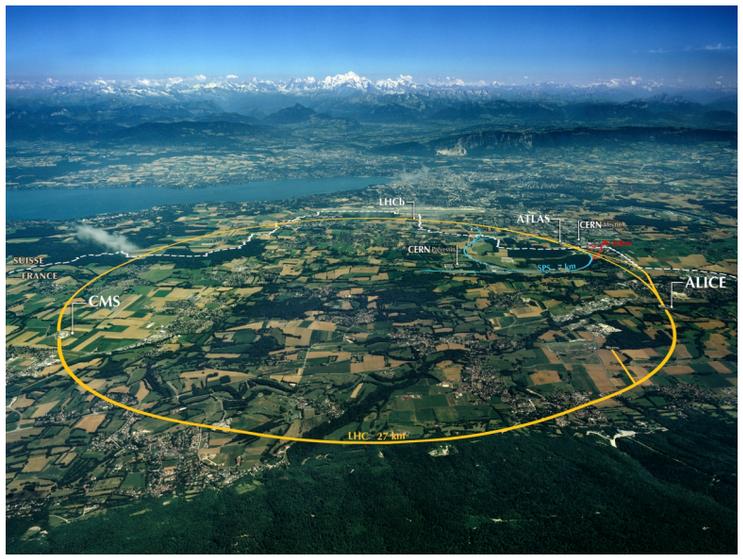
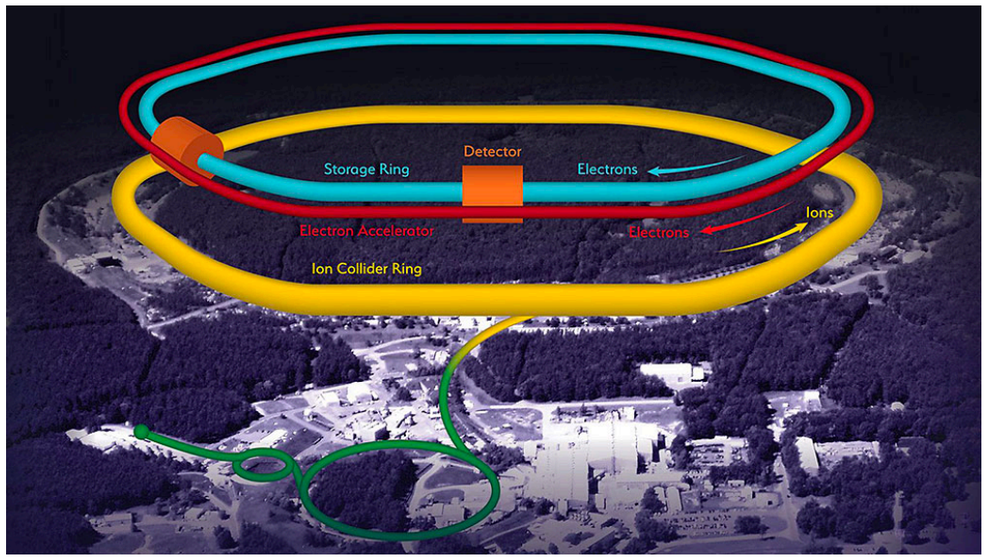
Proton and nuclear structure at the cross-roads between LHC and EIC

Juan Rojo, VU Amsterdam & Nikhef

Kick-off meeting: Synergies between the EIC and the LHC

CERN, 20/06/2022

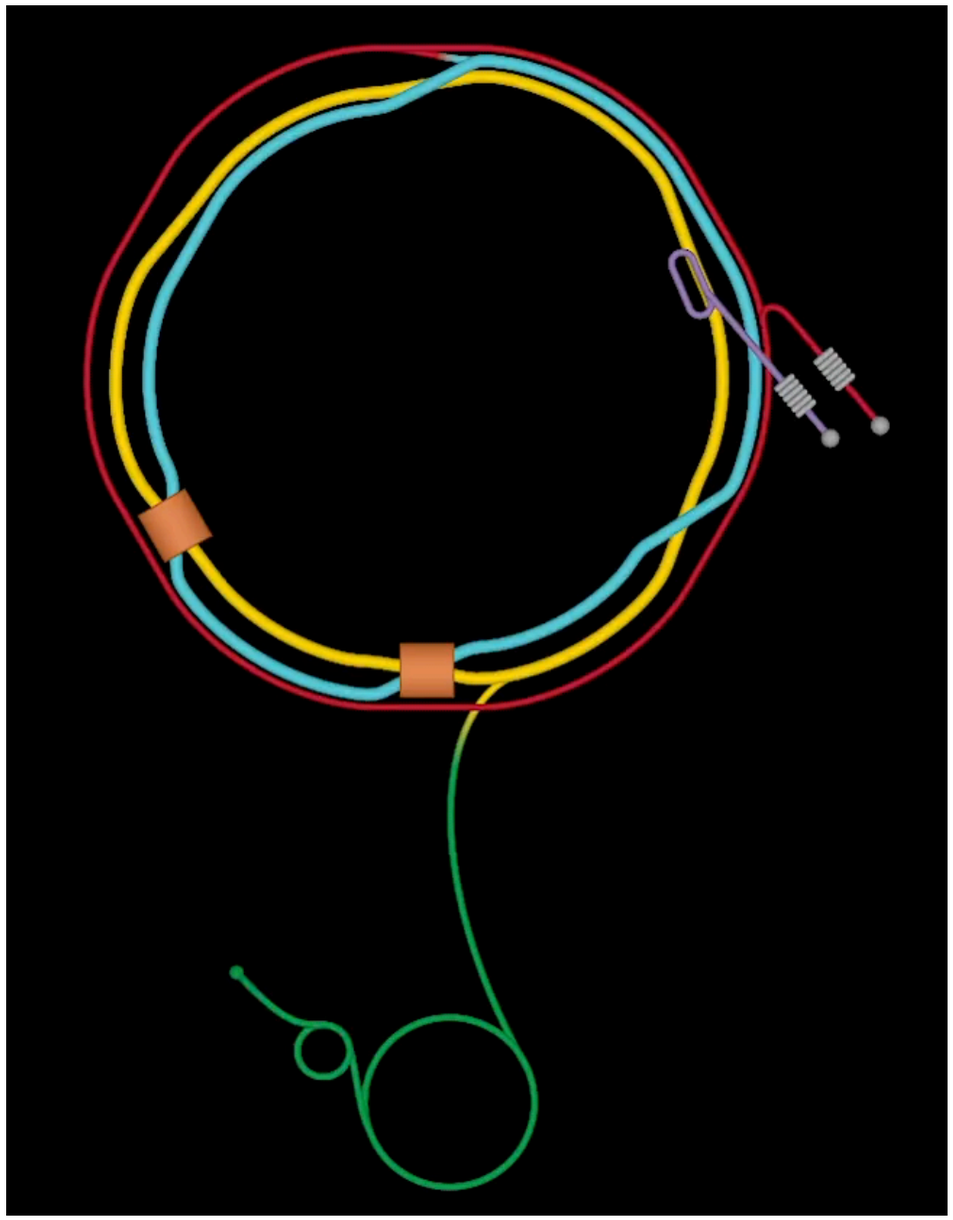




Global (n)PDF fits and the EIC

- **Deep-inelastic scattering** data provides the backbone of modern (n)PDF determinations, including measurements on **deuteron** and **nuclear targets**

- A key difference between proton and nuclear PDF fits is the **lack of ``HERA'' collider-DIS** in the latter: a gap that will be closed by the EIC



Global (n)PDF fits and the EIC

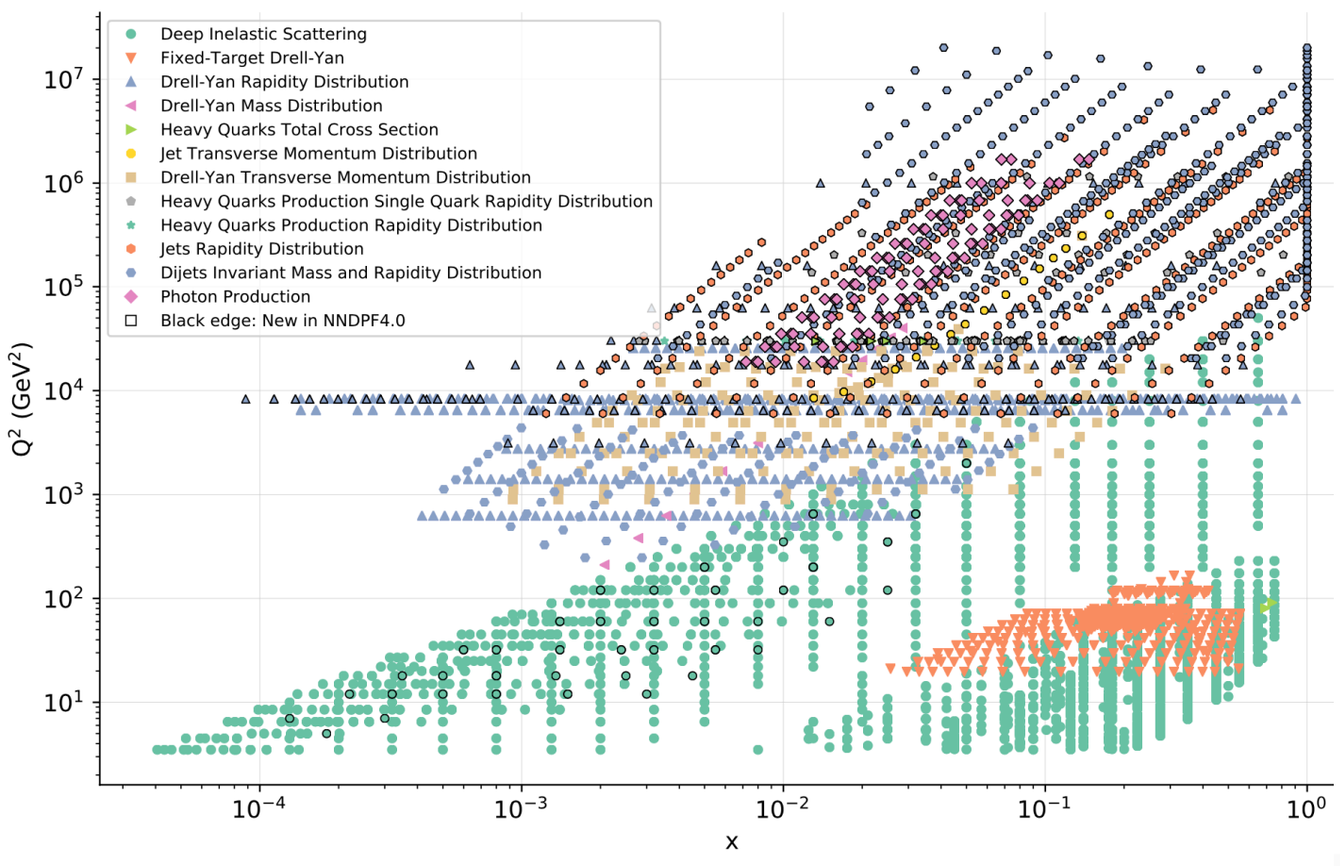
- **Deep-inelastic scattering** data provides the backbone of modern (n)PDF determinations, including measurements on **deuteron** and **nuclear targets**

- A key difference between proton and nuclear PDF fits is the **lack of ``HERA'' collider-DIS** in the latter: a gap that will be closed by the EIC

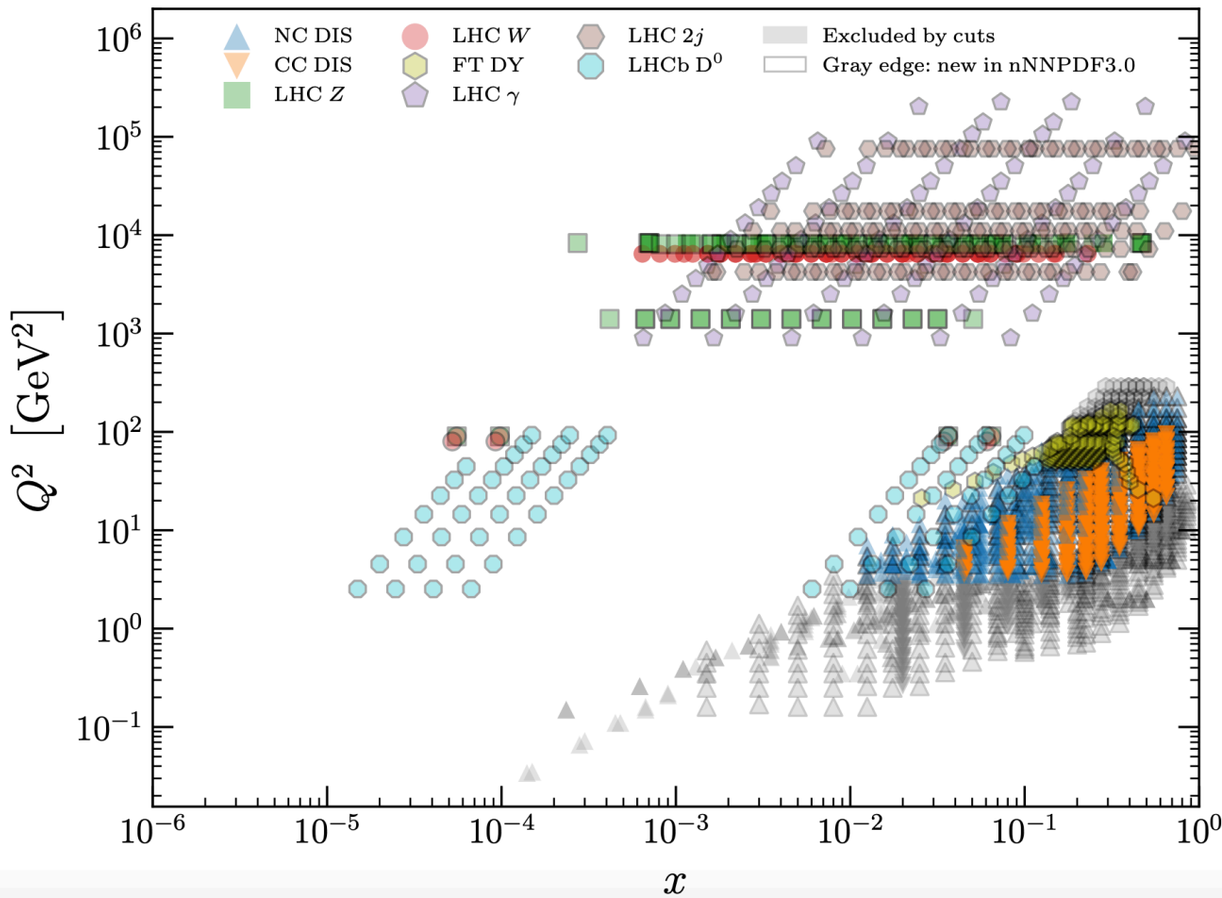
- Most data available for nPDF fits **only sensitive to A=208,** little constraints for other *A* values

- Proton and nuclear PDFs are determined **independently,** which is increasingly unjustified

Proton PDFs: NNPDF4.0 dataset

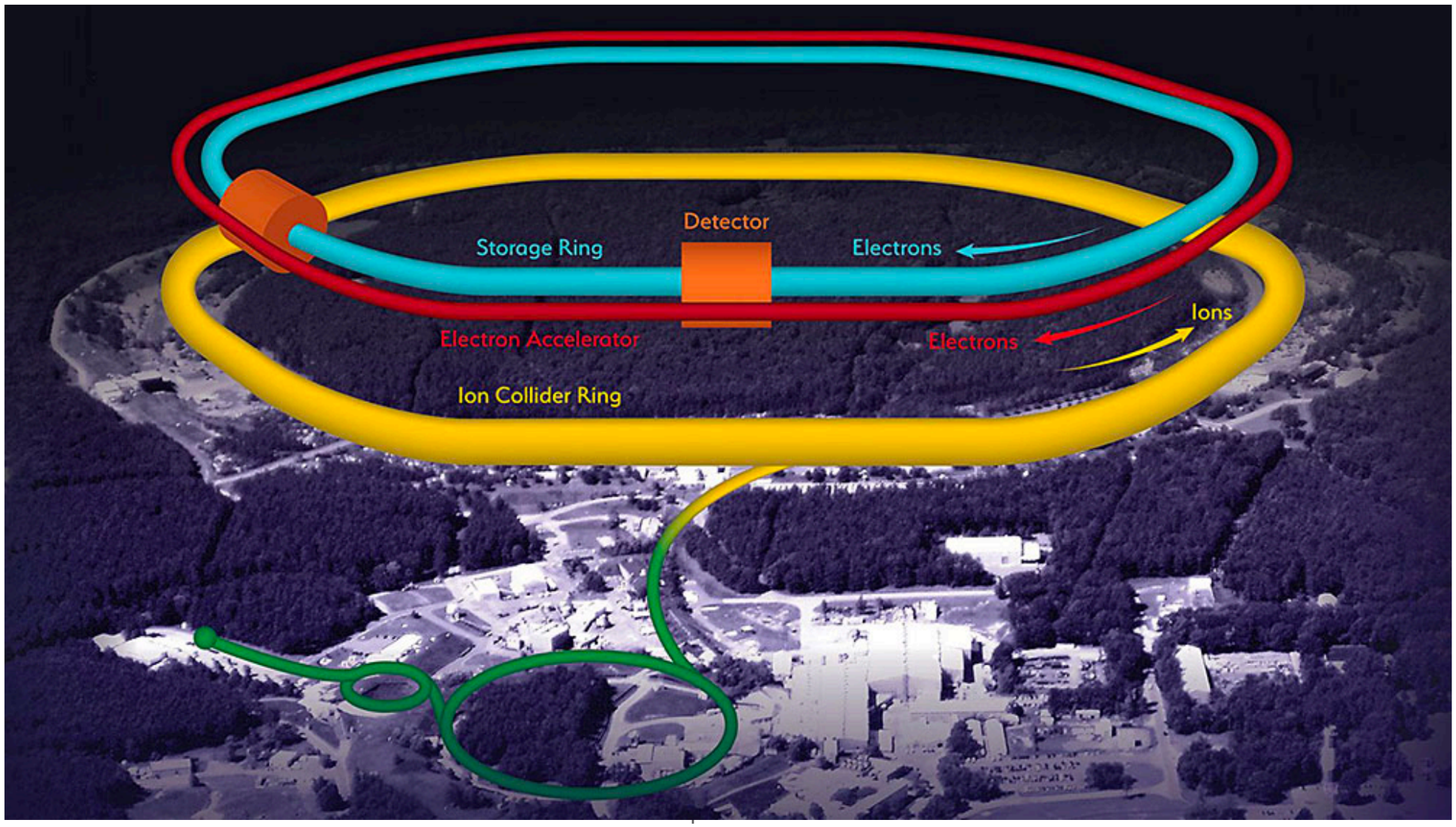


Nuclear PDFs: nNNPDF3.0 dataset

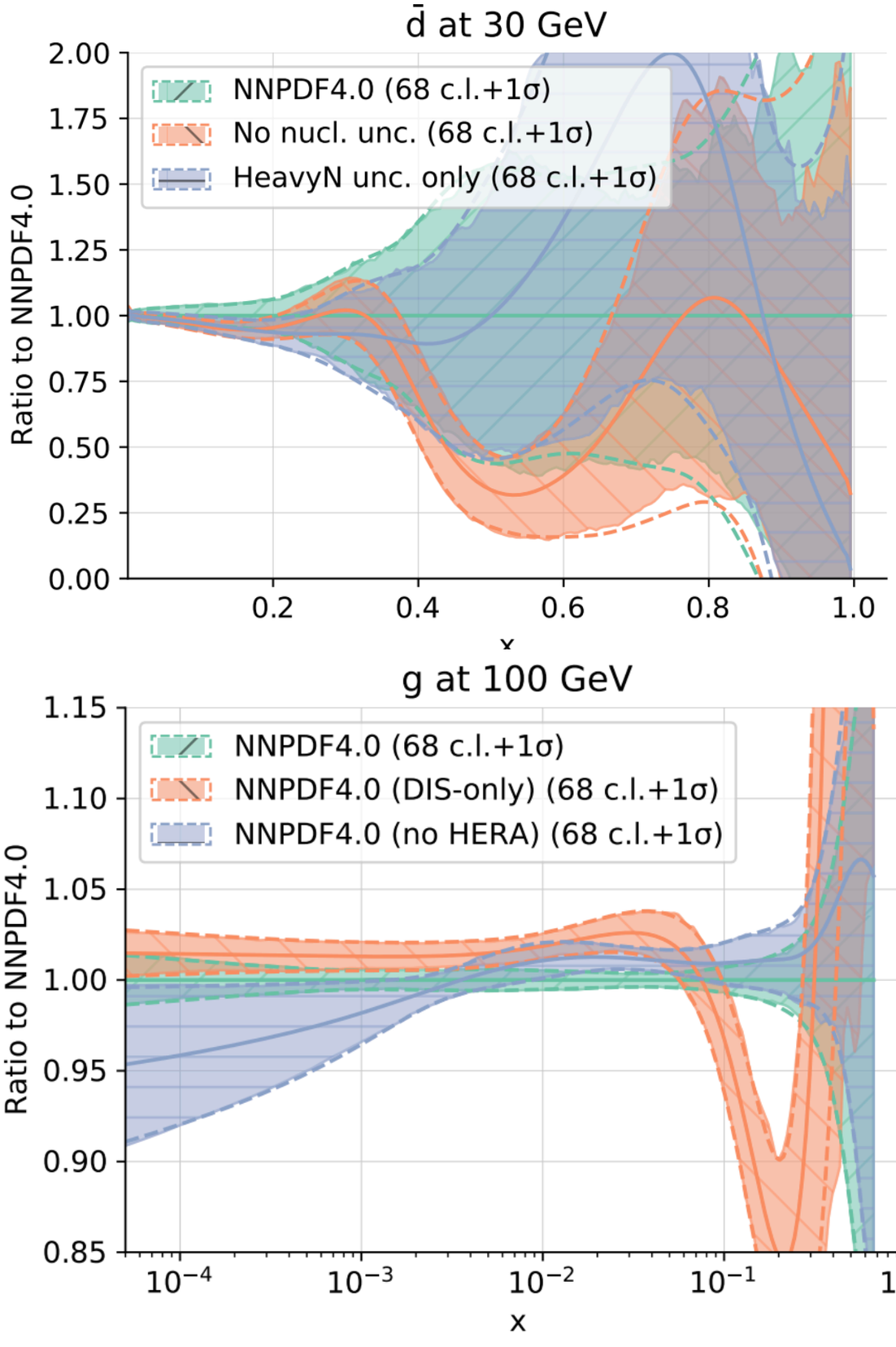


Outline

- ☑ PDF and nPDF impact of **EIC inclusive** measurements
- ☑ PDF impact of **EIC semi-inclusive** measurements
- ☑ Searches for **New Phenomena** both within the SM and beyond it
- ☑ Towards **integrated global QCD analyses** at the EIC



