HERAPDF2.0 approach to ATHENA data

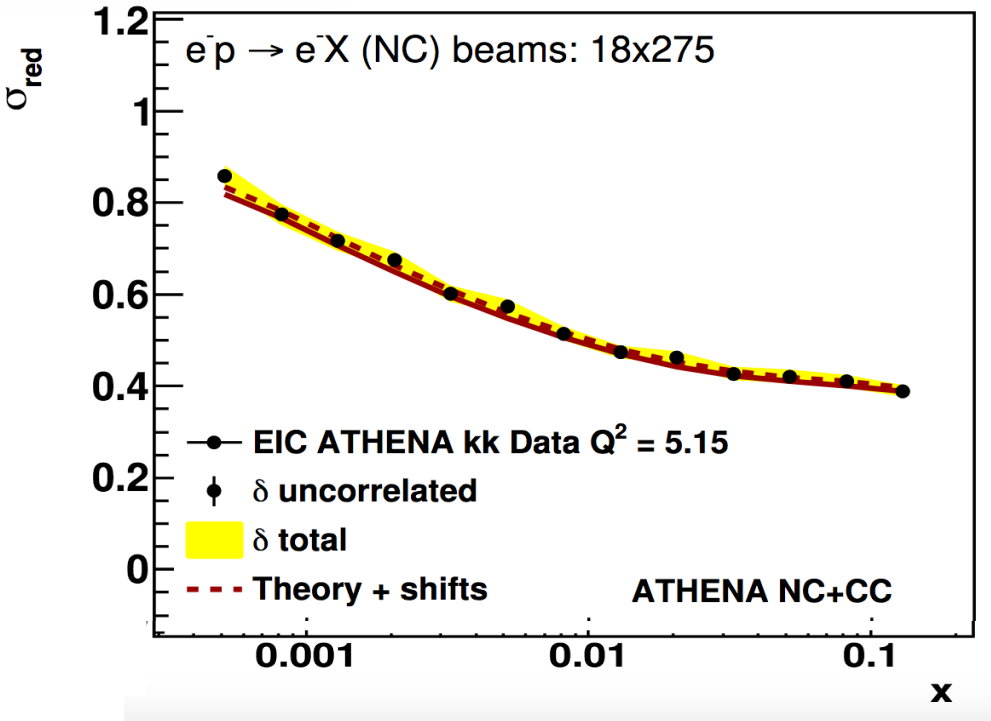
Studying impact of ATHENA data on parton distributions in proton using HERAPDF2.0 framework

Update

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



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

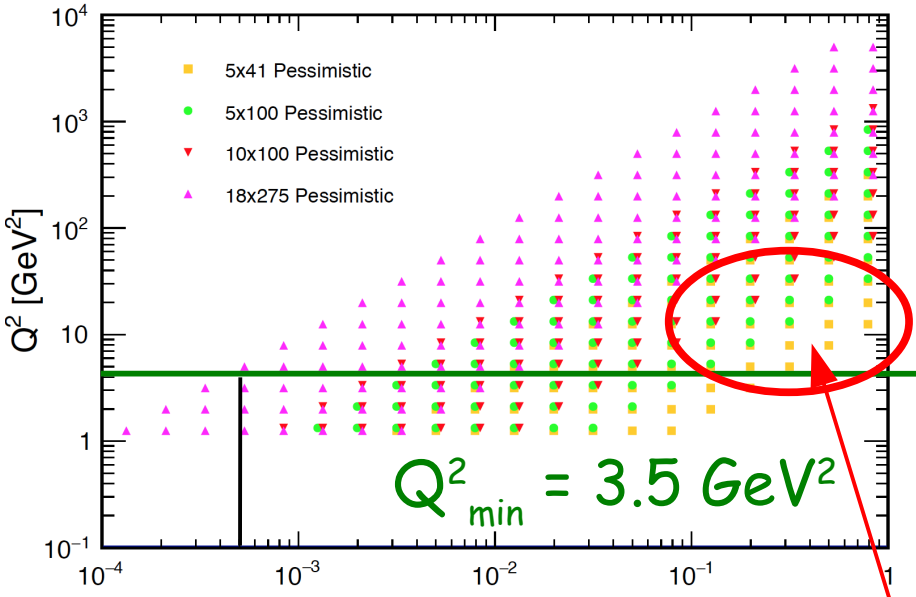
QCD fits performed using HERAFitter package

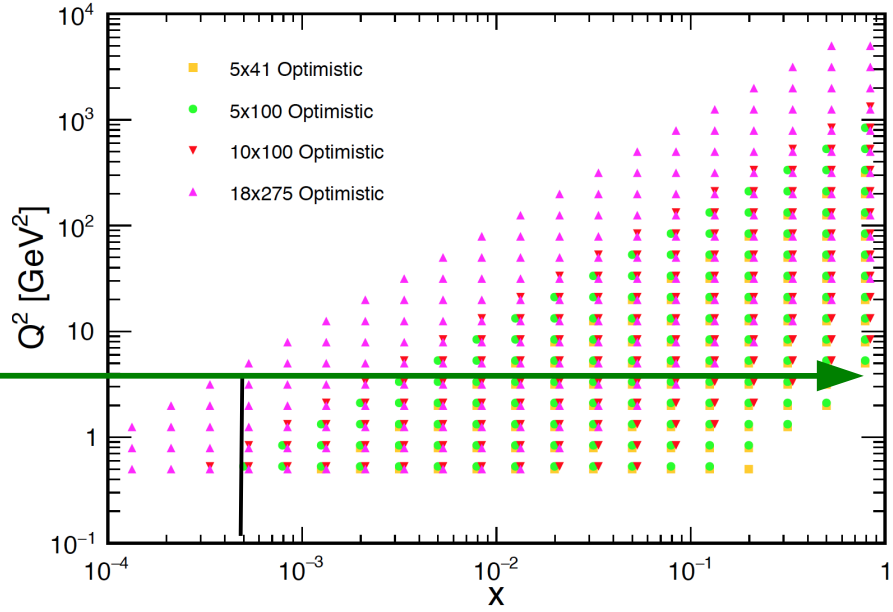
www.herafitter.org

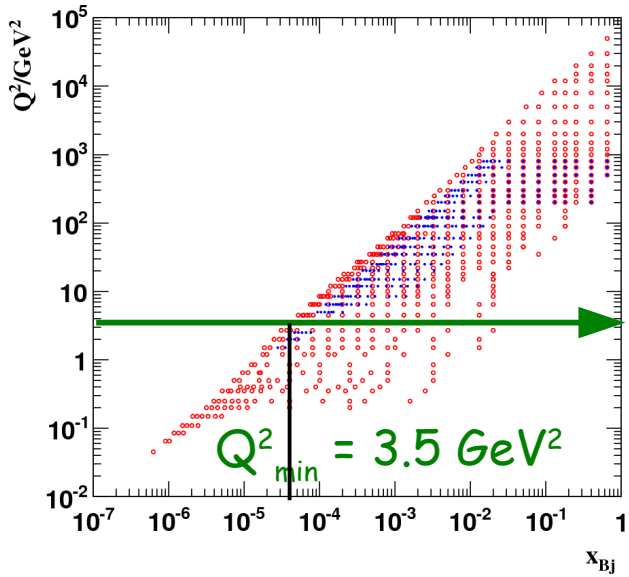
Analysis presented here is done @ NLO
→ can be easily repeated @ NNLO

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

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

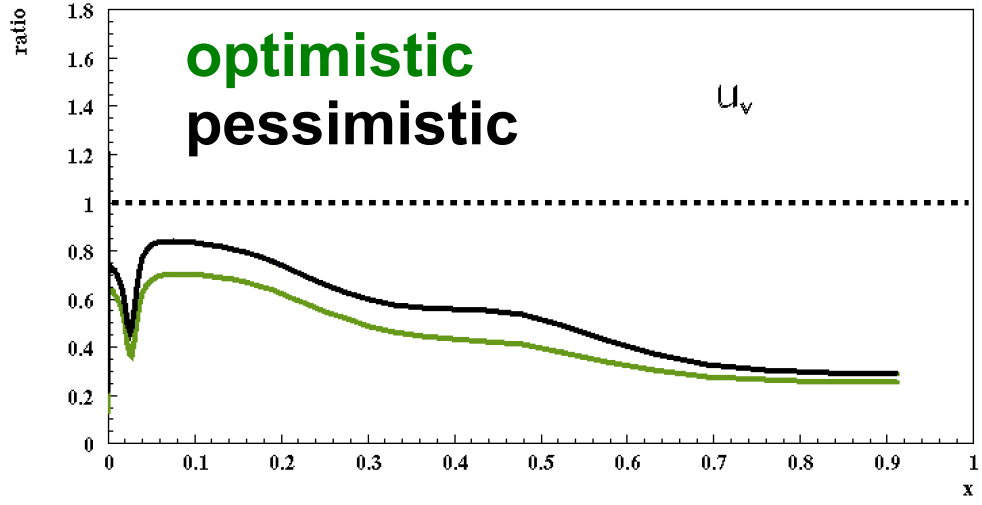


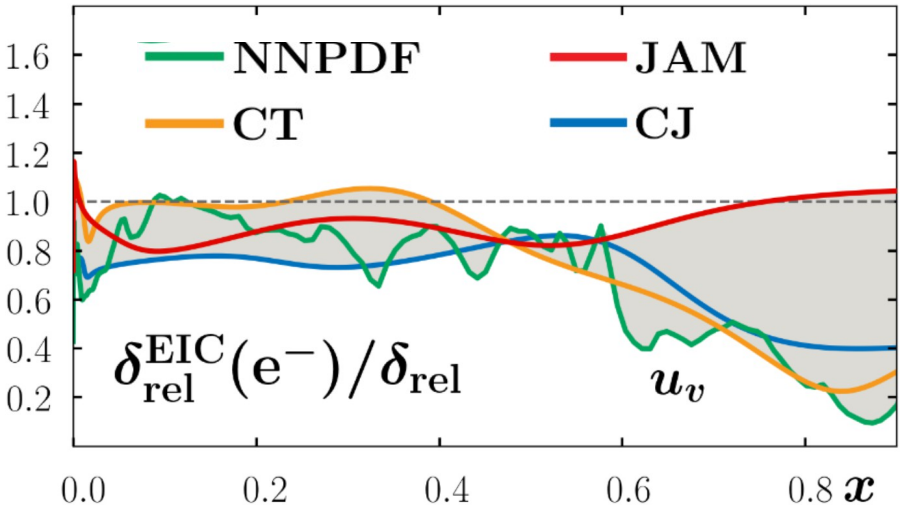


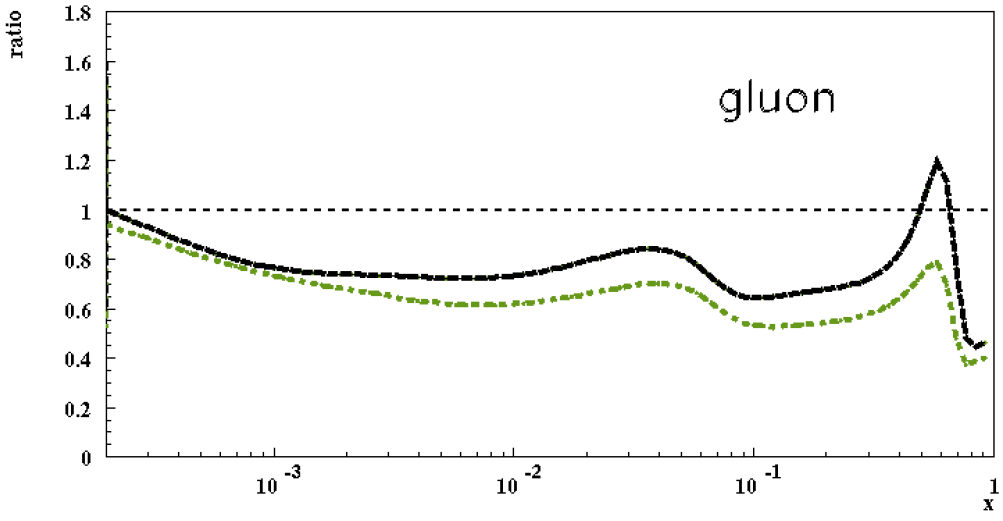


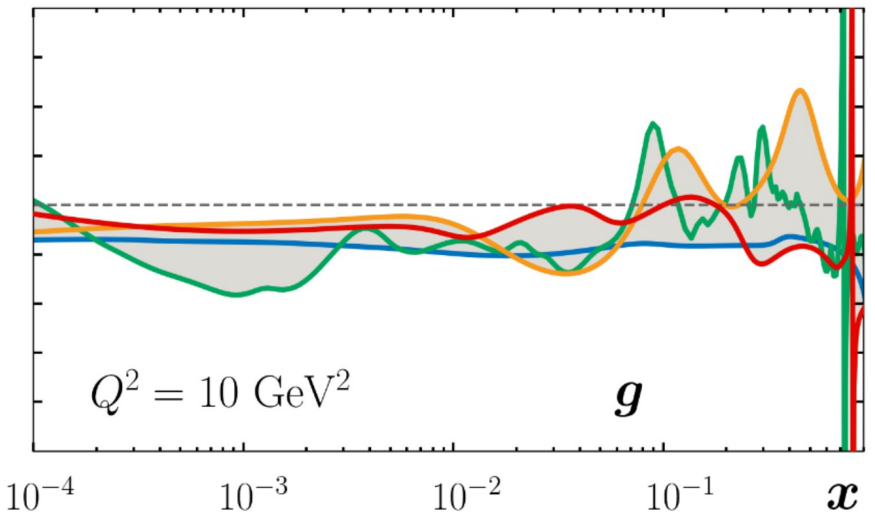
Region depleted in comparison to optimistic scenario → not covered by HERA, still lots of data in the high-x low-Q^2 corner

