Heavy quark production at the EIC: from polarised gluons to intrinsic charm

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ePIC Jets & Heavy Flavour Working Group

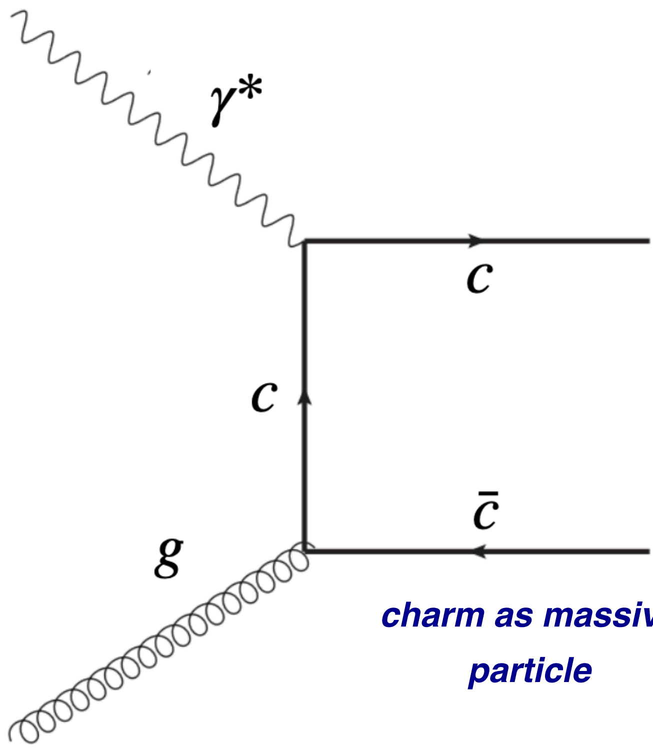
Zoom, 25th October 2023

Heavy Quark Production in (Polarised) DIS

Charm production in DIS

Charm production in (polarised) DIS: direct sensitivity to the gluon in the proton

Fixed-flavour scheme: no charm PDF, charm mass effects accounted for exactly



charm as massive particle

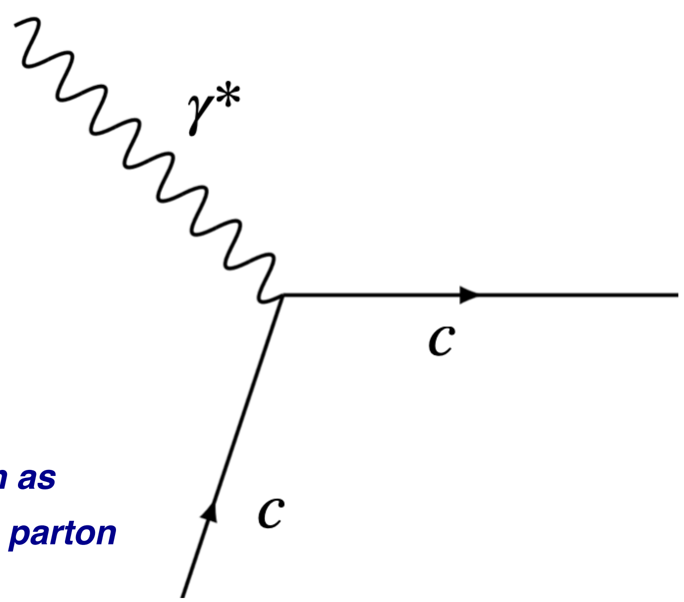
$$F_2^c(x, Q^2) \propto \sum_{i=g,u,d,s} C_i^{(n_f)}(\alpha_s, Q^2/m_c^2) \otimes f_i^{(n_f)}$$

exact in **threshold region**

not appropriate to describe ***$Q^2 >> m_c^2$*** region due to **large unresummed logs**

charm produced via perturbative radiation

Zero-mass scheme: charm PDF treated on the same footing as light quark flavours



charm as massless parton

$$F_2^c(x, Q^2) \propto \sum_{i=g,u,d,s,c} C_i^{(n_f+1)}(\alpha_s) \otimes f_i^{(n_f+1)}$$

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

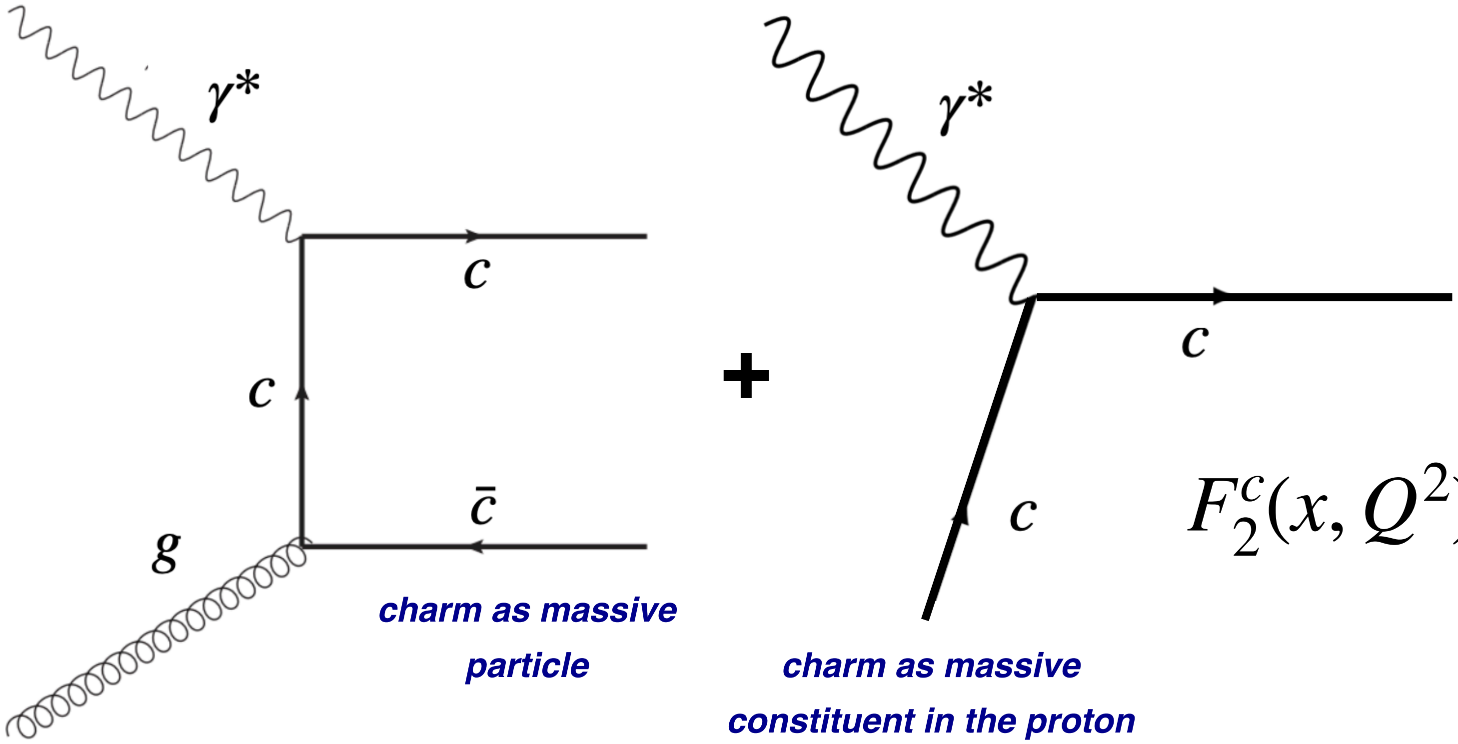
still depends on gluon!

