HERA collider physics

$\sqrt{s}$ = 318 GeV

$\Delta r \geq 0.001$ fm

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What had we planned what have we done?

1. Search for new particles and interactions

(this determined detector design)

-multileptons, missing ET, jets
(Leptoquarks, SUSY, top,…)
- Heavy W’, ….

2. Electroweak physics

- righthanded currents
- heavy new bosons
- charged currents

3. QCD studies

- parton densities, jets

1. precision studies on QCD

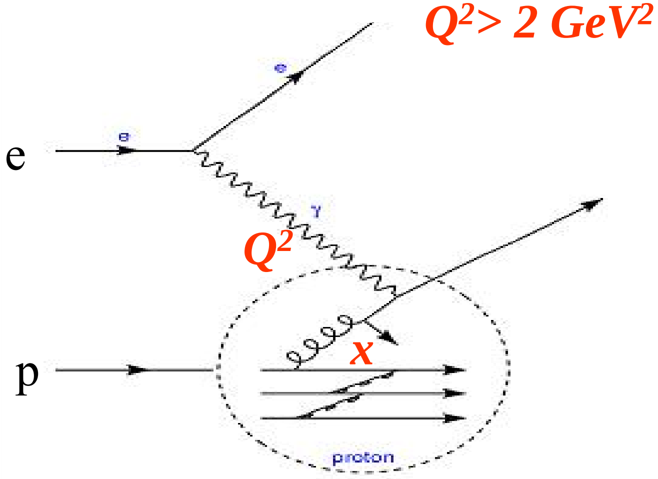
- gluon distribution, QCD evolution
- jet production, heavy quarks
- low x physics
- diffraction, saturation?

2. electroweak physics

3. new particles and interactions

1. QCD why at HERA?

Infinite momentum frame



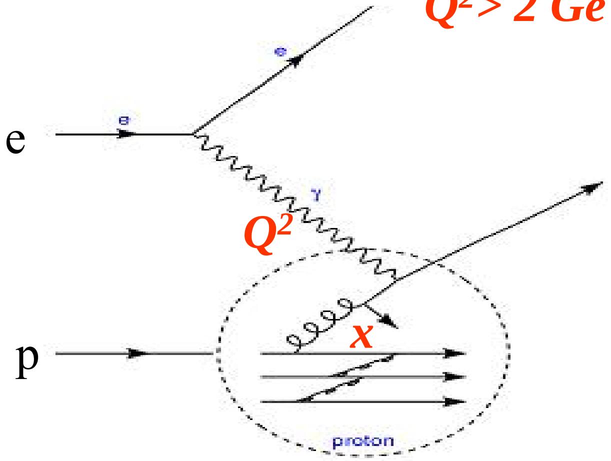
$Q^2 > 2\ GeV^2$

$x = Q^2/y*s$ (momentum fraction of parton)

Electrons as probes for quark Structure
-- parton densities, scaling violations ..

1. QCD why at HERA?

Infinite momentum frame



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Electrons as probes for quark Structure
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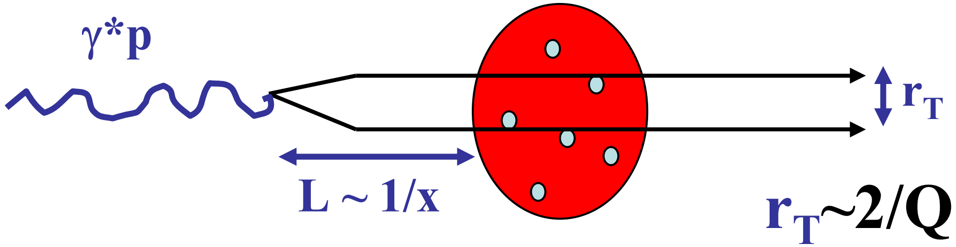
Proton rest frame



~ 50 fm!

$r_T \sim 2/Q$
(size of dipole)

~ 1→ .01 fm

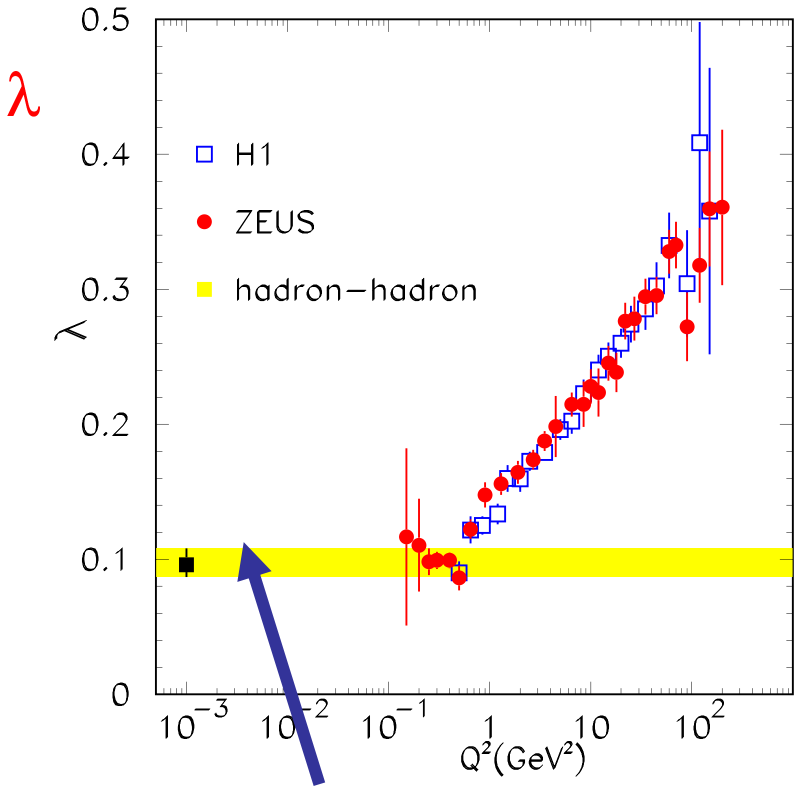
At low x<0.01 a color dipole of variable size 2/Q interacts with the proton at high CM energy $s^{\gamma p} = W^2 \approx Q^2/x \approx 1000 \div 90000$ GeV^2

Low x = high energy scattering!

Q^2 steers the transition from hard collisions (perturbative QCD) to soft hadron physics.

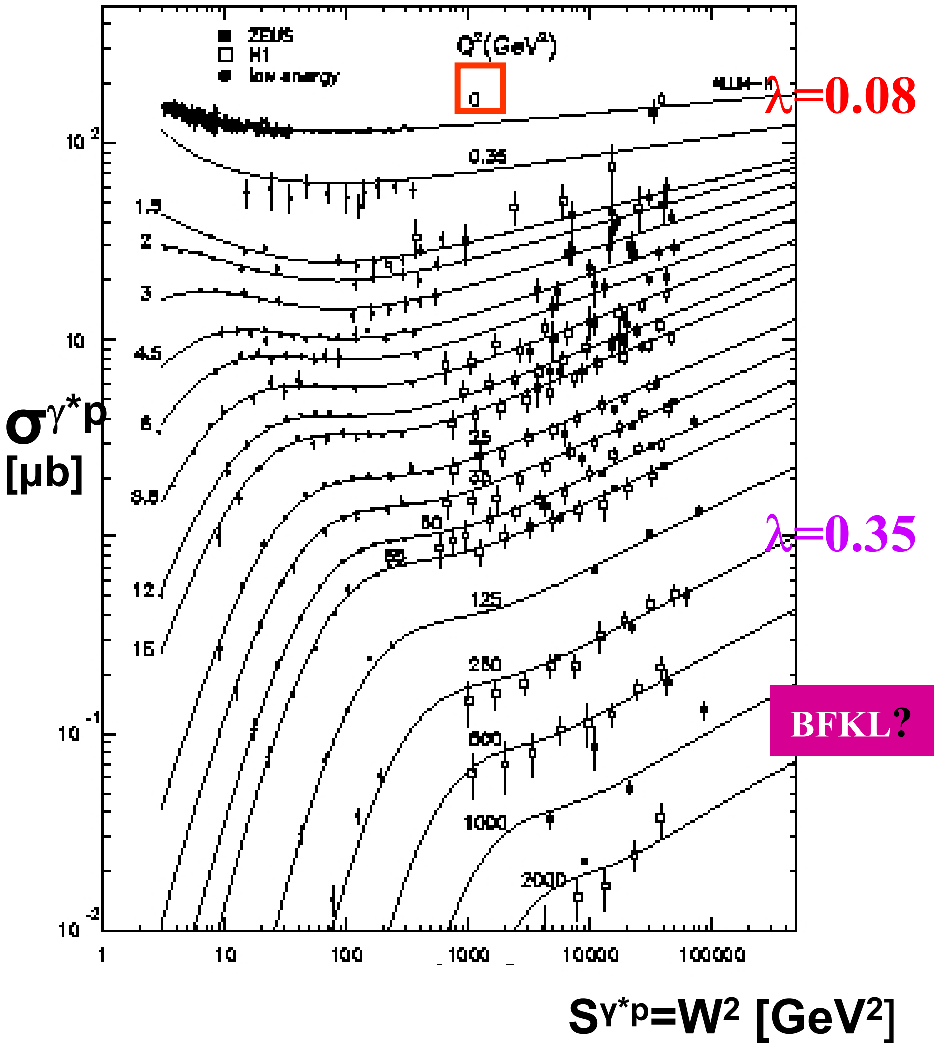
$$\boxed{F_2(x, Q^2) = F_2(W^2, Q^2) \approx 4\pi\alpha^2 Q^2 * \sigma^{\gamma^* p}(s_{\gamma p}, Q^2)}$$

$\gamma^* p$ cross section at high energy



soft Pomeron (p-p) intercept

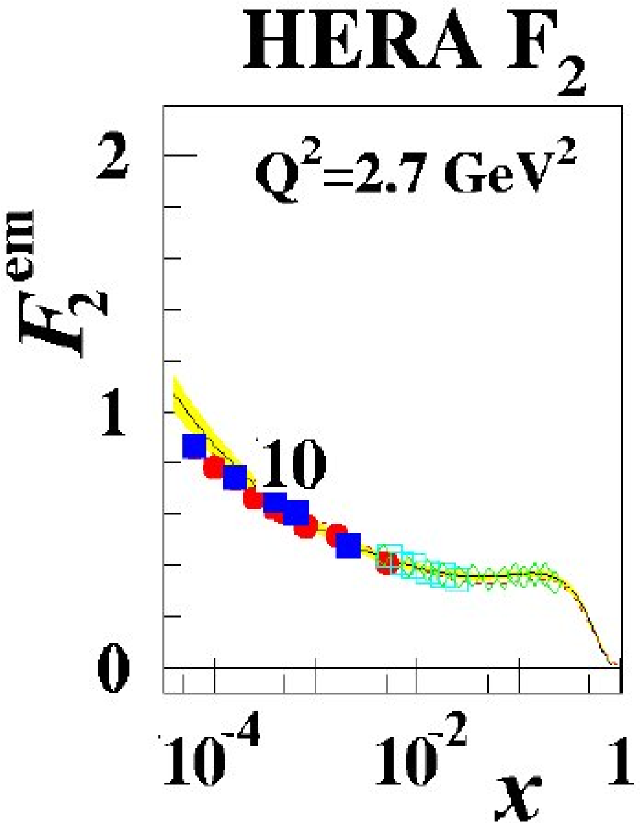
σ (pp) ~ $s^{0.08}$ = $s^{\alpha(0)-1}$ *at high energy*

