Saturation and Small x: from HERA to LHC

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"SMALL X PHENOMENOLOGY: SUMMARY AND STATUS". By Small x Collaboration (Jeppe R. Andersen et al.). DESY-03-220, to appear in Eur.Phys.J.C. e-Print Archive: hep-ph/0312333.

"SMALL X PHENOMENOLOGY: SUMMARY AND STATUS". By Small x Collaboration (Bo Andersson et al.). DESY-02-041, Eur.Phys.J.C25:77-101,2002. e-Print Archive: hep-ph/0204115

Introduction: Strong Interactions (SI) and QCD at the LHC

HERA has worked on the interface between pQCD and Strong Interactions (SI).

LHC will encounter both pQCD and SI.

Strong Interactions and QCD are the background to new physics
(extreme: QCD is unavoidable nuisance)

QCD and SI are of interest by themselves. Good reasons:
1) Need to understand nonperturbative strong interactions
(mass of the proton, different phases of matter, etc)
2) Need to understand nonperturbative dynamics in QFT:
QCD offers testable playground.

In the following a few ideas which, from my personal (a HERA person) point of view, may be interesting for this workshop and for LHC experiments:

- BFKL Physics
- Structure functions at small x, saturation, multiparton dynamics: transition to nonperturbative QCD
- Diffraction

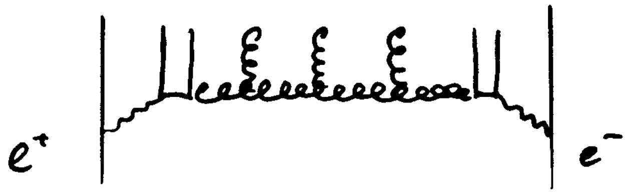
BFKL Dynamics

Motivations:
Structure functions at small x: evidence for BFKL dynamics
- k_t-factorization
- BFKL features in special final states
- modifications of DGLAP,resummation
- MC: no ordering in transverse momenta

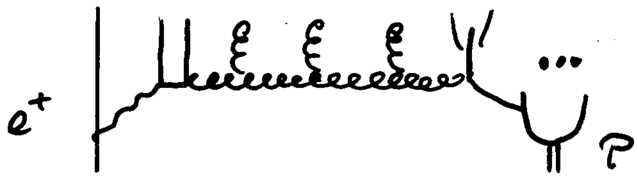
Why so interesting for theorists:
1) prediction of pQCD in the combined limit small (transverse) distances and high energies (Regge limit). Open interface to nonperturbative QCD, interpolates.
2) starting point:Saturation
3) BFKL is our chance to understand the small-x limit, the hadronic total cross section, elastic and diffractive scattering.
4) Seems to reflect a deeper underlying structure.
BFKL = simplest piece of a 2+1 dimensional field theory with conformal symmetry (string theory?).

Experimental signatures:

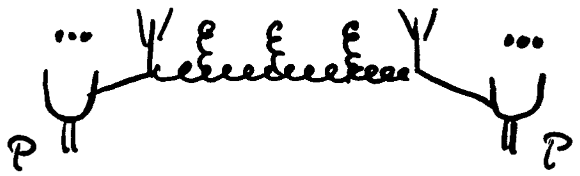
- $\gamma^*\gamma^*$ scattering in e^+e^- scattering (LEP, NLC)



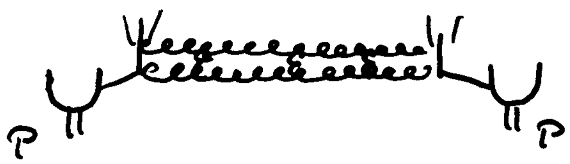
- forward jets, forwards pions at HERA (4 units)



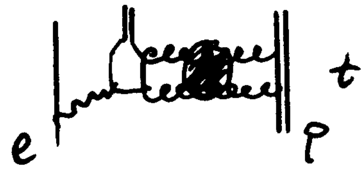
- Mueller-Navelet jets at Tevatron (6 units) $\alpha \sim 1.6$
  Mueller-Navelet jets at LHC (14 units?)



- Hard color singlet exchange



- Large-t Vector meson production in DIS
  Large-t $pp \rightarrow Xp$ at LHC (?)



Overall picture: not fully consistent

Best hopes: LHC and NLC

Comments:

Fadin, Lipatov
Ciafaloni et al.

