TERrA incognita at low x

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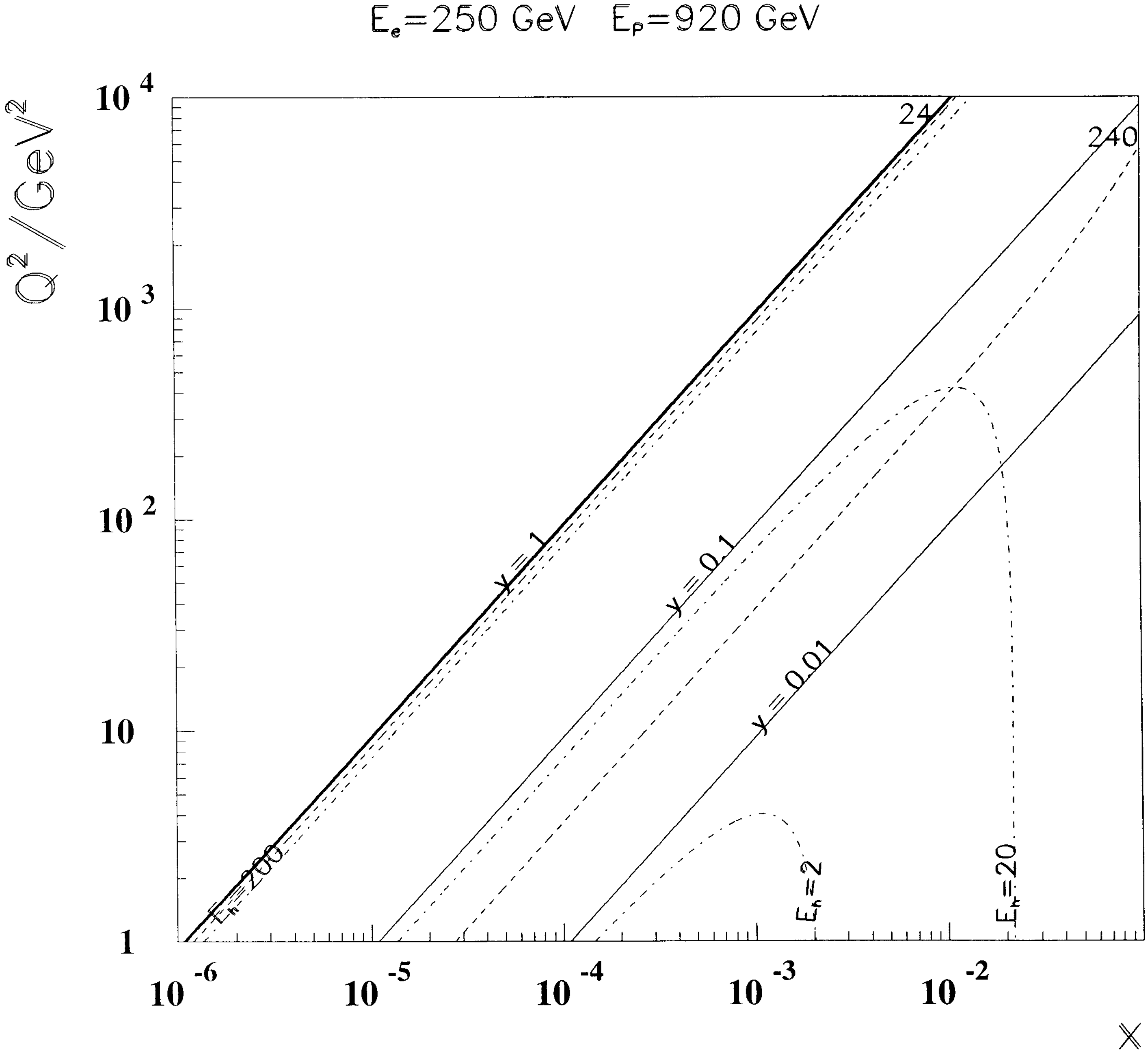
- Lessons from HERA.
- Theory status.
- What we need to do. (WWNTD)

Style: honest,
objective,
provocative and
personal
report
on ups and downs
in low x physics

"I got what I wanted, but it wasn't what I expected."


E_e=250 GeV E_p=920 GeV
Q^2/GeV^2
10^4
10^3
10^2
10
1
10^-6
10^-5
10^-4
10^-3
10^-2
X
y=1
y=0.1
y=0.01
24
240
E_h=200
E_h=2
E_h=20

at TERA we hope:

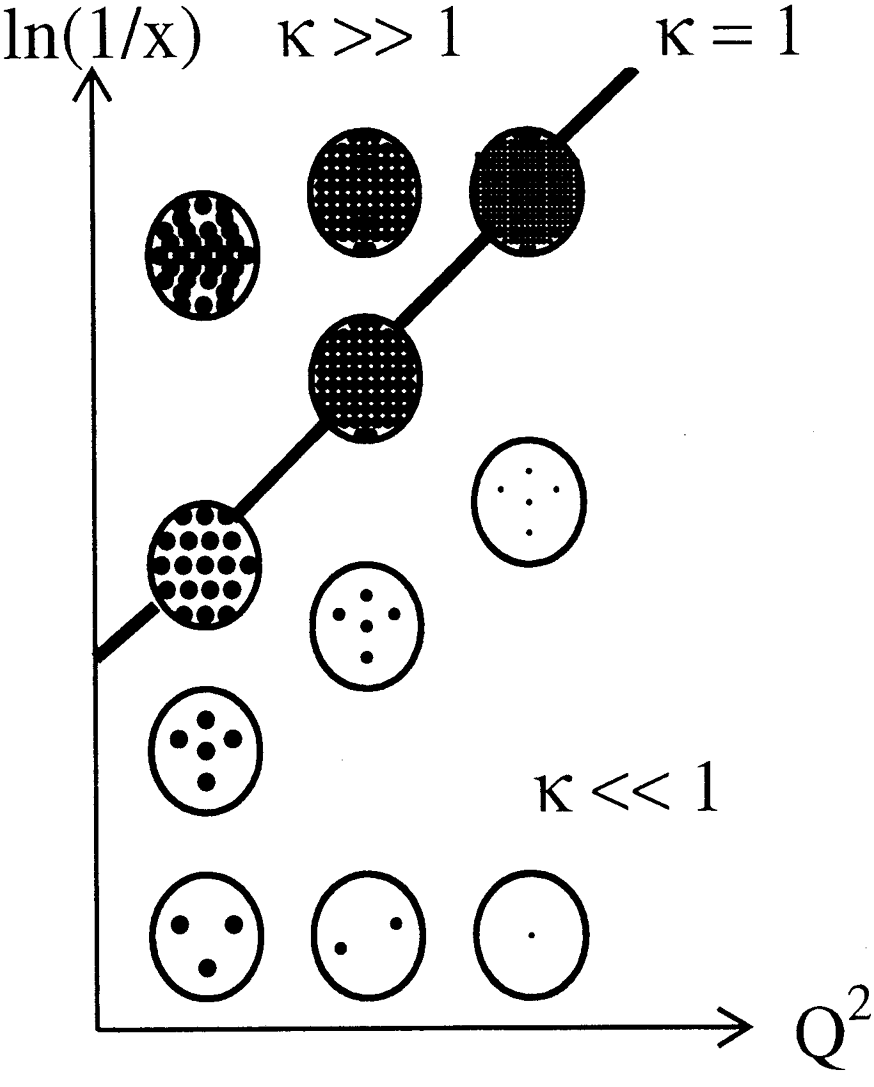
1. $x \longrightarrow 10^{-6}$

2. at HERA kinematic region ($x \approx 10^{-4}$) larger Q^2

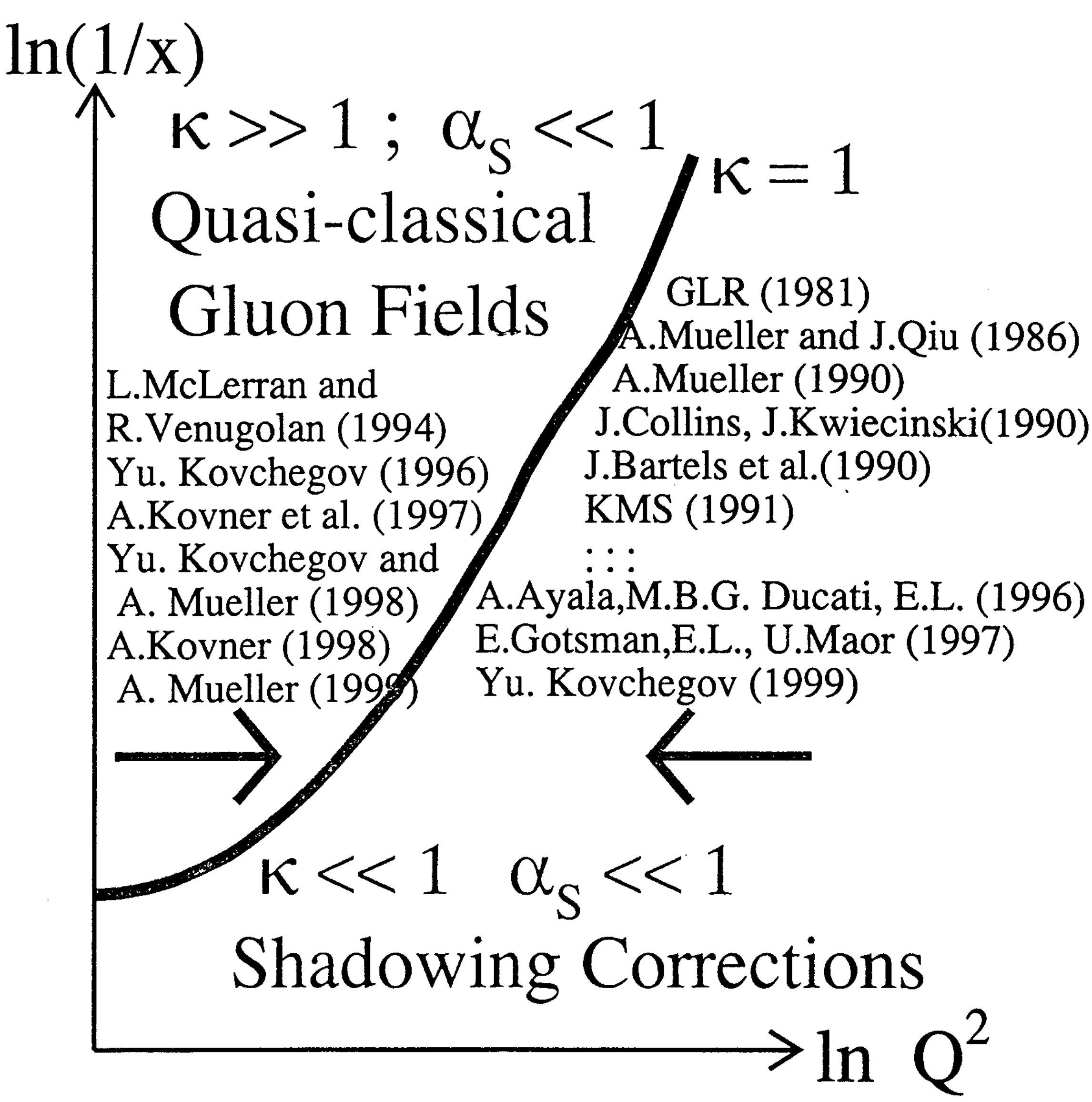
3. Better experimental detecting of the forward (proton fragmentation) jets.

High Parton Density QCD

(A reminder)



$$\kappa \;=\; \frac{3\,\pi^2\alpha_s}{2Q^2} \times \frac{xG(x,Q^2)}{\pi\,R^2}$$


ln(1/x)
κ >> 1 ; α_s << 1
Quasi-classical
Gluon Fields
κ = 1
L.McLerran and
R.Venugolan (1994)
Yu. Kovchegov (1996)
A.Kovner et al. (1997)
Yu. Kovchegov and
A. Mueller (1998)
A.Kovner (1998)
A. Mueller (1999)
GLR (1981)
A.Mueller and J.Qiu (1986)
A.Mueller (1990)
J.Collins, J.Kwiecinski(1990)
J.Bartels et al.(1990)
KMS (1991)
: : :
A.Ayala,M.B.G. Ducati, E.L. (1996)
E.Gotsman,E.L., U.Maor (1997)
Yu. Kovchegov (1999)
κ << 1 α_s << 1
Shadowing Corrections
ln Q^2

Theoretical status:

- κ is the parameter which controls the strength of SC;
- We know the correct defrees of freedom: colour dipoles (A. Mueller (1994));
- We know that the GLR - equation describes the evolution of the dipole density in the full kinematic region;

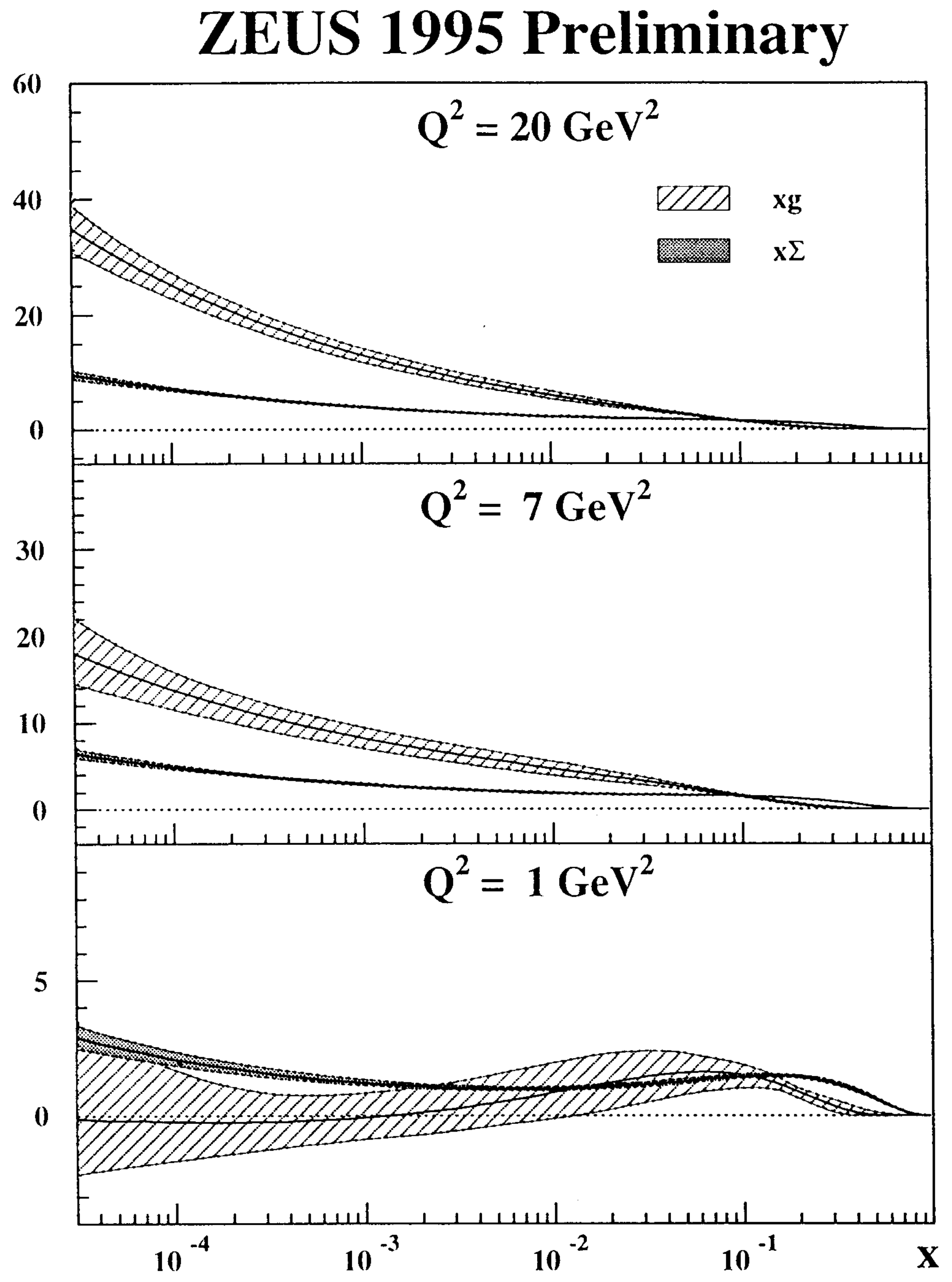
$$\frac{d\kappa(y,q^2)}{dy} = \frac{N_c\alpha_S}{\pi} \int \mathbf{K}^{BFKL}(q^2, q'^2)\ \kappa(y, q'^2) \left\{ 1 - \frac{1}{4}\kappa(y, q'^2) \right\}$$

Yu. Kovchegov (1999)

- We are very close to understanding of the parton density saturation (GLR (1983));

