FRONTIERS IN CONTEMPORARY PHYSICS - II
Vanderbilt, March 5–10 2001
parallel session

Tests of perturbative QCD at HERA

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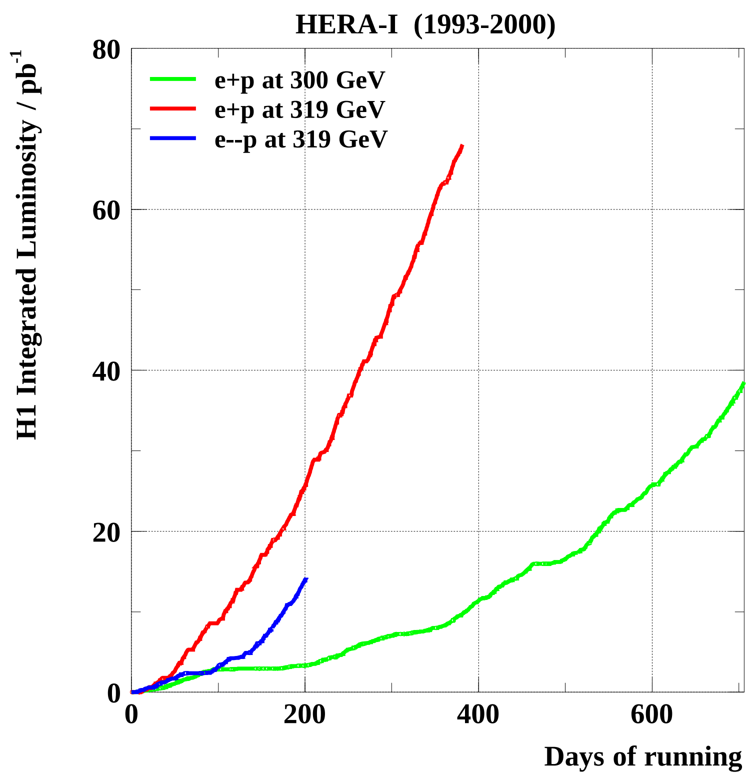
for the ZEUS and H1 collaborations

- The H1 and ZEUS experiments at HERA
- Inclusive measurements
  - Neutral current (structure functions, QCD interpretation)
  - Charged current (valence quarks)
- Exclusive measurements
  - Event shapes (NLO QCD, power laws)
  - Jets in DIS (α_s, gluon density)

The HERA storage ring at DESY

- 27.6 GeV e^+ or e^- beam
- 920 GeV proton beam
- center-of mass energy $\sqrt{s} = 320$ GeV



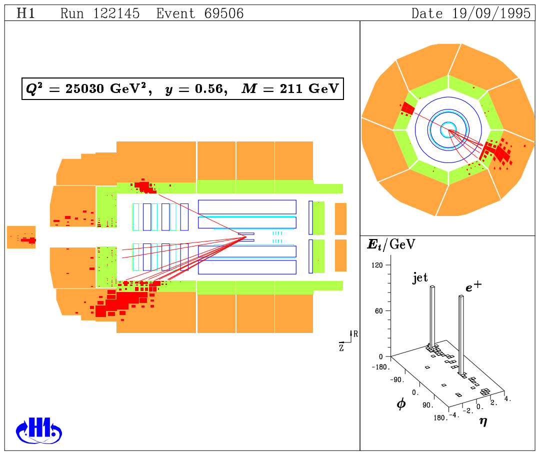
$\rightarrow$ HERA performance steadily increasing

The H1 and ZEUS experiments

Omni-purpose experiments, similar to LEP or Tevatron detectors

the H1 detector

$e^{\pm} \rightarrow$

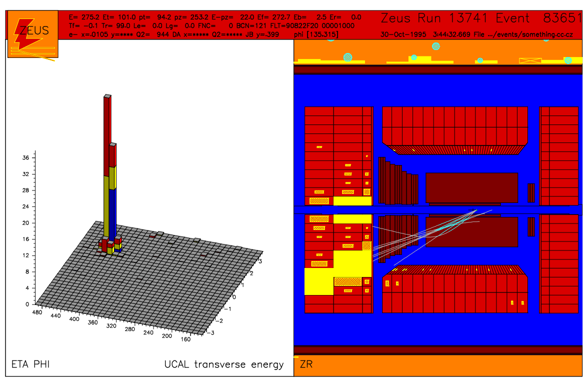


$\leftarrow p$

LAr calorimeter with high granularity

the ZEUS detector

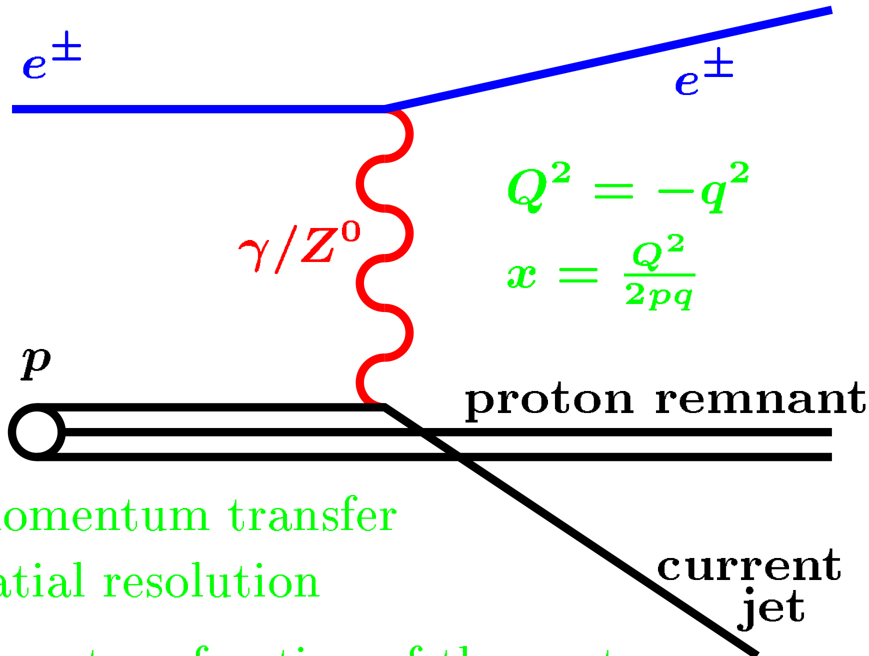
$e^{\pm} \rightarrow$



$\leftarrow p$

Compensating high resolution uranium calorimeter

Neutral Current DIS



Q^2: momentum transfer

$\frac{1}{Q}$: spatial resolution

x: momentum fraction of the proton carried by the struck quark

Leading order cross-section

$$\sigma_{\mathrm{NC}}^{e^{\pm}} \propto \frac{1}{Q^4} \; \frac{1}{x}\Big[Y_+ \sum_i A_i (xq_i + x\bar{q}_i) \quad : \; F_2$$

