QCD Analyses of HERA cross section data
- Determination of the proton PDFs and α_s -

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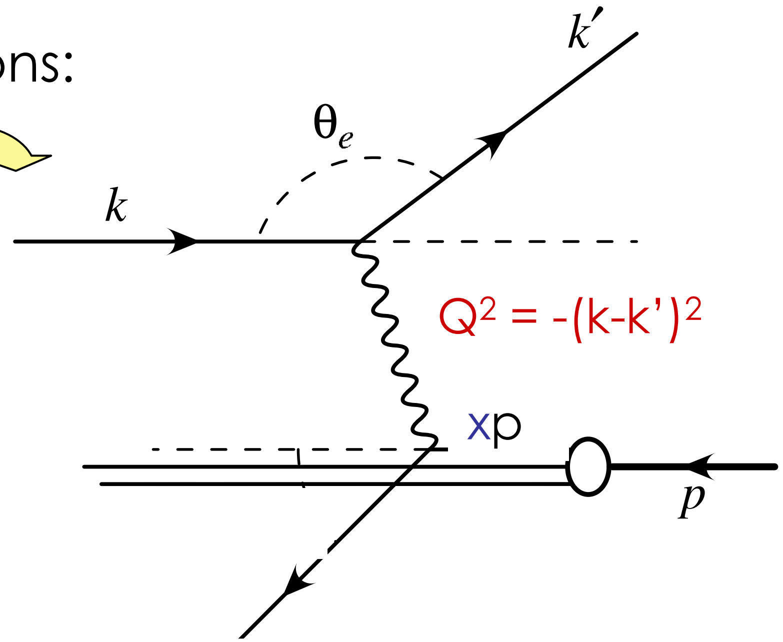
On behalf of the H1 and ZEUS Collaborations
Abstracts: 5-0263 and 5-0150

Deep Inelastic Scattering at HERA

Inclusive lepton-proton cross sections:

$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2} \sim Y_+F_2 - y^2F_L \mp Y_-xF_3$$

$$\frac{d^2\sigma_{CC}(e^{\pm}p)}{dxdQ^2} \sim Y_+F_2^{CC} - y^2 F_L^{CC} \mp Y_-xF_3^{CC}$$



STRUCTURE FUNCTIONS:

$F_2 \sim \sum x(q_i + \bar{q}_i)$ Dominates

$xF_3 \sim \sum x(q_i - \bar{q}_i)$ High Q^2

$F_L \sim \alpha_s . xg(x,Q^2)$ High y

x = momentum fraction of proton carried by quark (HERA: $10^{-6} \sim 1$)

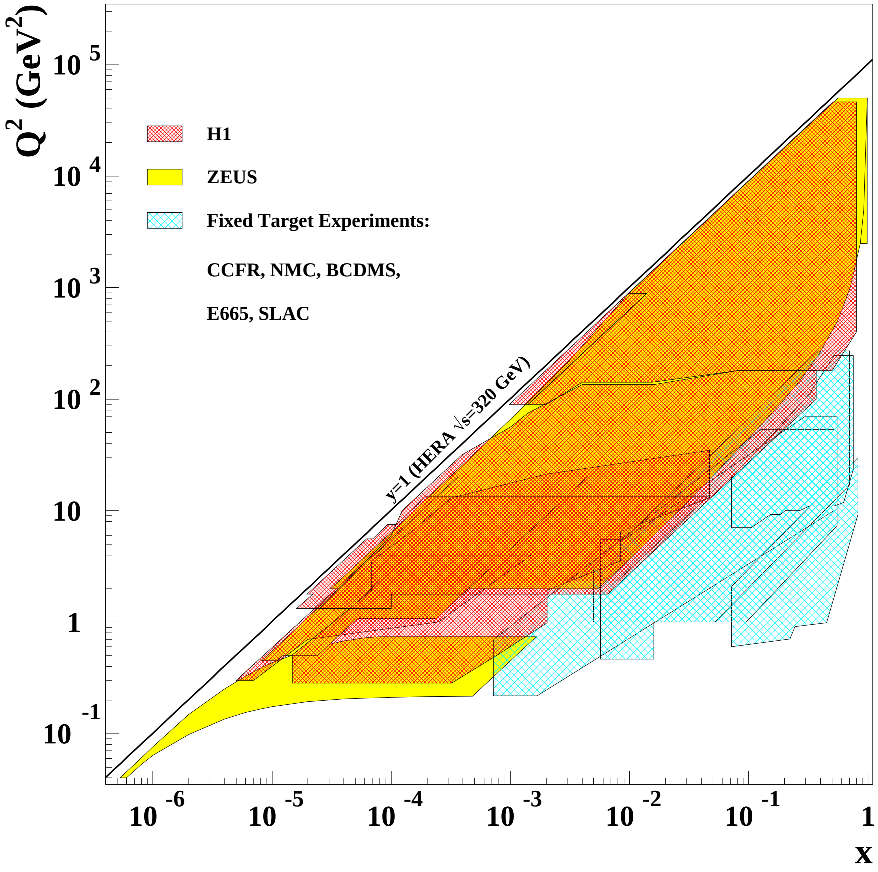
Q^2 = "resolving power" of probe

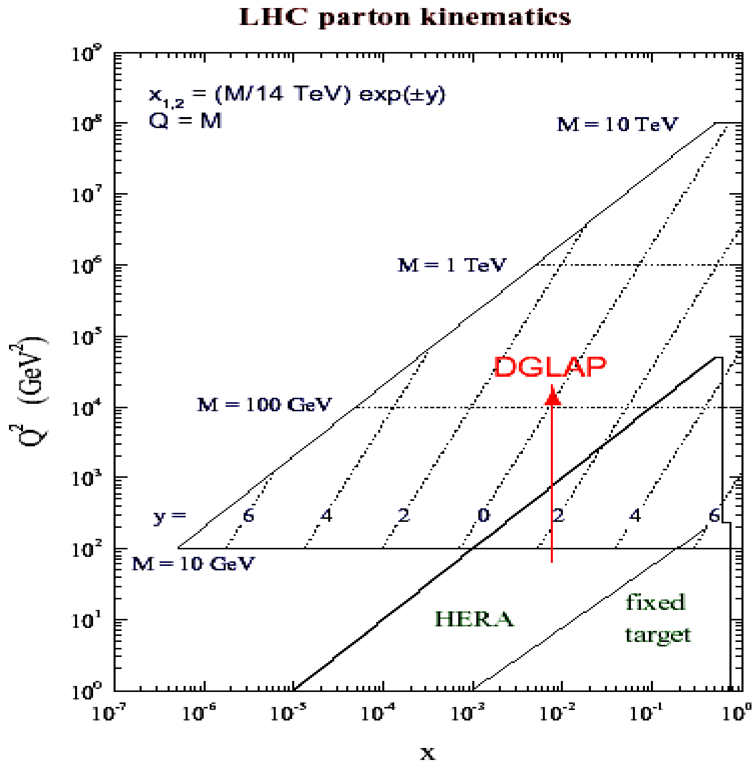
Factorisation: structure function = short range interaction ⊗ PDFs

Now, after the HERA I phase (1994-2000) of data-taking, the full set of e^+ and e^- inclusive Neutral Current (NC) and Charged Current (CC) cross sections are available for QCD analysis

HERA Kinematic (x,Q²) Range

- HERA data covers a large region in (x,Q²)
  - → Also in relevant x-region for LHC physics





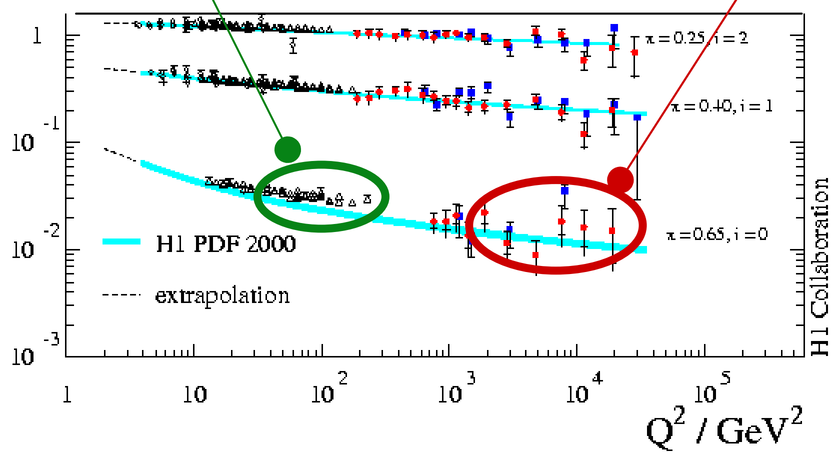
C.Gwenlan, QCD Analyses at HERA, ICHEP04

