α_s and gluon density from structure functions

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on behalf of

the H1 and ZEUS collaborations

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New Trends in HERA Physics 2001

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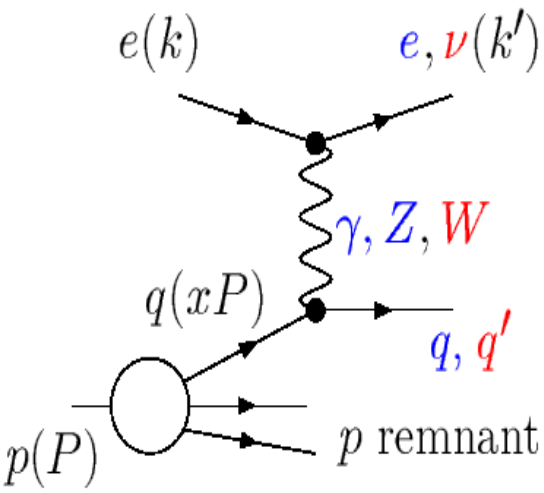
Deep Inelastic Scattering (DIS)

DIS is a straightforward tool to probe p structure



- Virtuality: $Q^2 \equiv -(k-k')^2$
  $\Rightarrow$ spatial resolution of probe
- Bjorken variable: $x \equiv Q^2/2p \cdot q$
  $\Rightarrow$ mom. fraction of struck parton

Inclusive DIS cross-sections $\Leftrightarrow$ Structure functions (SFs)

$$\frac{d^2\sigma}{dxdQ^2} \sim (1+(1-y)^2)(F_2(x,Q^2) - y^2 F_L(x,Q^2))$$

($y \equiv p \cdot k / p \cdot q$; inelasticity parameter)

Parton densities at NLO-QCD

- DGLAP eq. governs how the PDFs "evolve" with Q^2;

$$\frac{\partial q_i(x,\mu^2)}{d\ln\mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_x^1 \frac{dz}{z}[\sum_j q_j(z,\mu^2)P_{q_iq_j}(\frac{x}{z}) + g(z,\mu^2)P_{q_ig}(\frac{x}{z})],$$

$$\frac{\partial g(x,\mu^2)}{d\ln\mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_x^1 \frac{dz}{z}[\sum_j q_j(z,\mu^2)P_{gq_j}(\frac{x}{z}) + g(z,\mu^2)P_{gg}(\frac{x}{z})],$$

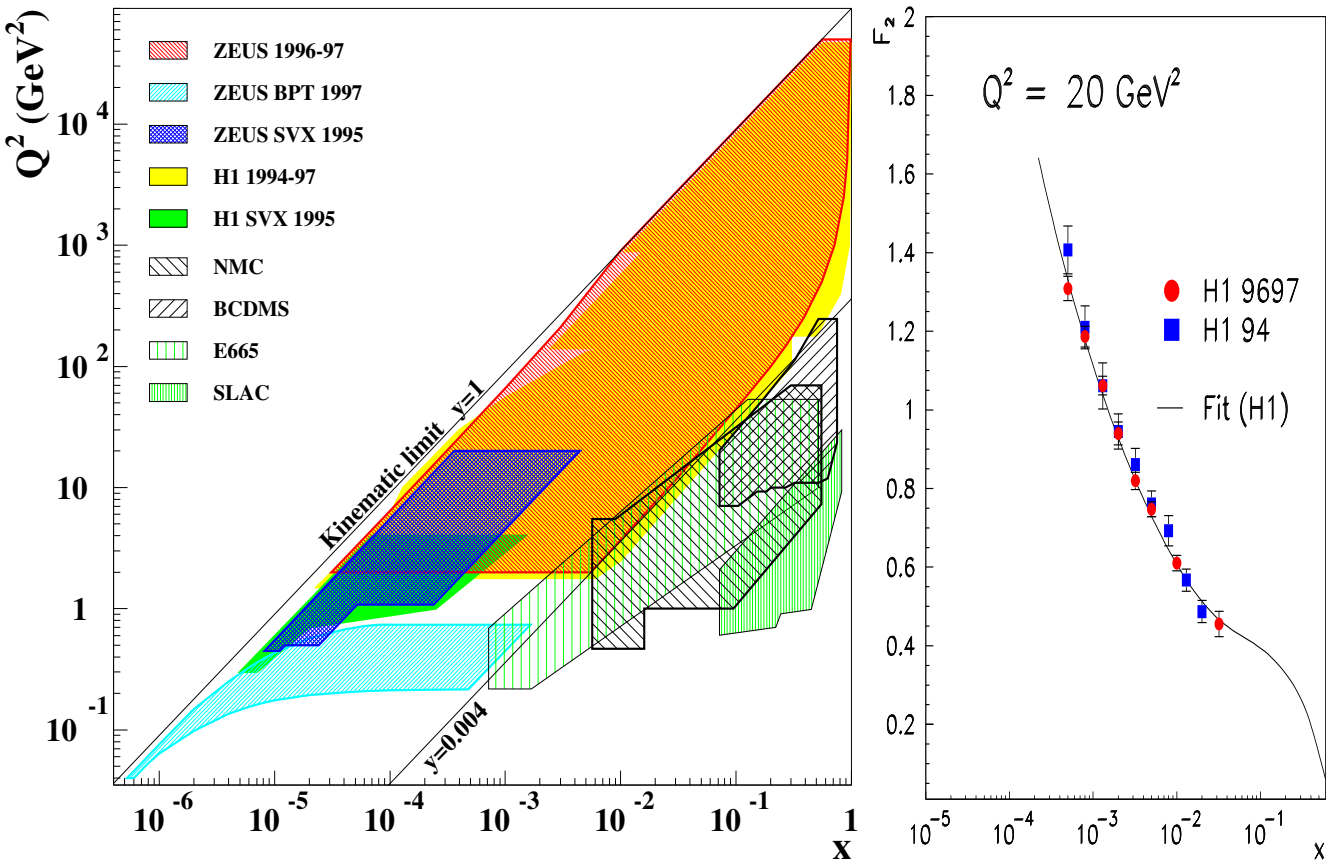
(q_f: quark density of flavour f, g: gluon density, $P_{q_iq_j}, P_{q_ig}, P_{gg}$: splitting functions)

- The input PDFs at Q_0^2 can be determined by fitting experimental data.
  $\Rightarrow$ This talk; the recent H1 and ZEUS NLO-QCD fits!

Highlights of H1 and ZEUS NLO-QCD fits

1. Data-sets: New precise F_2 measurement at HERA!
   - H1: $1.5 < Q^2 < 150$ GeV^2 (96−97: 20 pb^{-1})
     → DESY-00-181, submitted to *Eur.Phy.J.*

     $150 < Q^2 < 30000$ GeV^2 (96−97)
     → *Eur.Phy.J.* **C13** (2000) 609.
   - ZEUS: $2.5 < Q^2 < 30000$ GeV^2 (96−97: 30 pb^{-1})
     → DESY-01-064, submitted to *Eur.Phy.J.*



⇒ New HERA F_2 with much improved precision is available
   - typically, stat.$<$ 1 %, syst.$\sim$ 3 %
     → syst. errors must be considered in the fit

⇒ over wide range of kinematic plane!
   - from scaling violation, xg can be determined precisely and even α_s can be extracted simultaneously!

Highlights -cont'd-

2. Evaluation of uncertainties coming from experimental systematic errors

   - Point-to-point correlations taken into account.
   - Normalisation (luminosity) errors can also be considered as fully point-to-point correlated systematic errors.

   $\Rightarrow$ correct evaluation of uncertainties of PDFs etc.

3. Simultaneous α_s extraction was performed.
   (scaling violation: $dF_2/d\log Q^2 \sim \alpha_s \cdot g$ at low-x.)

   $\Rightarrow$ Uncertainties in α_s and PDF values can be evaluated by taking into account both:

   - correlations of experimental systematic errors
   - correlations between PDFs and α_s

Point-to-point correlation of systematic errors

"Pascaud and Zomer" method: (pre-print: LAL-95-05)

- assign a parameter, s_l, for each systematic source l.
- define χ^2 as:

  $\chi^2 \equiv \sum_i^{data} \frac{(t_i(p)/f_i(s) - m_i)^2}{(\delta_i^{stat})^2 + (\delta_i^{uncor.syst})^2} + \sum_l^{syst.source} (s_l)^2$

  $f_i = 1 + \sum_l^{syst.source} \beta_{il} s_l$,

  β_{il}: frac. syst.error of source l at point i.
- systematic errors: are propagated through Hessian matrix: $H_{ps} = \frac{\partial^2 \chi^2}{\partial p \partial s}$.

ZEUS:

- keep s_l=0 in minimising χ^2
  - χ^2 is constructed only from stat.nature errors.
  - data central values are fixed.

H1:

- s_l is also a parameter to be determined by the fit
  - data central values can be moved by a shift of s_l but with an additional penalty of s_l^2 to χ^2 .

$\Rightarrow$ Handling of correlated syst.errors is different between H1/ZEUS analyses (see M. Botje's talk).

H1 Analysis (preprint:DESY-00-181,submitted to *Eur.Phy.J*)

Strategy

- Limit data-set to minimum: H1 + BCDMS
  - use well-understood data-sets only.
  - proton data only $\longrightarrow$ avoid uncertainty in F_2^D.
- With proton data only, however, determination of d-quark is difficult. $\Rightarrow$ two(minimum) quark distributions $\oplus$ xg.

PDFs

With the usual Σ (singlet) and Δ (non-single) combination, number sum-rule cannot be applied.
$\Rightarrow$ rewrite flavour decomposition of PDFs

- Definition of "valence quarks" V and "sea quarks" A.
  - $V \equiv \frac{3}{4} \cdot \frac{1}{1+\epsilon}[(3+2\epsilon)u_V - 2d_V + (5+2\epsilon)(\overline{u}-\overline{d})]$
  - $A \equiv \frac{1}{4} \cdot \frac{1}{1+\epsilon}[(4\overline{u} - (u_V - 2d_V) - 5(\overline{u}-\overline{d}) + 2\epsilon(\overline{u}-\overline{d})]$
  - $s + \overline{s} = (\frac{1}{2} + \epsilon) \cdot (\overline{u} + \overline{d})$, ϵ=-0.08 from NuTeV measurement.