Global PDF fits and the EIC

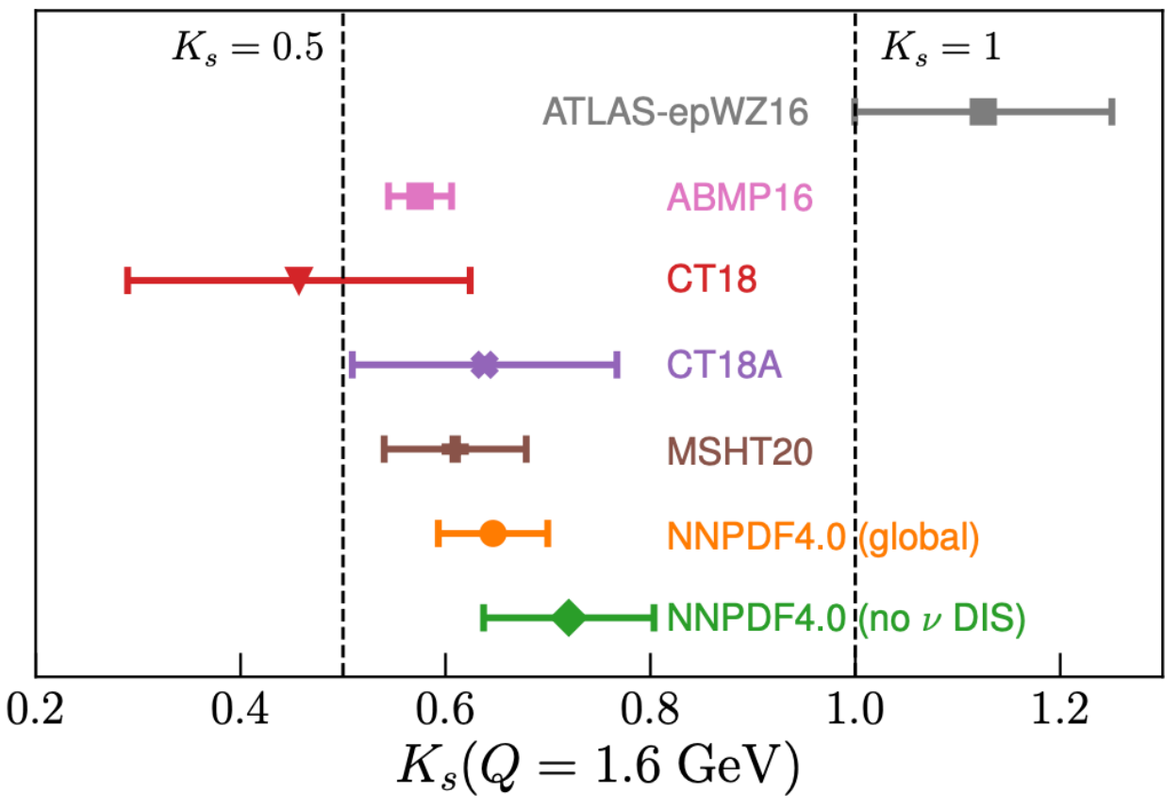


- ☑ Deuteron and nuclear data are key to constrain **proton quark flavour separation for** $x > 0.01$, requires accounting for nuclear corrections

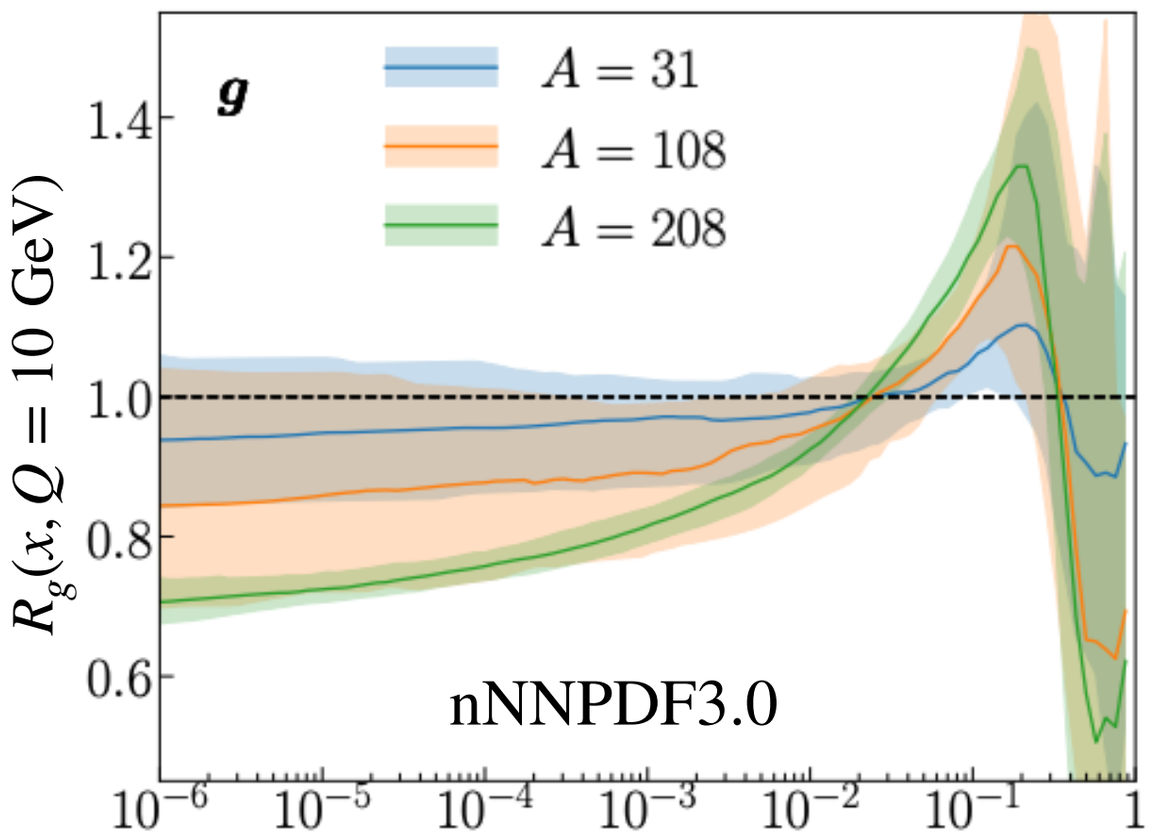
- ☑ The **no-HERA proton PDFs** are consistent with global analysis, with larger uncertainties

- ☑ **(Anti-)strange PDF** less constrained without neutrino (CC) DIS data

$$K_s \equiv \frac{\int_0^1 dx x[s(x,Q)+\bar{s}(x,Q)]}{\int_0^1 dx x[\bar{u}(x,Q)+\bar{d}(x,Q)]}$$



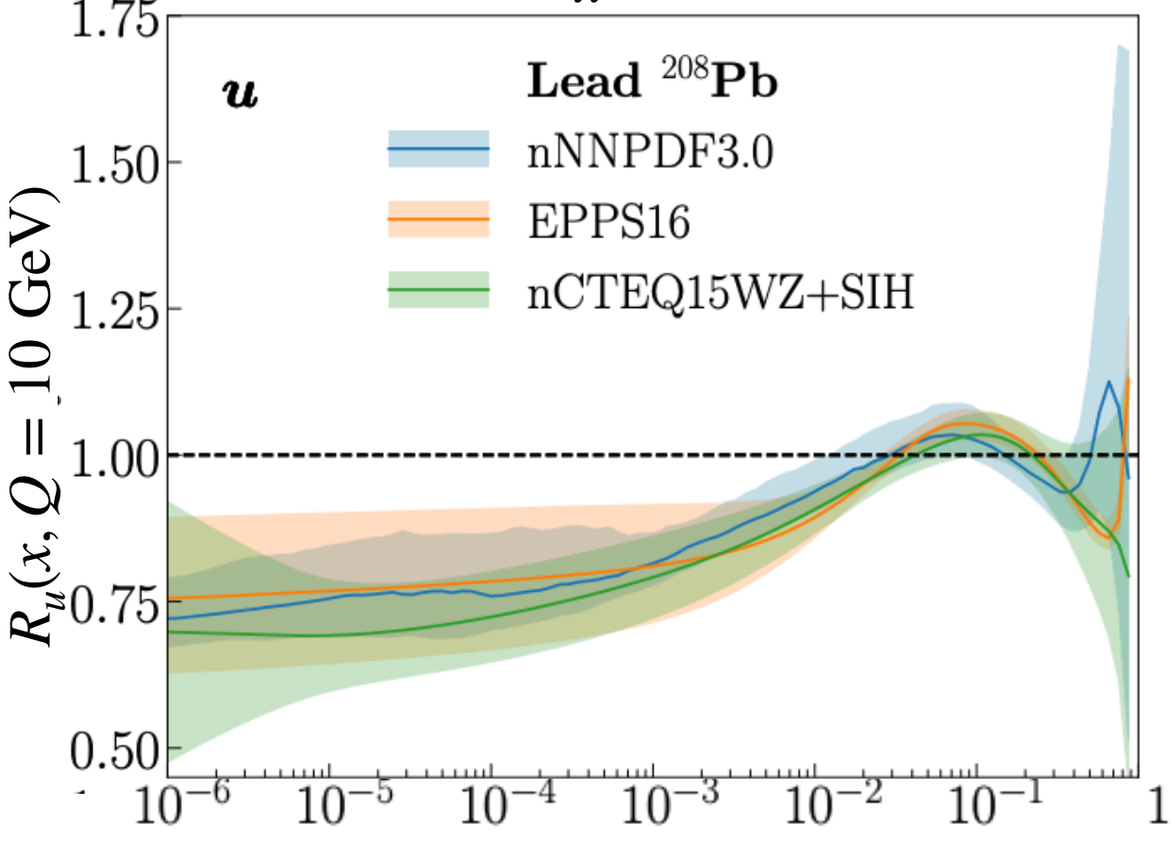
Global nPDF fits and the EIC

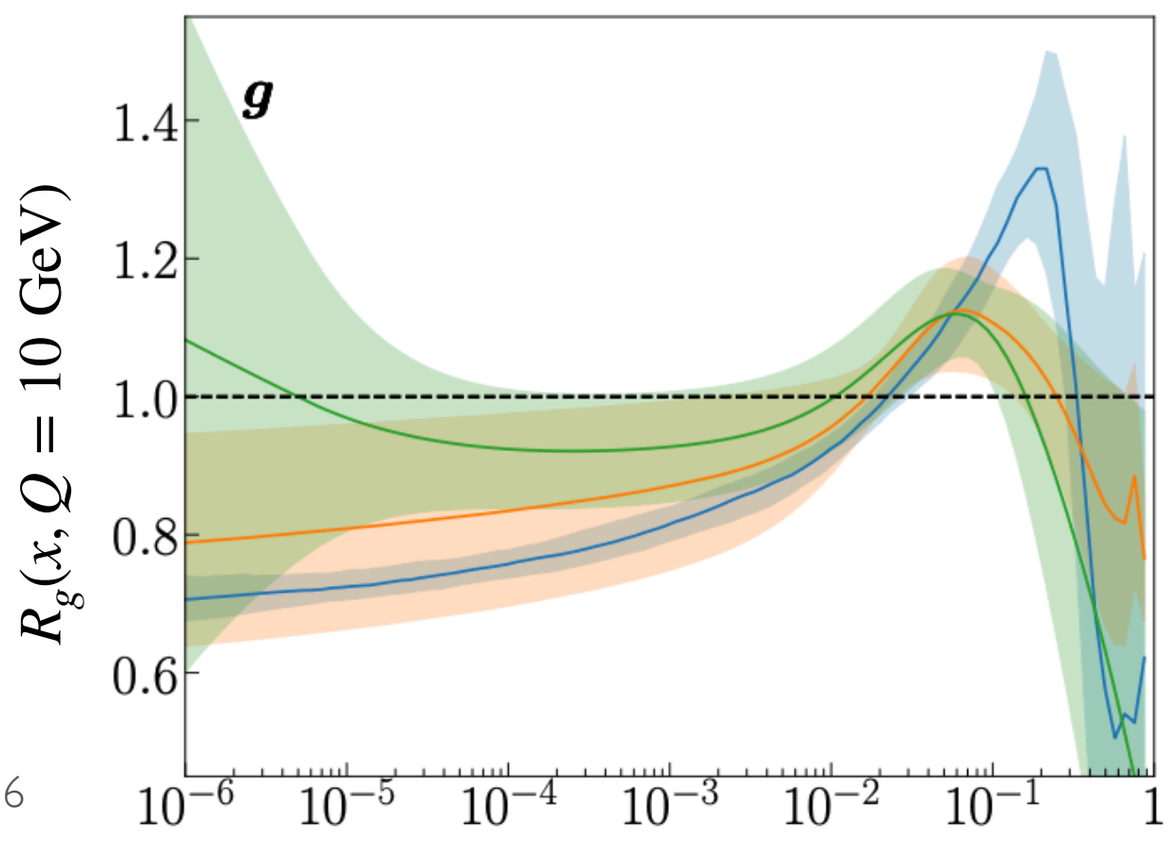


- ***A*-dependence** of nuclear PDFs poorly constrained: challenging to understand *A*-dependence of **nuclear modifications**

- **Small-*x* nPDF shadowing** in the gluon sector from *D*-meson production, affected by large MHOUs: need independent validation from **cleaner DIS data**

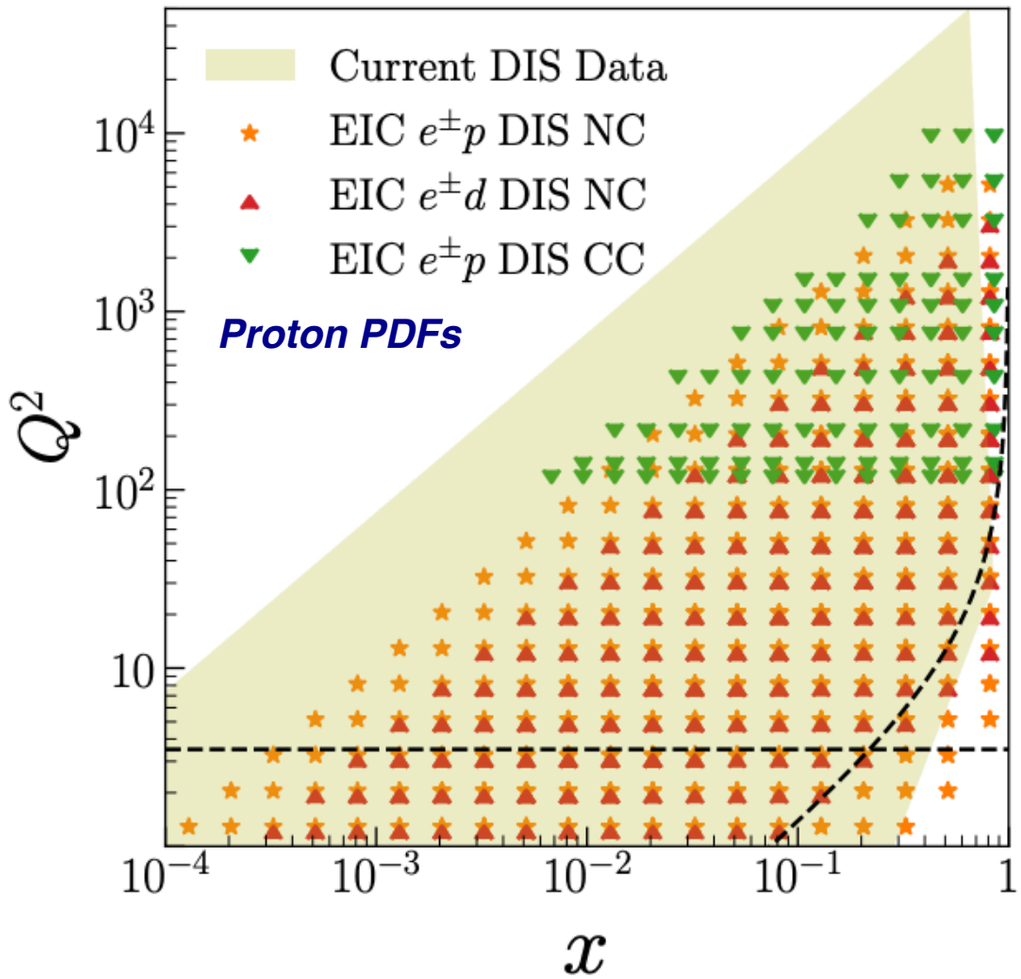
- Inclusive DIS measurements on nuclear targets are low-scale, wo correlations, little charm SF available: EIC will bring **nPDF analyses to a new dimension**

