Parton densities in the proton and α_s at HERA

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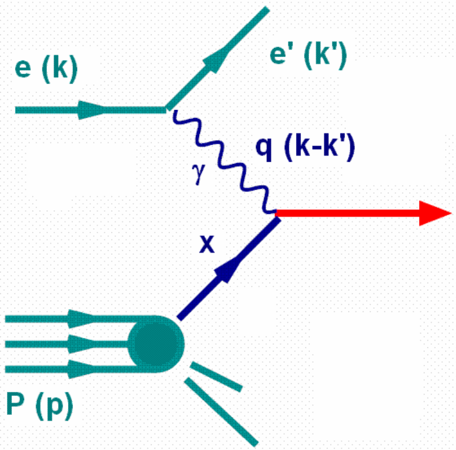
Outline of the talk:

- 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:

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

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

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

$(1 + \delta_{\mathrm{had}})$: 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:

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

is probing the quark content of the proton

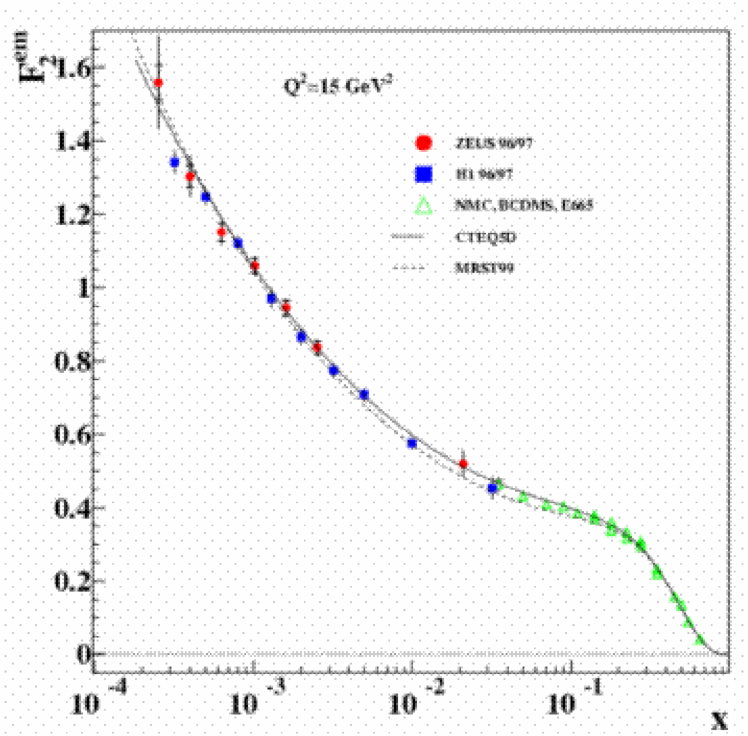
$$F_L = \frac{Q^2}{4\pi\alpha^2}\sigma_L \propto xg$$ (longitudinally polarized photons)

is probing the gluon content of the proton

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

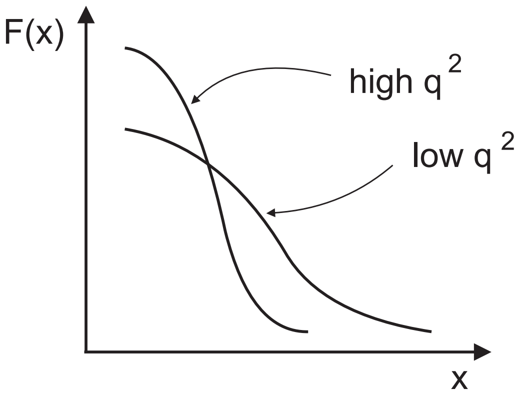
F_2 is dominating in most of the kinematic region covered by HERA. $F_L/F_2 \sim 0.2$ at high y.

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)



