An unified description of HERA and RHIC data

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Based on PLB 643, 273 (2006)

Italy, July, 2007

- Motivation
- Dipole approach
- Models
- Results
- Summary

- Signals of parton saturation have already been observed both in *ep* DIS at HERA and in *dAu* collisions at RHIC
- HERA and RHIC have similar saturation scales
- Universality of the saturation physics (gluon evolution in the target wavefunction)
- Therefore we may look for a single parameterization of the dipole cross section that will be able to describe both sets of data

- In the CGC formalism the relevant observables are related to $\mathcal{N}$ (= forward dipole scattering amplitude)
- In principle $\mathcal{N}$ is determined from the solution of the Balitski-Kovchegov (BK) equation
- Present theoretical accuracy of BK is not good enough to allow for fits to the data
- We shall use the parameterizations inspired by the behavior of the BK solution (free parameters)

DIS - Dipole approach

F_2 structure function is probed in *ep* process:

$$F_2^p(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{\rm em}}(\sigma_T^{\gamma^* p} + \sigma_L^{\gamma^* p})$$

where

$$\sigma_{L,T}^{\gamma^* p}(x,Q^2) = \sum_f \int dz\, d^2r |\Psi_{L,T}^{(f)}(z,r,Q^2)|^2 \sigma_{dip}(x,r)$$

and

$$\sigma_{dip}(x,r) = 2\int d^2\mathbf{b}\, \mathcal{N}(x,r,\mathbf{b})$$

We assume

$$\mathcal{N}(x,r,\mathbf{b}) = \mathcal{N}(x,r)S(\mathbf{b}) \Rightarrow \sigma_{dip}(x,r) = \sigma_0 \mathcal{N}(x,r)$$

Single-inclusive hadron production in h-h process

$$x_F \frac{d\sigma^{pp(A)\to hX}}{dx_F\, d^2p_t\, d^2b} =$$
$$\frac{1}{(2\pi)^2} \int_{x_F}^{1} dx_p \frac{x_p}{x_F} \left[f_{q/p}(x_p, Q_f^2)\, \mathcal{N}_{\mathcal{F}} \left(\frac{x_p}{x_F} p_t, b \right) D_{h/q} \left(\frac{x_F}{x_p}, Q_f^2 \right) + \right.$$
$$\left. f_{g/p}(x_p, Q_f^2)\, \mathcal{N}_{\mathcal{A}} \left(\frac{x_p}{x_F} p_t, b \right) D_{h/g} \left(\frac{x_F}{x_p}, Q_f^2 \right) \right]$$

$f(x_p, Q_f^2)$ is the distribution function of parton from projectile
$D(z, Q_f^2)$ is the fragmentation function of parton in hadron
$\mathcal{N}_{\mathcal{F}}(k, b)$ and $\mathcal{N}_{\mathcal{A}}(k, b)$ are the dipole scattering amplitudes in the fundamental and adjoint representations

GBW model

K. Golec-Biernat, M. Wüsthoff (1999)

GBW model

$$\mathcal{N}(x,r) = \left[1 - \exp\left(-\frac{(Q_s(\tilde{x})\, r)^2}{4}\right)\right]$$

Definitions

$$\begin{aligned} Q_s^2(\tilde{x}) &= Q_0^2 \left(\frac{x_0}{\tilde{x}}\right)^{\lambda} \ \mathrm{GeV}^2 \\ \tilde{x} &= x_{bj}\left(1 + \frac{4\, m_f^2}{Q^2}\right) \end{aligned}$$

Parameters

$\sigma_0 = 23.03$ mb, $\lambda = 0.288$ and
$x_0 = 3.04 \times 10^{-4}$

IIM model

E. Iancu, K. Itakura, S. Munier (2004)

IIM model

$$\mathcal{N}(x,r) = \mathcal{N}_0 \left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/rQ_s)}{\kappa\lambda y}\right)} \qquad rQ_s \leq 2$$

$$\mathcal{N}(x,r) = 1 - e^{-a\ln^2(b\, rQ_s)} \qquad rQ_s > 2$$

Definitions

$y \equiv \ln\frac{1}{x}$ and $Q_s \equiv Q_s(x) = Q_0(x_0/x)^{\lambda/2}$

Parameters

$\sigma_0 = 2\pi R^2,\ R = 0.641 fm,\ \mathcal{N}_0 = 0.7,\ \lambda = 0.253,\ \kappa = 9.9$

