Self-consistent determination of proton and nuclear PDFs at the Electron Ion Collider

Juan Rojo
VU Amsterdam & Theory group, Nikhef

EIC opportunities for Snowmass workshop

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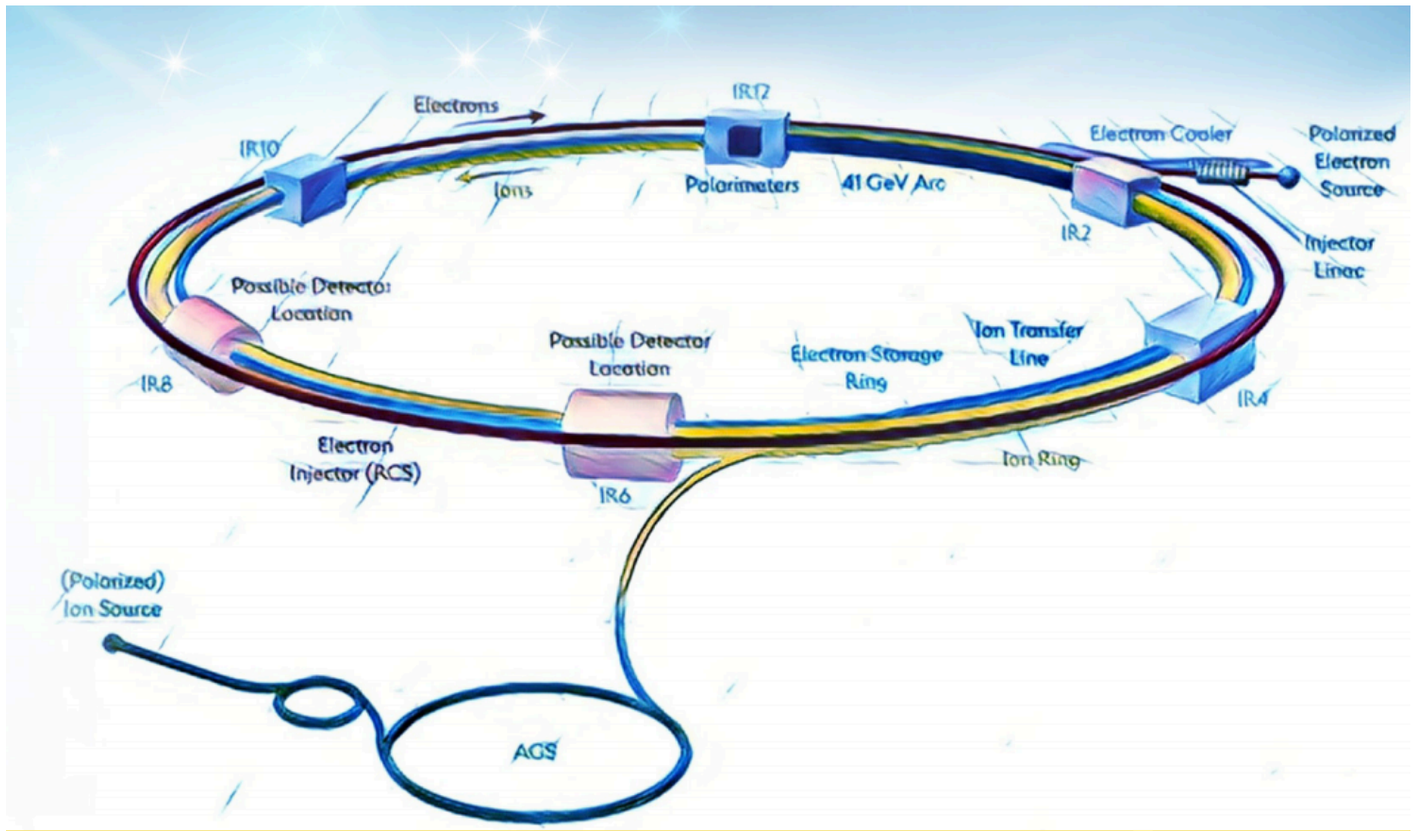
Based on an upcoming paper (this week) by Abdul-Khalek, Ethier, Nocera, JR

what the EIC can do for global (n)PDF fits?

- A broad range of **inclusive** and **semi-inclusive DIS measurements** taken on projectiles from proton (*A=1*) and deuteron (*A=2*) up to gold (*A=197*)

- Taken on state-of-the-art detectors for a range of centre-of-mass energies which provide fully correlated uncertainties between **different measurements and projectiles**

- For the first time ever, the EIC will make possible a self-consistent determination of (polarised and unpolarised) proton and nuclear structure as well as of hadron fragmentation: **all relevant measurements to be provided by the same machine!**

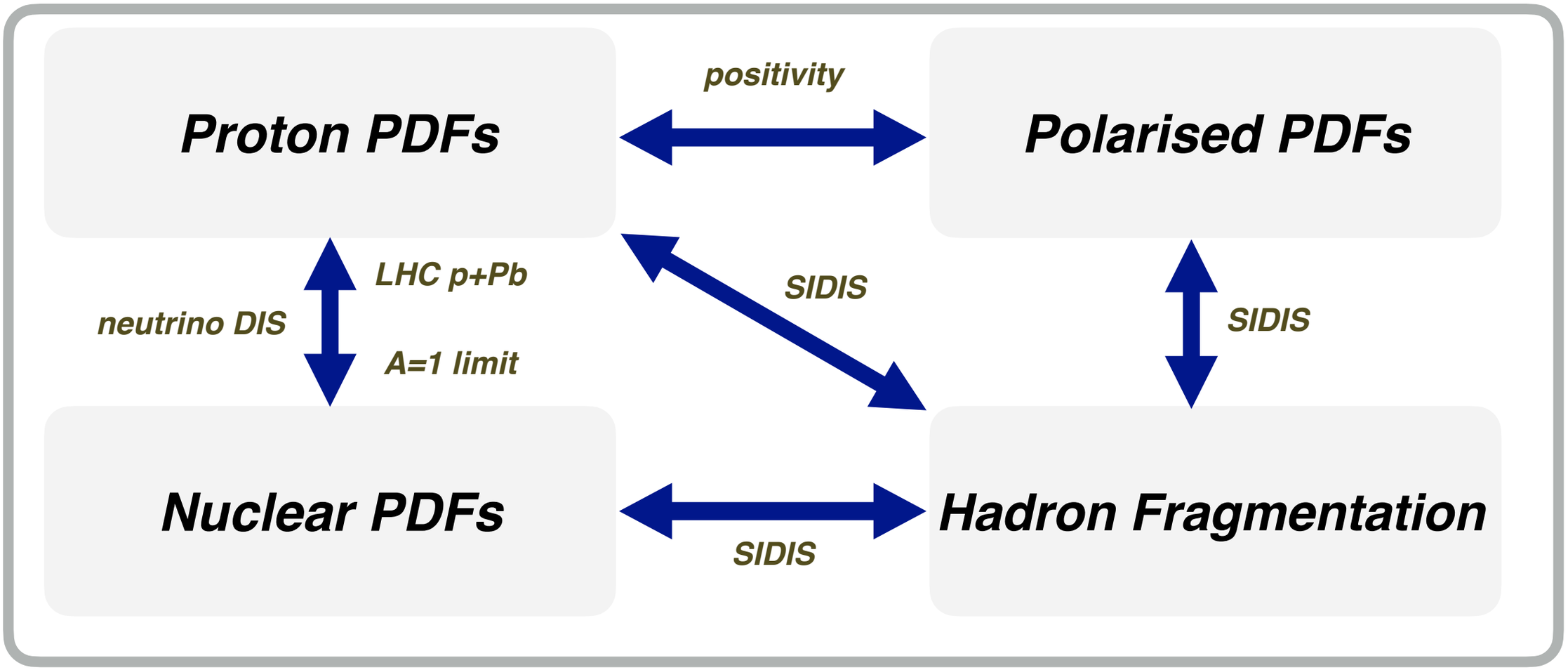


in practice, EIC measurements will be complemented by other datasets into an integrated global QCD analysis

New frontier in QCD investigations of proton & nuclear structure and fragmentation!

