QCD in the high energy limit: challenges in the low x region

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Divonne: LHeC Workshop, September 1, 2008

- Introduction
- Prospects for LHeC: low x physics (saturation)
- New Theoretical Developments: AdS/CFT
- Conclusions

Introduction

What is fundamental about QCD at high energies:

- structure of the proton at high energies reveals the nature of strong forces
  aspects of confinement
- at high energies standard model (QCD) must merge into any theory beyond the standard model. Some structure has already been made visible:
  integrability in evolution equations.

Regge limit contains information not accessible in the short distance (collinear) limit: unitarity; interface between short and long distance behavior. Starting point: BFKL

Experience has shown that deep inelastic ep-scattering is a very good place:
perturbative starting point, variation of photon virtuality Q^2 allows to interpolate between short and long distance regimes.

In this talk:

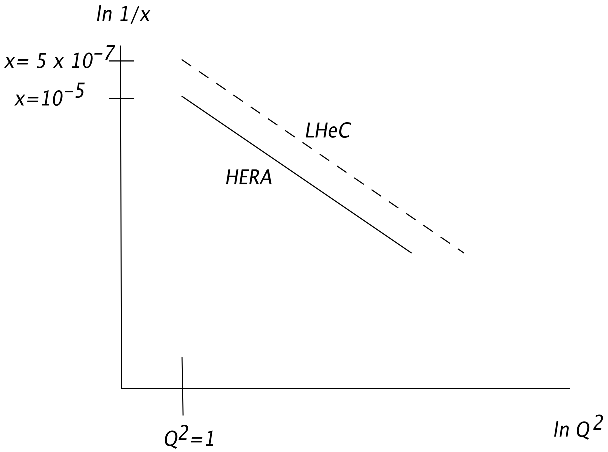
- Which aspects are explored by LHeC?
- Remarks on recent theoretical developents (AdS/CFT).

Prospects for LHeC

Comparison with HERA:

HERA: 800 GeV on 30 GeV, $x = 10^{-5}$ at $Q^2 = 1$ GeV^2, LHeC: 7 TeV on 70 GeV, $x \approx 0.5 \times 10^{-6}$ at $Q^2 = 1$ GeV^2:
gain by a factor of 20.

In addition:
the eA option.



Selected topics to be explored at the LHeC:

1) Structure functions at small x

$$\sigma_{tot}^{\gamma^* p} = \frac{4\pi\alpha}{Q^2} F_2(x, Q^2), \;\; W^2 = Q^2(\frac{1}{x} - 1)$$

2) BFKL

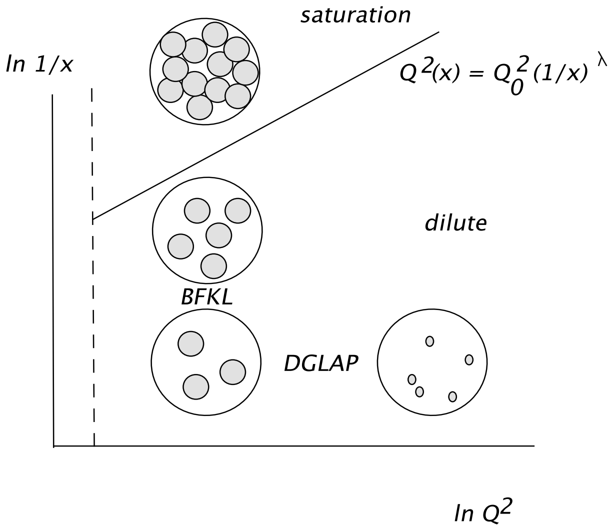
3) Saturation

4) Diffraction

1. Structure functions at small x

Larger kinematic region in x and Q^2, high energy is small x region.
Gain of factor 20, covers (approximately) LHC region.

Special interest: BFKL, BFKL resummation



2. BFKL

BFKL is the (leading log approximation) to high energy scattering in pQCD: important to search for experimental verification.
Applies to the scattering of two small-size (=large momentum scale) projectiles:

$\gamma^*\gamma^*$ (e^+e^- linear collider)

in ep: best are forward jets; structure functions at very small x; large-t vector production

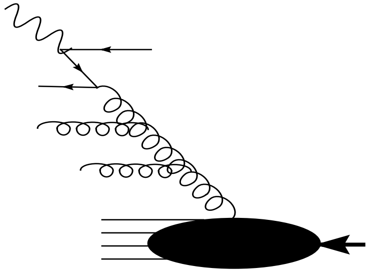
in pp: Mueller-Navelet jets.

