
Physics of parton saturation

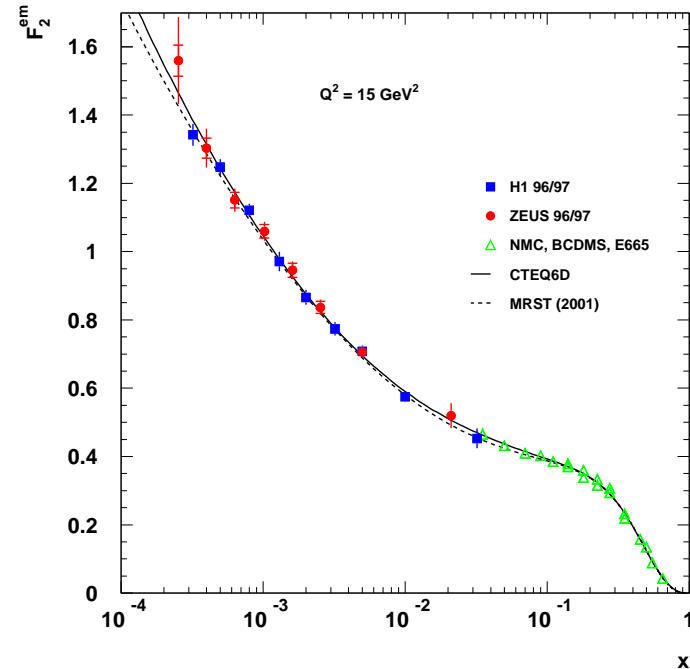
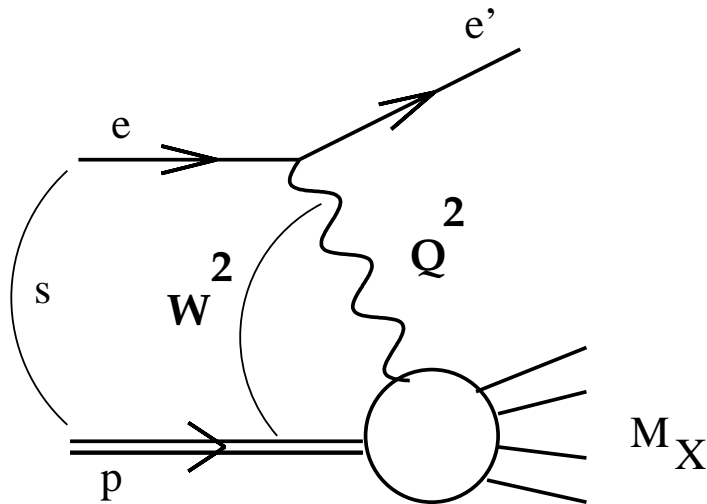
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Kielce, 15 -17 October 2004

Saturation in DIS - I

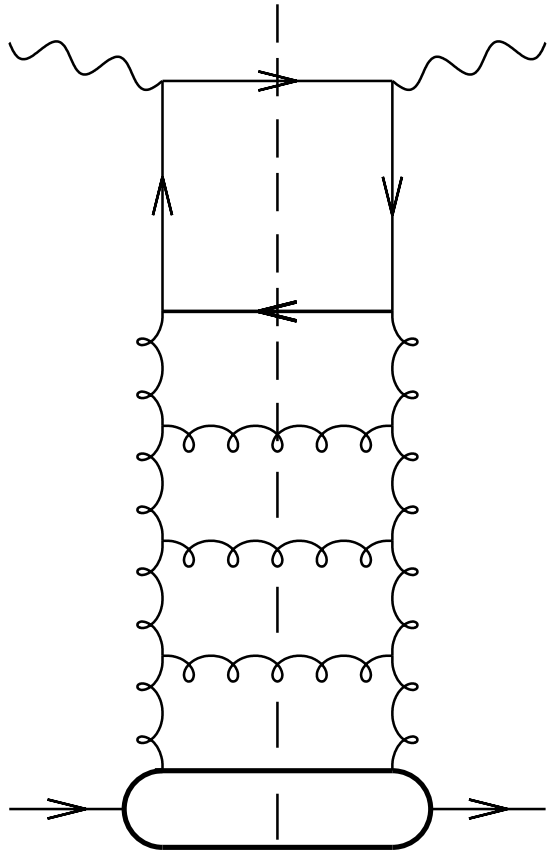
DIS **much simpler** than heavy ion scattering: $ep \rightarrow eX$



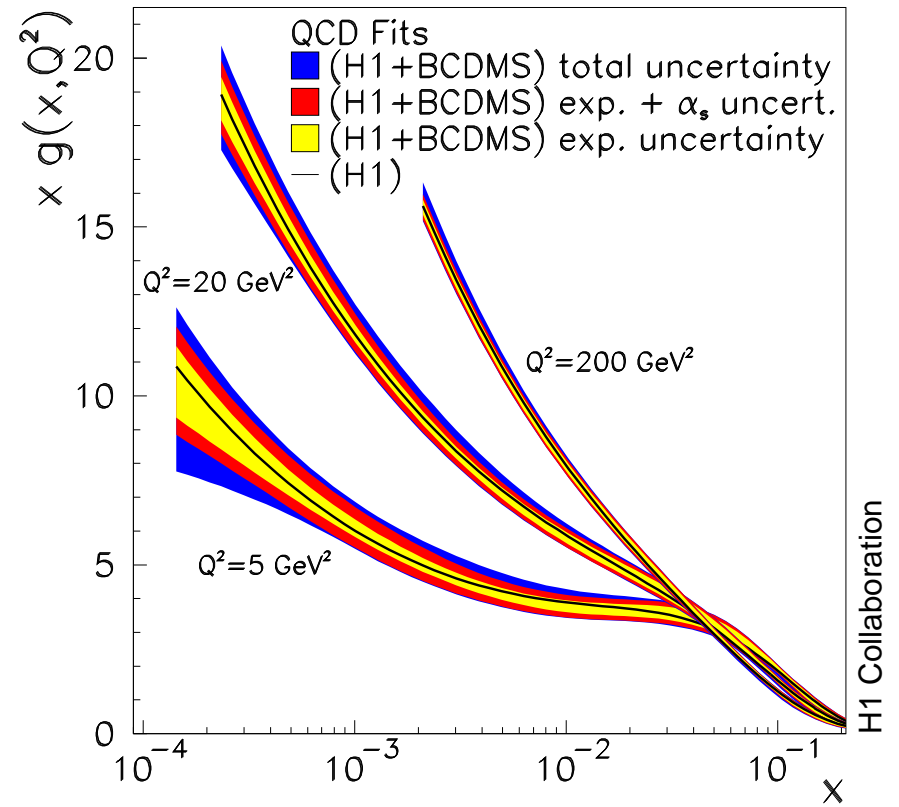
- small x limit: $x = Q^2/W^2 \rightarrow 0$
- structure function strongly rises: $F_2(x, Q^2) = \sum_i e_i^2 x(q + \bar{q}) \sim x^{-\lambda}$
- rise driven by gluons:

$$\partial G / \partial \ln Q^2 = P_{GG} \otimes G$$

Saturation in DIS - II



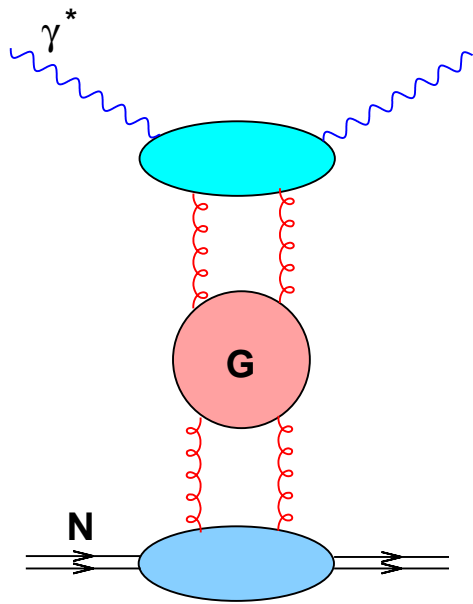
at small x scattering on sea quark



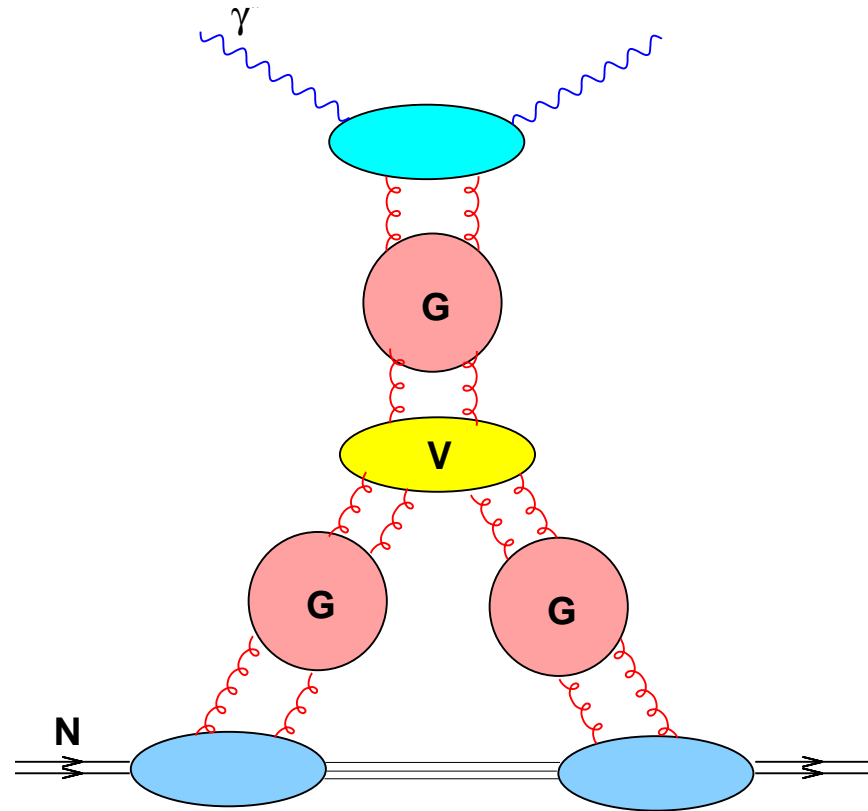
gluon distribution $G = xg$

Saturation in DIS - III

If gluon density large enough, gluon **recombination** is important



linear evolution eqs.



non-linear evolution eqs.

Saturation scale - I

- GLR evolution eq. for gluon distribution: $G(x, Q^2)$

$$\frac{\partial G}{\partial \ln Q^2 \ln(1/x)} = \frac{\alpha_s}{\pi} G - \left(\frac{\alpha_s}{\pi}\right)^2 \frac{1}{Q^2 R_H^2} G^2$$

(L.V. Gribov, E.M. Levin, M.G. Ryskin 83')