EIC yellow report style figures

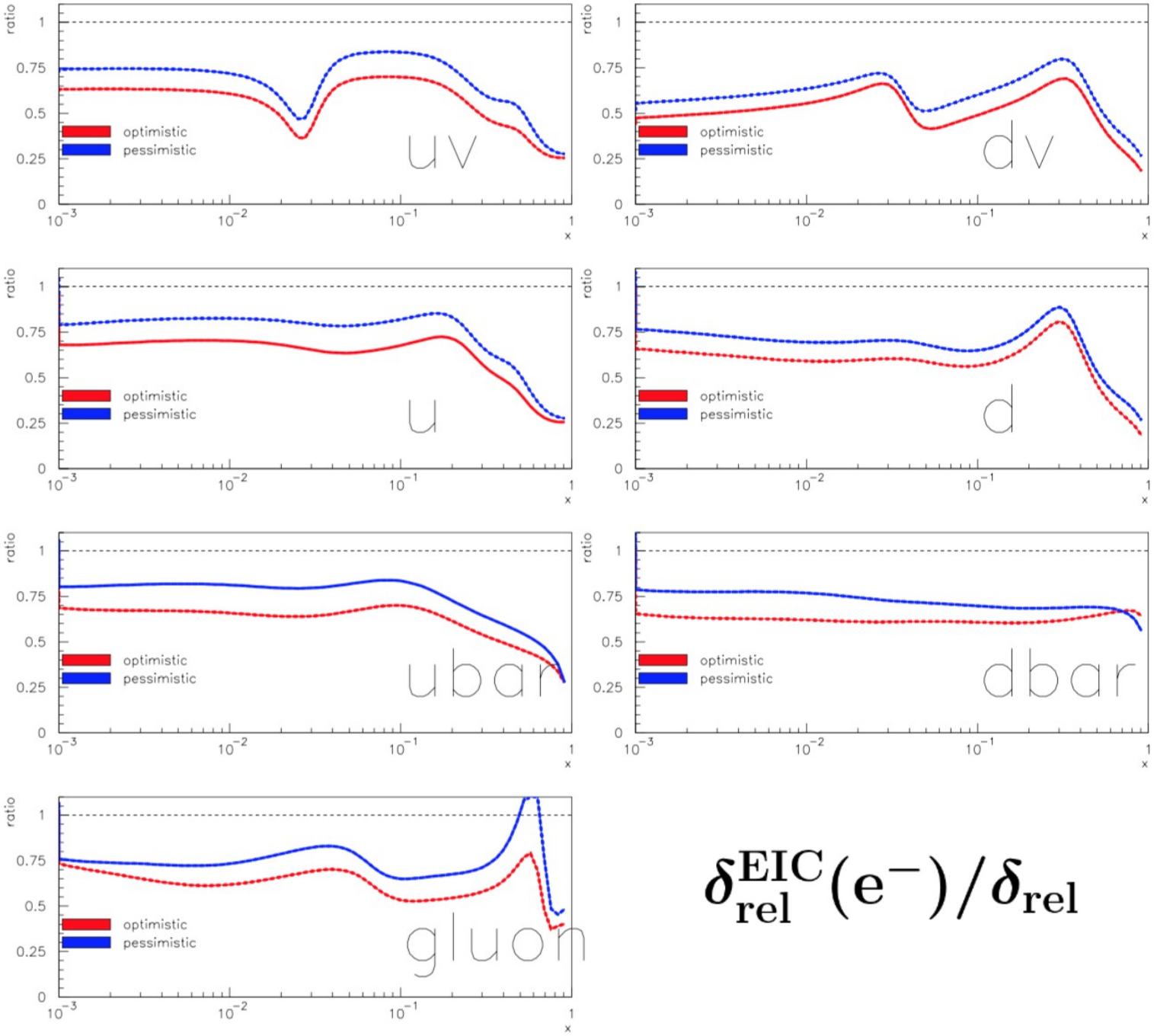






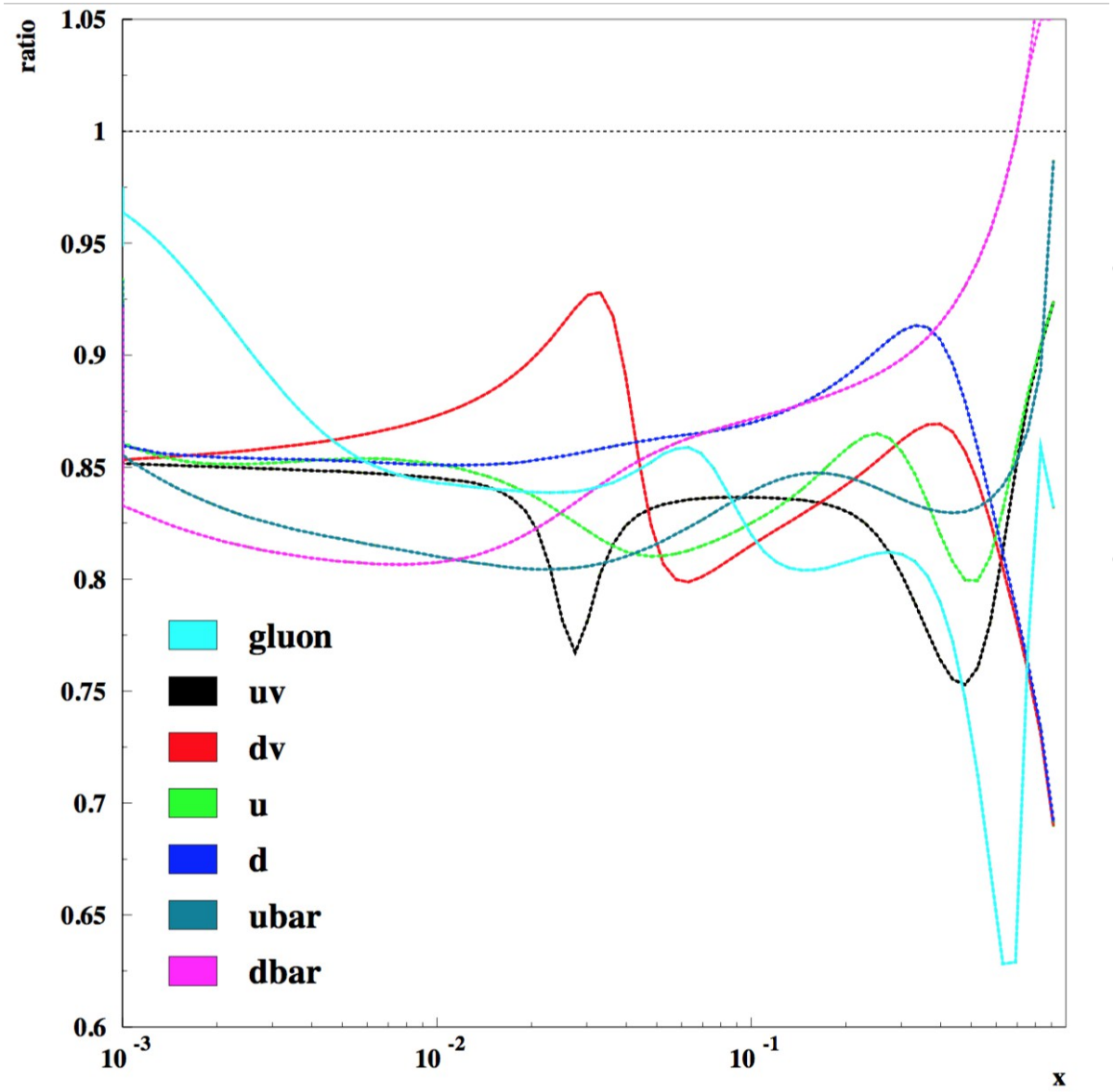


Generally drop of ratio for pessimistic scenario – try to asses by how much



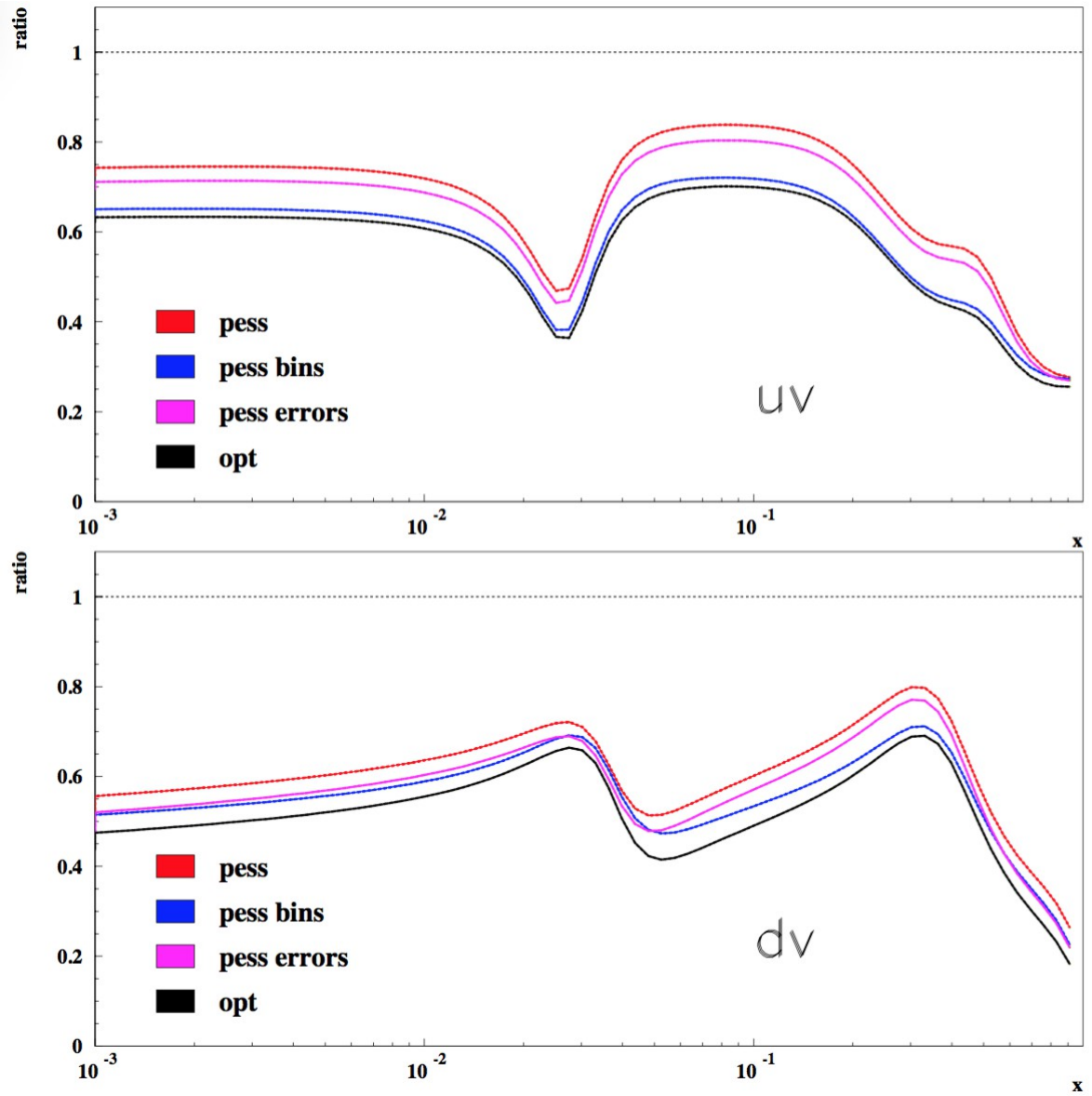
$$\delta_{\mathrm{rel}}^{\mathrm{EIC}}(\mathrm{e}^-)/\delta_{\mathrm{rel}}$$

Ratio of $\delta_{\mathrm{rel}}^{\mathrm{EIC}}(\mathrm{e}^-)/\delta_{\mathrm{rel}}$ for pessimistic/optimistic to asses how much we loose for pessimistic scenario

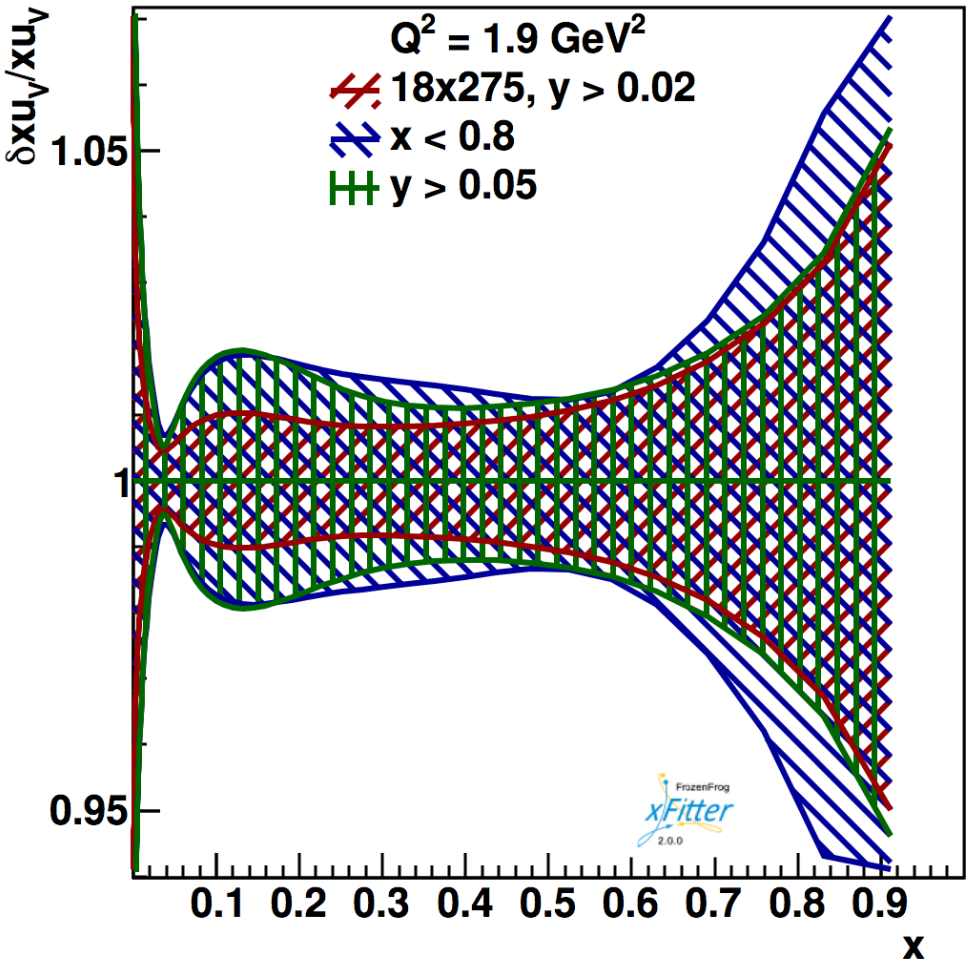


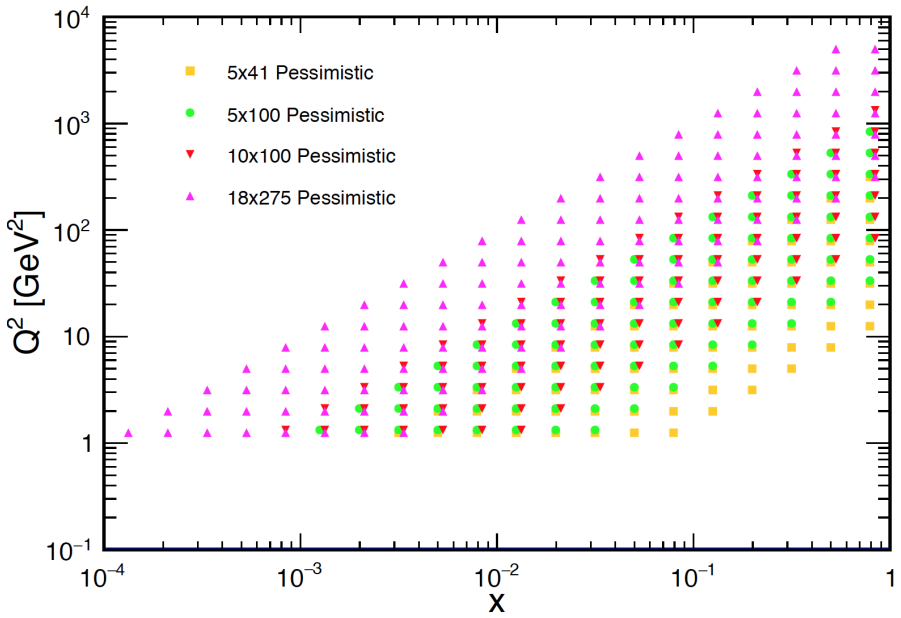
- We loose ~15-20% of relative impact on proton PDFs when pessimistic scenario assumed
- Seems worse for high-x region
  → high x is where most improvements is expected

Pessimistic scenario – what matters for PDFs?



Pessimistic scenario – what matters for PDFs?





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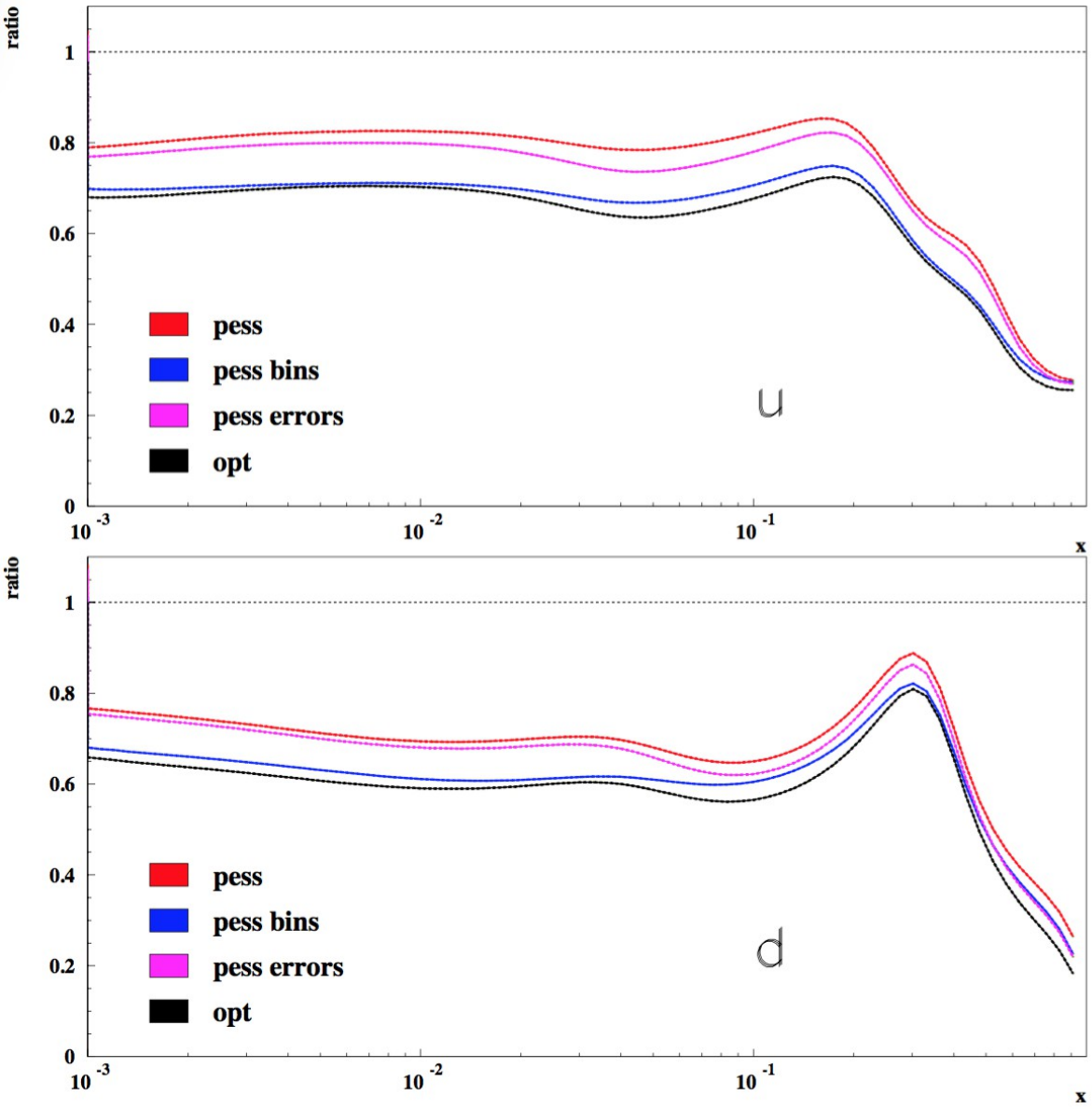
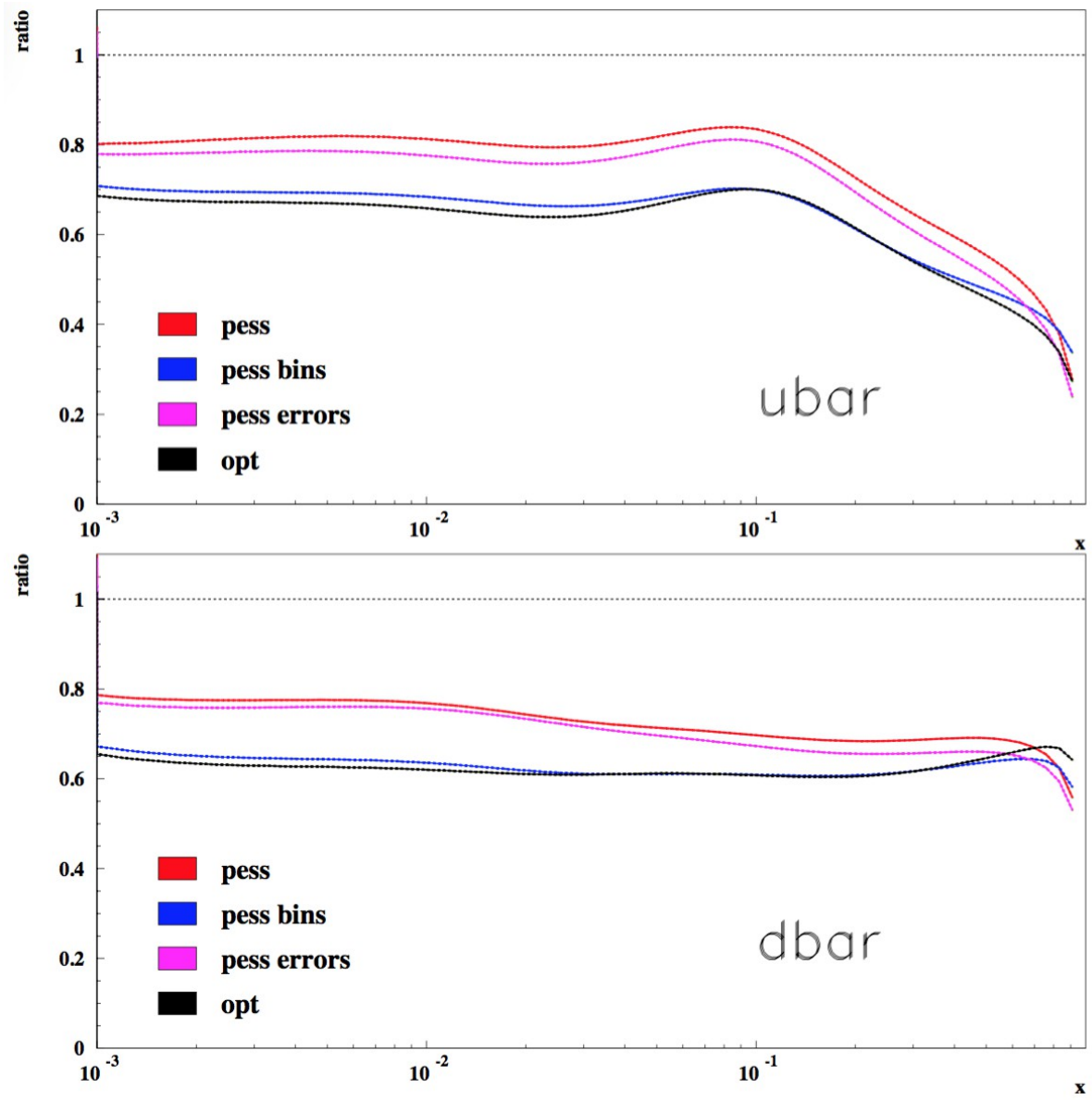
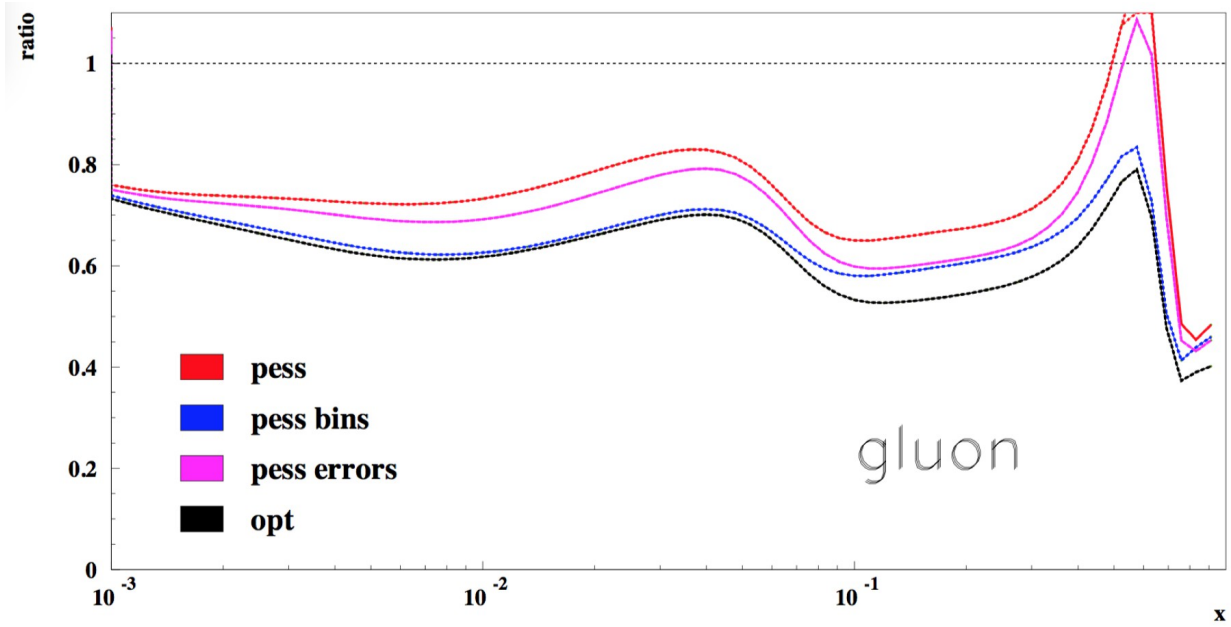


Pessimistic scenario – what matters for PDFs?