HERA proves that hd QCD region has been reached 1

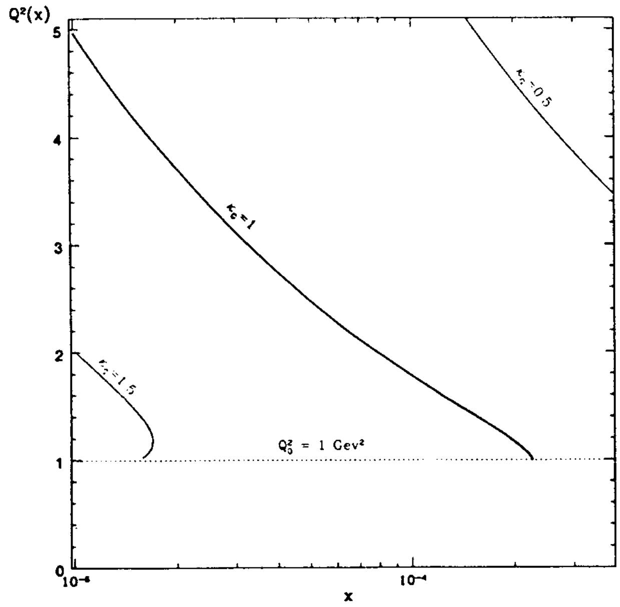
$x \to 1$

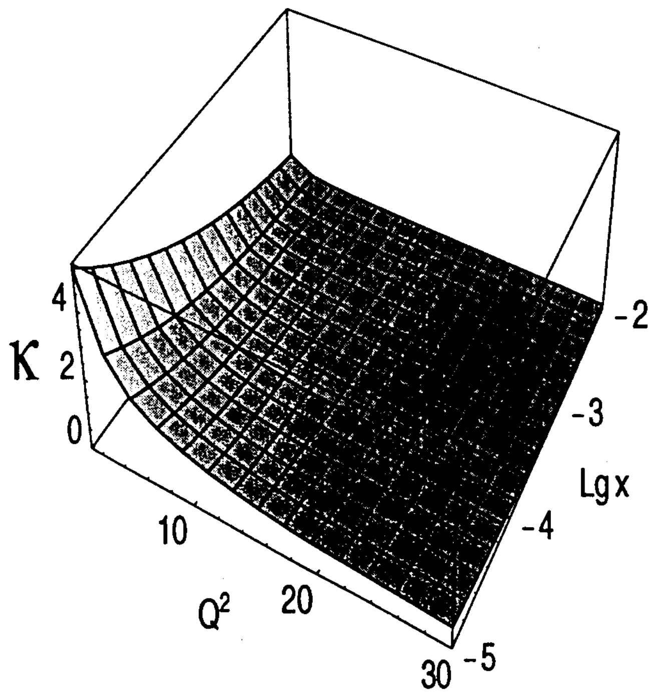

ZEUS 1995 Preliminary
Q² = 20 GeV²
xg
xΣ
Q² = 7 GeV²
Q² = 1 GeV²
60
40
20
0
30
20
10
0
5
0
10⁻⁴
10⁻³
10⁻²
10⁻¹
x

Where are SC?

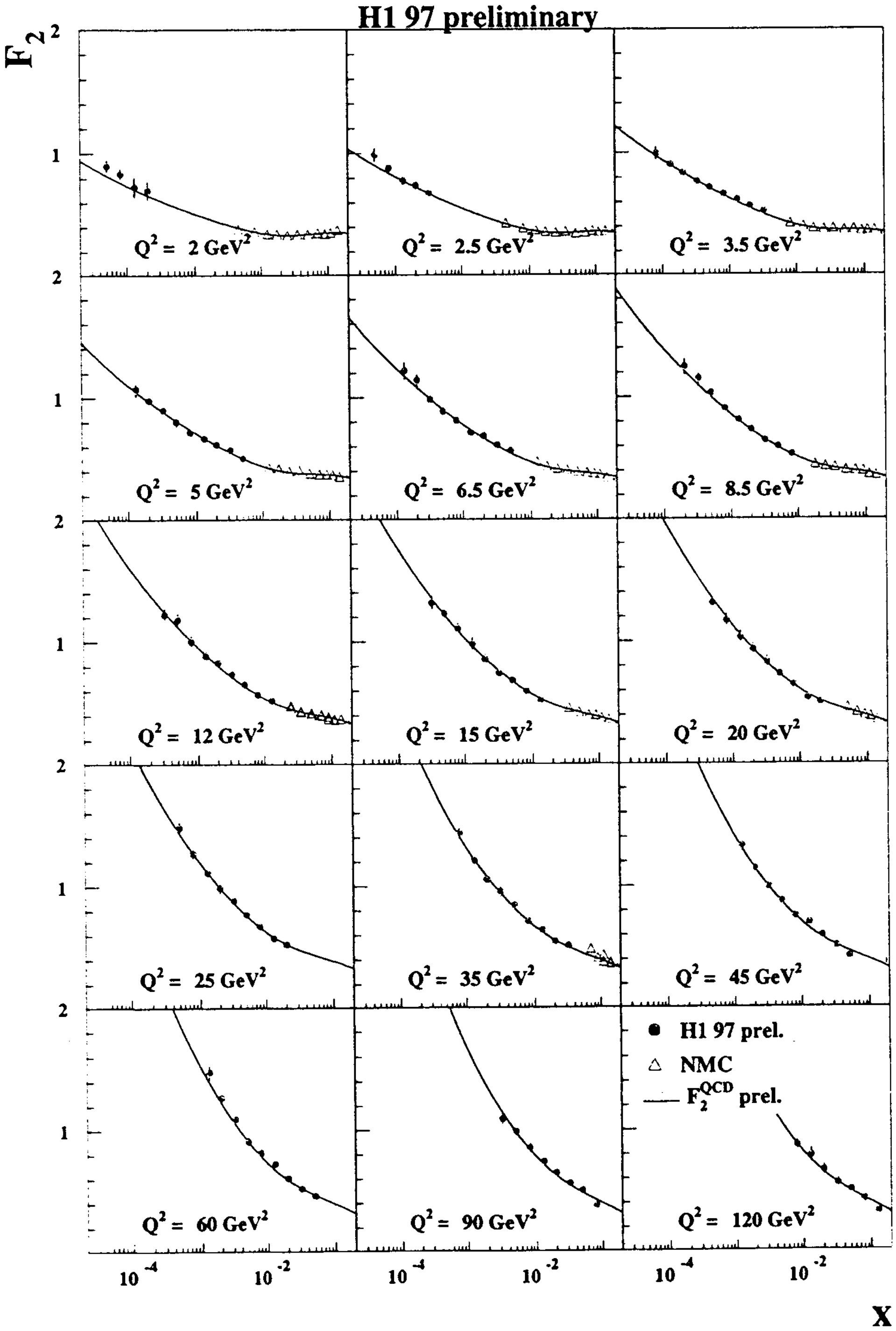
HERA puzzle :

- HERA $\Longrightarrow$ DGLAP evolution ;
- HERA $\Longrightarrow$ high parton (gluon) density ;





$F_2(x, Q^2)$ vs NLO QCD fit



- F_L assumption based on QCD fit (small influence)
- Precision: $\simeq$ 1% (stat) 3-4 % (syst)
- DGLAP describes the data very well...

  ...even at low Q^2 and low x!

Theory:

$*$ Scales in non-perturbative QCD:

1. Radius of confinement (Radius of hadrons)
   $R_{conf} \approx \frac{1}{\Lambda_{QCD}} \approx 1\,fm$ where $\alpha_S = \frac{4\pi}{b\ln(Q^2/\Lambda^2_{QCD})}$.