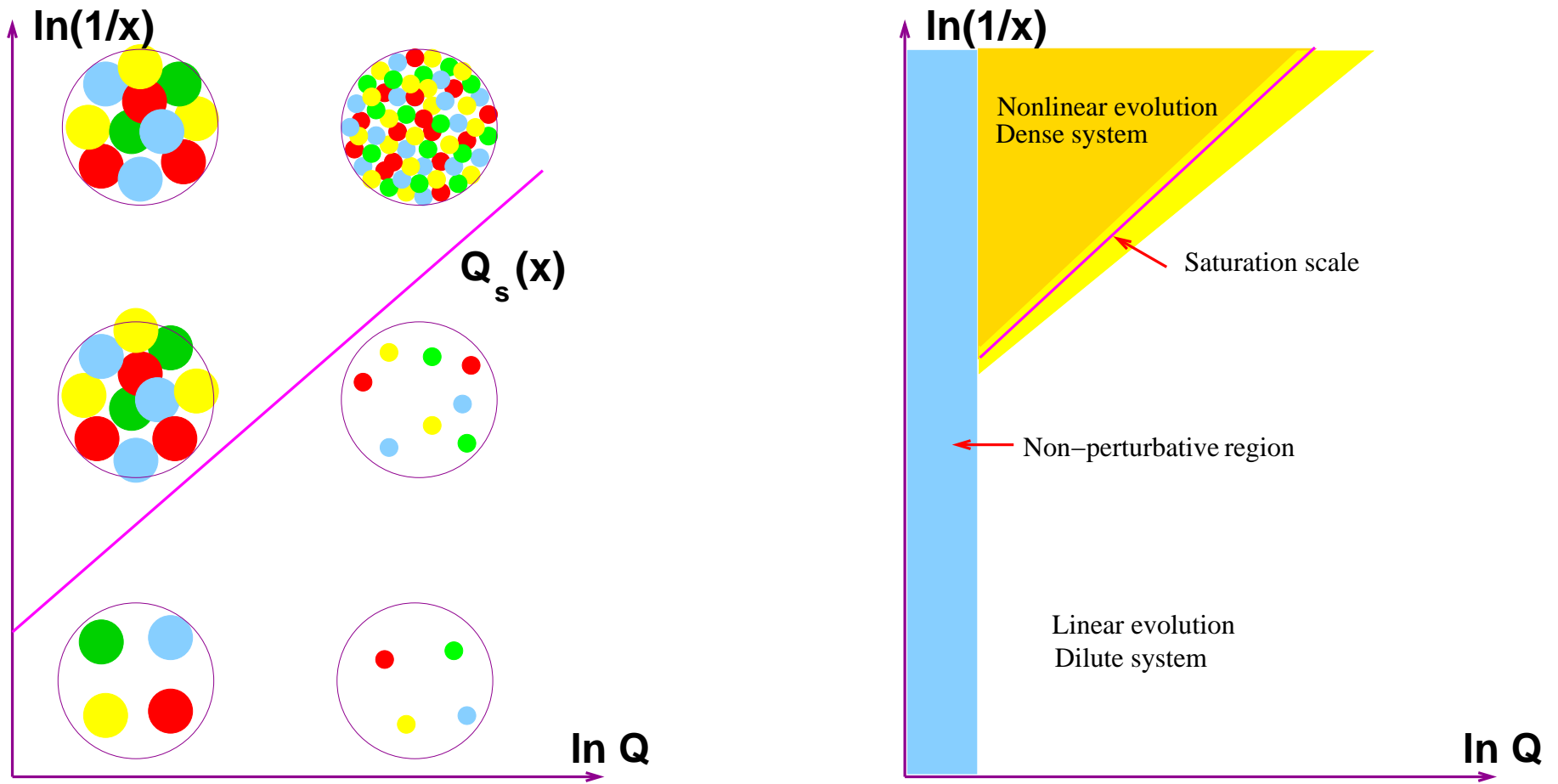
- nonlinearity important when **second term** \sim **first term**

$$\frac{\alpha_s(Q^2)}{Q^2} G(x, Q^2) \sim \pi R_H^2 \quad (1)$$

- gluon rise slows down (**saturate**) when $\sigma_{gg} \times N_g \sim \sigma_H$
- from condition (1) **saturation scale**:

$$Q = Q_s(x)$$

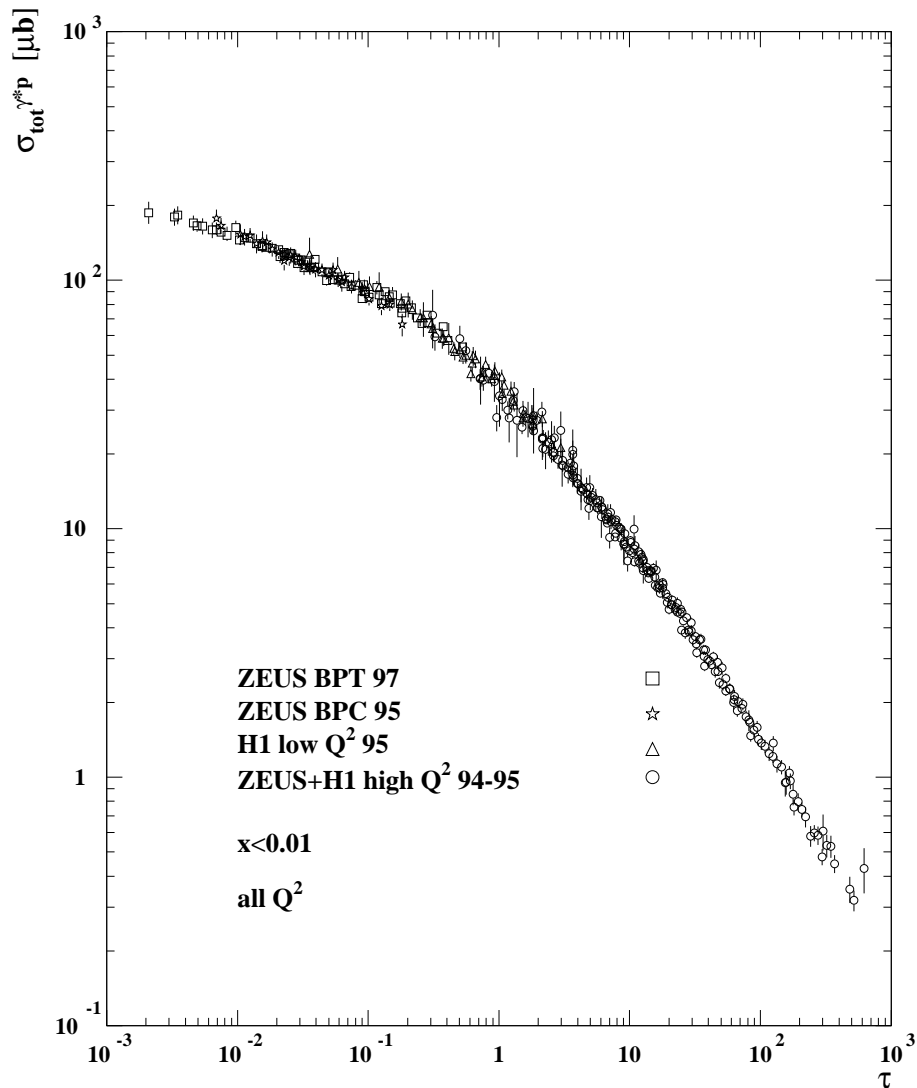
Saturation scale - II



(x, Q^2) -plane

Geometric scaling

Direct manifestation of saturation scale in DIS data: $\sigma^{\gamma^*p} = F_2/Q^2$