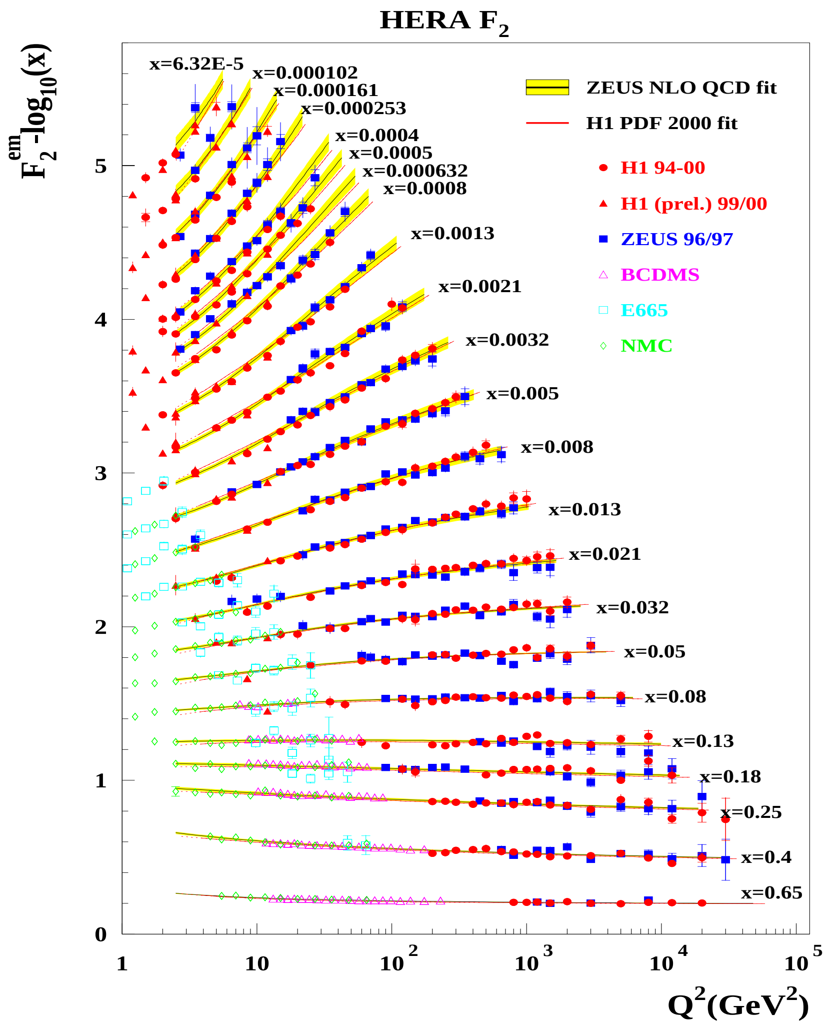
Neutral Current Processes

- F_2 dominates cross section
  - → direct information on quarks
  - → Information on gluon and sea through QCD radiation (scaling violations) at low-x
  - → HERA high-x data still less precise than fixed target

BCDMS: $\delta F_2/F_2$~7%

HERA: $\delta F_2/F_2$~30%



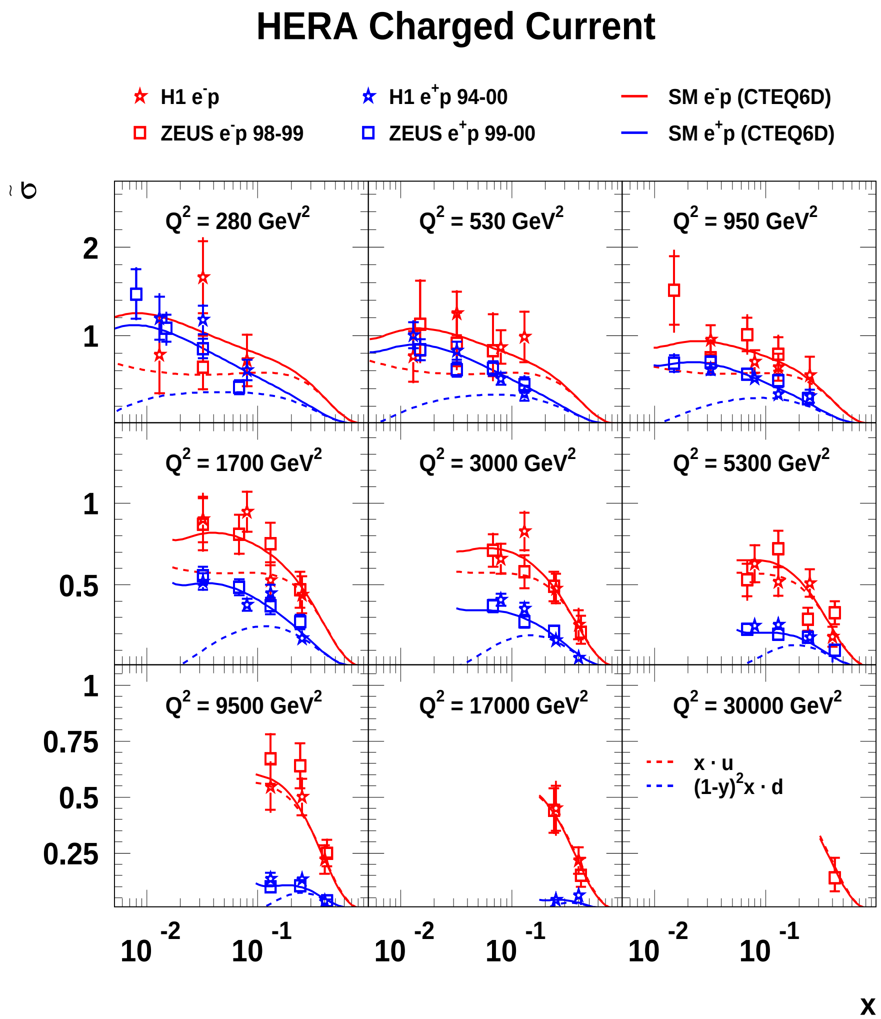


Typically 2-3% precision

Charged Current Processes

- Reduced cross sections:
  $\tilde{\sigma}^{+}_{CC} = x\,[\bar{u}+\bar{c}+(1-y)^2(d+s)]$
  $\tilde{\sigma}^{-}_{CC} = x\,[u+c+(1-y)^2(\bar{d}+\bar{s})]$
- Both e^+ and e^- needed for flavour separation in QCD fits

Typical systematic uncertainties are ~ 6%



Global versus HERA Only QCD Analyses

Where does the information come from in a global fit (colliding beam + fixed target DIS) compared to a HERA only fit ?

	Global	HERA Only
Valence	Predominantly fixed target data (ν-Fe and $\mu D/\mu p$)	High Q^2 NC/CC $e^{\pm}$ cross sections
Sea	Low-x from NC DIS High-x from fixed target Flavour from fixed target	Low-x from NC DIS High-x ? Flavour ?
Gluon	Low-x from HERA $dF_2/d\ln Q^2$ High-x from momentum sum	Low-x from HERA $dF_2/d\ln Q^2$ High-x from momentum sum

ANALYSES FROM HERA ONLY …

— Systematics well understood
  - measurements from our own experiments !!!