$$\mp Y_- \sum_i B_i (xq_i - x\bar{q}_i) \quad : \; xF_3$$

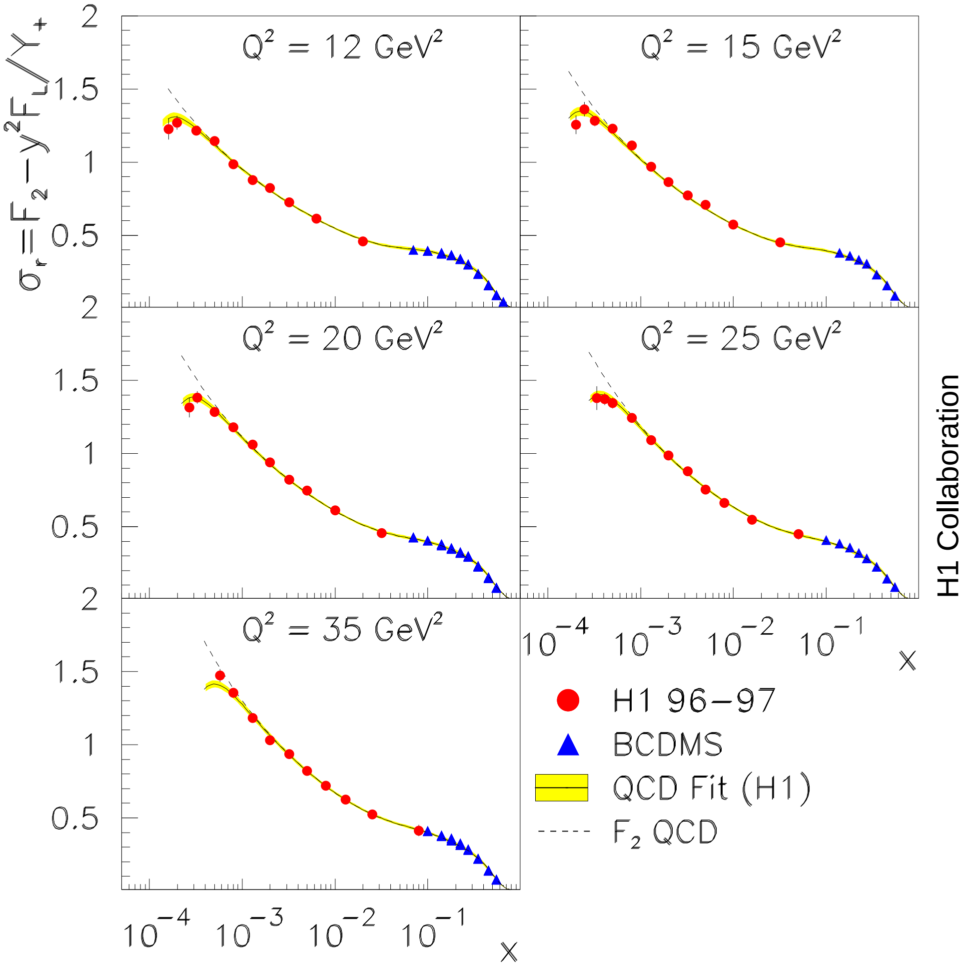
$$+\text{small } F_L \text{ contributions}\Big]$$

$\frac{1}{Q^4}$: propagator

F_2: sum of quark densities

xF_3: valence quark contributions

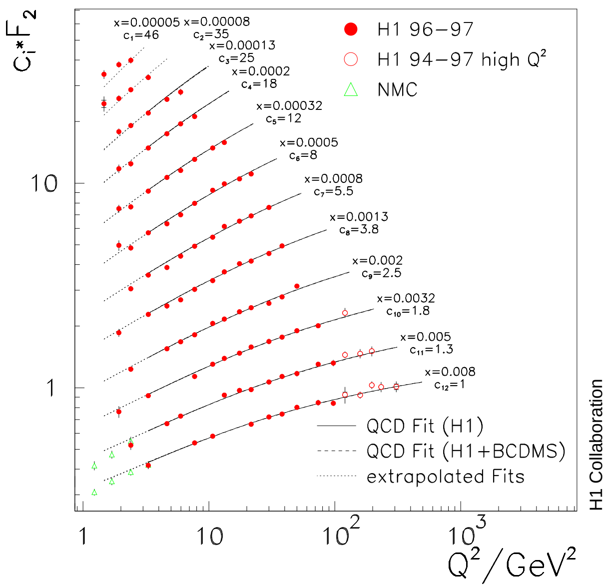
QCD evolution of the structure function



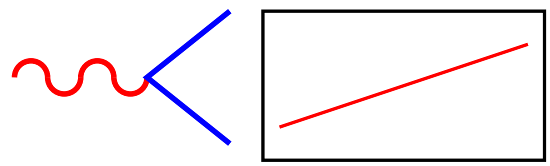
- At a given Q_0 the structure function $F_2(x, Q_0^2)$ is **not predicted** by QCD
  $\rightarrow$ measure it

- Once the function $F_2(x, Q_0^2)$ is known, $F_2(x, Q^2)$ is **predicted** by QCD for $Q^2 > Q_0^2$

NC cross-section and scaling violation

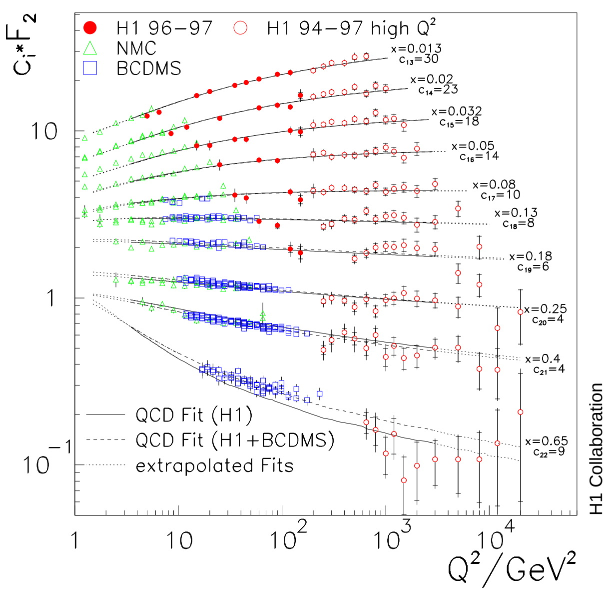


at low x



g enhances q density

F_2 rising with Q^2

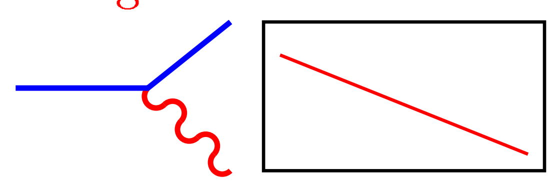


at $x \approx 0.1$

no Q^2 dependence

quark looks like a pointlike object

at high x



g radiation shifts q to low x

F_2 dropping with Q^2

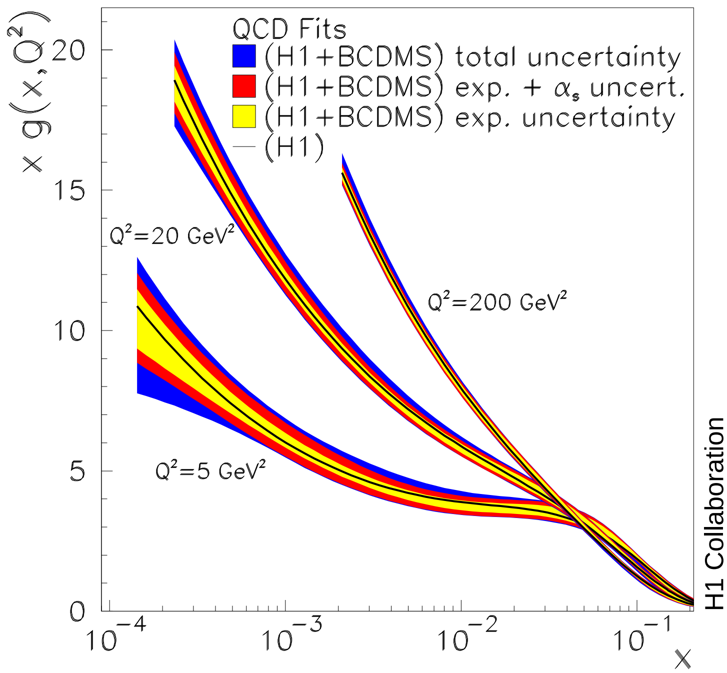
HERA data: high Q^2, low x,

improved precision: 1% stat., 3% syst.

