HERAPDF2.0 approach to ATHENA data

Studying impact of ATHENA data on parton distributions in proton using HERAPDF2.0 framework

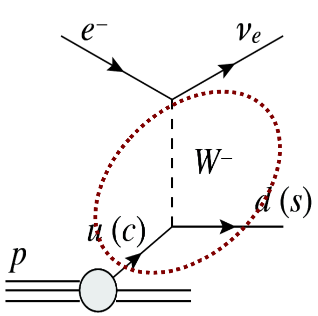
Very preliminary results

Neutral Current

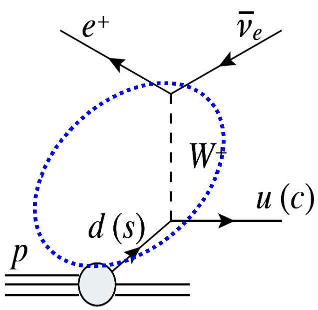
$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$

Proton structure functions:

- Sensitive to quarks $F_2 = x\sum e_q^2[q(x) + \bar{q}(x)]$
- Sensitive to valence distributions: $xF_3 = x\sum 2e_q a_q[q(x) - \bar{q}(x)]$
- Sensitive to gluon $F_L \sim \alpha_S\, x\, g$
- Gluon also from scaling violation and charm+jet data



Charge Current: flavor decomposition



$$\sigma^-_{CC} \sim x[u + c] + x(1-y)^2[\bar{d} + \bar{s}]$$

$$\sigma^+_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$

Global analysis of parton distributions

Goal: determination of the ***input distributions*** (for light quarks and gluons):

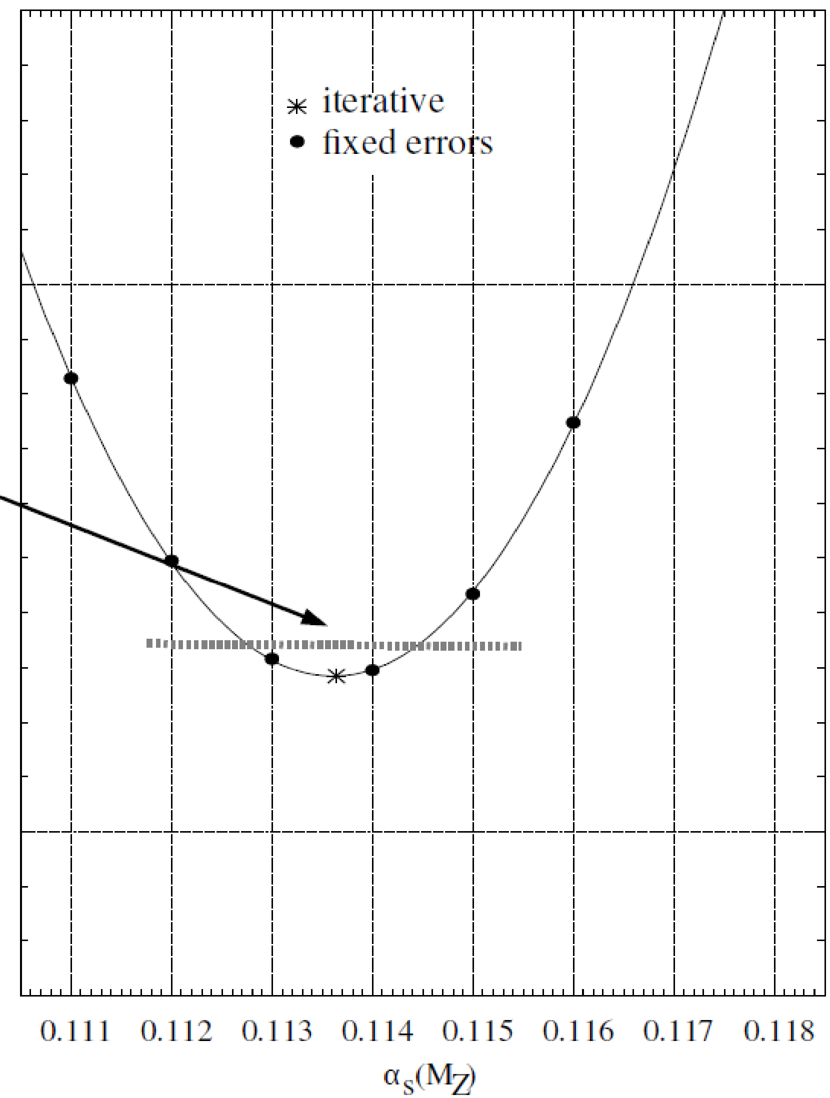
Method: Parametrizations $xf(x, Q_0^2) = Nx^a(1-x)^b \, \text{function}(x)$
and usual *statistical estimation* (fits):

$$\chi^2(p) = \sum_{i=1}^{N} \left(\frac{\text{data}(i) - \text{theory}(i,p)}{\text{error}(i)} \right)^2$$

Position of minimum gives the value and curvature gives the error (region within a certain "tolerance" $\Delta\chi^2 = 1$)

(Monte Carlo methods can also be used)

Usually the chi-square definition is more sophisticated, experimental correlations are also treated, etc.



1 fb^{-1} HERA data – exclusively! - used as input to global QCD fit HERAPDF2.0

- Parton densities parametrised @ $Q^2 = 1.9$ GeV^2

$$xf(x) = Ax^B (1-x)^C (1 + Dx + Ex^2)$$

$$xg(x), xu_v(x), xd_v(x), x\bar{U}(x), x\bar{D}(x)$$

- Evolution using DGLAP equations
- 14 parameters determined in paramerisation scan
- Heavy quarks from Roberts-Thorne Variable Flavor Number Scheme

QCD fits performed using HERAFitter package
www.herafitter.org

HERAPDF2.0 parameterisation

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

$$x\bar{s} = f_s x\bar{D} \text{ at } \mu^2_{f_0}$$

A_ubar = A_dbar

B_ubar = B_dbar

Parameters A_uv and A_dv are determined using quark counting rules and A_g using momentum sum rule

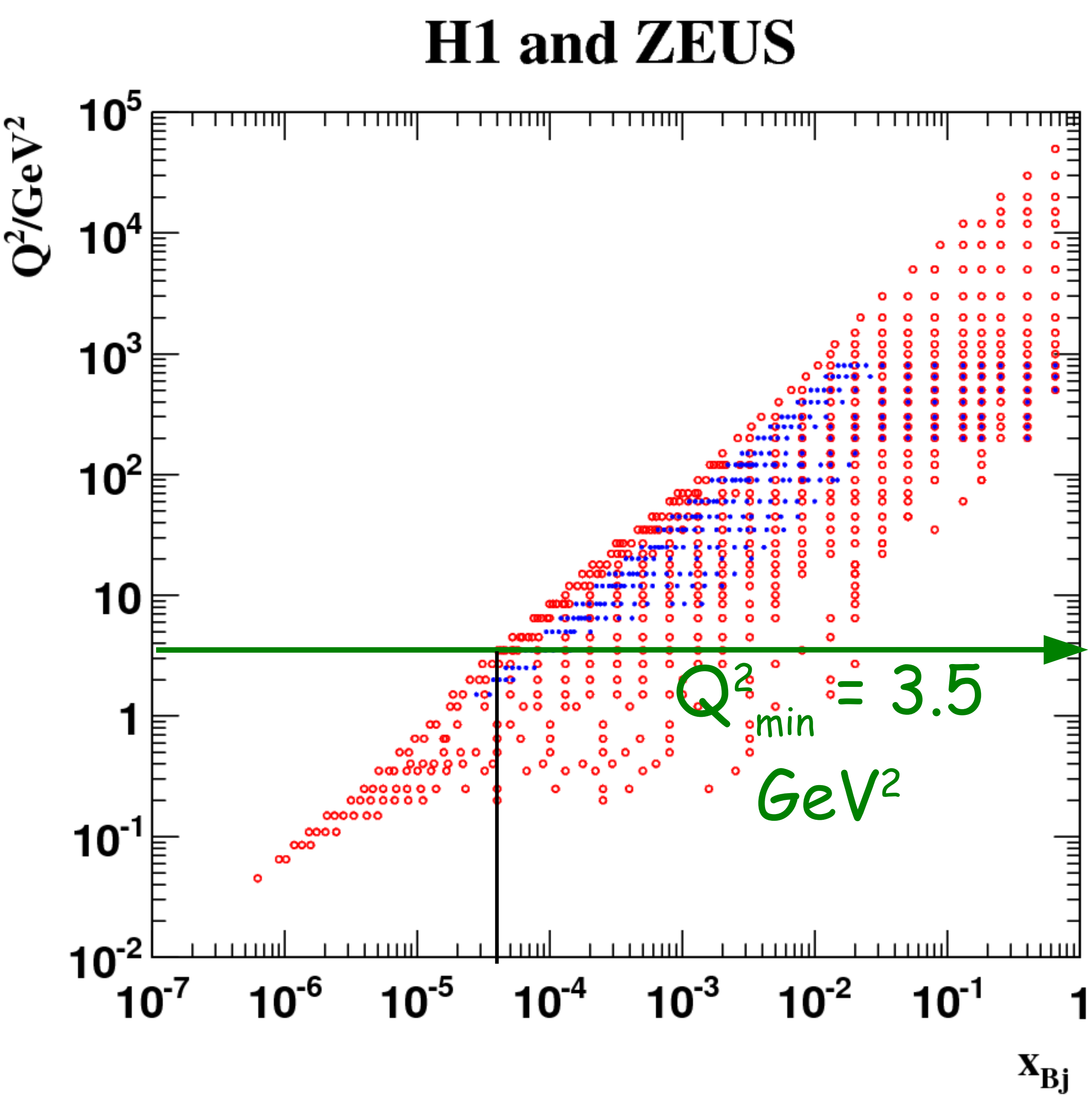
$$x\bar{U} = x\bar{u} \text{ and } x\bar{D} = x\bar{d} + x\bar{s}$$

Model parameters for HERAPDF2.0

Variation	Standard Value
Q^2_{min} [GeV^2]	3.5
M_c(NLO) [GeV]	1.47
M_b [GeV]	4.5
f_s	0.4
$\alpha_s(M_Z^2)$	0.118
μ_{f_0} [GeV]	1.9

- Lowest Q^2 of data points included in fit
- Masses of c and b quarks
- Strange fraction
- Starting scale

Data in HERAPDF2 fit



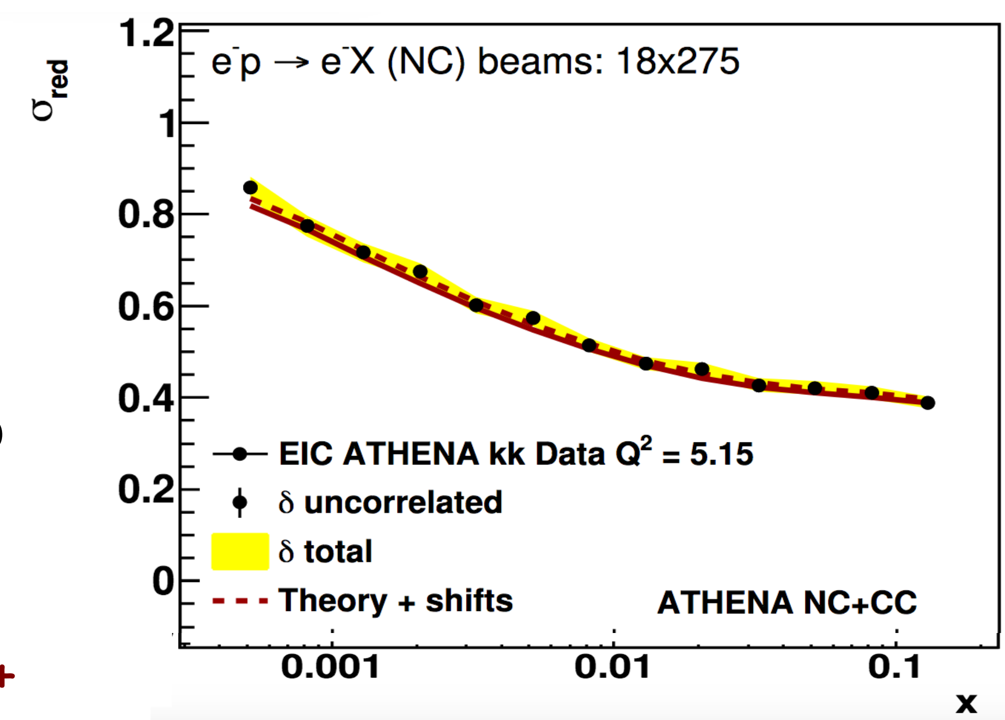
○ inclusive DIS, for E_p=920 GeV and E_p= 820 GeV data