KKT model

D. Kharzeev, Yu. Kovchegov, K. Tuchin (2004)

KKT model

$$\mathcal{N}(x,r) \;=\; 1-\exp\left[-\frac{1}{4}\left(\frac{C_F}{N_c}(r\,Q_s)^2\right)^{\gamma(y,r^2)}\right]$$

Definitions

$$\gamma(y,r^2) \;=\; \frac{1}{2}\left(1+\frac{\xi(y,r^2)}{\xi(y,r^2)+\sqrt{2\xi(y,r^2)}+7\zeta(3)c}\right)$$

$$\xi(y,r^2) \;=\; \frac{\ln\left[1/(r^2 Q_{s0}^2)\right]}{(\lambda/2)(y-y_0)}\,, \qquad Q_s^2(y) \;=\; \Lambda^2 A^{1/3} e^{\lambda y}$$

Parameters

$\Lambda = 0.6$ GeV, $\lambda = 0.3$, $y_0 = 0.6$ and $c = 4$.

DHJ model

Dumitru , Hayashigaki , Jalilian-Marian (2006)

DHJ model

$$\mathcal{N}(x,r) \quad = \quad 1 - \exp\left[-\frac{1}{4}\left(\frac{C_F}{N_c}(r\,Q_s)^2\right)^{\gamma(y,r^2)}\right]$$

Definitions

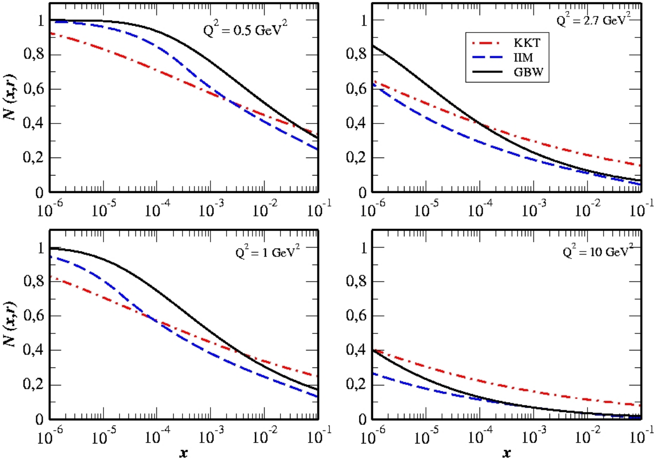
$$\begin{aligned} \gamma(Y,r^2) &= \gamma_s + \Delta\gamma(Y,r^2) \\ \Delta\gamma(Y,r^2) &= (1-\gamma_s)\frac{|\log\frac{1}{r^2 Q_T^2}|}{\lambda Y + |\log\frac{1}{r^2 Q_T^2}| + d\sqrt{Y}} \quad . \end{aligned}$$

Parameters

$$\lambda = 0.3,\ d = 1.2 \ \text{ and } \quad \gamma_s = 0.63.$$

Comparison

- Dipole scattering amplitude

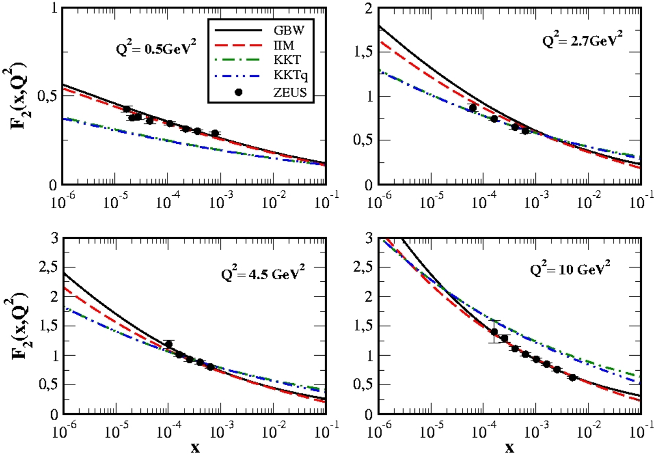


Comparison

- For large Q^2 (small separation of pair), the linear limit controls the amplitude
- GBW and IIM models show similar behavior
- KKT predicts a slow increase with the energy
- For large separation GBW and IIM predict that the amplitude should saturate and KKT shows a continuous increase in the same region

