Highlights from HERA I and II

Hamburg,

June 26, 2001

Peter Schleper

DESY

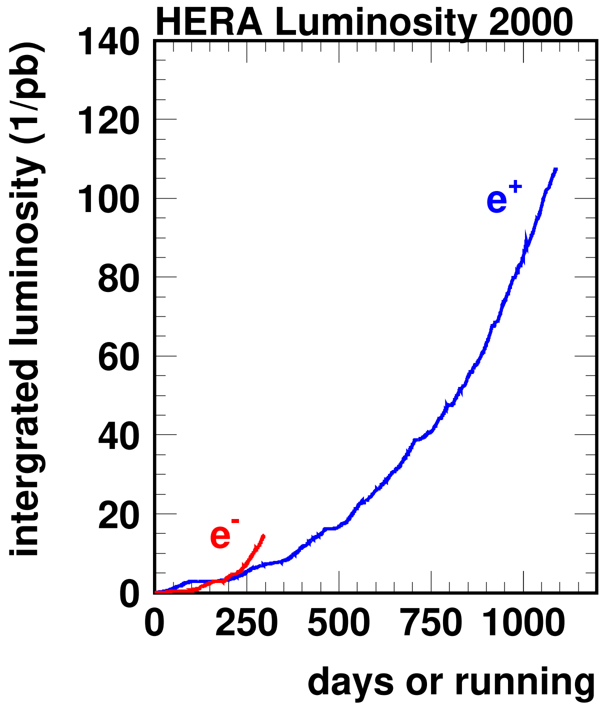
a personal selection

no attempt to do justice to the experiments

incomplete

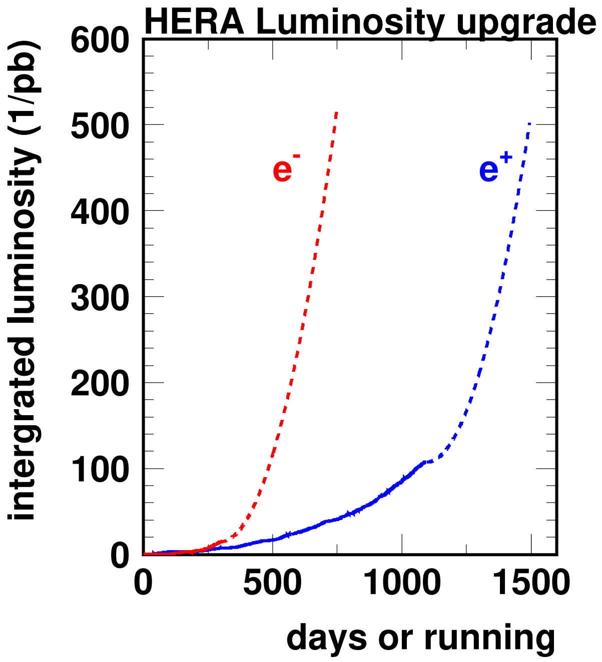
speculative

... from HERA I to II ...



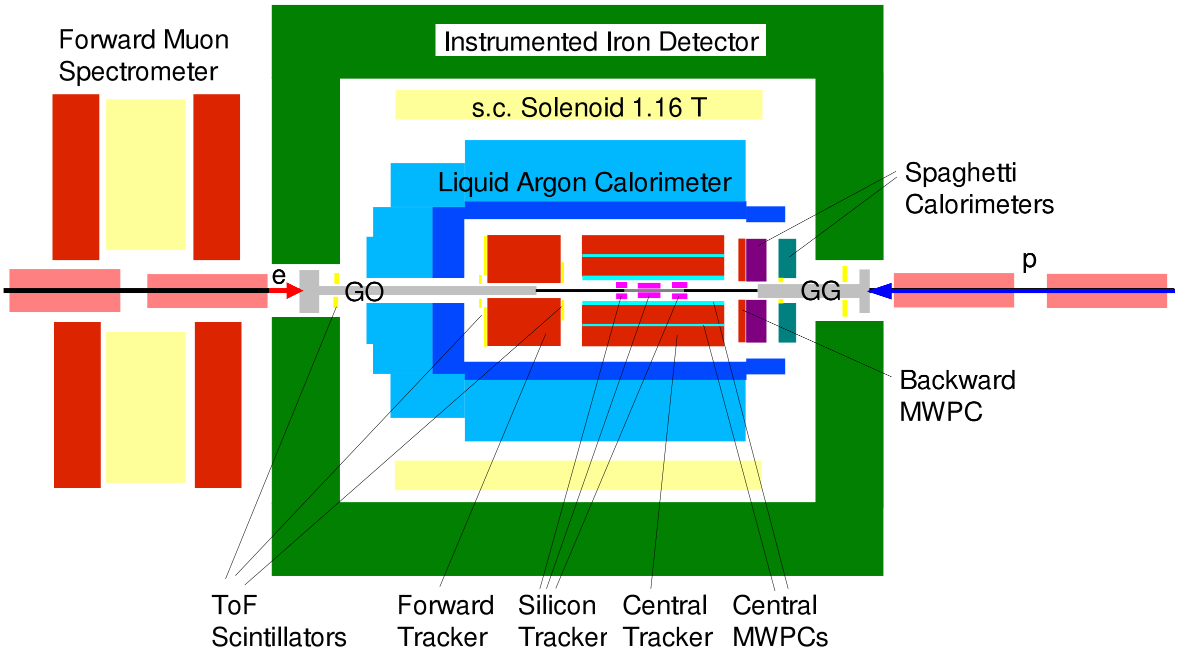
now

the future



Detector Upgrade

magnets inside main detector



The challenges:

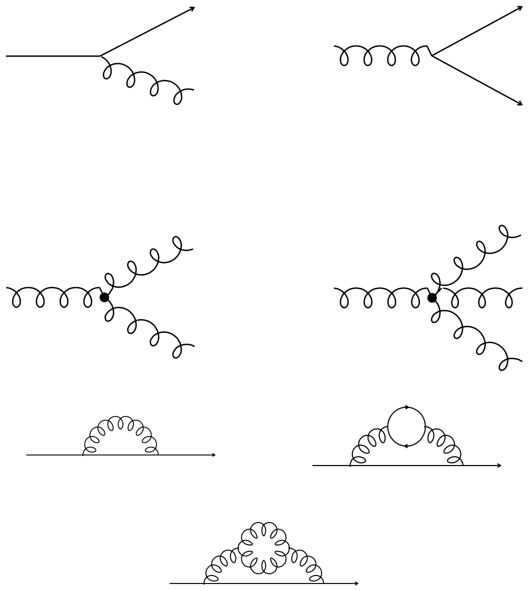
- larger event rates - trigger !
- back scattering from magnet:

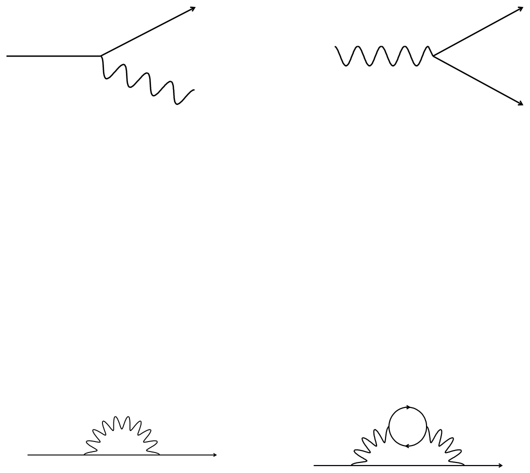
  $\longrightarrow$ deterioration of forward energies

  $\longrightarrow$ low-y kinematic reconstruction
- diffraction tag
- forward tracking
- systematics !

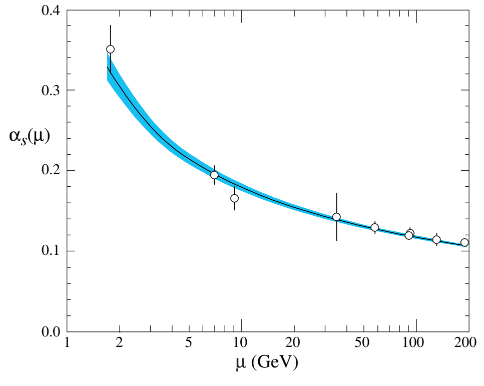
Strong Interaction

Quantum-Chromo-Dyn.	Quantum-Electro-Dyn.
8 gluons with colour	**1 γ, neutral**

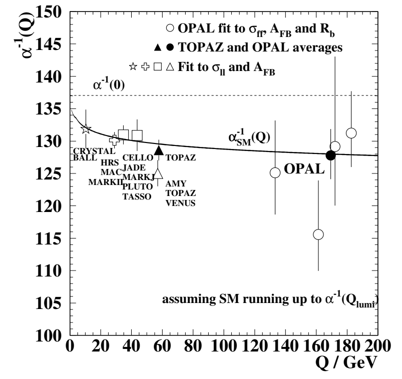




$\alpha_s \approx$ 0,1...1

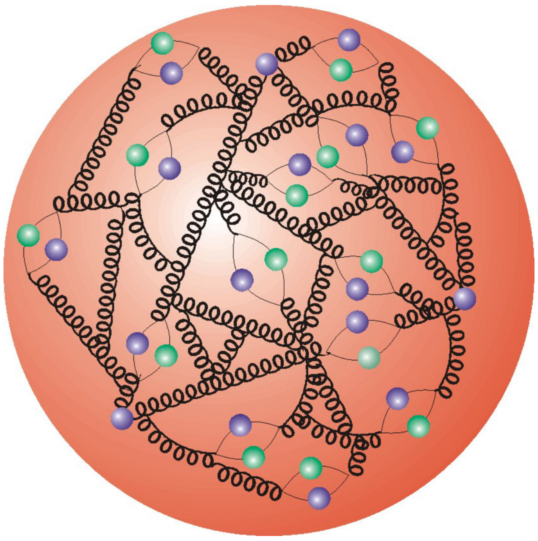


$1/\alpha_{elm}$



α_s large at *large* distances

Proton Structure

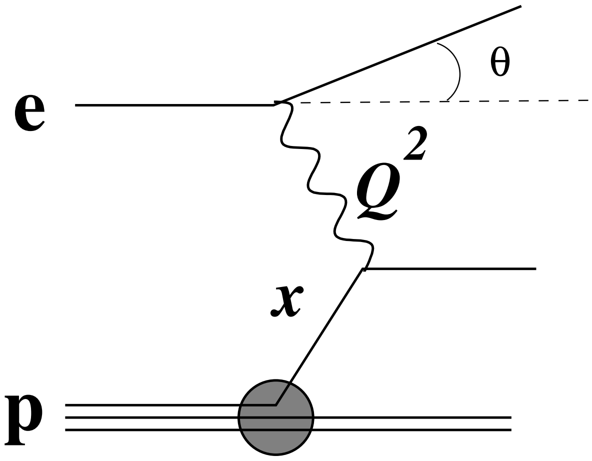


Confinement:

no free quarks,

gluons

measuring the deep parton structure



Q^2 = γ -virtuality

1/resolution

x = $E_{\text{parton}} \,/\, E_p$

W = $E_{cms}^{\gamma-p}$

QCD Interpretation

$Q^2 \gg 1/r^2_{proton} \quad \rightarrow \tau_{\gamma q} \ll \tau_{qq,qg}$

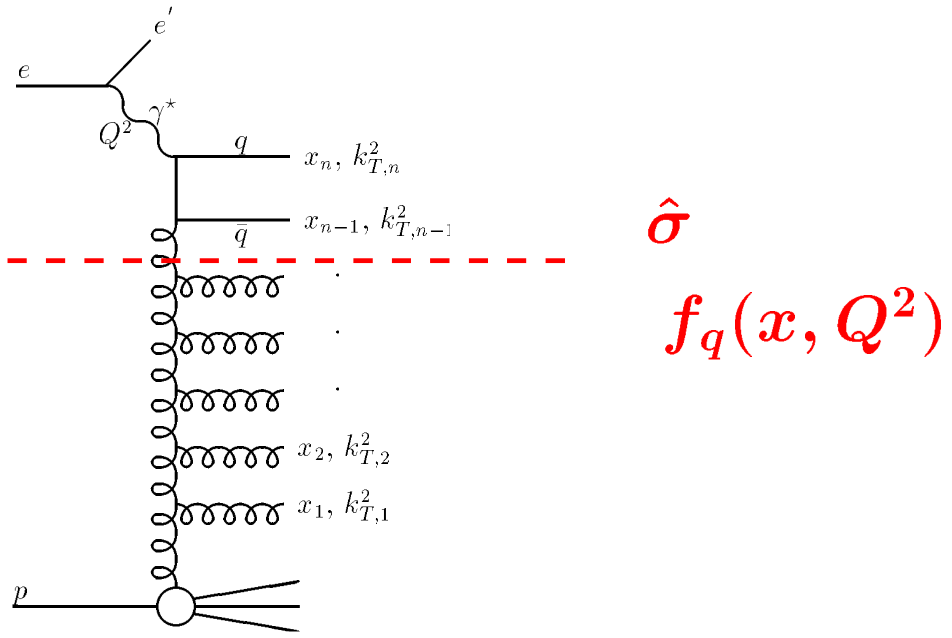
1) Altarelli-Paresi approximation (DGLAP)

