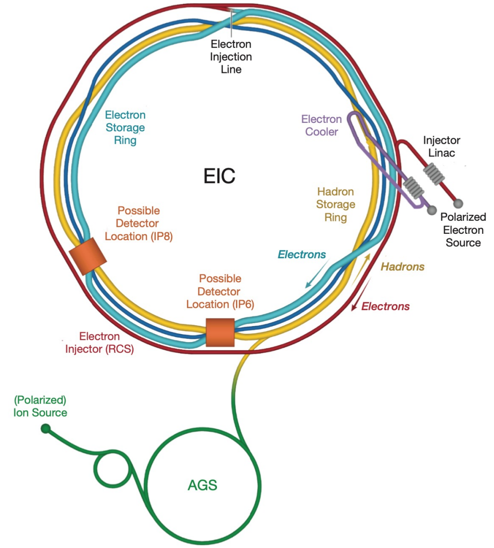
# Proton and Nuclear Collinear Parton Densities at the Electron-Ion Collider using simulated ATHENA data




DIS'22 (Santiago de Compostela)
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Paul Newman (Birmingham)
with
Nestor Armesto (Santiago de Compostela), Tom Cridge (UCL London),
Francesco Giuli (CERN), Lucian Harland-Lang (Oxford),
Barak Schmookler (UC Riverside), Robert Thorne (UCL London),
Katarzyna Wichmann (DESY), Qinghua Xu (Shandong)

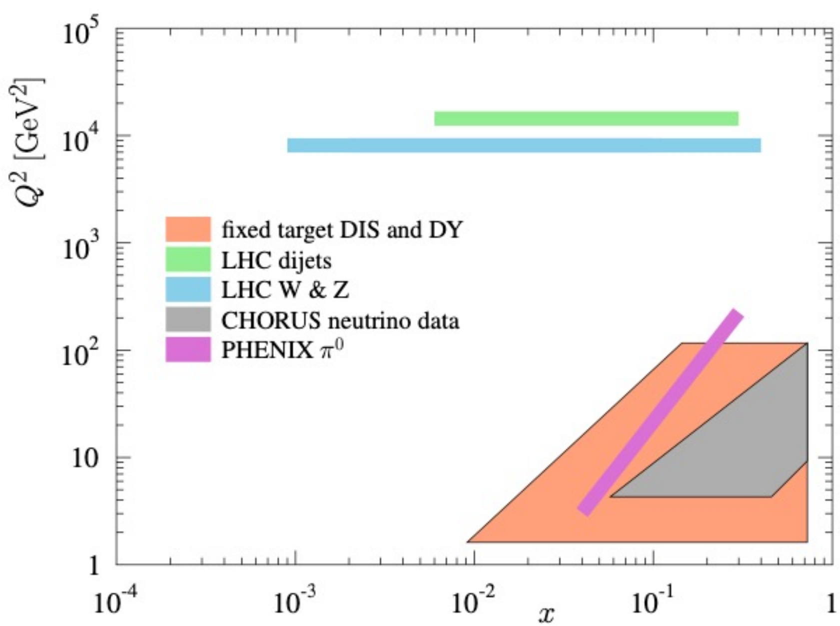
… with thanks to all colleagues who worked on the ATHENA proposal

# Collinear PDFs and the EIC

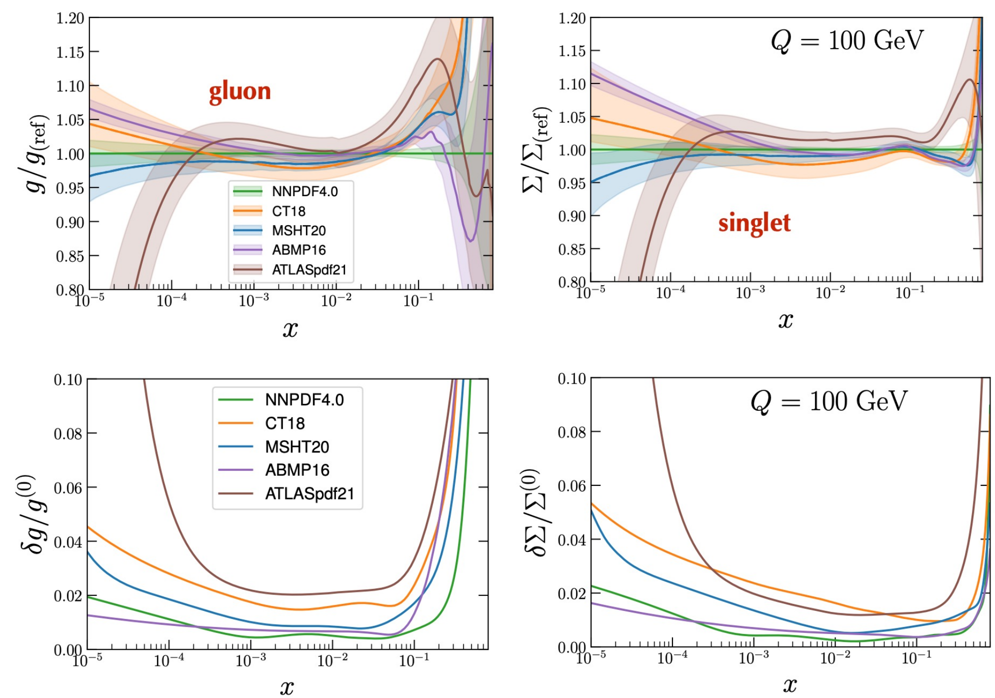
- EIC will be world's first … - eA collider
  - High lumi ep Collider
  - Polarised target collider

[Talks by T Kutz, B Schmookler]

- Here, explore potential EIC impact on our knowledge of unpolarised collinear eA and ep parton densities.




Input data to EPPS16 Nuclear PDFs



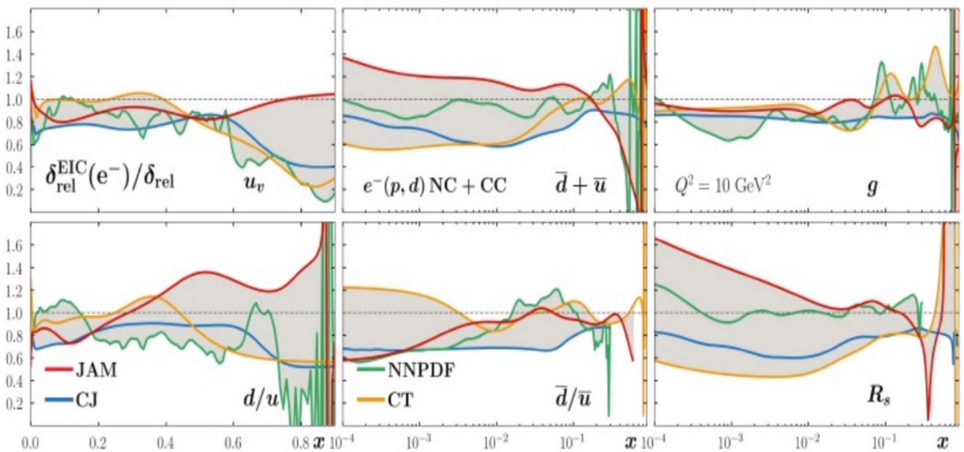

Comparison between global Proton PDF fits

[Talk by Jun Gao]

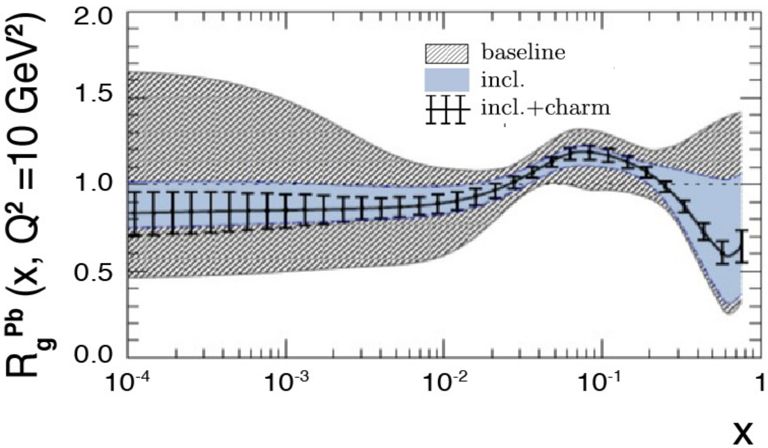
# Previous Work

- Several groups previously investigated EIC sensitivity to collinear PDFs, most recently in the context of the 2020/21 Yellow Report