Pessimistic scenario – what matters for PDFs?



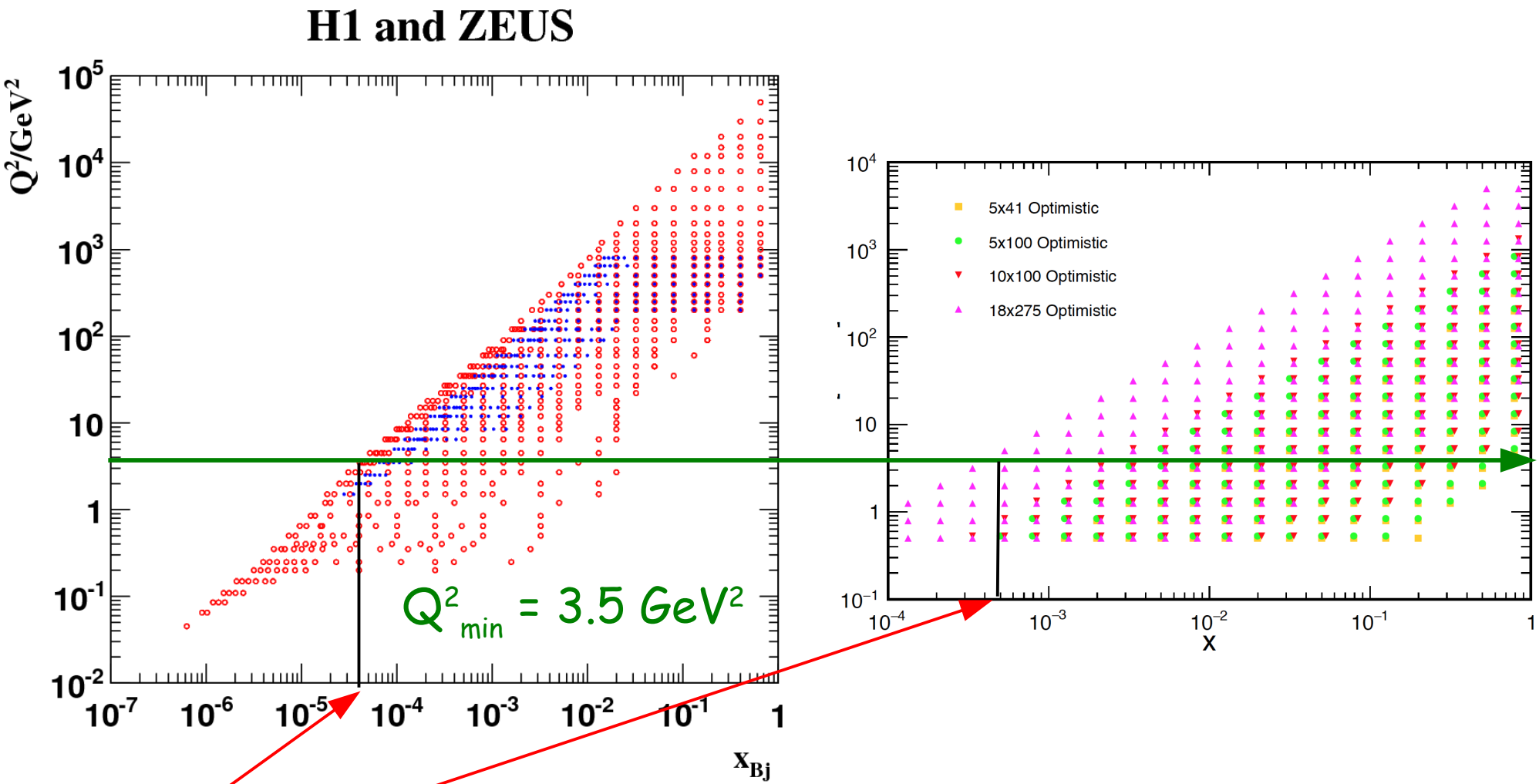
- Bins cut-out mostly for high x: y >~ 0.02
  → still many large-x bins left → impact on uncertainties not large
  → y cut much better than direct x cut
- Larger uncertainties affect all bins → larger effect expected and seen
- Concentrate on uncertainties?

Nuclear PDFs

- Last week discussed with Paul and Nestor plans for estimating impact of ATHENA data on nuclear PDFs
  → global nPDF fits at this stage not really feasible

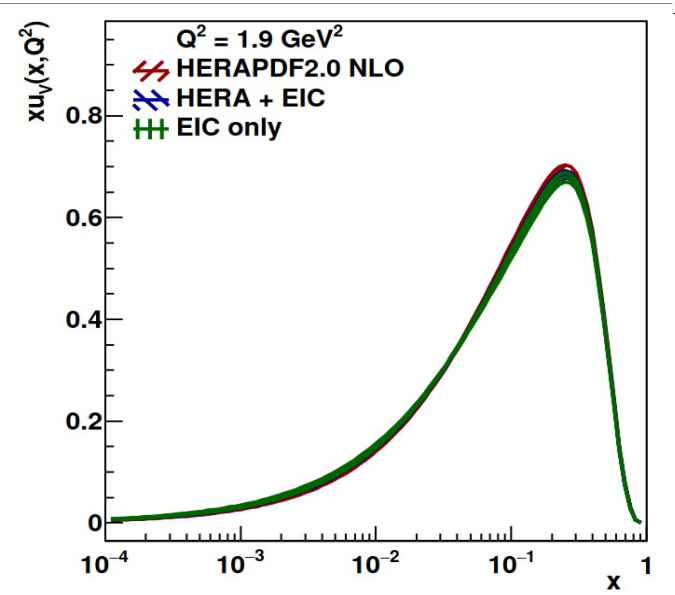
- However uncertainties on nuclear PDFs can be obtained from proton PDF uncertainties via nuclear modification factor
  → done this way for LheC by Nestor – he has his code
- Proposal to repeat this for ATHENA
  - Define nuclear PDF bins and uncertainties
  - Use ATHENA data only - no "HERA data" for nuclear PDFs (limited amount of nuclear data in any case)
  - ATHENA-only fits of proton PDF with nPDFs bins&uncertainties *to get uncertainties* (not central values!)
  - Nestor transforms it to nPDF uncertainties (not central values)
- First step – check ATHENA-only fits with proton bins&uncertainties

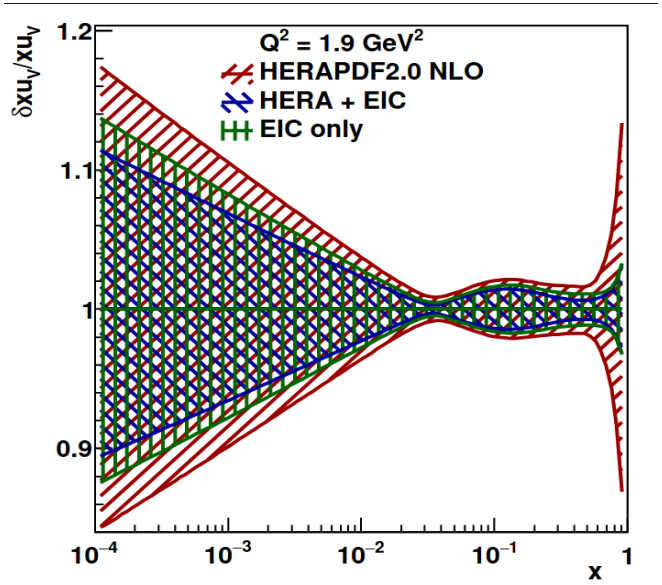
Reminder: HERA & ATHENA phase-space

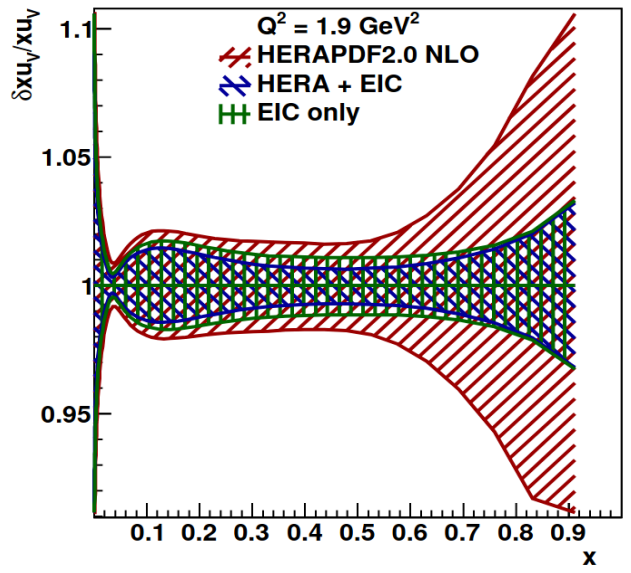


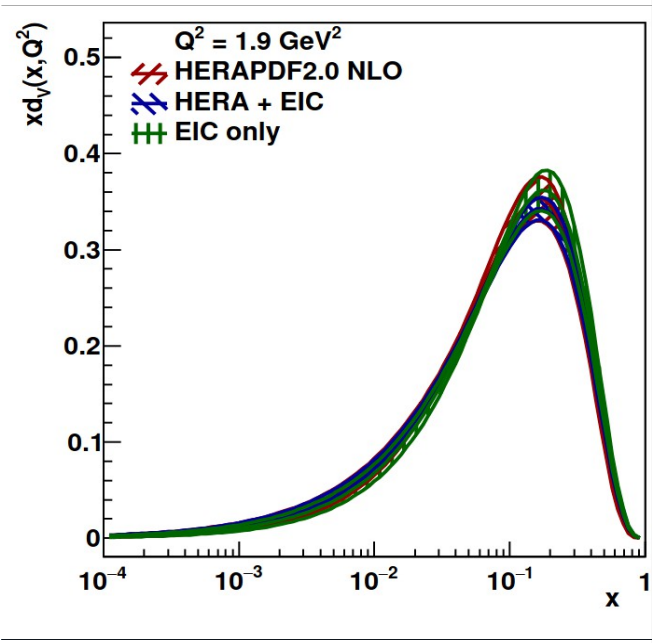
1) High-x egion not covered by HERA → impact on high-x PDFs expected

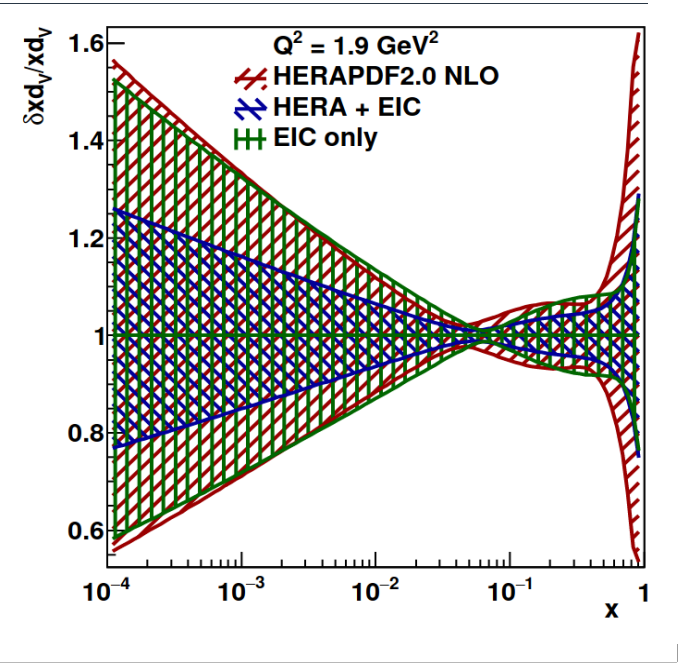
2) At HERA much lower x covered – so EIC-only fits reasonable down to ~10^{-3}