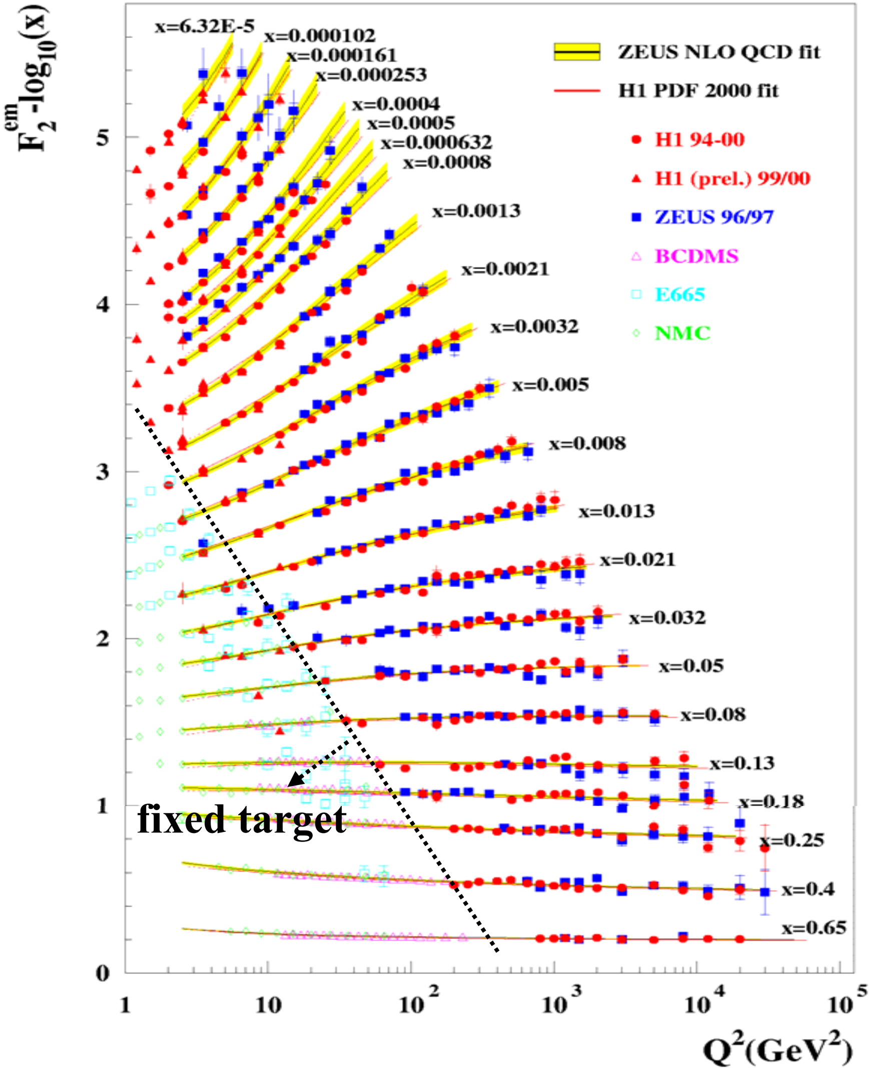


$$\sigma^{\gamma^* p}(W^2) \sim F_2(W^2,Q^2)/Q^2 \sim s^{\lambda}$$

1. gluon distribution and α_S

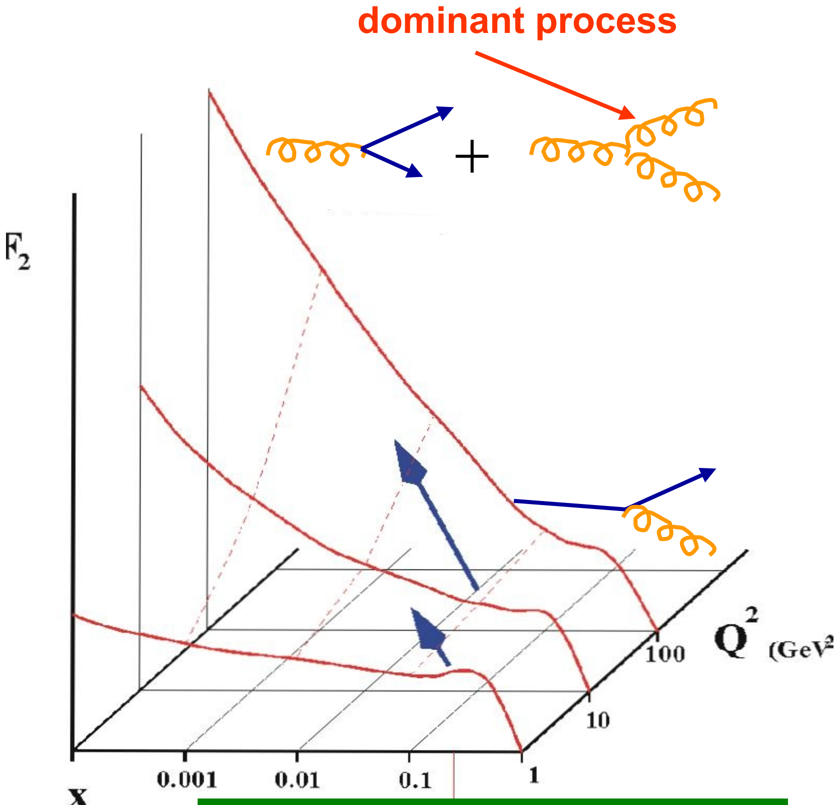
data basis:





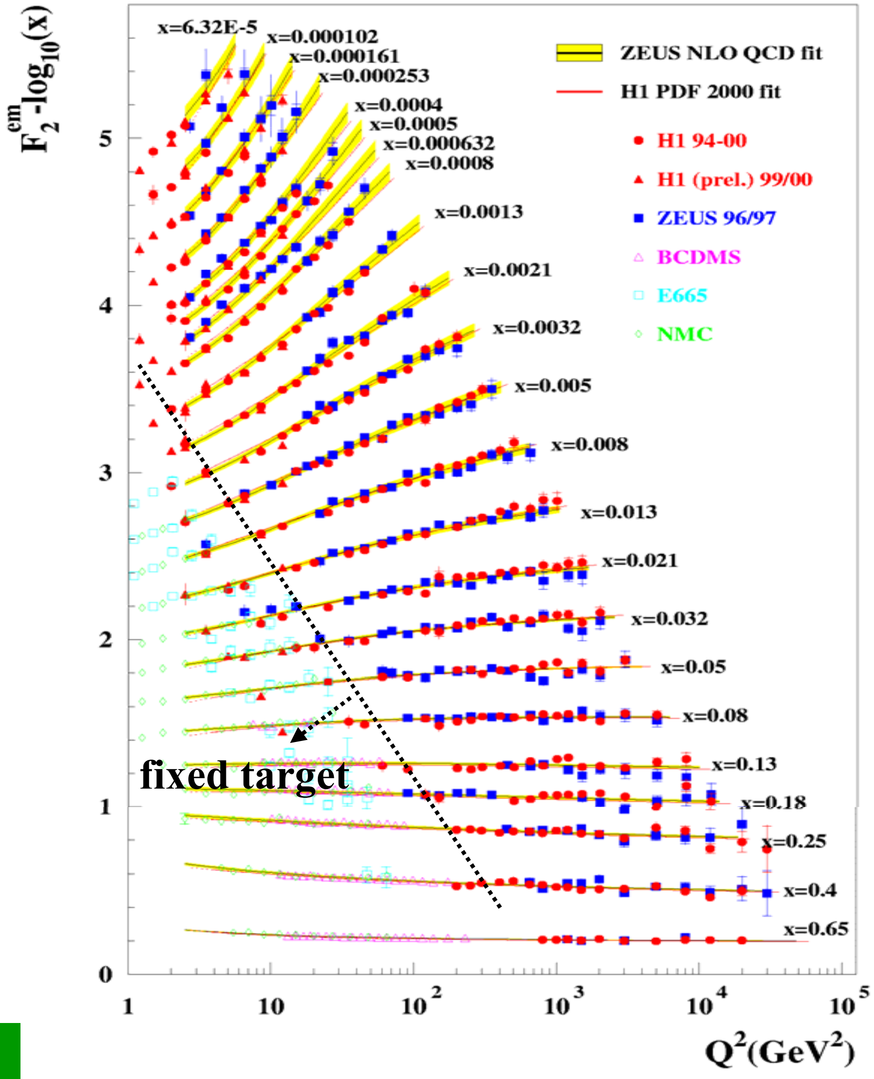
Fixed target: : 1-2% (low Q2, high-x)
HERA: bulk: 2-3% , 5% at high Q2 , large-x

1. gluon distribution and α_S



in L.O. :

$$\frac{dF_2(x,Q^2)}{d\log Q^2} \propto \alpha_s \times g(x,Q^2)$$



DGLAP evolution works over the full x-range for $Q^2 > \sim 2$ GeV^2

Parton densities :should we determine them?

Why should the HERA experiments care about doing NLO fits themselves?

there is a whole industry: MRST, CTEQ,……

The problem is data selection and treatment of systematic errors:

a) different data sets simply don't agree→ we don't gain by combining them we should rather choose "the best"

b) very often there are data point regions which are dominated by systematic errors.. Does it make sense to use them?

c) how can we treat systematic errors and determine the uncertainties of the parton densities

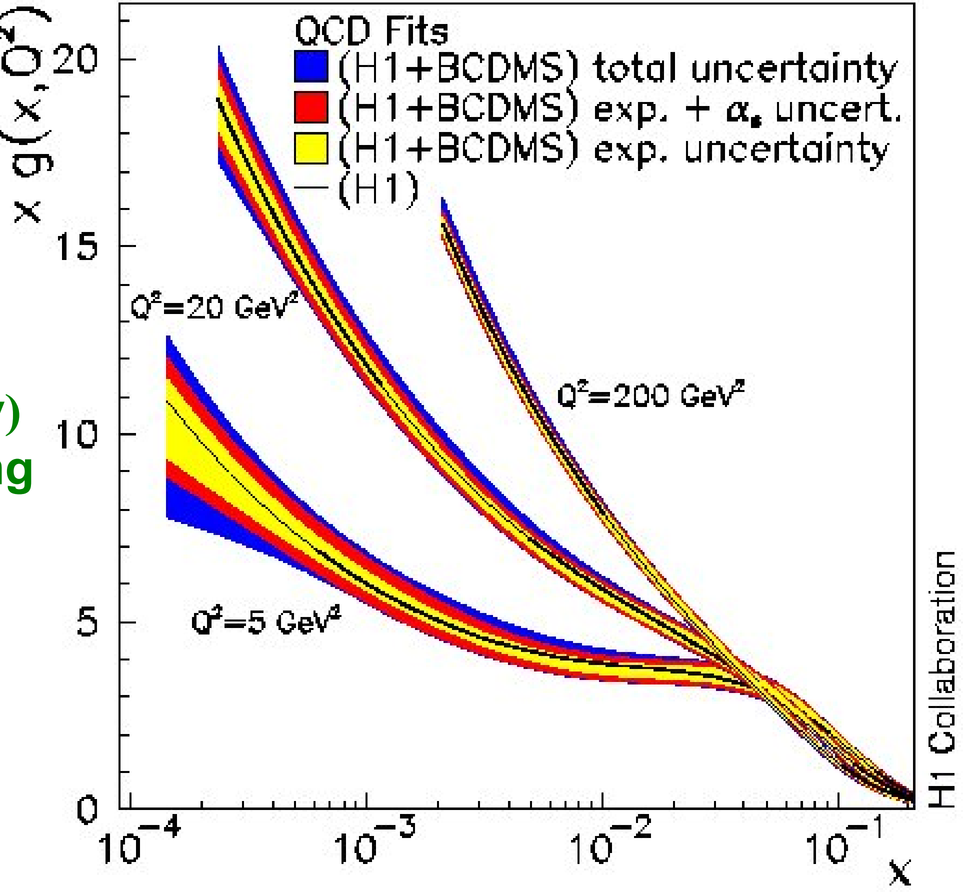
HERA experiments have taken a leading role there…we determine parton densities including their uncertainties

- **we don't have to separate the flavours in order to determine the gluon density which is the main issue of HERA**

gluons and α_S: minimal number of data sets (H1)

Most radical approach by H1 for gluon density and α_S:

1. choose the minimal necessary number of data sets: H1 and BCDMS (ep)
2. reject regions where the systematic errors are dominant (BCDMS low v)
3. fit the size of systematic errors using their functional form

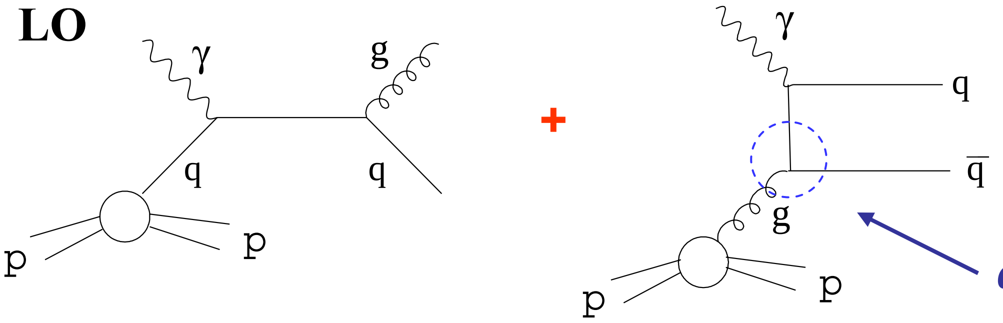


$\alpha_S (m_Z) = 0.1150 \pm .0019$

$\pm$ .005 (th. Scale error NLO fit)

will be reduced by new NNLO (α_S^3) analysis

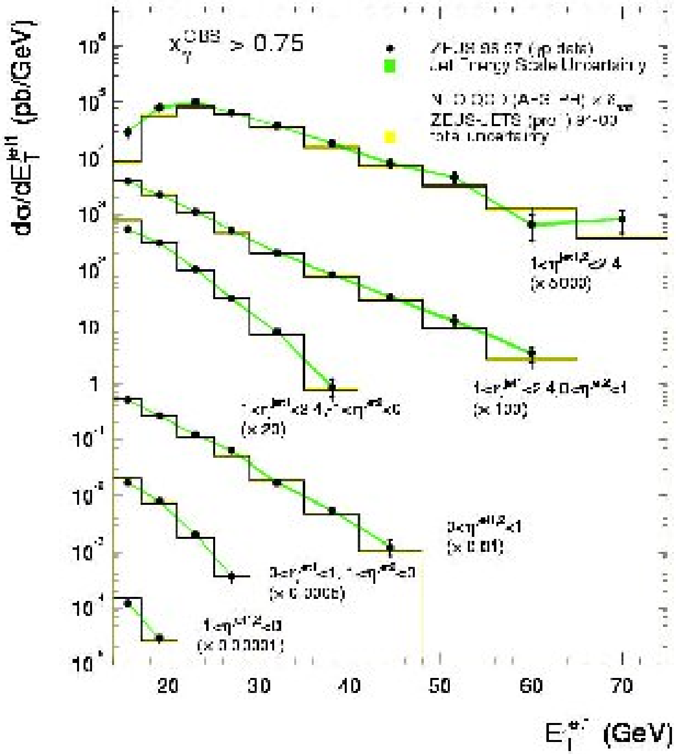
gluon and α_S: include also jet data (ZEUS)



dominant

- jets directly sensitive to gluons also at medium x~ 0.1
- reduction of α_S- gluon correlation