Proton PDFs [arXiv:2103.05419]




Nuclear PDFs
[PRD 96 (2017) 114005]




- Studies here are closely related, but more up-to-date on planned datasets at different $\sqrt{s}$ and backed up by much more detailed detector simulations

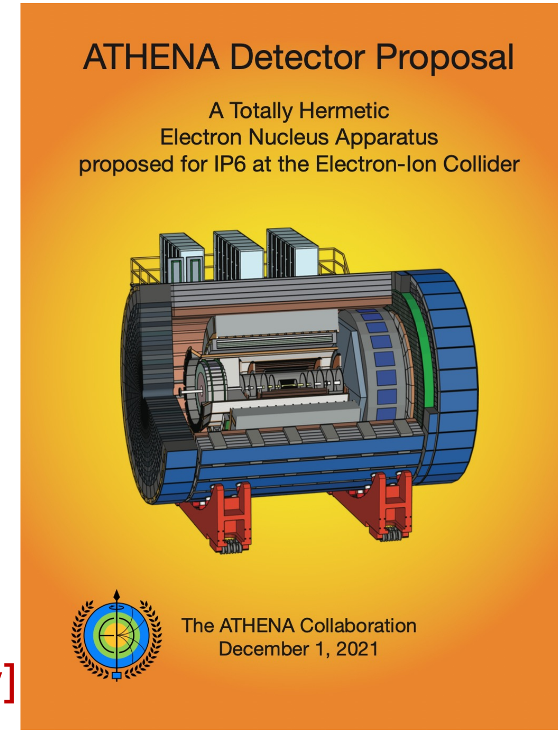
- They also introduce new global and non-global PDF fitting techniques.

# ATHENA @ EIC

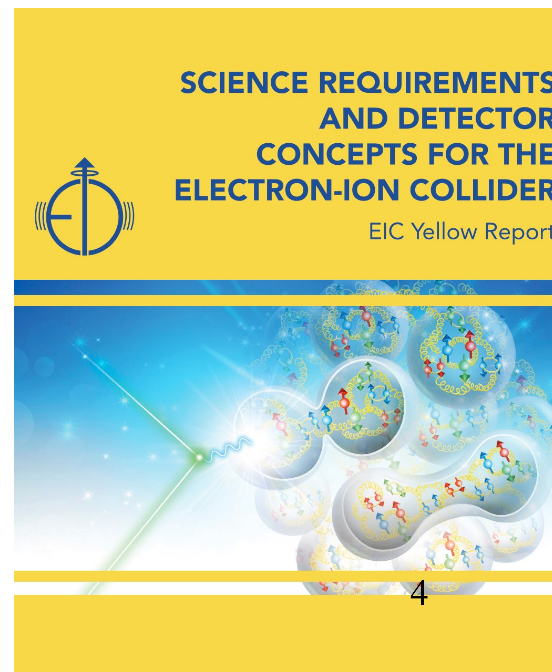
- ATHENA was one of three detector proposals for the EIC (publication in JINST pending).

- Input data here based on simulated ATHENA performance (acceptance, resolutions, systematics), building on studies in Yellow Report

[Talk by B Surrow]

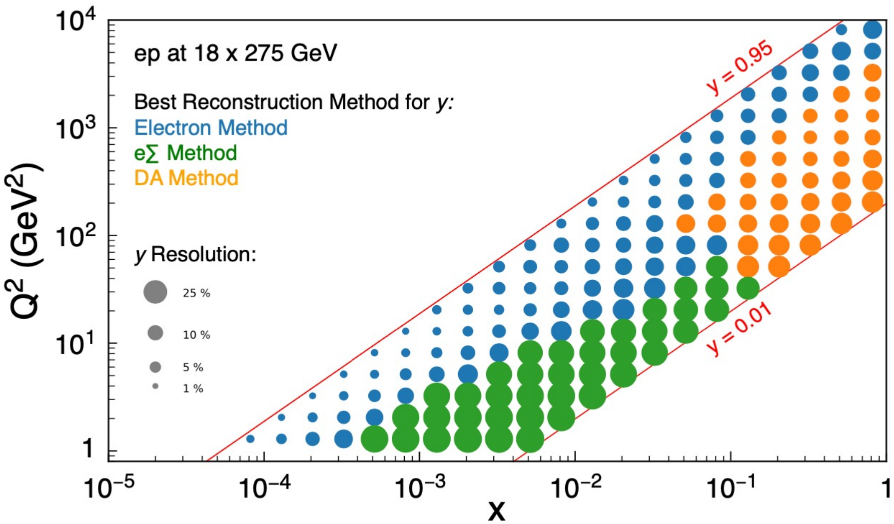



- Results here more-or-less equally applicable to any EIC general purpose detector (similar studies were done in ECCE context)

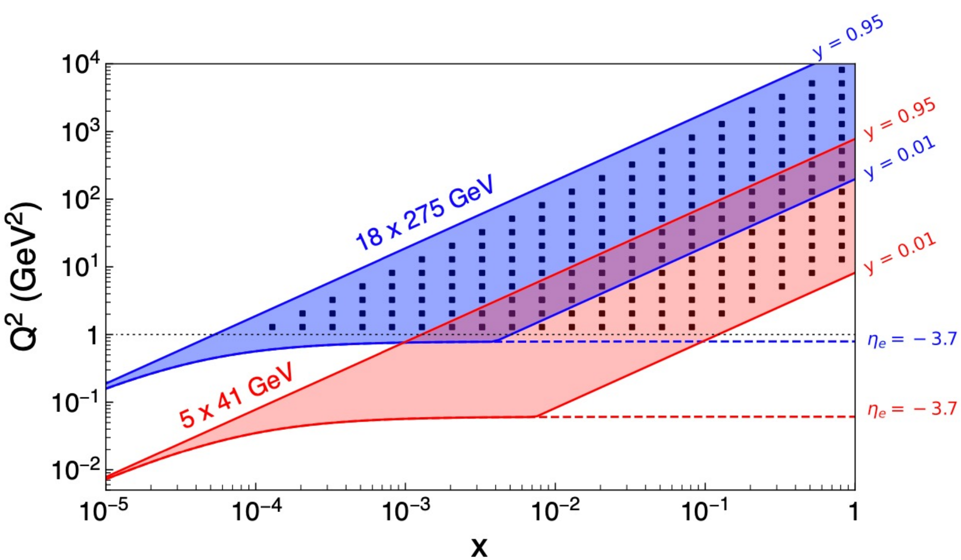



- Ongoing process to combine ATHENA with ECCE proposals → towards the EIC `project detector', as well as ongoing discussions about a second EIC detector

# Input Data (ep)




[Poster by S Maple]




- Detailed simulation work to optimise resolutions throughout phase-space
→ 5 bins per decade in x and $Q^2$

- Kinematic coverage: $Q^2$ > 1 $GeV^2$, 0.01 < y < 0.95, W > 3 GeV

- Lower y accessible in principle, but easier to rely on overlaps between data at different $\sqrt{s}$

- Highest x bin centre at x=0.815

| e-beam E | p-beam E | $\sqrt{s}$ (GeV) | inte. Lumi. ($fb^{-1}$) |
|---|---|---|---|
| 18 | 275 | 140 | 15.4 |
| 10 | 275 | 105 | 100.0 |
| 10 | 100 | 63 | 79.0 |
| 5 | 100 | 45 | 61.0 |
| 5 | 41 | 29 | 4.4 |

- CC data also included for highest $\sqrt{s}$

# Input Data (eA)

Similar approach for eA … Per-nucleon integrated luminosities:

| | |
|---|---|
| **5 x 41GeV:** | **4.4 $fb^{-1}$** |
| **10 x 110GeV:** | **79 $fb^{-1}$** |
| **18 x 110GeV:** | **79 $fb^{-1}$** |