Comparison

- Nucleon structure function



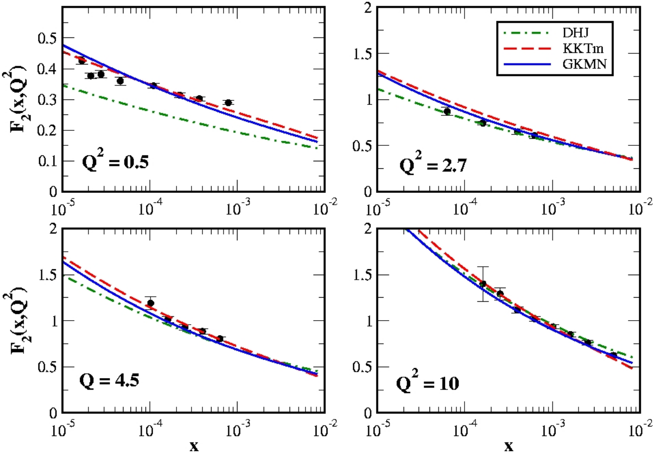
KKT predicts a slow dependence in energy which is slower than data

Comparison

- In Eur.Phys.J.C47:365(2006) a good description of the data at HERA for F_L was obtained with some changes in the original KKT model
- Here we make a small modification in the DHJ model, assuming that the typical scale has no dependence in energy: $Q_T = Q_0 = 1$ GeV

