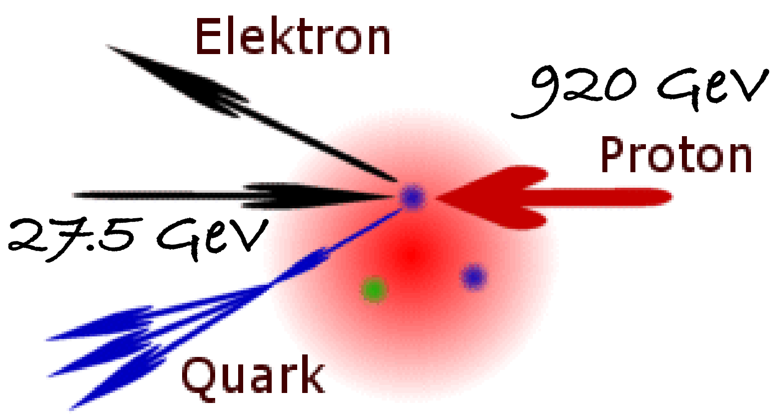
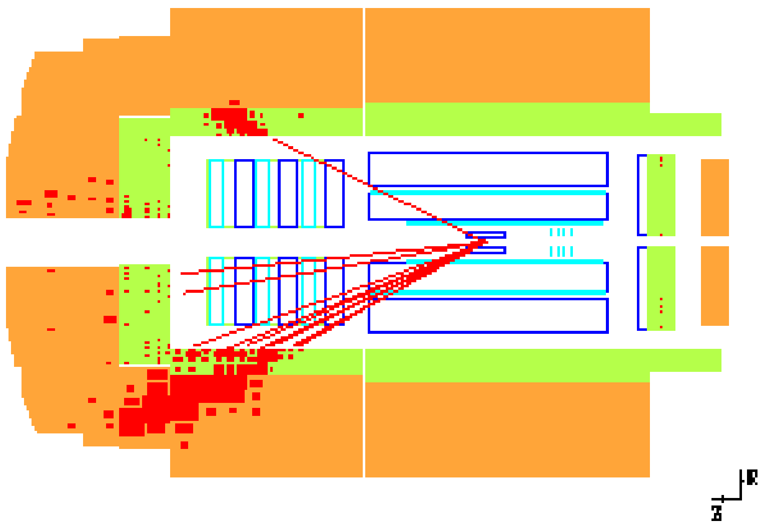
Probing QCD at HERA

E. Elsen (DESY)

Symposium on
Quarks in Hadrons and Nuclei II



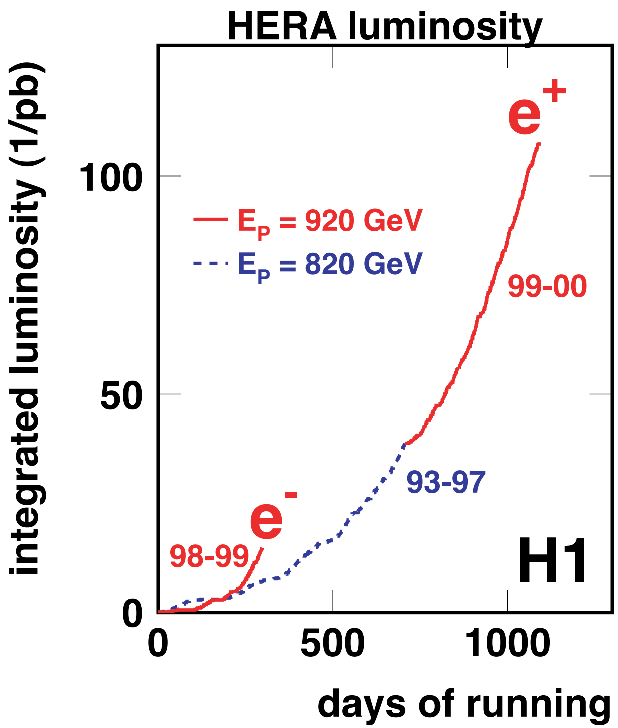
- Short Overview
- QCD Laboratory HERA
  - Proton Structure
  - eq-Scattering
  - Beyond perturbative QCD
- Outlook



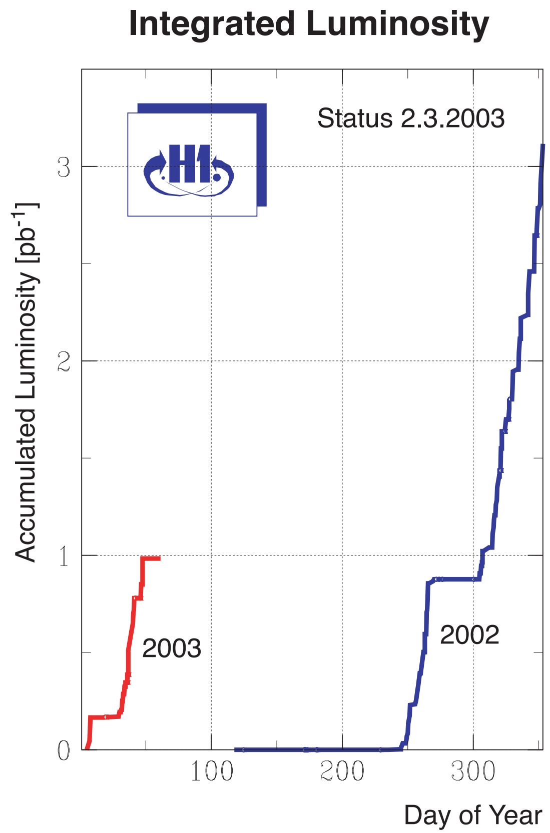
Integrated Luminosity at HERA I ... and HERA II

HERA I (1992-2000)

- > 100 pb^{-1} of e^+p available (more than half of that taken in 2000)
- > 15 pb^{-1} of e^-p available



HERA II (2002-...)



- slow start - mainly due to vacuum conditions

Goal is 1 fb^{-1}

HERA - the ideal QCD Laboratory

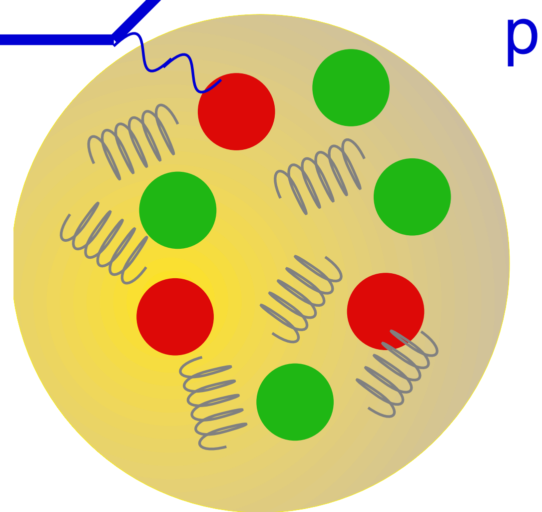
Proton - an elementary QCD bound uud-state raises questions

- size
- mass
- quark momenta $\sum x_{q,i} < 1$
- spin

to be probed by

Photon

- exclusively coupling to quarks
- not perturbing the strong IA



Use HERA to explore:

- Valence quarks
- Sea quarks

i.e. scattering centers and thus indirectly

- gluons

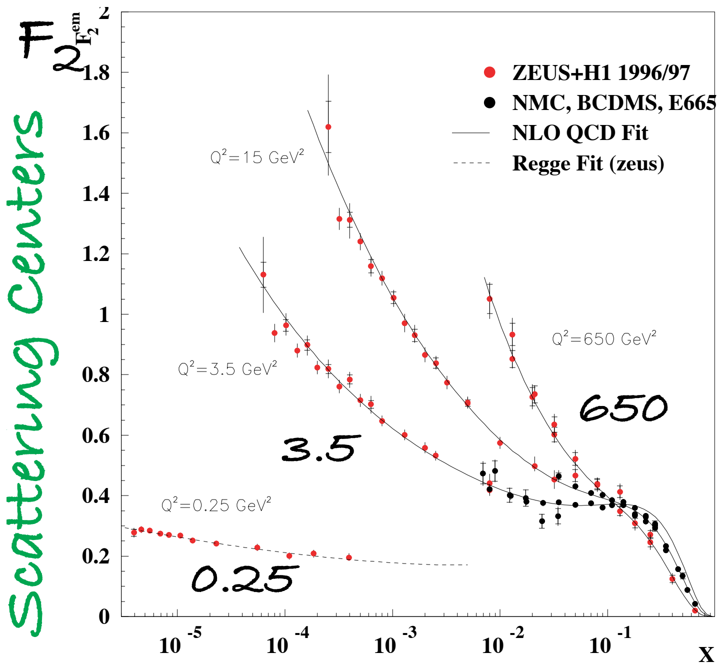
kin. range

$0.1 < Q^2 < 10^6\,\mathrm{GeV}^2$

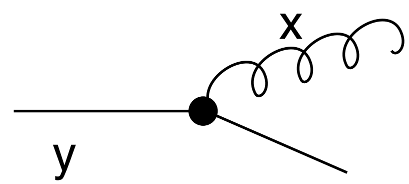
$r_p > b > 0.001 * r_p$

Strong Interaction - Perturbation Theory

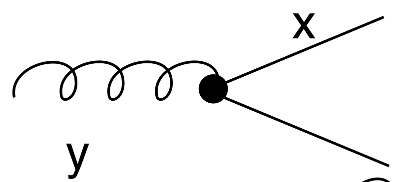
- Interaction between the constituents of the proton
- Parton density distributions $q_i(x)$ are Q^2 dependent:



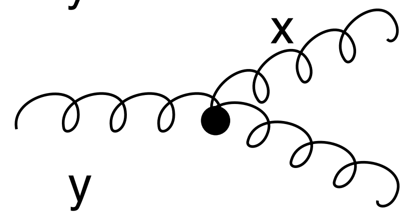
Bremsstrahlung



Pair creation

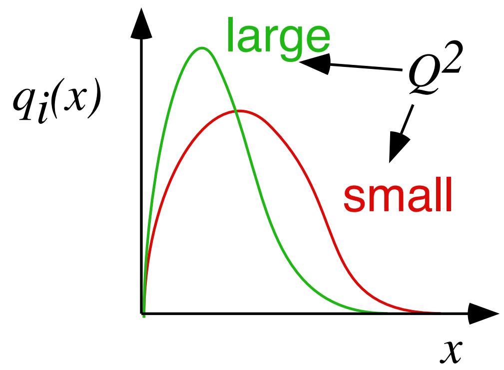


Gluon self-interaction



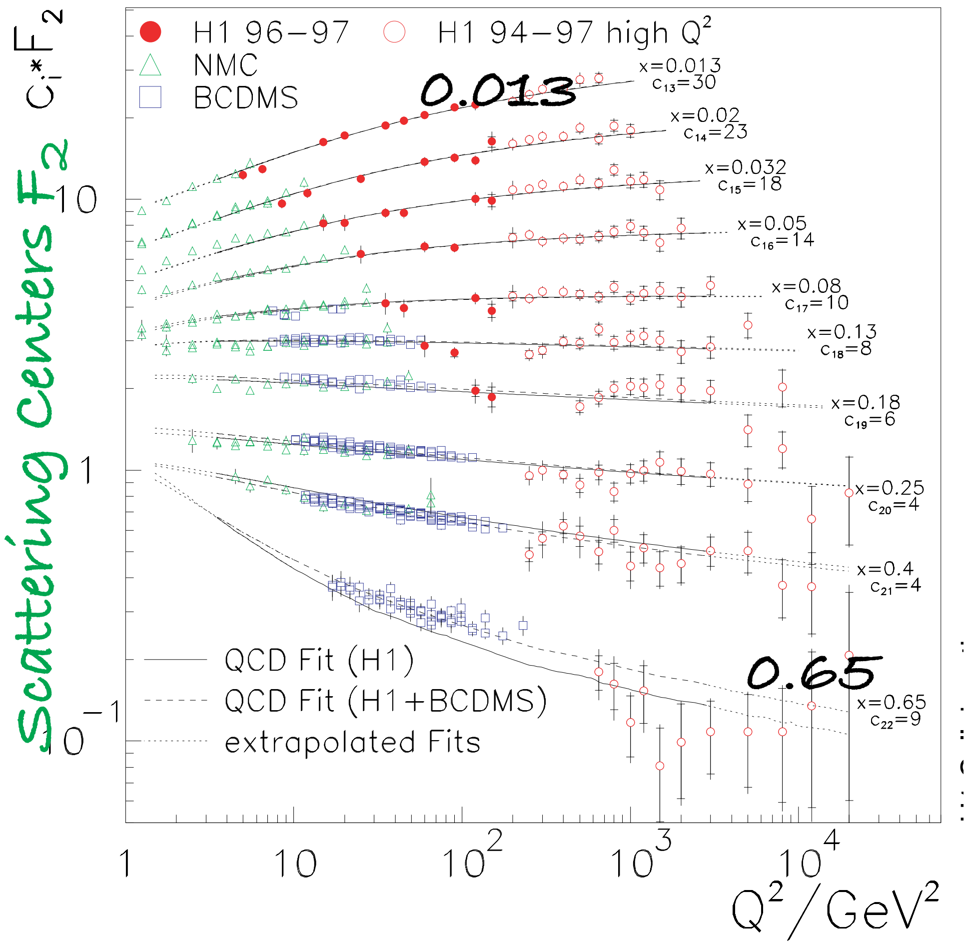
$$\frac{\mathrm{d}q_i(x,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y}\left(q_i(y,Q^2)P_{qq}\left(\frac{x}{y}\right) + g_i(y,Q^2)P_{qg}\left(\frac{x}{y}\right)\right)$$

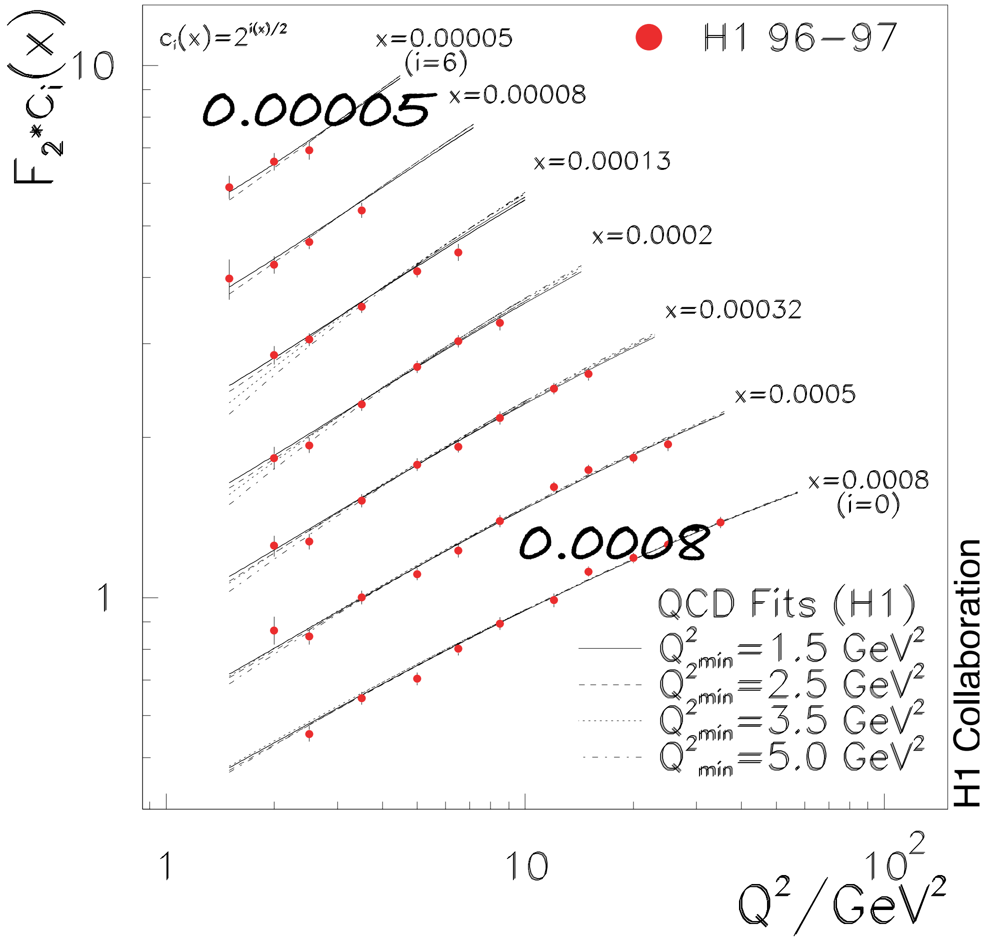
$q_i(x,Q^2)$ represent the density distributions of the scaled parton momenta.



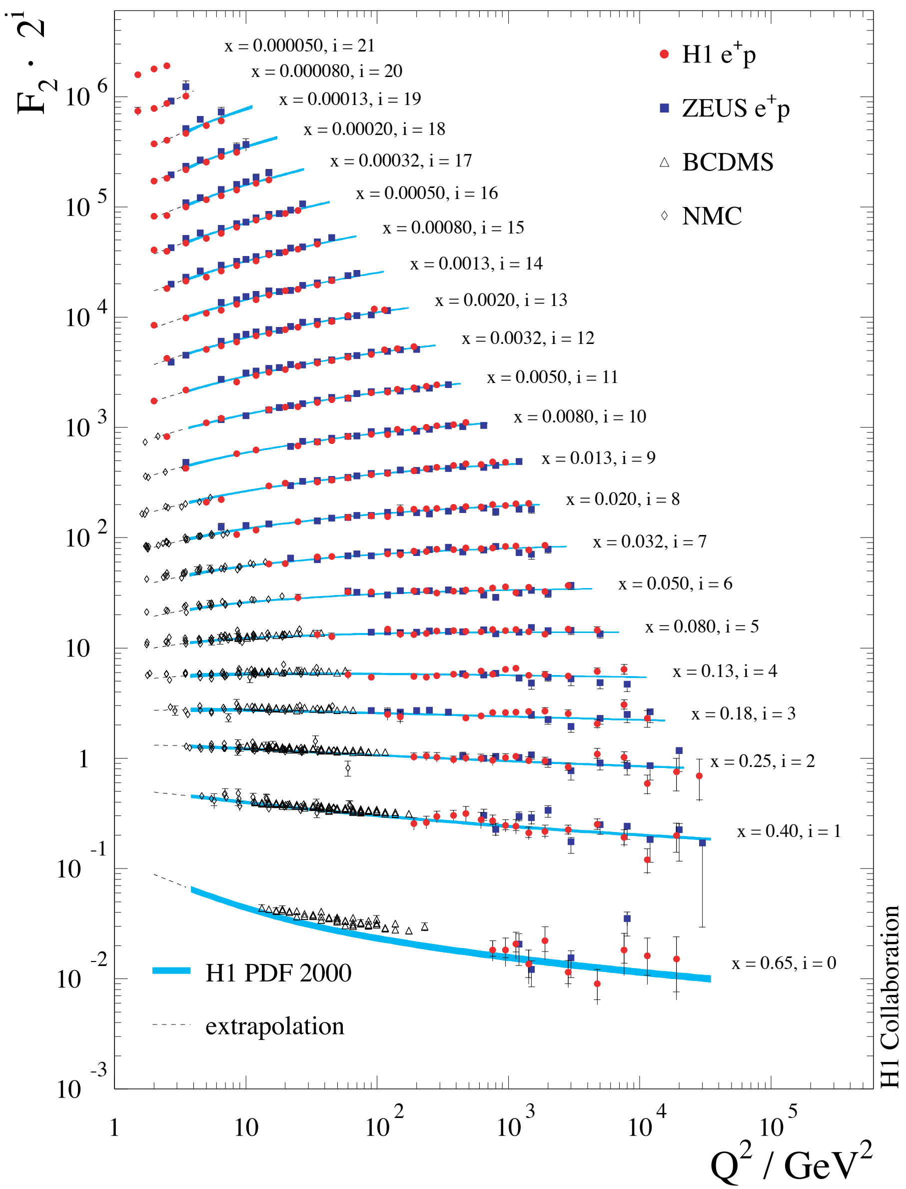
Scaling Violations

$$\frac{d\sigma}{dx dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4} \times F_2(x, Q^2)$$





F_2^{em}



$$\tilde{\sigma}^{\pm}_{NC} = Y_+ F_2 \mp Y_- xF_3 - y^2 F_L$$

correct F_2 for (small) electroweak contributions

$$F_2^{em}(x, Q^2) \sim x \sum_q e_q^2 (q + \bar{q})$$

dominated by u-quark contribution.

Slope variation sensitive to gluon and strong coupling.

