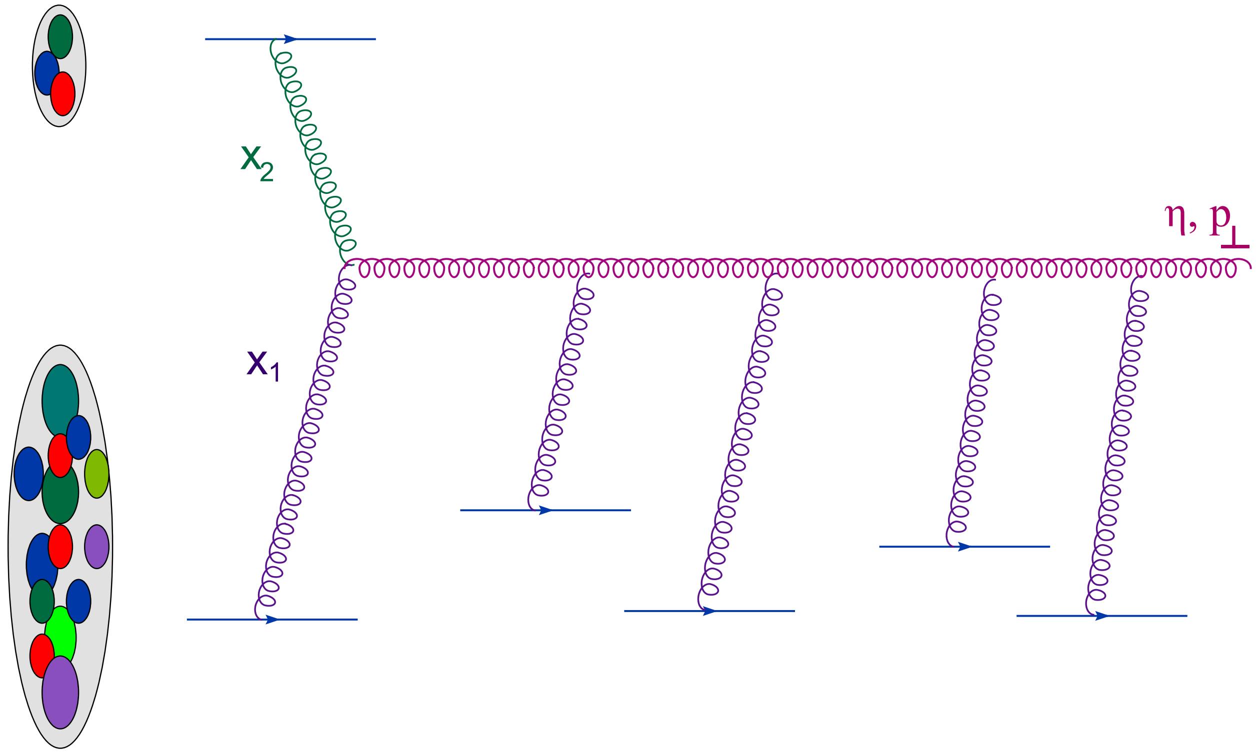
Gluon production in pA collisions



$$x_1 = \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{-\eta}\,, \qquad x_2 = \frac{p_\perp}{\sqrt{s}}\,\mathrm{e}^{\eta}$$

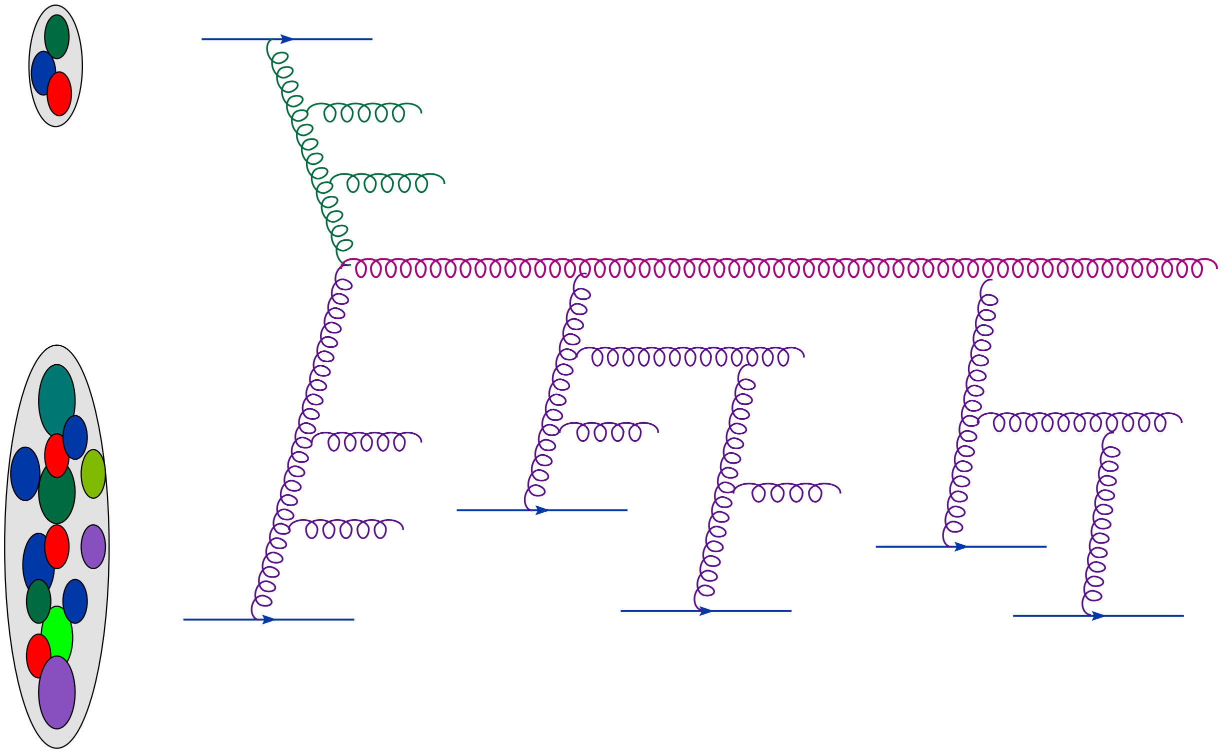
- Increasing $\eta \iff$ Decreasing x_1 for the nucleus
  - RHIC: $\eta \simeq 3$ & $\sqrt{s} = 200\,$GeV: $x_1 \sim 10^{-4}$ for $p_\perp = 2\,$GeV
  - LHC : $\eta \simeq 6$ & $\sqrt{s} = 8.8\,$TeV : $x_1 \sim 10^{-6}$ for $p_\perp = 10\,$GeV

Gluon production in pA collisions



- The picture above: 'Semiclassical' (MV model)
- Multiple scattering but no gluon evolution : "RHIC at $\eta = 0$"
  - ▷ Cronin effect
- LHC: Quantum evolution should be important at all η

Gluon production in pA collisions



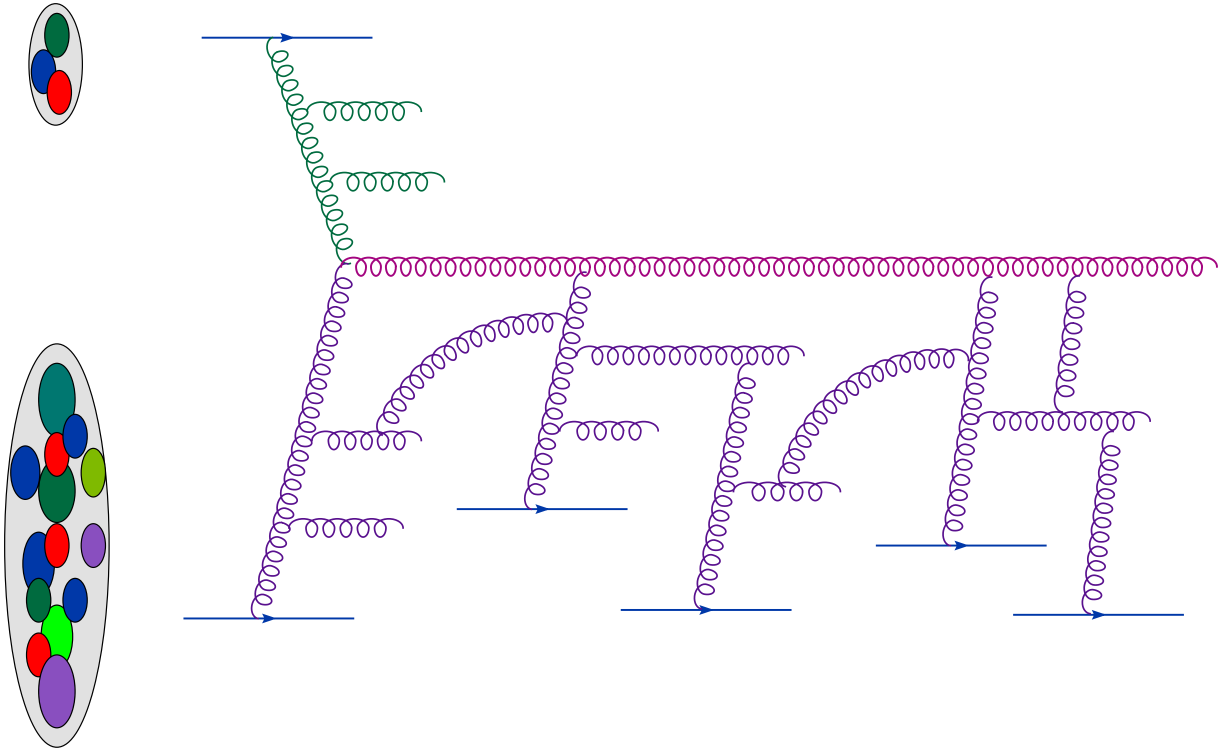
- Quantum evolution in the 'mean–field approximation'

  (BK, JIMWLK) : BFKL + saturation effects

- Most studies of R_{pA} are performed within this framework

  See however the later talk by Misha Kozlov !

Gluon production in pA collisions

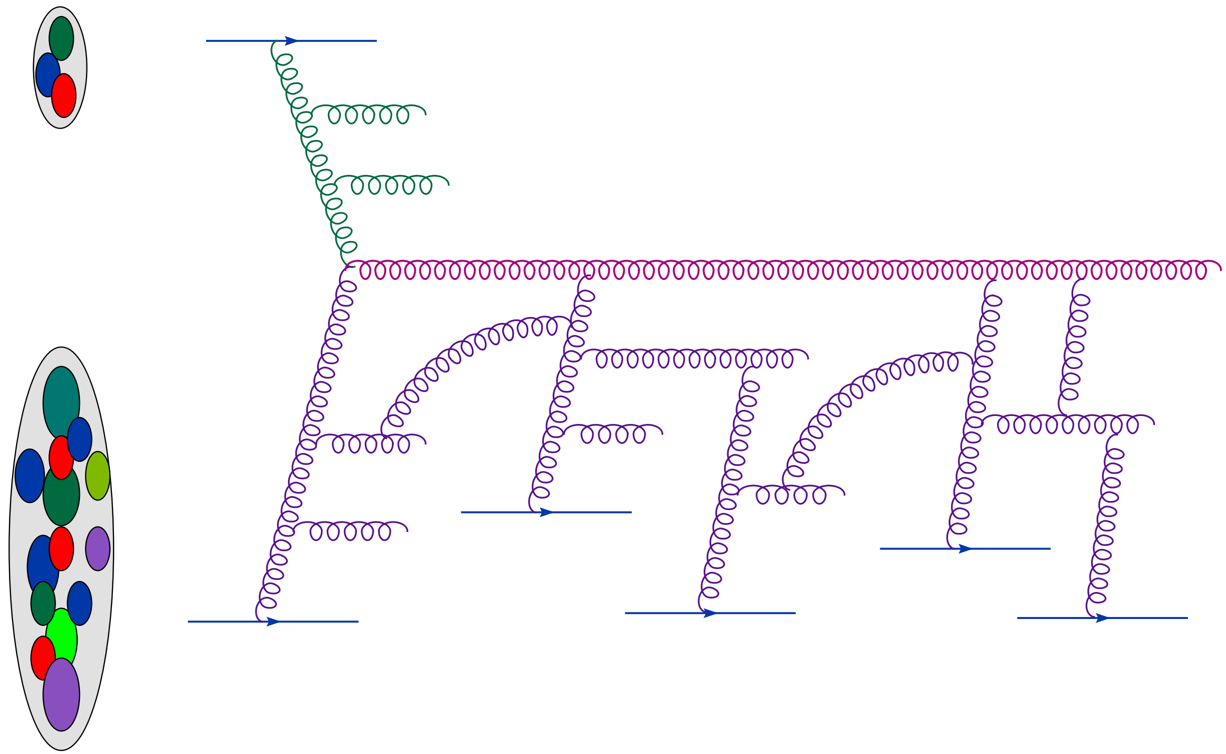


- Quantum evolution in the ‘Pomeron loop approximation’

  BFKL + saturation + gluon number fluctuations

  - *A priori*, fluctuations are important at low density
  - Even a nucleus has a low–density gluon tail at high $k_\perp$!
  - This low–density gluon tail controls the evolution !