At LHeC,forward jets: gain of factor 20 (compared to HERA) will be very helpful (jets can be harder) (→Jung's talk).

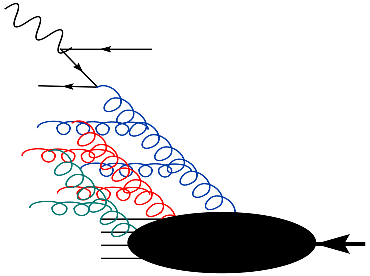
3. Saturation

Saturation: theory much less controversial than experimental evidence.
Theory: corrections to QCD parton picture, still within pQCD. Multiple interactions

Saturation (in DIS): at small distances (large Q^2) we have DGLAP:



DGLAP
(single chain)



saturation
(multichain)

Since gluon density grows with $1/x$, somewhere at small x corrections must become essential: two cascades, gluon annihilation, negative sign:

'At high density the gluon saturates'

Saturation scale: $Q_s(x) = Q_0(1/x)^{\lambda}$, $\lambda = 0.25 \ldots 0.3$, Q_0 to be fitted

Formulated in the dipole picture:

$$\sigma_{L,T} = \int dz \int d^2 r \psi(Q,r,z)_{L,T} \sigma_{q\bar{q}}(r,x) \psi^*(Q,r,z)_{L,T}$$

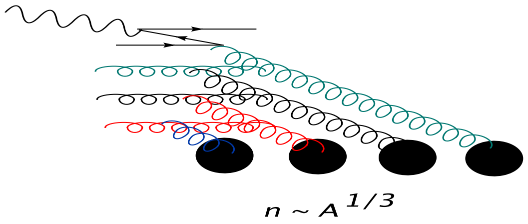
Essential quantity: dipole cross section $\sigma_{q\bar{q}}$: saturates at an x-dependent value. Current value of the saturation scale, obtained from F_2:

$$Q_s^2 \approx 0.8 \ at \ \ x = 10^{-4}, \ \ Q_s^2 \approx 3 \ at \ \ x = 10^{-6},$$

LHeC: saturation scale larger than at HERA, considerable improvement.

Cleaner signal of saturation in eA collisions:

photons 'sees' the gluons of many nucleons (number of nucleons $\sim A^{1/3}$): gluon density saturates at larger x-values: $Q_s^2 \sim A^{1/3}$.



Comment:

Saturation is a low-Q^2/small x phenomenon, for the transition region.
It is not an alternative to DGLAP. At large Q^2 saturation merges into DGLAP.

Gives an answer to a question which DGLAP does not address:
What are the first corrections to the (leading-twist) parton picture?
How does the transition to strong interactions start?
Saturation is the first step in this transition, still within pQCD.

Have experiments seen saturation? What will improve at LHeC?

HERA:
a) flattening of the small-x rise of F_2 of $xg(x, Q^2)$.
HERA: not seen. Likely: kinematic region too small, large errors in $xg(x, Q^2)$.
LHeC: certainly better chances.

b) Description of F_2 in the transition region:
phenomenological models (GBW), models inspired by nonlinear evolution (BK) equation.
Successful description with few parameters.
Other successful models without saturation.

c) geometric scaling: clear prediction of saturation

$$F_2(x, Q^2) = F_2(Q^2/Q_s^2(x))$$

Seen in the data.
Within DGLAP: also geometric scaling, at larger Q^2 (Forte).

d) Diffraction: ratio of diffractive over constant cross section

$$\sigma_{diff}^{\gamma^* p} / \sigma_{tot}^{\gamma^* p} \approx const$$

constant with energy (at fixed Q^2, M^2).

