A ZEUS NLO QCD analysis of data on deep inelastic scattering

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Aim of the Analysis

To assess the impact, in a global NLO DGLAP analysis, of the HERA I ZEUS DIS NC and CC incl. cross sections

In particular:

- Precise determination of the proton's sea and gluon densities
- Simultaneous fit of the Pdfs and strong coupling constant
- Applicability of the pQCD DGLAP Fit in the low Q^2 region
  - Realistic estimation of the unc. on the PDFs

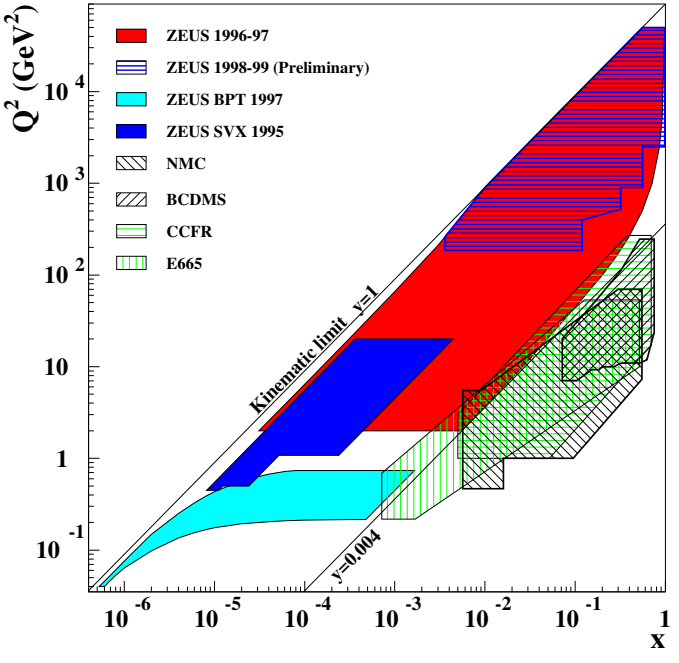
How good alone we are...

- Feasibility of a ZEUS-Only Fit
- Valence PDFs from the high-Q^2 DIS NC and CC cross sections

QCD analysis: Data sets

ZEUS-Standard and ZEUS-α_s Fits:

- Muon-induced F_2 from BCDMS, NMC, E665
- Deuterium-target data from NMC and E665
  → u, d separation
- The NMC data on the ratio F_2^D / F_2^p
  → u_v / d_v
- CCFR xF_3 data (NB $0.1 < x < 0.65$)
  → u_v, d_v at high x
- ZEUS 96-97 NC cross sections



ZEUS-Only Fits:

- All NC and CC inc. cross sections
  (published or preliminary)

Applied cuts:

$Q^2 > 2.5$ GeV^2 and $W^2 > 20$ GeV^2

Kinematical region:

$6.3 \times 10^{-5} < x < 0.65$

$2.5 < Q^2 < 30\,000$ GeV^2

QCD Analysis: DGLAP evolution

Evolution performed in terms of non-singlet, singlet and gluon densities:

$$\frac{\partial}{\partial \ln \mu_F^2} q_{NS}^{\pm} = P_{NS}^{\pm} \otimes q_{NS}^{\pm}$$

$$\frac{\partial}{\partial \ln \mu_F^2} \begin{Bmatrix} \Sigma \\ g \end{Bmatrix} = \begin{Bmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{Bmatrix} \otimes \begin{Bmatrix} \Sigma \\ g \end{Bmatrix} = \boldsymbol{P} \otimes q$$

Program: QCDNUM

- Two loops splitting functions and α_s :

$$\boldsymbol{P}(x) = a_s \boldsymbol{P}^{(0)}(x) + a_s^2 [\boldsymbol{P}^{(1)}(x) - \beta_0 \ln \frac{\mu_F^2}{\mu_R^2} \boldsymbol{P}^{(0)}(x)] \quad \text{with} \quad a_s = \frac{\alpha_s(\mu_R^2)}{4\pi}$$

$$\frac{d\ a_s}{d \ln \mu_R^2} = \beta(a_s) = -\sum_{l=0}^{\infty} a_s^{l+2} \beta_l \simeq a_s^2 \beta_0 + a_s^3 \beta_1 \quad \text{where} \quad \beta_0 = 11 - \frac{2}{3} N_F \ , \ \beta_1 = 102 - \frac{38}{3} N_F$$

- $\overline{\text{MS}}$ scheme with $\mu_R = \mu_F = Q$ (μ_R and μ_F varied in the model unc. study)

QCD Analysis: PDFs parameterisation

Parameterise PDFs at $Q_0^2 = 7\,\mathrm{GeV}^2$:

$$\left\{ \begin{array}{lcl} xg & & \\ xS & \equiv & 2x(\bar{d}+\bar{u}+\bar{s}+\bar{c}) \\ x\,\Delta & \equiv & x(\bar{d}-\bar{u}) \\ xd_V & \equiv & x(d-\bar{d}) \\ xu_V & \equiv & x(u-\bar{u}) \end{array} \right\} = p_1\, x^{p_2}(1-x)^{p_3}(1+p_4\sqrt{x}+p_5\,x)$$

Impose number and momentum sum-rules:

$$\int_0^1 (xg + x\Sigma)\,dx = 1, \quad \int_0^1 d_V\,dx = 1, \quad \int_0^1 u_V\,dx = 2$$

with $x\Sigma = xS + xu_V + xd_V$

This fixes p_1 for xu_V , xd_V and xg

Assume:

$$2\,x\bar{s} = 0.2\,x\,S$$

- p_2=0.5 for both valence dist.
- p_1 only free param. for xΔ

  $p_2(\Delta)=0.5$, $p_3(\Delta)=p_3(S)+2$, $p_5(\Delta)=0$
- p_5= 0 for xg

all these assumptions were varied during model unc. study

Observables and heavy-flavours treatment

QCD observables (F_2 , reduced cross sections) are obtained via a convolution of PDFs with coefficient functions.

e.g: singlet NLO QCD electromagnetic structure function F_2^{em} :

$$F_{2,S}(x,Q^2) = x\overline{e^2}\left[C_{2,q}(a_s,L_M)\otimes\Sigma + C_{2,g}(a_s,L_M)\otimes g\right] = \left[\boldsymbol{C}_2(a_s,L_M)\otimes\boldsymbol{q}\right]$$

where $\boldsymbol{C_2}(x,L_M) = \boldsymbol{C}_a^{(0)}(x) + a_s\boldsymbol{C}_a^{(1)}(x,L_M) + \ldots$ with $L_M = \ln\dfrac{Q^2}{\mu_F^2}$

The coefficient functions are specific to the HF formalism used...

In this analysis the scheme of Thorne and Roberts (TR-VFN) has been used to conveniently interpolate between the FFN and ZM-VFN schemes

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Cross-checked using FFN and ZM-VFN

QCD Analysis: PDFs Uncertainties

Model prediction for $F_i = F(x_i, Q_i^2)$:

$$F_i(p, s) = F_i^{QCD}(p) + \sum_j s_j \Delta_{ij}^{syst}$$

F_i^{QCD} = NLO QCD prediction
Δ_{ij} = correlated syst. uncert. from source j
p = set of fitted parameters
s_j = systematic parameters, i.i.d. $s_j \sim N(0,1)$

Least square fit:

$$\chi^2 = \sum_i \frac{[F_i(p, s) - F_i^{meas}]^2}{(\sigma_{i,stat}^2 + \sigma_{i,unc}^2)} + \sum_j s_j^2$$

s_j fixed to zero in the minimisation

Error analysis:

$$M_{ij} = \frac{1}{2}\frac{\partial^2 \chi^2}{\partial p_i \partial p_j} \quad , \quad C_{ij} = \frac{1}{2}\frac{\partial^2 \chi^2}{\partial p_i \partial s_j}$$