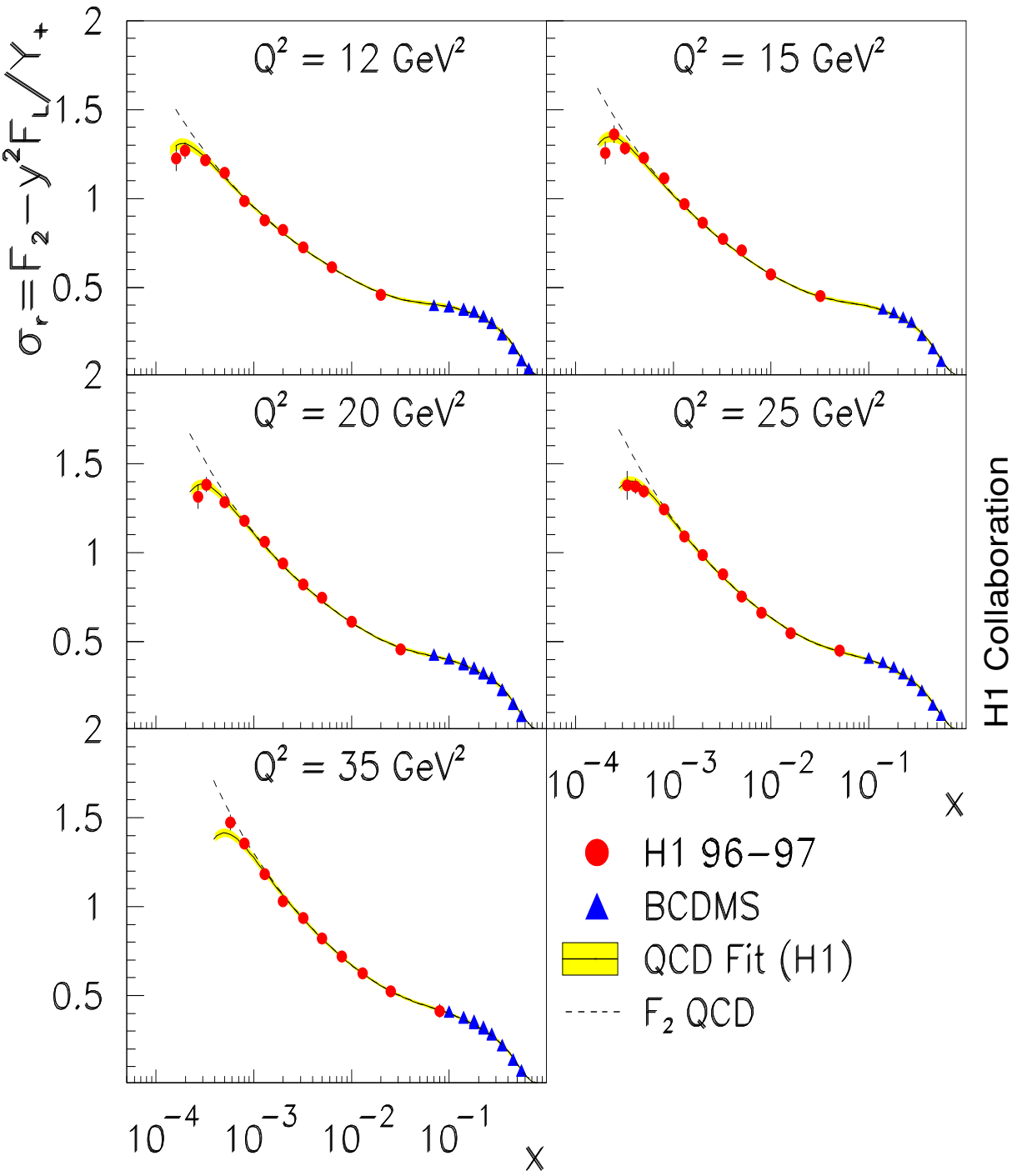
  $\Rightarrow$ a modified number sum-rule for V can be applied.
- Parameterisation:
  $xq(x) = ax^b(1-x)^c(1 + d\sqrt{x} + ex + fx^2)$
- Q_0^2=4 GeV^2
- Momentum sum-rule is constrained.

$\Rightarrow$ 13 free PDF parameters $\oplus$ 21 variable syst.params.

H1 NLO-QCD fits

- Fit reduced cross-section: $\sigma_r \equiv F_2 - \frac{y^2}{Y_+} F_L$
  - F_L is calculated in NLO-QCD.
- $Q^2_{min} > 3.5$ GeV^2
- Heavy-quark prod. scheme:
  $\Rightarrow$ FFN (Fixed-Flavour Number scheme)
  - calculate the BGF process to heavy-quarks ($\gamma^* g \rightarrow c\bar{c}$) correctly up to NLO.
    (only light quarks(u,d,s) are active)
- Two fits:
  1. H1+BCDMS fit
     - $y_{BCDMS} > 0.3$ cut.
     - α_s free.
       $\Rightarrow$ α_s=0.115 (details will be presented in later)
  2. H1 alone fit
     - α_s fixed to 0.115.

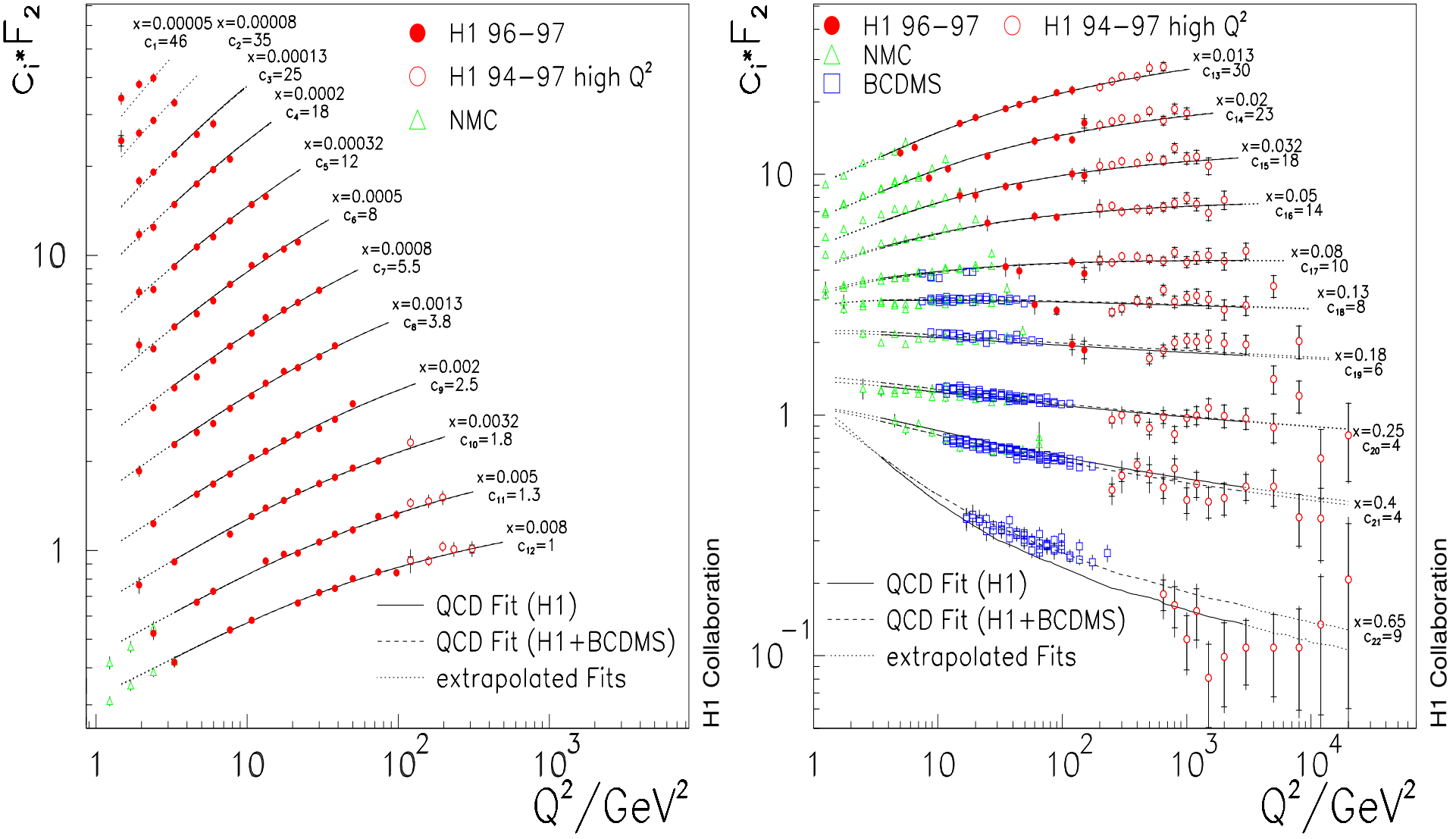
σ_r description [H1]



- NLO-QCD describes σ_r well and a clear effect of F_L is seen at lowest x, i.e. high y.

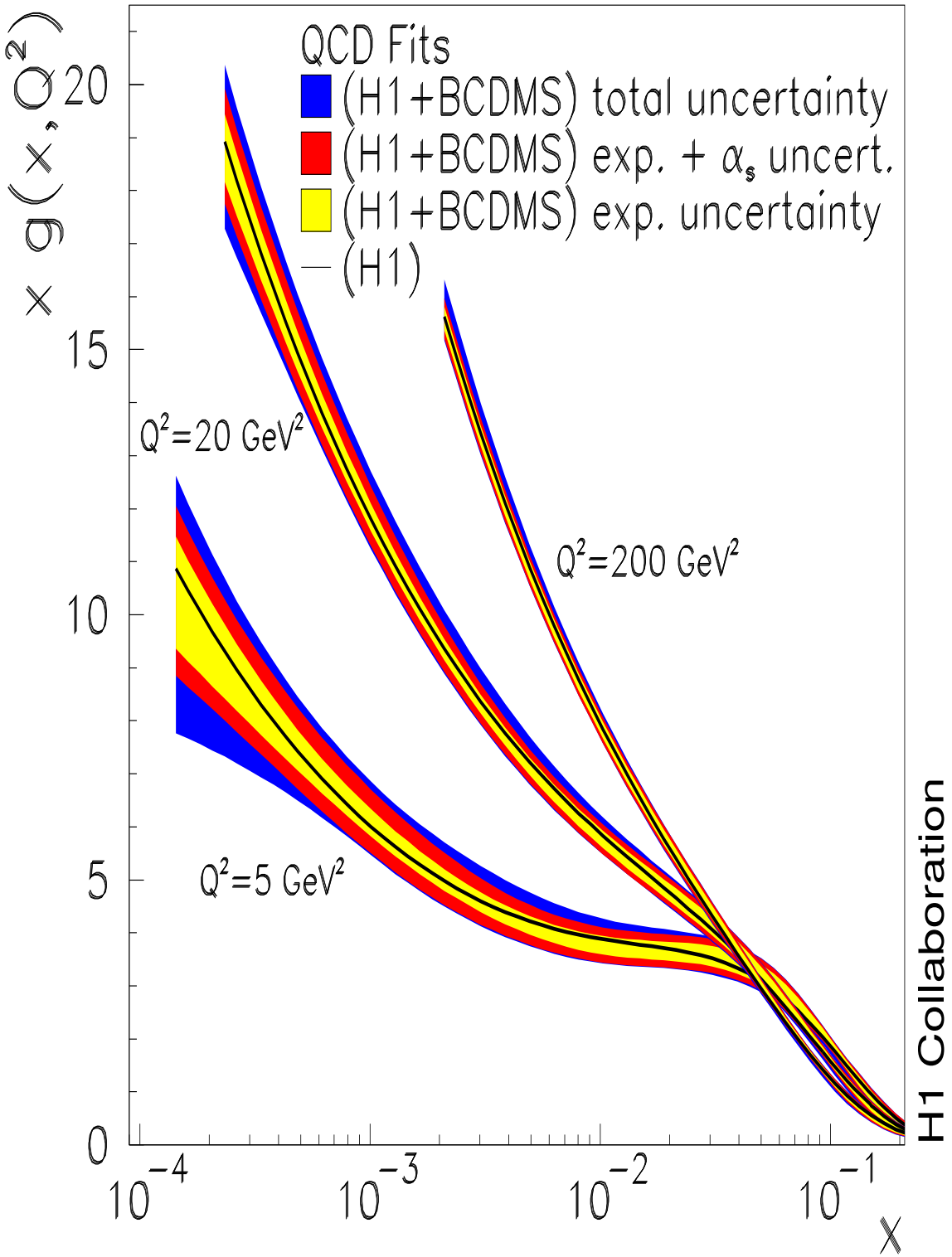
  $\Rightarrow$ F_L can be extracted by subtracting F_2(QCD) from σ_r (see N. Gogitidze's talk)

F_2 description: scaling violation [H1]



- Scaling violation well described by the NLO-QCD fit.