— No complications from heavy target Fe or D corrections

PDF Parameterisation

Conventional QCD predicts only the Q^2 dependence of PDFs

- Parameterise PDFs in x at (low) starting scale Q_0^2:
  - $xf(x) = Ax^b(1-x)^c P(x)$ ← P(x) should be both flexible and stable

    b: Low-x behaviour; c: high-x suppression
- Evolve PDFs with Q^2 using NLO DGLAP equations
- Convolute PDFs with coefficient functions to give predictions for structure functions (and hence cross sections)
- Parameters A, b, c, … optimised in fit for each PDF

NOTE: Some params. constrained by momentum and no. sum rules

$$\sum \text{mom.} = 1 \qquad \int u_v \, dx = 2 \qquad \int d_v \, dx = 1$$

<u>model assumptions</u>: form of parameterisation, starting scale Q_0^2, treatment of heavy quarks, sea flavour composition, cuts on data etc.
→ should be reflected in the PDF uncertainty

H1 PDF 2000 QCD Analysis

H1 inclusive Neutral and Charged Current 94-00 cross sections

(Eur. Phys. J. C30 (2003), 1; hep-ex/0304003)

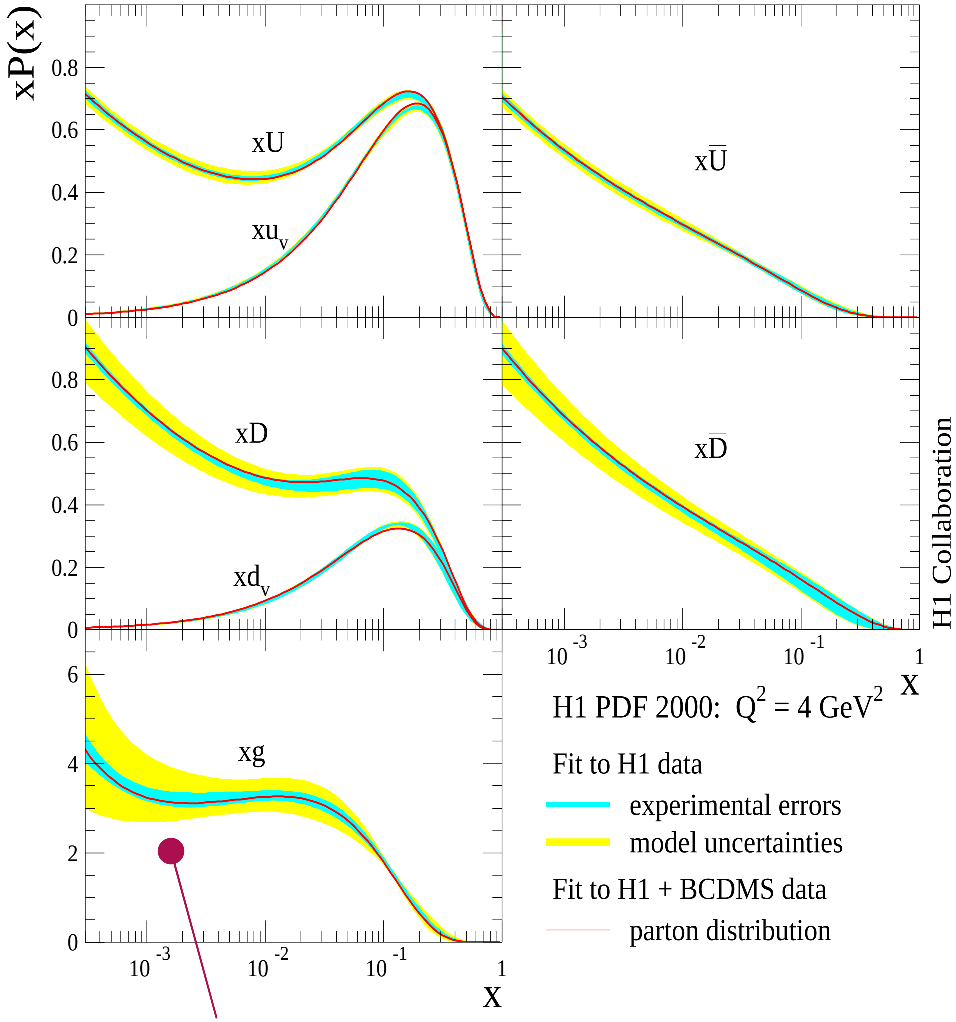
- Data span: 8 $10^{-5} < x < 0.65$, $1.5 < Q^2 < 30000$ GeV^2 (621 points)
  - Cuts on data included in fit, $Q^2 > 3.5$ GeV2
- Parameterisation at $Q^2_0 = 4$ GeV^2:
  - $xf(x) = A\, x^b\, (1-x)^c\, (1+ex+fx^2 + gx^3 + \ldots)$
- Choose to parameterise: $xU=x(u+c)$, $xD = x(d+s)$, $x\bar{U}$, $x\bar{D}$, xg
  - Valence not fitted directly
- Parameterise **each** PDF by searching for χ^2 saturation
- Perform fit in ZERO MASS scheme (appropriate for high Q^2)
- Use H1+BCDMS p and D data as a cross-check

H1 PDF 2000 QCD Analysis

10 free parameters:

$xU(x)=A_U x^{b_U}(1-x)^{c_U}(1+e_U x+g_U x^3)$
$xD(x)=A_D x^{b_D}(1-x)^{c_D}(1+e_D x)$
$x\bar{U}(x)=A_{\bar{U}} x^{b_{\bar{U}}}(1-x)^{c_{\bar{U}}}$
$x\bar{D}(x)=A_{\bar{D}} x^{b_{\bar{D}}}(1-x)^{c_{\bar{D}}}$
$xg(x)=A_g x^{b_g}(1-x)^{c_g}(1+e_g x)$

- Yellow band shows model uncert. with contributions from variation of:
  - input scale Q_0^2
  - minimum Q^2 cut
  - charm and strange fraction
  - quark masses
  - value of α_s
- Including precise BCDMS data yields consistent PDFs



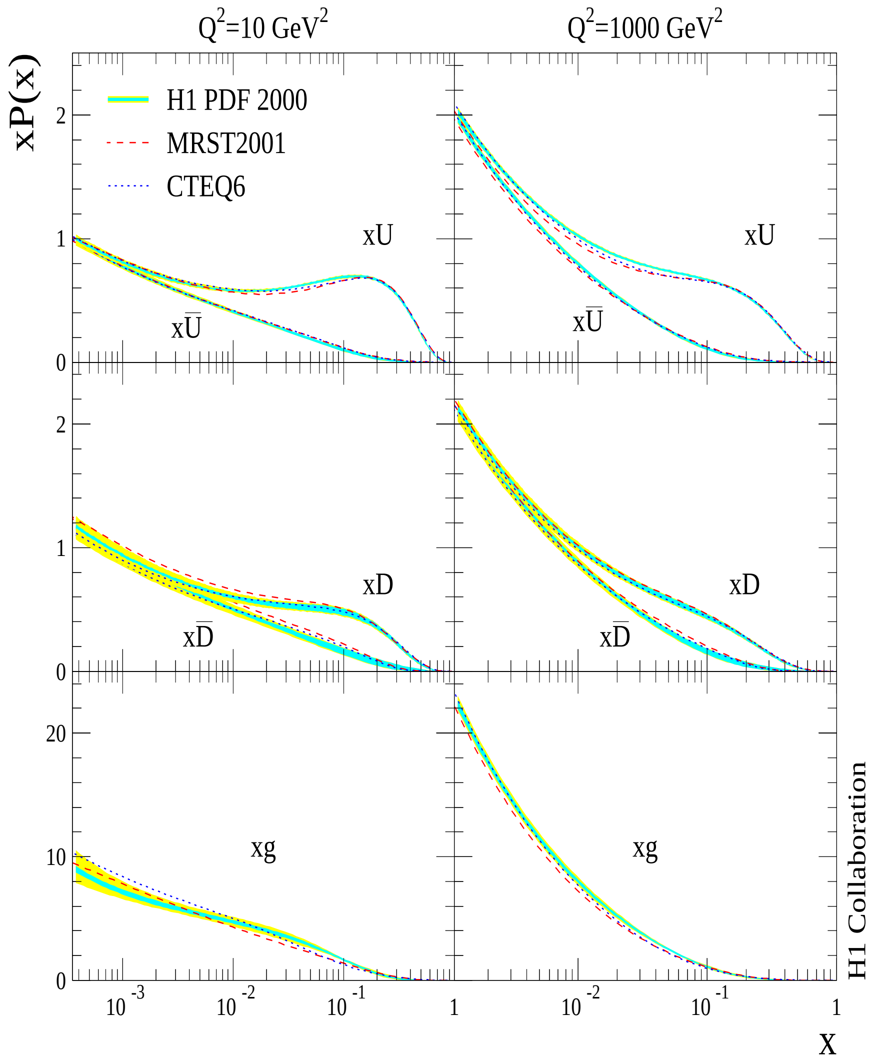
largest contribution to model uncertainty on gluon arises from variation of α_s

H1 PDF 2000 QCD Analysis

- Fit provides tight constraint on xU and xD:
  - → u-type quark precision:
    - 1% for x=0.001
    - 7% for x=0.65
  - → d-type quark precision:
    - 2%   for x=0.001
    - 30% for x=0.65

Look forward to higher luminosity for high-x region
→ HERA II data already here!