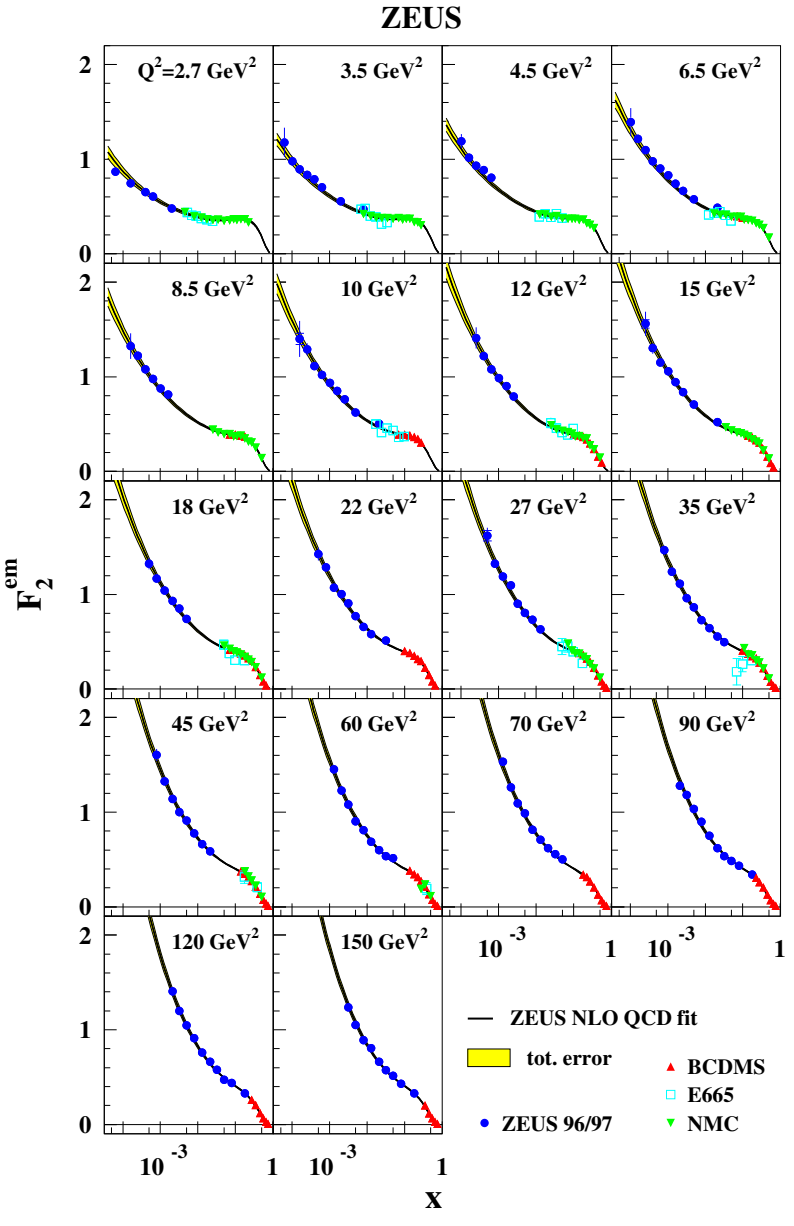
$$V^{stat} = M^{-1} \qquad V^{syst} = M^{-1} C C^T M^{-1}$$

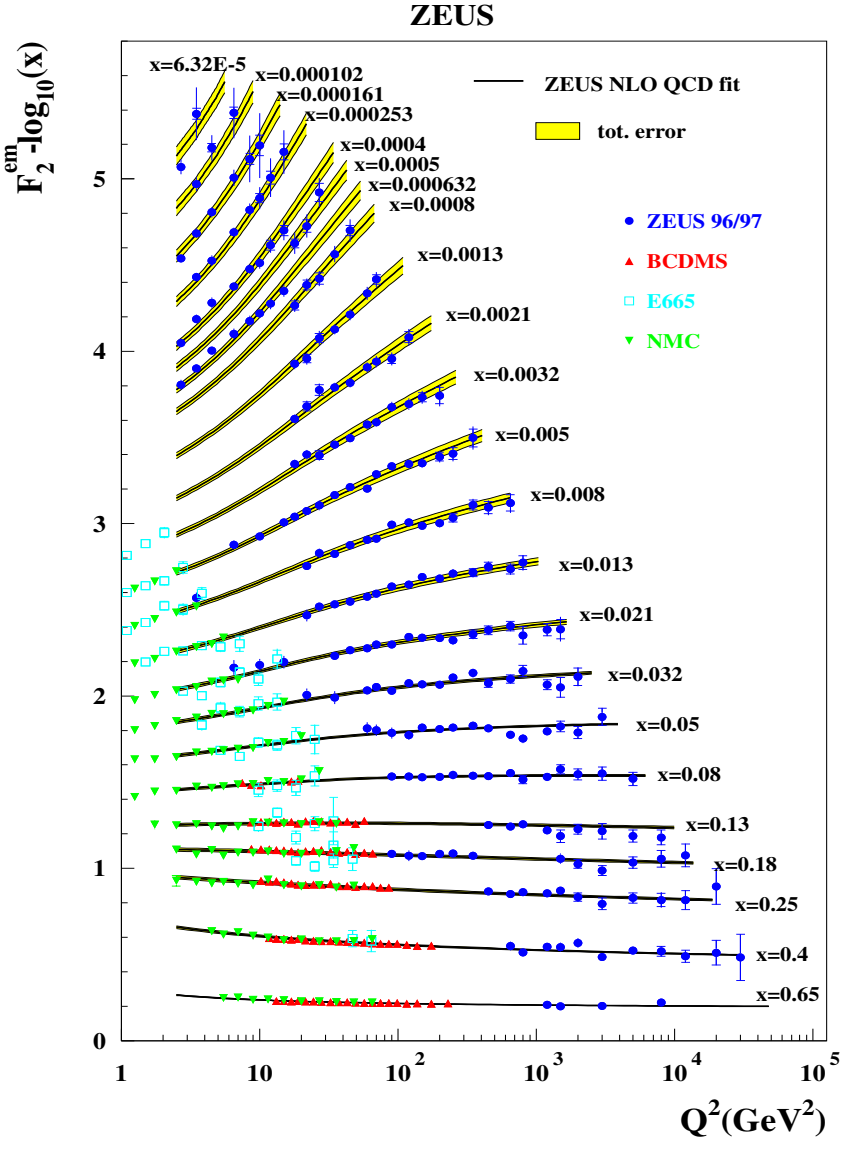
$$\overline{\Delta F}^2 = \sum_i \sum_j \frac{\partial F}{\partial p_i} V_{ij} \frac{\partial F}{\partial p_j}$$

where $V_{ij} = V_{ij}^{stat}, V_{ij}^{syst}$ or $V_{ij}^{tot} = V_{ij}^{stat} + V_{ij}^{syst}$

- normalisation of the data sets taken as published (except BCDMS ↓ 2 %)
- 71 independent sources of syst uncertainties (including normlisations unc.)

F_2^{em}





The fit gives an excellent description of the high-precision ZEUS and fixed target data.

QCD Analysis: goodness of fit

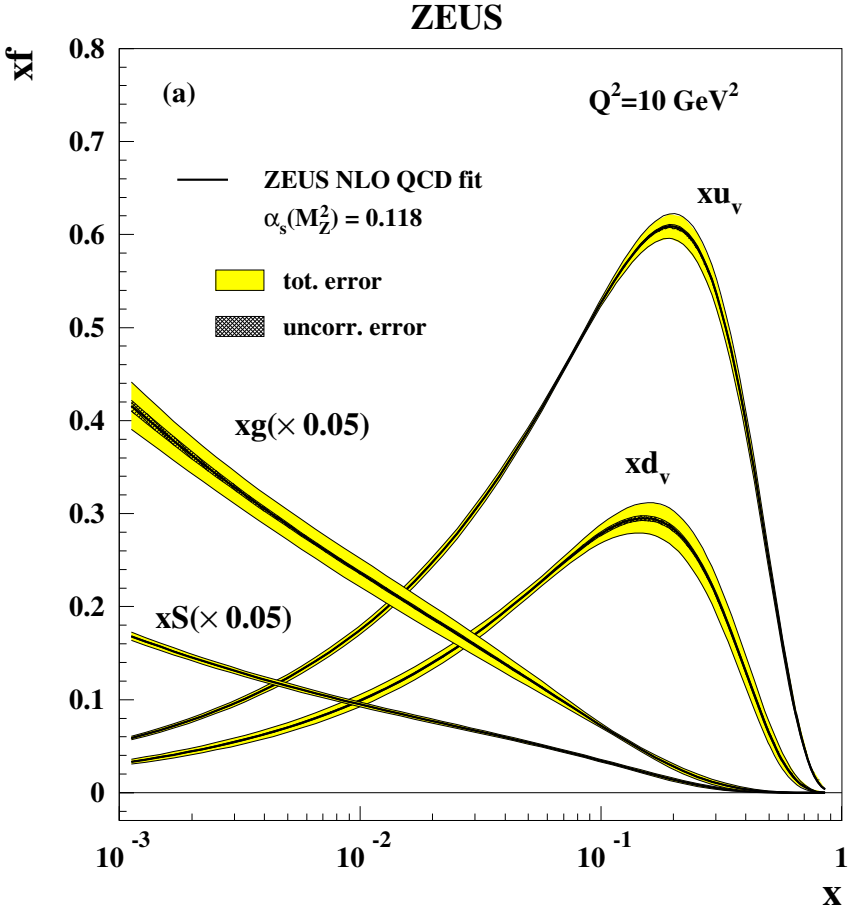
Total χ^2 per data point 0.95 (1263 data points, 11 parameters):