HERA F_2 QCD fits

NLO QCD fit of H1+BCDMS data:

$\rightarrow$ extract gluon-density and α_s

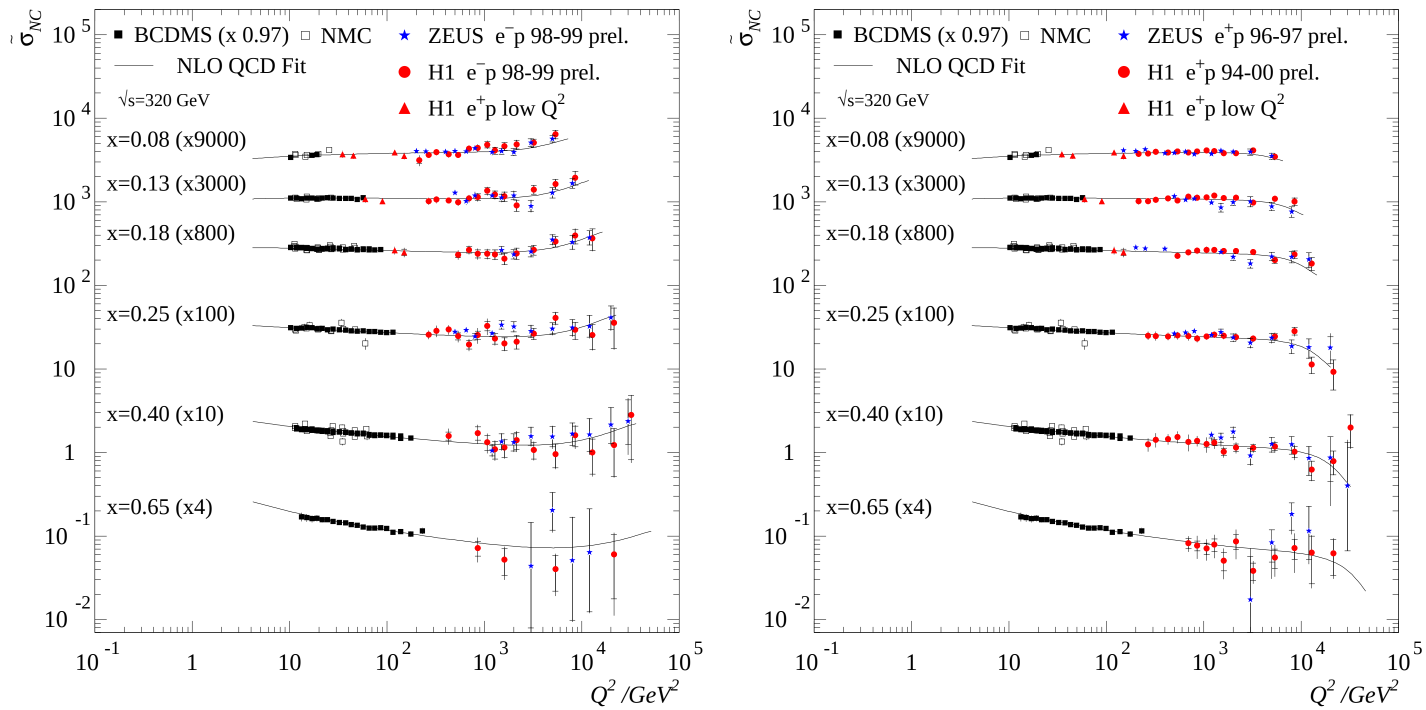


$$\alpha_s = 0.1150 \pm 0.0017(\mathrm{exp}) \;\; ^{+0.0009}_{-0.0005}(\mathrm{model})$$
$$\pm 0.005(\mathrm{scale})$$

World average: $\alpha_s = 0.1184 \pm 0.0031$

With NNLO calculations: expected uncertainties from choice of remormalisation scale $0.002 \ldots 0.003$

High Q^2 NC cross-section for e^+p and e^-p collisions

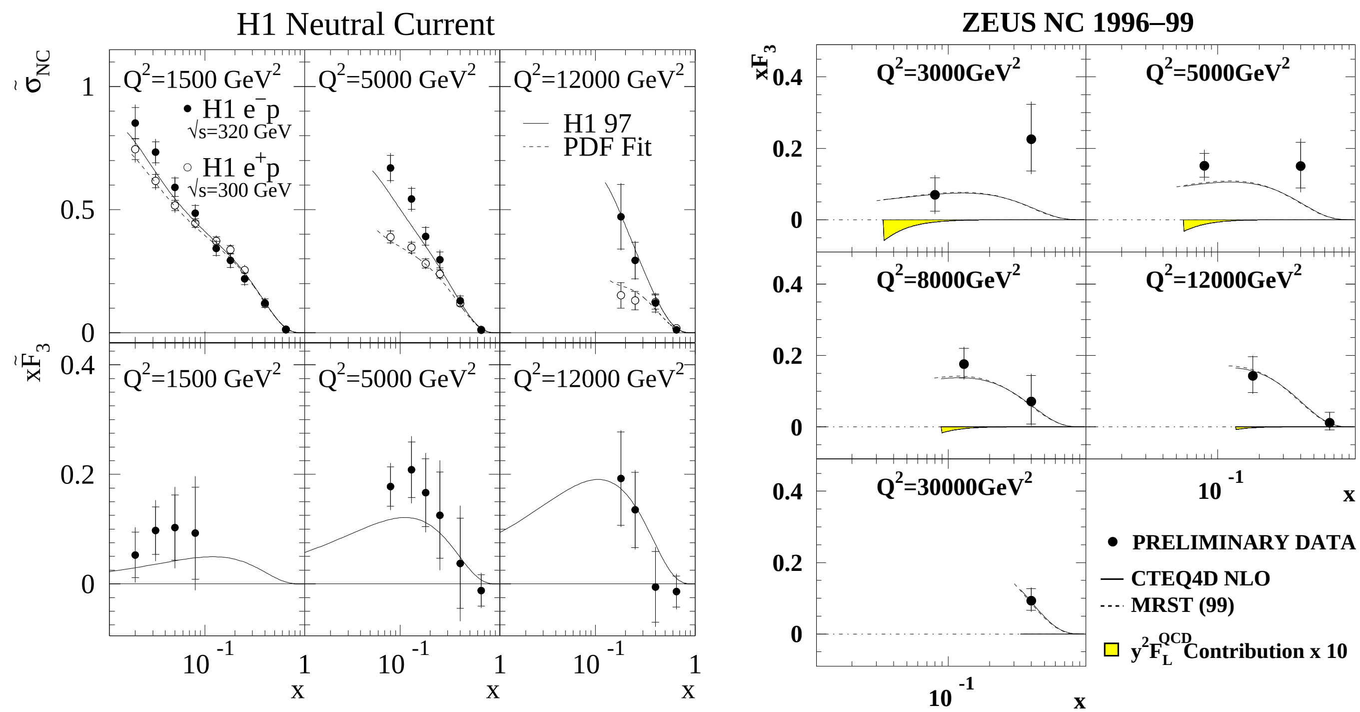


At $Q^2 \approx M_Z^2$: Electroweak effects

Constructive (e^-p) or destructive (e^+p) γZ^0interference

$\rightarrow$ measure $x\tilde{F}_3$ from the difference $\tilde{\sigma}^{\mathrm{NC}}(e^-) - \tilde{\sigma}^{\mathrm{NC}}(e^+)$