Saturation model (GBW) for diffractive $q\bar{q}$ production provides simple explanation.
So far: no alternative explanation

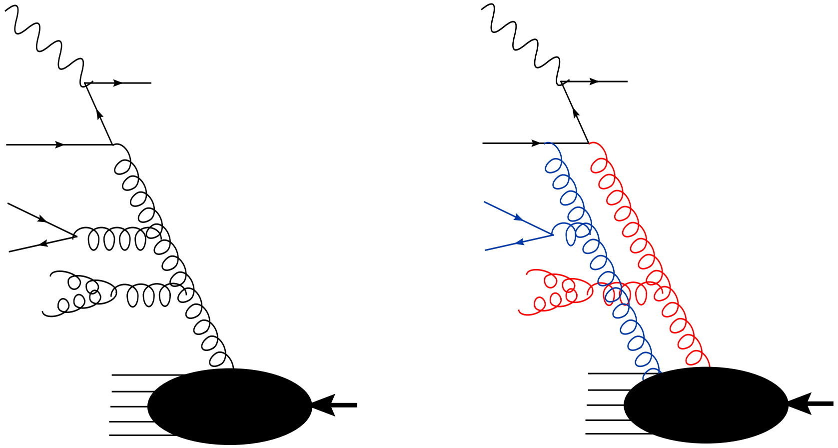
In three cases b) - d): saturation provides a 'simple explanation', but, in the cases b) and c), there are alternative 'explanations'.

RHIC: cannot discuss.

LHeC has better possibilities (larger kinematic region) than HERA:
saturation line, eA option

Suggestion: measure

correlations (e.g. two-jet) as reliable signal of saturation (multiple interactions):



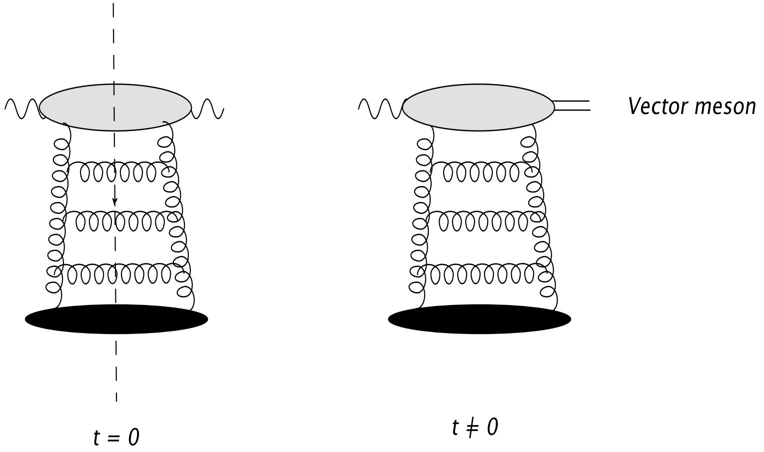
Correlations in rapidity, angle.

Was difficult at HERA (for larger Q^2),

for LHeC factor 2.0 in $1/x$ will help.

4. Diffraction

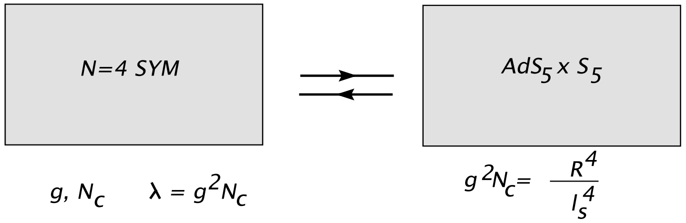
Only one aspect: t-dependence



Total cross section integrates over all transverse distances,
t-dependence (t-slope, shrinkage) measures transverse dependence,
transition from 'small' to 'large'.

Recent developments: AdS/CFT correspondence

Consider N=4 supersymmetric QCD:
N=4SYM: maximal symmetric, conformal symmetric, Yang Mills theory, no low energy phases, fixed coupling constant.
Duality conjecture (AdS/CFT correspondence): gauge field theory is the same theory as a string theory in 10 dimensions with $AdS_5 \otimes S_5$ geometry:



N=4 SYM $\rightleftharpoons$ $AdS_5 \times S_5$

$g, N_c \quad \lambda = g^2 N_c$

$g^2 N_c = \frac{R^4}{l_s^4}$

Weak coupling on the string side gives strong coupling of N=4SYM gauge theory.