on the interplay between PDFs and nPDFs

Conceptually, it is clear that the best strategy is to **determine simultaneously proton, deuteron, and heavy nuclear PDFs,** as well as fragmentation functions if SIDIS is used



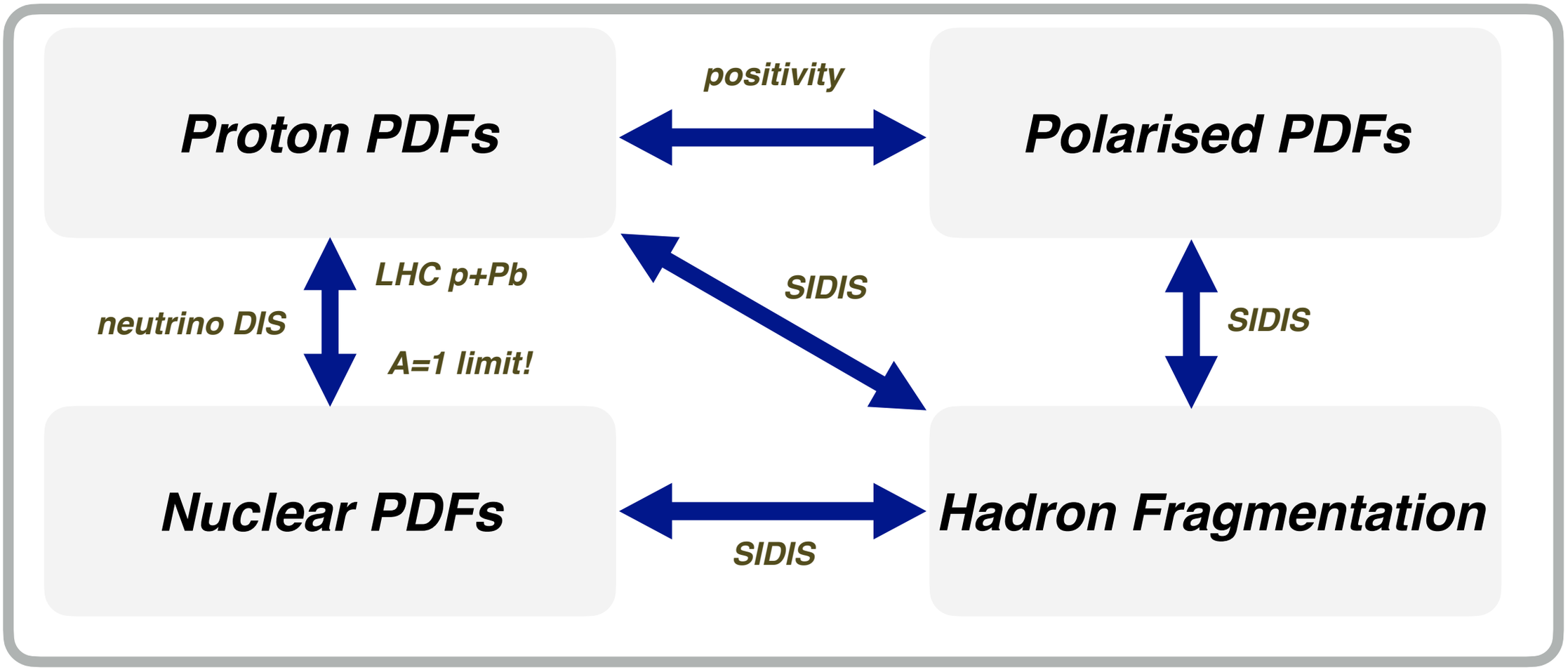
e.g. DY production in p+Pb collisions

$$\frac{d\sigma_{\rm DY}(y)}{dy} \equiv A\frac{d\sigma_{\rm DY}^{(N/A)}(y)}{dy} = Z\frac{d\sigma_{\rm DY}^{(p/A)}(y)}{dy} + (A-Z)\,\frac{d\sigma_{\rm DY}^{(n/A)}(y)}{dy}$$

need both free proton and heavy nuclear PDFs!

on the interplay between PDFs and nPDFs

Conceptually, it is clear that the best strategy is to **determine simultaneously proton, deuteron, and heavy nuclear PDFs,** as well as fragmentation functions if SIDIS is used



the usual assumption that the determination of proton and nuclear PDFs **can be decoupled** from each other **cannot be justified** given the precision of present and future data!

Analysis settings

- Start from a **global proton PDF analysis**, and augment it with EIC proton pseudo-data

we use the strangeness variant of NNPDF3.1

Faura, Iranipour, Nocera, JR, Ubiali 20

- Use the results as the **boundary condition** for a global nuclear PDF fit also augmented with EIC projections

$$\chi^2 \to \chi^2 + \lambda_{\rm BC} \sum_f \sum_{i=1}^{N_x} \left(q_f^{(p/A)}(x_i, Q_0, A=1) - q_f^{(p)}(x_i, Q_0) \right)^2$$

we use the nNNPDF2.0 determination for this

Abdul-Khalek, Ethier, JR, van Weelden 20

- With real data, one would then **iterate** and use the nuclear PDFs to account for deuteron and nuclear uncertainties in the neutrino DIS data fitted in the proton analysis

strategy developed by Ball, Pearson, Nocera 18,20

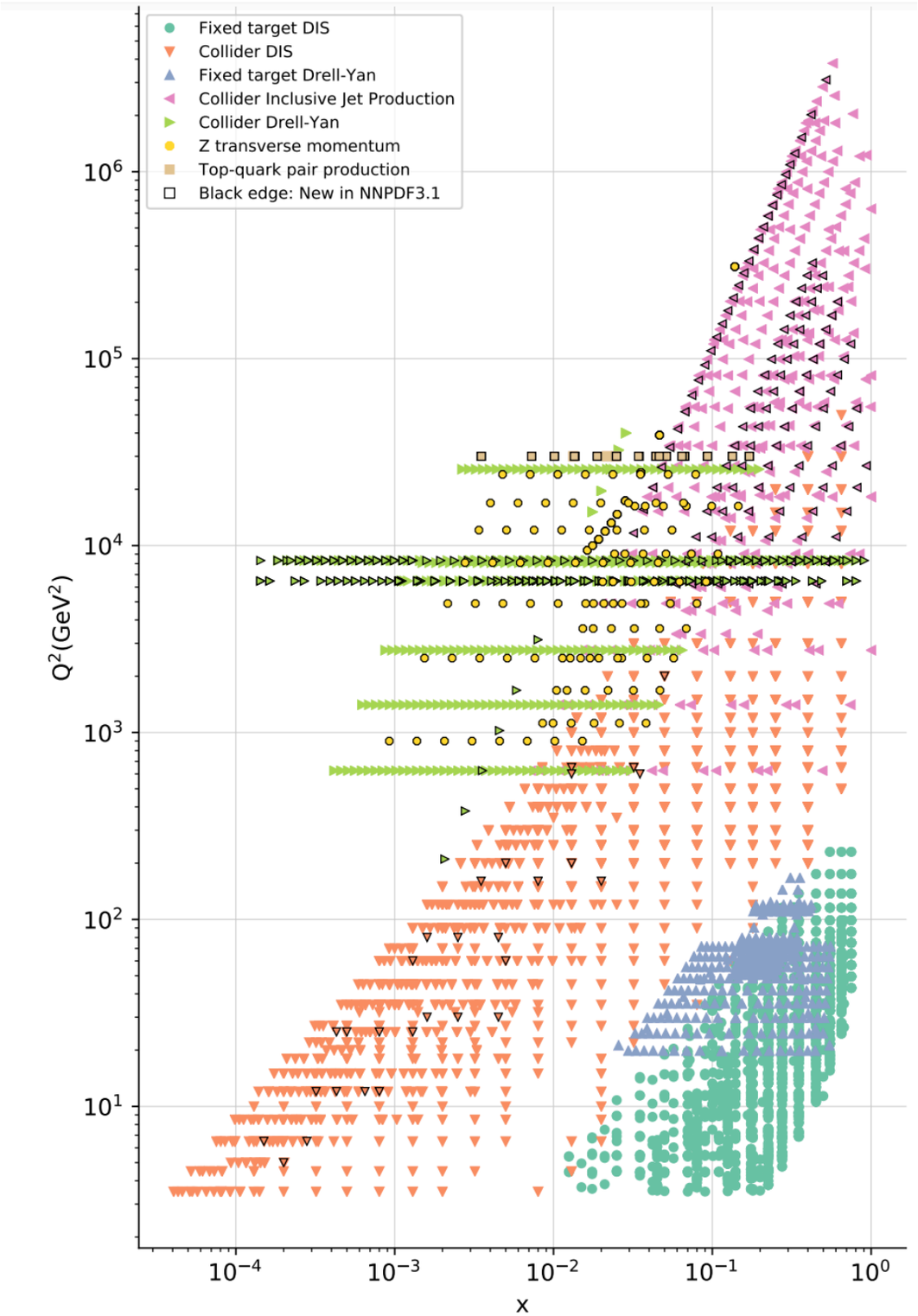
- Repeat until convergence is achieved: **self-consistent determination** of both proton and nuclear PDFs!