● Inclusive DIS, for E_p=575 GeV and E_p= 460 GeV data

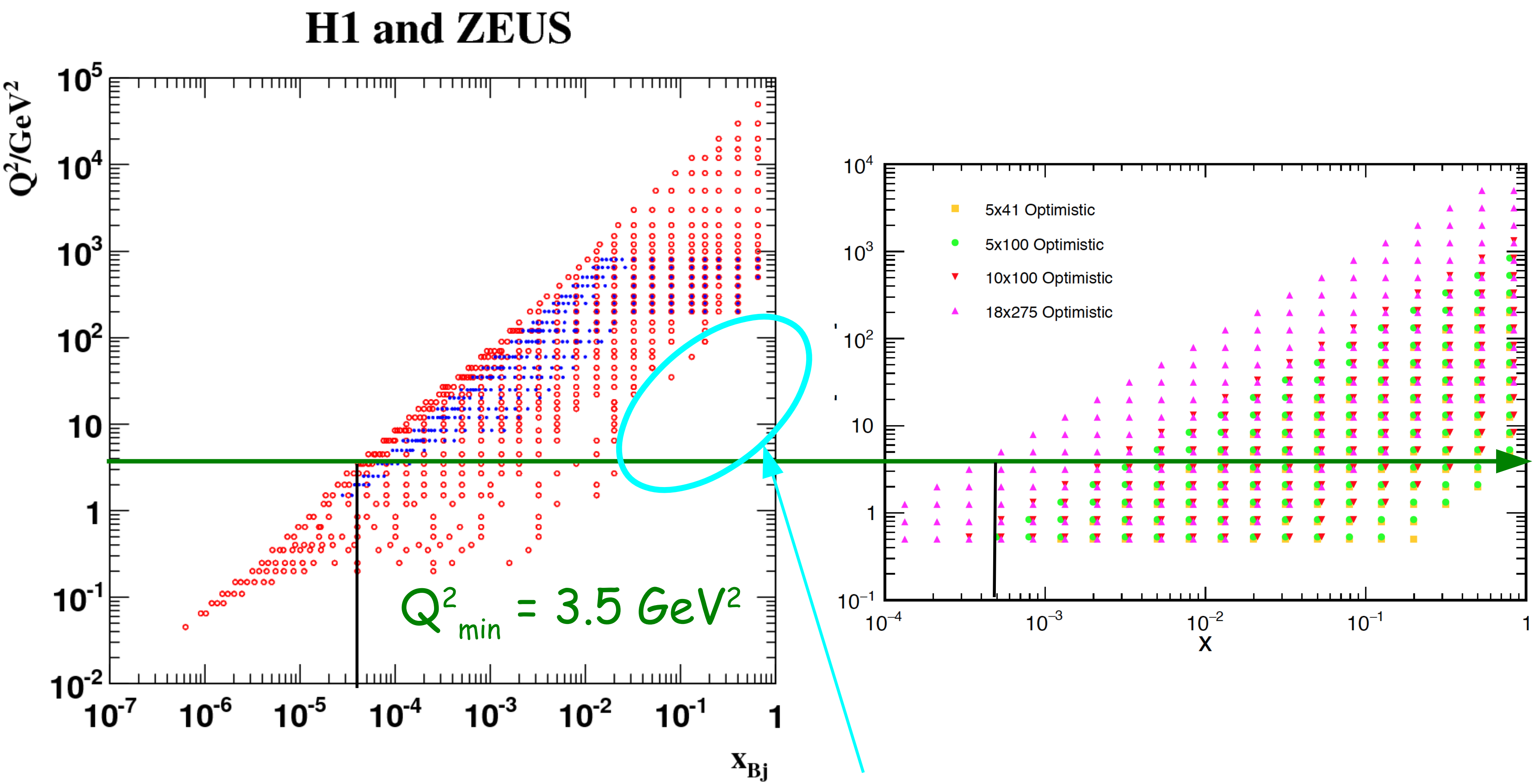
ATHENA data → from yellow report & HERAPDF2

- ATHENA pseudo-data used in fits:
  1) Get prediction from HERAPDF2.0 NLO in ATHENA x-Q^2 grid
  2) Smear with uncorrelated uncertainties point-by-point
  3) Smear with correlated systematic uncertainty each sample (same factor for each sample)

- ATHENA uncertainties used in fits, files from Barak:
  - Statistical
  - Total uncorrelated
  - Total correlated
- Bins & uncertainties according to EIC yellow report, optimistic & pessimistic options
- Pessimistic scenario → less bins + higher uncertainties

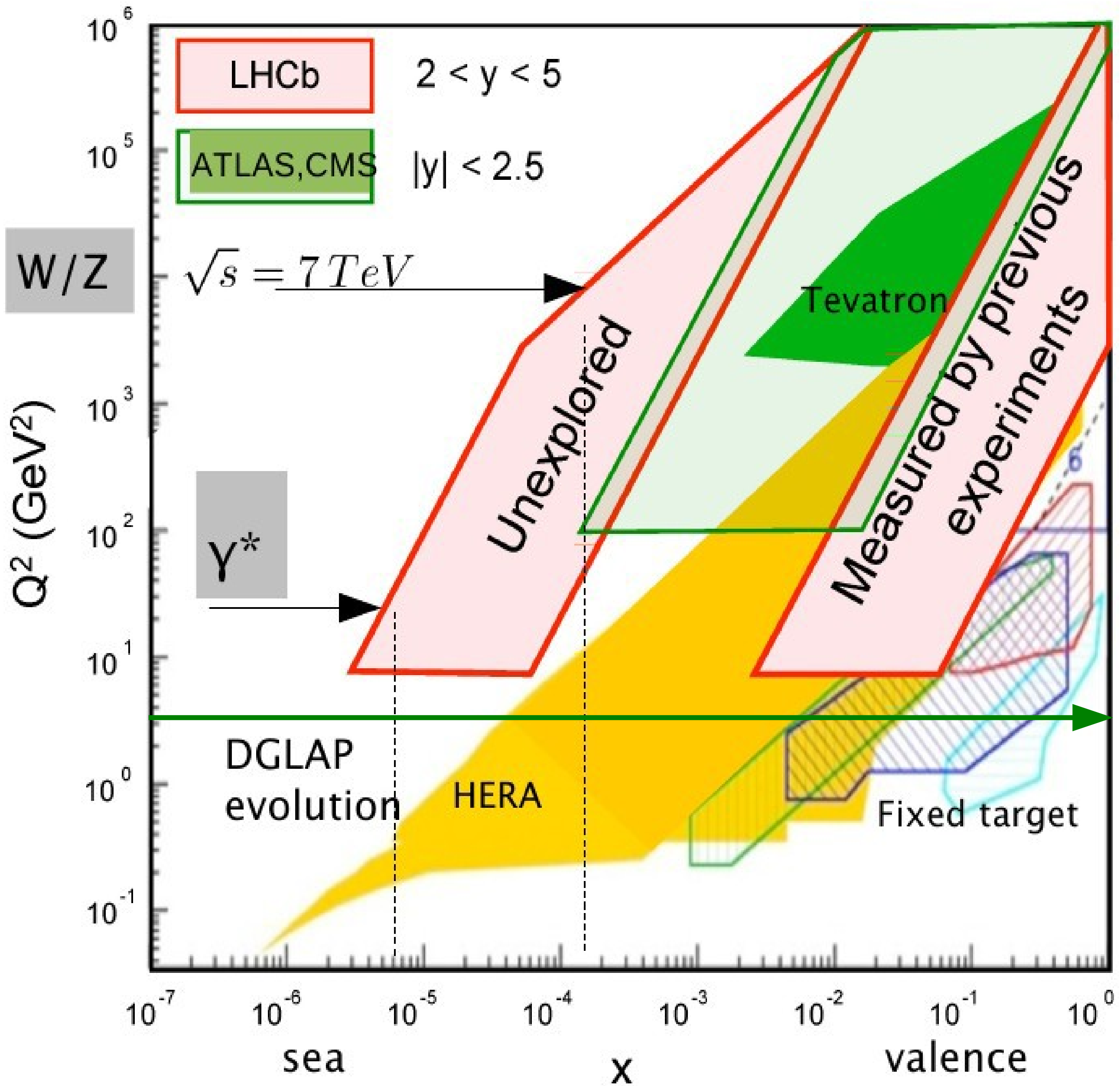


Data: HERA + ATHENA optimistic

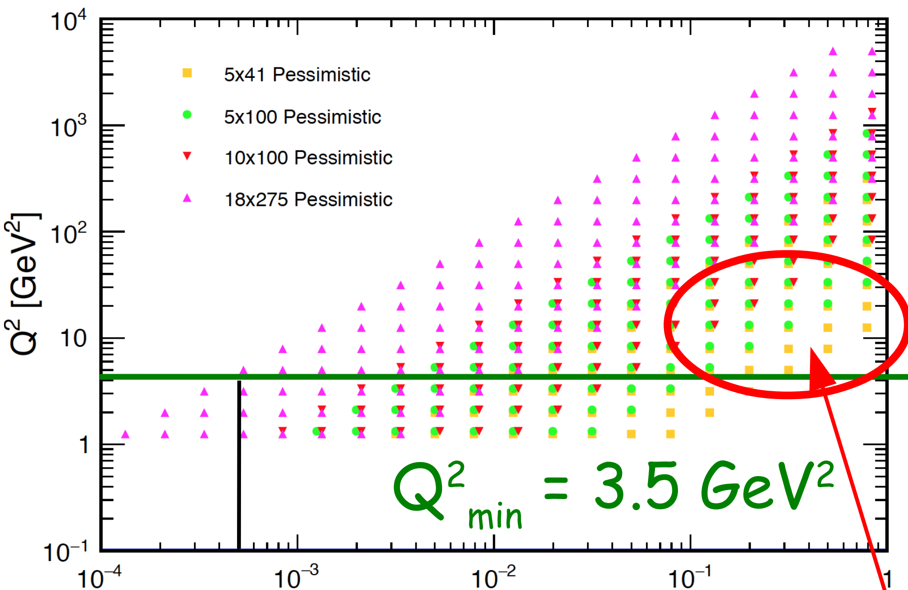


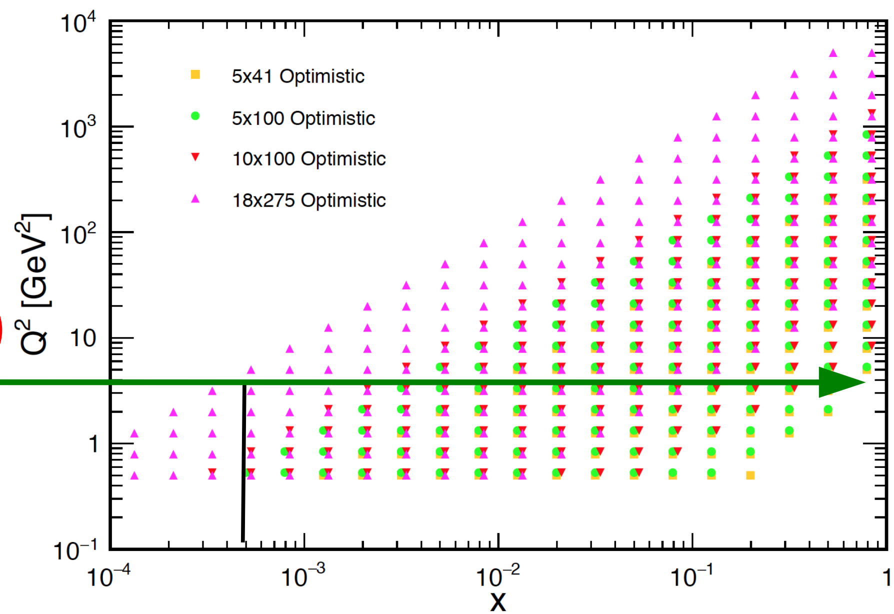
Region not covered by HERA →
impact on high-x PDFs expected