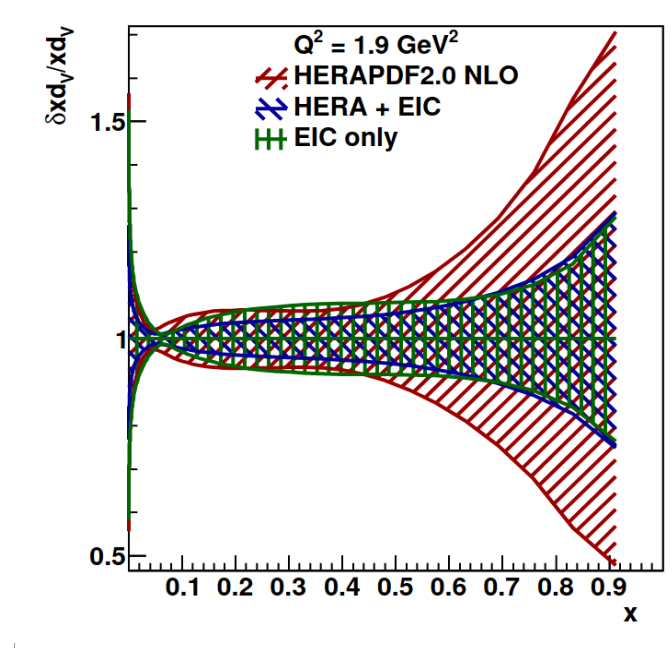

$xu_v(x,Q^2)$
Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
x

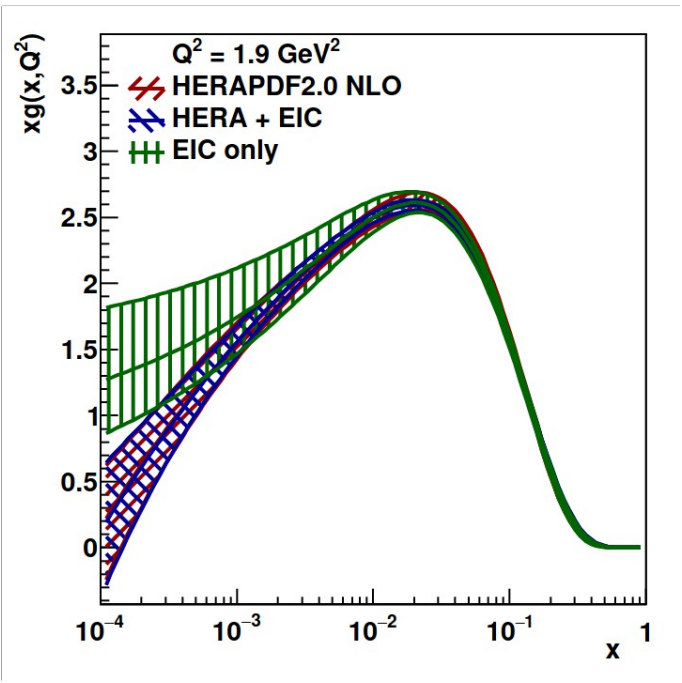

$\delta xu_v/xu_v$
Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
x

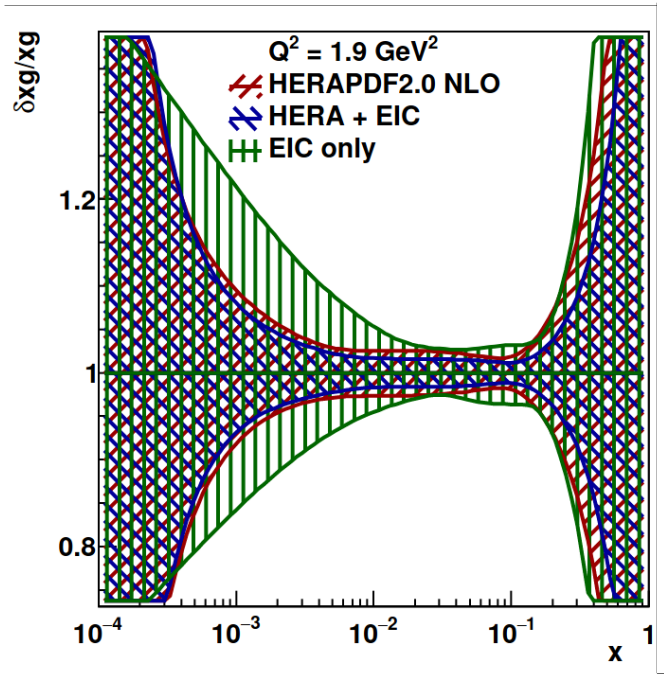

$\delta xu_v/xu_v$
Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
x

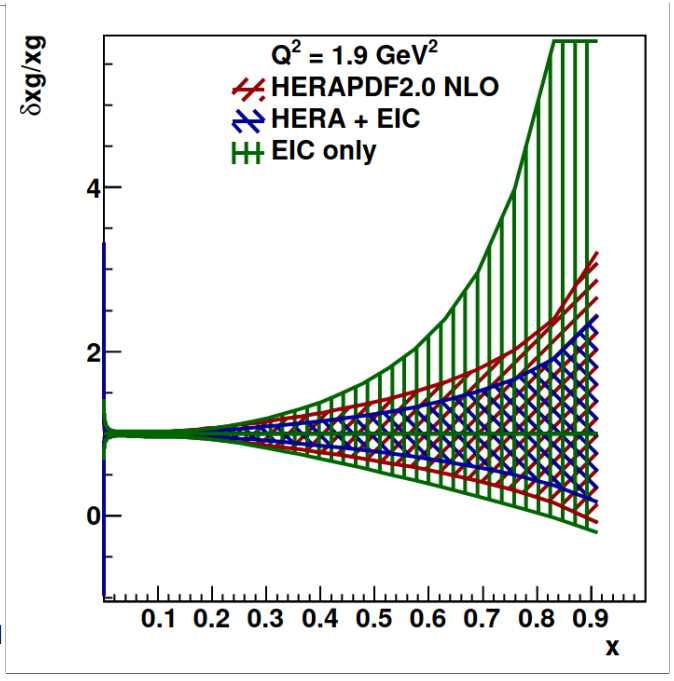

$xd_v(x,Q^2)$
Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
x

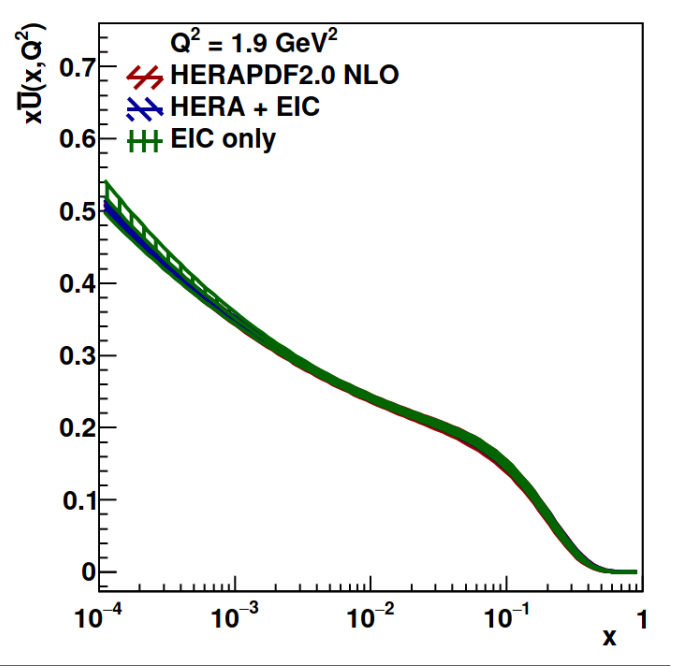

$\delta xd_v/xd_v$
Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
x

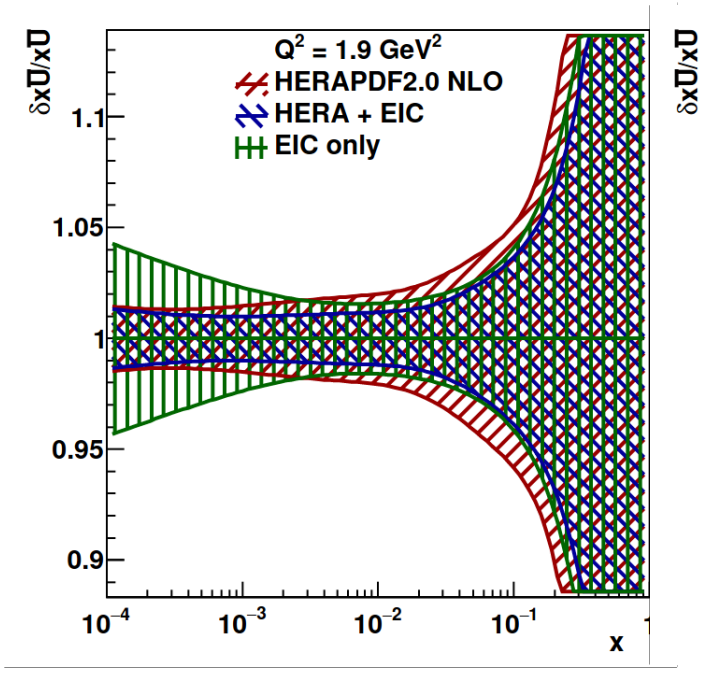

$\delta xd_v/xd_v$
Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
x

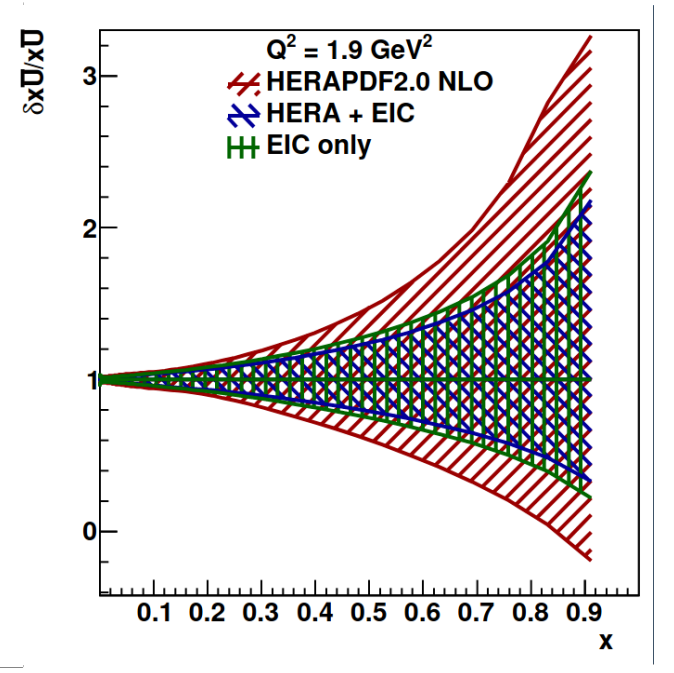

Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
$xg(x,Q^2)$
x


Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
$\delta xg/xg$
x

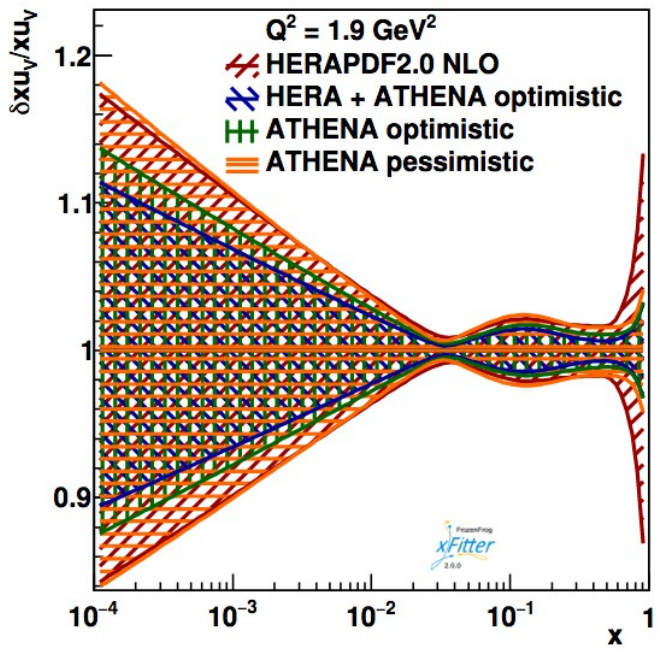

Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
$\delta xg/xg$
x

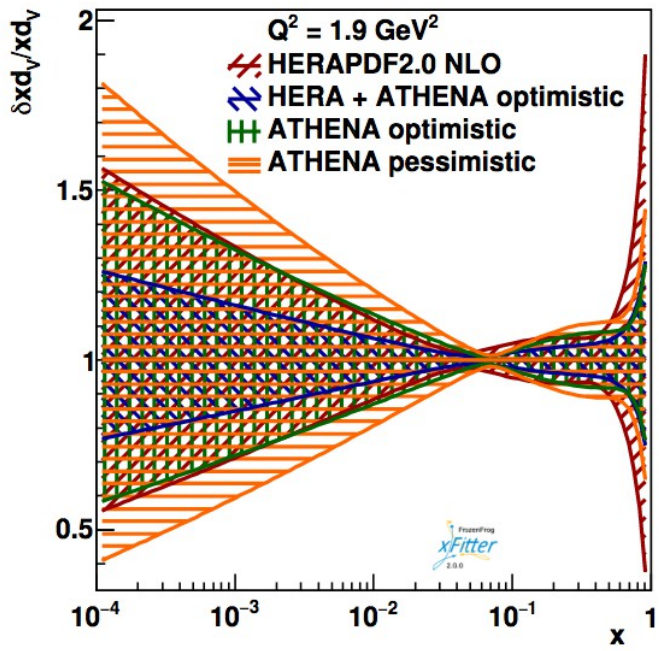

Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
$x\bar{U}(x,Q^2)$
x

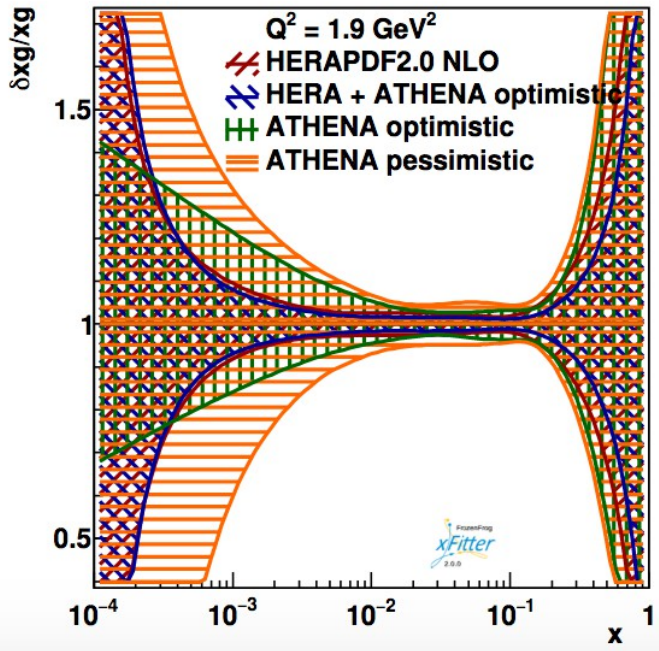

Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
$\delta x\bar{U}/x\bar{U}$
x

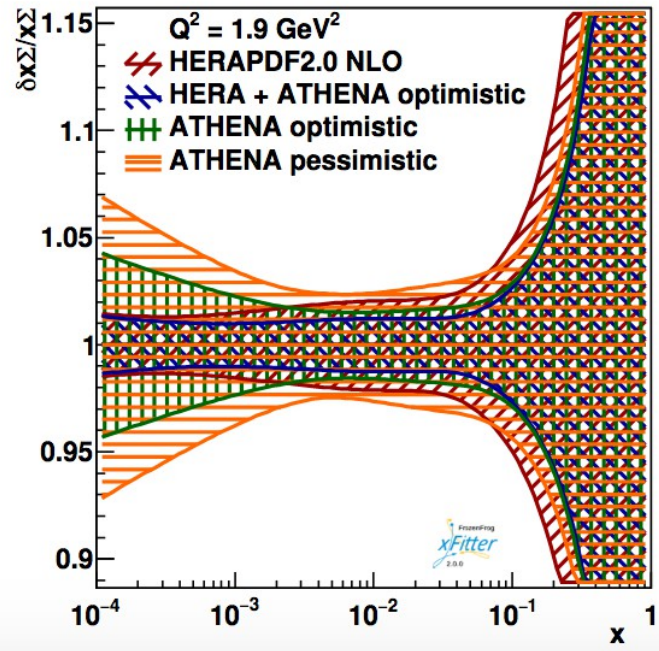

Q^2 = 1.9 GeV^2
HERAPDF2.0 NLO
HERA + EIC
EIC only
$\delta x\bar{U}/x\bar{U}$
x

EIC-only optimistic/pessimistic: low- & mid-x

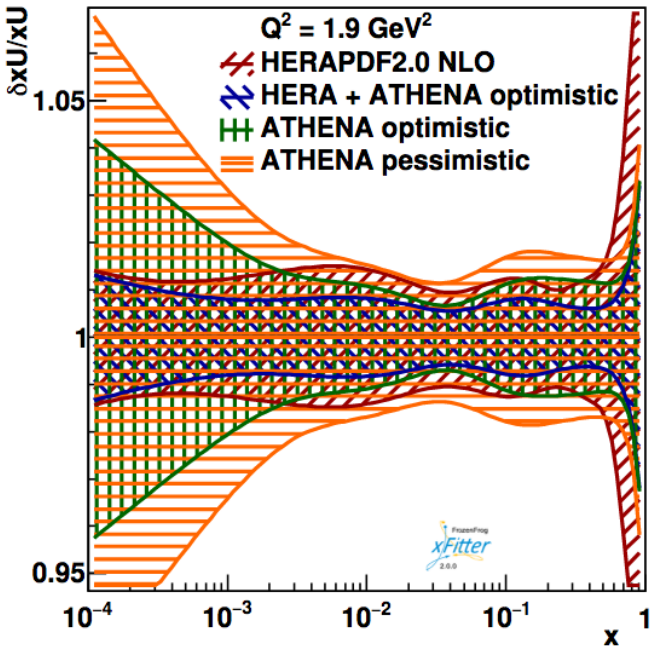


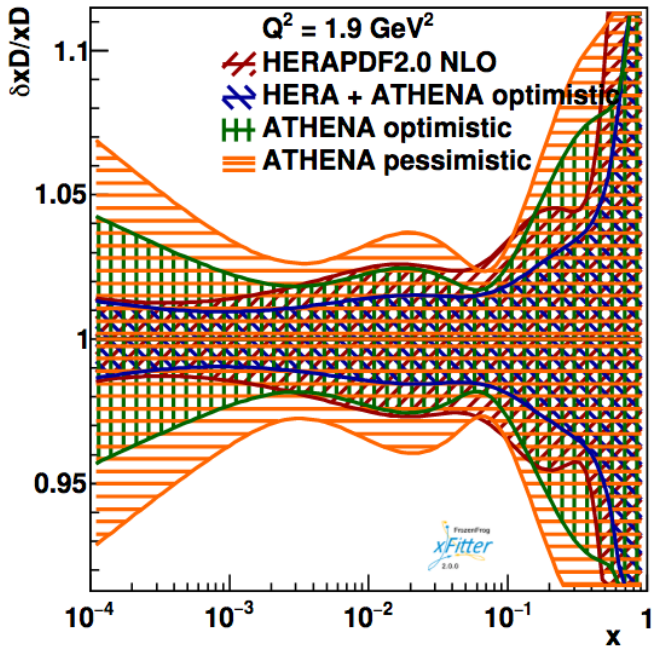


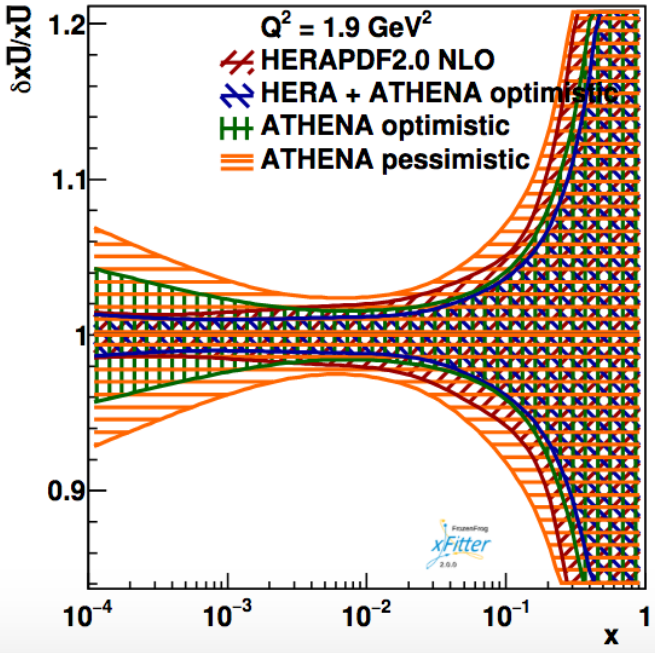


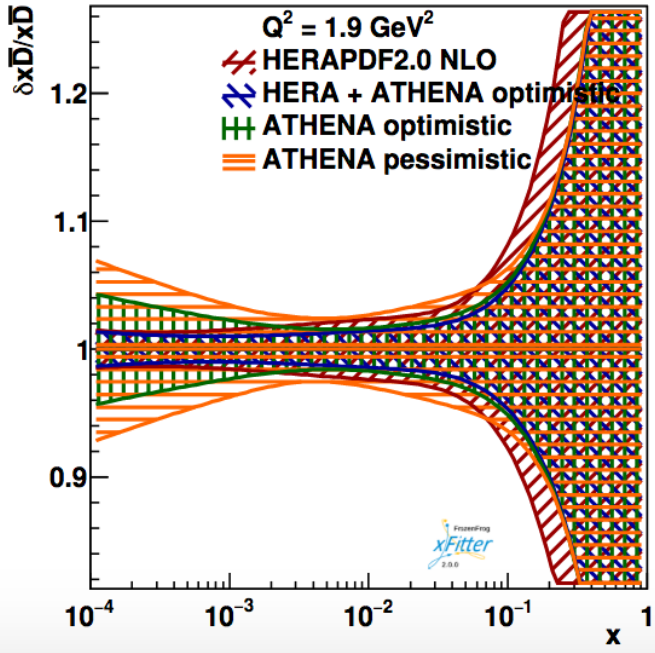


EIC-only optimistic/pessimistic: low- & mid-x



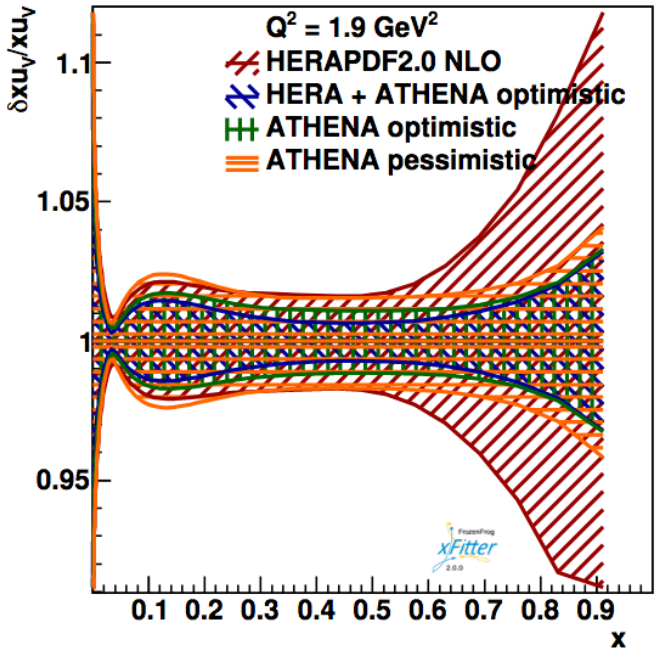


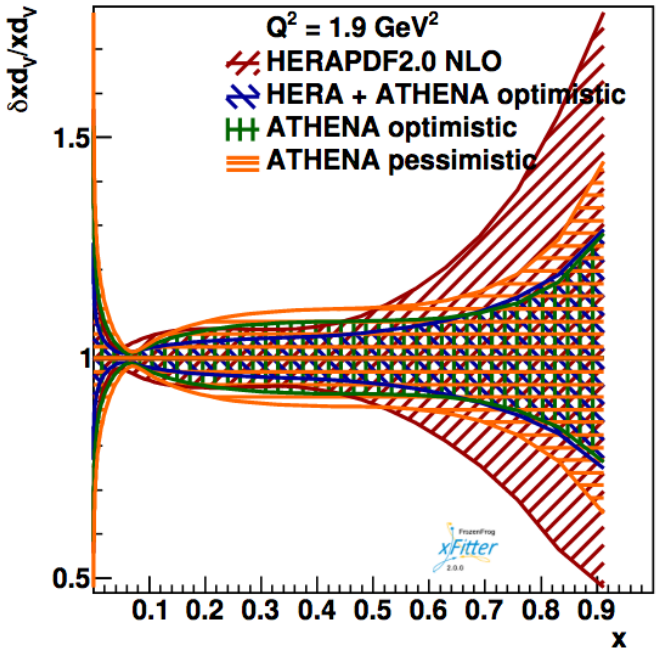


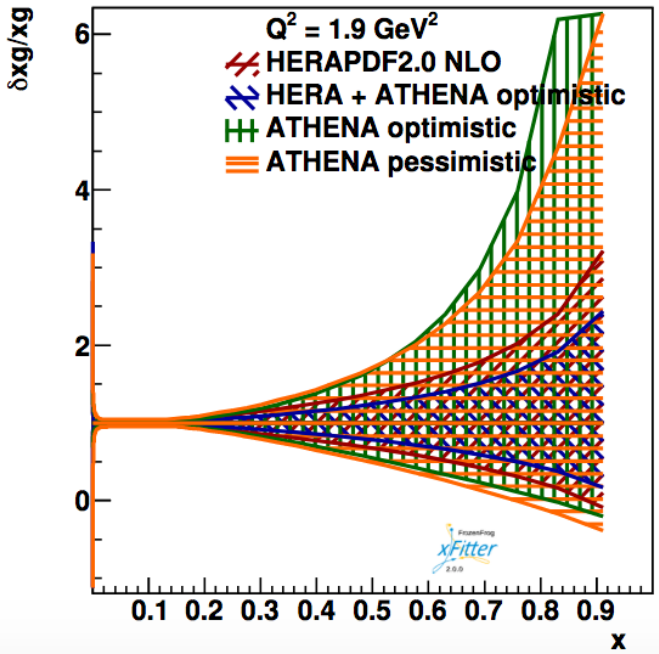


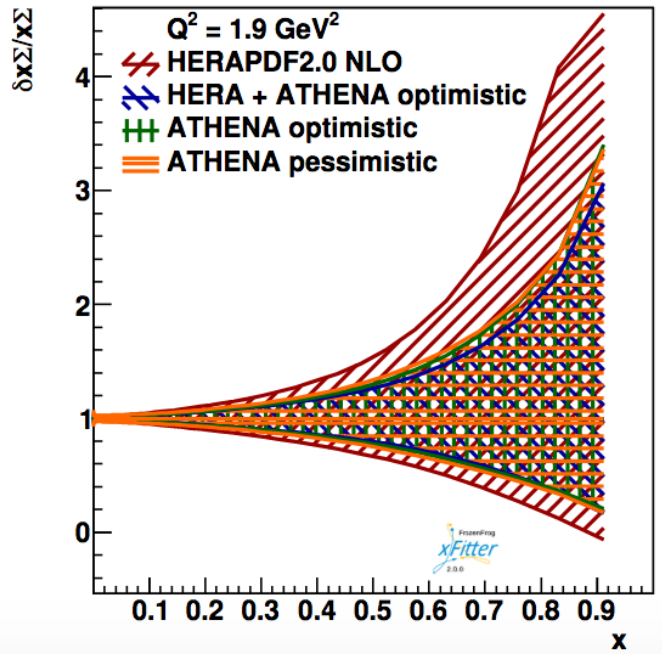
- Low- and mid-x: ATHENA-only proton PDF fits much worse than HER-only
- Pessimistic option makes it even worse