Measurement of the structure function $x\tilde{F}_3$



→ Data is in agreement with predictions from QCD fits

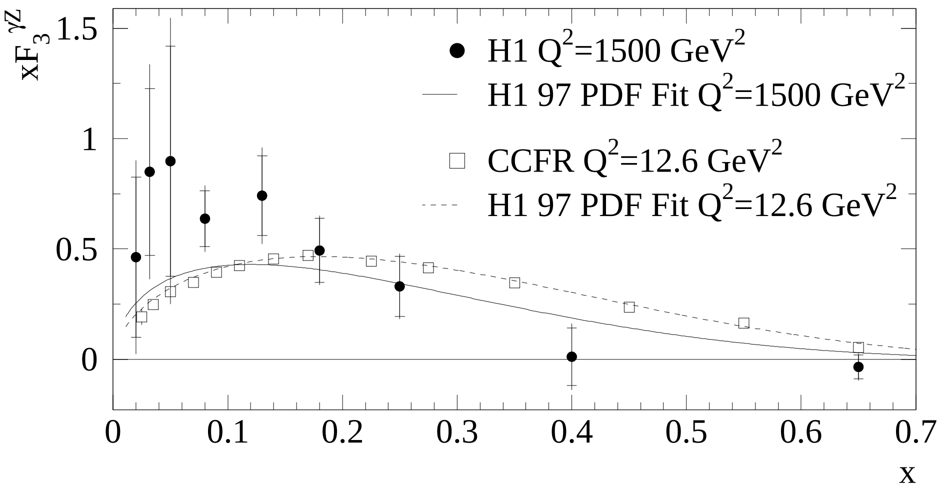
Interpretation of $x\tilde{F}_3$ results

HERA $x\tilde{F}_3$ is dominated by the γZ interference

$$x\tilde{F}_3 \approx xF_3^{\gamma Z} = x \sum_q 2e_q a_q (q - \bar{q}) \approx x(\tfrac{2}{3}u_v + \tfrac{1}{3}d_v)$$

Correction factor applied to νN data

$$\frac{xF_3^{\gamma Z}}{xF_3^{\nu N}}(x, Q^2) = \frac{2}{3}\frac{1+\frac{d_v}{2u_v}}{1+\frac{d_v}{u_v}} \approx \text{const.}$$



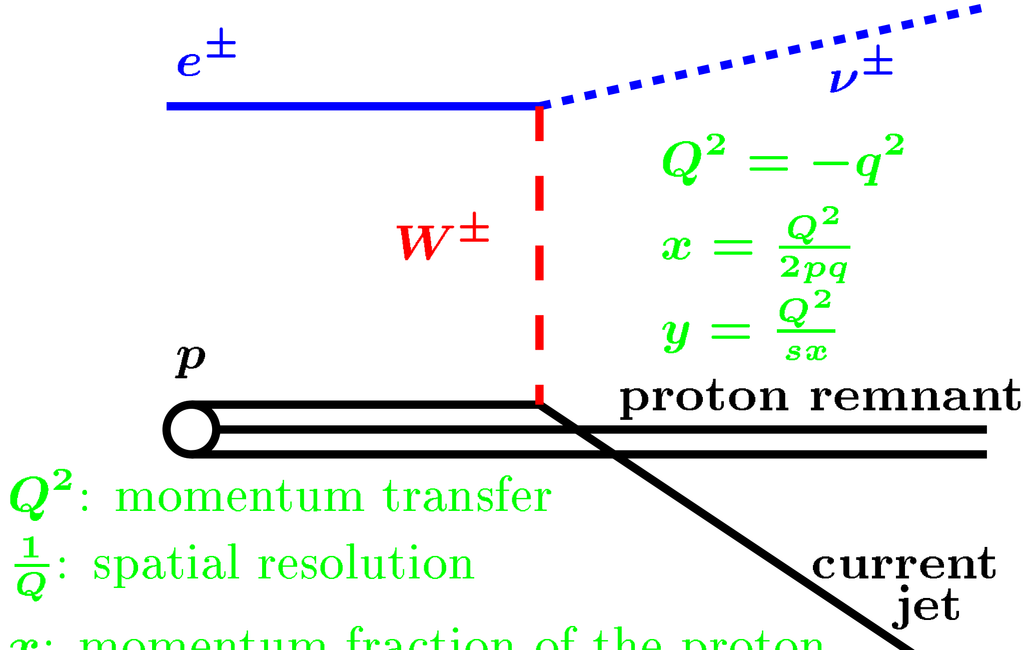
Softer structure function for ep is expected from DGLAP evolution to $Q^2 = 1500\,\text{GeV}^2$

QCD sum-rule: $\int_0^1 F_3^{\gamma Z} dx \approx 2 \times \frac{2}{3} + 1 \times \frac{1}{3}$

Data: $\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.88 \pm 0.35(\text{stat}) \pm 0.27(\text{sys})$

Expected: $\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.1$

Charged Current DIS ($W^\pm$ exchange)



Q^2: momentum transfer

$\frac{1}{Q}$: spatial resolution

x: momentum fraction of the proton carried by the struck quark

Cross-section in leading order

$$\sigma_{CC}^{e^+} \propto \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\left[\sum x\bar{u}_i + (1-y)^2 \sum x d_i\right]$$

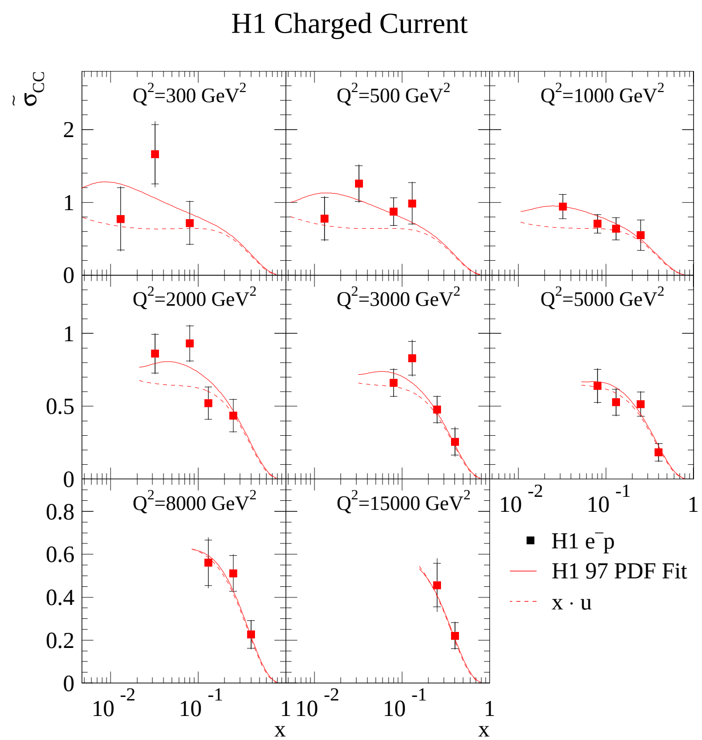
$$\sigma_{CC}^{e^-} \propto \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\left[\sum x u_i + (1-y)^2 \sum x \bar{d}_i\right]$$