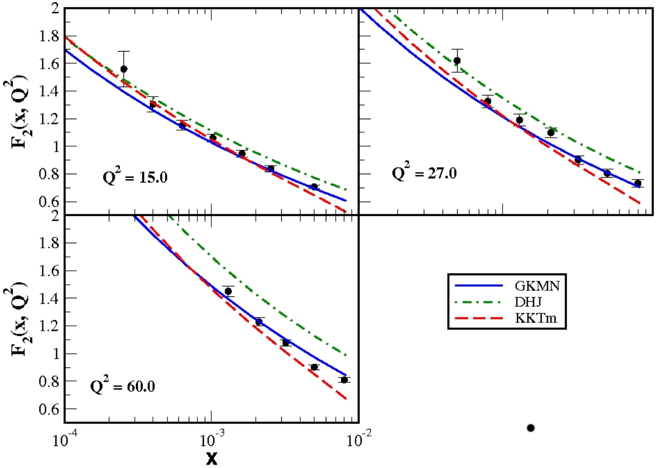
GKMN

- F_2^p

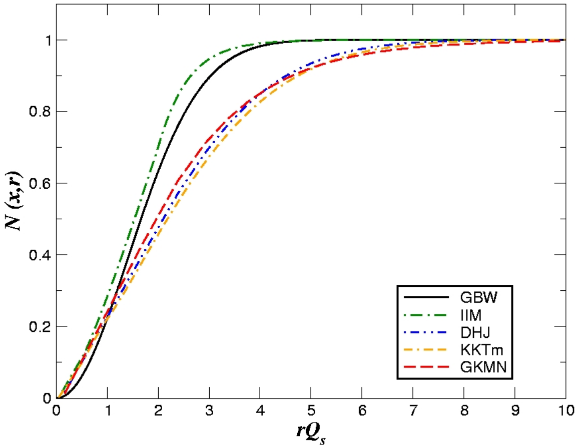


GKMN

- F_2^p

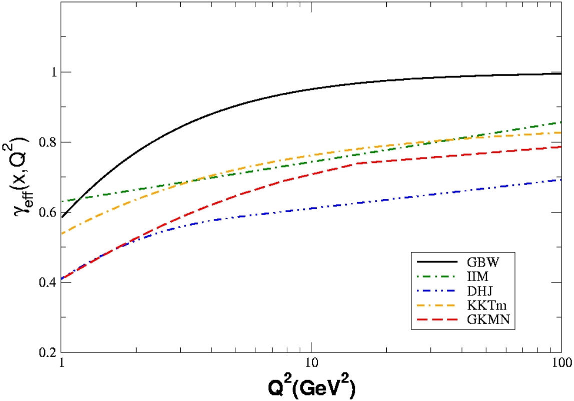

2
1.8
1.6
1.4
1.2
1
0.8
0.6
F2(x, Q2)
Q2 = 15.0
Q2 = 27.0
Q2 = 60.0
10-4
10-3
10-2
x
GKMN
DHJ
KKTm

GKMN



GKMN

- Anomalous dimension behavior: $\gamma_{eff} = \dfrac{d\mathcal{N}(rQ_s, Y)}{dln(r^2 Q_s^2/4)}$



$x = 3 \times 10^{-4}$

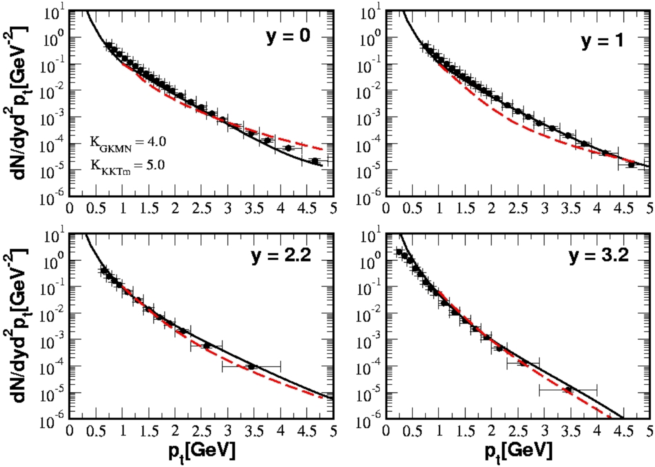
GKMN

- For large Q^2: GBW shows fast convergence; IIM increases moderately, converging to $\gamma \sim 0.85$; the same for KKTm
- At small Q^2 IIM and KKTm are different from each other
- DHJ and GKMN are similar at small Q^2 and differ from each other at large values of virtualities
- This difference can explain why the DHJ model doesn't describe the evolution in Q^2 of F_2

Can we describe *dAu* data with the changes in KKT (KKTm) and DHJ (GKMN) model?

GKMN

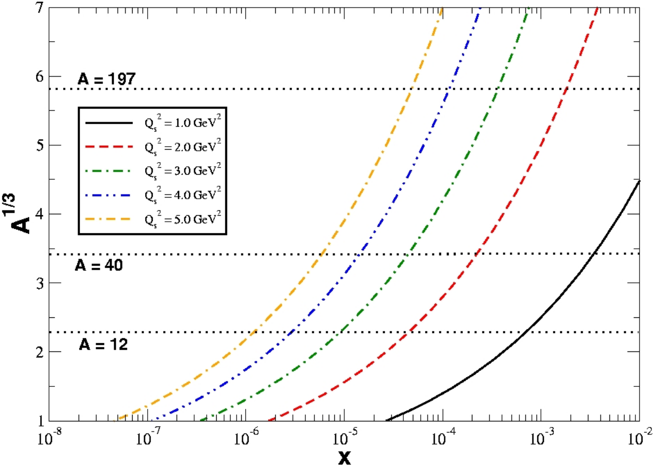
- Production of hadrons



- We have compared several models based in saturation physics
- The changes of KKT model made in EPJC47:365(2006) don't allow us to get a good description of *dAu* data
- Our modification in the DHJ model gives a good description of *ep* and *dAu* data in terms of an unique parameterization of the dipole scattering amplitude.