EIC-only optimistic/pessimistic: high x

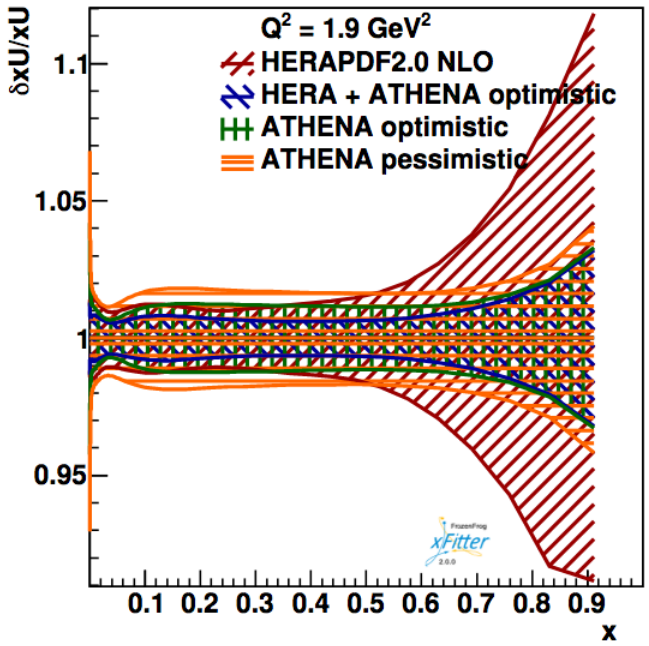


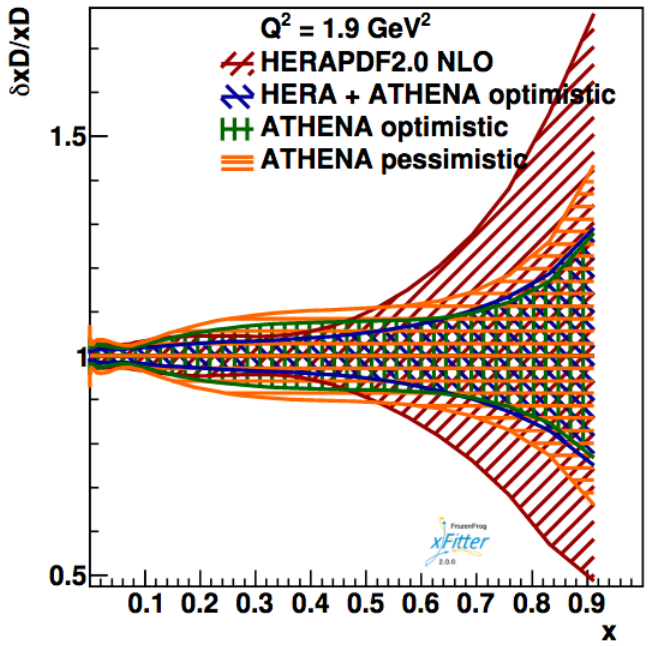


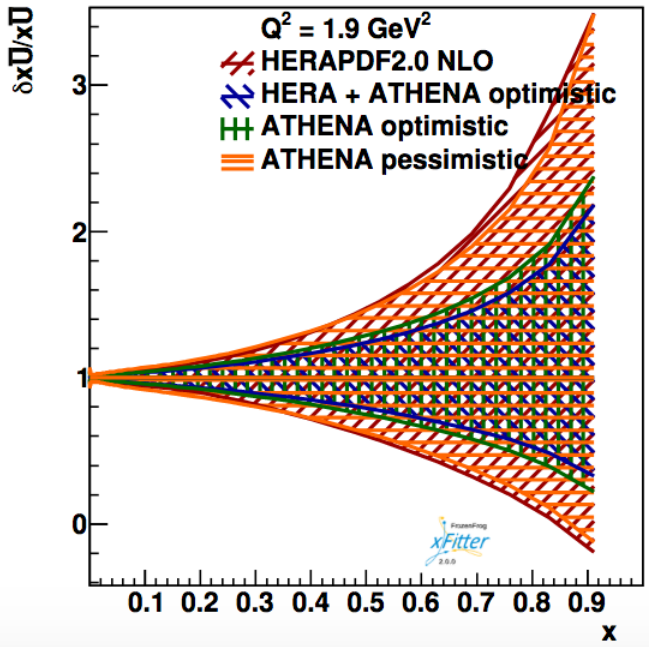


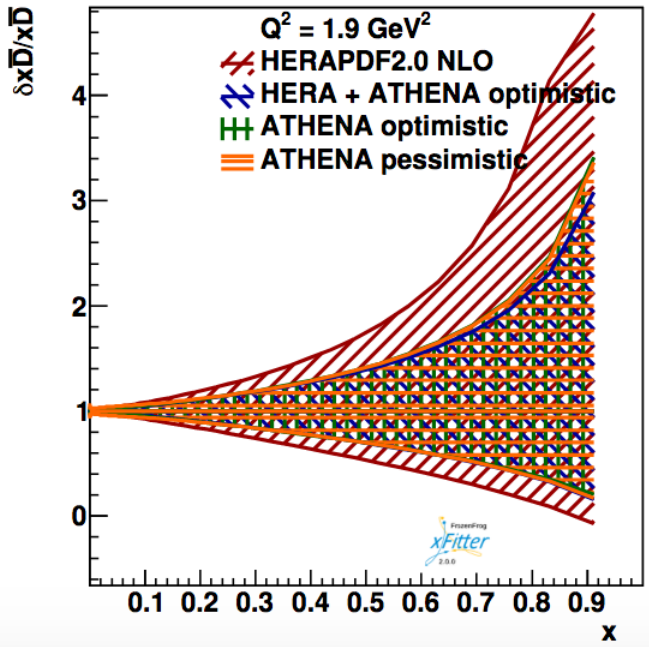


EIC-only optimistic/pessimistic: high x









- High x: ATHENA-only proton PDF fits mostly better than HERA-only → except for gluon and Ubar
- Pessimistic option worsens things, especially for x~0.1 → there worse than HERA-only

EIC-only: tentative conclusions

- Proton EIC-only fits give us access to estimation of uncertainties for nuclear PDFs
  → stable fits using present bins/uncertainties of ep measurements
  → good uncertainties for highest x, also for pessimistic scenario
  → uncertainties worse than HERAPDF2.0 fits for low- & mid-x, pessimistic not crucial
  → <u>for x~0.1 getting optimistic version seems very important</u>

- Technically ready – checked with Nestor about formats etc
  - Needed now nuclear PDF bins and uncertainties (estimations)
  - Can be done fast

Additional slides

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):

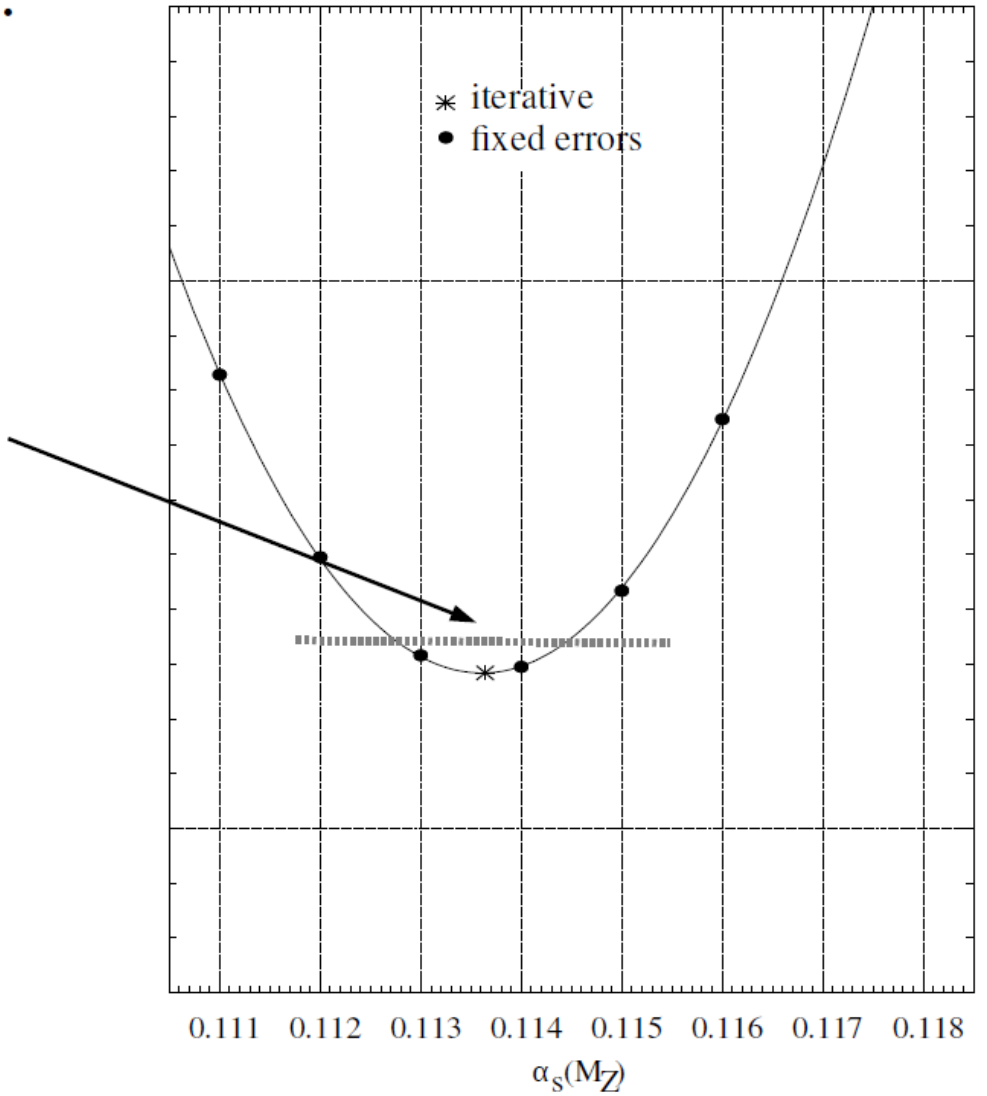
Method: Parametrizations $xf(x,Q_0^2) = Nx^a(1-x)^b\ \mathrm{function}(x)$
and usual *statistical estimation* (fits):

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

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.



HERAPDF2.0 parameterisation

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

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

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

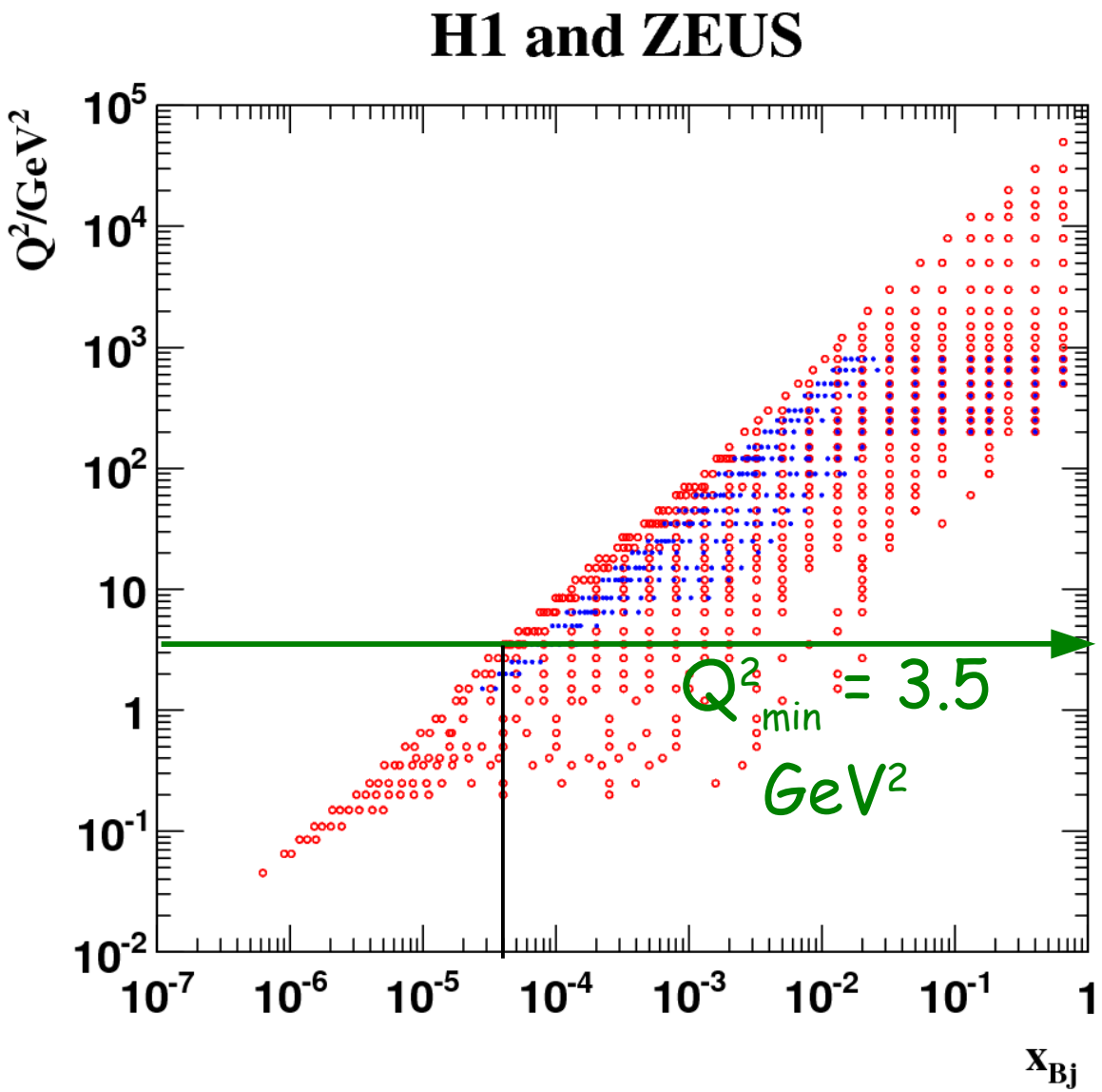
$$x\bar{U} = x\bar{u} \text{ and } x\bar{D} = x\bar{d} + x\bar{s}$$

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

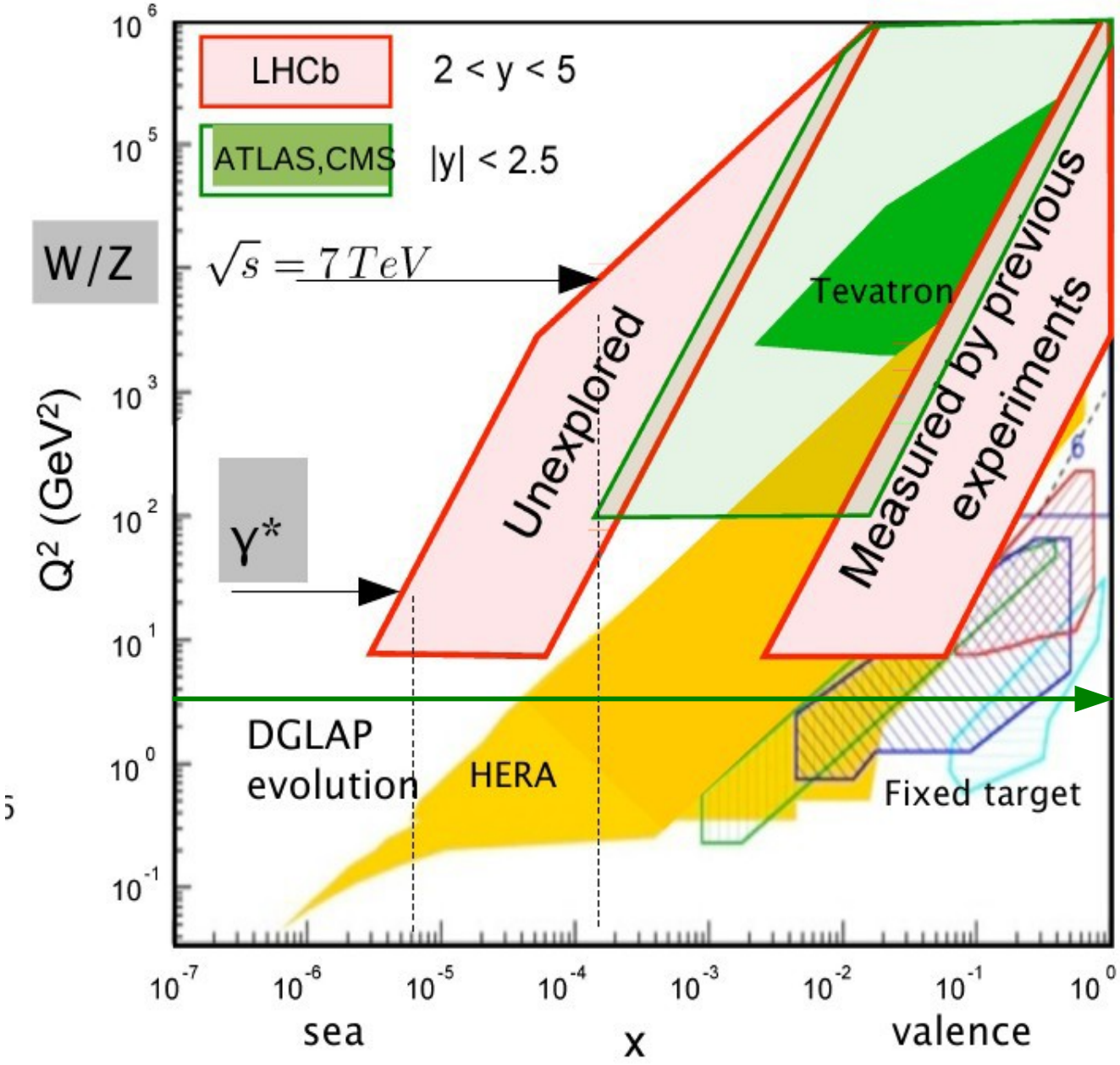
- Lowest Q^2 of data points included in fit
- Masses of c and b quarks
- Strange fraction
- Starting scale

Data in HERAPDF2 fit

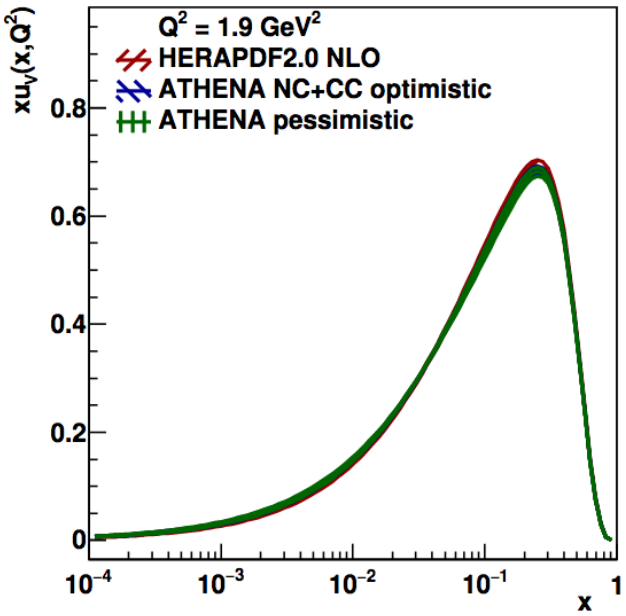


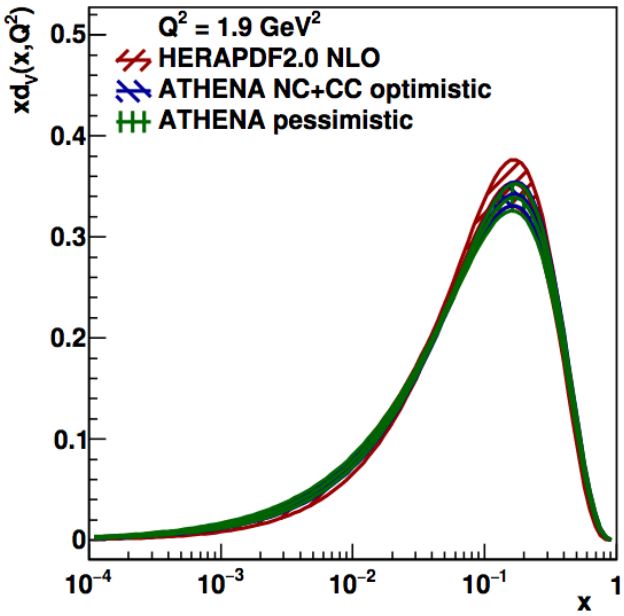
- inclusive DIS, for E_p=920 GeV and E_p= 820 GeV data
- Inclusive DIS, for E_p=575 GeV and E_p= 460 GeV data