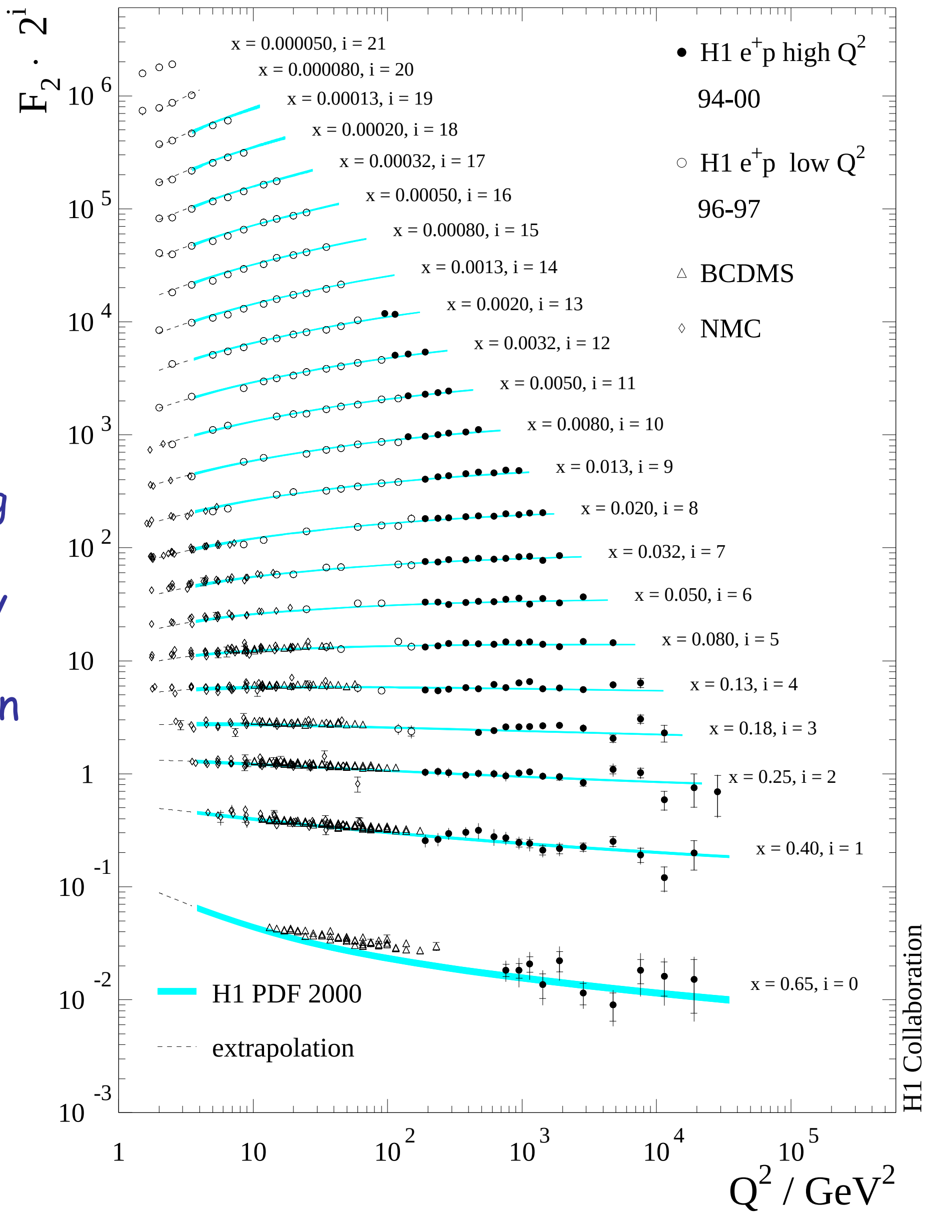
Scaling violation

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



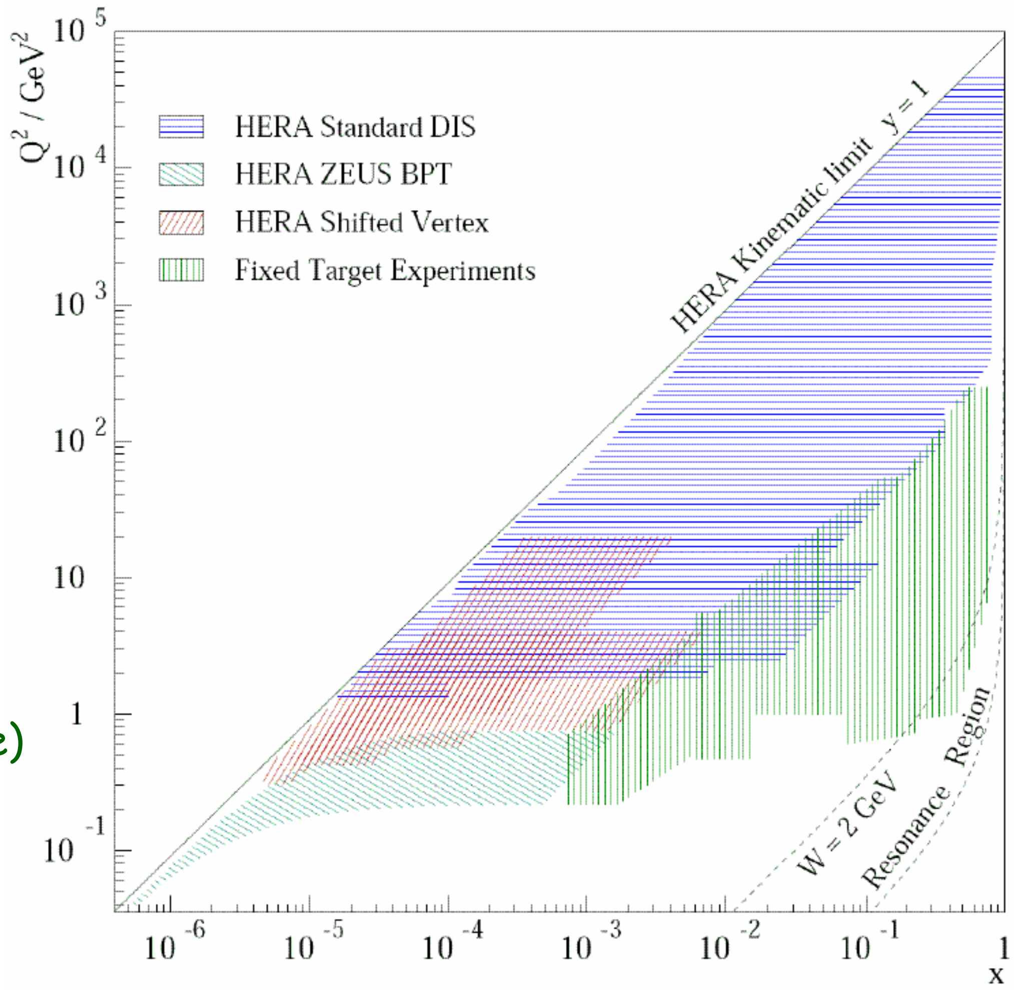
The pdfs are determined through global fits to various experimental data, at a smallest scale, Q_o^2, at which perturbative calculations are still expected to be valid. The DGLAP evolution can be used to define the pdf at an arbitrary Q^2.

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.

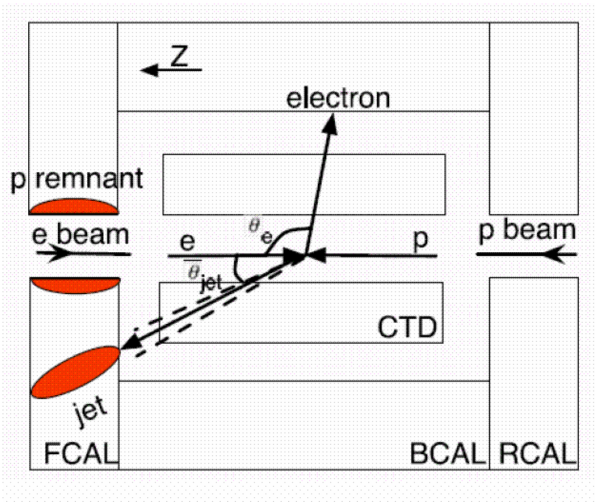
- Access to the low Q^2 region is obtained through:
- collisions at shifted vertex position
- lower electron beam energies
- radiative events.
- Low Q^2 and $x_{Bj} \Rightarrow$ large y $\Rightarrow F_L$ can be determined
- Data exist since 2001 (not covered here)

