ZEUS NLO-QCD fit to determine proton PDFs and α_s

Kunihiro Nagano (KEK)

on behalf of

the ZEUS collaboration

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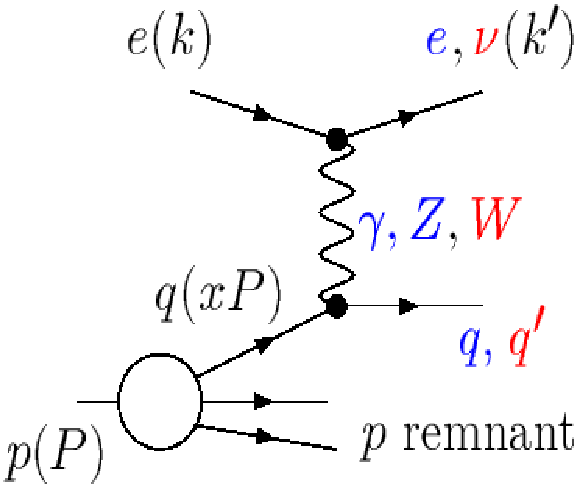
Deep Inelastic Scattering (DIS)

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)

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

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

SFs $\Leftrightarrow$ parton density functions (PDFs)

Naive QPM (or LO-QCD): $F_2(x) = x\sum_q e_q^2(q(x)+\overline{q}(x))$

Parton densities at NLO-QCD

- Factorization; SFs = Σ (short-range) $\otimes$ (PDFs)
- 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 flavor f, g: gluon density, $P_{q_iq_j}$, P_{q_ig}, P_{gg}: splitting functions)

- Needs experimental input to determine PDFs at Q_0^2 where evolution starts. $\Rightarrow$ this analysis.

Analysis method

- NLO evolution in $\overline{\mathrm{MS}}$ scheme (program: QCDNUM)
- μ_R=μ_F=Q^2
- No higher-twist (HT) correction
- Heavy-Quark prod.: RT-VFN scheme $\Rightarrow$ See Highlight

PDF parameterization

- PDFs are parameterized at Q_0^2=7 GeV^2 with the form of: $f = p_1 x^{p_2}(1-x)^{p_3}(1+p_4\sqrt{x}+p_5 x)$ a la MRST-group.
- PDFs to be determined: xu_V, xd_V, xg, xS, $x(\overline{d}-\overline{u})$.
- 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 used in the fit

Data sets: a global analysis $\Rightarrow$ See Highlight.

- DIS(HERA): ZEUS e^+ '96 – '97 reduced σ_{NC}
  $\Rightarrow$ Now, FINAL!.
- 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 $xu_V - xd_V$

Cuts on data

- $W^2 > 20$ GeV^2 (to minimize higher-twist effect)
- $Q^2 > 2.5$ GeV^2

Data normalization

- Data normalization is fixed except for BCDMS F_2^p ($\downarrow$ by 2 %) as usually done by professional fitters.

Treatment of experimental errors

- Experimental correlated errors are considered taking into account point-to-point correlations! $\Rightarrow$ See Highlight.

Highlights of this analysis

1. Improved heavy-quark production scheme: RT-VFN (R.S.Thorne,R.G.Roberts PLB 421(1998) 303)
   - fixed flavor number scheme (FFN)
     - calculate the BGF process to heavy-quarks ($\gamma^* g \to c\bar{c}$) correctly up to NLO. (only light quarks(u,d,s) are active)
     - but does not take ln Q^2/m_c^2 terms.
   - zero-mass variable flavor number scheme (ZM-VFN)
     - re-sums ln Q^2/m_c^2 terms into heavy-quark parton distributions which obey the usual DGLAP evolution.
     - but cannot be right near threshold: $Q^2 \sim m_c^2$.

   ⇒ RT-VFN: a practical procedure for a smooth transition between these two schemes.

2. Data-sets: ZEUS 96/7 (now FINAL!) + fixed-target exps.
   - ZEUS '96 – '97: $\sim$ 12 times more luminosity than previous published measurement ('94).
     ⇒ more precise gluon / Sea distributions.
   - Fixed-target data (μ-P, μ-D, ν-N) were also used to constrain PDFs at high-x.
     ⇒ a global analysis on 1263(ZEUS:242) data points!
     ⇒ all of the precise DIS data were used.

Highlights of this analysis -cont'd-

3. Evaluation of uncertainties coming from experimental systematic errors
   - 71 systematic errors were considered taking into account their point-to-point correlations.
   - Normalization (luminosity) errors were also considered as fully point-to-point correlated systematic errors.

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

4. Simultaneous α_s extraction was performed.
   - Central fit: we fixed α_s=0.118.
   - A fit with free α_s was also performed.

     (scaling violation: $dF_2/d\log Q^2 \sim \alpha_s \cdot g$ at low-x.)

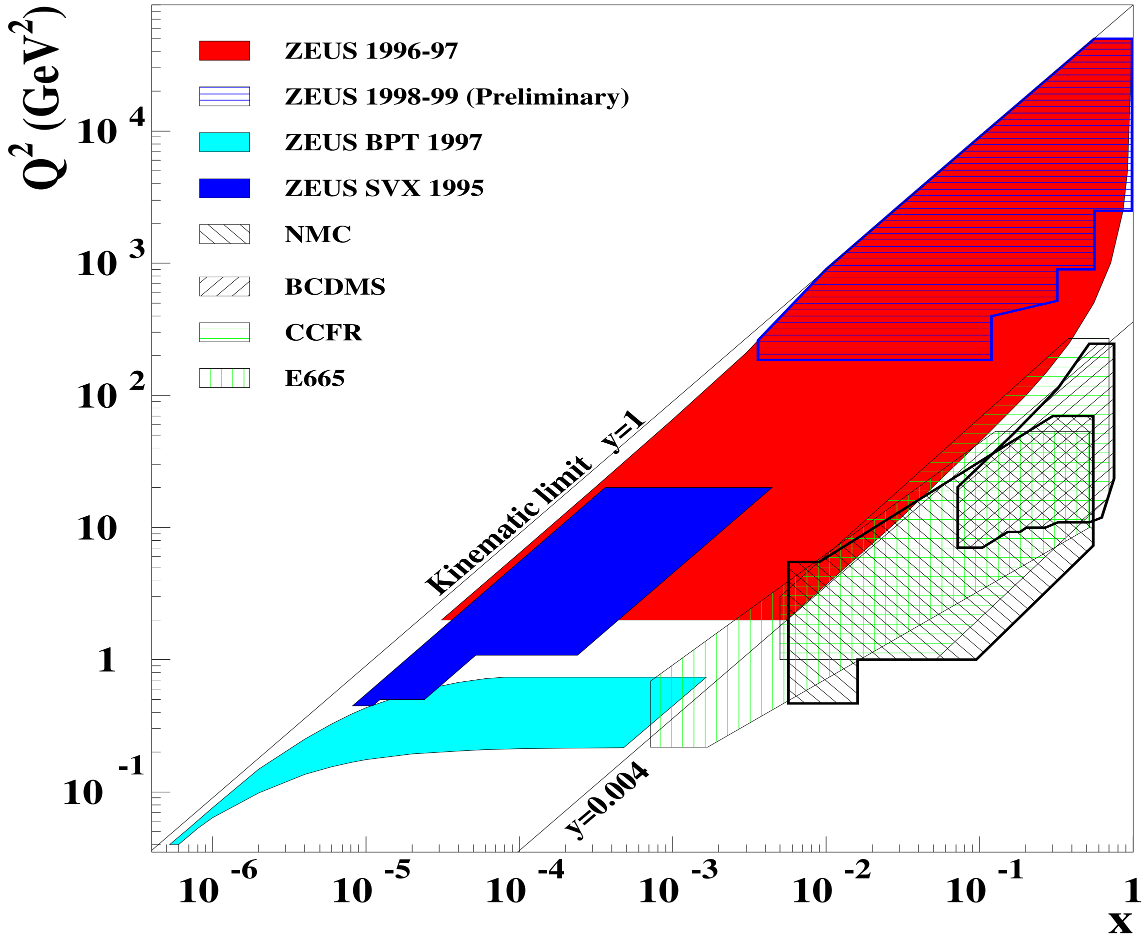
     $\Rightarrow$ Uncertainties in α_s and PDF values can be evaluated by taking into account both:
     - correlations of experimental systematic errors
     - correlations between PDFs and α_s

5. We will demonstrate importance of ZEUS data in the global fit by showing the two special fits:
   - A fit without ZEUS
   - A fit only with ZEUS

beam	year	luminosity	measurement
e^+	'96 – '97	47 pb^{-1}	NC: $2.5 < Q^2 < 30000$ GeV^2
			CC: $200 < Q^2 < 17000$ GeV^2
e^-	'98 – '99	16 pb^{-1}	NC: $200 < Q^2 < 30000$ GeV^2
			CC: $200 < Q^2 < 17000$ GeV^2

NOTE: we use ONLY NC e^+ in central fits.
But, we use ALL; NC/CC e^+/e^-, for ZEUS-ONLY fit.

