

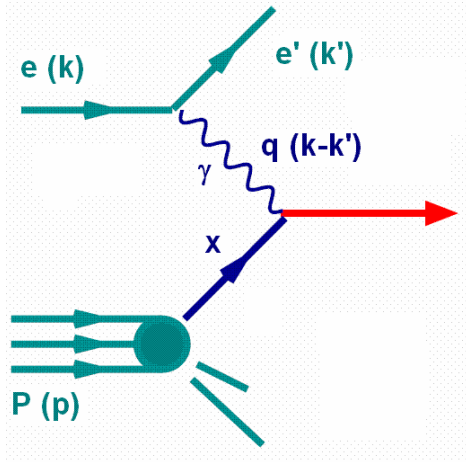
Parton densities in the proton and α_s at HERA

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Outline of the talk:

- Basic concepts
- Parton densities and structure functions
- Pdf's at high x
- Polarization measurements
- F_3
- Determination of α_s
 - combined fits
 - inclusive jets
 - multijets
 - jet radius
- Summary

Deep Inelastic Scattering



$Q^2 = -q^2$: the resolution power of the photon
 $x = Q^2/(2p \cdot q)$: the Bjorken scaling variable (the momentum fraction of the scattered parton in QPM events)
 $y = (p \cdot q)/(p \cdot k)$: the inelasticity (the E_γ/E_e fraction transferred by the photon in the proton rest frame)
 $s = (p+k)^2$: total c.m. energy squared
 $Q^2 = s \cdot x \cdot y$

The cross section may be factorized:

$$\sigma = \left[\sum_{i=g,q,\bar{q}} \int dx f_i(x, \mu_f, \underline{\alpha}_s(\mu_f)) \hat{\sigma}_{\text{pQCD}}(x, \mu_f, \mu_r, \underline{\alpha}_s(\mu_r)) \right] (1 + \delta_{\text{had}})$$

$\hat{\sigma}_{\text{pQCD}}(x, \mu_f, \mu_r, \underline{\alpha}_s(\mu_r))$: the hard scattering cross section (analytically calculable)

$f_i(x, \mu_f, \underline{\alpha}_s(\mu_f))$: the parton density function (determined experimentally)

$(1 + \delta_{\text{had}})$: hadronization corrections (estimated from MC calculations)

μ_f : the factorization scale (scale used for the parton evolution)

μ_r : the renormalization scale (scale used for the expansion of α_s)

Experimental measurement

From experimental measurements of cross sections the structure functions of the proton can be extracted:

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[\left(1 + (1-y)^2\right) \tilde{F}_2(x, Q^2) - \frac{y^2}{2} \tilde{F}_L(x, Q^2) \mp \left(y - \frac{y^2}{2}\right) x\tilde{F}_3(x, Q^2) \right]$$

The structure functions are related to the parton densities:

$$F_2 = \frac{Q^2}{4\pi\alpha^2} (\sigma_L + \sigma_R) = x \sum e_q^2 (q + \bar{q})$$

is probing the quark content of the proton

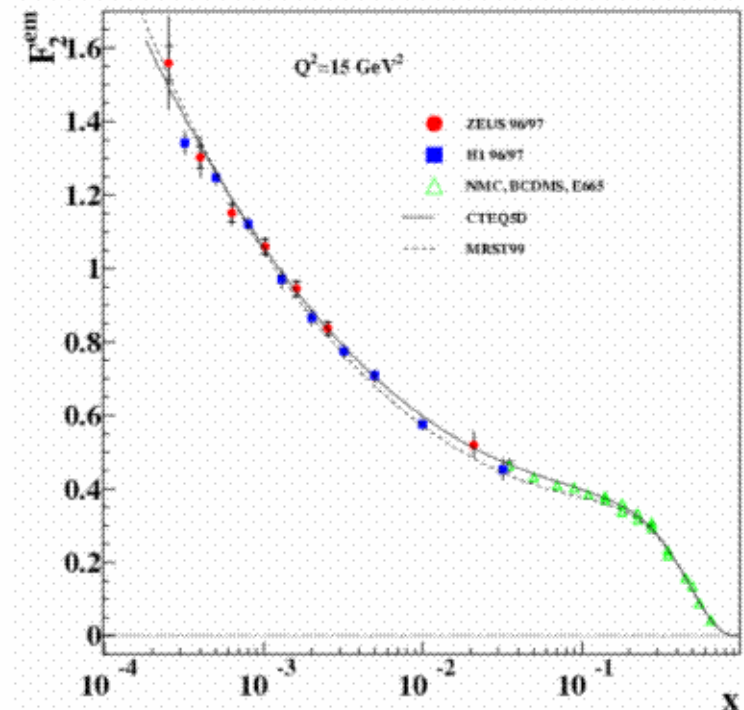
$$F_L = \frac{Q^2}{4\pi\alpha^2} \sigma_L \propto xg \quad (\text{longitudinally polarized photons})$$

is probing the gluon content of the proton

$x\tilde{F}_3(x, Q^2)$ gives the γZ interference, important at high Q^2

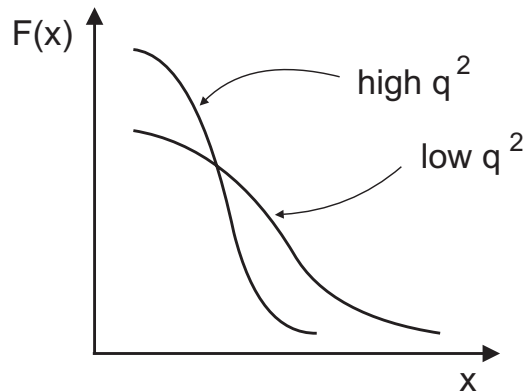
F_2 is dominating in most of the kinematic region covered by HERA. $F_L/F_2 \sim 0.2$ at high y .

A structure function gives the probability to find a parton carrying a fraction x of the proton momentum if the proton is probed at some scale (e.g. Q^2)



Scaling violation

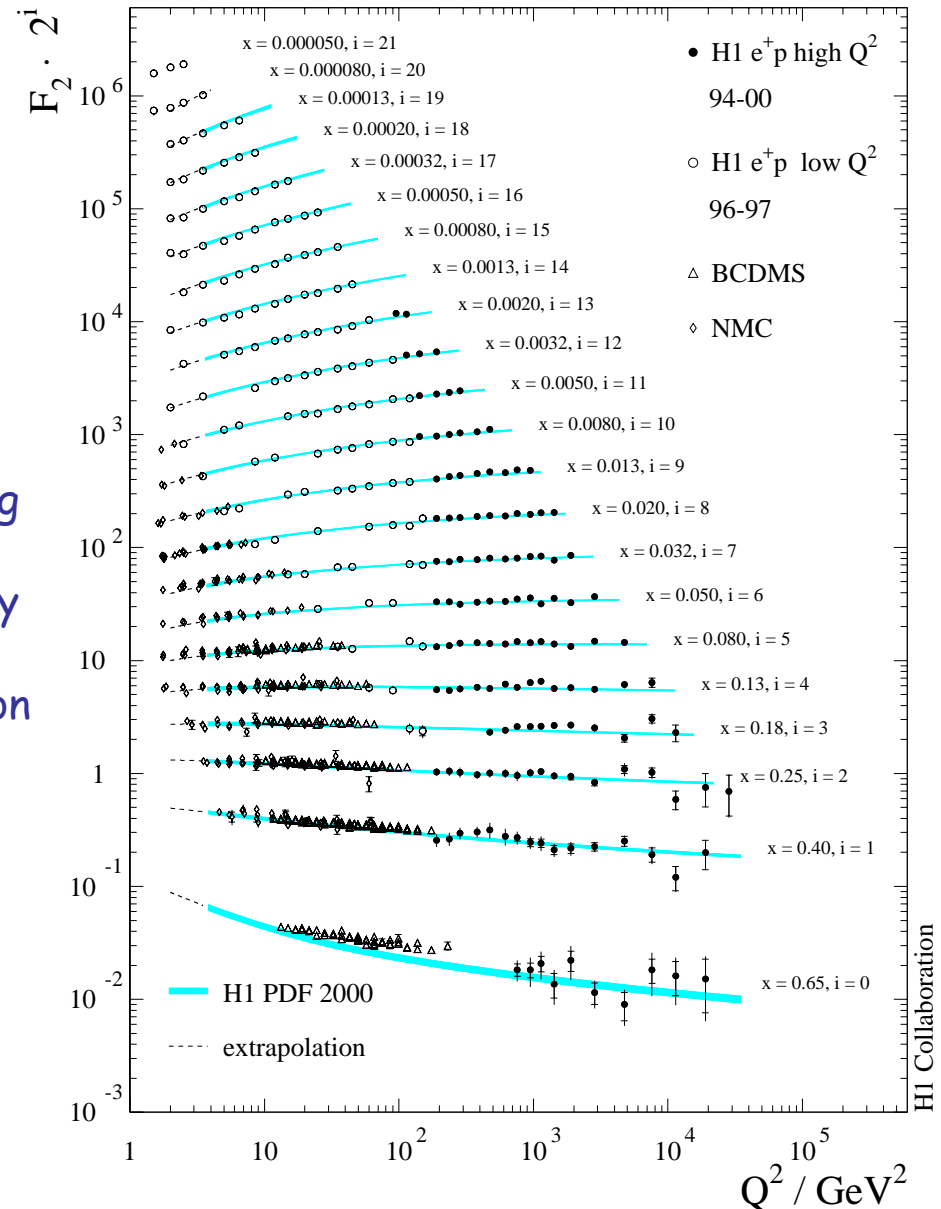
For scattering against point-like quarks, **scaling** is expected i.e. F_2 should not depend on the scale e.g. Q^2 . However, clear experimental evidence for **scaling violation** is observed. This effect is related to the resolution of the probe (the photon).