   Q $\longrightarrow \Lambda_{QCD}$ $\alpha_S \longrightarrow \infty$

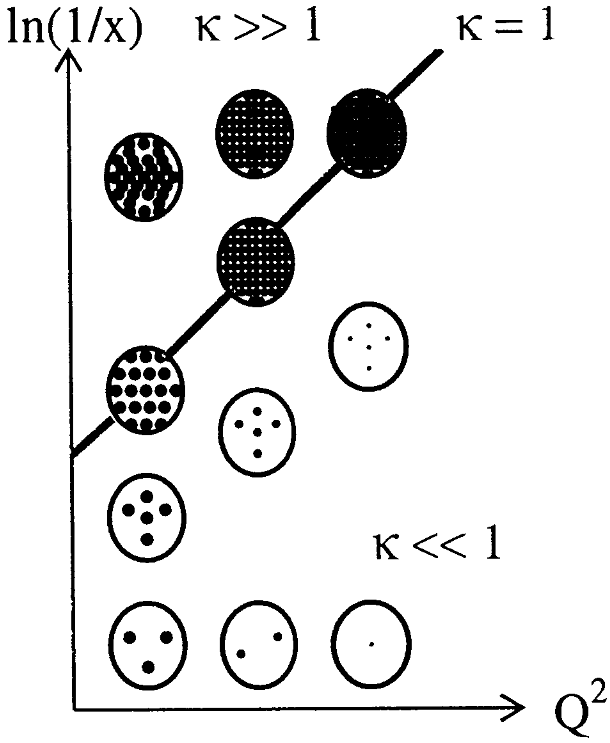
2. Radius of chiral symmetry breaking (Radius of a constituent quark)
   $R_{SB} \sim <\rho> \approx 0.2\,fm$ where $<\rho>$ is the average size of the instanton in a hadron (Schafer and Shuryak, RMP (1998))

$$\mathbf{R}_{conf} \gg R_{SB}$$

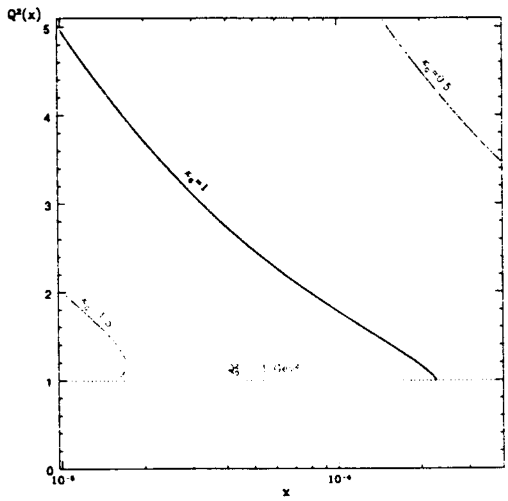
3. Scale of factorization breaking

$R_{BF} \approx \frac{1}{Q_0(x)}$ where $Q_0(x)$ is the average transverse momentum in the parton cascade of the fast hadron.

GLR (1981)
Mueller and Qiu (1986)
....
Mueller (1997)



$R_{conf} >> R_{SB} >> R_{BOPE}$



Equation for $Q_0(x)$:

$$\kappa = xG(x,Q^2)\frac{\sigma(GG)}{\pi R_h^2} = \frac{3\pi\alpha_s(Q_0^2(x))}{Q_0^2(x)\ R_h^2}\, xG(x,Q_0^2(x)) = 1$$

Golec - Bierat and Wüsthoff approach:

- $\sigma(\gamma^* \mathbf{p}) \;=\; \int\int \mathbf{d^2 r_\perp \, dz} \, |\Psi(\mathbf{Q^2; z, r_\perp})|^2 \, \sigma(\mathbf{x, r_\perp})$;

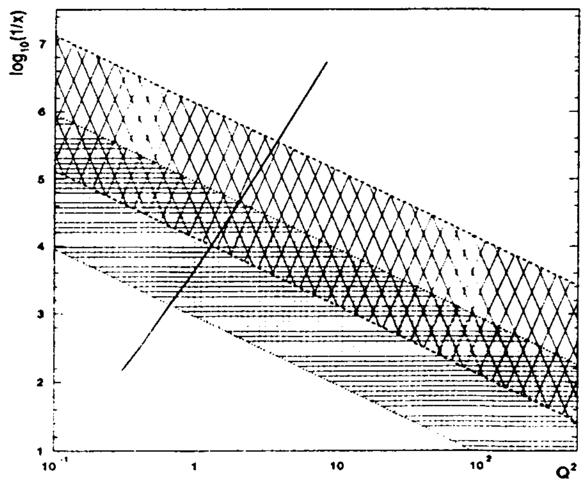
- $\sigma(\mathbf{x, r_\perp}) \;=\; \sigma_0 \left\{ \mathbf{1} \;-\; \mathbf{e}^{-\frac{\mathbf{r_\perp^2}}{\mathbf{R^2(x)}}} \right\}$;

- $\mathbf{R^2(x)} \;=\; \mathbf{1/Q_0^2(x)}$, where $\mathbf{Q_0^2(x)} \;=\; \mathbf{Q_0^2} \left(\frac{\mathbf{x}}{\mathbf{x_0}} \right)^{-\lambda}$;

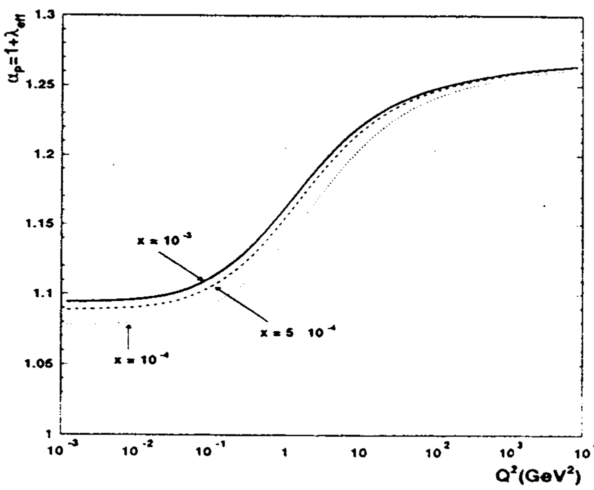
HERA TERA

$Q_0^2(x) = 0.7 - 2\,GeV^2 \quad 2 - 5\,GeV^2$

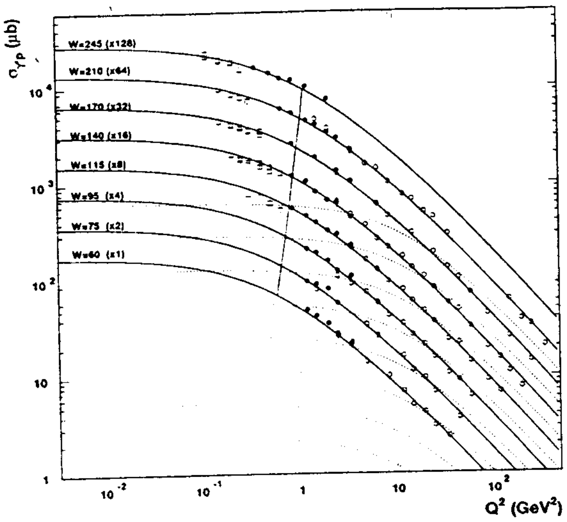
- $\sigma_0 = \mathbf{23.03\,mb}$
$\lambda = \mathbf{0.288}$
$\mathbf{x_0} = \mathbf{3.04\,10^{-4}}$
$\mathbf{Q_0^2} = \mathbf{1\,GeV^2}$



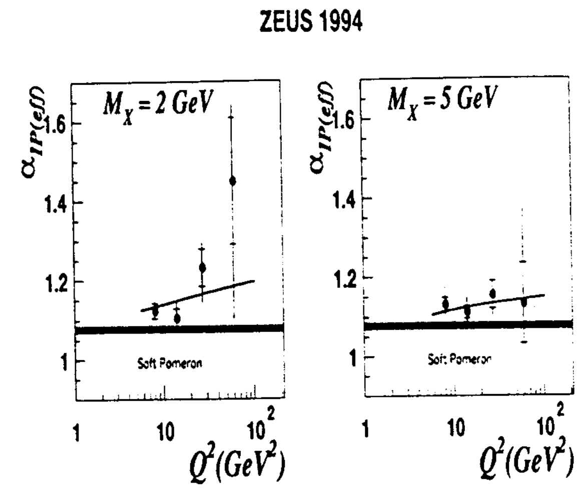
- **The critical line** $\mathbf{Q^2 = Q_0^2(x)}$



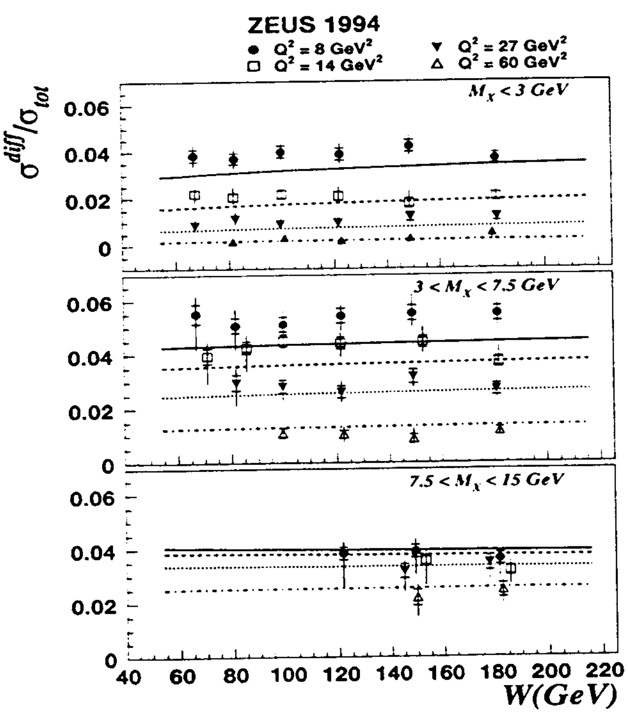
- **The effective** $\alpha_{\mathbf{P}}(0)$



- $\sigma_{\rm tot}(\gamma^* {\rm p})$



- **The effective** $\alpha_{\rm P}(0)$



- **Ratio** $\sigma_{\rm DD}/\sigma_{\rm tot}$

HERA experiments 2 are not selective Because they are unique

- Only in F_2 and DD we can reach $x \sim 10^{-4}$
- Practically, we cannot measure $Q_0^2(x)$ as a scale for violation of the factorization theorem. →
- We have not found yet an observable which is the most sensitive to hd QCD effects

But we have two (Q.5) indications for hd QCD:

$*$ How to measure R_{BT}. ?