Recent results in the large x region

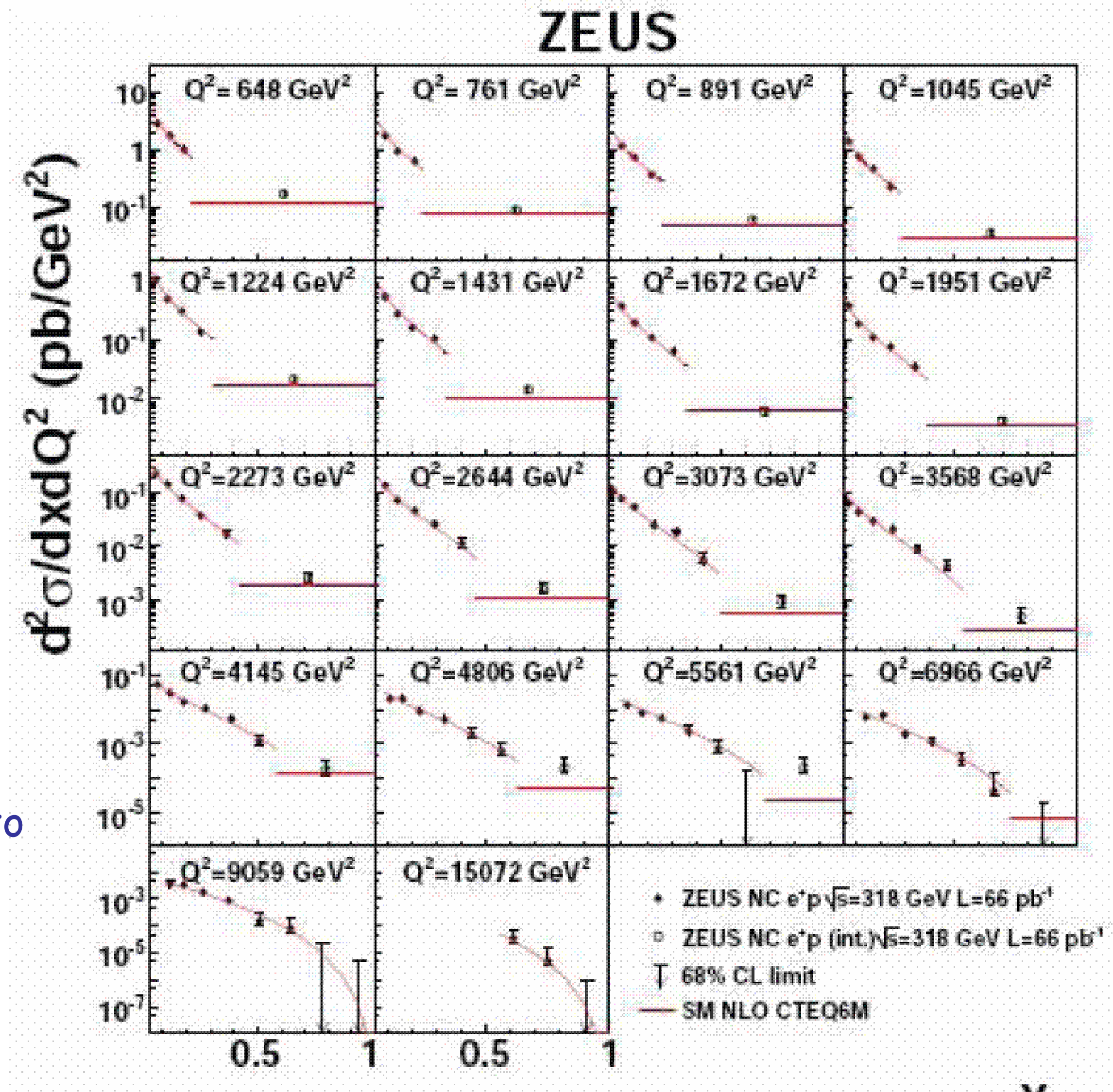


Pdf's at high x

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

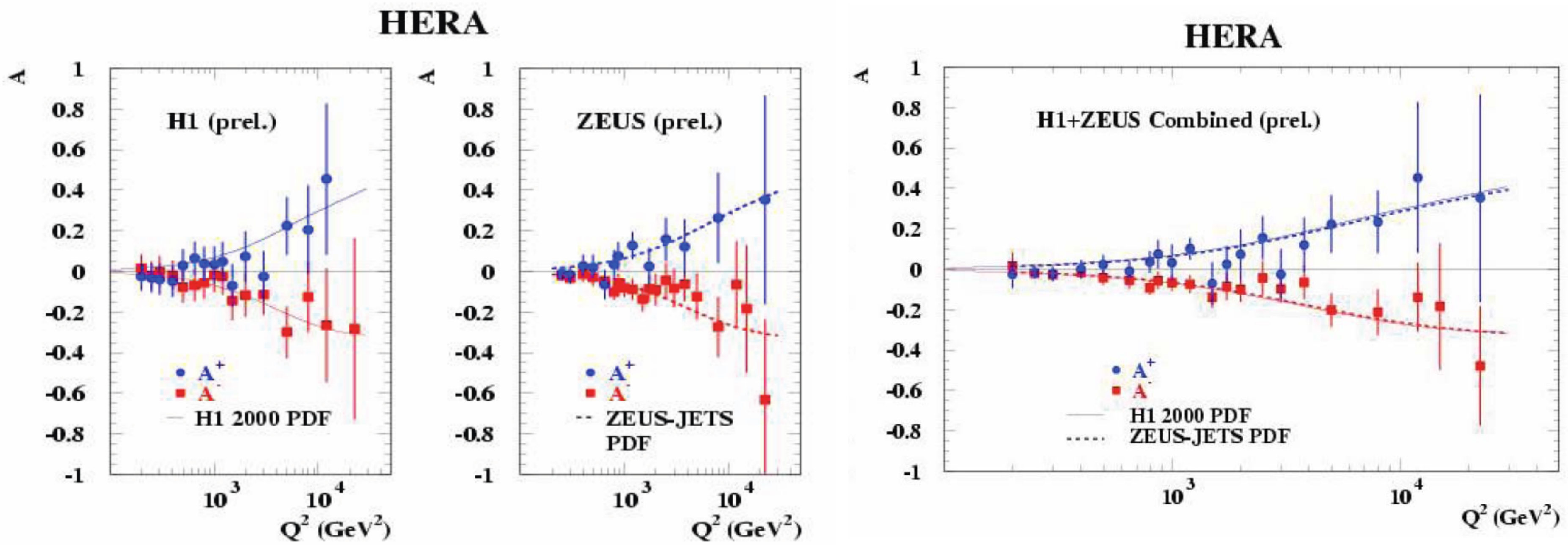
$$\begin{aligned} \tilde{F}_2 &= F_2 + \; k(-v_e \mp P a_e) x F_2^{\gamma Z} + \; k^2(v_e^2 + a_e^2 \pm P v_e a_e) x F_2^Z \\ x\tilde{F}_3 &= \; k(-a_e \mp P v_e) x F_3^{\gamma Z} + \; k^2(2 v_e a_e \pm P(v_e^2 + a_e^2)) x F_3^Z \end{aligned}$$

where the P-terms wontain the parity violation

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

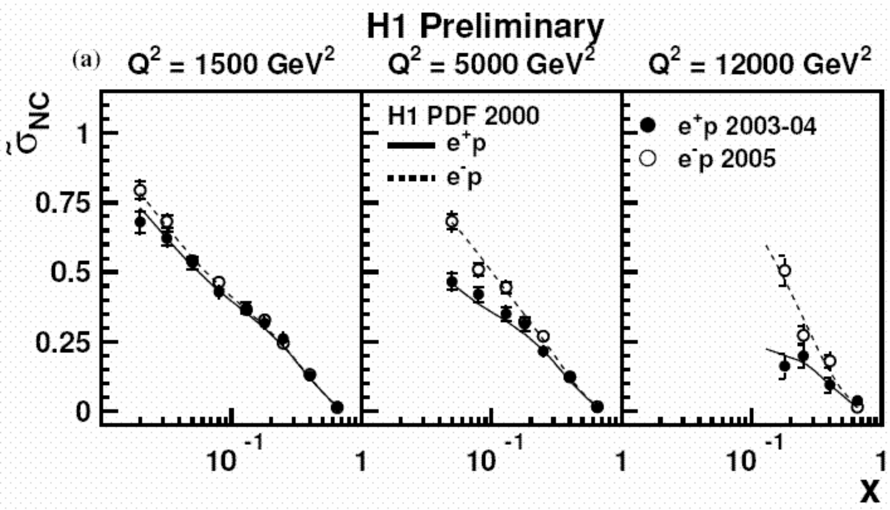
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