- Strong rise in gluon (and sea) as Q^2 increases

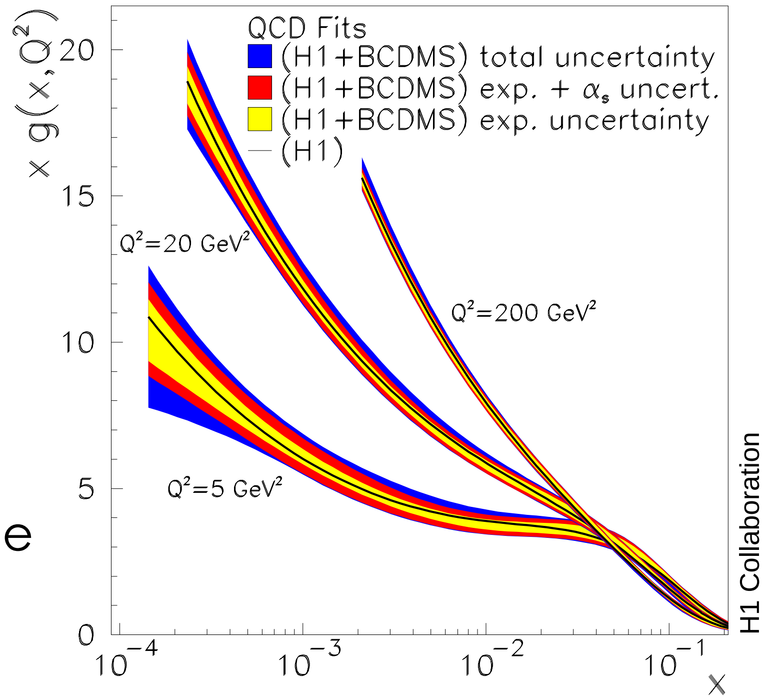


H1 Gluon and α_s Determination

- Perform dedicated QCD analysis to determine gluon density and α_s
- Use precise H1 and BCDMS-p F_2 data to constrain valence region
  - Proton targets only ⇒ no nuclear correction required
- Parameterisaton:
  - $xf(x)=Ax^b(1-x)^c(1+d\sqrt{x}+ex+fx^2)$

  Model uncertainty evaluation only
- Choose to parameterise:
  - xg
  - $xV = 9/4u_v + 3/2d_v$
  - $xA = u + 1/4(u_v+2d_v)$

  with $F_2= 1/3xV + 11/9xA$
- Use massive 3-flavour number scheme



- Extracted value of $\alpha_s(M_Z)$:

$\alpha_s(M_Z)= 0.1150 \pm 0.0017(\text{exp.})^{+0.0009}_{-0.0007}(\text{model})$ with scale uncertainty of 0.005

ZEUS Only QCD Analyses

Inclusive Neutral and Charged Current 94-00 cross sections
(contributed paper to ICHEP04, abstract: 5-0263)

- Data span $6.3\ 10^{-5} < x < 0.65$, $2.7 < Q^2 < 30000\ \mathrm{GeV}^2$ (507 points)
  - Cuts on data included in fit, $W^2 > 20\ \mathrm{GeV}^2$ (removes higher twist)
- Parameterisation at $Q^2_0 = 7\mathrm{GeV}^2$:
  - $xf(x) = A\, x^b\, (1-x)^c\, (1+ ex)$ ← no χ^2 advantage in more terms
- Choose to parameterise xu_v, xd_v, xS (sea), xg, $x\Delta = x(\bar{d}-\bar{u})$
  - fix A_Δ consistent with Gottfried sum rule (no sens. in HERA data)
- Perform fit in Roberts-Thorne Variable Flavour No. scheme

Compared to global fits, information lost on high-x sea and gluon:

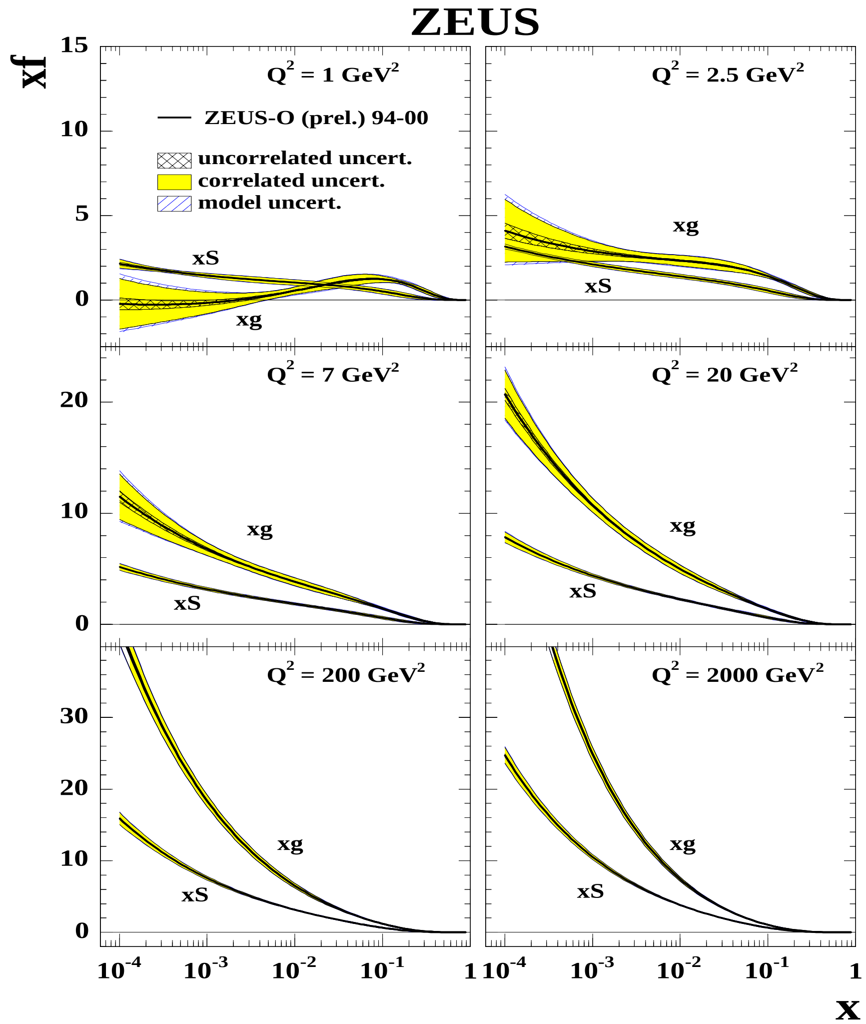
→ Use ZEUS global fit to constrain high-x sea and gluon (c_S & c_g)