# Systematic Precision

- Dominant sources at HERA were
  - Electron energy scale (intermediate y)
  - Photoproduction background (high y)
  - Hadronic energy scale / noise (low y)

- EIC will improve in all areas (e.g. dedicated ATHENA particle ID detectors allow $\pi$/e contamination at $10^{-6}$ level at low momenta)

- ATHENA systematic precision compatible with assumptions in Yellow report:

  → **1.5-2.5% point-to-point uncorrelated**
  → **2.5% normalisation (uncorrelated between different $\sqrt{s}$ )**

# Investigating impact on PDF sets: Fitting procedure

1) Get prediction from PDF set for each ATHENA pseudodata ($x$-$Q^2$) point

2) Smear pseudodata with uncorrelated uncertainties point-by-point

3) Smear pseudodata with normalisation systematic uncertainty at each $\sqrt{s}$

4) Perform fit with standard input data plus ATHENA data

5) Compare uncertainties with those from fit without ATHENA data

# Impact on HERAPDF2.0 Proton PDFs

- \`DIS-only', HERA (or HERA+EIC/ATHENA) data

[EPJ C75 (2015) 580
Takl by K Wichmann]

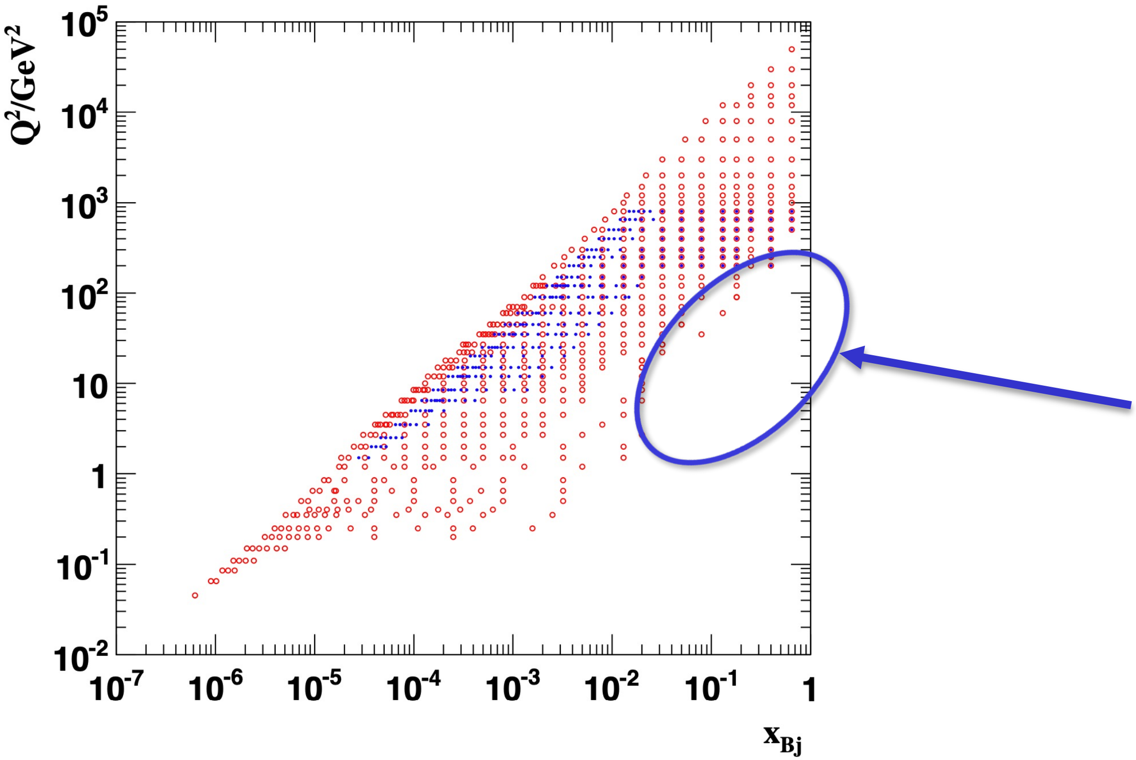
- Using xFitter framework [EPJ C75 (2015) 304
Talk by F Giuli,]

- PDF parameterisations (14 parameters)

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2) \text{ ... for ...}$$

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

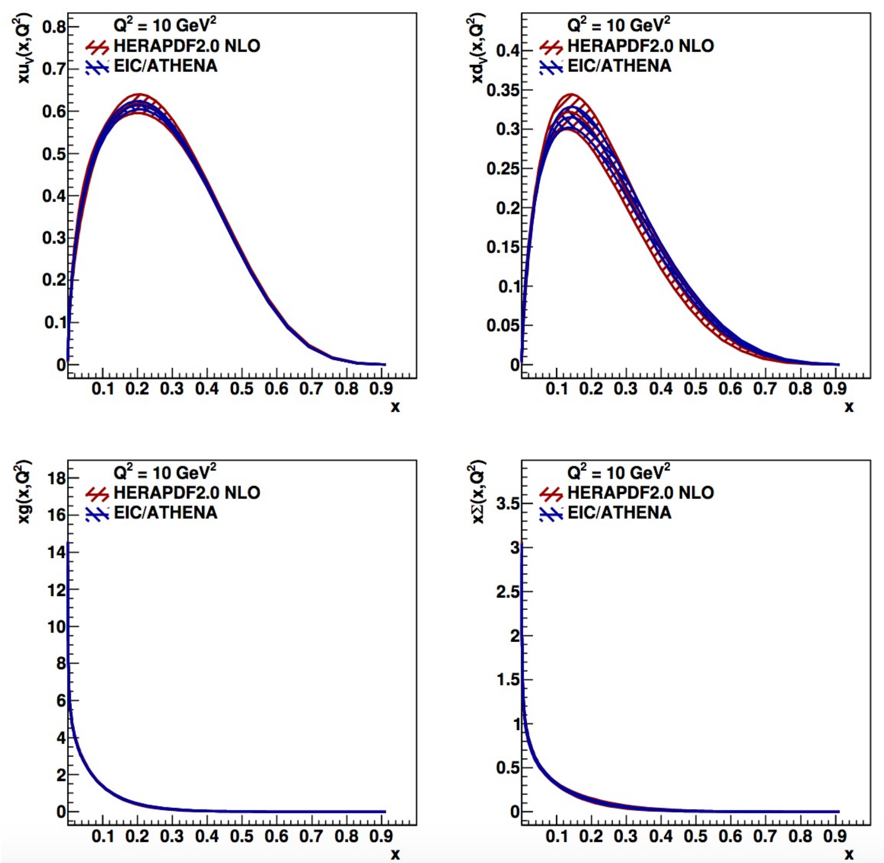
| Variation | Standard Value |
|---|---|
| $Q^2_{\mathrm{min}}$ [GeV$^2$] | 3.5 |
| $Q^2_{\mathrm{min}}$ [GeV$^2$] HiQ2 | 10.0 |
| $M_c$(NLO) [GeV] | 1.47 |
| $M_c$ (NNLO) [GeV] | 1.43 |
| $M_b$ [GeV] | 4.5 |
| $f_s$ | 0.4 |
| $\alpha_s(M_Z^2)$ | 0.118 |
| $\mu_{f_0}$ [GeV] | 1.9 |




HERA data have limited high x sensitivity due to kinematic correlation between x and $Q^2$ and $1/Q^4$ factor in cross section