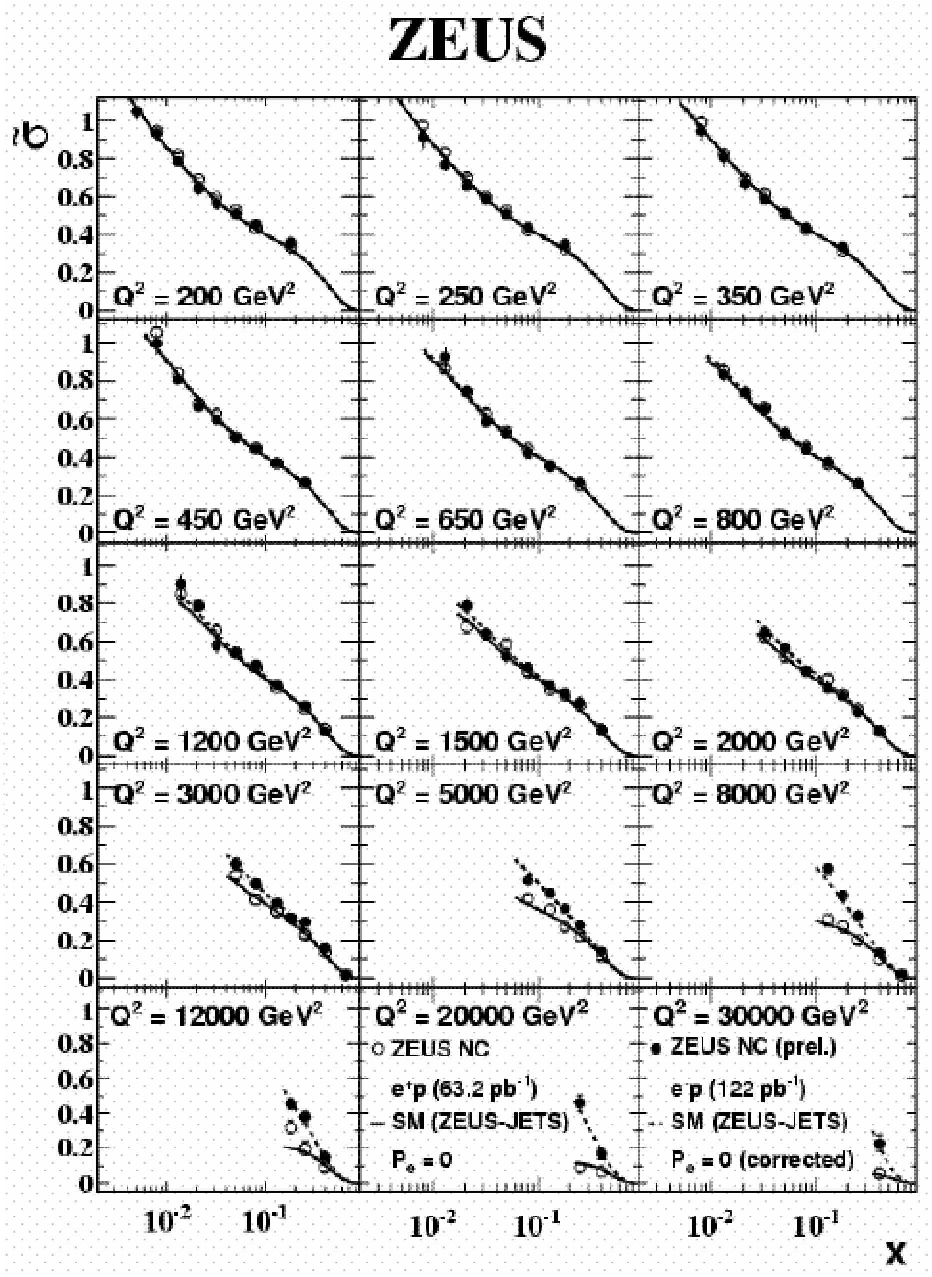
A^+ and A^- of opposite signs; $dA = A^+ - A^- \approx 0$ for low Q^2; and $\neq 0$ for high Q^2



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 xF_3 have been compared to SM predictions





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

F_3

- xF_3 is extracted from the unpolarized reduced cross section

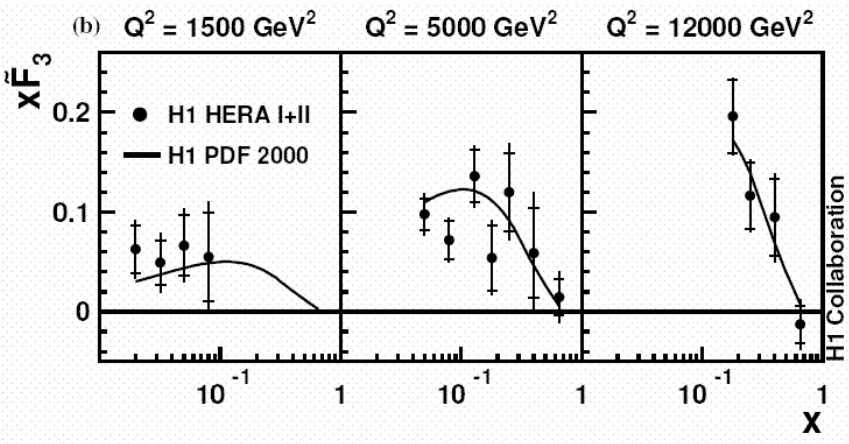
$$\tilde{\sigma}^{e^\pm p} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = F_2(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)$$ where $$Y_\pm \equiv 1 \pm (1-y)^2$$

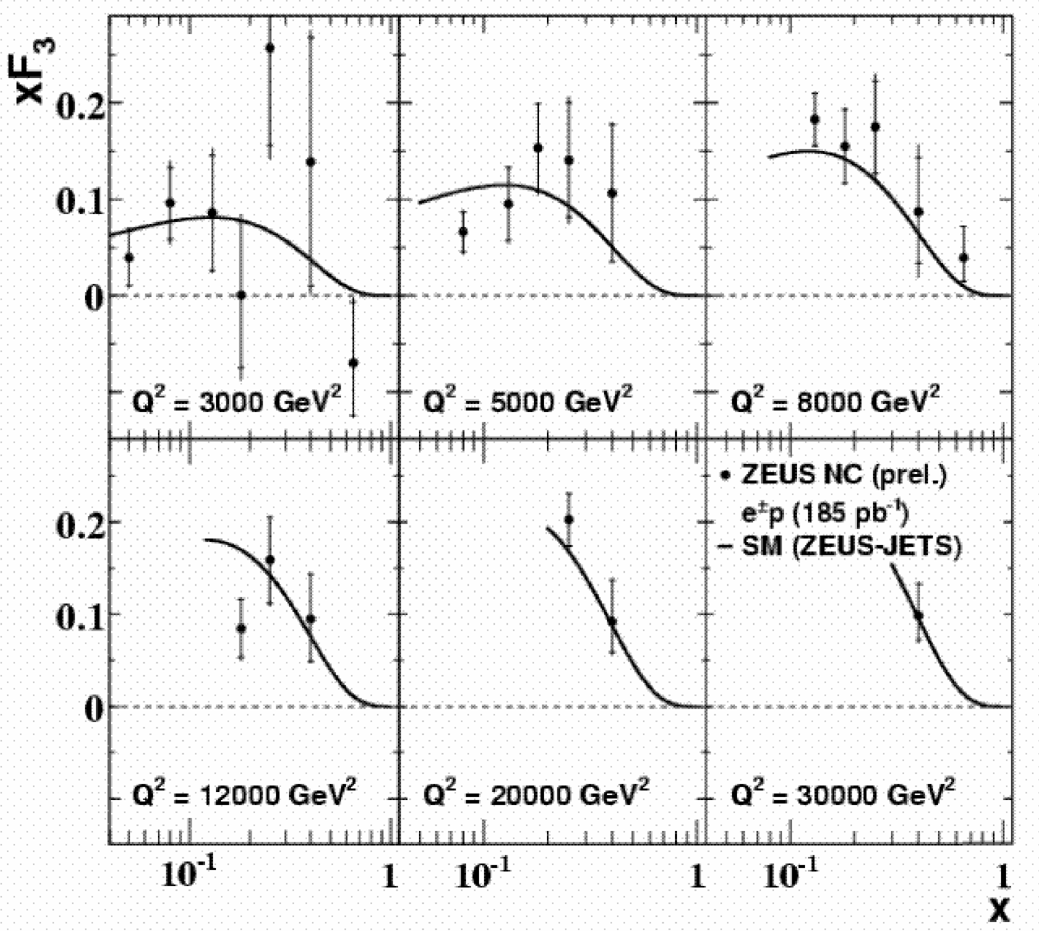
$$xF_3(x,Q^2) = \frac{Y_+}{2Y_-}(\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p})$$