Gluon production: Factorization



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\mathrm{d}^2\boldsymbol{p}} = \frac{\bar{\alpha}_s}{p_\perp^2}\int \frac{\mathrm{d}^2\boldsymbol{k}}{(2\pi)^2}\;\Phi_1(\boldsymbol{p}-\boldsymbol{k},x_1)\,\varphi_2(\boldsymbol{k},x_2)$$

- Most interesting regime: $p_\perp \gtrsim Q_s(A,x_1) \gg Q_s(p,x_2)$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\mathrm{d}^2\boldsymbol{p}} \simeq \frac{\bar{\alpha}_s}{p_\perp^2}\,\Phi_1(\boldsymbol{p},x_1)\;x_2 G_p(x_2,p^2)$$

The R_{pA} ratio

$$\text{Nuclear modification factor}: \quad R_{pA} \equiv \frac{1}{A}\,\frac{\mathrm{d}N_{pA}/\mathrm{d}^2p_\perp \mathrm{d}\eta}{\mathrm{d}N_{pp}/\mathrm{d}^2p_\perp \mathrm{d}\eta}$$

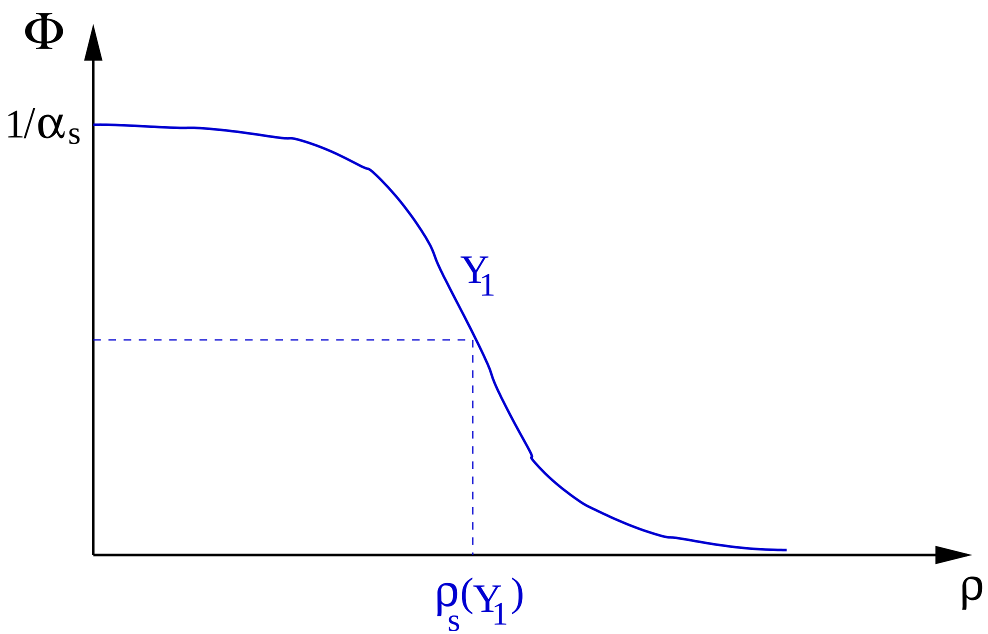
- "High–$p_\perp$" : $p_\perp \gtrsim Q_s(A, x_1) \gg Q_s(p, x_2)$

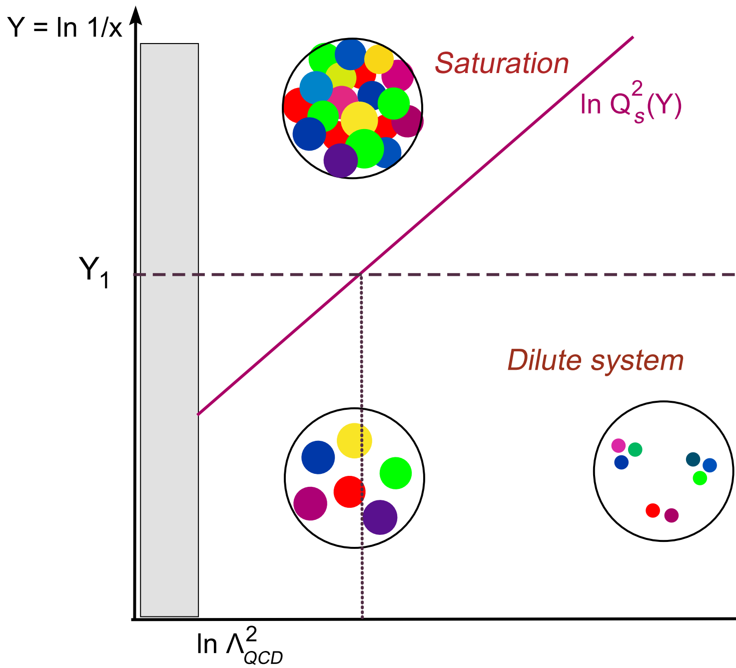
$$R_{pA} \approx \frac{1}{A^{1/3}}\,\frac{\Phi_A(x, p_\perp)}{\Phi_p(x, p_\perp)}$$

- Fixed impact parameter & $x \equiv x_1 = (p_\perp/\sqrt{s})\,\mathrm{e}^{-\eta}$
  below, I shall use : $Y \equiv \ln(1/x) = Y_c + \eta$
- Note for the experts: The different definitions for Φ agree with each other at such high $p_\perp$.

Mean field: Saturation front

- Gluon occupation number $\Phi(Y, k_\perp)$ as a function of $\rho \equiv \ln k_\perp^2$

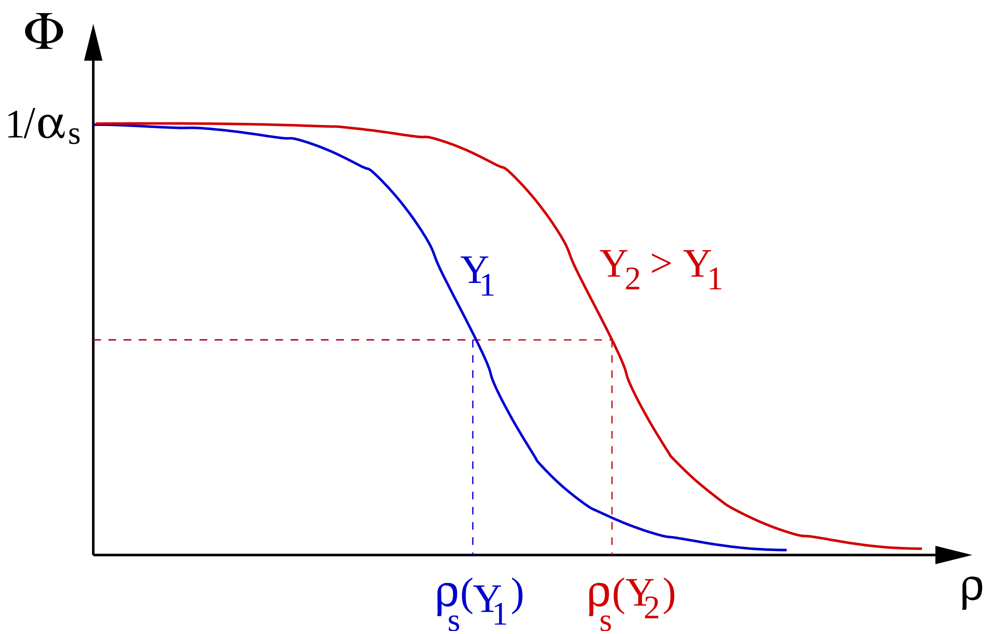


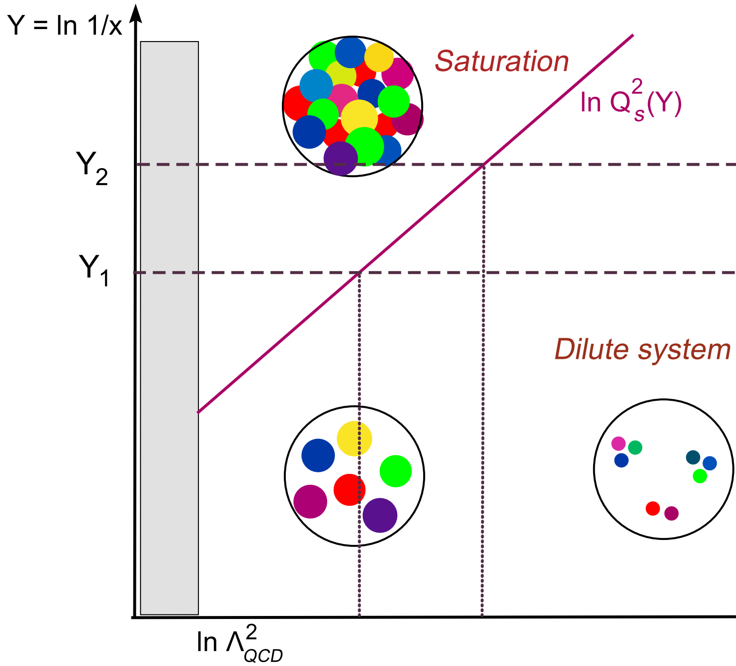


- $\rho_s(Y) \equiv \ln\{Q_s^2(Y)/\Lambda^2_{\rm QCD}\}$: "saturation momentum"
- $\rho_s(Y)$ increases with Y

Mean field: Saturation front

- Gluon occupation number $\Phi(Y, k_\perp)$ as a function of $\rho \equiv \ln k_\perp^2$

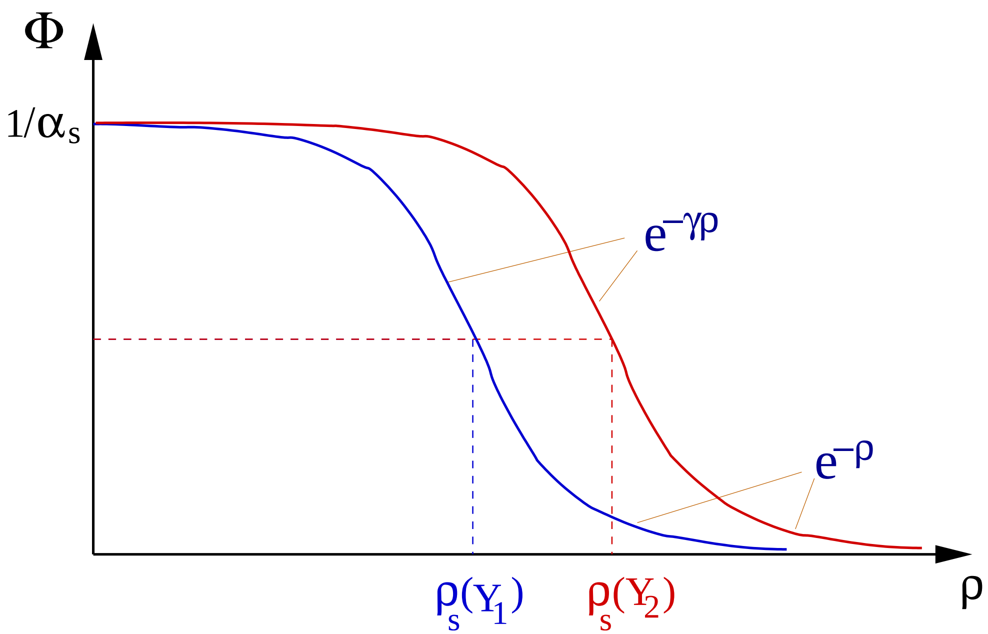


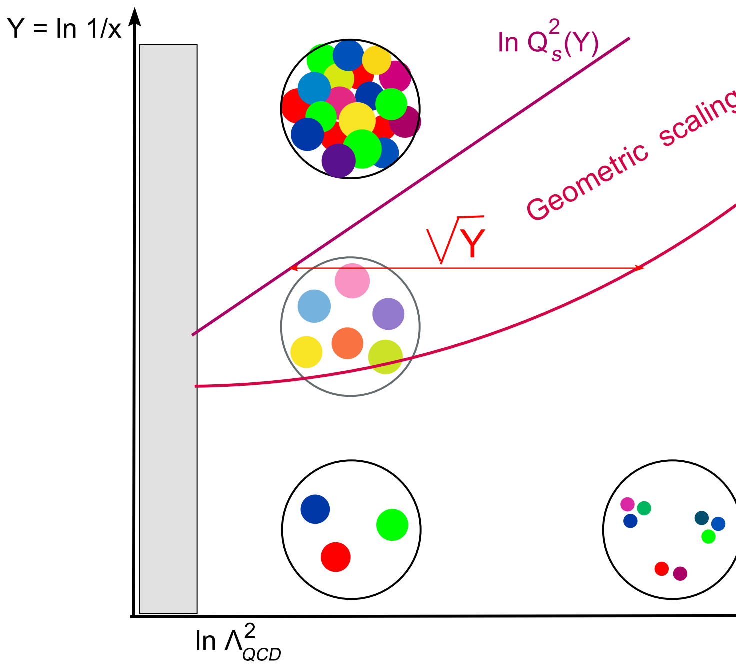


- BK & Fixed coupling : $\rho_s(Y) \simeq \lambda_0 \bar{\alpha}_s Y$ with $\lambda_0 = 4.88$
- BK & Running coupling : $\rho_s(Y) \simeq \sqrt{\beta \lambda_0 Y}$ with $\beta = 2.78$