Kinematic plane where world data lie

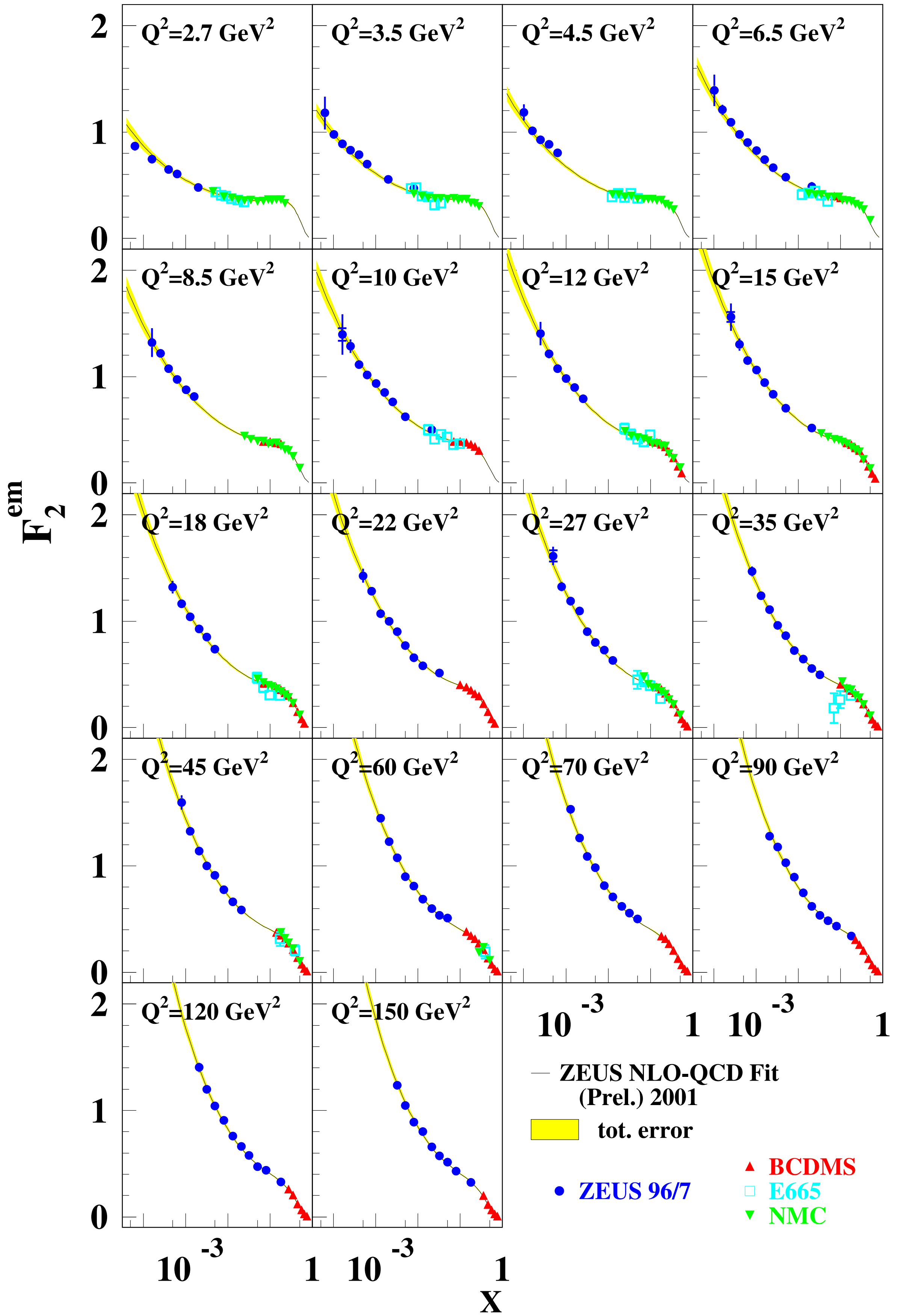


...and χ^2 table

Experiments	χ^2/N_{data} (vs stat.⊕syst.)		N_{data}
ZEUS 96/7	1.75	(0.85)	242
NMC P	1.74	(1.21)	218
NMC D	1.52	(0.92)	218
NMC D/P	0.98	(0.94)	129
BCDMS	1.29	(0.94)	305
E665 P	1.33	(1.16)	47
E665 D	1.14	(0.94)	47
CCFR xF_3	1.79	(0.40)	57
Total	1.48	(0.95)	1263
Total [FFN]	1.59	(1.01)	1263
Total [ZM-VFN]	1.48	(0.95)	1263

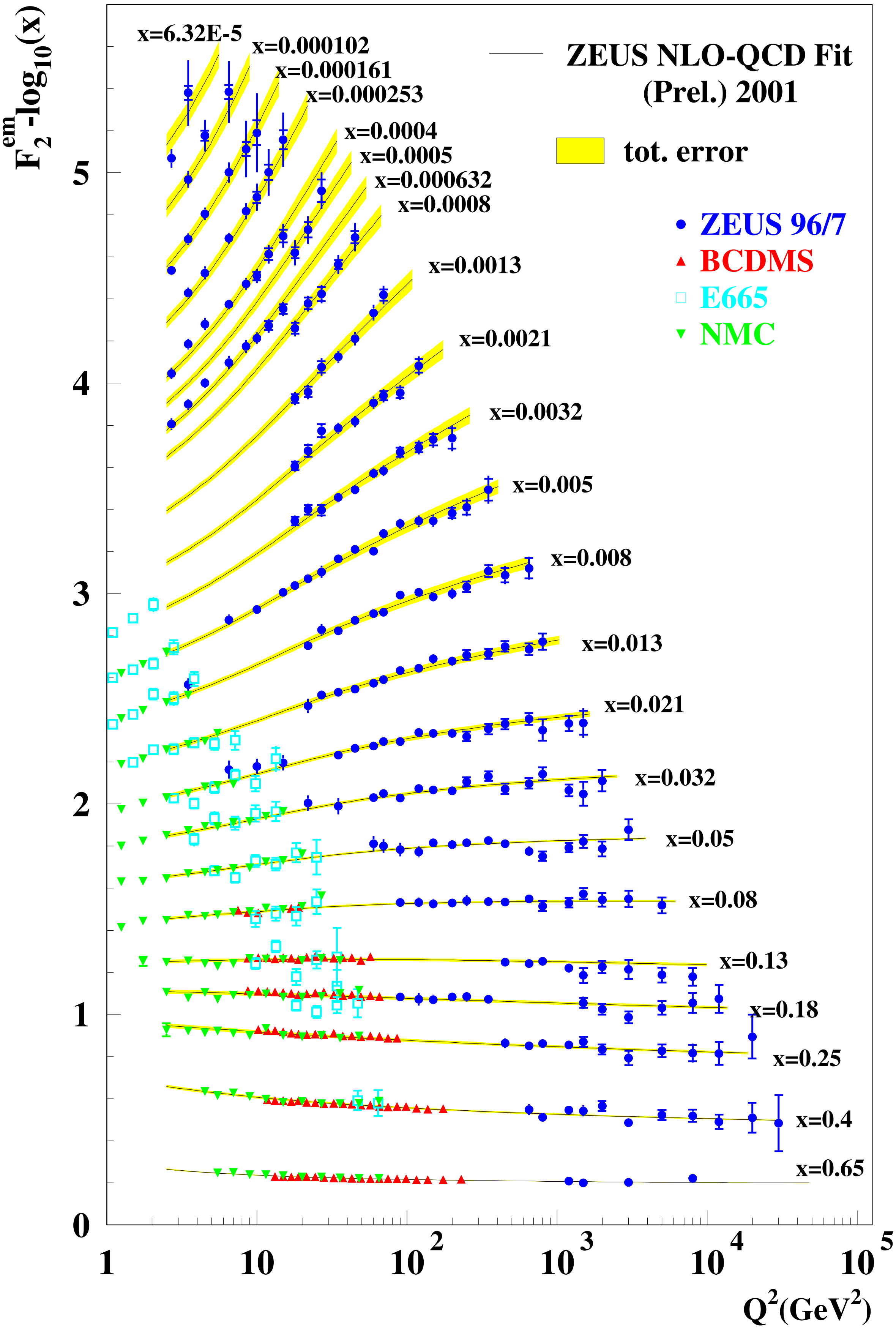
- The fit gave a good description over full range of world data.
- RT-VFN gave a better(or similar) χ^2 than FFN/ZM-VFN.