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

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

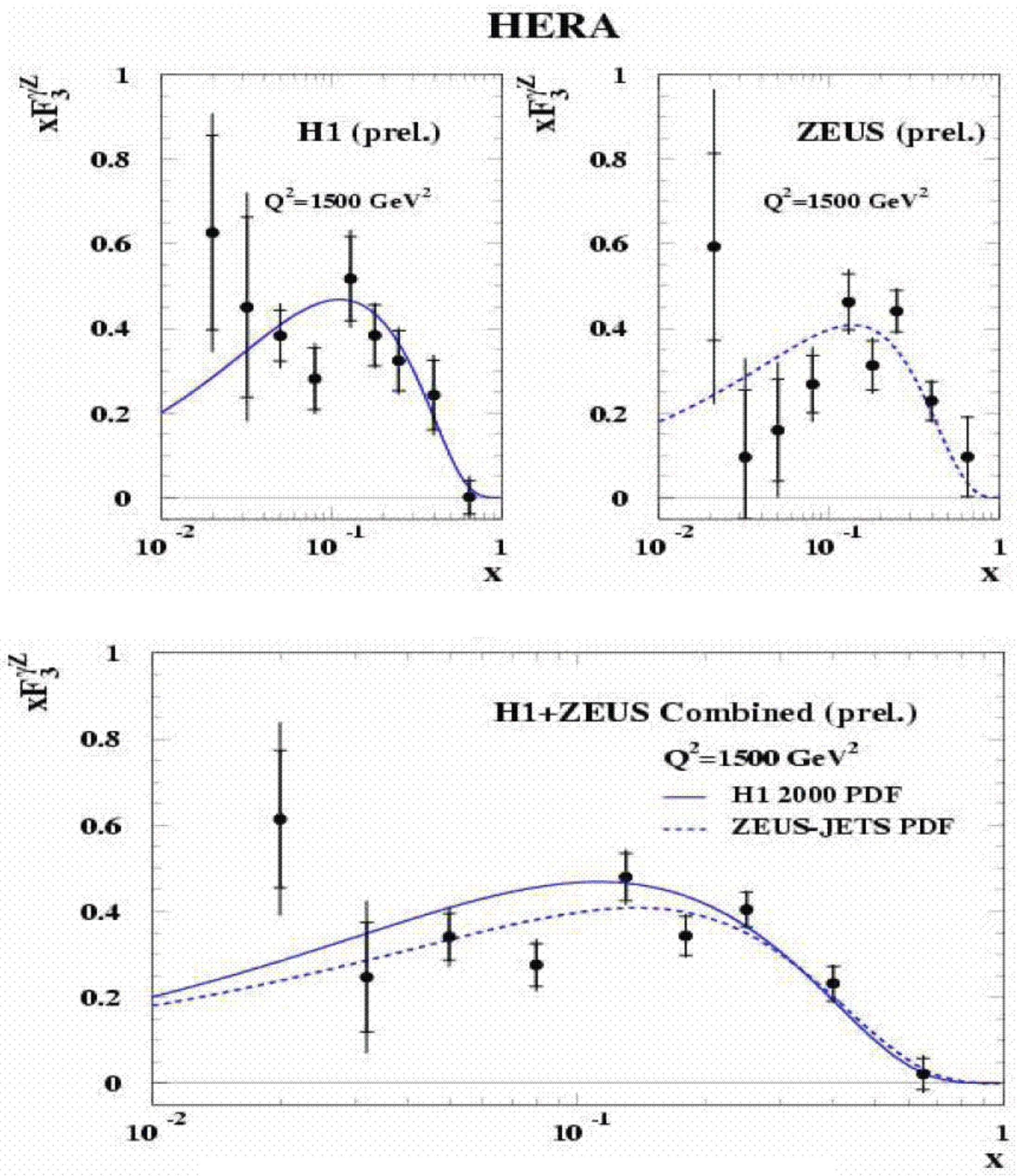
Data comprise in total 478.8 pb^{-1} from the HERA II running





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

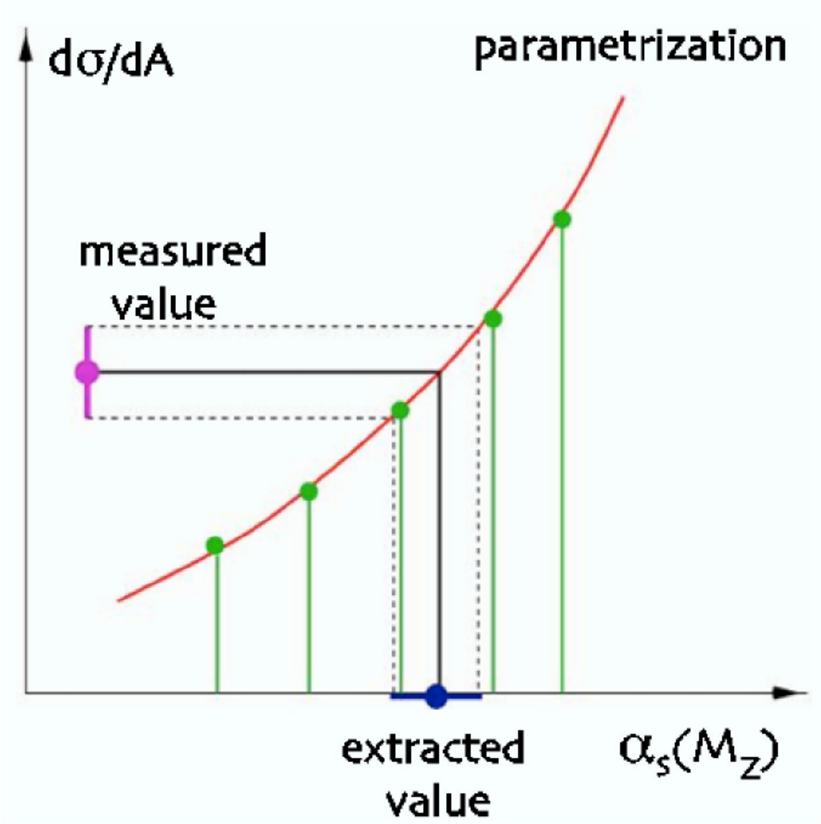


Determination of α_s

- 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 Renormalization Group Equation to extract the 'running' α_S



Measurement of α_s from combined fits

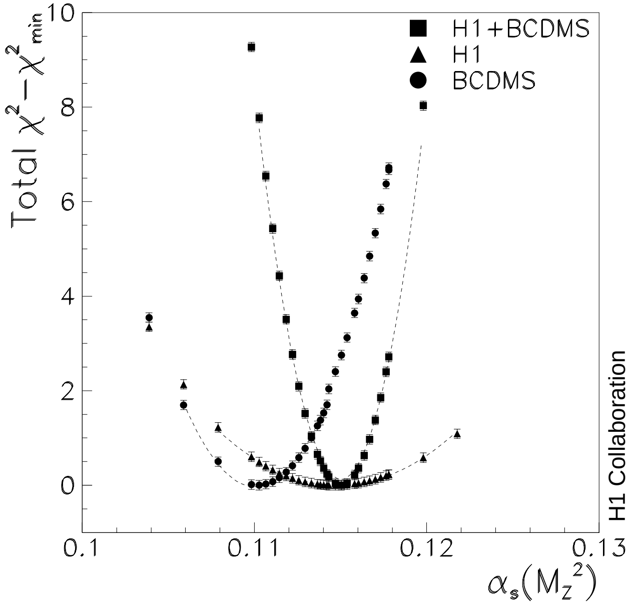
H1: QCD fit to the combined H1 and BCDMS (fixed target) data sets on F_2

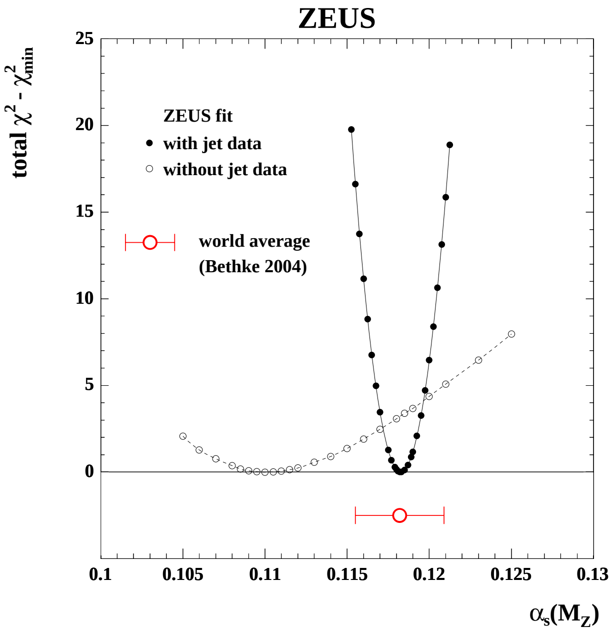
$$\Rightarrow \quad \alpha_s(M_Z) = 0.1150 \pm 0.0017_{\,exp.} \; {}^{+0.0009}_{-0.0005}\,{}_{model}$$