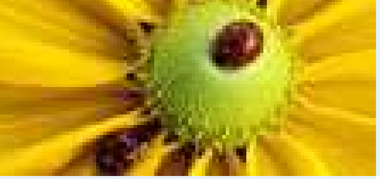
Mean field: Geometric scaling

$$\Phi(Y,k_\perp) \simeq \mathrm{e}^{-\gamma(\rho-\rho_s(Y))} \equiv \left(\frac{Q_s^2(Y)}{k_\perp^2}\right)^\gamma \quad \text{with } \gamma \approx 0.63$$

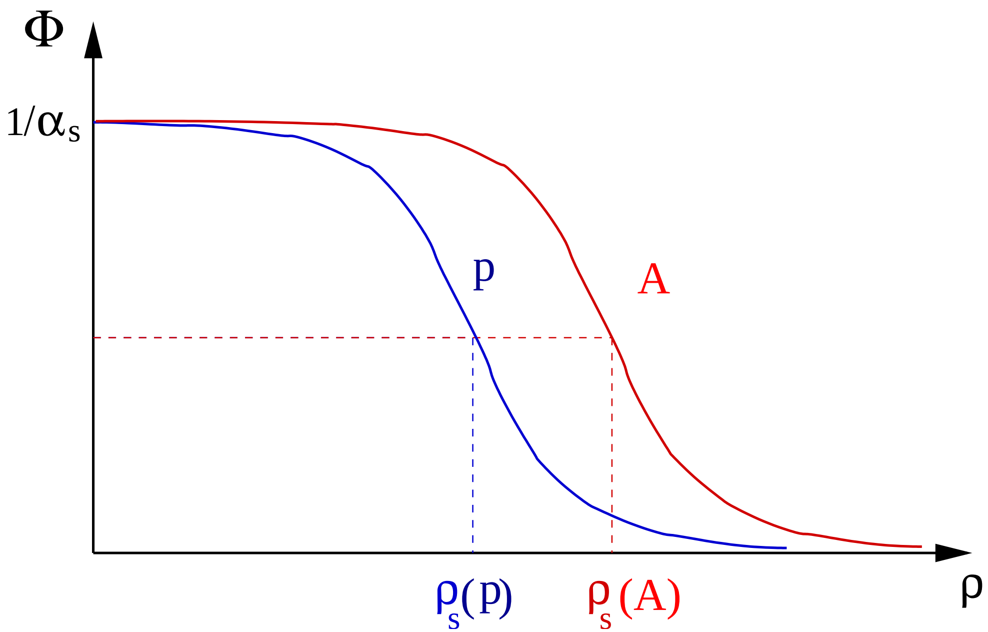


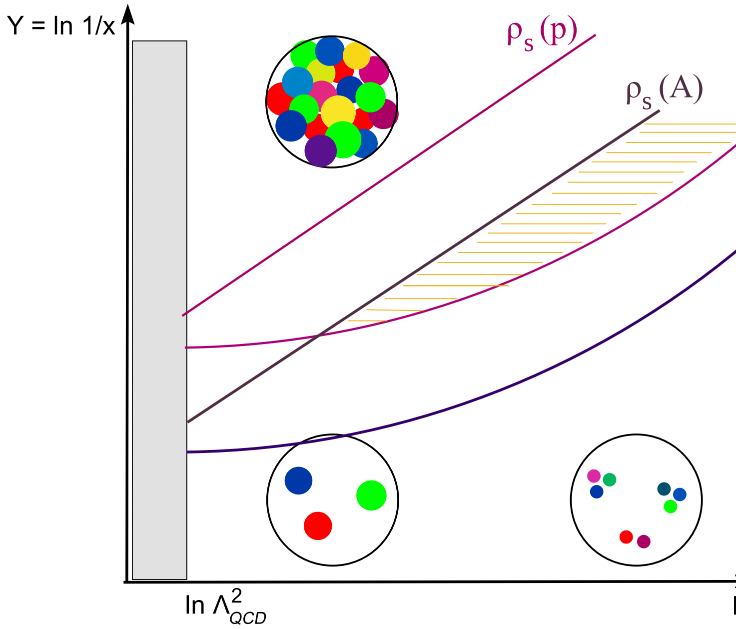


- Fixed coupling : $\rho_g - \rho_s \propto Y^{1/2}$
- Running coupling : $\rho_g - \rho_s \propto Y^{1/6}$
- The running coupling evolution is considerably slower !



Nuclear effects





- $Q_s^2(A) \simeq A^{1/3}\, Q_s^2(p)$ at $Y = Y_0 \sim 3$
- Fixed coupling : $\rho_s(A,Y) - \rho_s(p,Y) \;=\; \text{const.} \;\simeq\; \ln A^{1/3}$
- Running coupling : $\rho_s(A,Y) - \rho_s(p,Y) \;\propto\; (\ln A^{1/3})^2/\sqrt{Y}$

R_{pA} in the 'double scaling' window

$$R_{pA}(k_\perp,\eta) \approx \frac{1}{A^{1/3}}\left(\frac{Q_s^2(A,Y)}{Q_s^2(p,Y)}\right)^\gamma \quad \text{for} \quad Q_s(A,Y) < k_\perp < Q_g(p,Y)$$

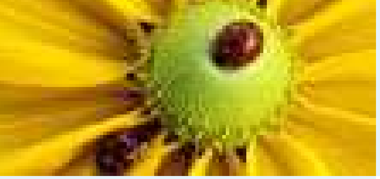
- Very robust prediction ! (at mean–field level, at least)
- 'Fixed coupling'–like scenarios :

$$Q_s^2(A,Y) \,=\, A^{1/3}\, Q_s^2(p,Y), \qquad Q_s^2(p,Y) \,=\, Q_0^2\, \mathrm{e}^{\lambda(Y-Y_0)}$$

▷ Most models assume such a behaviour with $\lambda \sim 0.3$

$$R_{pA}(k_\perp,\eta) \,\approx\, \frac{1}{A^{(1-\gamma)/3}} \,\approx\, \frac{1}{A^{0.12}} \quad : \quad \text{indep. of } k_\perp,\, \eta$$

- The maximal suppression one can get at $k_\perp > Q_s(A,Y)$



R_{pA} in the 'double scaling' window

$$R_{pA}(k_\perp, \eta) \approx \frac{1}{A^{1/3}} \left(\frac{Q_s^2(A,Y)}{Q_s^2(p,Y)} \right)^\gamma \quad \text{for} \quad Q_s(A,Y) < k_\perp < Q_g(p,Y)$$

- Very robust prediction ! (at mean–field level, at least)
- Running coupling : the A–dependence goes away at large Y

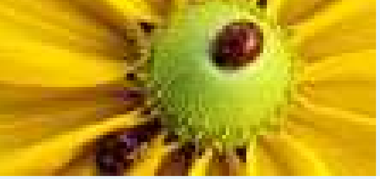
$$Q_s^2(A,Y) \,=\, \Lambda^2_{\rm QCD}\, {\rm e}^{\sqrt{\rho_A^2 + \lambda(Y-Y_0)}} \quad \text{with} \quad \rho_A \sim \ln A^{1/3}$$

$$R_{pA}(k_\perp, \eta) \quad \approx \quad \frac{1}{A^{1/3}}\, {\rm e}^{\frac{\rho_A^2}{\sqrt{\lambda Y}}}$$

$$\longrightarrow \quad \frac{1}{A^{1/3}} \quad : \text{'total shadowing'}$$

- Running coupling leads to a much stronger suppression

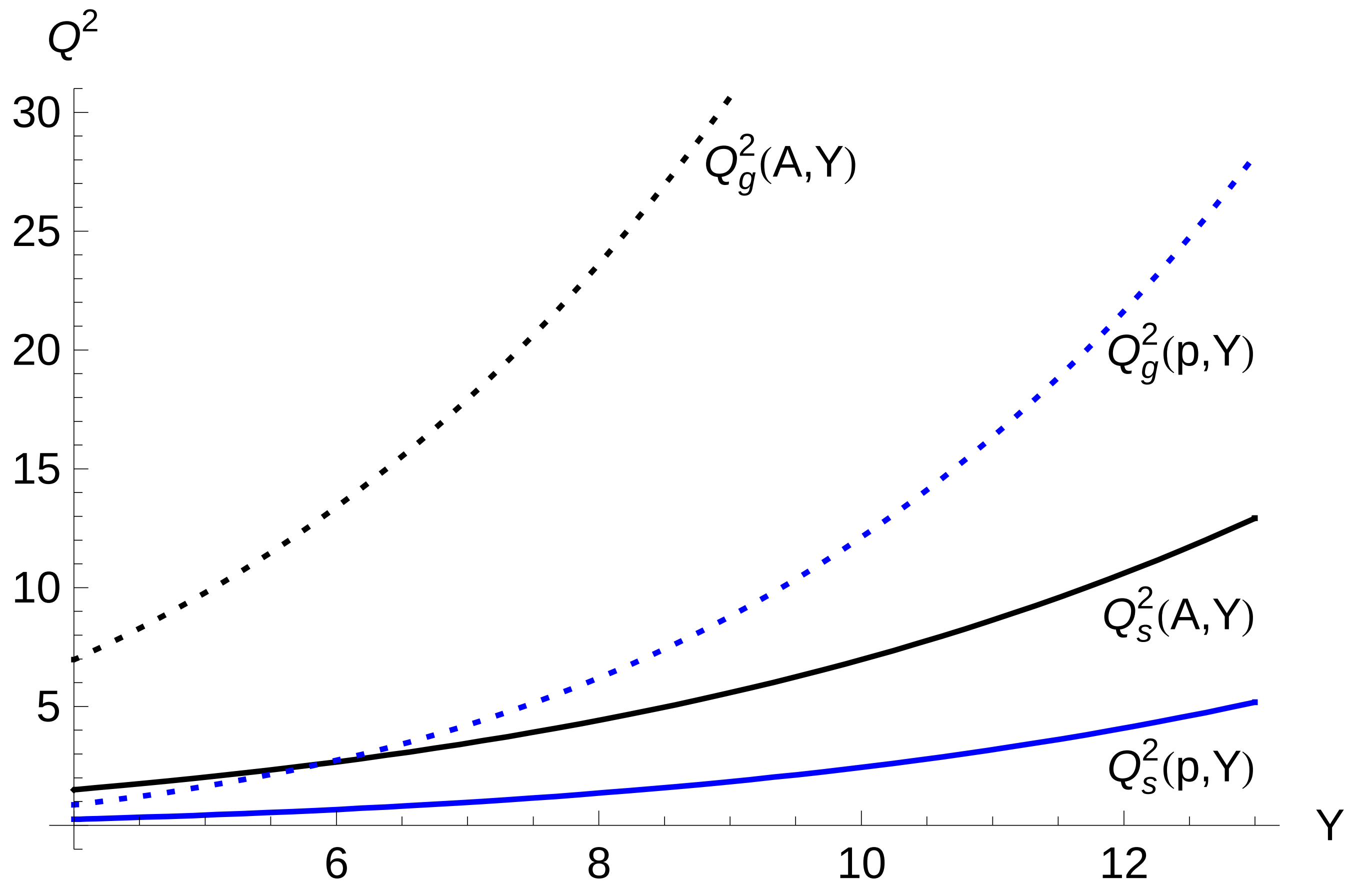
E.I., K. Itakura, D. N. Triantafyllopoulos, hep-ph/0403103 (87 pages !!)