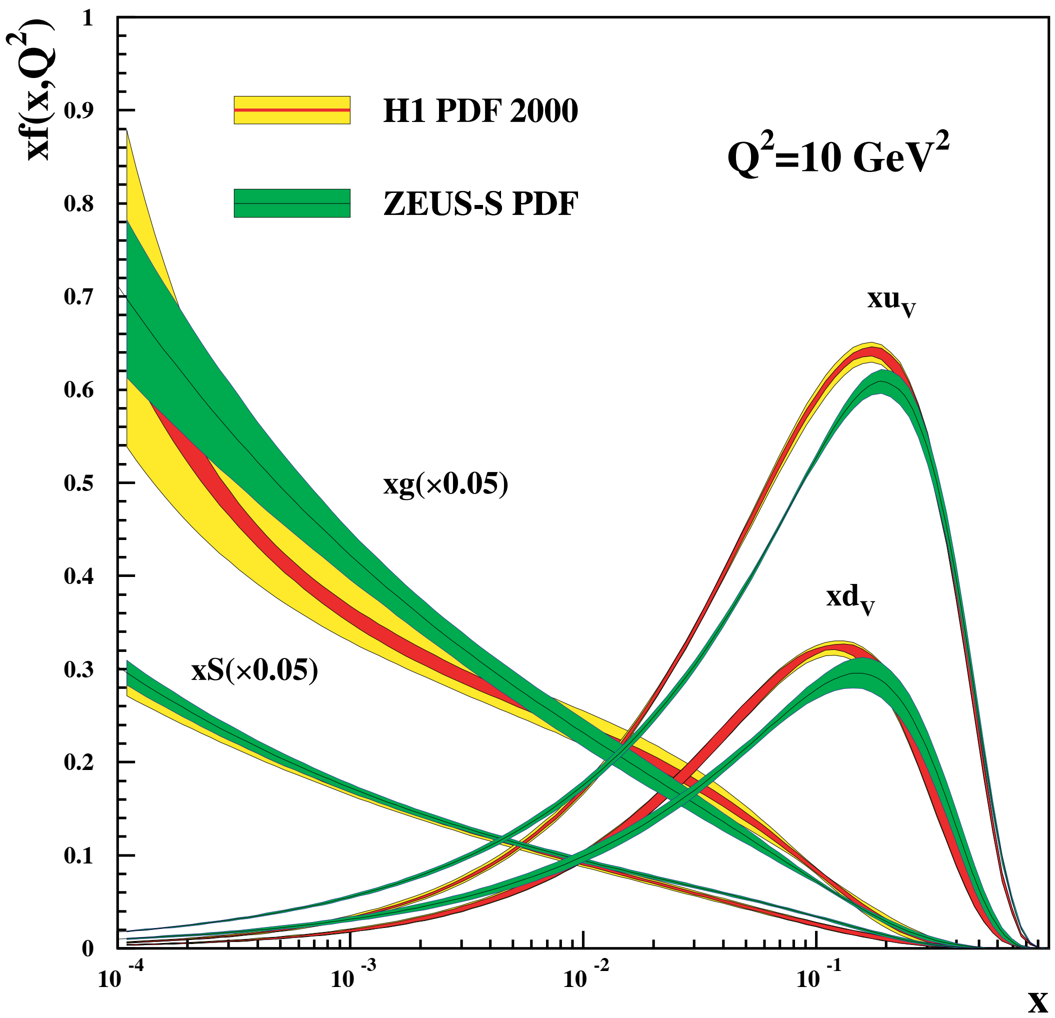
Parton Distribution and α_s

e.g. H1

$\alpha_s = 0.1150$
$\pm\, 0.0017$ (exp)
$^{+0.0009}_{-0.0007}$ (model)
$\pm\, 0.0050$ (scale)

- NNLO calculations start to be available
- theoretical residual uncertainty ~1%

large x experimentally!



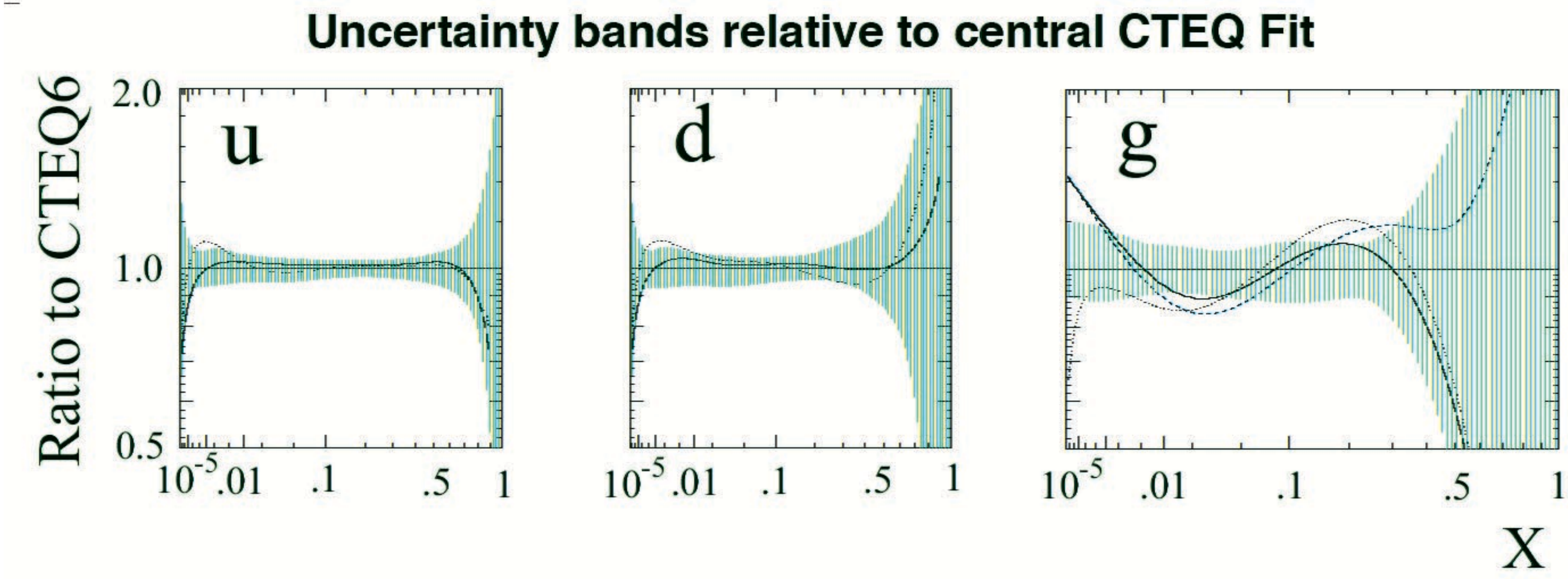
PDF Uncertainty Assessment

CTEQ at $Q^2 = 10\ GeV^2$

- u best constraint
- d less well known both at small and large x
- gluon unknown at large x

Precision required for LHC:

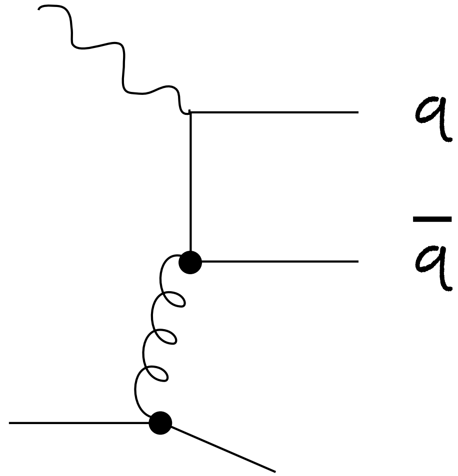
- $10^{-6} < x < 1$ and
- $100 < Q^2 < 10^8\ GeV^2$



Jet Production

Accessing high x

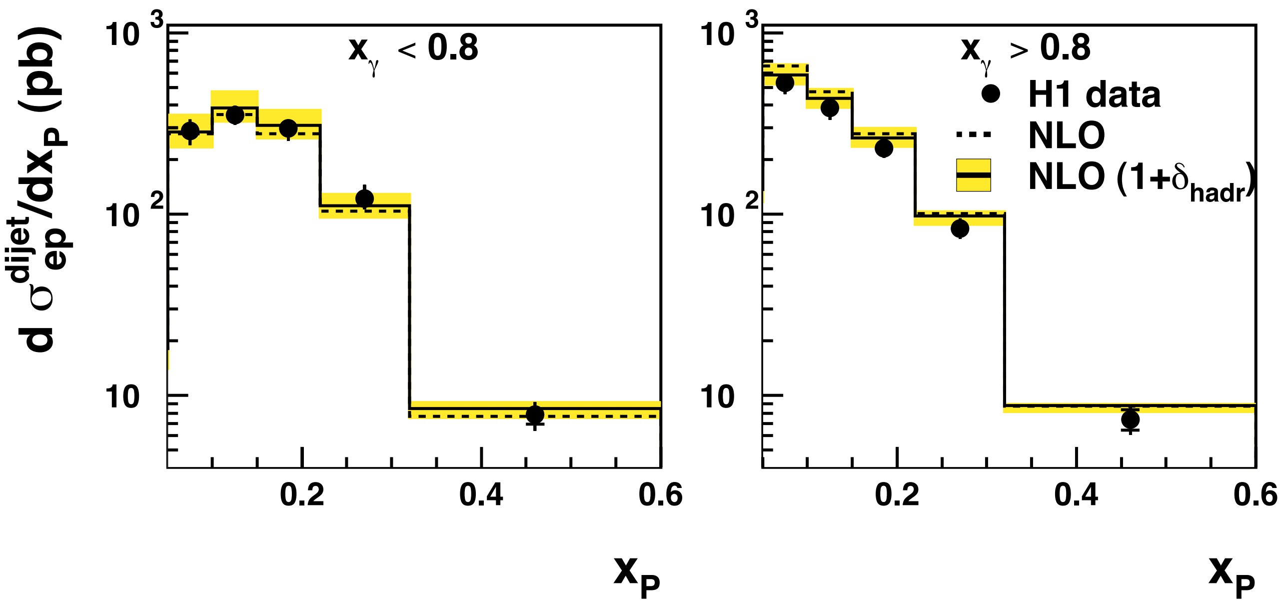
- 2 jet production at large E_T is sensitive to the large x-component in the proton
- independent handle on, e.g. the gluon in the large x-region



typically

$30 < E_T < 80$ GeV

avoids the high x - high Q^2 correlation

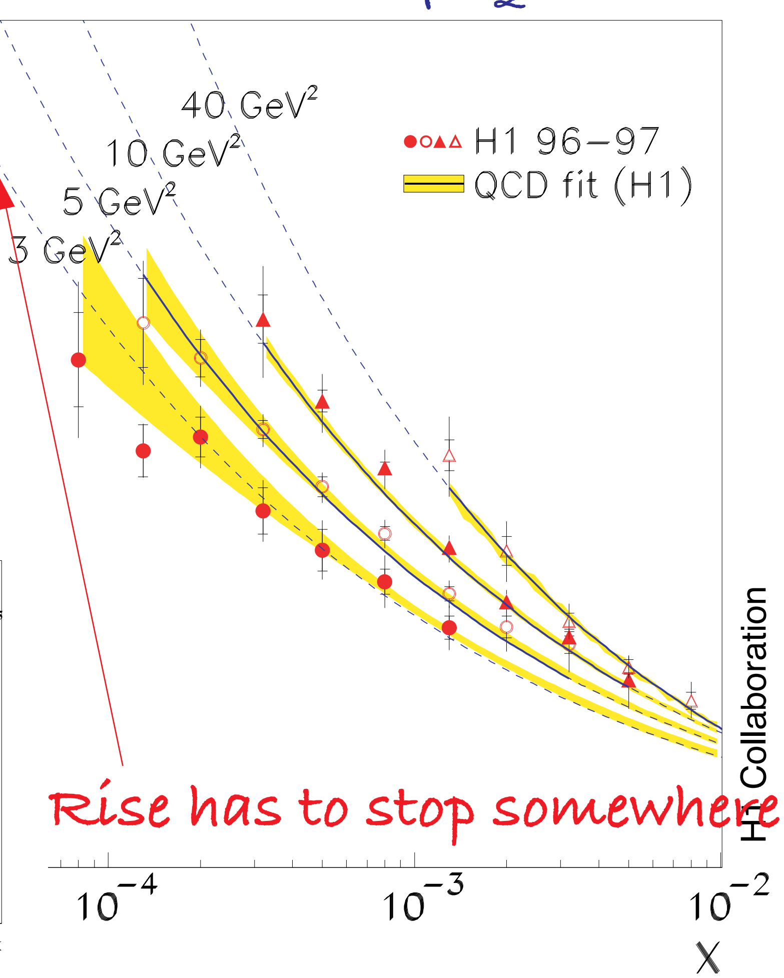


Limits of Validity of Perturbative QCD Calculations

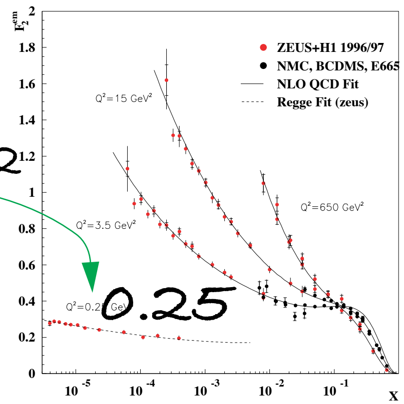
Expansion in Q^2

- Perturbation theory valid down to small x
- Rise at small x is "unchanged"
- only at smaller Q^2 is the rise moderated
- Perturbation theory safely applicable for $Q^2 > 1$ GeV^2