appropriate description at high energies

fails for ***Q^2*** close to ***m_c^2*** due to lack of **mass corrections**

Charm production in DIS

Fixed-flavour scheme with intrinsic charm



$$F_2^c(x, Q^2) \propto \sum_{i=g,u,d,s,c} C_i^{(n_f)}(\alpha_s, Q^2/m_c^2) \otimes f_i^{(n_f)}$$

General-mass variable flavour number scheme: combines massless and massive calculations & accounts for possible charm in the proton

massive xsec *high-Q2 xsec* *scheme matching* *massless PDFs*

$$F(x,Q^2) = \sum_{i,j=g,q,\bar{q},h,\bar{h}} \left[C_i^{(3)}\left(\frac{Q^2}{m_h^2}\right) - C_i^{(3,0)}\left(\frac{Q^2}{m_h^2}\right)\right] \otimes K_{ij}^{-1}(Q^2) \otimes f_j^{(4)}(Q^2)$$
$$+ \sum_{i,j=g,q,\bar{q},h,\bar{h}} C_i^{(4)} \otimes f_i^{(4)}(Q^2),$$

massless xsec *massless PDFs*

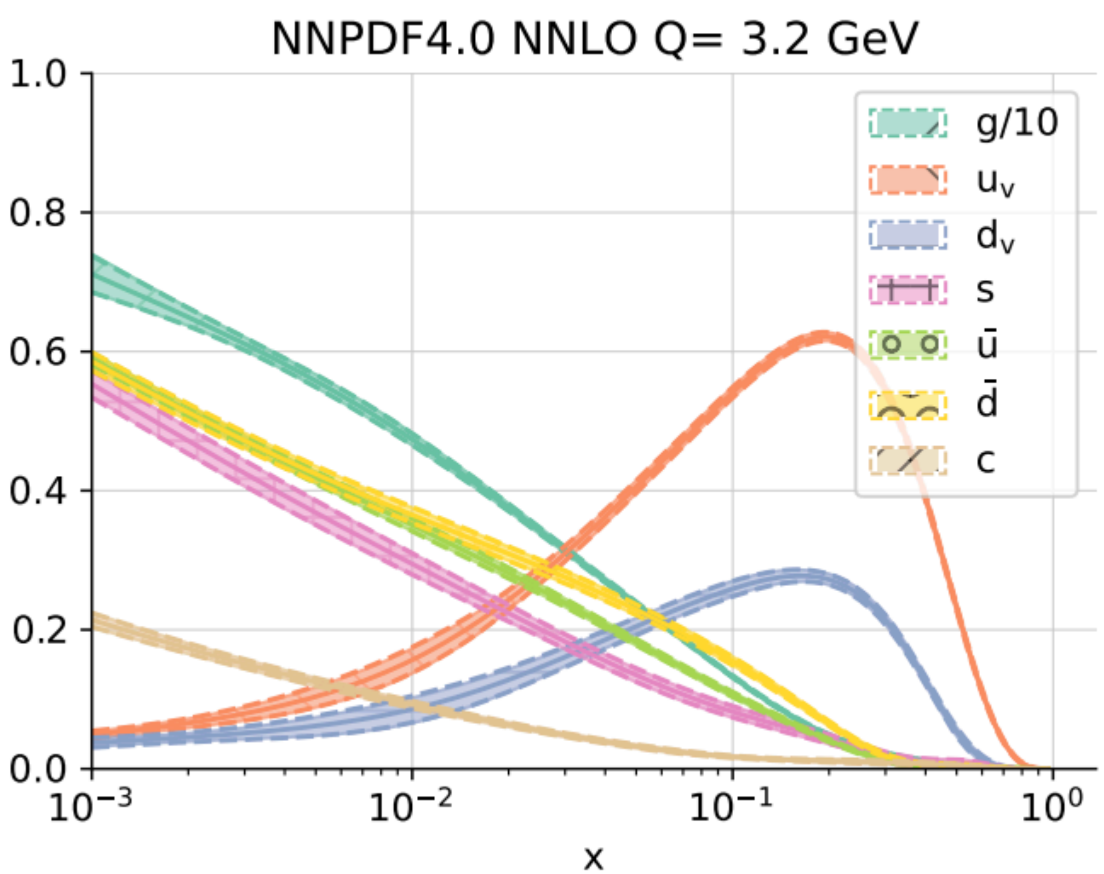
FONLL: Forte, Laenen, Nason, Rojo 1001.2312