assumption: strong order in k_T :

$$Q^2 >> k_{T,i} >> k_{T,i-1} \ldots$$

$\rightarrow$ factorisation in hard and soft parts:

$$\sigma = \sum \hat{\sigma} \times f_q$$



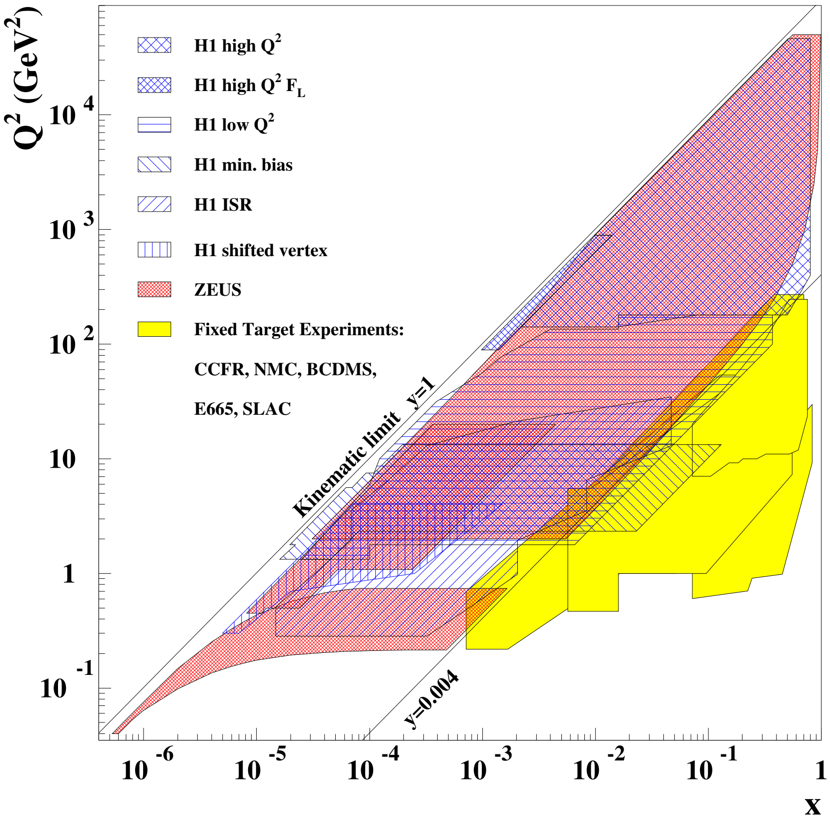
- **DGLAP can not be valid if:**
  - **Q^2 too small (how small ?)**
  - **x too small (phase space !)**

    (long ladder $\rightarrow$ no k_T order)

HERA

HERA: $E_{cms} = 320$ GeV

before: $E_{cms} < 20$ GeV



$$R_{proton} < 1/Q < R_{proton}/1000$$

$$10^{-6} < x < 1$$

factor 100 larger in Q^2 / smaller in x

$\longrightarrow$ **reason why H1 / ZEUS are the leading QCD experiments**

Virtues of ep scattering at HERA

- **large Q^2 lever arm: precision QCD**
  α_s, quark and gluon densities
- **small - x: high parton densities**
  novel quantum system
- **small Q^2: large distance QCD**
  non-perturbative, confinement
- **large CMS energy:**
  (beyond) the EW standard model
  (largest E_{CMS} with lepton in initial state)

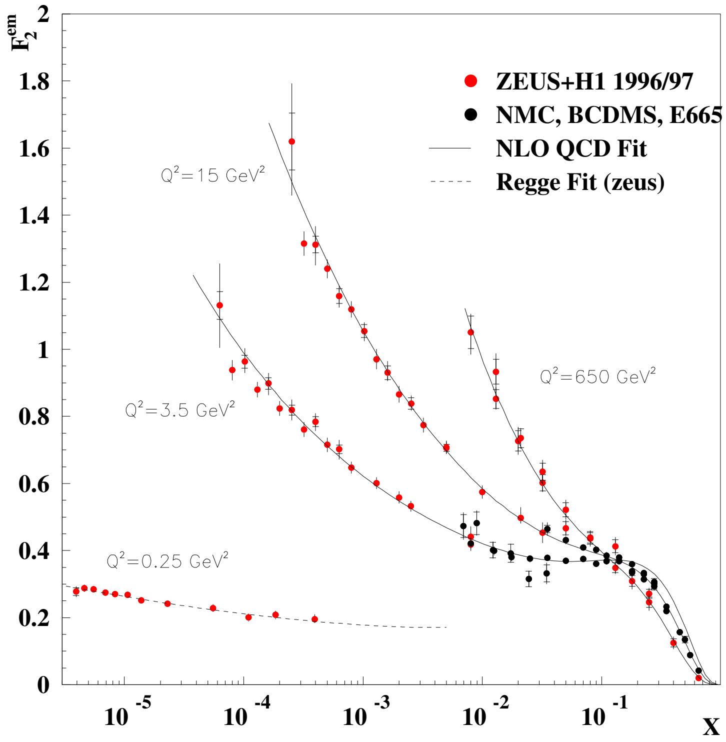
Partons in the Proton

$ep \to eX$ **at small** $\mathbf{Q^2}$**:**

$$\frac{d^2\sigma}{dx\, dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4}\, F_2$$

momentum distribution of quarks:

$$F_2\left(x, Q^2\right) \approx \sum e_q^2 f_q\left(x, Q^2\right)$$



small $x \longrightarrow$ **high quark density**

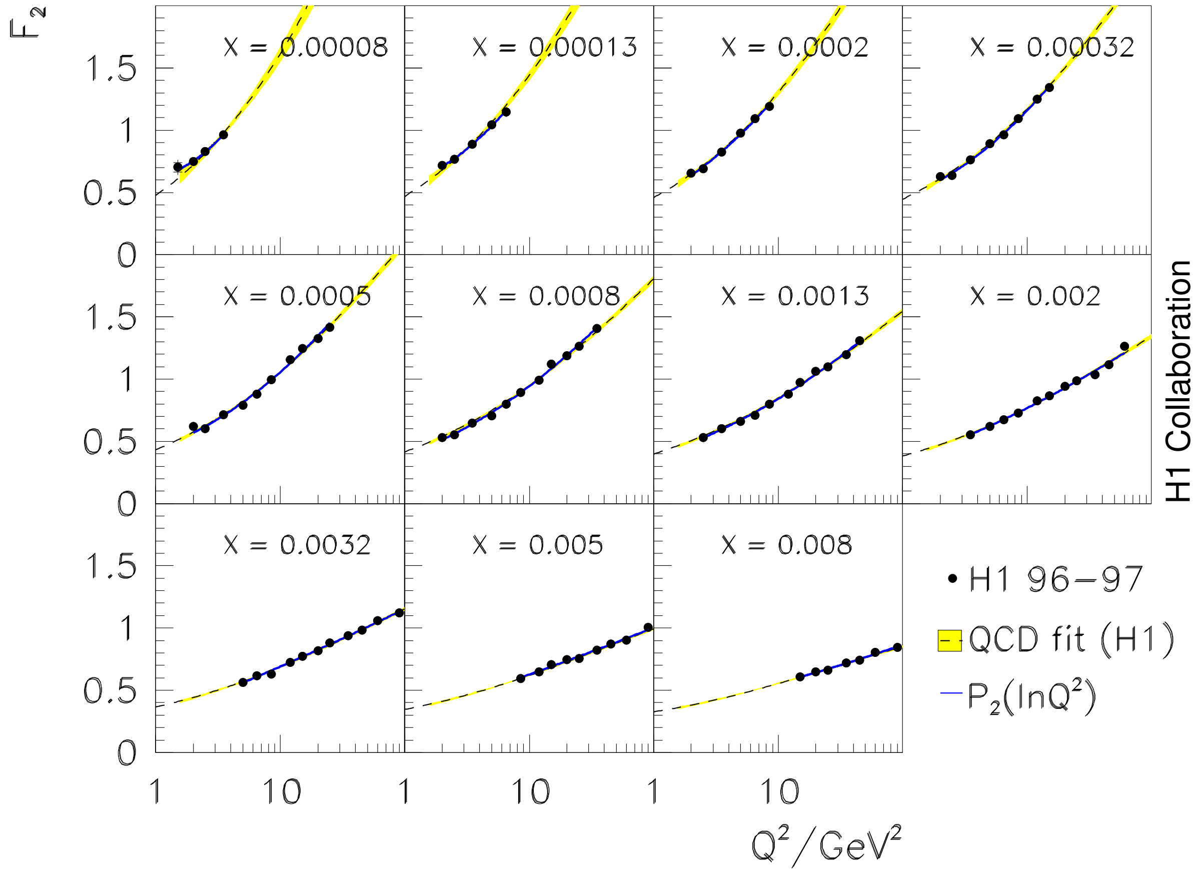
large $Q^2 \longrightarrow$ **strong rise of quark density** $\longrightarrow$ **high gluon density**

Partons in the proton

pointlike partons:

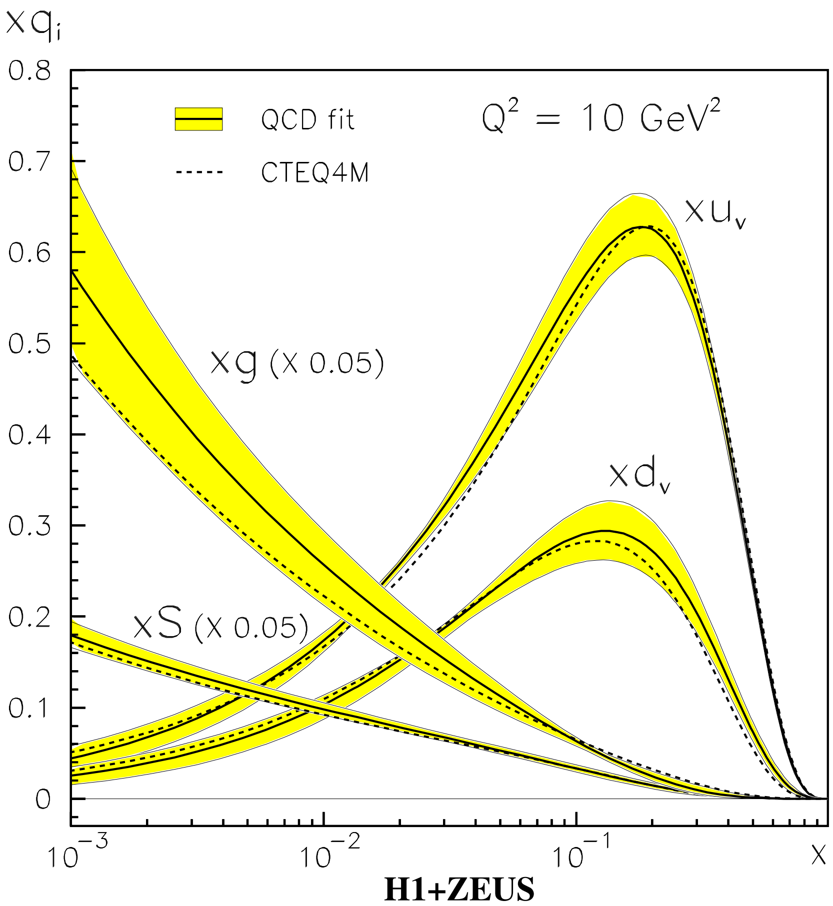
$\rightarrow$ F_2 independent of Q^2 $g \rightarrow q\bar{q}$:

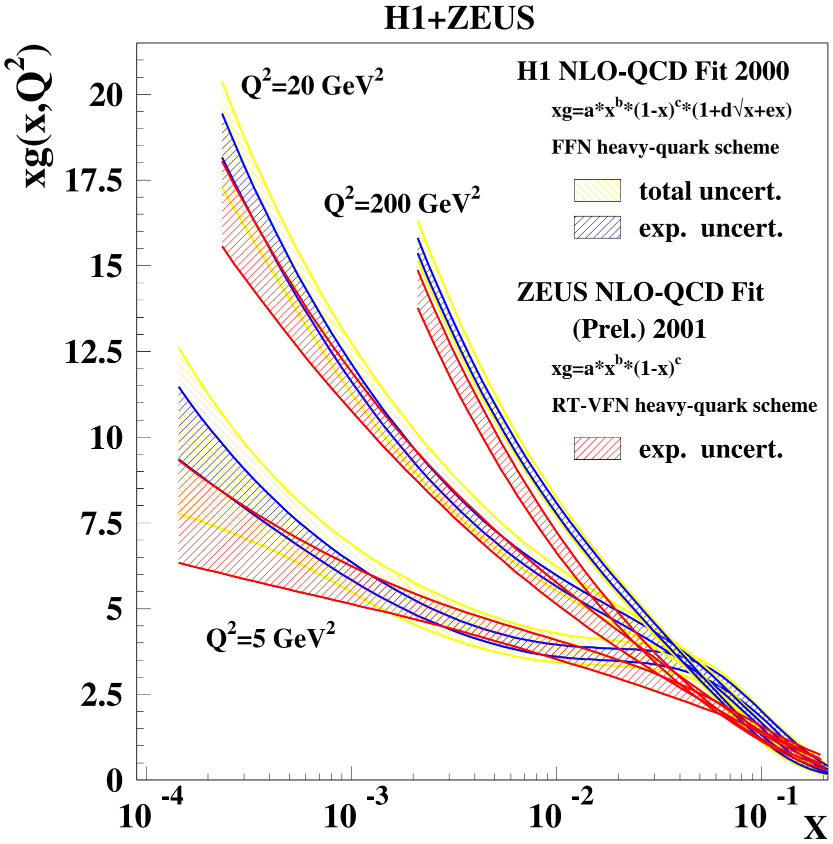
$\rightarrow$ slope $dF_2/d\ln Q^2|_x \approx \alpha_s$ Gluondichte



needs percision !

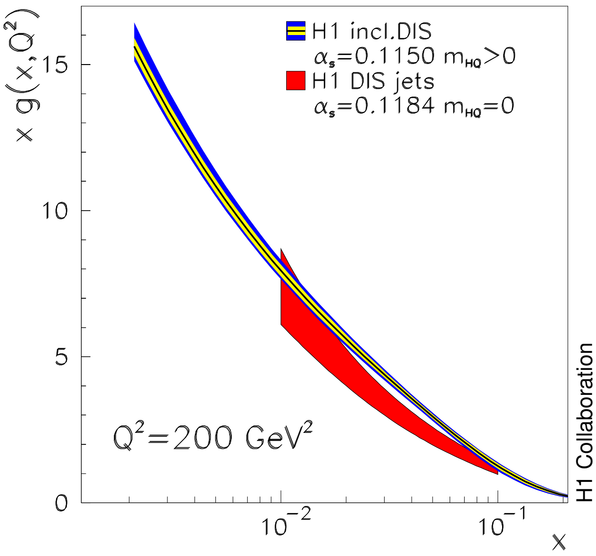
Quark/Gluon Verteilungen im Proton



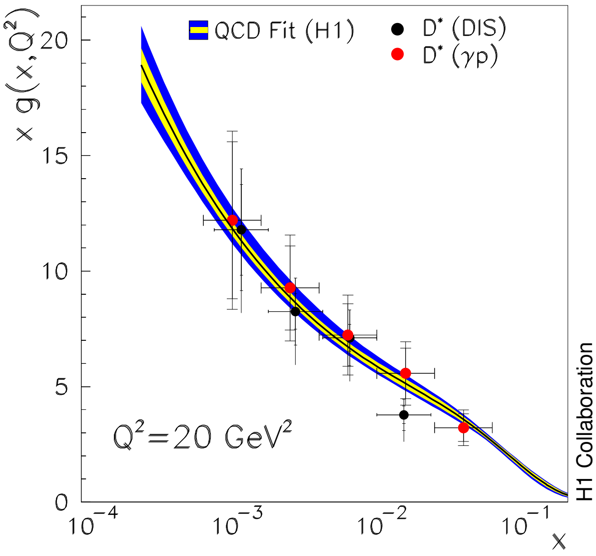


Gluon induced processes

verification of gluon density



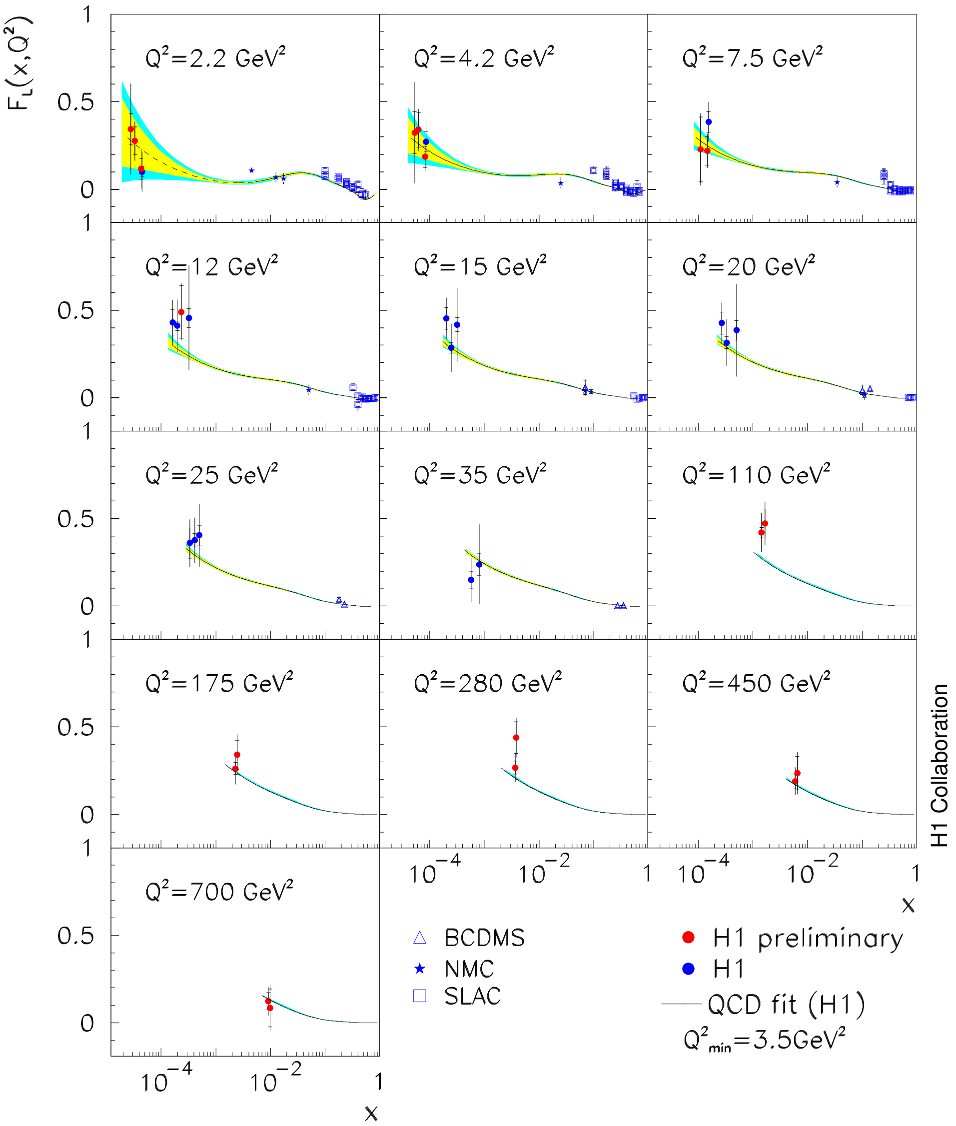
jet production



charm production

Gluon induced processes

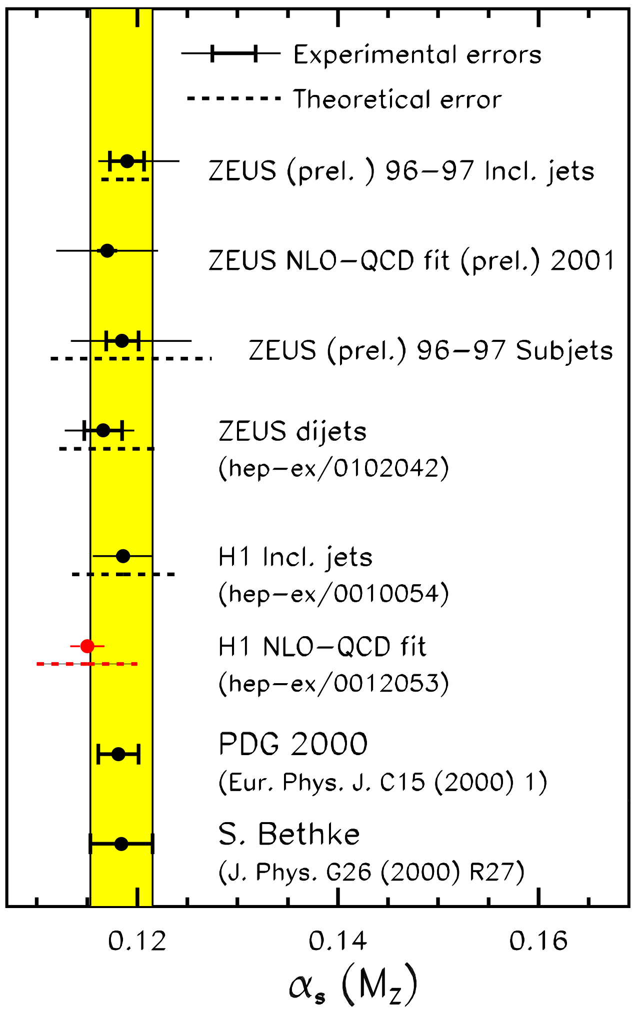
longitudinal structure function



needs different beam energies for better precision !

$\longrightarrow$ HERA low energy run

HERA summary on α_s



- **NNLO calculations for F2 (and 2-jet production ?)**

$\rightarrow$ reduction of scale errors by factor 2-3 !!

the CHALLENGE: get best α_s ($\pm$ 1%)

needs reduction also of experimental errors !!