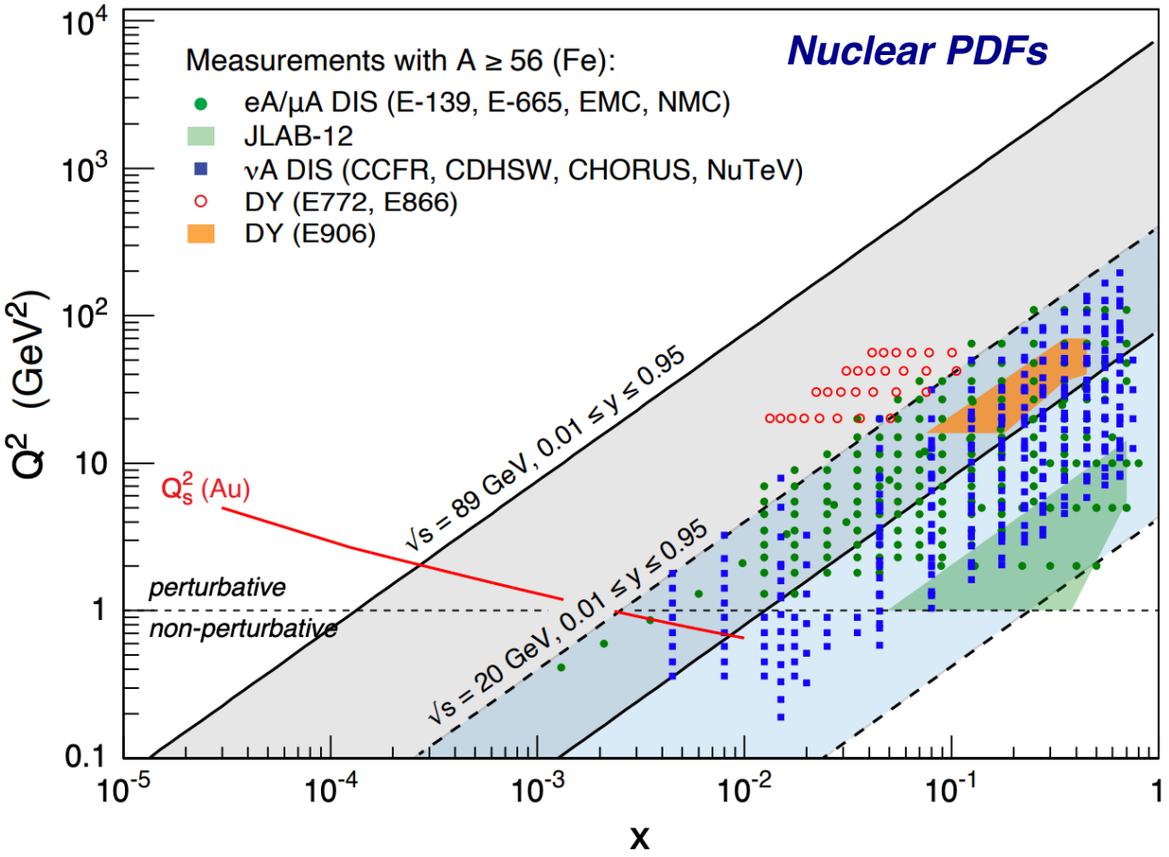


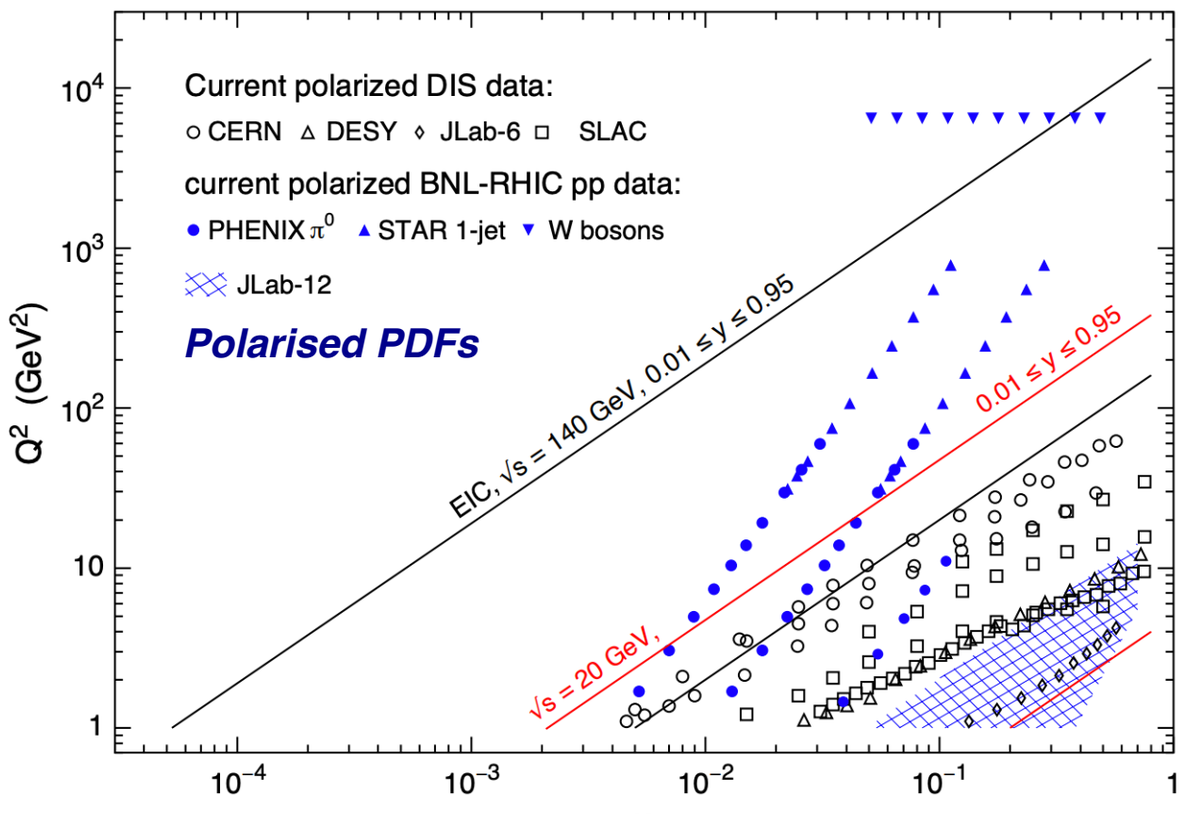


EIC inclusive DIS measurements

- ☑ Proton PDFs: improved **coverage of medium and large-*x* region**, complements existing data, extends **F_2^c to large-*x***
- ☑ Nuclear PDFs: **extends range** as compared to available DIS data, many **different nuclei**
- ☑ Exciting program of **polarised measurements**, but limited synergy with LHC (exception: LHCSpin)







EIC inclusive DIS measurements

	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
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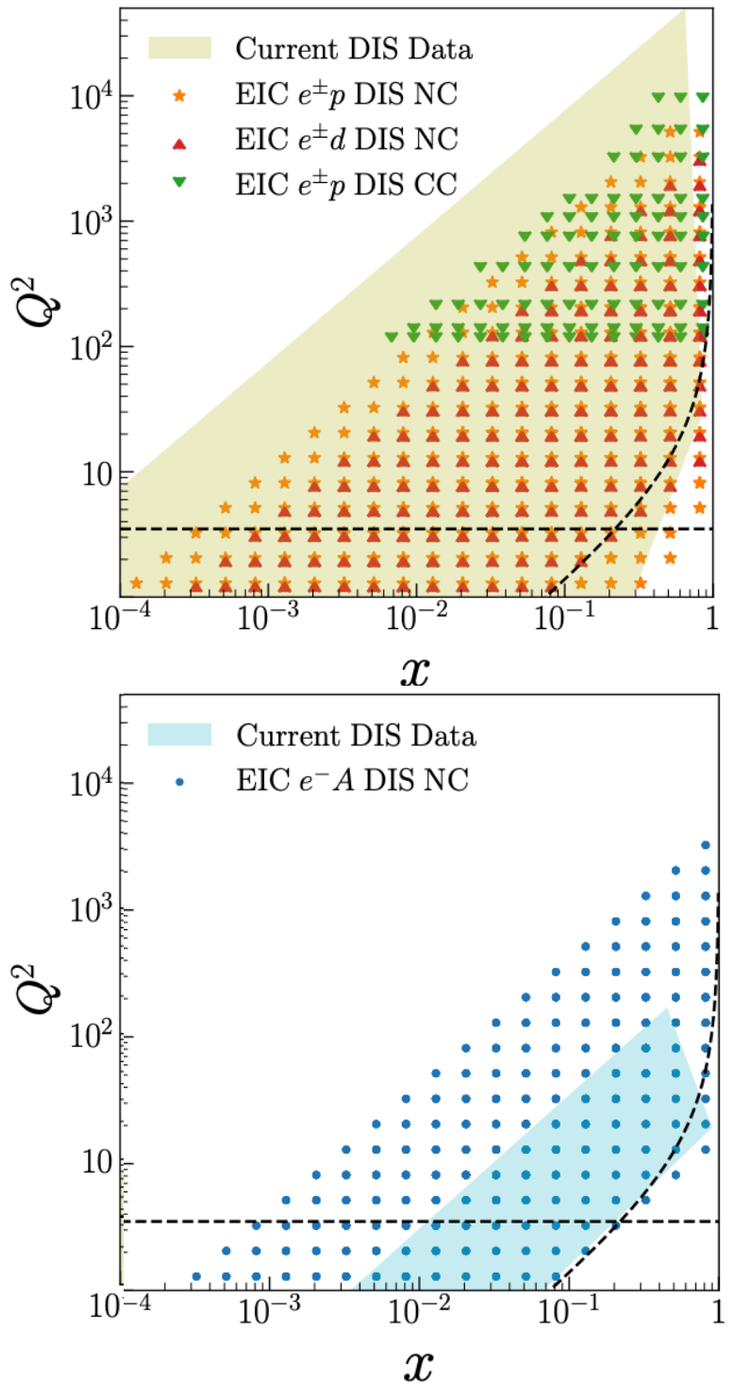
11	e^-d	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
12			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
13			76(45)/76(45)	5×41	28.6	10	1.5/2.3	2.5/4.3
14	e^+d	NC	116(92)/116(92)	18×110	89.0	10	1.5/2.3	2.5/4.3
15			107(83)/107(83)	10×110	66.3	10	1.5/2.3	2.5/4.3
16			76(45)/76(45)	5×41	28.6	10	1.5/2.3	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



Abdul-Khalek, Ethier, Nocera, JR (2021)

(similar pseudo-data as in Yellow Report exercise)

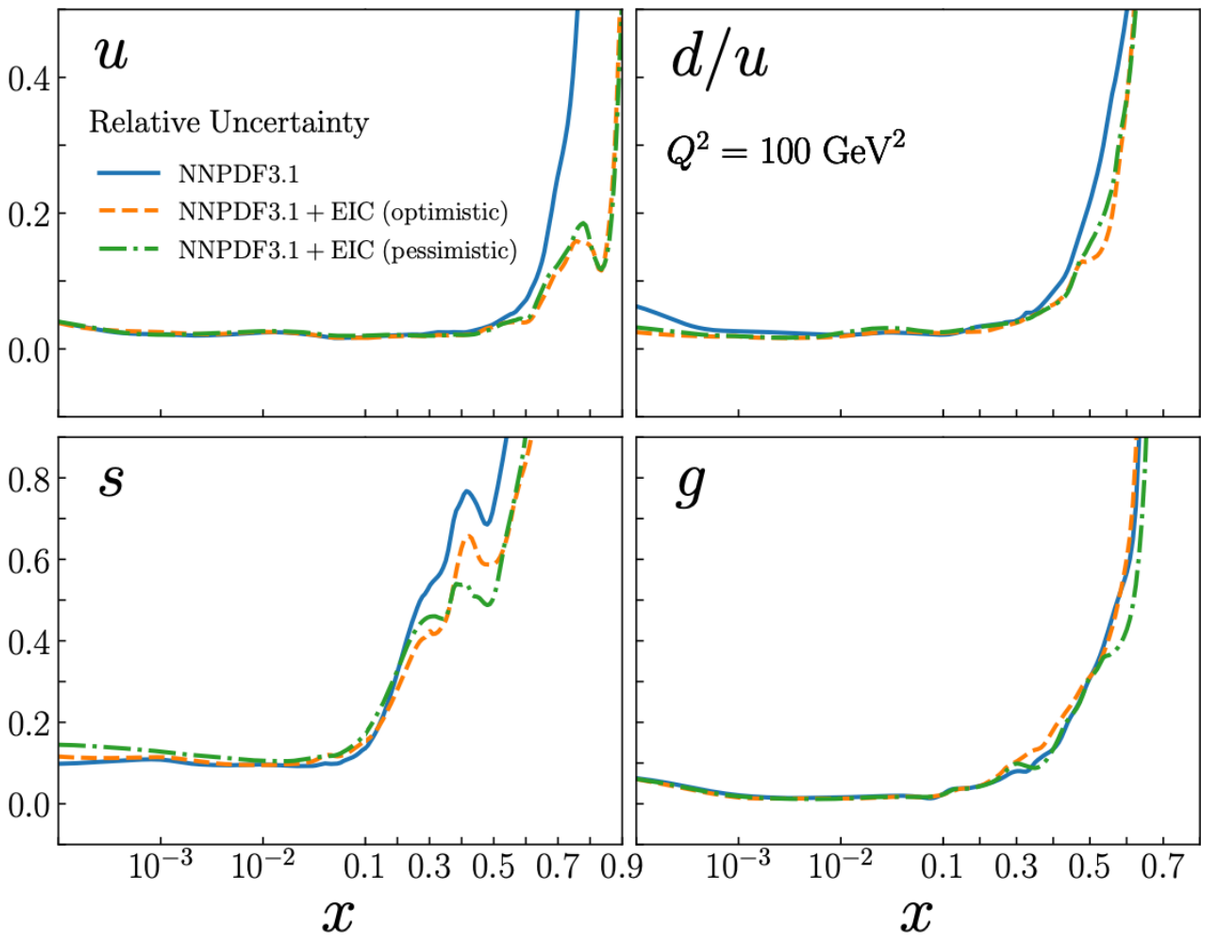
EIC inclusive DIS measurements

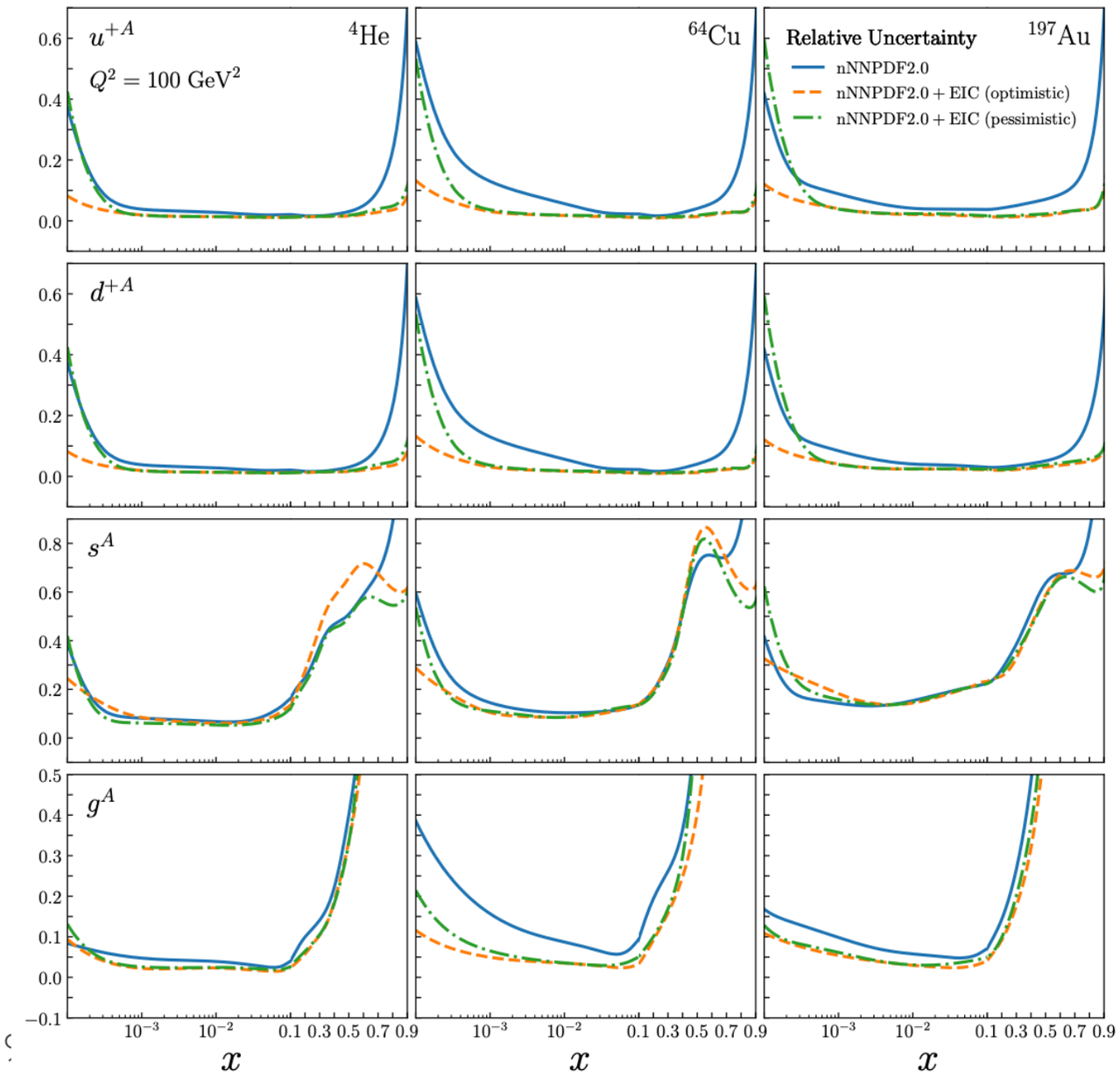
☑ **Self-consistent determination** of the impact of EIC inclusive SFs on proton and nuclear PDFs

☑ First include them in proton baseline (NNPDF3.1), subsequently used as ***A*=1 boundary condition** for the nuclear fit (based on nNNPDF2.0)

Abdul-Khalek, Ethier, Nocera, JR (2021)

☑ Keep track of **correlations between *A*=1 and *A* > 1:** cannot treat PDFs and nPDFs as independent





moderate impact on proton PDFs, localised at large-x

large reduction of nPDF uncertainties, specially at large and small-x and at intermediate A values, little pull on strangeness