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

$$\Rightarrow \quad \alpha_s(M_Z) = 0.1183 \pm 0.0007_{\,uncorr.} \pm 0.0022_{\,corr.} \pm 0.0016_{\,norm.} \pm 0.0008_{\,model}$$

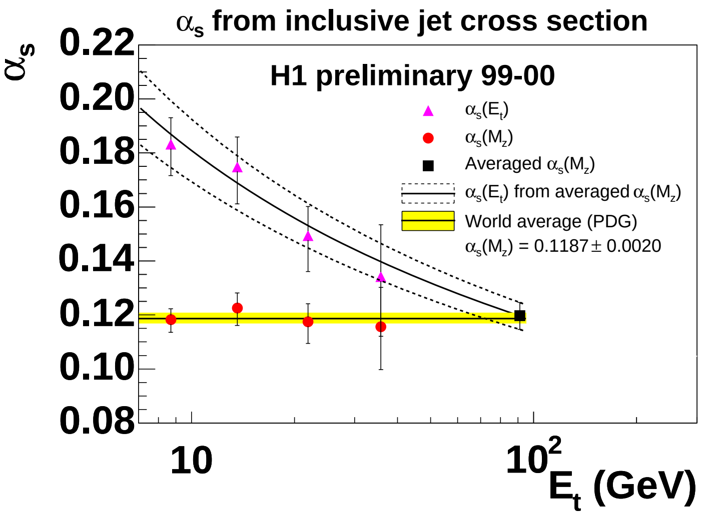
The jet data contribute significantly to constrain the gluon density, which leads to a much more precise determination of α_s

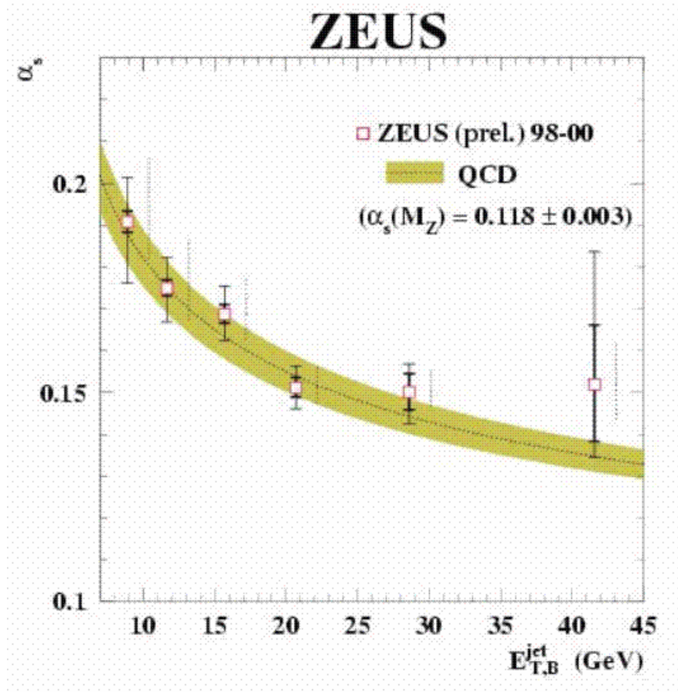


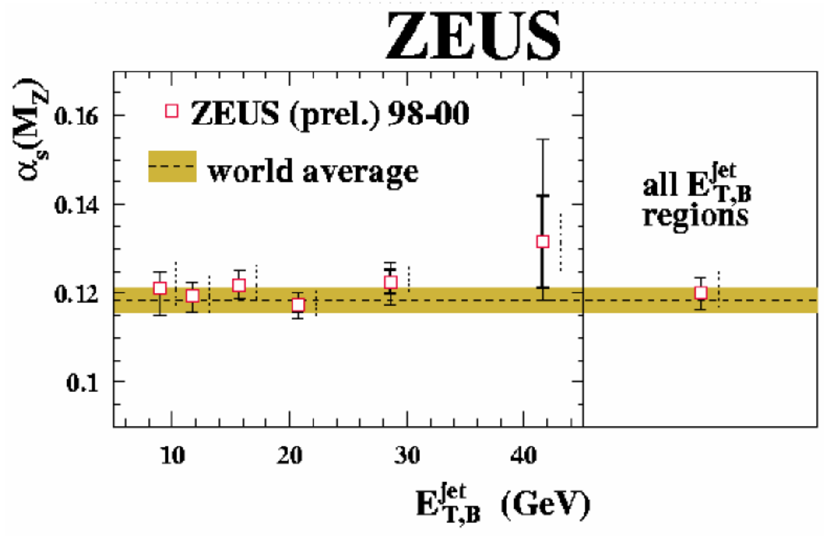


Measurements of α_s from inclusive jets at high Q^2

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 $Q^2 > 500$ GeV^2 has been used to extract $\alpha_s(M_Z)$







Results:

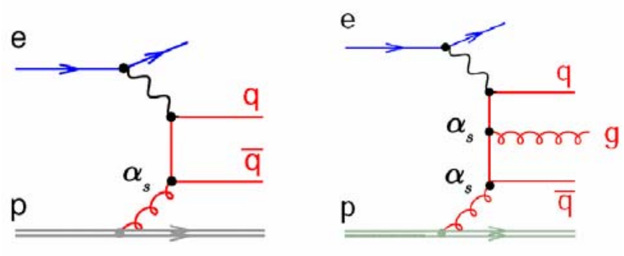
ZEUS: $\alpha_s(M_Z) = 0.1196 \pm 0.0006(\text{stat.})^{+0.0019}_{-0.0025}(\text{exp.})^{+0.0029}_{-0.0017}(\text{th.})$

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

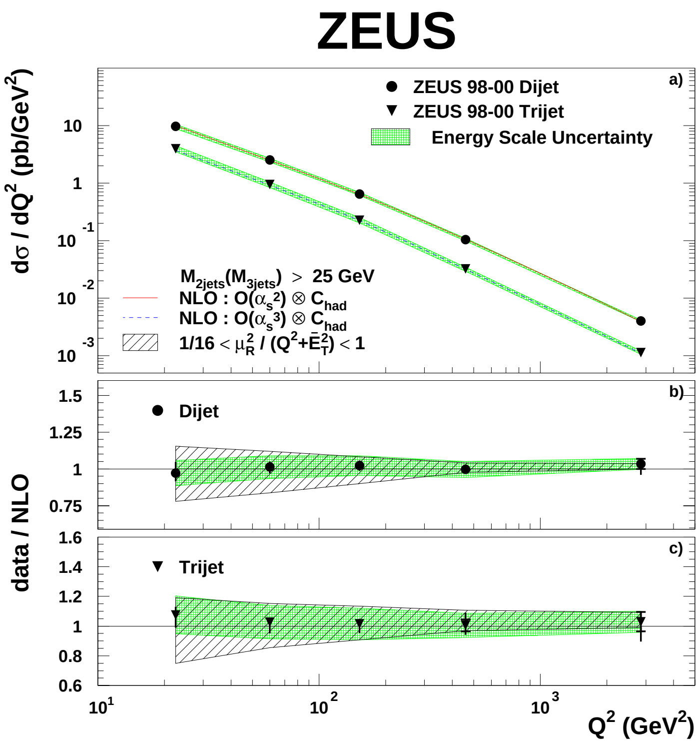
Use the ratio between 2- and 3-jet events to measure α_s.