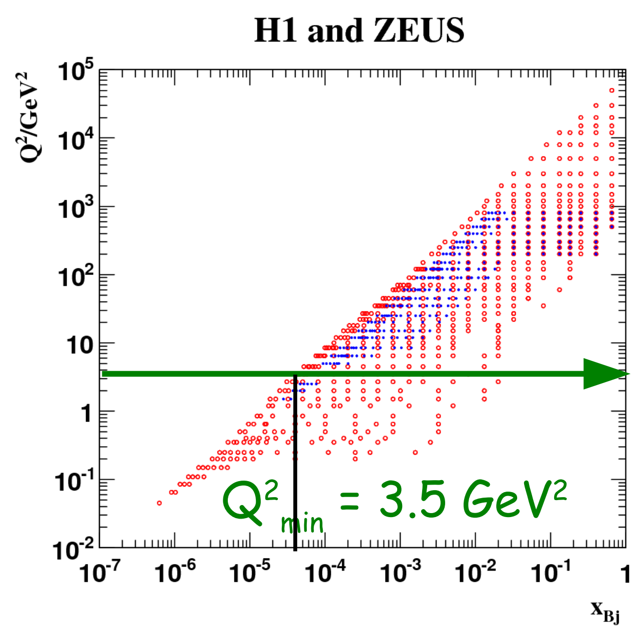
Various data in other PDF sets



ATHENA x-Q^2 grids
pessimistic .vs. optimistic





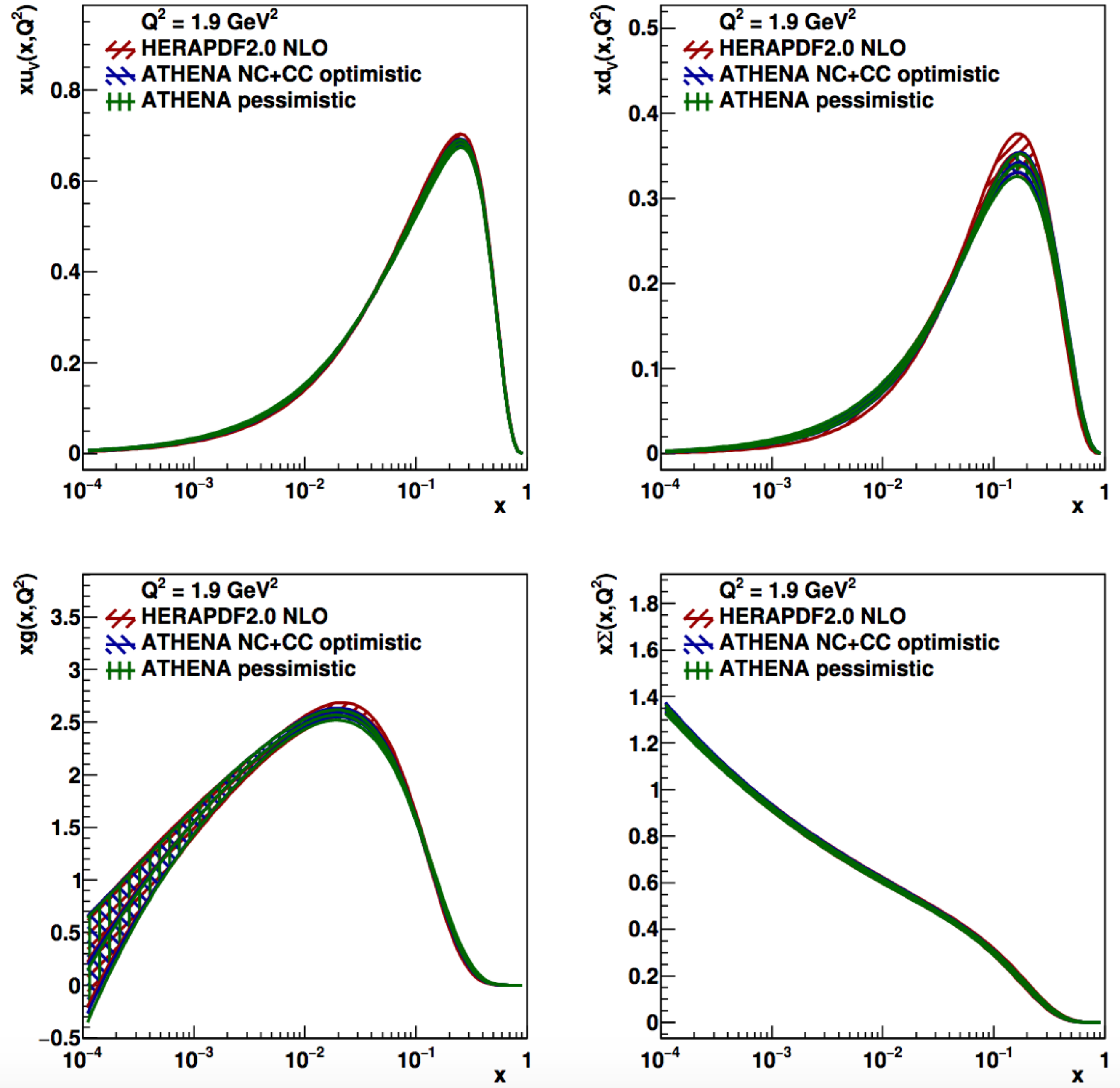


Region depleted in comparison to optimistic scenario → not covered by HERA, still lots of data in the high-x low-Q^2 corner

Analysis presented here is done @ NLO
→ can be easily repeated @ NNLO

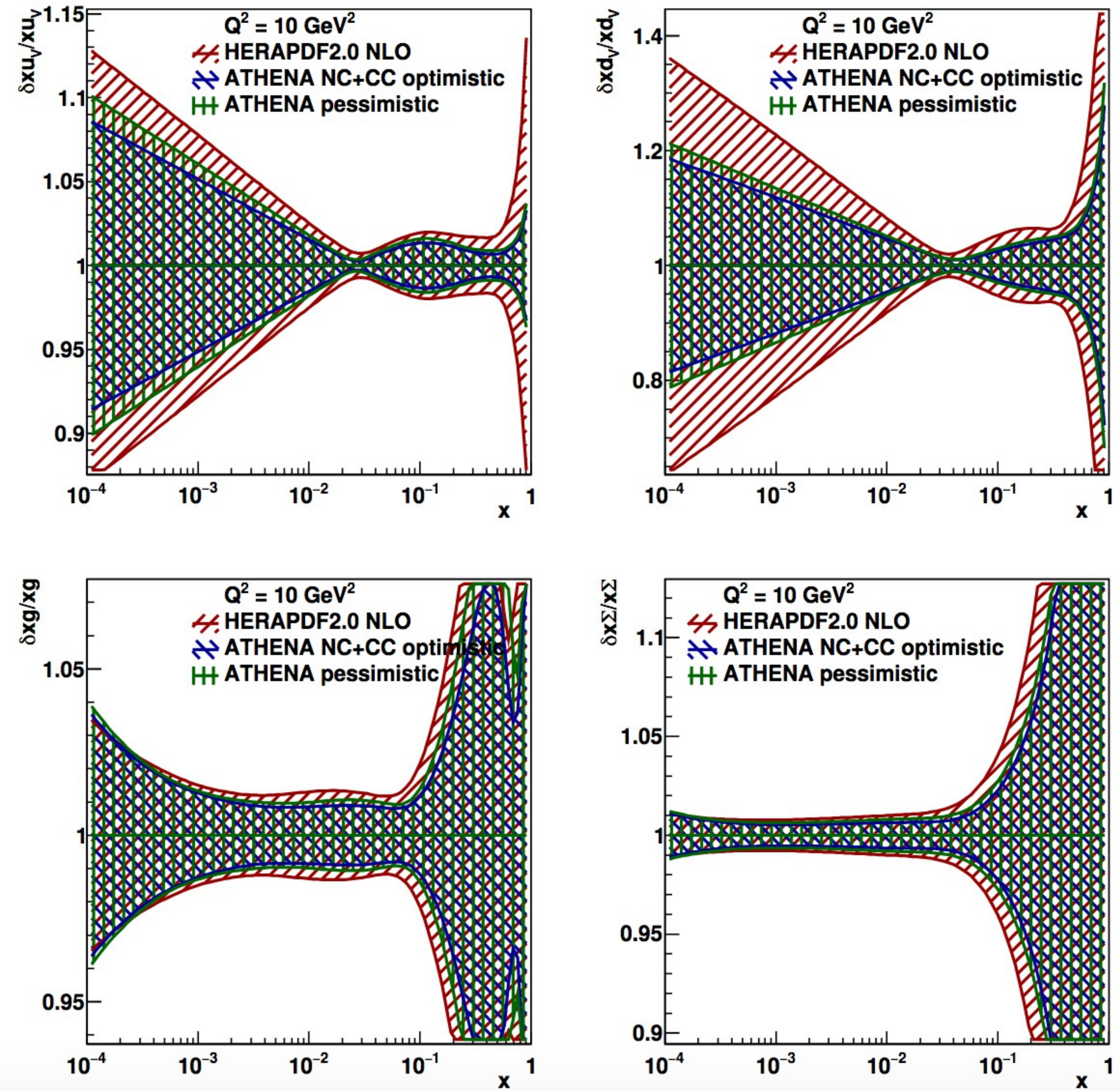
Analysis presented here includes experimental uncertainties only
→ total uncertainty can be easily included

PDFs with HERA and ATHENA data

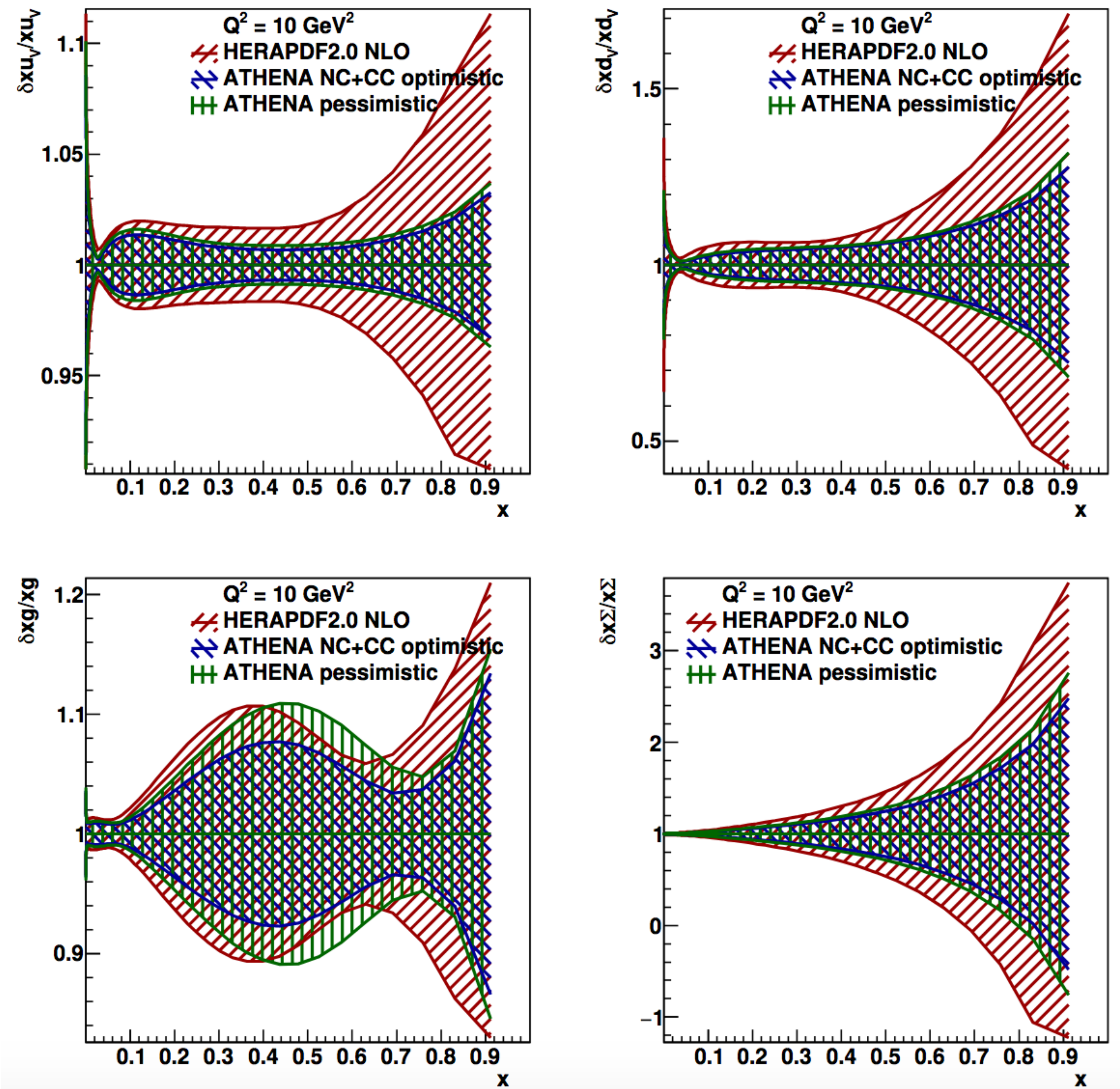


- Shown PDFs for
  - HERAPDF2.0 NLO
  - ATHENA NC+CC
    - Optimistic
    - Pessimistic
- PDF very similar
- Uncertainties very interesting → let's have a look