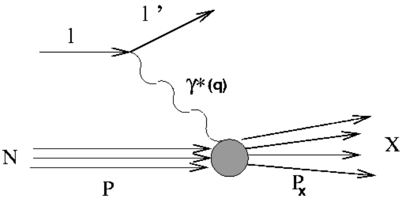

BASILICATA
Mare Jonio
Mare Tirreno
Mare Jonio

The saturation scales at HERA and RHIC are similar.



$$Q_s^2 \propto A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$$

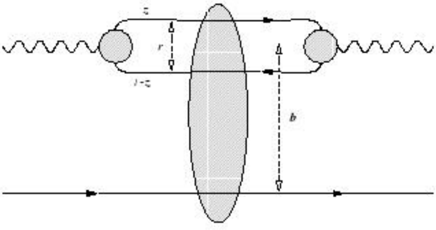
Kinematic



$$s = (l + P)^2$$
$$q^2 \equiv -Q^2 = (l - l')^2 = -4EE' sen^2(\theta/2)$$
$$W^2 = (P + q)^2$$
$$x = \frac{Q^2}{2m_N \nu} = \frac{Q^2}{2P.q} = \frac{Q^2}{Q^2 + W^2 - m_N^2}$$
$$y = \frac{P.q}{P.l}$$
$$xy = \frac{Q^2}{s - m_N^2} \approx \frac{Q^2}{s}$$

x is the Bjorken variable
y is the energy fraction of the initial electron transfers to hadron
W is the energy of system γ^*-nucleon

DIS - Dipole approach



At high energy the dipole time life is higher than the interaction time

DGLAP

- DGLAP equation (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)

$$\frac{\partial g(x,Q^2)}{\partial lnQ^2} = \frac{\alpha_s}{2\pi}\left[\int_x^1 \frac{dx_1}{x_1}\left(P_{gq}(\frac{x}{x_1})q_S(x_1,Q^2) + P_{gg}(\frac{x}{x_1})g(x_1,Q^2)\right)\right]$$

$$P_{gg}(x/x_1) = 2N_C\left[\frac{x/x_1}{(1-x/x_1)} + \frac{1-x/x_1}{x/x_1} + x/x_1(1-x/x_1)\right] + \ldots$$

q_S is the quark-singleto distribution

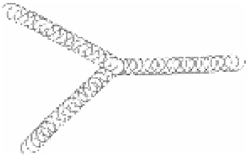
- If $x \ll 1 \Rightarrow$ gluons domain!
- Solution: $G(y,\Gamma) = G(\omega_0,\Gamma_0)\frac{\alpha_s N_c}{\pi}\frac{\Gamma^{\frac{1}{4}}}{(\frac{\alpha_s N_c}{\pi}y)^{\frac{3}{4}}}e^{2\sqrt{\frac{\alpha_s N_c}{\pi}\Gamma y}}$

  Double leading log aproximation (DLLA)
  $(y = ln(1/x),\, \Gamma = ln(Q^2/Q_0^2))$
- Number of gluons increase fastly.

GLR

- GLR equation

(Gribov-Levin-Ryskin)



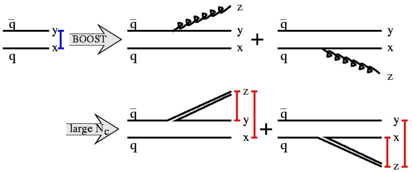
As the number of gluons is large, process of recombination become very important in the evolution. Competition between recombination and bremestalung effects of gluons in the DGLAP equation, when $\alpha_s xg(x, Q^2) \sim R^2 Q^2$.

$$Q^2 \frac{\partial^2 xg(x, Q^2)}{\partial ln(1/x)\ \partial Q^2} = \frac{\alpha_S N_c}{\pi} xg(x, Q^2) - \frac{4\alpha_S^2 N_c}{3C_F R^2} \frac{1}{Q^2} [xg(x, Q^2)]^2$$

The gluon saturation occurs to $Q = Q_s(x)$.

BK

- Balitsky-Kovchegov equation



$$\frac{\partial N_Y(r)}{\partial Y} = \int \frac{d^2 z}{2\pi} \overline{\alpha}_s \frac{r^2}{r_1^2 r_2^2} [N_Y(r_1) + N_Y(r_2) - N_Y(r) - N_Y(r_1) N_Y(r_2)] \quad (Y = ln(1/x))$$