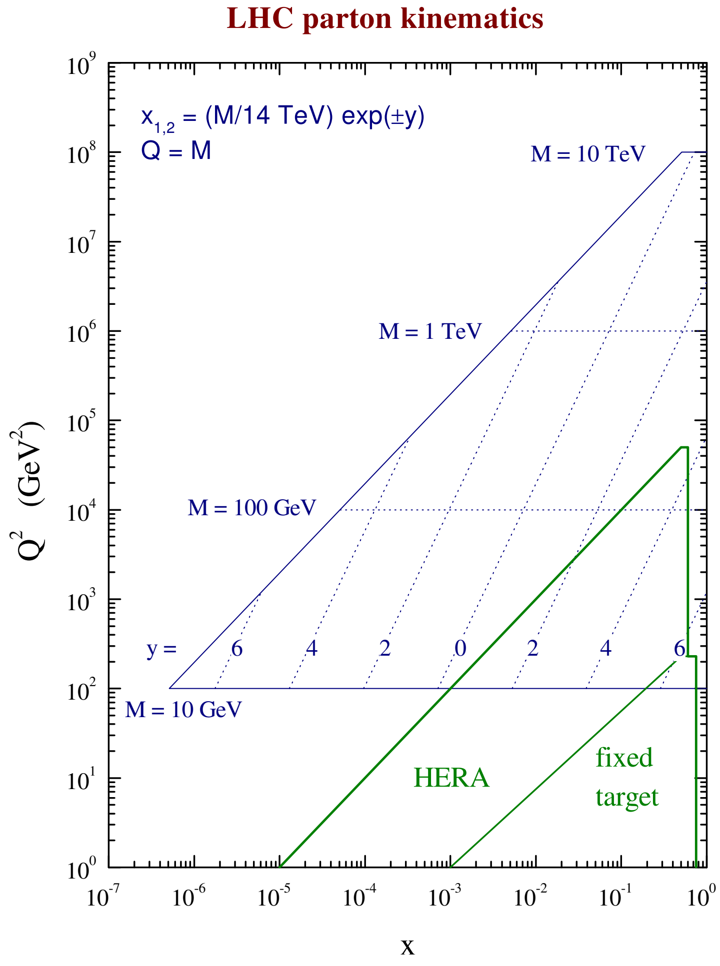
Interest in small x

- Parton-Dynamics: test of QCD after many radiations
- Limits of parton densities ?
  Gluon-Interference (saturation)
- Confinement
- Application at LHC: W,Z, Higgs
- Application in heavy ion collisions, kosmic rays

$\longrightarrow$ **Boom in low-x physics**

Higgs Produktion at LHC

$M_{\mathrm{H}} >$ 108 GeV



depends on gluon density at $x \lesssim 10^{-3}$

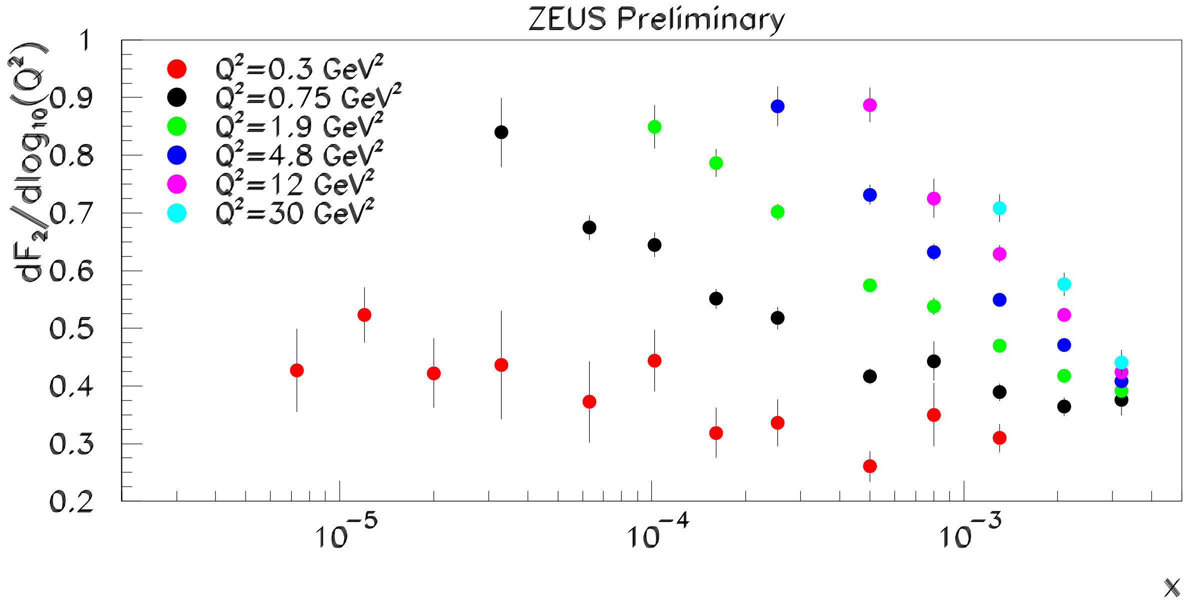
only process: DIS at HERA

but: $x \lesssim 10^{-4} \rightarrow Q^2 \lesssim 1$ GeV

Saturation of parton densities

extremly small x (high gluon density)

kinematics: also transition to $Q^2 \rightarrow 0$

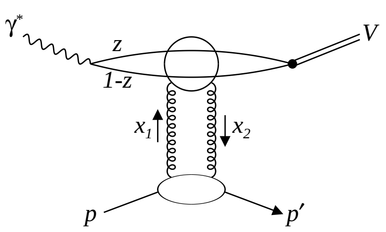


no tampering of rise to small x visible at any fixed Q^2

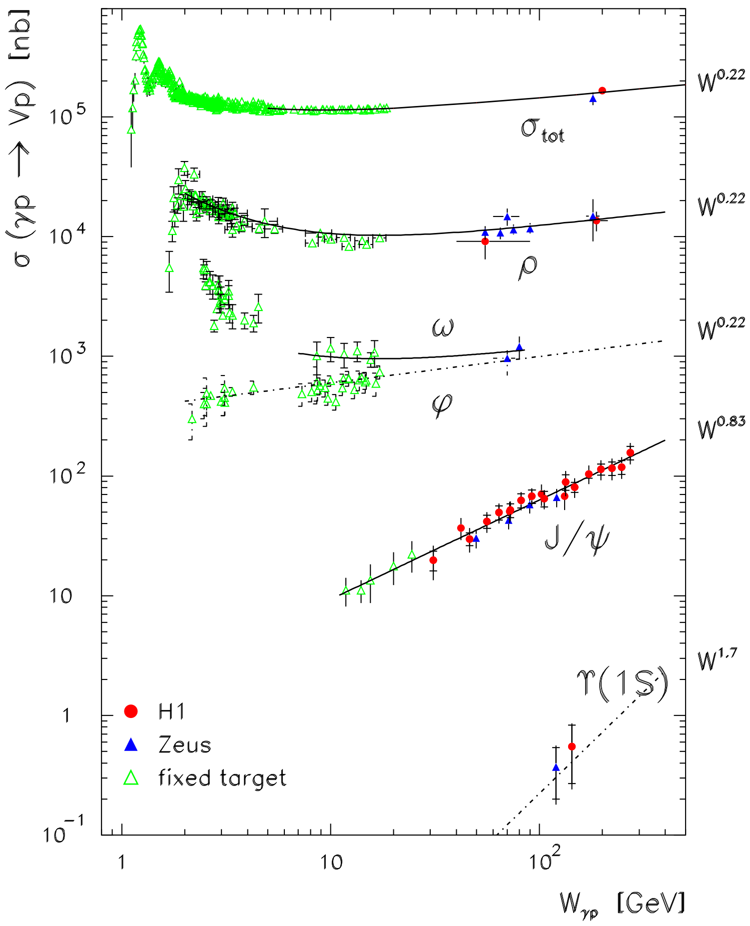
$Q^2 \rightarrow 0$: no resolution/ structure, $F_2 \rightarrow 0$

$Q^2 < 1$GeV^2: difficult to disentangle effects at small x from those at small Q^2

Elastic vector meson production



"Skewed Parton Distributions $f(x_1, x_2, Q^2)$ "

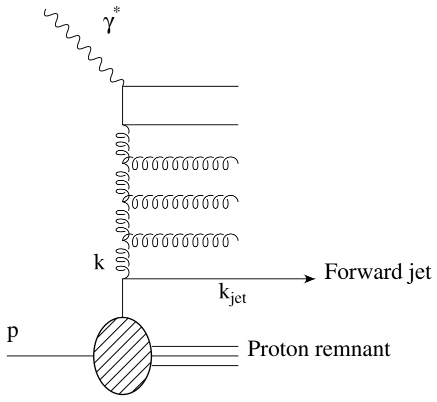


Rise of gluon density must stop !

Factorisation in QCD

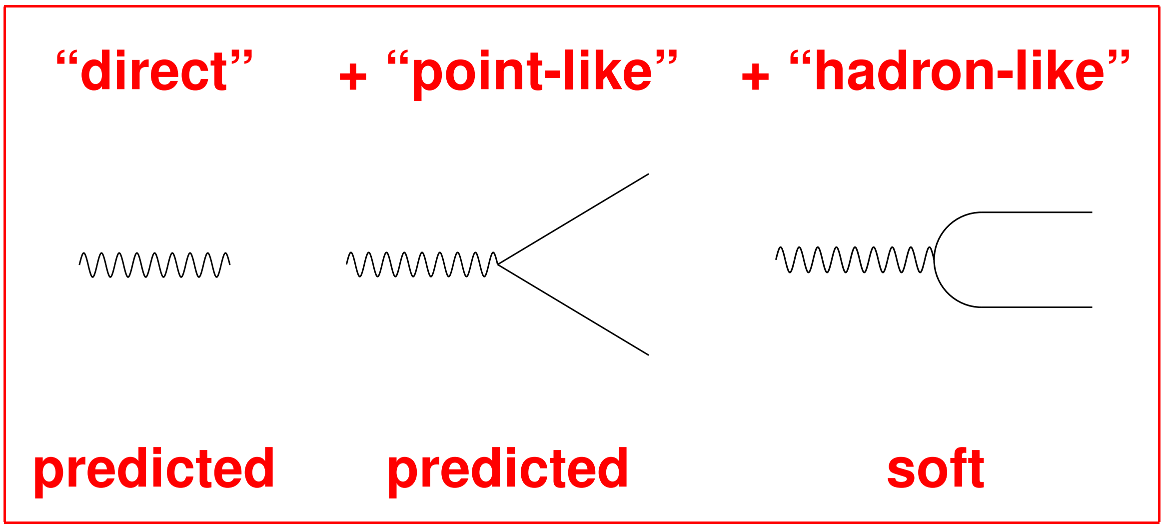
eg. jets close to proton:

no clear order from Q^2 to k_T^2

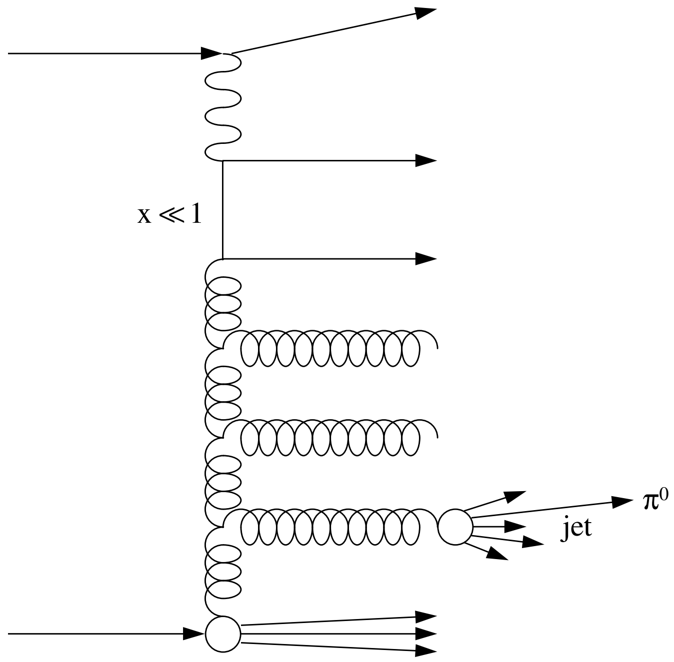


alternatives to DGLAP:

- *unintegrated parton densities:*
  $f(x, k_T^2, Q^2)$
  BFKL, CCFM
- virtual photon structure
  Fluctuation of γ in colour dipol ($q\bar{q}$, $q\bar{q}g$,)



QCD Dynamics



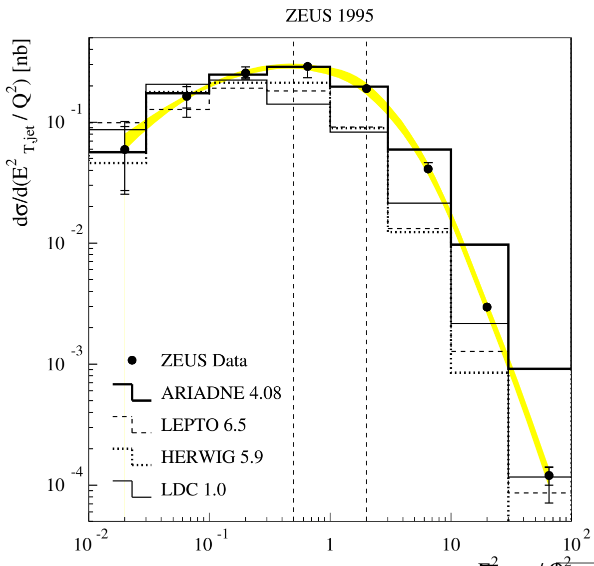
select:

- small -x
- forward jets (π^0)
- $Q^2 \approx E^2_{T,jet}$

no k_T order

- testcase for BFKL, CCFM, colour-dipol

QCD Dynamics: Jets



DGLAP:

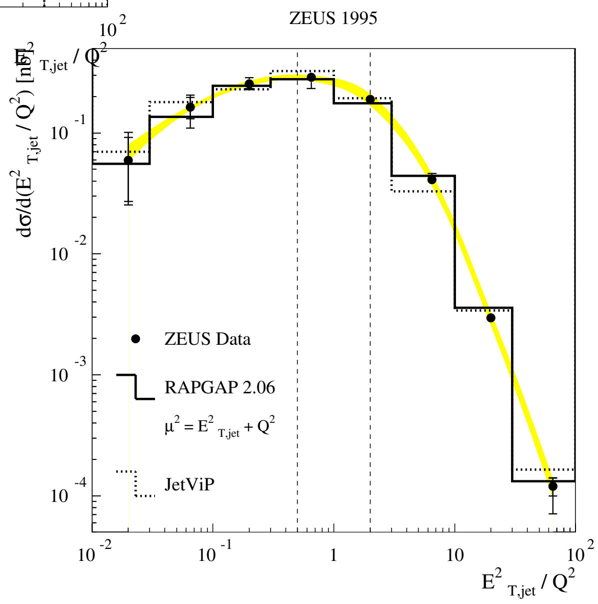
fails for

$Q^2 \lesssim E^2_{T,jet}$

colour-dipol

o.k.:

no k_T order



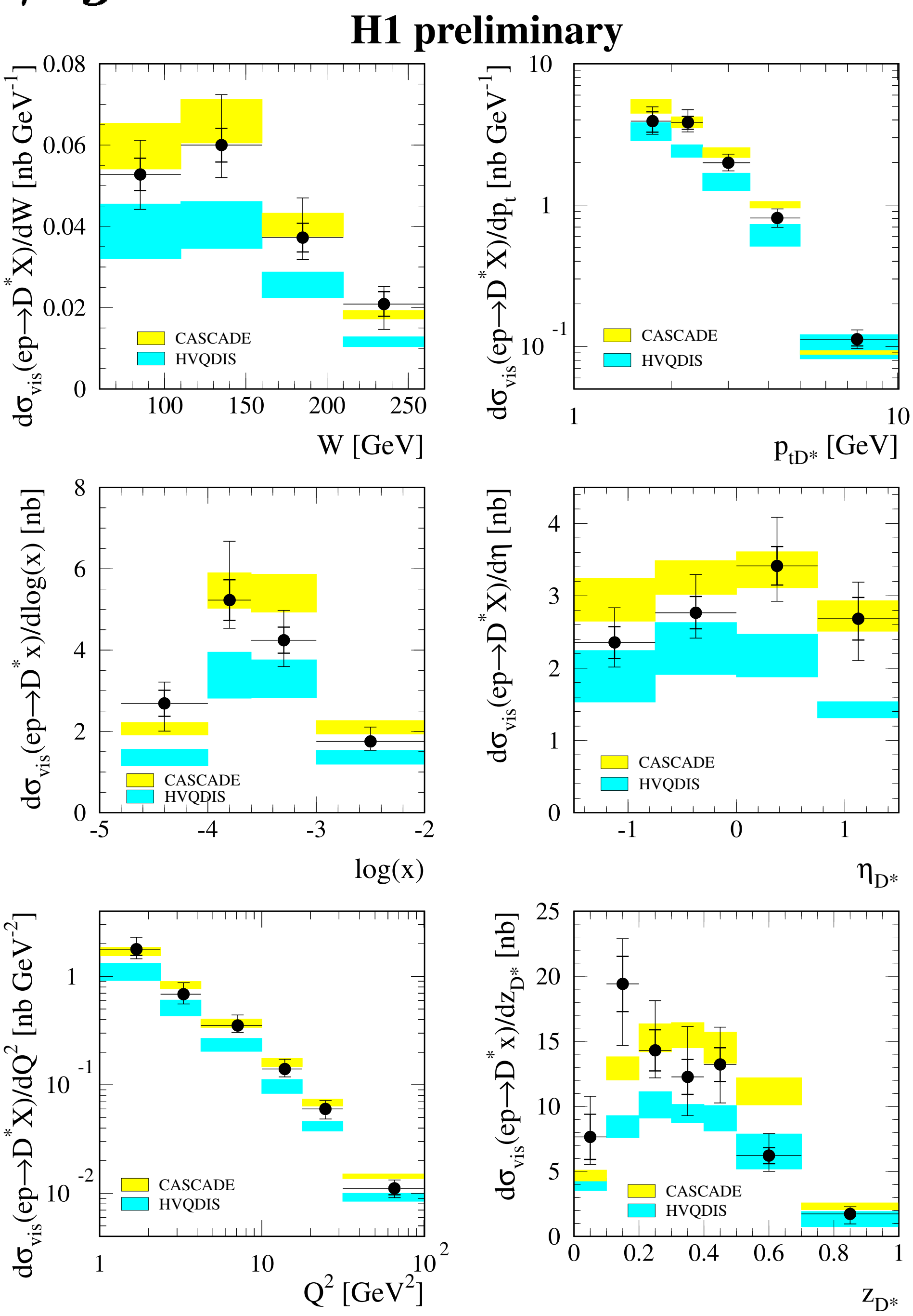
missing:

dynamical evidence for unordered K_T

needs final state studies along parton ladder

QCD Dynamik: Charm und CCFM

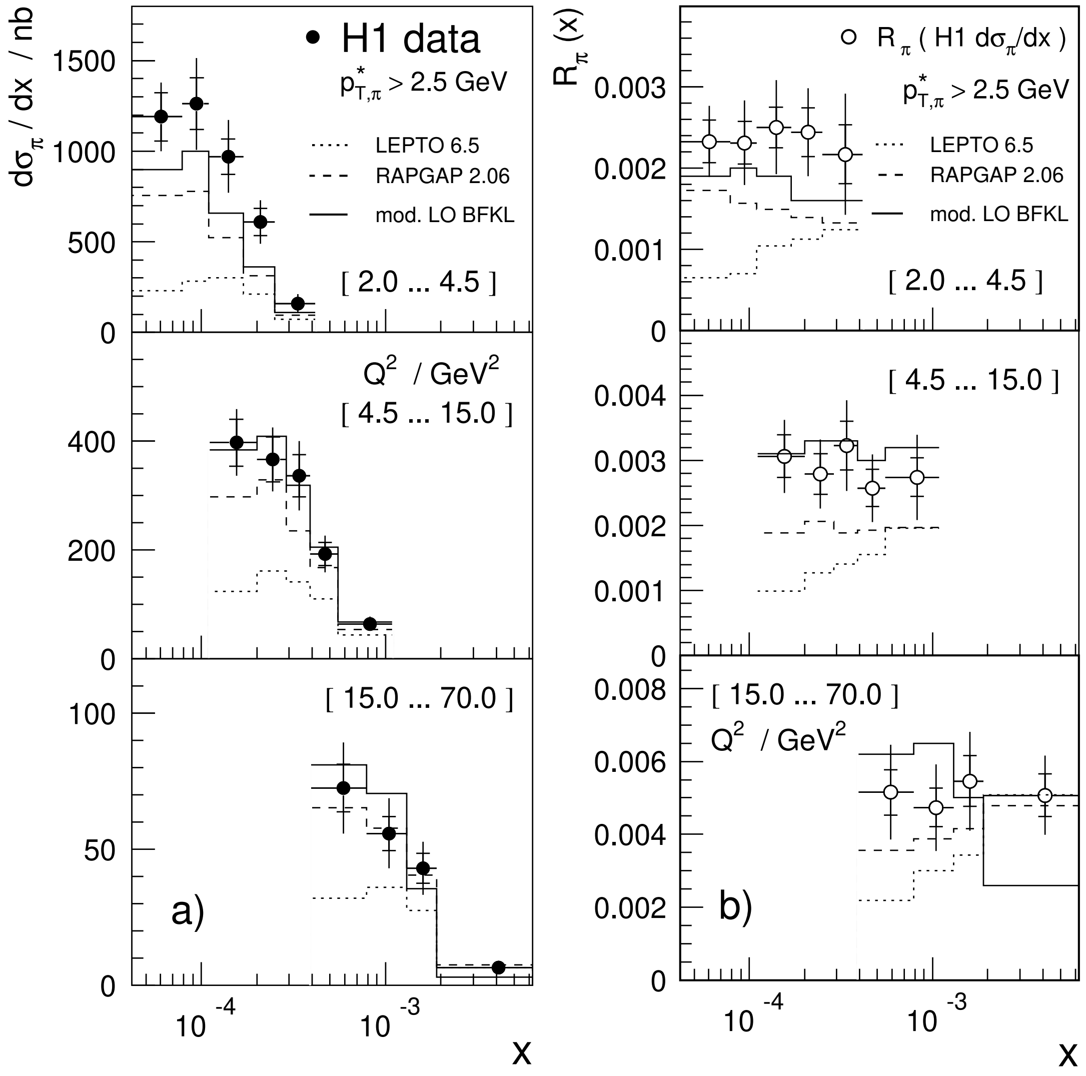
$\gamma^* g \to c\bar{c}$: charm Masse ist 2. harte Skala



CCFM slightly better than DGLAP

QCD dynamics: Forward π^0

high E_T π^0 in very forward direction



missing:

dynamical evidence for unordered K_T

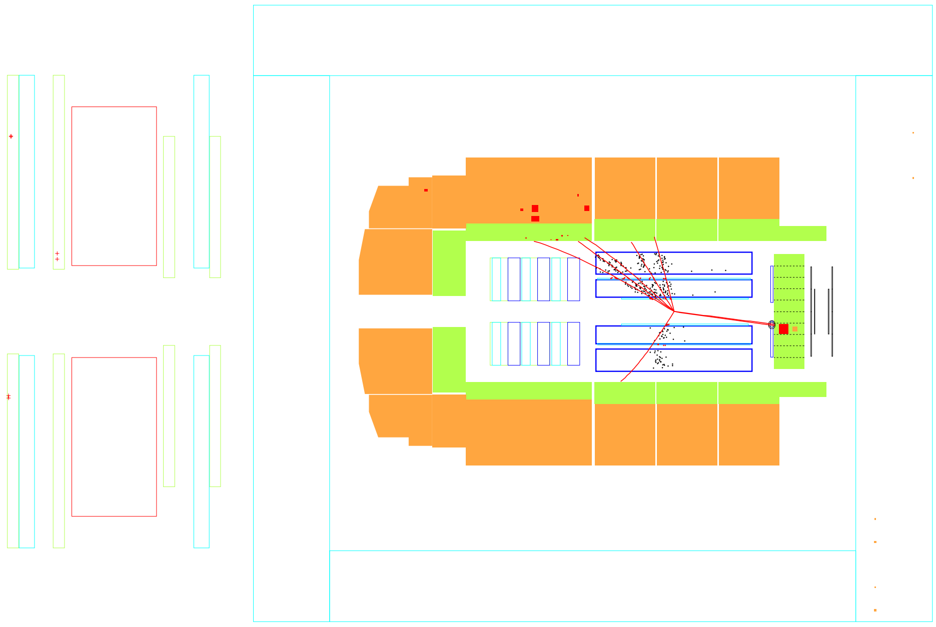
needs final state studies along parton ladder