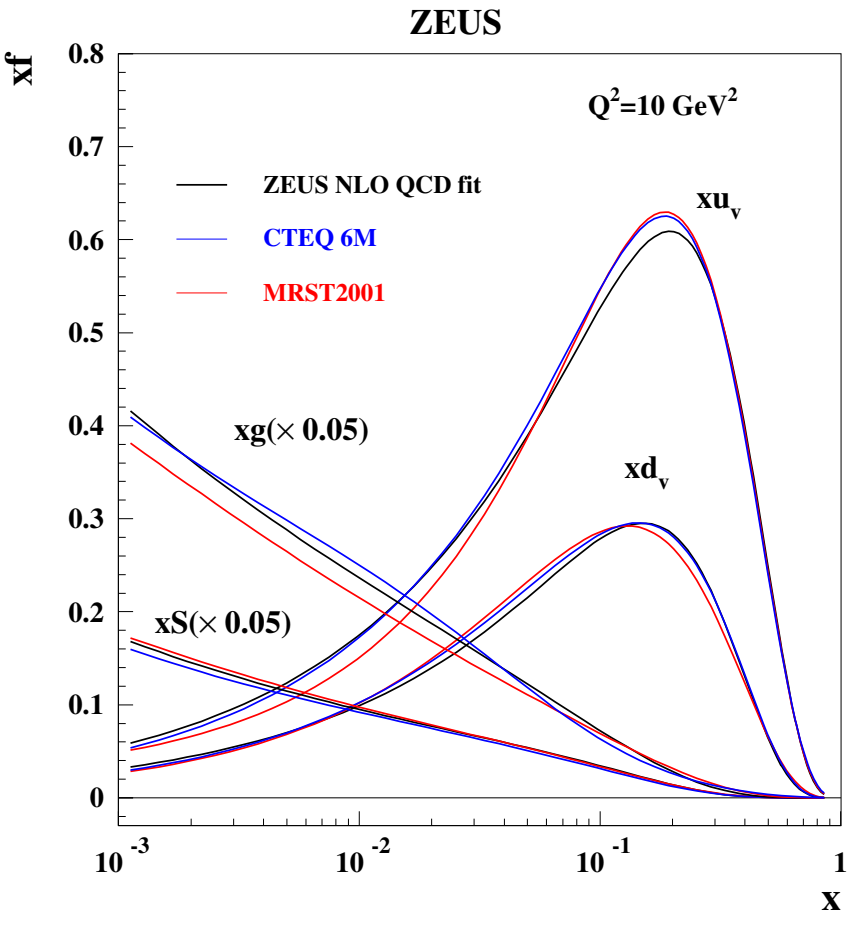
Experiment	Number of data points	χ^2 per data points	Number of correlated systematic uncertainties	Number of normalisation uncertainties
ZEUS 96/97	242	0.85	10	2
BCDMS p	305	0.94	5	5
NMC p	218	1.21	12	4
NMC D	218	0.92		
NMC D/p	129	0.94	5	0
E665 D	47	0.94	7	2
E665 p	47	1.16		1
CCFRxF3	57	0.40	18	0

PDFs parameters at Q_0^2 as determined from the ZEUS-Standard fit

PDF	p_1	p_2	p_3	p_5
xu_v	$(1.69 \pm 0.01 \pm 0.06)$	0.5	$4.00 \pm 0.01 \pm 0.08$	$5.04 \pm 0.09 \pm 0.64$
xd_v	$(0.96 \pm 0.01 \pm 0.08)$	0.5	$5.33 \pm 0.09 \pm 0.48$	$6.2 \pm 0.4 \pm 2.3$
xS	$0.603 \pm 0.007 \pm 0.05$	$-0.235 \pm 0.002 \pm 0.01$	$8.9 \pm 0.2 \pm 1.2$	$6.8 \pm 0.4 \pm 2.0$
xg	$(1.77 \pm 0.09 \pm 0.49)$	$-0.20 \pm 0.01 \pm 0.04$	$6.2 \pm 0.2 \pm 1.2$	0
$x\Delta$	$0.27 \pm 0.01 \pm 0.06$	0.5	$(10.9 \pm 0.2 \pm 1.2)$	0