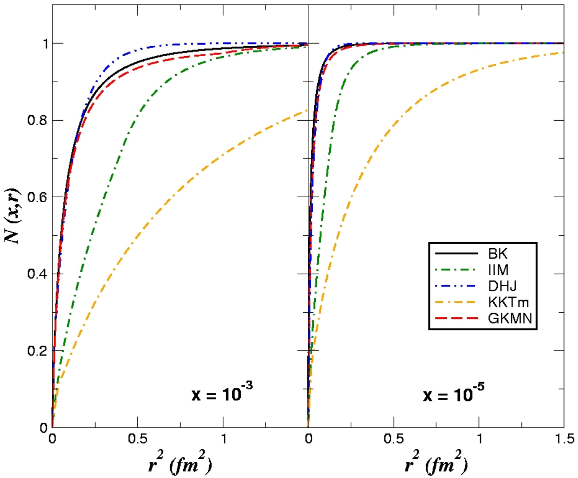
- For small dipoles $r \ll 1/Q_s(Y) \Rightarrow$ BFKL

$$N \simeq e^{\omega \overline{\alpha}_s Y} \frac{e^{\frac{1}{2} r}}{\sqrt{2\pi \beta \overline{\alpha}_s Y}} \exp\left\{ - \frac{r^2}{2\beta \overline{\alpha}_s Y} \right\}$$

- For large dipoles $r \gg 1/Q_s(Y) \Rightarrow$ Levin-Tuchin law

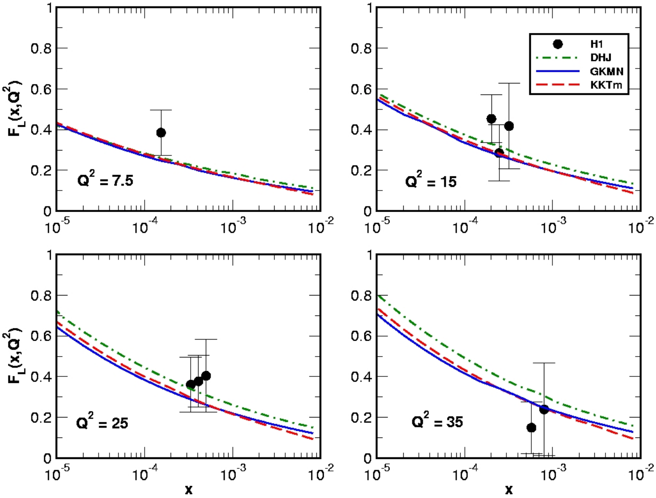
$$N(r, Y) \sim 1 - \kappa \exp\left(- \frac{1}{4c} ln^2(r^2 Q_s^2(Y)) \right)$$

GKMN

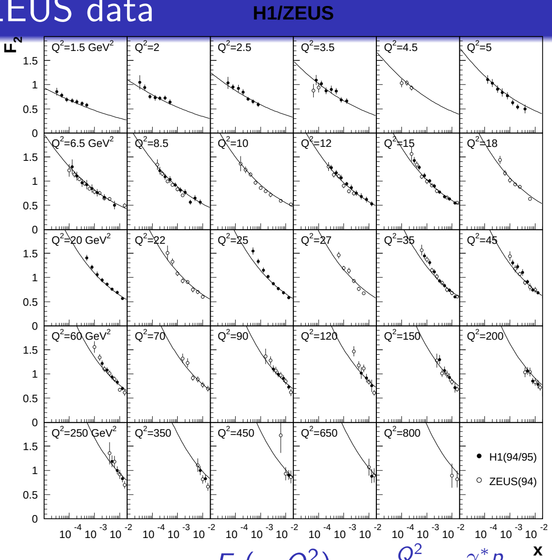

N (x,r)
1
0.8
0.6
0.4
0.2
0
0
0.5
1
0
0.5
1
1.5
r² (fm²)
r² (fm²)
x = 10⁻³
x = 10⁻⁵
BK
IIM
DHJ
KKTm
GKMN