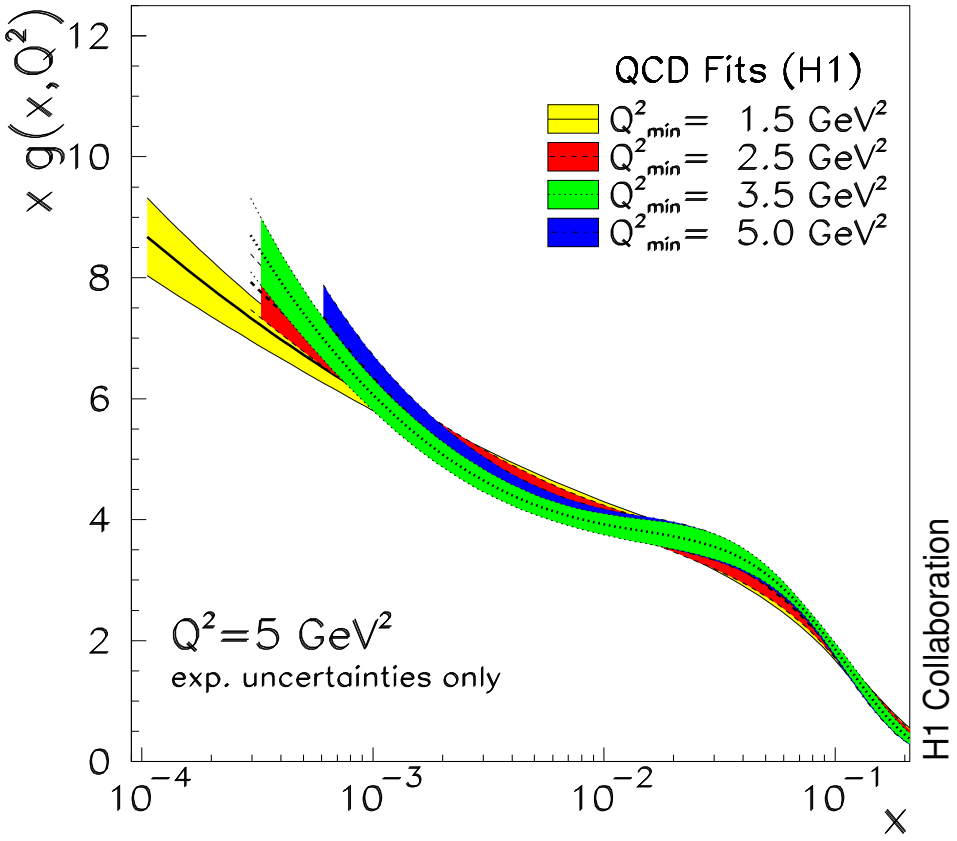
xg [H1]



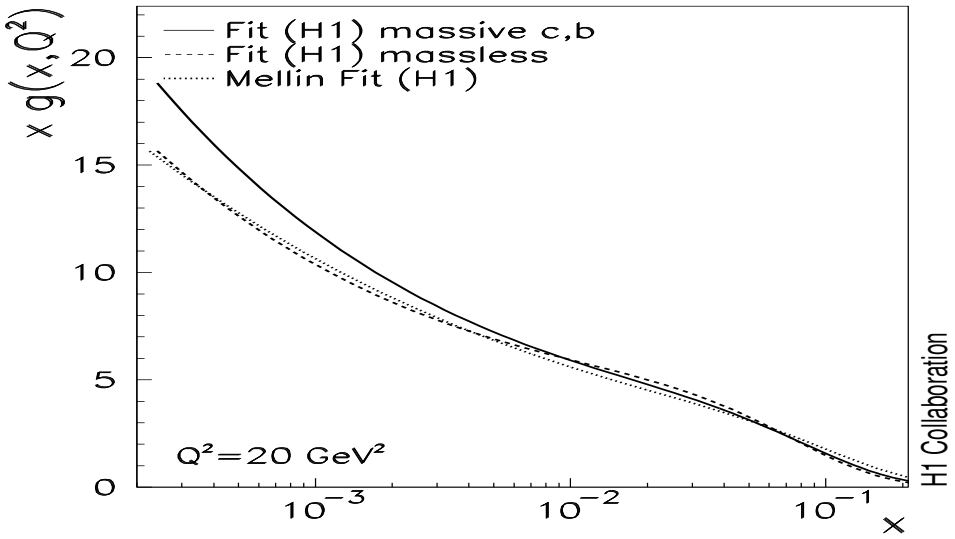
- Centre values: H1 alone fit.
- Errors are shown separately for: exp. only, exp.+α_s uncert, and total uncertainty which adds various checks on theoretical assumptions ("model error").

Model error of xg [H1]

$Q^2_{\rm min}$



Heavy quark prod. scheme

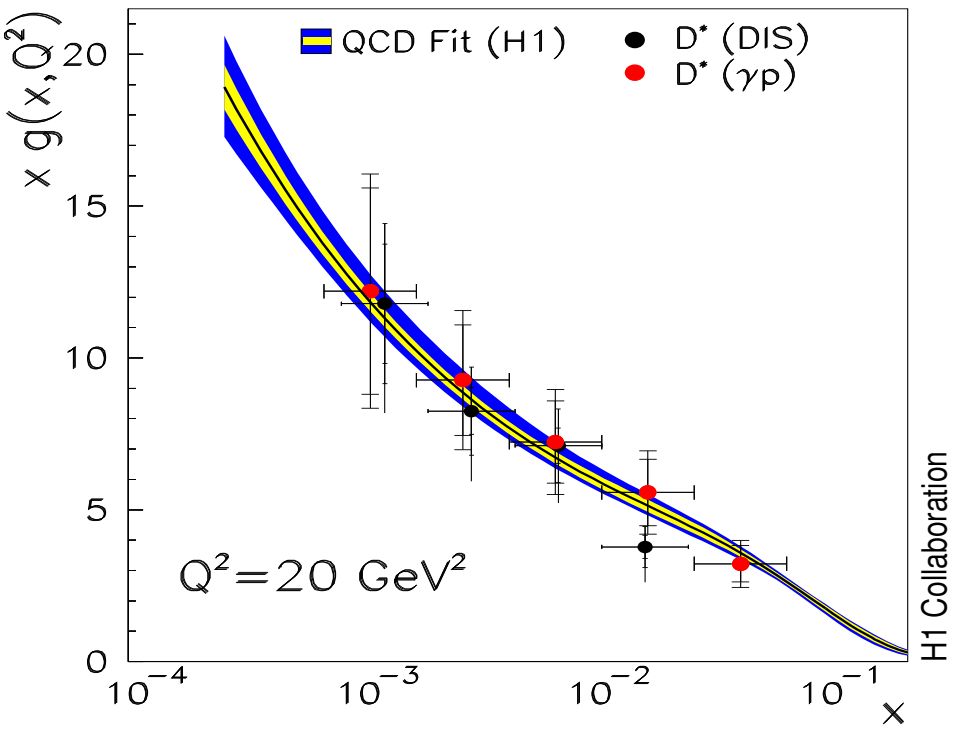


- massive c,b: FFN.
- massless c,b: Zero-Mass Variable Flavour Number scheme (ZM-VFN)
  - re-sums $\ln Q^2/m_c^2$ terms into heavy-quark parton distributions which obey the usual DGLAP evolution.

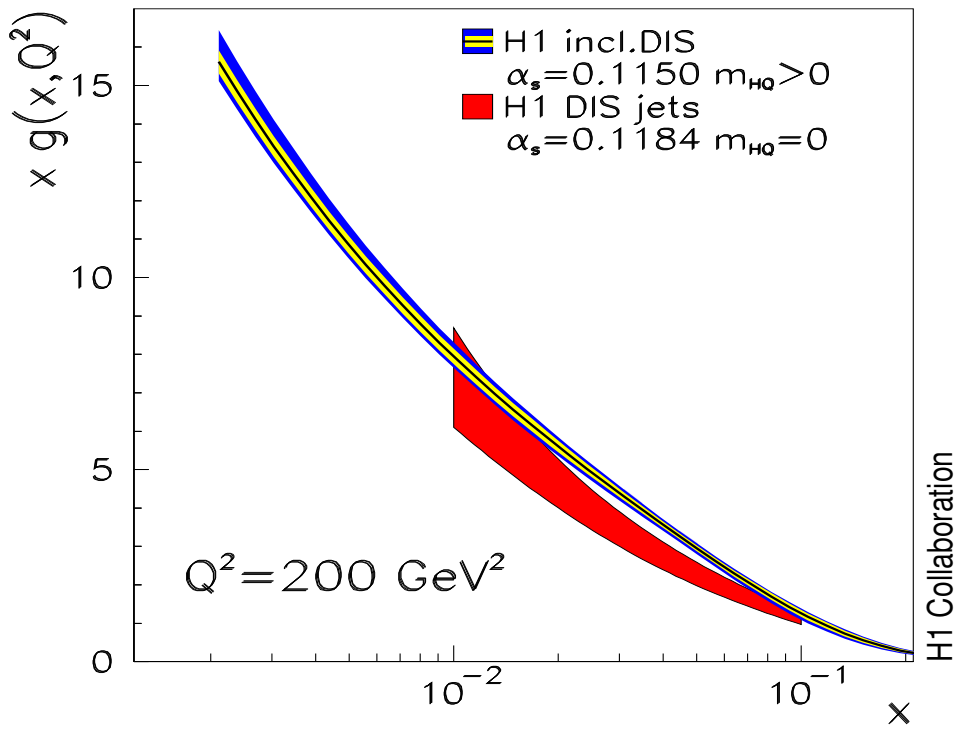
- The largest 'model error' is: $Q^2_{\rm min}$ and m_c.
  - other checks, e.g. Q^2_0 dependence, were found to give small effects.
- Difference between FFN and ZM-VFN schemes was found to be sizeable.
  $\rightarrow$ not included in 'model error'.

xg comparisons [H1]

D^* in DIS and γP ($\gamma g \to c\bar{c}$)

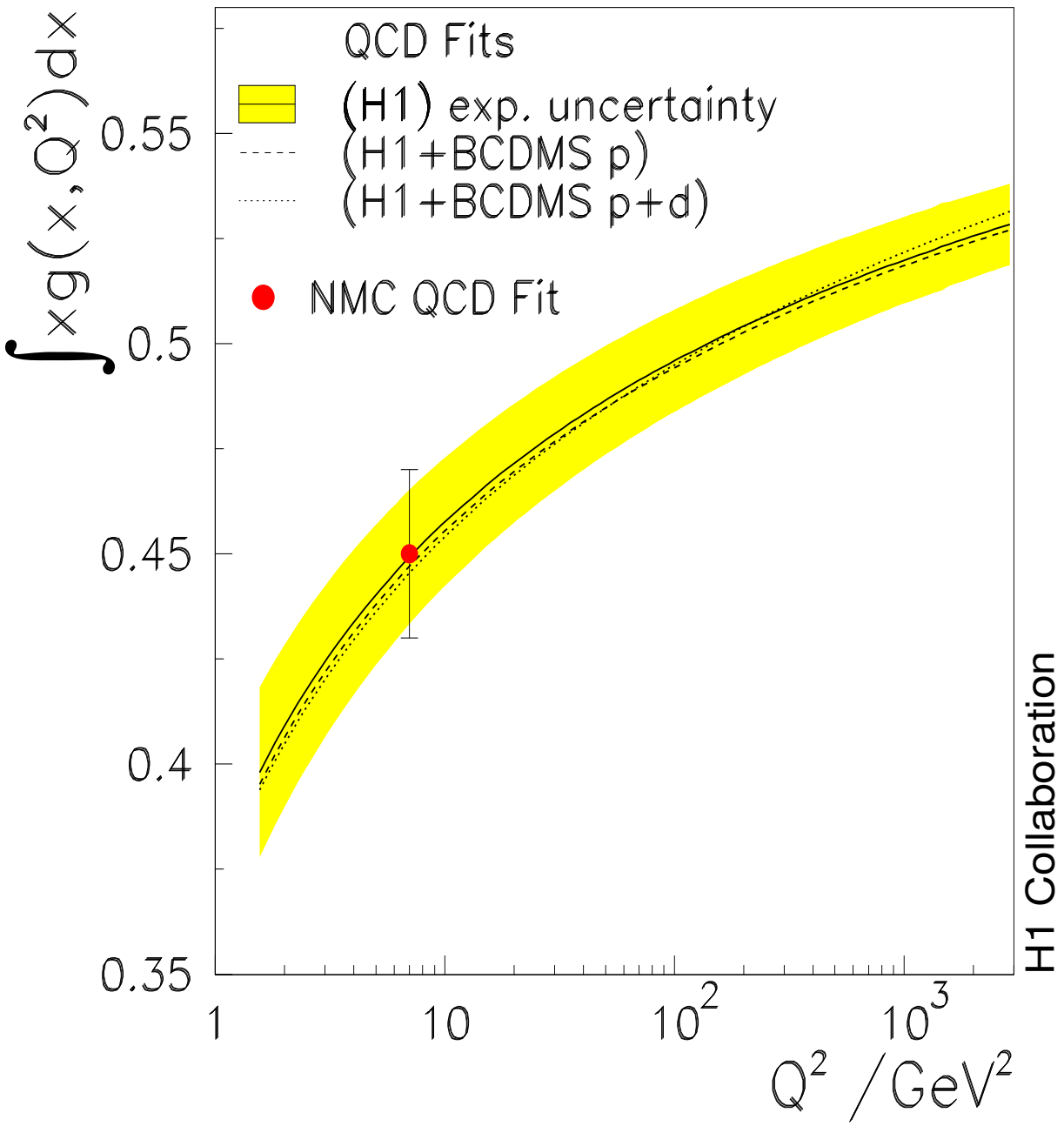


DIS jets ($\gamma^* g \to j\bar{j}$)