EIC inclusive DIS measurements

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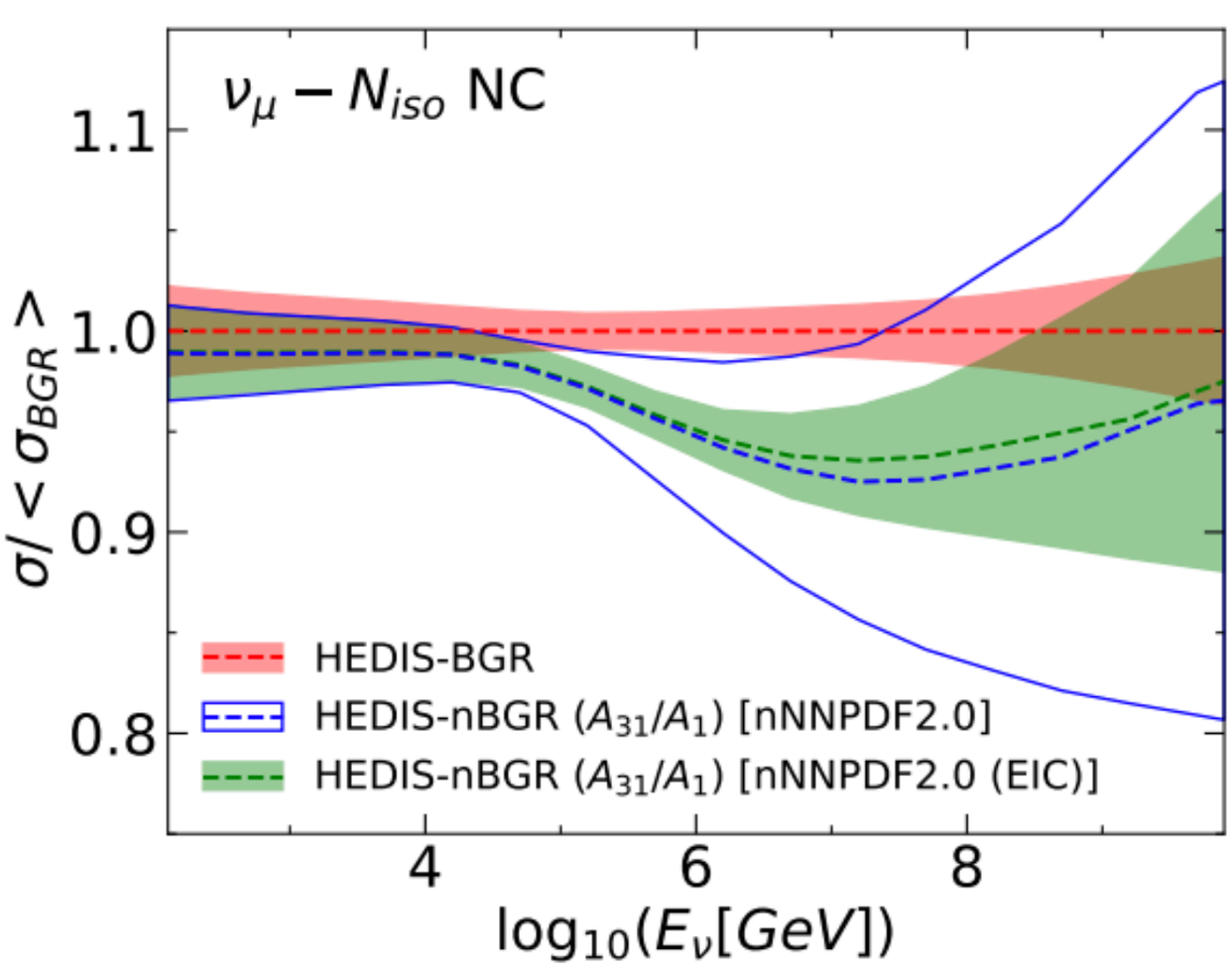
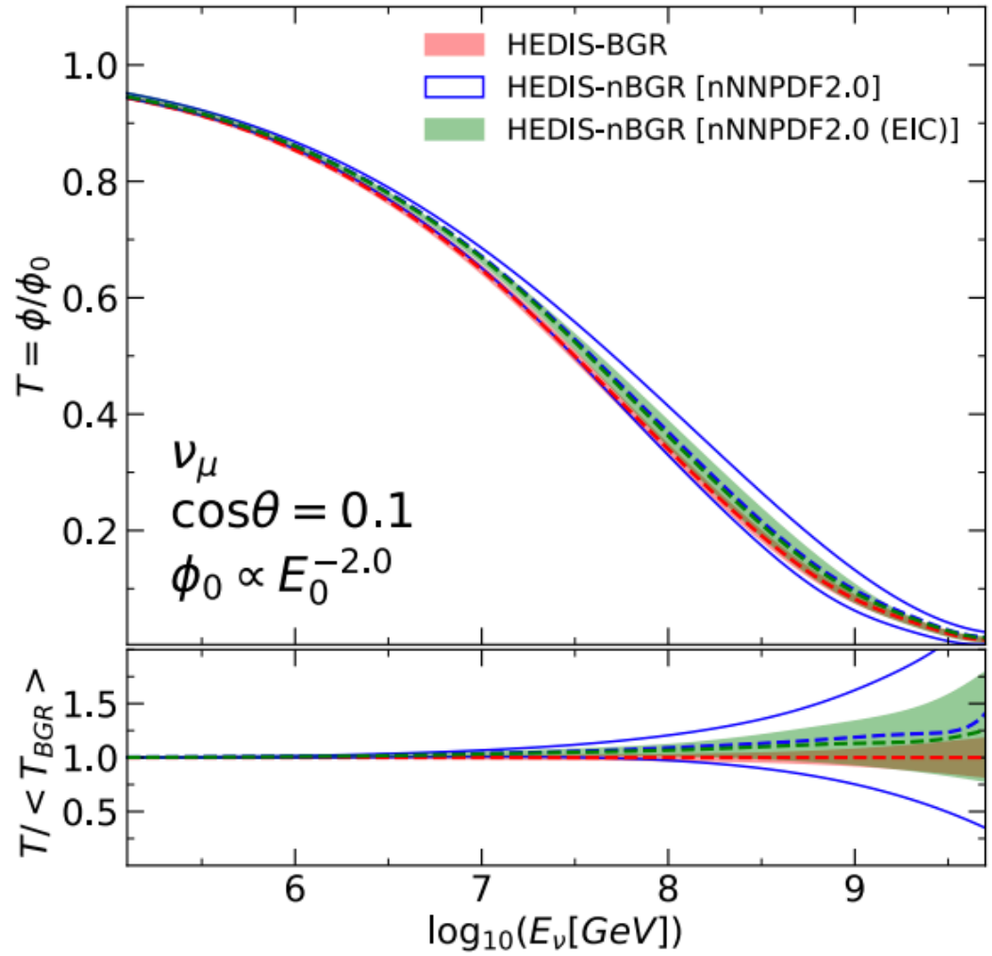
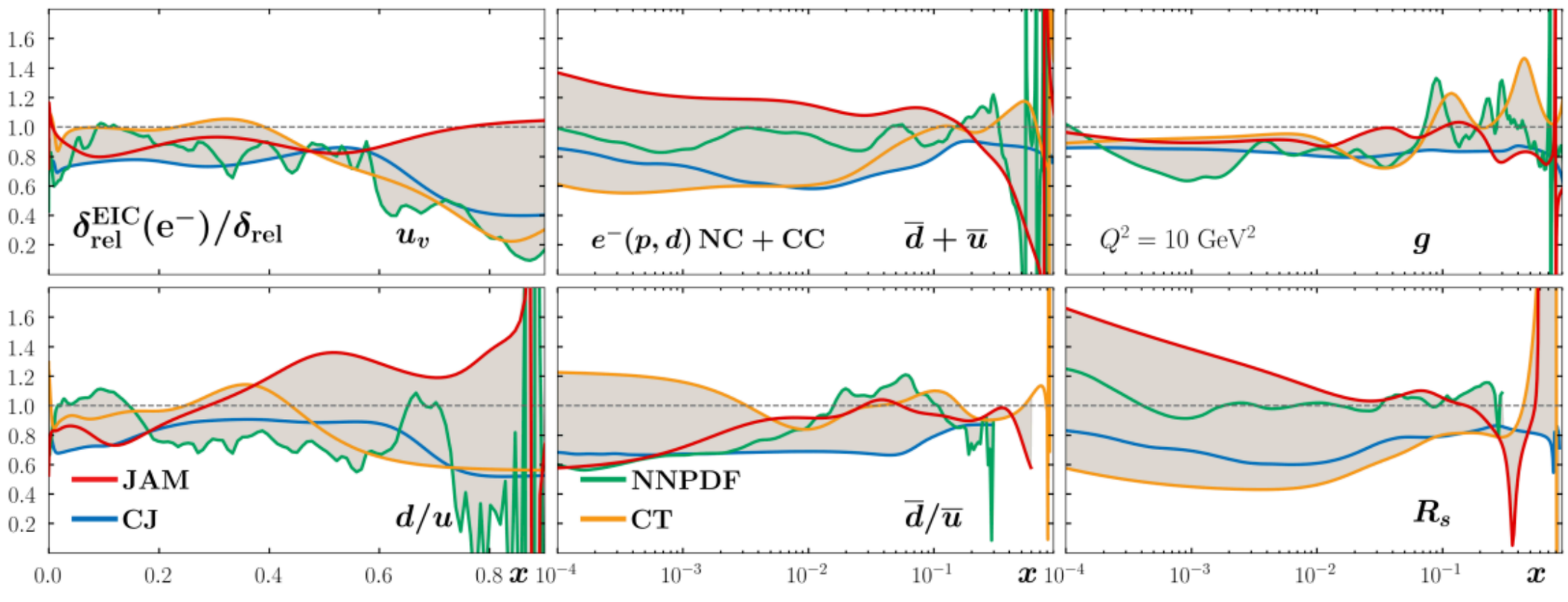
- ☑ First include them in proton baseline (NNPDF3.1), subsequently used as ***A*=1 boundary condition** for the nuclear fit (based on nNNPDF2.0)
- ☑ Keep track of **correlations between *A*=1 and *A* > 1:** cannot treat PDFs and nPDFs as independent

Improved predictions for DIS on nuclear targets key for UHE neutrino astrophysics: scattering cross-sections and flux attenuation rates





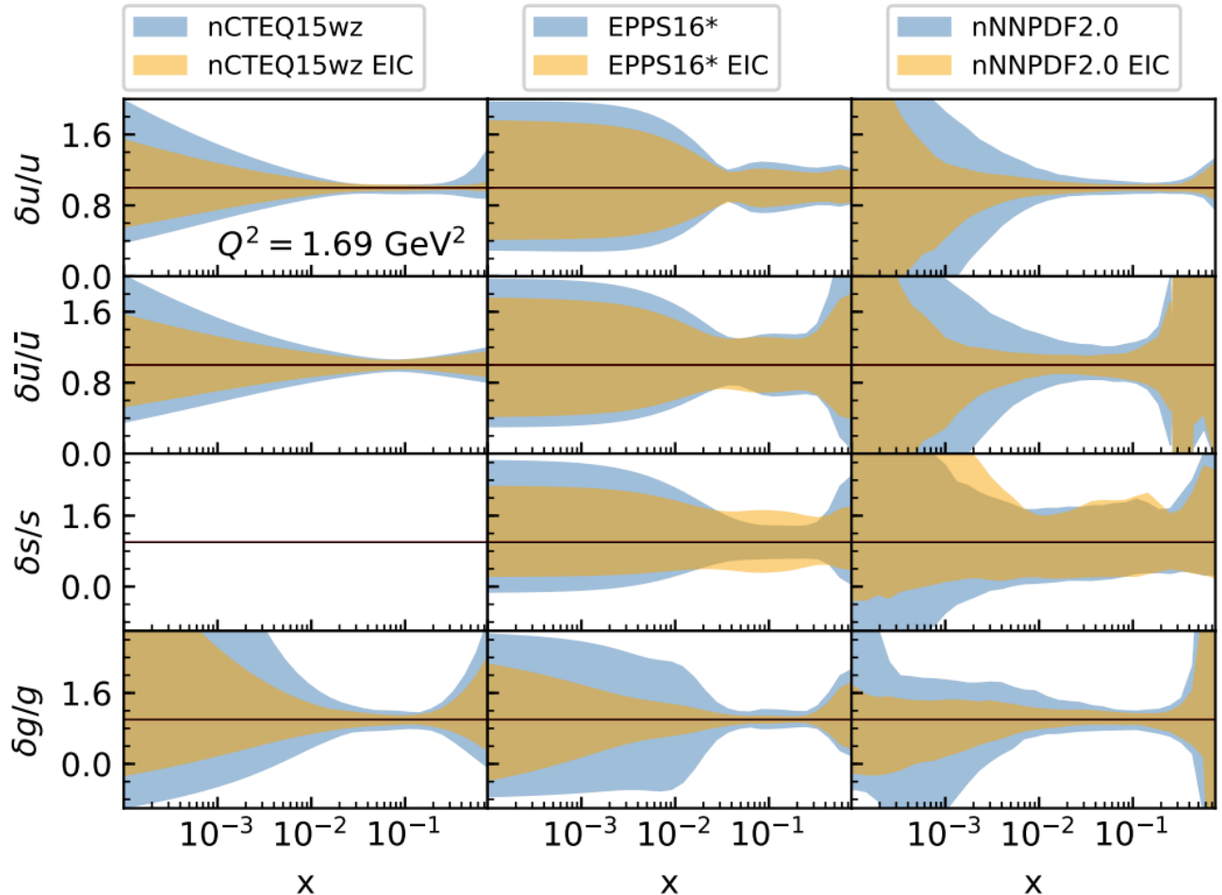
EIC inclusive DIS measurements



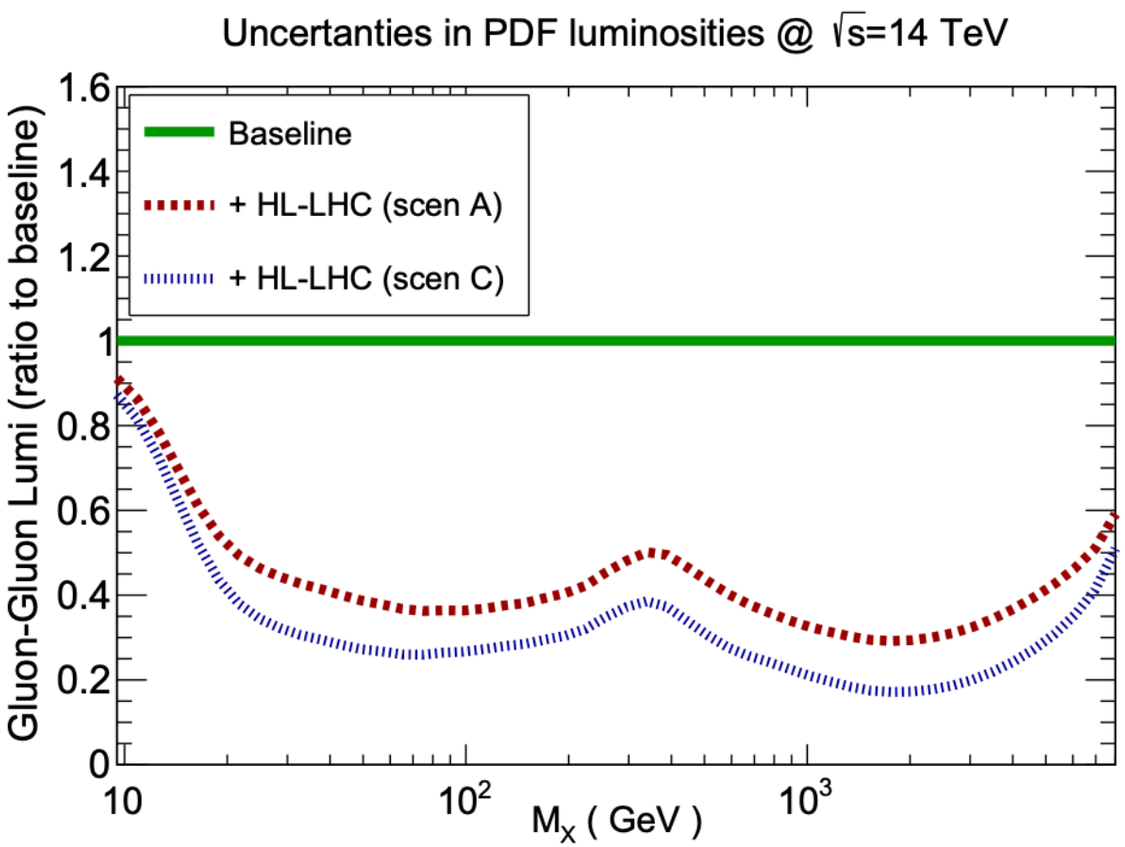
- Impact projections of EIC inclusive SFs **depend on choice of baseline PDF set** (differences in prior dataset, fitting methodologies etc)

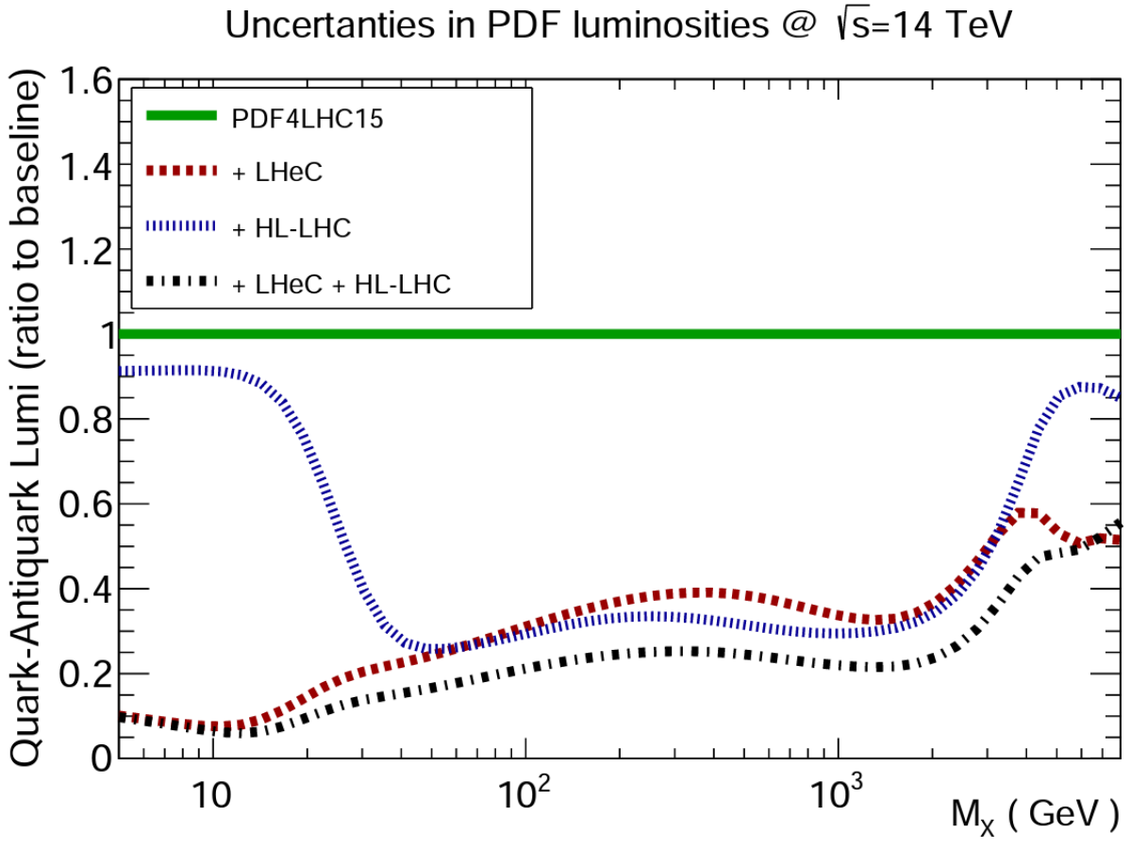
- Specially in the **nuclear case**, marked improvements are reported in all cases

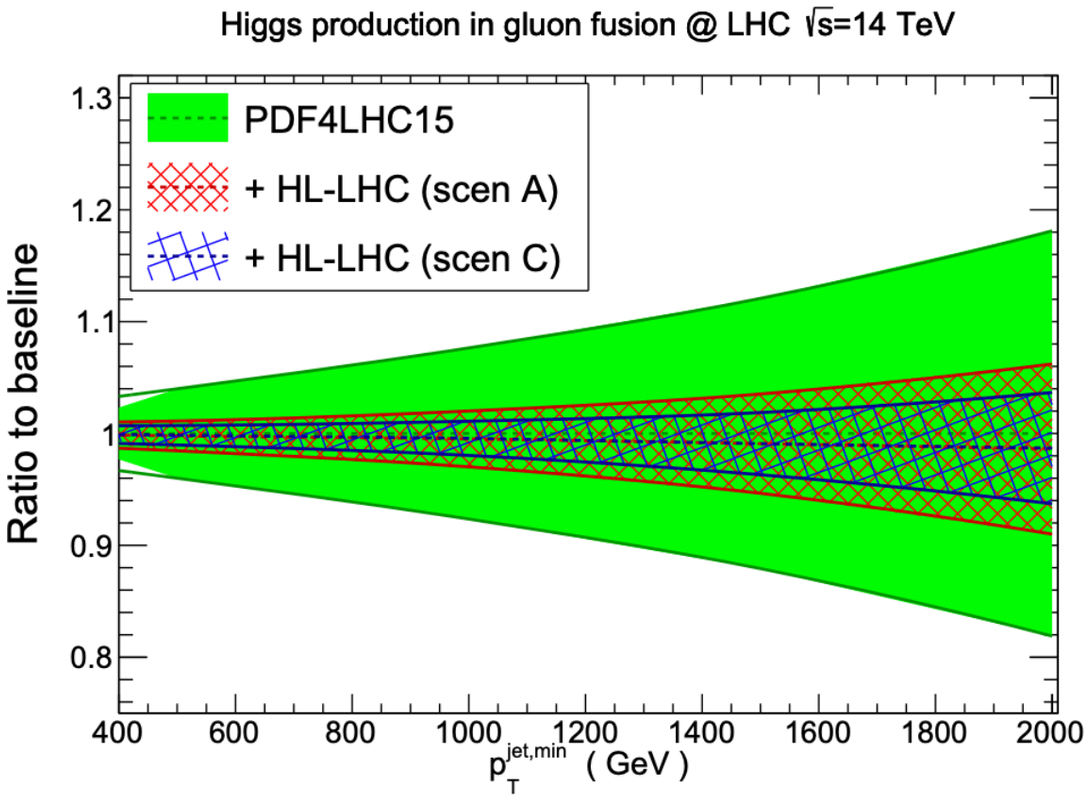
- Would be interesting to redo the exercise with **latest releases** of the three global nPDF sets



Comparison with HL-LHC projections







- ☑ Projections for the **HL-LHC Yellow Reports** quantify PDF improvements from future LHC data
- ☑ These projections account only for ``standard'' processes for PDF constraints (e.g. DY, top, jets): one could do better by considering other processes
- ☑ Crucial to account for **theory uncertainties**, *e.g.* MHOUs, when interpreting future LHC measurements

Gao et al,18

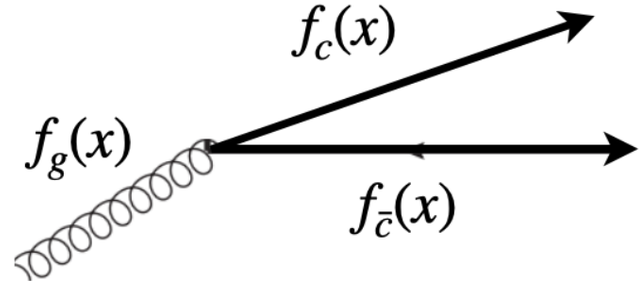
EIC and intrinsic charm

common assumption: the proton wave function contains intrinsic up, down, strange (anti-)quarks but **no intrinsic charm quarks**

the charm PDF is then **generated perturbatively** from radiation off gluons and quarks

$$f_c^{(n_f)} = 0 \quad \rightarrow \quad f_c^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