Diffraction

no

proton

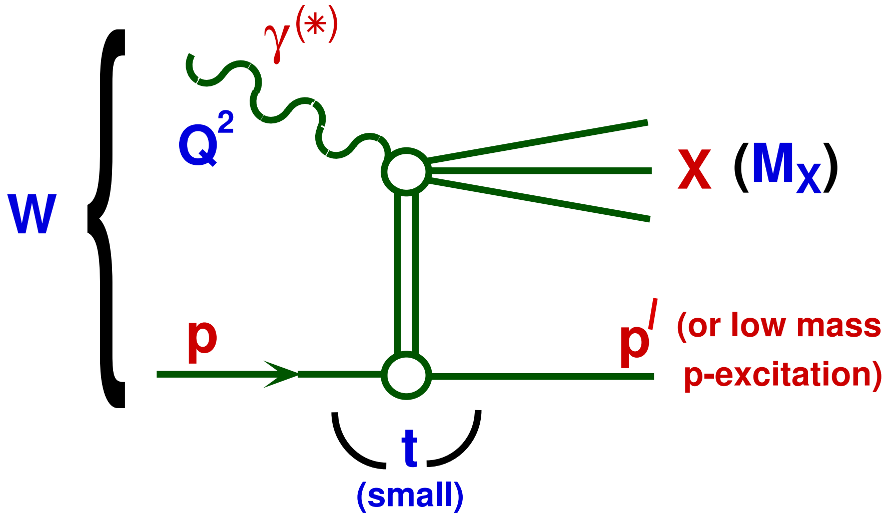
remnants



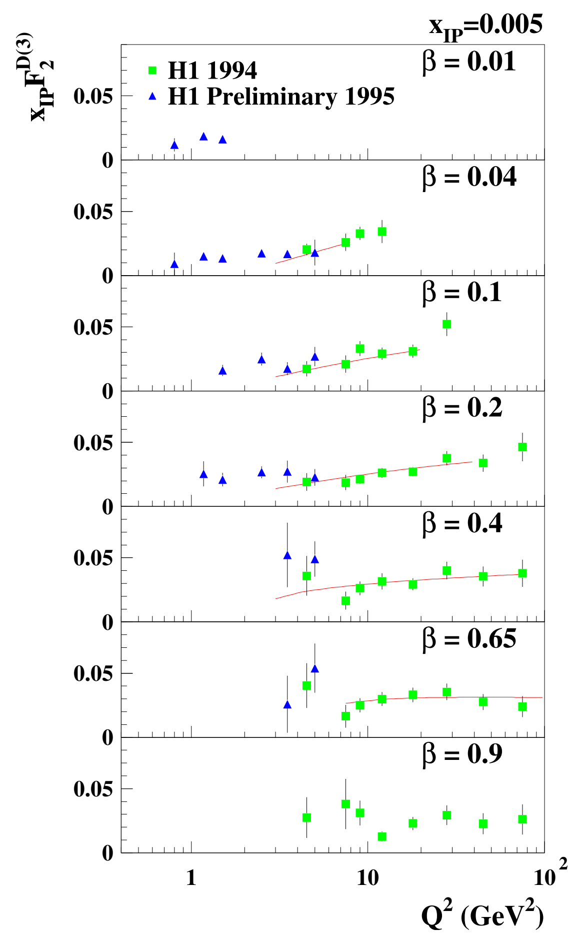
Hard Diffraction:

colour singlet exchange on more than one parton (2 gluons or more)

$\longrightarrow$ Correlations

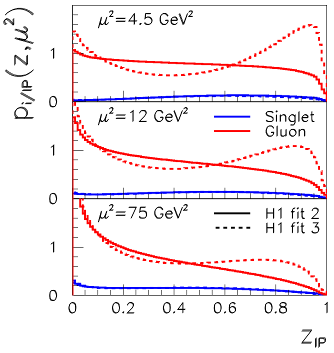


Diffractive parton densities



$F_2^{D(3)}$ rises with Q^2:

$g \to q\bar{q}$



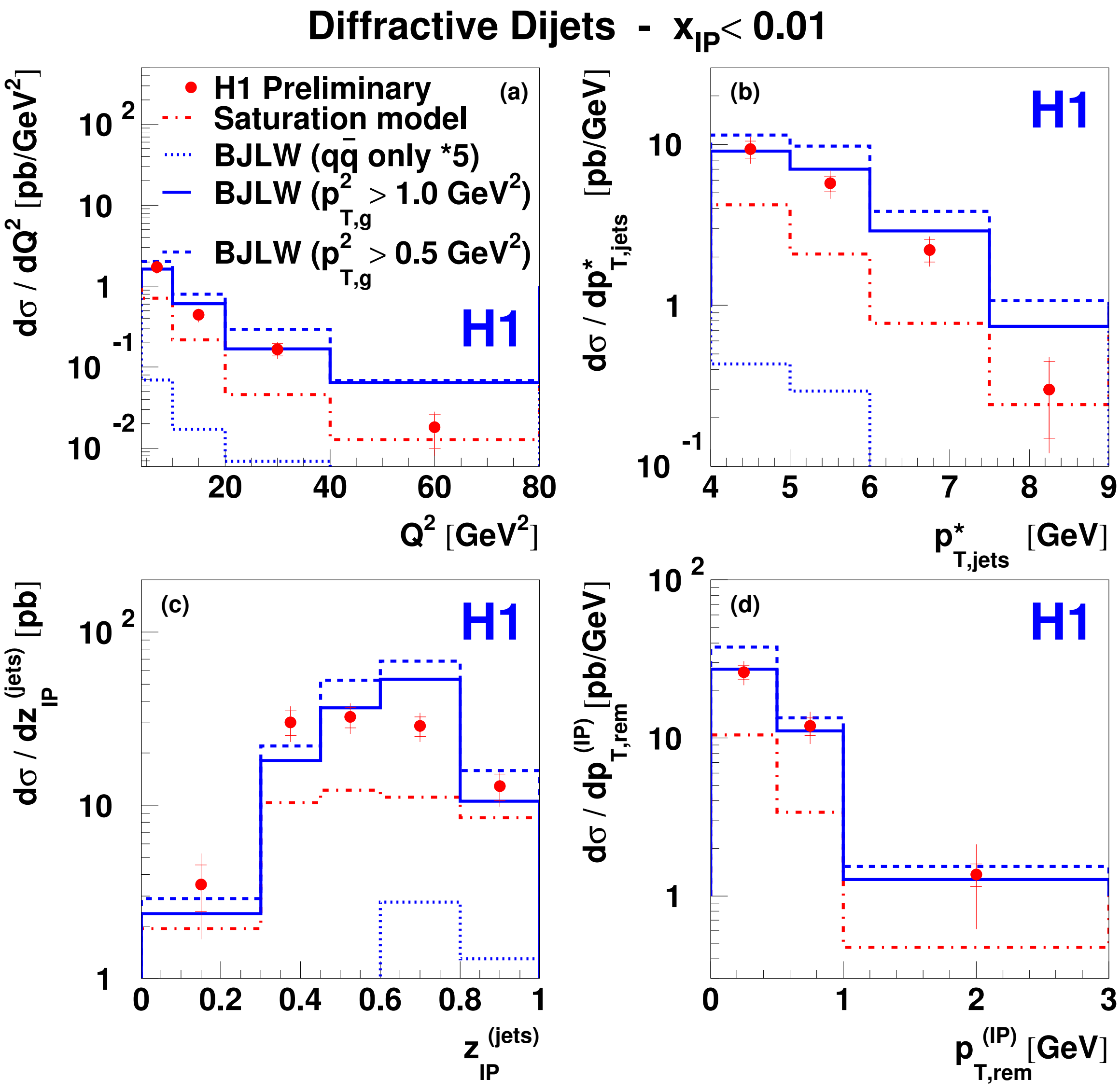
assuming Regge factorisation

Proof of hard QCD factorisation !

$\longrightarrow$ **diffractive parton distributions**

Jet production in Diffraction

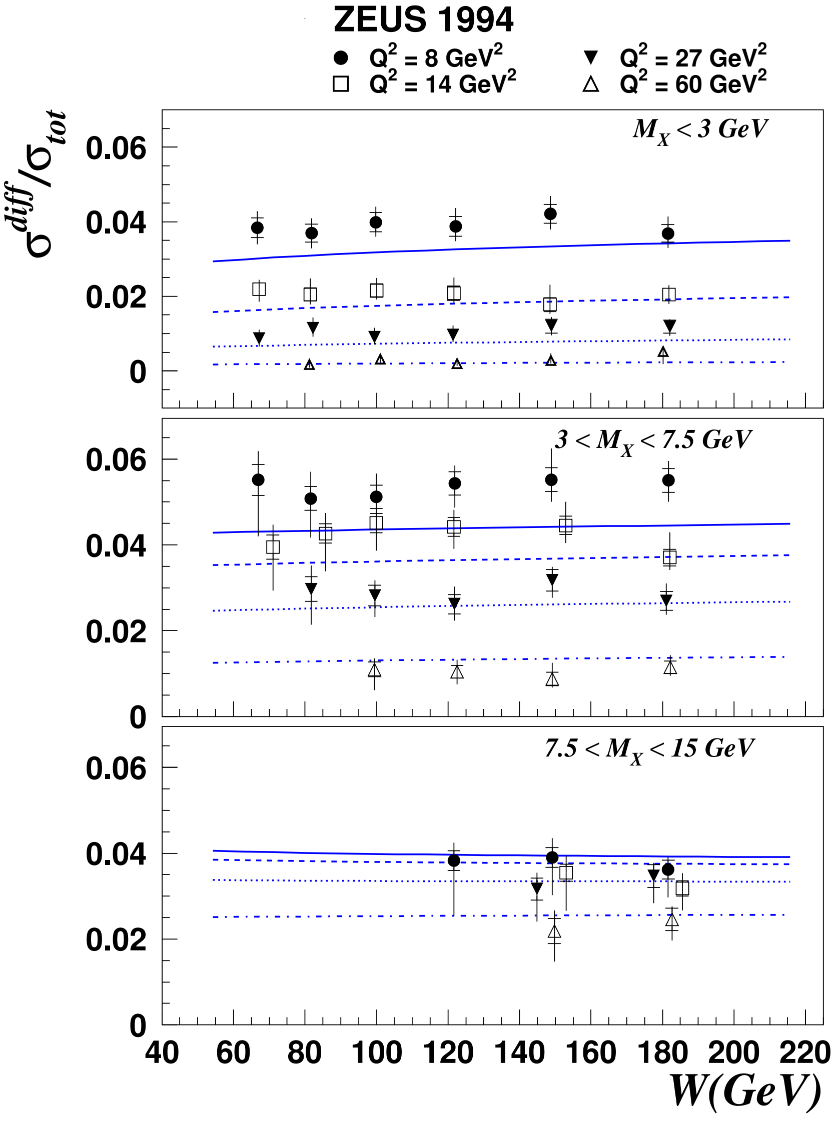
Comparison with QCD calculation for 2-gluon exchange $\sigma \sim |g(z,Q^2)|^2$



Note: reasonable agreement, considerable energy not contributing to hard process: remnant of colour singlet at low P_T