- The xg from scaling violation (this analysis) is consistent with and is more precise than that measured in D^*.
- DIS jets: a small difference in middle-x (10^{-2} to 10^{-1}) $\rightarrow$ may be related to high-x behaviour of xg. (but also note: HQ scheme is different)
- c.f.: F_L ($\sim g$) was also compared to the measurements by fixed-target experiments $\Rightarrow$ found to be consistent (see N. Gogitidze's talk)

Momentum fraction of xg [H1]



- Consistent with NMC analysis.
- Increase as Q^2 evolves.

α_s extraction [H1]

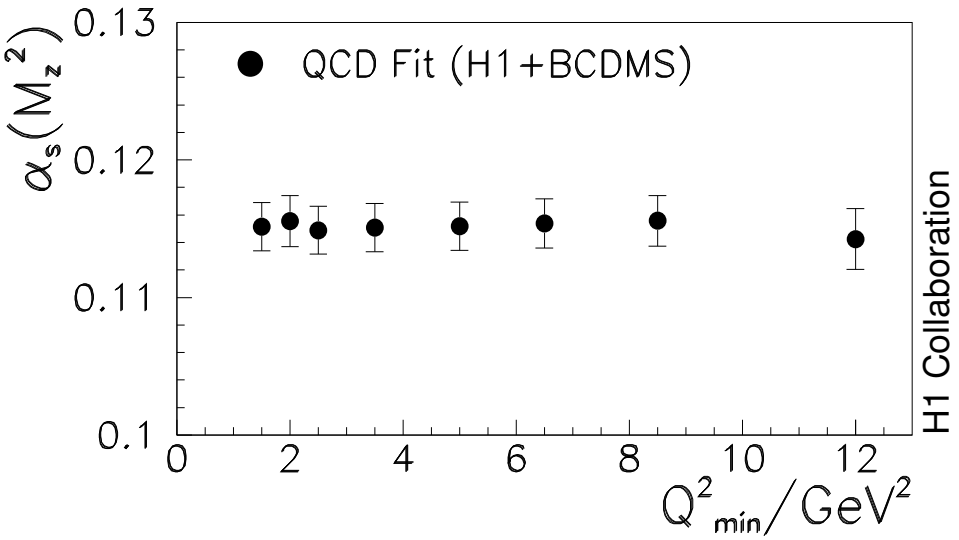
H1 + BCDMS fit gives: $\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp)^{+0.0009}_{-0.0005}(model)$

Model errors on α_s

analysis uncertainty	+$\delta\ \alpha_s$	-$\delta\ \alpha_s$
$Q^2_{min} = 2$ GeV^2		0.00002
$Q^2_{min} = 5$ GeV^2	0.00016	
parameterisations	0.00011	
$Q^2_0 = 2.5$ GeV^2	0.00023	
$Q^2_0 = 6$ GeV^2		0.00018
$y_e < 0.35$	0.00013	
$x < 0.6$	0.00033	
$y_\mu > 0.4$	0.00025	
$x > 5 \cdot 10^{-4}$	0.00051	
uncertainty of $\overline{u} - \overline{d}$	0.00005	0.00005
strange quark contribution $\epsilon = 0$	0.00010	
$m_c + 0.1$ GeV	0.00047	
$m_c - 0.1$ GeV		0.00044
$m_b + 0.2$ GeV	0.00007	
$m_b - 0.2$ GeV		0.00007
total uncertainty	0.00088	0.00048

scale uncertainty(not in table): ~ 0.005

α_s dependence on Q^2_{min}

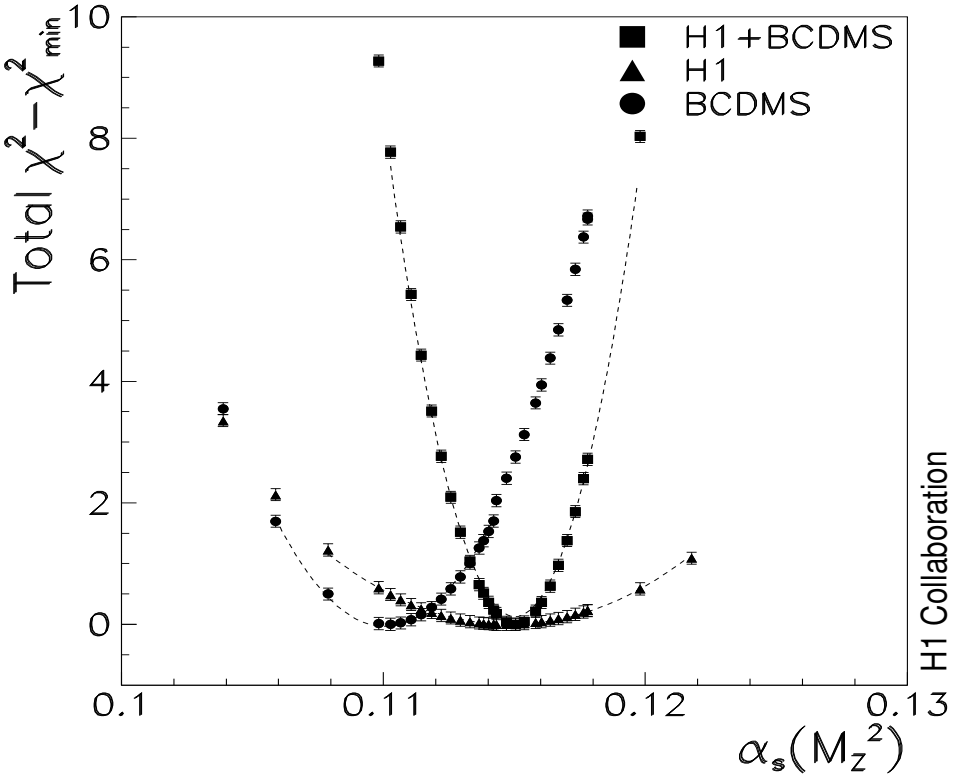


$\rightarrow$ α_s stable against Q^2_{min} cut.

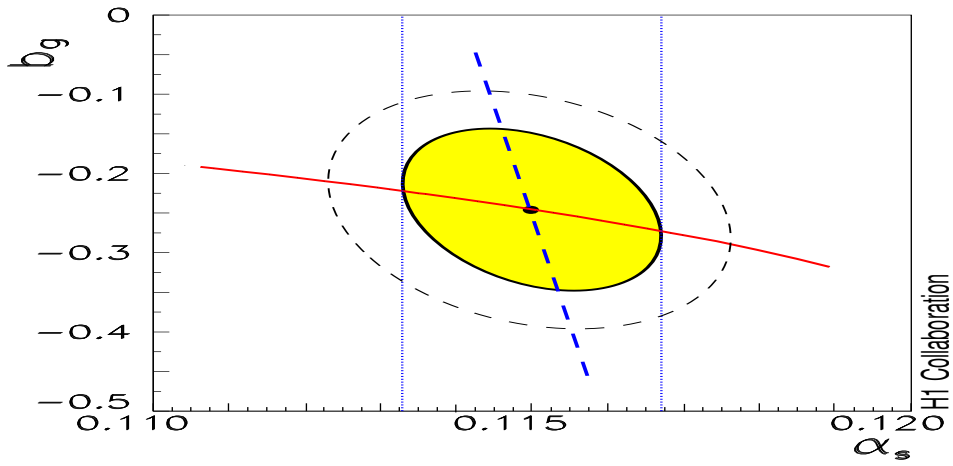
- The α_s was determined precisely.
  - The largest model errors: m_c and x-cut.
- However, scale uncertainty was found to be large $\sim 0.005 \rightarrow$ impact of NNLO?

α_s extraction from H1 data only [H1]

χ^2 .vs. α_s



correlation between b_g and α_s



- Remind: $xg \sim x^{-b_g}$ at low-x.

- H1 alone fit also gave: $\alpha_s = 0.115 \pm 0.005(exp)$.
- However, BCDMS alone fit gave: $\alpha_s = 0.111 \pm 0.0003(exp)$.
  $\rightarrow$ a negative correlation between α_s and b_g which owes xg behaviour at low-x.
  $\rightarrow$ b_g resulted in a positive value, i.e. valence like, with a small α_s
  $\Rightarrow$ HERA data provide xg at low-x and determine α_s.

ZEUS Analysis (preliminary in Apr.'01)

Strategy

- A global fit: ZEUS and all precise fixed-target experiments
  - Deuterium target and ν-beam data were also used.
- standard flavour decomposition,xu_V, xd_V, $xSea$, $x(\overline{d}-\overline{u}) \oplus xg$

PDFs

- Parameterisation:
  $xq(x) = p_1 x^{p_2}(1-x)^{p_3}(1+p_4\sqrt{x}+p_5 x)$
- Some assumptions:
  - fix p_4=0 for all PDFs.
    $\rightarrow$ not enough constraint for high-x PDFs.
  - fix p_2=0.5 both for xu_V and xd_V.
    $\rightarrow$ not enough constraint for low-x valences.
    (MRST/CTEQ use W asymmetry at TEVATRON)
  - fix p_2=0.5 and p_5=0 for $x(\overline{d}-\overline{u})$.
  - assume $p_3(x(\overline{d}-\overline{u}))$=$p_3(xSea)$+2 a la MRST.
    $\rightarrow$ only p_1 is free just to check Gottfried sum-rule.
  - fix p_5=0 for xg.
    $\rightarrow$ not enough constraint for high-x gluon
    (MRST uses prompt-γ at TEVATRON,
    CTEQ uses CDF inclusive jet)
- Number sum-rules for u and d valences and momentum sum-rule are constrained.

$\Rightarrow$ 11 free parameters.

Data sets [ZEUS]

- DIS(HERA): ZEUS e^+ '96 – '97 reduced σ_{NC}.
- DIS ($\mu N \to \mu X$): NMC F_2^p, F_2^D and F_2^D/F_2^p, BCDMS F_2^p, E665 F_2^p and F_2^D.
  - deuterium correction is made a la SLAC.

  $\to F_2^D$ is needed for xd_V
- DIS($\nu N \to \mu N$): CCFR $xF_3^{\nu N}$.
  Heavy-target correction was applied a la MRST.
  - use $0.1 < x < 0.75$ region:
    (large uncertainty in heavy-target corr. at high-x etc.)