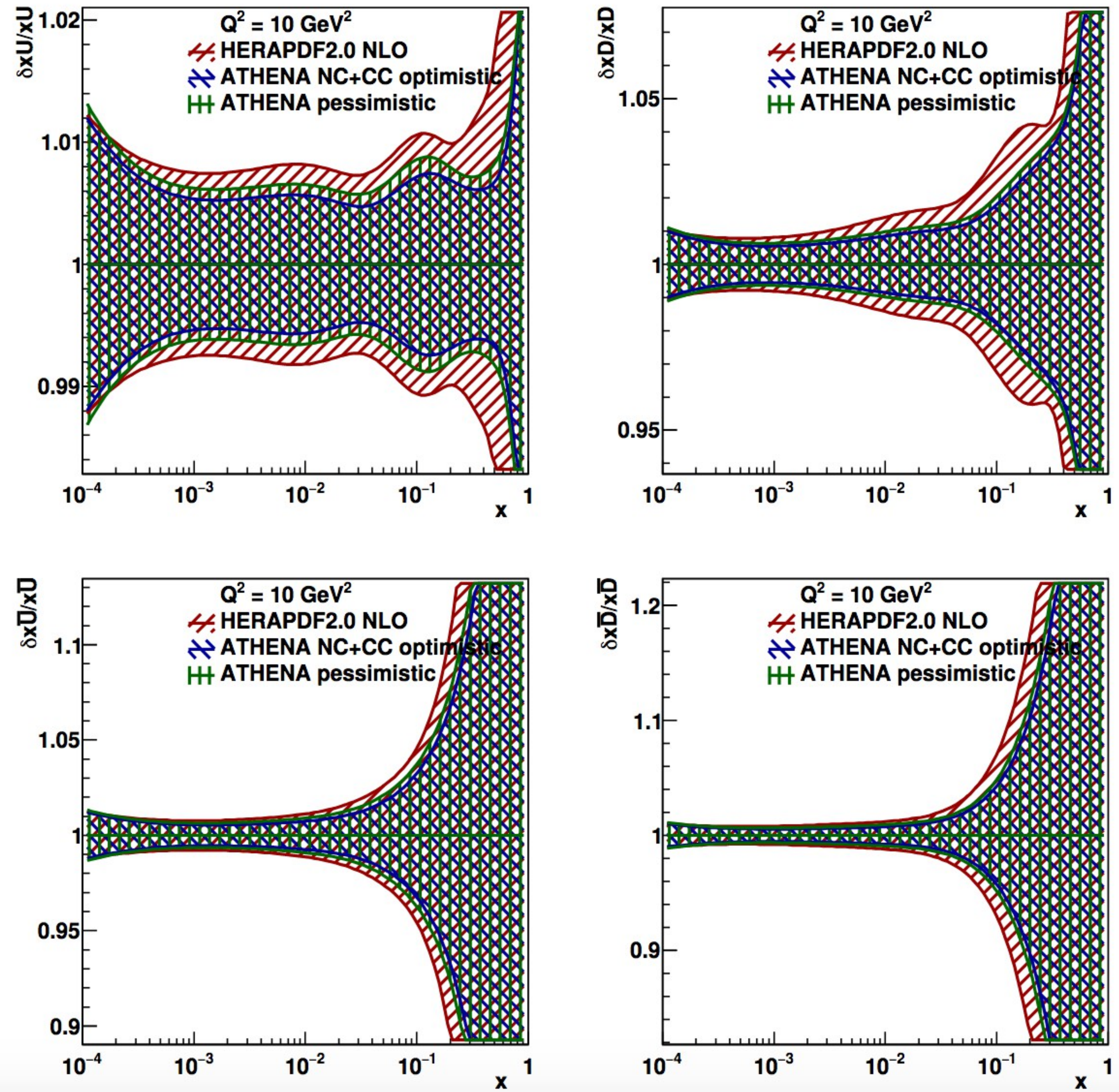
Relative uncertainties: some improvement for low & middle x and rapid decrease of uncertainties for low x



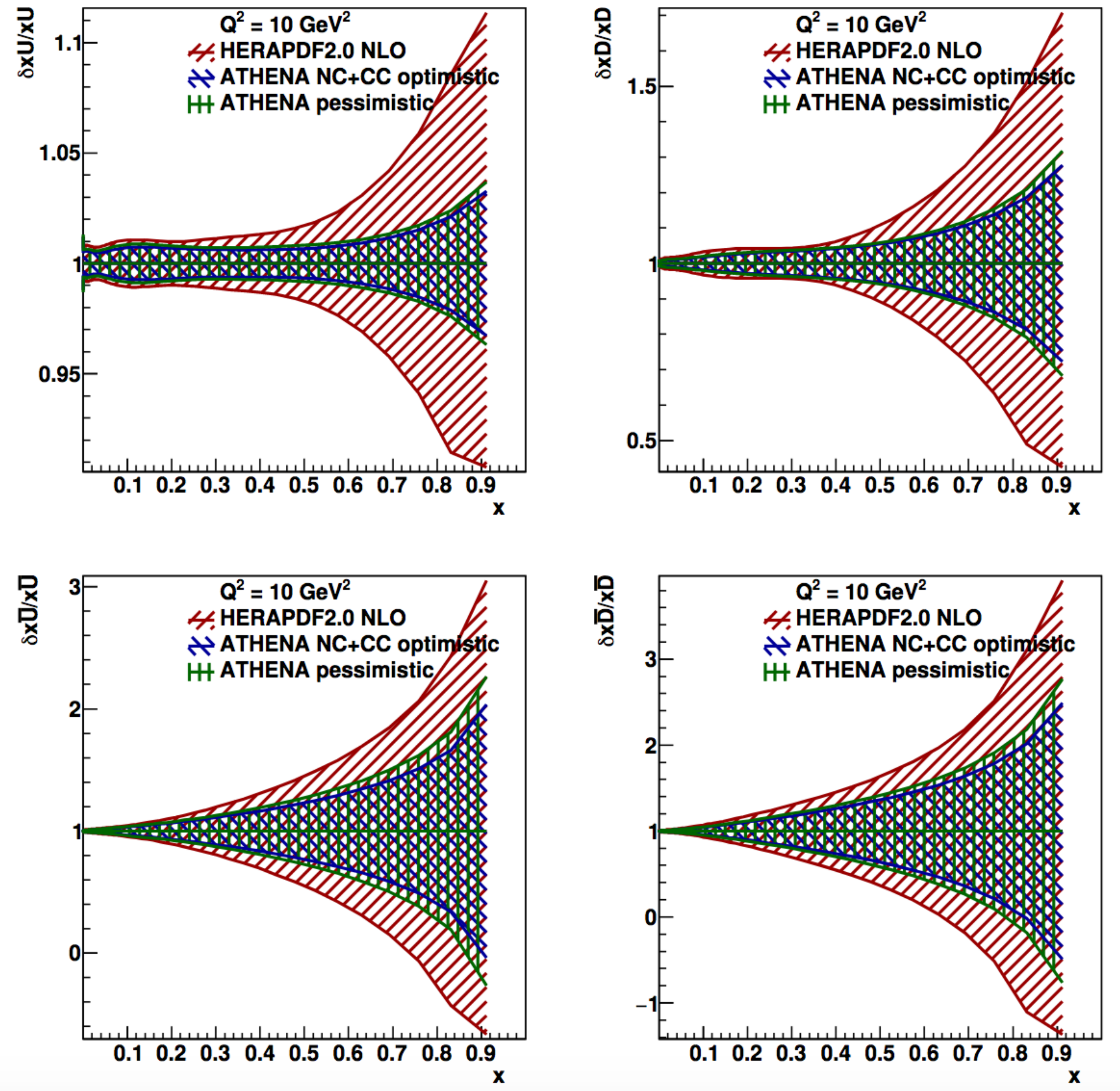
High-x region better visible



Relative uncertainties: quarks

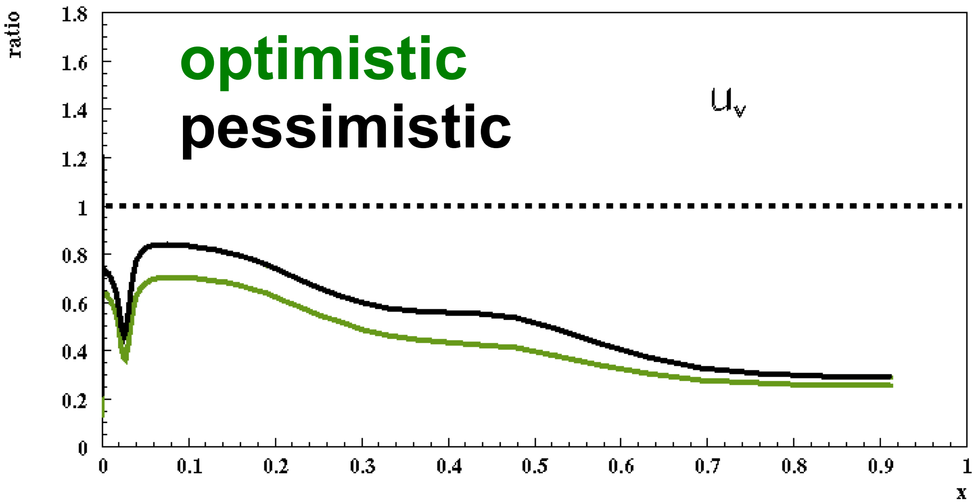


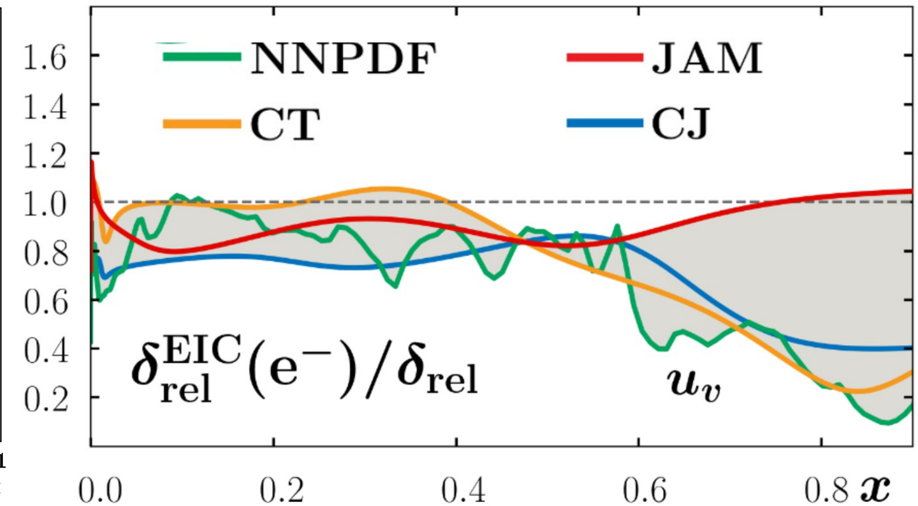
High-x region better visible: quarks

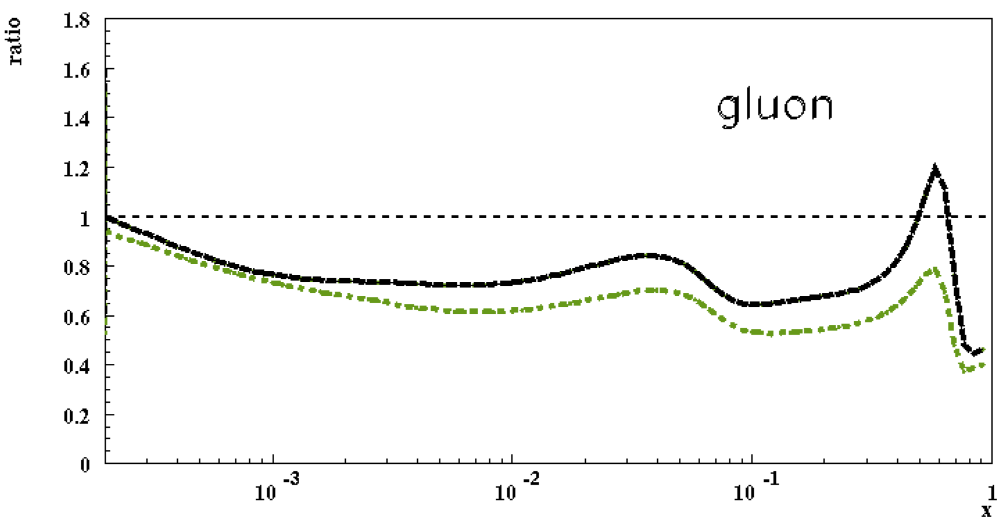


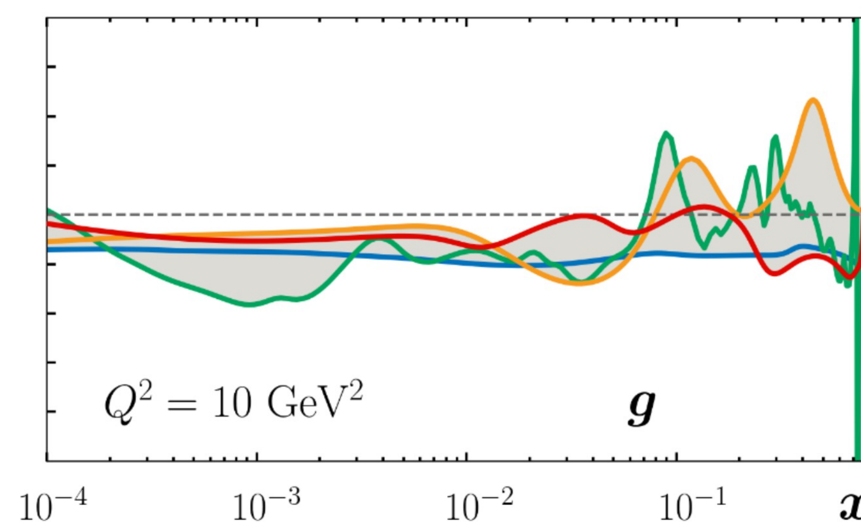
K. Wichmann, 13.09.21, HERAPDF2-style fits for ATHENA