ZEUS (γp)



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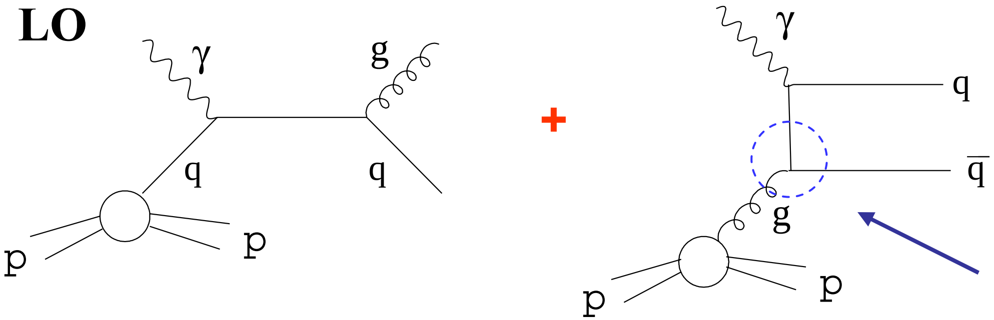

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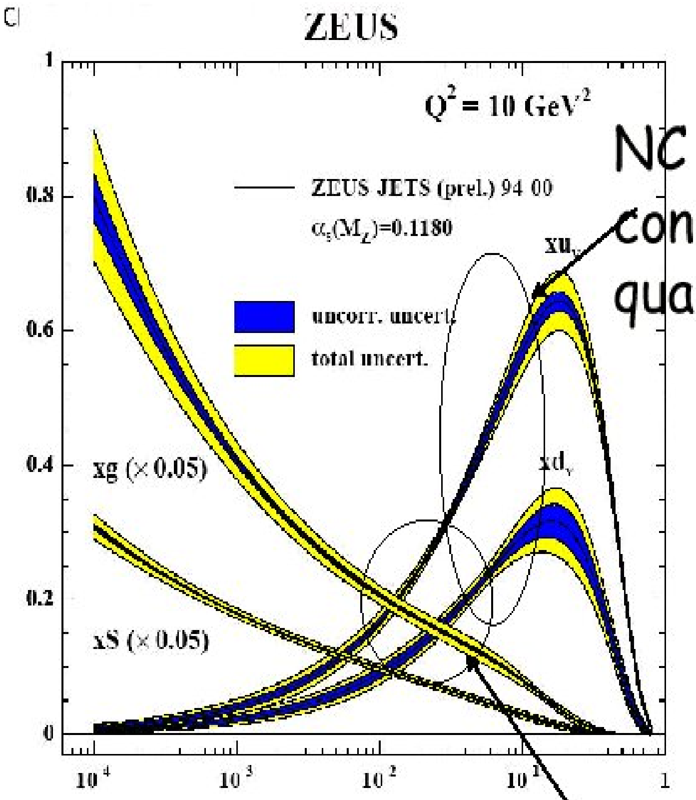
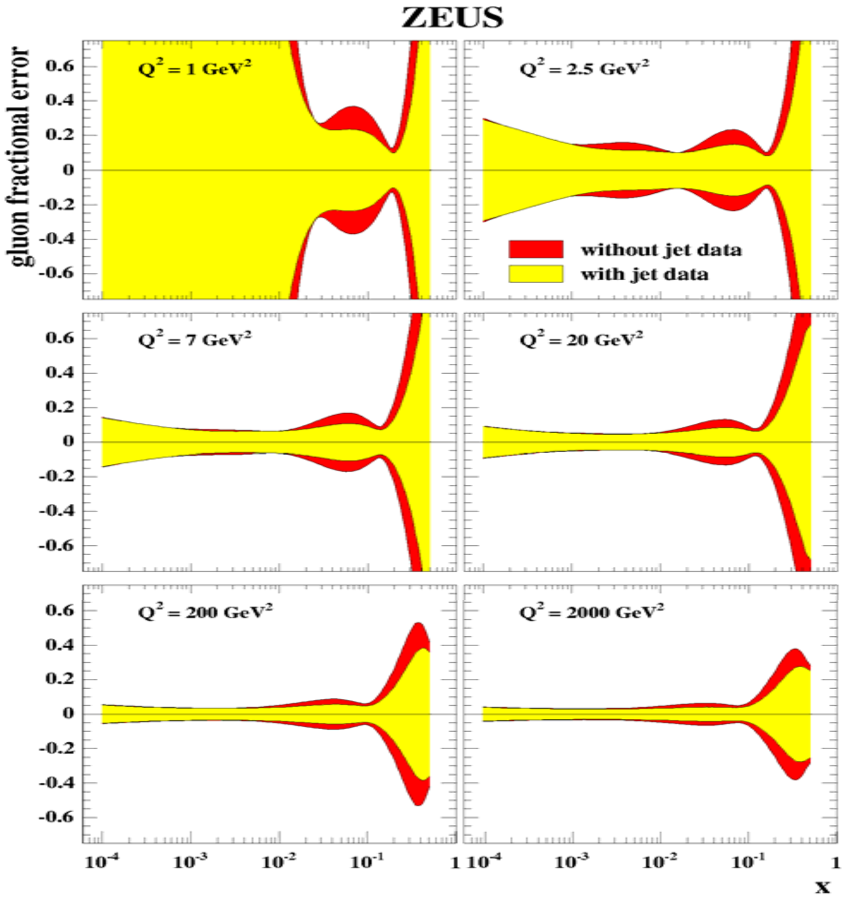
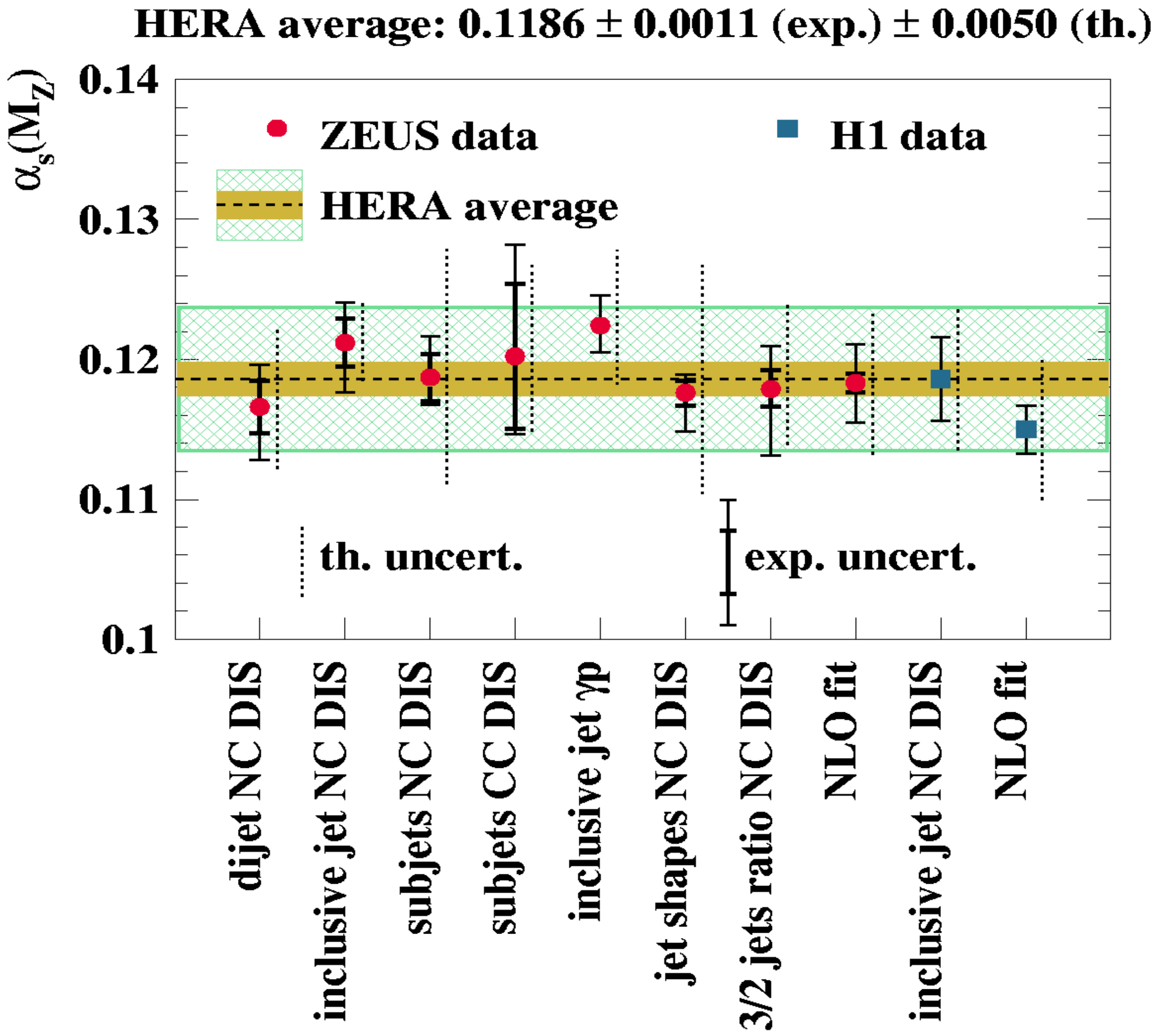


NC and CC constrain quarks

jets constrain gluon



strong coupling from HERA



To be compared to
an error of 0.002
given as world error by
the particle data group

Error from fit to F_2 will be Reduced by NNLO fit!

every value represents a pQCD analysis….

….. Study of multiscale problems lik e.g heavy quark production …

Parton dynamics at low x physics?

A step beyond the oversimplified treatment of pQCD

- **The DGLAP evolution equations do not include all the leading terms in the low x limit. It neglects terms ~ α_s ln(1/x) which become large for x< 10^{-2}**

DGLAP approximation

terms in the evolution of splitting functions

$[\alpha_s \ln(Q^2)]^n$ $\quad$ $[\alpha_s \ln(Q2) * \ln(1/x)]^m$ $\quad$ $[\alpha_s \ln(1/x)]^n$

BFKL approximation

Do we need the Lipatov effect (Lipatov Pomeron) to describe HERA data at low x?