$$\Rightarrow dF_2/d\ln Q^2 \sim \alpha_s x g$$

\Rightarrow The gluon density can be determined from scaling violation

The pdfs are determined through global fits to various experimental data, at a smallest scale, Q_0^2 , at which perturbative calculations are still expected to be valid. The DGLAP evolution can be used to define the pdf at an arbitrary Q^2 .

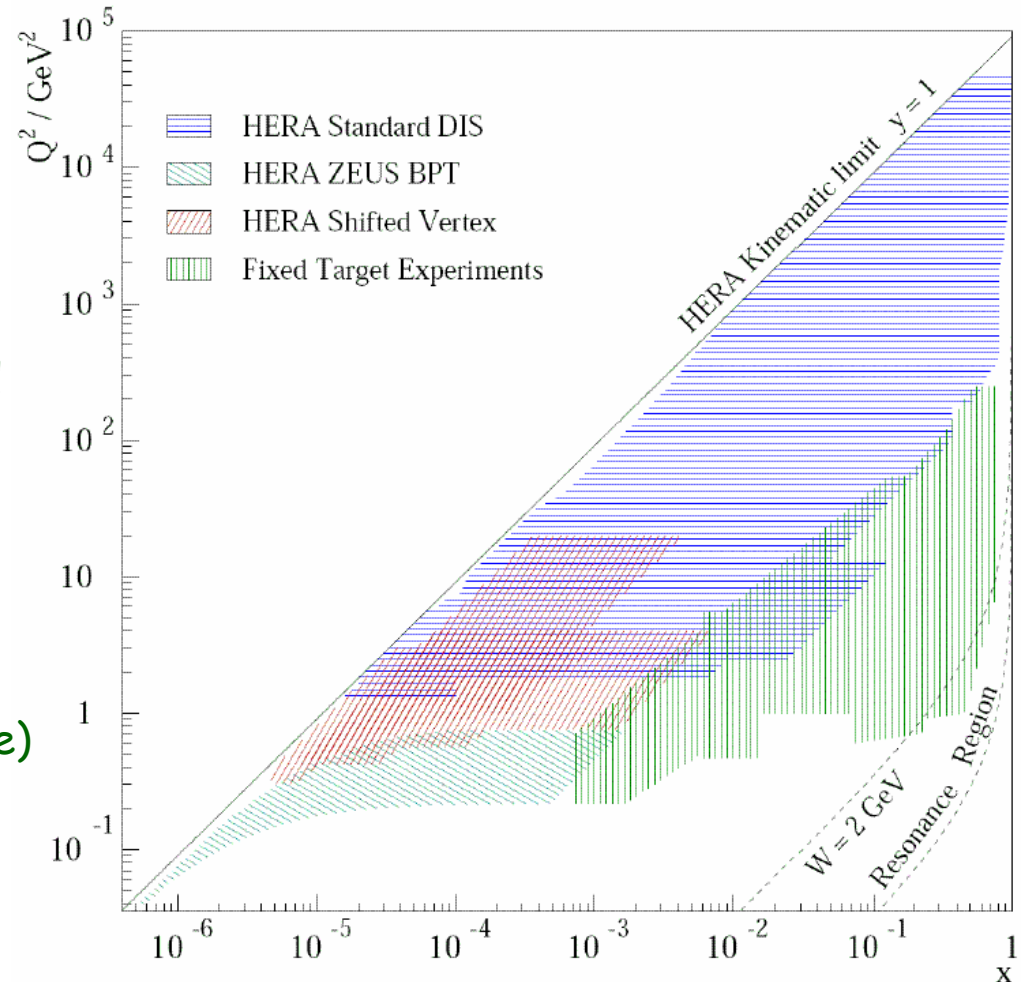


Kinematic range

HERA has measured the proton structure over a large kinematic range covering almost 5 orders of magnitude in x_{Bj} and Q^2 .

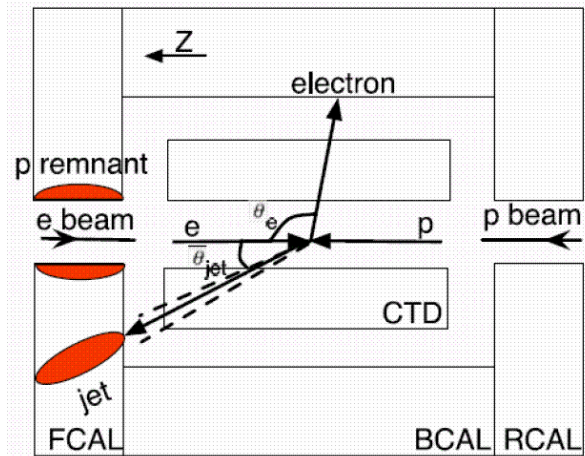
- Access to the low Q^2 region is obtained through:
 - collisions at shifted vertex position
 - lower electron beam energies
 - radiative events.
- Low Q^2 and $x_{Bj} \Rightarrow$ large $y \Rightarrow F_L$ can be determined
- Data exist since 2001 (not covered here)