R_{pA} at the LHC *(prediction)*

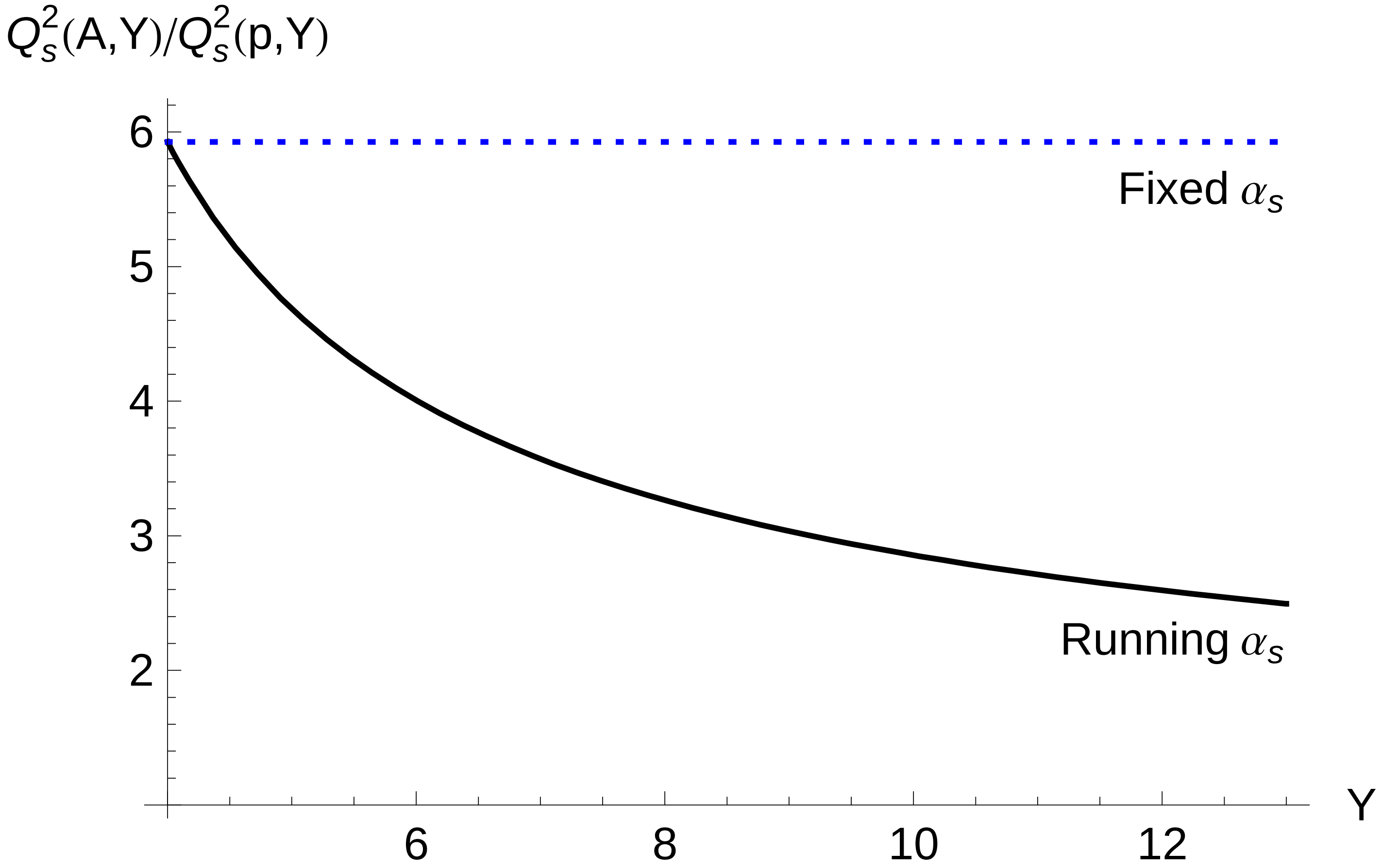
Summary
Gluon production
Saturation (mean field)
Prediction (mean field)
● RpA: double scaling
● RpA at LHC
Pomeron loops
Conclusions
Backup

- Should we expect this phenomenon at the LHC ?



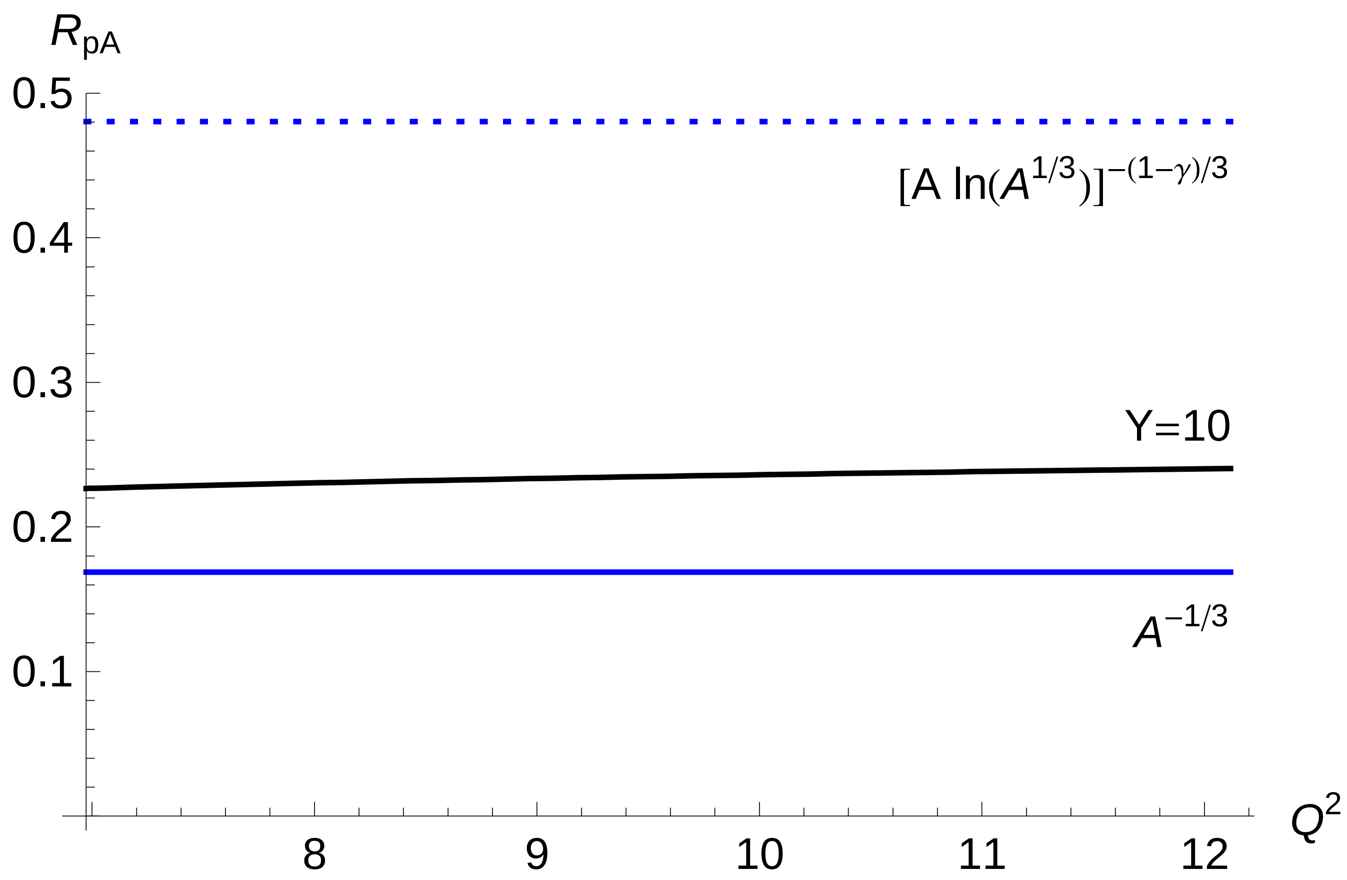
- Realistic initial conditions ($A = 208$, $Y_0 = 4$)
- Analytic approximations to BK with running coupling

R_{pA} at the LHC *(prediction)*



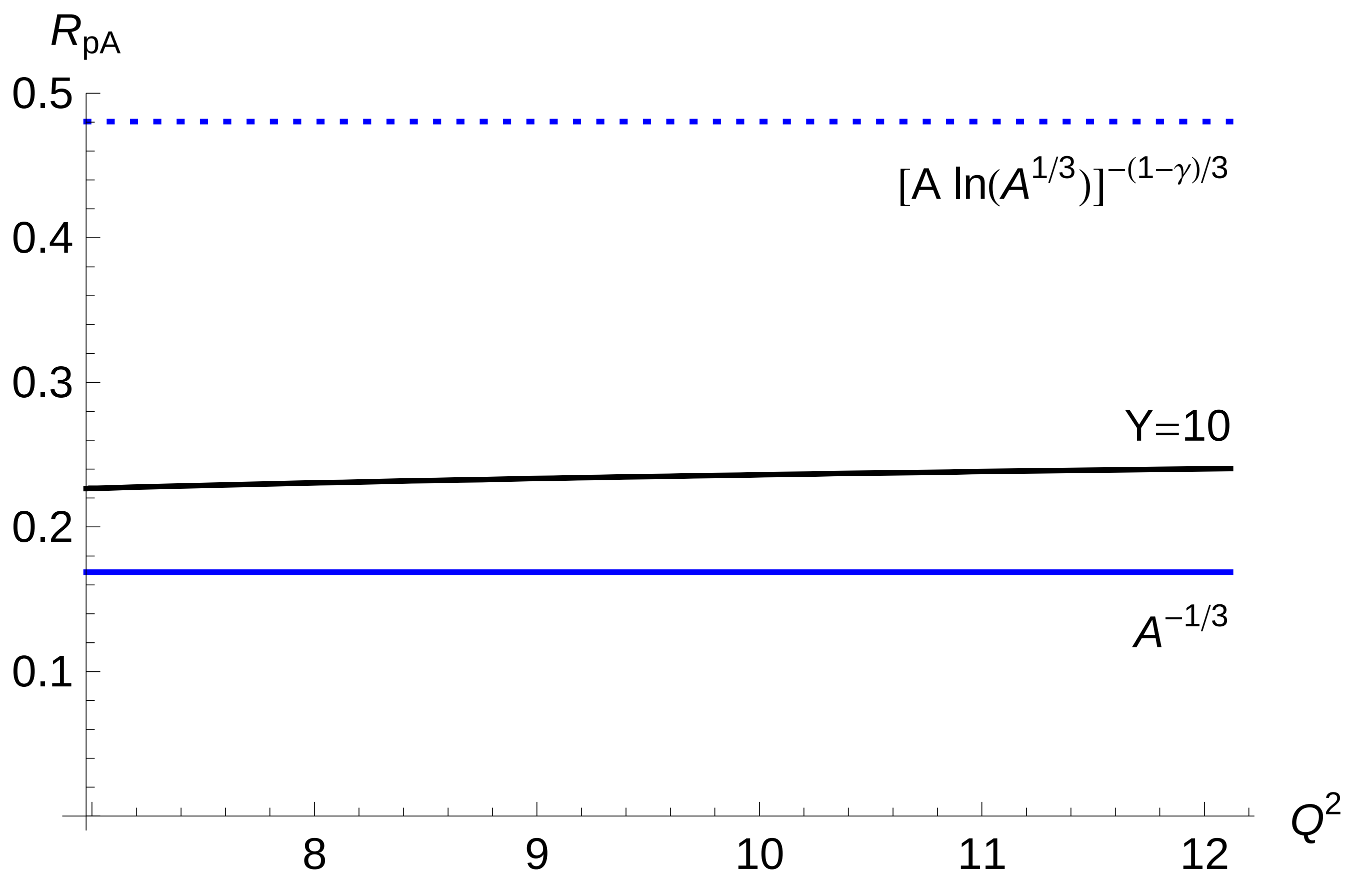
- Decrease by a factor of 2 at $Y = 10$

R_{pA} at the LHC *(prediction)*

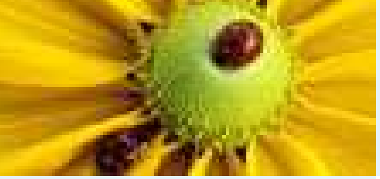


- Significant discrepancy from ‘fixed coupling’ scenario
- Close to total gluon shadowing for $Y \gtrsim 10$
- Flat behaviour within a quite large window in $k_\perp$