GKMN

- F_L



H1 e ZEUS data

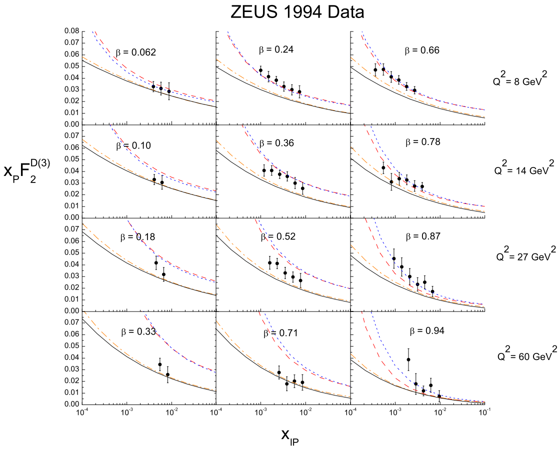


K. Golec-Biernat, M. Wusthoff (1999)

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

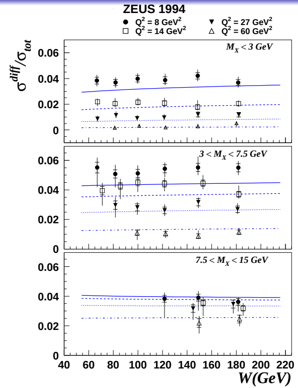
H1 and ZEUS data

- ZEUS



J.R.Forshaw, R.Sandapen, G.Shaw (2004)

H1 and ZEUS data

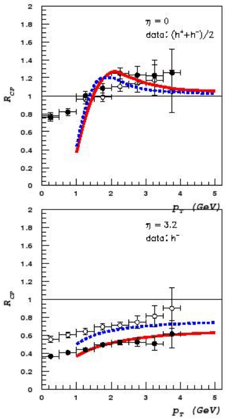


- The ratio is a flat function with the energy and decrease to large Q^2
- $\sim 10\%$ of events at HERA are difractives

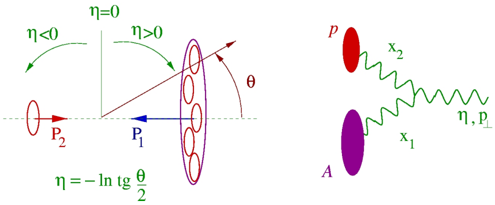
K. Golec-Biernat, M. Wusthoff (1999)

Nuclear modification factor

Collisons dAu - RHIC:



Kinematic:



$$x_1 \equiv \frac{p_\perp}{\sqrt{s}}\, e^{-\eta} \qquad x_2 \equiv \frac{p_\perp}{\sqrt{s}}\, e^{\eta} \quad \eta = \frac{1}{2} ln(\frac{x_2}{x_1})$$

$p_\perp = 2$ GeV	$\eta = 0$	$\eta = 3.2$
RHIC ($\sqrt{s} = 200$)	$\approx 10^{-2}$	$\approx 10^{-4}$
LHC ($\sqrt{s} = 5500$)	$\approx 10^{-4}$	$\approx 10^{-5}$

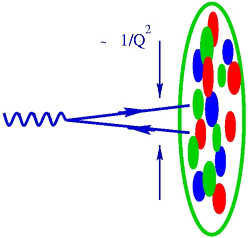
- When $R_{CP} > 1 \rightarrow$ "Pico Cronin"
- When $R_{CP} < 1 \rightarrow$ Supress of "Pico Cronin"

How is obtain Q_s ?

- When the linear and non-linear terms are the same in the GLR equation

$$Q_s^2 = \frac{4\pi\alpha_s}{3C_F}\frac{1}{R^2}xg(x, Q^2)$$

- By geometric arguments



$$r \propto \frac{1}{\sqrt{Q^2}} \quad (1)$$

How obtain Q_s ?

- Each gluon has the transverse area π/Q^2 and

$$\sigma_{dip-g} \sim \alpha_s(Q^2)\frac{\pi}{Q^2}$$

  The transverse area of target will be $S_A \sim \pi R_A^2$.

- When:

$$S_A = N_A\sigma \rightarrow N_A \sim \frac{S_A}{\sigma} \sim \frac{R_A^2}{\alpha_s}Q^2$$

  the recombination happens!

- Then the saturation scale will be:

$$Q_s^2 \sim \alpha_s\frac{N_A}{R_A^2} \sim \frac{\alpha_s}{R_A^2}Axg(x,Q^2) \sim \alpha_s A^{1/3}xg(x,Q^2)$$

"Cartoon" of QCD evolution