Recent results in the large x region

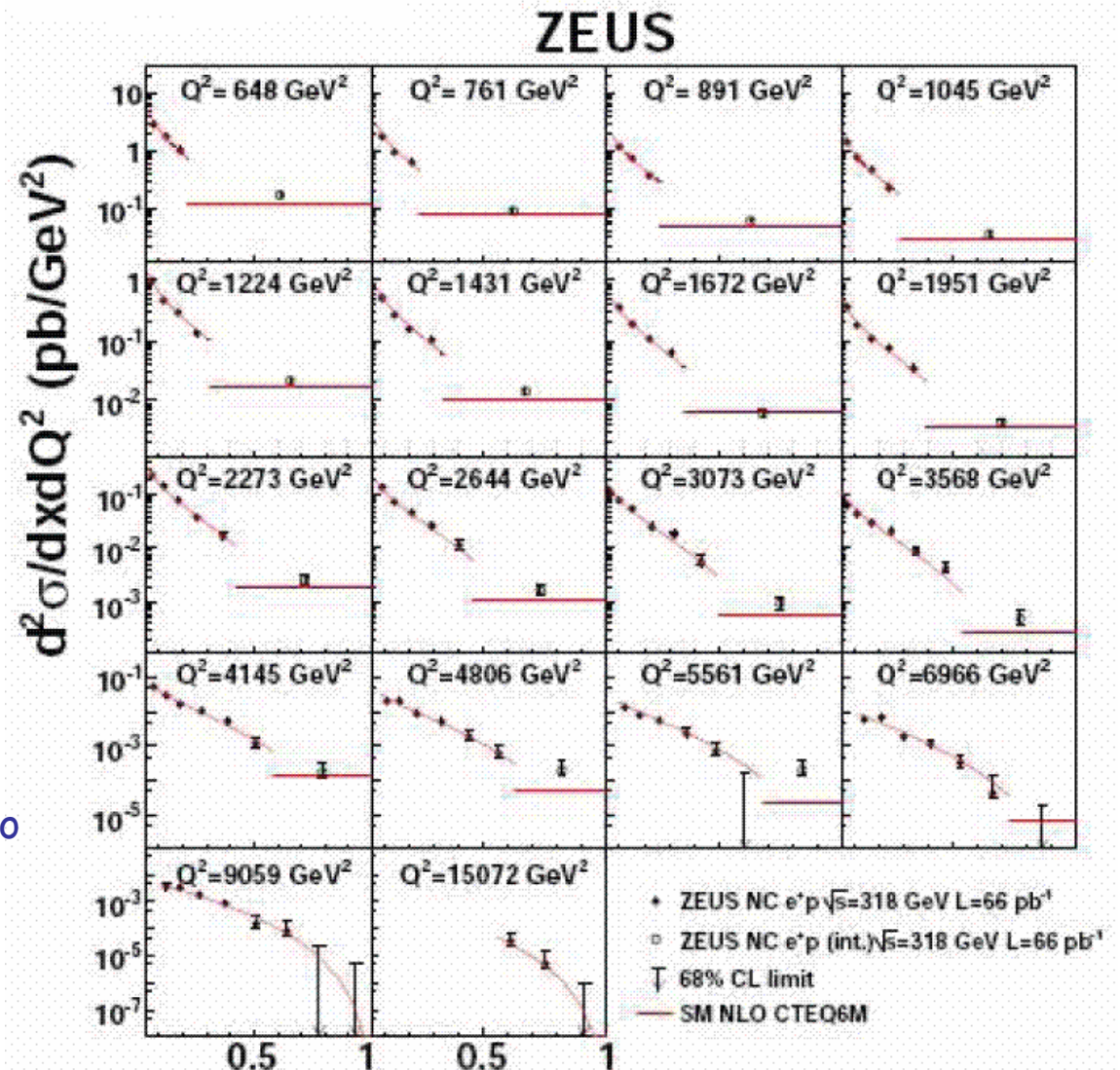


Pdf's at high x

The experimental challenge: the scattered quark proceeds close to the beam pipe



- The scattered electron was used to reconstruct Q^2
- The energy and angle of the jet used to calculate x
- In case of no reconstructed jet $\Rightarrow x_{edge} < x < 1$



Generally good agreement with NLO calculations
Data tend to be slightly high in the highest x -bins

Measurements with polarized e-beams

F_2 and F_3 contain terms, on γZ interference and Z exchange, which depend on the e-beam polarization

$$\begin{aligned}\tilde{F}_2 &= F_2 + k(-v_e \mp Pa_e)x F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm P v_e a_e)x F_2^Z \\ x\tilde{F}_3 &= k(-a_e \mp P v_e)x F_3^{\gamma Z} + k^2(2v_e a_e \pm P(v_e^2 + a_e^2))x F_3^Z\end{aligned}$$

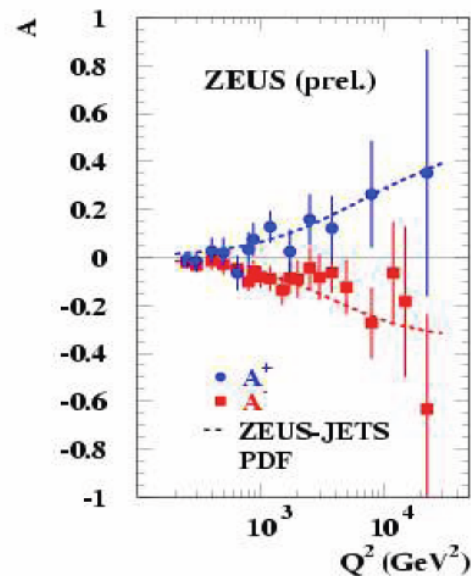
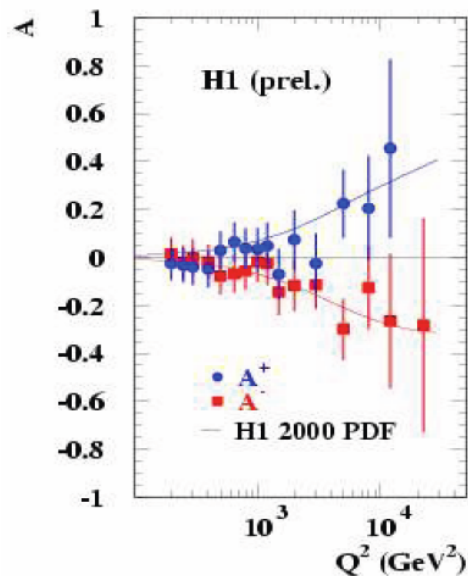
where the P-terms wontain the parity violation

Measure the cross section asymmetry for left- and right handed $e^\pm p$ scattering

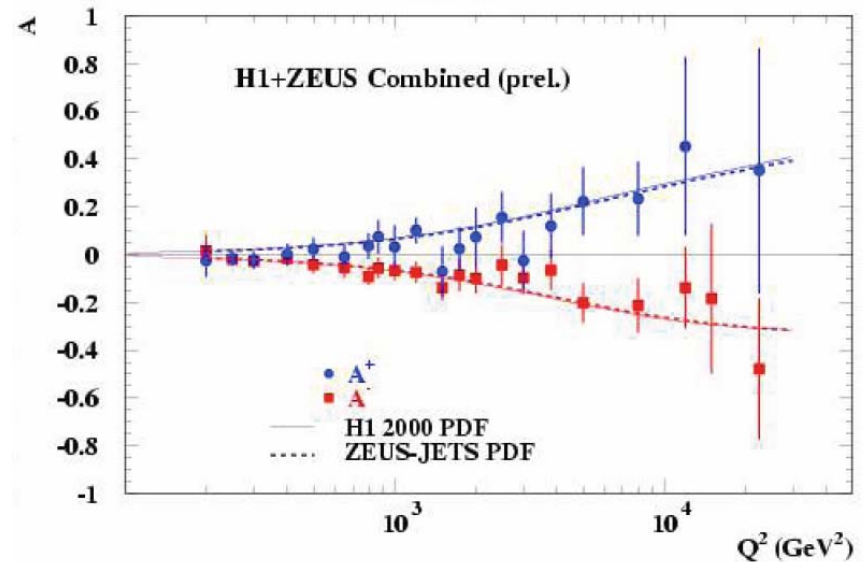
$$A^\pm = \frac{2}{P_R - P_L} \cdot \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)}$$

A^+ and A^- of opposite signs; $dA = A^+ - A^- \approx 0$ for low Q^2 ; and $\neq 0$ for high Q^2