here restrict ourselves for first two steps, which are those relevant for pseudo-data projections

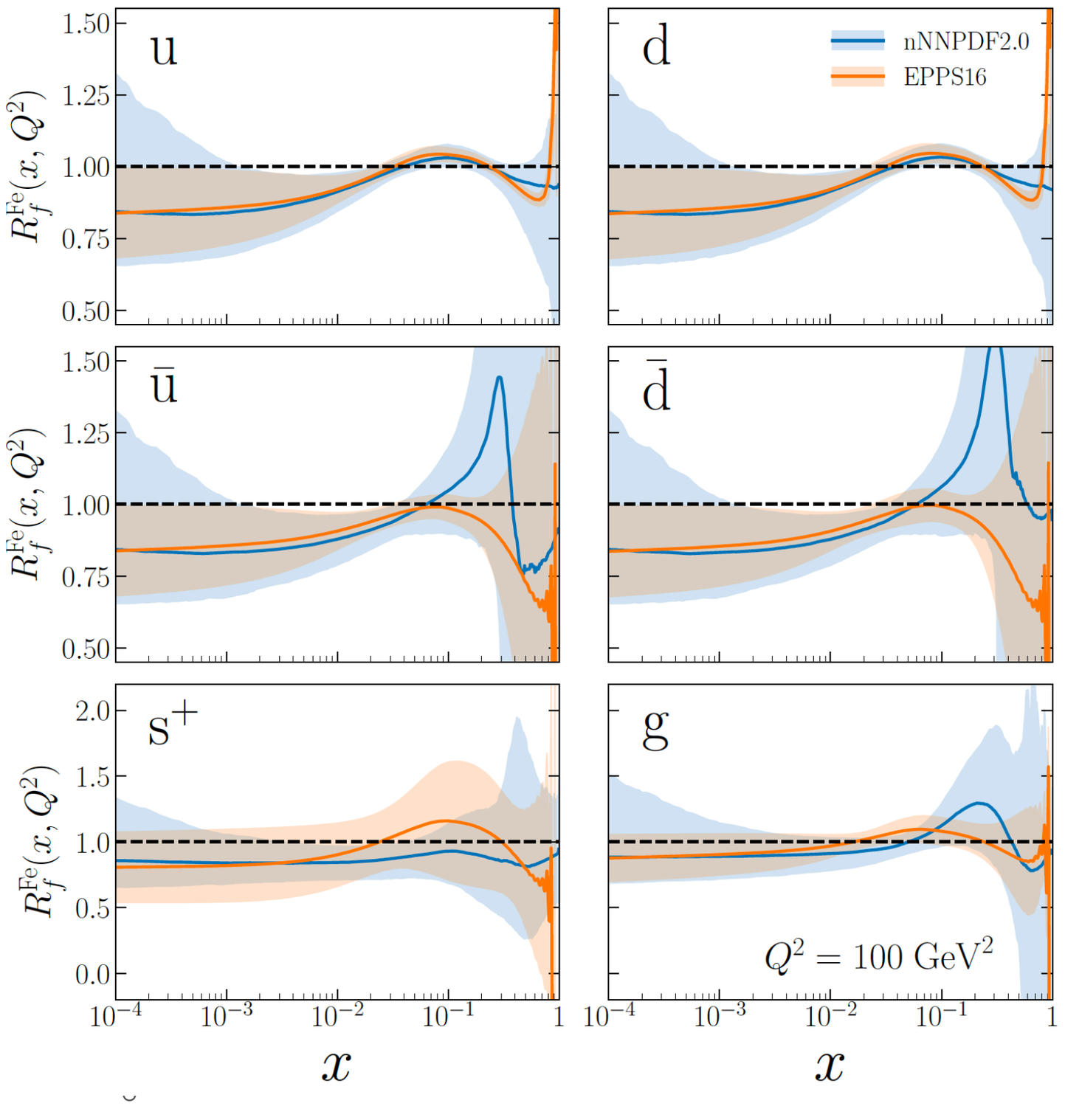
alternative approach: joint PDF+nPDF fit

Analysis settings

NNPDF3.1 (proton)

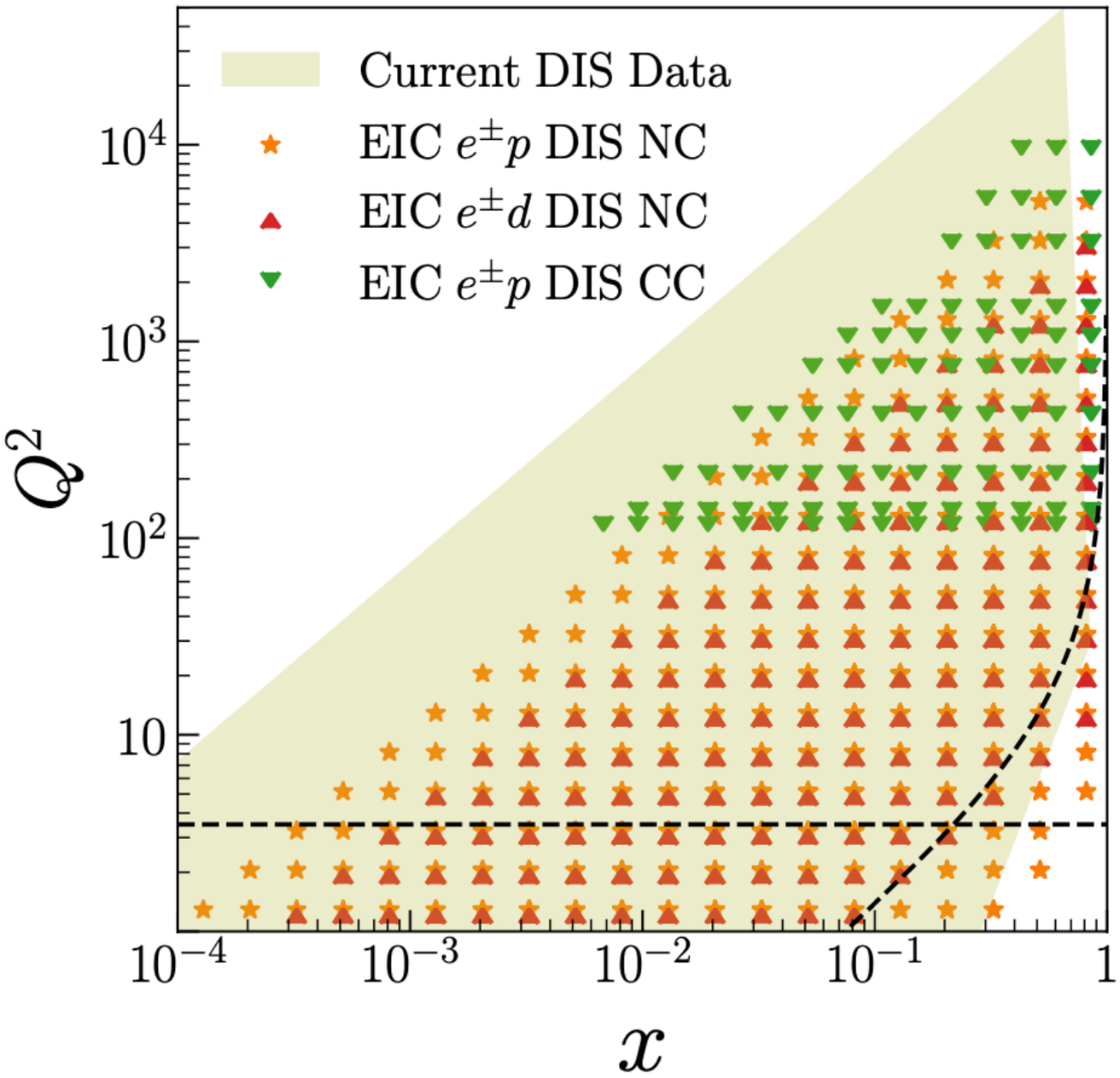


nNNPDF2.0 (nuclear)