$x < 0.01$

● Scaling property

$$\sigma^{\gamma^*p}(x, Q^2) = \sigma^{\gamma^*p}(Q^2/Q_s^2(x))$$

(A. Staśto, K.Golec-Biernat, J. Kwieciński 00')

● saturation scale (G-B, Wuesthoff 99')

$$Q_s^2 = Q_0^2 x^{-0.28}$$

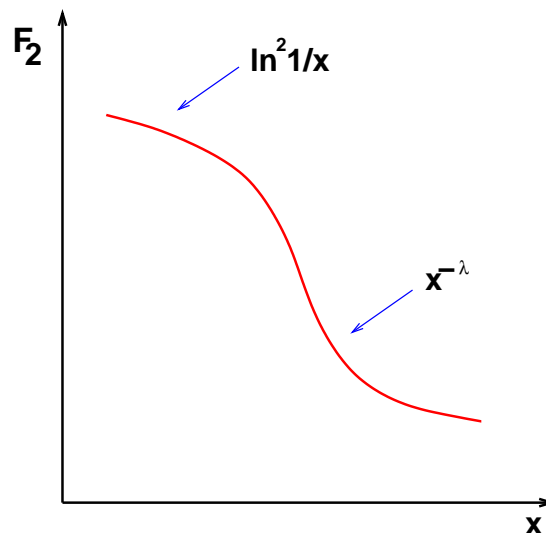
Saturation and unitarity

- **Froissart** bound for high energy behaviour in hadronic reactions

$$\sigma_{TOT} \leq \frac{\pi}{m_\pi^2} \log^2 s$$

- Power-like behaviour in DIS too strong

$$F_2 \sim x^{-\lambda} \sim (W^2)^\lambda \quad \xrightarrow{\text{SATURATION}} \quad F_2 \sim \log^2(1/x)$$



Saturation in heavy ion collision



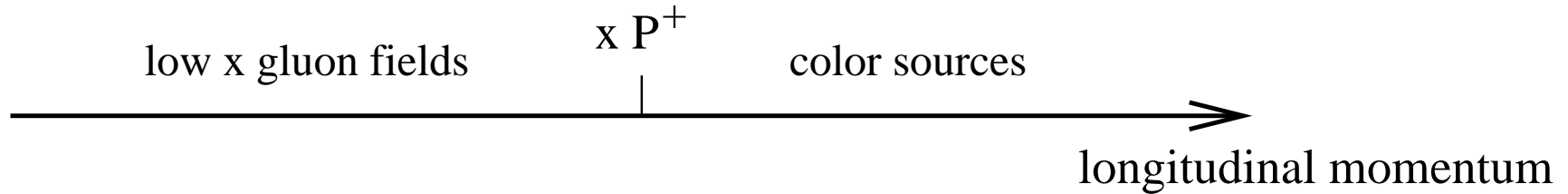
- at the earliest stage of collision, two **high density** gluon systems due to **high energy** and/or **large A**
- QCD effective theory: *(L. McLerran, R. Venugopalan 94')*

Color Glass Condensate

- Idea: **static** quarks are sources of **classical** color fields describing low x gluons

$$\rho^a(x^-, x_\perp) \xrightarrow{Y-M \text{ eqs.}} A^a[\rho] \sim 1/g_s$$

JIMWLK equations



- important correlation functions of gauge fields, e.g.

$$\langle A(X)A(Y) \rangle_x = \int \mathcal{D}[\rho] W_x[\rho] A[\rho, X] A[\rho, Y]$$

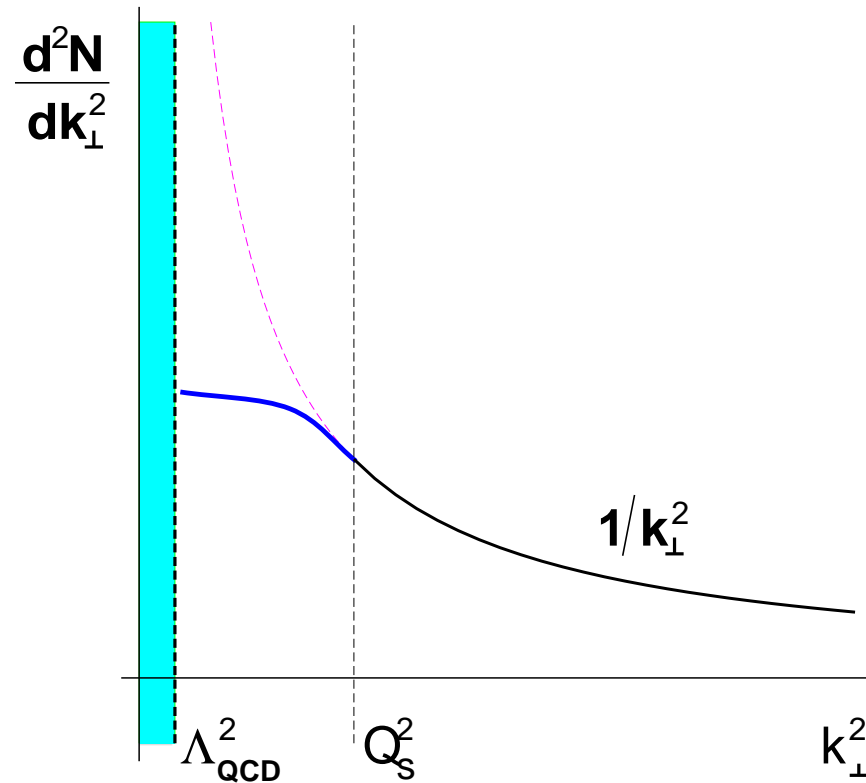
averaging over color sources with weight $W_x[\rho]$