HERA

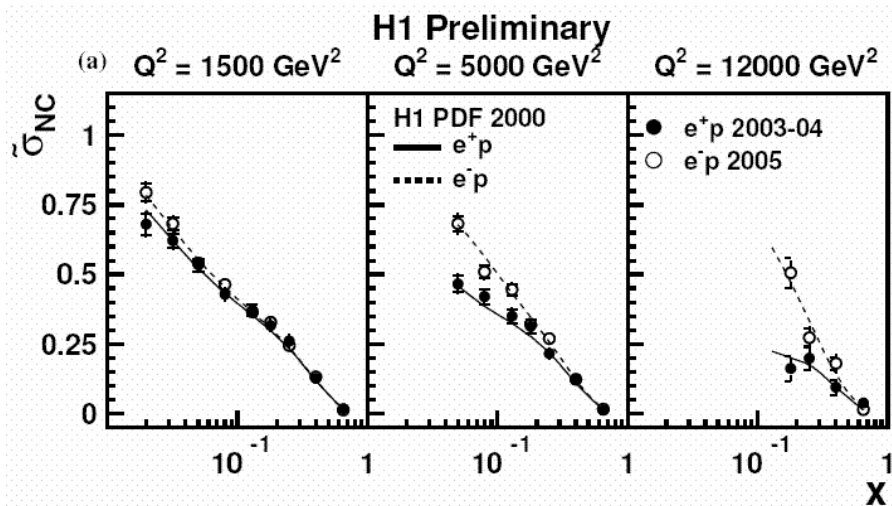


HERA



F_3

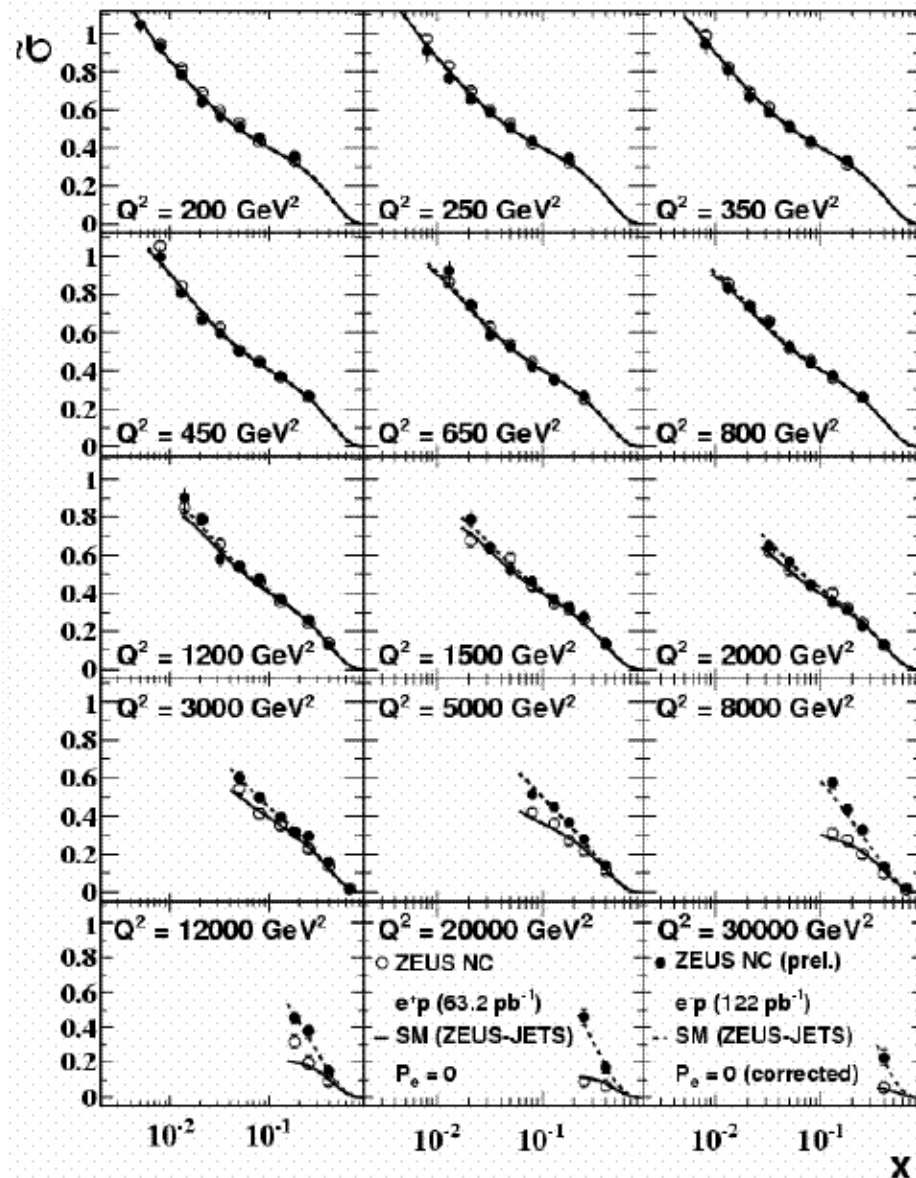
At high Q^2 the NC cross sections for e^+p and e^-p scattering are different
Results on measured cross sections and on the structure function $x F_3$ have been compared to SM predictions



Results:

Data from the two experiments are consistent and in good agreement with SM predictions

ZEUS



F₃

- xF_3 is extracted from the unpolarized reduced cross section

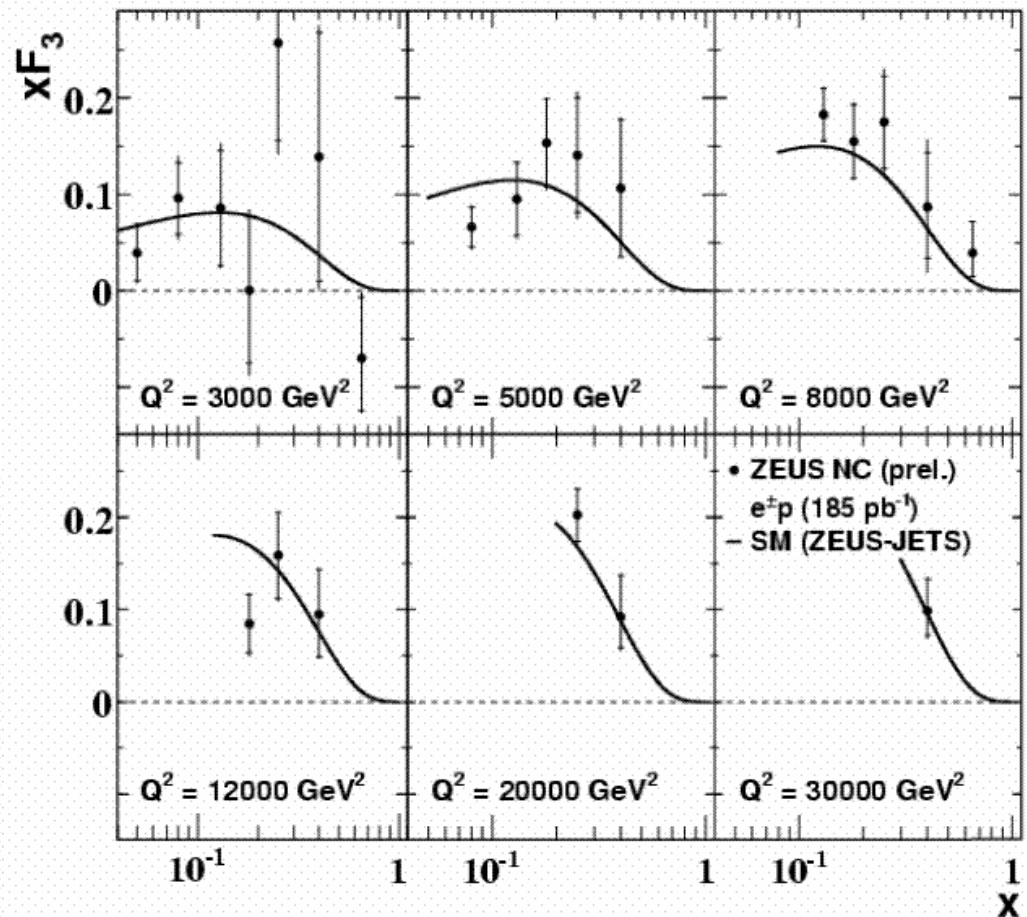
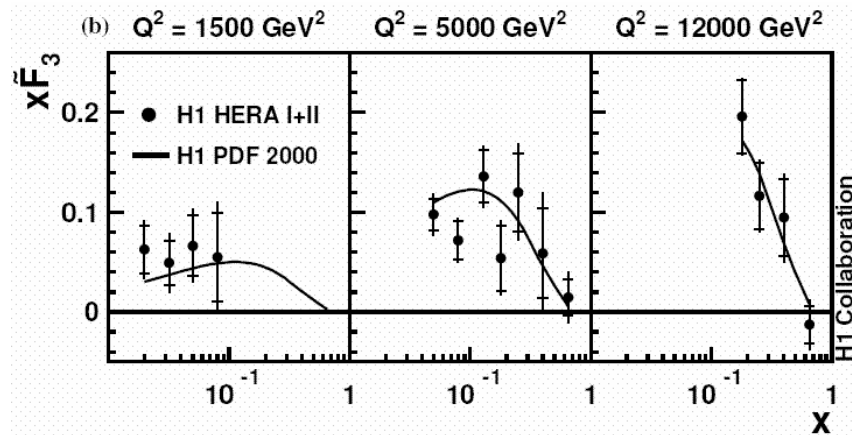
$$\tilde{\sigma}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2} \frac{1}{Y_+} \frac{d^2\sigma(e^\pm p)}{dx dQ^2} = F_2(x, Q^2) \mp \frac{Y_-}{Y_+} xF_3(x, Q^2) \quad \text{where} \quad Y_\pm \equiv 1 \pm (1-y)^2$$

$$xF_3(x, Q^2) = \frac{Y_+}{2Y_-} (\tilde{\sigma}^{e^- p} - \tilde{\sigma}^{e^+ p})$$

- F_3 is dominated by the γZ interference
- It measures the difference in the quark and antiquark momentum distribution