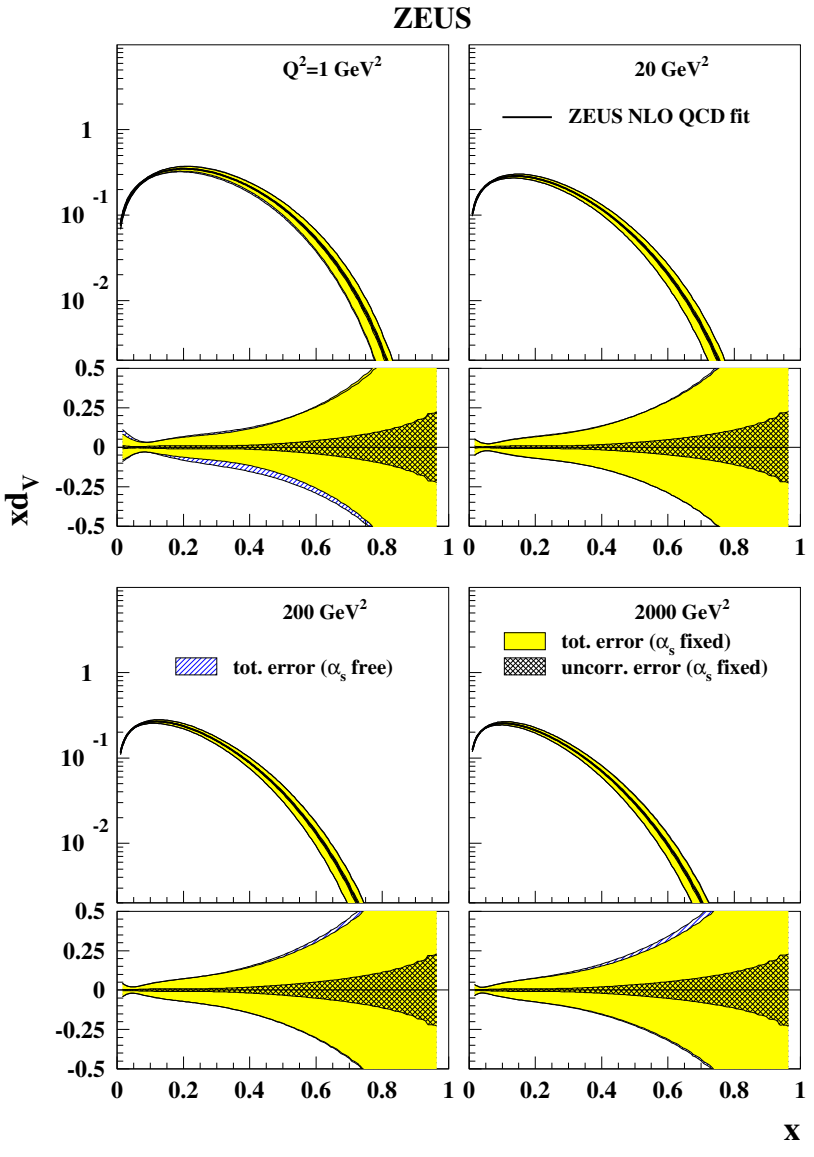
The ZEUS PDFs

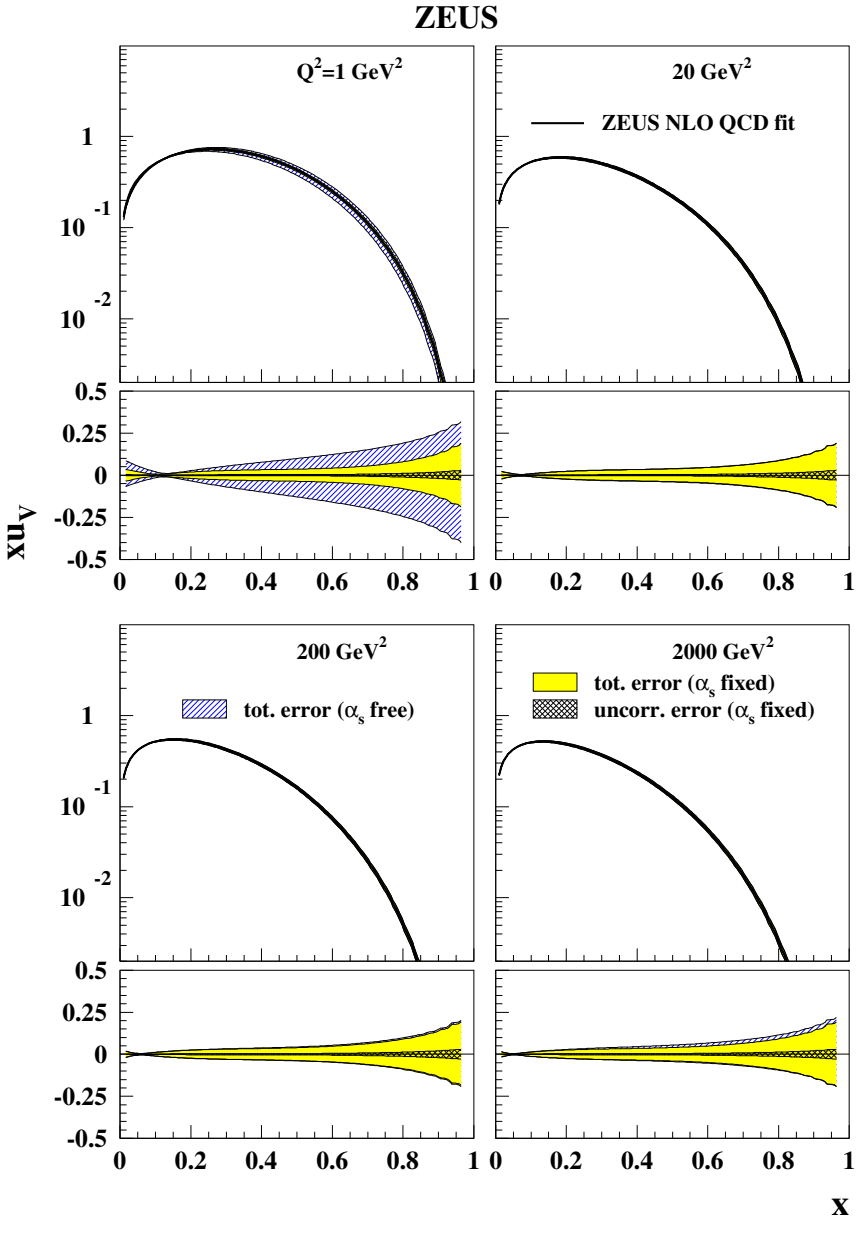




- Strong coupling fixed to the PDG value
- Improved accuracy respect to previuos analyses based on 94-95 data
- Agreement with the recent MRST and CTEQ analyses

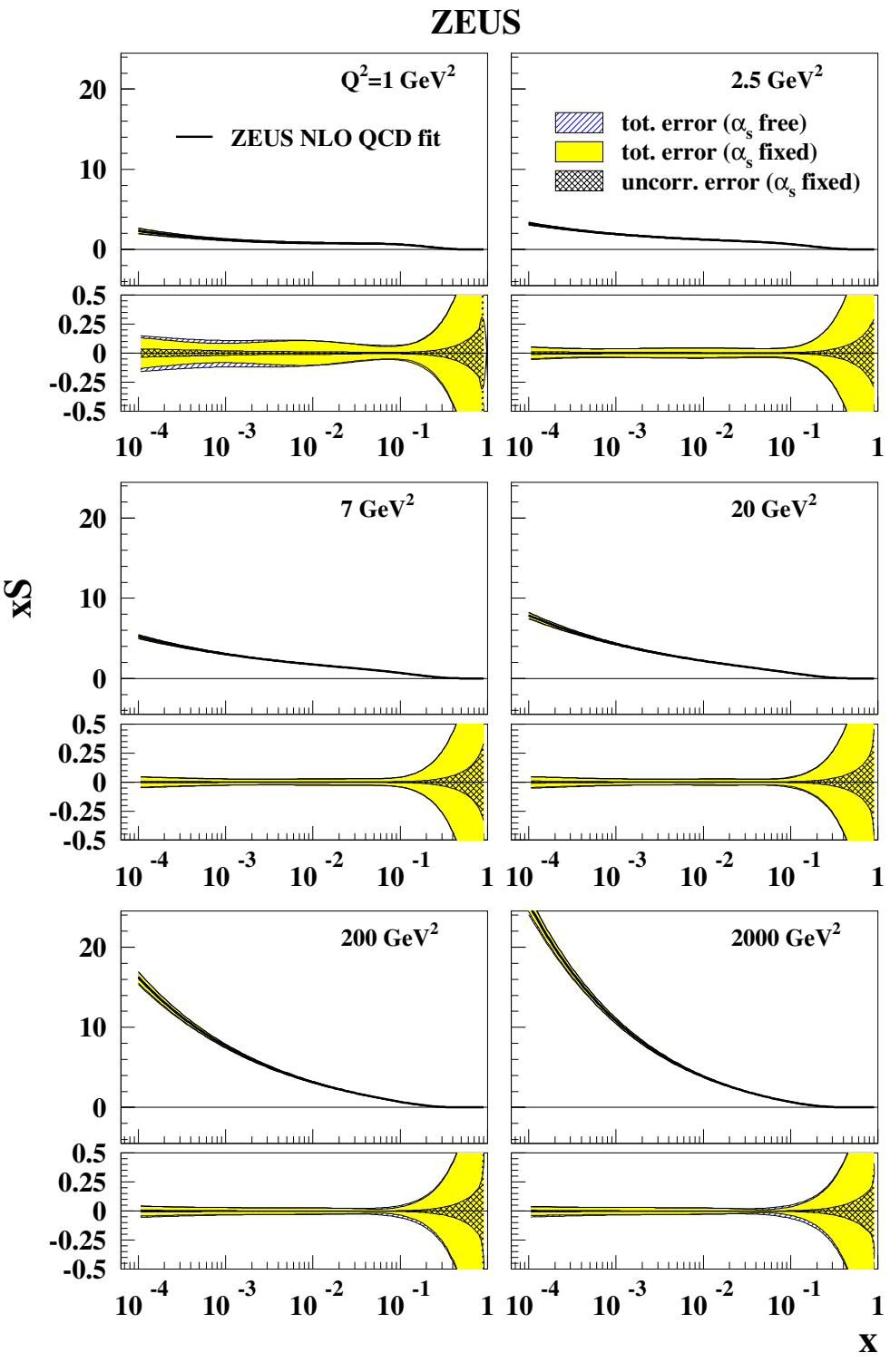
valence: xd_v , xu_v





xu_v much better determined than xd_v

(fixed-target data more sensitive to xu_v)