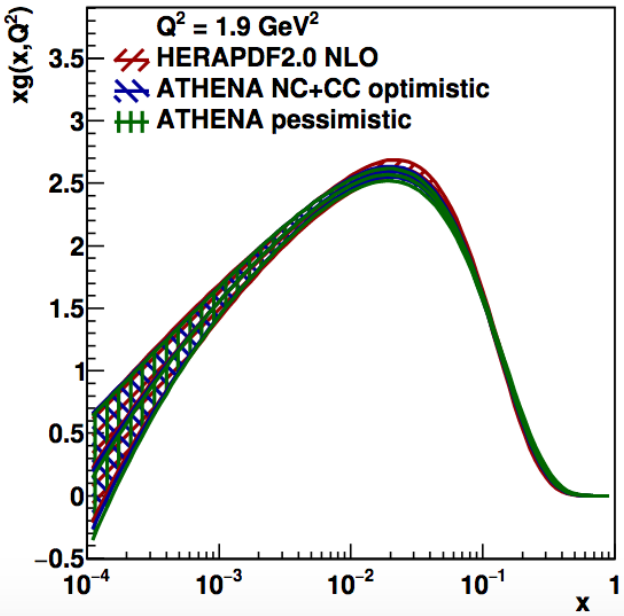
Various data in other PDF sets

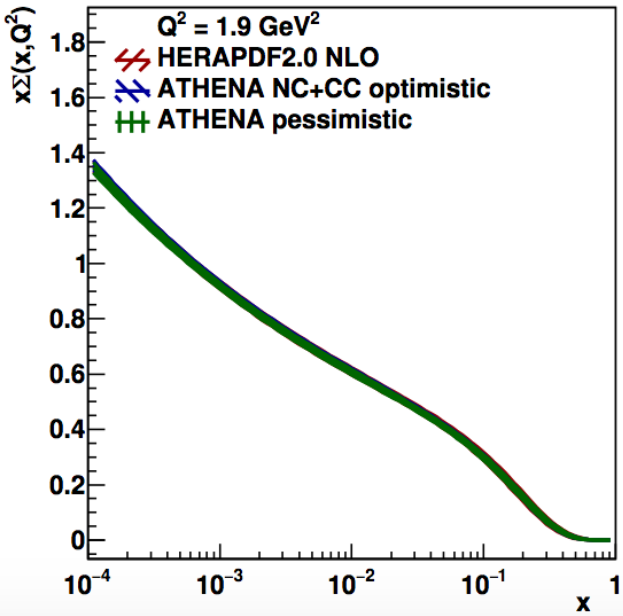


PDFs with HERA and ATHENA data



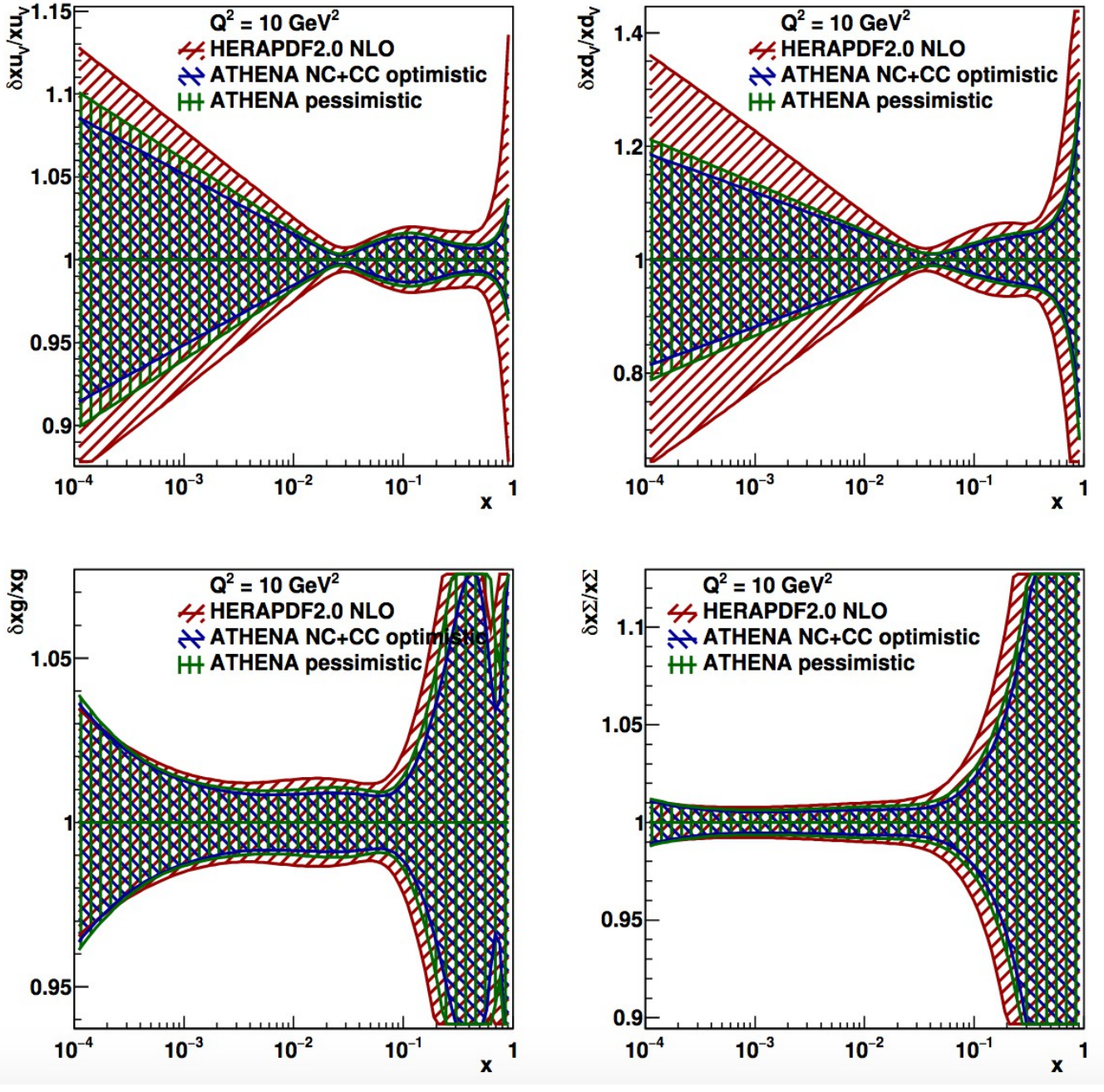




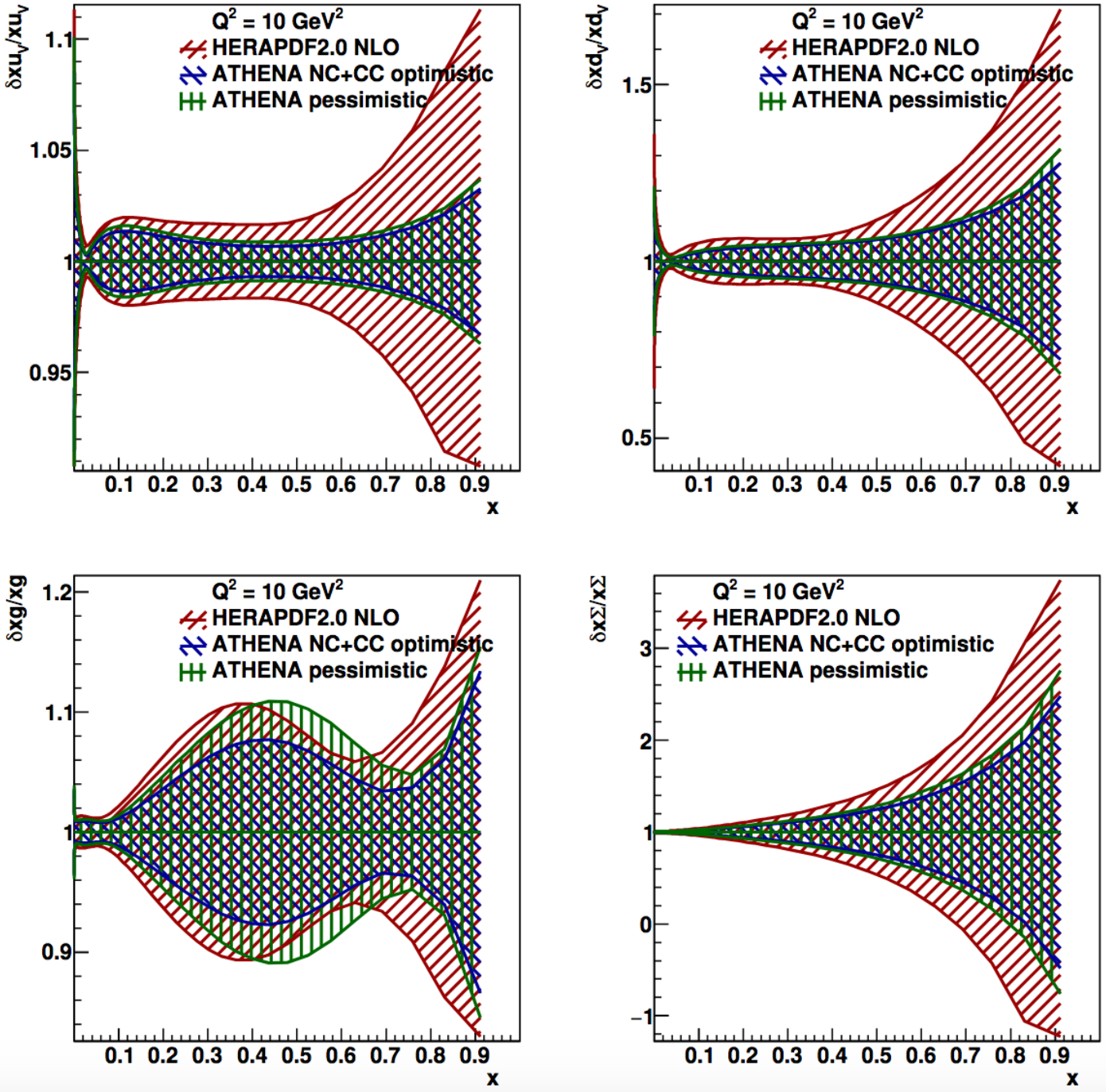


- Shown PDFs for
  - HERAPDF2.0 NLO
  - ATHENA NC+CC
    - Optimistic
    - Pessimistic
- PDF very similar
- Uncertainties very interesting → let's have a look

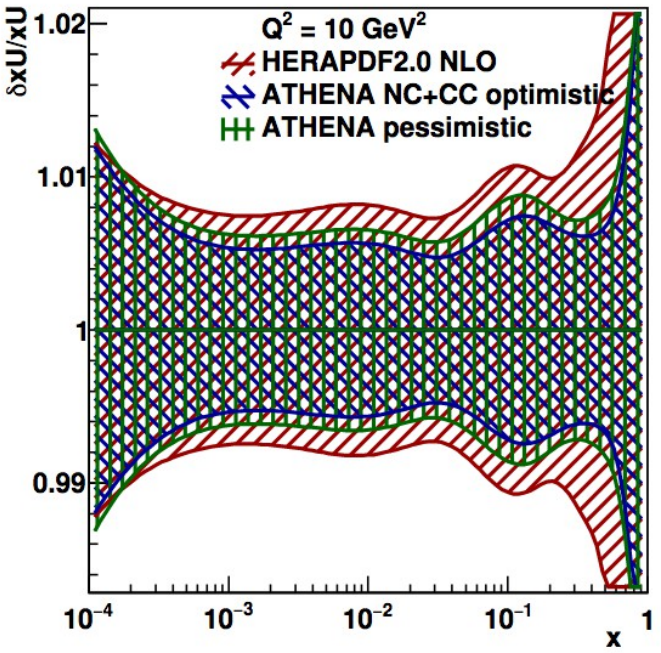
Relative uncertainties: some improvement for low & middle x and rapid decrease of uncertainties for low x