+ IC: Ball, Bertone, Bonvini, Forte, Rojo, Rottoli 1510.00009

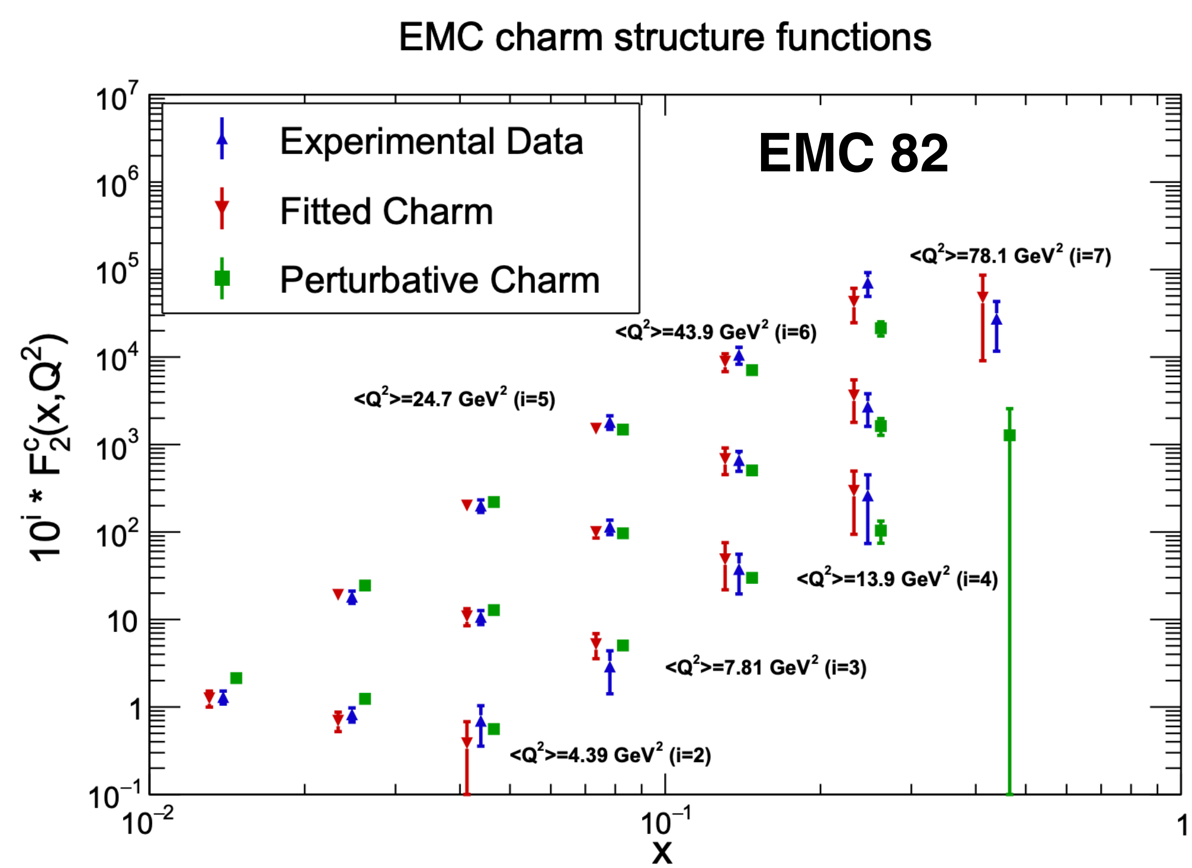
Charm production in DIS

The **precise modelling** of charm production in DIS is relevant for many important applications

Probe small-*x* gluon: charm production is up to 25% of inclusive cross-section in HERA region



Probe large-*x* charm , dominated by possible intrinsic component



Charm production will be instrumental for the **physics program of the EIC**:

Heavy quark mass effects in polarised DIS, and impact on fits of the **polarised gluon**

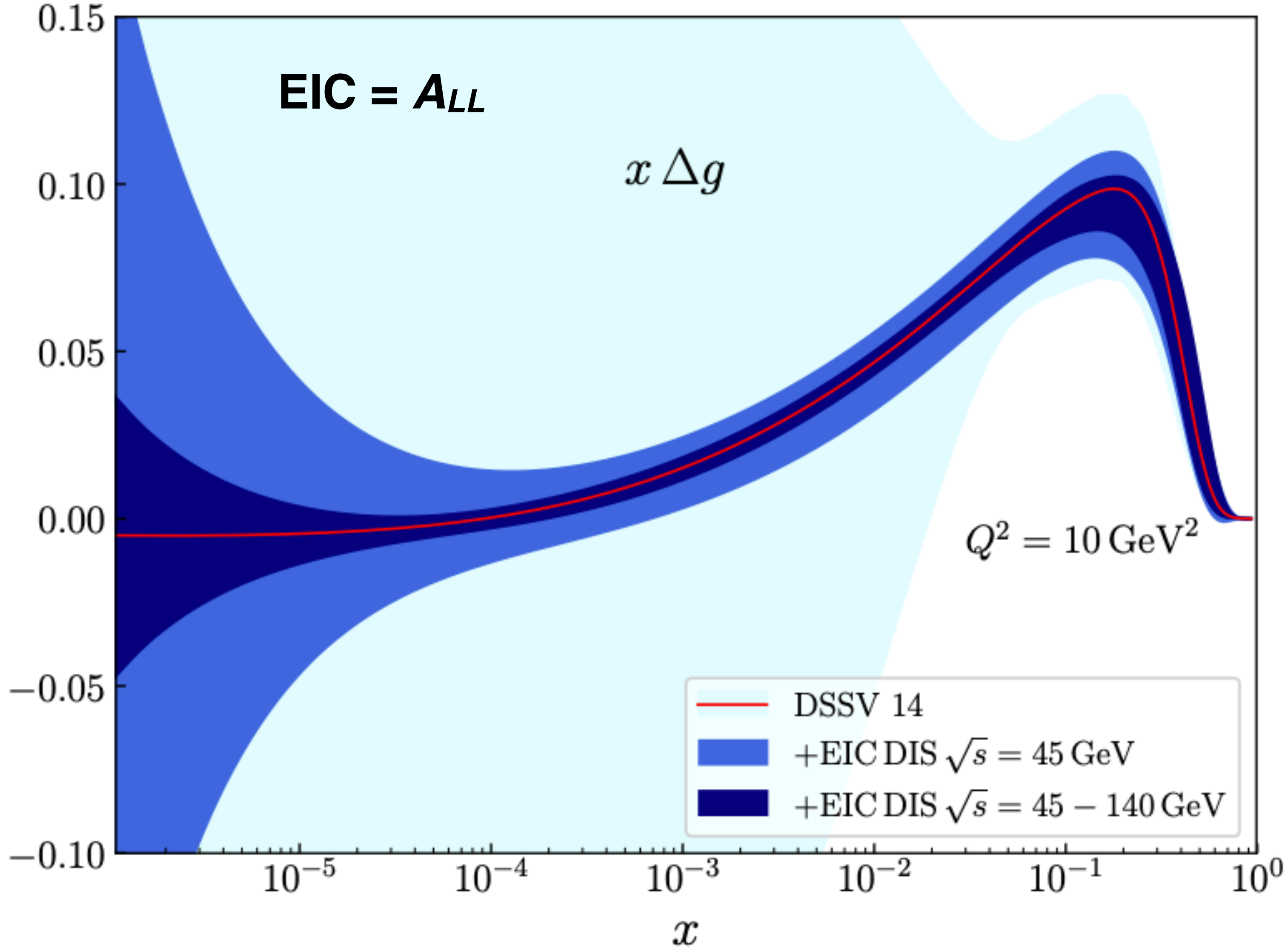
Charm production at large-*x* and constraints on the **charm valence content** of the proton

A General-Mass Scheme for Polarised DIS at the EIC

F. Hekhorn, E. R. Nocera, G. Magni, T. R. Rabemananjara, & **J. Rojo**, A. Schaus, & R. Stegeman, ***in preparation***

Charm production in polarised DIS

Polarised DIS at the EIC provides unique constraints on the **spin structure of the proton**



Existing projections based on treating the **charm contribution to the EIC polarised asymmetries** as **purely massless**. Is this justified? And what are constraints from charm-tagged asymmetries?

To answer this question, we need first a general-mass VFN scheme for polarised structure functions!