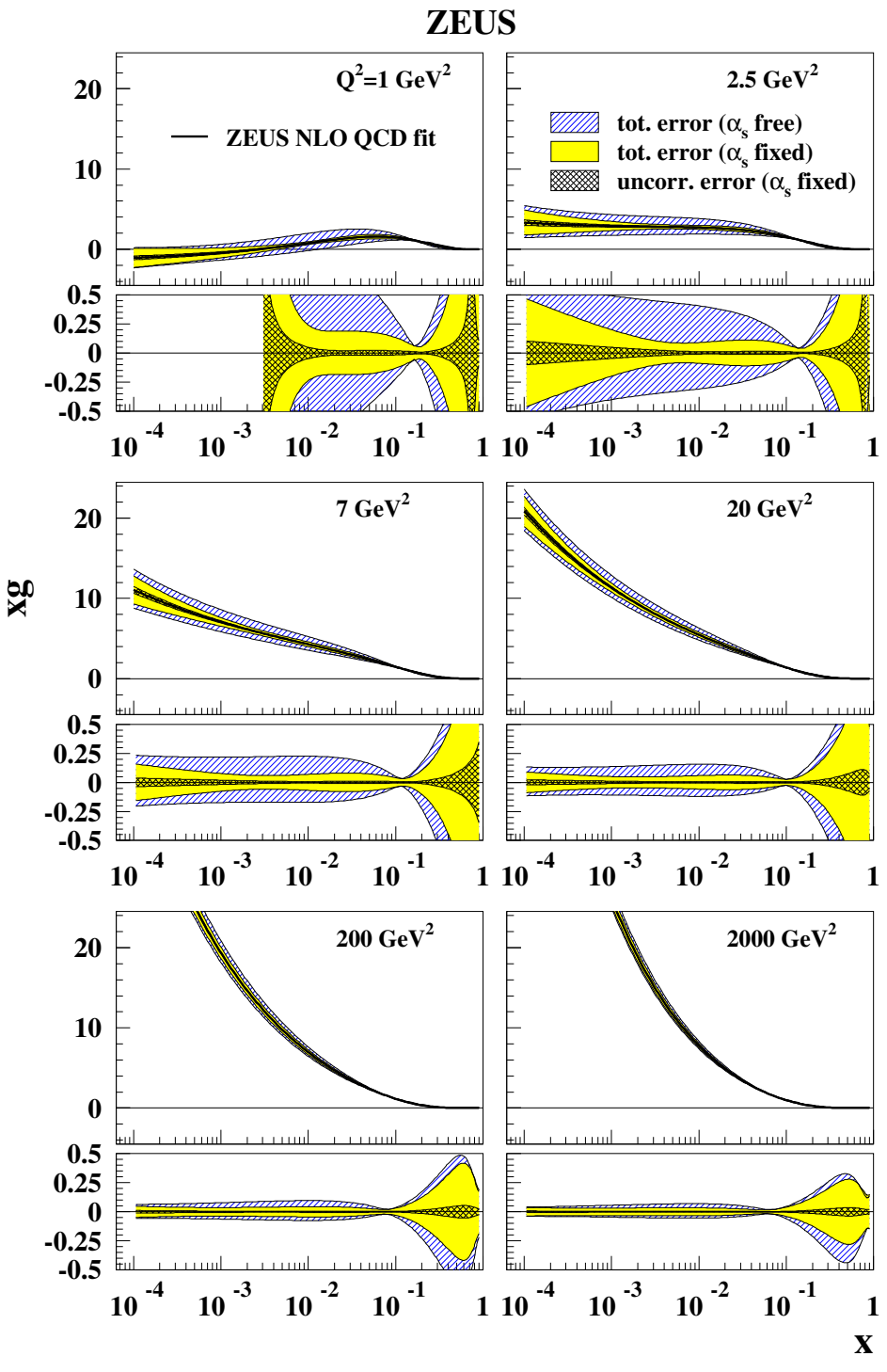


Sea

Uncertainty on xS is ≤ 5% for $Q^2 > 2.5$ GeV^2 and $10^{-4} < x < 10^{-1}$

Rise persists even when the the fit is extrapolated back to $Q^2 = 1$ GeV^2

Considerable uncertainty remains at very high-x



Gluon

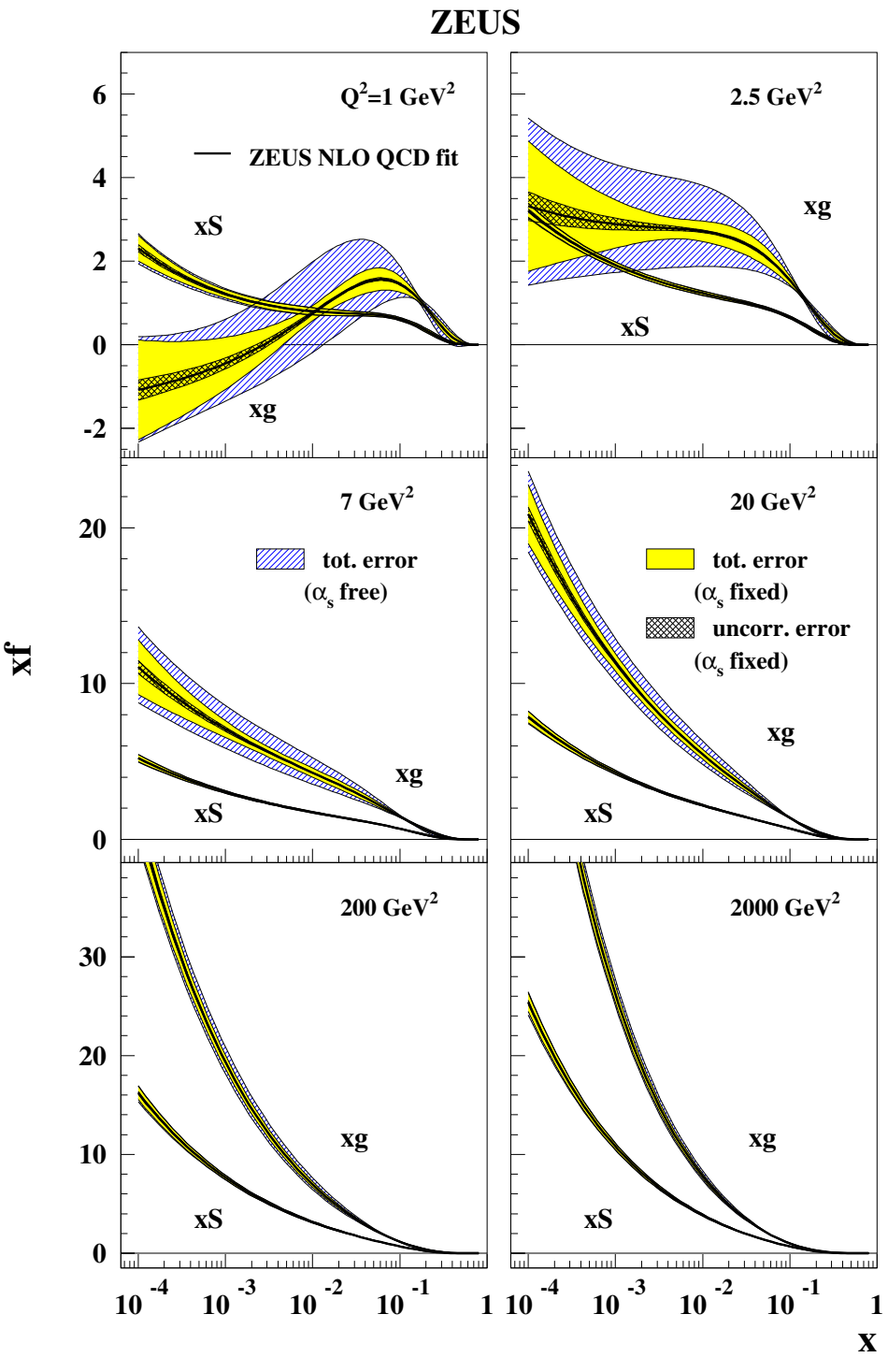
The gluon density is determined to within ~10% for

$Q^2 > 5$ GeV^2 and

$10^{-4} < x < 10^{-1}$

Considerable uncertainty remains for $x > 0.1$ (no Tevatron jet xsec.)

