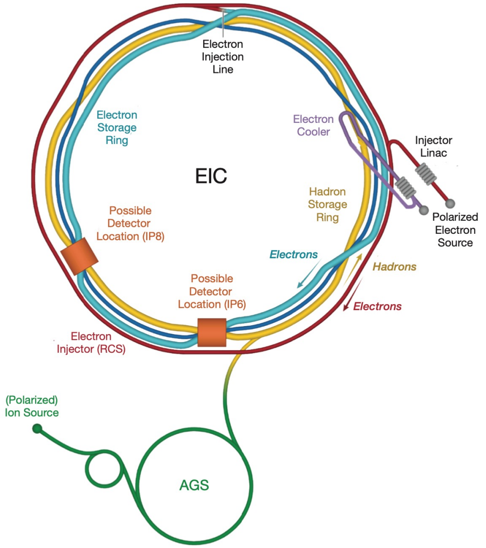
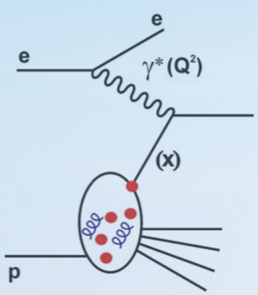
Potential of the Electron-Ion Collider to Constrain Parton Densities and the Strong Coupling





QCD@LHC’23 (Durham)
4-8 September 2023

Paul Newman (Birmingham)
and
Nestor Armesto (Santiago de Compostela), Salim Cerci (Adiyaman),
Tom Cridge (DESY), Zuhal Seyma Demiroglu (Stony Brook),
Abhay Deshpande (Stony Brook), Francesco Giuli (CERN),
Lucian Harland-Lang (UCL London), Barak Schmookler (UC Riverside),
Deniz Sunar Cerci (Adiyaman), Robert Thorne (UCL London),
Katarzyna Wichmann (DESY),

… with thanks to all colleagues who work towards realising the EIC

Contents

Impact of Inclusive Electron Ion Collider Data on Collinear Parton Distributions

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In litt.

Abstract

A study is presented of the impact of simulated inclusive Electron Ion Collider Deep Inelastic Scattering data on the determination of the proton and nuclear parton distribution functions (PDFs) at next-to-next-to-leading order in QCD. The influence on the proton PDFs is evaluated relative to the HERAPDF set, which uses inclusive HERA data only, and also relative to the global fitting approach of the MSHT PDFs. The impact on nuclear PDFs is assessed relative to the EPPS16 global fits and is presented in terms of the nuclear modification ratios. For all cases studied, significant improvements in the PDF uncertainties are observed for several parton species. The most striking impact occurs for the nuclear PDFs in general and for the region of high Bjorken x in the proton PDFs, particularly for the valence quark distributions.

Extraction of the strong coupling with HERA and EIC inclusive data

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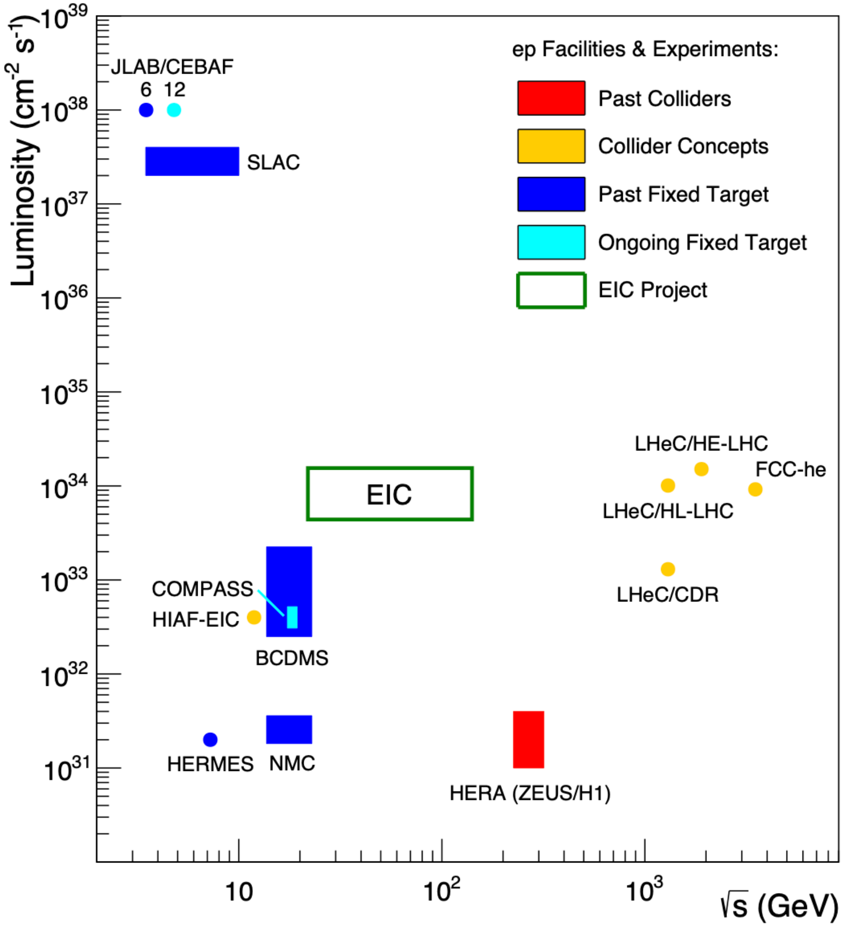
arXiv:2307.01183

Abstract

The sensitivity to the strong coupling $\alpha_S(M_Z^2)$ is investigated using existing Deep Inelastic Scattering data from HERA in combination with projected future measurements from the Electron Ion Collider (EIC) in a next-to-next-to-leading order QCD analysis. A potentially world-leading level of precision is achievable when combining simulated inclusive neutral current EIC data with inclusive charged and neutral current measurements from HERA, with or without the addition of HERA inclusive jet and dijet data. The result can be obtained with significantly less than one year of projected EIC data at the lower end of the EIC centre-of-mass energy range. Some questions remain over the magnitude of uncertainties due to missing higher orders in the theoretical framework.

The Electron-Ion Collider (BNL 2030++)



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

… its energy range will be roughly $30 < \sqrt{s} < 140$ GeV, accessing moderate-to-large x values by comparison with HERA

Physics targets include:

- 3D proton structure
- Proton mass
- Proton spin
- Dense partonic systems in nuclei

Here, explore potential EIC impact on 'conventional' analyses of unpolarised collinear ep and eA parton densities and on the strong coupling

Context of this work

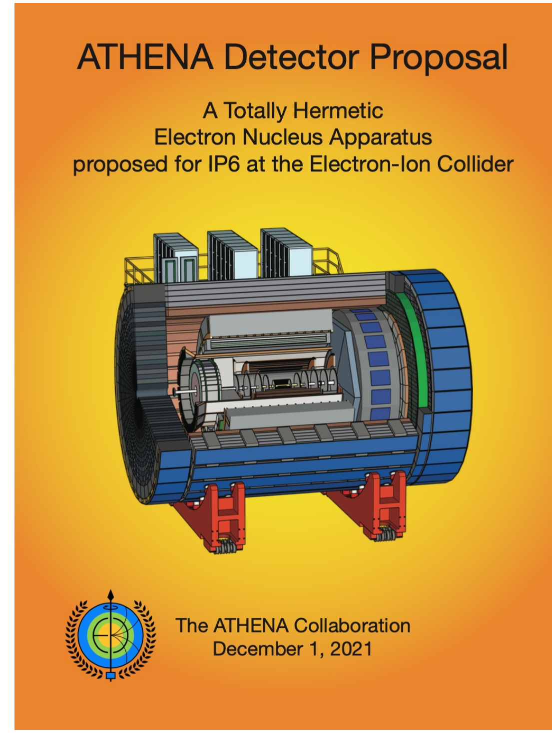
- Input data based on simulated performance (acceptance, resolutions, systematics) of the ATHENA detector design (JINST 17 P10019), building on studies in the earlier EIC Yellow Report (arXiv:2103.05419) and elsewhere.

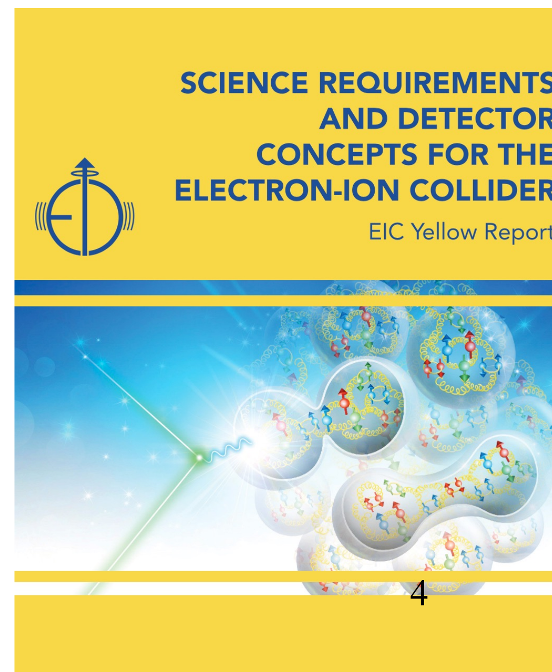
- Adding new techniques and more detailed simulations relative to previous studies (e.g. Phys Rev D96 (2017) 114005).