EIC yellow report style figures



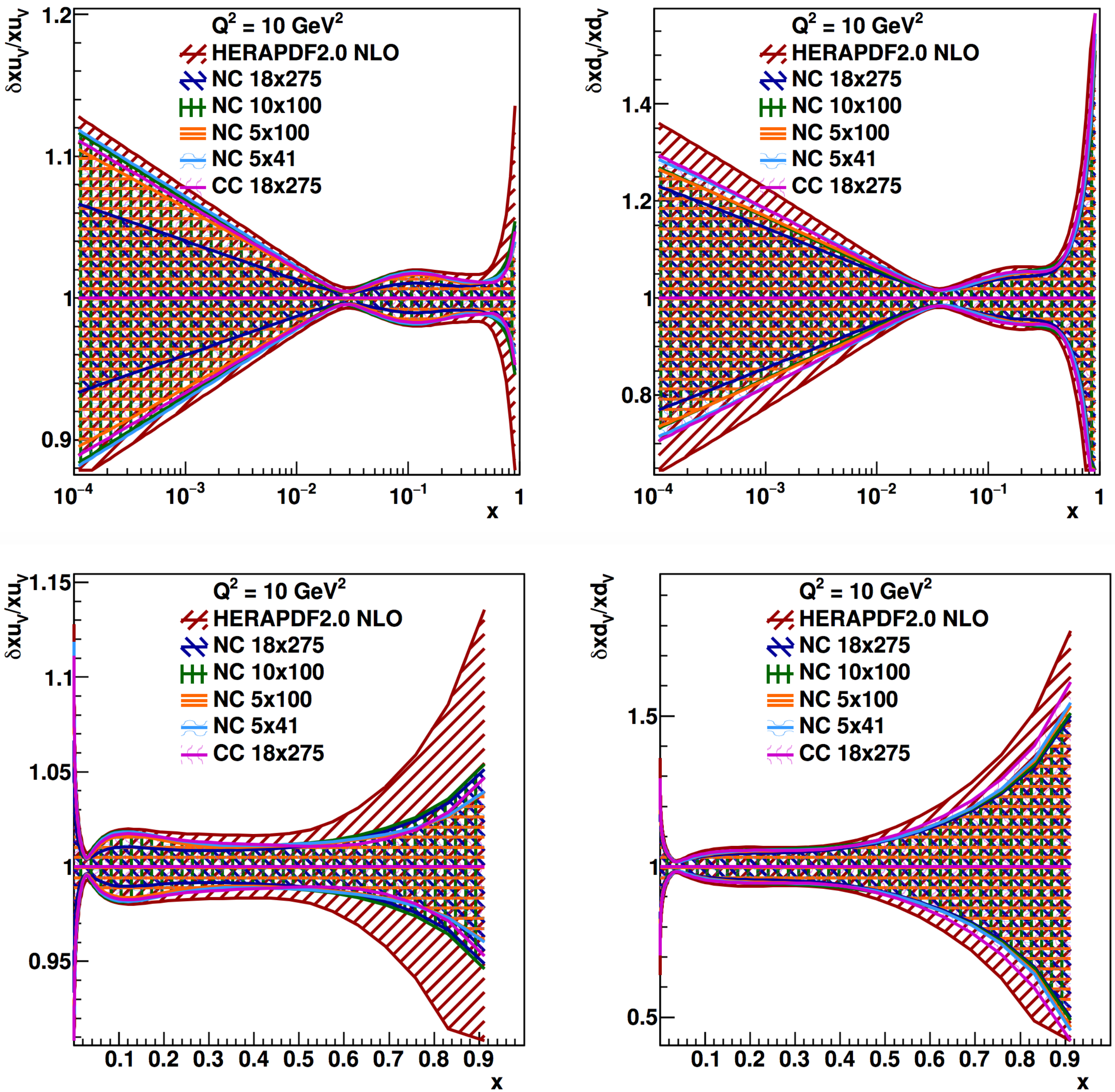






Impact of separate data samples

→ similar trends observed for sea quarks



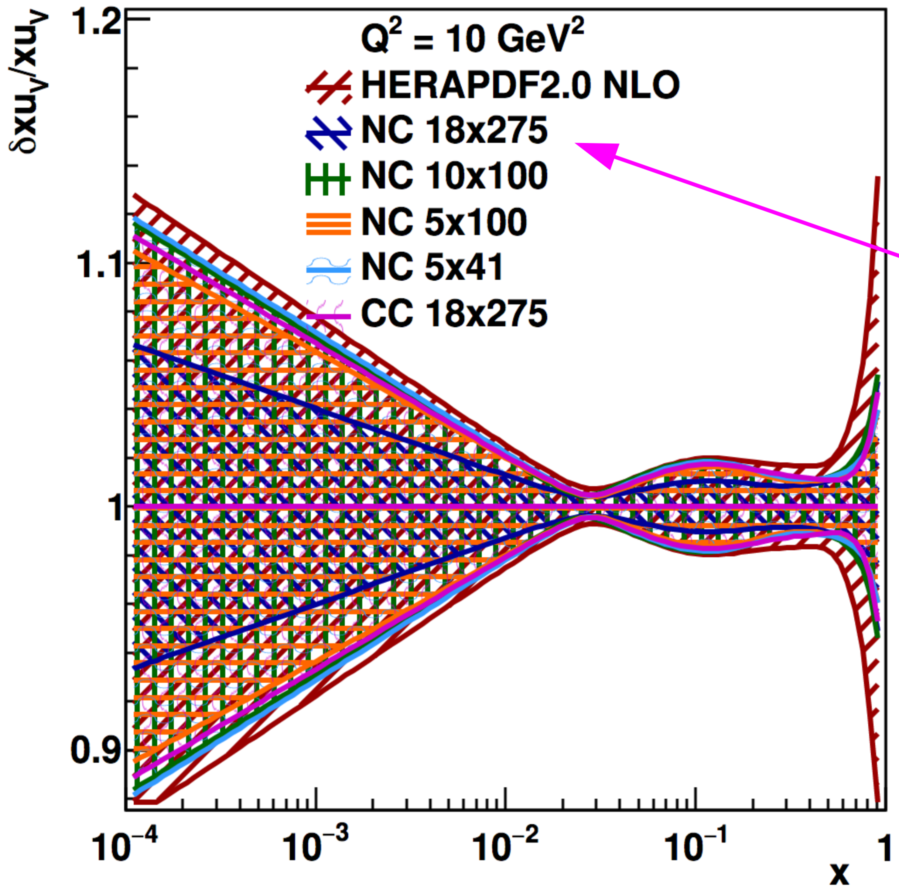
<u>Low & middle x</u>

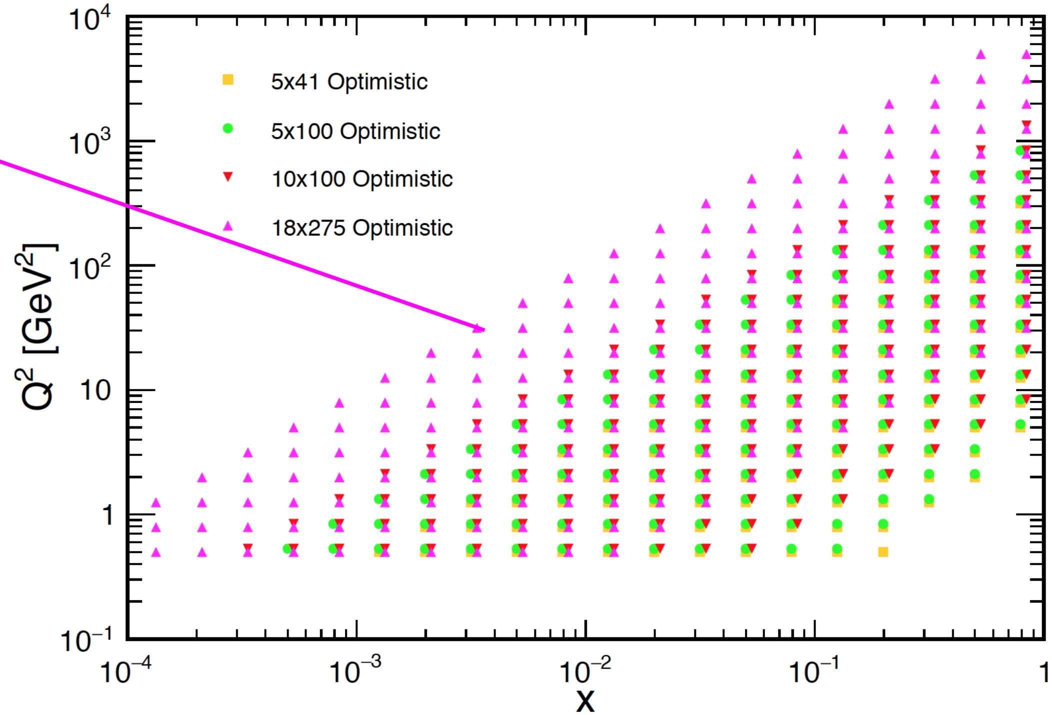
- NC 18x275 sample seems to have largest impact on valence quarks low-x uncertainties
  → see next slide for explanation

<u>High x</u>

- Similar impact of various beam samples
  → they all cover phase-space "empty" at HERA

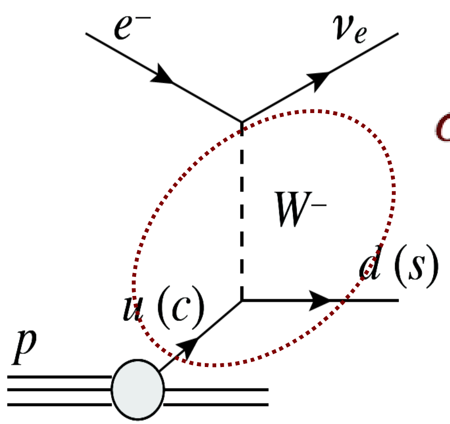
Impact at low & middle x



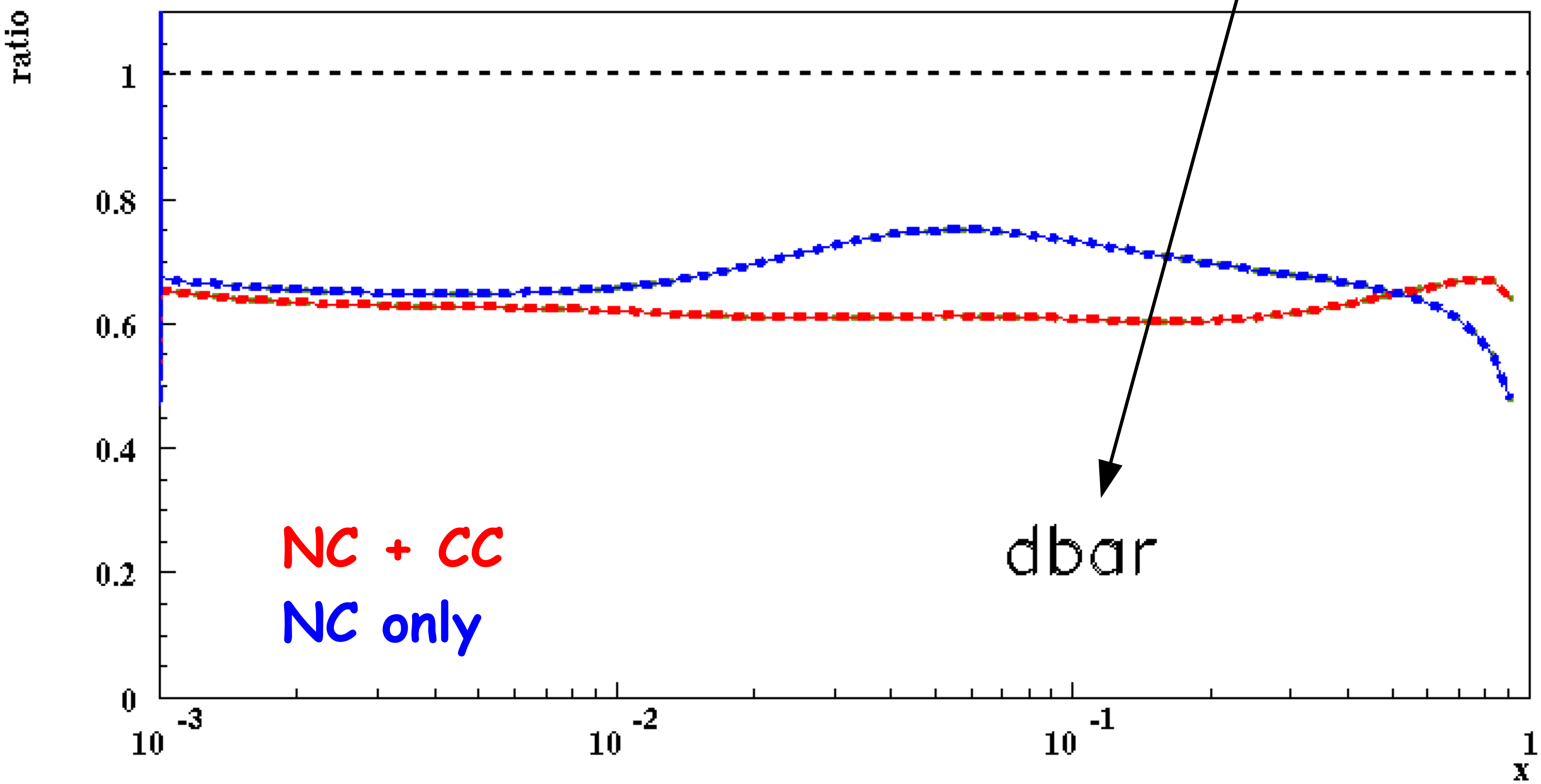


- NC 18x275 data add huge amount of statistics at low & middle x not present for other energies → effect on this kinematic region more significant