R_{pA} at the LHC *(prediction)*

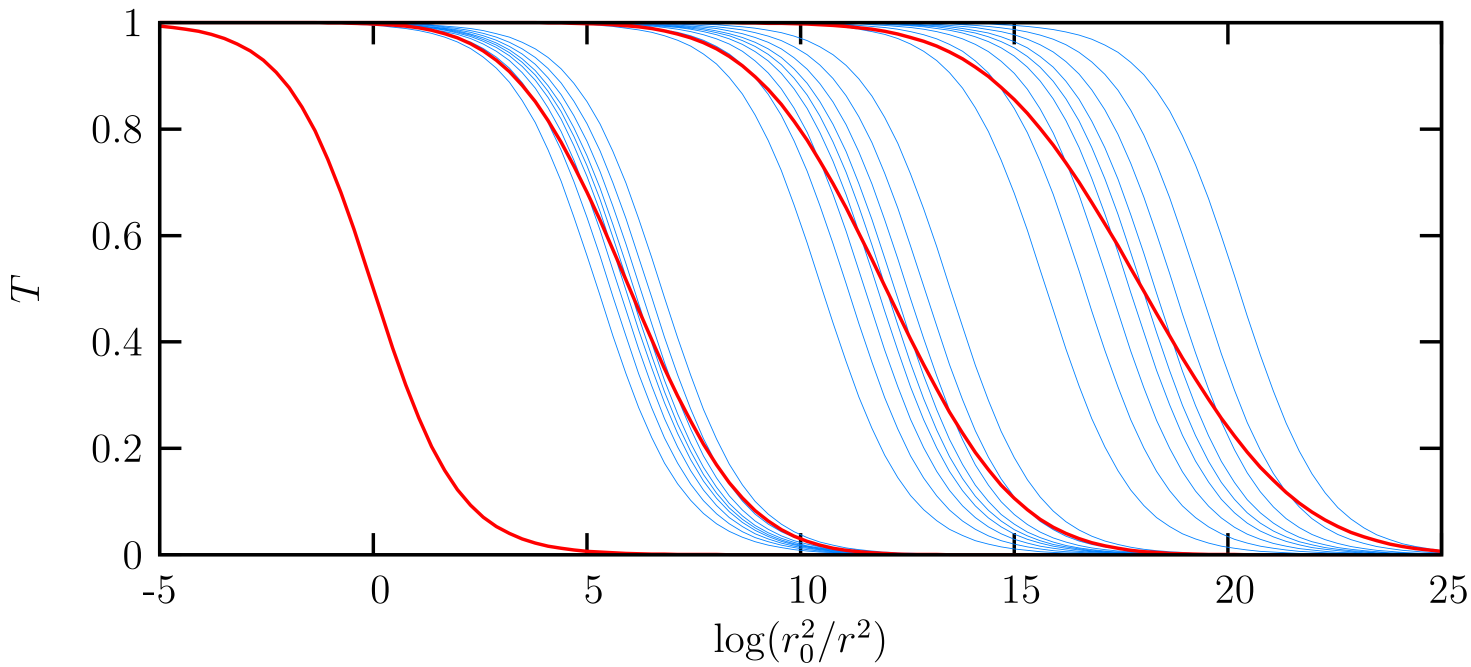


- Will this whole analysis survive to fluctuations ??



Front diffusion through fluctuations

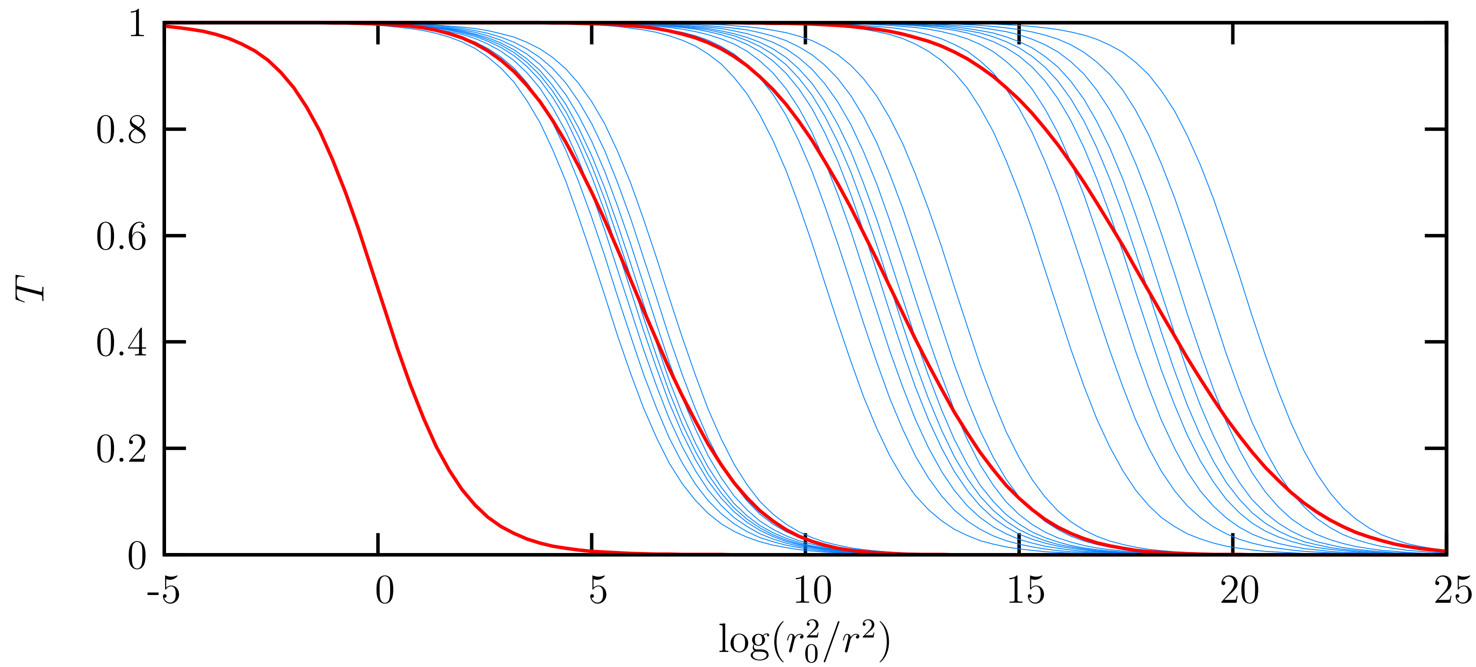
- The saturation momentum $\rho_s \equiv \ln Q_s^2$ becomes a random variable : $\langle \rho_s(Y) \rangle, \quad \sigma^2(Y) \equiv \langle \rho_s^2 \rangle - \langle \rho_s \rangle^2$



- With increasing energy, the fronts spread from each other $\Longrightarrow$ geometric scaling is progressively washed out !
- $\sigma^2(Y) \gtrsim 1 \Longrightarrow$ a totally new picture : 'diffusive scaling'

Front diffusion through fluctuations

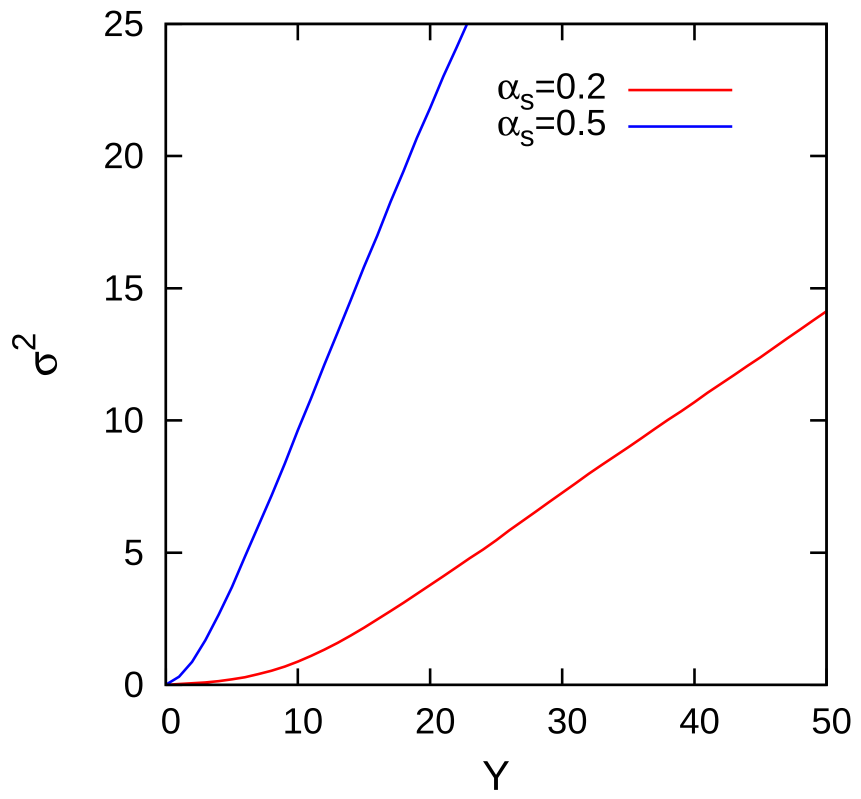
- The saturation momentum $\rho_s \equiv \ln Q_s^2$ becomes a random variable : $\langle \rho_s(Y) \rangle, \quad \sigma^2(Y) \equiv \langle \rho_s^2 \rangle - \langle \rho_s \rangle^2$



- With increasing energy, the fronts spread from each other $\Longrightarrow$ geometric scaling is progressively washed out !
- Will this new picture be visible at LHC ?

Dispersion: Fixed coupling

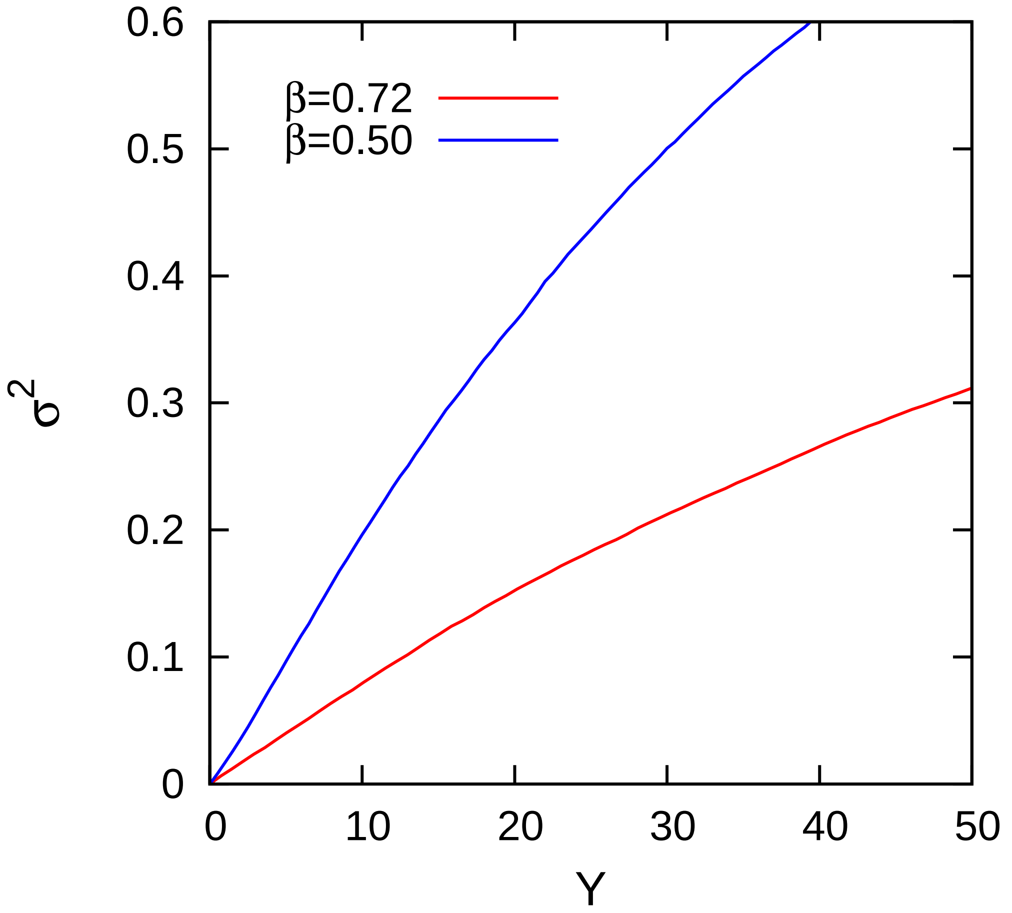
- $\sigma^2(Y) \simeq D\bar{\alpha}_s Y$ with $D \sim \mathcal{O}(1)$



- Fluctuations effects are clearly important ($\sigma^2 > 1$ for $Y = 10$)
- ... and lead to ‘total shadowing’ in R_{pA} at fixed coupling !
  (cf. the talk by Misha Kozlov)