- ATHENA now merged with ECCE into a single EIC 'project detector' collaboration: 'ePIC'

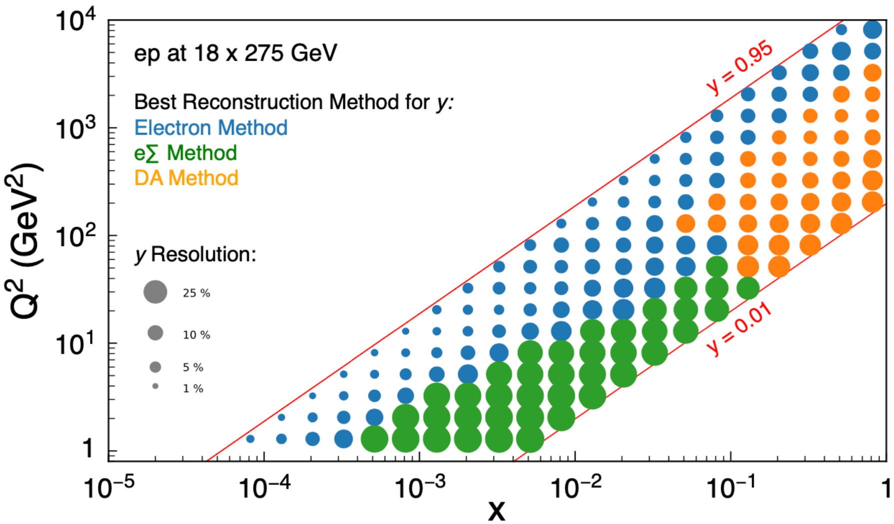
- Ongoing discussions about a second EIC detector

Results here are more-or-less equally applicable to any EIC general purpose detector





Input Data (ep)



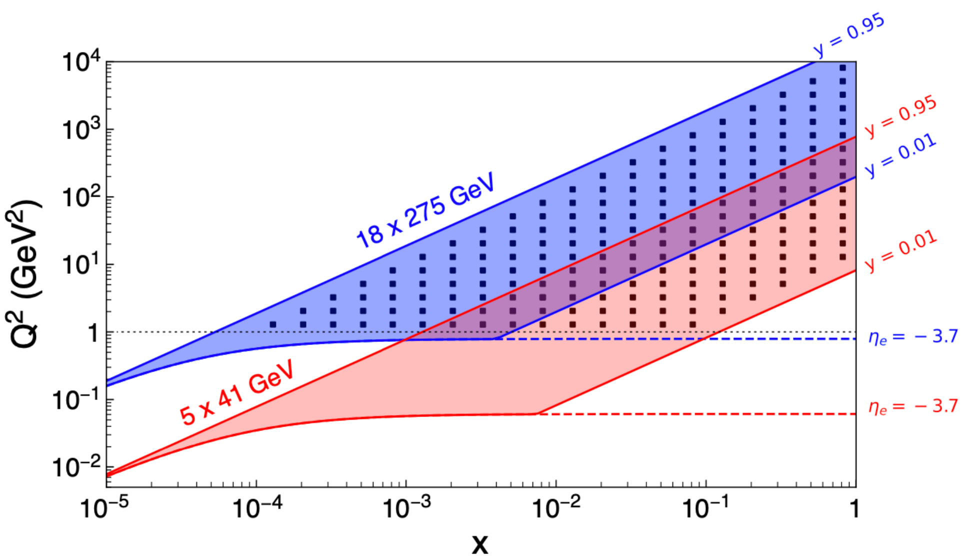
- Detailed simulation work to optimise resolutions throughout phase-space
→ 5 bins per decade in x and Q²

- Kinematic coverage:

$Q^2 > 1\ \mathrm{GeV}^2$,

$0.01 < y\ (= \frac{Q^2}{sx}) < 0.95$,

$W^2\ (= \frac{Q^2(1-x)}{x}) > 10\ \mathrm{GeV}^2$



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

- One nominal year of NC data at each of five beam energies:

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

- Highest x bin centre at x=0.815
- CC data also considered @ 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 particle ID detectors suppress π/e contamination to below 10^{-6} level at low momenta)

- Assumed systematic precision conservative compared with Yellow report:

→ 1.9% point-to-point uncorrelated (growing to 2.75% at low y)
→ 3.4% normalisation (uncorrelated between different $\sqrt{s}$)

Investigating impact on PDF fitting relative to existing sets

1) Get prediction from PDF set for each EIC 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 using existing method with standard input data plus EIC data

5) Compare uncertainties from fits with and without EIC data

Analyses carried out at NNLO for proton case and NLO for nuclei

Impact on HERAPDF2.0 Proton PDFs

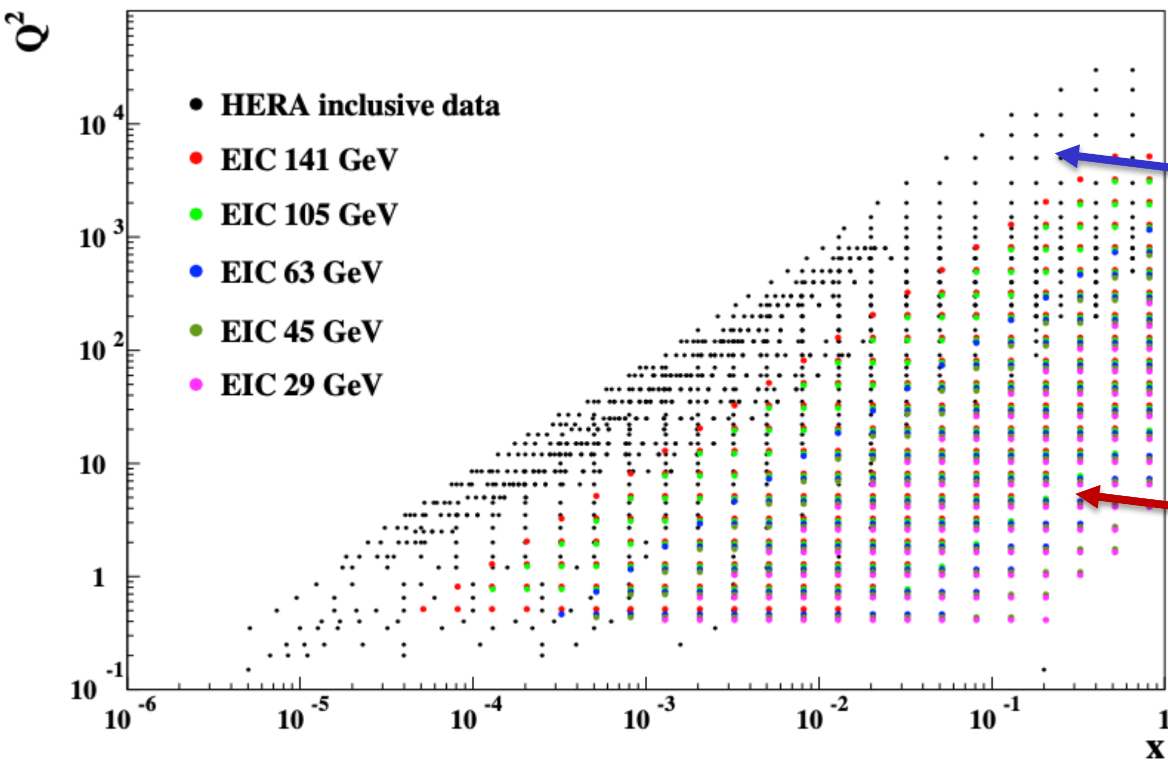
- `DIS-only', HERA (or HERA+EIC) data

- Using xFitter framework

- 14 free parameters for PDFs

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25}; \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right); \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}; \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right); \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- Q^2_{min} = 3.5 GeV^2
- M_c = 1.41 GeV
- M_b = 4.2 GeV
- f_s = 0.4
- Q^2_0 = 1.9 GeV^2