3FNS charm — *4FNS charm* — *4FNS gluon*



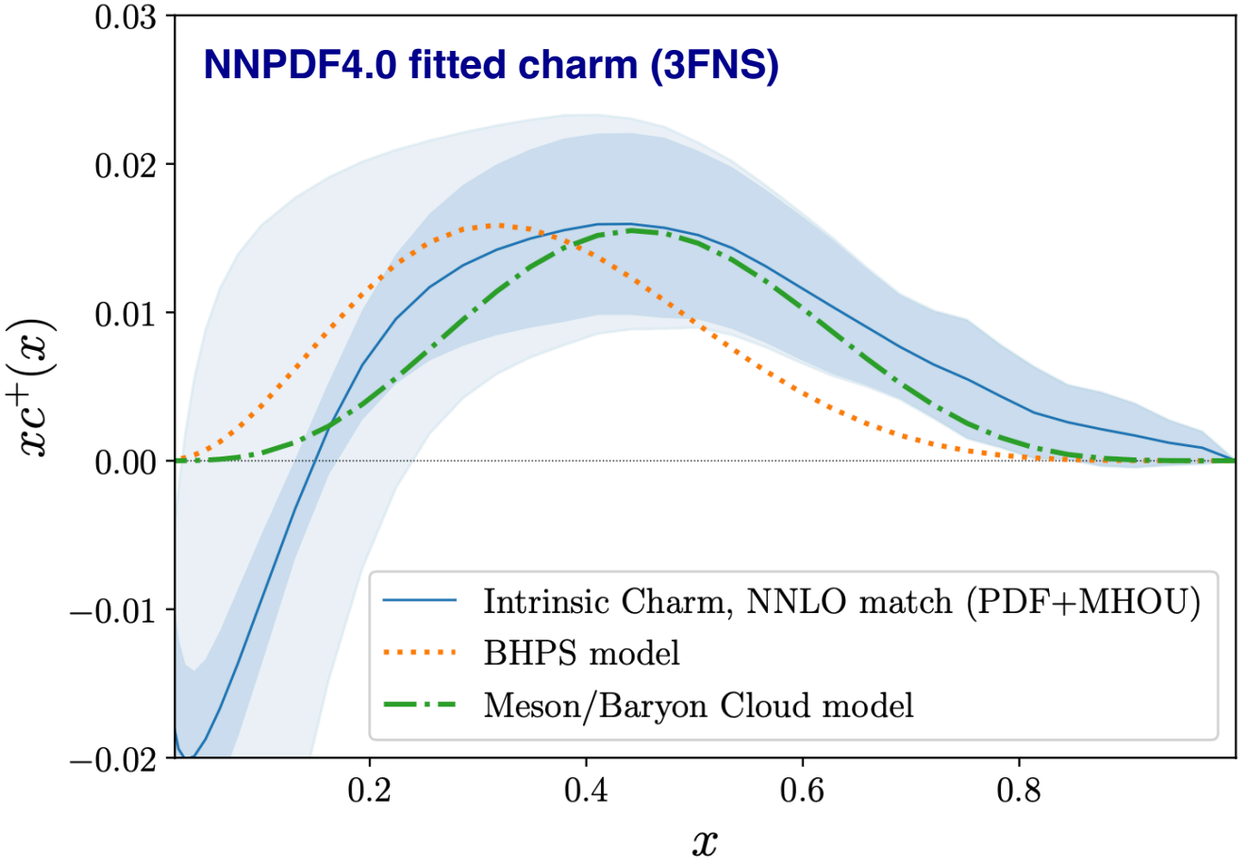
In the **intrinsic charm scenario** predicted by many models, the charm PDF extracted from data contains both **perturbative** (DGLAP) and **intrinsic** components

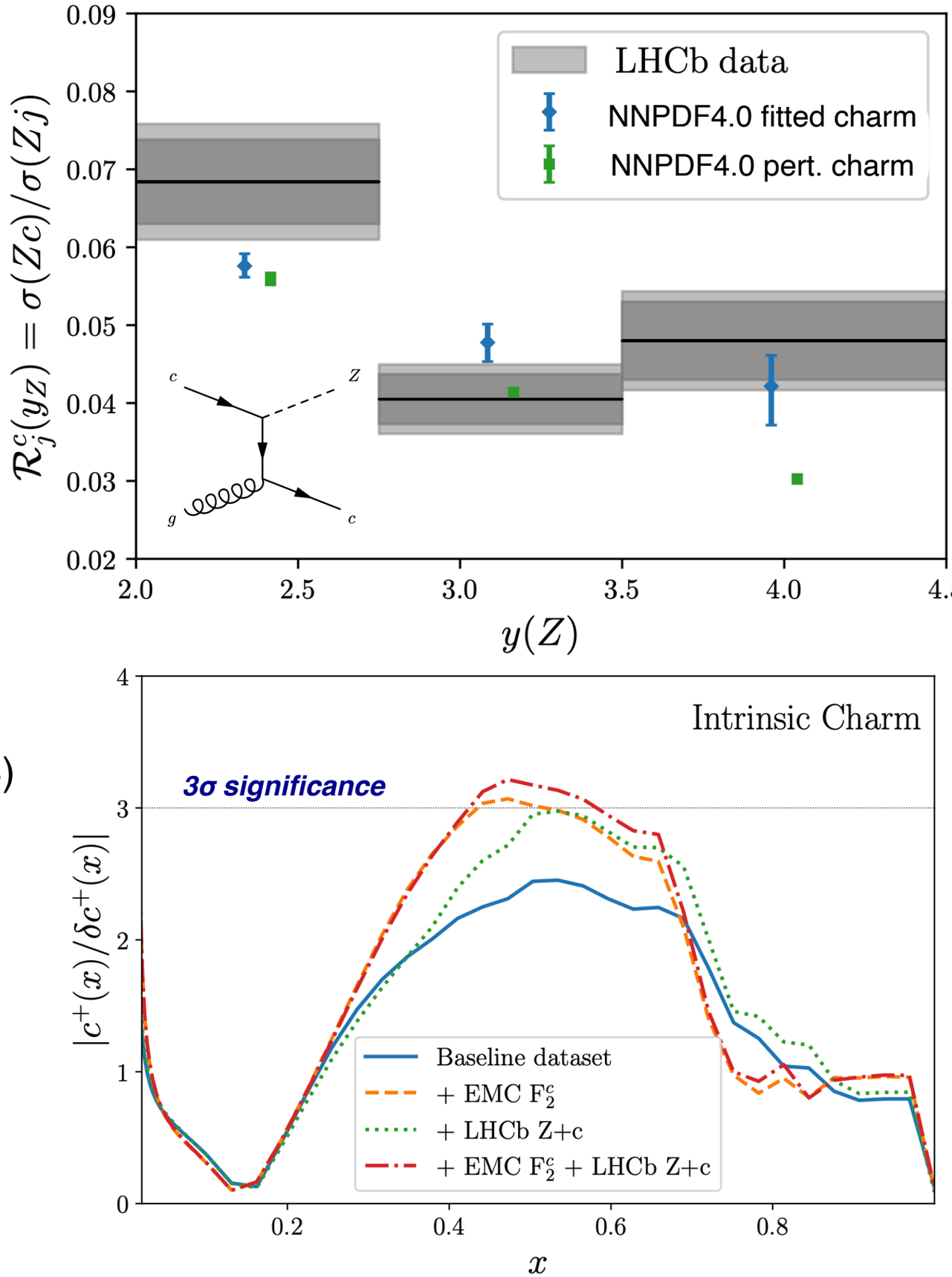
$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{(\text{pert})}(x,Q) + c^{(n_f=4)}_{(\text{intr})}(x,Q)$$

Extracted phenomenologically from data — *from QCD evolution and matching* — *from intrinsic component* $c^{(n_f=3)}_{(\text{intr})}(x) \neq 0$

The intrinsic component can be disentangled by *i)* a model-independent, **data-driven extraction** of the 4FNS charm PDF followed by *ii)* **transformation to the 3FNS**

EIC and intrinsic charm



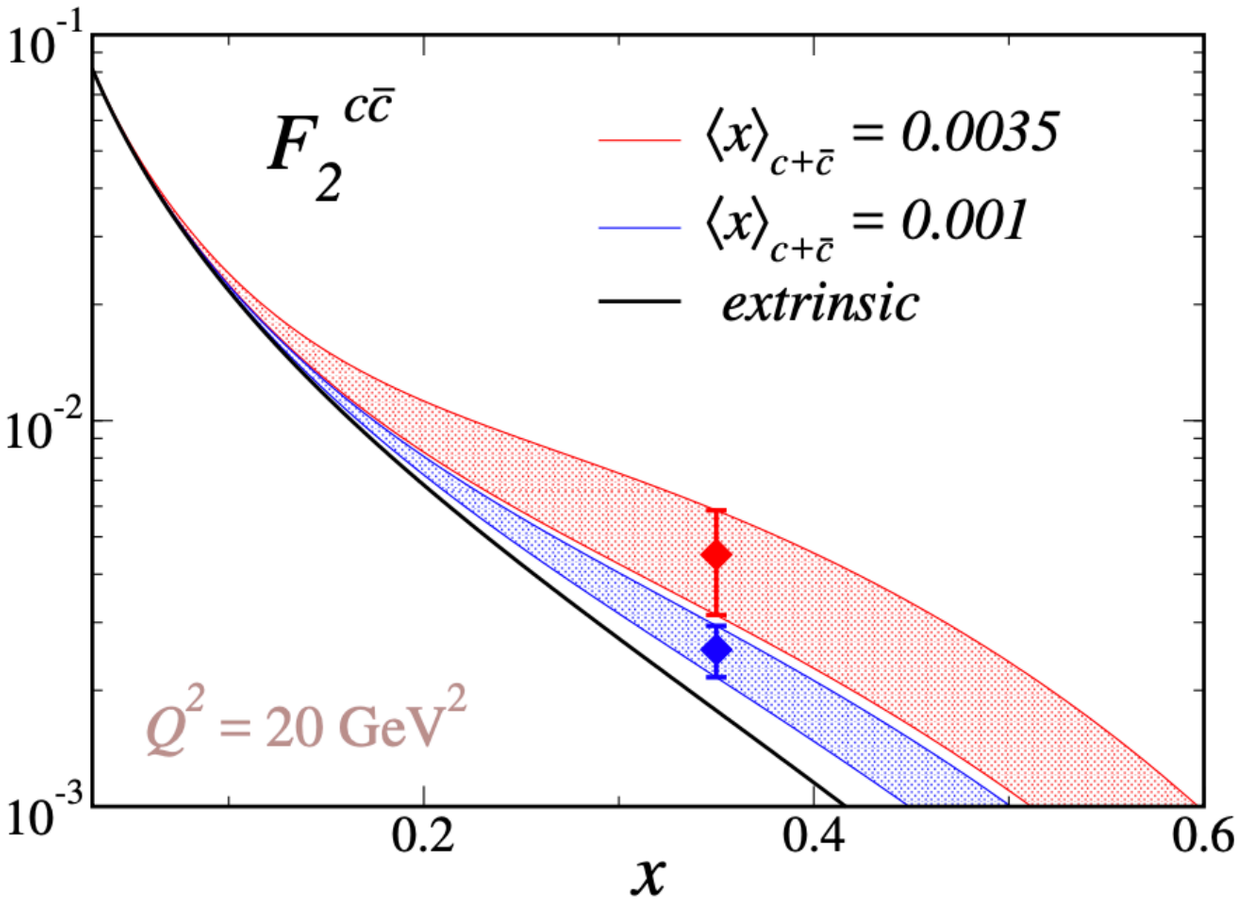


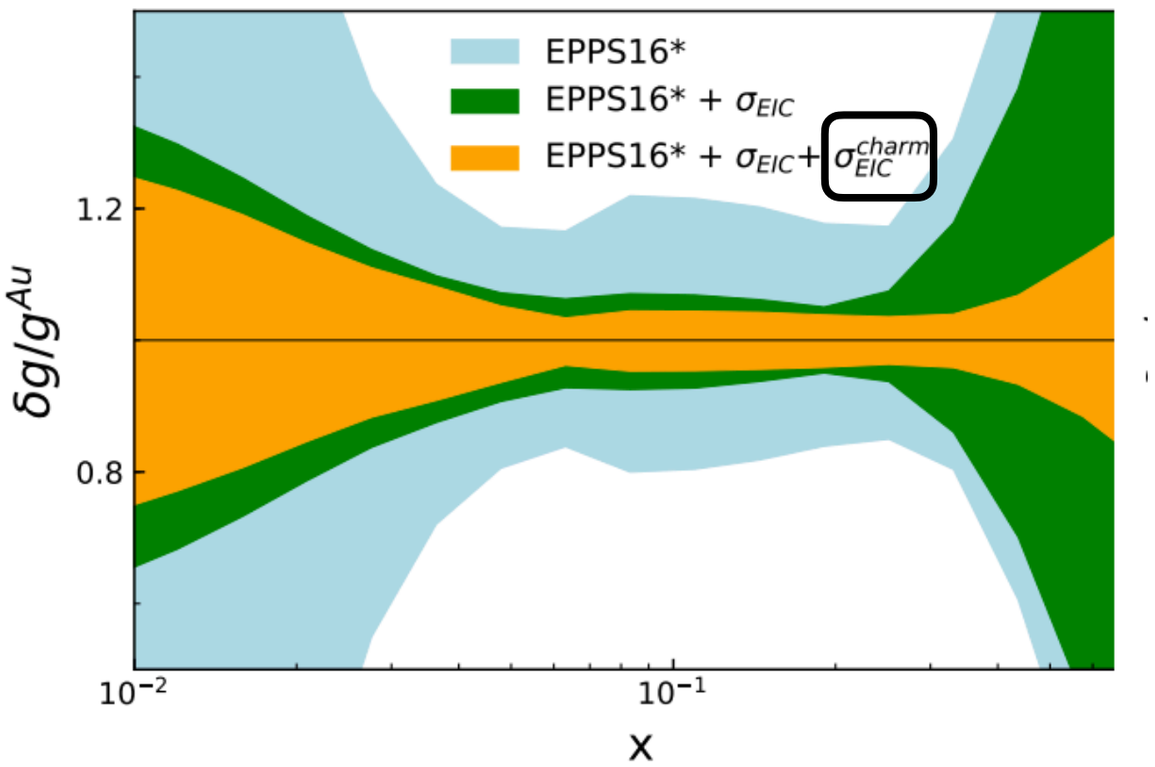
- ☑ **Evidence for intrinsic charm** at large-*x* from NNPDF4.0, in agreement with models (e.g. BHPS)

- ☑ Confirmed by independent constraints from ***Z+c*** **forward data from LHCb**

- ☑ **Consistency** between indirect (e.g. LHC *W,Z*) and direct (LHCb Z+c, EMC F_2^c) constraints

EIC and intrinsic charm



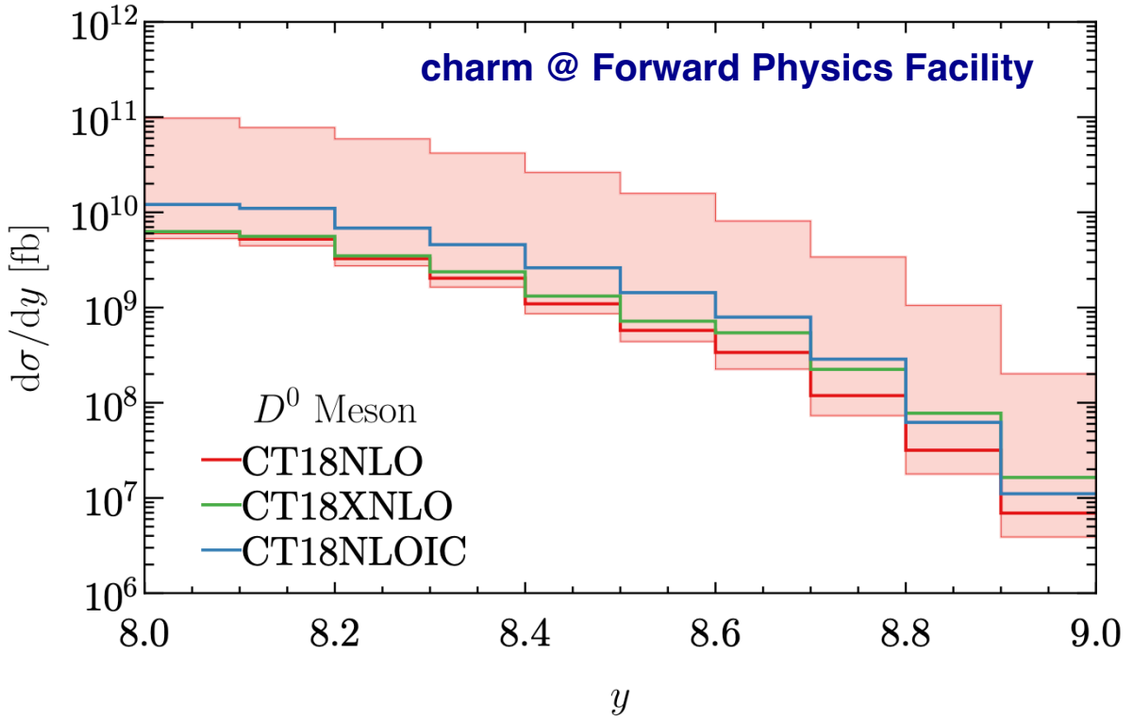


- ☑ EIC will measure **large-*x* charm structure functions** to further study intrinsic charm

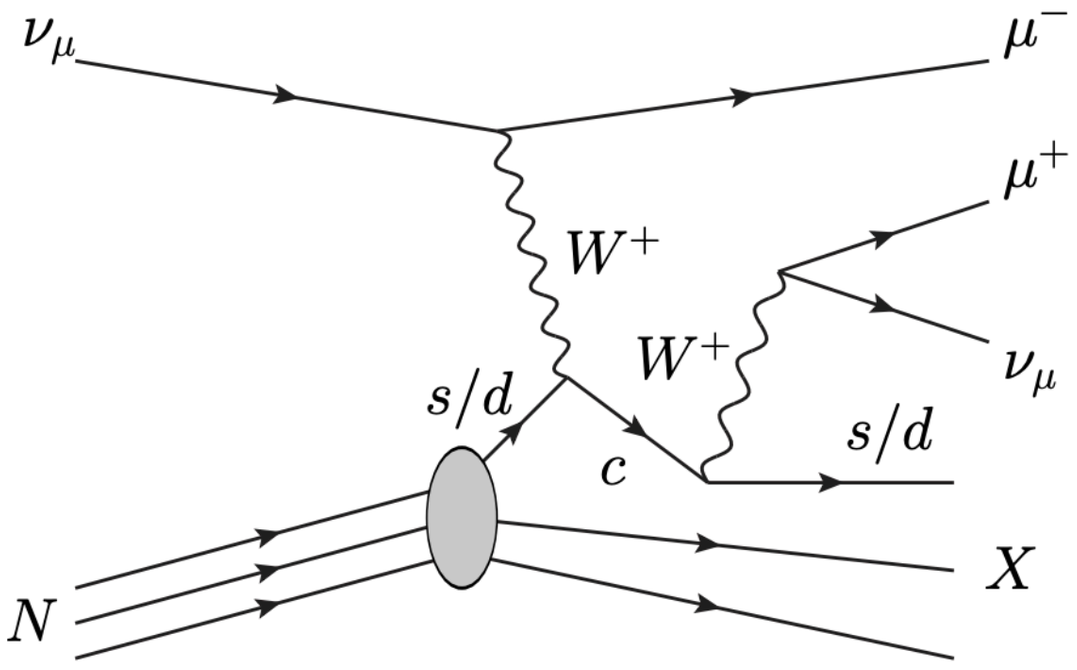
NNPDF4.0 analysis finds:

$$\langle x \rangle_{c+\bar{c}} = \left(0.62 \pm 0.28_{\mathrm{pdf}} \pm 0.54_{\mathrm{mhou}}\right)\ \%$$

- ☑ The EIC can also access, for first time, **nuclear modifications** of the charm SFs
- ☑ Precise determination of IC (and nuclear modifications) required for **UHE neutrino** astrophysics (*e.g.* prompt fluxes) and **forward charm production** at LHC