$*$ "Hard" factorization (Collins,Soper and Sterman (1988)) :

- Formulation:
  $\sigma(A+B\to jets(p_t)+X)\ =$
  $F^i_A(\mu^2)\otimes F^i_A(\mu^2)\otimes\sigma^{hard}(partons\ with\ p_t\geq k_t\geq\mu)$

- *Factorization theorem does not work for* $\mu\ll p_t\ll Q_0(x)=1/R_{BF}$

  Mueller and Qiu (1986)
  Kwiecinski (1991)
  E.L.,Ryskin, Shuvaev (1992)
  Mueller (1990)
  Laenen and E.L. (1994)
  Mueller (1997)

- Experimental checks and theoretical studies are needed on F T

1. $\frac{dF_2}{d\ln Q^2}$

2. $\sigma_{DD} \sim \left(\frac{1}{x}\right)^{\alpha_{eff}}$

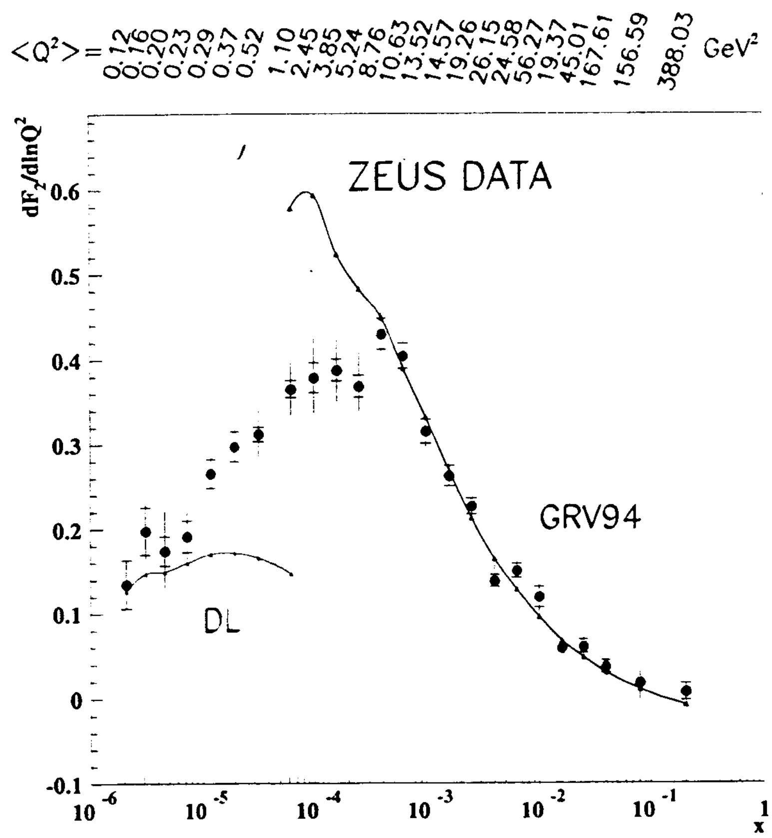
$\alpha_{eff} > \alpha_{soft}$

2.5. $\frac{\sigma_{DD}}{\sigma_{tot}} = Const(s)$

The effect of screening on the x and Q^2 dependances of the F_2 - slopes

- E. Gotsman, E.L.& U. Maor : Phys. Lett. B 425 (1998) 369;
- E. Gotsman, E.L., U. Maor & E. Naftali: hep-ph/9808257.

ZEUS 1995 Preliminary



- ZEUS (1998) (Caldwell - plot)

Questions and Hopes :

- A new sufficiently large scale ($Q \approx 1.5 - 2\,GeV$) for transition from "hard" to "soft" interaction ?

- A manifestation of SC ?

- A hope for theoretical approach to npQCD ?

- Our hope and ideas:

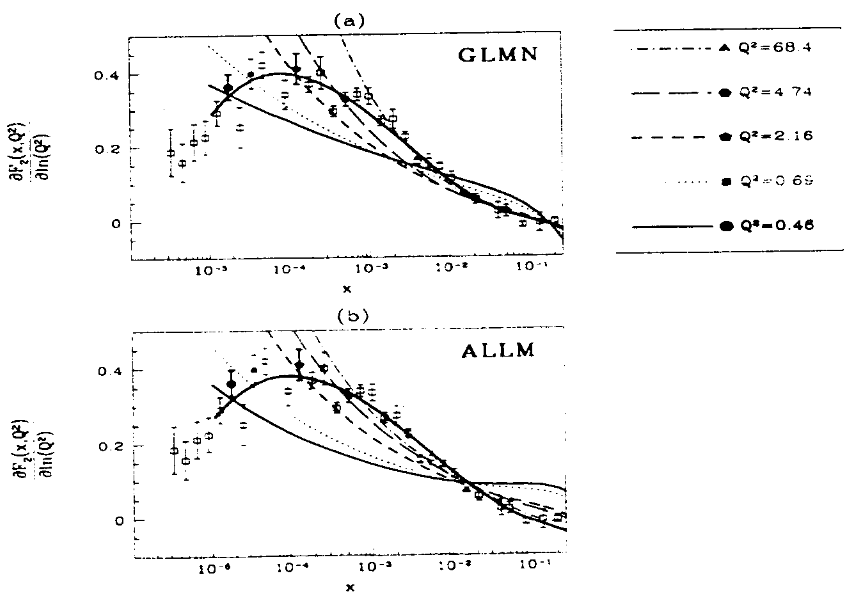
  1. SC for description of the transition between "hard" and "soft" processes ;

  2. Use of the ALLM'97 parameterization as a pseudo date base .

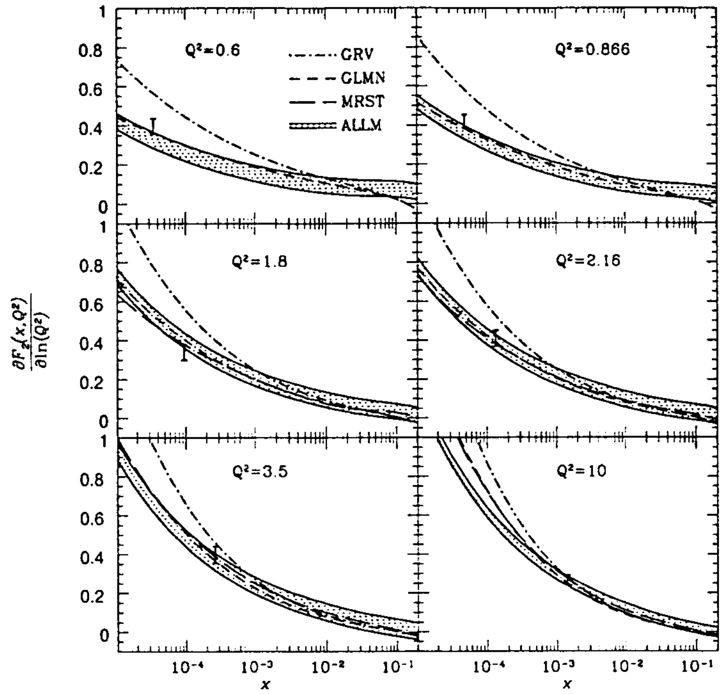
* *
* *

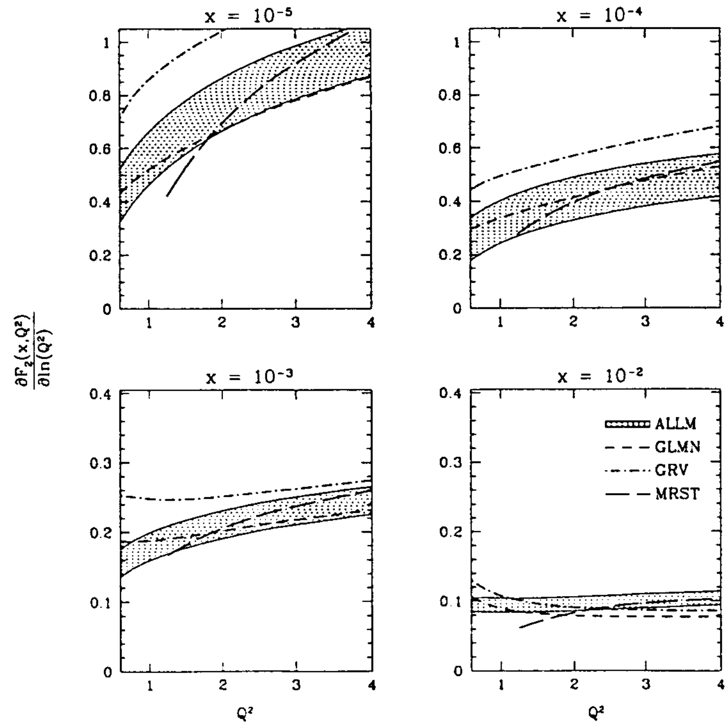
It is not so bad, is it?