  $\to xF_3^{\nu N}$ is needed for $xu_V - xd_V$
- $Q^2 > 2.5$ GeV^2, $W^2 > 20$ GeV^2

Heavy-quark prod. scheme [ZEUS]

Improved heavy-quark production scheme: RT-VFN
(R.S.Thorne,R.G.Roberts PLB 421(1998) 303)

$\Rightarrow$ RT-VFN: a practical procedure for a smooth transition between FFN and ZM-VFN schemes.

ZEUS NLO-QCD fits

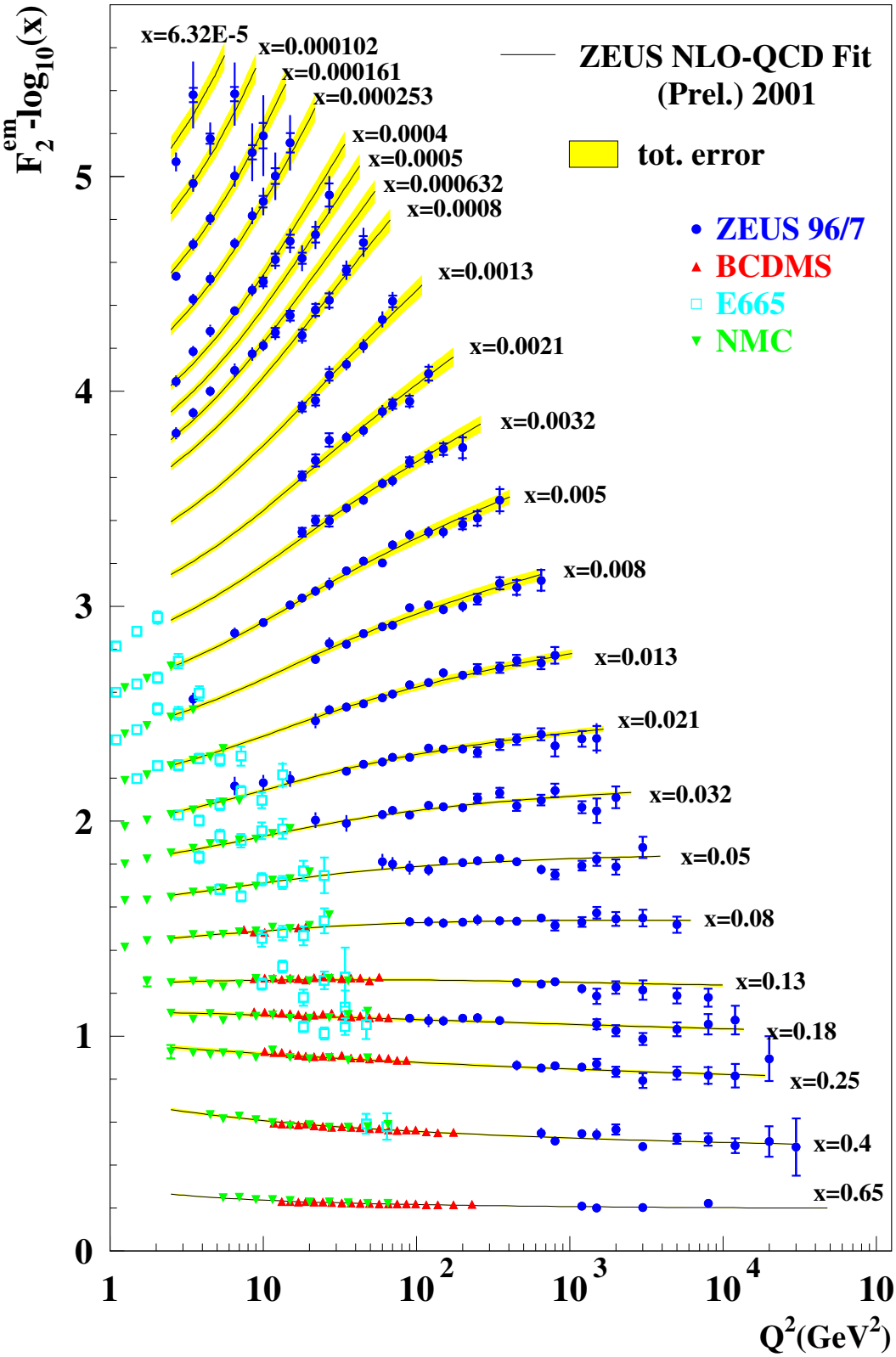
- fit σ_r for ZEUS: F_L from NLO-QCD.
- all systematic errors (71!) were taken into account from all experimental data-sets.
- fits:
  1. α_s fixed fit (α_s=0.118) $\Rightarrow$ central fit.
  2. α_s free fit
  3. ZEUS alone fit.(α_s is fixed)
  4. without ZEUS fit.(α_s is fixed)

χ^2 table

Experiments	χ^2/N_{data}	N_{data}
ZEUS 96/7	1.75	242
NMC P	1.74	218
NMC D	1.52	218
NMC D/P	0.98	129
BCDMS	1.29	305
E665 P	1.33	47
E665 D	1.14	47
CCFR xF_3	1.79	57
Total	1.48	1263
Total [FFN]	1.59	1263
Total [ZM-VFN]	1.48	1263

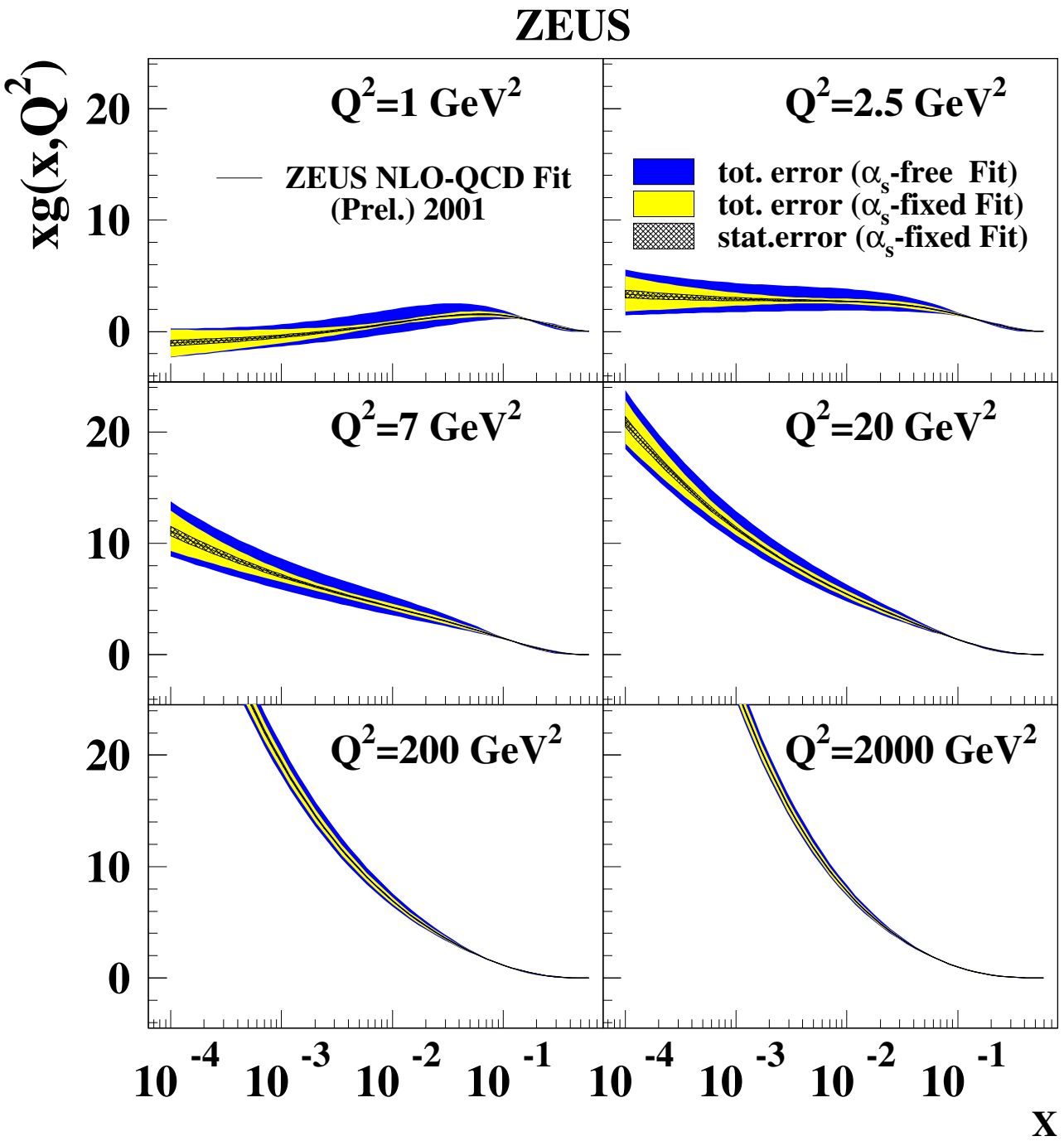
- The fit gave a good description over full range of world data.
- RT-VFN gave a better(or similar) χ^2 than FFN/ZM-VFN.

F_2^{em} : scaling violation [ZEUS]



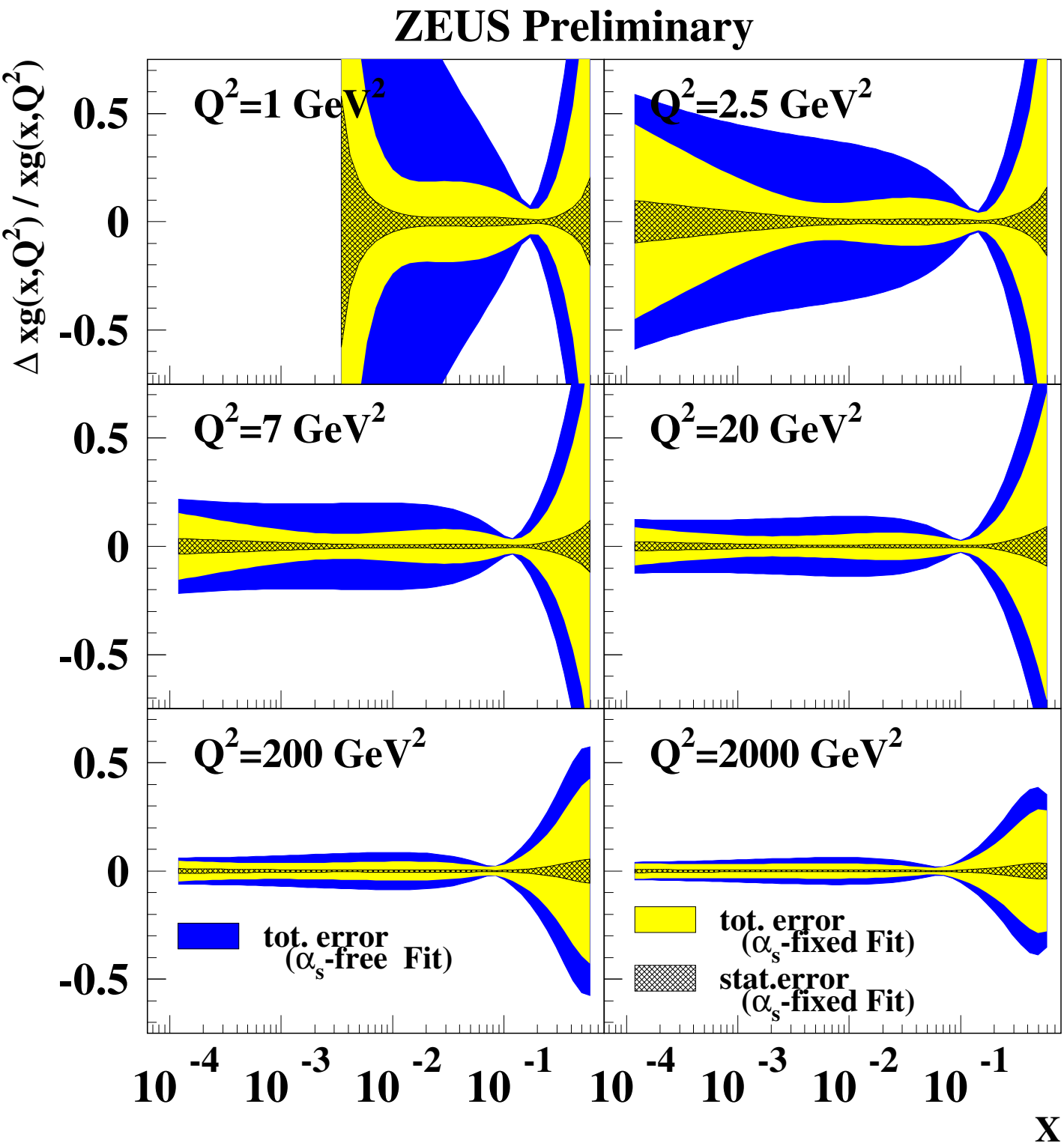
- NLO-QCD fit describes data well both for ZEUS and fixed-target experiments.