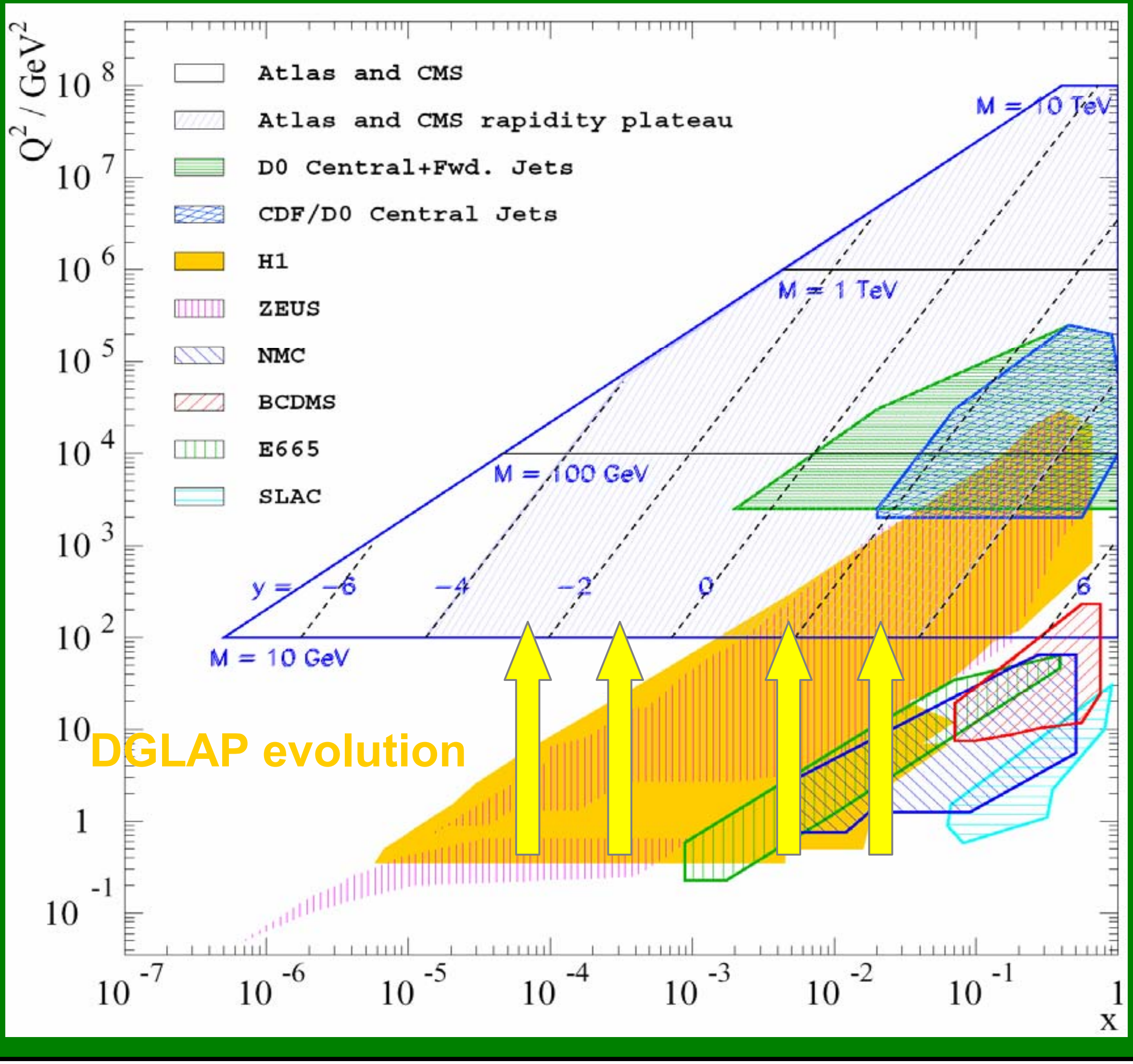
- **inclusion of the ln(1/x) terms leads to a strongly rising γ^*p cross-section at high energy or equivalently to $F_2 \sim x^{-\lambda}$ for x→0 with $\lambda \approx 0.5$ and enhanced gluon radiation**

For very high parton densities the cross section must saturate!

low x results

- the scaling violation of $F_2(x,Q2)$ are not specific enough to detect the presence ln(1/x) terms, they also show no evidence for saturation ($Q^2 > 2$ GeV^2)

  → we have a solid basis for transfering HERA PDFs to LHC



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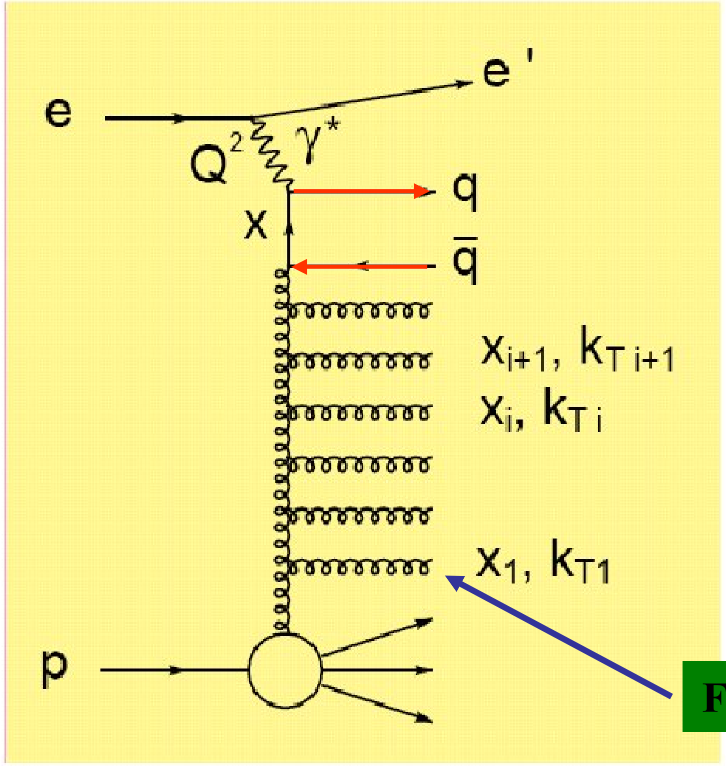
- → look for final state partons

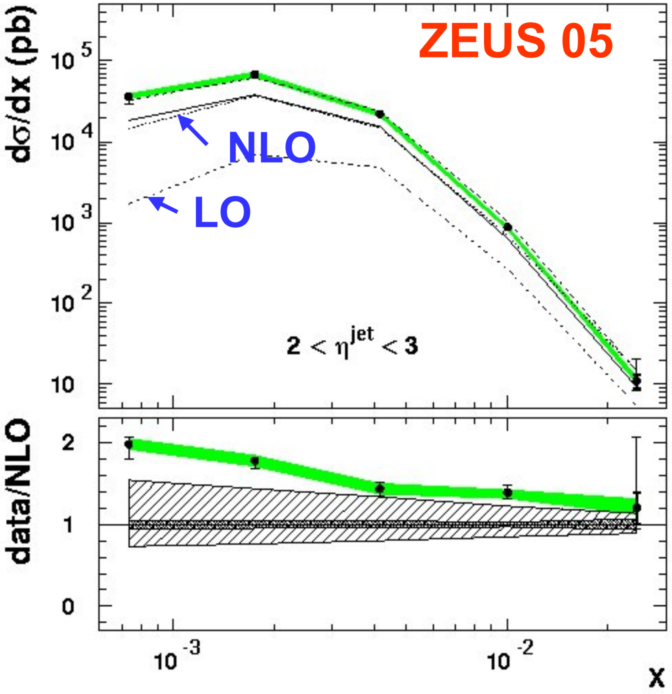
- a low x parton comes from a cascade of subsequent radiations

DGLAP approximation:
$k_{T1} \ll k_{T2} \ll k_{T3}$ .. (few hard jets near proton direction)
BFKL approximation:
$x_1 \ll x_2 \ll x_3$ … (hard forward jets and more partons with high k_T expected)
(A. Mueller)



Forward jet, forward π^0

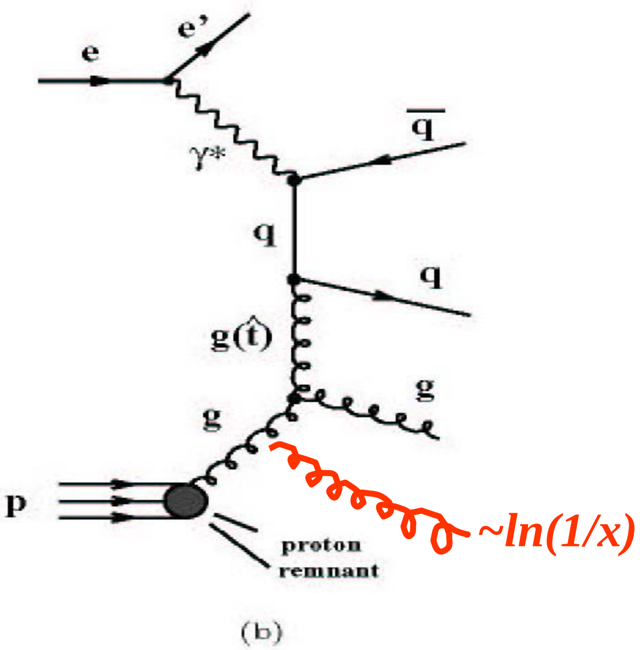
low x dynamics: Forward jets



Area of study for the last 10 years

- **excess of jets at low x in 'BFKL phase space region'** **(similar results from forward π^0 and energy flow)**
- **huge corrections from LO→ NLO (α_s^2) at low x** **NLO includes the 3-jet topology for the first time** **→ what happens in NNLO (α_s^3)** ??

low x dynamics: Forward jets



Area of study for the last 10 years

- **excess of jets at low x in 'BFKL phase space region' (similar results from forward π^0 and energy flow)**
- **huge corrections from LO→ NLO (α_s^2) at low x NLO includes the 3-jet topology for the first time**
  → what happens in NNLO (α_s^3) ??

Will be answered by
H1 analysis

3- and 4 – jet events at low x
compared to NNLO

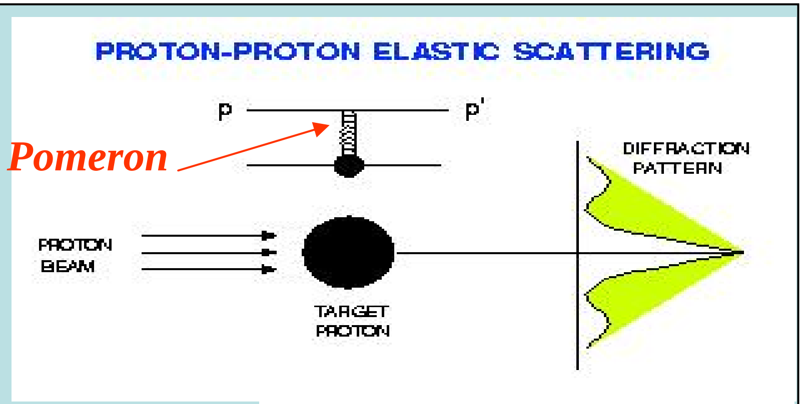
Wait for summer conferences

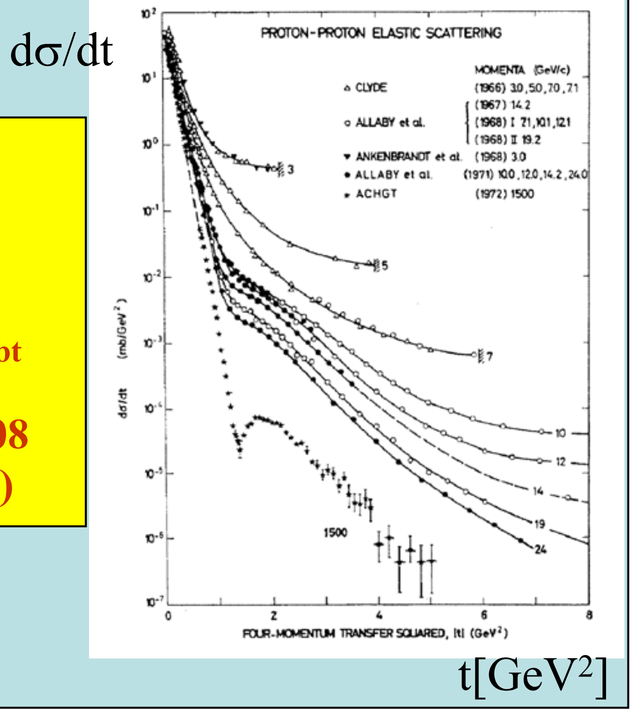
NNLO fixed order includes 4-jet topologies and therefore ln(1/x) terms for the first time (1 gluon can be radiated over the whole phase space)

→ We have to find agreement at some level!