F_2^{em} description: $2.7 < Q^2 < 150$ GeV^2



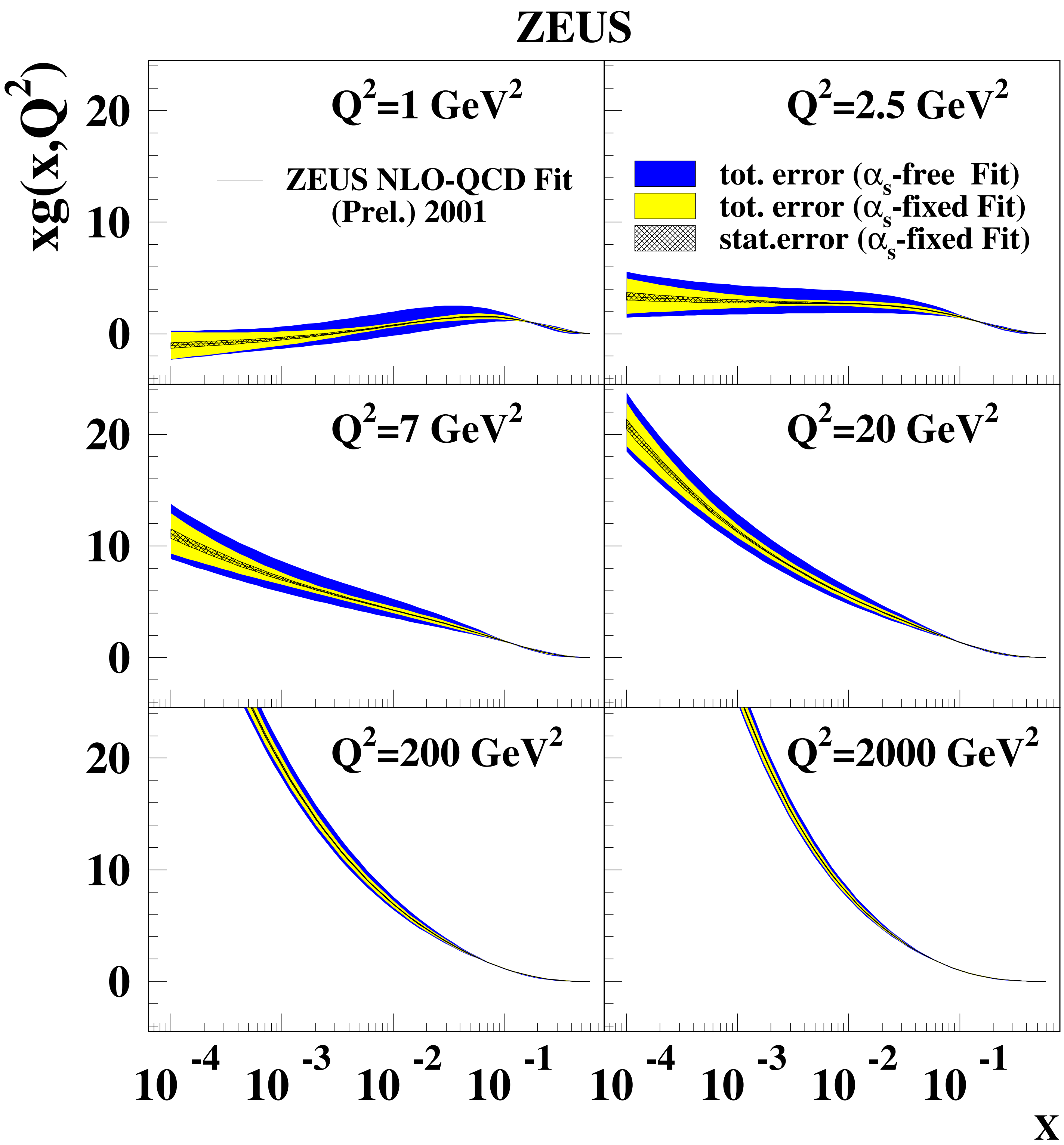
- NLO-QCD fit describes data well both for ZEUS and fixed-target experiments.

F_2^{em} : scaling violation



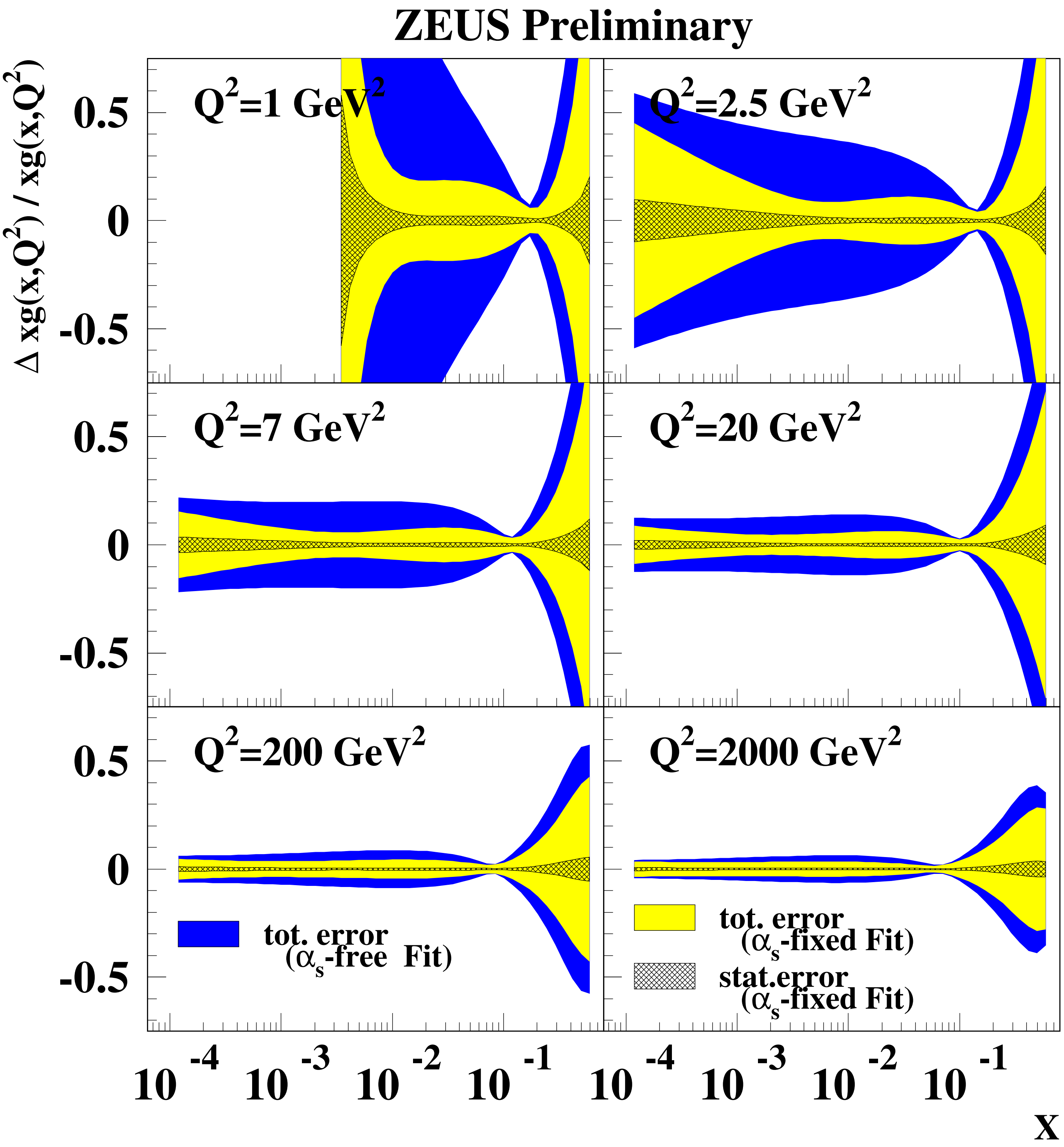
- NLO-QCD fit describes data well both for ZEUS and fixed-target experiments.

$xGluon$ distribution



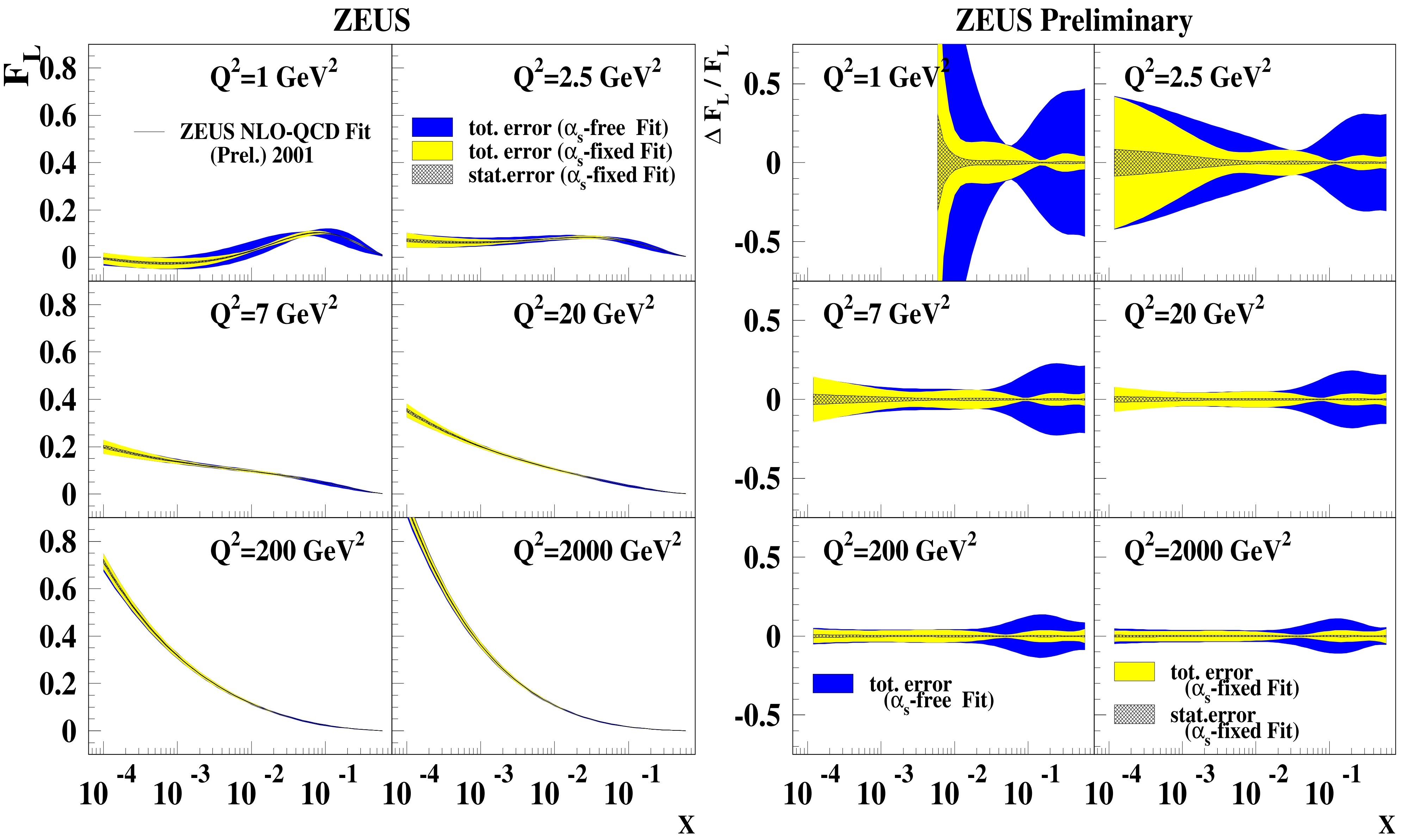
- Total uncertainty (due to exp.errors) of the "α_s-FREE fit" is also displayed.
- At $Q^2 = 1$ GeV^2: valence like, consistent with 0 at low x.
- Consistent with ZEUS '95 gluon and H1 '00 gluon. (See R. Walley's talk)