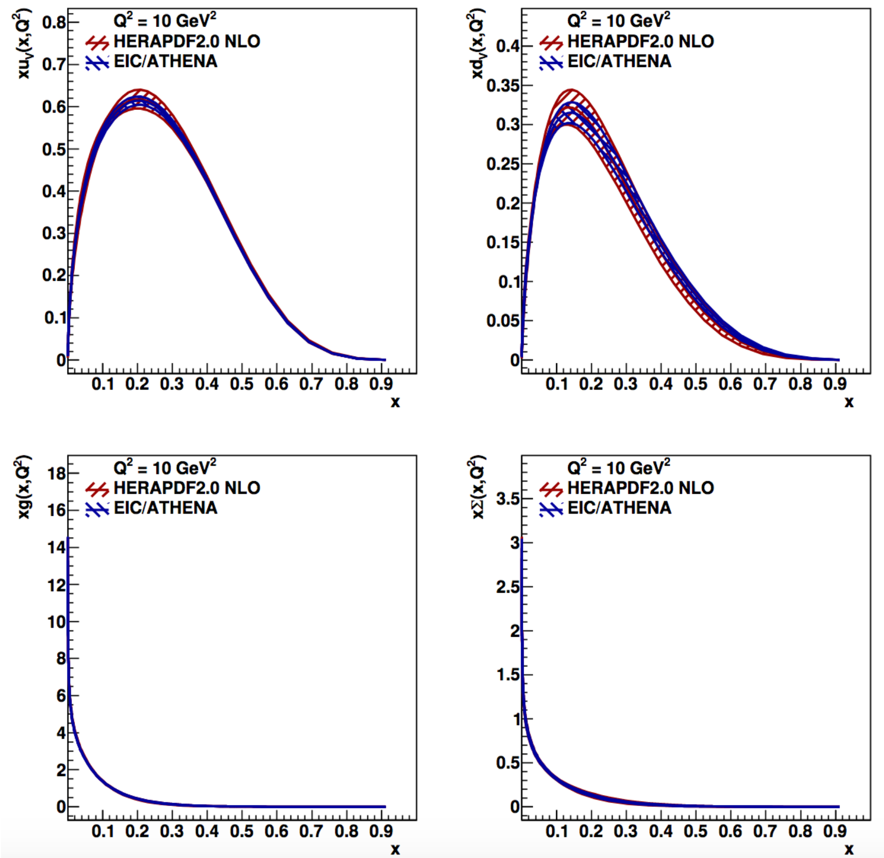


HERA data have limited high x sensitivity due to kinematic correlation between x and Q^2 and $1/Q^4$ factor in cross section

EIC data fills in large x, modest Q^2 region with high precision

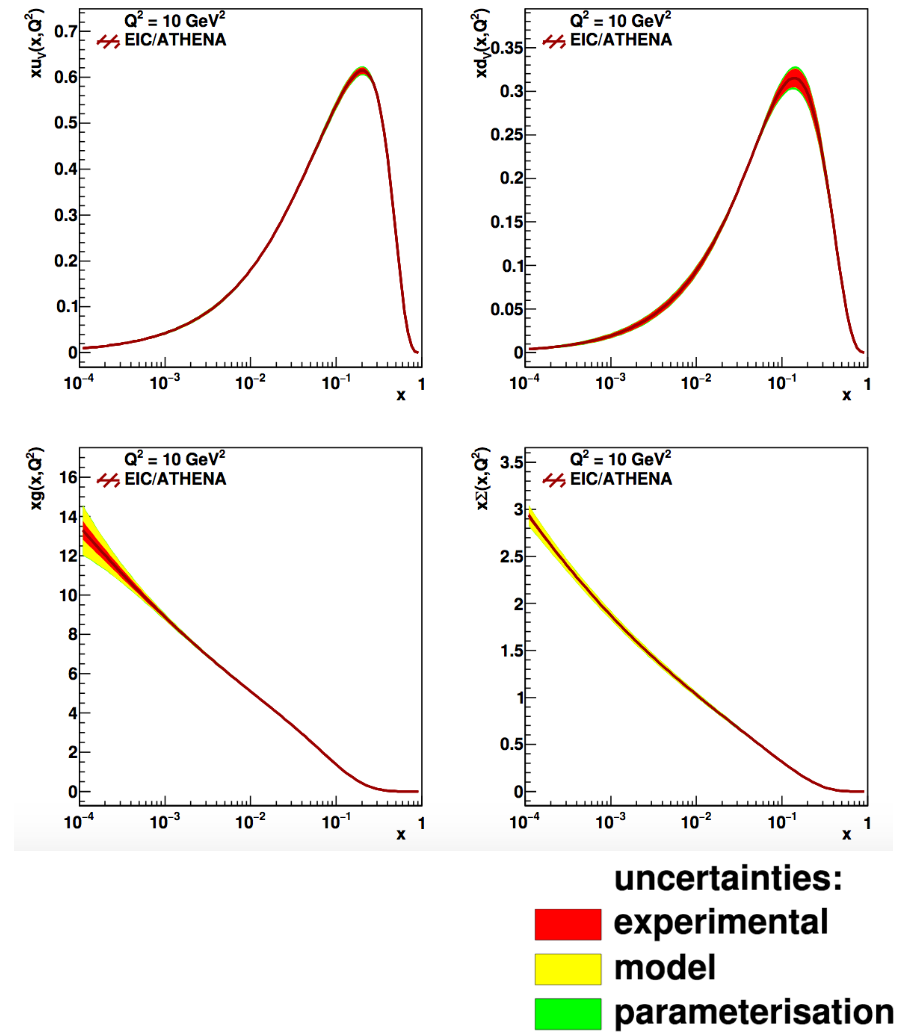
PDFs from HERAPDF2.0 (Q^2 = 10 GeV^2)

[Linear x scale]



[Total uncertainties]

[Logarithmic x scale]



By construction, PDFs not changed by adding simulated EIC data

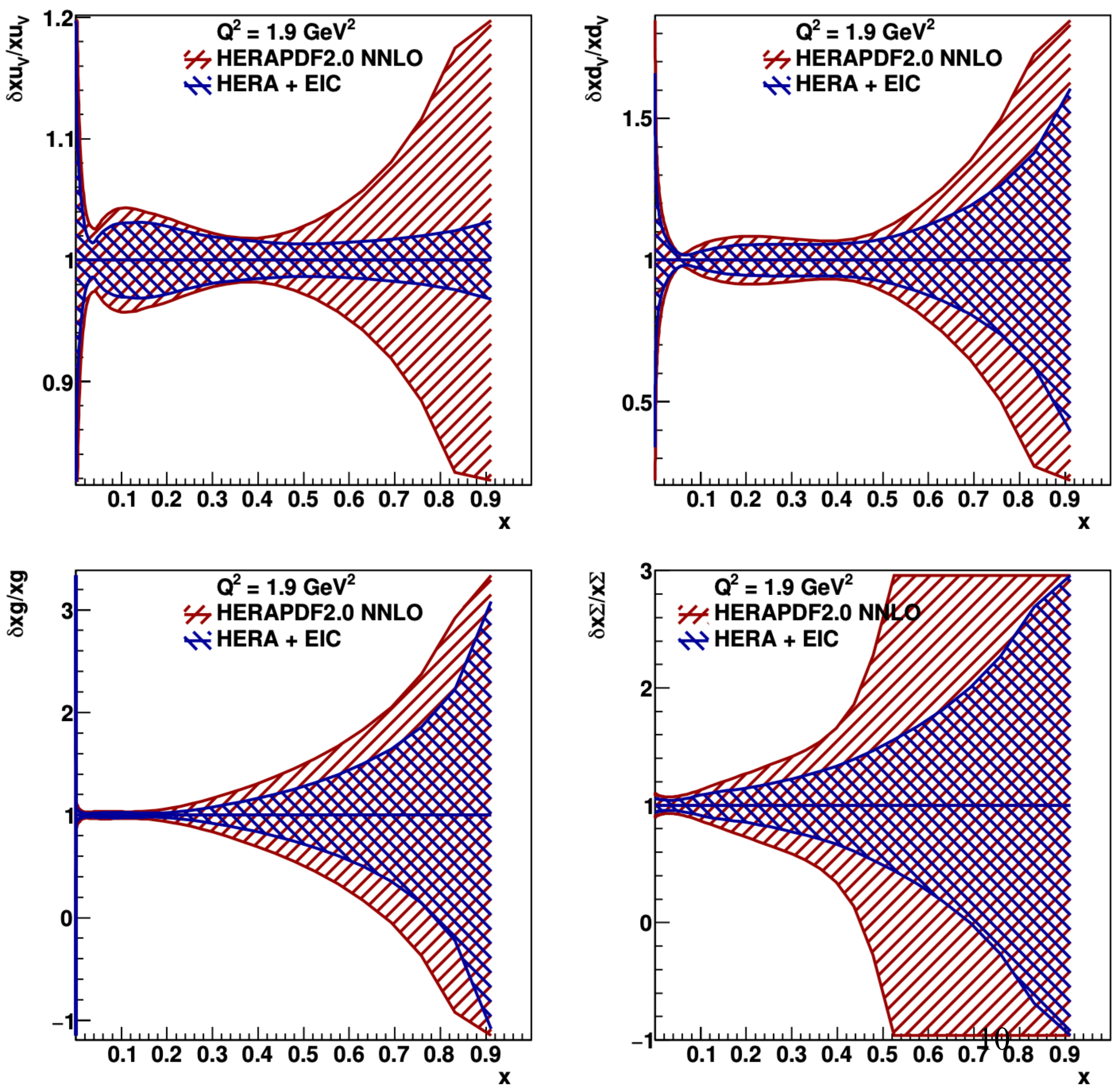
Impact of EIC/ATHENA on HERAPDF2.0

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

(linear x scale, $Q^2 = Q_0^2$)