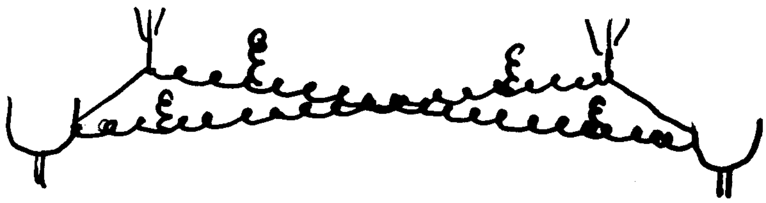
NLO correction of BFKL kernel have been computed and analysed.

Algorithms for NLO BFKL Greens functions available.

Ciafaloni et al., Salam,
Sabio-Vera

Need NLO corrections for jet vertex, in progress. JB, Colferai, Vacca

What about competing mechanism, two parton chains?



First step beyond the linear BFKL evolution: nonlinear BK equation, saturation, see below.

Balitski, Kovchegov

Another aspect of BFKL physics:
pQCD predicts the existence of an Odderon with intercept one (as bound state of three gluons).
If we are interested in the BFKL dynamics, we have to search for this (perturbative) Odderon.

Structure Functions at small x (and low momentum scale), saturation

Very quick summary of current status:
HERA has measured structure functions at small x at sizable Q^2.

Crucial question: what is the region of applicability of parton densities
and of linear QCD evolution (DGLAP) equations?

No generally agreed answer.

F_2 may be a too liberal quantity.

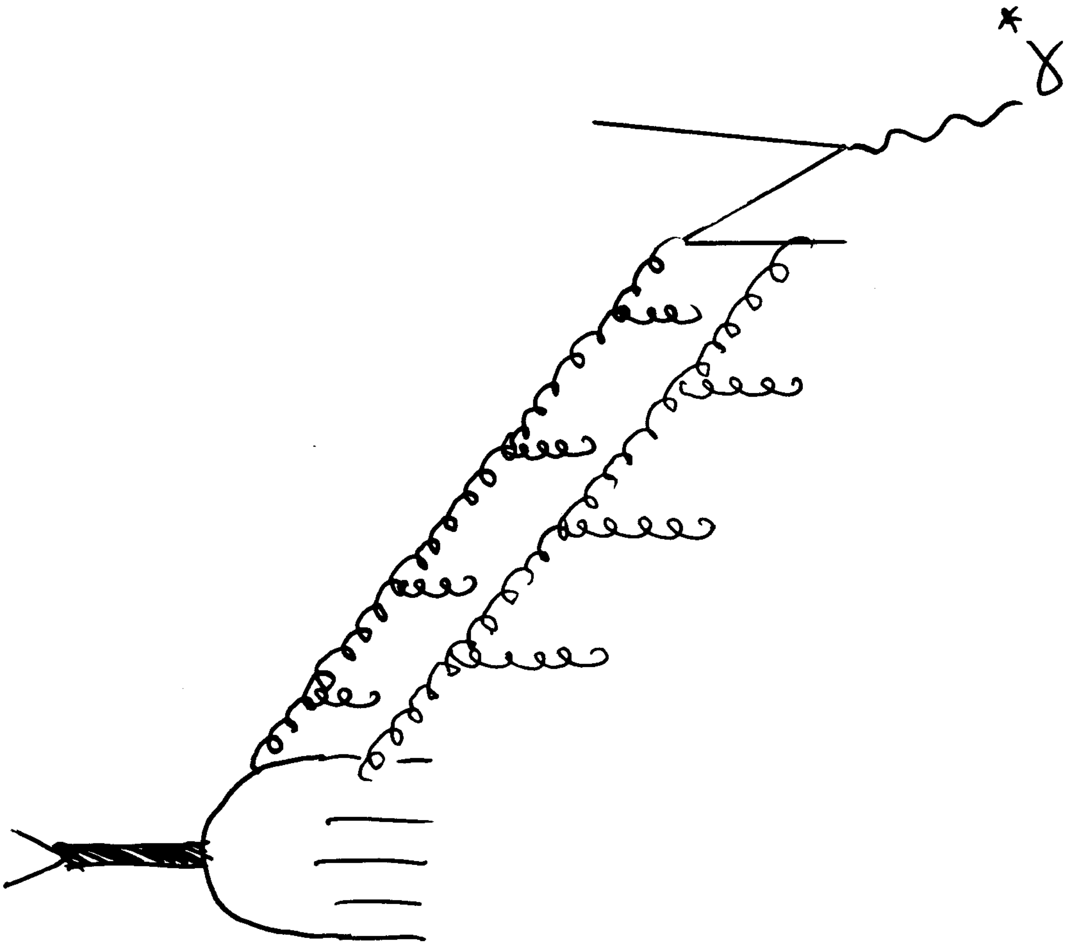
Improvements of DGLAP (resummation) may slightly extend the region of validity,
but they also may mislead us.