Energy dependence of diffraction

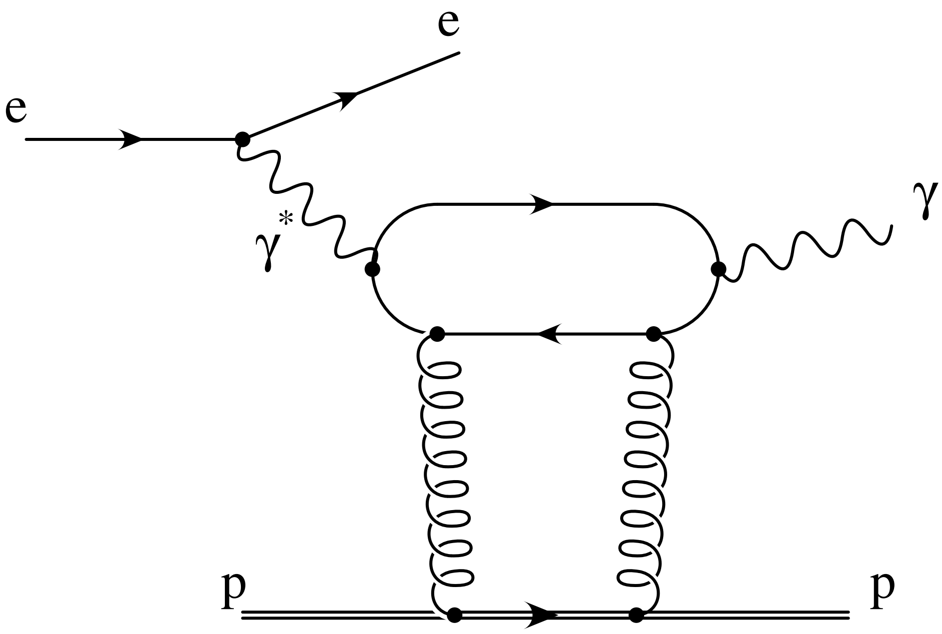
ratio diffractive / non-diffractive

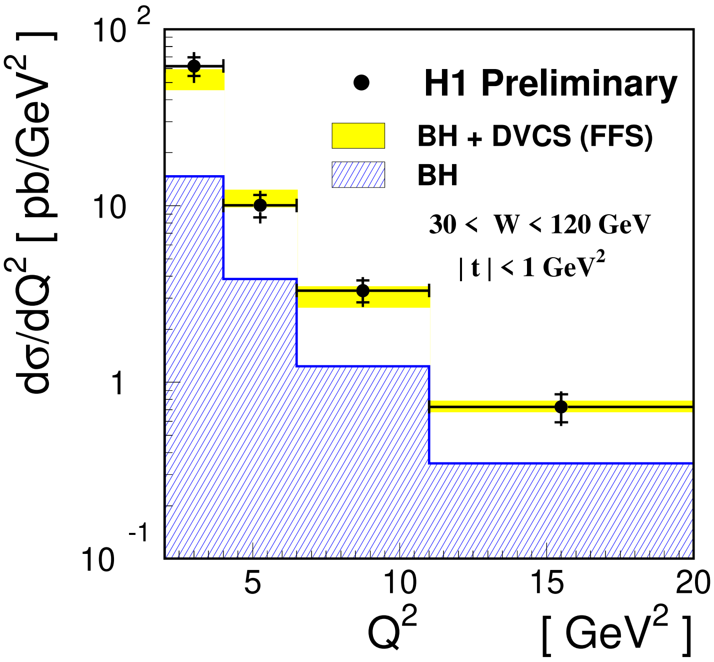


no change with energy

$\longrightarrow$ contradiction to 2-gluon exchange ?

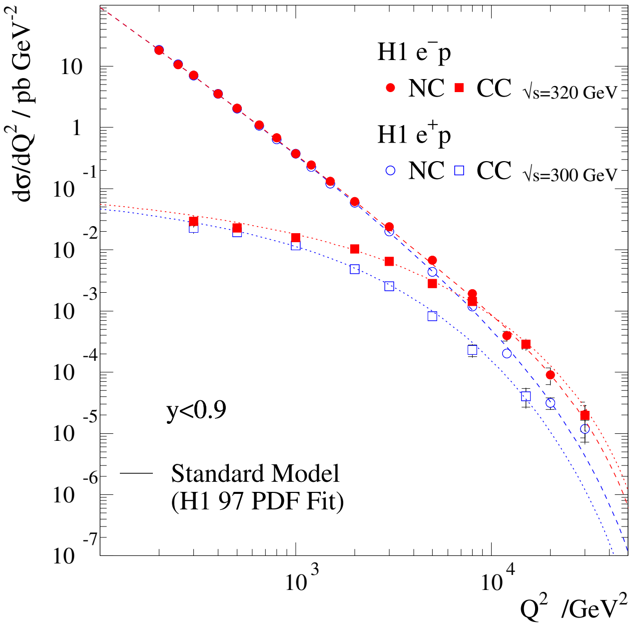
Deeply Virtual Compton Scattering





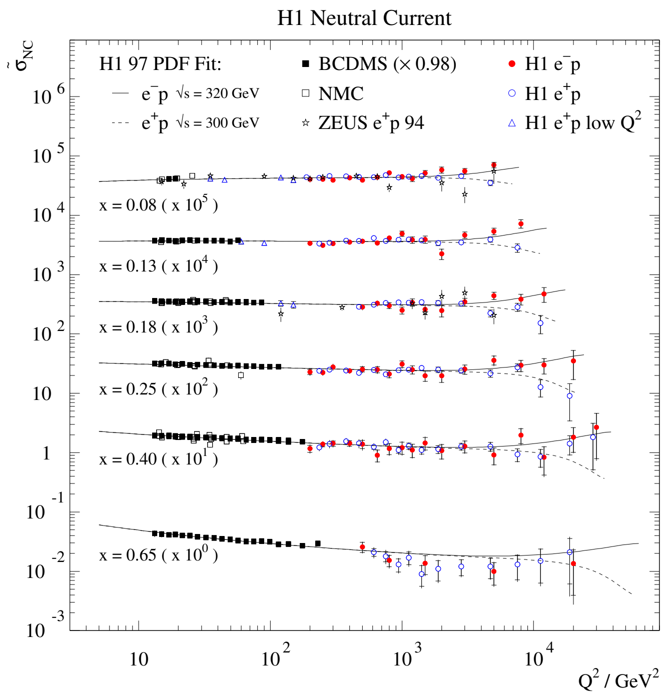
γ- $\times$ gluon-pair describes data !

Weak Interaction



$\gamma/Z \approx W$

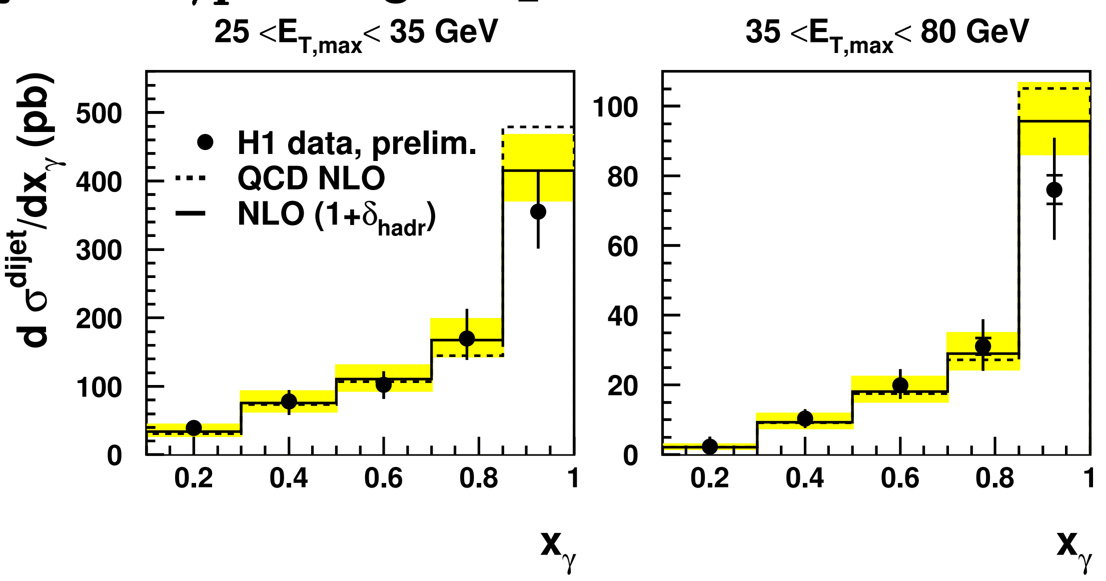
Unification



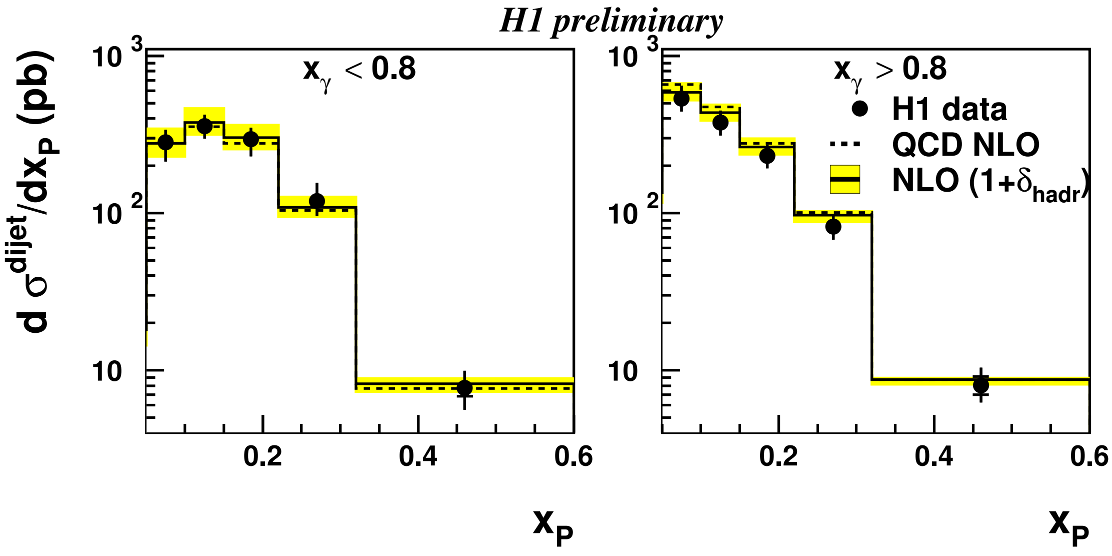
needs more data at large x, Q^2 !

Photon and Proton at High x

jets in γp at high E_T



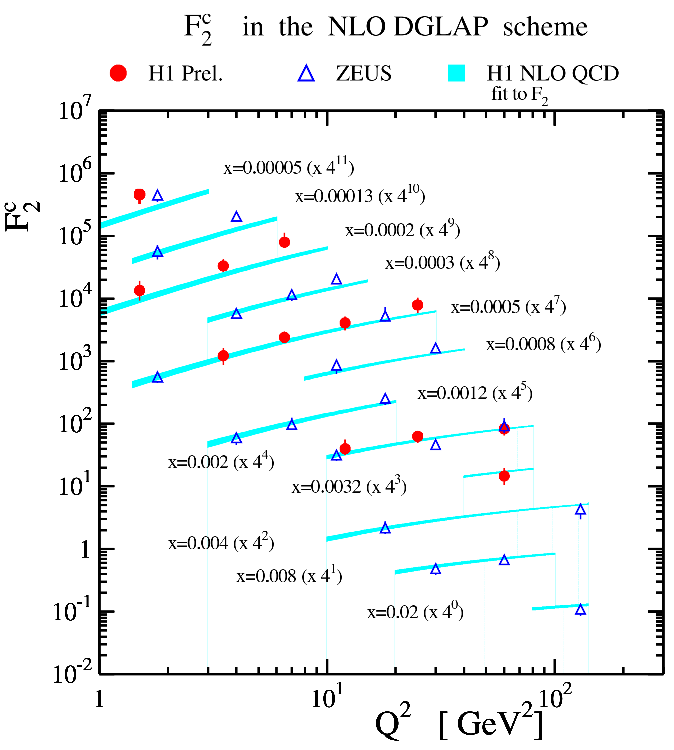
access to proton at high x !