Variation of F_2



F_2

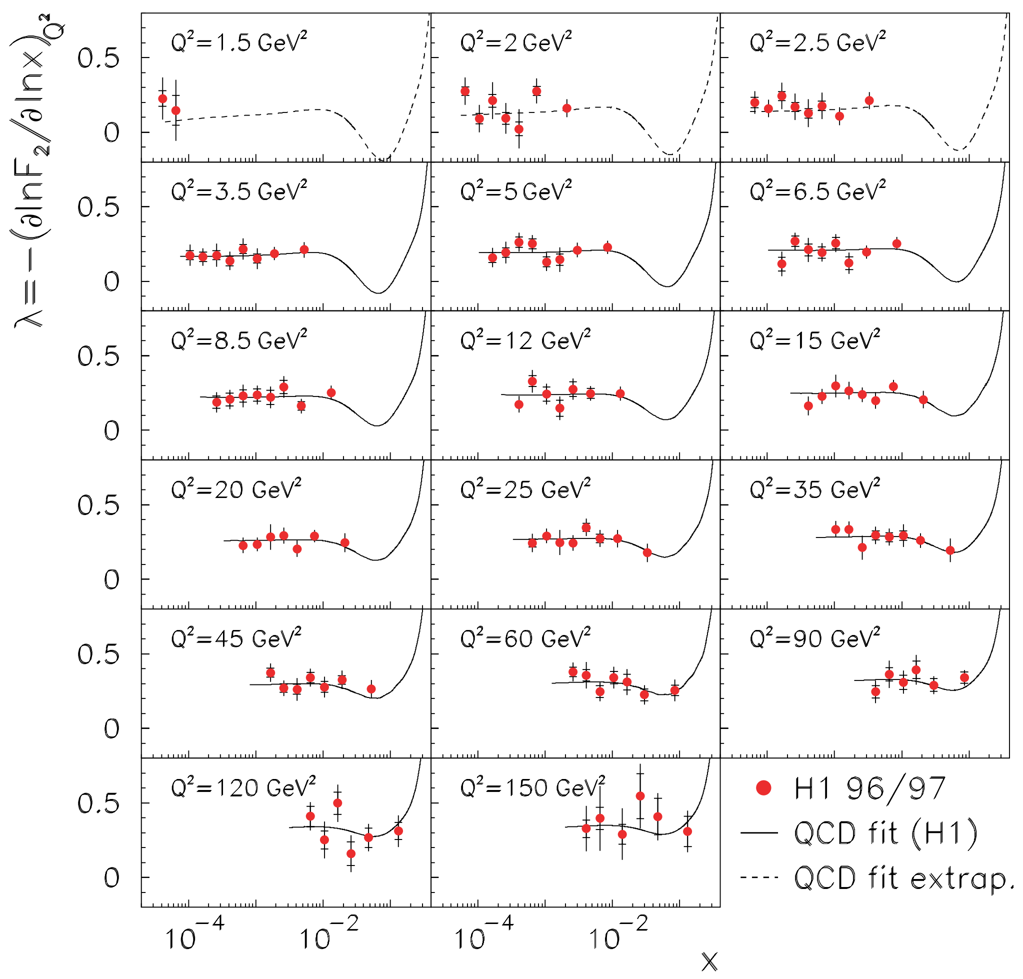


New quantum system?

Behaviour at small x

Transition to high energies

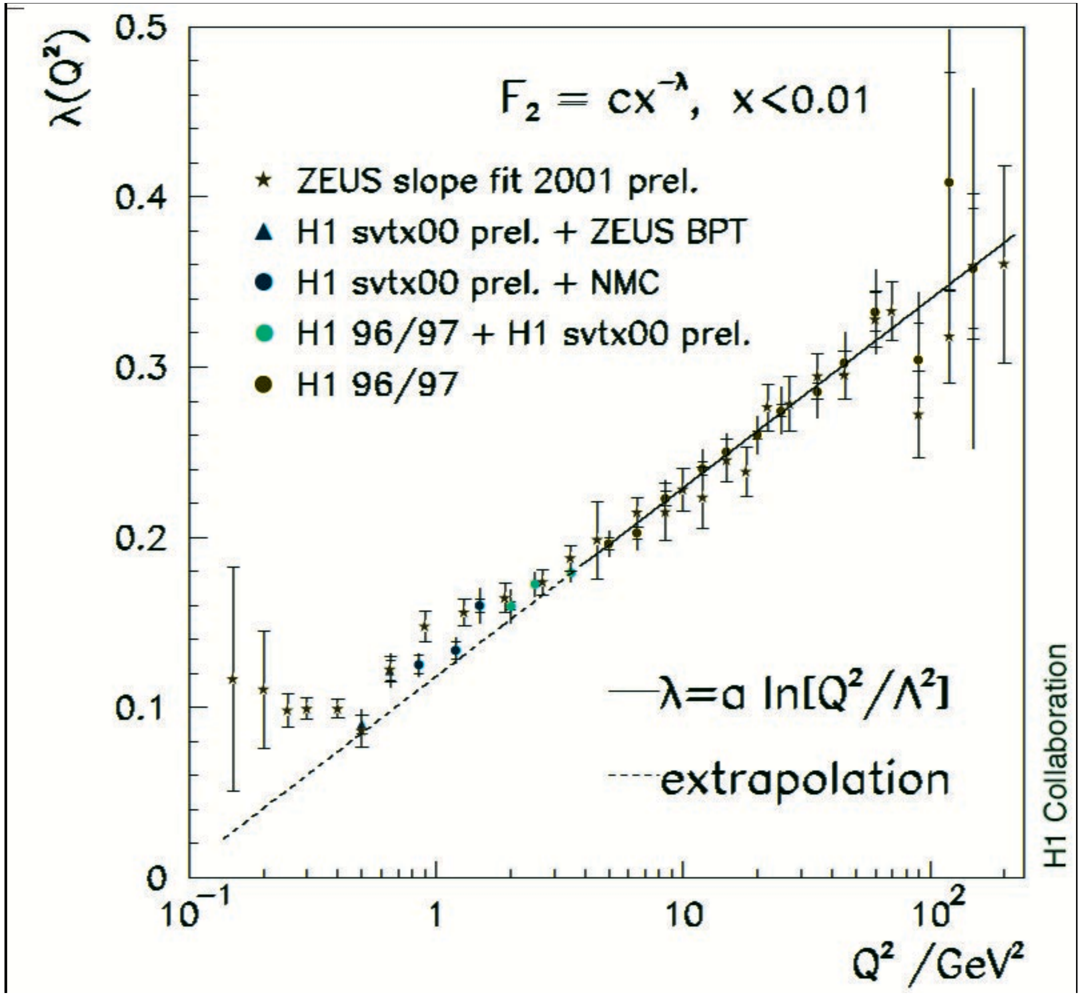
- $$W^2 = \frac{Q^2}{x}(1-x) \approx Q^2/x$$
- for x<0.01 the variation of the structure functions seem to be independent of x
- $$F_2 = c(Q^2)x^{-\lambda(Q^2)}$$



Fractal structures in the proton?

- $c(Q^2)$ is roughly constant

x-dependence



$Q^2 > 3$ GeV^2

- $\lambda \sim \ln Q^2$ ...linear rise

$Q^2 < 1$ GeV^2

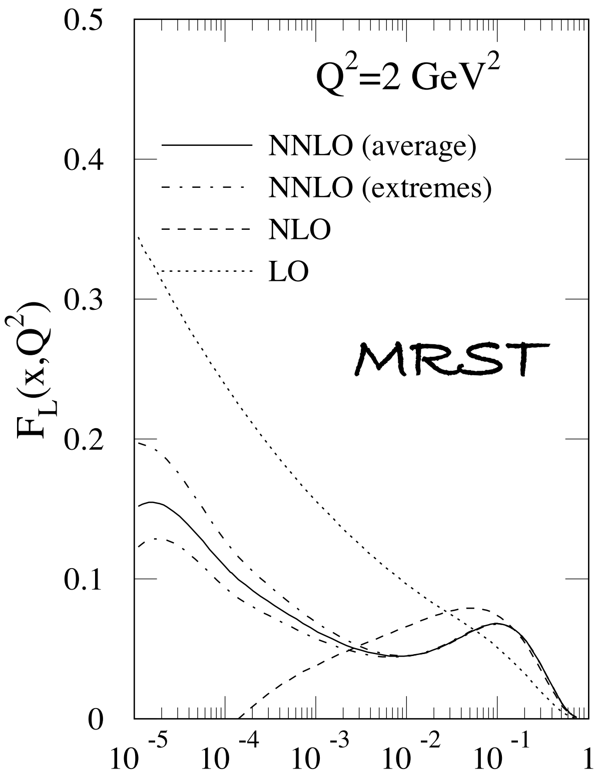
- $\lambda \rightarrow \alpha_P - 1 \approx 0.08$ ... const.