e^+p at large x: mainly d valence quarks

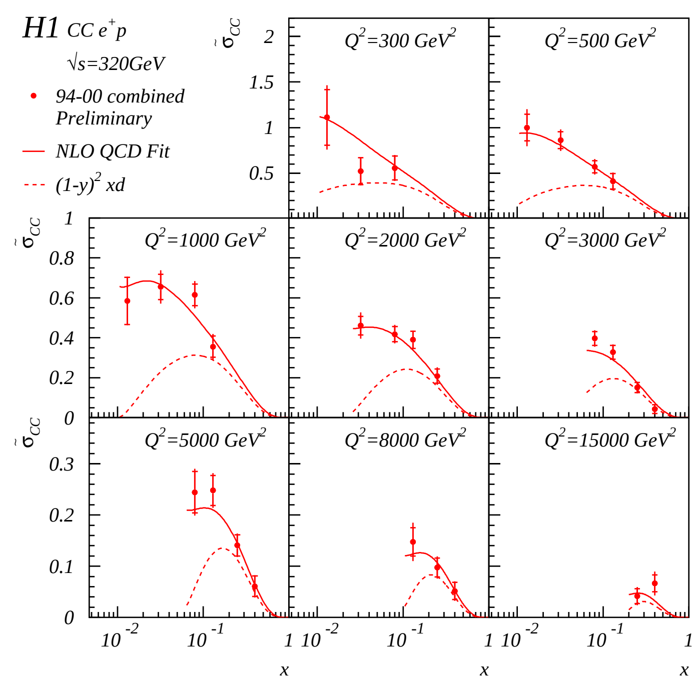
e^-p at large x: mainly u valence quarks

Charged current cross-section

$e^- p$ data



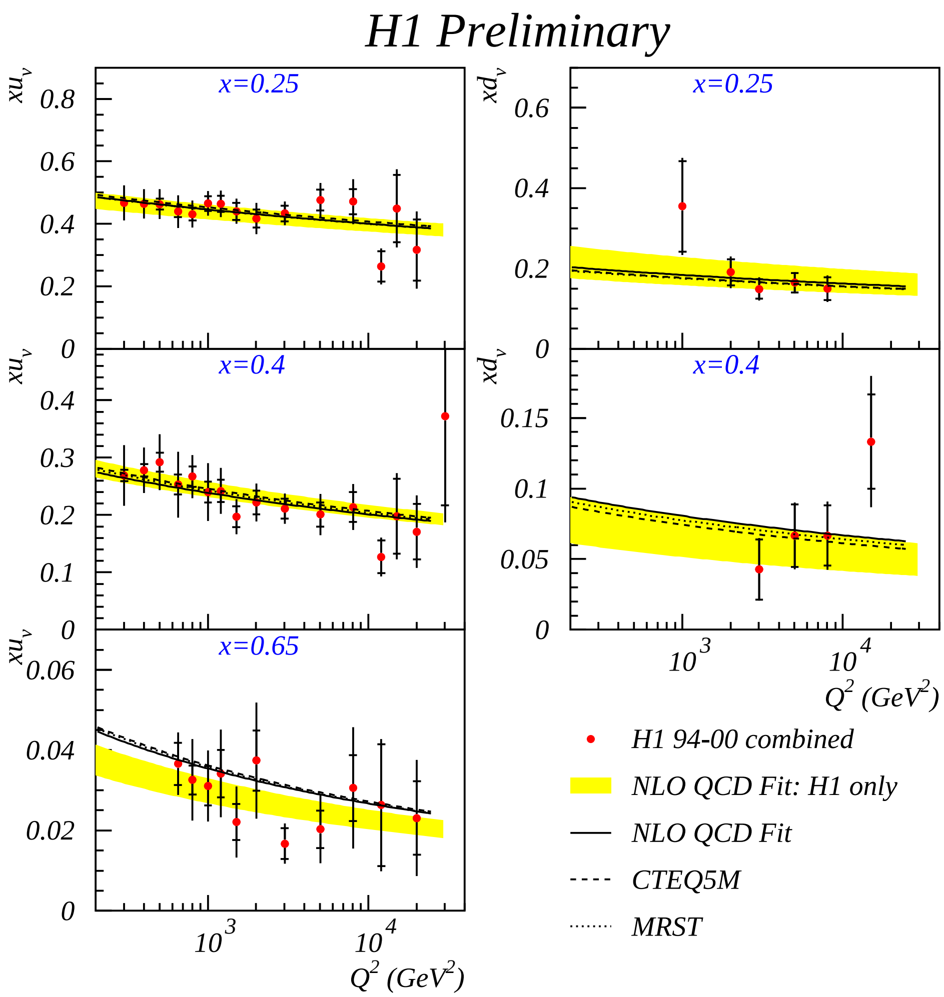
$e^+ p$ data



$\rightarrow$ Measure the valence-quark densities xu_{v} and xd_{v} at high Q^2

Valence quark distributions at high Q^2

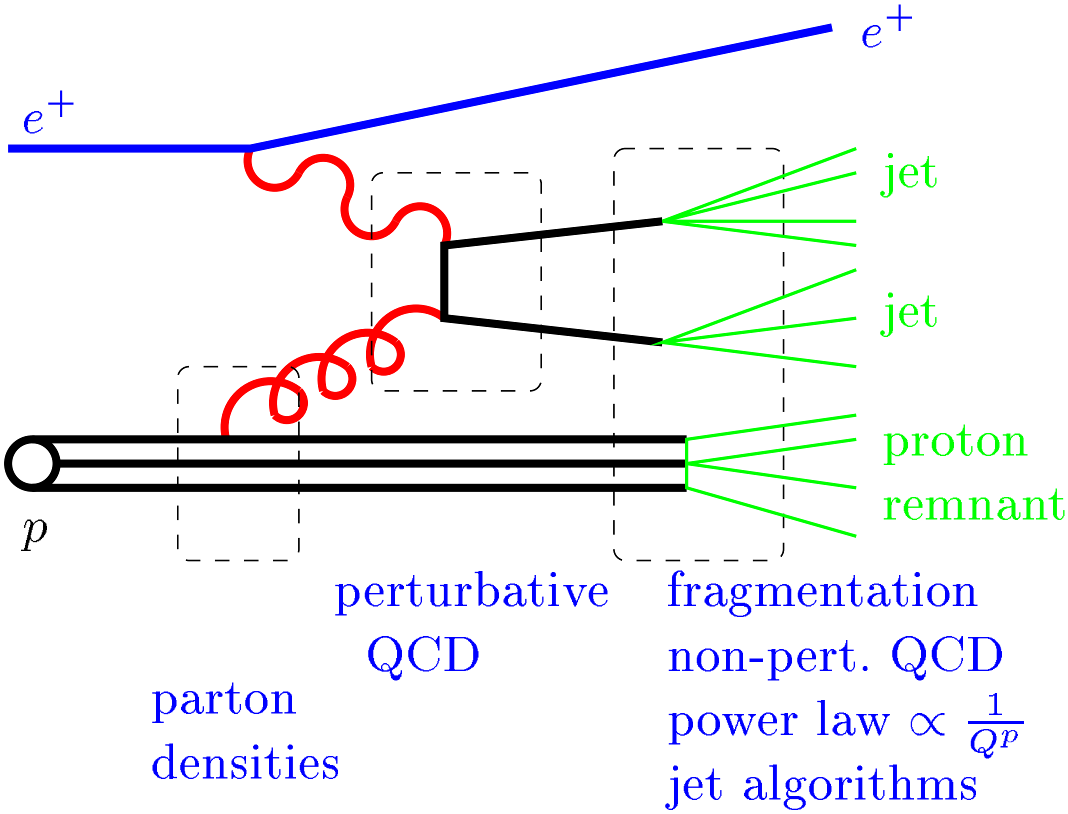
extracted from e^+p and e^-p NC and CC data



Direct determination of the valence quark densities is in agreement with NLO QCD fit results.