N.B. Unc. band narrowing at x~0.1 due to momentum sum rule



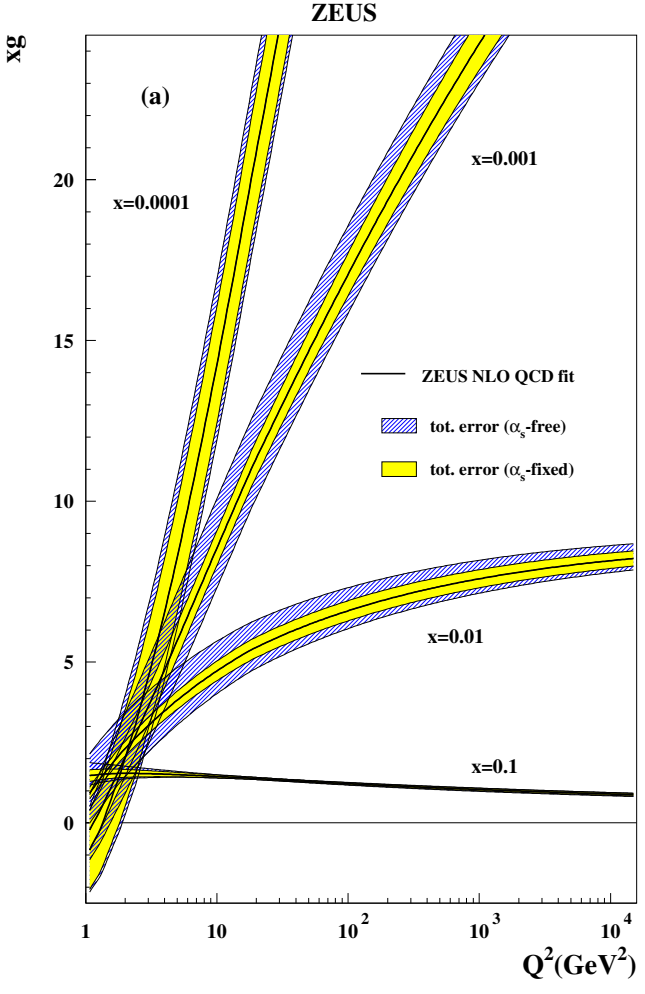
Glue and Sea

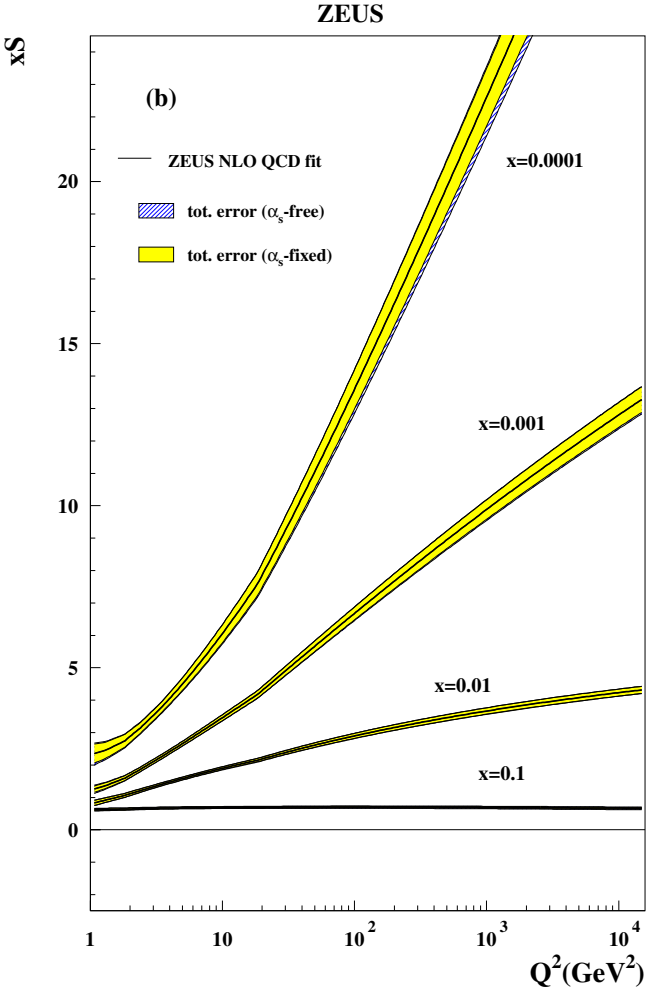
For $Q^2 \geq 5$ GeV^2 the gluon density becomes much larger than the Sea

At lower Q^2, xS continues to rise at low x whereas the gluon density becomes valence like and tends to become negative (although consistent with zero within the quoted unc.)

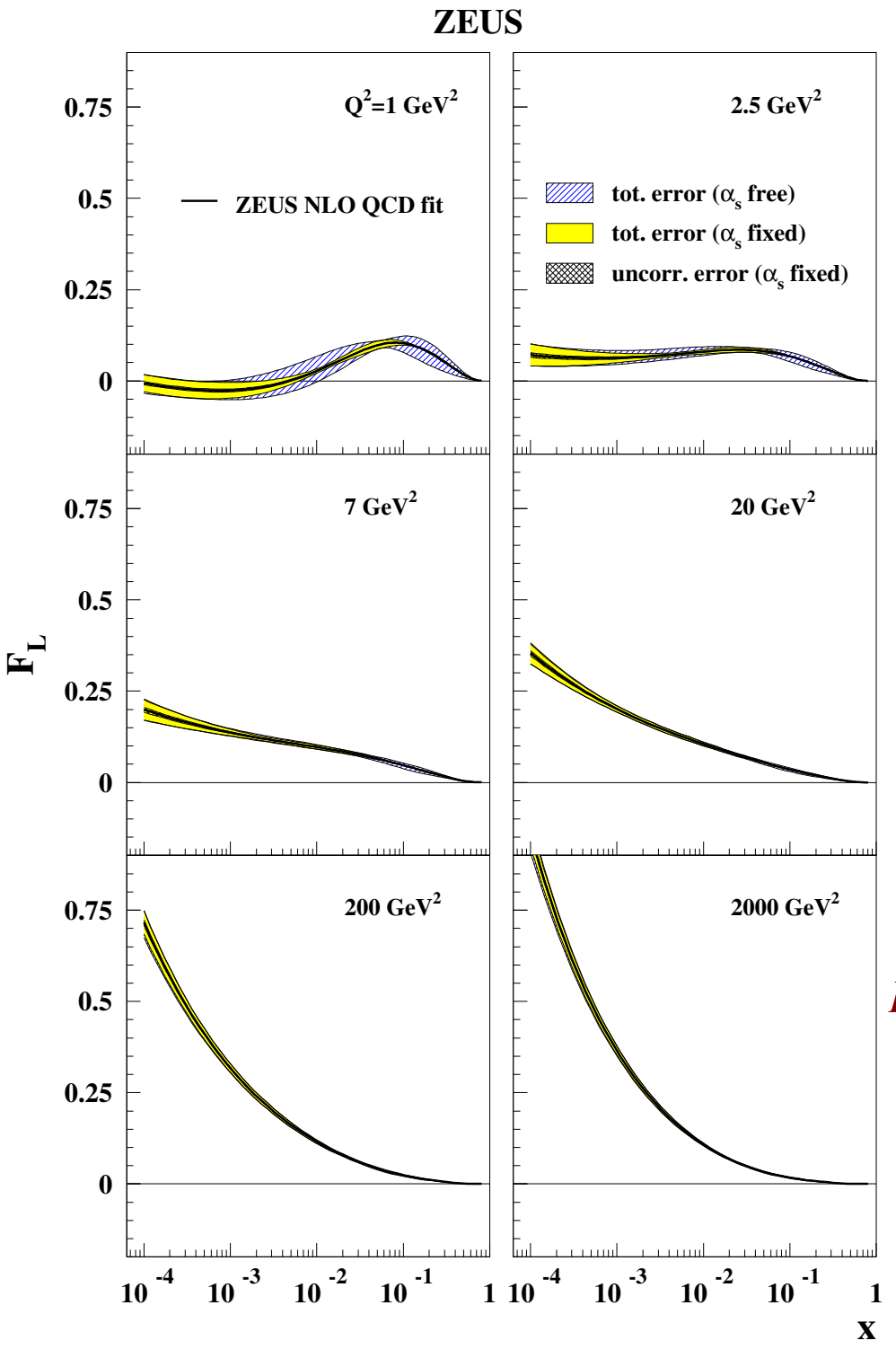
The present analysis shows this contrasting behaviour of the gluon and sea densities even more strongly than previous analyses based on the ZEUS 94-95 data.

Gluon and Sea





Striking scaling violation for xg
(singular behaviour of the P_{gq} and P_{gg} splitting functions as $x \rightarrow 0$)



F_L

Similar behaviour as xg:

slight tendency to become negative at low Q^2 (although compatible with zero within the quoted unc.)

$$F_L(x,Q^2) = \frac{5}{18}\, x[\Sigma \otimes C^S_{L,q} + g \otimes C_{L,g}] + \frac{1}{6}\, x[q_{NS} \otimes C^{NS}_{i,q}]$$

for even number of flavours

Simultaneous fit to α_s and PDFs

Central result from the fit:

$$\alpha_s(M_Z^2) = 0.1166 \pm 0.0008\,(\text{uncorr}) \pm 0.0032\,(\text{corr}) \pm 0.0036\,(\text{norm})$$

Model uncertainty: $\Delta\alpha_s = \pm 0.0018$

- varying Q_0^2, Q_{min}^2, x_{min} and W_{min}^2
- PDFs parameterisations
- Heavy-flavour schemes
- Included Tevatron jet production

Small variations on α_s and PDFs...