Dispersion: Running coupling

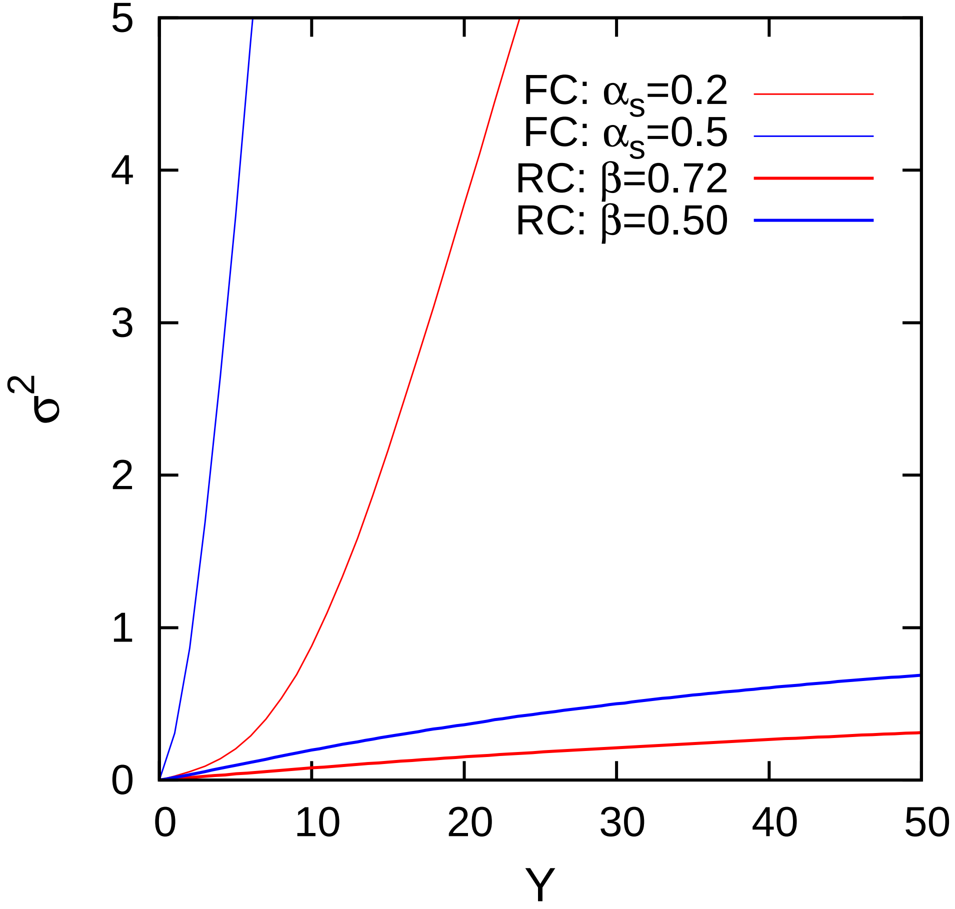
- The dispersion keeps rising with Y ...



- ... but now it is tremendously smaller !

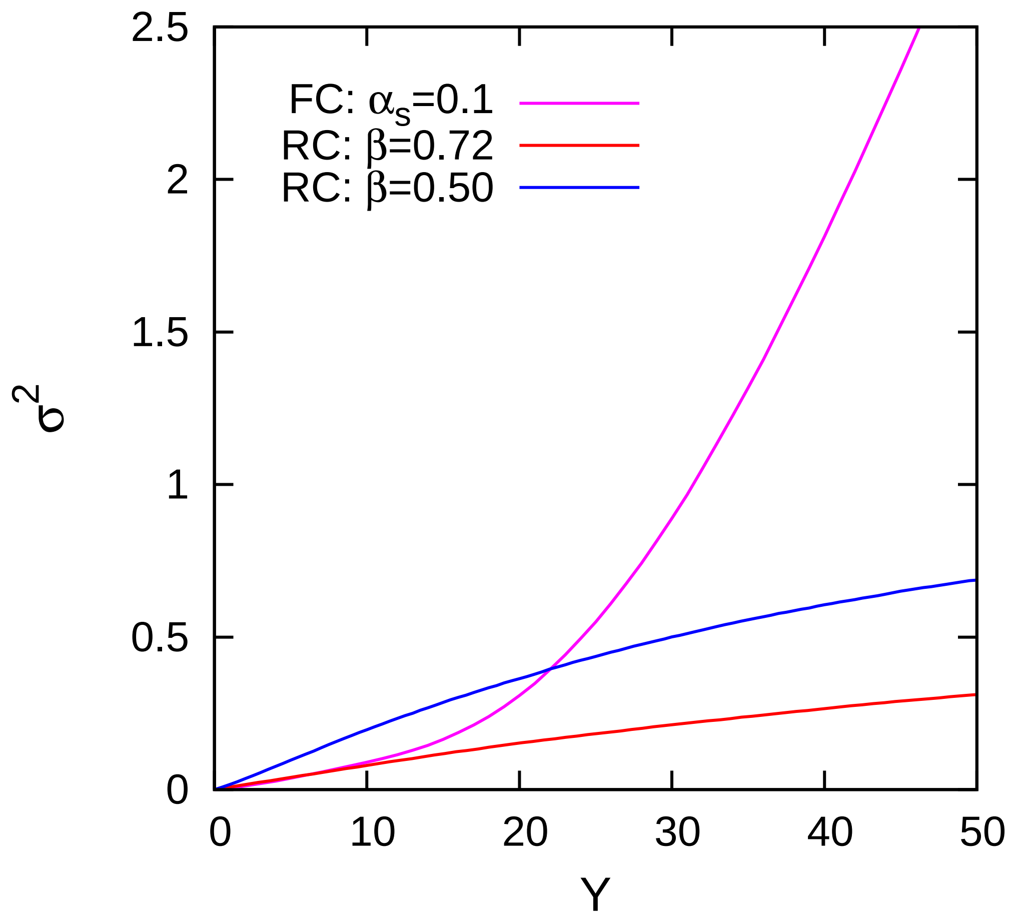
Dispersion: Running coupling

- The dispersion keeps rising with Y ...



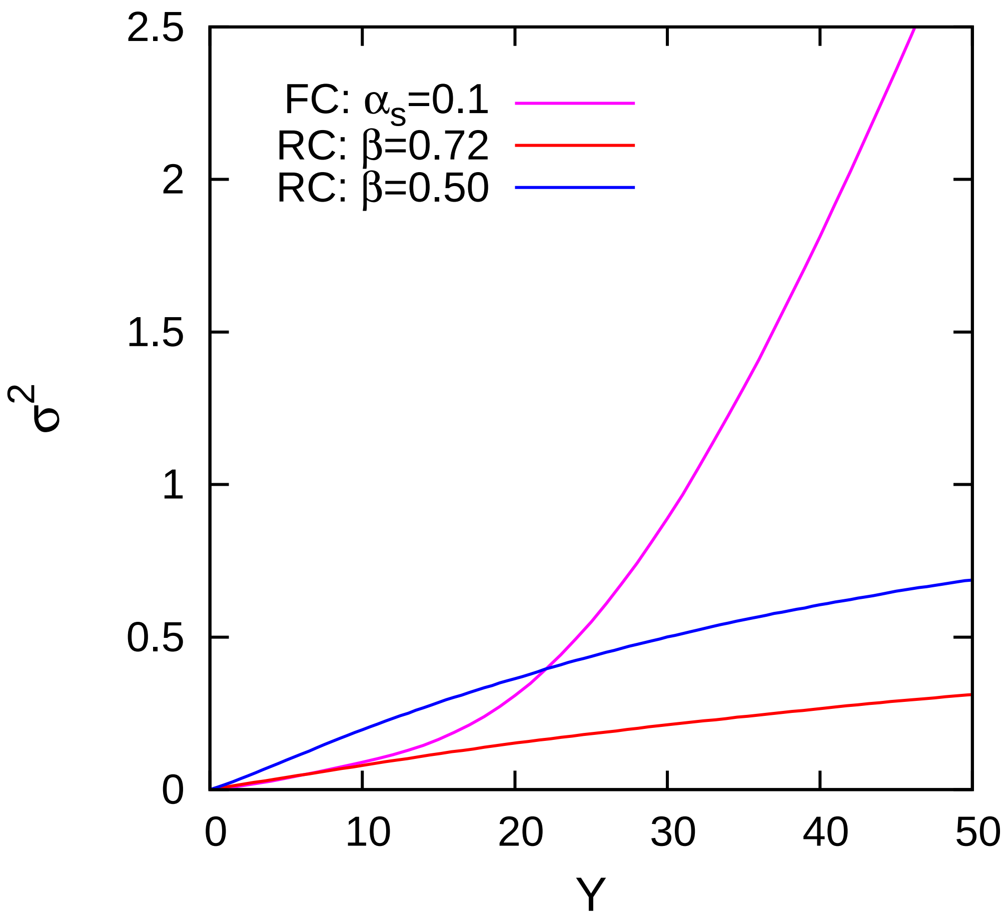
- ... but now it is tremendously smaller ! (by a factor ~ 100)

Why ?



- The naive answer: “Because the coupling is smaller.”
- The smallest value of the coupling reached in the ‘running–coupling’ simulation is about 0.1 !

Why ?



- The correct answer: Because the evolution is much slower.
- 'Formation time' $Y_{\rm form} \sim 10$ for fixed coupling $\alpha_s = 0.1$, but about $Y_{\rm form} \sim 10^3 = 1000$ for running coupling !

Conclusions

- Running–coupling effects are truly essential within the high–energy evolution

  quantitatively and qualitatively

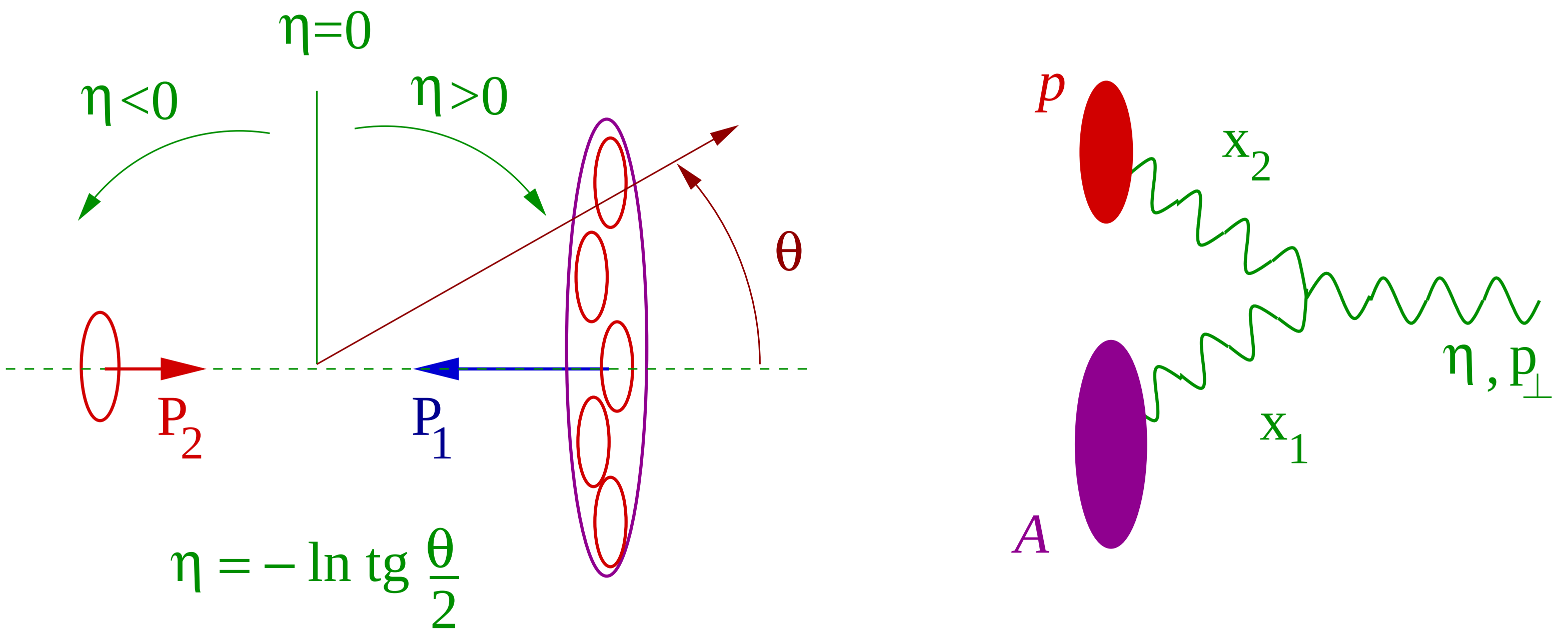
- Nearly total gluon shadowing in R_{pA} in a kinematical range accessible at LHC

  (based on analytic estimates;
  to be checked against fully numerical calculations)

- Pomeron loop effects are negligible at LHC

  (and most likely at all but trans–Planckian energies)

Gluon production in pA collisions: Kinematic



$$x_1 = \frac{p_\perp}{\sqrt{s}}\, \mathrm{e}^{-\eta}, \qquad x_2 = \frac{p_\perp}{\sqrt{s}}\, \mathrm{e}^{\eta}$$

- Increasing η $\Longleftrightarrow$ Decreasing x_1 for the nucleus
  - RHIC: $\eta \simeq 3$ & $\sqrt{s} = 200\,$GeV: $x_1 \sim 10^{-4}$ for $p_\perp = 2\,$GeV
  - LHC : $\eta \simeq 6$ & $\sqrt{s} = 8.8\,$TeV : $x_1 \sim 10^{-6}$ for $p_\perp = 10\,$GeV