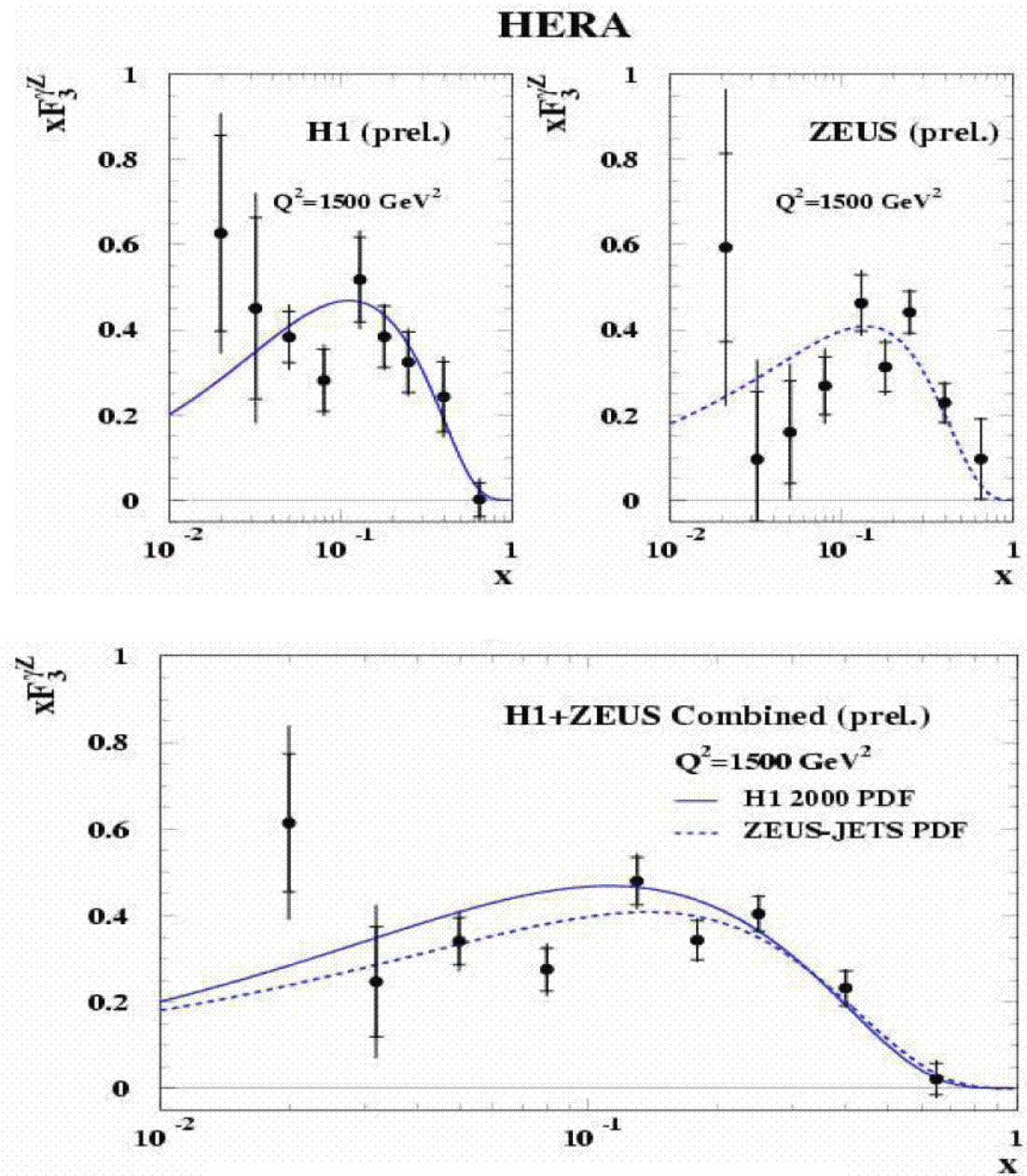
$$xF_3^{\gamma Z} = 2x \sum_q (e_q a_q)(q - \bar{q}) = 2x(2u_v + d_v)$$

Data comprise in total 478.8 pb⁻¹ from the HERA II running



F_3

- Due to the weak dependence of F_3 on Q^2 data has been:
- transformed into one Q^2 value of 1500 GeV^2
 - combined for the two experiments

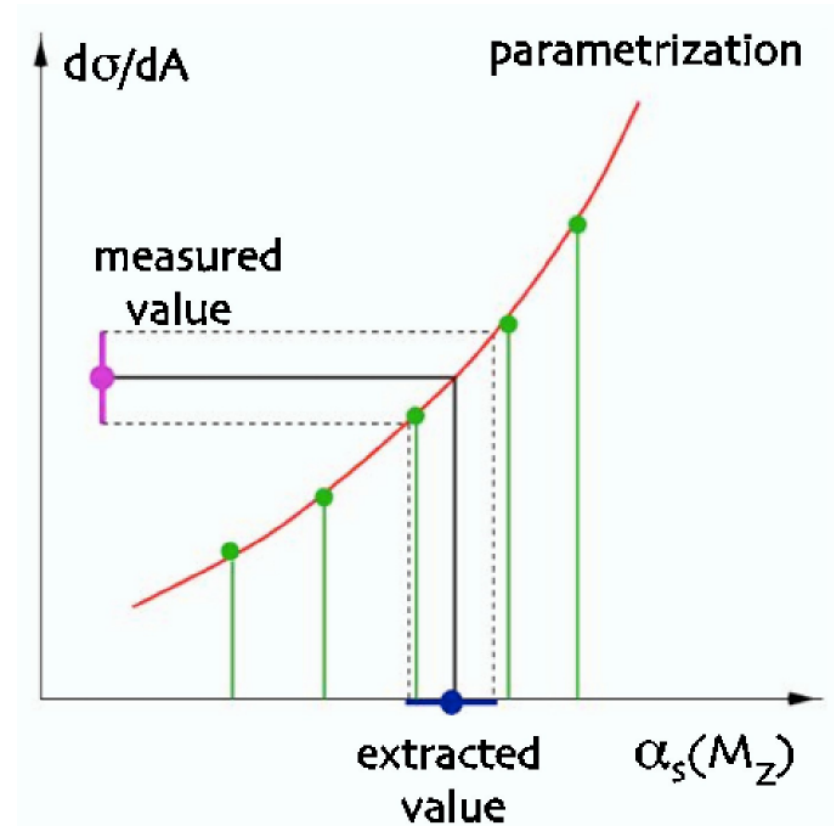


Determination of α_s

- Use various parametrization of the proton pdf's to perform NLO calculations for different values of $\alpha_s(M_Z)$
- Using different sets of pdf's gives an estimate of the correlations in the NLO calculations
- Parametrize the $\alpha_s(M_Z)$ dependence of the measured variable $d\sigma/dA$ according to:

$$d\sigma/dA = C_1 \cdot \alpha_s(M_Z) + C_2 \cdot \alpha_s^2(M_Z)$$

- Use the curve to convert the measured $d\sigma/dA$ into an $\alpha_s(M_Z)$ value
- The errors in the measurement relates to the errors in $\alpha_s(M_Z)$ via the slope of the curve
- Use the **R**enormalization **G**roup **E**quation to extract the 'running' α_s



Measurement of α_s from combined fits

H1: QCD fit to the combined H1 and BCDMS (fixed target) data sets on F_2

$$\Rightarrow \alpha_s(M_Z) = 0.1150 \pm 0.0017 \begin{matrix} +0.0009 \\ -0.0005 \end{matrix}$$

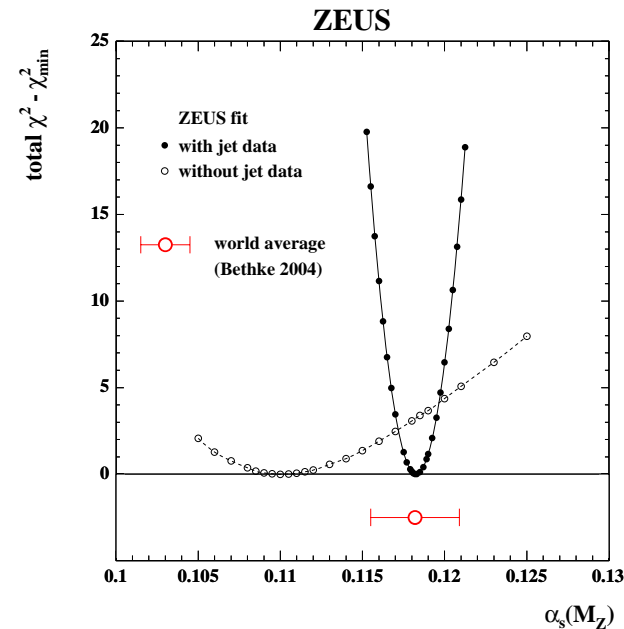
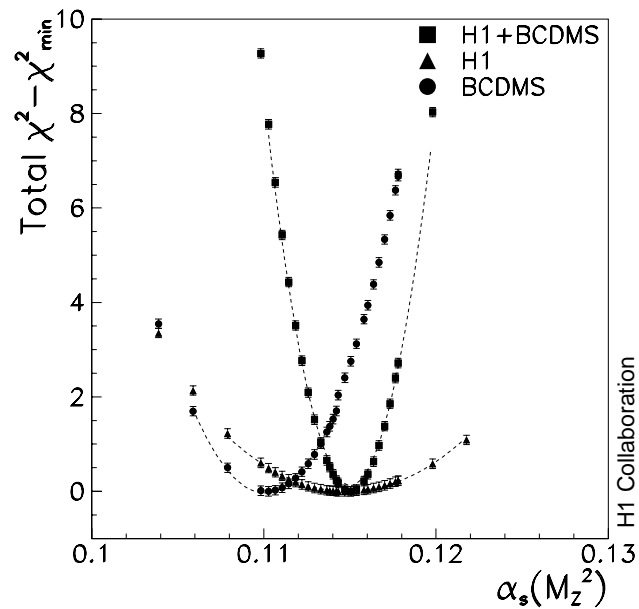
exp. model