xg distribution [ZEUS]



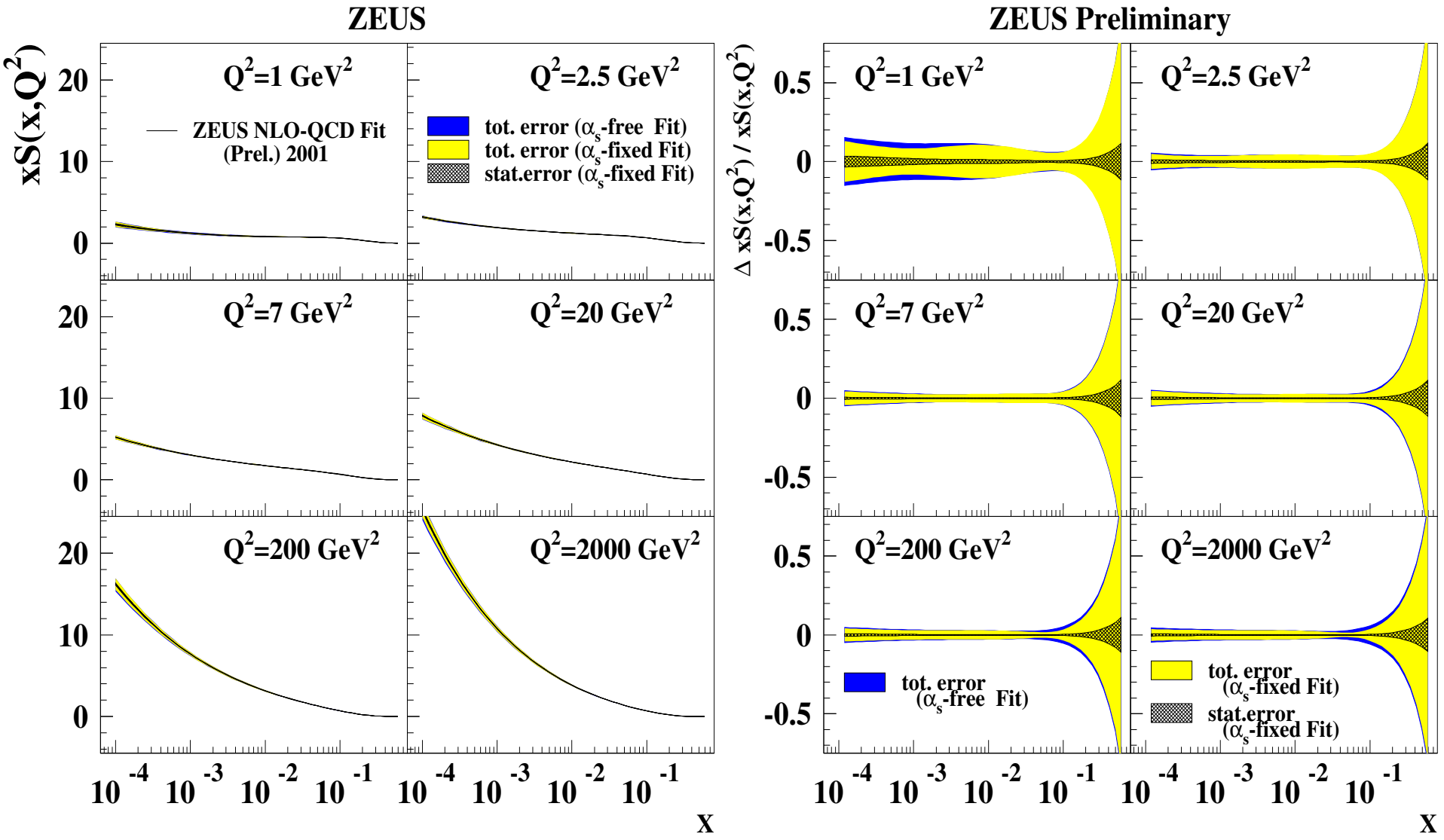
- Total uncertainty = exp.errors, i.e. stat.+syst.
  No model error(like H1) is not yet evaluated.
- Total uncertainty of the "α_s-FREE fit" is also displayed.
- At $Q^2 = 1$ GeV^2: valence like, consistent with 0 at low x.

uncertainty of xg distribution [ZEUS]



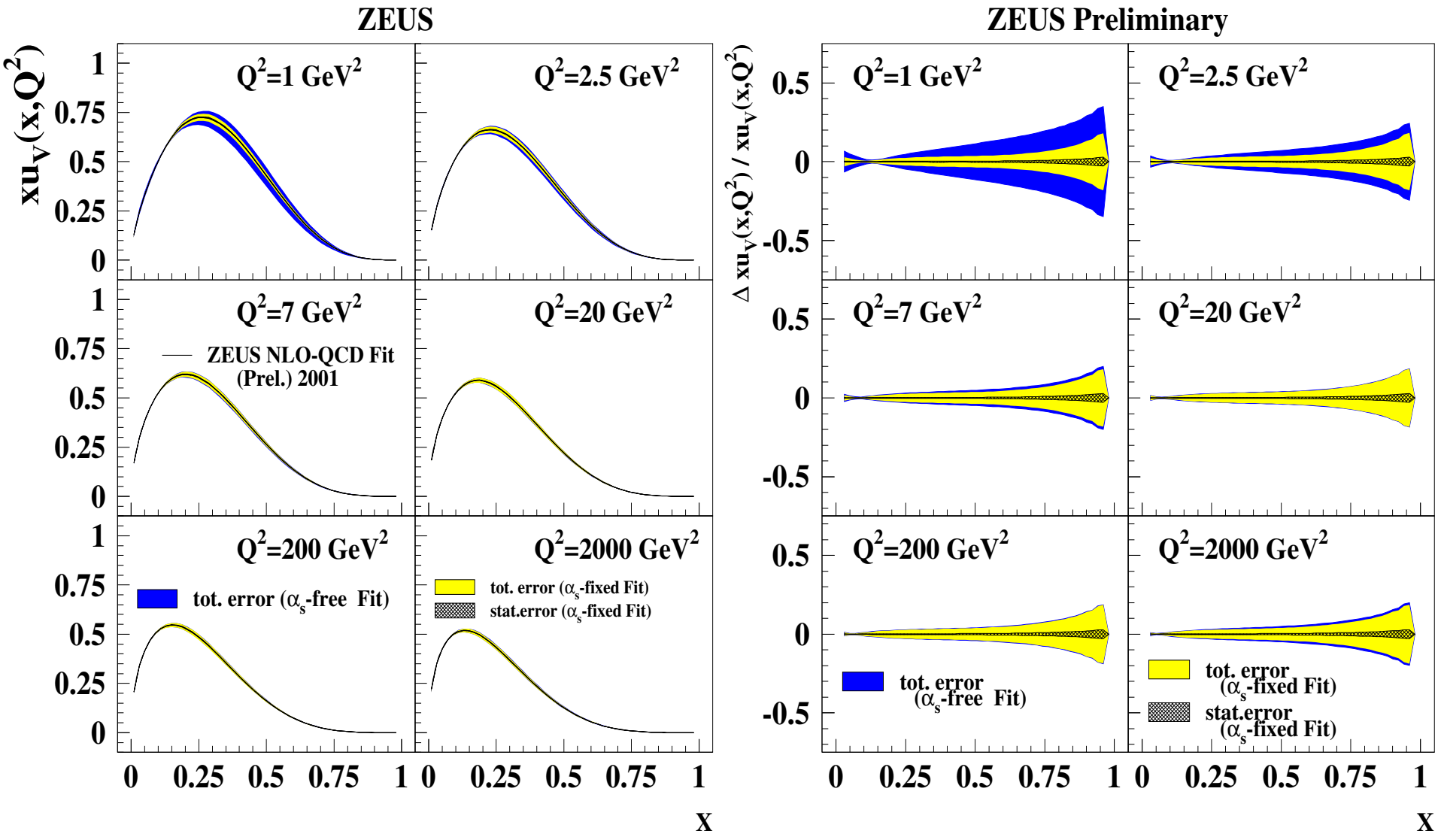
- Uncertainty is reduced as Q^2 evolves.
- $10^{-3} < x < 10^{-1}$: well determined within $\lesssim 10\%$.
- $x \gtrsim 10^{-1}$: large uncertainty.

$xSea$ distribution [ZEUS]



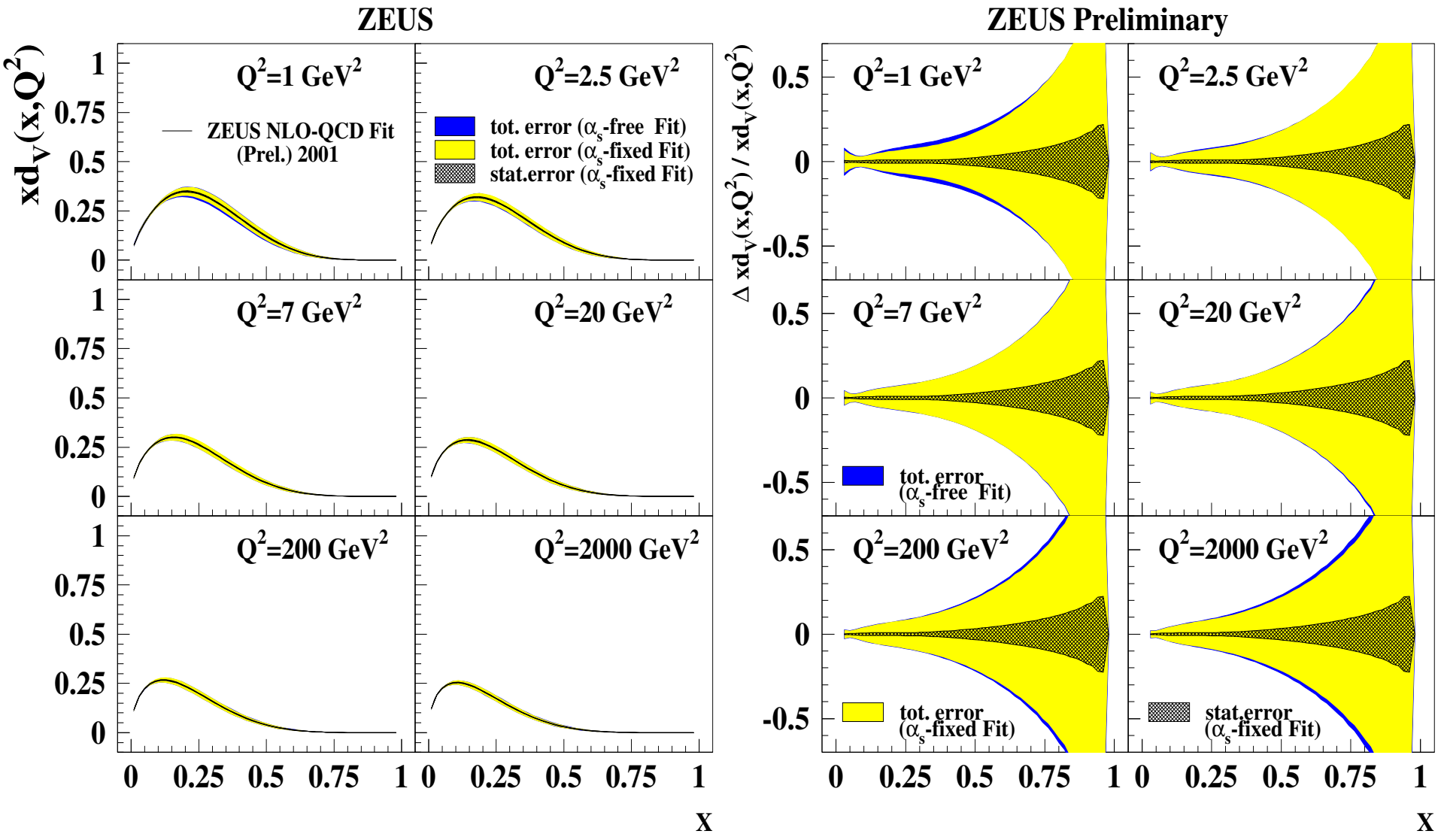
- At $Q^2 = 1$ GeV^2: still slightly rising.
- Uncertainty: typically $\lesssim 5\%$.