* *
* *



Comparison with the pseudo data base (ALLM'97):





Alternative description (MRST - parameterization):

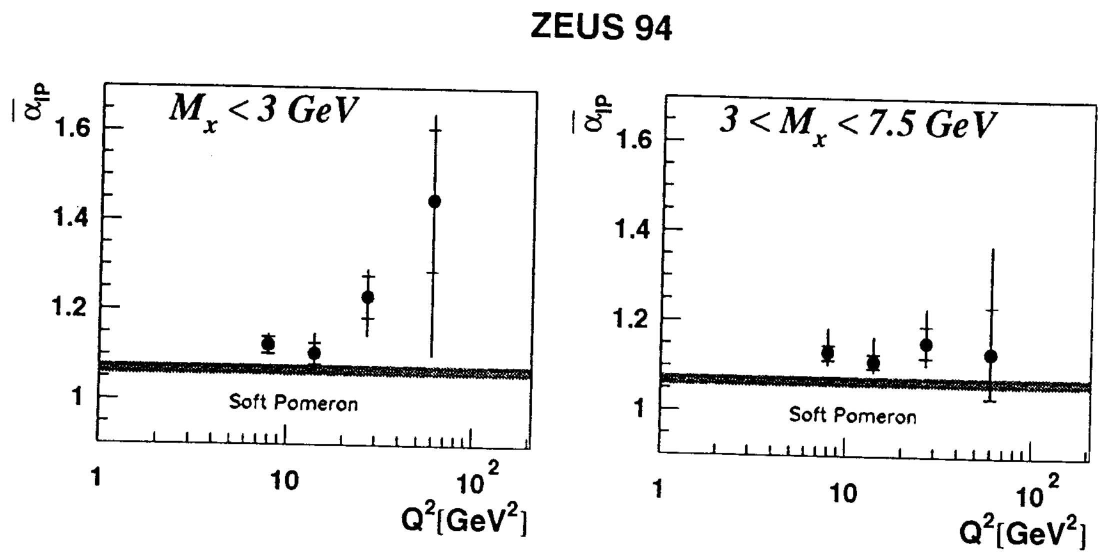
$$\frac{\partial F_2}{\partial \ln Q^2} = \frac{2\alpha_S}{9\pi}\, x\, G^{DGLAP}(x, Q^2)$$

- **The DGLAP evolution equation $+$ essential decrease of xG at small x for initial gluon distribution .**

x_P - dependance of σ_{DD} :

- E. Gotsman, E.L.& U. Maor : Nucl. Phys. B493 (1997) 354.

DATA:



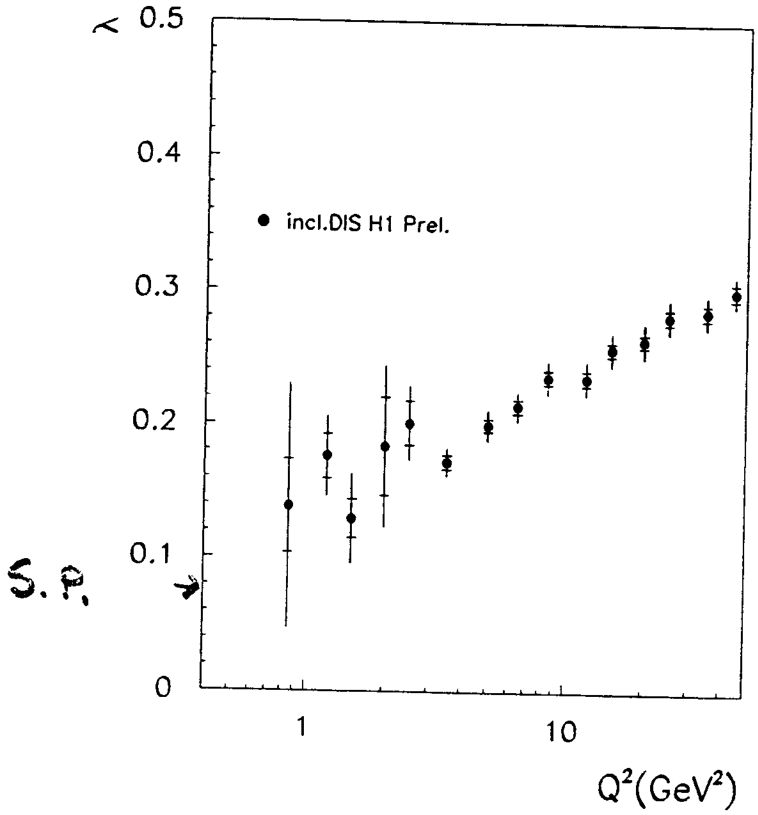
$$\sigma_{DD} \propto \frac{1}{x^{2\,\Delta_P}}$$

where $\Delta_P = \alpha_P(0) - 1.$

H1 : $\alpha_P = 1.2003 \pm 0.020$ (stat.) $\pm$ 0.013 (sys.) ;

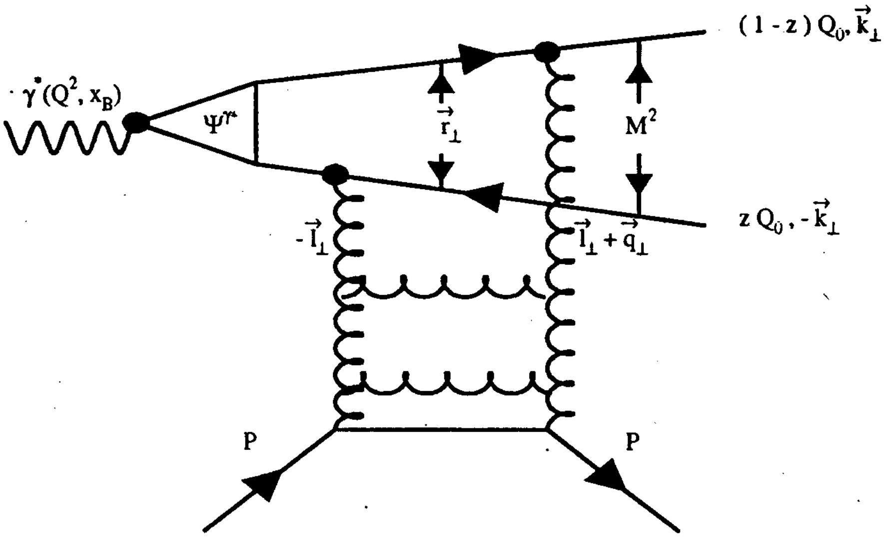
ZEUS : $\alpha_P = 1.127 \pm 0.009$ (stat.) $\pm$ 0.012 (sys.) ;

$$\sigma_{\text{tot}} \propto \frac{1}{x^{\Delta_P}} \propto F_2(x, Q^2)$$



HERA $\Longrightarrow$ $\frac{\sigma_{DD}}{\sigma_{\text{tot}}}$ $\Longrightarrow$ **Const (energy)**

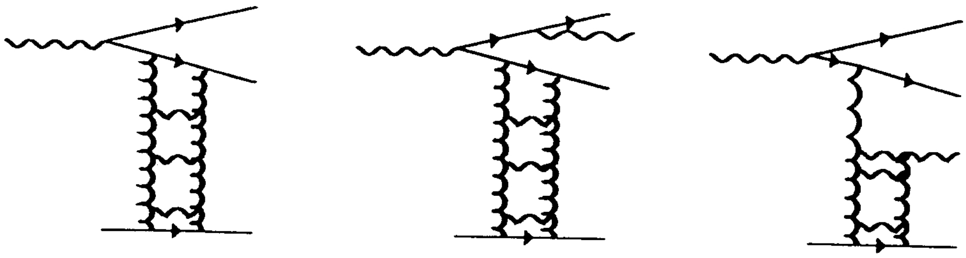
Why is it surprising (interesting, refreshing) ?