uncertainty of $xGluon$ distribution



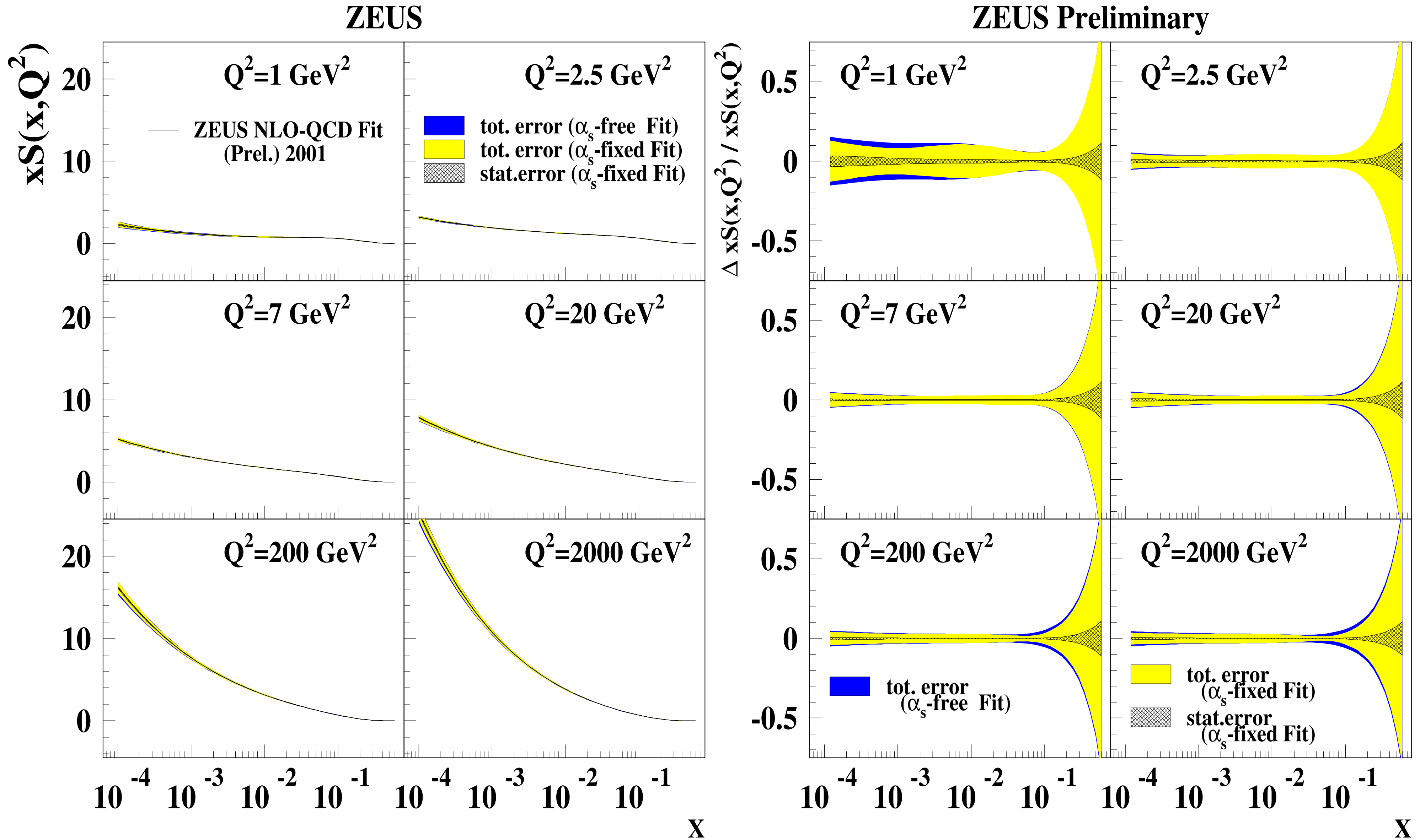
- Uncertainty is reduced as Q^2 evolves.
- $10^{-3} < x < 10^{-1}$: well determined within $\lesssim$ 10%.
- $x \gtrsim 10^{-1}$: large uncertainty.

F_L prediction



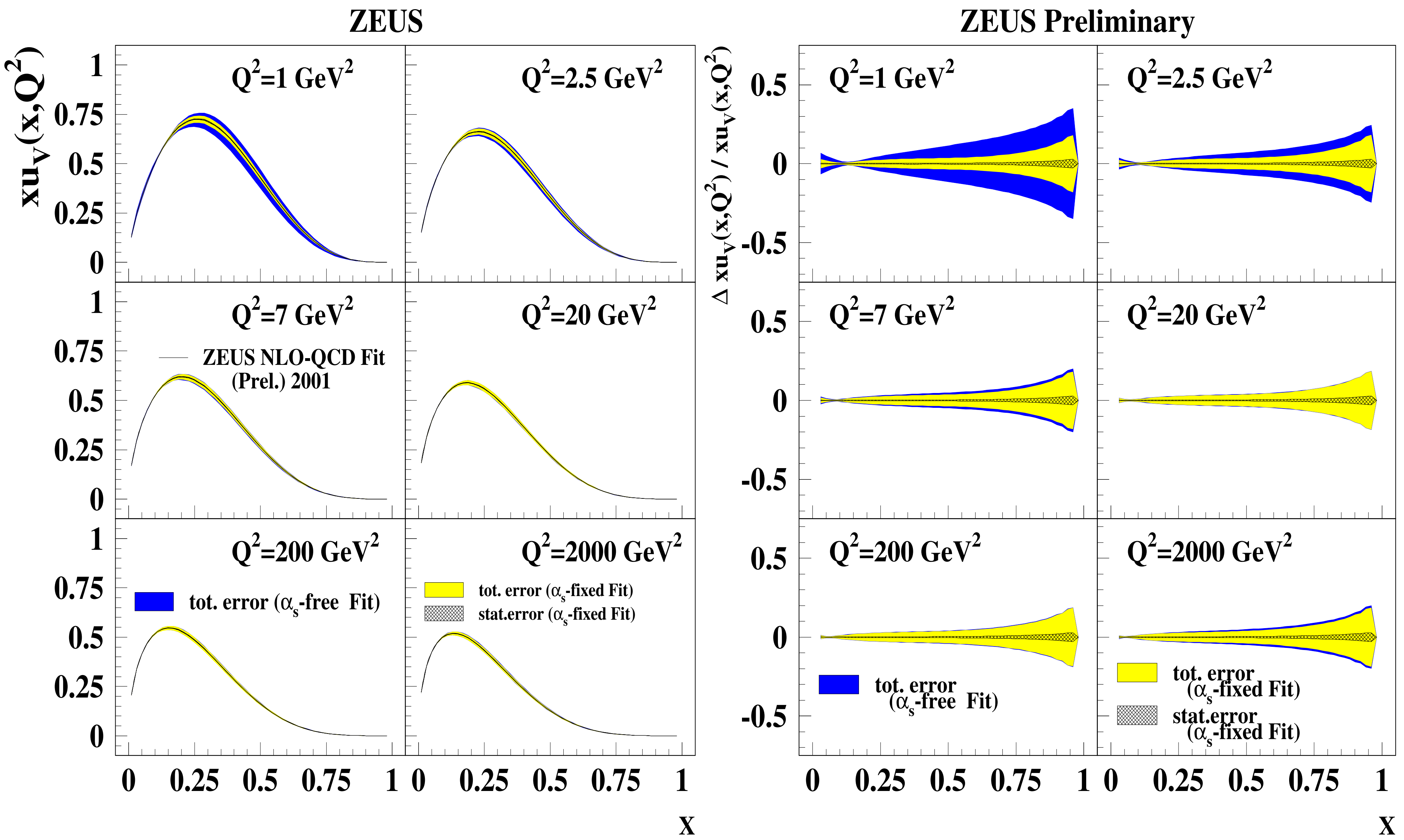
- At $Q^2 = 1$ GeV^2 and low-x where gluon gets negative, F_L is also negative. (See more later)