BFKL dynamics is not a dominant feature at HERA also theoretically understood by now

3. Diffraction: the structure of the Pomeron





for large s:

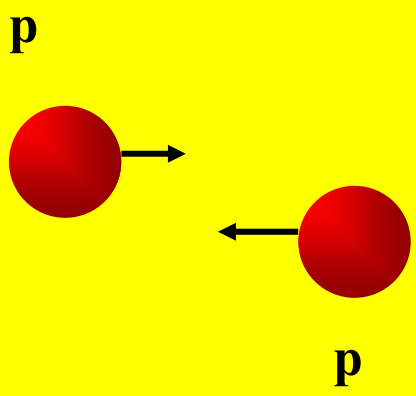
$\sigma_{tot} = b\, s^{\lambda}$

$ds/dt \sim s^{2\lambda}\, e^{-bt}$

$\lambda=\alpha(0)-1=0.0808$
(soft Pomeron)

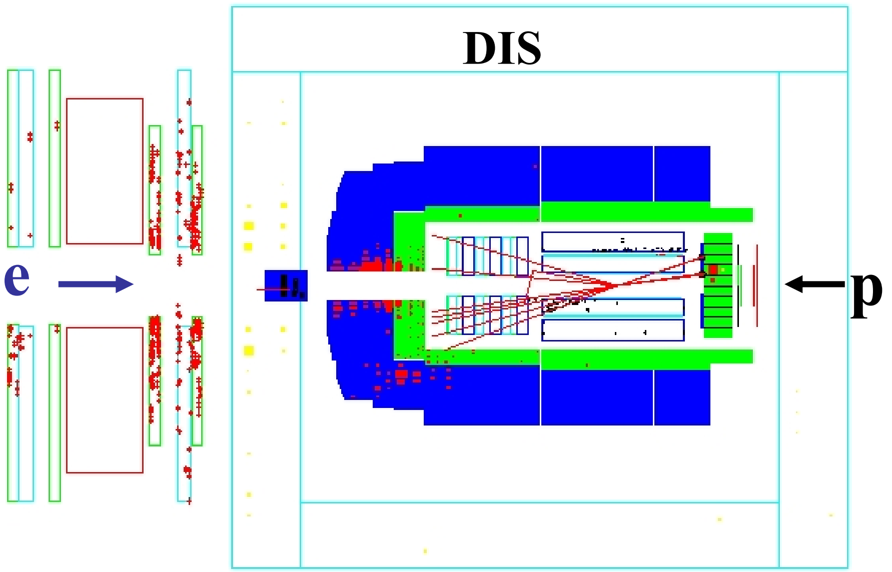
p-p scattering at high energies:
total cross section and elastic scattering

$\sigma_{tot} \sim \mathrm{Im}\,[\,A_{el}\,(t=0)] \sim s^{\alpha(0)-1}$



We don't understand this process where we exchange energy, momentum but no Quantum numbers or charges (color)

In QCD exchange has to be described by (several) quarks and/or gluons
Neither pQCD nor lattice calculations work

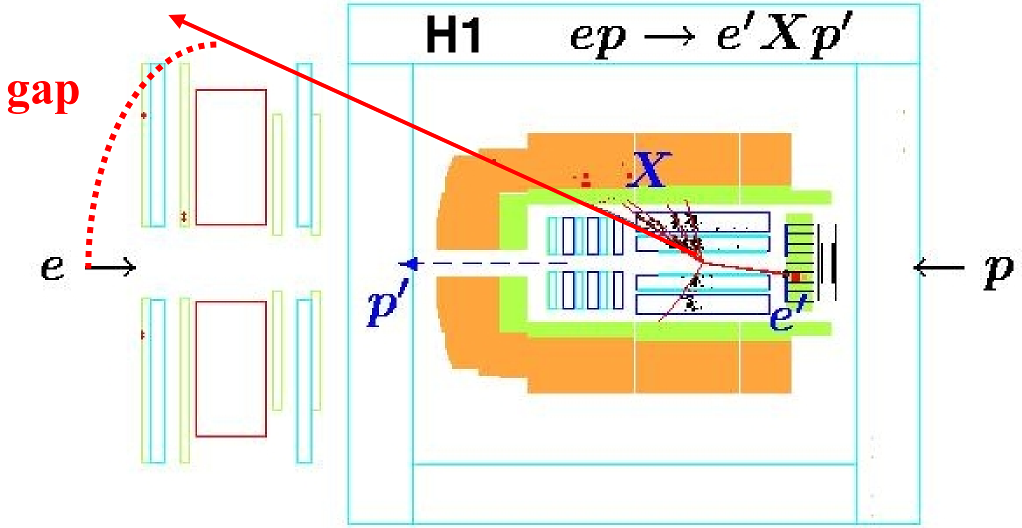


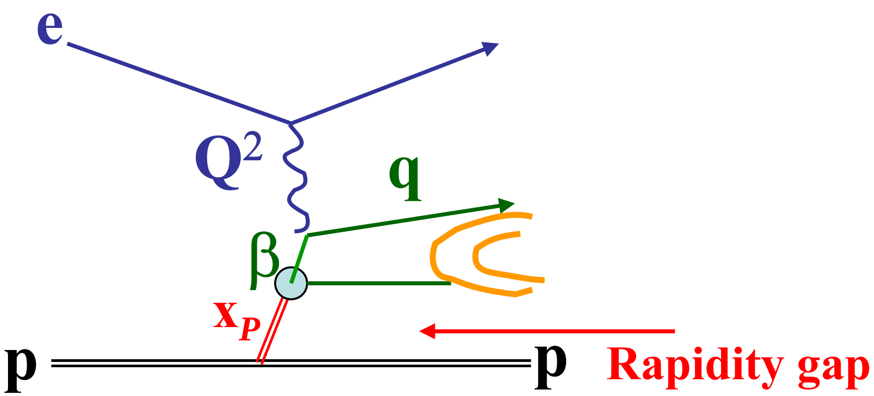
diffractive scattering at HERA (~10% of all events)

1. elastically scattered proton!

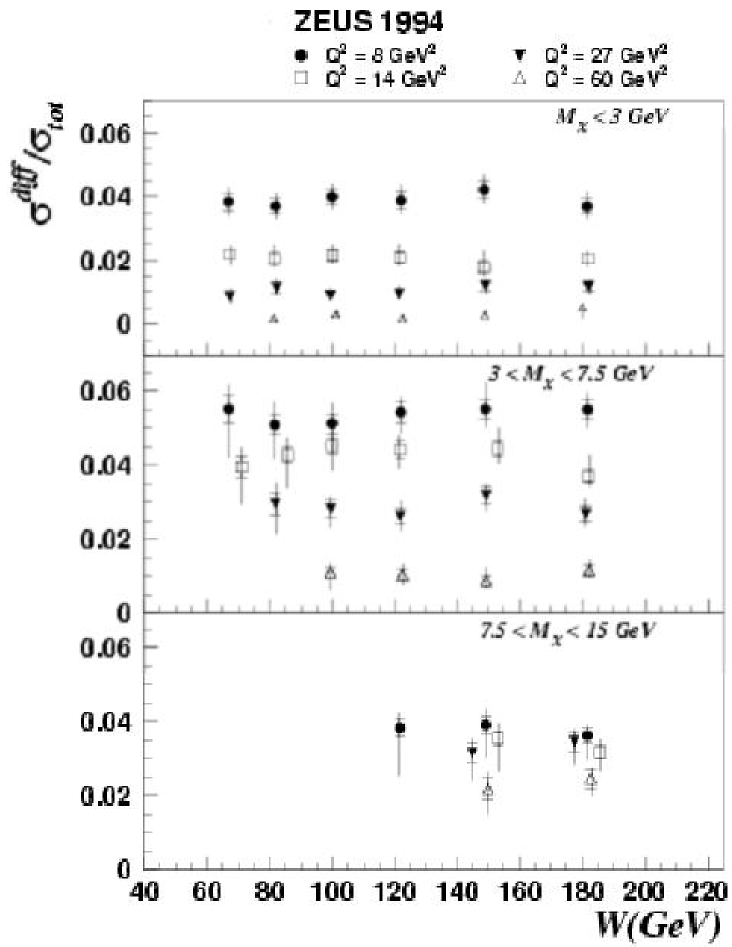
(would be best, but low acceptance)

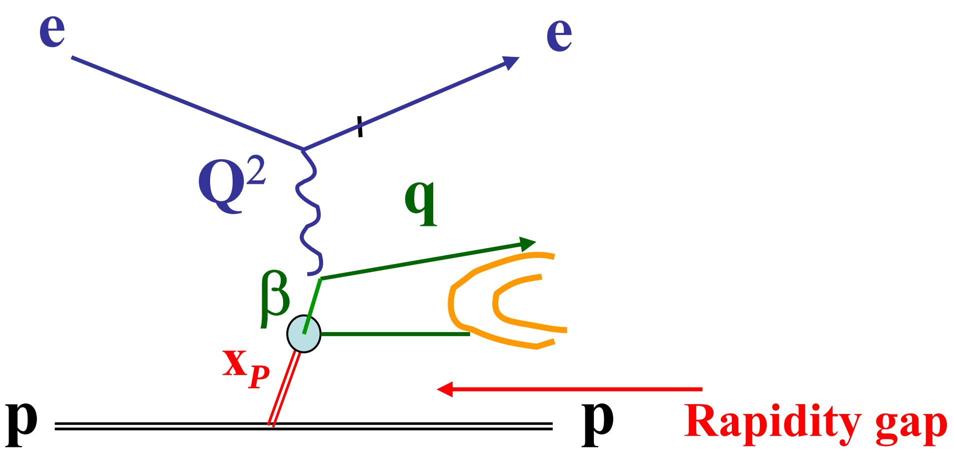
2. no ‚forward energy'
(rapidity gap event)





Basic facts on diffractive events at HERA



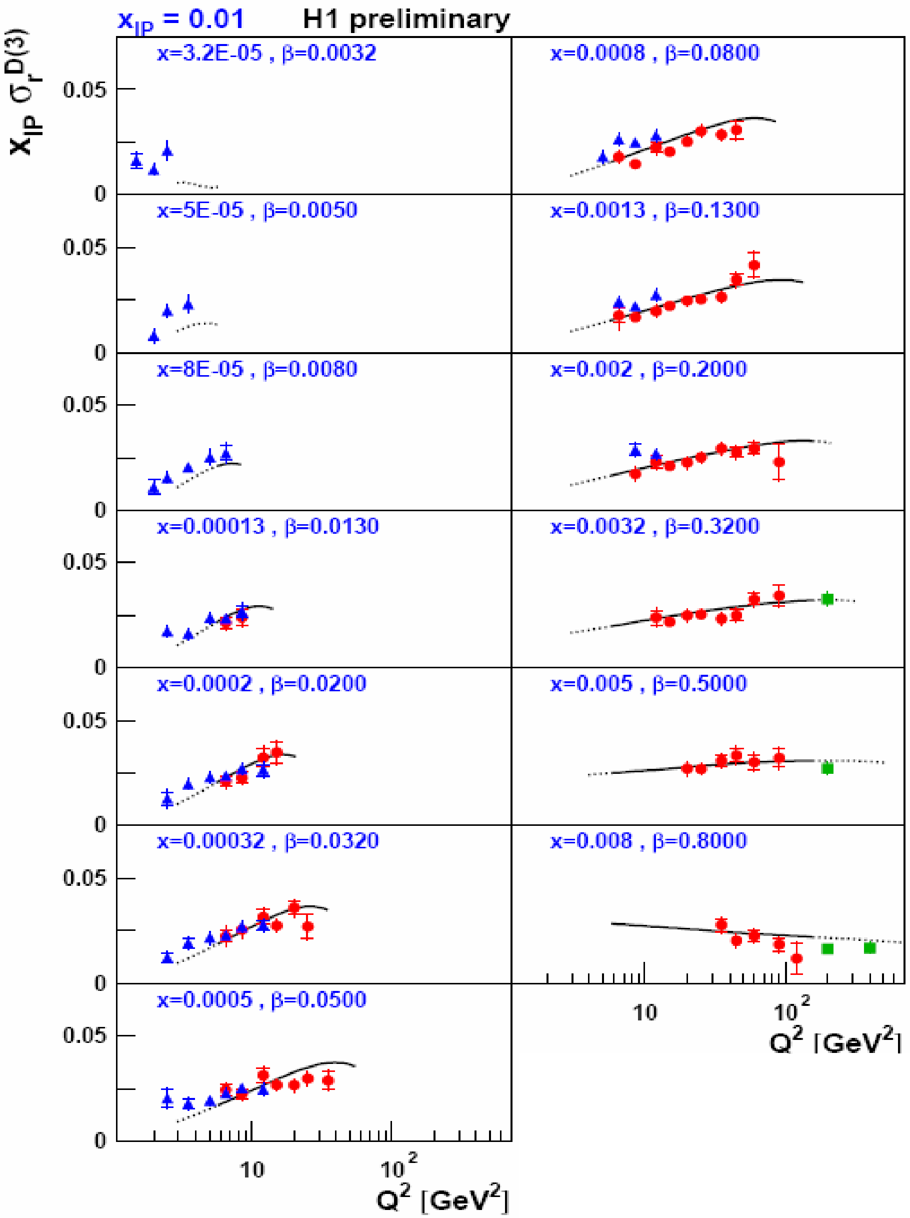


1. the ratio of diffractive to standard DIS events is constant vs. energy W , … ??? *simple message ??*