- evolution equation

$$\frac{\partial W_x[\rho]}{\partial \ln(1/x)} = \int_{X_\perp, Y_\perp} \frac{\delta}{\delta \rho(X_\perp)} \chi(X_\perp, Y_\perp) \frac{\delta}{\delta \rho(Y_\perp)} W_x[\rho]$$

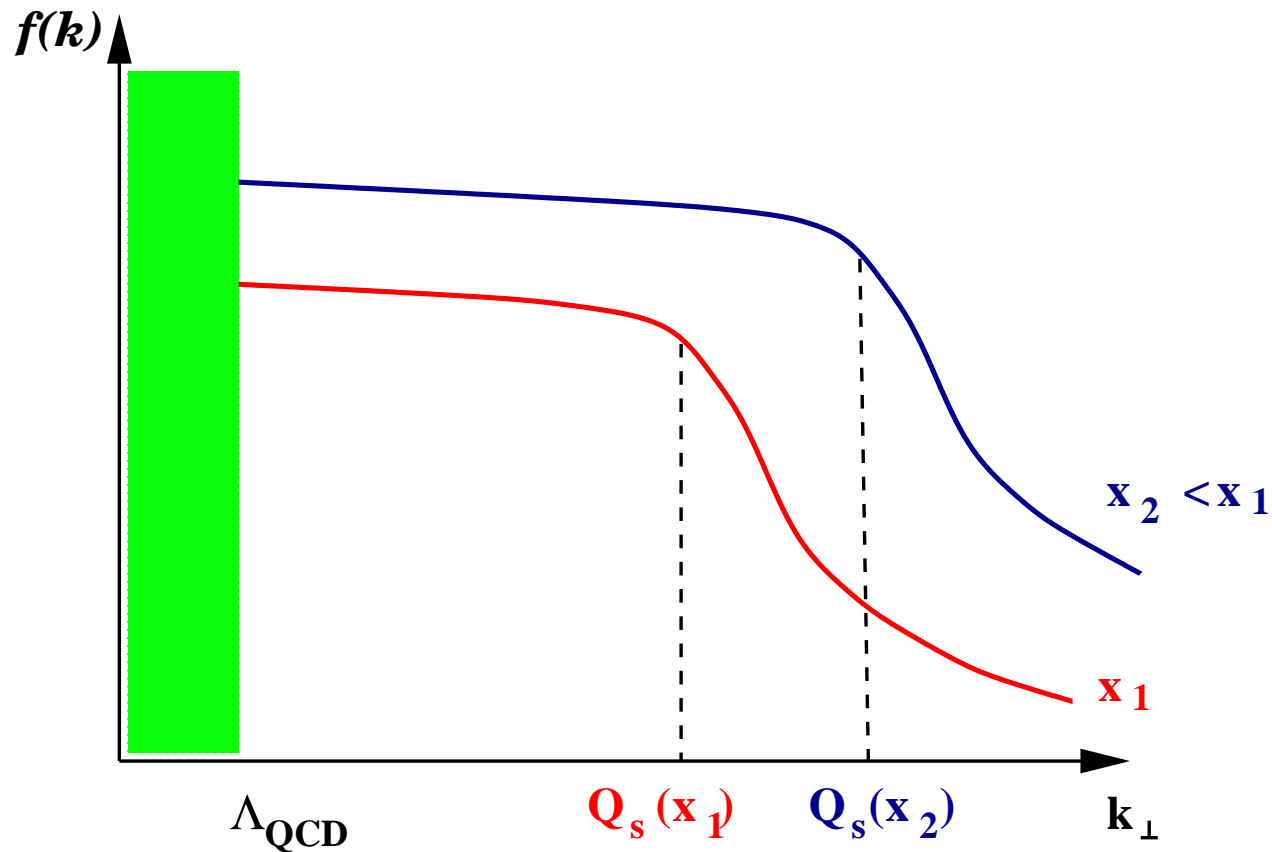
(Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner, 97'-01')

Saturation of gluon distribution - I



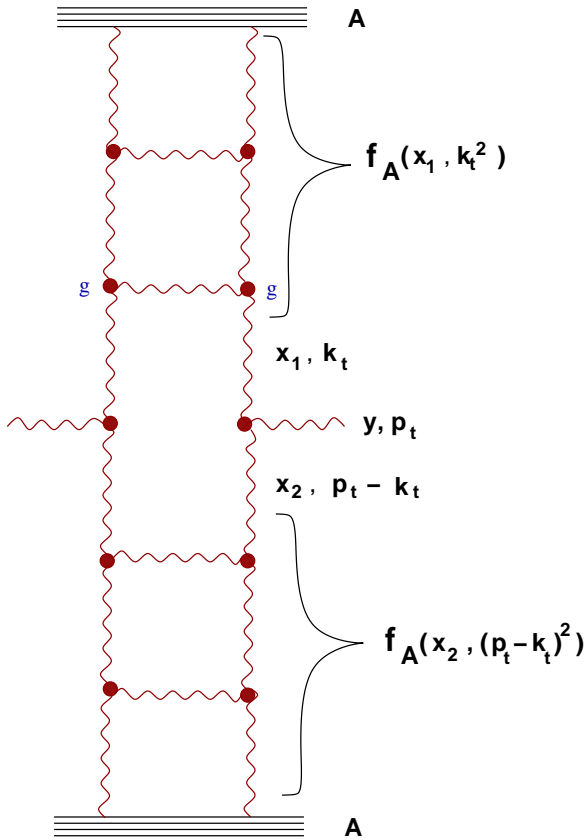
- saturation scale emerges: $Q_s^2(x, A) \sim (1/x)^\lambda A^{1/3}$
- pQCD behaviour $1/k_{\perp}^2$ changed into saturated one: $\ln(Q_s^2/k_T^2)$