Additional Cross-checks

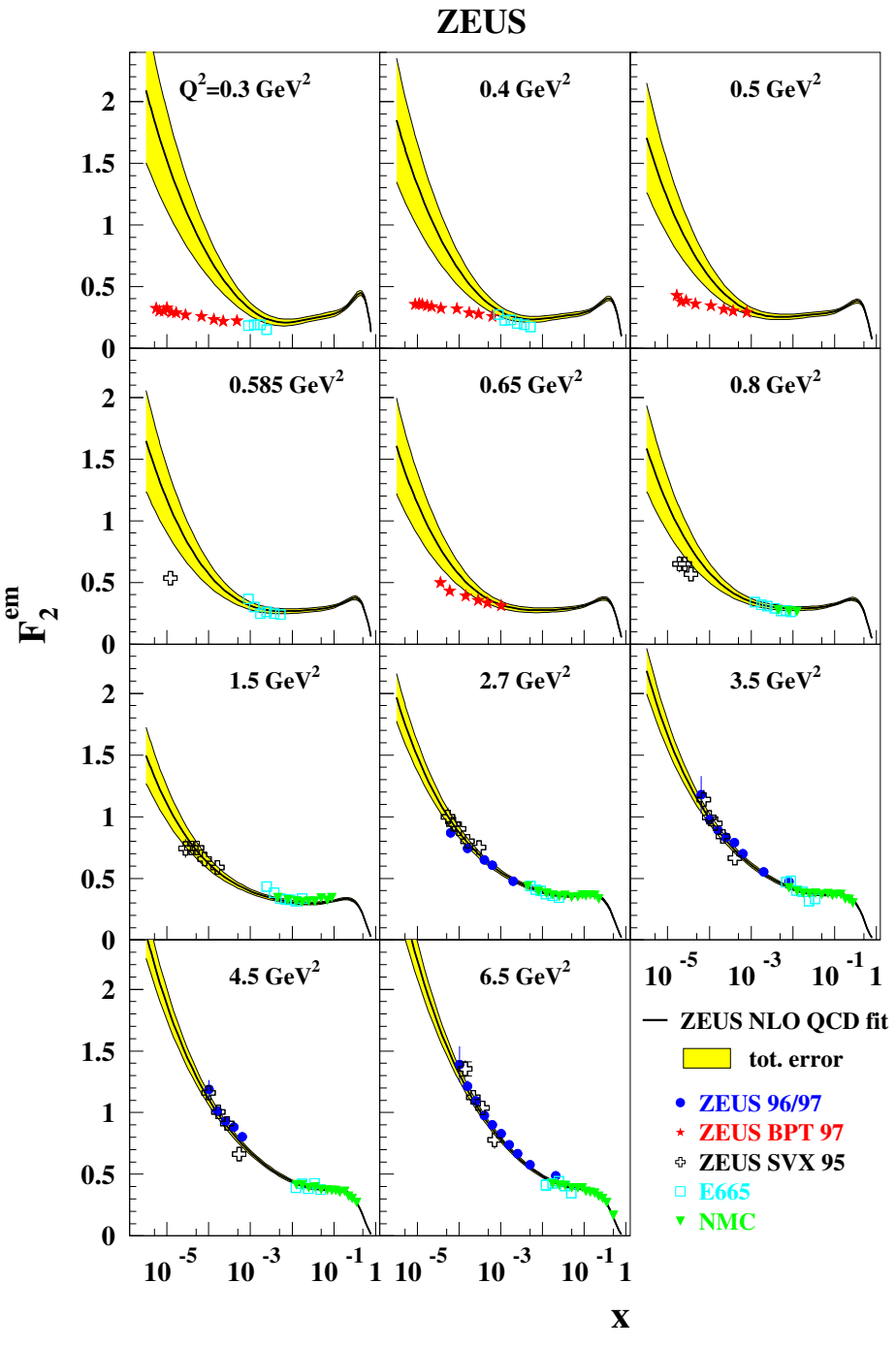
Higher-orders : $\Delta\alpha_s = \pm 0.0040$ [$Q^2/2 < \mu_R, \mu_F < 2\,Q^2$]

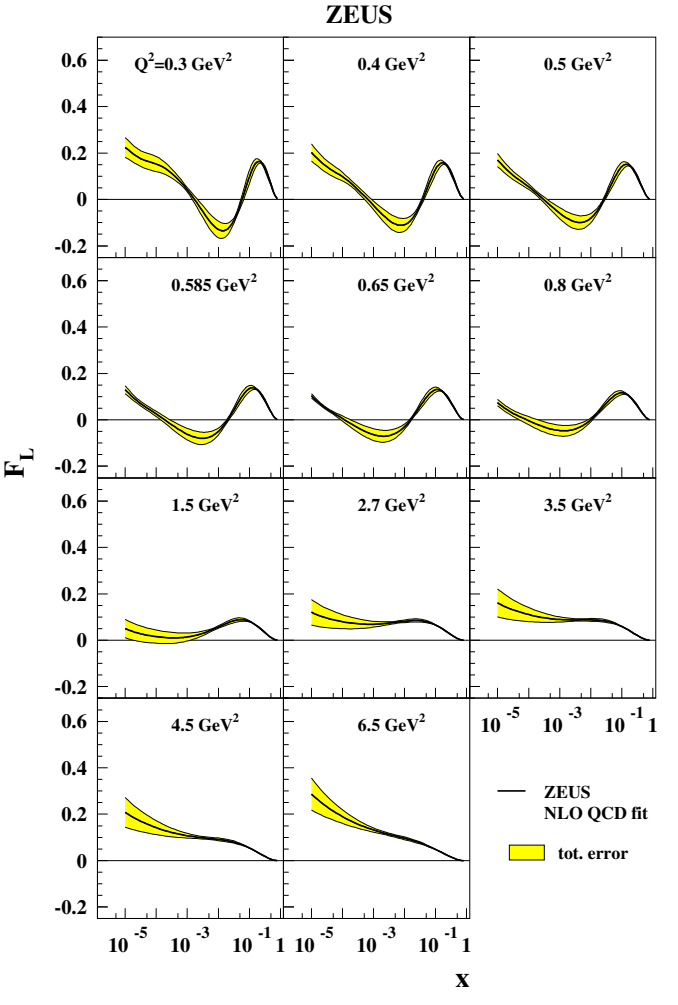
(N.B. NNLO-based estimates give $-0.0035 < \Delta\alpha_s < -0.001$)

Higher-Twists: $\Delta\alpha_s = -0.0032$

Theoretical uncertainties most probably large but difficult to quantifies

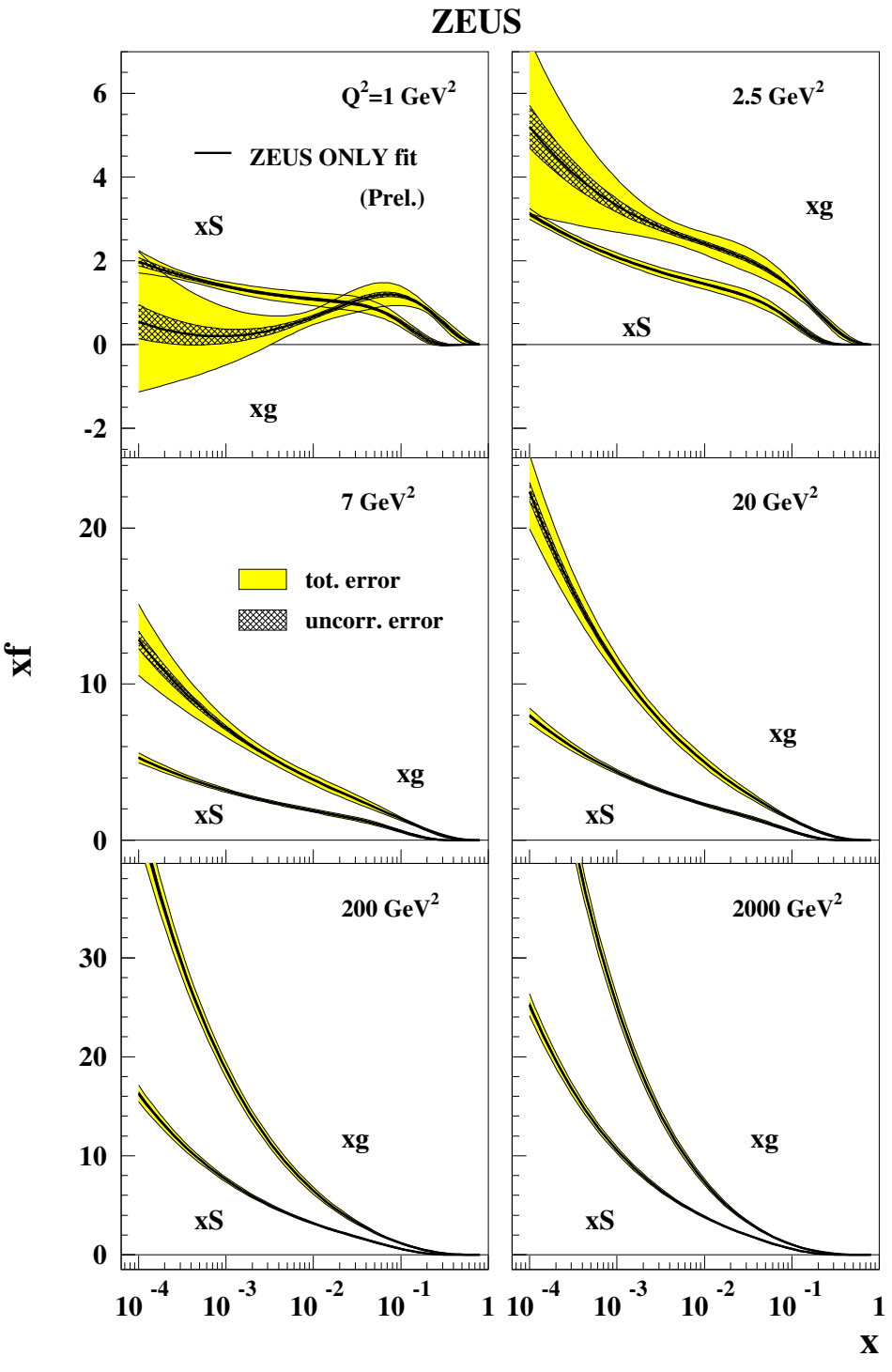
F_2^{em} at low Q^2





F_L: unphysical behaviour for $Q^2 \leq 0.8$ GeV^2

NLO DGLAP unable to describe BPT data.