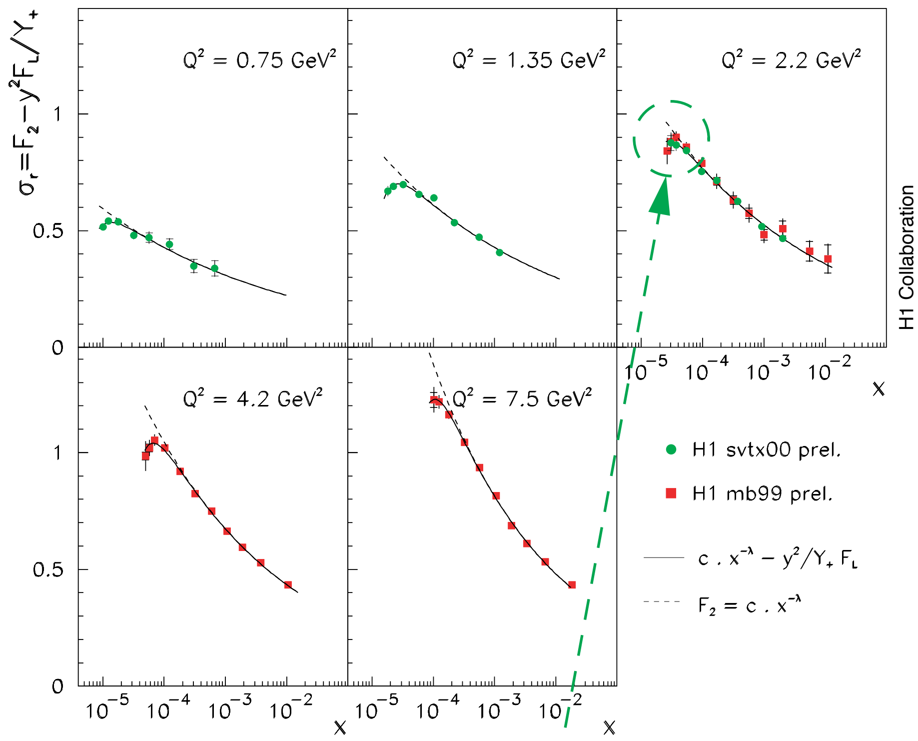
Indicative of transition to hadronic degrees of freedom at a scale of 0.3 fm.

Are here clues to understanding confinement?

Extraction of F_L

The longitudinal structure function F_L is little constraint from the existing data.



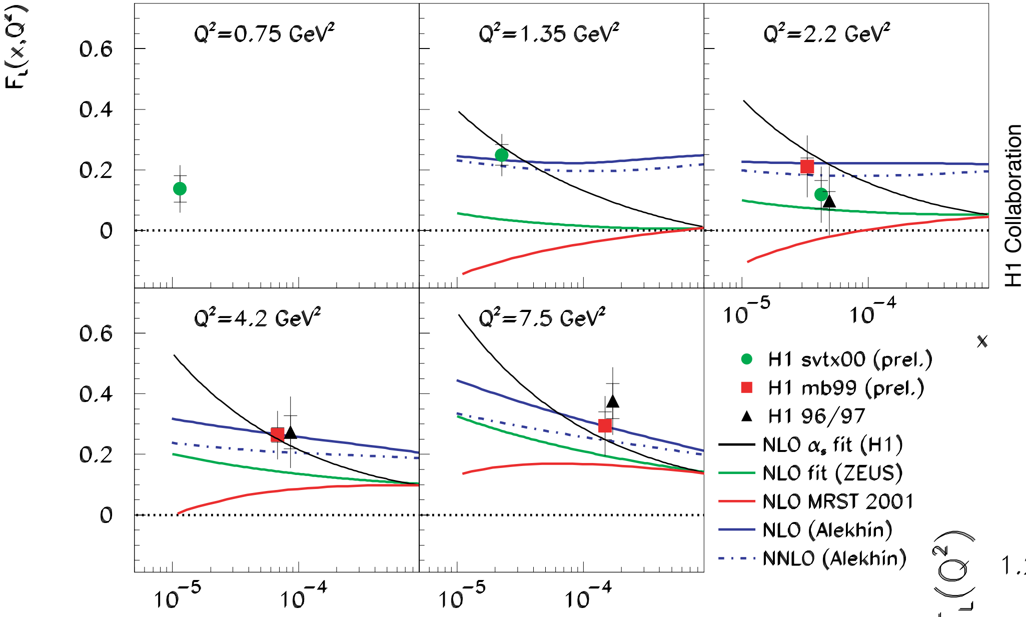


Reaching to the lowest x and using

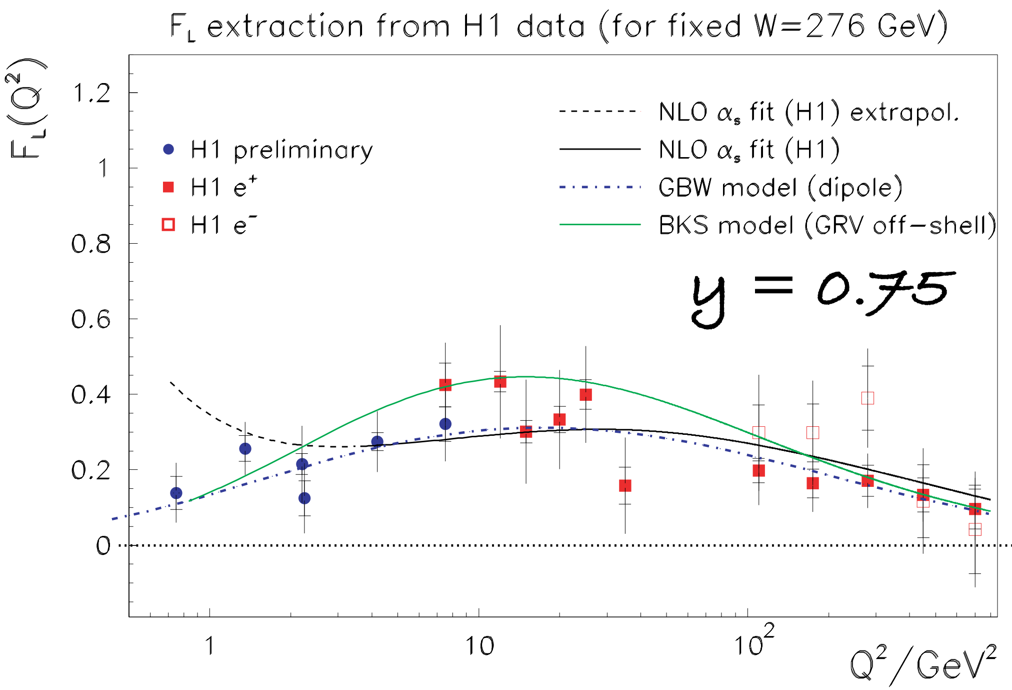
$$\sigma_r = cx^{-\lambda} - \frac{y^2}{1+(1-y)^2} F_L$$

determine F_L at $Q^2 \approx 1\ \mathrm{GeV}^2$

New Determination of F_L



Can be used to discern between different theoretical models particularly when approaching the low Q^2 region.



For a full understanding one has to measure

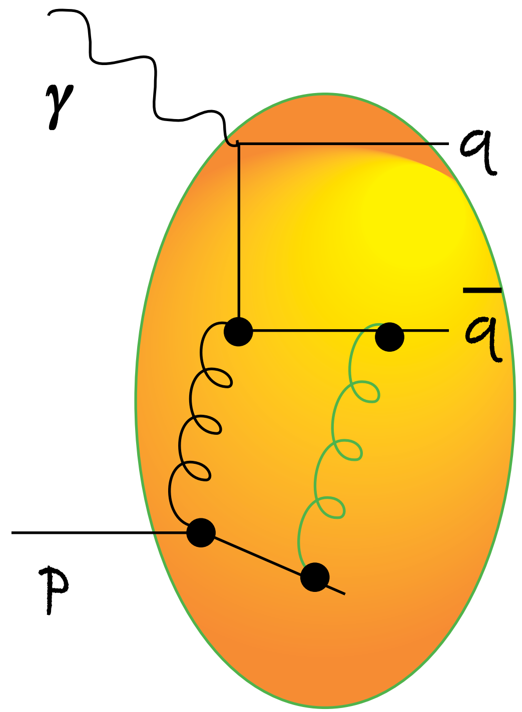
- Q^2 ... spatial extent
- x ... time of interaction

independently. Runs at low E_p!

Gluon Radiation in Colored Matter

QCD Bremsstrahlung

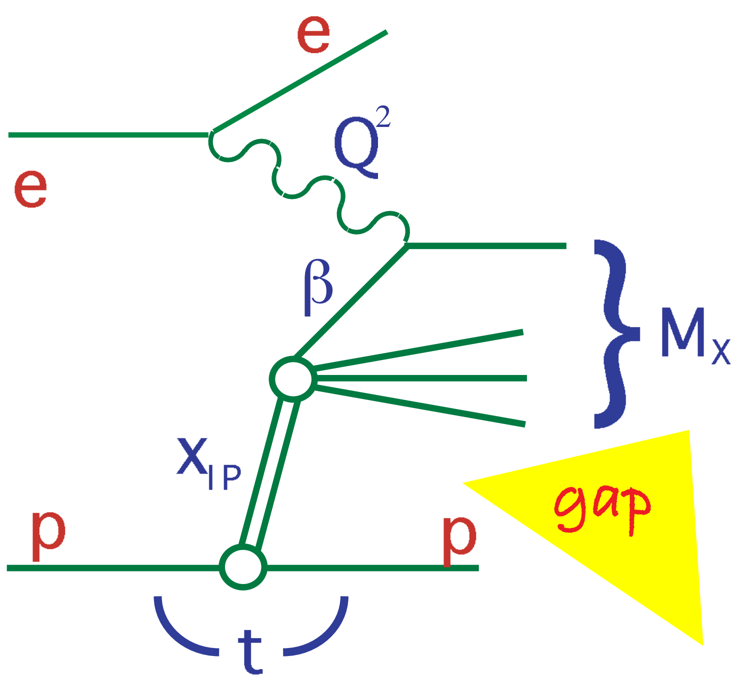
- exchange of a hard gluon
- accelerated charge radiates gluons (analogous to QED)
- rate $\sim \alpha_s$
- recombination with other strongly interacting quanta to form colorless system



Color singlet formation - statistical process?