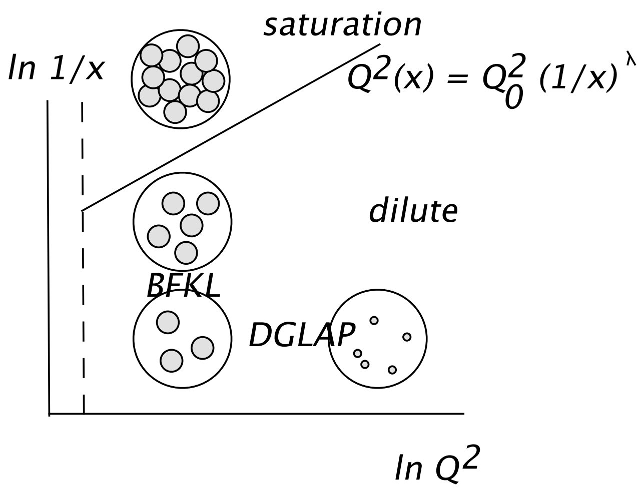
Finite temperature (above all low energy phases): blackhole on the string side.
Most promising applications (viscosity etc).

Application to high energy behavior:

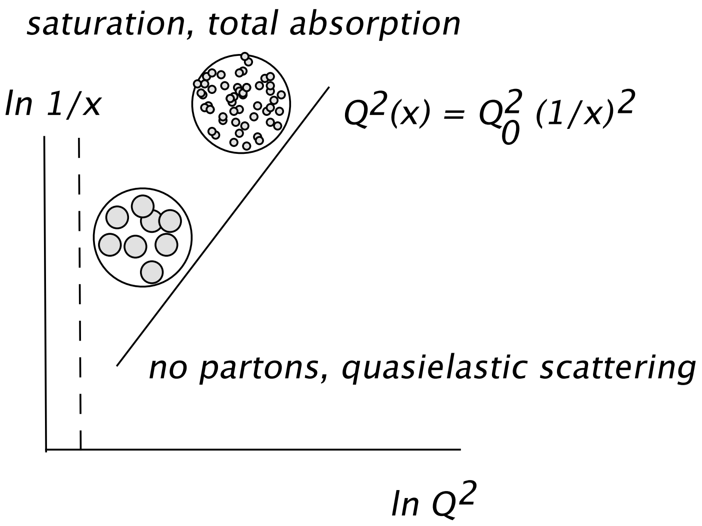
- mimic QCD by introducing a scale, address explicitly DIS in AdS/CFT (Polchinski et al; Mueller et al.)
- gluon scattering amplitudes at all orders in coupling g (BDS formula). (Bern et.al)

1. DIS in AdS/CFT

Complicated calculations, show only plot of E.Iancu:



real QCD (weak coupling)

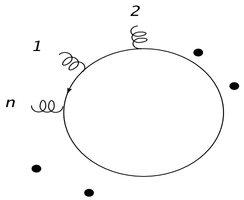


N=4 SYM with scale (strong coupling)

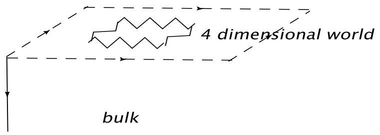
Quite different physics at strong coupling.

2. The BDS formula

Conjecture:
for n-gluon scattering amplitudes,
maximal helicity violating, large-N_c (planar), in $D = 4 - 2\epsilon$ dimensions



compute amplitudes



compute surfaces

$$A_n = A_n^{Born} \times M_n, \ln M_n = \sum_{l=1}^{\infty} a^l \Big(f^{(l)}(\epsilon)(\Big(I_n^{(l)}(l\epsilon) + F_n(0) \Big) + C^{(l)} + E_n^{(l)} \Big)$$

Example: for $2 \longrightarrow 2$ scattering (up to corrections of order ϵ)

$$M_4 = \Gamma(t)(-s)^{\omega(t)}\Gamma(t) = \Gamma(s)(-t)^{\omega(s)}\Gamma(s)$$

Regge behavior, duality.

Also: 5-point amplitudes

Discrepancy: M_n for $n > 5$, beyond one loop. Studies in progress.

Perspectives:

- help in calculations of hard subprocess with many legs
- high energy scattering with vacuum quantum number (Pomeron): comes at cylinder level, use planar amplitudes + unitarity.
- Expect: Duality between BFKL on the weak coupling, gauge theory side and graviton on the strong coupling string theory side.

Conclusions

- Need to solve the problem of strong interactions (QCD)
- High energy behavior (Regge limit) is important part of strong interactions
  Two (theoretical) directions:
  - find the long distance (in transverse size) extension of small distance behavior
  - to which theory beyond the standard model is QCD the 'low energy part'?
- deep inelastic scattering is the most helpful experimental environment