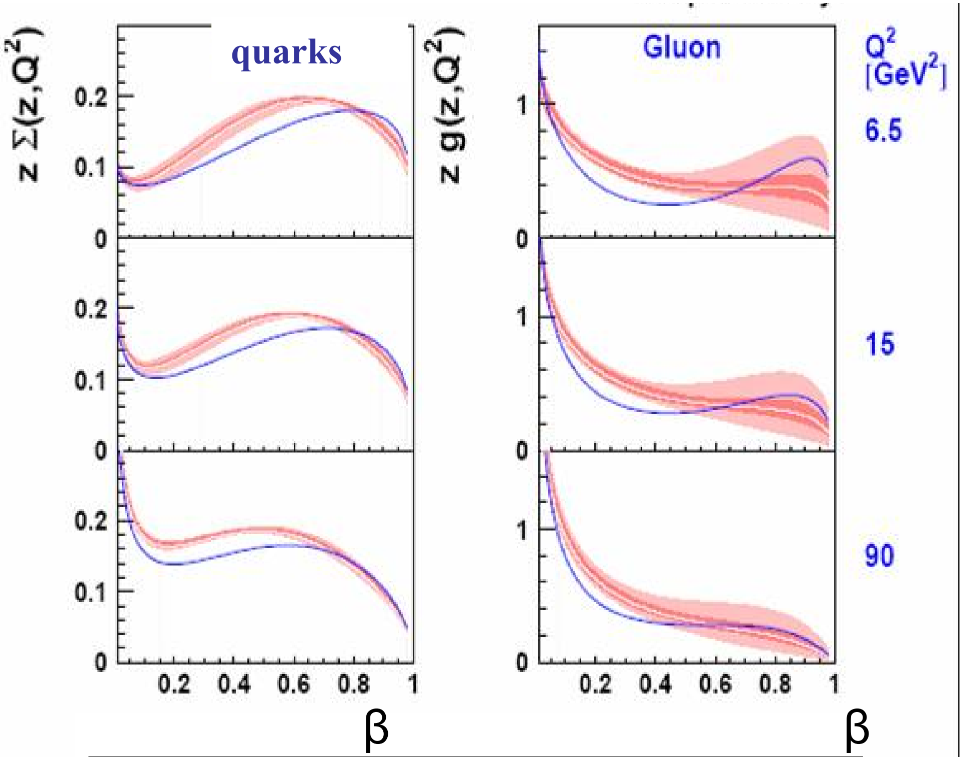
2. We can determine diffractive quark and gluon densities of the proton by deep inelastic scattering as usual but with the additional requirement that the proton is elastically scattered. (scattering off partons in the Pomeron)

gluons by the analysis of scaling violations

diffractive parton densities



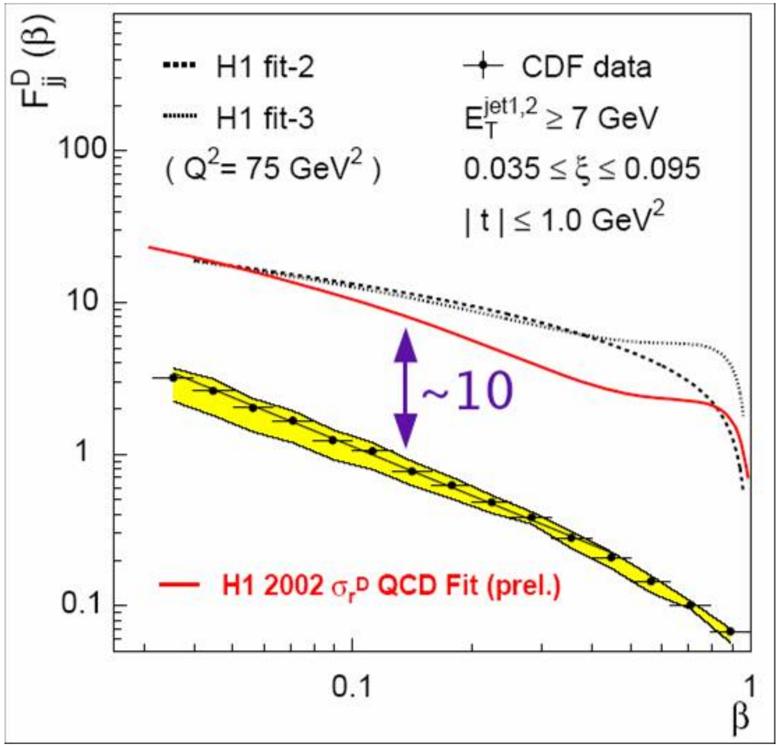
H1 NLO analysis (2002)



gluons carry 75±15 % of Pomeron momentum!

can we use these gluon and quark densities to predict other processes?
QCD factorisation?

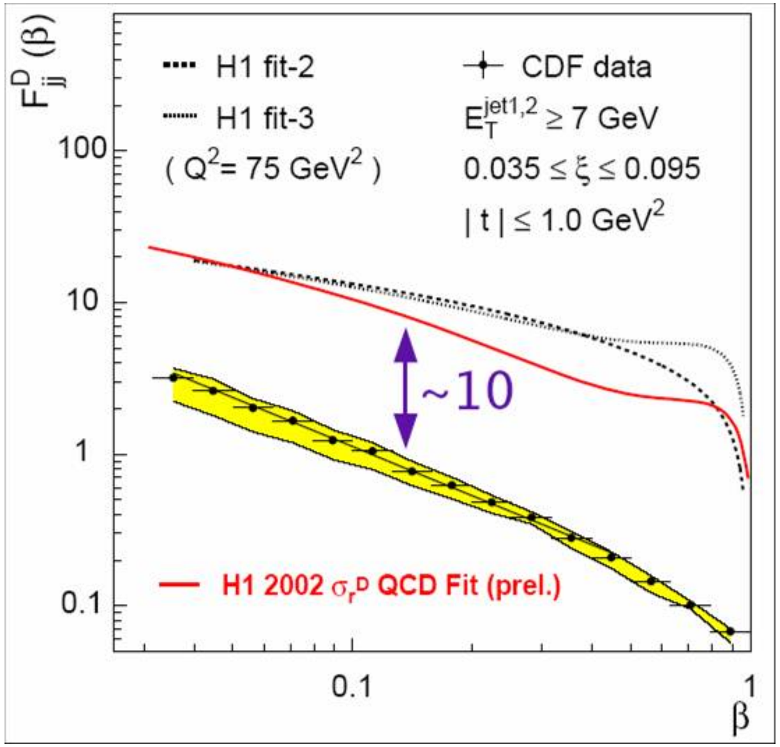
Prediction of other diifractive hard processes? QCD factorisation?



Tevatron pp :factorisation fails

described by models of 'gap survival probability' which is small due to spectator interactions

Prediction of other diifractive hard processes? QCD factorisation?



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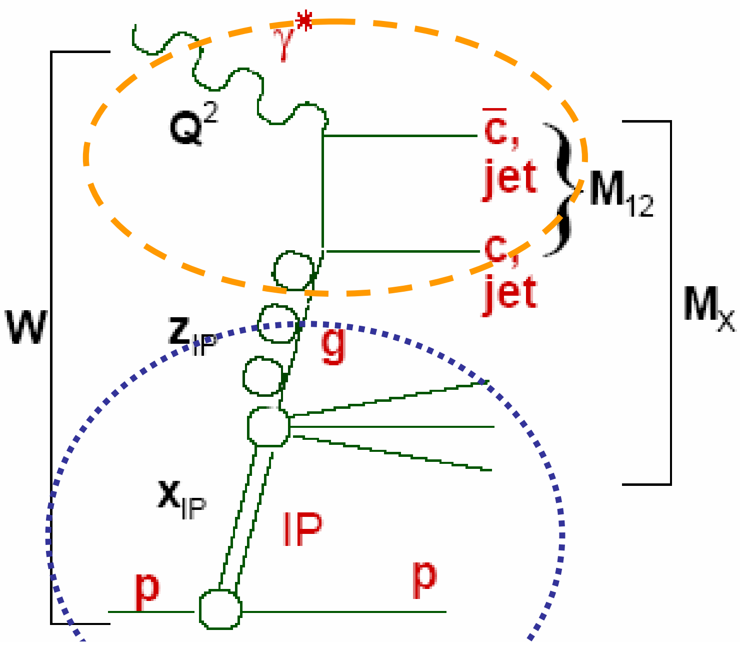
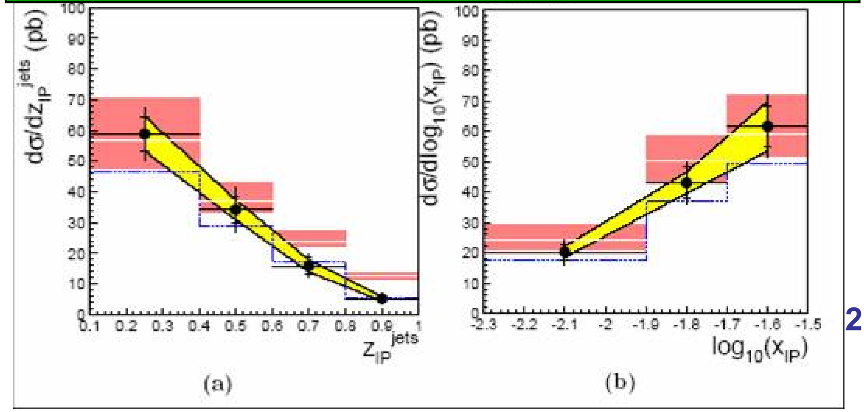
parton-parton cross sections



DIS: QCD factorisation works! ***(Collins..)***

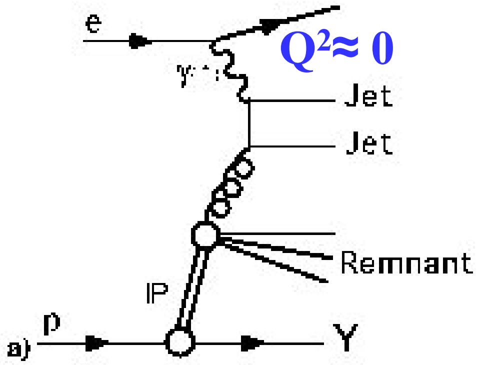


(a)

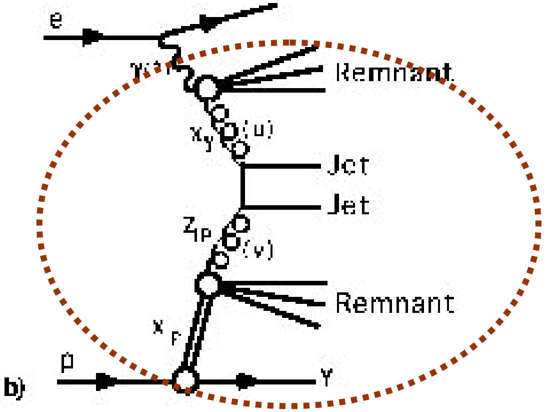
(b)

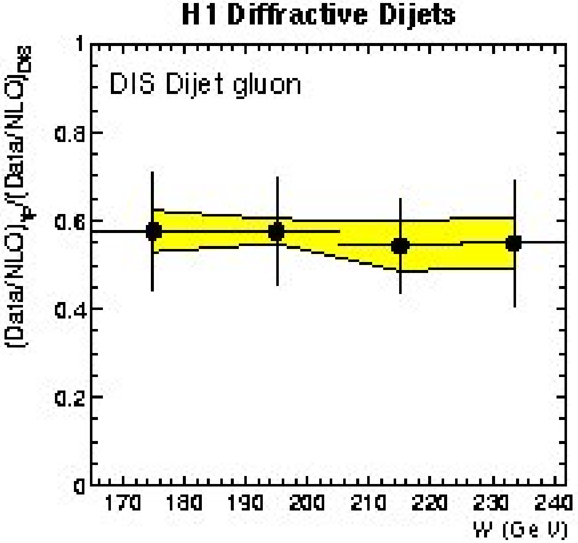
diffraction: QCD factorisation in γp ?

direct γ (DIS-like)