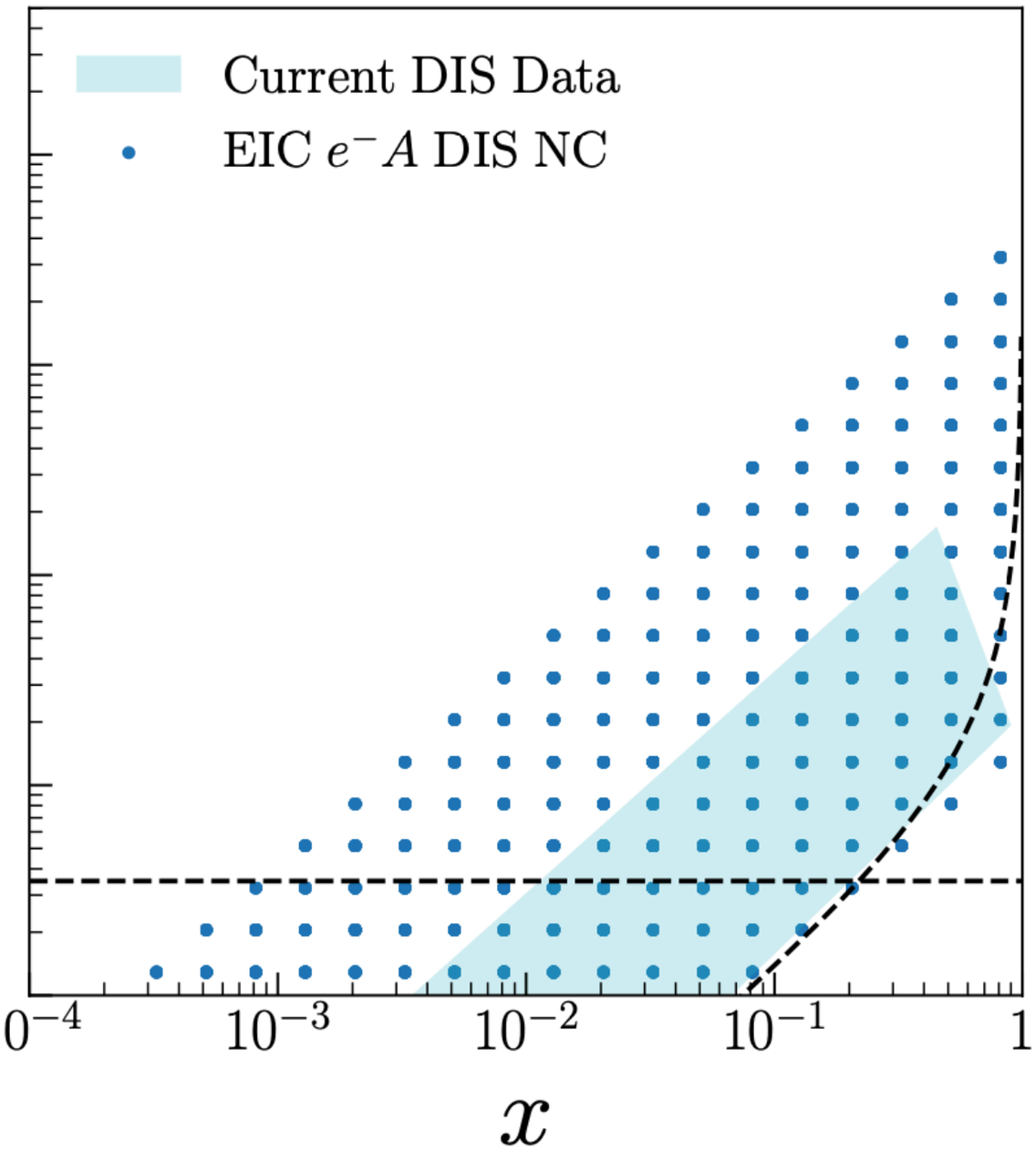


kinematical coverage

EIC proton+deuteron



EIC heavy nuclear



pseudo-data generated in the context of the **upcoming EIC Yellow Report** studies

Two scenarios considered (*optimistic* and *pessimistic*) for the systematic errors