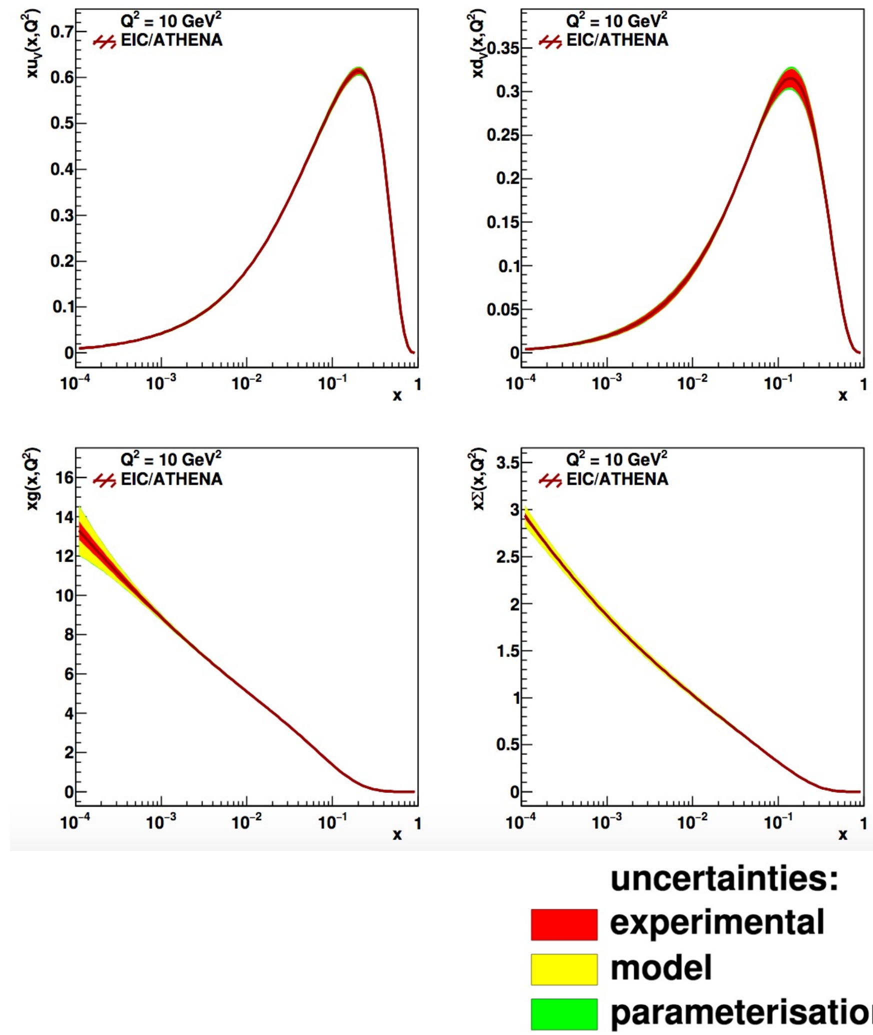
# PDFs from HERAPDF2.0 ($Q^2$ = 10 GeV$^2$)

[Linear x scale]




[Total uncertainties]

[Logarithmic x scale]





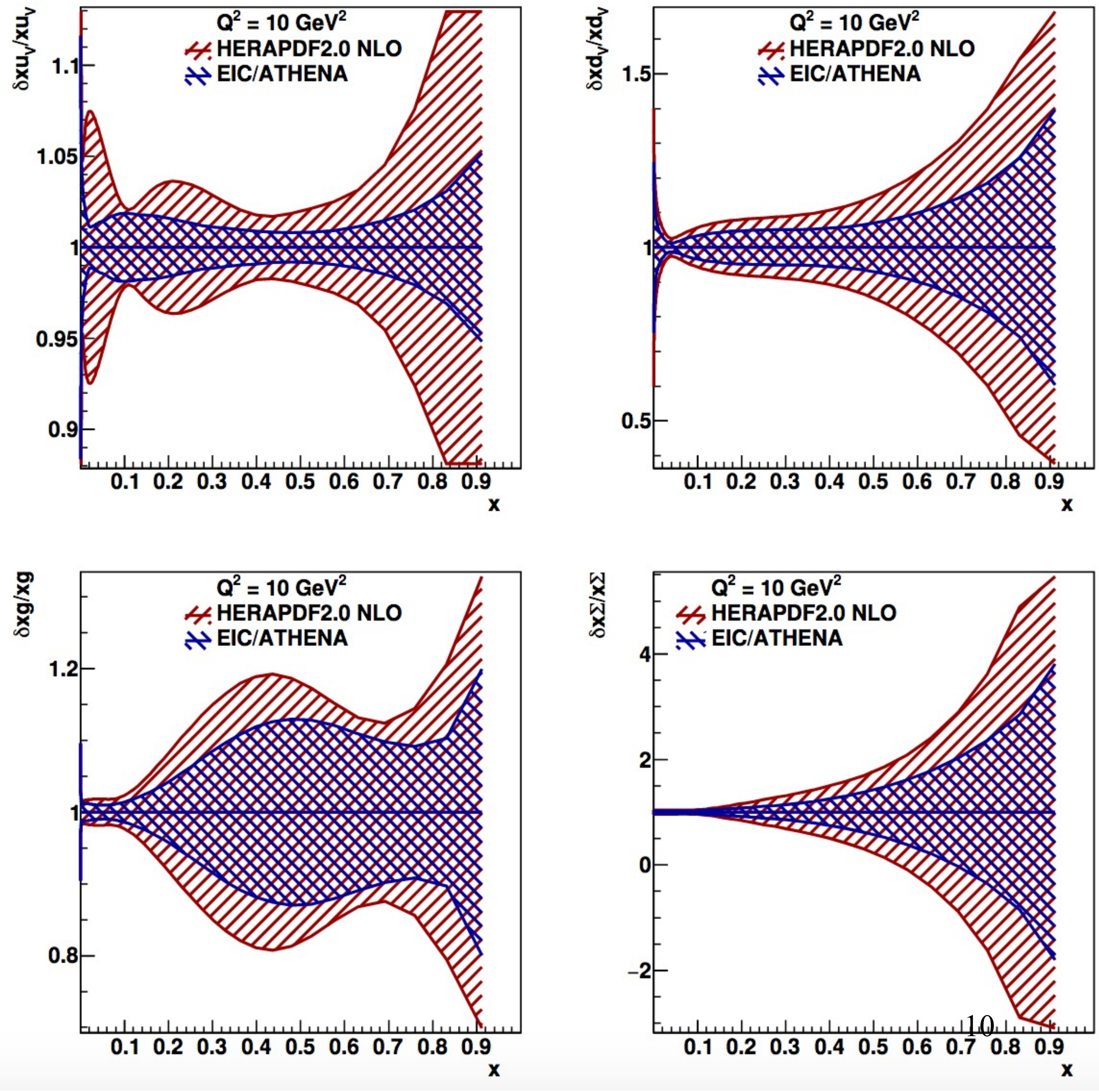

By construction, PDFs not changed by adding ATHENA data

# Impact of EIC/ATHENA on HERAPDF2.0

Fractional total uncertainties with / without EIC / ATHENA data included along with HERA

(linear x scale)

… EIC will bring significant reduction in uncertainties for all parton species at large x