Saturation of gluon distribution - II



Saturation scale gets **bigger** with increasing energy or A

CGC and RHIC data - I

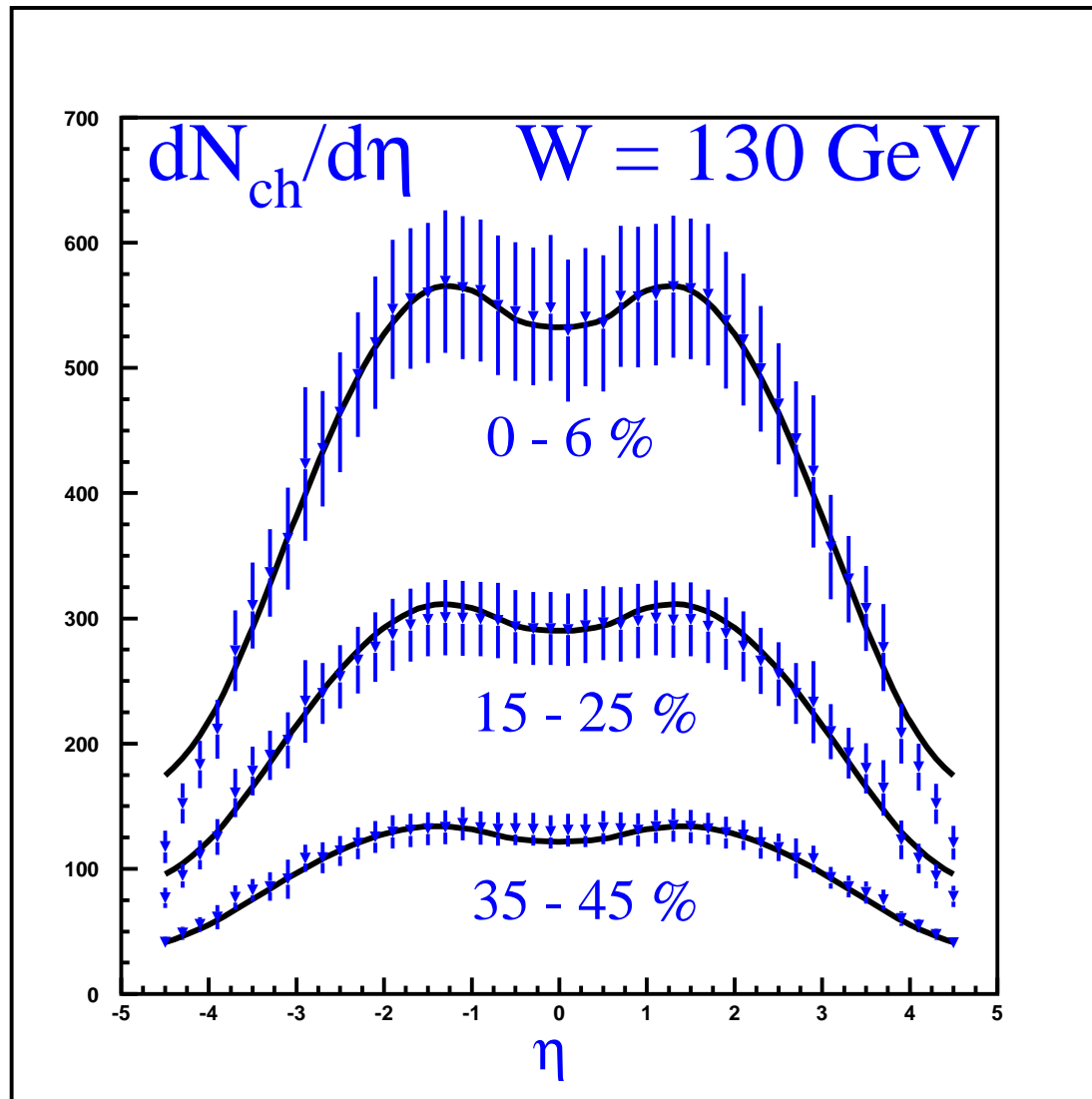


(Kharzeev, Levin, Nardi, 01'-02')

- central rapidities: energy deposited in form of **gluons**
- **parton-hadron** duality
- final state effects are not important
- k_{\perp} - factorization formula

$$\frac{dN}{dy} \sim \int \frac{d^2 p_{\perp}}{p_{\perp}^2} \int d^2 k_{\perp} \alpha_s f_A(x_1, k_{\perp}^2) f_A(x_2, (p_{\perp} - k_{\perp})^2) \quad x_{1,2} = \frac{p_{\perp}}{\sqrt{s}} e^{\pm y}$$

CGC and RHIC data - II



CGC and RHIC data - III

- Transition between initial and final state **is** important - **hydrodynamics**
- CGC distributions as **initial conditions** for hydro evolution

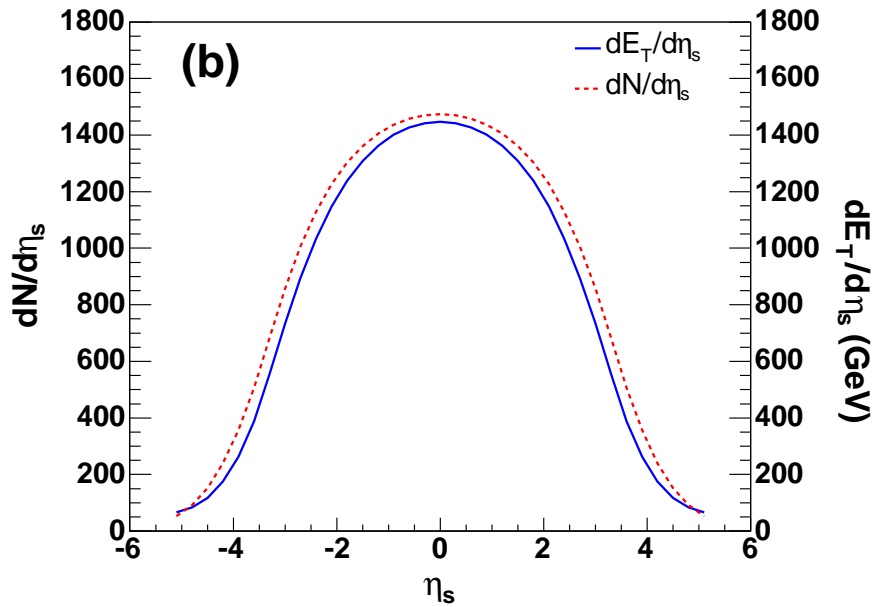
$$n_g(\tau_0, \vec{x}) = \frac{dN_g}{\tau_0 d\eta_s d^2x_\perp} \qquad e_g(\tau_0, \vec{x}) = \frac{dE_T}{\tau_0 d\eta_s d^2x_\perp}$$