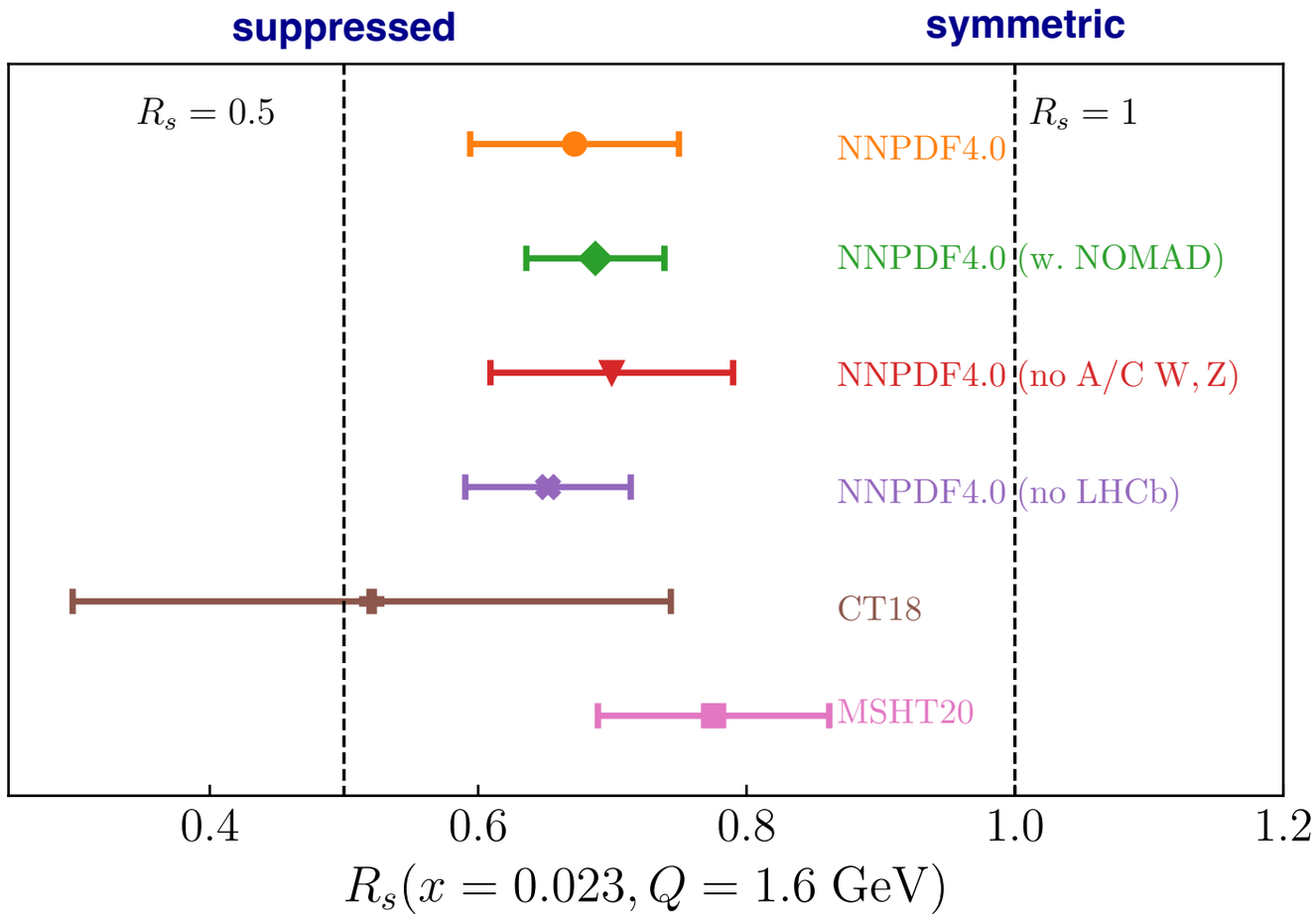
EIC and strangeness



- Long-standing discussion about the proton strangeness: **suppressed or symmetric** (as compared to up and down quark sea)?

$$R_S \equiv \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

- In proton PDF fits, strangeness constrained by **neutrino DIS** (dimuon process) and by collider **gauge boson production**



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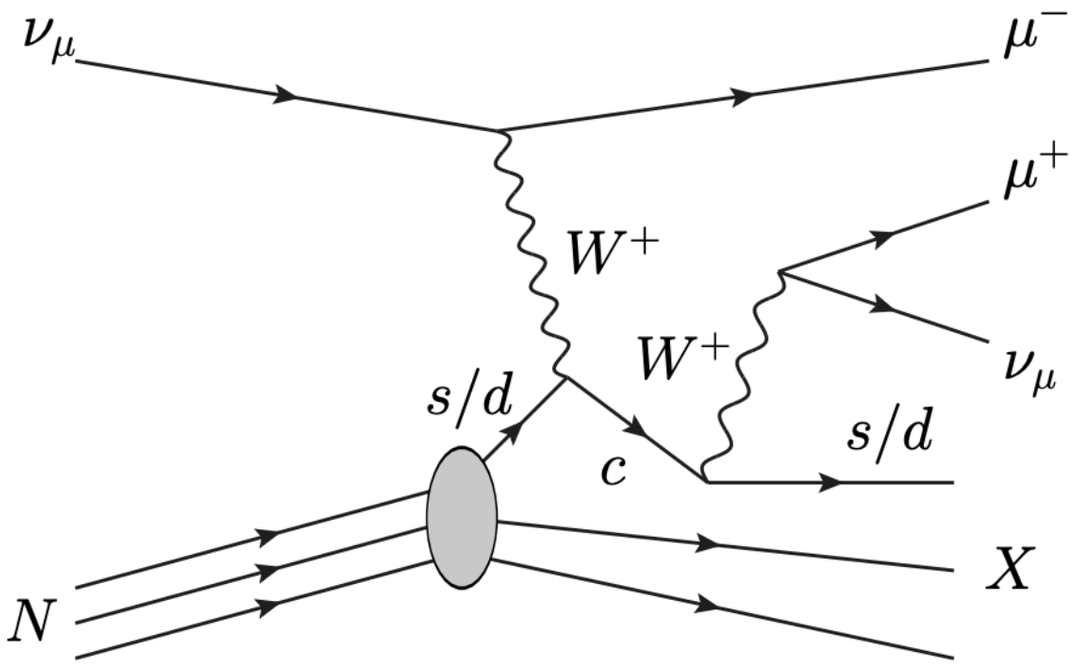

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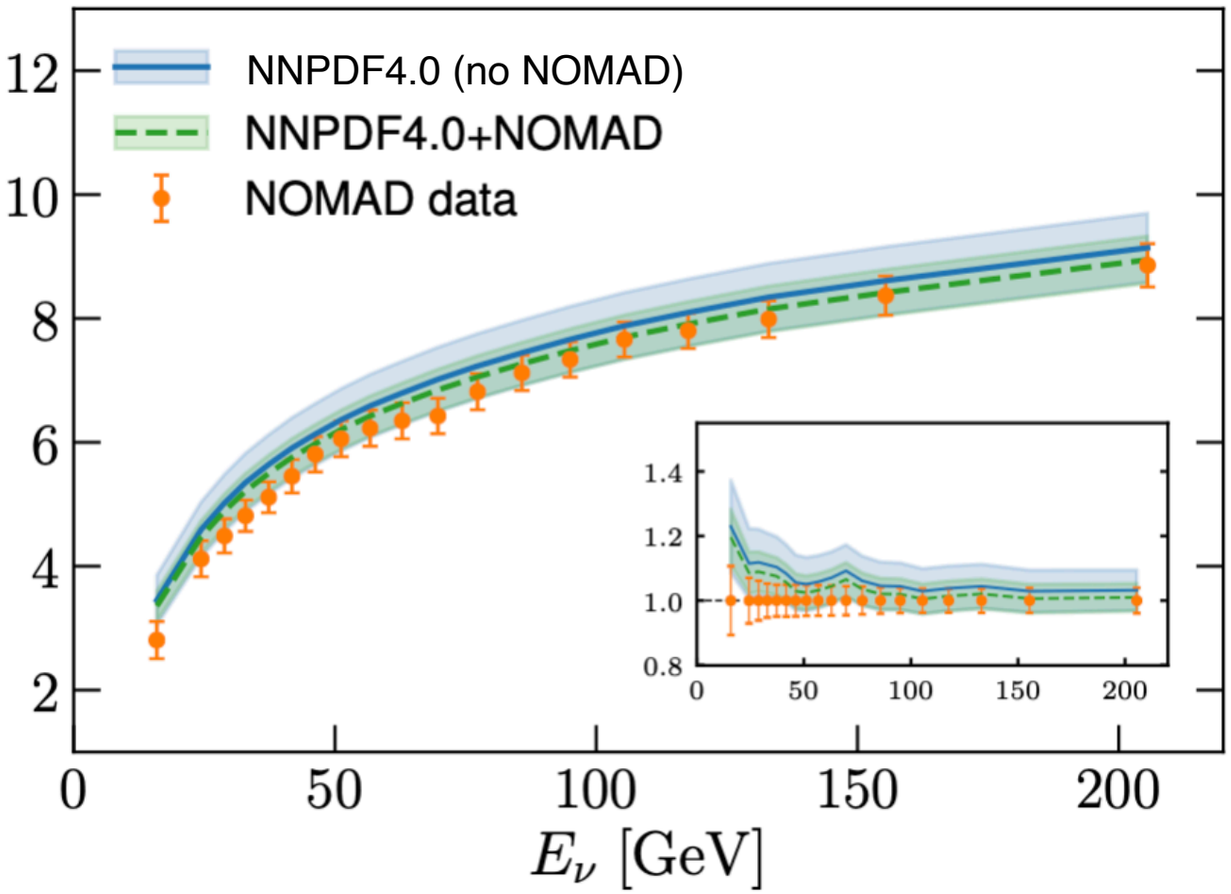


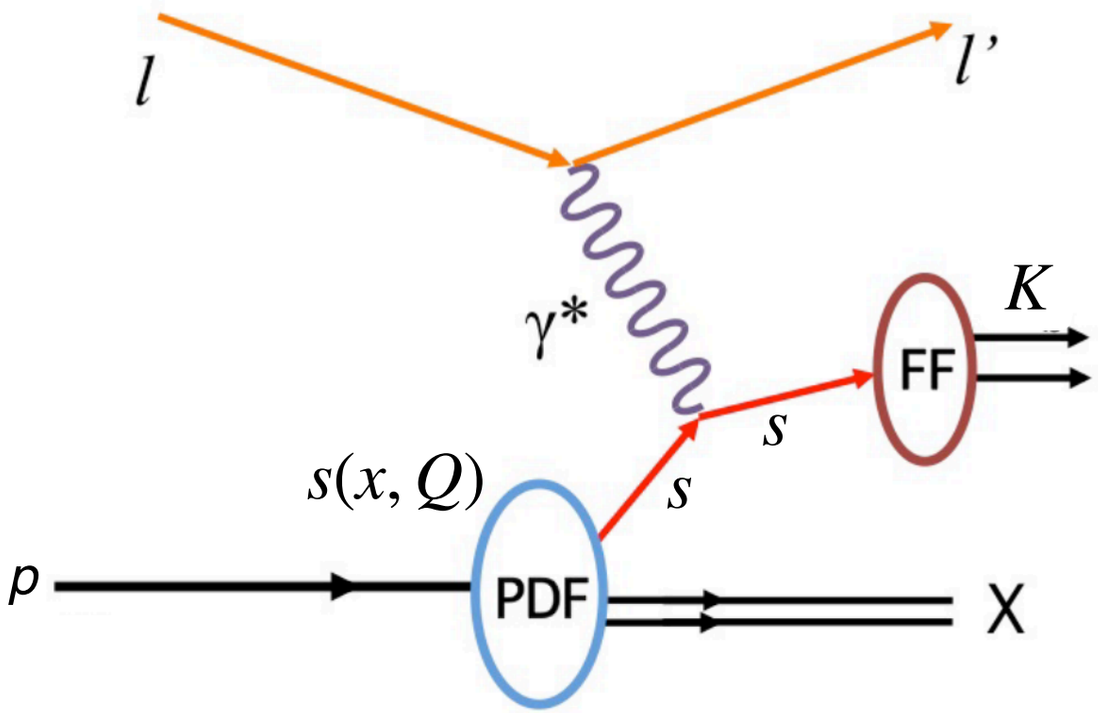
- NNPDF4.0 predictions consistent with **NOMAD dimuon data**
- **No tension** between LHC and DIS neutrino data observed

NNPDF4.0 + NOMAD

$$R_S(0.023, 1.6\ \text{GeV}) = 0.68 \pm 0.05$$

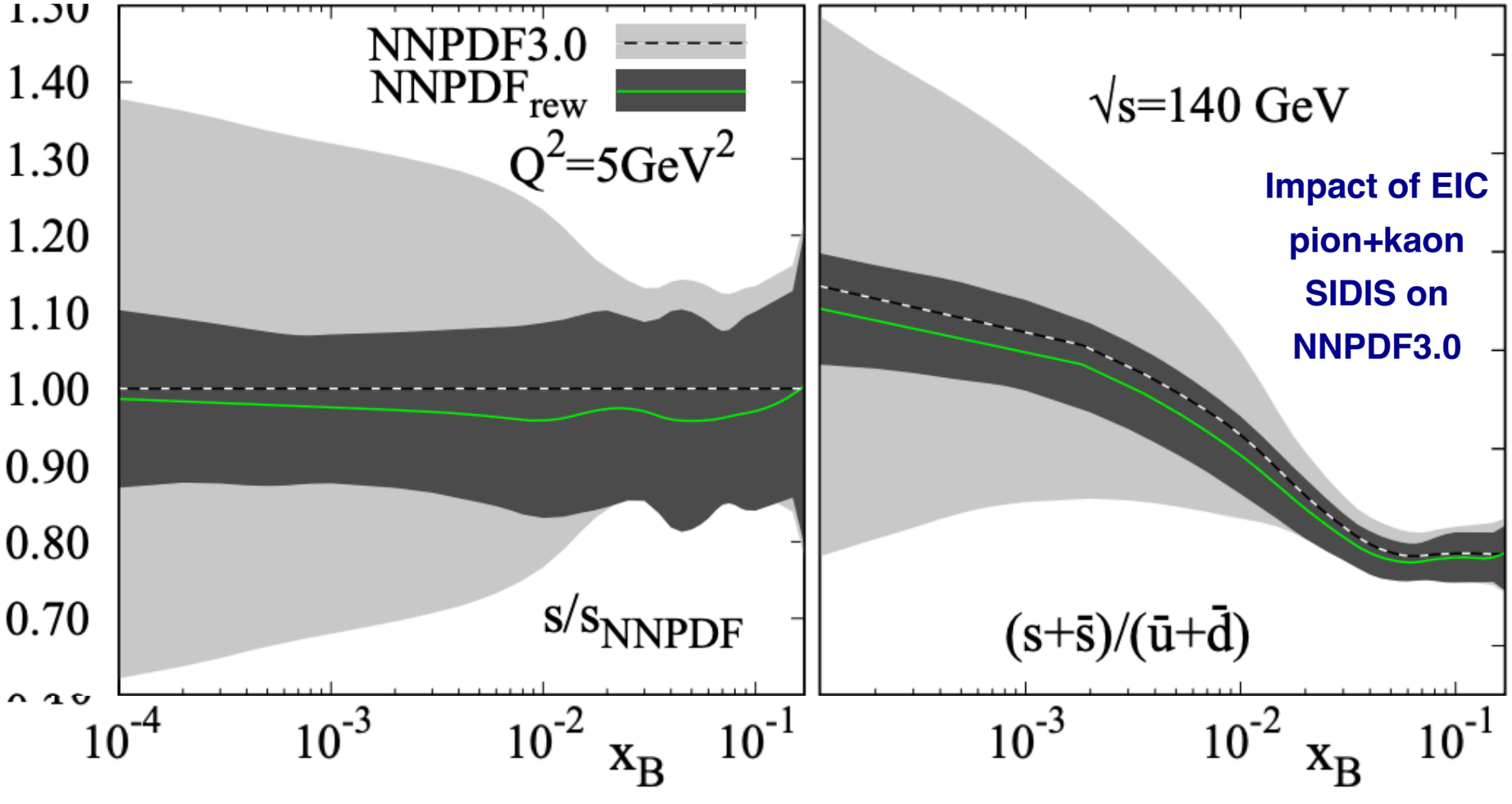
strangeness **moderately suppressed** with respect to up and down sea

EIC and strangeness

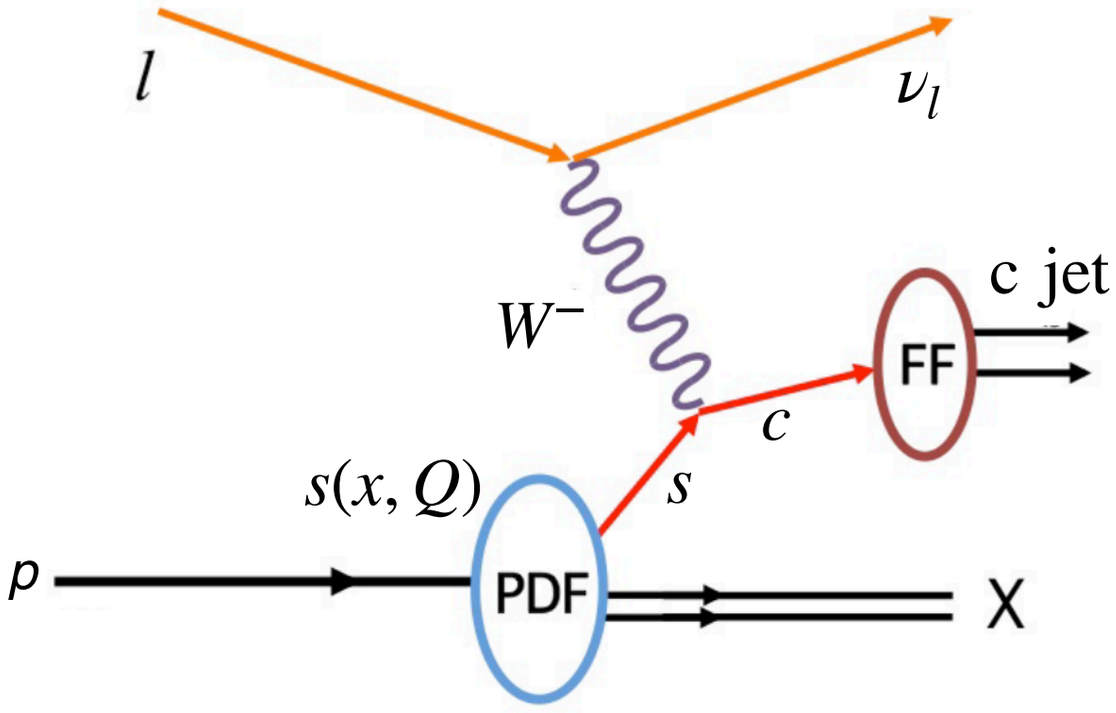


- ☑ At the EIC, strangeness can be constrained from **kaon production in semi-inclusive DIS**
- ☑ Also information from **CC inclusive DIS** measurements (high-luminosity phase)
- ☑ Also important constraints on **nuclear strangeness** and **polarised strangeness**

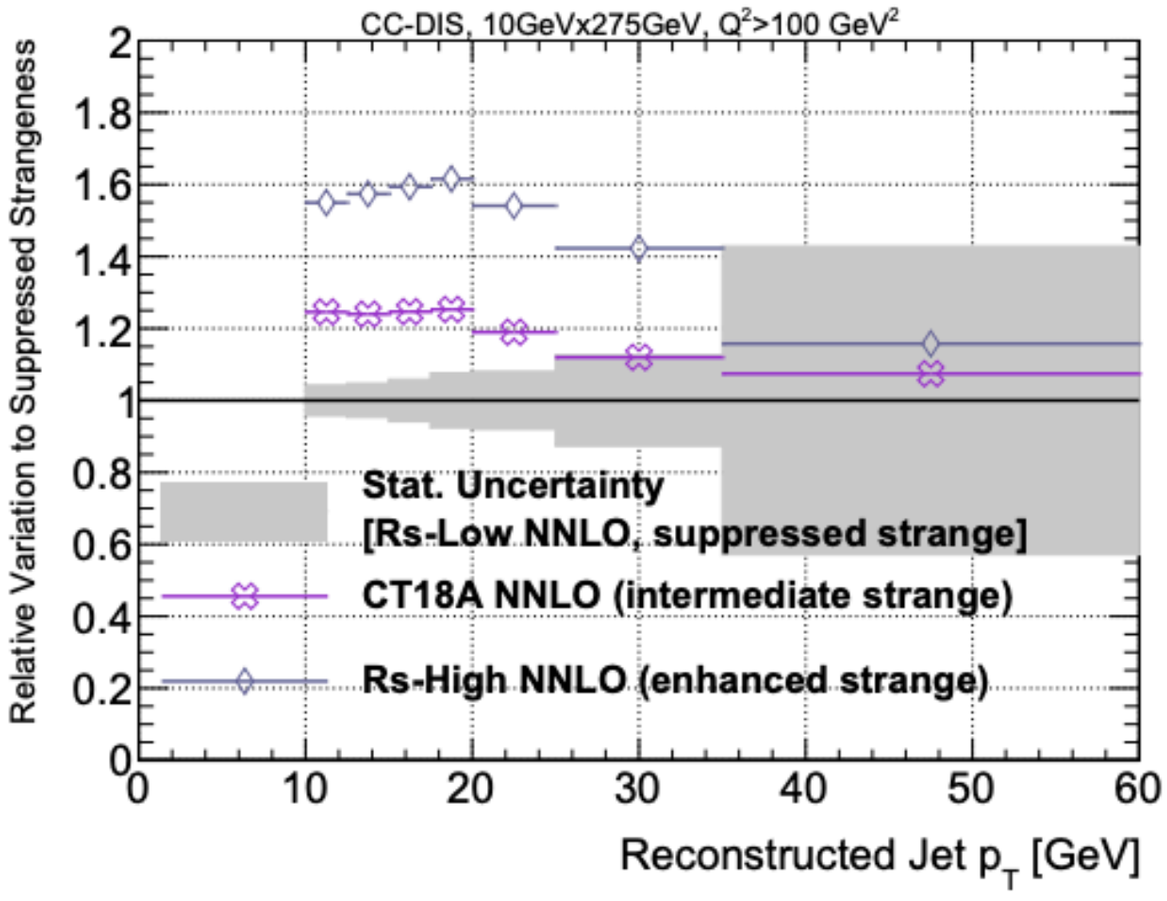
exploiting SIDIS data @ EIC requires simultaneous extraction of (polarised, nuclear) PDFs and FF