Q^2- photon virtuality ; $\quad x_P = \frac{Q^2+M^2}{s}; \quad \beta = \frac{Q^2}{Q^2+M^2};$

$$x_P \frac{d\sigma^T_{DD}(\gamma^* \rightarrow q + \bar{q})}{dx_P dt} \propto \int^{\frac{M^2}{4}}_{Q_0^2} \frac{dk^2_\perp}{k^2_\perp} \times \frac{\left(\alpha_S\, x_P\, G(x_P, \frac{k^2_\perp}{1-\beta})\right)^2}{k^2_\perp}$$

$$x_P \frac{d\sigma^L_{DD}(\gamma^* \rightarrow q + \bar{q})}{dx_P dt} \propto \int^{\frac{M^2}{4}}_{Q_0^2} \frac{dk^2_\perp}{Q^2} \times \frac{\left(\alpha_S\, x_P\, G(x_P, \frac{k^2_\perp}{1-\beta})\right)^2}{k^2_\perp}$$



$$x_P \frac{d\sigma^T_{DD}(\gamma^* \;\to\; q \;+\; \bar{q} \;+\; G)}{dx_P dt} \propto \int_{Q_0^2}^{\frac{M^2}{4}} \frac{dk^2_\perp}{k^2_\perp} \times \ln(M^2/4k^2_\perp)$$

$$\times \frac{\left(\alpha_S \; x_P \, G(x_P, k^2_\perp)\right)^2}{k^2_\perp}$$

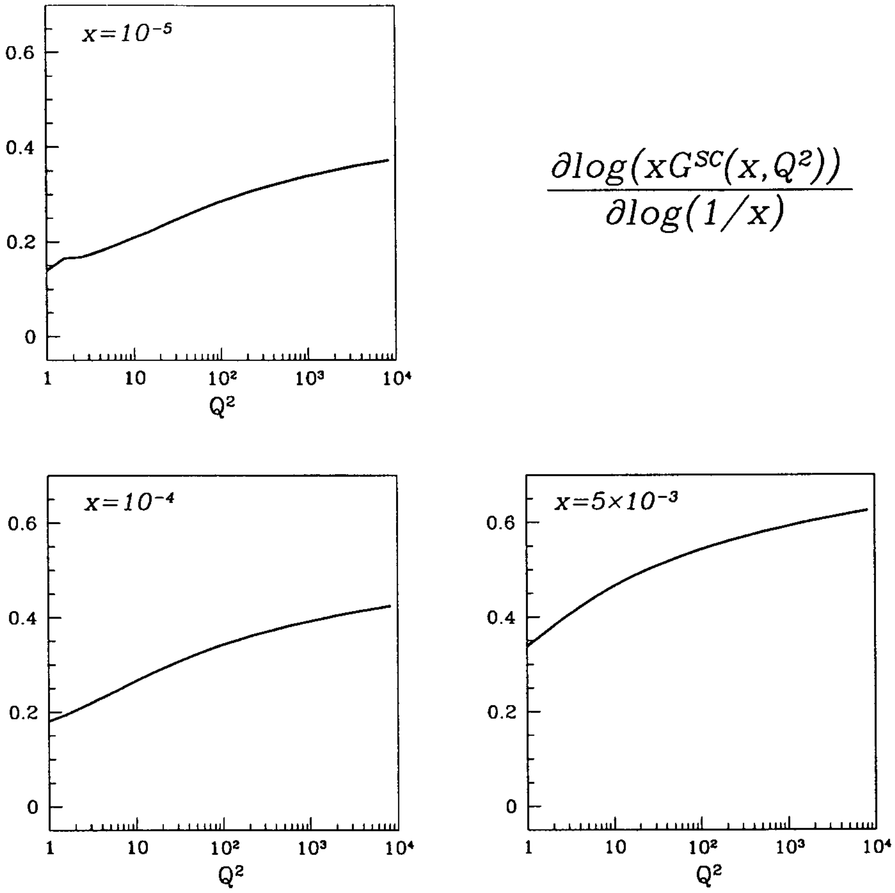
SC (asymptotic predictions):

$$x_P G(x_P, k_\perp^2) \propto \int_{\frac{1}{k_\perp^2}}^{\infty} \frac{dr^2}{r^4} \int db_t^2 \, \{ \, 1 \; - \; e^{-\kappa \, S(b_t)} \, \}$$

where $S(b_t) \; = \; e^{-\frac{b_t^2}{R^2}}$.

- $x_P G(x_P, k_\perp^2) \quad \Longrightarrow \quad k_\perp^2 \, R^2$

- $x_P \frac{d\sigma_{DD}}{dx_P dt} \quad \Longrightarrow \quad \left(x_P \, G(x_P, Q_0^2(x_P)) \right)^2 \; \times \; \frac{1}{Q_0^2(x_P)}$



$$\frac{\partial log(xG^{SC}(x,Q^2))}{\partial log(1/x)}$$

- **From the above picture for** $Q_0^2(x)$

$$\mathbf{Q_0^2(x) \;=\; 1\ GeV^2 \left(\frac{x}{x_0}\right)^{-\lambda}}$$

- $\lambda = 0.54$ **(above picture)**
- $\lambda = 0.288$ **(Golec-Bierat and Wüsthoff (1998))**

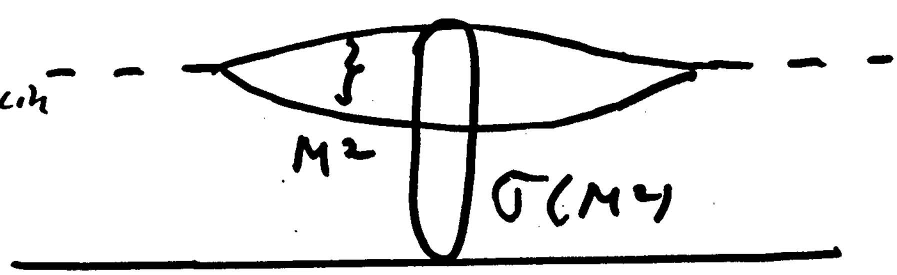
HERA gave the first[3] possibility to study interface between SOFT and HARD processes

$\sigma(\gamma^* p)$ vesus Q^2 and W

Two different approaches:

1. "Soft" + "Hard"

E. Gotsman, E.L., U. Maor
A. Martin, A. Stasto, M. Ryskin
. . . . .



$M < M_0$ np QCD

$M > M_0$ pQCD

2. Only "Hard" + Saturation
Golec - Bierat and Wüsthoff

- We need more theory for "soft" processes.

Pomeron 1. perfectly describes exp. data

$\Delta = \alpha_P(0) - 1 = 0.08$

$\alpha' = 0.25\ GeV^{-2}$

2. no theory justification.

- D. Kharzeev and E. L

Pomeron is closely related to scale anomaly of QCD.

Θ^{μ}_{μ} ← trace energy-momentum tensor

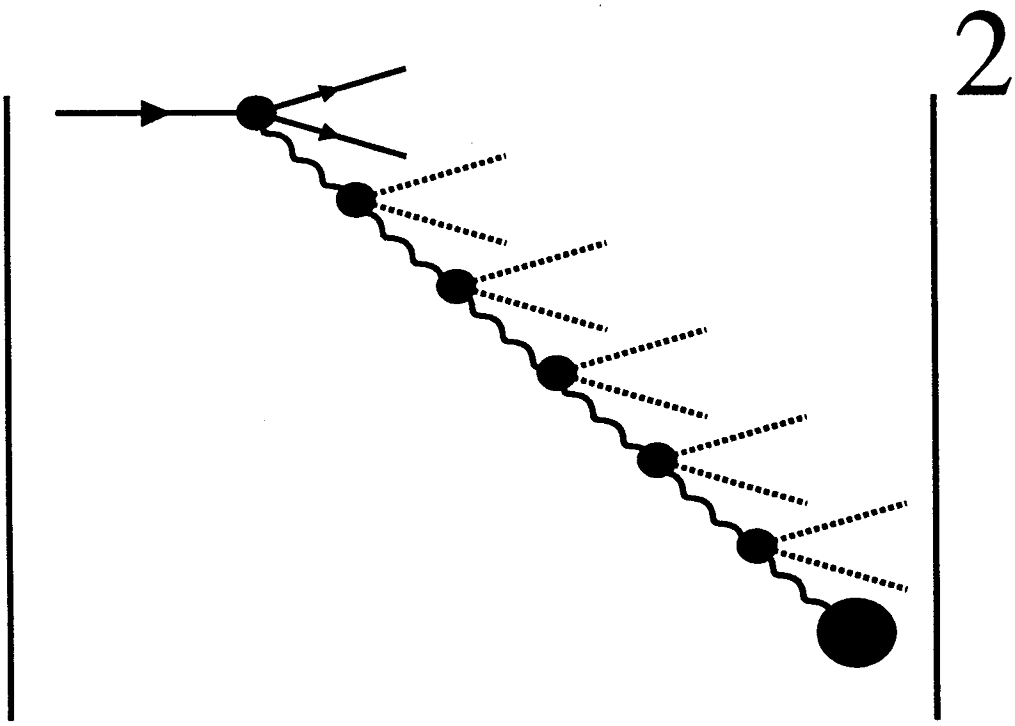
$$\Theta^{\mu}_{\mu} \neq 0 = \frac{\alpha_S \beta}{8\pi} F_{\mu\nu}^2$$