A more discriminative test would be a direct measurement of the longitudinal structure function, F_L, in DIS.

What comes after the breakdown of linear evolution at small x and/or low Q^2? Saturation. Gribov, Levin, Ryskin

Basic idea:

- linear evolution based upon assumption of diluteness of partons inside the hadron, one parton radiates until it enters the hard interaction.
- growth of gluon density at small x comes into conflict with diluteness assumption. Two (and more) partons inside one hadron may become relevant: multiparton contributions $\rightarrow$ strong classical field ('color glass condensate') McLerran, Venugopalan ...
- leads to a state of high gluon density
- multiparton contributions lower the total cross section. Concept of parton density no longer valid.
- new scale: $Q_s^2(x) = c(1/x)^\lambda$, $\lambda \approx 0.3$


γ*

What is the evidence for saturation at HERA?

1) scaling at low/medium Q^2: Golec-Biernat et al.

$$F_2(Q^2, x) = F(Q^2/Q_s^2(x)) \quad Q_s^2(s) = c(1/x)^\lambda$$

2) most successful model(s) for F_2 at low/medium Q^2 is based upon saturation Golec-Biernat, Wüsthoff ...

3) consistent with essential features of DIS diffraction.

Further evidence for saturation comes from RHIC (next talk).

Summary in simple words:

"Small-x partons originate from regions where gluon density is high"

From a successful model:
numerical determination of the saturation scale.
Provides an estimate of the boarder line of applicability of DGLAP.

JB, Golec-Biernat, Kowalski

F_2

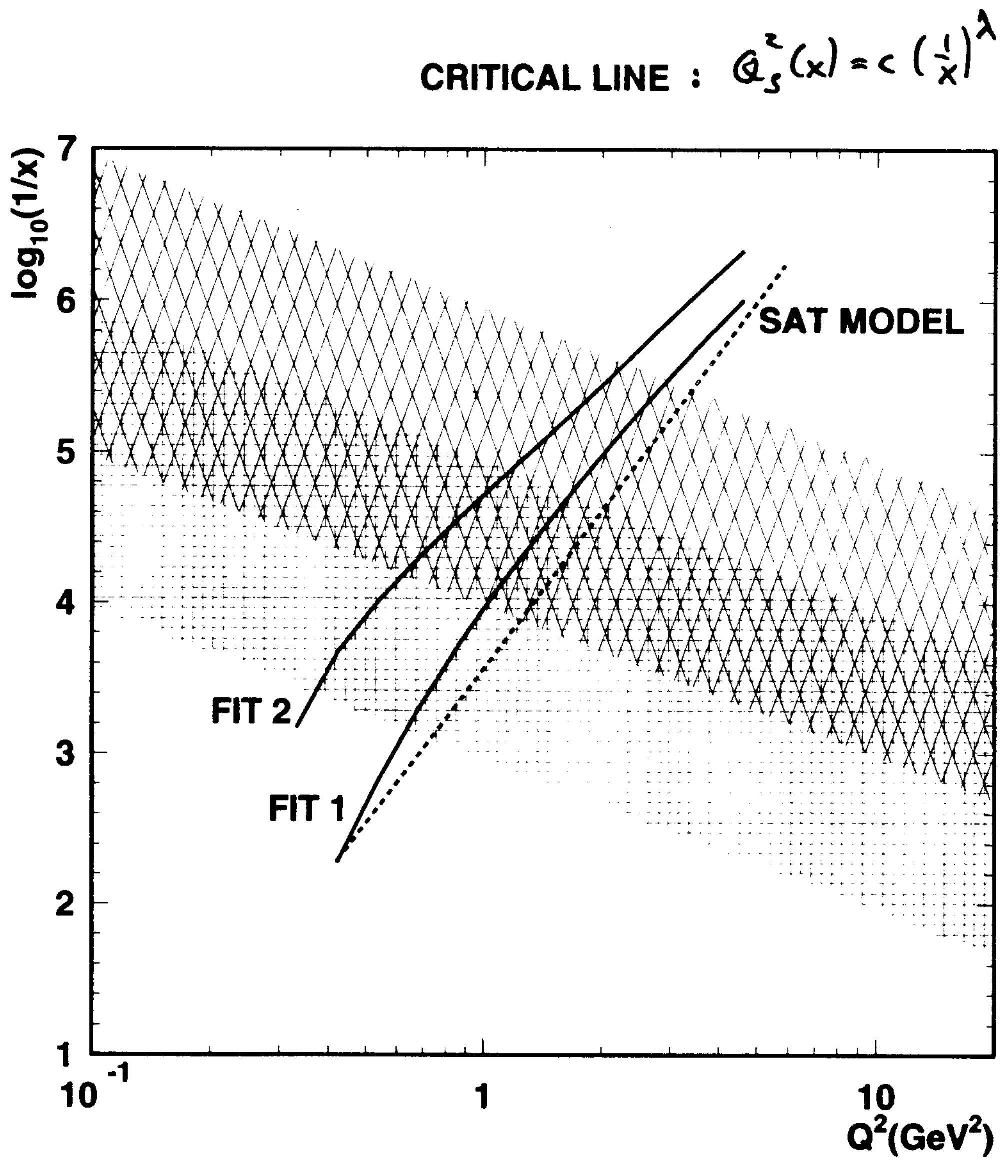
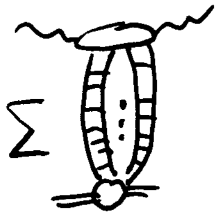