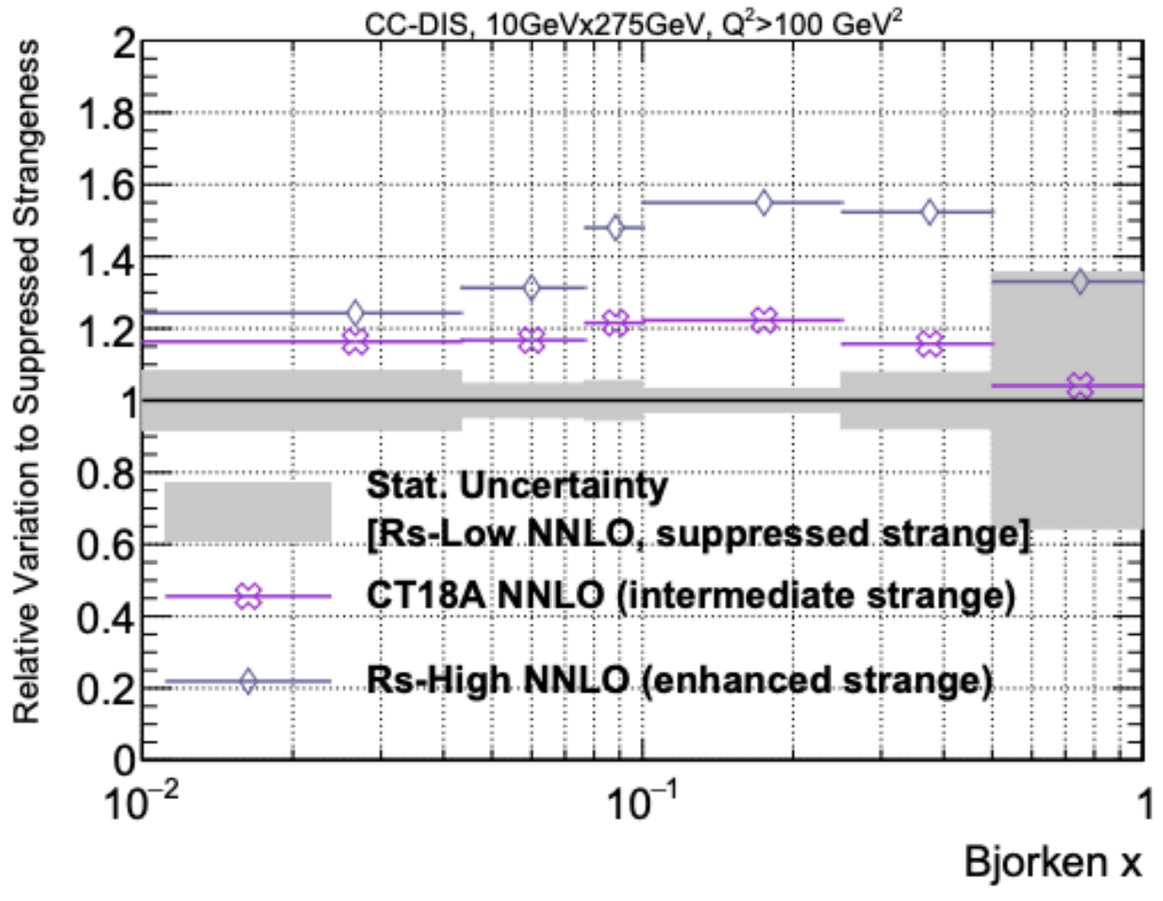


EIC and strangeness



- ☑ At the EIC, strangeness can be also constrained from **charm jet production** in semi-inclusive CC DIS
- ☑ As compared to SIDIS, reduced dependence on the light hadron FFs, but also less statistics
- ☑ A symmetric strange sea would **increase the charm jets in CC** yield by up 60%





Universal QCD fits

Pushing the **precision frontier** of **QCD fits** at the EIC requires accounting for **cross-talk** between different non-perturbative QCD quantities

	standard approach	universal QCD analysis
fragmentation functions	$N(p+p\to\pi)\propto\sum_{i,j,k}\widetilde{\sigma}_{ij\to k}\otimes f_i^{(p)}\otimes f_j^{(p)}\otimes f_{k\to\pi}$	$N(p+p\to\pi)\propto\sum_{i,j,k}\widetilde{\sigma}_{ij\to k}\otimes f_i^{(p)}\otimes f_j^{(p)}\otimes f_{k\to\pi}$
nuclear PDFs	$N(p+\mathrm{Pb}\to W)\propto\sum_{i,j}\widetilde{\sigma}_{ij\to W}\otimes f_i^{(p)}\otimes f_j^{(A)}$	$N(p+\mathrm{Pb}\to W)\propto\sum_{i,j}\widetilde{\sigma}_{ij\to W}\otimes f_i^{(p)}\otimes f_j^{(A)}$
proton PDFs	$N(\nu+\mathrm{Pb}\to\mu^+\mu^-)\propto\sum_i\widetilde{\sigma}_{i\to\mu^+\mu^-}\otimes f_i^{(p)}\times\left(\frac{f_i^{(A)}}{f_i^{(p)}}\right)$	$N(\nu+\mathrm{Pb}\to\mu^+\mu^-)\propto\sum_i\widetilde{\sigma}_{i\to\mu^+\mu^-}\otimes f_i^{(p)}\times\left(\frac{f_i^{(A)}}{f_i^{(p)}}\right)$

theory fitted fixed (standard approach) — theory fitted (universal QCD analysis)

***e.g.* proton PDFs fit data on heavy nuclear targets, while nuclear PDF fits reduce to proton baseline for A=1**

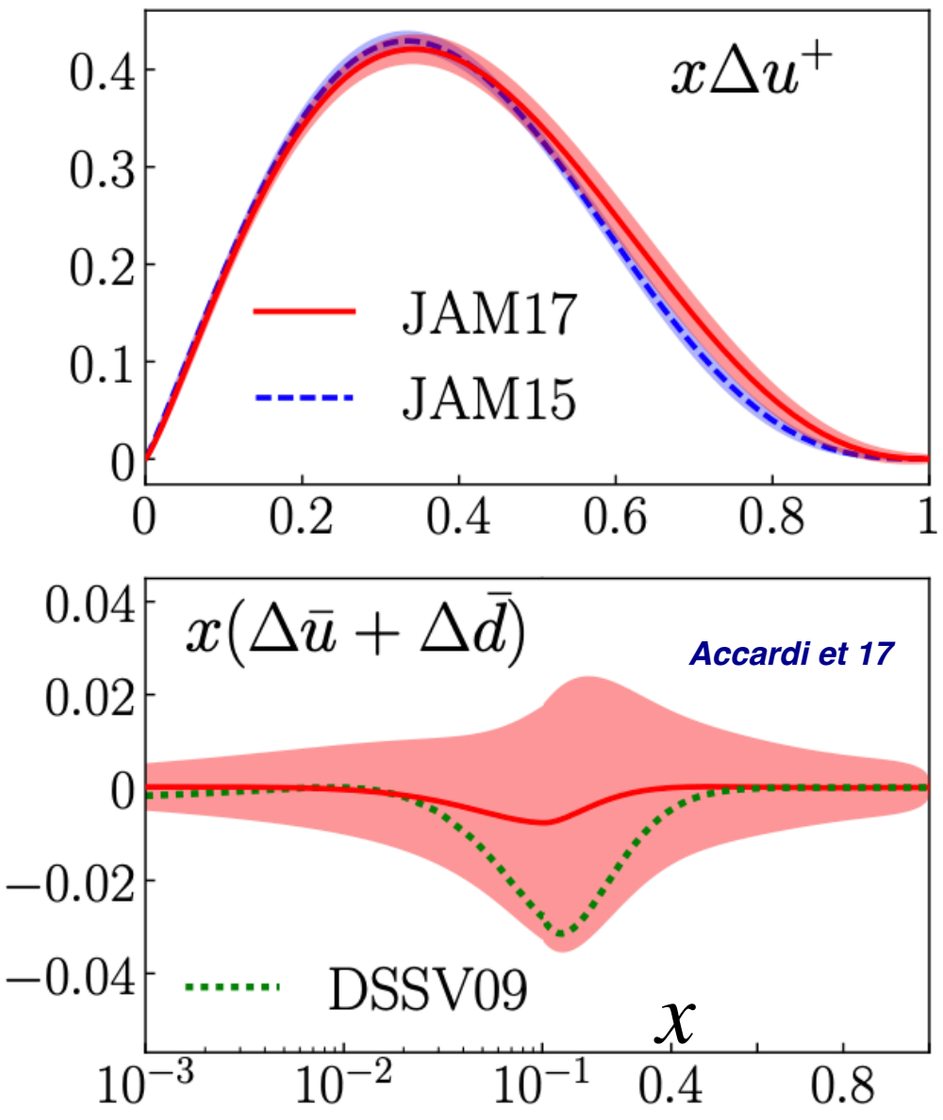
Exploiting the EIC potential for **strong interaction studies** demands the combination of unpolarised & polarised proton PDFs, nuclear PDFs and FFs into an **integrated QCD fit**

major methodological challenge!

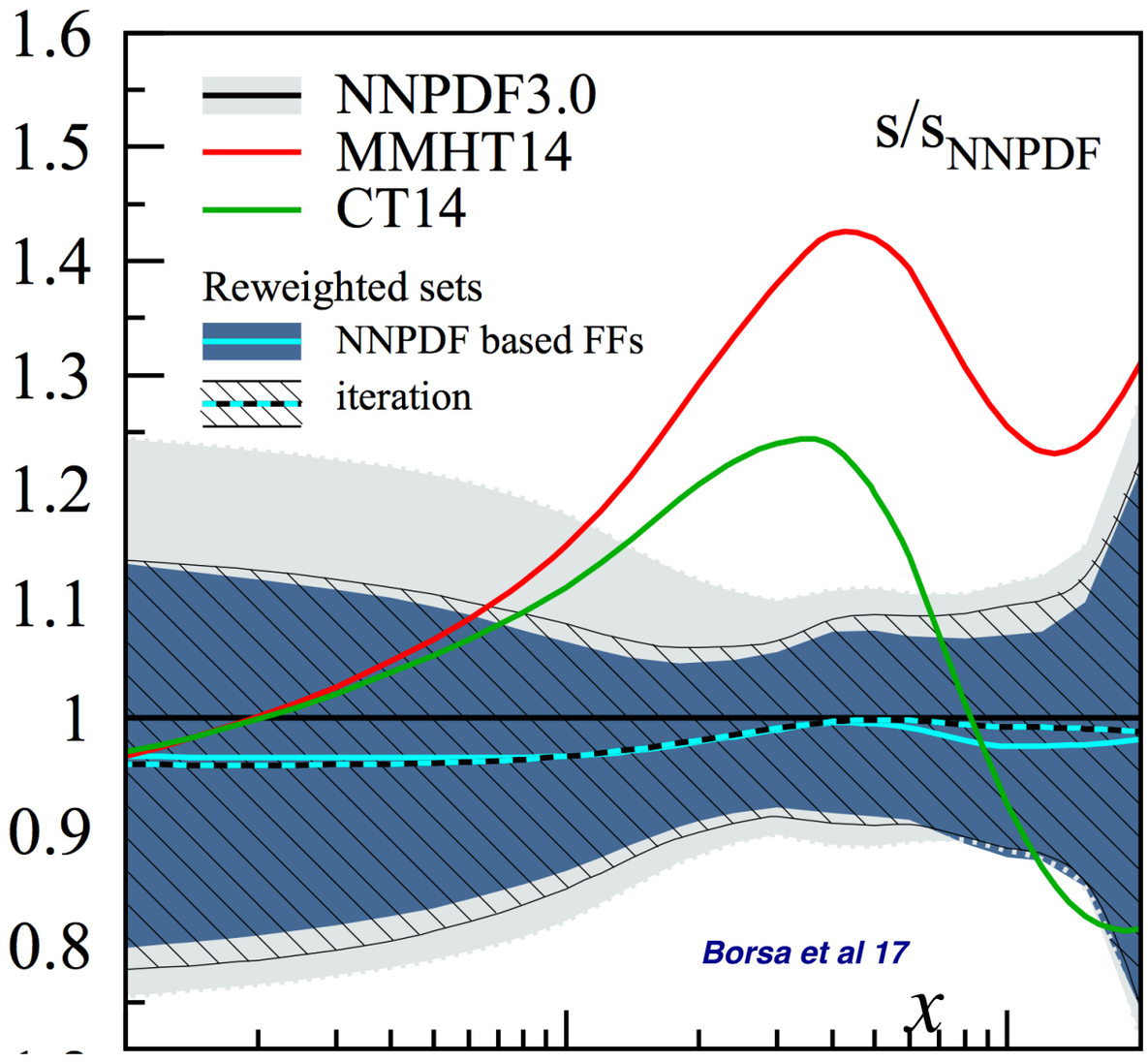
Universal QCD fits

Pushing the **precision frontier** of **QCD fits** at the EIC requires accounting for **cross-talk** between different non-perturbative QCD quantities

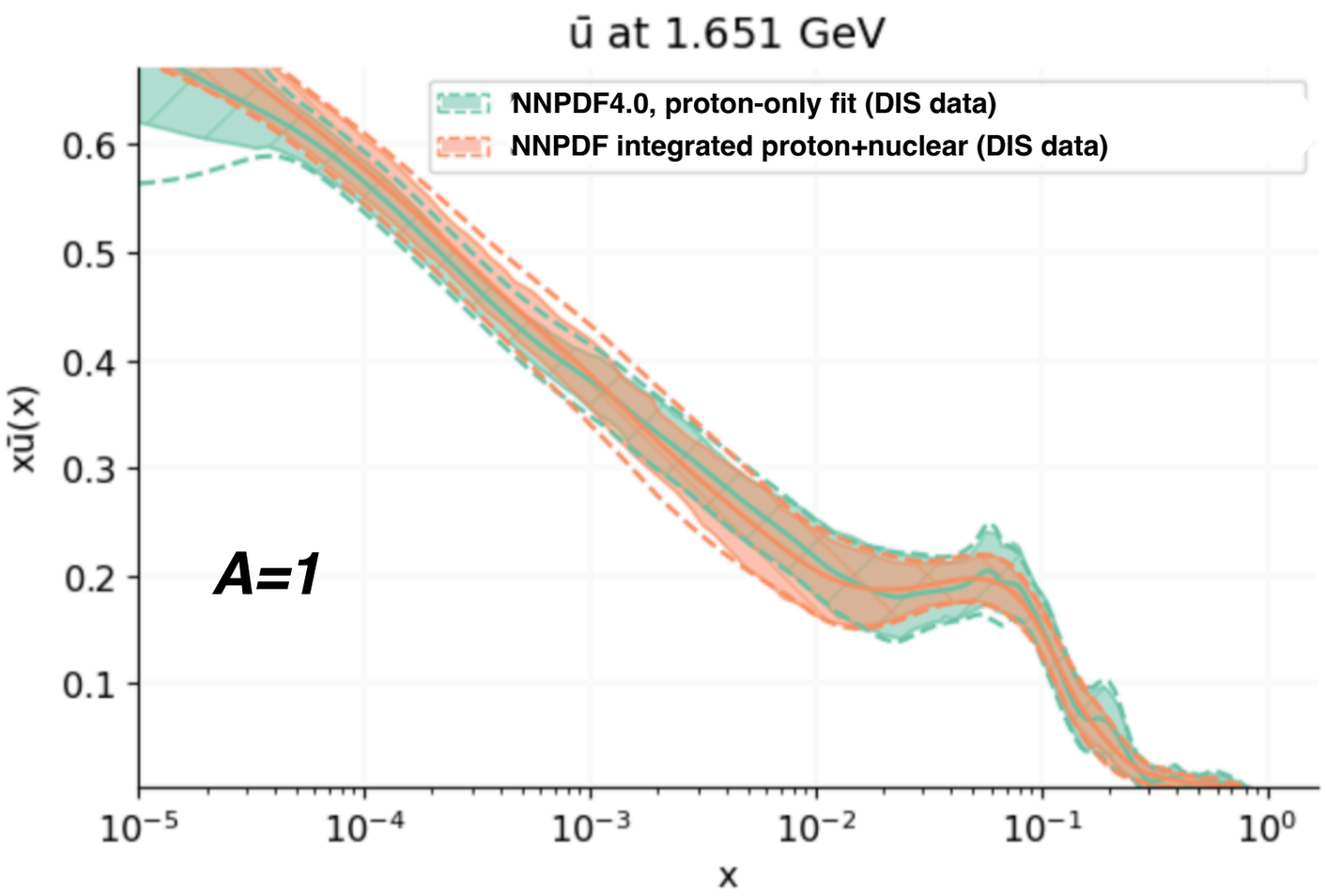
Polarised PDFs + FFs



Unpolarised PDFs + FFs



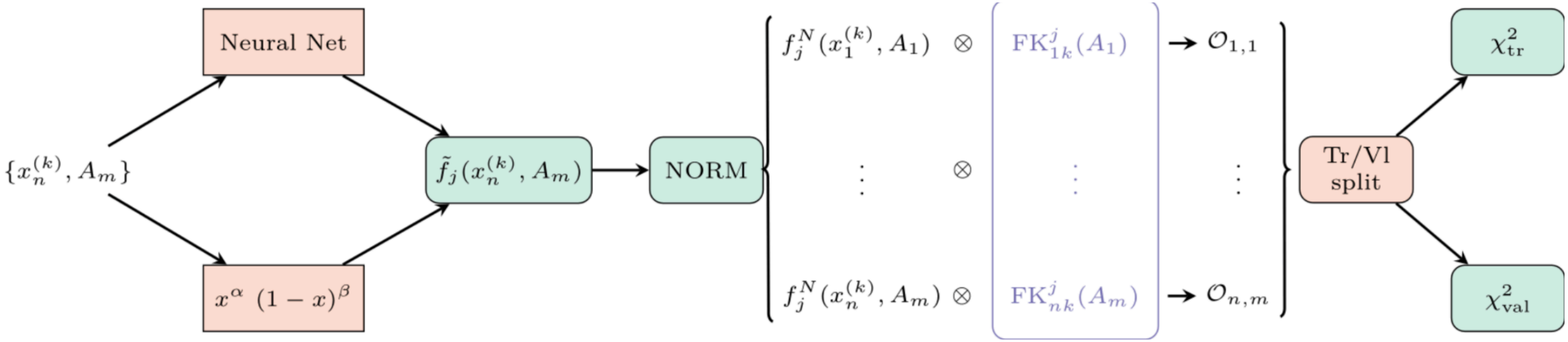
Universal QCD fits



- Ongoing work towards the integration of **nuclear PDF fits** (nNNPDF3.0) into the **NNPDF4.0** proton PDF framework

- Goal: joint extraction of **PDFs from *A=1* to *A=208*** from a single dataset, with fully consistent theory and methodology inputs

- Eventually to be extended to **polarised PDFs** and to **fragmentation functions**, to match the EIC precision requirements