# Impact of EIC/ATHENA on HERAPDF2.0

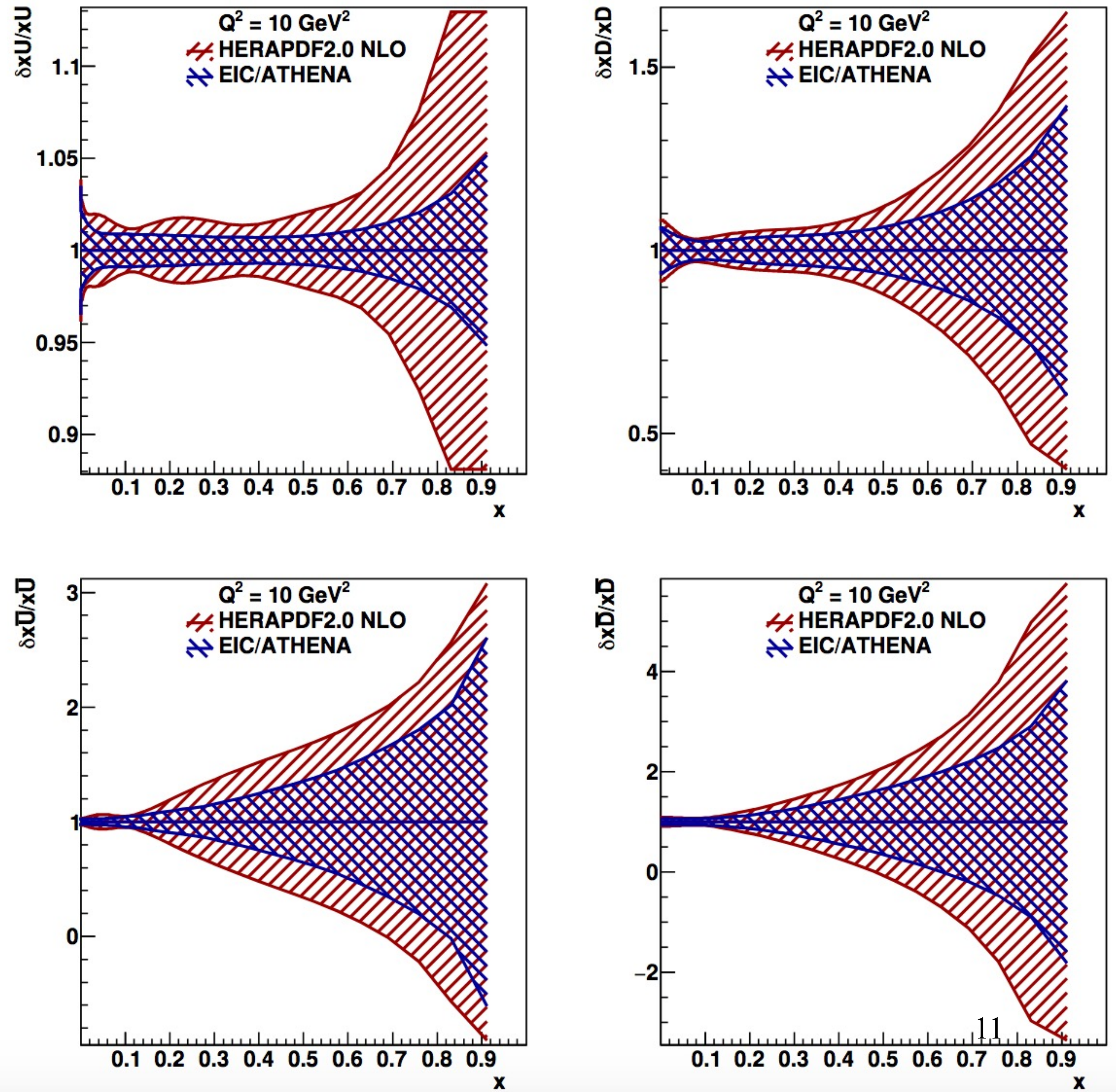
Same again, but in standard HERAPDF parameterisation:

$$xU = xu + xc$$

$$x\bar{U} = x\bar{u} + x\bar{c}$$

$$xD = xd + xs$$

$$x\bar{D} = x\bar{d} + x\bar{s}$$



# Impact relative to Global Fits

- Global fits connstrain high x region with fixed-target (eA) DIS + PDF-sensitive LHC data → improves precision, but adds theoretical complexity, requiring increased tolerances where there are tensions

## MSHT20

[EPJ C81 (2021) 4
Talk by L Harland-Lang]

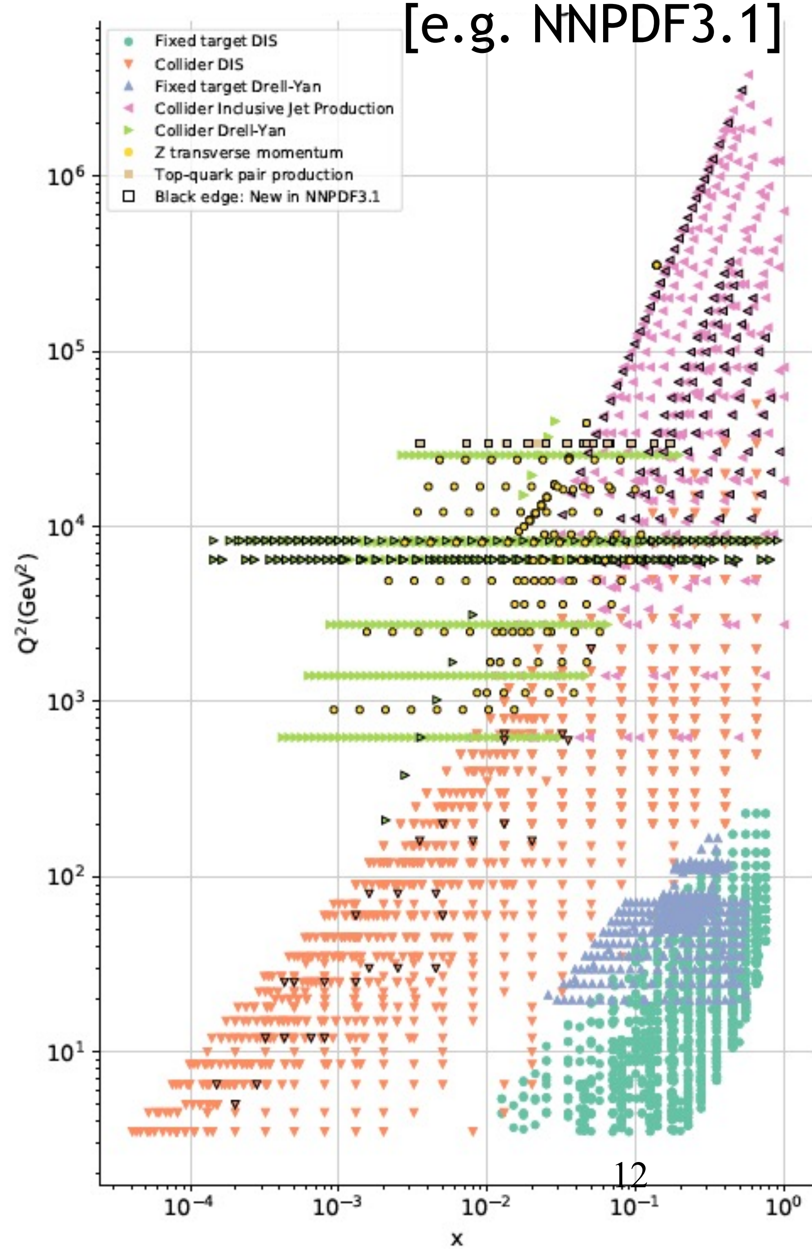
- Parameterisations using Chebyshev polynomials (52 parameters in total)

$$xf(x, Q_0^2) = A(1-x)^\eta x^\delta \left(1 + \sum_{i=1}^{n} a_i T_i^{\mathrm{Ch}}(y(x))\right)$$

- Data with $Q^2 > 2$ GeV$^2$, $W^2 > 15$ GeV$^2$

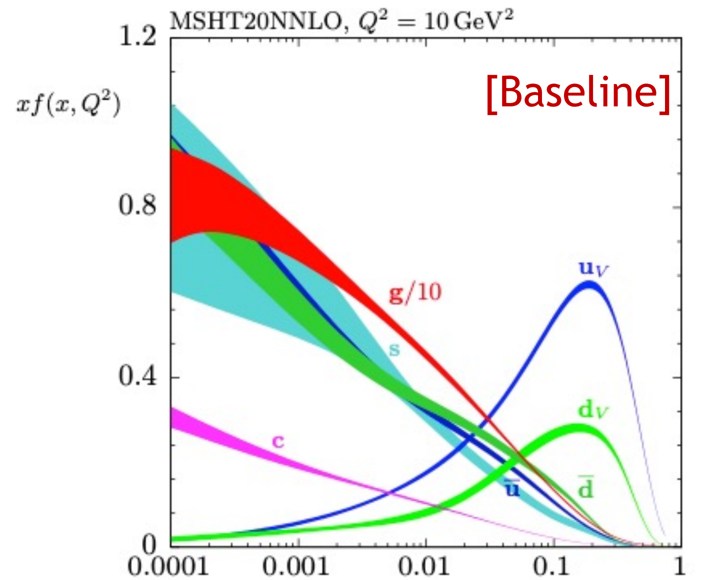
- $m_c = 1.40$ GeV, $m_b = 4.75$ GeV,
  $\alpha_s = 1.118$, starting scale $\mu_{f0} = 1.0$ GeV