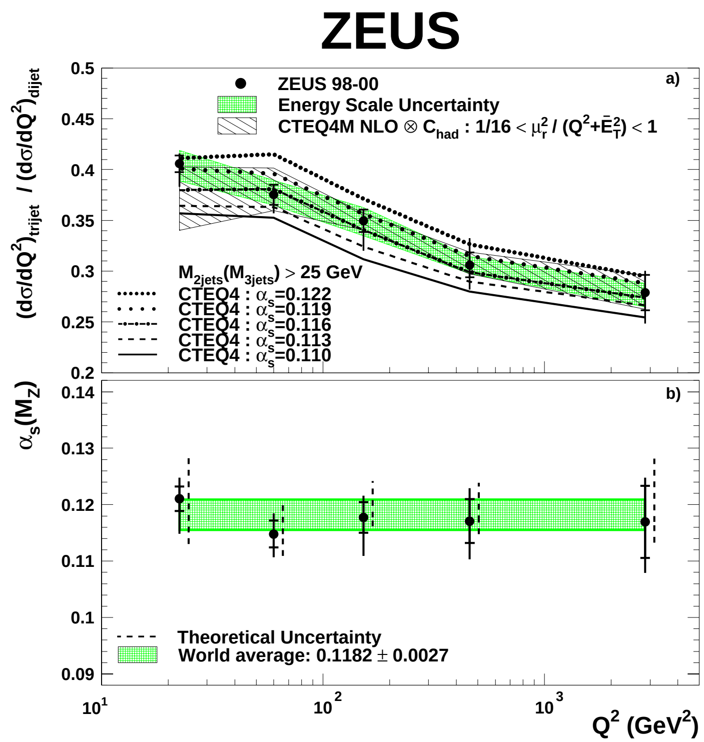


order α_s order α_s^2

Advantage: cancellation of uncertainties
Disadvantage: small statistics

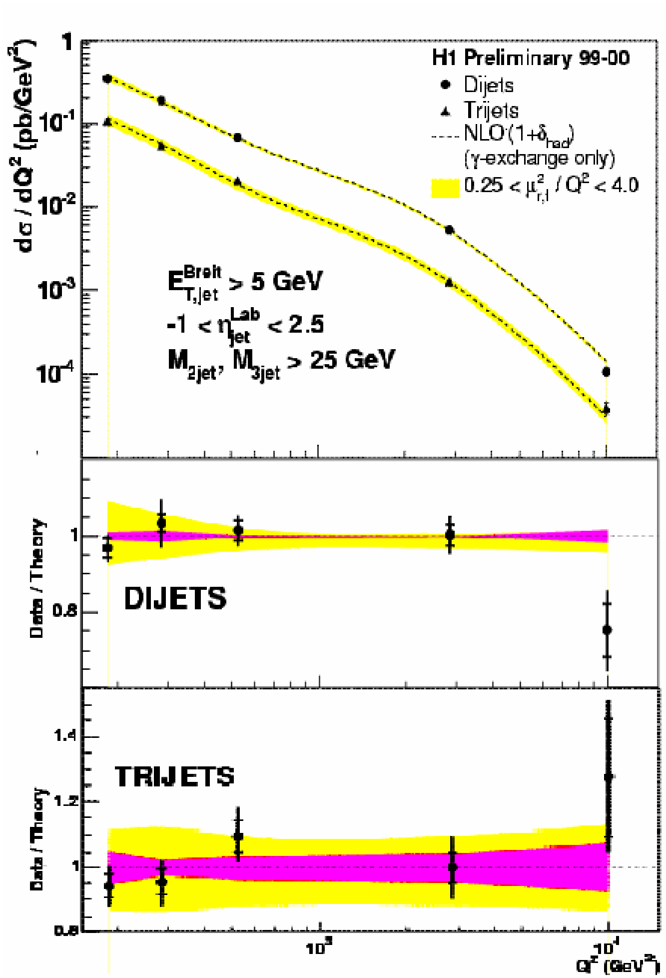
Data: 82 pb^{-1}
M_{2jet} and M_{3jet} > 25 GeV
10 < Q^2 < 5000 GeV2
0.04 < y < 0.6
-1 < η_{lab} < 2.5
NLO QCD: NLOJET++(CTEQ5M)

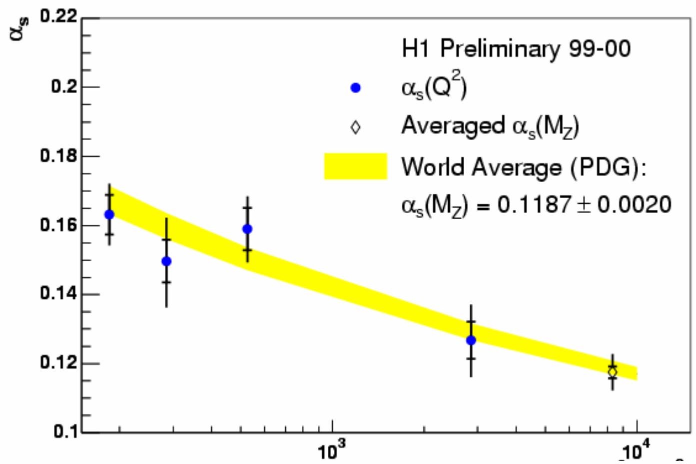


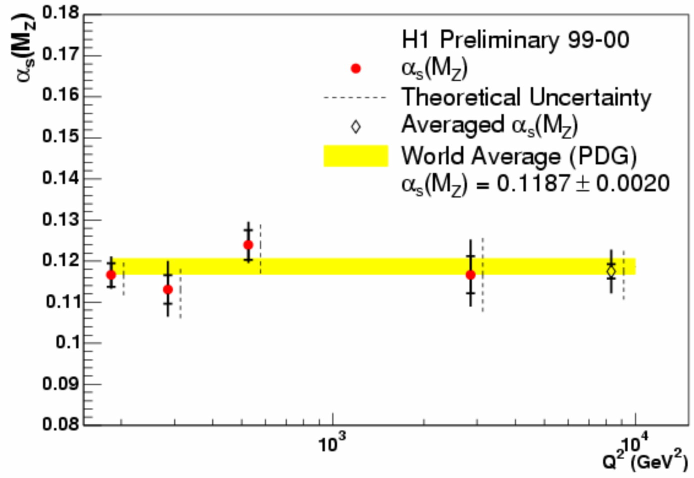


Measurement of α_s from multijets

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







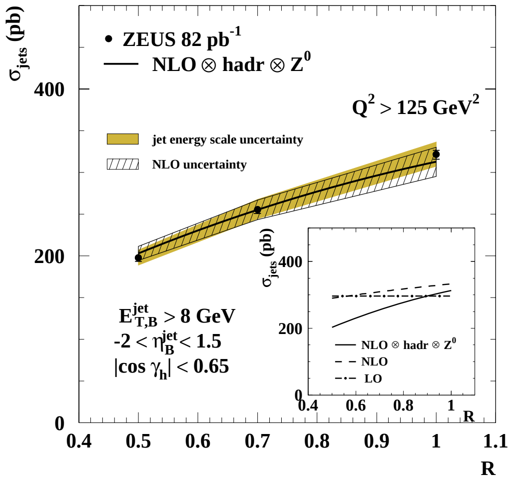
Results:

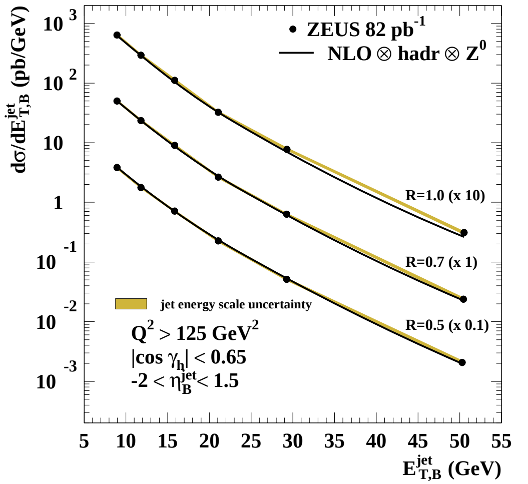
Zeus: $\alpha_s(M_Z) = 0.1179 \pm 0.0013(\text{stat.})^{+0.0028}_{-0.0046}(\text{exp.})^{+0.0064}_{-0.0046}(\text{th.})$

H1: $\alpha_s(M_Z) = 0.1175 \pm 0.0017(\text{stat.}) \pm 0050(\text{exp.})^{+0.0054}_{-0.0068}(\text{th.})$

Jet radius studies

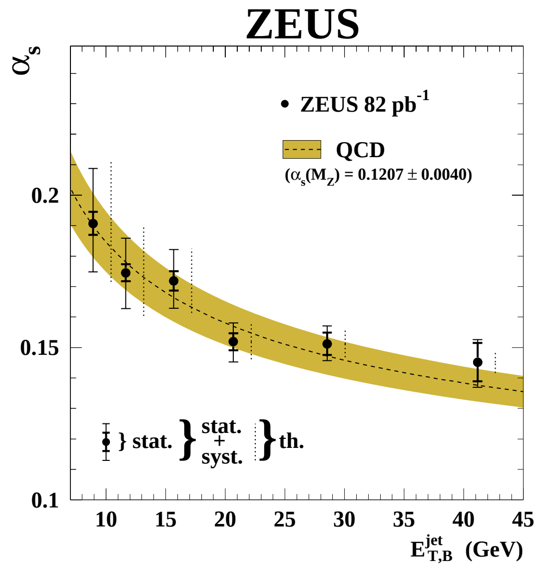
The jet cross section is measured as a function of the jet radius, R, in the k_T algorithm





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

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

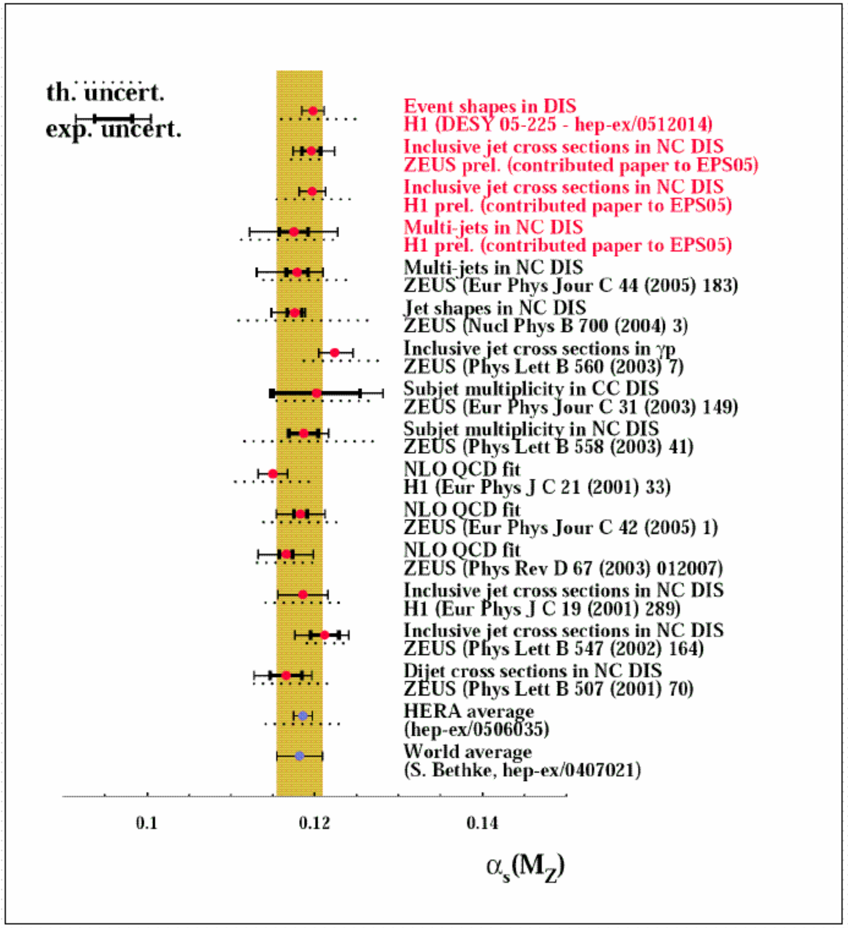


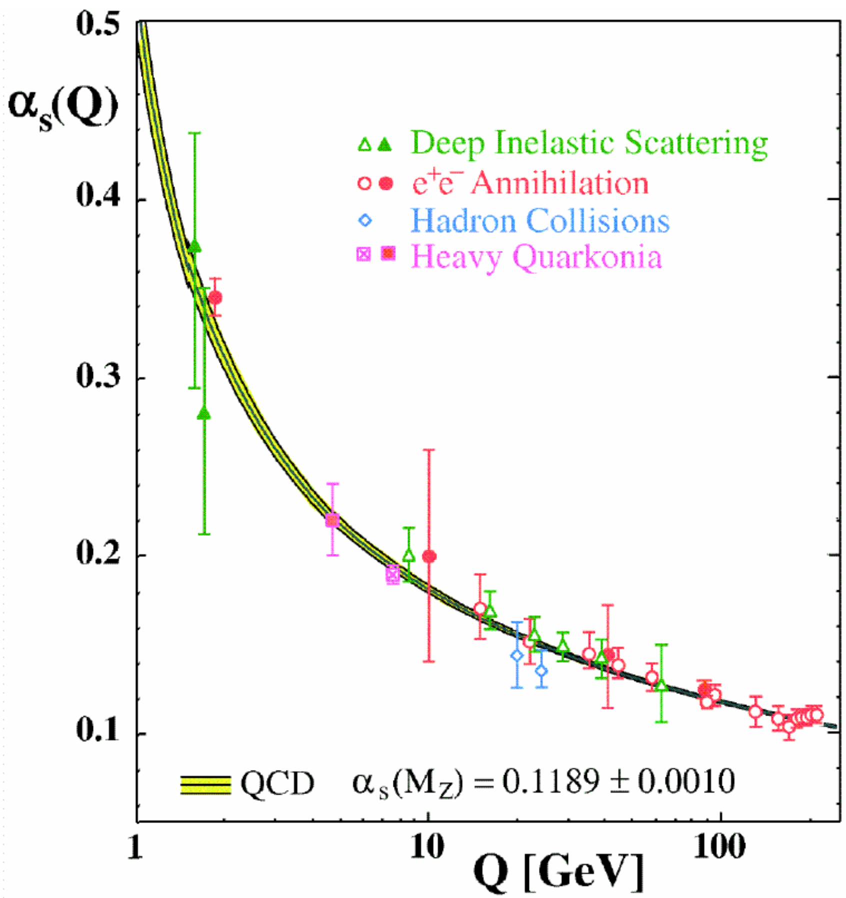
α_s extracted from the $d\sigma/dQ^2$ for $Q^2 > 500$ GeV^2, using R=1 in the k_T algorithm gives the smallest uncertainty

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

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

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.