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

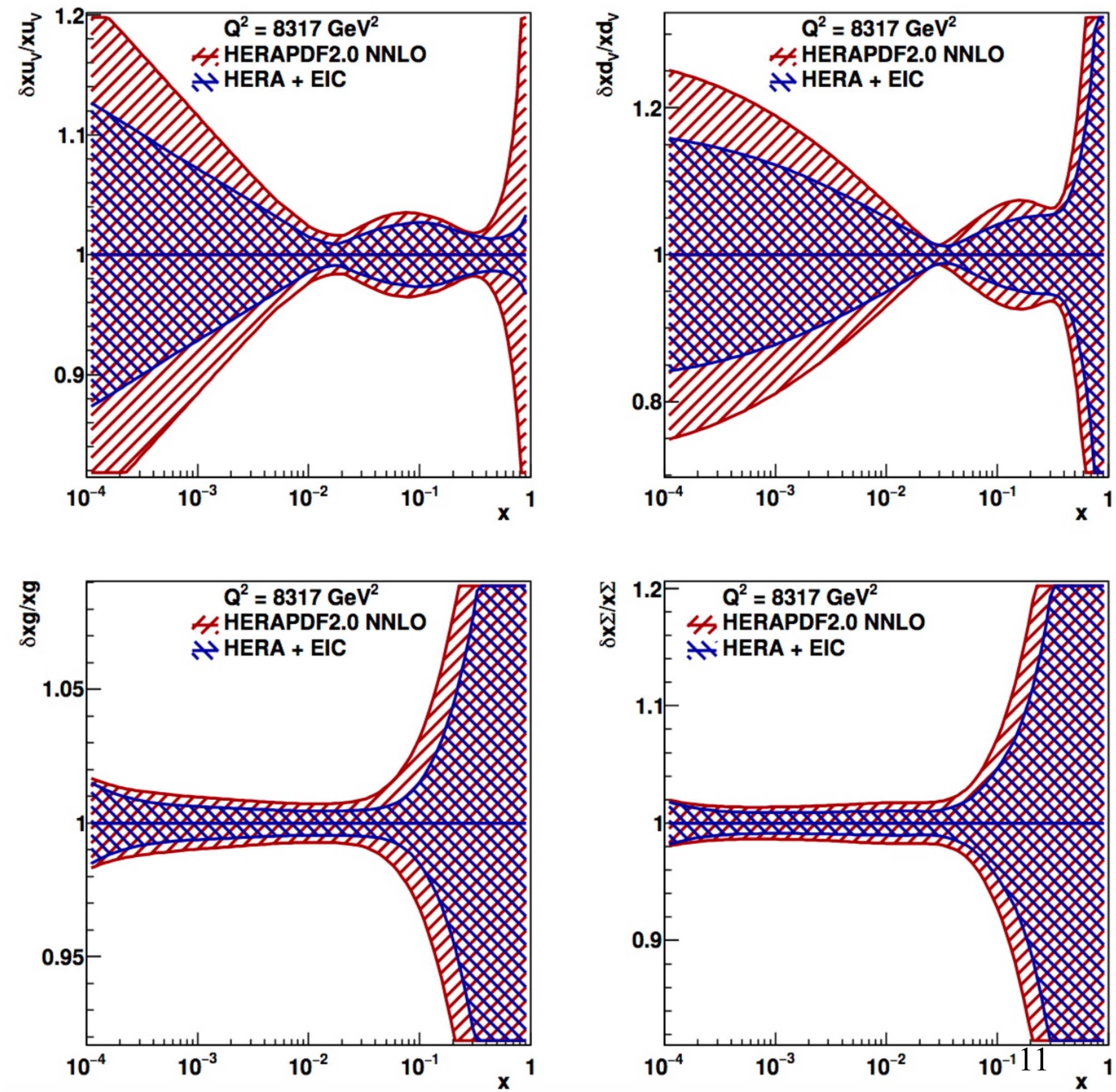
… most notable improvements for up quarks (charge-squared weighting)



Impact of EIC/ATHENA on HERAPDF2.0

Same again, but at electroweak scale and on log-x scale

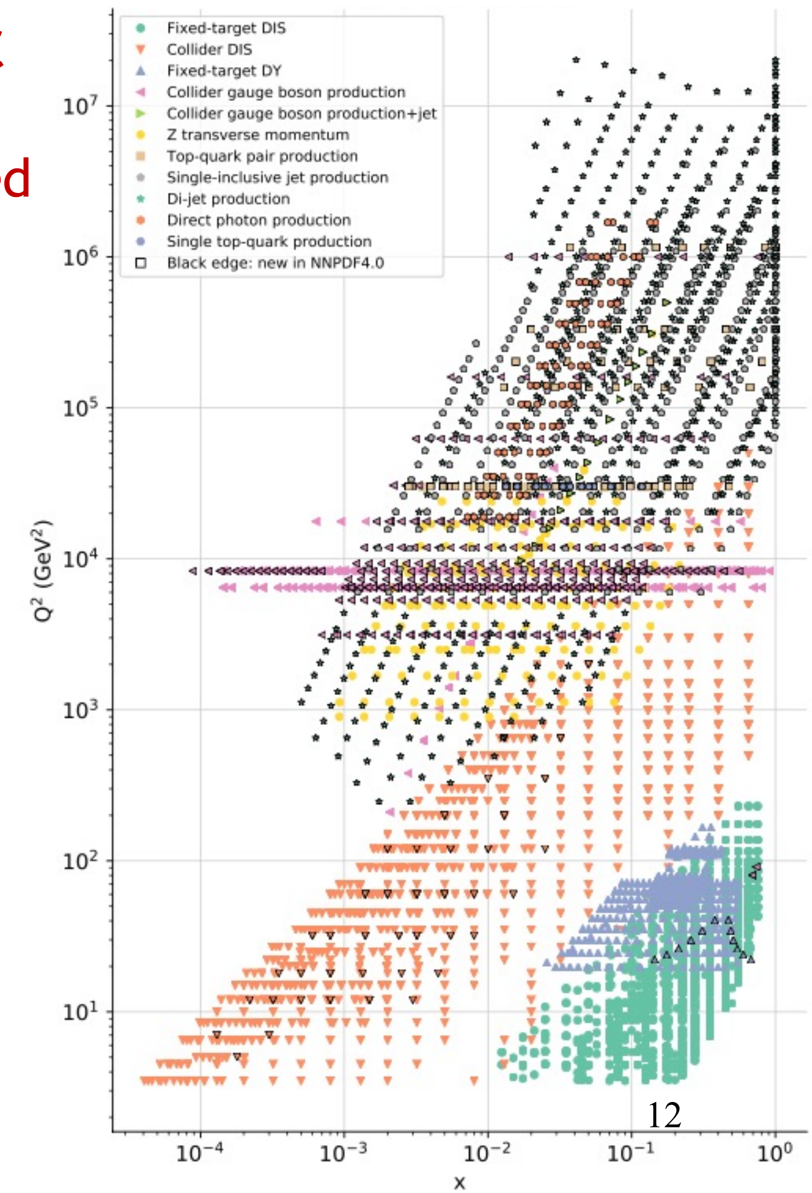
… Valuable impact throughout kinematic range, including low-x region (correlations with large x via number sum rules)



Impact relative to Global Fits

Global fits constrain 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

[e.g. NNPDF4.0]



MSHT20 Approach

- Parameterisations using Chebyshev polynomials (52 parameters in total)

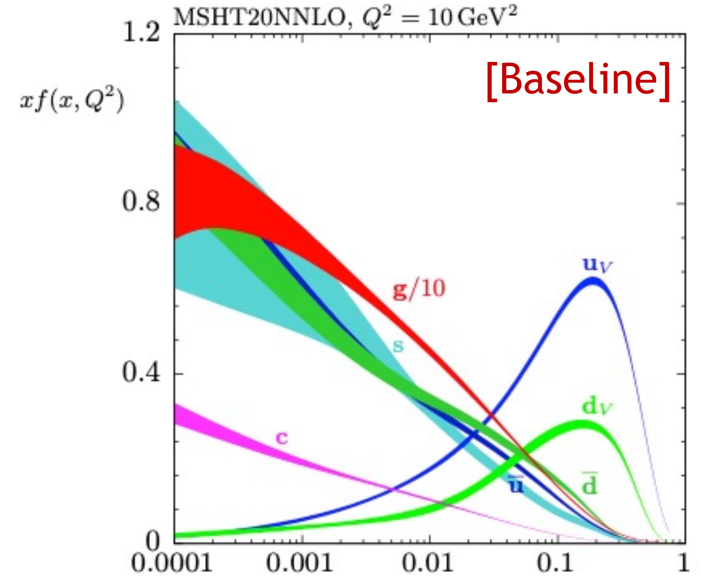
$$xf(x, Q_0^2) \;=\; A(1-x)^{\eta}x^{\delta}\left(1+\sum_{i=1}^{n}a_i T_i^{\mathrm{Ch}}(y(x))\right)$$