- examine rates and topologies of final states (Jets, vector mesons, charm, etc.)
- contrast with other production processes: can we obtain a common picture with pp-scattering where the survival of the colorless state is affected by the presence of other strongly interacting constituents

Understanding Color Singlet Exchange in QCD



- Color-singlet exchange involving >1 parton, correlated parton density

Generalized Parton Density

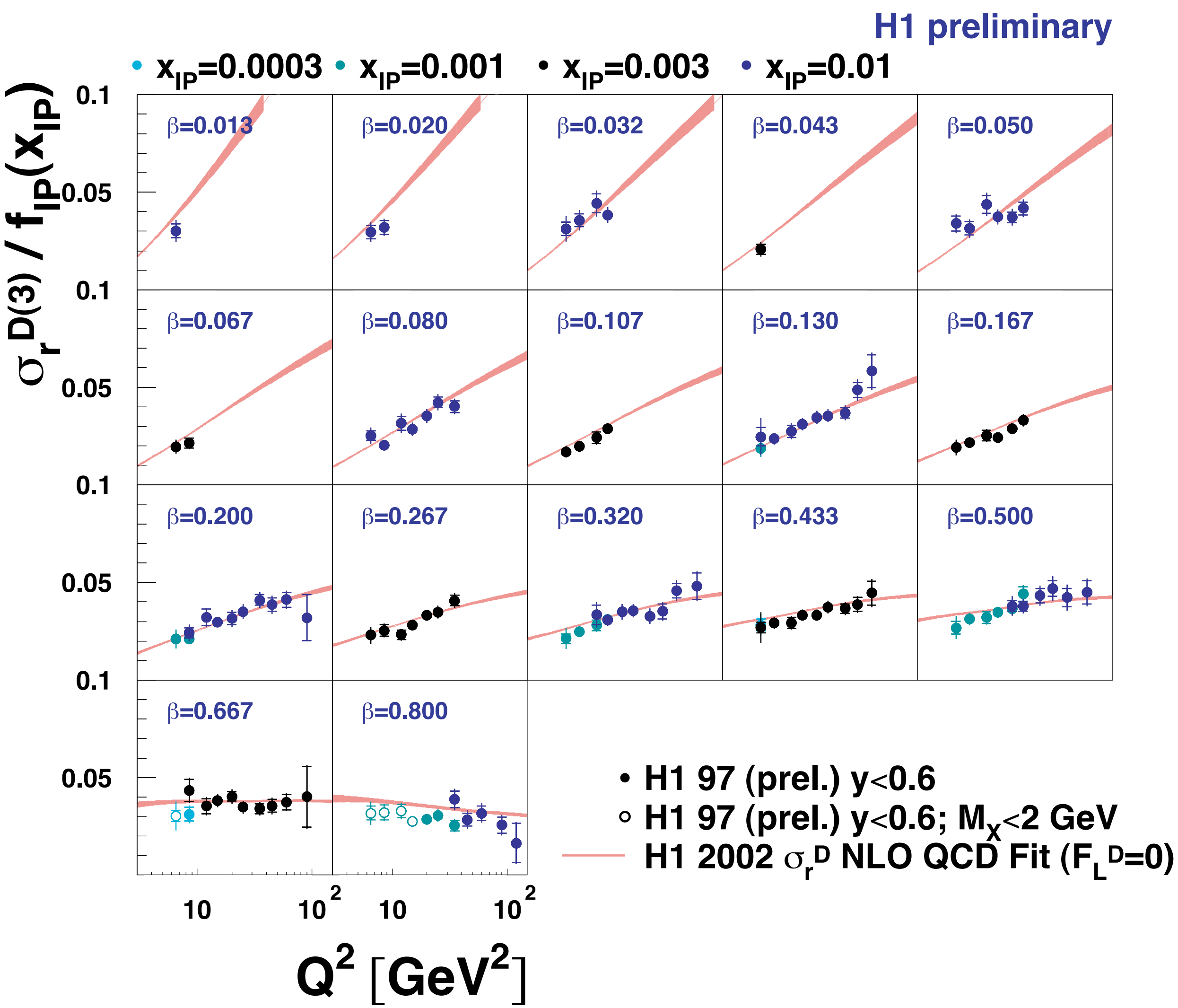
- $f_{i/p}(x_1, x_2, Q^2)$
- DVCS
- Vector meson-Production

Factorization

- $\sigma \sim$ flux * elem. X-section proven in hard diffraction (for fixed x,t)

→ QCD interpretation of diffraction

Diffractive Structure Functions

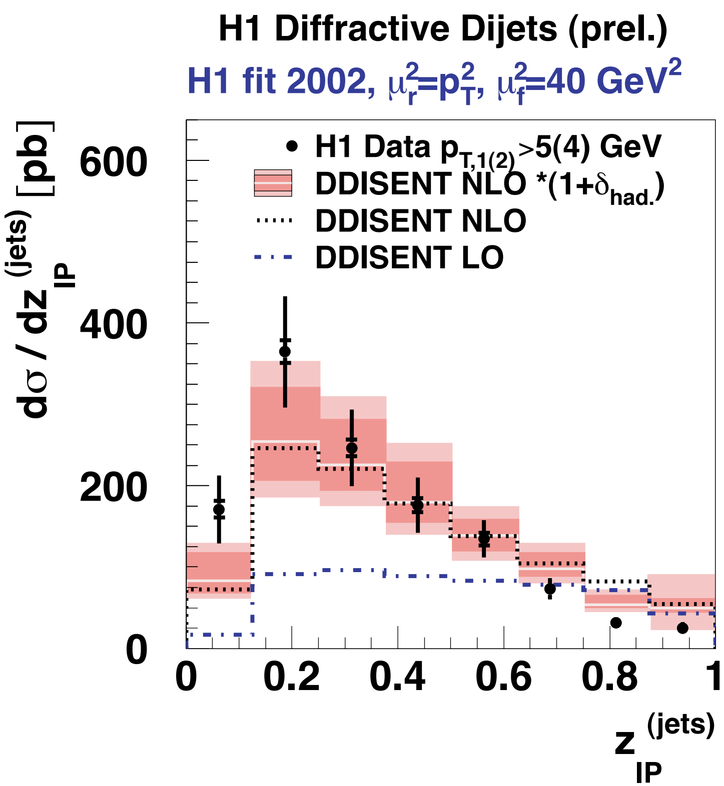


NLO QCD Fit

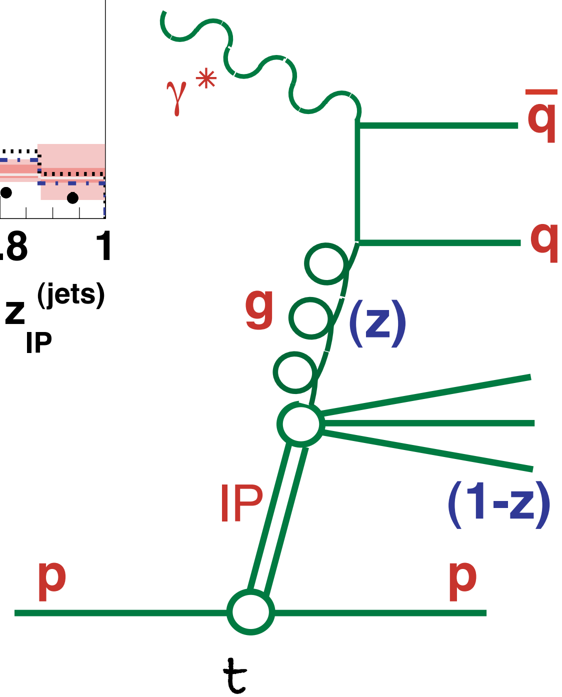
Precision of data leads to non-trivial results

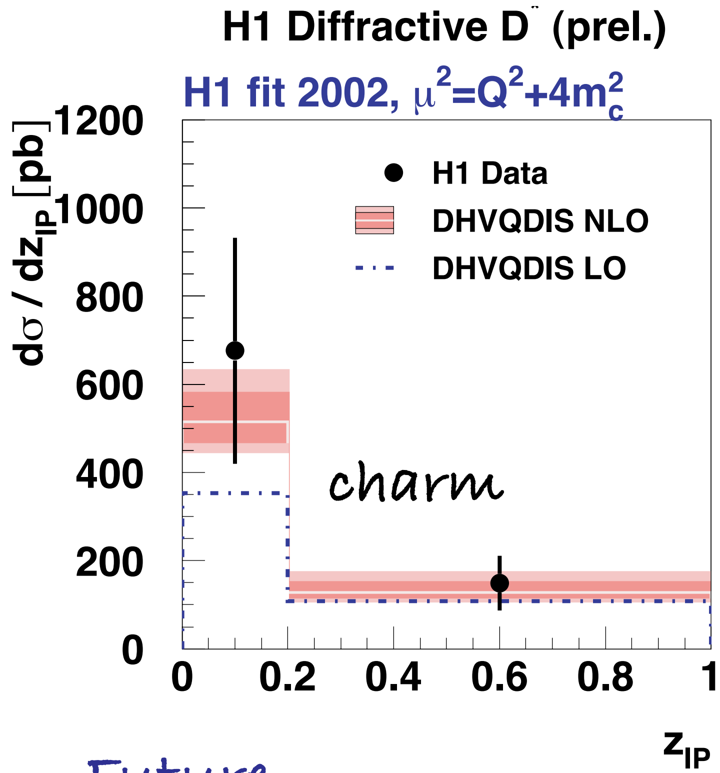
- factorization picture holds
- strong scaling violations – Gluon dominates
- seek understanding at more fundamental level

Diffraction for Charm und Jets



Diffractive tests in exclusive channels





Parton Interpretation

- ok in NLO
- QCD picture is applicable

Future

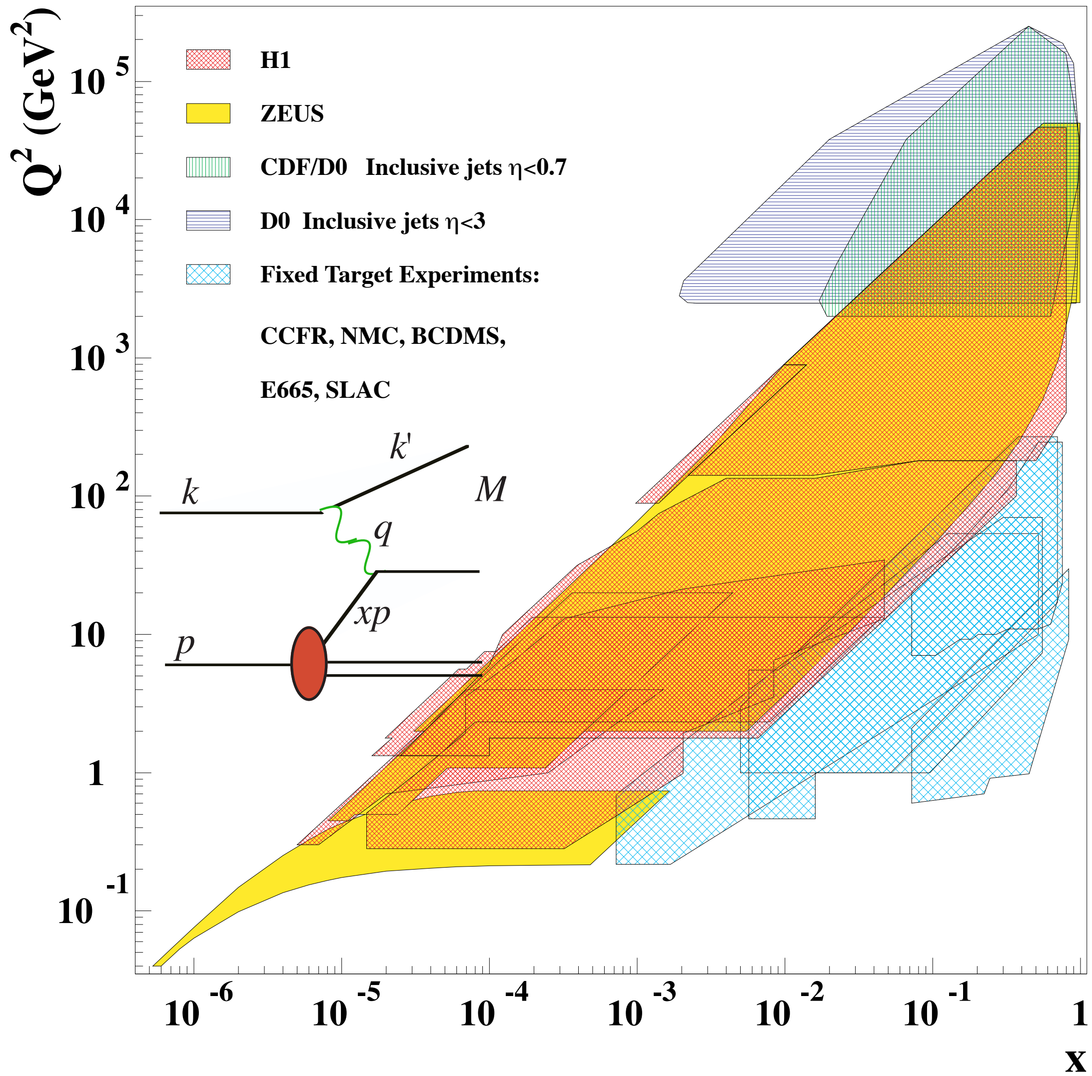
- more differential cross sections
- t-dependence