Charm production in polarised DIS

Extend FONLL to polarised DIS: for $\mathbf{g_1^p}$, all required results up to $\boldsymbol{O(\alpha_S^2)}$ are available

Implemented in the **EKO** and **YADISM** open source codes

Starting point are the **massive** (3FNS) and **massless** (4FNS) calculations

$$g^{[3]}(x,Q^2) = \int_x^1 \frac{dz}{z} \sum_{i=g,q,\bar{q}} \Delta f_i^{[3]}\left(\frac{x}{z},Q^2\right) \Delta C_i^{[3]}\left(z,\alpha_s^{[3]},\frac{m_h^2}{Q^2}\right),$$

$$g^{[4]}(x,Q^2) = \int_x^1 \frac{dz}{z} \sum_{i=g,q,\bar{q},c,\bar{c}} \Delta f_i^{[4]}\left(\frac{x}{z},Q^2\right) \Delta C_i^{[4]}\left(z,\alpha_s^{[4]}\right),$$

Asymptotic (high-Q limit) 3FNS

$$g^{[3,0]}(x,Q^2) = \int_x^1 \frac{dz}{z} \sum_{i=g,q,\bar{q}} \Delta f_i^{[3]}\left(\frac{x}{z},Q^2\right) \Delta C_i^{[3,0]}\left(z,\alpha_s^{[3]},\log\frac{m_h^2}{Q^2}\right)$$

PDFs in the 3FNS are transformed to the 4FNS via the **matching relations**

$$\alpha_s^{[4]}(m_h^2) = \alpha_s^{[3]}(m_h^2) + \sum_{n=2}^{\infty} c_n \left(\alpha_s^{[3]}(m_h^2)\right)^n,$$

$$\Delta f_i^{[4]}(x,m_h^2) = \int_x^1 \frac{dz}{z} \sum_{j=g,q,\bar{q}} \Delta f_i^{[3]}\left(\frac{x}{z},m_h^2\right) \Delta K_{ij}\left(z,\alpha_s^{[4]},\frac{m_h^2}{Q^2}\right)$$

Charm production in polarised DIS

Extend FONLL to polarised DIS: for $\mathbf{g_1^p}$, all required results up to $O(\alpha_S^2)$ are available

Implemented in the **EKO** and **YADISM** open source codes

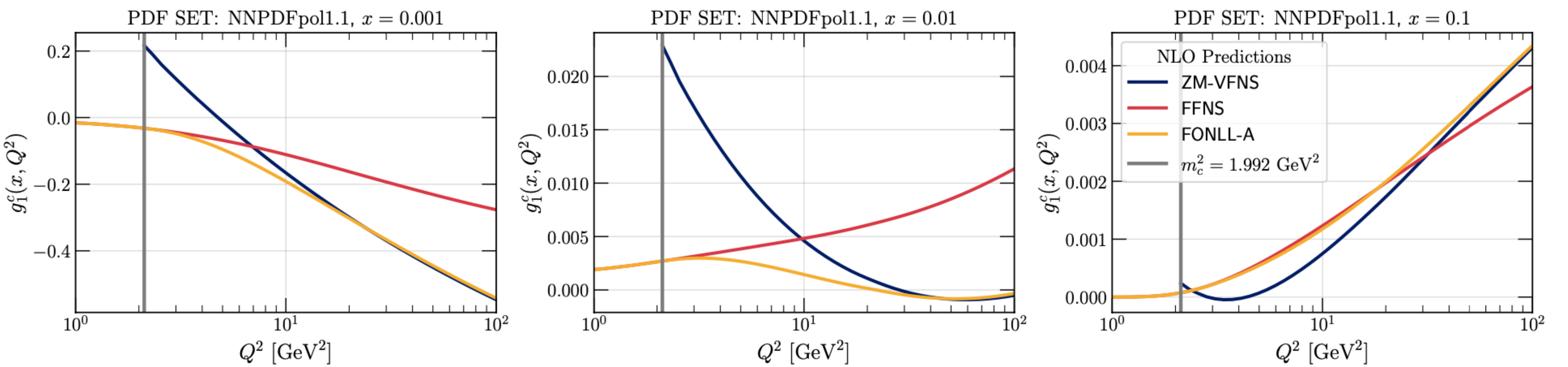
Starting point are the **massive** (3FNS) and **massless** (4FNS) calculations

PDFs in the 3FNS are transformed to the 4FNS via the **matching relations**

Combine the 4FNS and 3FNS calculations **removing double counting**

$$g^{[4]}_{\rm FONLL}(x,Q^2) = g^{[4]}(x,Q^2) + g^{[3]}(x,Q^2) - g^{[3,0]}(x,Q^2)$$

Subleading effects can be large close to threshold, may be damped with dedicated prescriptions

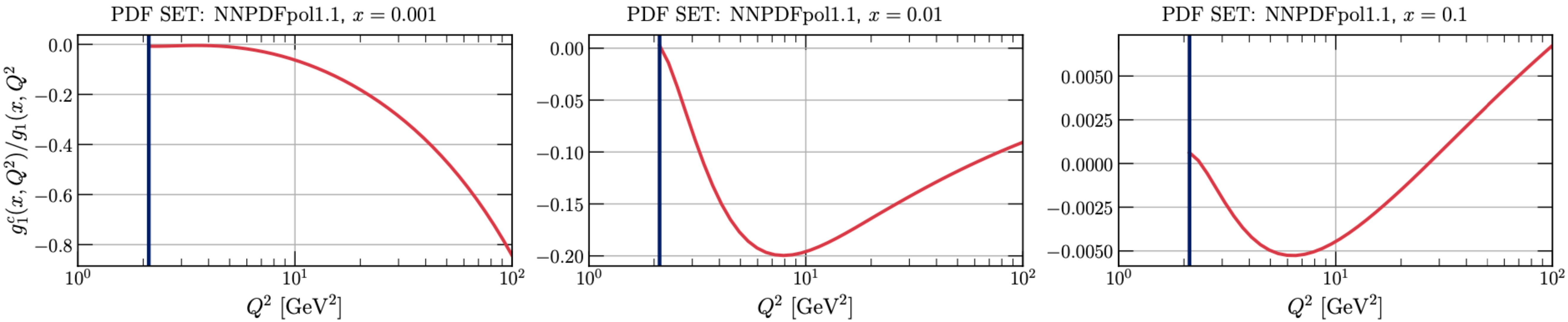


Smooth interpolation between massive and massless calculations

Now that FONLL is available for polarised DIS, what do we learn of **relevance for the EIC?**