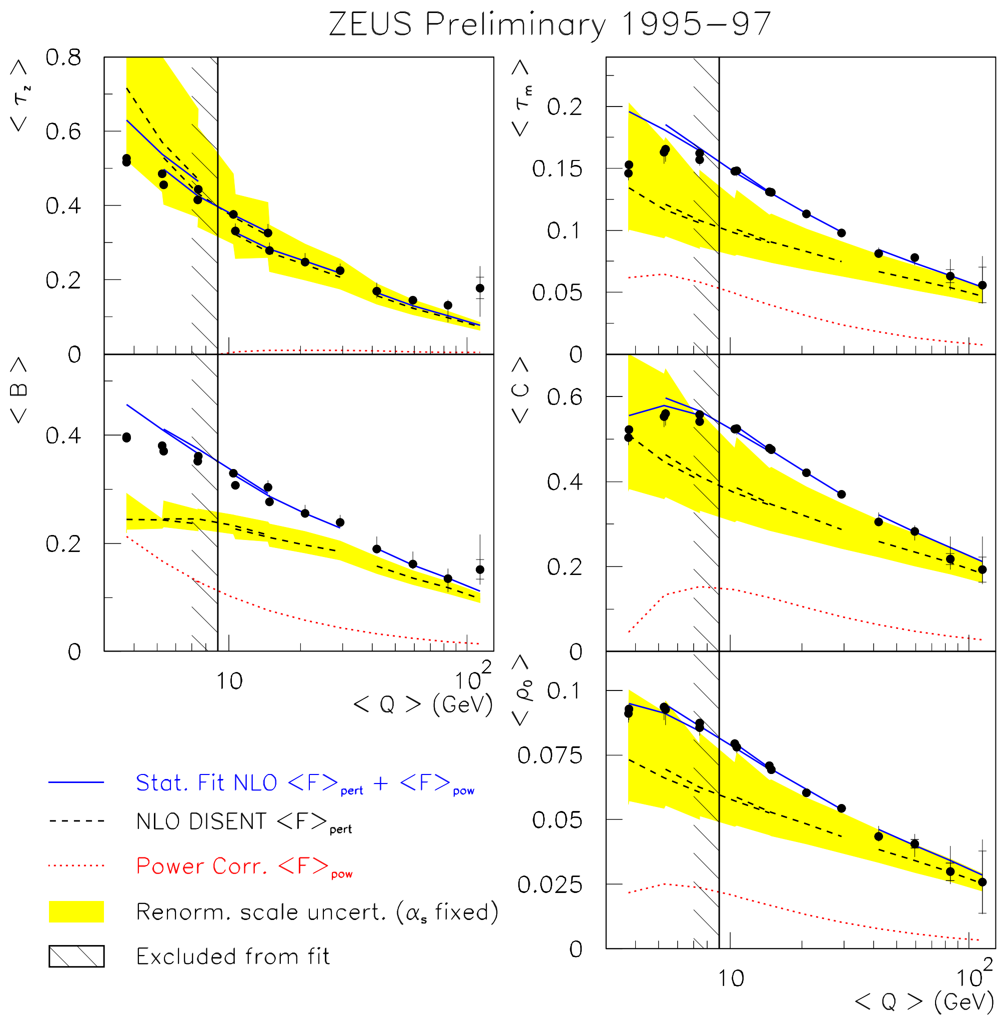
Exclusive measurements

Derive QCD results from the hadronic final state



- look at event shape variables (thrust, ...)
  describe the data by NLO QCD plus power law corrections
- look at jets
  compare the data to NLO fits

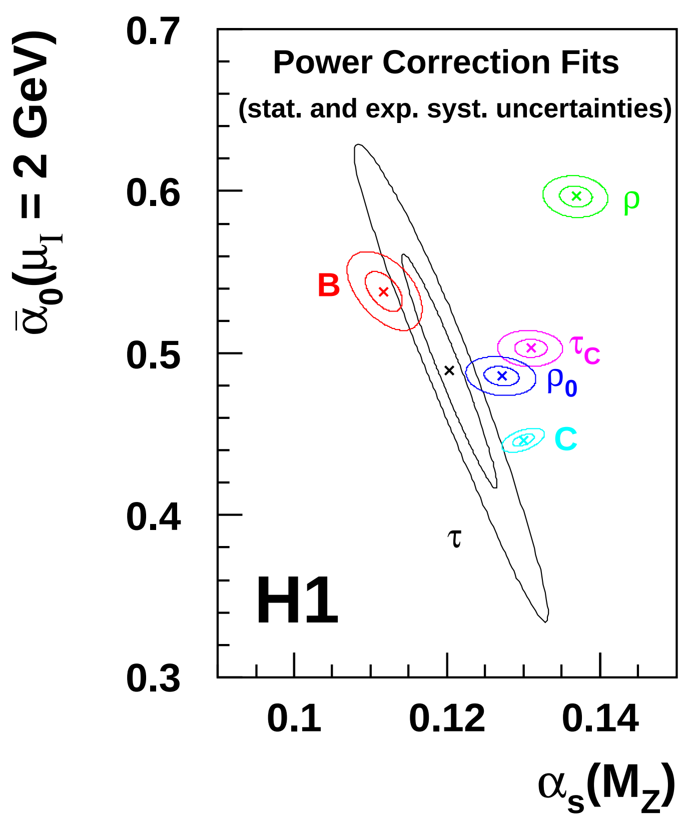
Event shapes measured in DIS



Mean of event shape variables as a function of Q^2 (Thrust, jet broadening, jet mass, ...)

→ The data are consistent with a fit to NLO calculation + power corrections

Event shape fit results



Fit with two free parameters:
α_s and non-pert. parameter $\bar{\alpha}_0$

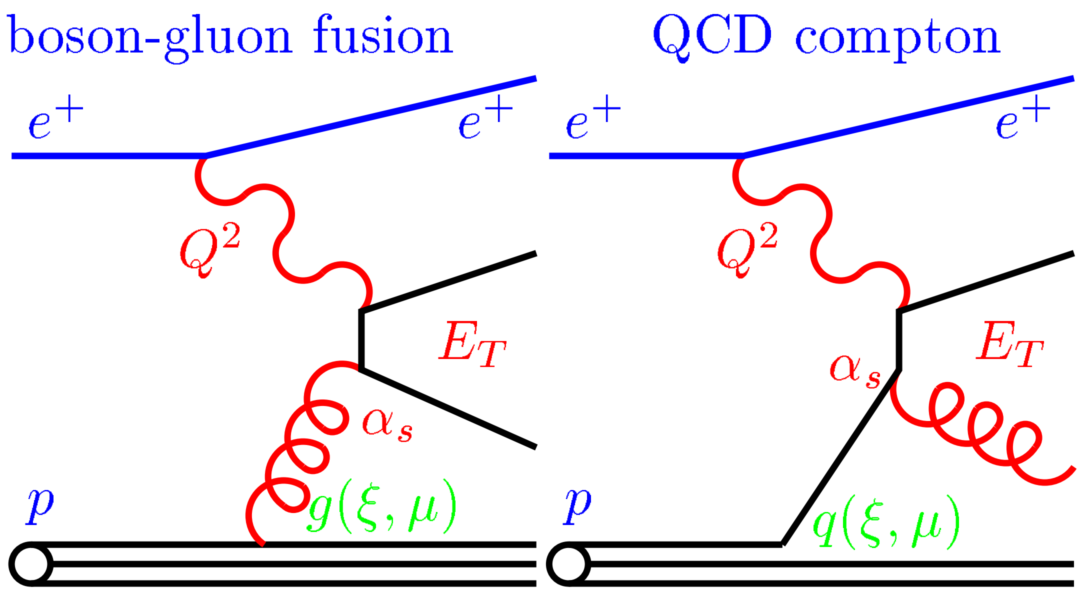
Expect the same fit results for all event shapes