$xSea$ distribution



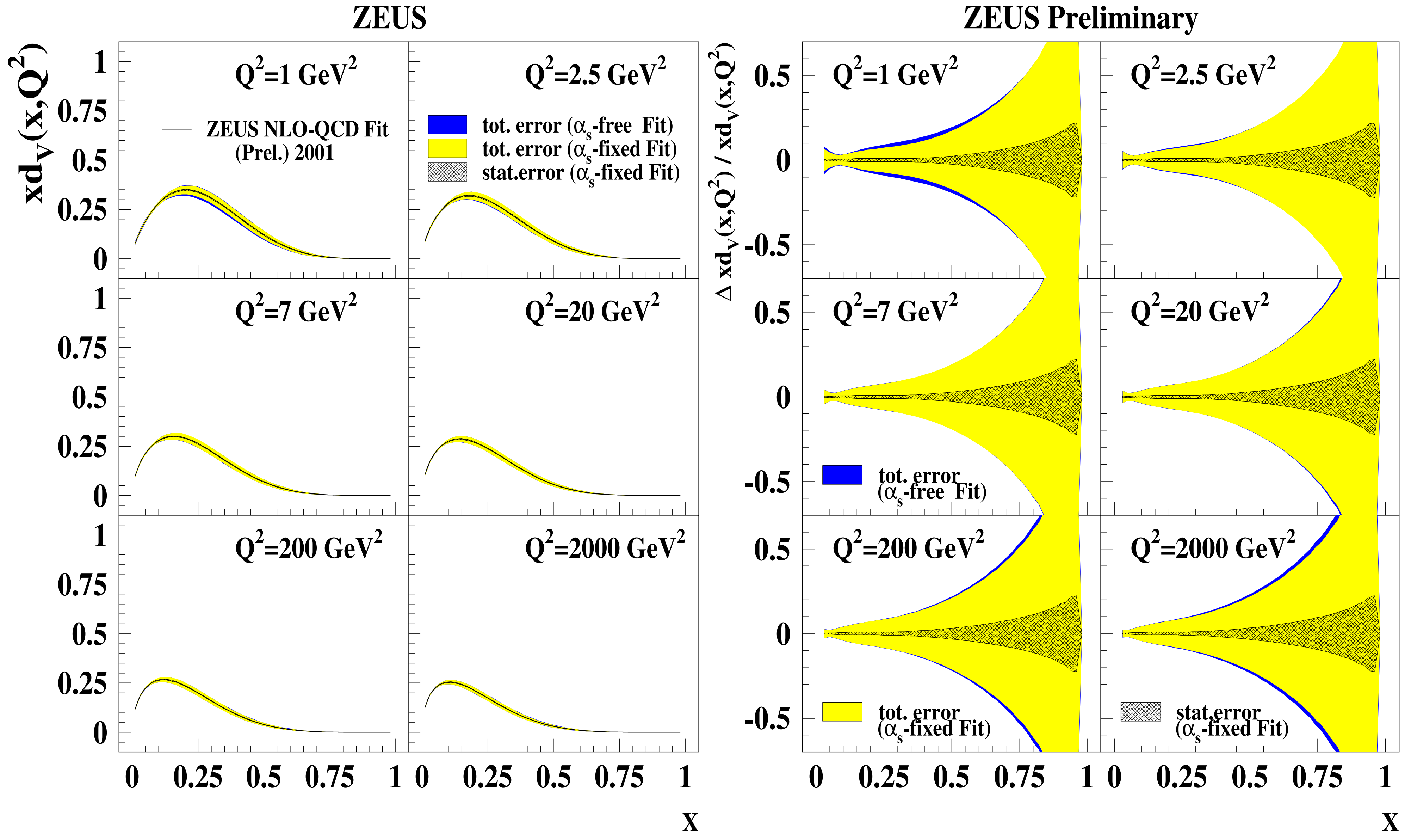
- At $Q^2 = 1$ GeV^2: still slightly rising.
- Uncertainty: typically $\lesssim$ 5%.

xU_V distribution



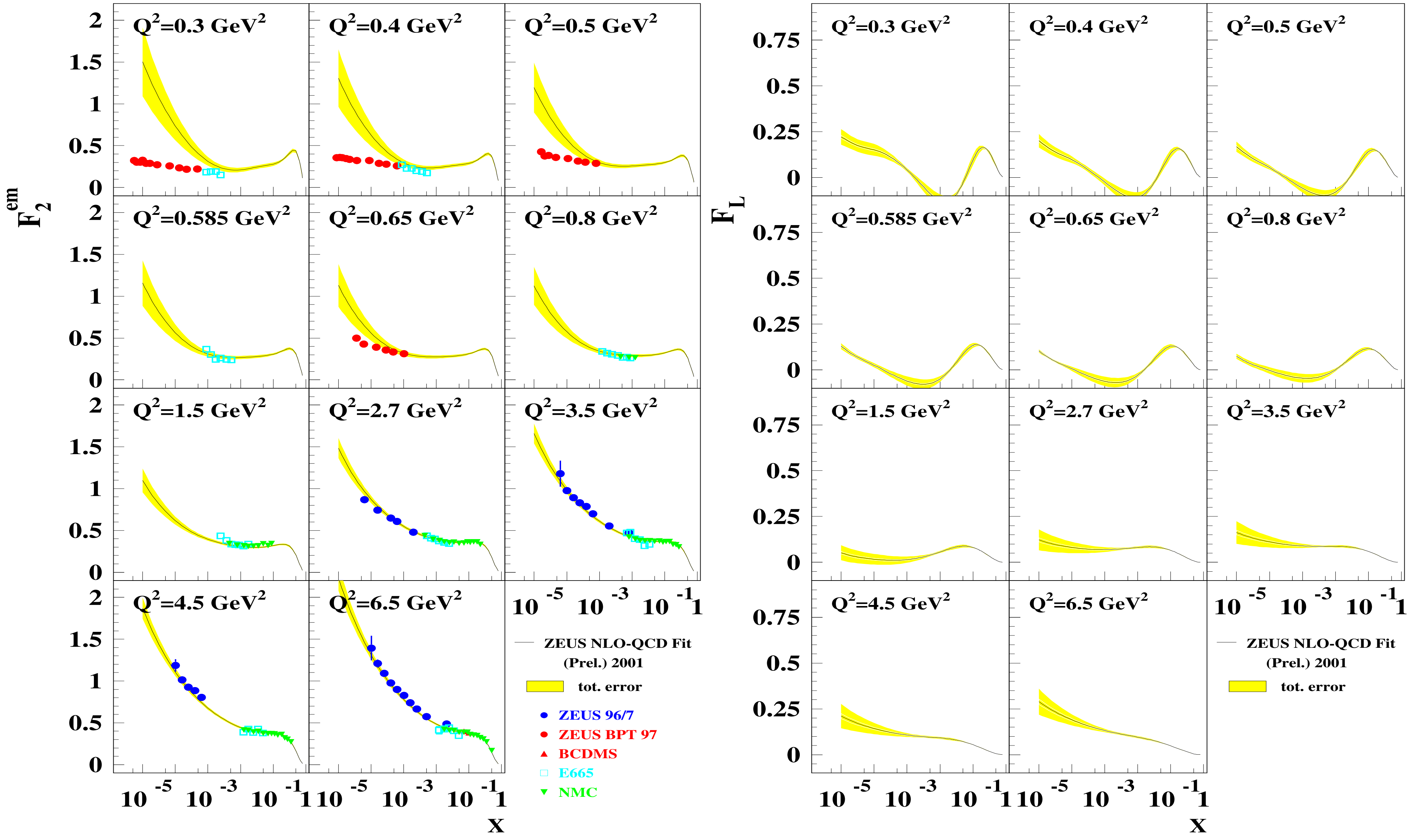
- Well determined within about 5% up to very large $x \sim 0.6$.
  Remind: $F_2^p \propto x(4u + d)$