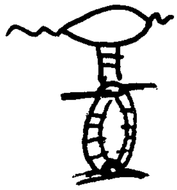
Figure 8: *The position of the critical line in the (x, Q^2) plane in the DGLAP improved model (solid lines) and the original saturation model (dshed line). The bands indicate acceptance regions for the colliders HERA (lower) and future THERA (upper).*

Consequences of high density of gluons for DIS: Abramovsky, Gribov, Kancheli
multiparton contributions, AGK rules
(to be verified at HERA; rapidity range as large as JB, Ryskin
possible):

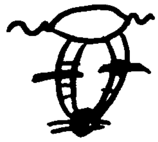
- total cross section becomes smaller



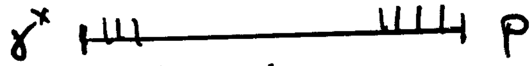
- cross section for one pair of jets:
  multiparton chains cancel, but cross section becomes smaller



- cross section for two pairs of jets:
  two-parton chain contributes, long range rapidity correlation.



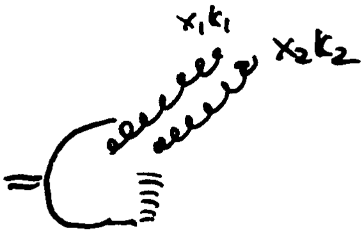
- fluctuations in multiplicities of jets (particles)



A good quantity: two-jet correlation function

$$\rho(y_1, y_2) \sim \frac{1}{\sigma^{tot}_{\gamma^* p}} \left(\frac{d^2\sigma}{dy_1 dy_2} - \frac{1}{N} \frac{d\sigma}{dy_1} \frac{d\sigma}{dy_2} \right)$$

From DIS saturation model: probability of finding two, three... gluons inside proton.