ZEUS: QCD fit to F_2 and jet data (inclusive jets in NC DIS + dijets in photoproduction)

$$\Rightarrow \alpha_s(M_Z) = 0.1183 \pm 0.0007 \pm 0.0022 \pm 0.0016 \pm 0.0008$$

uncorr. corr. norm. model

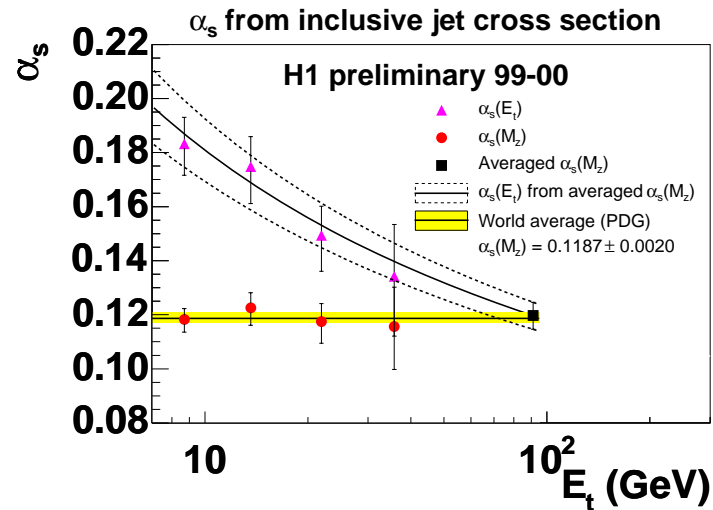
The jet data contribute significantly to constrain the gluon density, which leads to a much more precise determination of α_s



Measurements of α_s from inclusive jets at high Q^2

H1: $\alpha_s(M_Z)$ extracted from $d\sigma/dE_t$ in four bins of Q^2 ($150 < Q^2 < 5000$; total 20 data points)

ZEUS: $d\sigma/dQ^2$ for $Q^2 > 500 \text{ GeV}^2$ has been used to extract $\alpha_s(M_Z)$

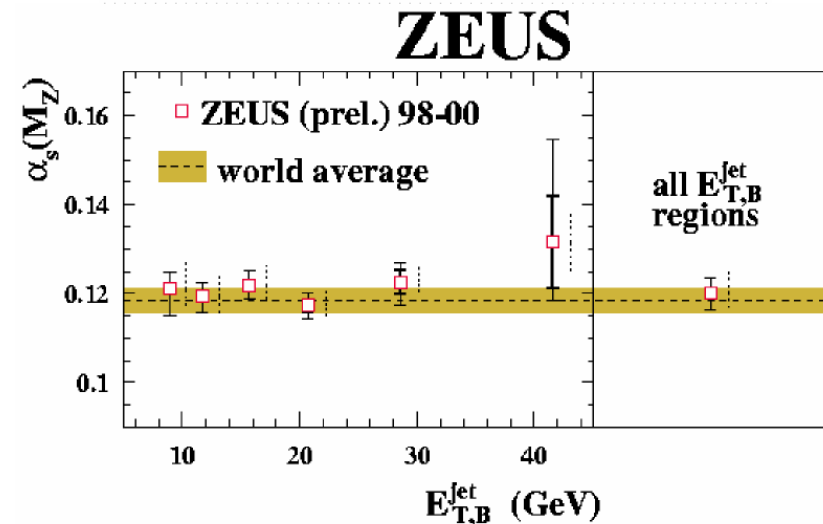
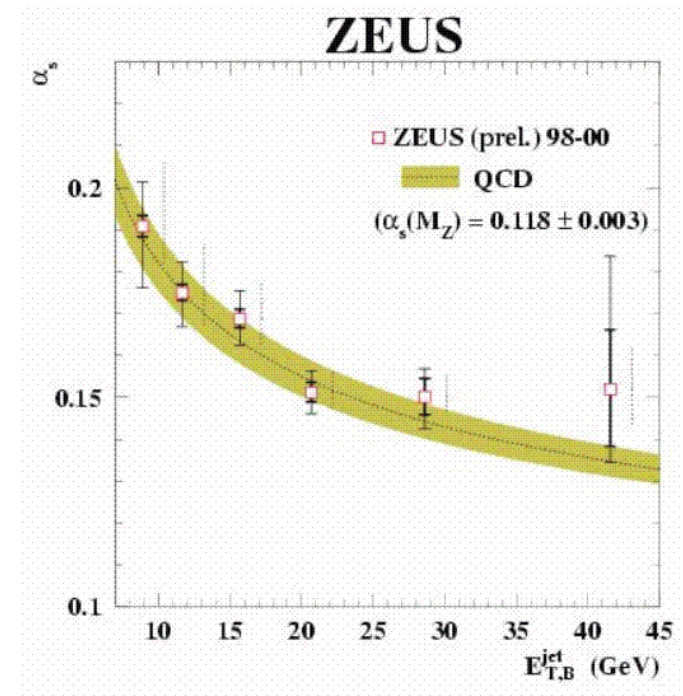


Results:

ZEUS: $\alpha_s(M_Z) = 0.1196 \pm 0.0006(\text{stat.})^{+0.0019}_{-0.0025}(\text{exp.})^{+0.0029}_{-0.0017}(\text{th.})$

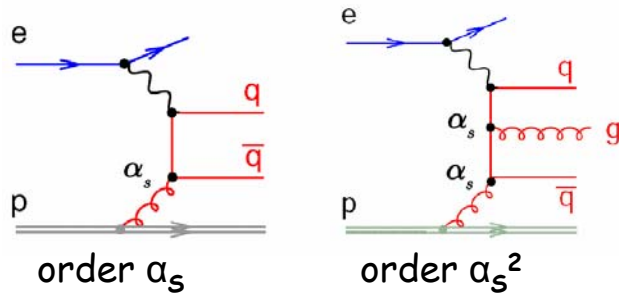
H1: $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\text{exp.})^{+0.0046}_{-0.0048}(\text{th.})$

- Consistent with world average
- Theory error dominates



Measurement of α_s from multijets

Use the ratio between 2- and 3-jet events to measure α_s .