xD_V distribution



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

Transition region: extrapolation down to very low $Q^2 \sim 0.3$ GeV^2

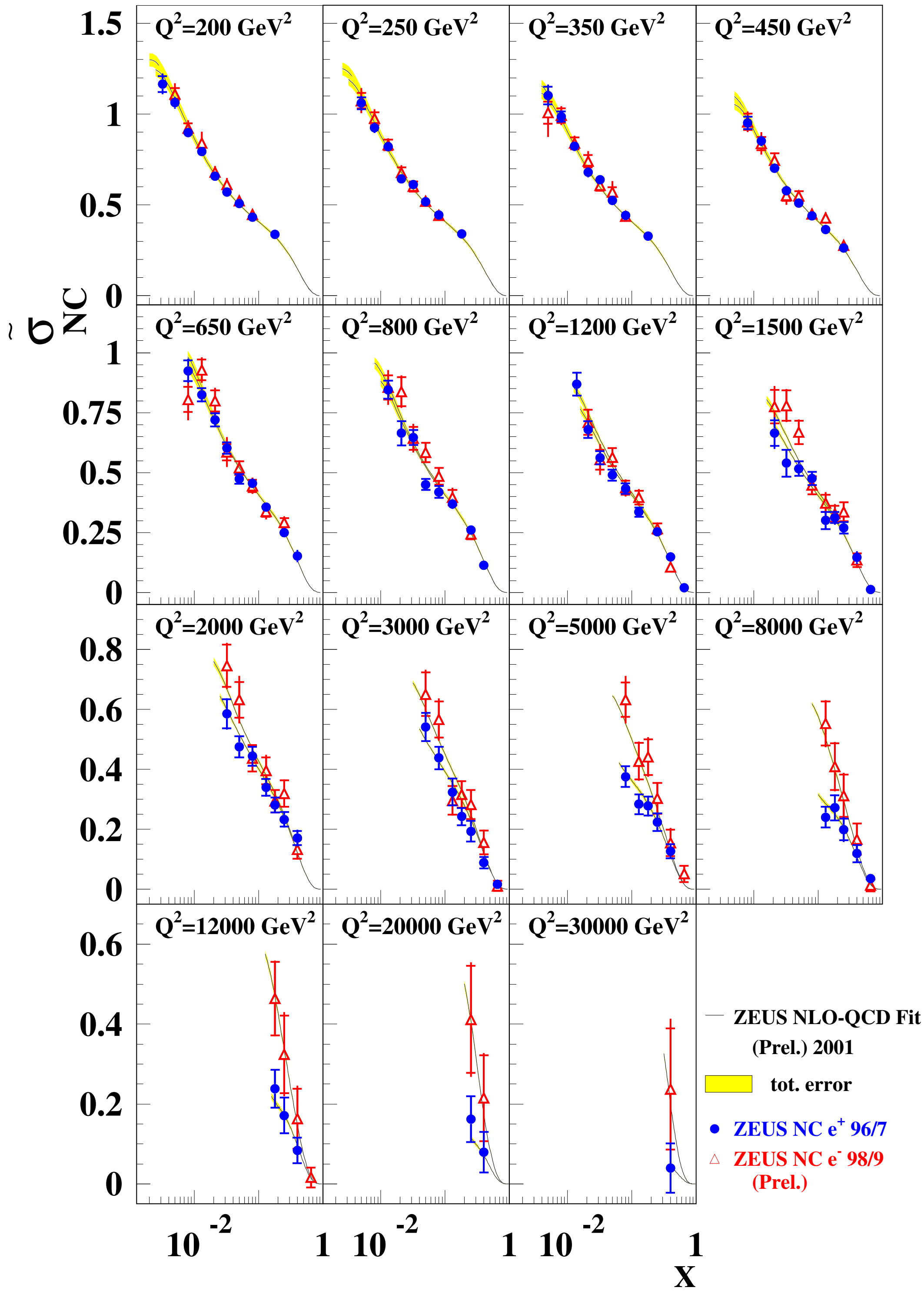


- QCD-fit tends to overshoot ZEUS BPT data points.
- Limit of pQCD: seems to be $Q^2 \sim 1$ GeV^2; F_L goes negative.

High-Q^2 NC reduced $\tilde{\sigma}_{NC}$

- Note: e^-p is NOT used in the fit.

$$\tilde{\sigma}_{NC}(e^{\pm}p) \equiv \left(\frac{Q^2 x}{2\pi\alpha^2 Y_+}\right)\frac{d^2\sigma}{dxdQ^2} = F_2^{NC} \mp \frac{Y_-}{Y_+} xF_3^{NC} - \frac{y^2}{Y_+}F_L^{NC}$$

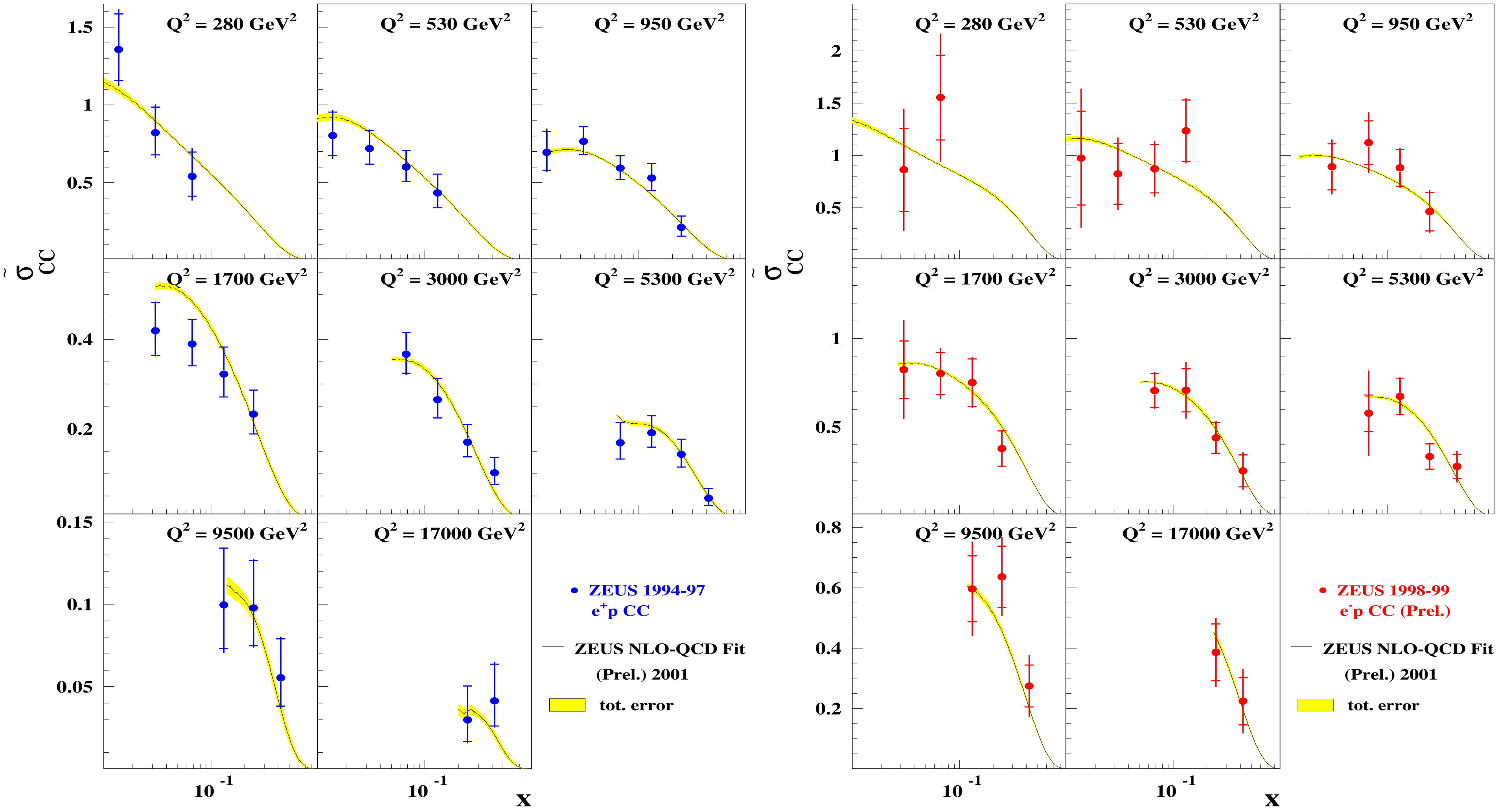


- NLO-QCD gives good description both for e^+p and e^-p .
  $\Rightarrow xF_3^{NC}$ component (i.e. Z^0 effect coupling to valence PDFs).

High-Q^2 CC reduced $\tilde{\sigma}_{CC} \equiv \frac{{G_F}^2}{2\pi x}\left(\frac{{M_W}^2}{{M_W}^2+Q^2}\right)^2 \frac{d^2\sigma}{dx\,dQ^2}$

- Note: CC were NOT used in the NLO-QCD fit.

$$\tilde{\sigma}_{CC}(e^+p) = x \sum_{i=1,2} [\overline{u_i} + (1-y)^2 d_i] \qquad \tilde{\sigma}_{CC}(e^-p) = x \sum_{i=1,2} [u_i + (1-y)^2 \overline{d_i}]$$



- NLO-QCD gives good description both for e^+p and e^-p CC. (flavor specific)

Extraction of α_s; α_s-FREE Fit

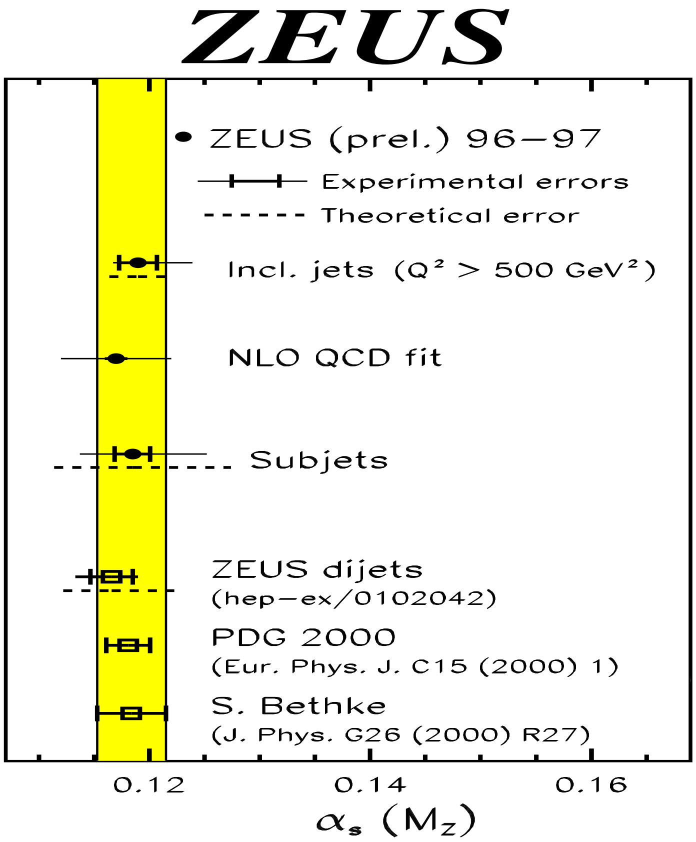
Let α_s free to be determined in the global fit, together with PDFs. This method gives α_s value and uncertainty for which:

- correlation between α_s and PDFs, and,
- effect of experimental systematic errors (including their point-to-point correlations)

are properly considered.

$$\Downarrow$$

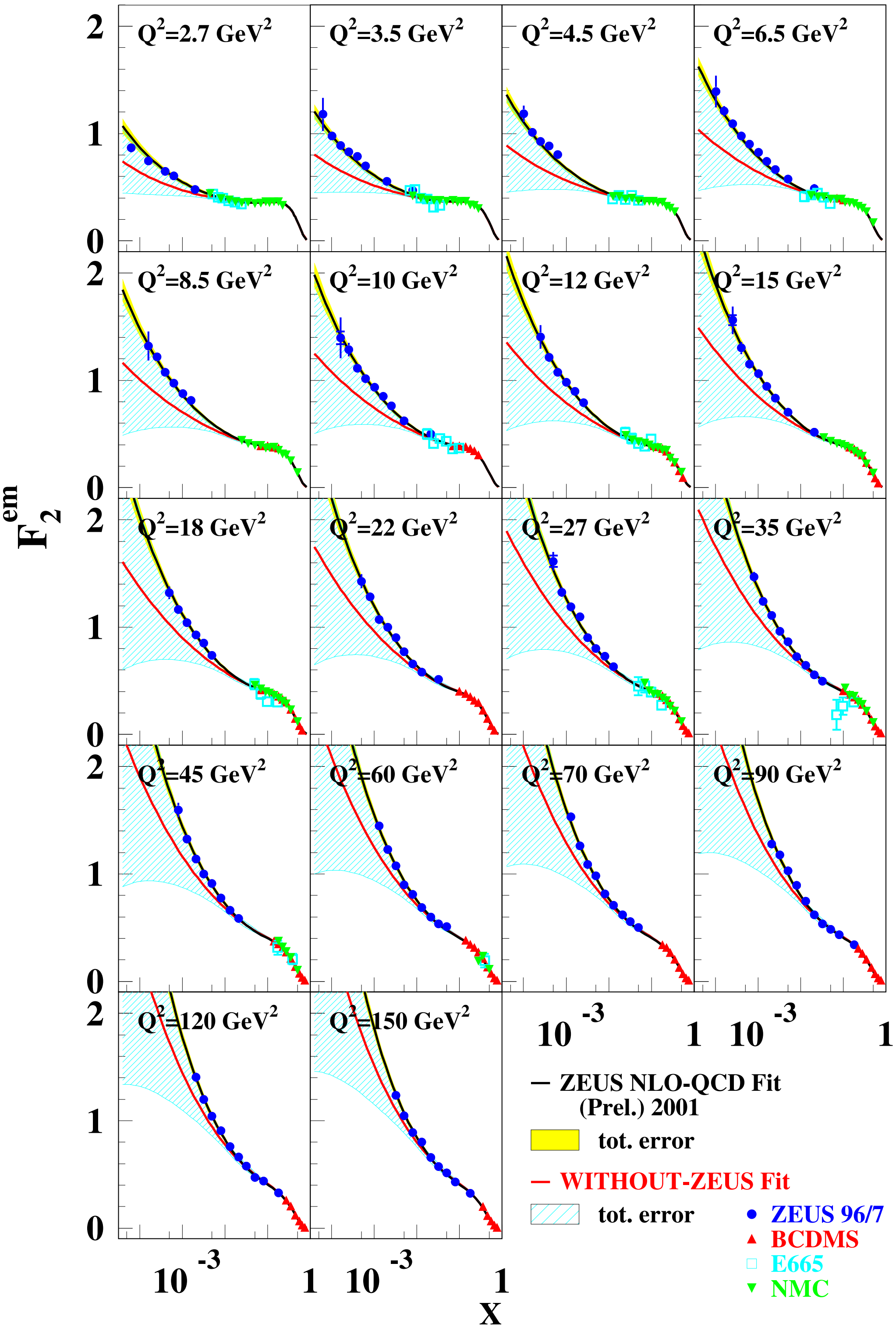
$$\alpha_s = 0.1172 \pm 0.0008(\text{stat.}) \pm 0.0054(\text{syst.})$$



- 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 favored by CDF jet cross-section.

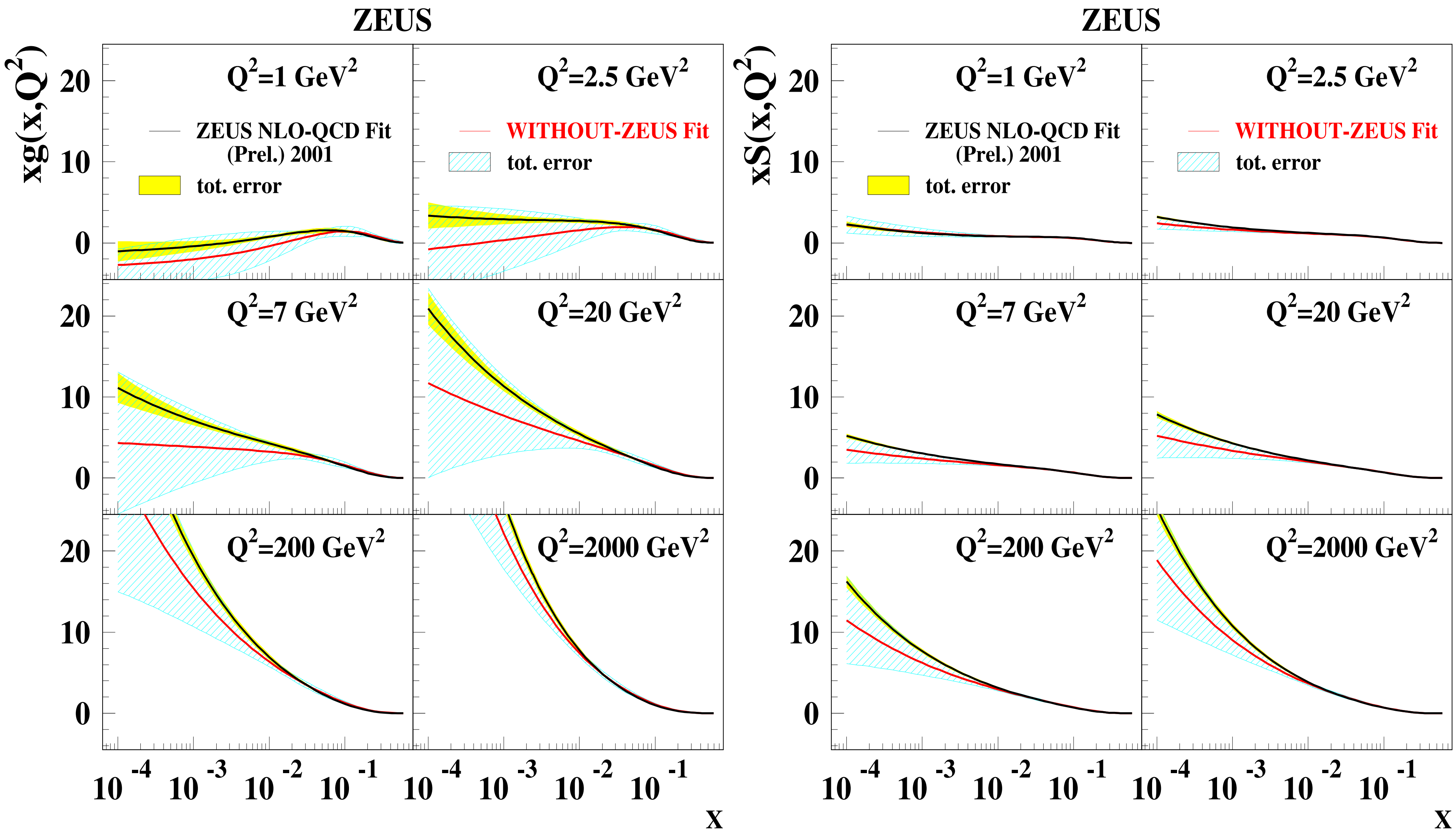
A fit without ZEUS [F_2^{em}]

...yes, we were already once astonished in '92 on the unexpectedly steep F_2 at HERA, but, let us re-visit this with the current precision of our measurement!