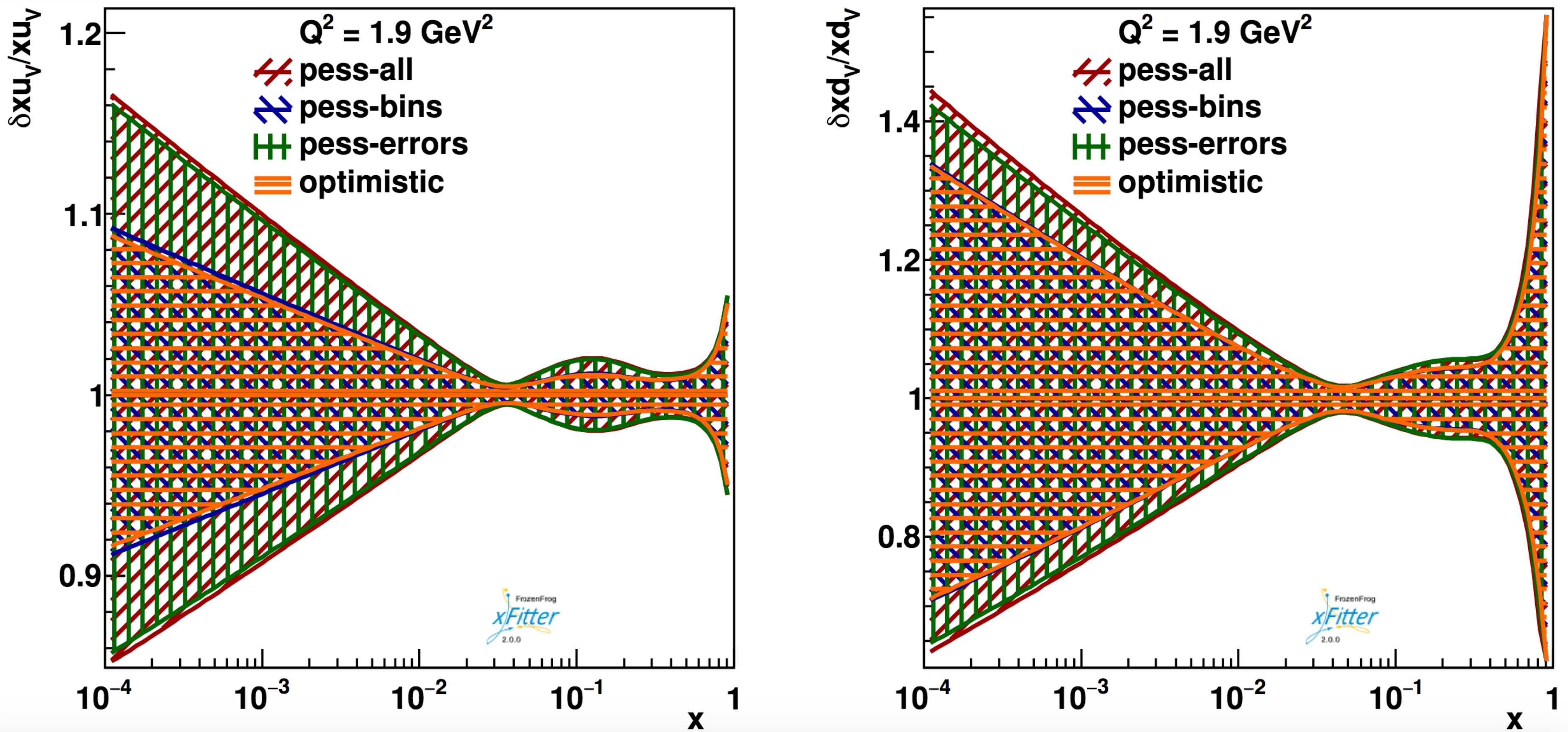
Impact of CC



$$\sigma^-_{CC} \sim x[u+c] + x(1-y)^2[\bar{d}+\bar{s}]$$



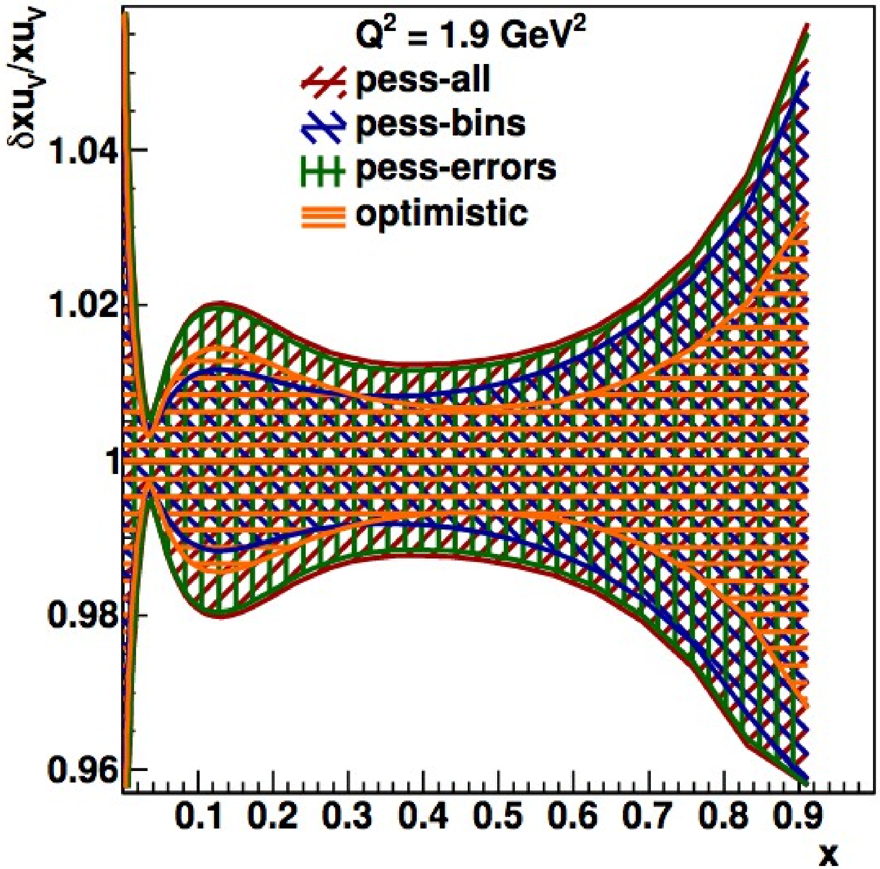
Pessimistic option - what matters for PDFs?

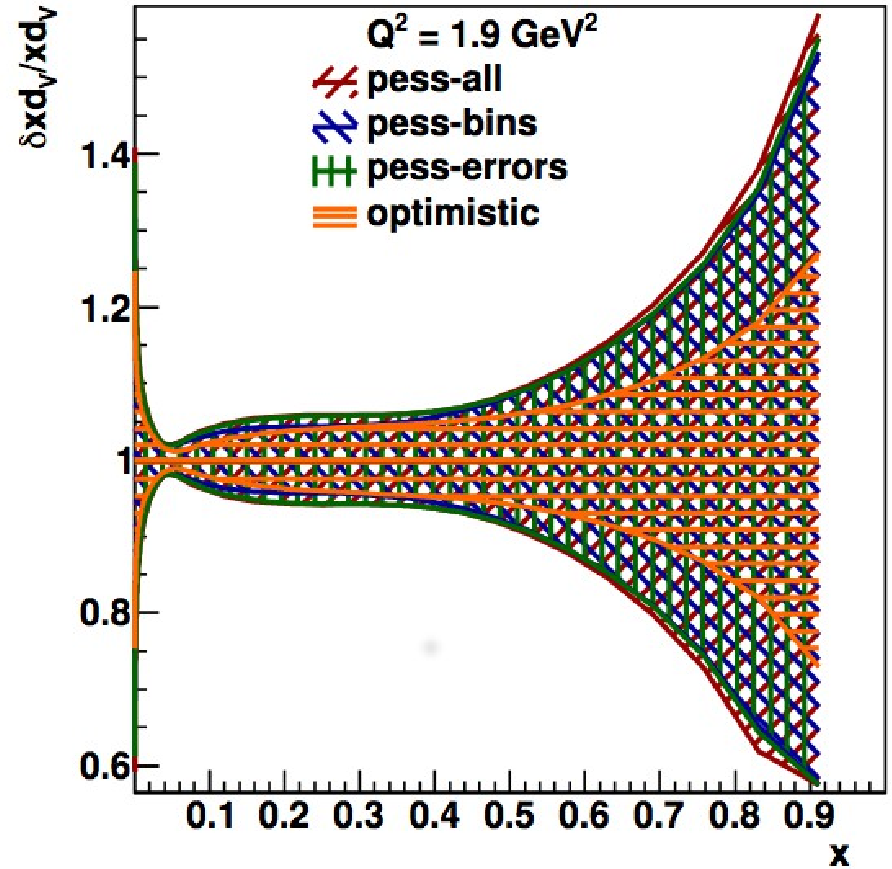


- At low & middle x bins are not cut out in pessimistic version

→ impact on uncertainties comes from decreased precision of data

Pessimistic option – what matters for PDFs?





- At high x and low Q^2 bins are cut out in pessimistic version

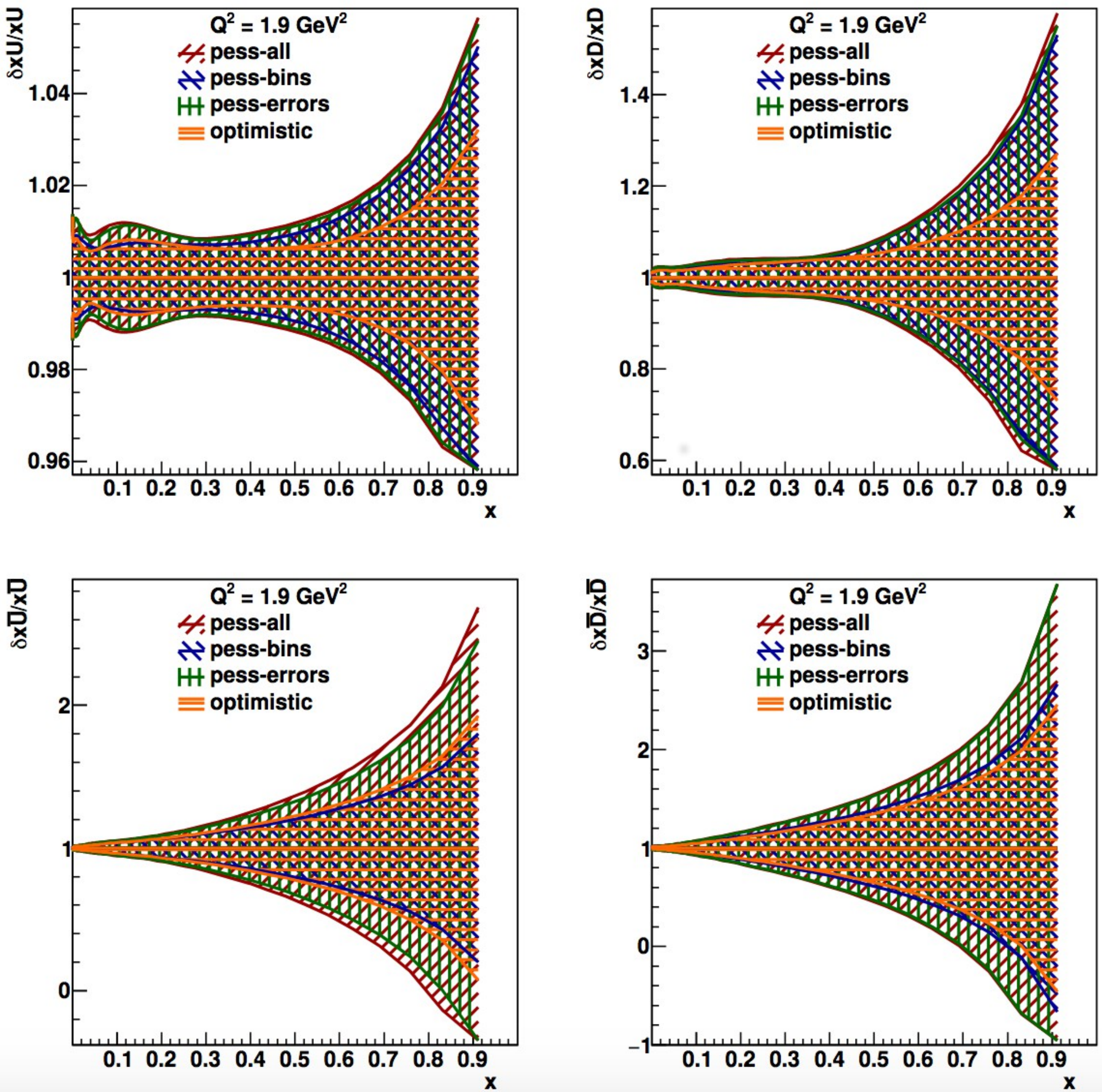
→ similar impact on valence quarks from cut-out bins and increased uncertainties