kinematical coverage

CC proton

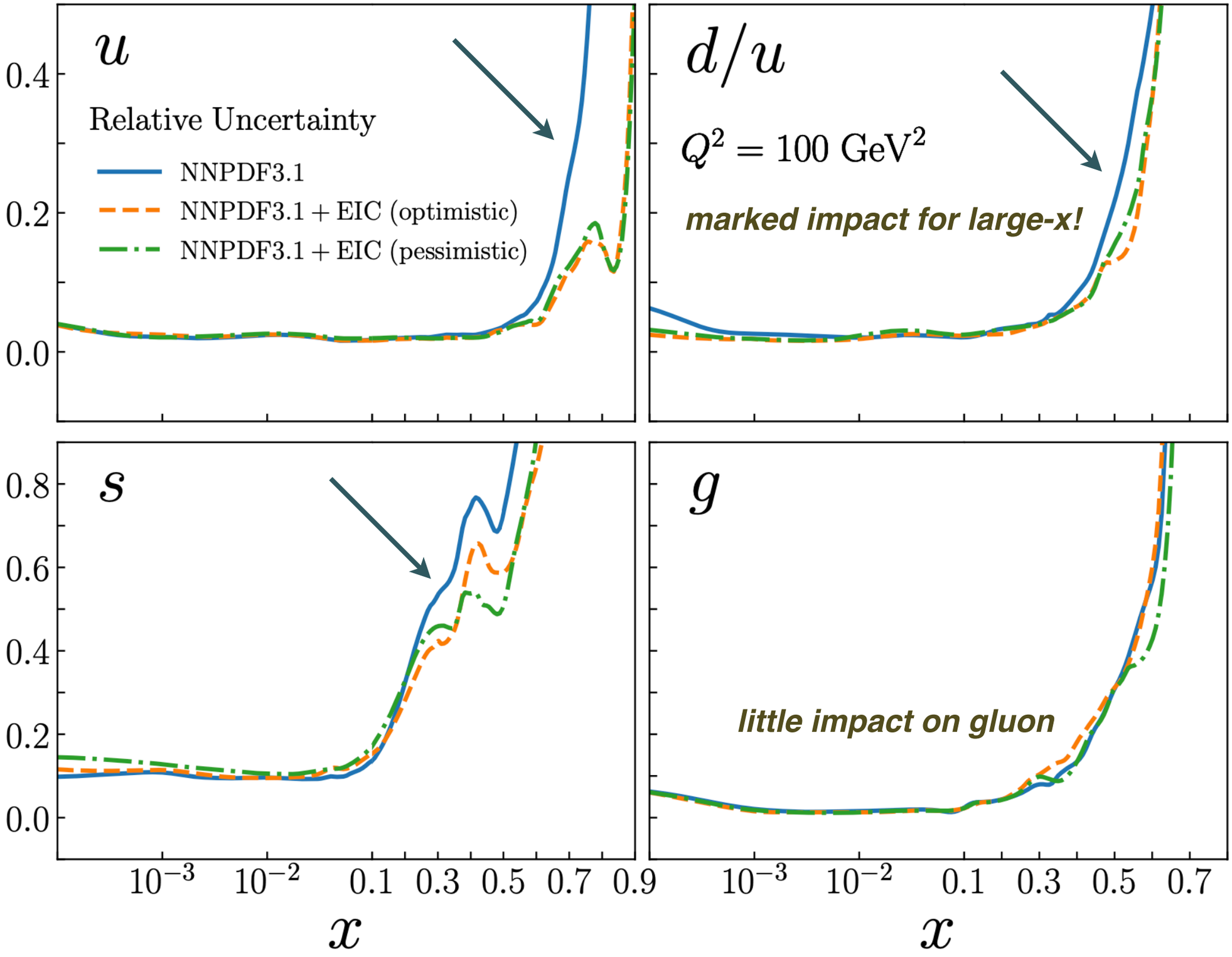
NC proton

NC deuteron

NC nuclear

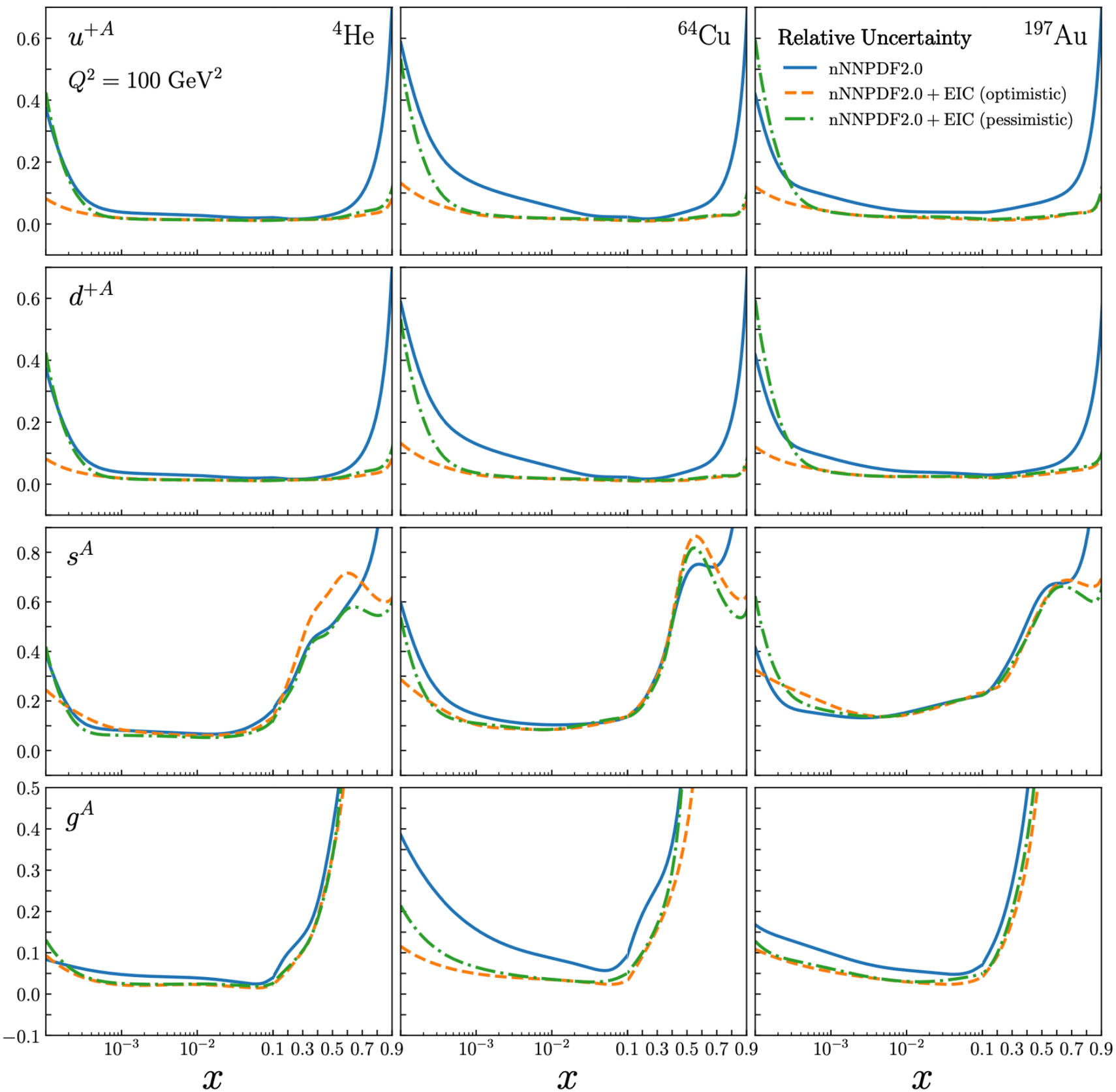
	DIS process		$N_{\rm dat}$	$E_\ell \times E_p$ [GeV]	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]	σ_u [%]	σ_c [%]
1	e^-p	CC	89(89)/89(89)	18×275	140.7	100	2.0/2.0	2.3/5.8
2	e^+p	CC	89(89)/89(89)	18×275	140.7	10	2.0/2.0	2.3/5.8
3	e^-p	NC	181(140)/131(107)	18×275	140.7	100	1.5/2.3	2.5/4.3
4			126(81)/91(70)	10×100	63.2	100	1.5/2.3	2.5/4.3
5			116(68)/92(66)	5×100	44.7	100	1.5/2.3	2.5/4.3
6			87(45)/76(45)	5×41	28.6	100	1.5/2.3	2.5/4.3
7	e^+p	NC	181(140)/131(107)	18×275	140.7	10	1.5/2.3	2.5/4.3
8			126(81)/91(70)	10×100	63.2	10	1.5/2.3	2.5/4.3
9			116(68)/92(66)	5×100	44.7	10	1.5/2.3	2.5/4.3
10			87(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
11	e^-d	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
12			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
13			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
14	e^+d	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
15			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
16			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
17	$e^-{}^4$He	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
18			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
19			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
20	$e^-{}^{12}$C	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
21			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
22			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
23	$e^-{}^{40}$Ca	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
24			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
25			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
26	$e^-{}^{64}$Cu	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
27			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
28			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
29	$e^-{}^{197}$Au	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
30			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
31			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3

Constraints on proton PDFs



EIC will map in detail the **large-*x* quark PDFs**: crucial for high-mass BSM searches at LHC!