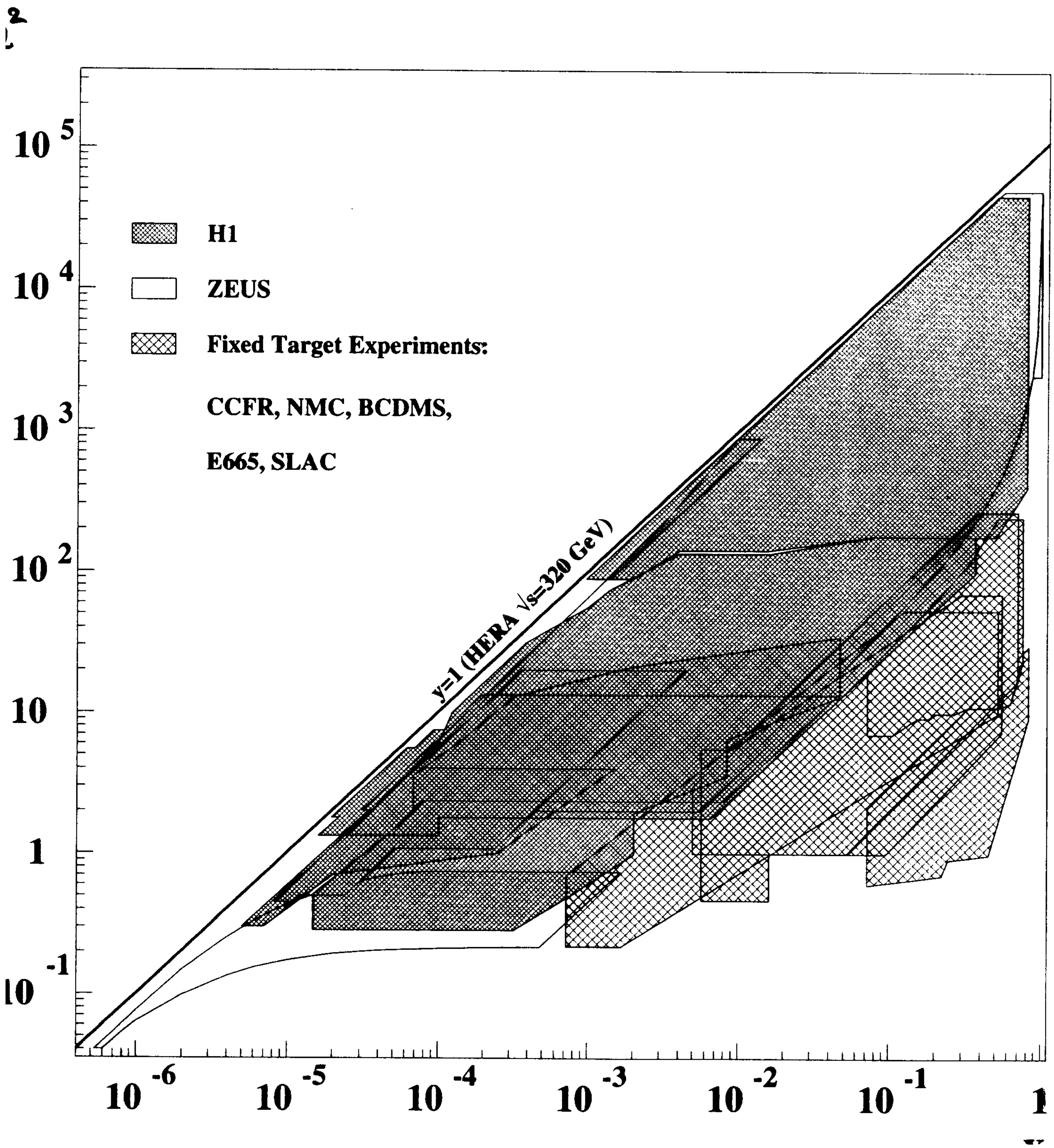
Consequences of high parton density for LHC:

A) Tests of this high density state:
(i) cross section of pair of jets ~~of~~ or Drell-Yan at very small x: asymmetric configuration $x \gg x'$: $x' > \frac{4p_t^2}{xs} \sim few \cdot 10^{-6}$ at $p_t \sim 10$: compare to DIS structure function
(ii) cross section for two pairs of jets: correlation function
An asymmetric configuration: Mueller-Navelet jets.

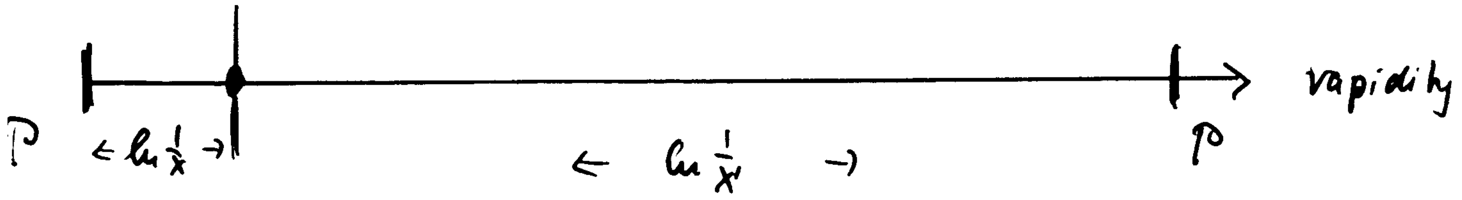
B) Background to new physics: multijet cross sections
whenever one gets close to the saturation scale, multiparton contributions should become important.