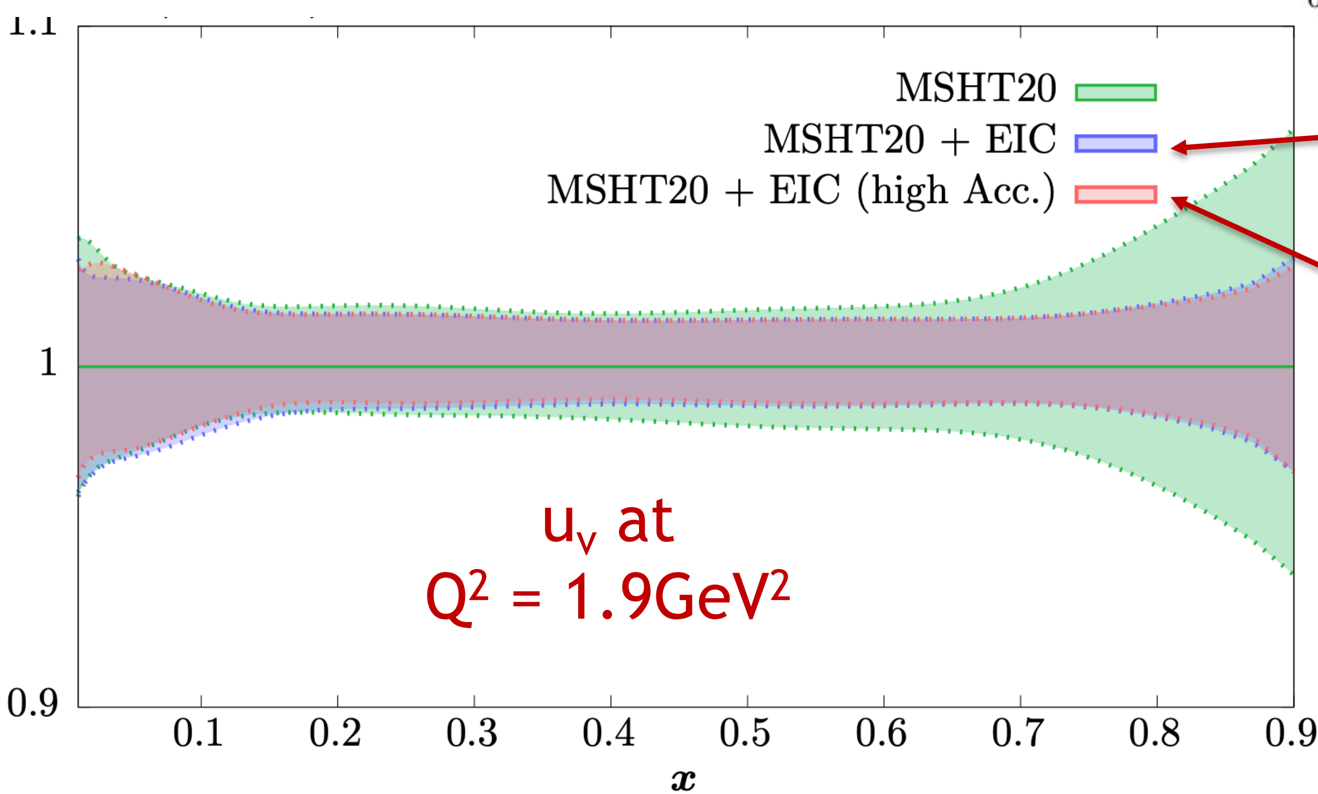
- Data with Q^2 > 2 GeV^2, W^2 > 15 GeV^2

- m_c = 1.40 GeV, m_b = 4.75 GeV,
  α_s = 1.118, starting scale μ_0 = 1.0 GeV

EIC Impact relative to MSHT20 (NNLO)

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

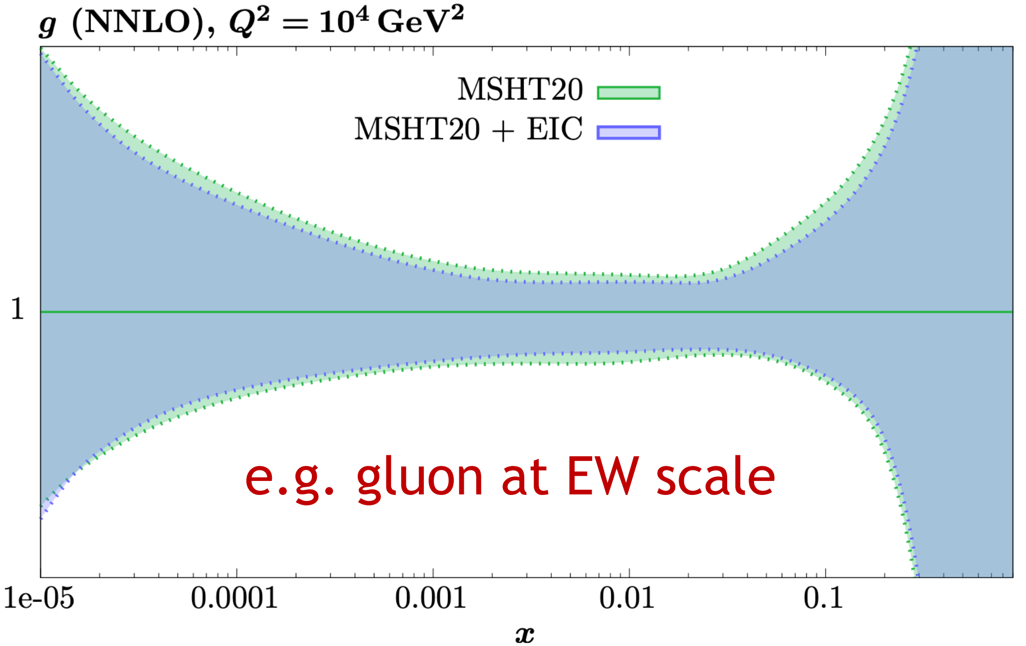




$y > 10^{-2}$

$y > 10^{-3}$

Impact relative to MSHT20

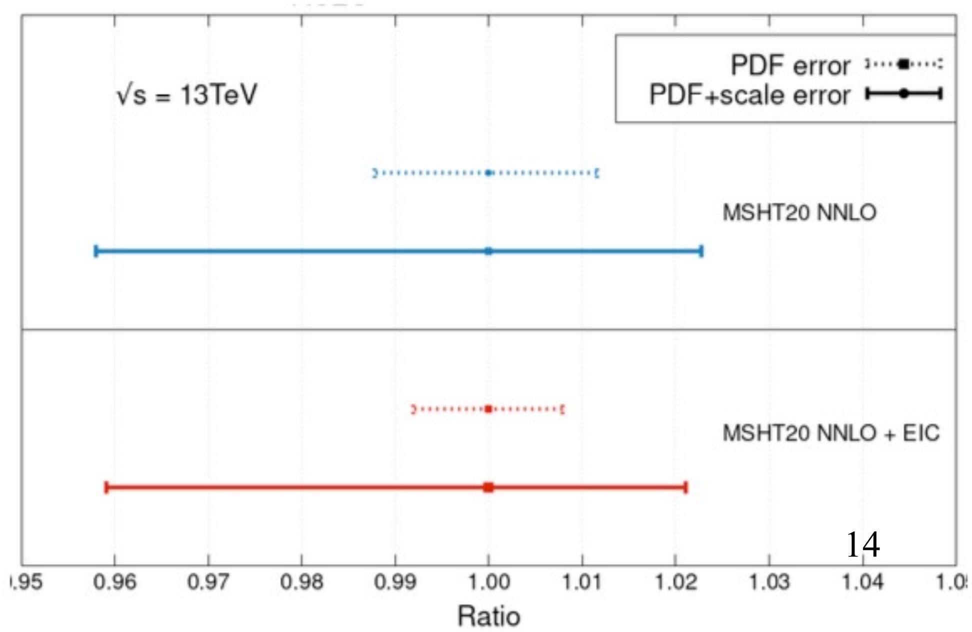


… small, but valuable improvements in all parton species at all x, Q^2

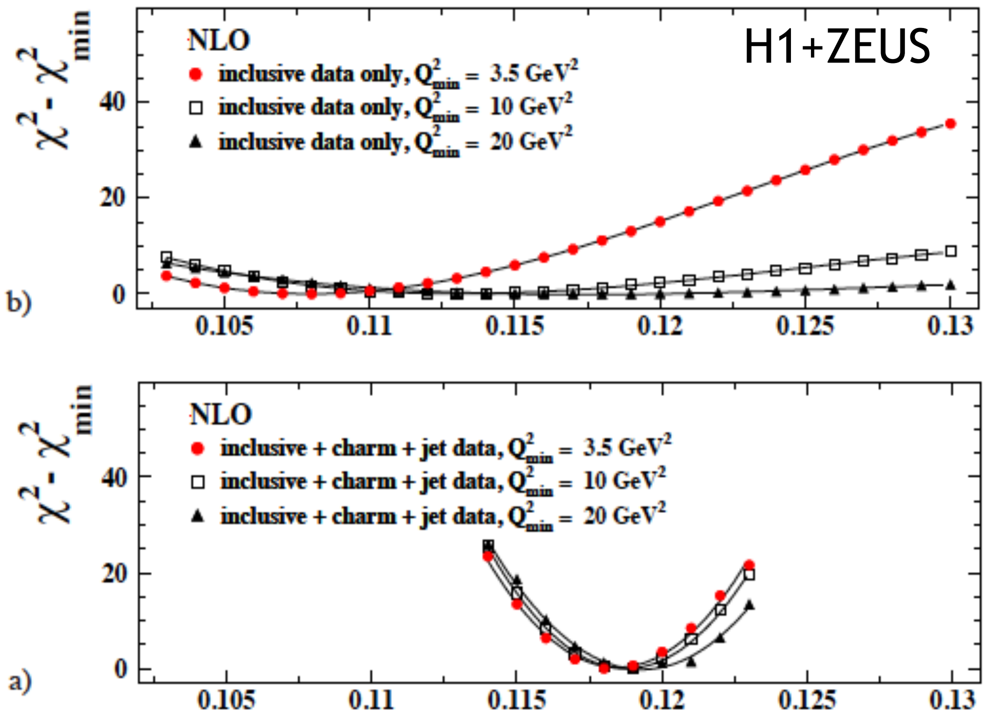
σ(gg→H) uncertainties at LHC [N^3LO matrix elements with NNLO PDFs]

… feeds through parton-parton luminosities to significant improvement in PDF uncertainty on gg→H at LHC

… scale uncertainty (varying μ_r and μ_f by factors of 2 about $m_H/2$) remains dominant



Taking α_s as an additional free parameter



When using HERA data only …

- HERAPDF2.0 shows only limited sensitivity when fitting inclusive data only.