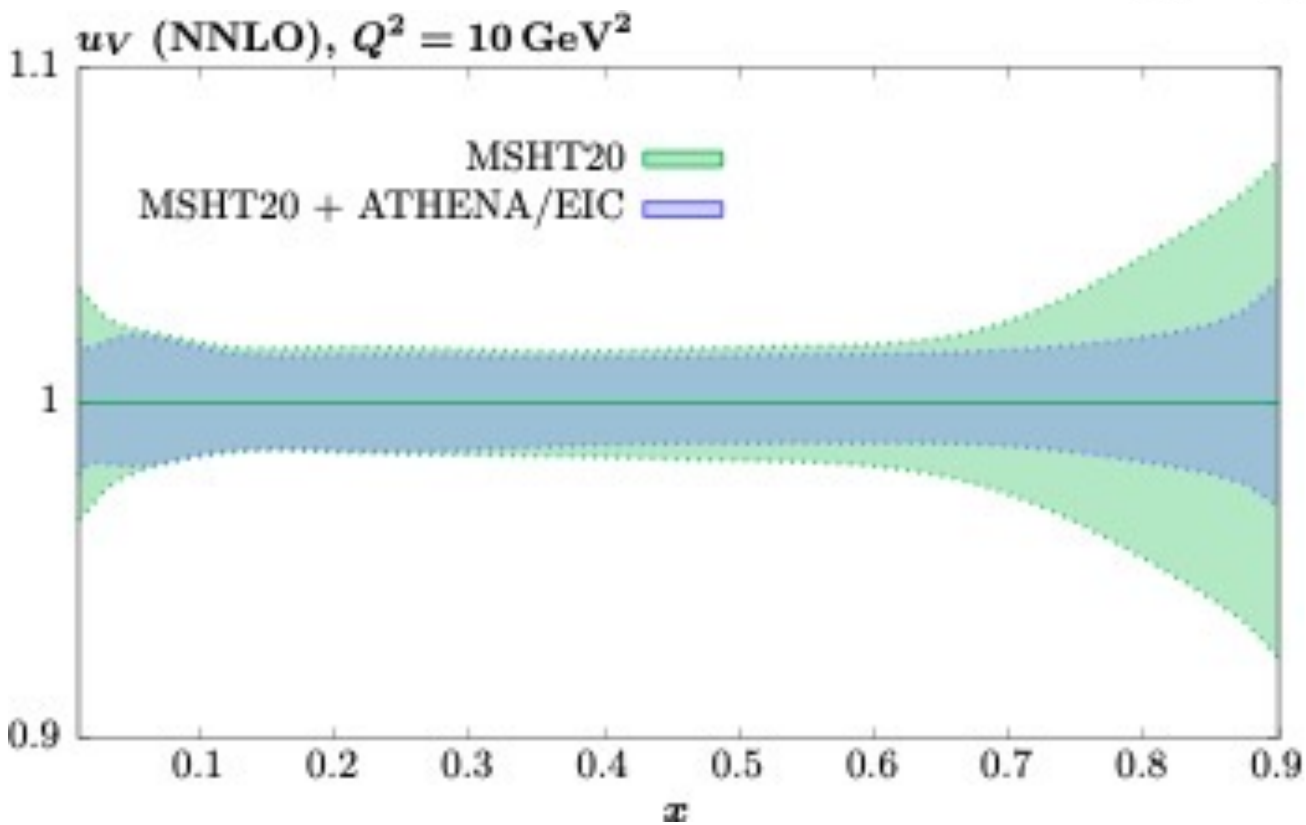
[e.g. NNPDF3.1]



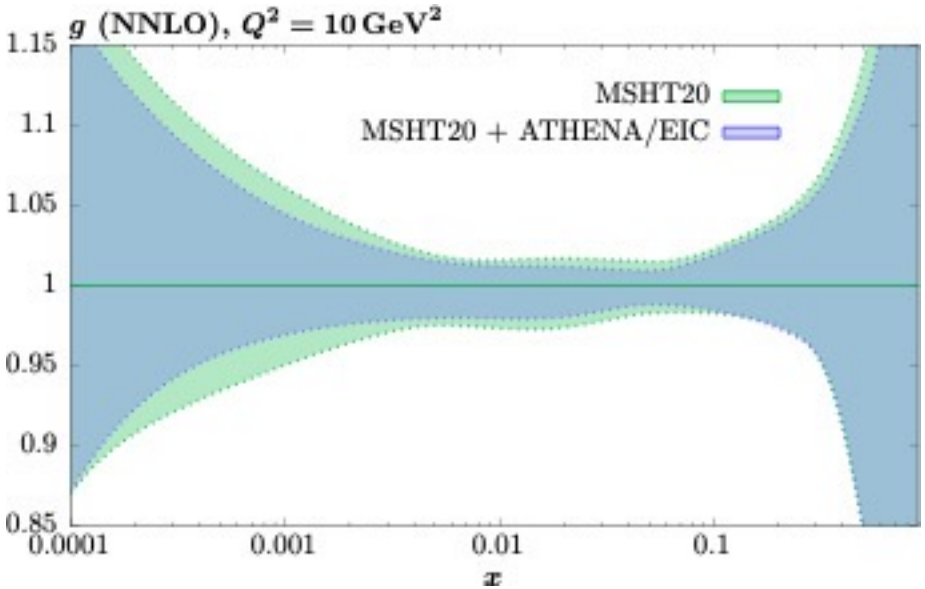
# Impact relative to MSHT20 (NNLO)

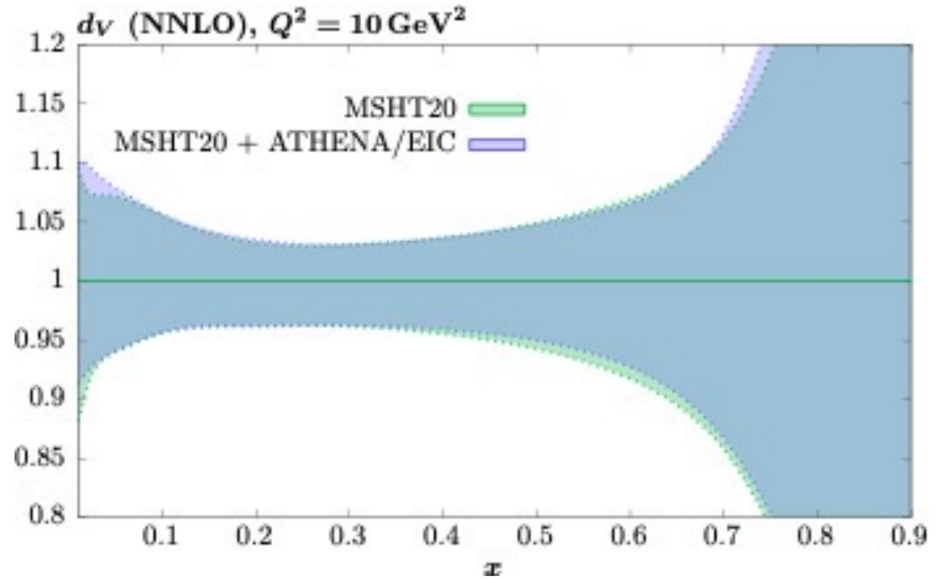
Significant impact of EIC/ATHENA data in up quark precision as x→1 (charge-squared weighting)