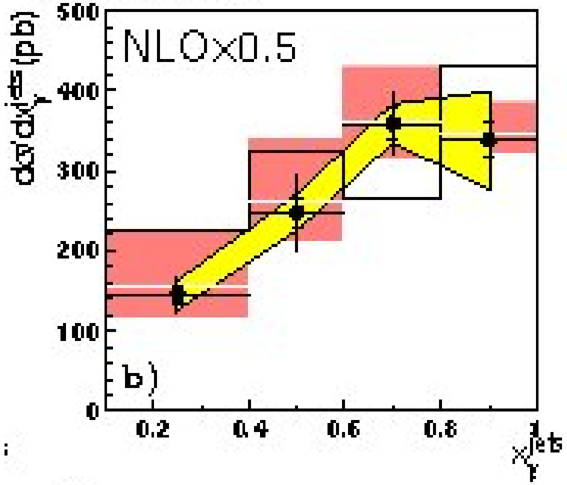


hadron-like





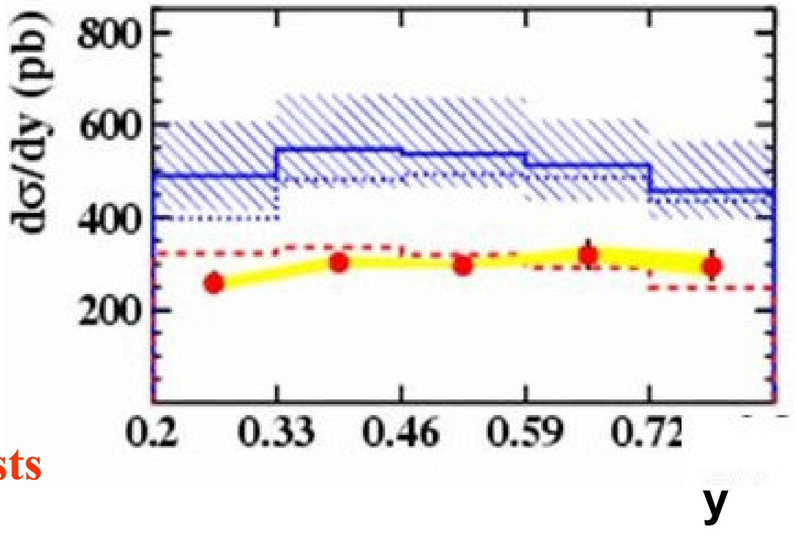
QCD factorisation in γp is broken by global factor ~0.6



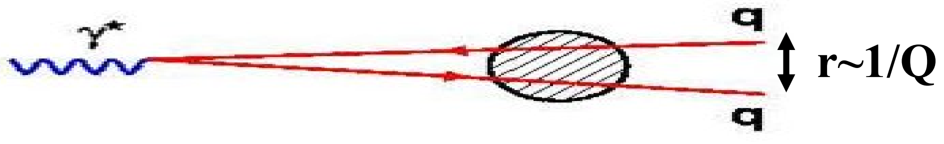
H1: factorisation is broken also in direct interactions by same factor!

this is not understood and against expectations of most theorists

ZEUS gamma-p



from hard to soft physics: do we see saturation?



- We measure high energy scattering of a color dipole with the proton
- We can choose the transverse size of the dipole via Q^2

$$\sigma^{\gamma^* p}(x,Q^2) \sim F_2(x,Q^2)/Q^2$$

$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r}\int_0^1 d\alpha\,|\Psi_{T,L}(\alpha,\mathbf{r})|^2\,\hat{\sigma}(x,r^2)\,,$$

F_2

dipole WF in the photon (calc.)

dipole-p cross-section

$$\sigma_{T,L}^{\text{diffr}} = \frac{1}{16\pi B}\int d^2\mathbf{r}\int_0^1 d\alpha\,|\Psi_{T,L}(\alpha,\mathbf{r})|^2\,\underline{\hat{\sigma}^2(x,r^2)}$$

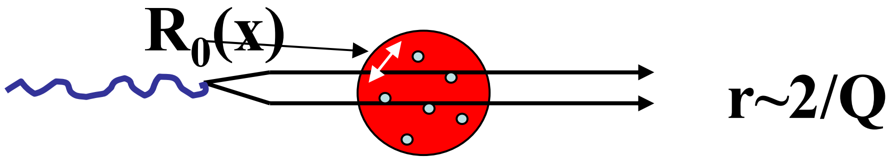
diffraction (F_2^D)

The only unknown in principle is the dipole-p cross section which depends on:

- **x ~ 1/t**
- **the transverse size of the dipole**
- **the distribution profile of the gluons in the proton and their transverse momentum distibution**

can it be calculated? xxx

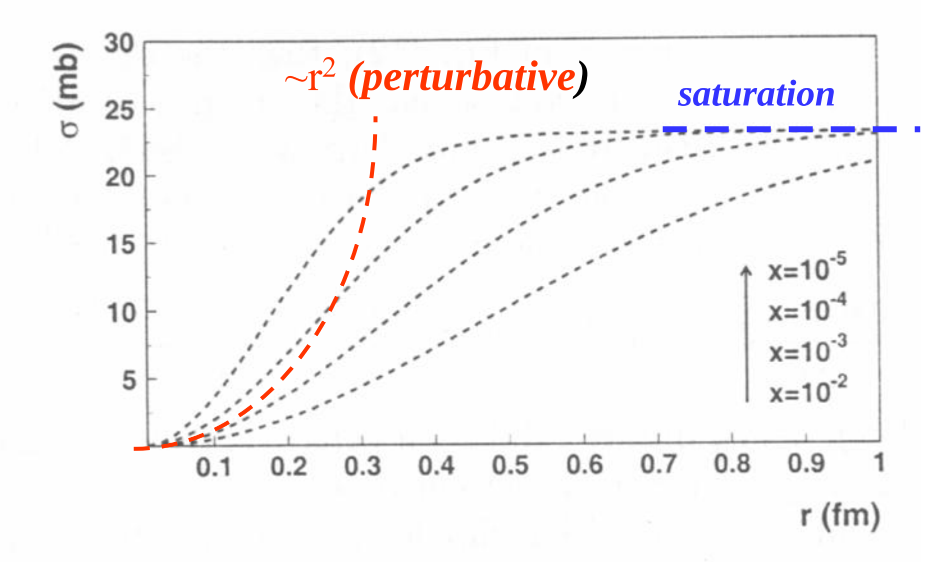
the dipole –p cross section: the saturation model



$$\hat{\sigma}(x,r^2) = \sigma_0 \left\{1 - \exp\left(-\frac{\sigma_{q\bar{q}}}{4R_0^2(x)}\right)\right\},$$

$$\sigma_{qq} = \pi_2/N_c\, r^2\, \alpha_S\, (\mu^2)\, xg(x,\mu^2)$$

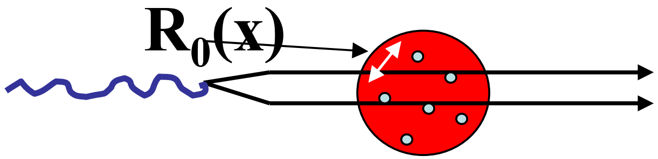
perturbative QCD predicition for small dipole sizes ~r²



simplest version: Golec-Biernat ,
Wüsthoff 99 **:** *$R_0(x) = (x/x_0)^{\lambda}$* * 1 GeV²
improvements: + Bartels, Kowalski

$R_0(x) \sim (1/x)^{\lambda}$: average gluon distance at which saturation sets in. Depends also on transverse gluon profile T(b).

the dipole –p cross section: the saturation model



r~2/Q

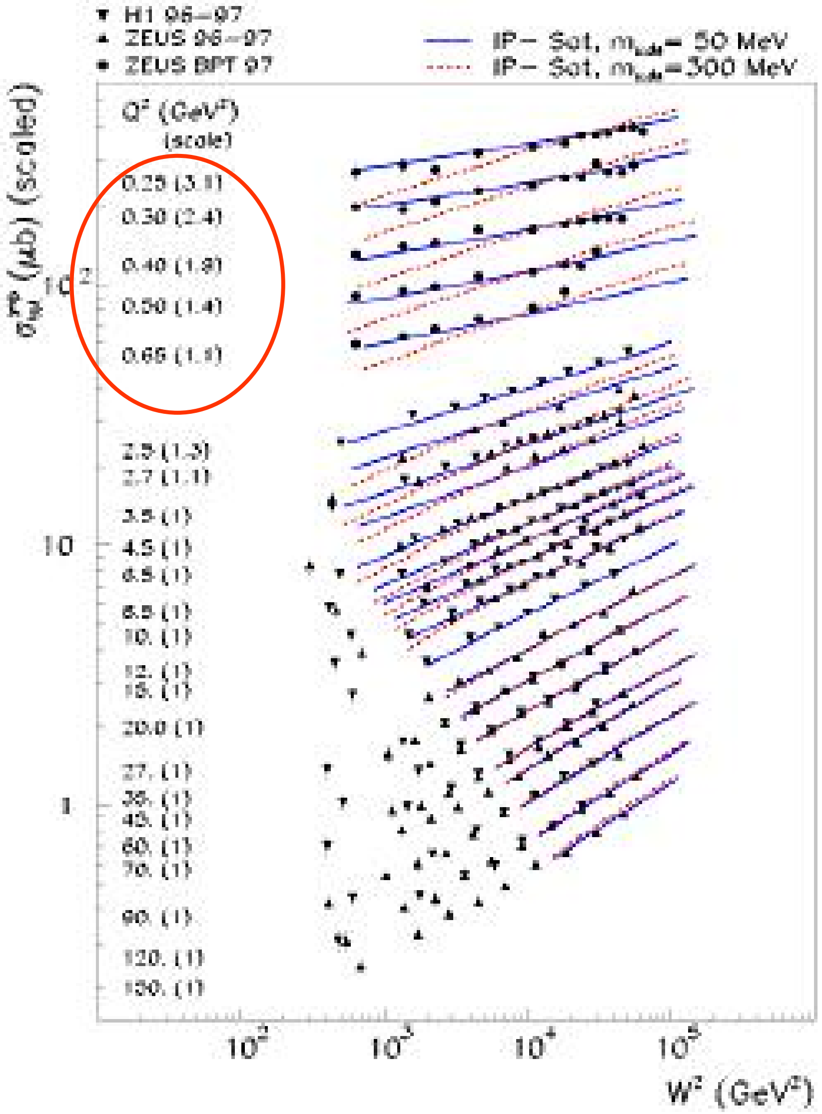
$$\hat{\sigma}(x,r^2) = \sigma_0 \left\{ 1 - \exp\left(-\frac{\sigma_{q\bar{q}}}{4R_0^2(x)} \right) \right\} ,$$

$$\sigma_{qq} = \pi^2/N_c\, r^2\, \alpha_S(\mu^2)\, xg(x,\mu^2)$$

perturbative QCD predicition
for small dipole sizes ~r^2

$R_0(x)$ ~ $(1/x)^\lambda$: average gluon distance at which saturation sets in. Depends also on transverse gluon profile T(b).

confront to data: Fits to F_2 at $x<10^{-2}$ to determine free parameters:
→ $x_0 = 3\ 10^{-4}$, $\lambda = 0.15$,



describes transition to soft physics!

successes of dipole saturation model

1. describes F_2 at small x and transition to small Q^2

2. predicts 'geometric scaling' of F_2 at small x

   $F_2(x,Q^2) = F_2(\,Q^2{*}\,R_0^2(x)\,)$ eqiv.

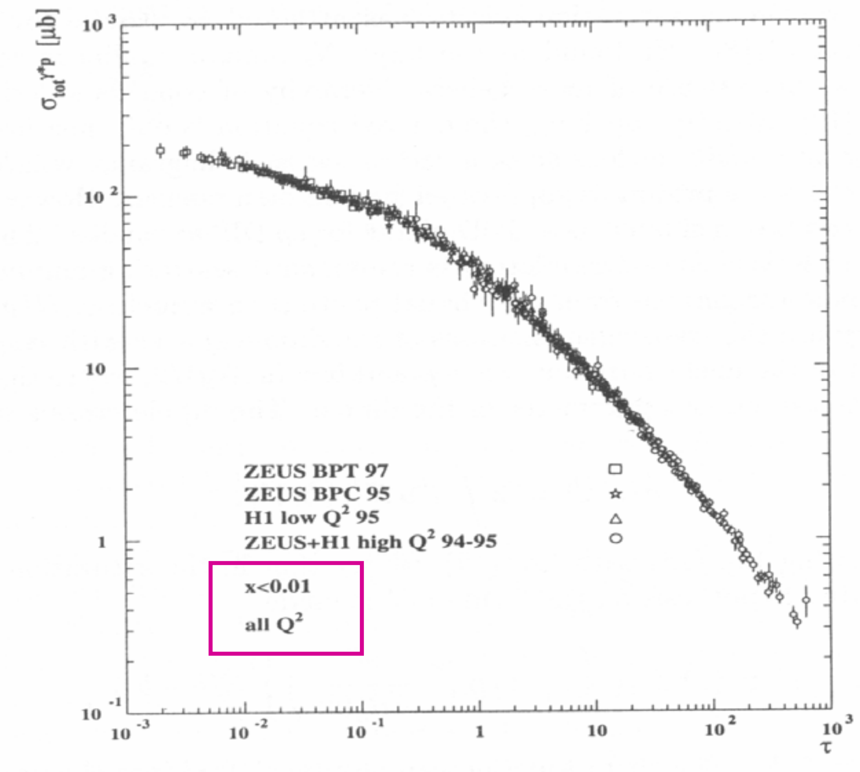
   dimensionless variable ↗

   $\sigma^{\gamma^* p} = \sigma^{\gamma^* p}\,(Q^2{*}R_0^2(x))$

3. predicts the ratio DIS diffractive/ DIS = constant vs. energy

   → *this was one of the simple messages of the data which are not easily explained*

4. detailed predictions concerning diffractive processes (needs more theoretical work to make use of strong constraints)



$\tau = Q^{2*}\,R_0^2(x)$

This is of course no proof of saturation but several disconnected effects are successfully predicted…
→ very appealing though not compelling

very much discussed and worked on in Heavy Ion community (e.g. RHIC) (Color Glass Condensate), unfortunately less so in our community

Summary QCD: next steps?