The Saturation Momentum

- Parametrization:

$$Q_s^2(A,Y) = \Lambda^2 \exp \sqrt{B(Y - Y_0) + \rho_A^2}$$

with: $\Lambda = 0.2\mathrm{GeV}, \;\; B = 2.25, \;\; Y_0 = 4, \;\; Q_s^2(A, Y_0) = 1.5\mathrm{GeV}^2$

- Proton : $\rho_A \;\longrightarrow\; \rho_p$ such that $Q_s^2(p, Y_0) = 0.25\mathrm{GeV}^2$

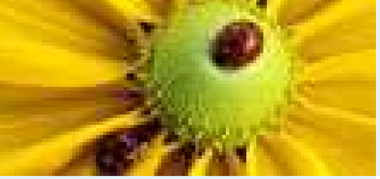
- Consistent with ‘geometric scaling’ fits to HERA

Gelis, Peschanski, Soyez, Schoeffel, hep-ph/0610435

- Gluon distribution in the geometric scaling window :

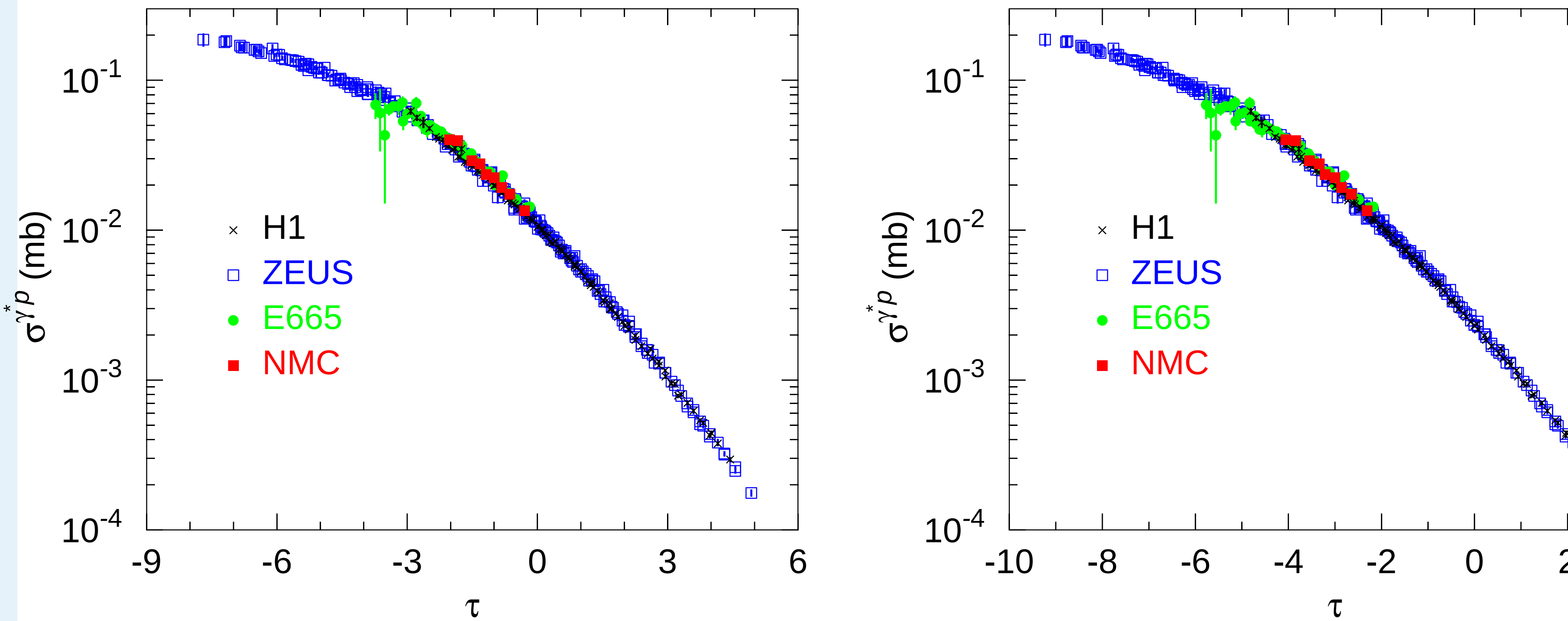
$$\Phi(k_\perp, Y) \;\propto\; \left[\frac{Q_s^2(Y)}{k_\perp^2}\right]^\gamma \left(\ln \frac{k_\perp^2}{Q_s^2(Y)} + c\right)$$

with: $\gamma = 0.63, \;\; c = 1/\gamma$



Geometric Scaling in DIS at small x

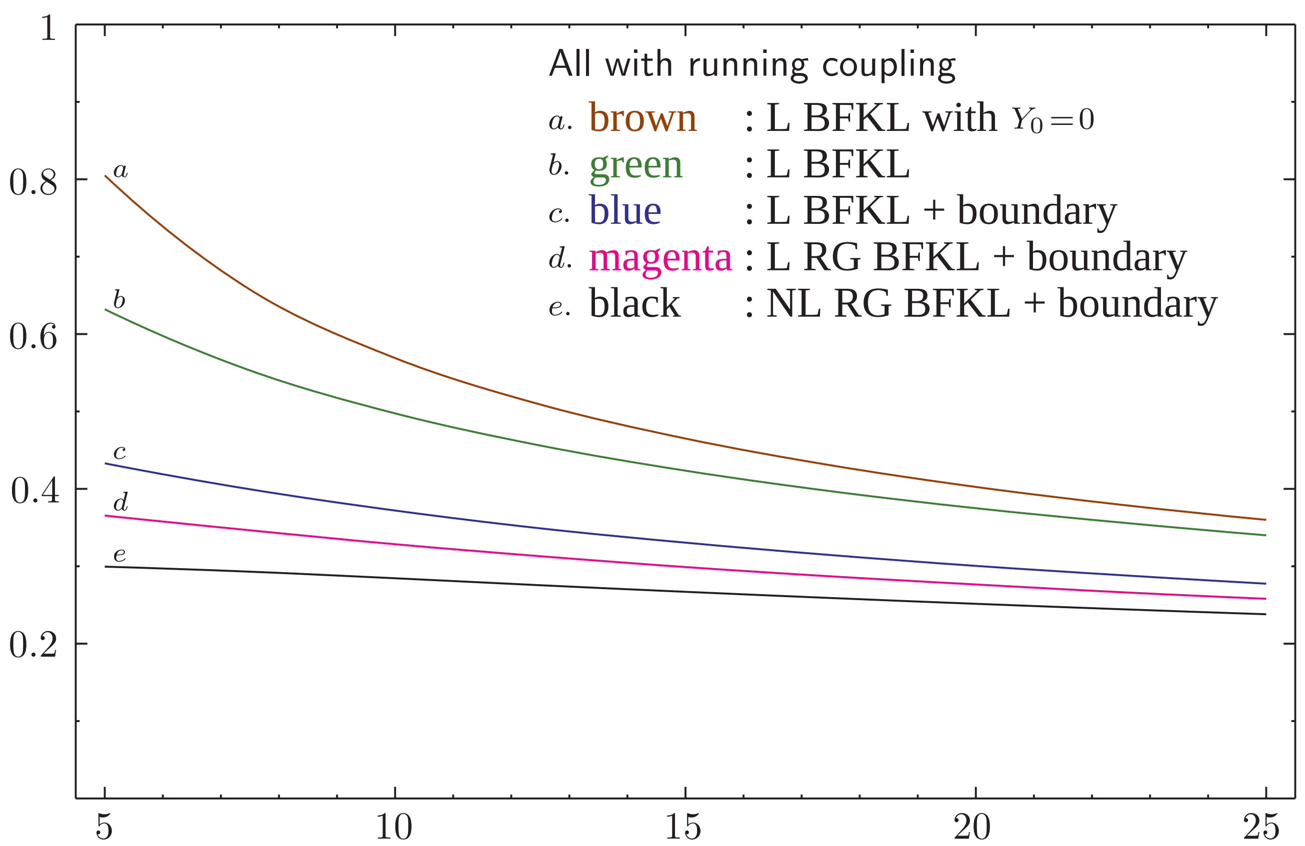
Gelis, Peschanski, Soyez, Schoeffel, hep-ph/0610435



- Left: $\tau \equiv \log Q^2 \ -\lambda Y$, with $\lambda = 0.32$
- Right: $\tau \equiv \log Q^2 \ -\lambda\sqrt{Y}$, with $\lambda = 1.62$

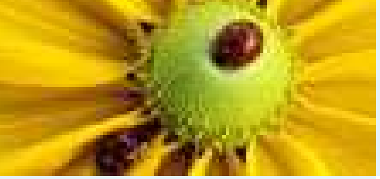
The energy dependence of Q_s

D.N. Triantafyllopoulos, 2002



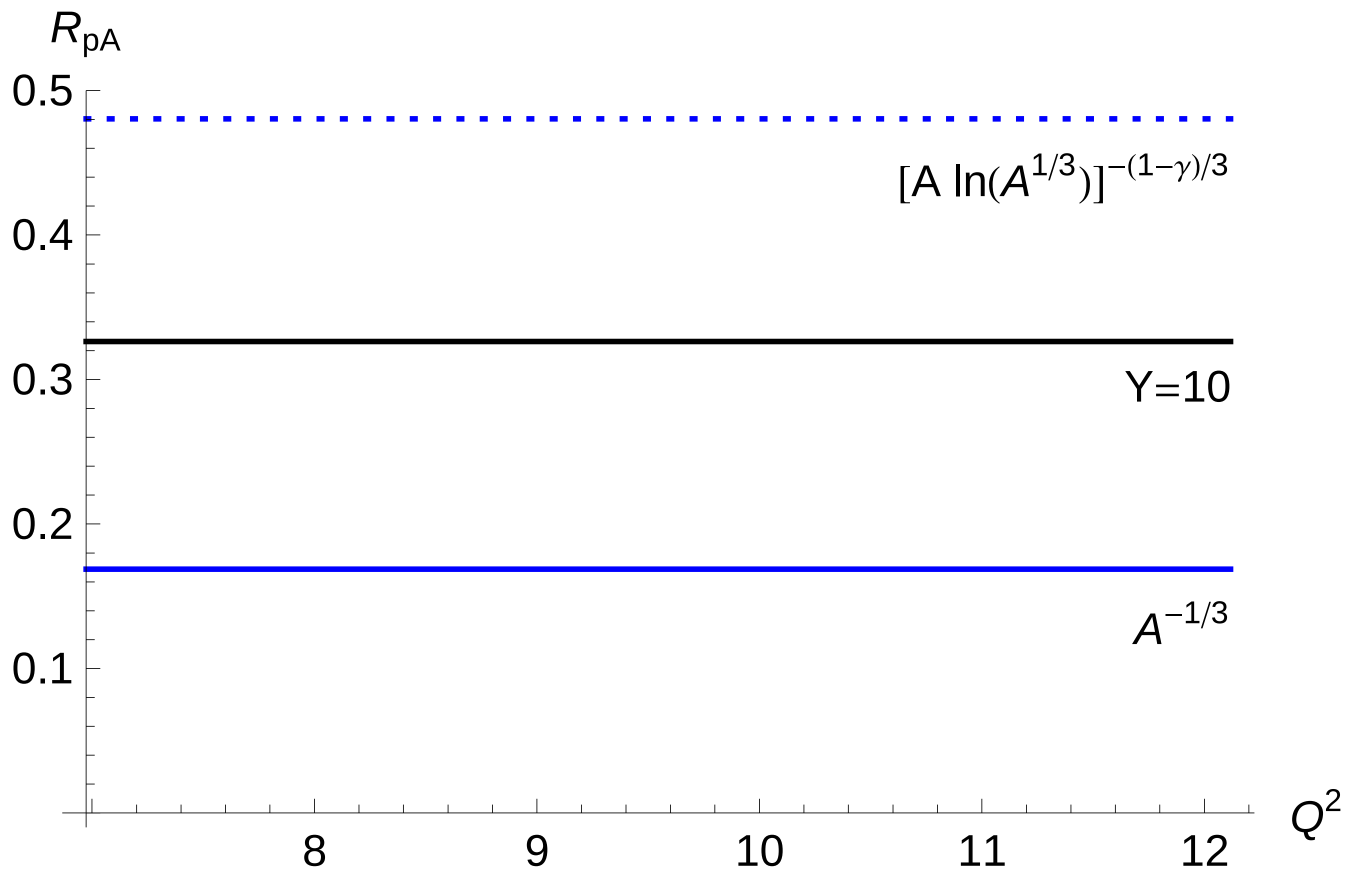
$$\lambda(Y) \equiv \frac{\mathrm{d} \ln Q_s^2(Y)}{\mathrm{d}Y}$$