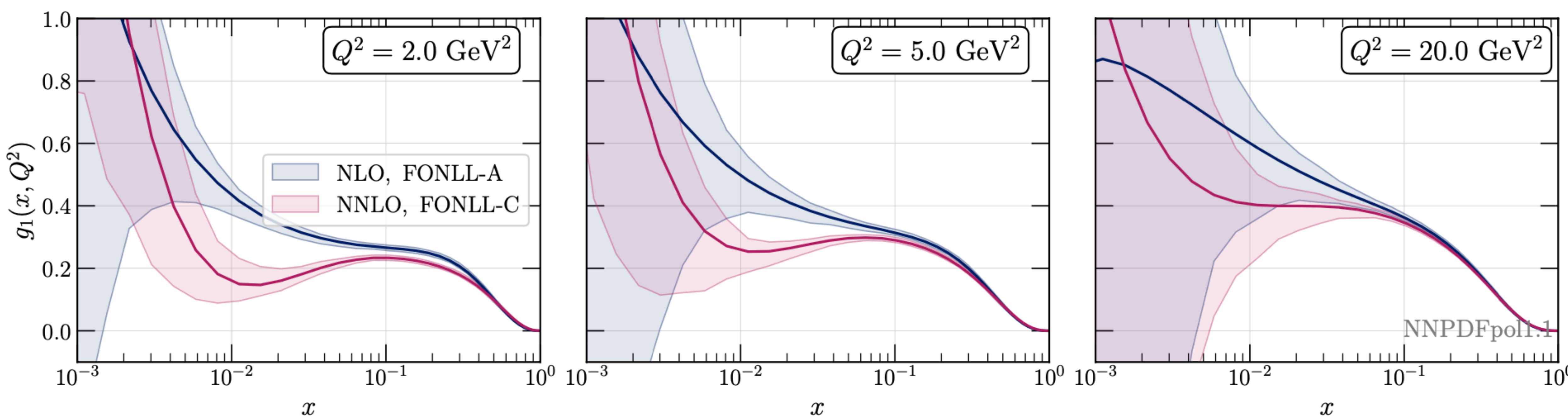
Impact for the EIC

Is the **charm contribution** to polarised structure functions sizable?



Yes, in the region covered by the EIC charm production is **up to 30% of g_1**

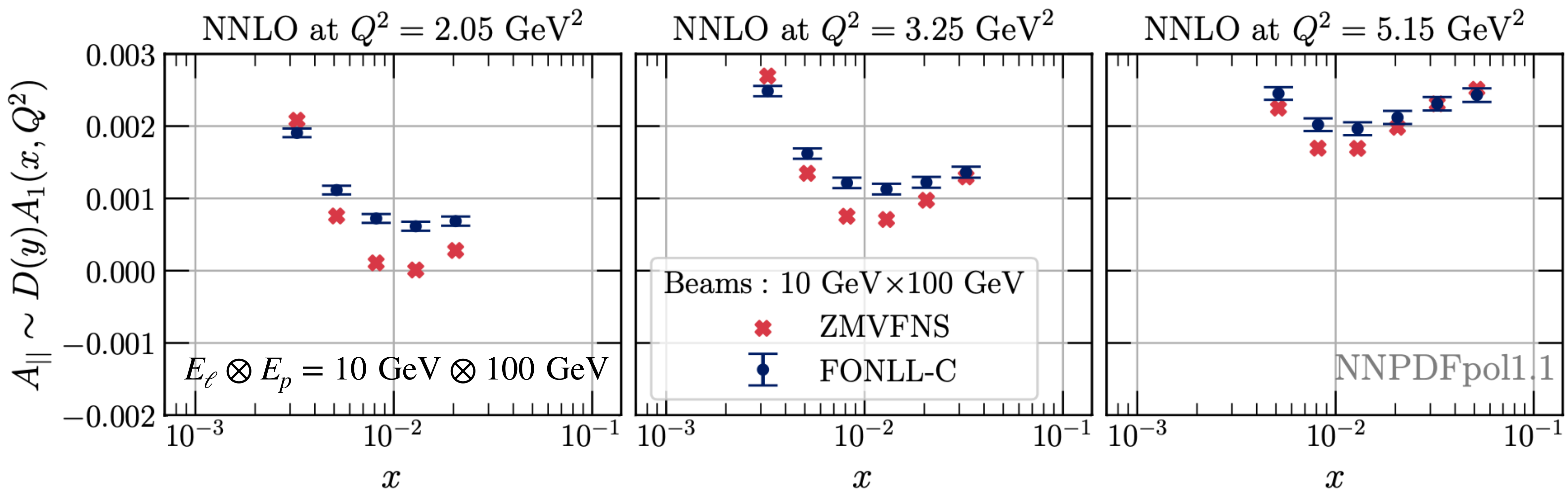
Are **NLO QCD calculations** sufficiently accurate for EIC physics?



No, **NNLO corrections are large** both for charm-tagged and for inclusive polarised structure functions

Impact for the EIC

Can I reliable model inclusive asymmetries with a massless calculation?



No, charm mass effects are much larger than **projected experimental uncertainties**

Can I reliable model charm-tagged asymmetries with a massless calculation?

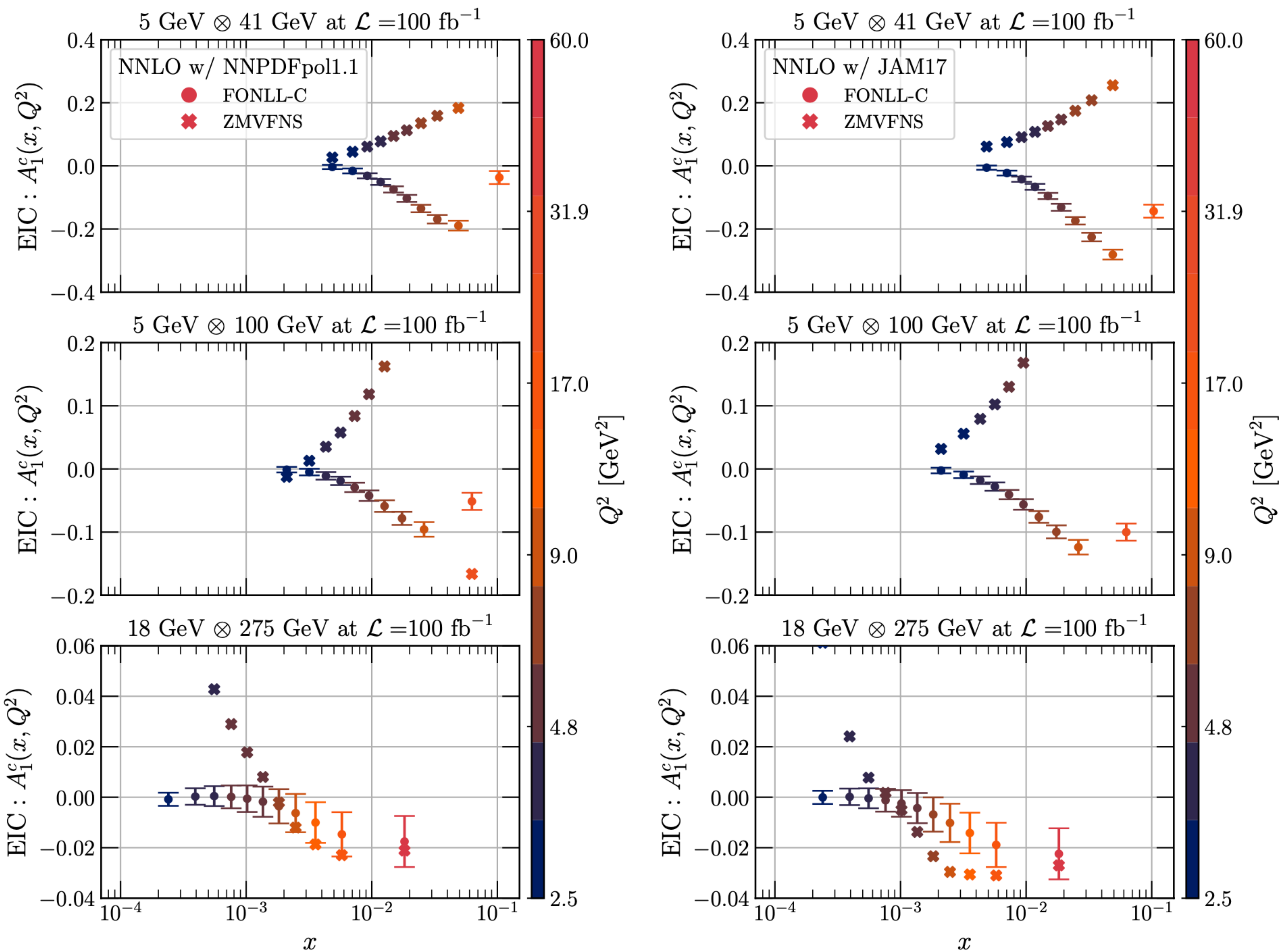
This is an even worse approximation!