ZEUS Only QCD Fit: Sea and Gluon

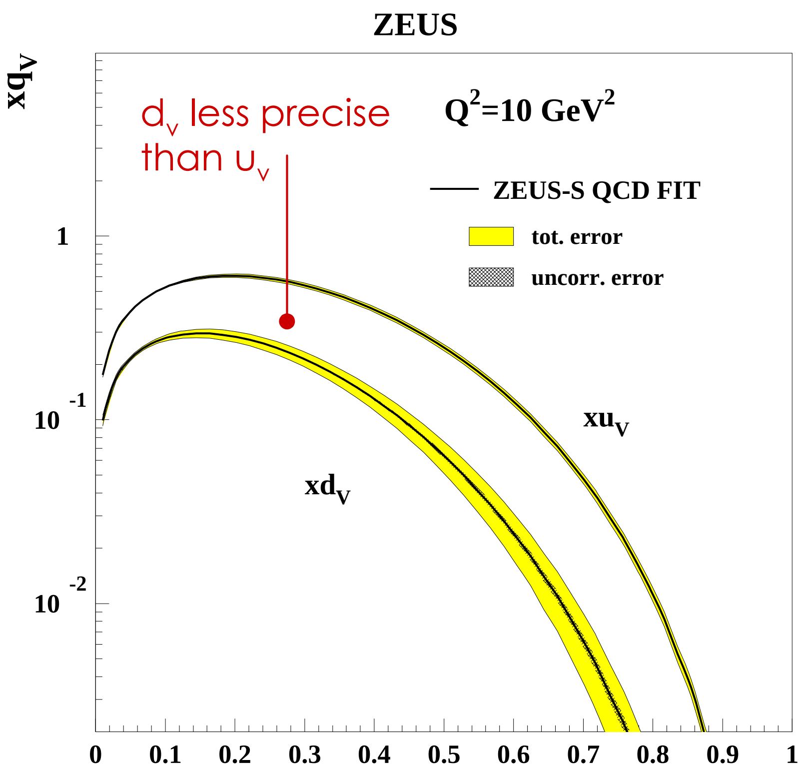
- Blue hatched band represents model uncertainties with contributions from varying:
  - Starting scale Q_0^2
  - Form of parameterisation
  - Values of c_g and c_S

- Compatible with global fits (see later)

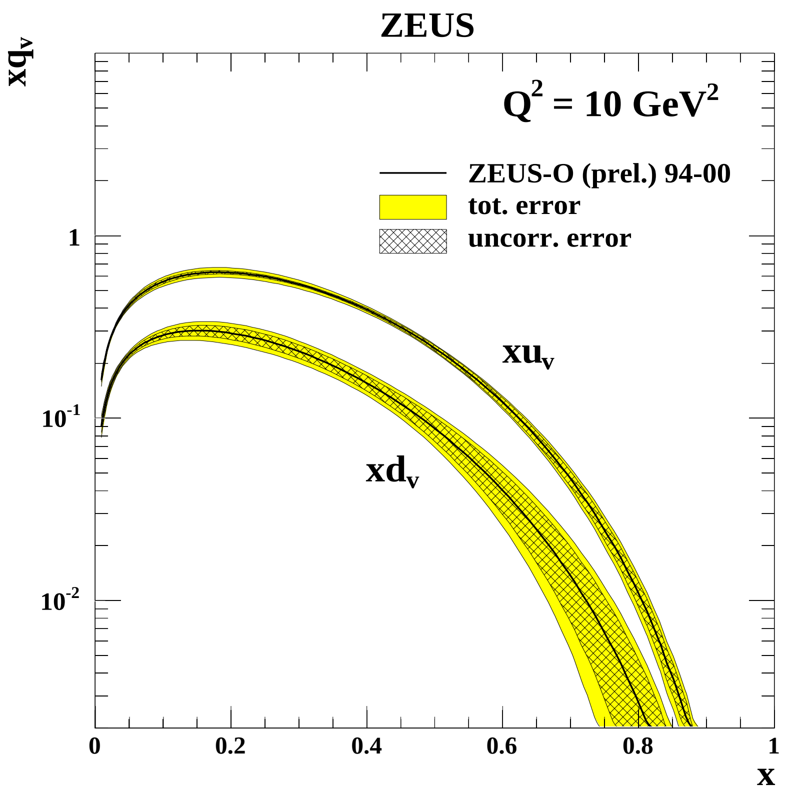
  → low-x information comes from HERA data anyway



ZEUS Only QCD Fit: Valence



ZEUS Global Fit



ZEUS Only Fit

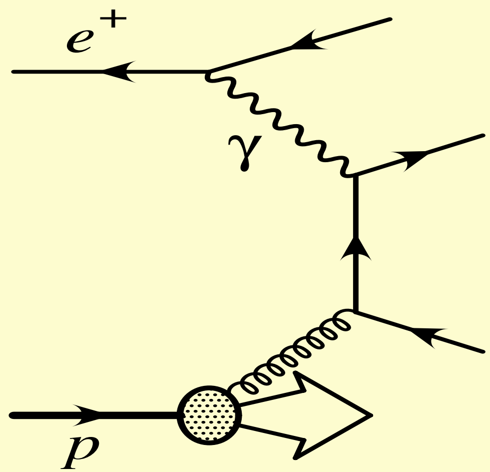
- Information in HERA Only fits from high Q^2 NC/CC data
  - → Comparable to global fit BUT now more **potential for improvement**
    - — now use proton target data only (particularly important for d_v)
      - Uncertainties are statistics dominated → improvement from HERA II

ZEUS JETS QCD Analysis

Inclusive Neutral and Charged current cross sections + JET DATA

Jet cross sections directly sensitive to gluon through Boson-Gluon-Fusion process →

- sensitivity of included data: x ~ 0.01- 0.1



DIS: $Q^2 >> 1\ GeV^2$
γp: $Q^2 \sim 0\ GeV^2$

Two data-sets from 96-97 ($\sim 40 pb^{-1}$):

1. Inclusive jet DIS data ($Q^2 > 125\ GeV^2$
2. Two-jet γp ($Q^2 \sim 0\ GeV^2$, $E_T > 14,11\ GeV$)

- Same assumptions/parameterisation as ZEUS Only EXCEPT:

— now have direct information on gluon ⇒ retain all of b_g, c_g and e_g **free**

Addition of Jet Data: The Method

A full NLO calculation for jet cross sections, for each iteration of the χ^2 minimisation, would be prohibitively slow

1. Use NLO QCD program **initially**, to produce grid of weights in (x,μ_F^2), giving perturbatively calculable part of cross section

2. Convolute with PDFs to produce fast prediction for cross section:

$$\sigma = \sum_{a=g,q,\bar{q}} \int dx\, \alpha_s^n(\mu_R)\, c_{a,n}(x,\mu_F^2)\, f_a(x,\mu_F^2) \times (1+\delta_{had})$$

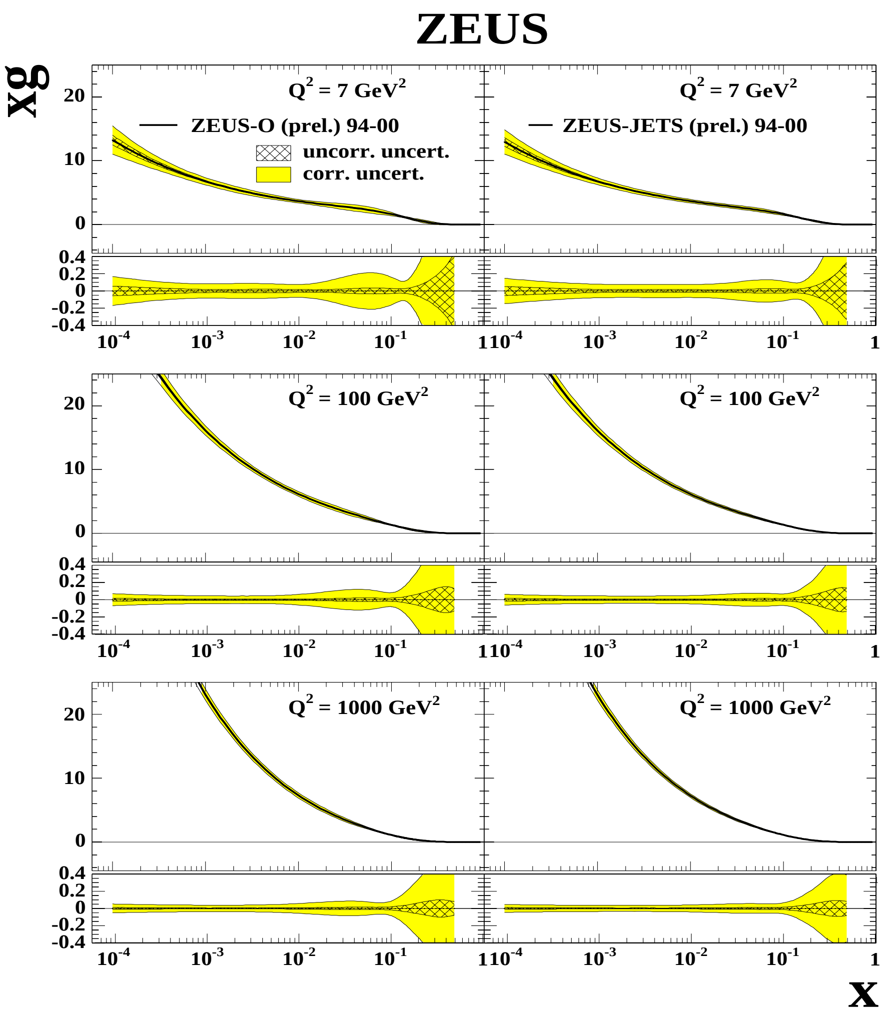
$c_{a,n}$= weight ; f_a= PDF of parton a ; $(1+\delta_{had})$= hadronisation correction