- NLO BFKL + Collinear resummation + Saturation Boundary

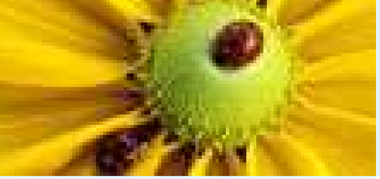


R_{pA} without the log

- Without the logarithm in the gluon distribution :



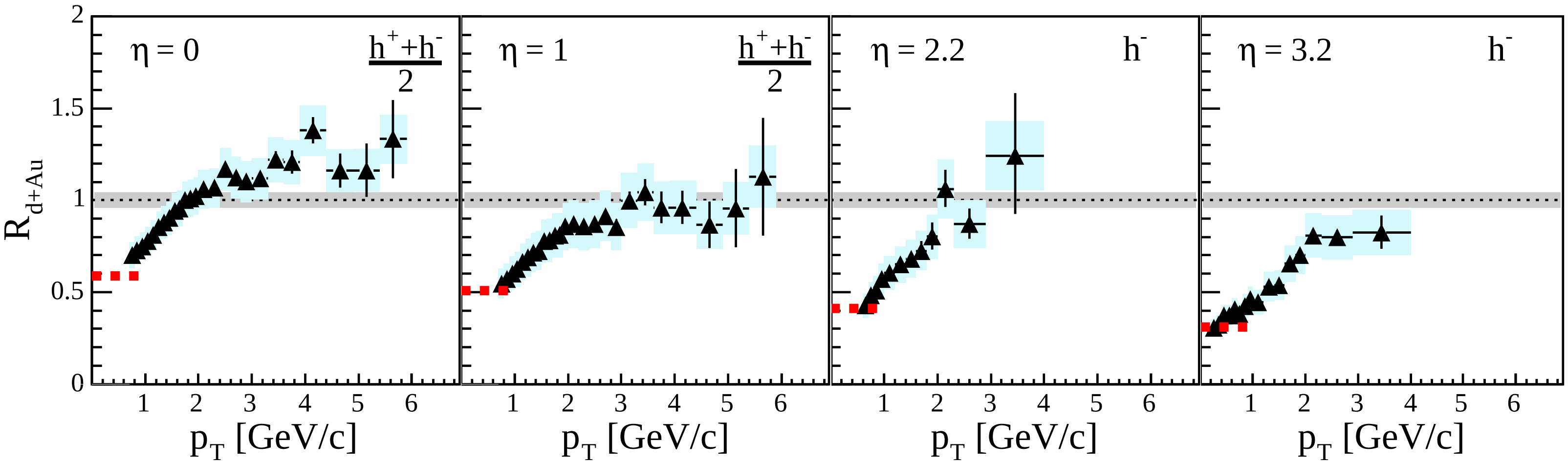
- The suppression remains substantial.



High–$p_\perp$ suppression in d+Au at RHIC

Nuclear modification factor : $R_{\mathrm{d+Au}} \equiv \dfrac{1}{2A}\, \dfrac{dN_{\mathrm{d+Au}}/d^2p_\perp d\eta}{dN_{\mathrm{pp}}/d^2p_\perp d\eta}$

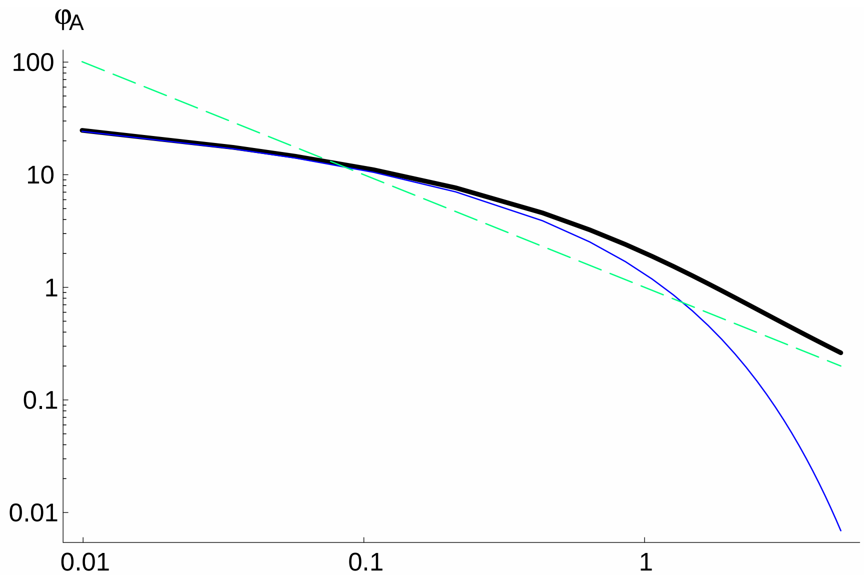
$R_{\mathrm{d+Au}}$ would be one if nucleus = incoherent superposition of A nucleons

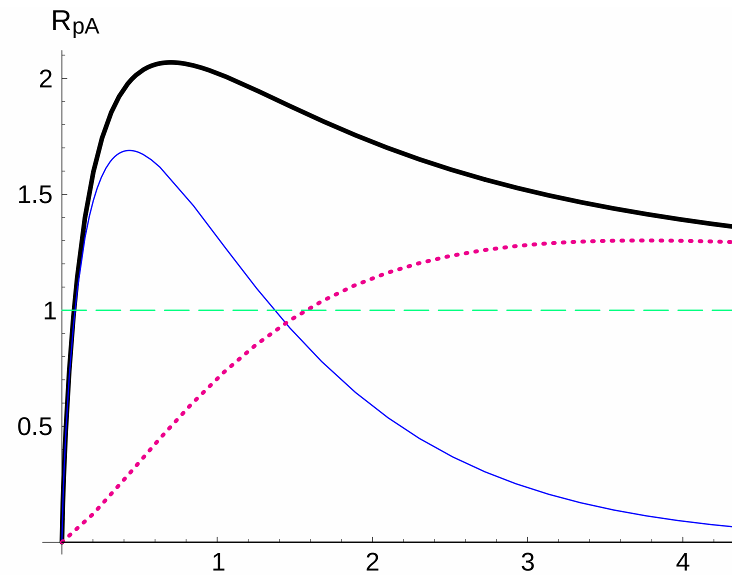


- One finds *(BRAHMS [arXiv:nucl-ex/0403005])* :
  - $\eta = 0$: Cronin peak ($R_{\mathrm{d+Au}} > 1$ for intermediate $p_\perp$)
  - $\eta \simeq 3$: Suppression ($R_{\mathrm{d+Au}} < 1$ for all $p_\perp$)

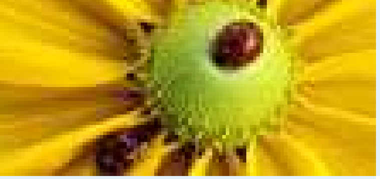
Cronin peak ($\eta = 0$)

- Non–linear effects (stronger at low $p_\perp$) 'push' the gluons in the nucleus towards larger values of $p_\perp$

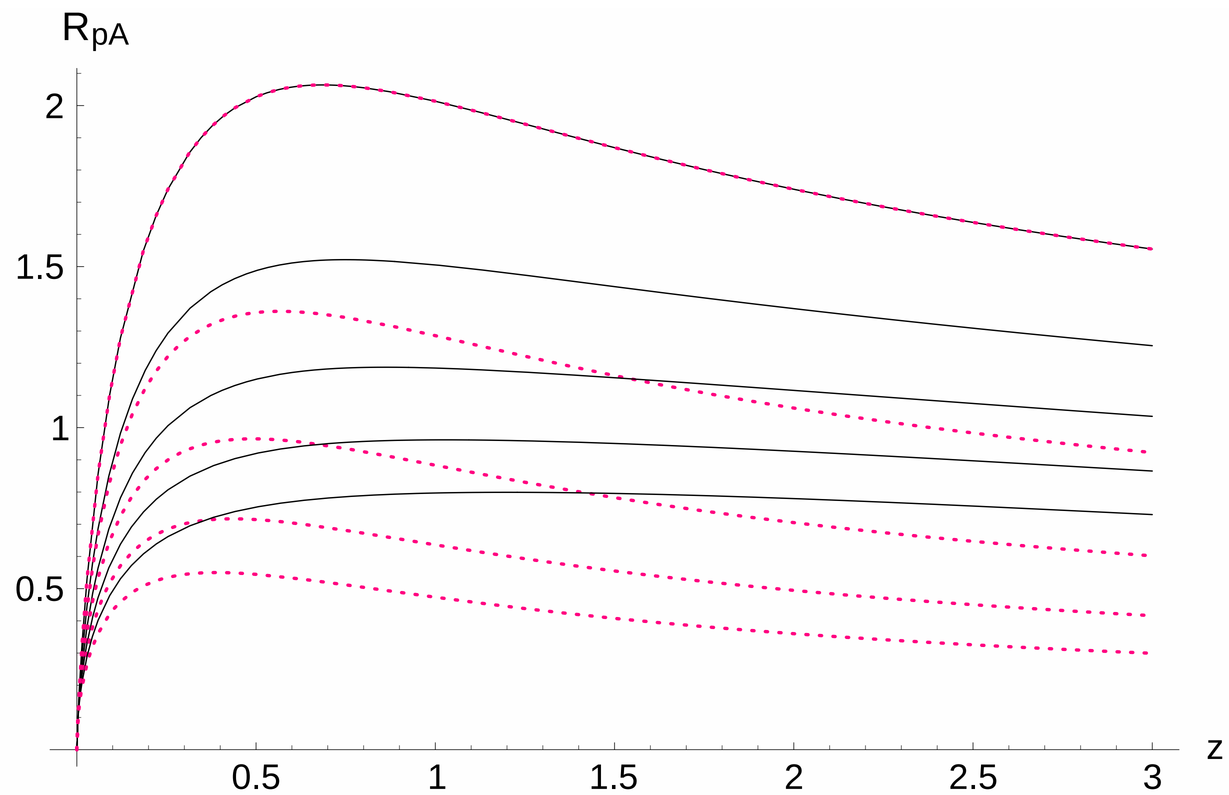




$$R_{pA}(k_\perp) \sim \rho_A \sim \ln A^{1/3} \qquad \text{for} \qquad k_\perp \sim Q_s(A)$$

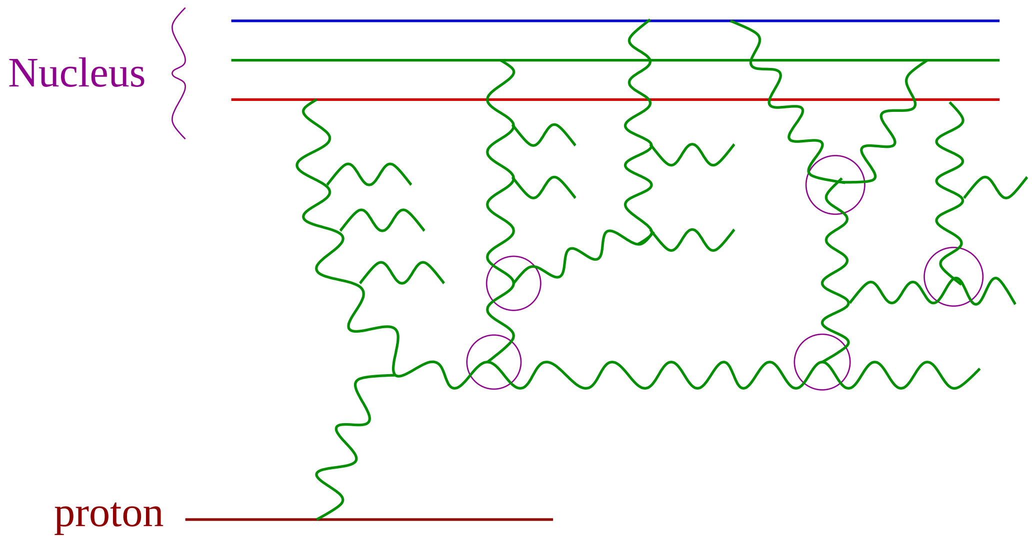


The flattening of the Cronin peak



- $k_\perp \sim Q_s(A, Y)$ with $Y = Y_c + \eta$:
  - $\eta = 0: \; R_{pA} \sim \rho_A \sim \ln A^{1/3} > 1$
  - $\eta = \eta_0: \; R_{pA} \simeq 1 \implies \eta_0 \sim \ln \rho_A < \rho_A \sim 1/\alpha_s$

High–$p_\perp$ suppression



- With increasing η (i.e., decreasing x_1), the gluon distribution in the target evolves as a CGC

  N.B. : ‘target’ = Au for d+Au, but ‘target’ = p for p+p

- The proton evolves faster than the nucleus since

$$Q_s(A) > Q_s(p)$$

  $R_{\mathrm{d+Au}}$ decreases since the denominator (the proton) evolves faster than the numerator (the nucleus) !