- Including jet and charm data allows simultaneous α_s (and m_c) extractions to comepitive precision without significant impact on PDFs

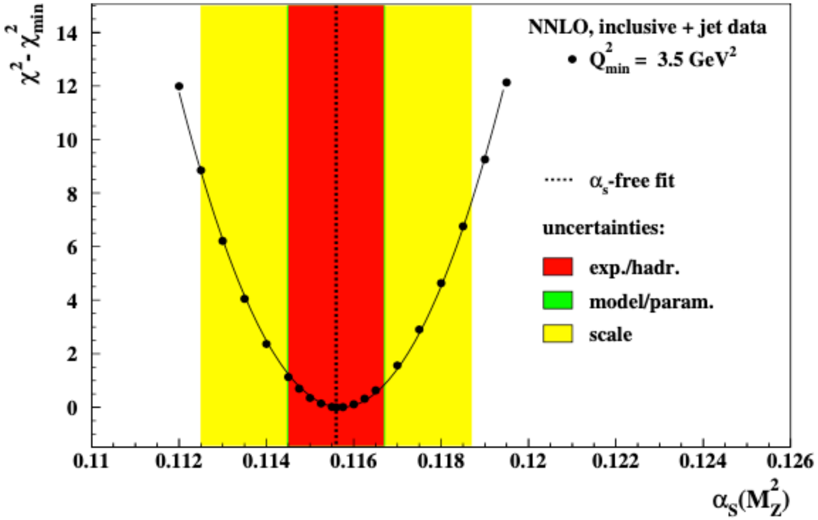
What happens when fitting HERA+EIC data together?...

… repeat HERAPDF fits with α_s as free parameter (input value 0.1160)

… $\mu_r^2 = \mu_f^2 = Q^2 + p_T^2$ (jets)   or = Q^2 (inclusive)

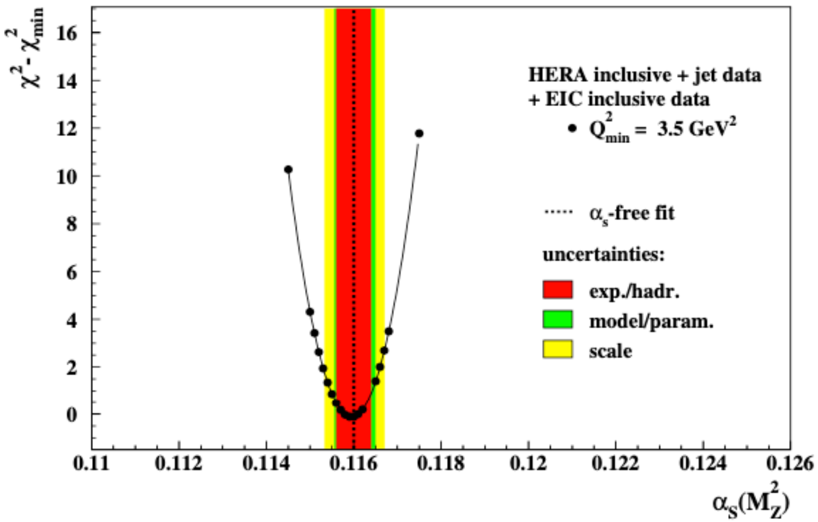
… fit details otherwise as for HERAPDF2.0

α_s from HERA (with jets) + EIC



HERA inclusive + jet only

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp)}$$
$$^{+0.0001}_{-0.0002} \text{ (model + parameterisation)} \pm 0.0029 \text{ (scale)}.$$



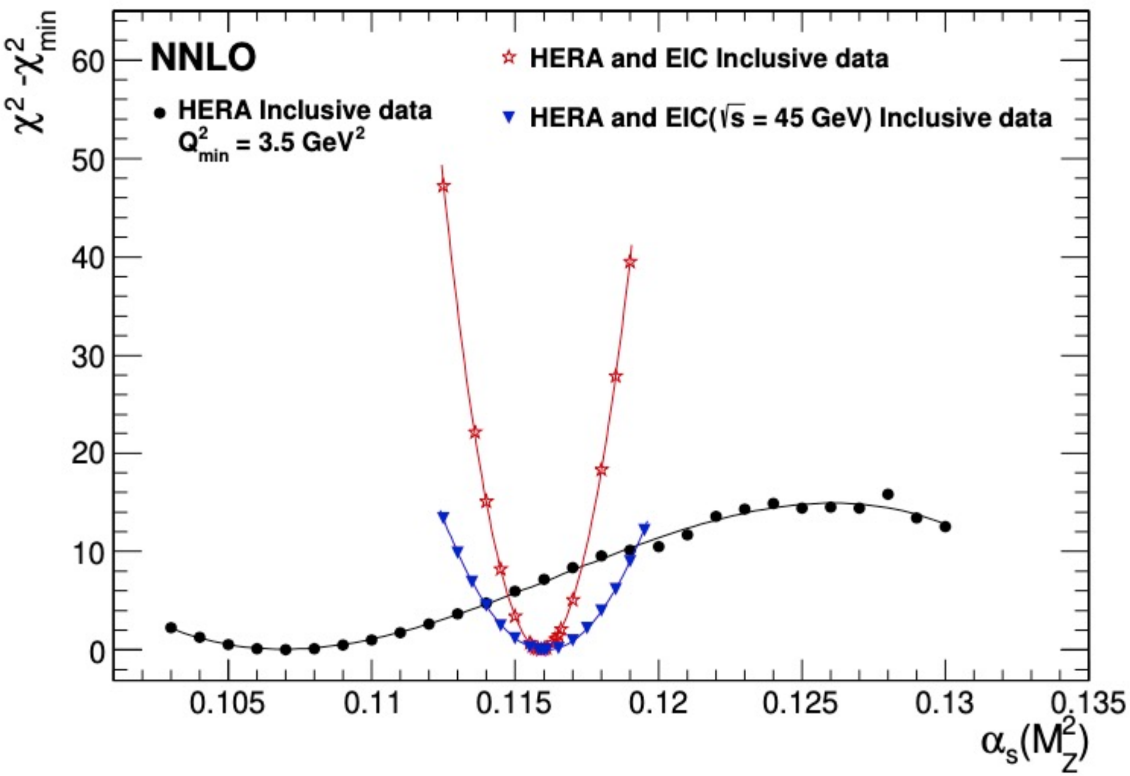
HERA inclusive + jet and EIC inclusive

$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0004 \text{ (exp)}$$
$$^{+0.0003}_{-0.0002} \text{ (model + parameterisation)} \pm 0.0005 \text{ (scale)}.$$

- Simulated EIC inclusive data has a remarkable impact on experimental uncertainty (arising from statistical and systematic errors on data)

- Scale uncertainty obtained by varying μ_r and μ_f by factors of 2 for jet data. Currently not assessed for inclusive data (as in global fits)