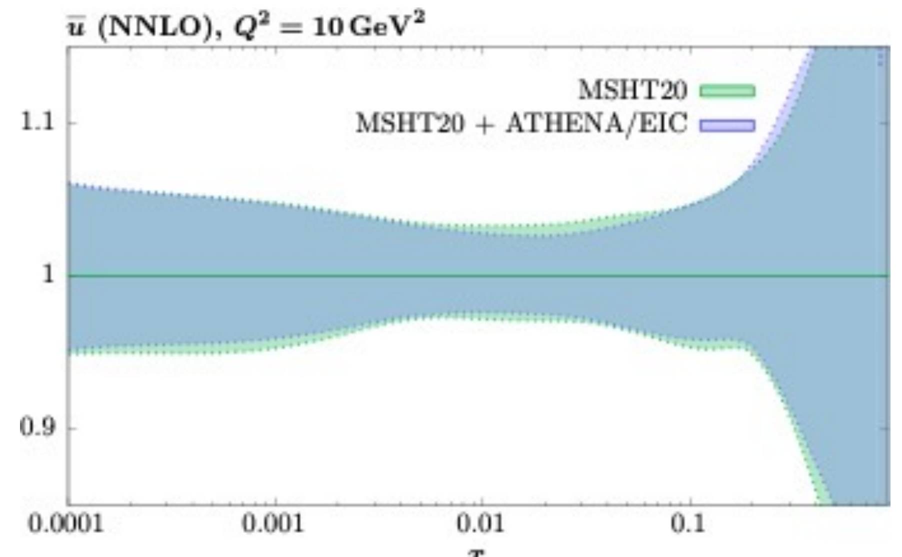


# Impact relative to MSHT20



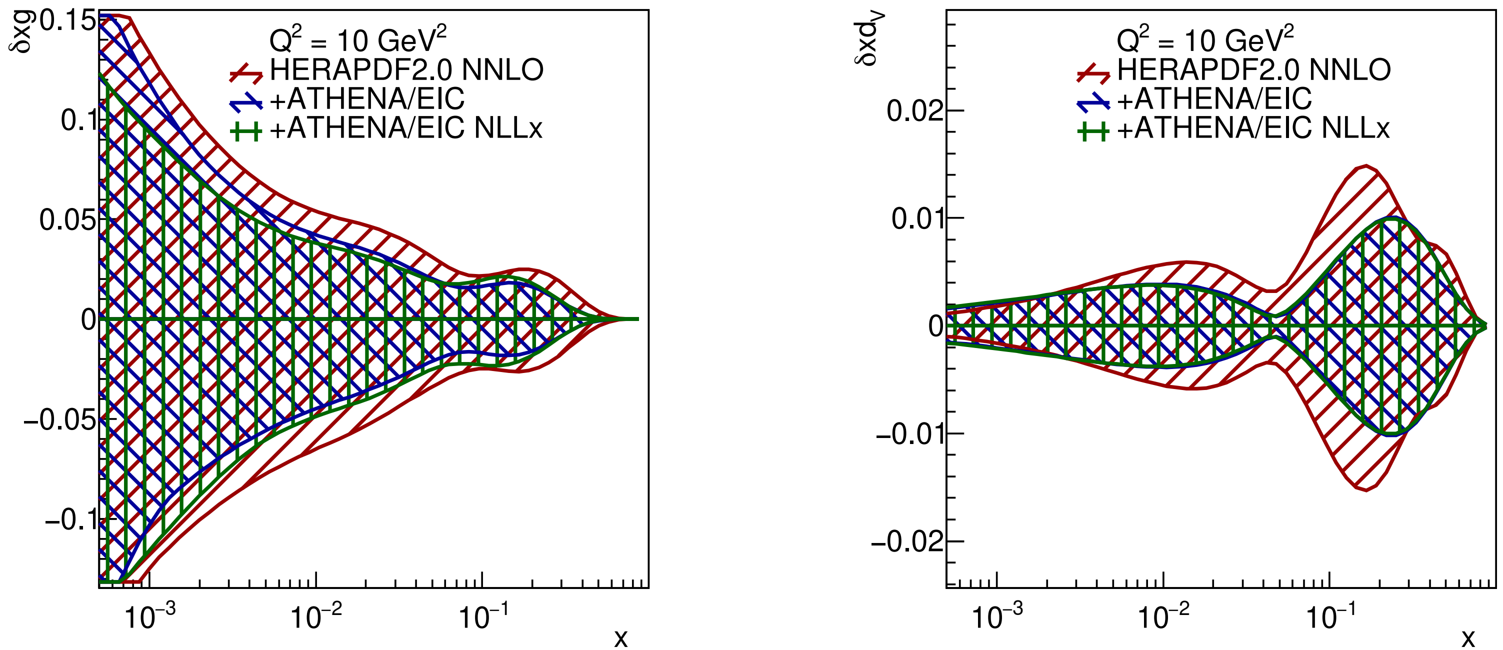




Small, but valuable improvements in all parton species at all x, $Q^2$, notably the gluon

# Sensitivity to Low x Effects in ep?

- HERAPDF fits repeated with inclusion of log(1/x) resummation in simulated data and for fitting (NLLx via HELLx+APFEL, starting from $Q^2$ = 2.5 GeV$^2$)

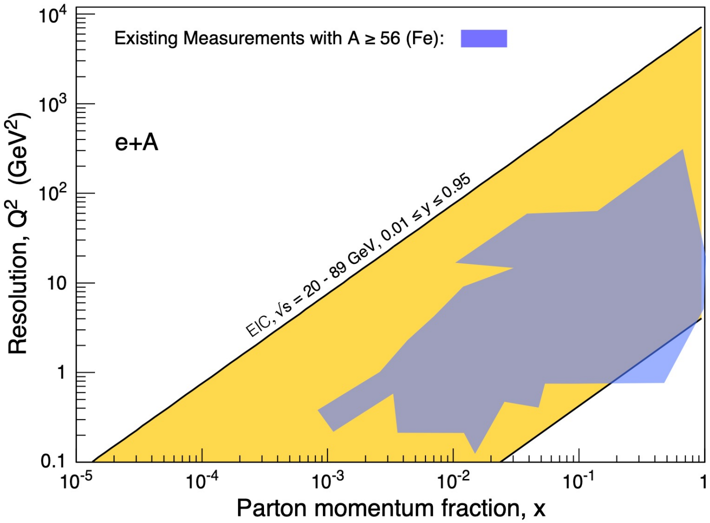



- EIC/ATHENA gives mild effect on gluon uncertainty at low x. Other PDFs unaffected

- Little or no sensitivity in ep data, due to restricted low x kinematic range compared with HERA

- Similar studies with nuclear targets will be interesting …

# EIC / ATHENA and nuclear PDFs




EIC will have revolutionary impact on eA phase space: → most promising environment to observe novel low x effects

Studies performed in xFitter framework to assess sensitivity of ATHENA relative to EPPS16

# EPPS16 [EPJ C77 (2017) 163]

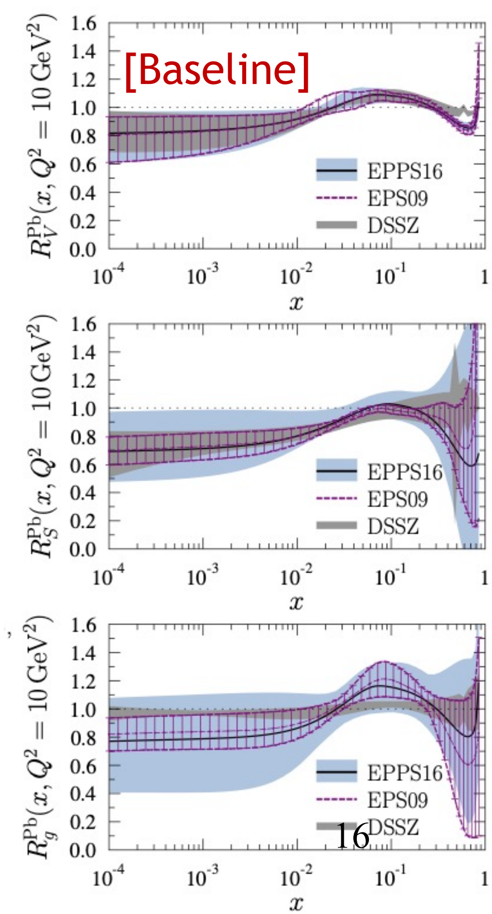
- Uses fixed target DIS and Drell-Yan data, hard processes from pA at the LHC and PHENIX $\pi^0$ data

$$f_i^{\mathrm{p}/A}(x,Q^2) = R_i^A(x,Q^2) f_i^{\mathrm{p}}(x,Q^2)$$

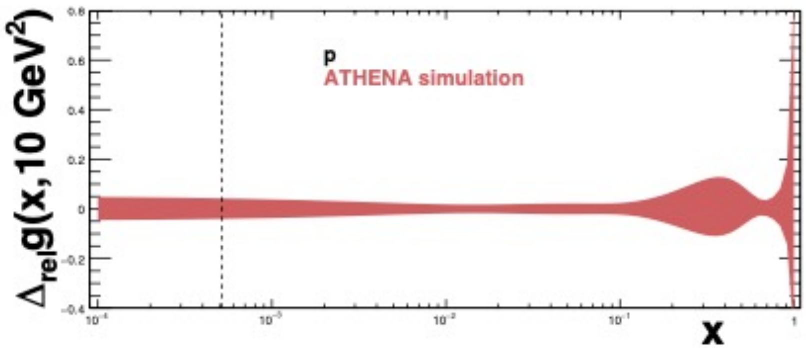
20 free params:

$$R_i^A(x,Q_0^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1, \end{cases}$$