- dominated by direct + pointlike part of γ
- significant contribution from gluon in proton

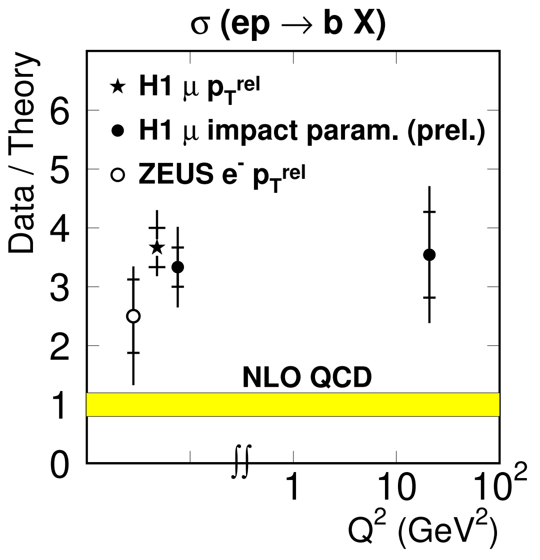
  $\rightarrow$ Tevatron high E_T jets

Schwere Quarks



Gluon induced:

$\gamma g \to c\bar{c}$



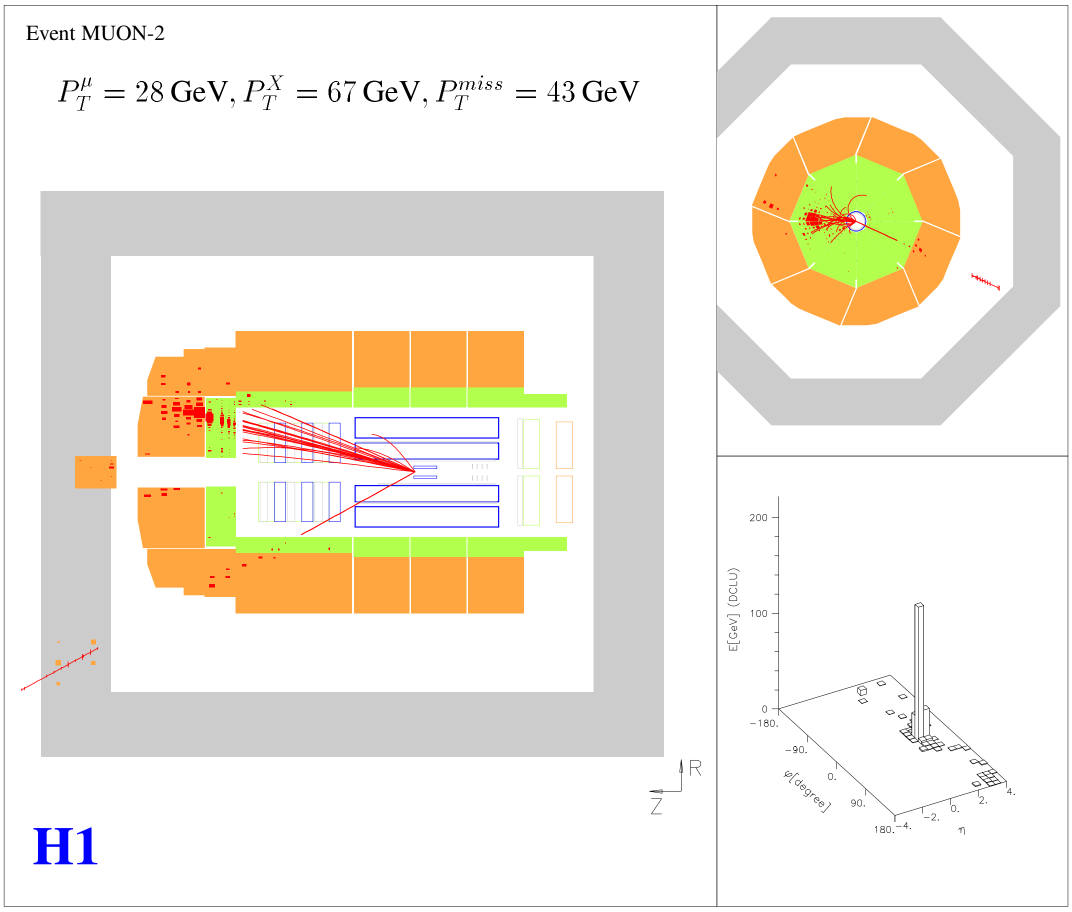
Gluon induced:

$\gamma g \to b\bar{b}$

c.f. Tevatron

The unexpected

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



no explanation up to now !

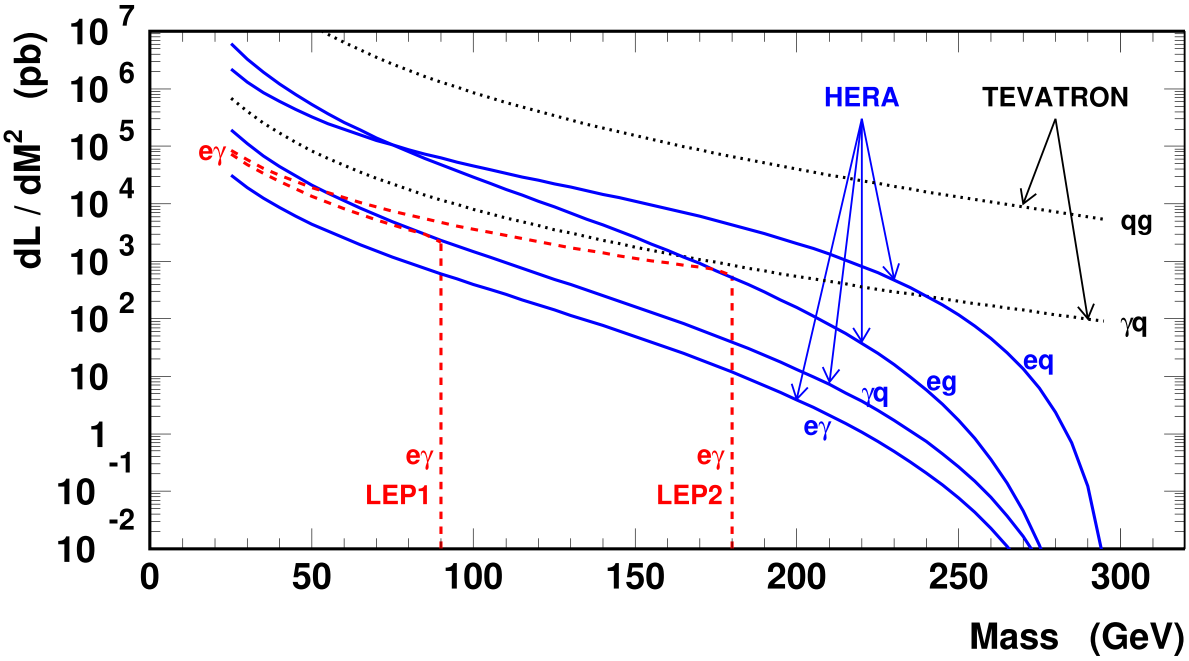
anomalous W production, $e \to \mu$,

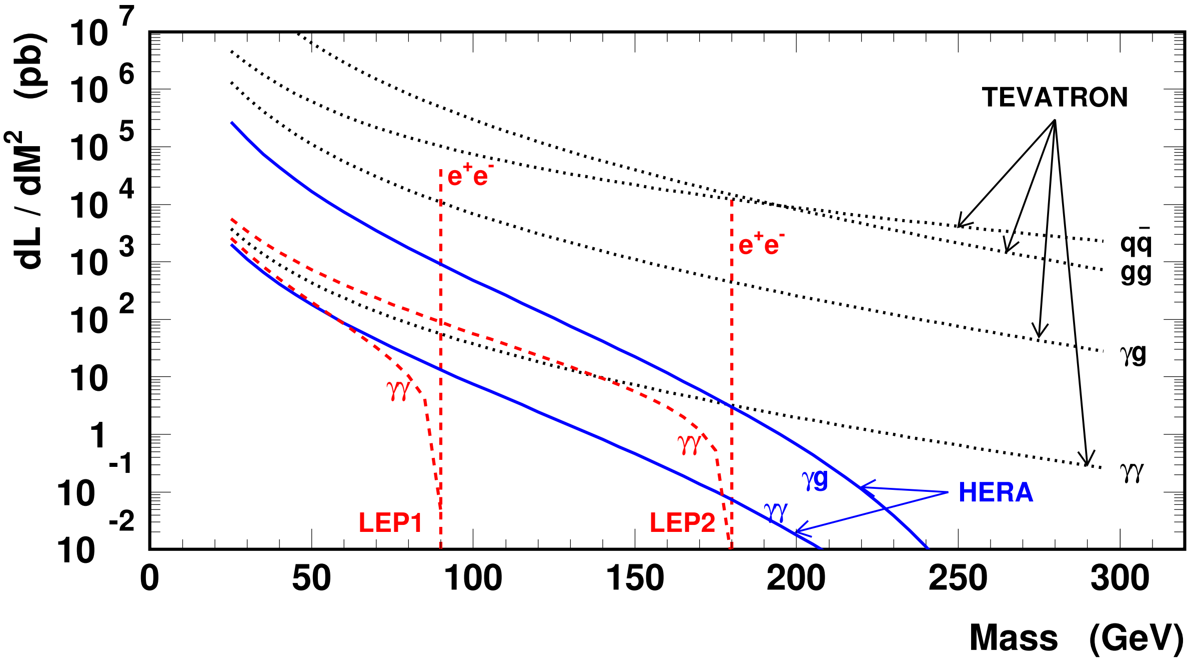
supersymmetry ?

Beyond the Standard Model

Parton luminosities: $\sigma_c \approx \hat{\sigma}_{ab\to c}\; dL/d\hat{s}$

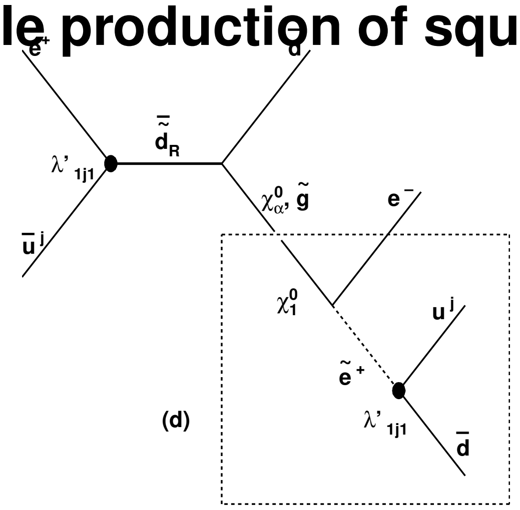
$$\frac{dL}{d\hat{s}} = \frac{1}{s}\int_{\frac{\hat{s}}{s}}^{1} \frac{dx_a}{x_a}\, f_A(x_A,\hat{s})\, f_B\!\left(\frac{\hat{s}}{sx_A},\hat{s}\right)$$

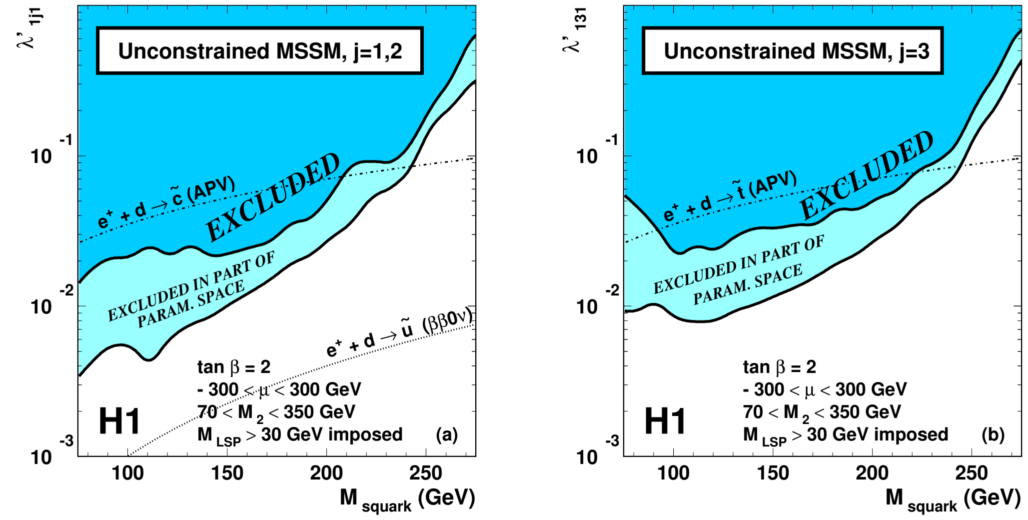




Supersymmtrie

single production of squarks





nothing found, but also no competition from LEP/Tevatron

Summary

What did / will we learn from HERA ?

- low-x: new regime of QCD

  the main theoretical activity so far

  BFKL ??

- precision QCD:

  world best value of α_s

  proton structure at HIGH x

- high Q^2: only just started

  luminosity upgrade

  precision test of SM at 10^{-18} m

- searches:

  high P_T lepton events

  Supersymmetry with R_P violation

  contact interactions

  \+ ??