Advantage: cancellation of uncertainties

Disadvantage: small statistics

Data: 82 pb⁻¹

$M_{2\text{jet}}$ and $M_{3\text{jet}} > 25 \text{ GeV}$

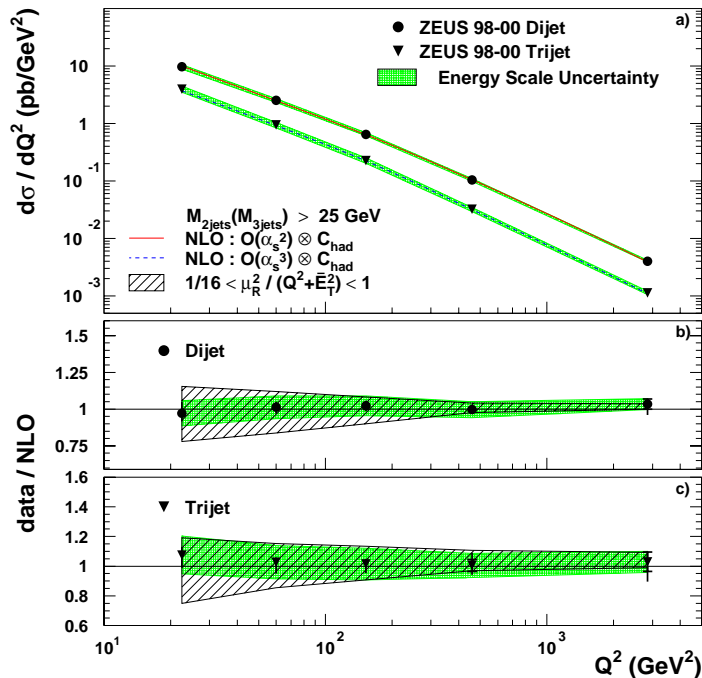
$10 < Q^2 < 5000 \text{ GeV}^2$

$0.04 < y < 0.6$

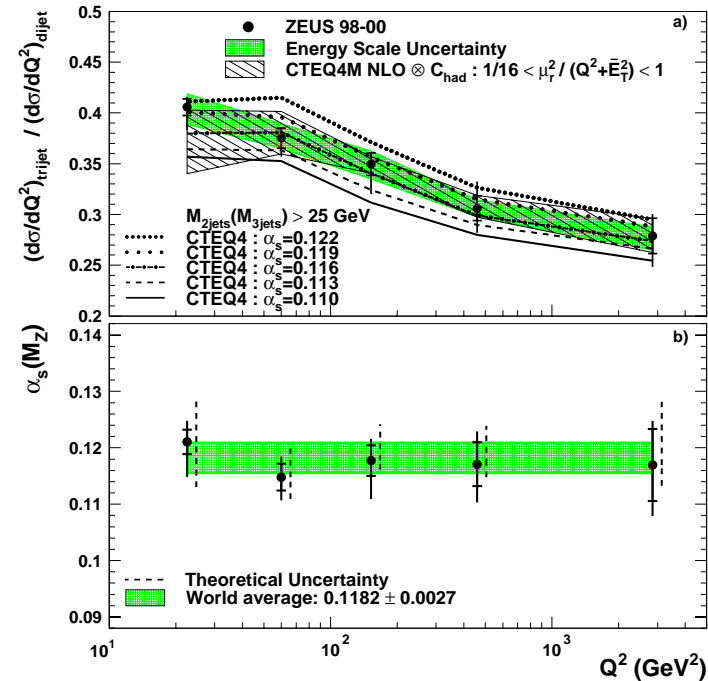
$-1 < \eta_{\text{lab}} < 2.5$

NLO QCD: NLOJET++(CTEQ5M)

ZEUS

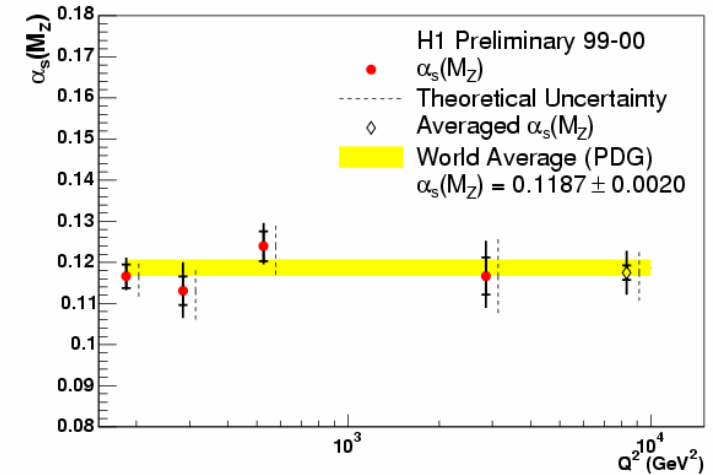
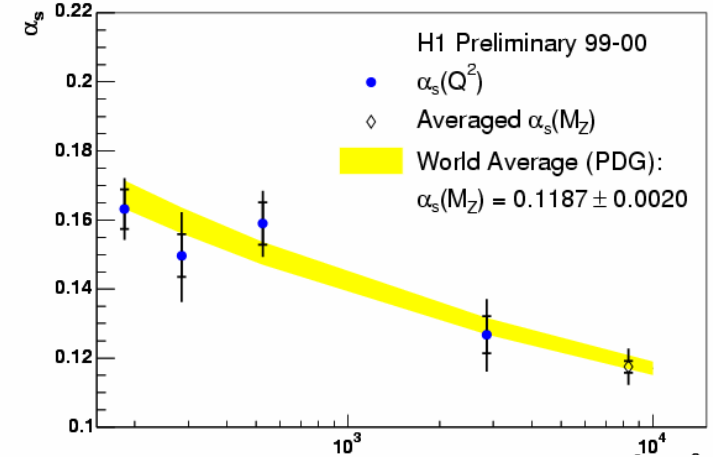
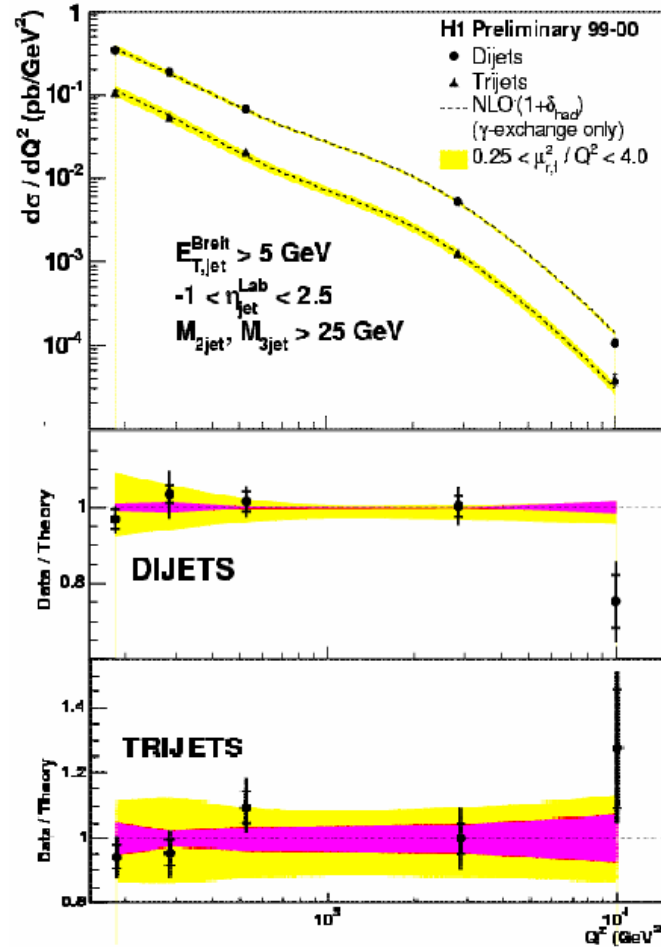


ZEUS



Measurement of α_s from multijets

Data: 65pb^{-1}
 $125 < Q^2 < 15000 \text{ GeV}^2$
 $0.2 < y < 0.6$
 $E_{\text{jet}} > 5 \text{ GeV}$
 $M_{\text{jet-jet}} > 25 \text{ GeV}$
 $-1 < \eta_{\text{lab}} < 2.5$



Results:

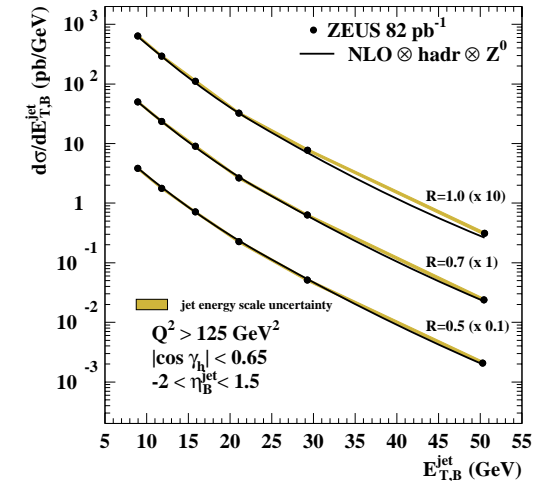
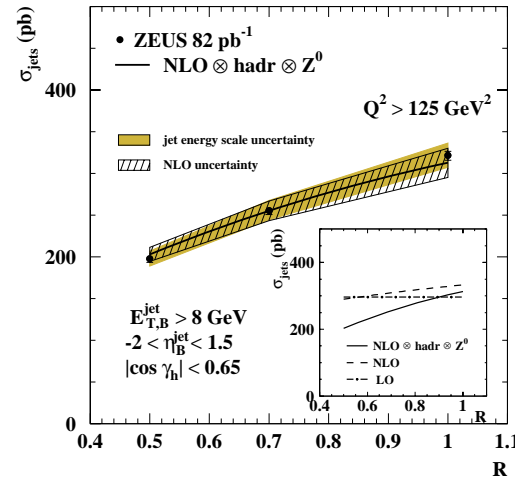
Zeus: $\alpha_s(M_Z) = 0.1179 \pm 0.0013(\text{stat.})^{+0.0028}_{-0.0046}(\text{exp.})^{+0.0064}_{-0.0046}(\text{th.})$