Grid cross sections reproduce real NLO predictions to better than 0.5%

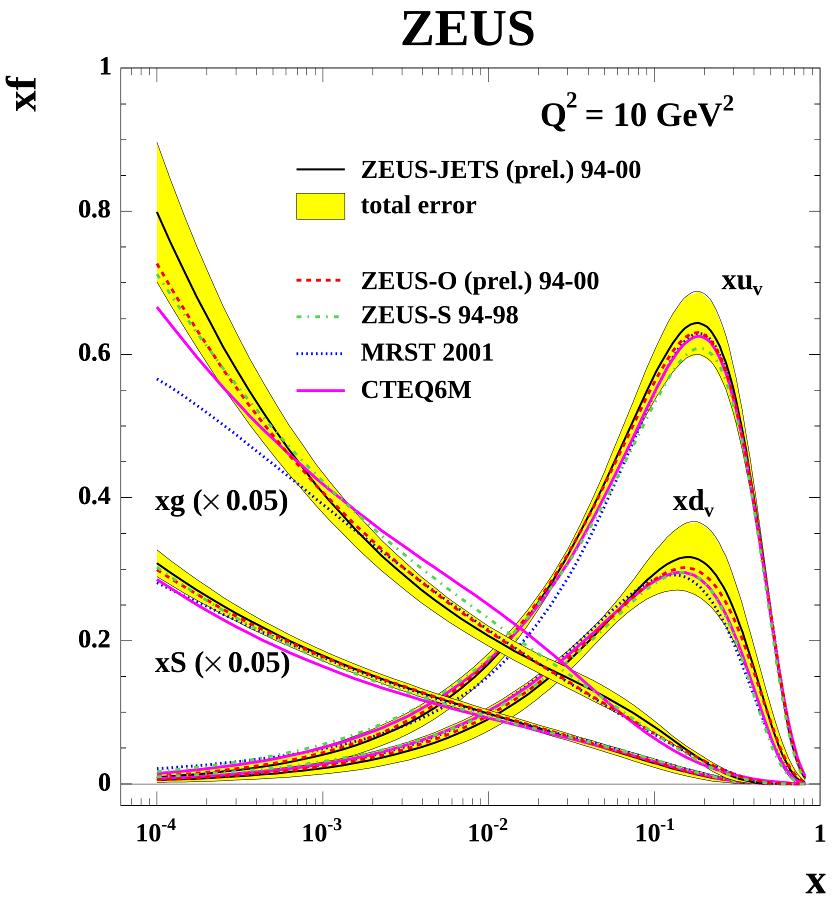
Gluon Distribution

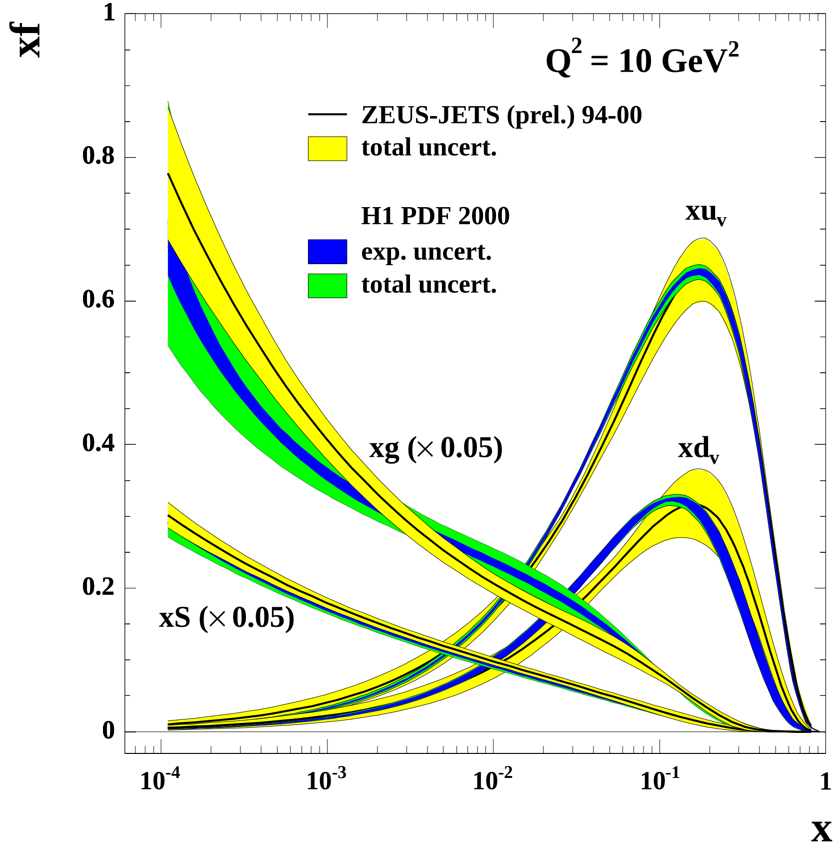
$$xg(x) = A_g x^{b_g} (1-x)^{c_g} (1+e_g x)$$

- Compare to equivalent fit without jet data
  → Significant improvement in determination of gluon at mid-to-high-x
    - persists to high scales



ZEUS-JETS versus Other PDFs



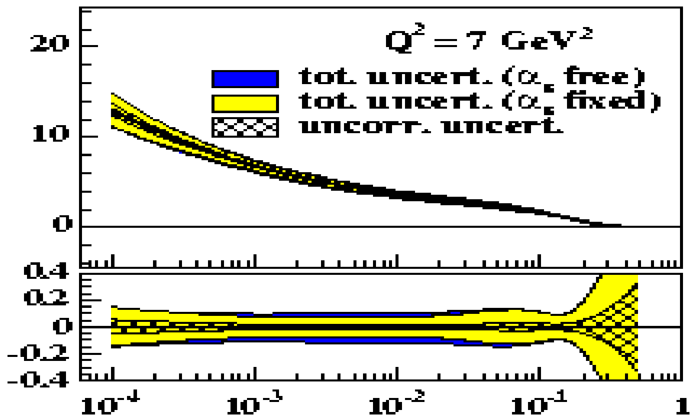


ZEUS-JETS: χ^2/ndf = 0.83

- Compatible with other fits given different data and fitting schemes

Extraction of α_s from ZEUS-JETS Fit

- Extra information on gluon allows a competitive determination of α_s using only HERA data ⇒ treat α_s as free parameter in fit
  - → leads to larger uncertainty on gluon (represented by blue band)



SOURCES OF UNCERTAINTY ON α_s

uncorr:	Statistical and uncorrelated systematic uncertainties
corr:	Correlated systematics
model:	Model uncertainties

$\alpha_s(M_Z) = 0.1183 \pm 0.0007(\text{uncorr.}) \pm 0.0027(\text{corr.}) \pm 0.0008(\text{model})$