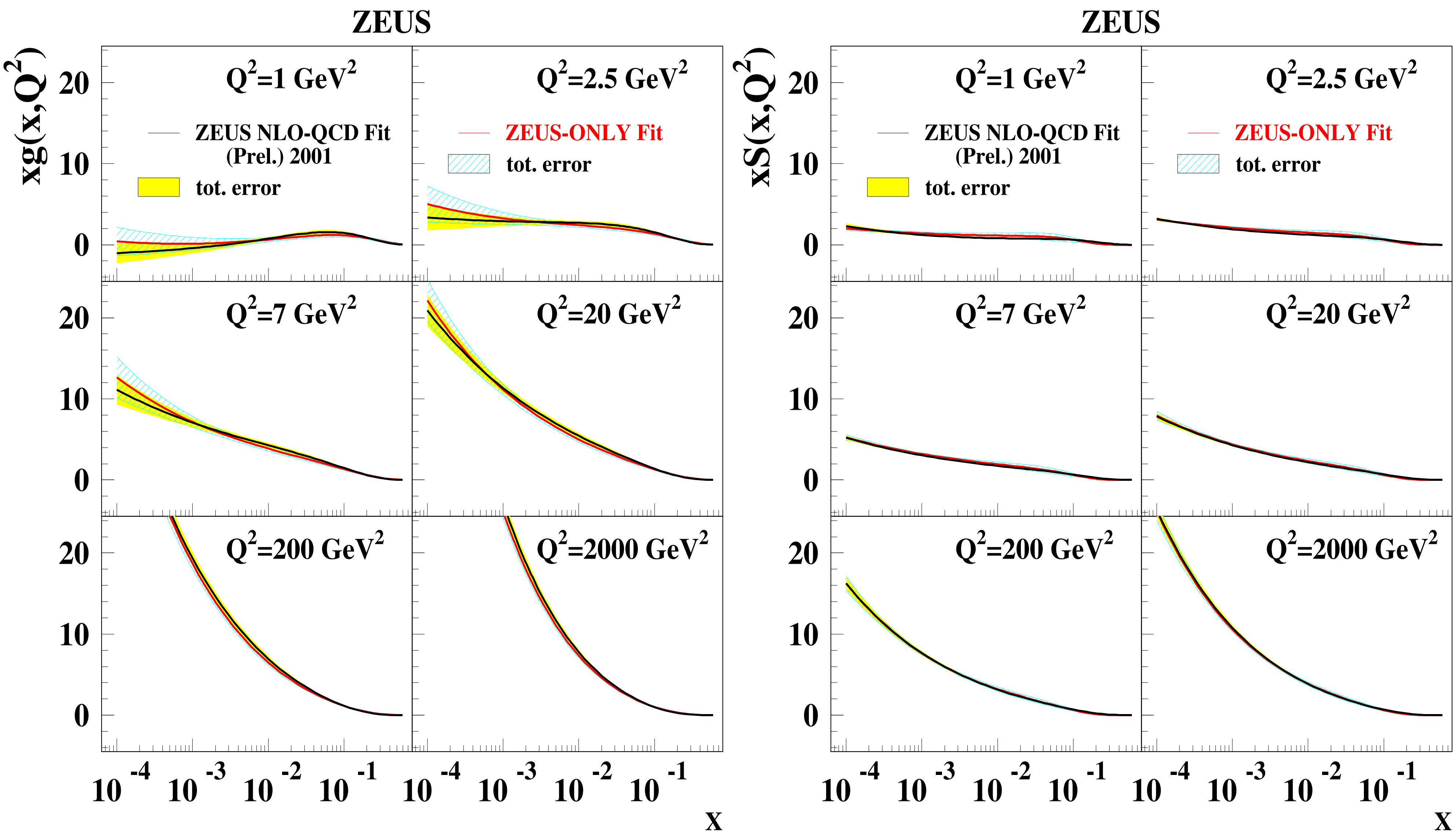
- ZEUS F_2 is steeper than expected from fixed-target experiments even up to $Q^2 \sim 200$ GeV^2.
- Much smaller uncertainties with ZEUS.

A fit without ZEUS [$xGluon$ and $xSea$]



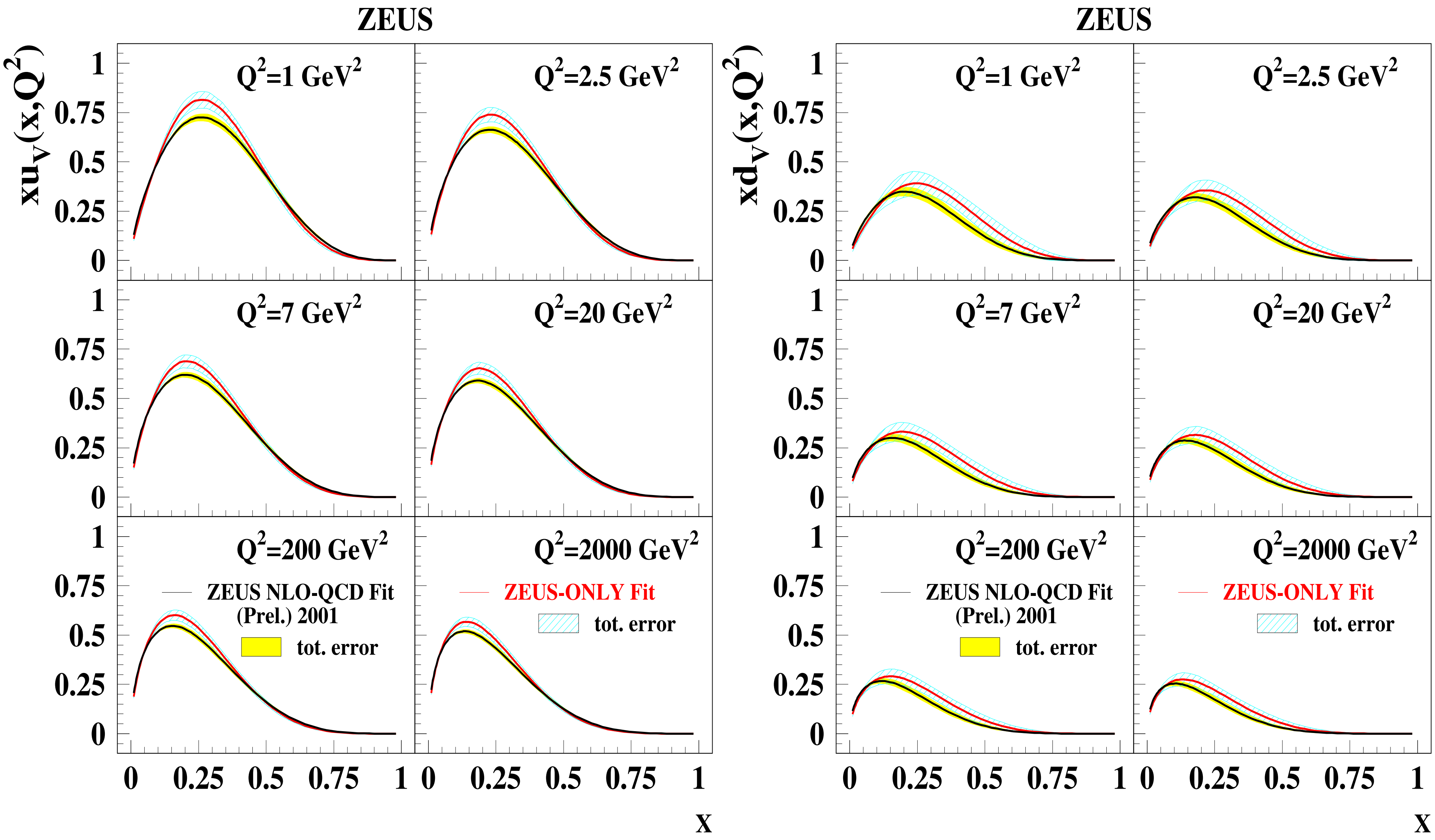
- ZEUS determines gluon and sea; stronger rise than expected from fixed-target exps.
- Much smaller uncertainties of gluon and sea were obtained with ZEUS.
- For xU_V and xD_V: comparable to the global fit (not shown).

A fit only with ZEUS [$xGluon$ and $xSea$]



- Only with ZEUS: F_2 96/97 + high-Q^2 e^-p NC and CC, e^+p CC.
- ZEUS prefers a slightly steep gluon.
- Comparable error-size to the global fit's.

A fit only with ZEUS [xU_V and xD_V]



- We can determine valence distributions with our data alone! (thanks mostly to high-Q^2 data; e.g. CC $e^+p \Rightarrow xD_V$)
- ZEUS prefers a shift of xD_V to higher-x and larger xU_V.

Summary

A global NLO-QCD fit was performed on DIS data.

- based on: the new ZEUS '96 – '97 F_2 data + fixed-target experiments.
- we considered all the systematic errors of all experiments taking into account point-to-point correlation.

$$\Downarrow$$

- Gluon and Sea densities were determined with correctly evaluated errors.
- Data description by NLO-QCD fit:
  - F_2: good description for both ZEUS and fixed-target experiments, and also for proton and deuterium targets.
  - low-Q^2: good description up to $Q^2 \sim 1$ GeV^2, but, overshoots ZEUS BPT at $Q^2 \lesssim 1$ GeV^2.
  - high-Q^2: good description both for NC/CC, e^+p/e^-p.

Extraction of α_s:

- $\alpha_s = 0.1172 \pm 0.0008(\text{stat.}) \pm 0.0054(\text{syst.})$
- A large error comes from correlated experimental systematic errors.

Two special fits concerning on impact of ZEUS data

- ZEUS determines Gluon/Sea.
- Even with ZEUS alone, we can determine valence distributions.