Results: $\bar{\alpha}_0(\mu_I = 2\,\mathrm{GeV}) \approx 0.5 \pm 0.1$
comparable to e^+e^- results

α_s compatible with world average

Note: theoretical uncertainties are not shown

Probing QCD with jets in DIS



→ Extract α_s and the gluon density

N.B.: $\mathcal{O}(\alpha_s^2)$ calculations are used in the fit

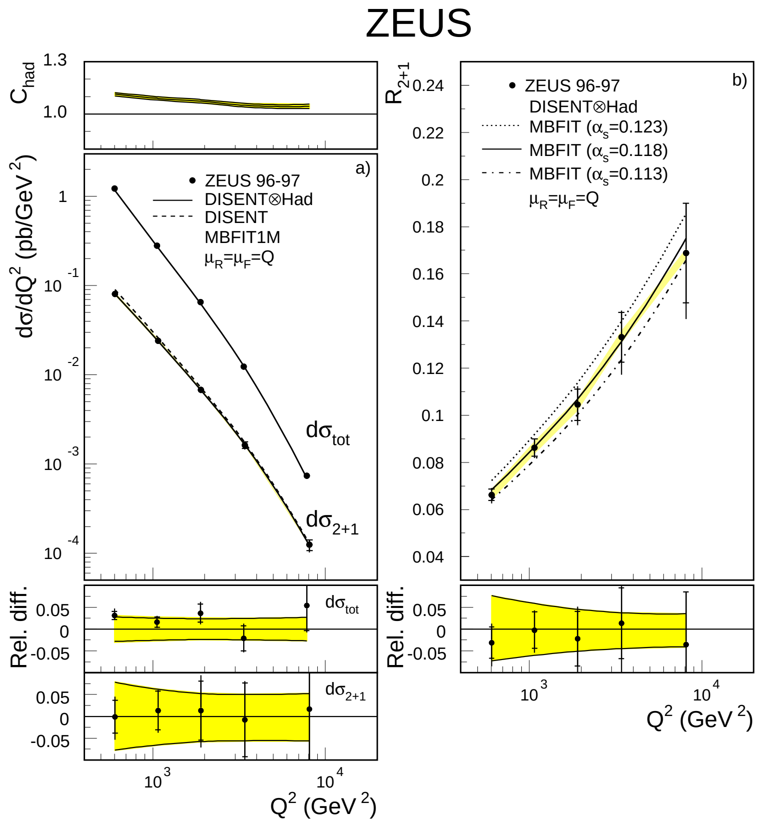
Two hard scales:

- Momentum transfer Q^2
- Transverse momentum E_T in the jet-jet system

Dijet cross section as a function of Q^2

define jets with transverse energies (Breit-frame)

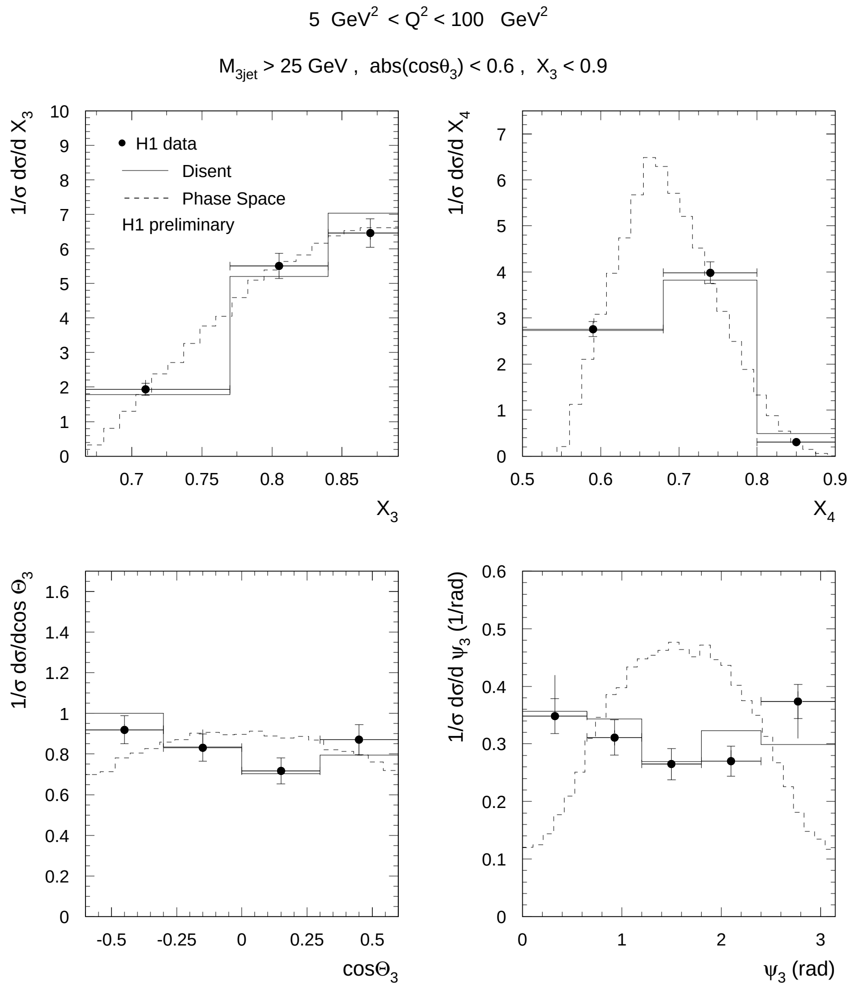
$E_{T,1} > 8\,\mathrm{GeV}$, $E_{T,2} > 5\,\mathrm{GeV}$



- two-jet rates are described well by NLO fits
- differential jet rate increases with Q^2
- high precision over four orders of magnitude

What about three jets?