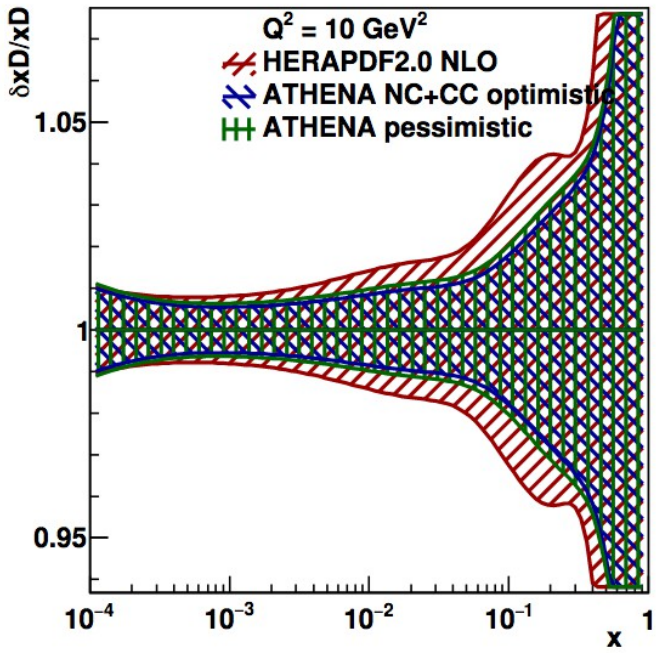


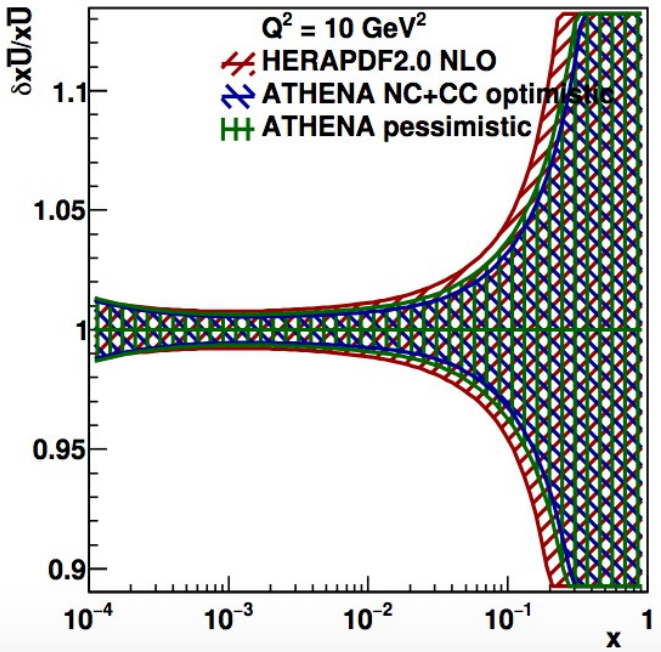
High-x region better visible

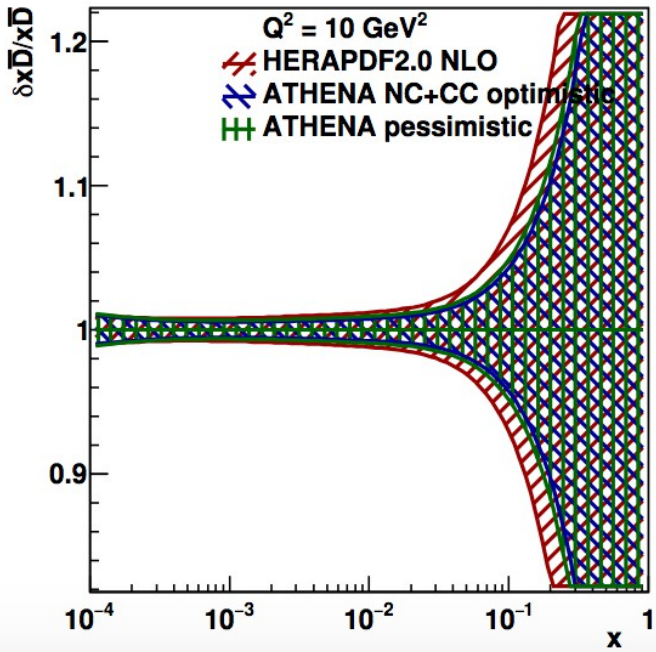


Relative uncertainties: quarks

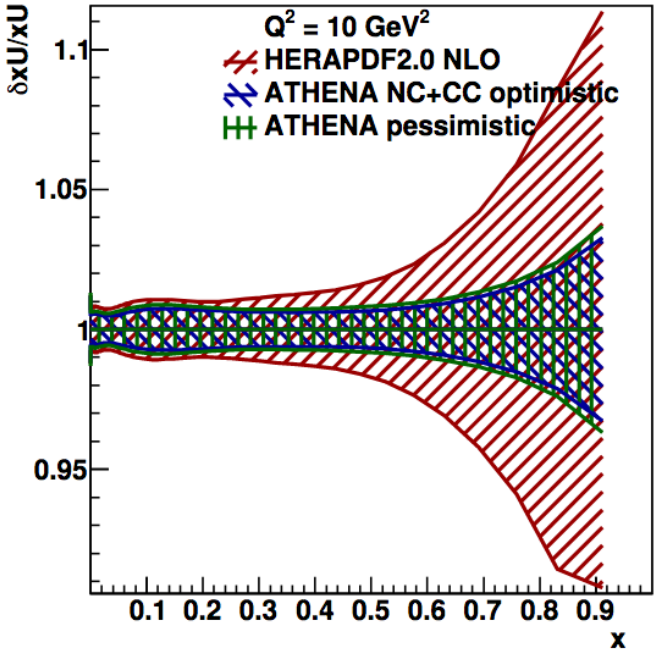


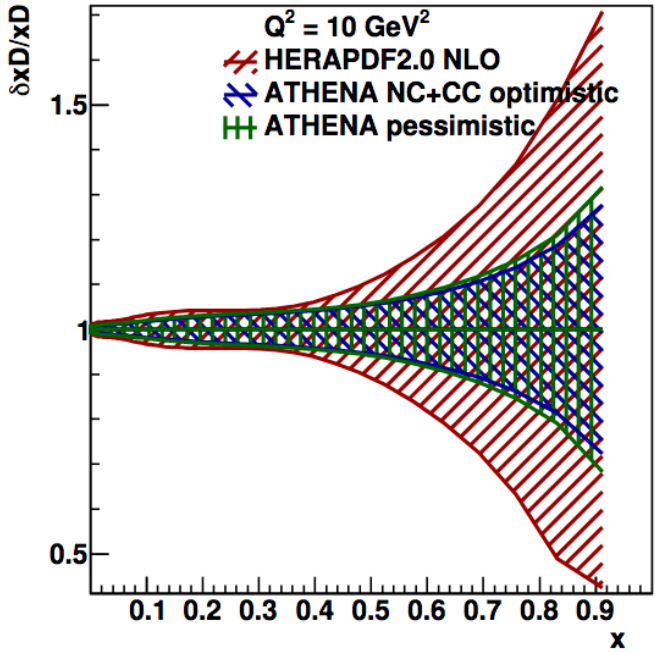


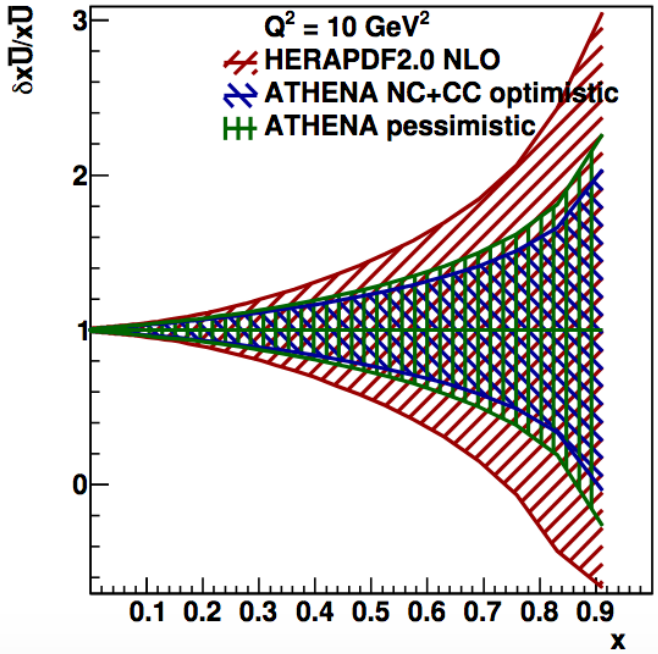


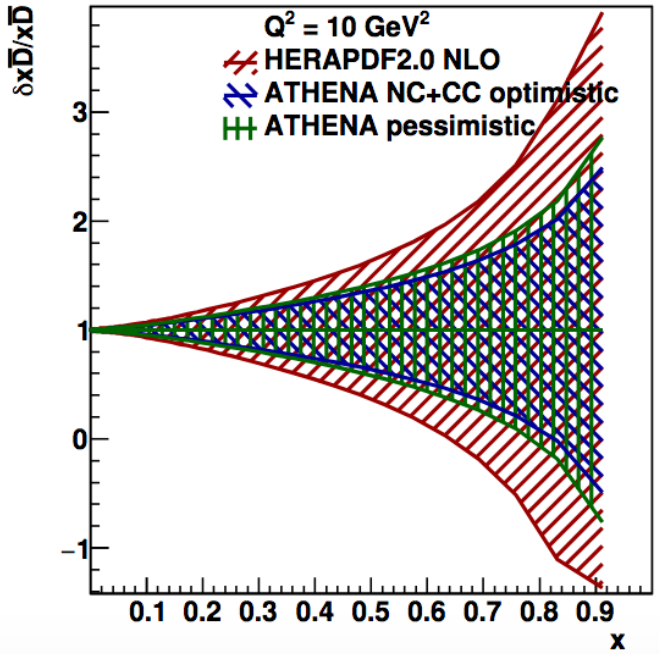


High-x region better visible: quarks



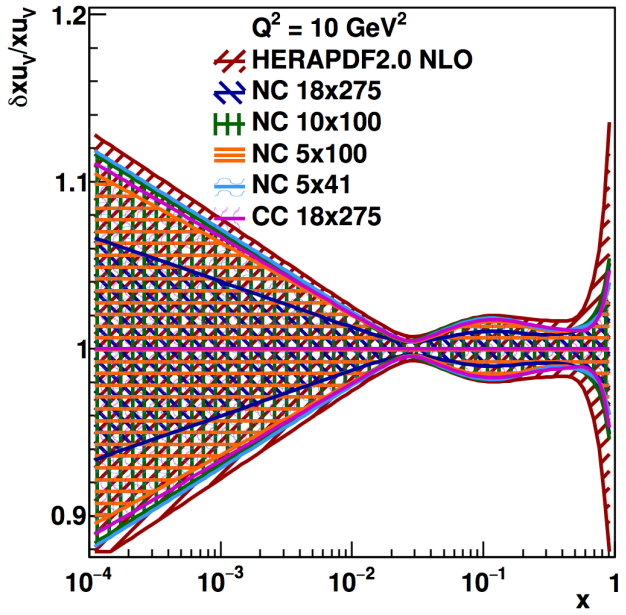


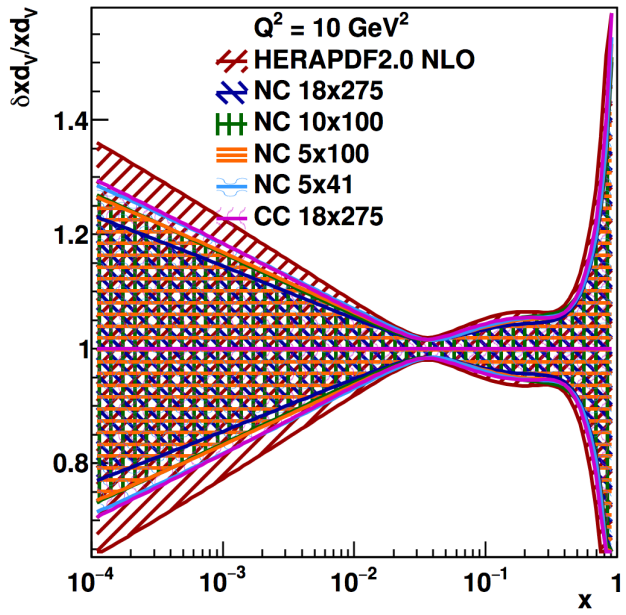


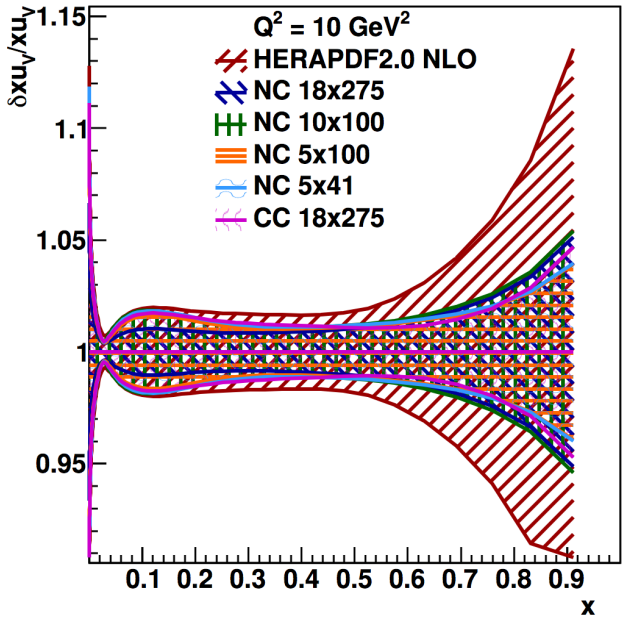


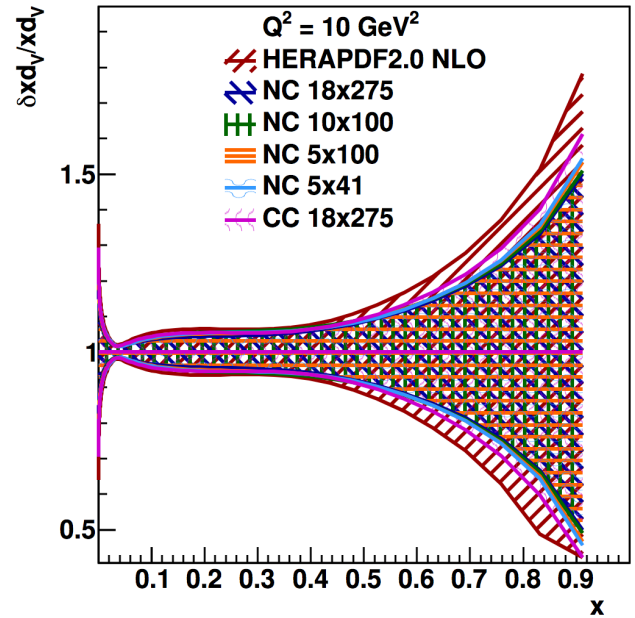
Impact of separate data samples

→ similar trends observed for sea quarks









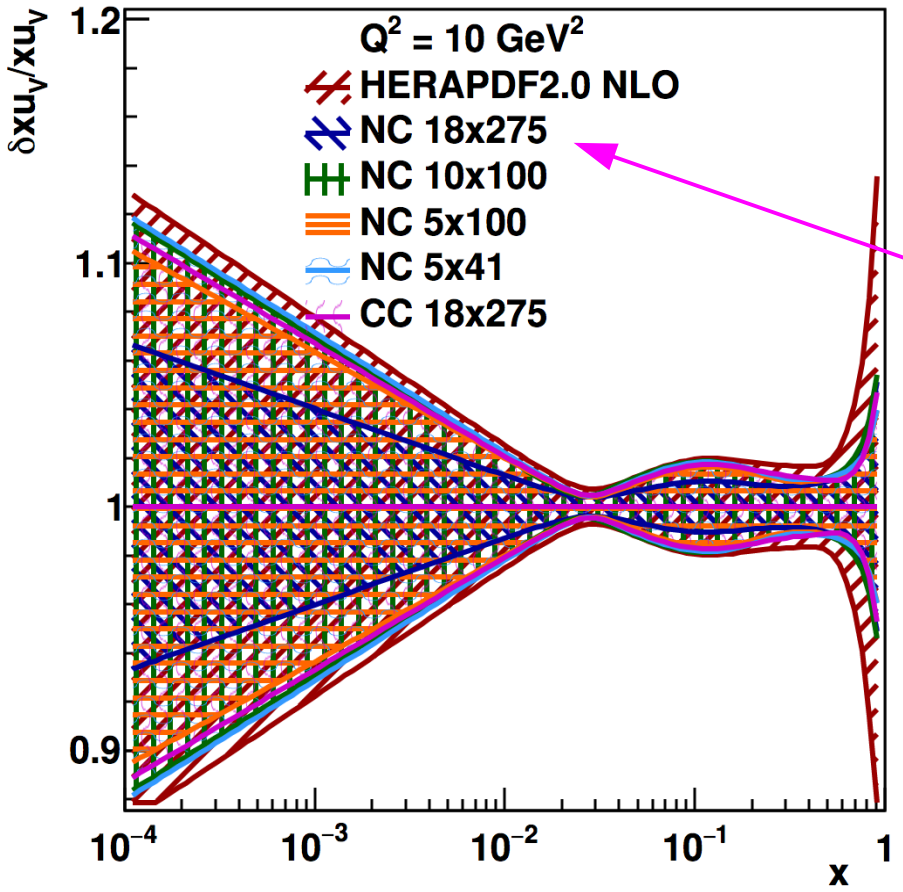
<u>Low & middle x</u>

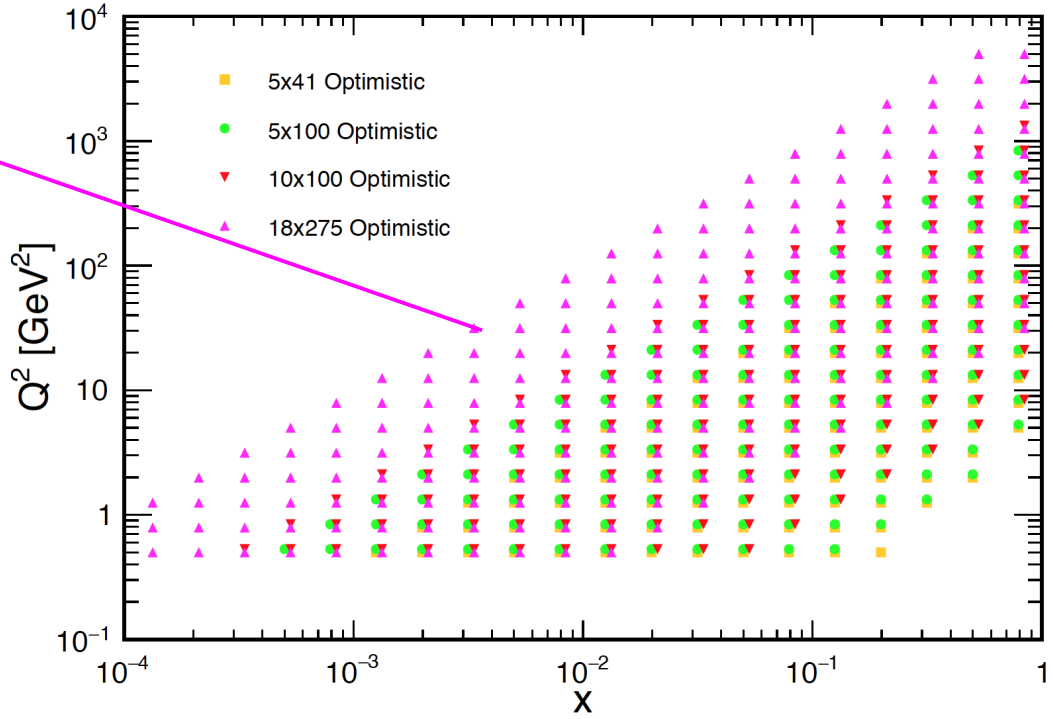
- NC 18x275 sample seems to have largest impact on valence quarks low-x uncertainties
  → see next slide for explanation

<u>High x</u>

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

Impact at low & middle x

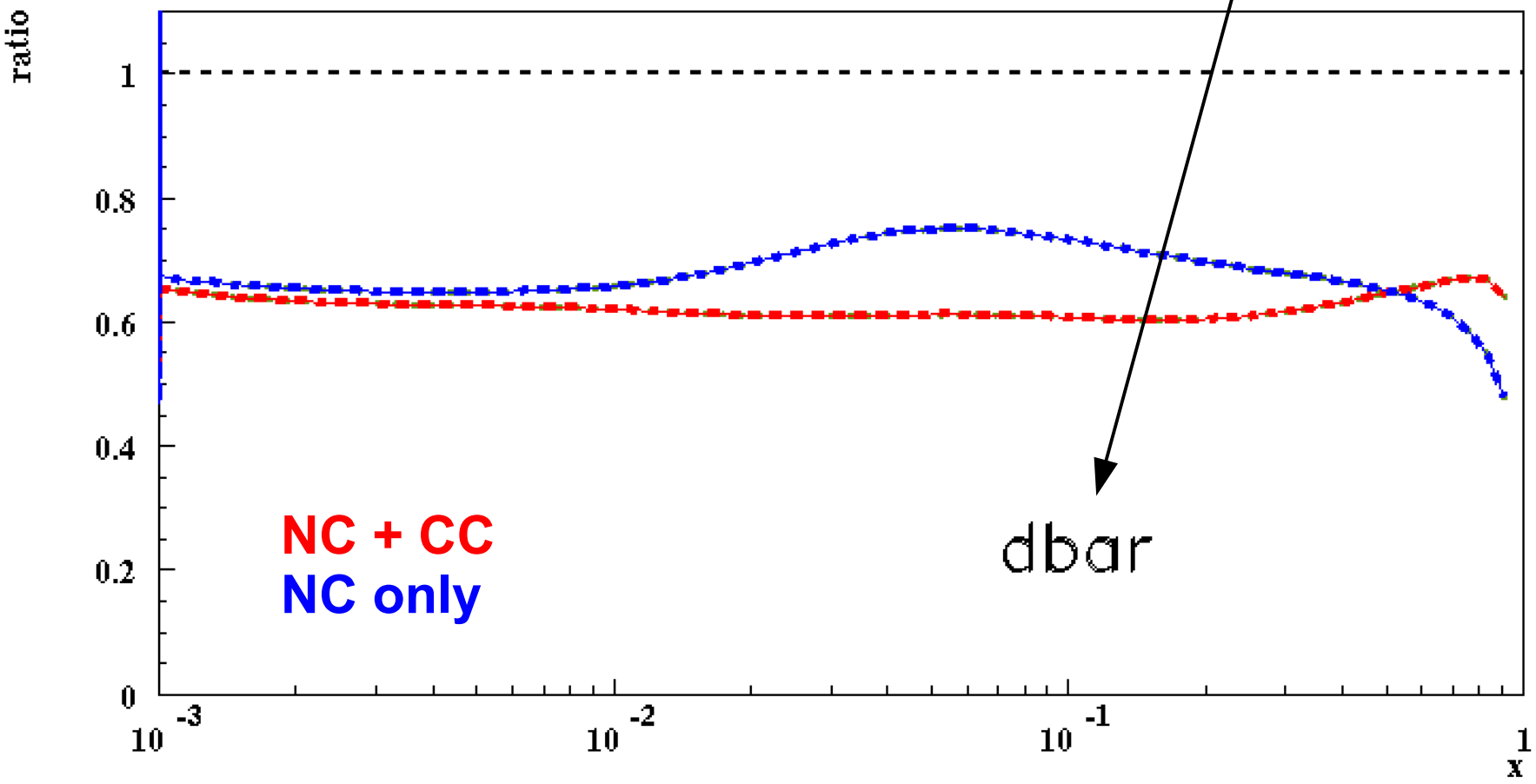




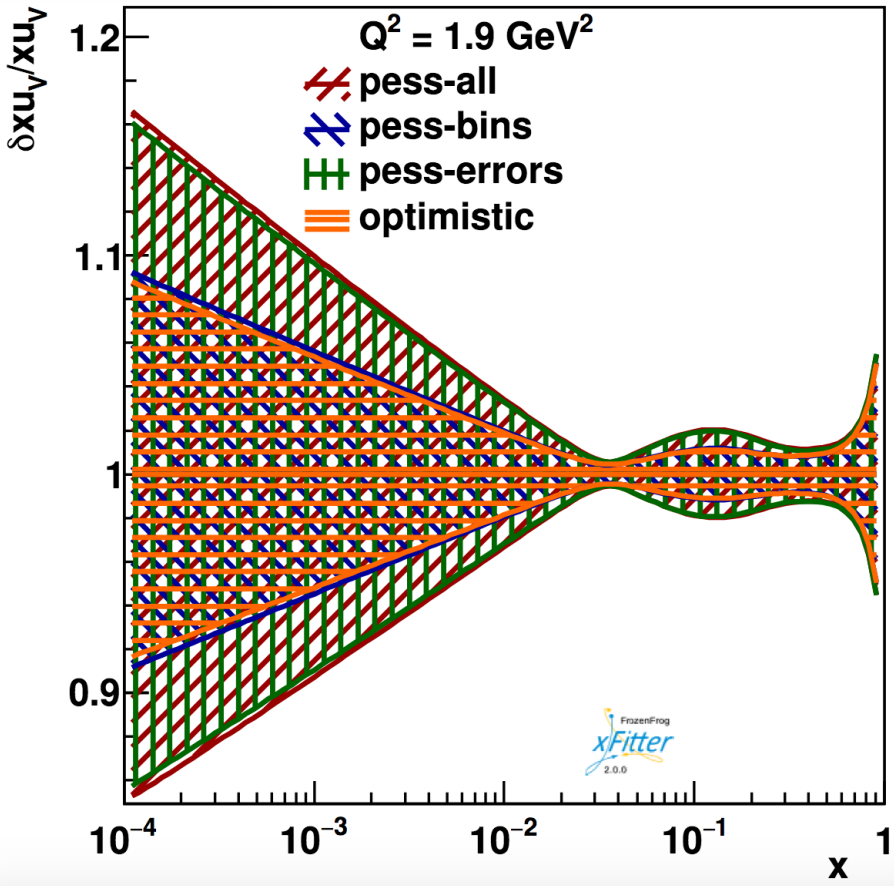
- NC 18x275 data add huge amount of statistics at low & middle x not present for other energies → effect on this kinematic region more significant

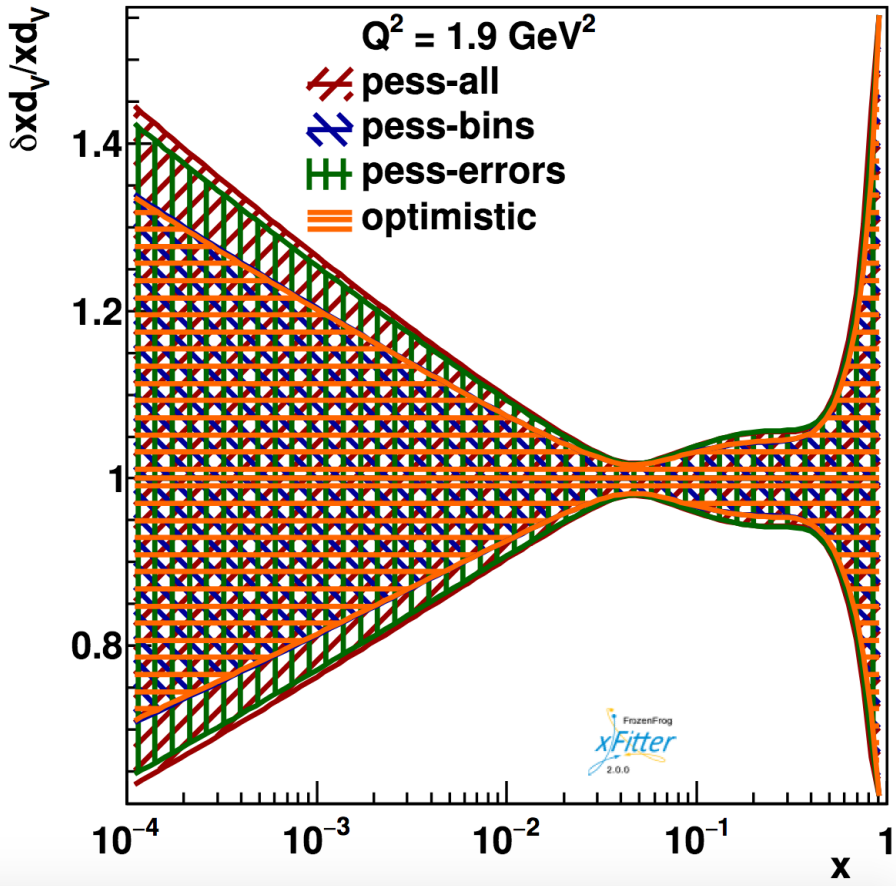
Impact of CC

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



Pessimistic option – what matters for PDFs?