Note that a GM-VFNS is required to include both inclusive and charm-tagged asymmetries into a **global polarised PDF determination**

Inclusive EIC projections: arXiv:2210.09048 [ATHENA study]

Charm-tagged EIC and EicC projections: arXiv:2110.04489.

Impact for the EIC



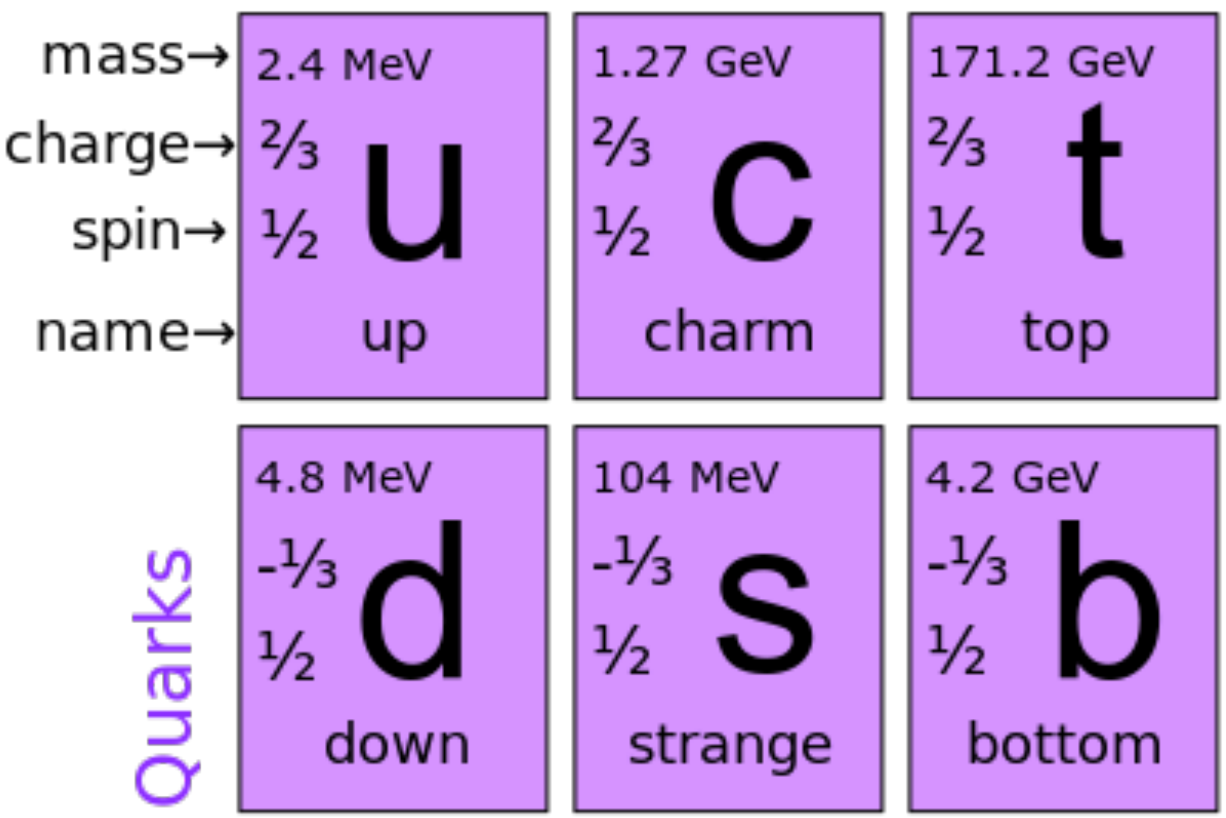
The Valence Charm PDF at the EIC

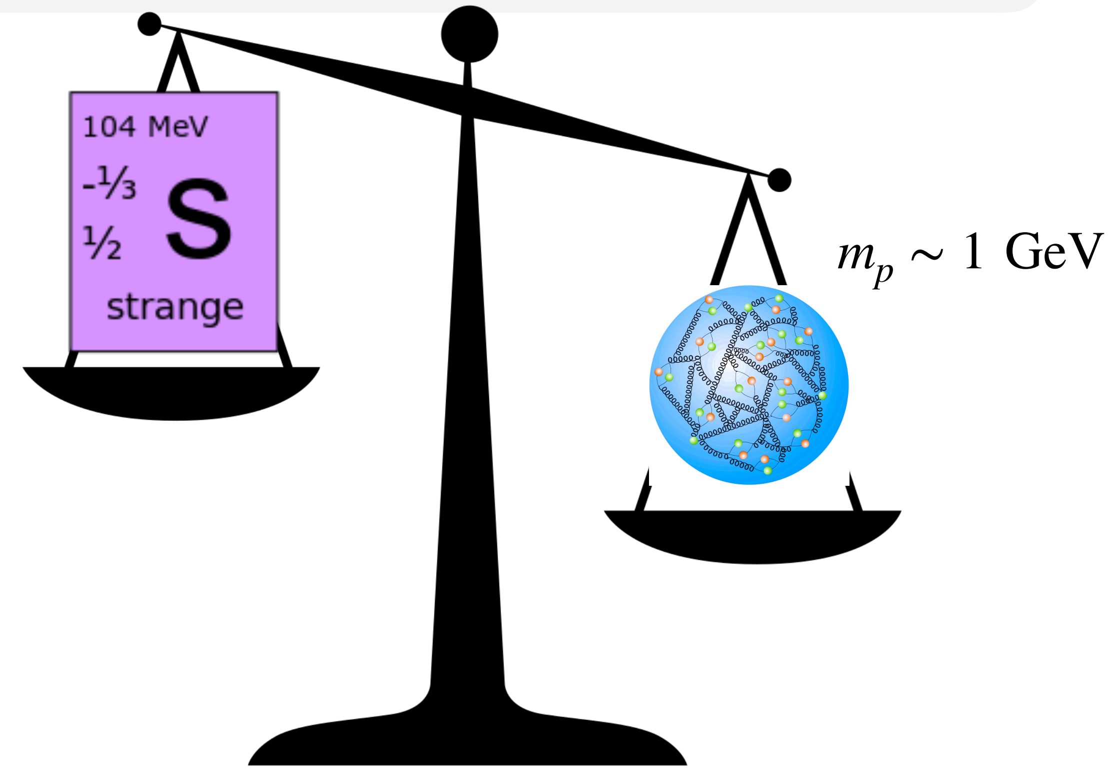
R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, K. Kudashkin, G. Magni & J. Rojo, ***Nature*** **608 (2022) 7923, 483-487**