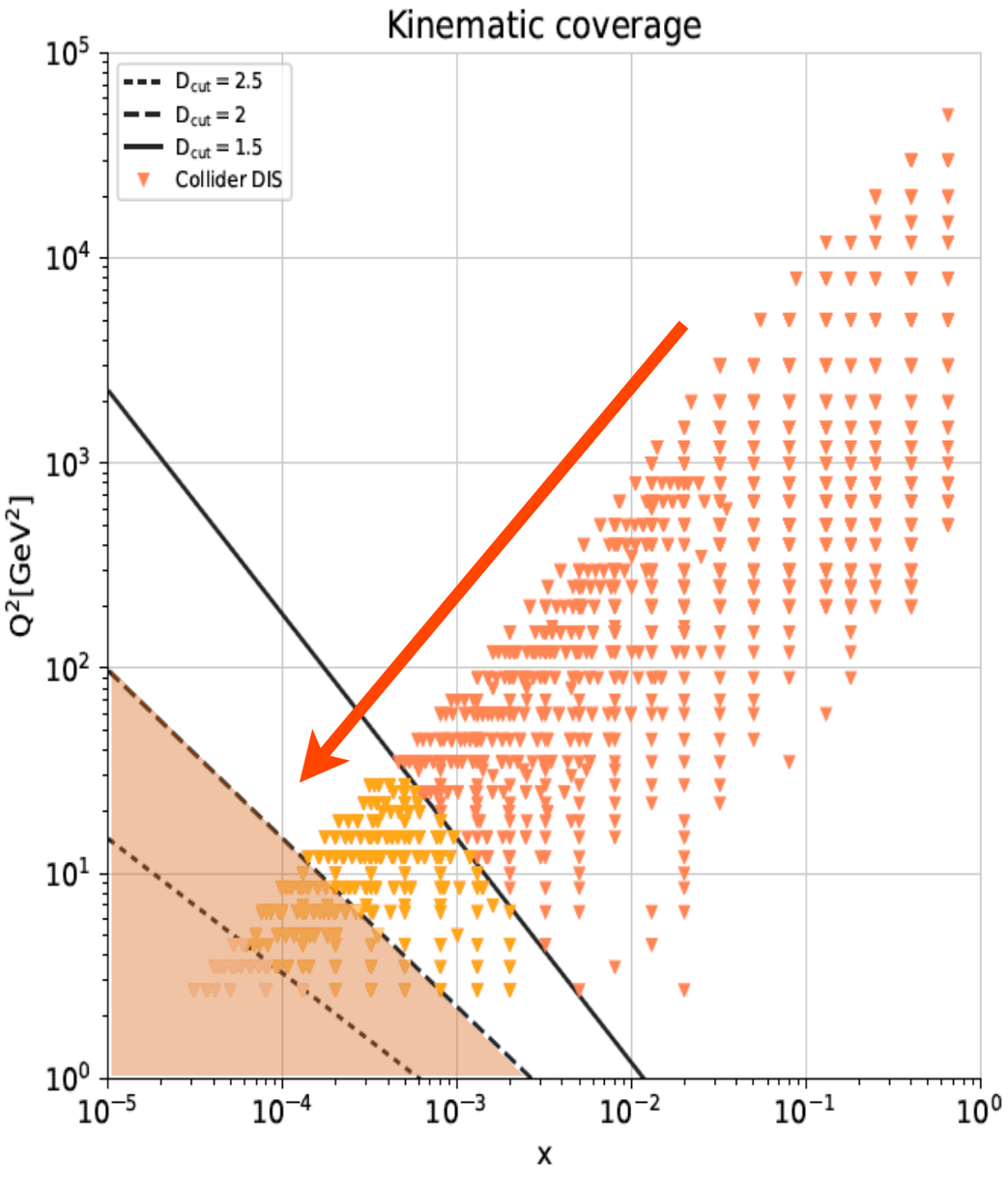
Nocera, Rabemananjara, Rojo, in progress

New phenomena within QCD

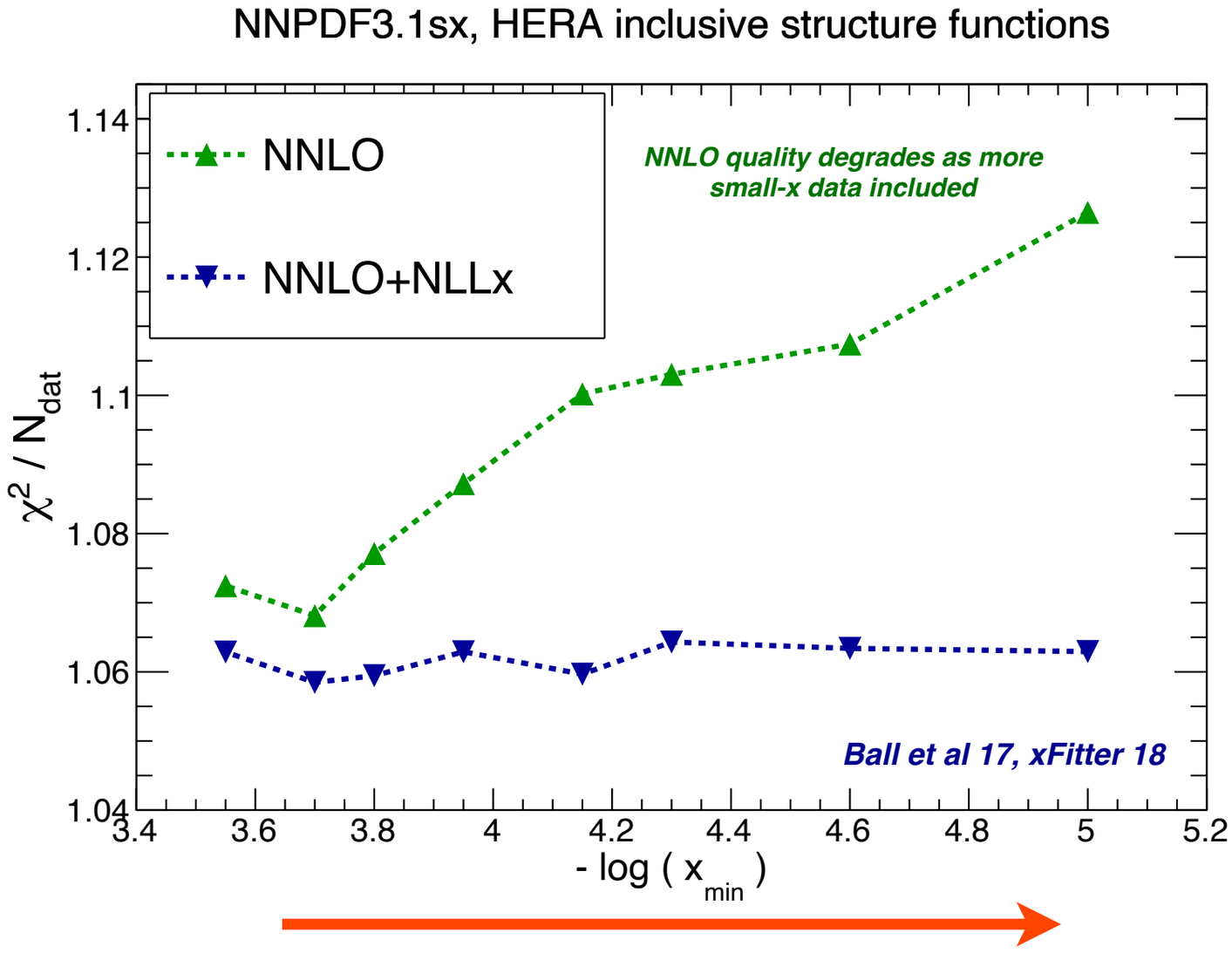
BFKL dynamics stablished from HERA data from inclusive and charm SFs

Accessible also at EIC? What about electron-ion collisions? Interplay with **non-linear QCD studies?**

Similar techniques to pinpoint **saturation?**



Monitor the fit quality in small-*x* region



Best description of **small-*x* HERA data: BFKL resummation**

New phenomena beyond the SM

``*How can you be sure you are not reabsorbing BSM physics into your PDFs?*''

perhaps most frequent question I am asked in talks!

Assuming the **SM**, the theory calculations that enter a global PDF fit are:

$$\sigma_{\rm LHC}(\boldsymbol{\theta}) \propto \sum_{ij=u,d,g,\ldots} \int_{M^2}^{s} d\hat{s}\ \mathscr{L}_{ij}(\hat{s}, s, \boldsymbol{\theta})\, \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M))$$

SM PDFs

However in the case of BSM physics, here parametrised by the **SMEFT,** the correct expression is:

$$\sigma_{\rm LHC}\left(\boldsymbol{c}, \Lambda, \boldsymbol{\theta}\right) \simeq \left(\int_{M^2}^{s} d\hat{s}\ \mathscr{L}_{ij}(\hat{s}, s, \boldsymbol{\theta})\, \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M)) \right) \times \left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}}{\Lambda^4} \right),$$

SMEFT PDFs

PDF parameters

SMEFT coefficients

How different are ``SM PDFs'' & ``SMEFT PDFs''? Can we quantify the risk of **fitting away BSM** in PDFs?

New phenomena beyond the SM

Exp.	$\sqrt{s}$ (TeV)	Ref.	$\mathcal{L}$ (fb^{-1})	Channel	1D/2D	$n_{\rm dat}$	$m_{\ell\ell}^{\rm max}$ (TeV)
ATLAS	7	[120]	4.9	e^-e^+	1D	13	[1.0, 1.5]
ATLAS (*)	8	[86]	20.3	$\ell^-\ell^+$	2D	46	[0.5, 1.5]
CMS	7	[121]	9.3	$\mu^-\mu^+$	2D	127	[0.2, 1.5]
CMS (*)	8	[87]	19.7	$\ell^-\ell^+$	1D	41	[1.5, 2.0]
CMS (*)	13	[122]	5.1	e^-e^+, $\mu^-\mu^+$ $\ell^-\ell^+$	1D	43, 43 43	[1.5, 3.0]
Total						**270 (313)**	

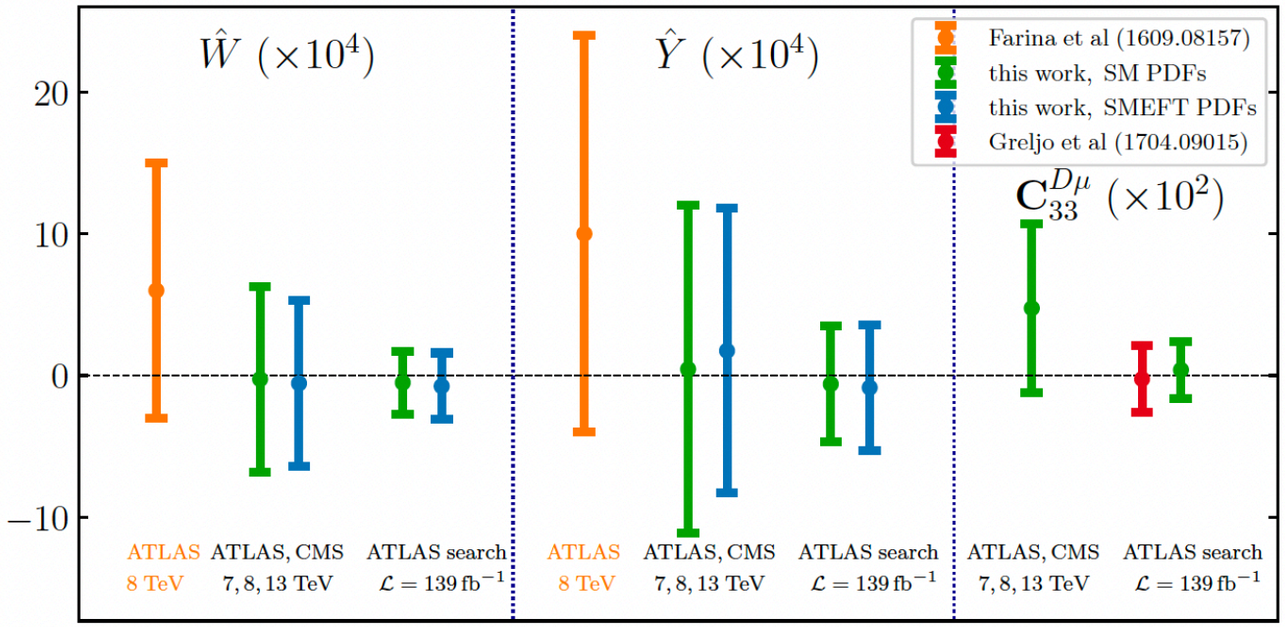
Extract PDFs from global fit where **high-mass DY cross-sections** account for EFT effects in two benchmark scenarios

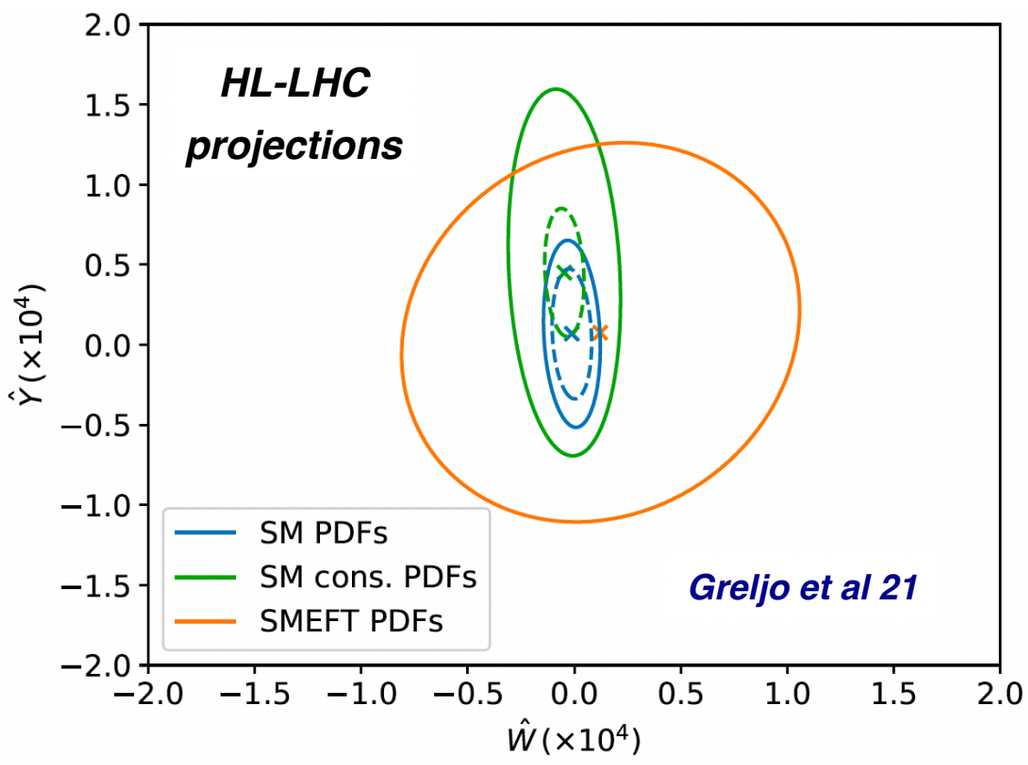
$$d\sigma_{\rm SMEFT} = d\sigma_{\rm SM} \times K_{\rm EFT}$$

$$K_{\rm EFT} = 1 + \sum_{n=1}^{n_{\rm op}} c_n R^{(n)}_{\rm SMEFT} + \sum_{n,m=1}^{n_{\rm op}} c_n c_m R^{(n,m)}_{\rm SMEFT}$$

Available data: limited interplay between PDF and EFT fits, best constraints from **searches**

HL-LHC: EFT effects, if present, would be **reabsorbed into PDFs**





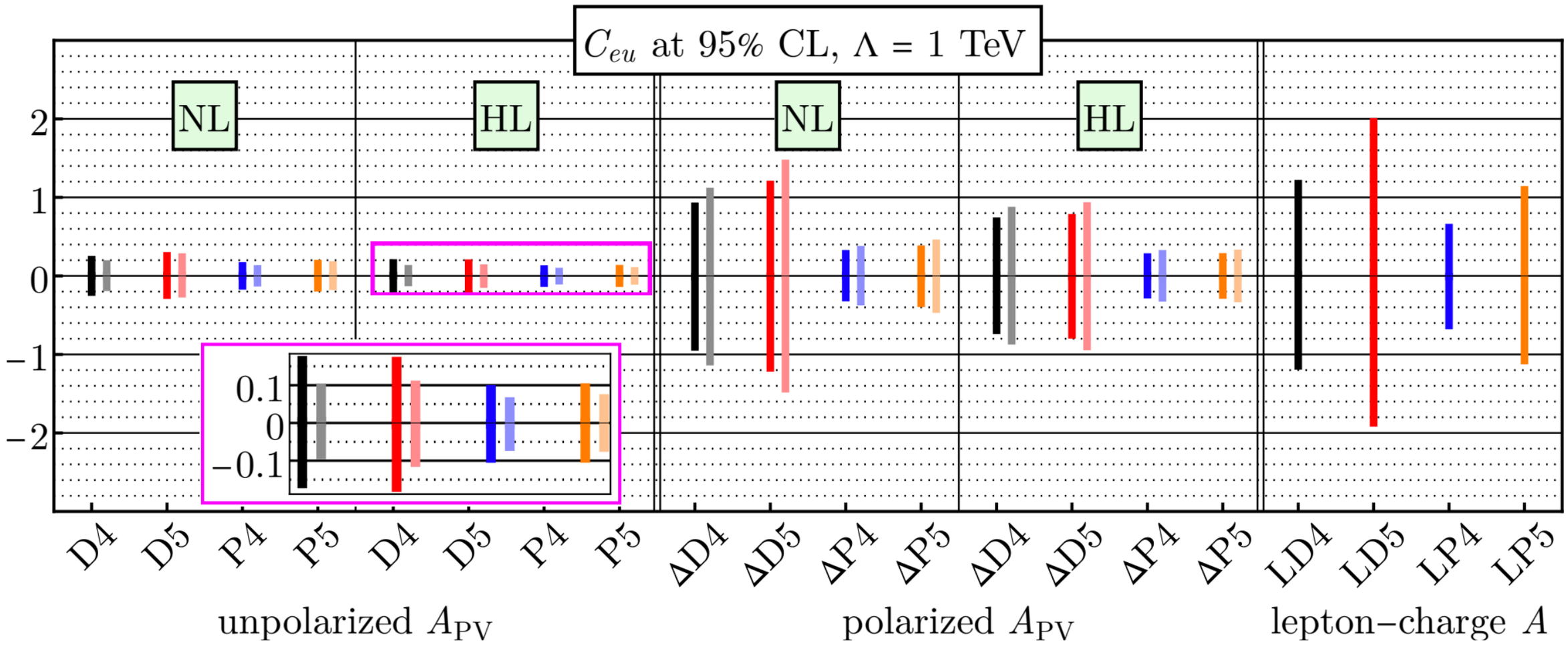
SMEFT PDFs required to exploit the PDF/BSM interplay in future LHC runs!

New phenomena beyond the SM

C_r	$\mathcal{O}_r$	$\tilde{C}_r$	$c^e_{V_r}$	$c^e_{A_r}$	$c^u_{V_r}$	$c^u_{A_r}$	$c^{d,s}_{V_r}$	$c^{d,s}_{A_r}$
$C^{(1)}_{\ell q}$	$\mathcal{O}^{(1)}_{\ell q} = (\bar{L}_L\gamma^\mu L_L)(\bar{Q}_L\gamma_\mu Q_L)$	$C^{(1)}_{\ell q}/4$	1	1	1	1	1	1
$C^{(3)}_{\ell q}$	$\mathcal{O}^{(3)}_{\ell q} = (\bar{L}_L\gamma^\mu\tau^I L_L)(\bar{Q}_L\gamma_\mu\tau^I Q_L)$	$C^{(3)}_{\ell q}/4$	1	1	-1	-1	1	1
C_{eu}	$\mathcal{O}_{eu} = (\bar{e}_R\gamma^\mu e_R)(\bar{u}_R\gamma_\mu u_R)$	$C_{eu}/4$	1	-1	1	-1	0	0
C_{ed}	$\mathcal{O}_{ed} = (\bar{e}_R\gamma^\mu e_R)(\bar{d}_R\gamma_\mu d_R)$	$C_{ed}/4$	1	-1	0	0	1	-1
$C_{\ell u}$	$\mathcal{O}_{\ell u} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma_\mu u_R)$	$C_{\ell u}/4$	1	1	1	-1	0	0
$C_{\ell d}$	$\mathcal{O}_{\ell d} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma_\mu d_R)$	$C_{\ell d}/4$	1	1	0	0	1	-1
C_{qe}	$\mathcal{O}_{qe} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma_\mu e_R)$	$C_{qe}/4$	1	-1	1	1	1	1

EIC measurements can **constrain EFT directions** which are not covered by e.g. LHC Drell-Yan measurements

Boughezal et al 22,
based on full detector simulation (ECCE)



Quantifying **PDF/BSM interplay** crucial for a robust interpretation of EIC data!

Connections with other EIC4LHC topics

Interplay between **PDF measurements** at the LHC and the EIC

Lucian's talk

Inputs for **forward charm and neutrino production** at the LHC & connection with UHE neutrinos and cosmic rays

Maria Vittoria, Hans,, Sebastian's talks

Input for **TMD analyses** (collinear PDFs are boundary condition)

Alessandro's talk

EW & BSM physics at the EIC/LHeC

Stefano's talk

Studies of **non-linear QCD**, saturation, connection with heavy ions

Heikki's talk

Fragmentation function analyses

Valerio's talk

Connection with the **Fixed Target program** of the LHC

Cynthia's talk

and many other exciting topics!

Summary and outlook

- The EIC represents a unique opportunity to **fingerprint the strong interactions** and **proton/nuclear structure** at an unprecedented level

- Inclusive DIS measurements will have a moderate impact on proton PDFs, with potentially larger constraints from **semi-inclusive data** (SIDIS, charm SFs, charm jets in CC)

- Excellent prospects for nPDF studies, in particular with **first measurement of *A* dependence of nuclear modifications**, and clean probes of **small-*x* phenomena** such as shadowing or non-linear QCD

- Fully exploiting the potential of the EIC for QCD & BSM studies requires to develop nover methodologies suitable to i) the **integration of different QCD analyses into a unified framework** and ii) assessing the **interplay between (polarised) PDF fits and EW/BSM constraints**

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- Excell… **de**… …**nomena** such as sha…

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Thanks for your attention!