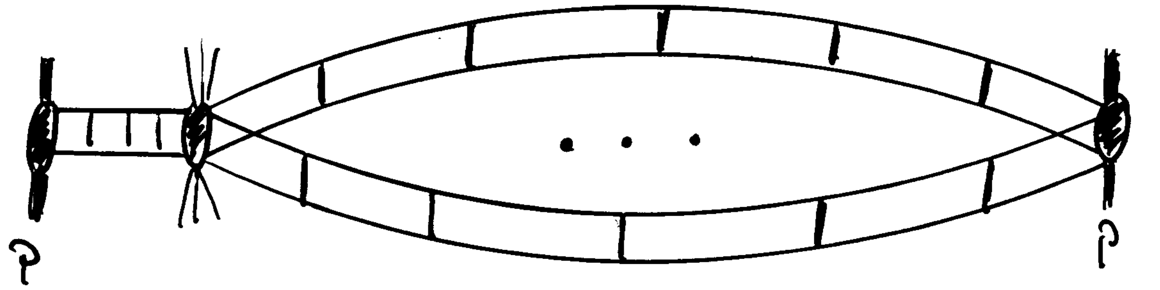
Theoretical questions:

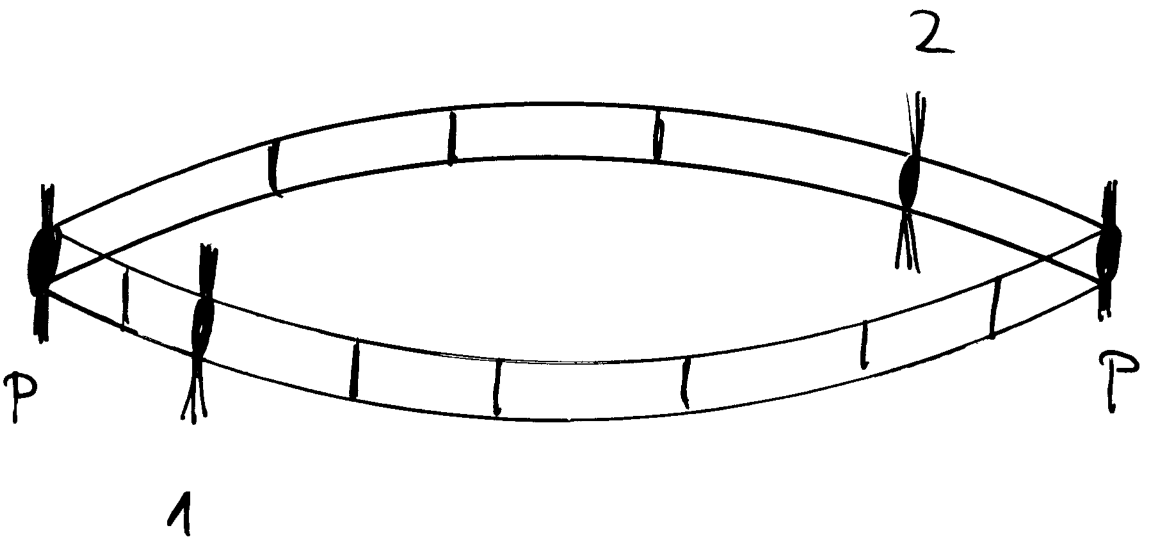
combinatorics, AGK rules
'derive' models from QCD (BK equation, JIMWLK...): exciting new theoretical developments
Question of universality of many-parton correlators (higher twist quasipartonic operators)
High parton density in heavy ion collisions (next talk)...



H1
ZEUS
Fixed Target Experiments:
CCFR, NMC, BCDMS,
E665, SLAC
y=1 (HERA √s=320 GeV)
10 5
10 4
10 3
10 2
10
1
10 -1
10 -6
10 -5
10 -4
10 -3
10 -2
10 -1
1


P
← ln 1/x →
← ln 1/x' →
P
rapidity


P
P


2
P
P
1

Diffraction

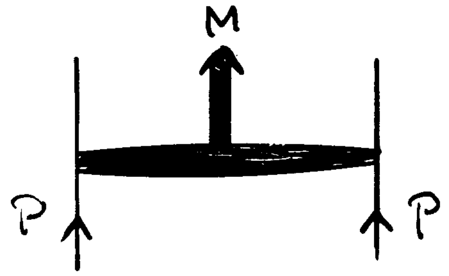
Diffractive processes: partly exclusive, projectiles stay intact (more or less), confinement aspects, nonperturbative physics is close.