Constraints on nuclear PDFs

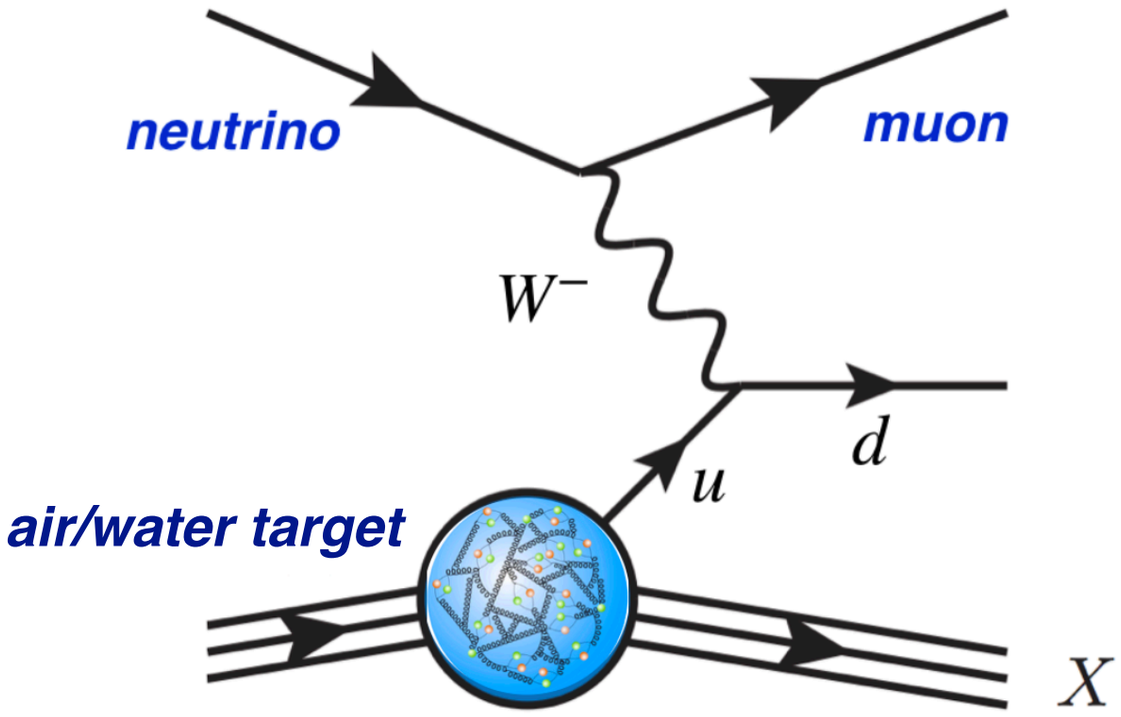


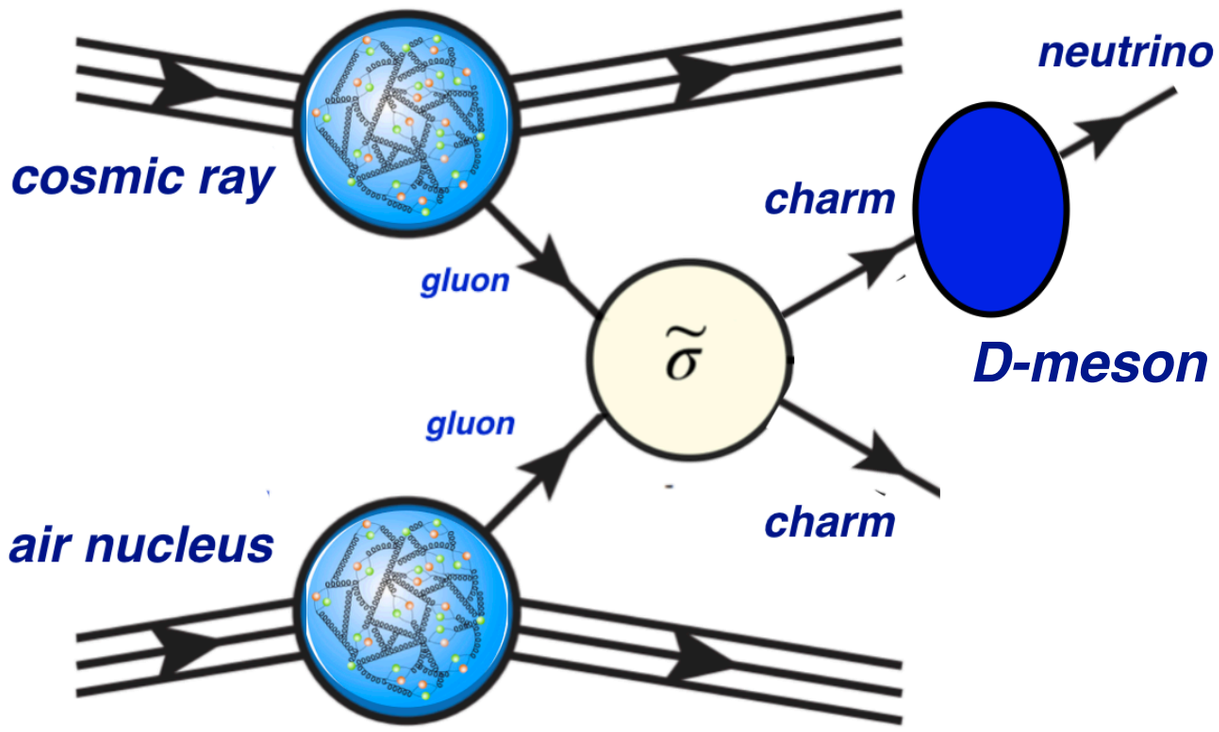
- Precision mapping of nuclear structure, in particular of its ***A* dependence**
- Small nPDF uncertainties at small-*x* are a prerequisite for searches for new QCD phenomena such as **saturation**
- Implications for the p+Pb and Pb+Pb **heavy ion program** at the LHC and future colliders