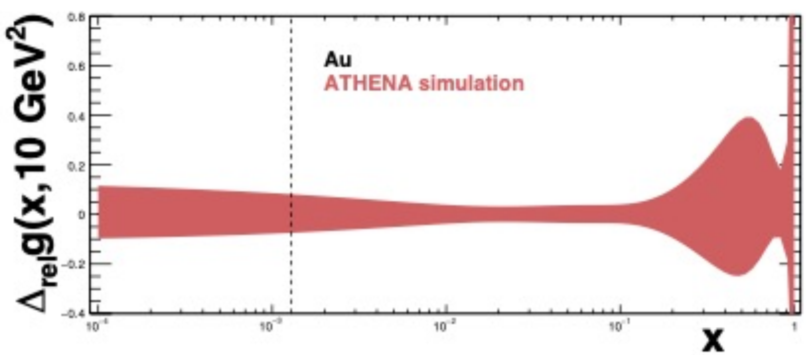
$\mu_{f0} = m_c = 1.3$ GeV, $m_b = 4.75$ GeV, $\alpha_s = 1.118$



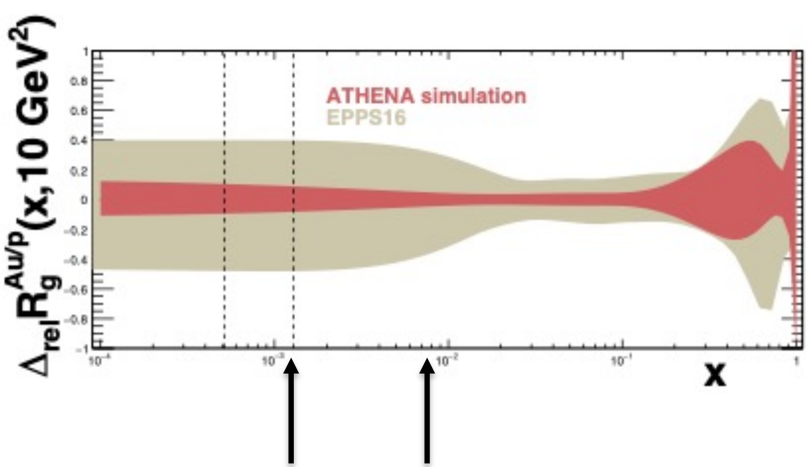
# Impact on Nuclear PDFs: Gluon




Projected uncertainty
on gluon density of proton
from ATHENA-only fit




Projected uncertainty
on gluon density of (gold) nucleus
from ATHENA-only fit → ~10%




EIC eA data limit

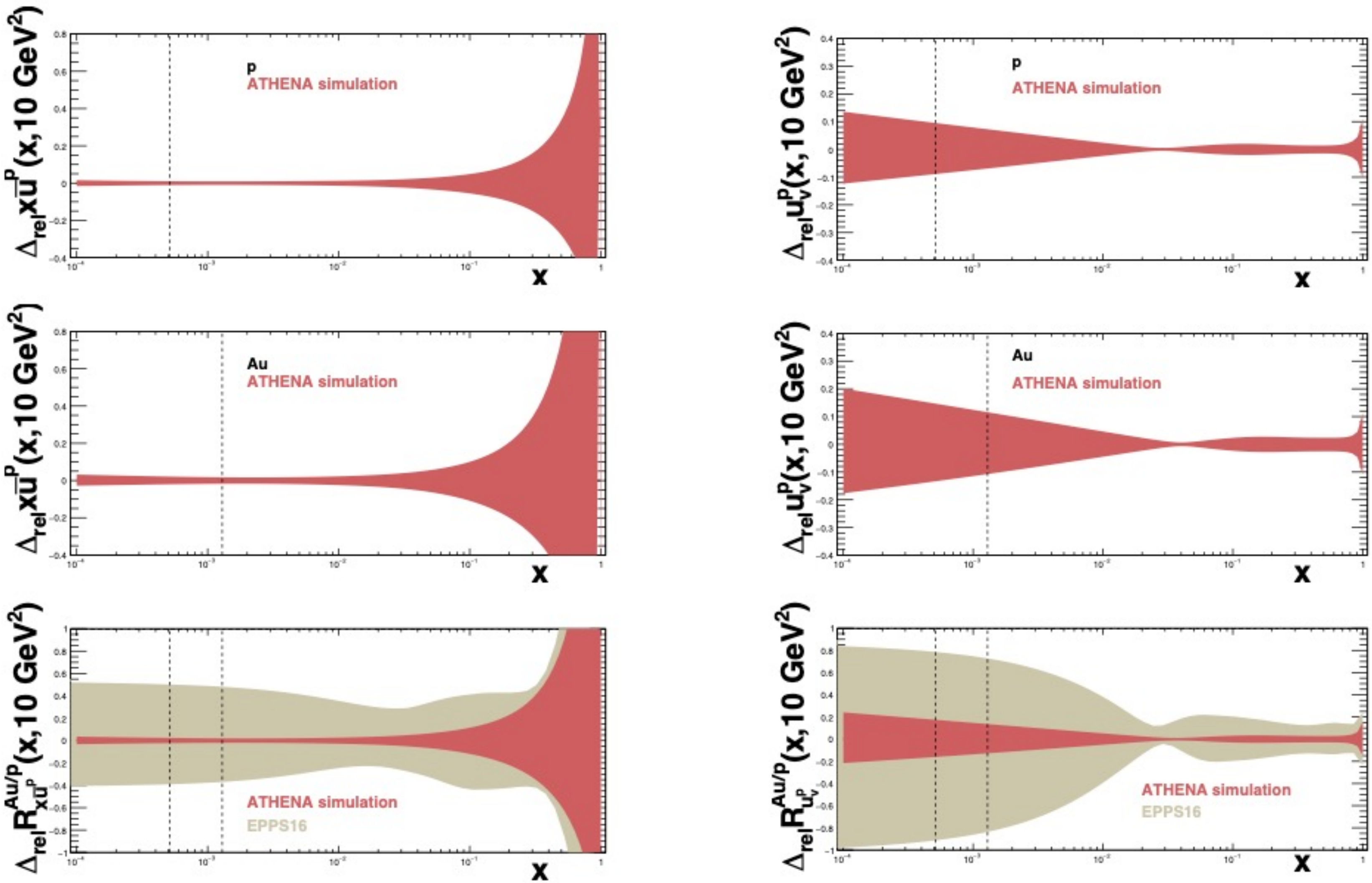
EPPS16 data limit

Projected uncertainty on nuclear modification factor, ATHENA-only compared with EPPS'16

→ Factor ~ 2 improvement at x~0.1 (tolerances)

→ Very substantial improvement in newly accessed low x region

# Impact on Nuclear PDFs: ubar and $u_v$




Similarly compelling improvements at low x for quark distributions

# Summary

**General Purpose Detectors at the Electron Ion Collider will provide transformational input to collinear parton densities with wide-ranging impact**

- eA measurements in the low x region for the first time
  → Knowledge of nuclear PDFs (especially gluon) in the low x region
  → Key to EIC physics programme of exploring new strong interaction dynamics in densely packed gluon systems.

- Precise ep data in large x region covering wide range of large(ish) $Q^2$:
  → Precision on all proton PDF species from an experimentally and theoretically cleaner DIS-only extraction
  → Key to optimizing sensitivity to new BSM physics near to kinematic limit at the LHC and elsewhere