α_s from HERA (without jets) + EIC



HERA inclusive +
EIC inclusive

Experimental precision is retained when fitting only inclusive data

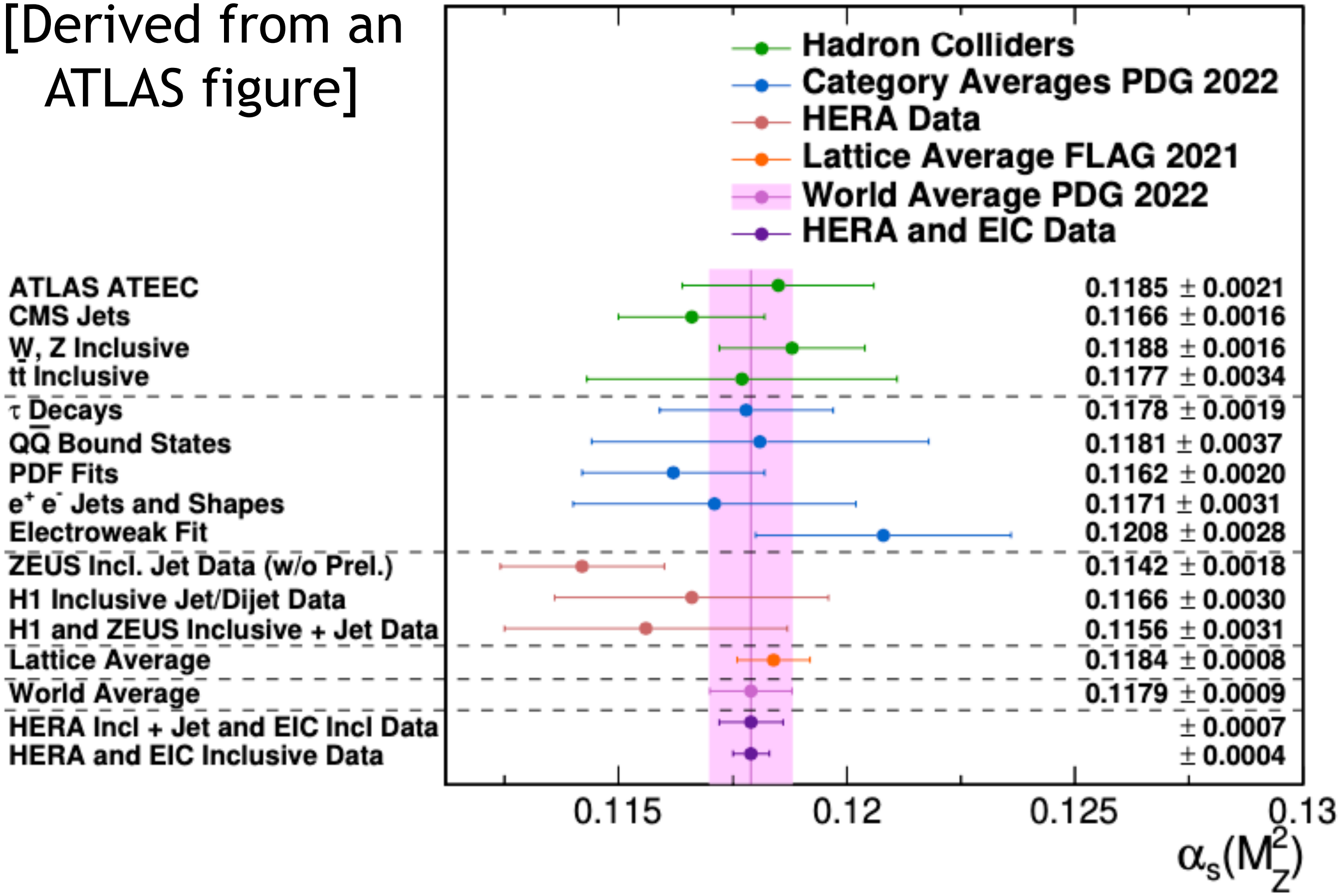
$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004 \text{ (exp) } ^{+0.0002}_{-0.0001} \text{ (model + parameterisation)}$$

Precision is only a factor ~2 worse when fitting only one (low $\sqrt{s}$)
EIC beam energy … result achievable in ~1 year of early data taking.

[Scale uncertainty yet to be determined]

... in a Global Perspective ...

[Derived from an ATLAS figure]



Adding EIC data to HERA can lead to α_s precision a factor ~2 better than current world experimental average, and than lattice QCD average, using inclusive DIS data alone

Scale uncertainties remain to be understood ...

Comments on Scale Uncertainties

- 'Scale' uncertainties express uncertainties due to missing higher orders beyond NNLO in the theory
- Expected to be small for inclusive data, and covariances with other uncertainties have to be considered (hence generally omitted in global fits)
- Moving the machinery to N^3LO will make them even smaller.
- Ongoing work by global fitting groups (eg NNPDF arXiv:1906.10698) to develop a consistent framework

→ outcomes eagerly awaited

→ may become very important in EIC era!

Comment on Origin of EIC Impact

- Restricting data range by imposing Q^2_{min} (or x_{min}) cuts has only very small impact on the result.

→ EIC impact traceable to the large x, moderate Q^2 region

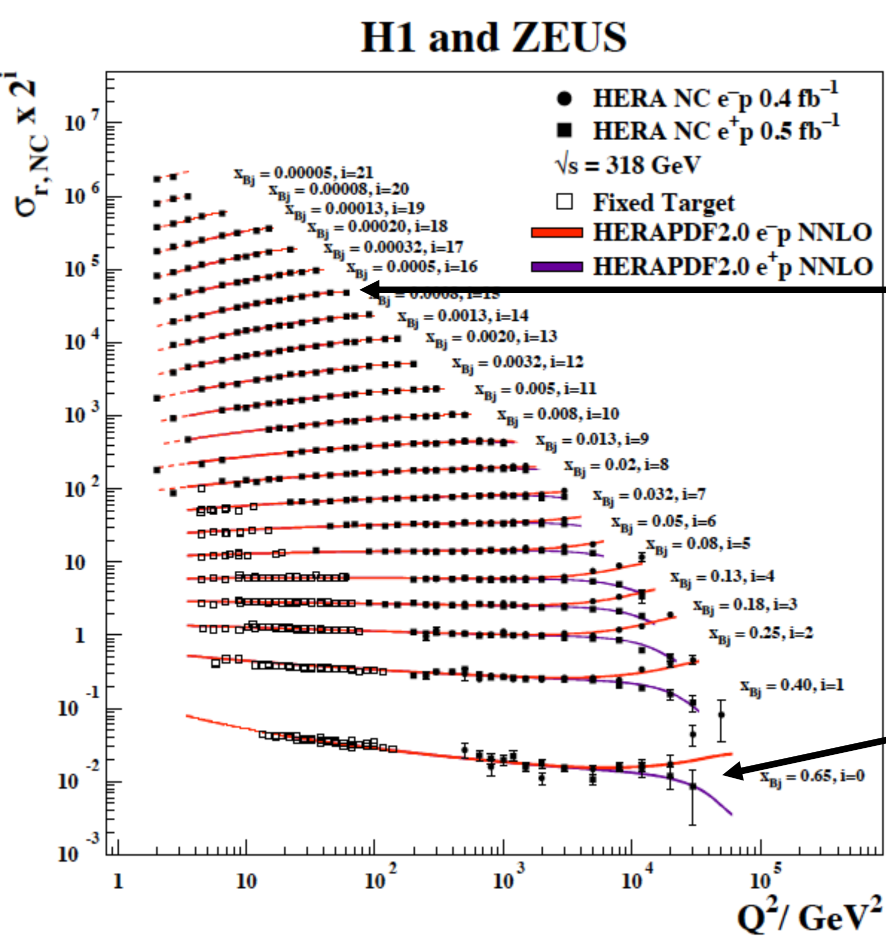
- There is, however some sensitivity to the W^2 cut:

Default (> 10 GeV^2) yields experimental precision 0.004

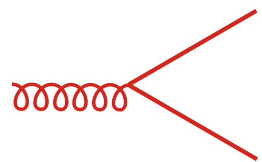
Switching to > 15 GeV^2 leads to experimental precision 0.006

→ Important to avoid sensitivity to higher twist or resummation effects

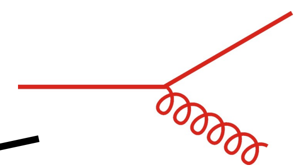
Why does large x, intermediate Q^2 data improve precision so markedly?



$$\frac{d\sigma_r}{dQ^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes q\right]$$



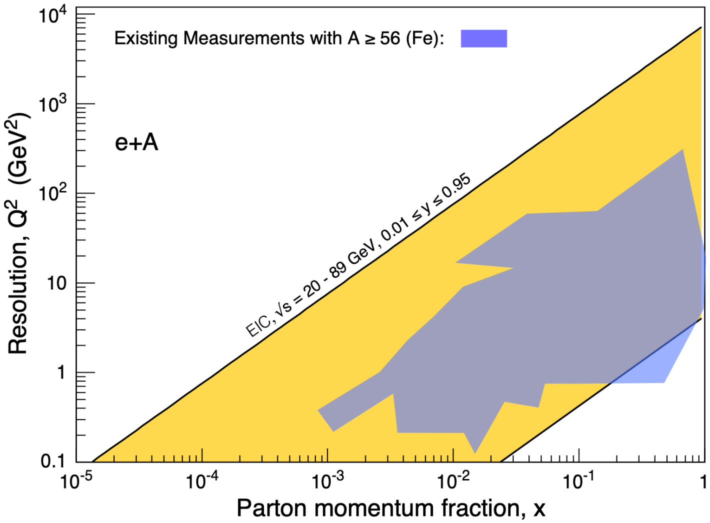
At low / intermediate x, scaling violations are driven by $g \to gg$, $g \to q\bar{q}$
[most sensitive to α_s.g(x)]



At largest x, scaling violations are driven by $q \to qg$
[most sensitive to α_s.q(x)]