Neutrino telescopes as QCD microscopes

***signal**: cosmic neutrino - nucleus scattering*

***background**: prompt charm production*



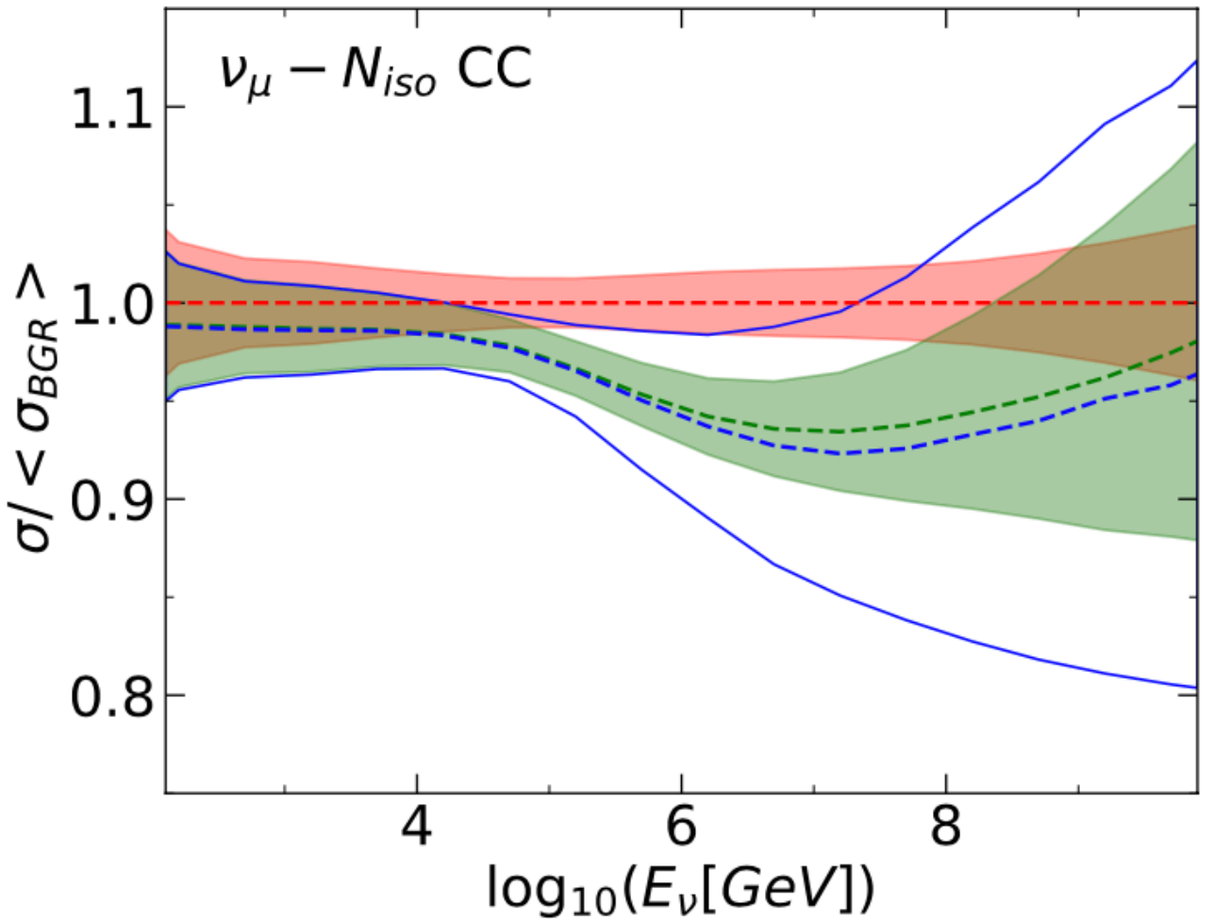


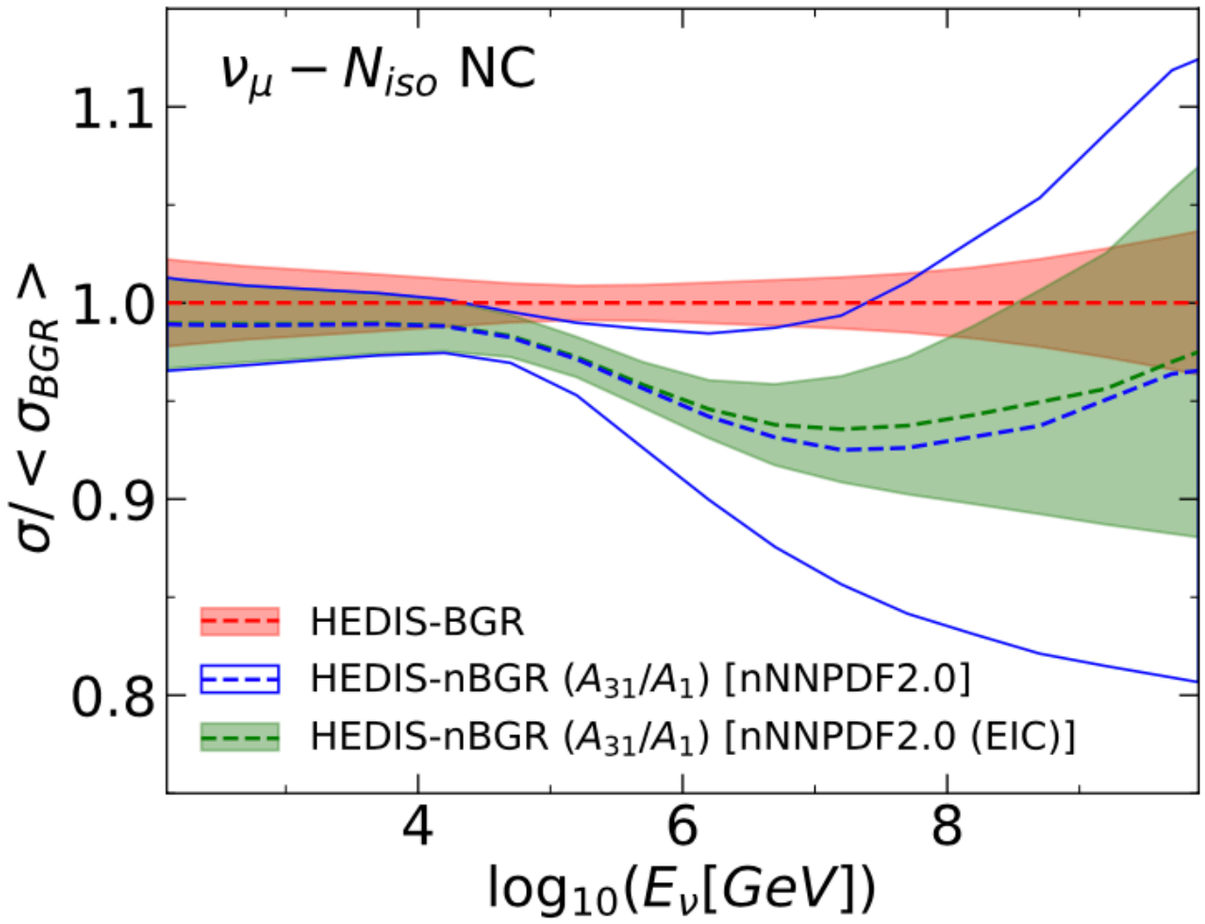
Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ $\mathbf{10^{-8}}$ and **Q** ≃ $\mathbf{M_W}$

Sensitive to **small-*x* gluons** down to **x** ≃ $\mathbf{10^{-6}}$ and **Q** ≃ $\mathbf{M_{charm}}$ in the **centre-of-mass frame**

Nuclear PDF errors represent now **leading theory error** for UHE cross-sections!