with $\tau_0 = 0.5 - 1$ fm/c. (*Hirano, Nara, 04'*)

- CGC gluons are **thermalized** (*Baier, Mueller, Schiff, Son, 01'*)

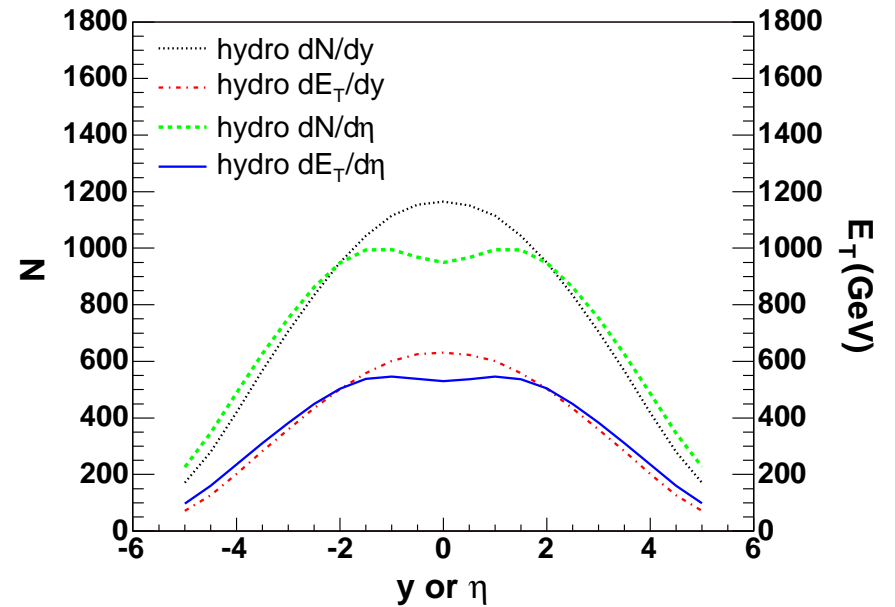
CGC and RHIC data - IV

Initial



$$E_T/N_g \approx 1 \text{ GeV}$$

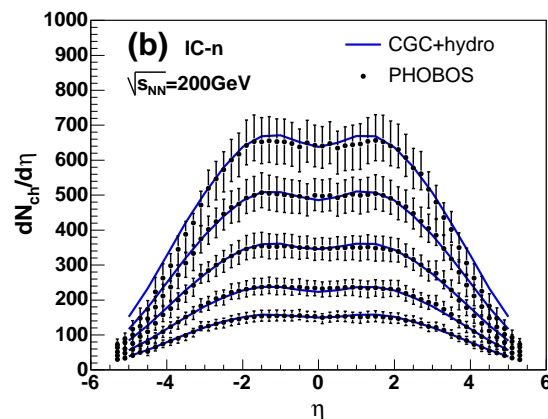
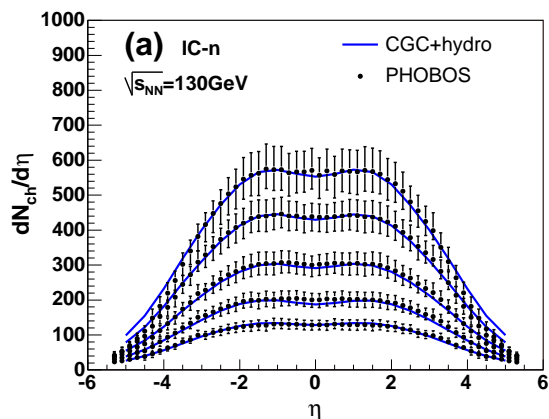
Final