Experimental signature is clean (empty rapidity regions), sizable fraction of cross section is diffractive!

A) Hard Diffraction (see: Tevatron)
Hard: a hard scale at one (at least) end of the rapidity gap
Partly calculable: gluon density and survival factor.

A few examples:
1) Double diffractive production: two rapidity gaps

$$p + p \rightarrow p + M + p$$

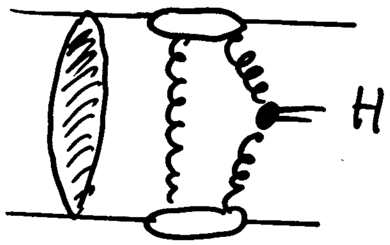


Why so attractive:
two empty regions
reconstruct mass of the produced system from tagged protons - need forward detectors.

Most interesting: production of a (light) Higgs $\rightarrow b\bar{b}$

Intensely debated, differences in estimates of the size of the cross section:
definition of final states, survival factor.

Bialas, Landshoff
Durham coll.
Saclay coll
Uppsala coll
CERN coll



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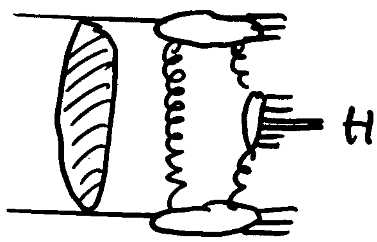
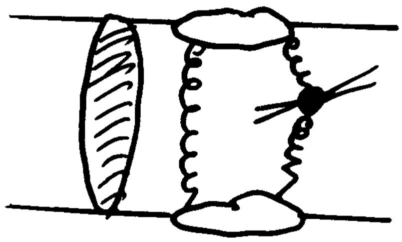
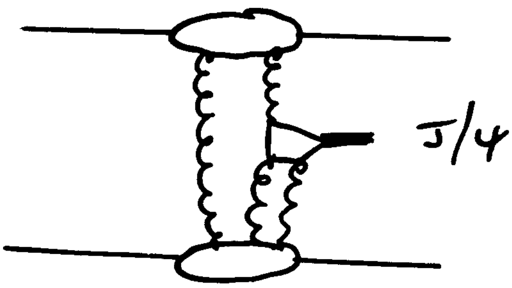


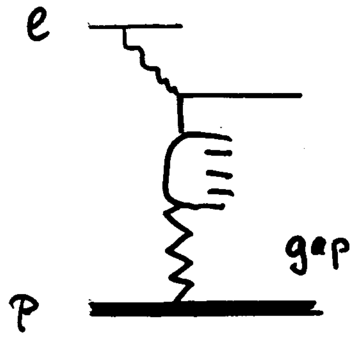
Help: comparison with double diffractive di-jet production.



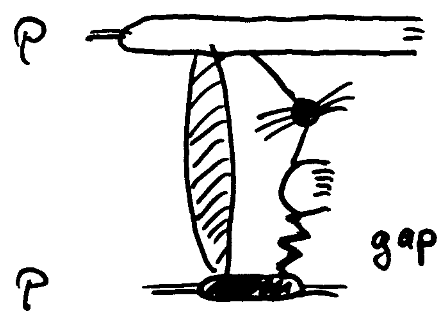
Other candidates:
double diffractive production of heavy χ states
double diffractive production of glueballs
$pp \rightarrow Mp$ at large t ...
double diffractive production of J/ψ, as a candidate for odderon exchange (background: photon exchange)



2) Diffractive parton densities HERA: has measured diffractive parton densities (rapidity gap events) sound theoretical basis.



Hadron collider: single diffractive production of dijets, heavy bosons, b-quark: Ingelman, Schlein

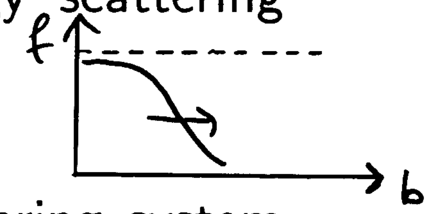


does not see the same quantity - soft final or initial interaction (survival factor):
suppression by factor ~ 10 (Tevatron)
But: similar shape. Theory?