ZEUS-Only Fit 1

Zeus-Only Fits

DGLAP analyses exploiting only the ZEUS measurements

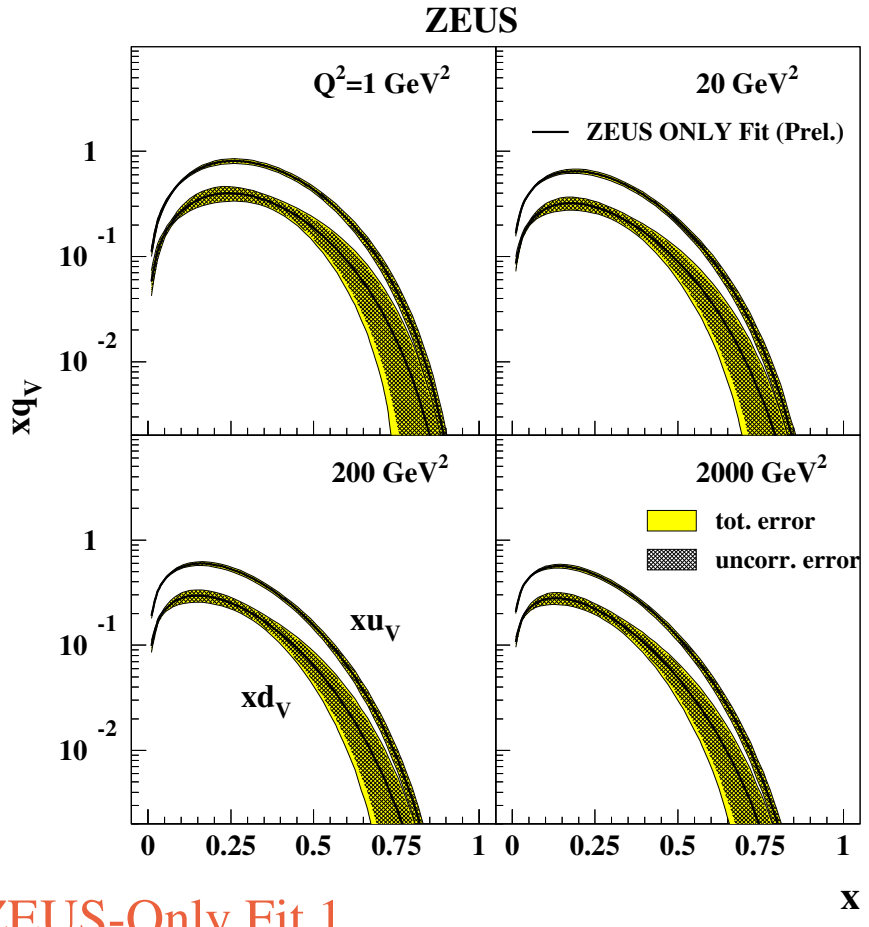
In addition to the ZEUS published DIS NC 96-97 and CC 94-97 cross sections:

- Include the prel. ZEUS DIS 98-99 e^-p CC and NC cross sections
  - ZEUS-Only Fit 1
- Also include the prel. ZEUS DIS 99-00 CC and NC cross sections
  - ZEUS-Only Fit 2

Reminder :

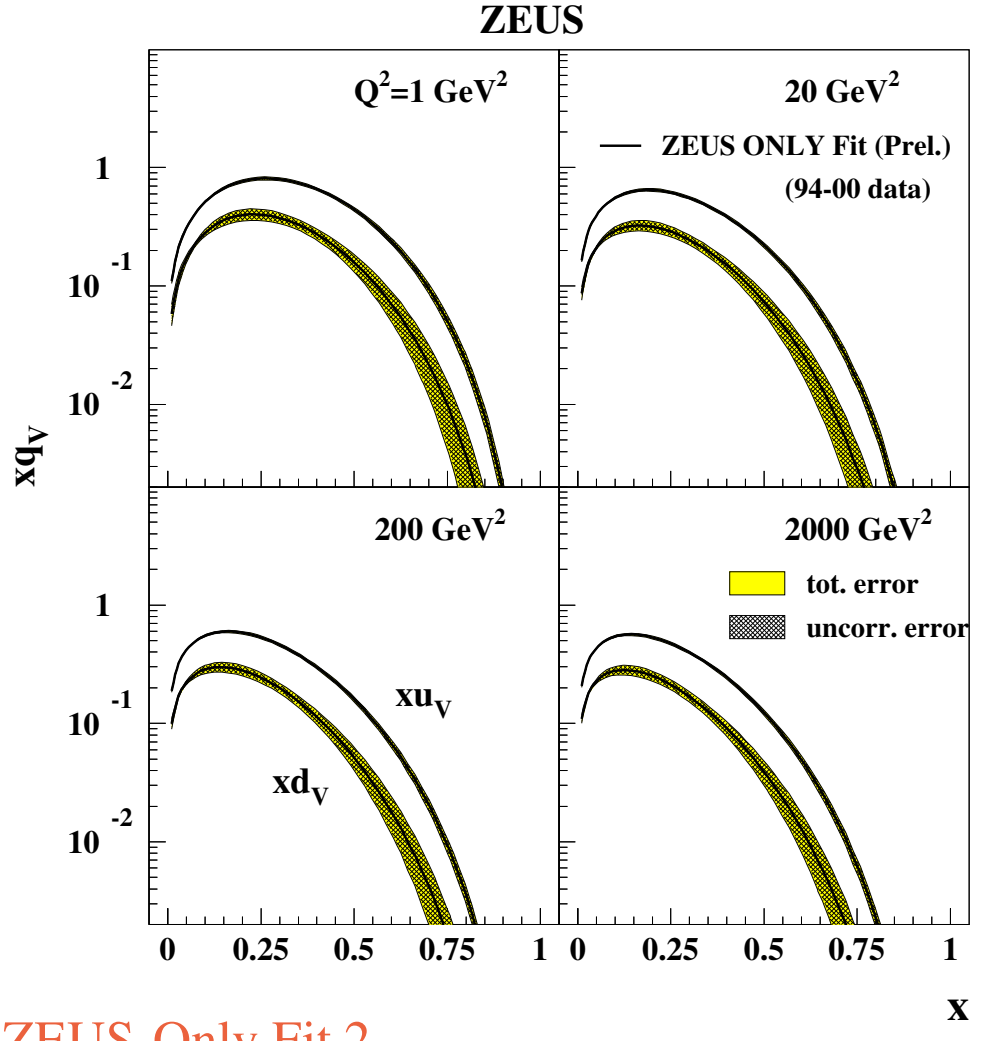
$$\tilde{\sigma}_{CC}\left(e^- p\right) = x[\bar{u}+\bar{c}+(1-y)^2(d+s)]$$
$$\tilde{\sigma}_{CC}\left(e^+ p\right) = x[u+c+(1-y)^2(\bar{d}+\bar{s})] \text{ at LO}$$

ZEUS-Only : xu_v, xd_v



ZEUS-Only Fit 1

Inclusion of the high-Q^2 NC and CC cross sections able to significantly constrain valence distributions at high-x



ZEUS-Only Fit 2

Conclusions

ZEUS-Standard and ZEUS-α_s Fits:

- The precise ZEUS NC 96-97 cross sections have allowed an improved determination of the gluon and total sea over a large phase-space region.
- A simultaneous fit of α_s and PDFs, using ZEUS and fixed-target data, results in a α_s value well in agreemen with the world average.
- The NLO QCD DGLAP formalism, in its present form, is unable to describe the ZEUS very precise low Q^2 data.

ZEUS-Only Fits:

- preliminary DGLAP analyses using only ZEUS data are now feasible and able to significantly constrain the valence quark densities at relatively high-x

→ HERA II