H1: $\alpha_s(M_Z) = 0.1175 \pm 0.0017(\text{stat.}) \pm 0.0050(\text{exp.})^{+0.0054}_{-0.0068}(\text{th.})$

Jet radius studies

The jet cross section is measured as a function of the jet radius, R , in the k_T algorithm

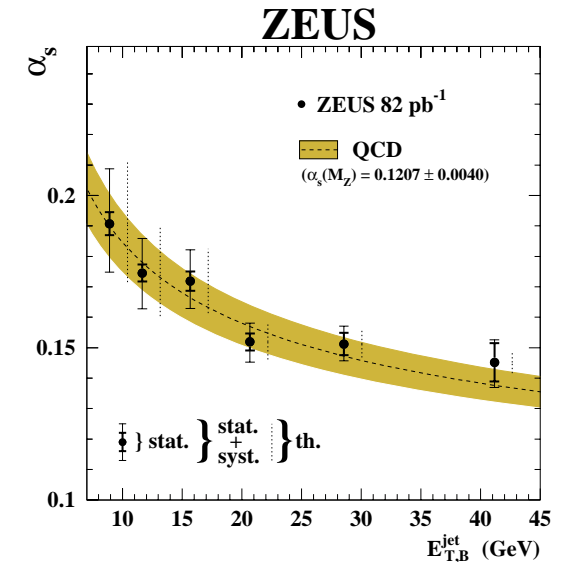
Data: 81.7 pb^{-1}
 $Q^2 > 125 \text{ GeV}^2$
 $|\cos \gamma_h| < 0.65$
 $E_{T,\text{jet}} > 8 \text{ GeV}$ (Breit frame)
 $-2 < \eta_{\text{jet}} < 1.5$ (Breit frame)



NLO calculations to order α_s^2 , including hadronization corrections, provide good description of $d\sigma/dE_{T,\text{jet}}$ (and $d\sigma/dQ^2$) for all jet radii

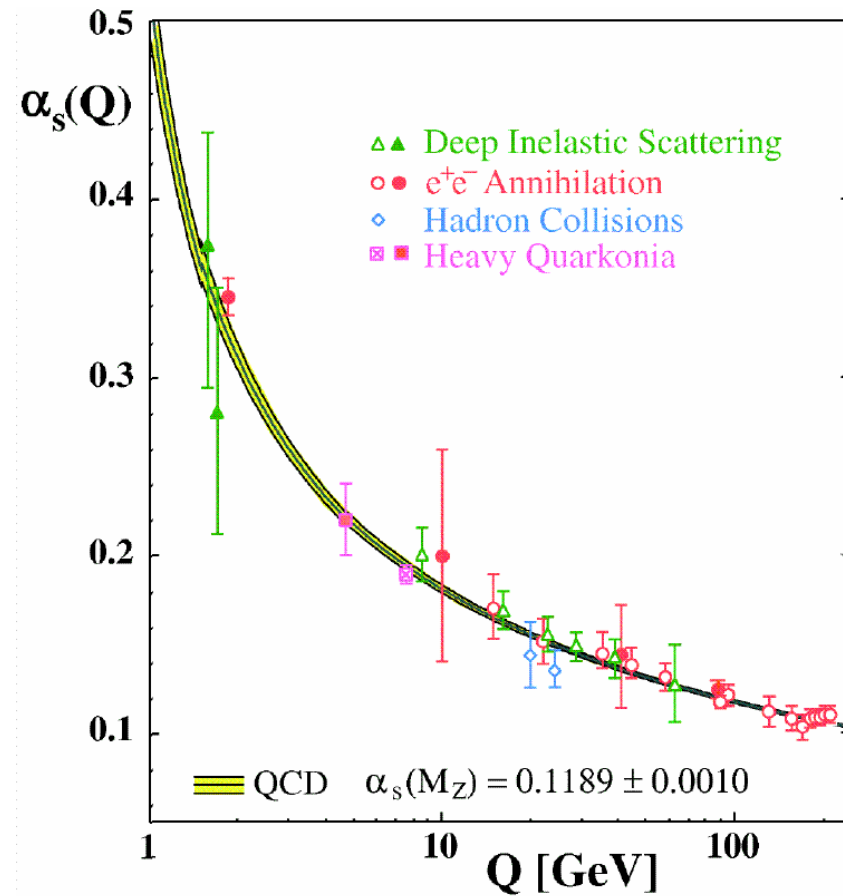
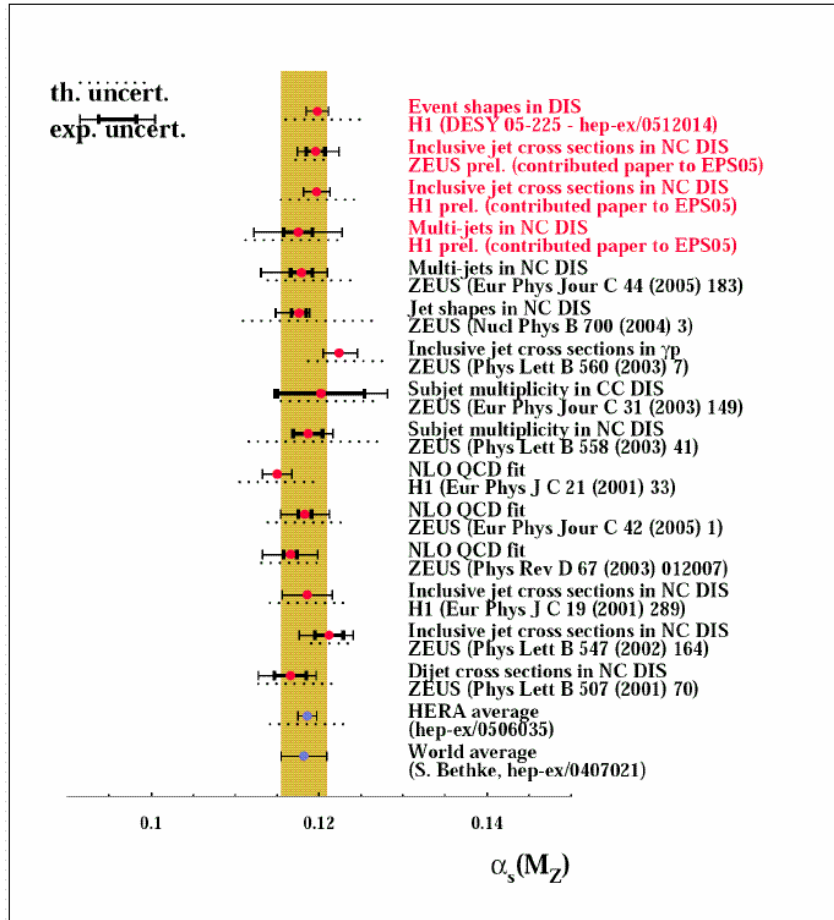
α_s extracted from the $d\sigma/dQ^2$ for $Q^2 > 500 \text{ GeV}^2$, using $R=1$ in the k_T algorithm gives the smallest uncertainty

Energy scale dependence extracted from $d\sigma/dE_{T,\text{jet}}$ with $R=1$



Result: $\alpha_s(M_Z) = 0.1207 \pm 0.0014$ (stat.) $^{+0.0030}_{-0.0028}$ (exp.) $^{+0.0022}_{-0.0023}$ (th.)

Summary on α_s



Summary

On PDF's:

- High precision F_2 data over almost 5 orders of magnitude in x_{Bj} and Q^2 .
- The structure function xF_3 , sensitive to the valence quark distribution, has been measured.
- Measurements with polarized beams have provided clear evidence of parity violation in NC interactions at high Q^2 .
- The standard model gives excellent agreement with data.

On α_s :

- Different methods have been used to determine α_s from HERA data.
- All measurements consistent with each other and the world average.
- The precision is competitive with results from e^+e^- data.
- NLO calculations contribute the dominating error.
- NNLO calculations needed.
- New data from HERAII will improve the precision even more.