- **HERA delivers the decisive information about the gluon distribution**

- **it has delivered the data to guide theory how to describe low energy QCD e.g. the transition from hard to soft physics**
this has triggered large theoretical progress regarding dynamic QCD evolution, saturation, understanding of diffraction and high energy scattering…

unfortunately theoretical situation is not very transparent –
→difficult to present in a convincing and appealing way
→but every effort is justified

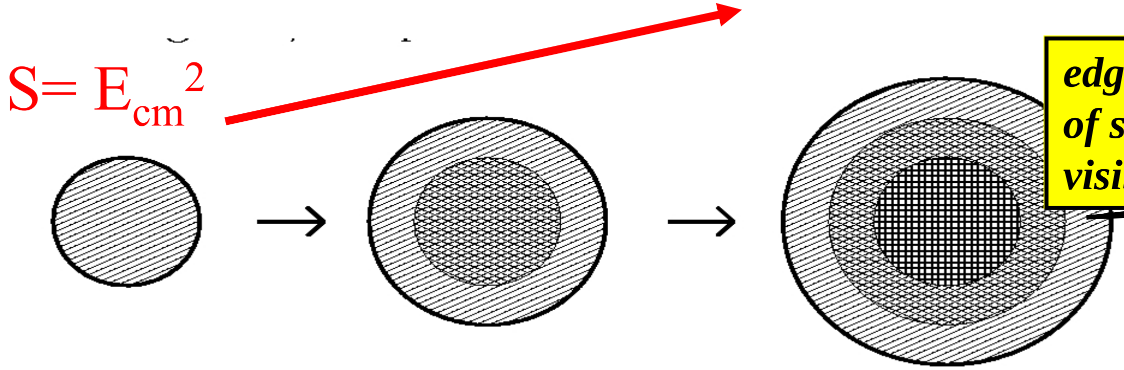
QCD is the most beautiful example of a gauge theory - so we better learn to understand it where it shows its genuine features best

next forseeable steps of new quality :

- **measure impact paramter dependence of dipole cross section (started already by *diffractive vectormeson production at high t*)**
- **Measure gluon-gluon correlations in the proton → *DVCS***
- **instantons..**

→ see next talk

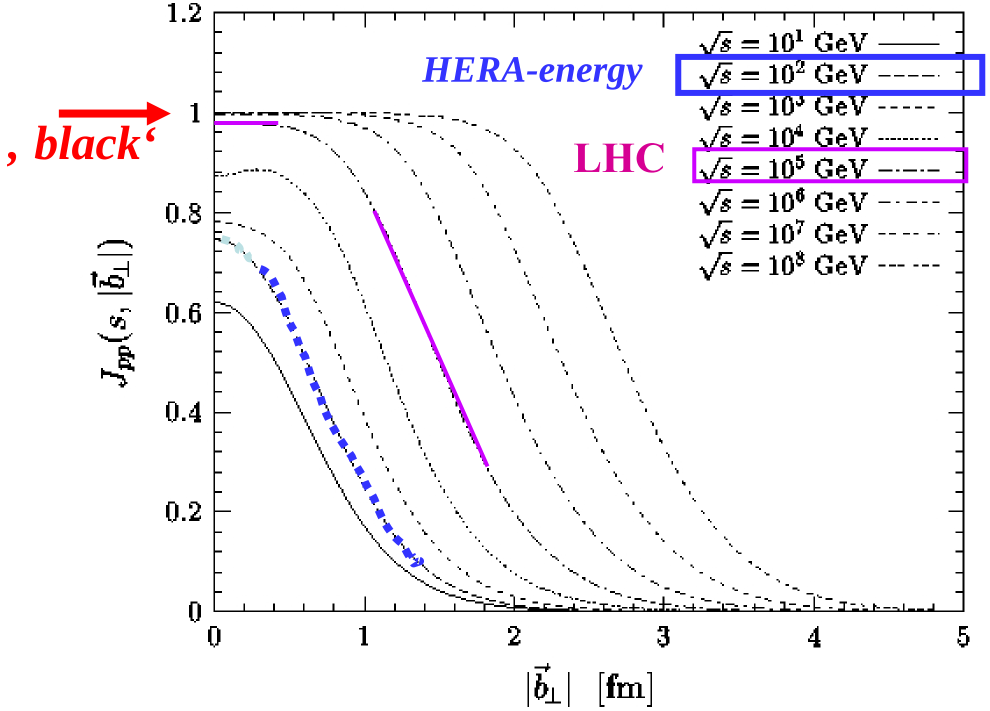
how does the proton-proton scattering look like at high energy?

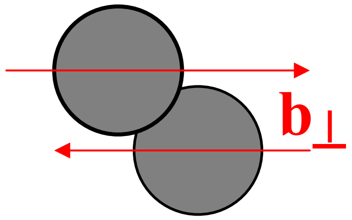


edge area increases due to the evolution of soft gluons which become visible (active) at high energy

proton gets blacker and inceases its size with increasing CM energy

Profile function



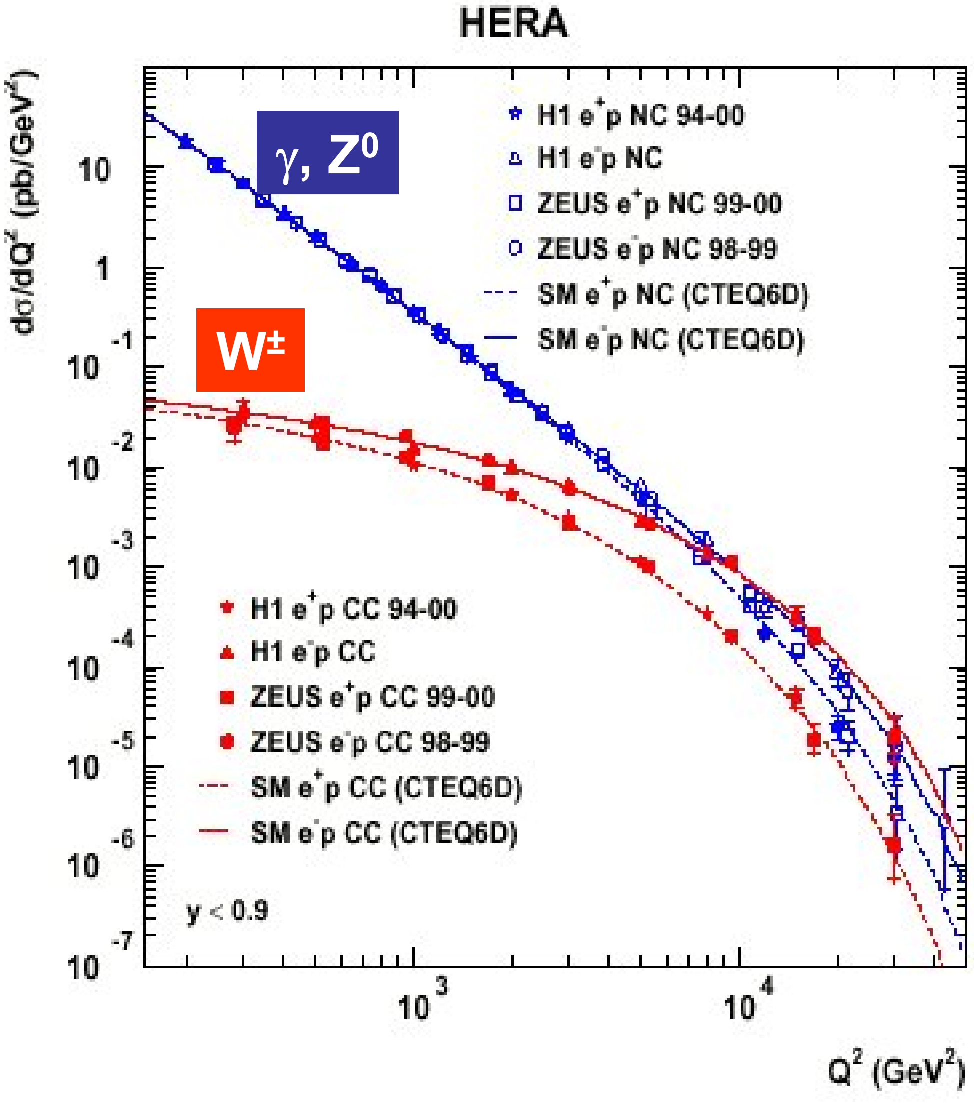


example:
model of Pirner, Shoshi, Steffen ,2002

could be consolidated much better by HERA measurements and their theoretical interpretation

-2

2. electroweak physics



EW Unification

electromagnetic and weak forces become equally strong at $Q^2 \sim M_W^2$

precision?
→ next talk

3. new physics at HERA?

- **we have finally seen the spectacular events for which we have buildt our detector: (H1)**

- leptons, missing energy, jets-

(but we suffer from the 'ALEPH syndrom')

standard model process is single W-production

- **rate too high (for H1)**
- **excess events are not W-like**
- **excess grows with increasing statistics at (HERAII) with same rate!**

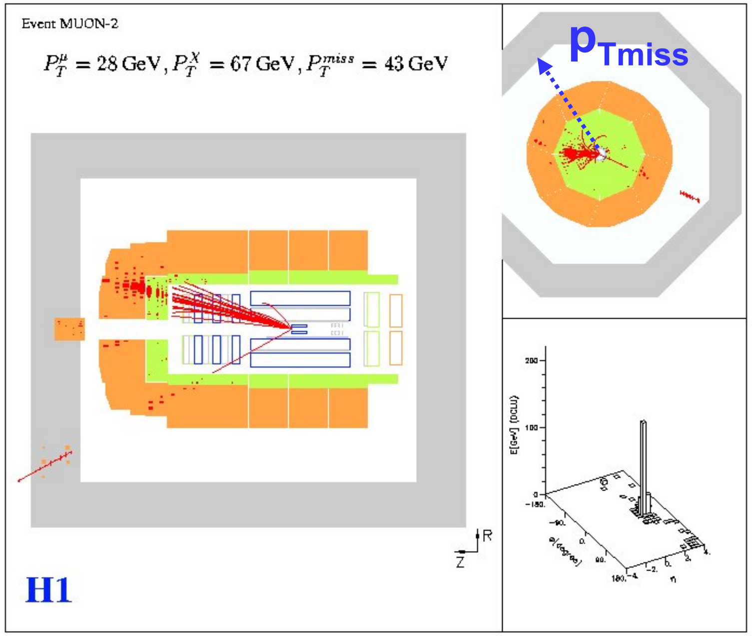
events with P_{Tjet}>25 GeV
16 events / 5.3 expected (4.5 $W^\pm$)

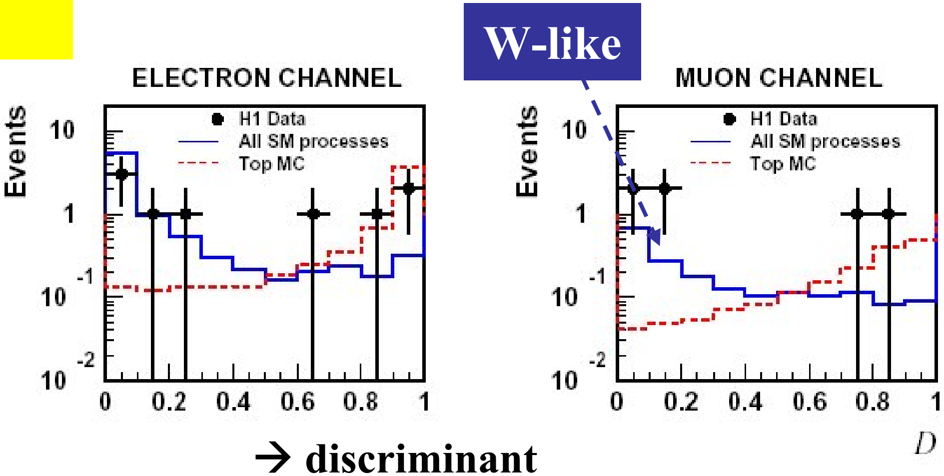
7 events/ 5.7 expected (HERA I)

→Hope, but more data needed
(should be settled since a long time)

→ next talk, thank you

$e^+p \rightarrow \mu^+X$





→ discriminant