B) Nonperturbative (soft) diffraction:

total pp cross section, elastic scattering, (soft) diffractive cross section. Is there a fundamental interest?

$\frac{d\sigma_{el}}{dt}$ measures composition high energy scattering system:



$$T(s, \vec{q}^2) = s \int d^2 b e^{i\vec{q}\vec{b}} f(s, \vec{b})$$

Profile function f tells how the scattering system looks in the transverse plane: interaction region 'becomes black' (saturation!) and expands with energy (shrinkage).

In particular: the t-slope in elastic scattering:

$$\frac{d\sigma}{dt} \sim e^{-2B(s)|t|} \quad , B(s) = B_0 + \alpha' \ln s$$

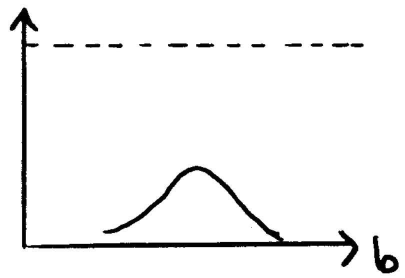
$$f(s, \vec{b}) \sim e^{-\vec{b}^2/4B(s)}$$

The parameter $\alpha' \approx 0.25 \;\; GeV^{-2}$ measures rate of transverse expansion, logarithmic with energy.
In pQCD:
cross section has power-like increase with energy,
$f(s, \vec{b})$ has powerlike fall-off: system expands rapidly
$\Rightarrow \alpha'$ (dimension of length^2) is a parameter related to QCD forces!

Puzzle of high-mass diffractive cross section: $\frac{d^2\sigma}{dtdM^2}$ disagrees the with simple Donnachie Landshoff Pomeron pole picture:

$$\alpha_P = 1.08 + \alpha' t$$

In transverse plane: mostly from peripherie (large $\vec{b}$), from the point of view of transition to npQCD the most interesting region.



C) What about critical behavior at high energies?

Empirically: energy dependence of the hadronic total cross section is not far from constant.
ISR, S$p\bar{p}S$, Tevatron, HERA

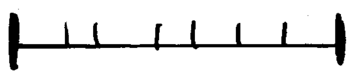
$$\sigma_{tot} \sim \ln^2 s$$

or

$$\sigma_{tot} \sim s^{0.08}$$

Simple model building:

- at low/medium energies 'Pomeron echange' due to multiperipheral chain (ladder).

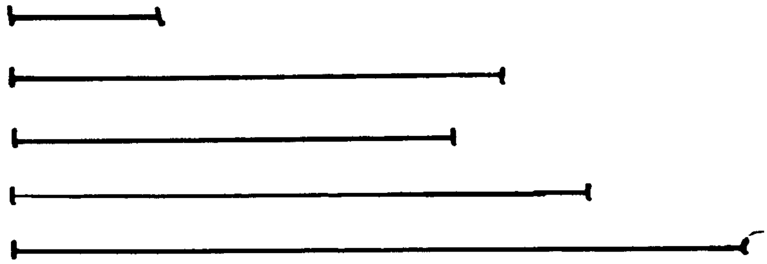


- at higher energies multiple exchange of such chains

- with the same arguments as above: fluctuation in multiplicity/density, long range rapidity correlations...

Consider pp scattering as a one-dimensional system, extension determined by the available rapidity:

	$\sqrt{s}$	$\ln s$
ISR	50	3.9
S$p\bar{p}$S	600	12.8
HERA	300	11.5
Tevatron	1800	15
LHC	14 000	19



System will never be infinite, but is the system at LHC already 'large enough' to see onset of 'boiling', of long range rapidity correlations, approach to critical behavior?

Energy dependence of total cross section may indicate whether we are getting closer to criticality.

Better: look into final states, multiplicities, correlations.

Speculation: is a critical behavior in pp scattering (at large $\vec{b}$) related to quark-gluon plasma in the center??

Conclusion: soft diffraction is of fundamental interest.

Summary

HERA: lots of QCD phenomena at the interface from hard to soft QCD (SI); $\gamma^* p$ is rather clean

LHC, much higher energies, very rich menu:

- BFKL (short distance)
- saturation (interface)
- Hard diffraction (interface)
- soft diffraction (SI)

$\Rightarrow$ Transition from pQCD to SI

Consequences:

- LHC Detectors: need for rapidity region as large as possible (close to the beam)
- Theorists, experimentalists: work to be done during this workshop