"Strong Tasks" for HERA II

Domains

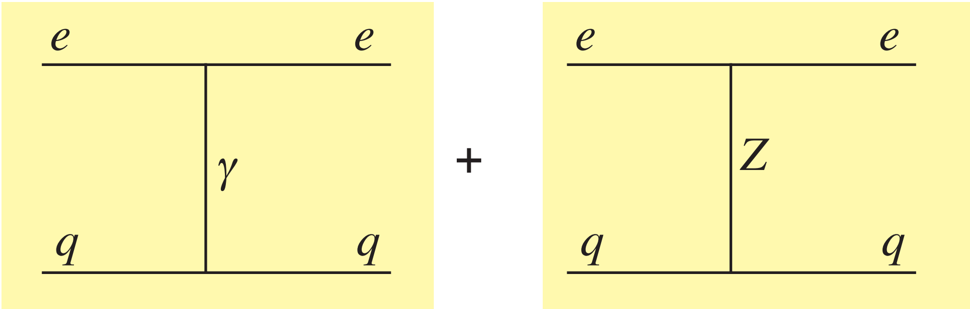
- Region of large Q^2:
  α_s, parton densities
- small x:
  high Parton densities
  towards dynamic model?
- small Q^2:
  Confinement-region
- large CMS Energy:
  EW-Tests and
  "Beyond the SM"

→ QCD Experiments under well defined conditions



Electroweak Processes at HERA

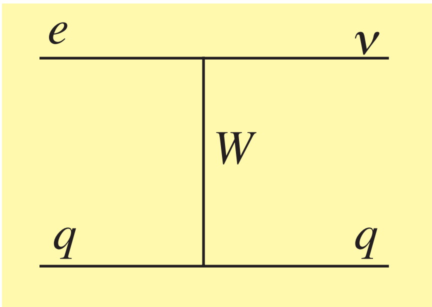
Neutral Current (NC)



$$\frac{xQ^4}{2\pi\alpha^2}\frac{\mathrm{d}\sigma(e^{\pm}p)}{\mathrm{d}x\mathrm{d}Q^2} = Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3$$

with $\quad Y_{\pm} = 1 \pm (1-y)^2$

Charged Current (CC)



purely electroweak interaction

characterized as

- $1/Q^4$ dominates
- Z-contribution with $1/(1+(M_Z/Q)^2)$ and $1/(1+(M_Z/Q)^2)^2$ dampened
- xF_3, γZ-Interference, charge sensitive and partially parity violating
- W-Propagator $1/(1+(M_W/Q)^2)^2$

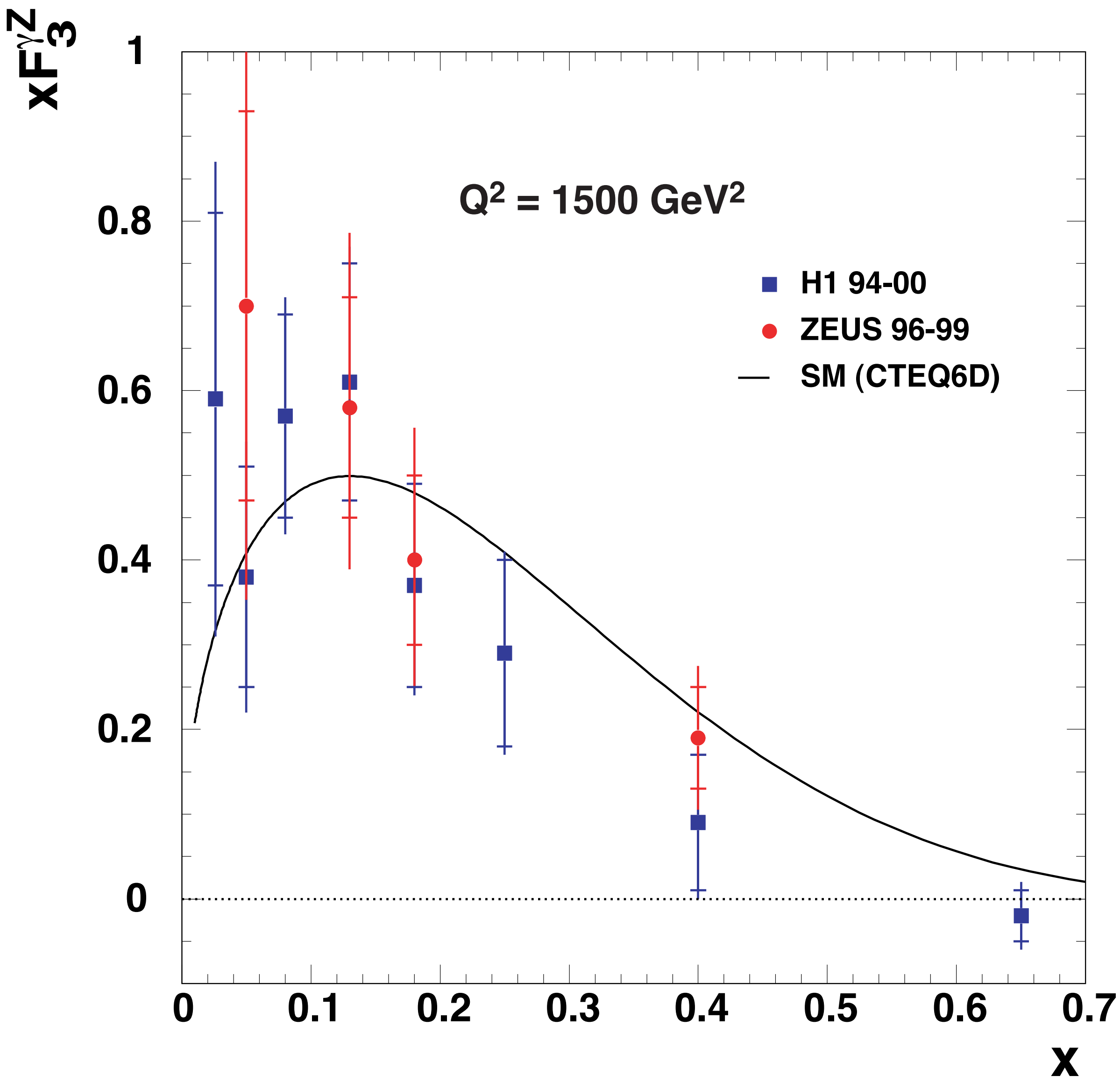
$xF_3(x,Q^2)$

Interference

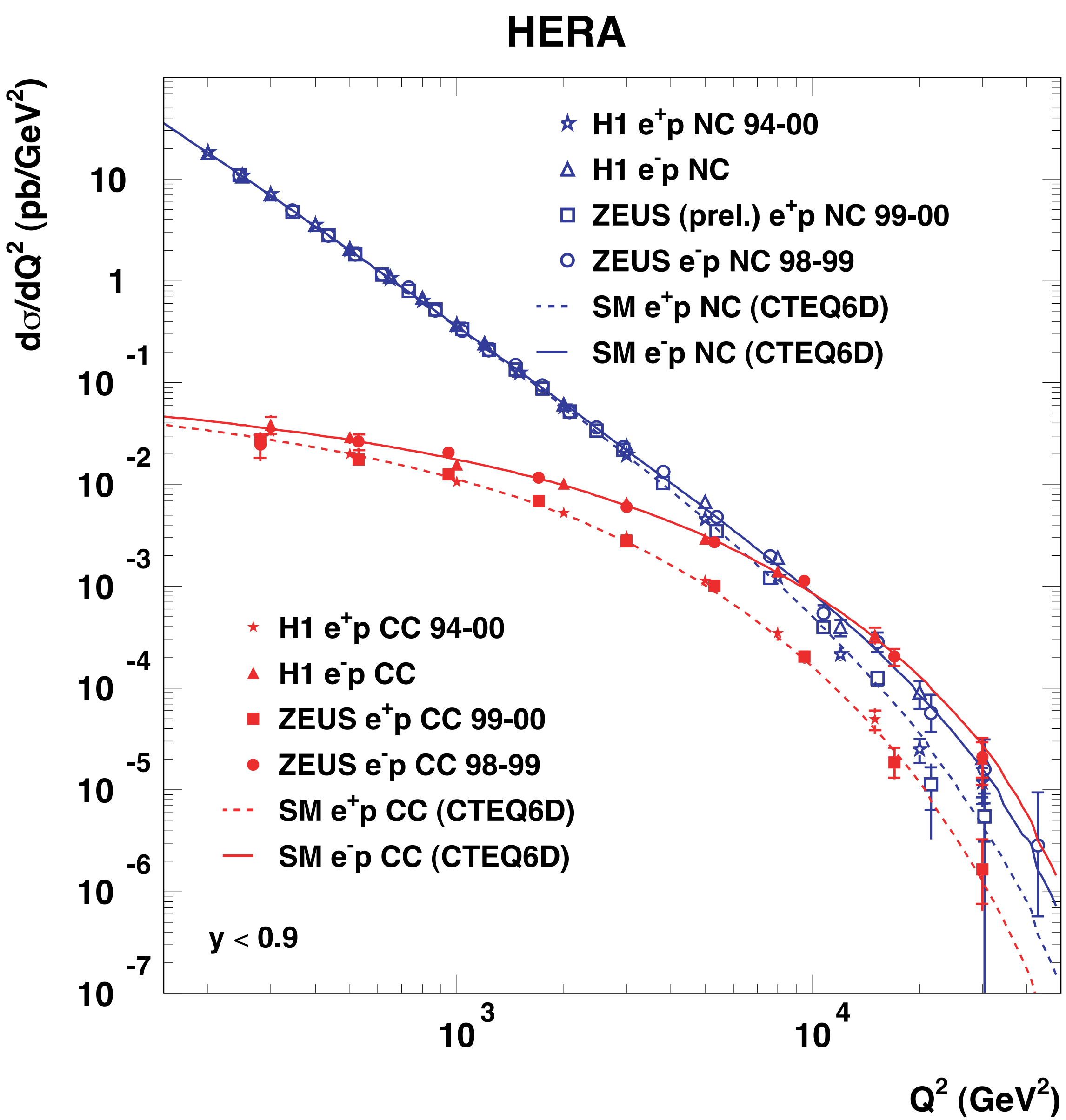
$$xF_3 = \frac{1}{2Y_-}(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC})$$

$$xF_3 = -a_e\kappa\frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + \kappa^2\Delta Z^2$$

- $xF3 \sim q(x) - \bar{q}(x)$
- valence quark distribution
- need more e^-p data.
- sum rules for xF_3 integrals will be tested



Electroweak Unification



For

$$Q^2 \approx M_Z^2, M_W^2$$

neutral and charged current are roughly of equal strength.