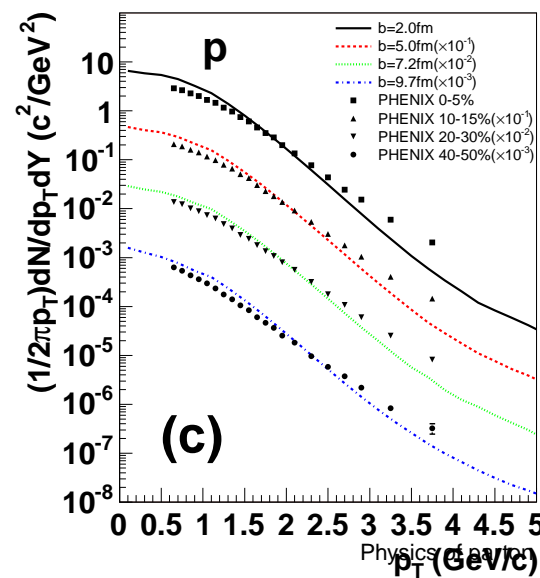
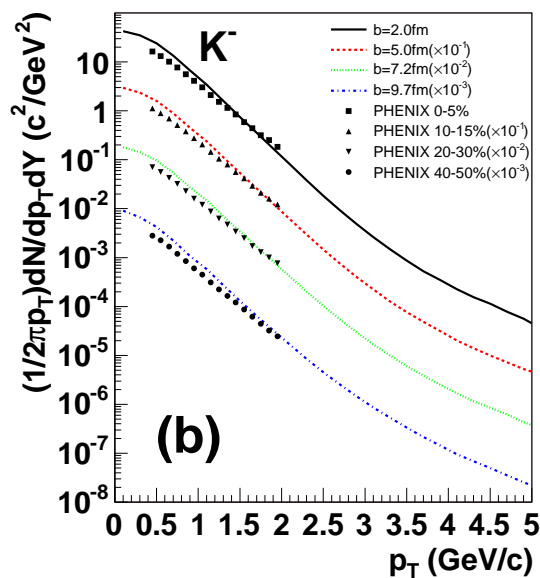
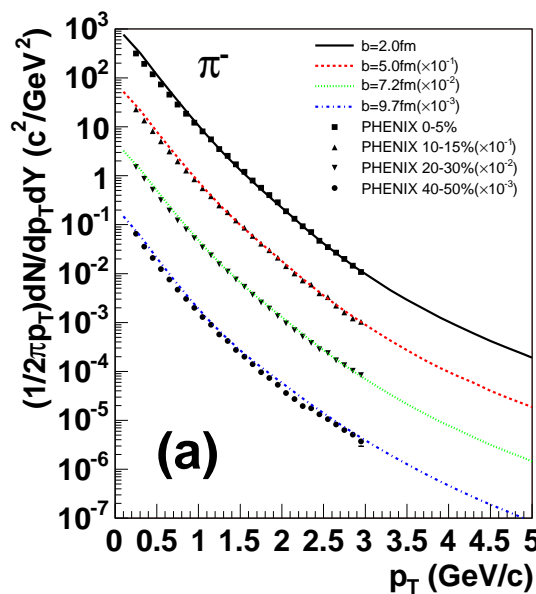
$$E_T/N_g \approx 0.5 \text{ GeV}$$

CGC and RHIC data - V

pseudorapidity spectra



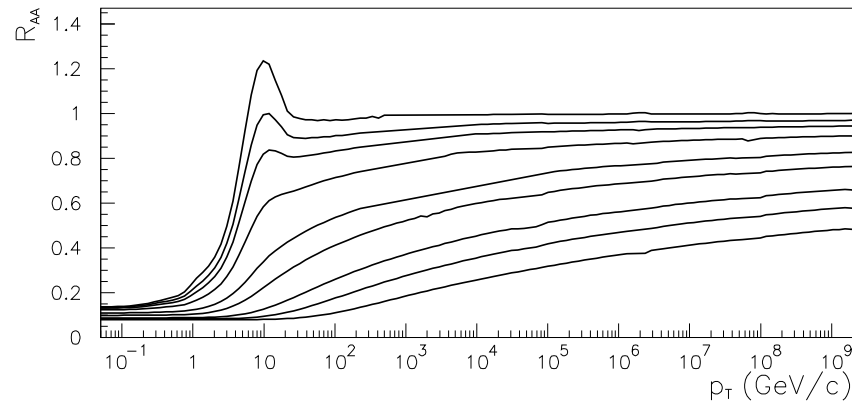
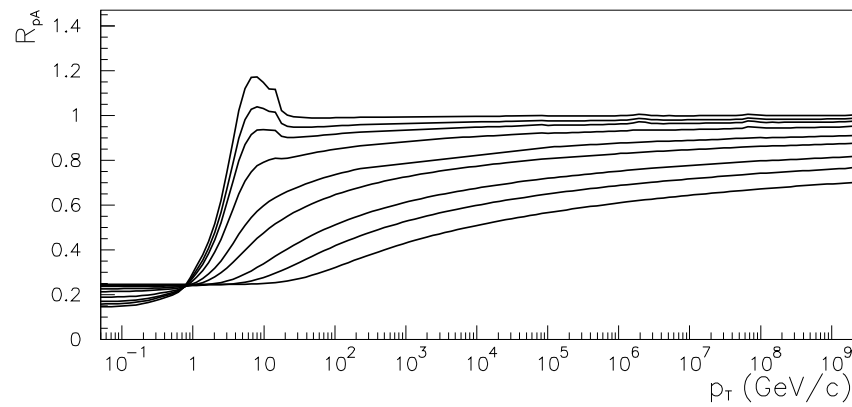
transverse momentum spectra



CGC and RHIC data - VI

Other effects:

- elliptic flow: **no** $v_2 \rightarrow 0$ with rising k_{\perp}
- Cronin effect: qualitatively **yes** (*Armesto et al., Kovchegov et al. 03'*)

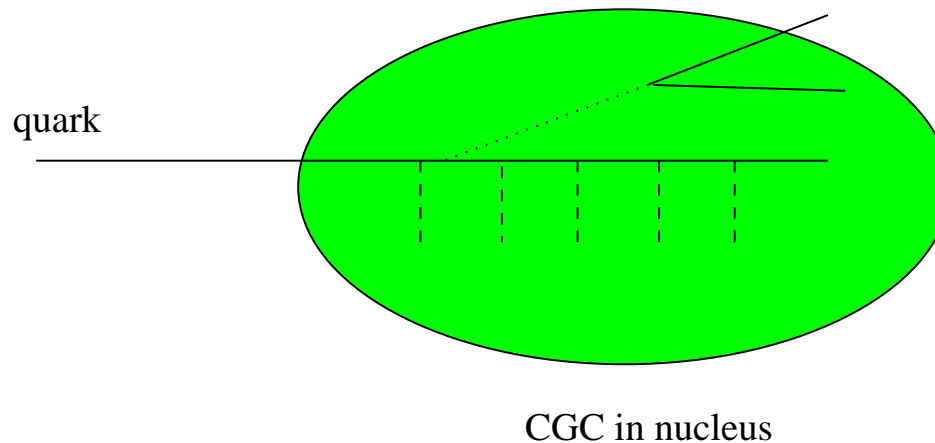


CGC and RHIC data - VII

Dedicated processes:

- photon production in dA collision
- dilepton production in dA collision
- forward quark jets in dA
- heavy quark production

Quark probe interacting with CGC.



Summary

- Color Glass Condensate is a new coherent state of gluonic matter
- up till now, no compelling evidence for CGC existence
- dedicated processes in dA collision give a chance