— additional scale uncertainty: 0.005

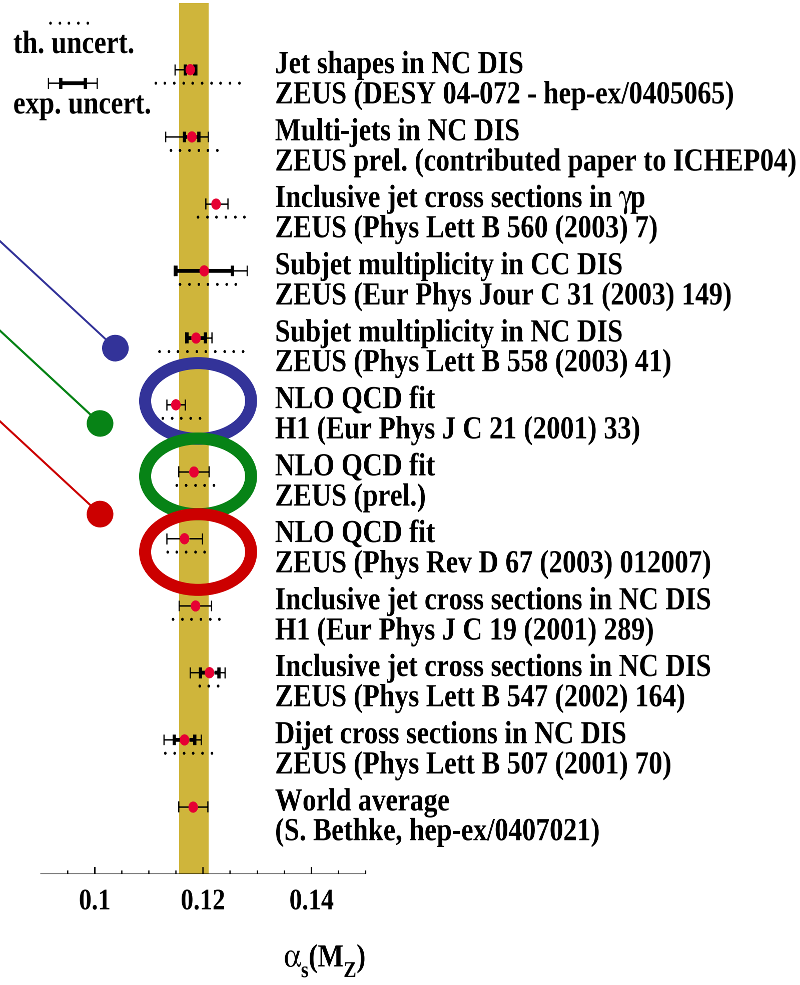
Summary of HERA α_s Measurements

Three competitive extractions of $\alpha_s(M_Z)$ from HERA QCD fits

→ H1+ BCDMS

→ ZEUS-JETS

→ ZEUS Global (not discussed here)



QCD Fit	$\alpha_s(M_Z)$
H1+BCDMS	$0.1150 \pm 0.0017(\text{exp.})^{+0.0009}_{-0.0007}(\text{model})$
ZEUS-JETS	$0.1183 \pm 0.0028(\text{exp.}) \pm 0.0008(\text{model})$
ZEUS Global	$0.1166 \pm 0.0049(\text{exp.}) \pm 0.0018(\text{model})$

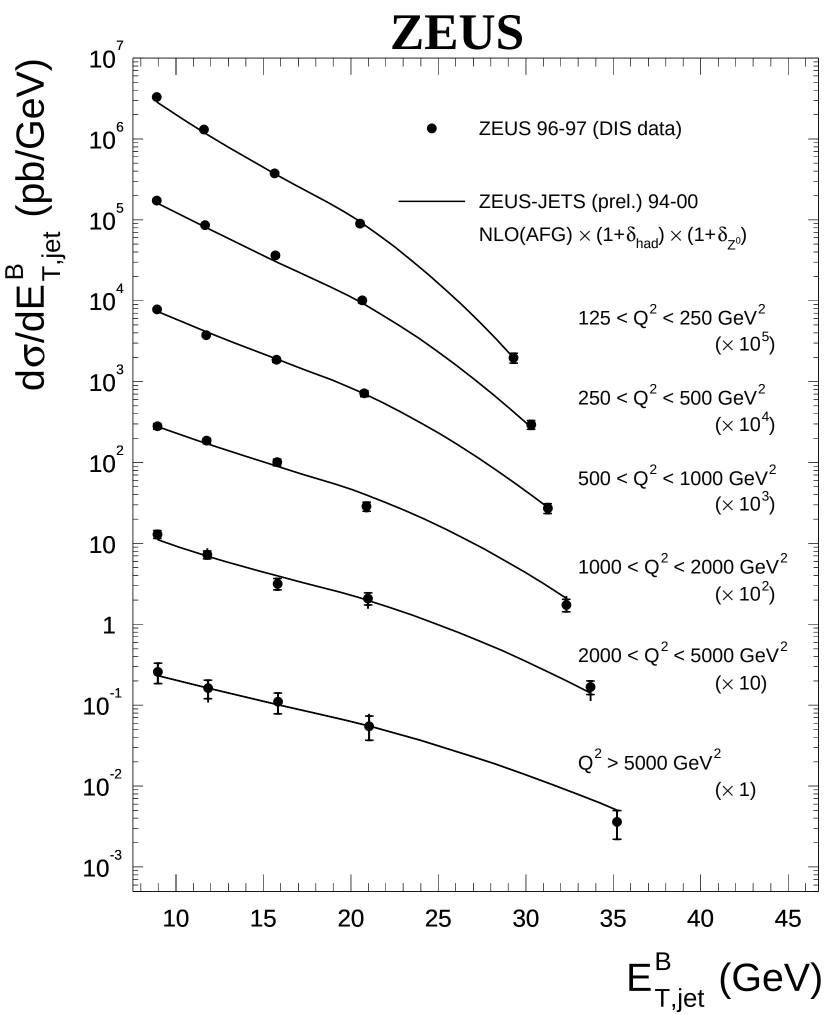
- Limiting factor in the precision are the scale uncertainties (~0.004-0.005)
  - → NNLO analyses are expected to significantly reduce these