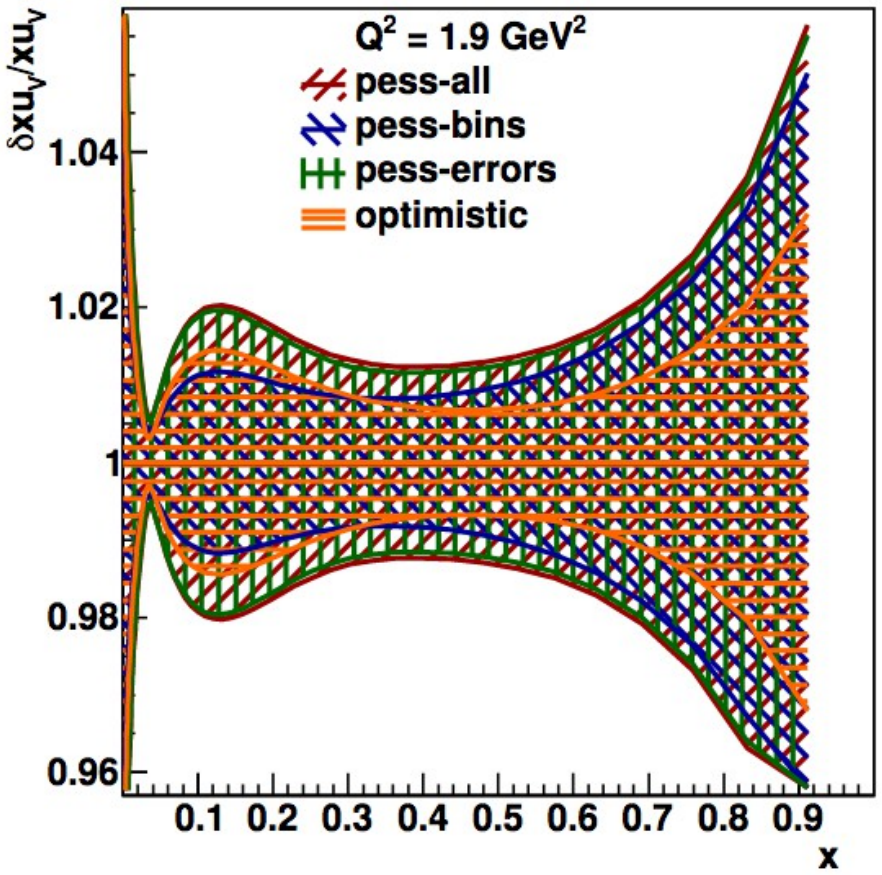


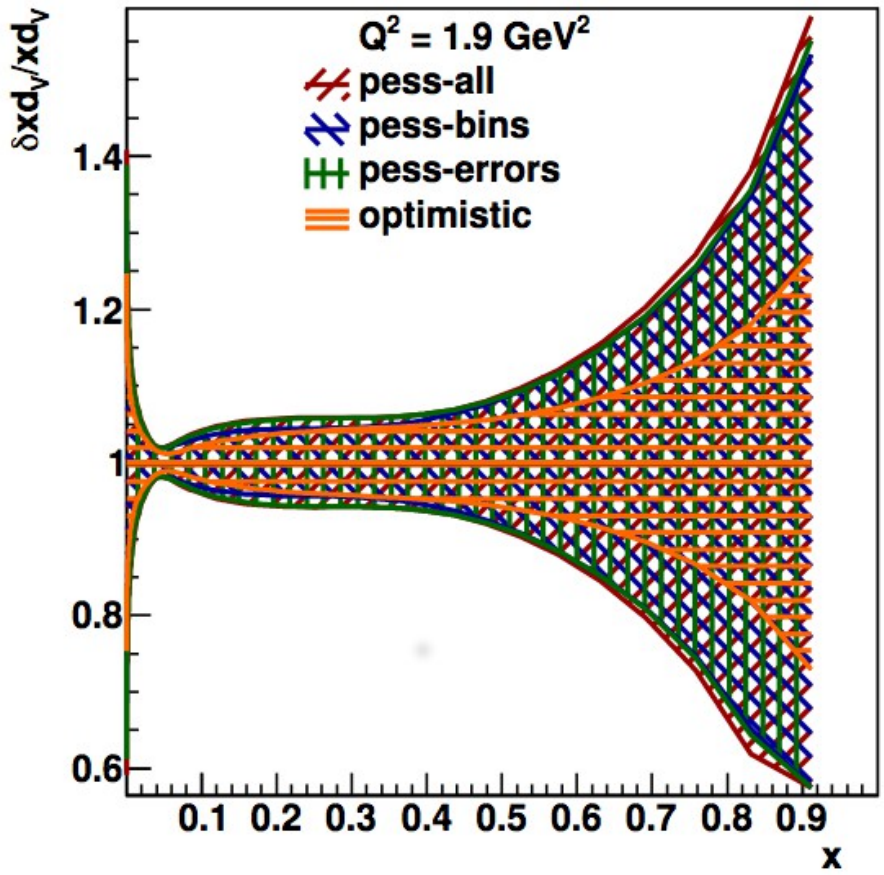


- At low & middle x bins are not cut out in pessimistic version

→ impact on uncertainties comes from decreased precision of data

Pessimistic option – what matters for PDFs?





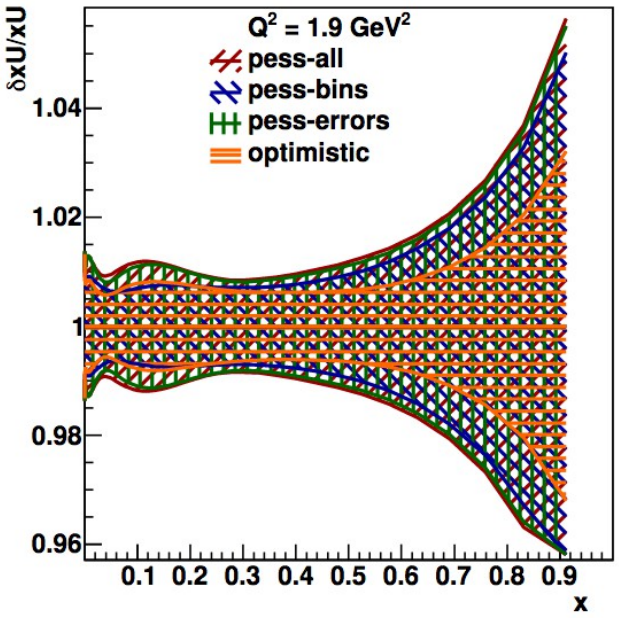
- At high x and low Q^2 <u>bins are cut out</u> in pessimistic version

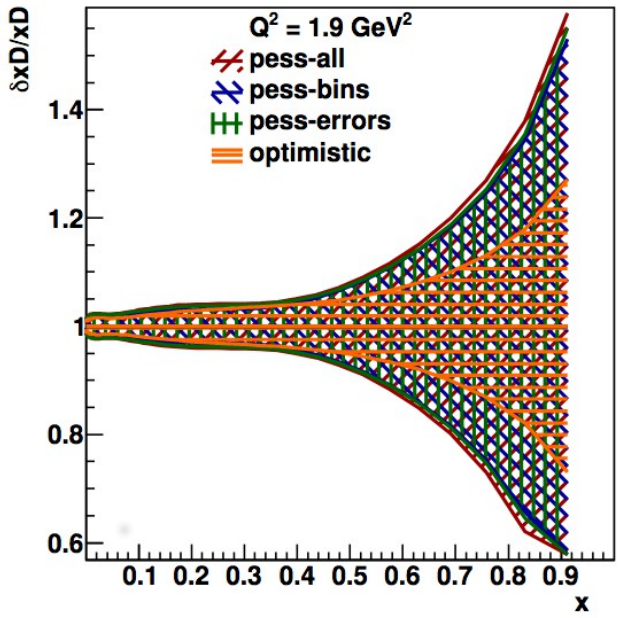
→ similar impact on valence quarks from cut-out bins and increased uncertainties

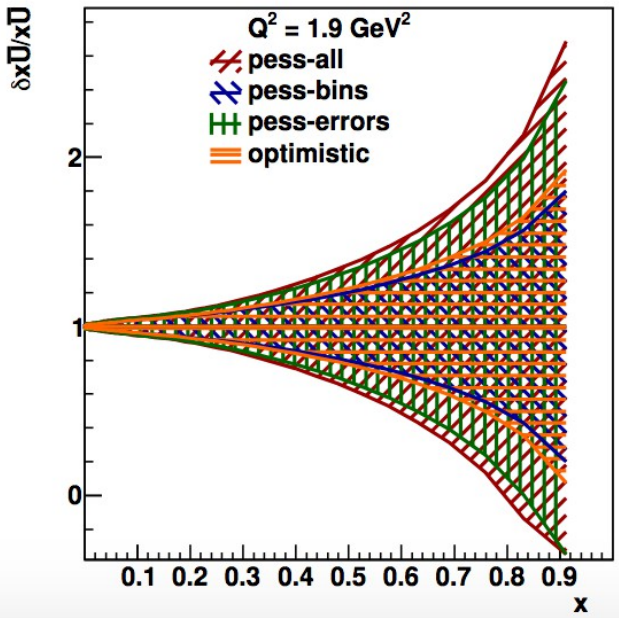
Brief summary / Outlook

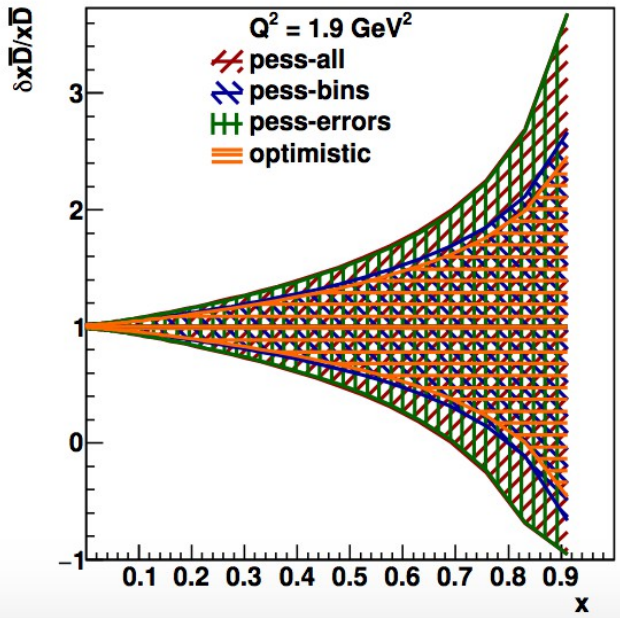
- Impact of ATHENA data on PDF precision can be studied in a clean way using HERAPDF2.0 approach
- Preliminary studies using EIC yellow report numbers show clear huge improvement of PDF uncertainties at high x and also at low&mid x
- This kind of studies can be repeated with various assumptions on data 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

Pessimistic option – what matters for PDFs?



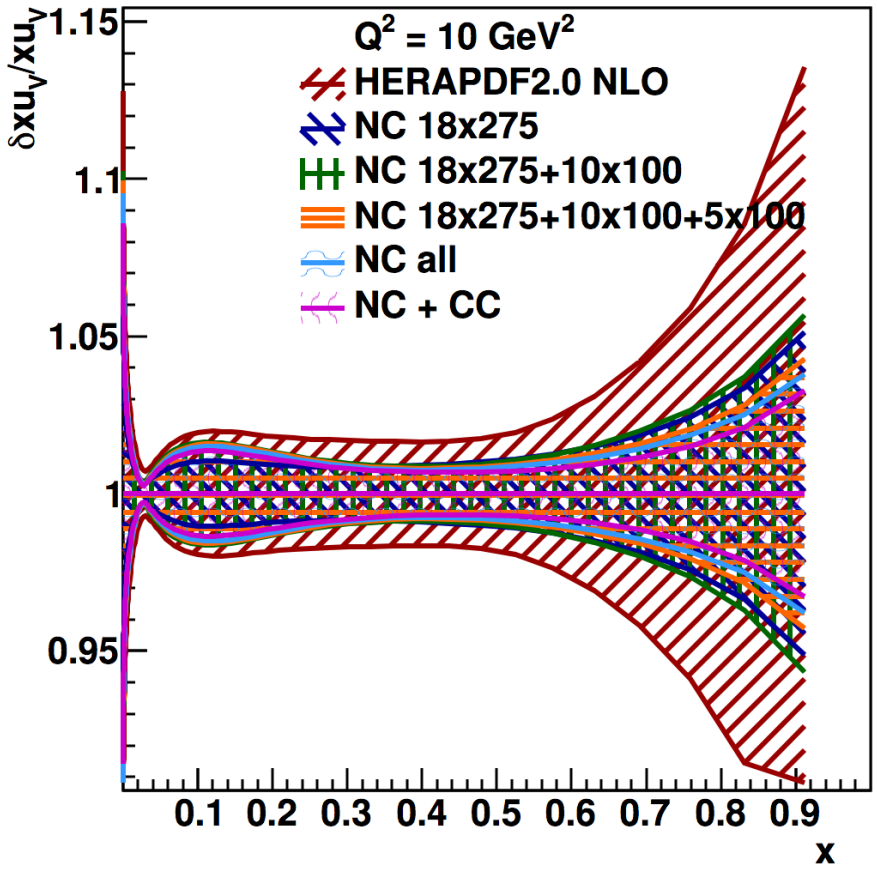


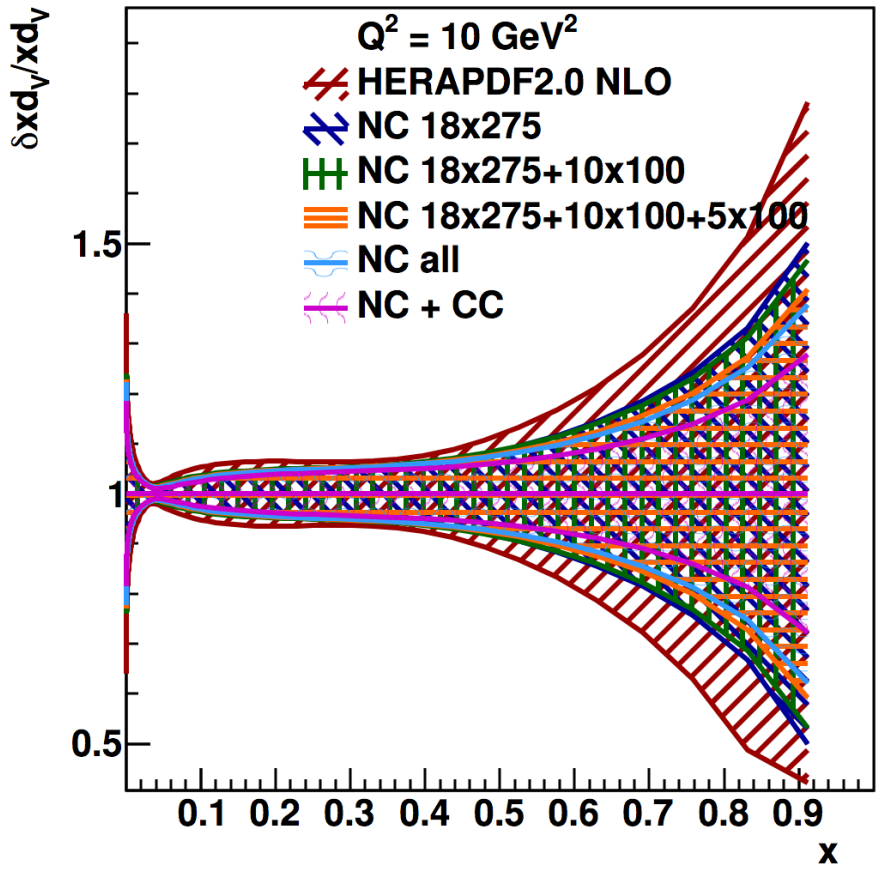




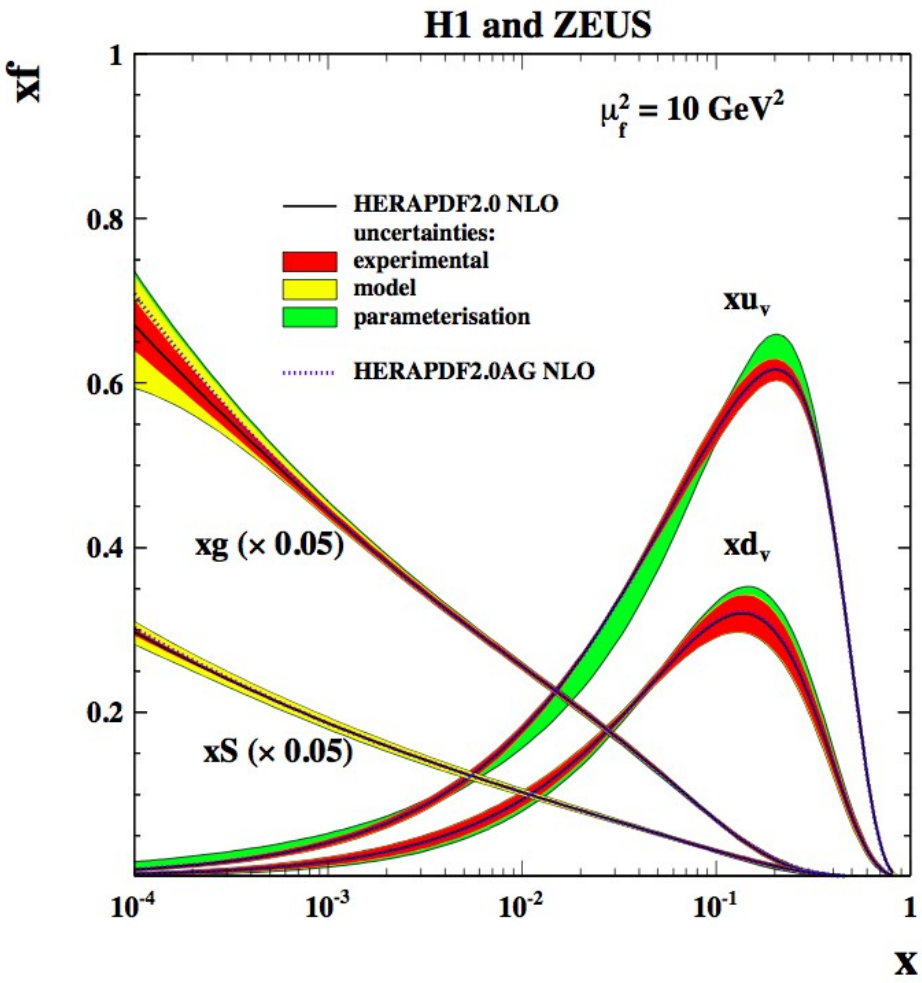
- At high x and low Q^2 <u>bins are cut out</u> in pessimistic version
  → similar impact on quarks from cut-out bins and increased uncertainties
  → no impact of cut-out bins on anti-quarks
- Quite surprising, I need to understand this

Cumulative impact - high x





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