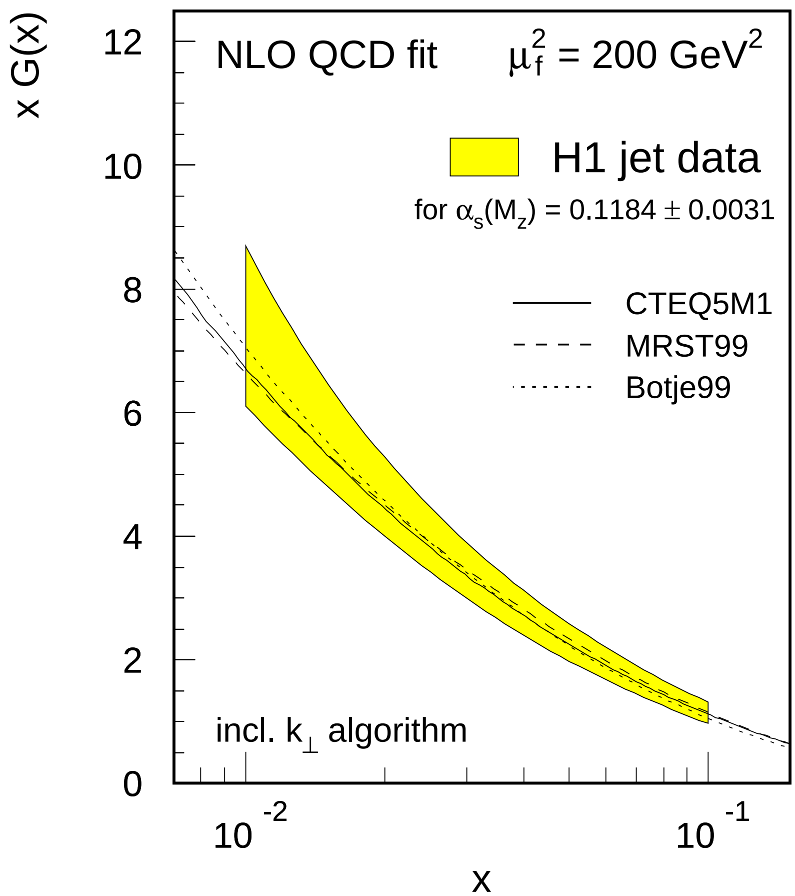
Check matrix elements of three-jet LO calculations (Dalitz variables, jet-jet angles, . . .)



- pure phase-space model is excluded
- consistent with pQCD expectations

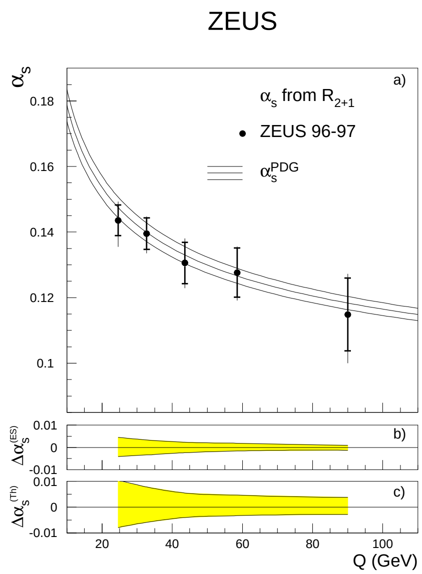
Fit the gluon-density from dijet data

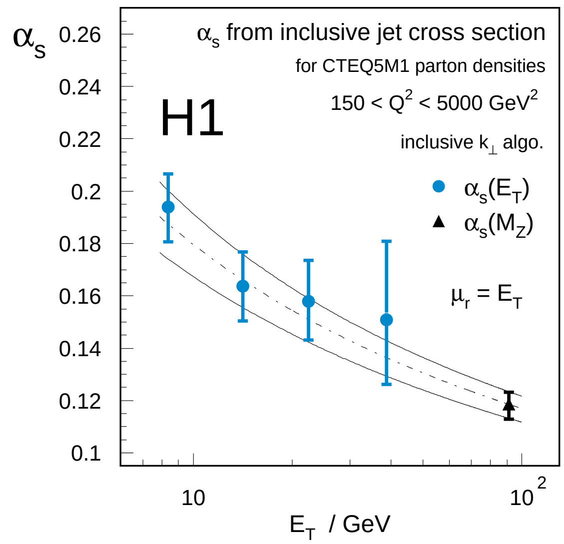
By the boson-gluon fusion process the dijet rates are sensitive to the gluon-content of the proton



→ excellent agreement with results from global fits to inclusive data (F_2)

Determination of α_s





determine α_s as a function of the scale μ

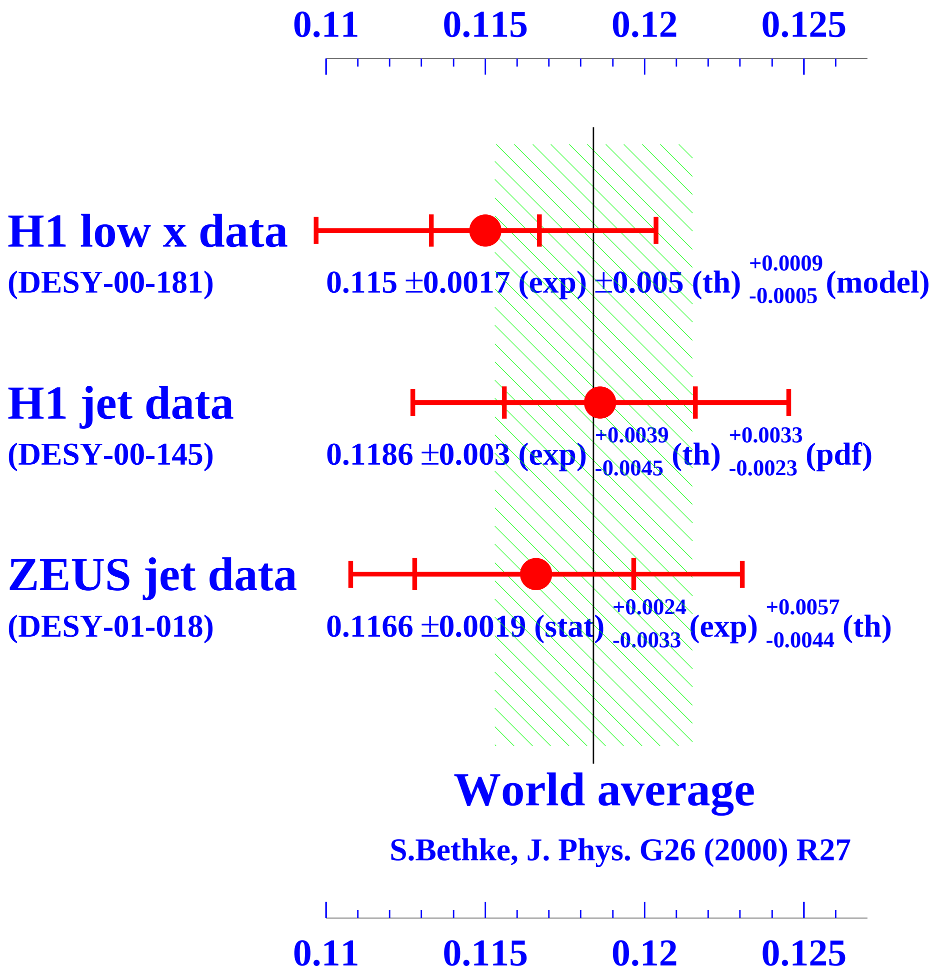
$\rightarrow$ observe the running of $\alpha_s(\mu)$ in a single experiment.

ZEUS: use Q^2 as renormalization scale

H1: use E_T as normalization scale

Consistent results!

Recent α_s measurements at HERA



→ Consistent picture of α_s measurements from HERA.

Summary and outlook

- Inclusive cross-sections
  probe QCD at very small distances (high Q^2)
  and at very low x (gluons in the proton)
  measure gluon density and α_s
- Compare e^+p and e^-p
  measure structure function xF_3 at high Q^2
  $\rightarrow$ new connection to νN data
- Combining NC and CC data of both polarities
  $\rightarrow$ valence-quark densities of the proton
- Access pQCD at HERA using jets
  $\rightarrow$ independent determination of α_s and the gluon density

HERA upgrade (new data by the end of the year)

- expect luminosity increase $\times 5$
  $\rightarrow$ improve statistically limited analyzes
- polarized lepton beam
  $\rightarrow$ electroweak physics