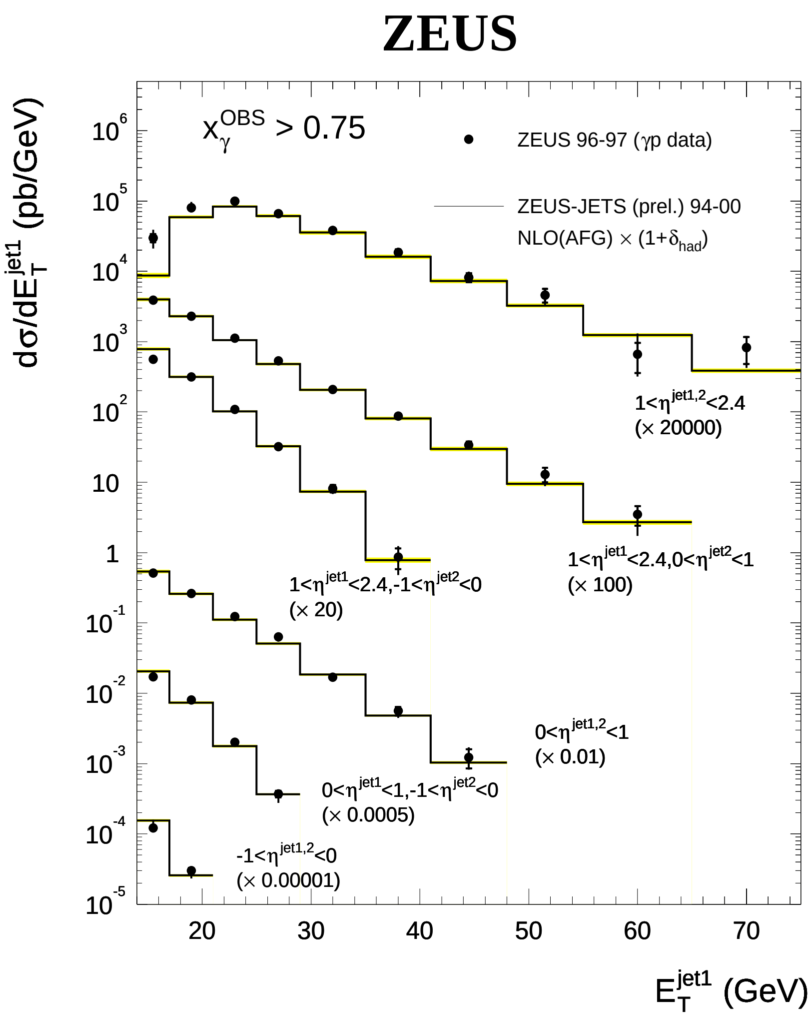
Summary and Outlook

- Proton PDFs extracted by H1 and ZEUS using HERA data alone
  - Using only pure proton target data avoids uncertainties due to heavy target corrections (particularly important for d-valence)
  - Uncertainties arising from combining systematics from different experiments are reduced in HERA Only fits
- Jet data have been added in an independent ZEUS QCD fit
  - Significant improvement to constraint of gluon at mid-to-high-x
- Precise extractions of α_s from HERA QCD analyses
- Look forward to HERA II data for:
  - more precise valence (xF_3 from NC/ flavours from CC)
  - more precise high-x sea
  - LOW ENERGY RUNNING AT HERA II ? For higher-x and for gluon (F_L)

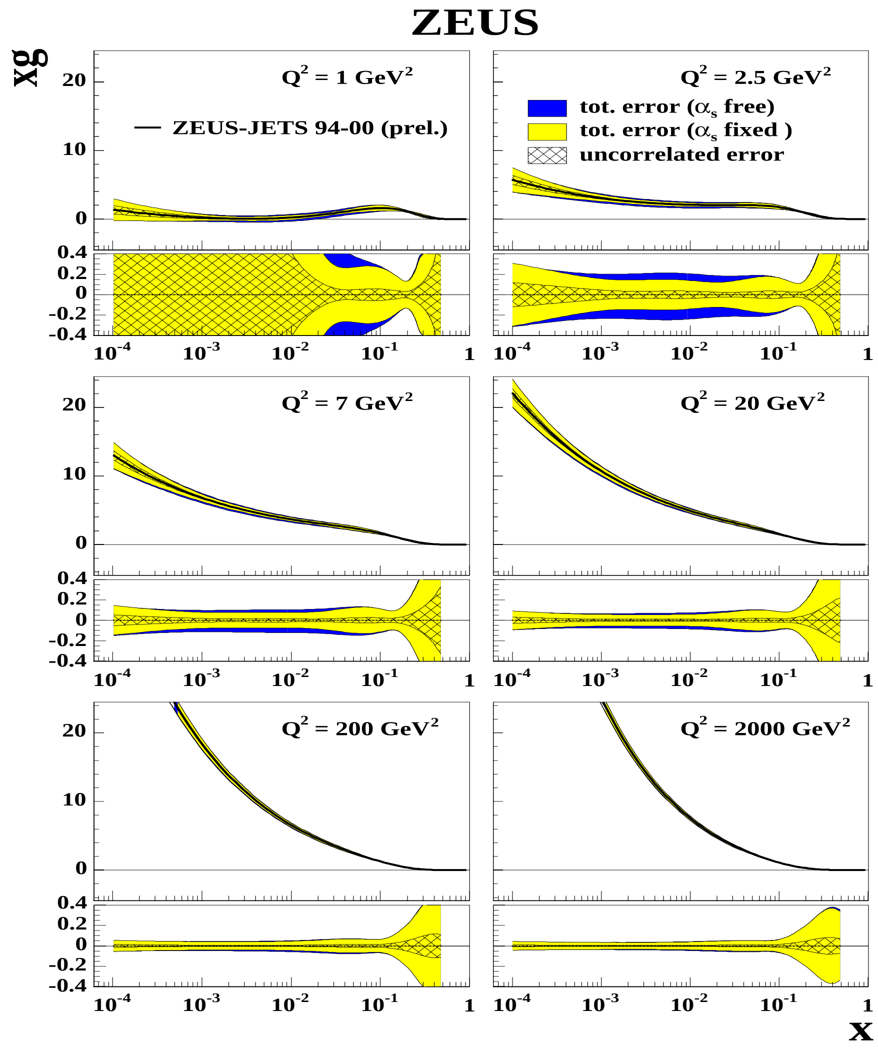
Extras …

ZEUS-JETS: Comparison with Data





Full ZEUS-JETS Fit Gluon Summary



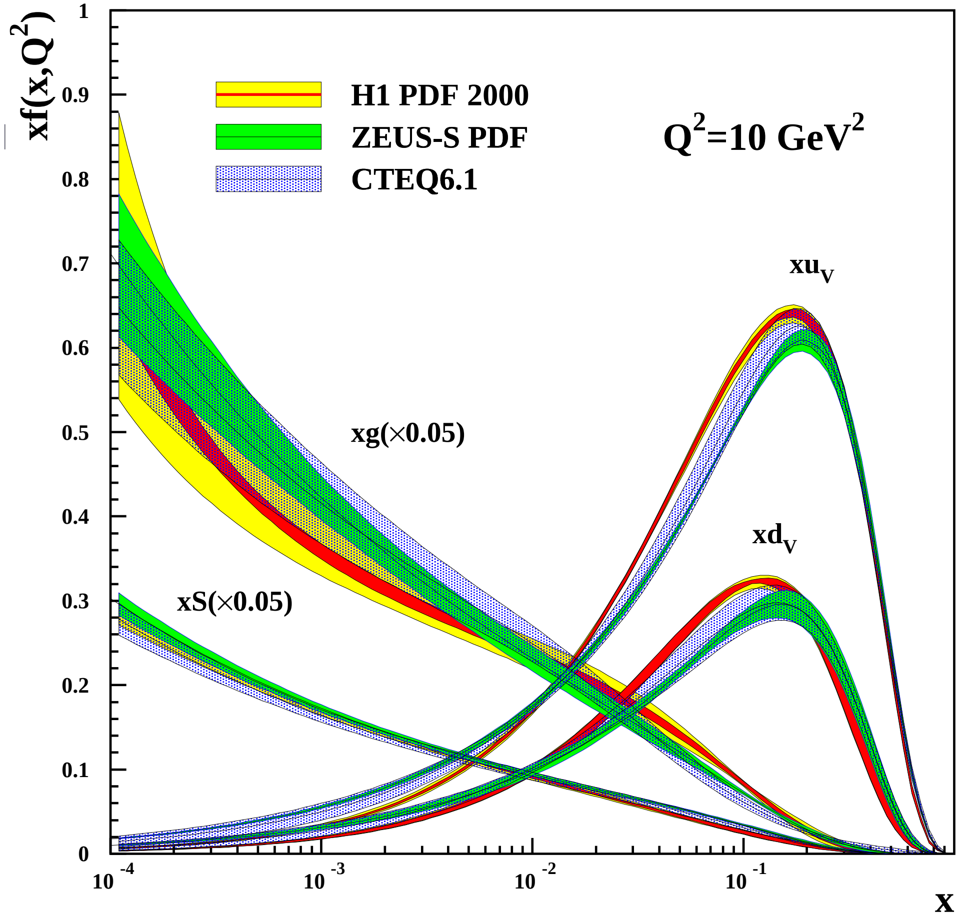
PDF Determination in QCD Analyses

- Provided the structure of the electroweak interaction is well understood, perturbative QCD can be used to extract parton densities (or any other parameter entering the cross section e.g. α_s) using QCD evolution

Now, after the HERA I phase (1994-2000) of data-taking, the full set of e^+ and e^- inclusive Neutral Current (NC) and Charged Current (CC) cross sections are available for QCD analysis

HERA II results already here $\rightarrow$ to be used in future QCD analyses

H1 PDF 2000 versus Global Fits



H1PDF 2000: χ^2/ndf=0.88

- Reasonable agreement between fits given the different data and fitting schemes
- CTEQ generally lies between H1 PDF 2000 and the ZEUS global fit