Details are depending on electroweak couplings to individual quark flavours.

HERA is sensitive to flavour decomposition.

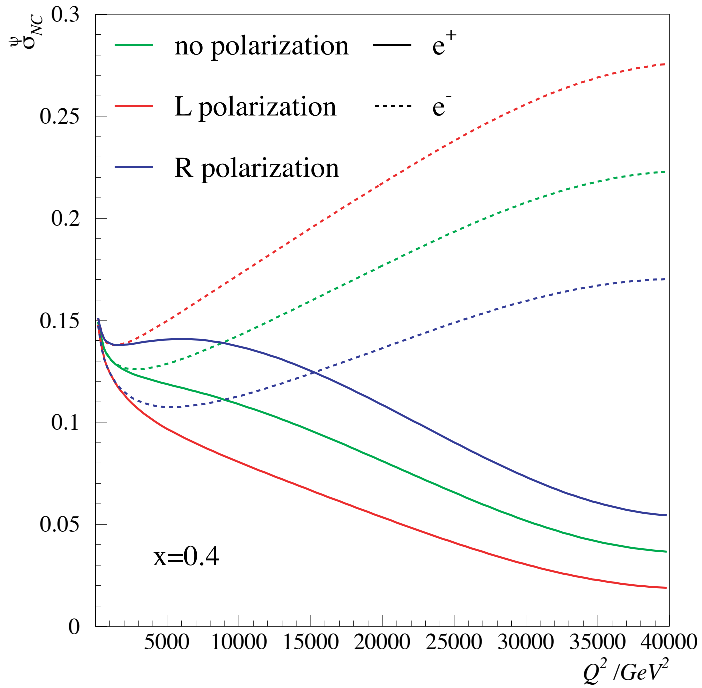
Expectation for Parity Violation with Polarized Beams

Neutral Current

- axial and vector couplings only from pure Z-term:
- kinematical suppressed, relevant only for $Q^2 > 10000$ GeV^2

NC

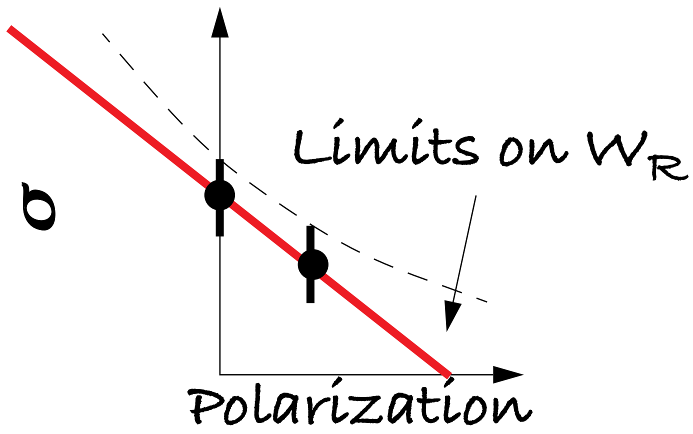
$\sim Q^4 * d\sigma$



Charged Current

- $\sigma_{pol} = \sigma_{unpol} * (1+P)$ since $\sigma(e_L^+ p) = 0$
- "textbook experiment" feasible with a few 10 pb^{-1}

CC



HERA II - the High Luminosity Phase

Goal

- 1 fb^{-1} till end 2006
- Polarization (~55%)
- Runs with reduced Ep (e.g. 300, 365, 400 GeV) to measure F_L

Method

- strong focussing of the beams at the Interaction Point

using

- superconducting quadrupoles in the experiment

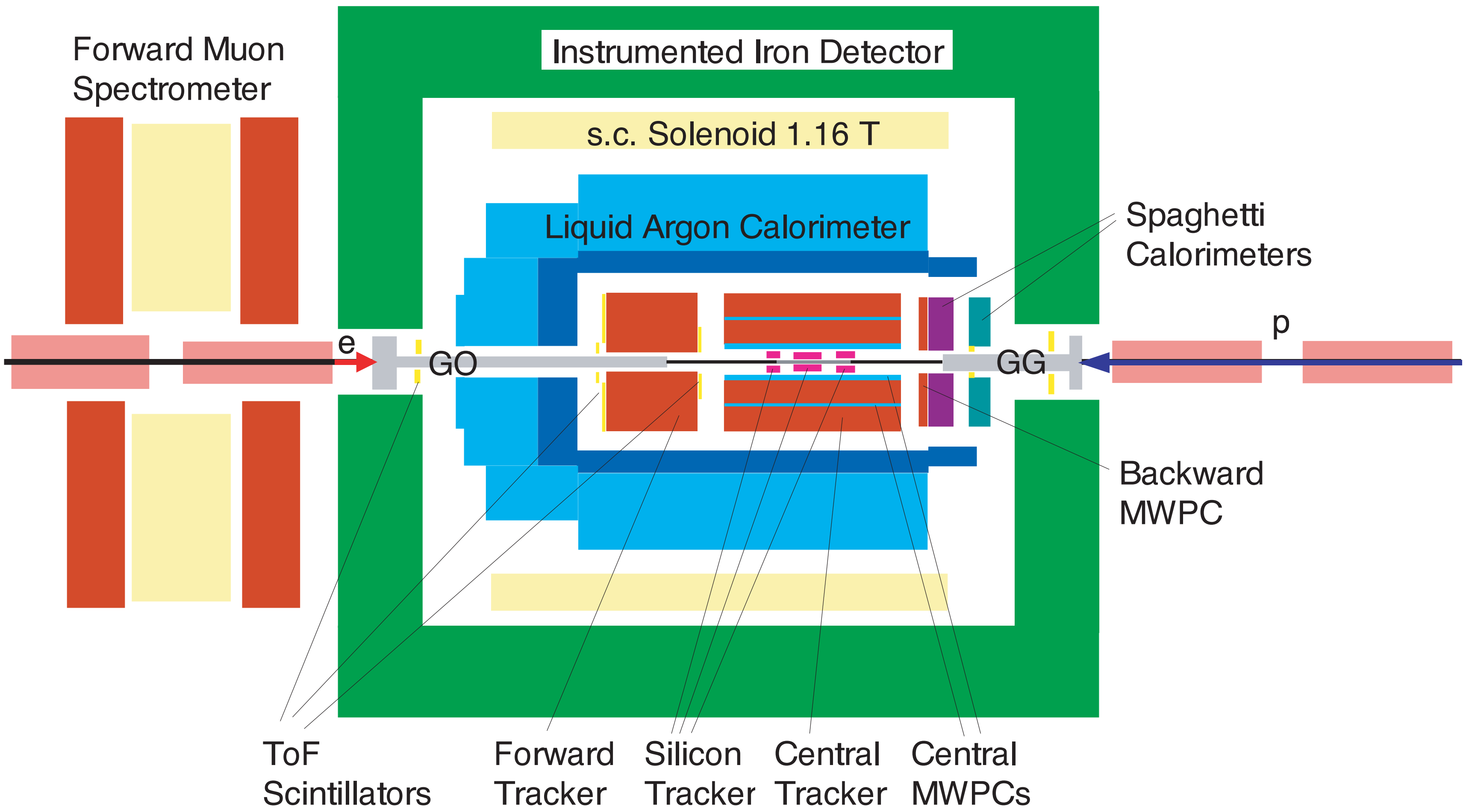
Consequences

- Synchrotron radiation is generated in the interaction region
- no compensating magnets
- space restrictions

Status

- spec. Luminosity has been achieved (design 1.8*...) $\sim 1.5 * 10^{30} cm^{-2} s^{-1} (mA)^{-2}$
- and best HERA II luminosity of 2000 has been surpassed with $I_e * I_p$ a quarter of the 2000 value

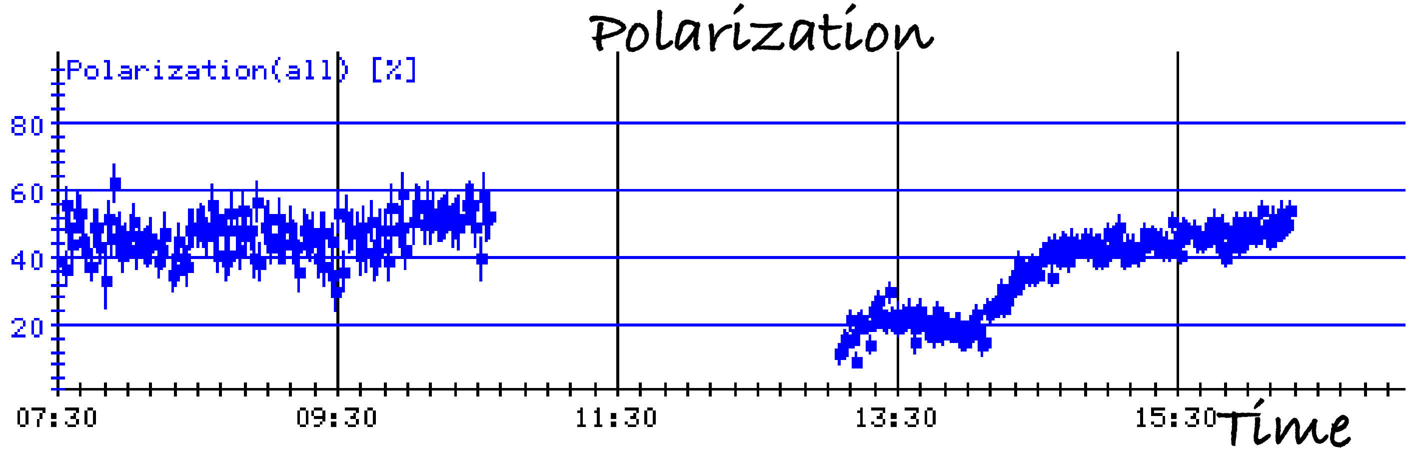
H1 Detector Upgrade



Polarization on track...

Longitudinal Polarization

- pair of spin rotators around each interaction point
- main solenoids not compensated.



50% polarization achieved on March 2, 2003 with all solenoids on in luminosity optics

Outlook for HERA II

Goals

1fb-1

- Search at small scales
- Electroweak effects
- Solution to the remaining puzzles

"Tevatron aspect" of HERA

Strong Interaction:

- Parton structure (F_2, F_L, ...), charm, bottom, jets
- Diffraction
  inclusive and final states:
  charm, (bottom), γ
- dynamic model of QCD

"LEP aspect" of HERA

Eagerly watching HERA II turn on after shutdown in summer 2003. Positive indications from first beams. However, learnt to be patient with vacuum conditioning.