Implications for UHE neutrinos



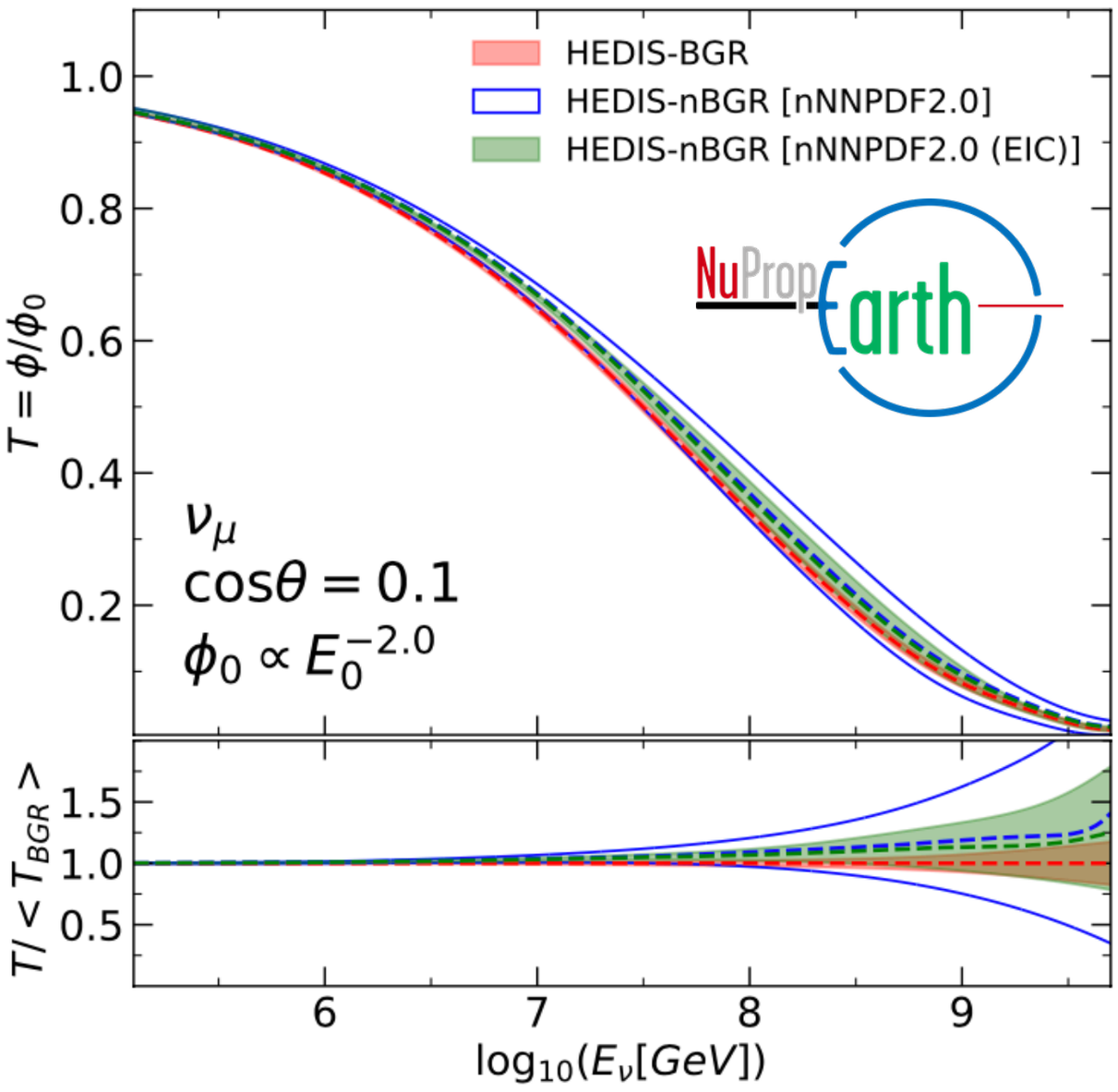


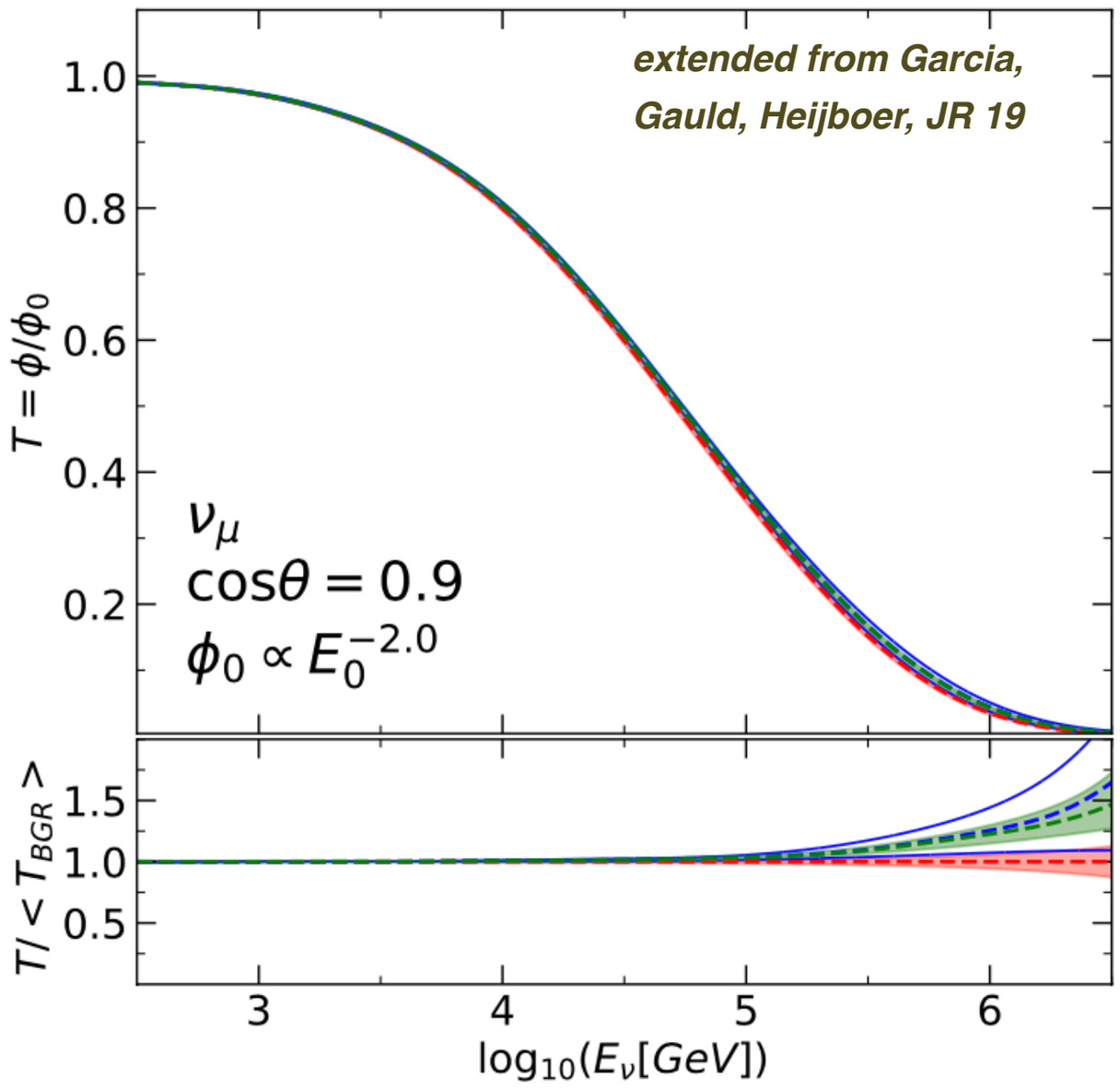
Extend BGR18 calculation of UHE cross-sections with the **nPDFs constrained by EIC projections**

BGR: Bertone, Gauld, JR 18

Significant reduction of **nPDF errors to the UHE cross-sections** thanks to EIC!

Implications for UHE neutrinos



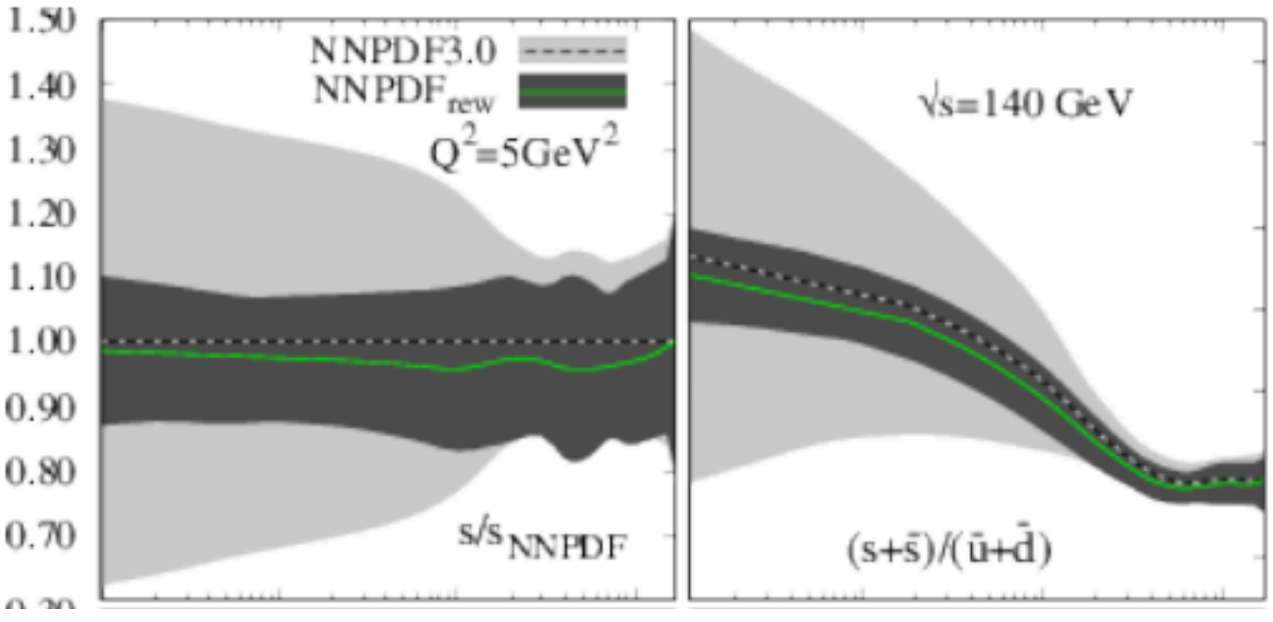


Implemented the nNNPDF2.0+EIC nPDFs into **NuPropEarth,** a code that simulates the propagation of UHE neutrinos through Earth and evaluated the **attenuation rates:** also there marked reduction of theory errors in the attenuation calculation

beyond inclusive reactions

At the EIC, the global proton+nuclear QCD analysis presented here should be extended to **semi-inclusive reactions** and those based on **jets and heavy quarks**

Processes / Topics	Inclusive	Semi-Inclusive	Jets, Heavy Quarks	Exclusive	Diffractive, Forward Tagging
Global properties & parton structure	**incl. SF**	**h, hh**	**jet, Q**	**excl. $Q\overline{Q}$**	**incl. diffraction, tagged DIS on D/He**
Multidimensional Imaging		**h**	**jet, di-jet, jet+h, Q, $Q\overline{Q}$**	**DVCS, DVMP, elast. scattering**	
Nucleus	**incl. SF**	**h, hh**	**jet, di-jet, Q, $Q\overline{Q}$**	**coh. VM, di-jet, h, hh, D/He FF**	**diffr. SF, incoh. VM, di-jet, h, hh, nucl. fragments**
Hadronization		**h, hh, jet+h**	**jet, Q, $Q\overline{Q}$**		
Other fields	**incl. SF with e^+, $\sigma^{tot}_{\gamma A}$**	**charged curr. DIS, $\sigma_{\gamma A \to hX}$**		$\sigma^{elast}_{\gamma A}$	$\sigma^{diffr}_{\gamma A}$



from EIC Yellow Report

for instance, **proton strangeness** can be constrained by SIDIS measurements

Borsa et al (EIC YR)

Summary and outlook

- The Electron Ion Collider will **revolutionise our understanding of the strong interactions** and open new frontiers in global QCD analysis of proton and nuclear structure & fragmentation

- We have quantified the impact of EIC pseudo-data into both the proton and nuclear PDFs by means of a **self-consistent approach** whereby the proton PDFs fix the *A=1 limit* of the nuclear PDFs

- Implications for Snowmass: connections with **Energy Frontier** (LHC physics with improved large-*x* PDFs for BSM at LHC, better nPDFs for heavy ion collisions) and with **Cosmic Frontier** (neutrino astrophysics**,** reduced TH uncertainties in UHE cross-sections and attenuation rates)

- Our study just **scratches the potential of the EIC for QCD fits**, many more exciting possibilities will become a reality!