Brief summary / Outlook

- Impact of ATHENA data on PDF precision can be studied in a clean way using HERAPDF2.0 approach
- Preliminary studies using EIC yellow report numbers show clear huge improvement of PDF uncertainties at high x and also at low&mid x
- This kind of studies can be repeated with various assumptions on data and uncertainties
  - Also at NNLO and with full uncertainties
- I would be really happy to hear your suggestions/advice what to study, where to look, how to approach different issues

Additional slides

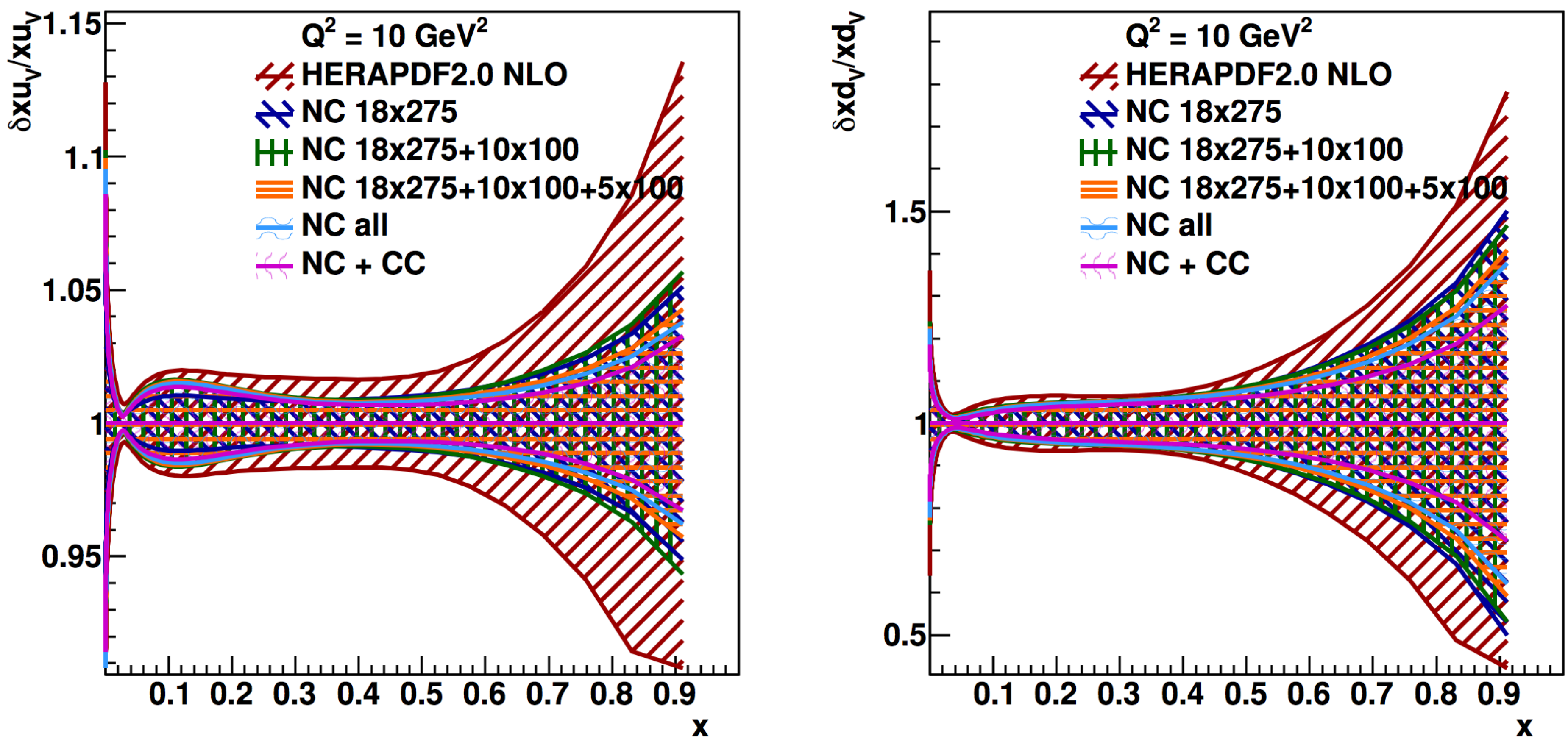
Pessimistic option – what matters for PDFs?



- At high x and low Q^2 bins are cut out in pessimistic version
  → similar impact on quarks from cut-out bins and increased uncertainties

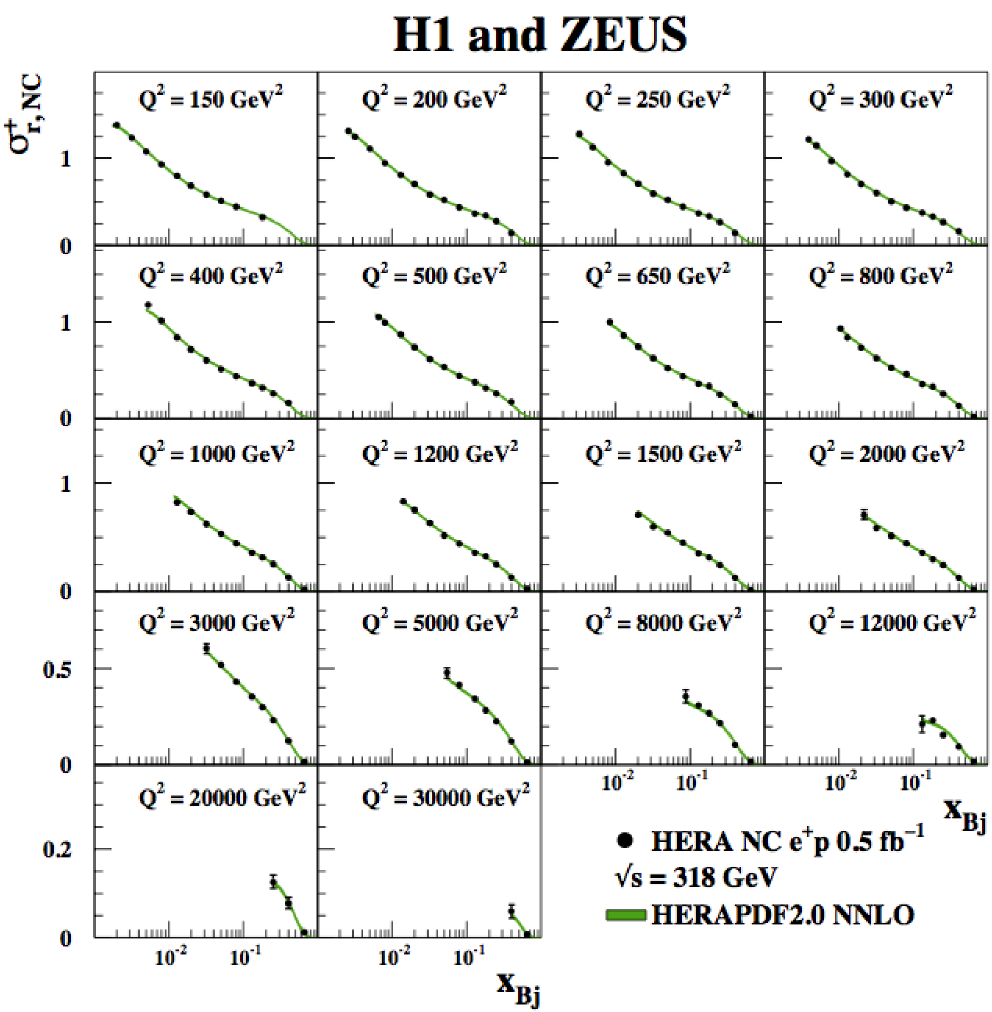
  → no impact of cut-out bins on anti-quarks
- Quite surprising, I need to understand this

Cumulative impact - high x



Neutral Current

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_- xF_3 - y^2 F_L\right]$$



Proton structure functions

$$F_2 = x\sum e_q^2[q(x) + \bar{q}(x)]$$

- Sensitive to quarks

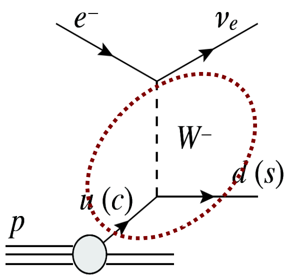
$$xF_3 = x\sum 2e_q a_q[q(x) - \bar{q}(x)]$$

- Sensitive to valence distributions

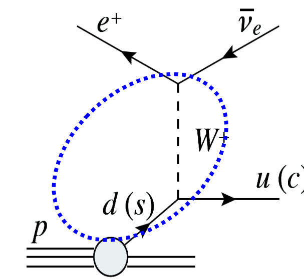
$$F_L \sim \alpha_S\, x\, g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