… precision high x data decouple α_s from gluon density …

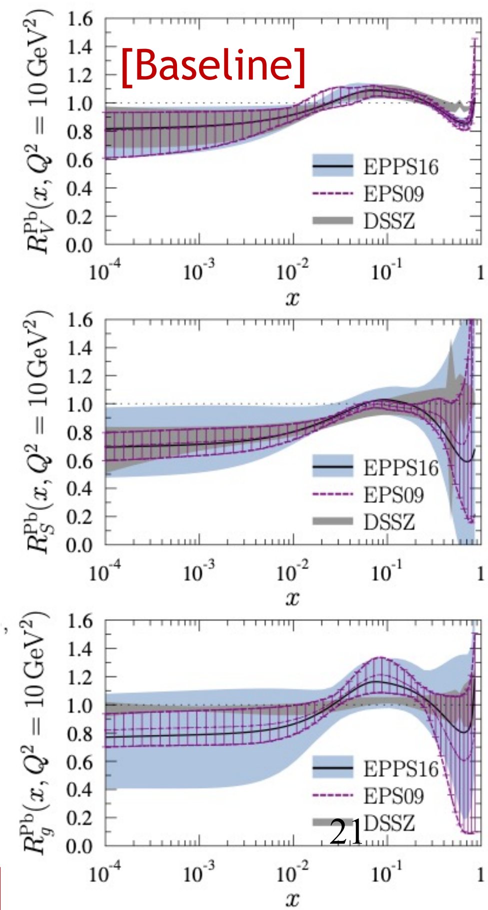
EIC and nuclear PDFs



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 EIC relative to EPPS16

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



EPPS16 [EPJ C77 (2017) 163]

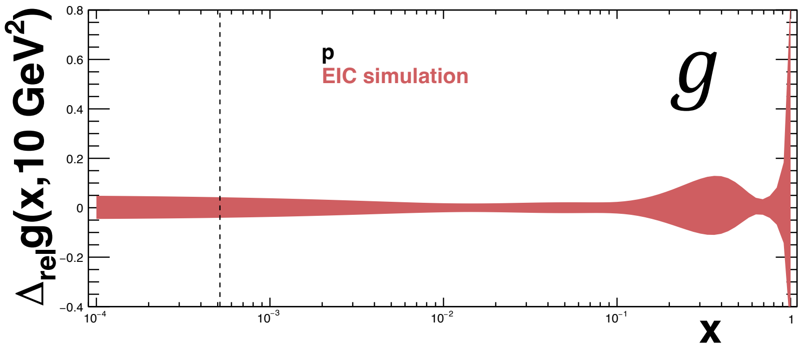
- Uses fixed target DIS and Drell-Yan data, hard processes from pA at the LHC and PHENIX π^0 data

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

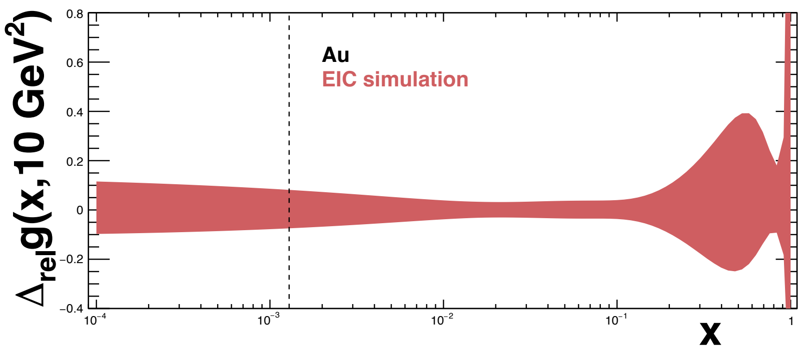
$\mu_0 = m_c = 1.3$ GeV, $m_b = 4.75$ GeV, $\alpha_s = 1.118$

[More recent global fits up to factor of 2 better at low x]

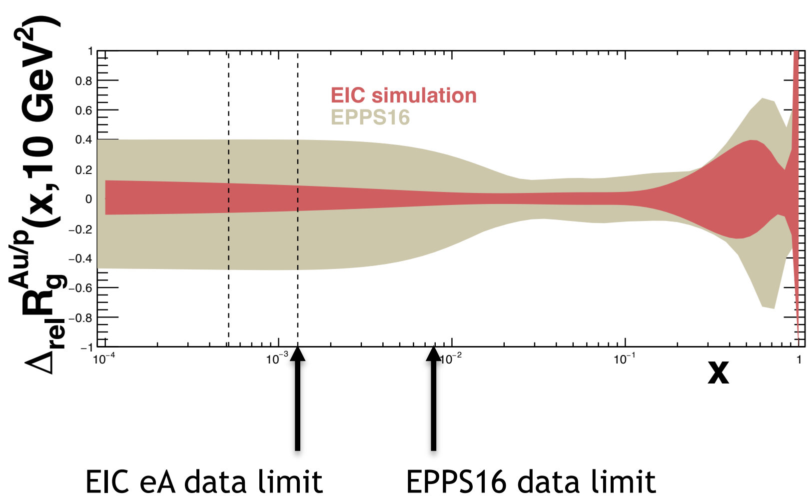
Impact on Nuclear PDFs: Gluon



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



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

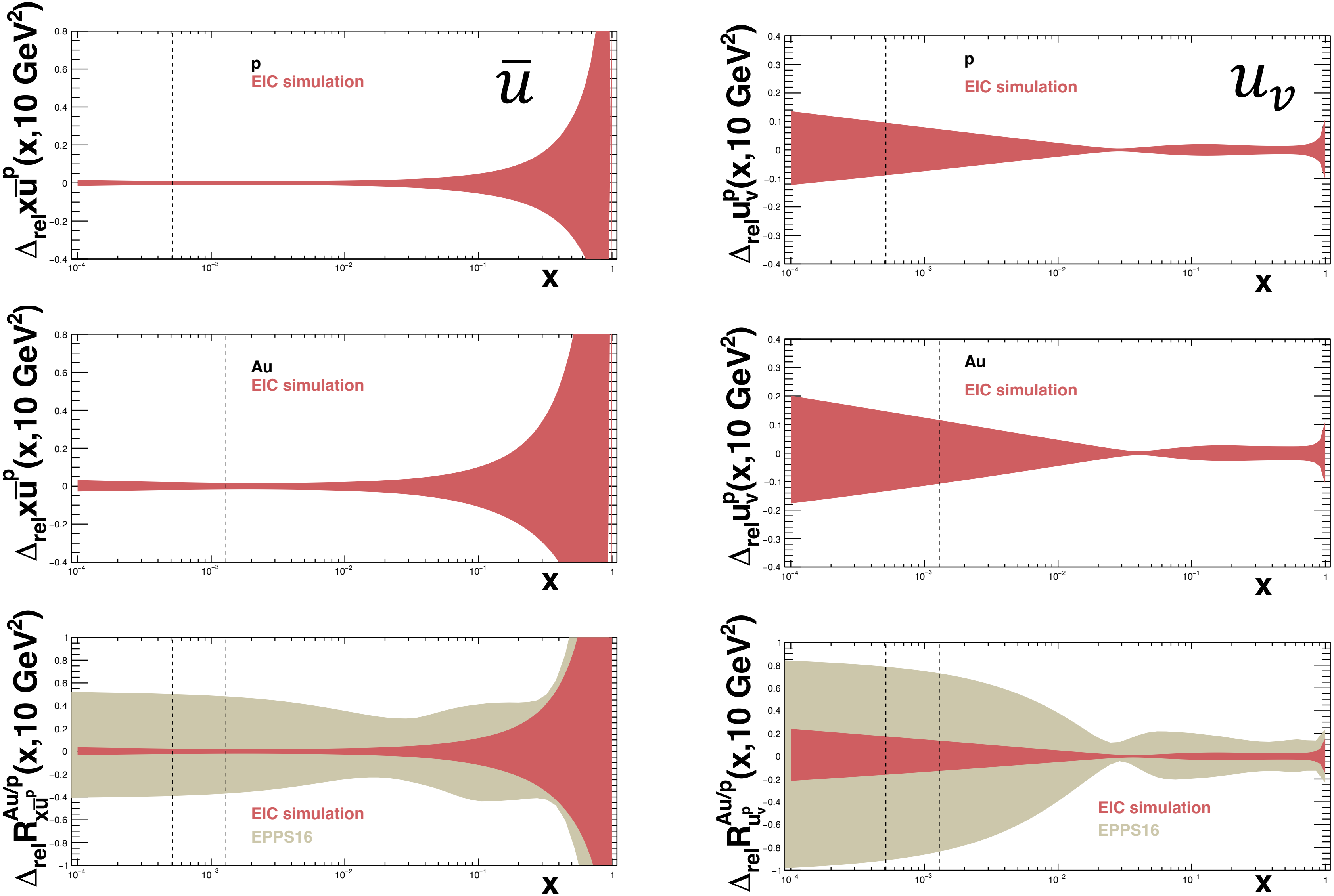


Projected uncertainty on nuclear modification factor, EIC-only compared with EPPS'16

→ Factor ~ 2 improvement at x~0.1

→ Very substantial improvement in newly accessed low x region

Impact on Nuclear PDFs: quarks



Similarly compelling improvements at low x in particular

Summary

General Purpose Detectors at the Electron Ion Collider may provide transformational input to collinear parton densities and the strong coupling, with wide-ranging impact

- Precise ep data in large x, intermediate Q^2 region:

  → Precision on all proton PDF species from an experimentally and theoretically cleaner DIS-only extraction

  … Key to optimising sensitivity to new BSM physics near to kinematic limit at the LHC and elsewhere

  → Potentially world-leading sensitivity to α_s if missing higher order uncertainties can be understood & controlled

- eA measurements in the low x region for the first time

  → 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.