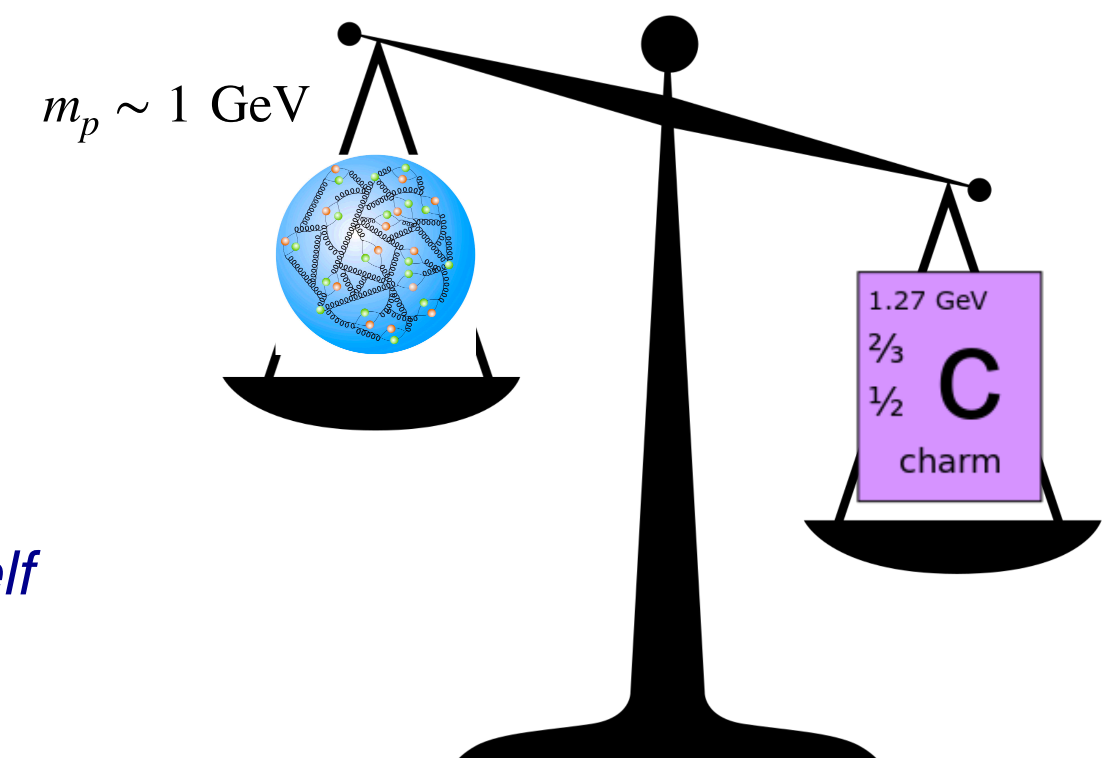
R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, E. R. Nocera, G. Magni, J. Rojo & R. Stegeman, ***in preparation***

The charm content of the proton

common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**







charm quarks heavier than the proton itself

The charm content of the proton

common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

the charm PDF is **generated perturbatively** (DGLAP evolution) from radiation off gluons and quarks

$$\underbrace{f_c^{(n_f)}}_{\text{3FNS charm}} = 0 \quad \rightarrow \quad \underbrace{f_c^{(n_f+1)}}_{\text{4FNS charm}} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes \underbrace{f_g^{(n_f+1)}}_{\text{4FNS gluon}} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

NLO matching

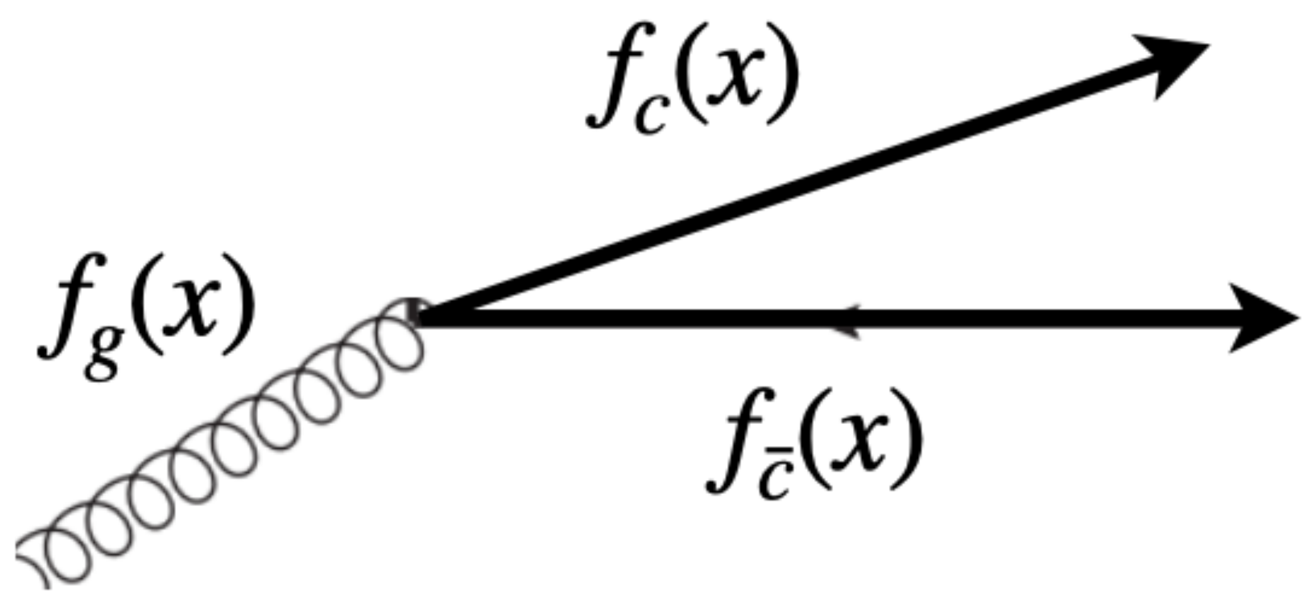
4 flavour scheme, $Q > m_c$

$u^{(4)}, d^{(4)}, s^{(4)}, c^{(4)} g^{(4)}$

↕ ↕

3 flavour scheme, $Q < m_c$

$u^{(3)}, d^{(4)}, s^{(3)}, g^{(3)}$



If charm is **perturbatively generated**, the charm PDF is **trivial**

The charm content of the proton

common assumption: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

It does not need to be so! An **intrinsic charm component** predicted in many models