xU_V distribution [ZEUS]



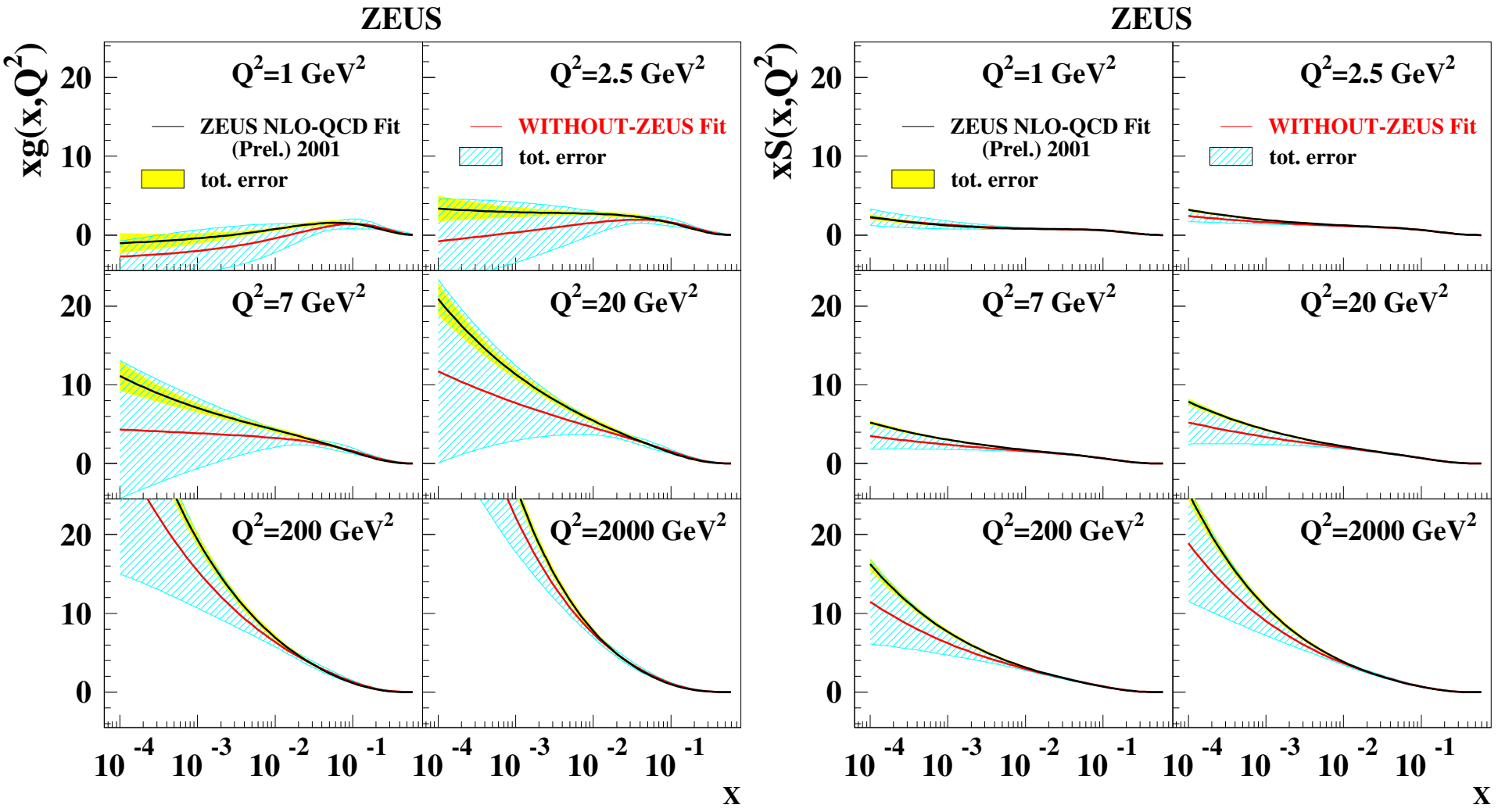
- Well determined within about 5% up to very large $x \sim 0.6$.
  Remind: $F_2^p \propto x(4u + d)$

xD_V distribution [ZEUS]



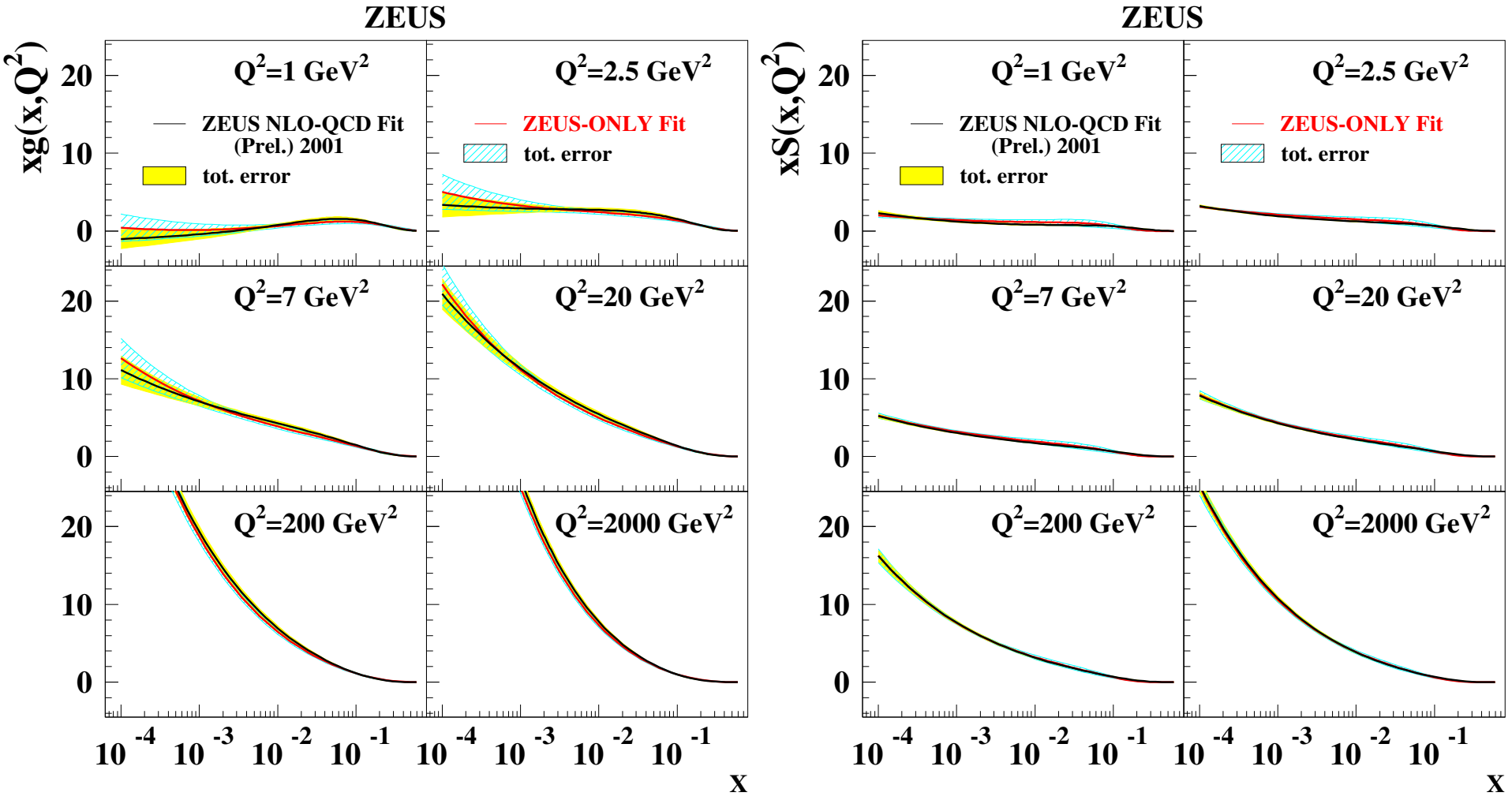
- Large error band compared to that of xU_V.
  Remind: $F_2^p \propto x(4u+d)$, $F_2^D \sim (F_2^p + F_2^n)/2 \propto x(u+d)$

xg and $xSea$ from WITHOUT ZEUS fit



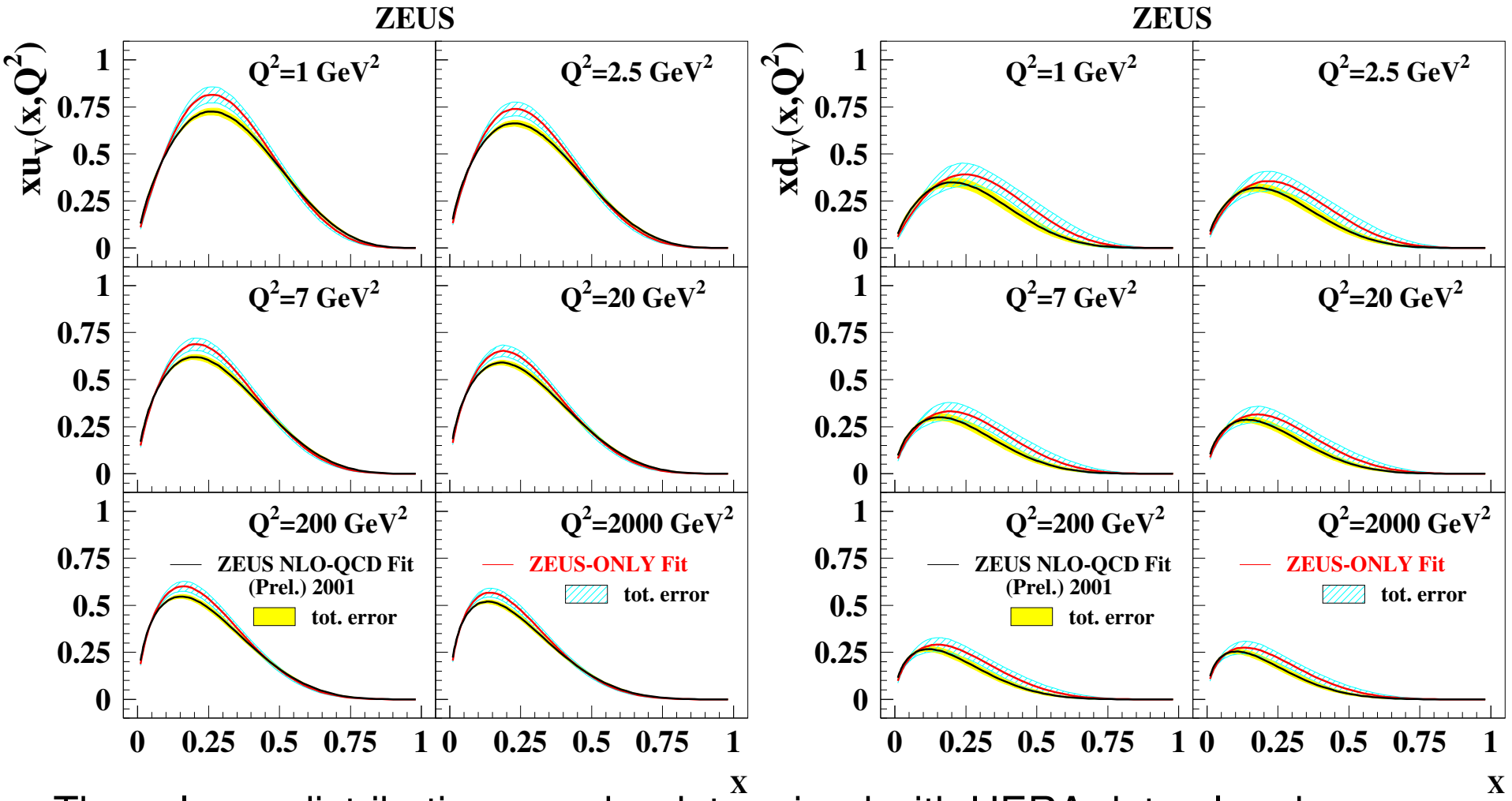
- Flatter xg and $xSea$ without ZEUS $\Leftarrow$ remind: the same was observed in BCDMS alone fit by H1 which resulted in a small α_s.
- Much smaller uncertainties of xg and $xSea$ were obtained with HERA data.