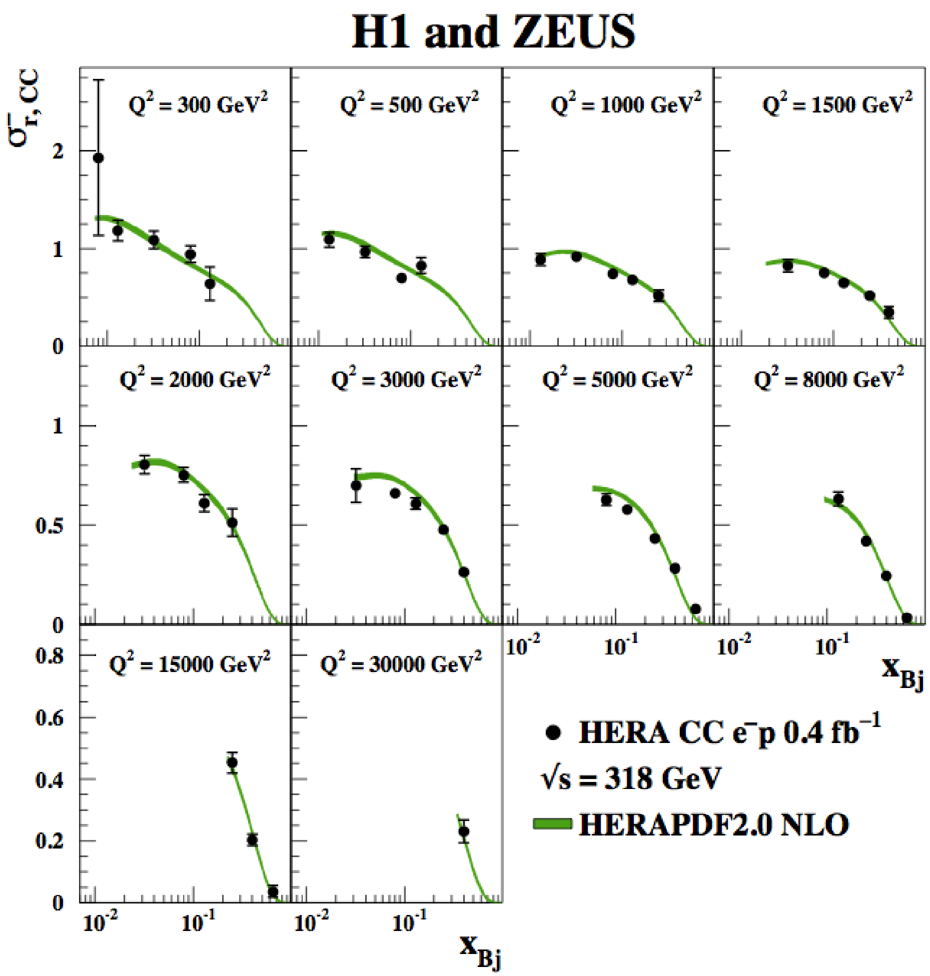


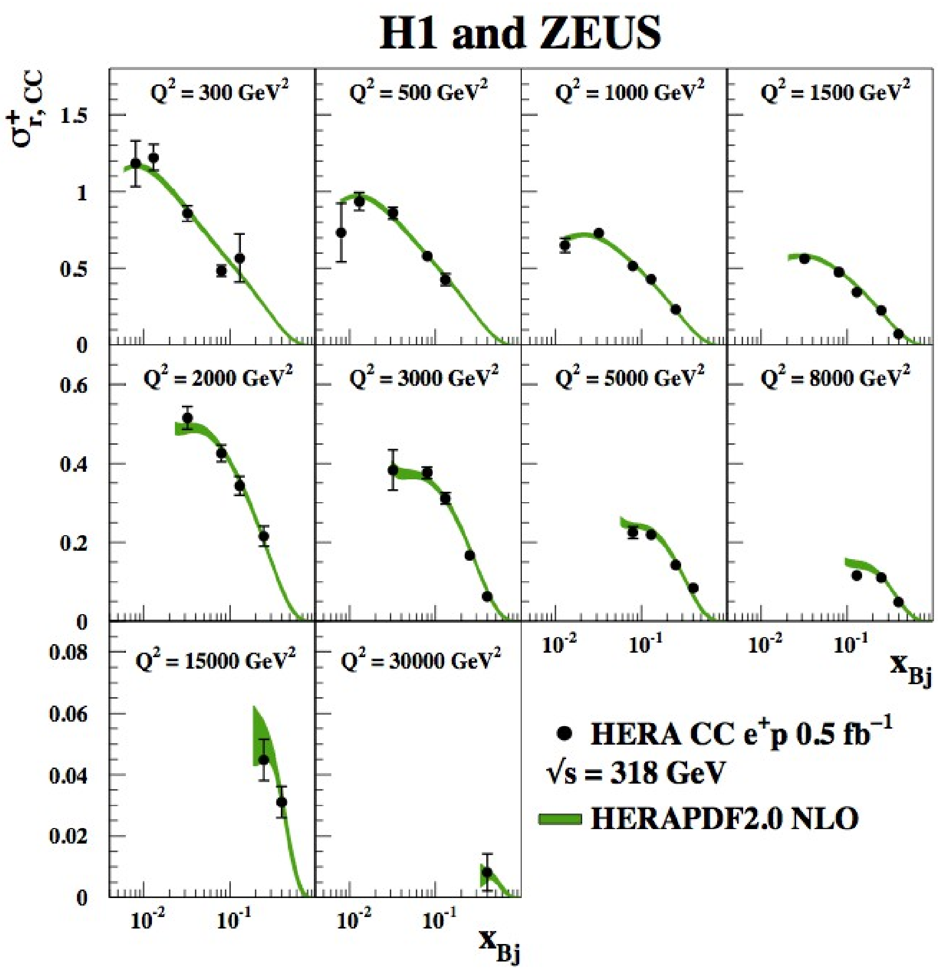
Charge Current: flavor decomposition



$$\sigma^-_{CC} \sim x[u + c] + x(1 - y)^2[\bar{d} + \bar{s}]$$

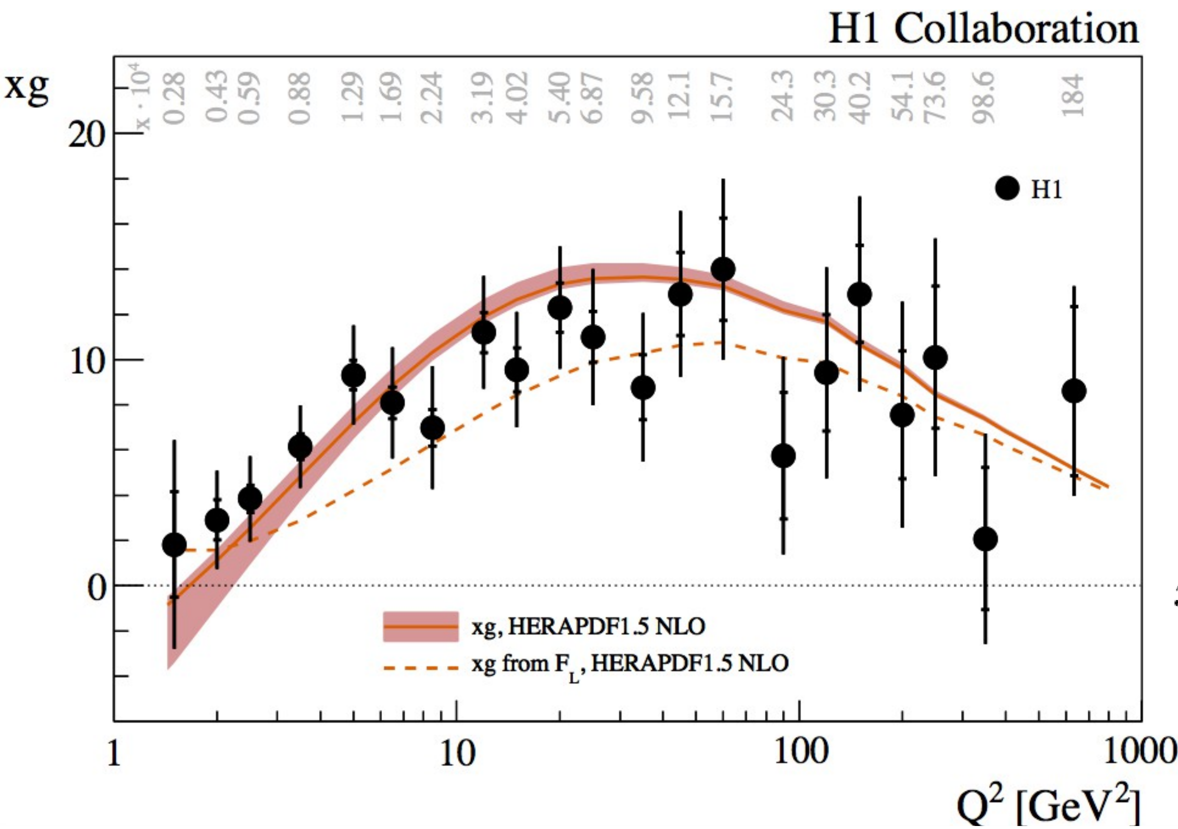
$$\sigma^+_{CC} \sim x[\bar{u} + \bar{c}] + x(1 - y)^2[d + s]$$





Gluon meets F_L

- H1 performed direct extraction of gluon density from F_L measurement @NLO



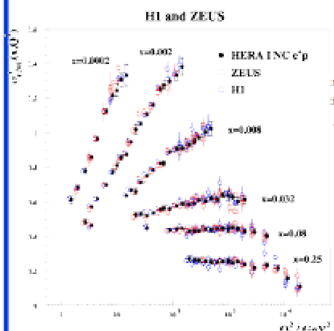
- Direct extraction of gluon density from F_L using approximation

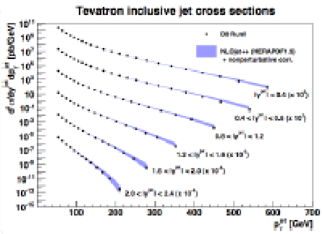
$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$

Gluon approximated from F_L agrees with gluon determined from scaling violations

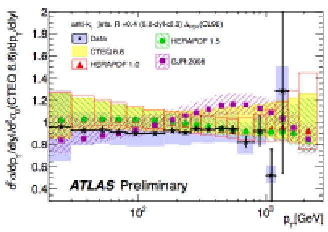
https://www.herafitter.org

experimental input





experiments:
HERA, Tevatron, LHC, fixed target



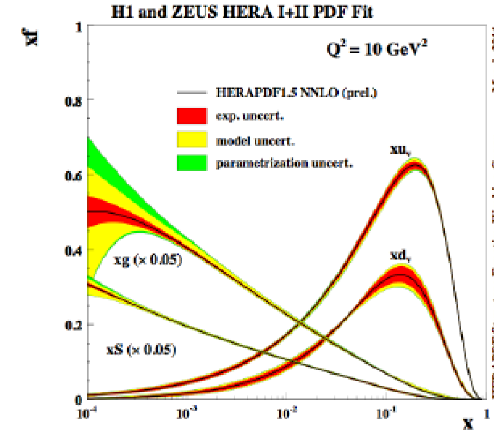
processes:
NC, CC DIS, jets, diffraction, heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or uPDF or DPDF

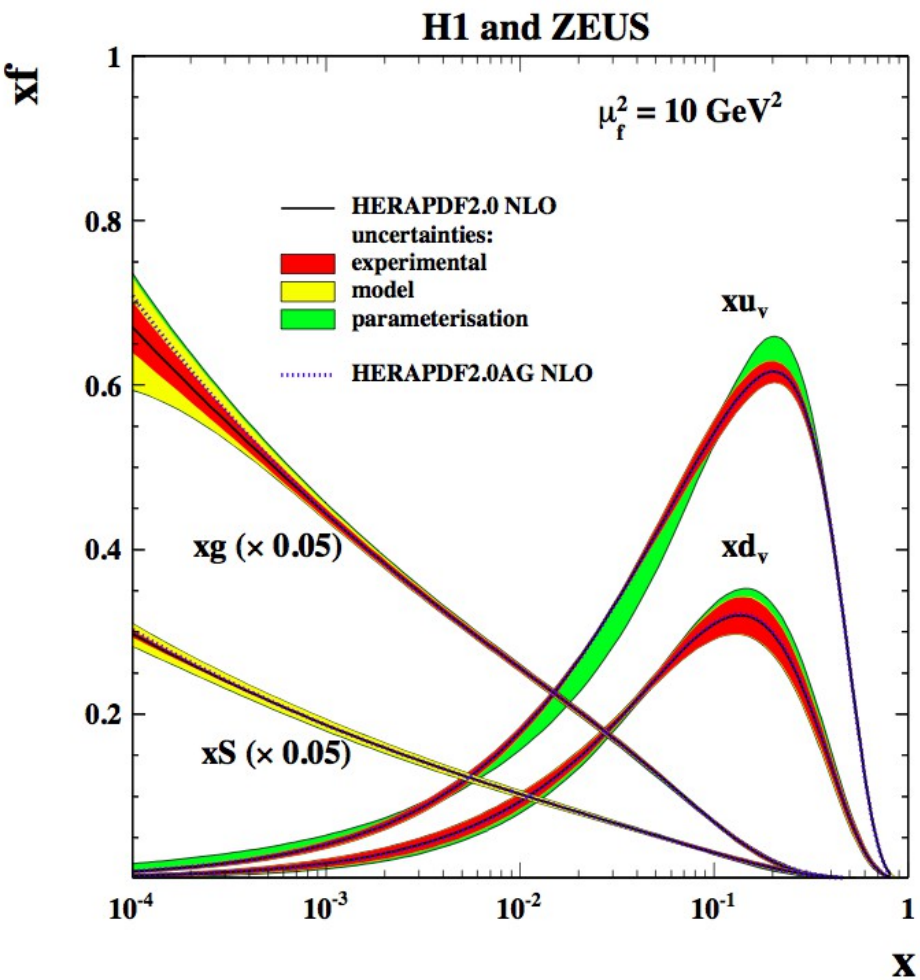
$\alpha_S(M_Z), m_c, m_b, m_t, f_s, ..$

Theory predictions

Benchmarking

Comparison of schemes

Color decomposition of uncertainties



- **Experimental uncertainties:**
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

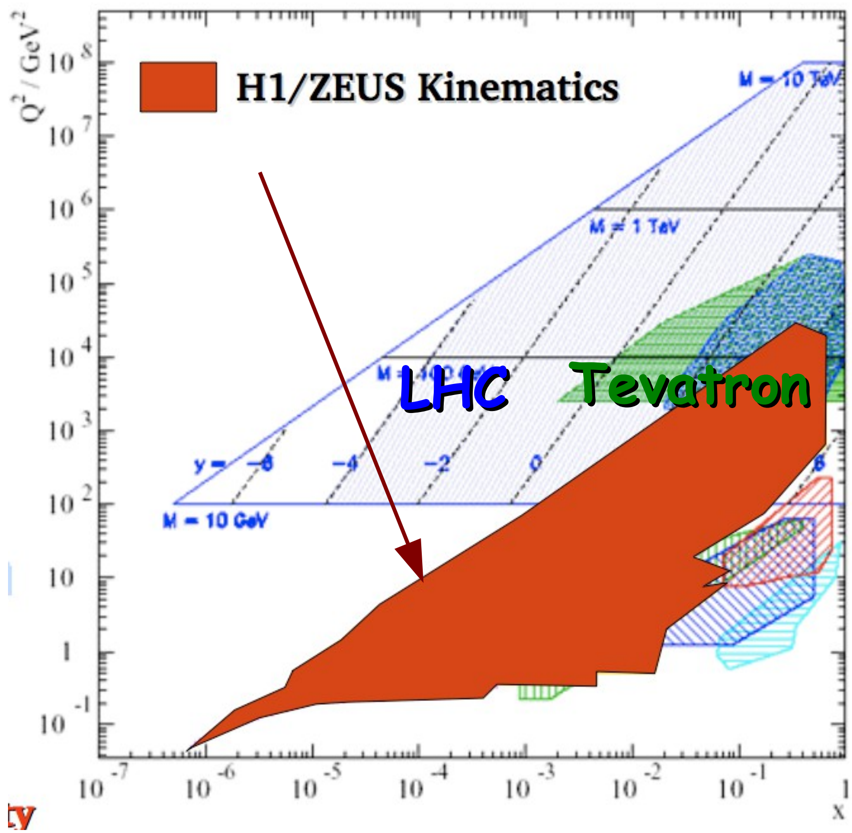
Adding D and E parameters to each PDF

- **Parametrisation uncertainties**
  - largest deviation
- **Model uncertainties**
  - all variations added in quadrature

Proton structure

Inclusive measurements from HERA are core of every parton density extraction

- PDFs used in interactions with proton: LHC, Tevatron, HERA
- Precision of many measurements often limited by PDF uncertainty
  - Higgs/top properties



Will we tunnel?...