$$4\langle 0|\Theta^{\mu}_{\mu}|0\rangle = \int_{M_0} \frac{\langle 0|\Theta^{\mu}_{\mu}|n\rangle\langle n|\Theta^{\mu}_{\mu}|0\rangle\, dM^2}{M^2}$$

'' 16 Evac

$M_0^2 \simeq 4\ GeV^2$

Physical Interpretation:



t - channel gluon scatters off sem-classica; vacuum gluon fields. This scattering leads to exitation of the quark zero modes $\longrightarrow$ pion production.

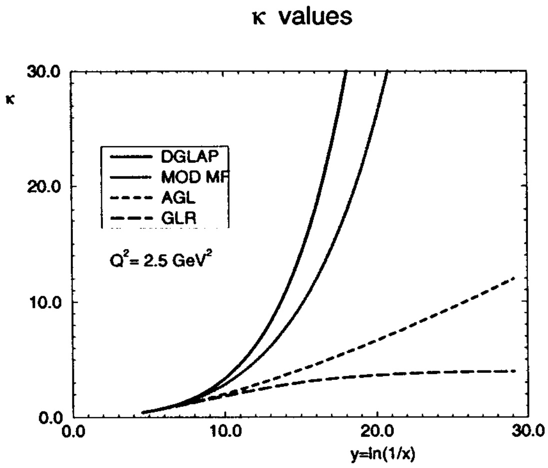
This picture is very close to one that J. Bjorkem has guessed (J. Bjorken hep-ph/9712240)

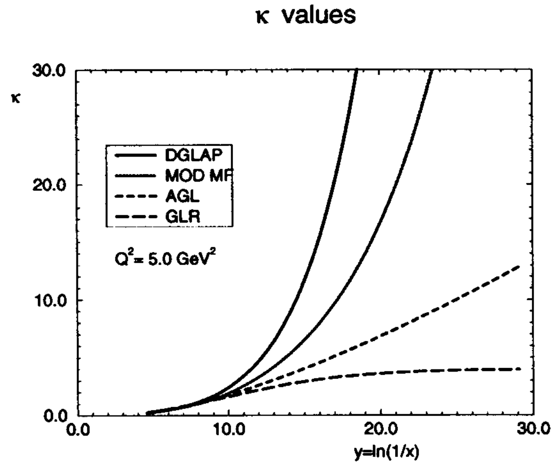
HERA teaches us 4
that gluons are responsible
for everything bad or/and
good at small x

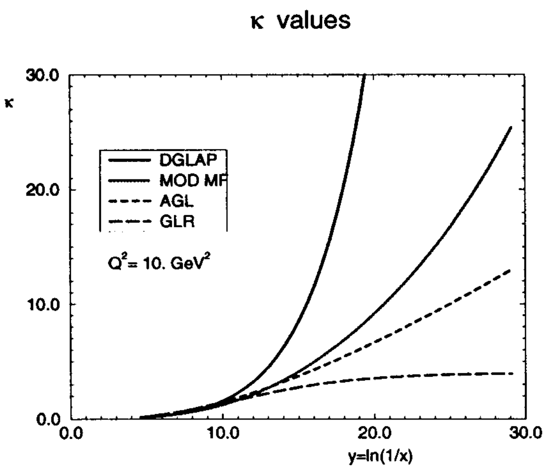
- hd QCD effects are small in F_2;
- hd QCD effects are essential in $\frac{d F_2}{d \ln Q^2} \sim x G(x, Q^2)$ for DGLAP ev. eqs.
- hd QCD effects can be differentiated for $x G(x, Q^2)$ in TERA kinematic region.

Fig. →

SC for F_2

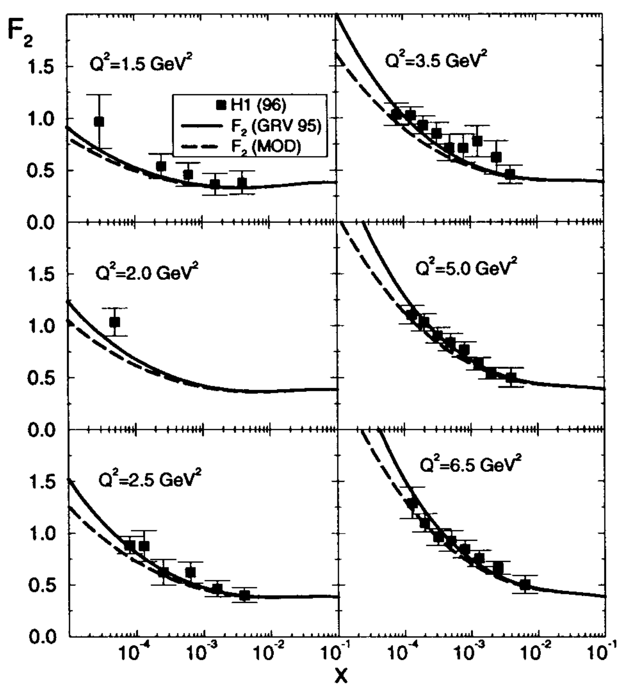


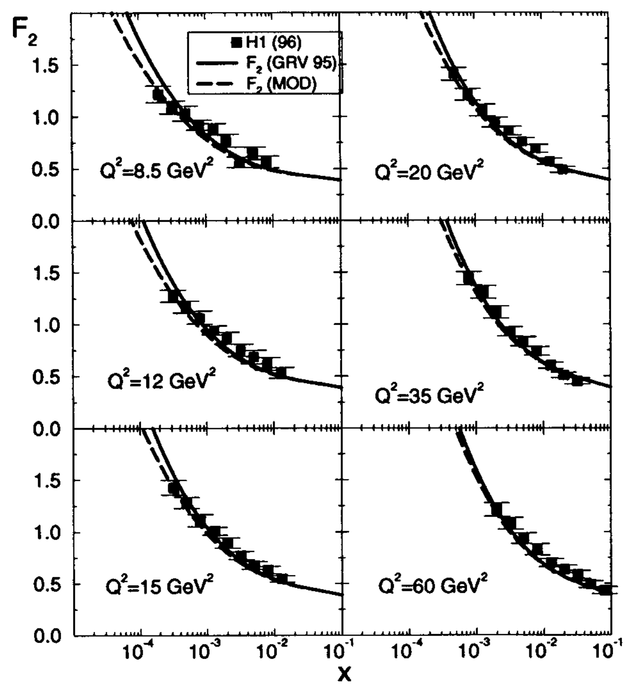




Results:

- SC are large for $xG(x,Q^2)$ but their values do not depend on the way how we take SC into account;
- SC are rather small for F_2 ;





- What we need to do:

1. Provide a reliable estimates for hd QCD effects in known exp. observables:

$\frac{dF_2}{d\ln Q^2}$; F_2^L

$\sigma_{DD} \sim \left(\frac{1}{x}\right)^{\alpha_{eff}}$; $\frac{\sigma_L^{DD}}{\sigma_T^{DD}}$

$\frac{\sigma_{DD}}{\sigma_{tot}}$; ;

F_2 (charm) ; ;

at TERA

2. Using our experience in hd QCD theory, to give an estimates for a violation of the factorization theorem

3. Reconsider the structure of DIS events to show a manifestation of the new QCD scale $Q_s^2(x)$ ($Q_s^2(x)$, $\mu(x)$,...) (incl. x sections, correlations ....)

4. Try to find the theoretical predictions for Q^2 dependence of $\sigma(\gamma^* p)$ based on all known features of QCD predictions for "soft" processes.

5. Try to find new exp. observables, sensitive to hd QCD effects.

If You Don't
Peay
You Can't
Win