xg and $xSea$ from ZEUS alone fit



- Only with ZEUS: F_2 96/97 + high-Q^2 e^-p NC and CC, e^+p CC.
- Gluon is slightly steeper than the central (ZEUS+fixed-target) fit.
- The size of error is comparable to that of the central fit's.

xU_V and xD_V from ZEUS alone fit



- The valence distributions can be determined with HERA data alone! (thanks mostly to high-Q^2 data; e.g. CC $e^+p \Rightarrow xD_V$)
- ZEUS data prefer a shift of xD_V to higher-x and larger xU_V compared to those obtained in the central (ZEUS+fixed-target) fit.

Extraction of α_s; α_s-FREE Fit [ZEUS]

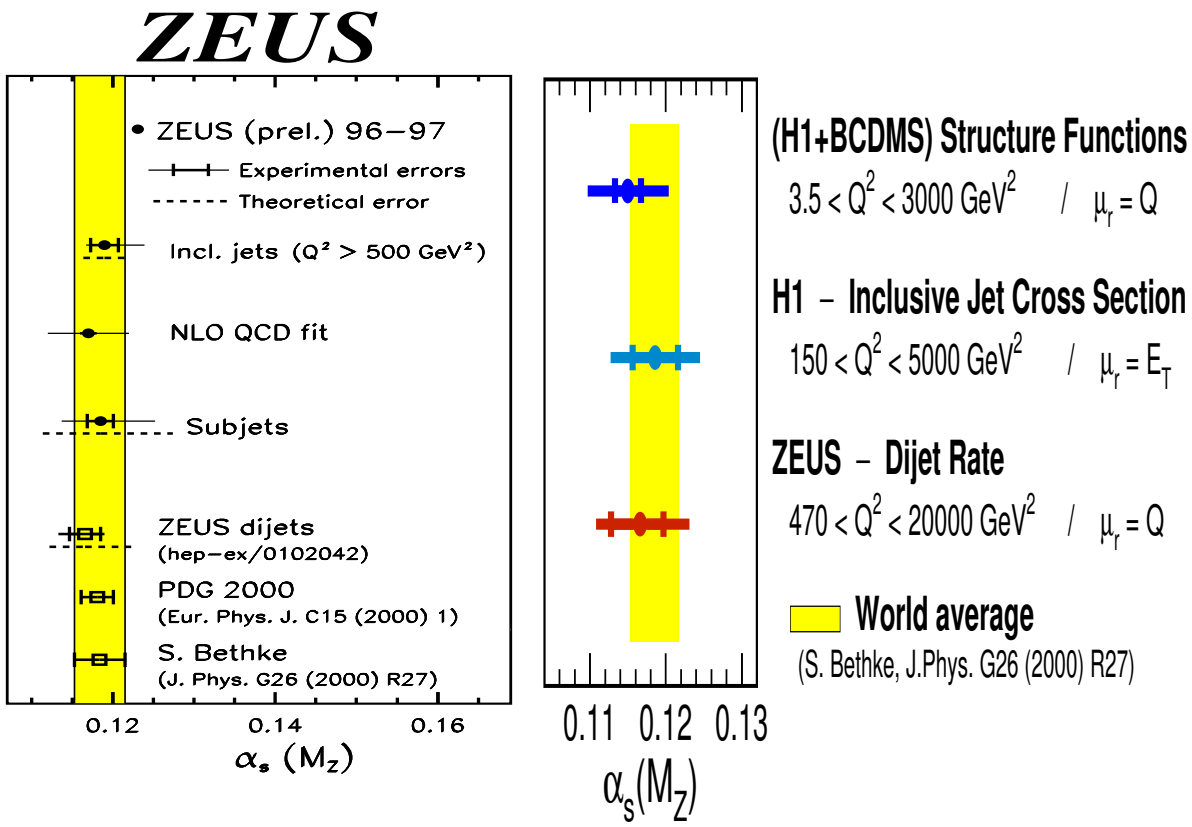
Let α_s free to be determined in the global fit, together with PDFs.

$$\Rightarrow \alpha_s(M_Z^2) = 0.1172 \pm 0.0008(\text{stat.}) \pm 0.0054(\text{syst.})$$

- Note: NO theoretical uncertainty (e.g. renorm. scale uncertainty) is evaluated yet.
- Consistent with the world average of α_s=0.118 (PDG).
- A large uncertainty due to correlated systematic errors was obtained.
  $\Rightarrow$ this covers α_s=0.120 as measured at LEP
  and as favoured by CDF jet cross-section.

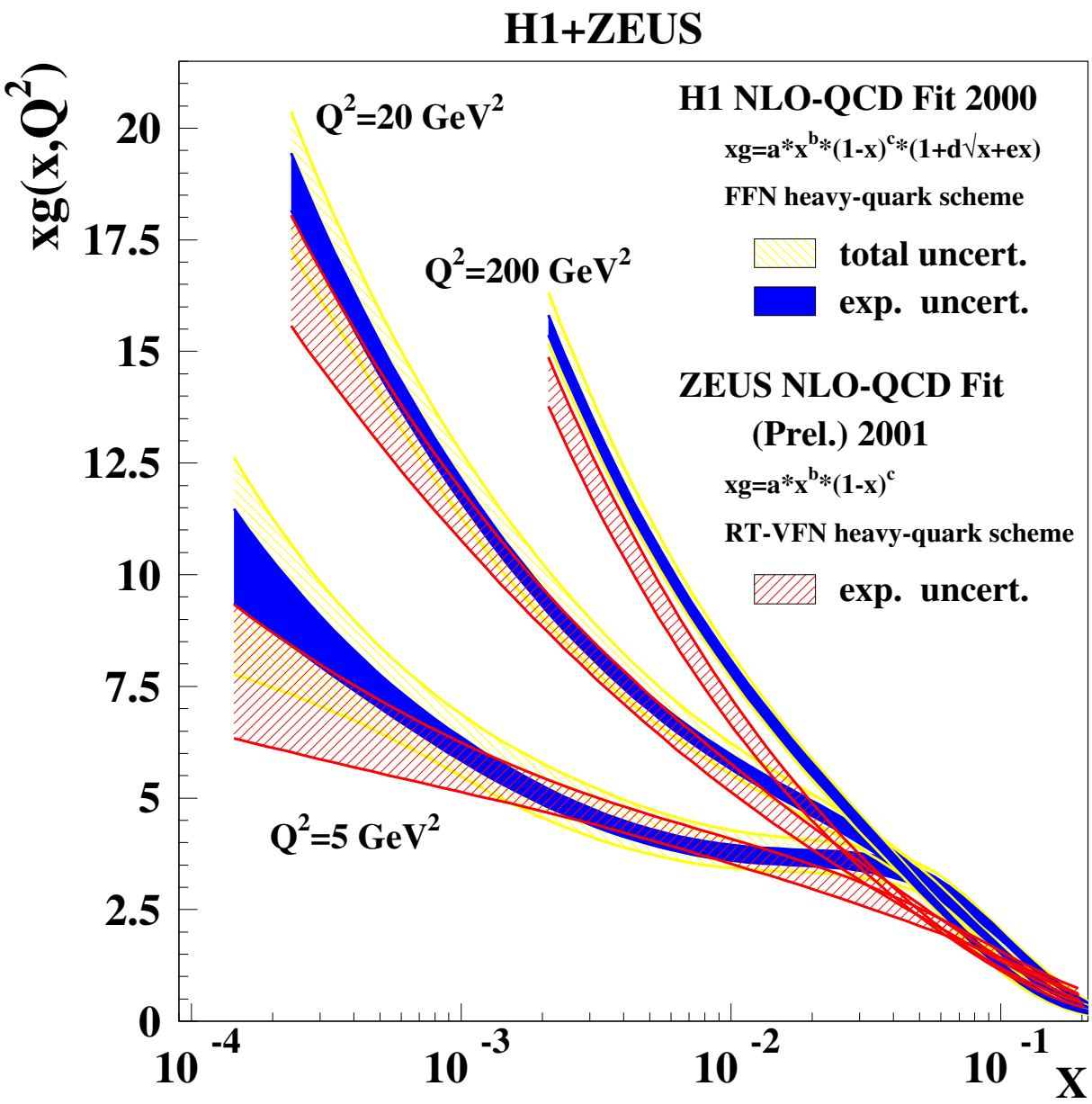
α_s comparison [H1 and ZEUS]

	ZEUS (prelim.)	H1
α_s	0.1172	0.1150
experimental error	± 0.0008 (stat.) ± 0.0054 (syst.) ± 0.0055 (exp.)	± 0.0017 (exp.)
model error		$^{+0.0009}_{-0.0005}$
scale uncertainty		~ 0.005



- The α_s both from H1 and ZEUS are consistent with world average and also with those obtained from jets.
- The α_s error due to experimental errors is different between H1 and ZEUS.
  $\Rightarrow$ different treatment of correlated syst.errors.

A combined plot of xg [H1 and ZEUS]



- There are several differences between H1/ZEUS analysis methods which may account for:
  - High-x($x \sim 10^{-1}$) shape: xg parameterisation
  - Slope: heavy-quark prod. scheme
  - Uncertainty: treatment of correlated syst.errors

$\Rightarrow$ H1 and ZEUS gluons reasonably agree with each other considering these differences.

Summary

Both H1 and ZEUS collaborations performed NLO-QCD analysis on the recent precise structure function measurements at HERA

- Data were well described by NLO-QCD fits.
- we considered experimental systematic errors taking into account point-to-point correlation.

Gluon density:

- Consistent to and more precise than those extracted from D^* and di-jet measurements.
- A great sensitivity of HERA data to gluon and Sea densities was shown.
- Given the different fit assumptions used by each experiment, H1 and ZEUS gluons 'reasonably' agree.

Extraction of α_s:

- H1: $\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp.)^{+0.0009}_{-0.0005}(model)$
- ZEUS: $\alpha_s(M_Z^2) = 0.1172 \pm 0.0008(stat.) \pm 0.0054(syst.)$
- The α_s error due to experimental errors are different between H1 and ZEUS. It may be due to different treatment of correlated systematic errors.(under investigation)
- HERA data constrain the gluon at low-x and enable extraction of α_s.