THE INTRINSIC CHARM OF THE PROTON

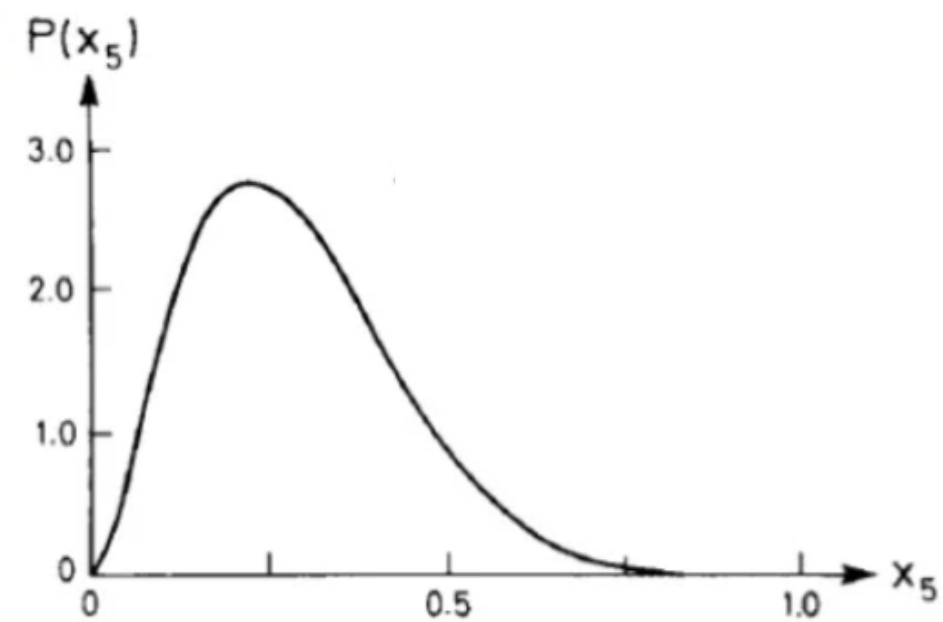
S.J. BRODSKY [1]
Stanford Linear Accelerator Center, Stanford, California 94305, USA

and

P. HOYER, C. PETERSON and N. SAKAI [2]
NORDITA, Copenhagen, Denmark

Received 22 April 1980

$$p\rangle = \mathscr{P}_{3q}\ uud\rangle + \mathscr{P}_{5q}\ uudc\bar{c}\rangle + \ldots$$



Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible uudc$\bar{c}$ Fock component. The interesting consequences of such a hypothesis are explored.

within global PDF fit:

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

Extracted from data

from QCD radiation and matching

from intrinsic component

Disentangling intrinsic charm

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

Extracted phenomenologically from data

from pQCD evolution and matching

from intrinsic component $c^{(n_f=3)}_{\text{(intr)}}(x) \neq 0$

4FNS Charm PDF constrained by experimental data for $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF 4.0 methodology

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

QCD evolution

subtract perturbative component

4FNS to 3FNS transformation

NNLO or N^3LO matching conditions

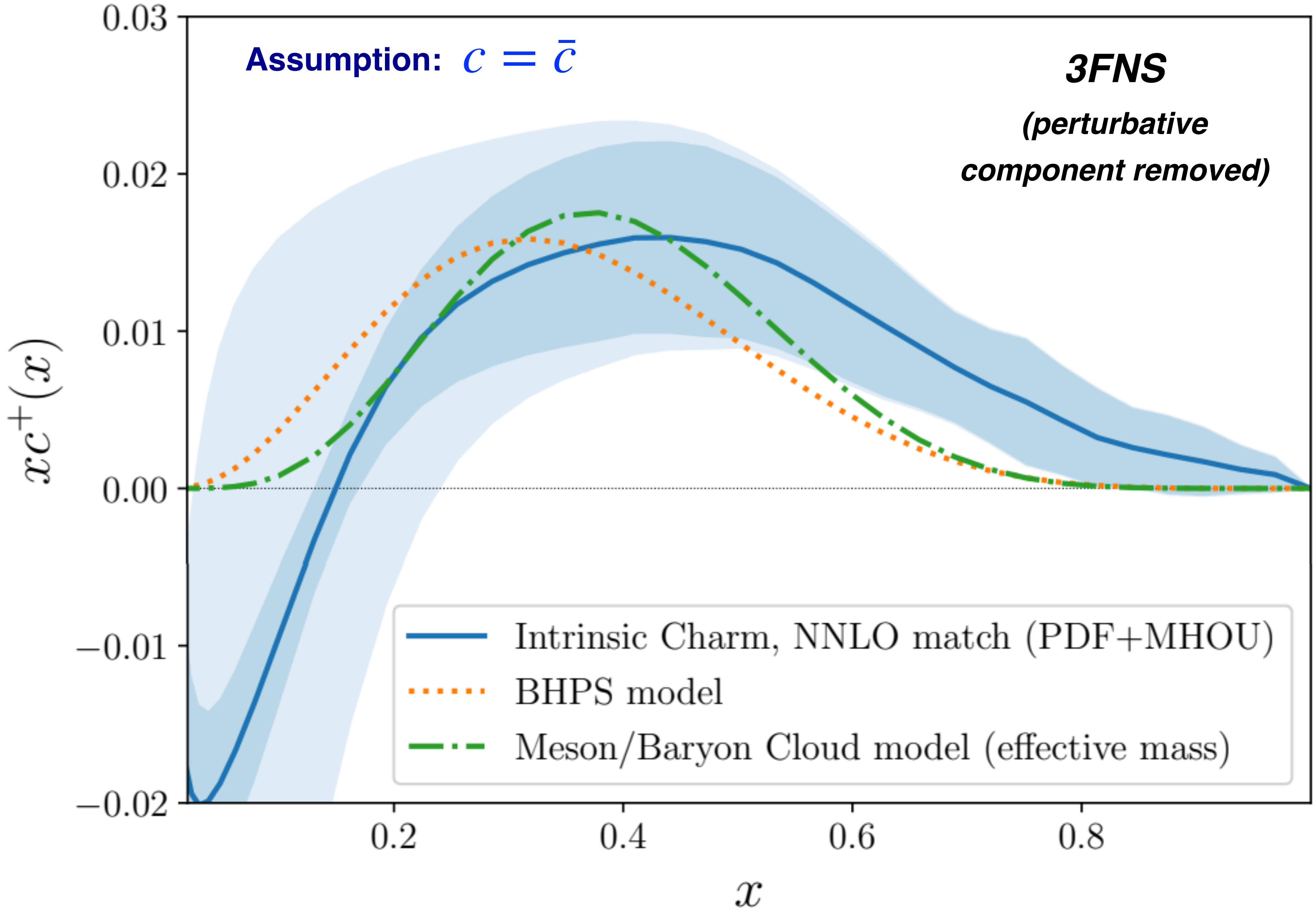
EKO
Evolution Kernel Operators

$$c^{(n_f=3)}(x,Q) = c_{\text{(intr)}}(x)$$

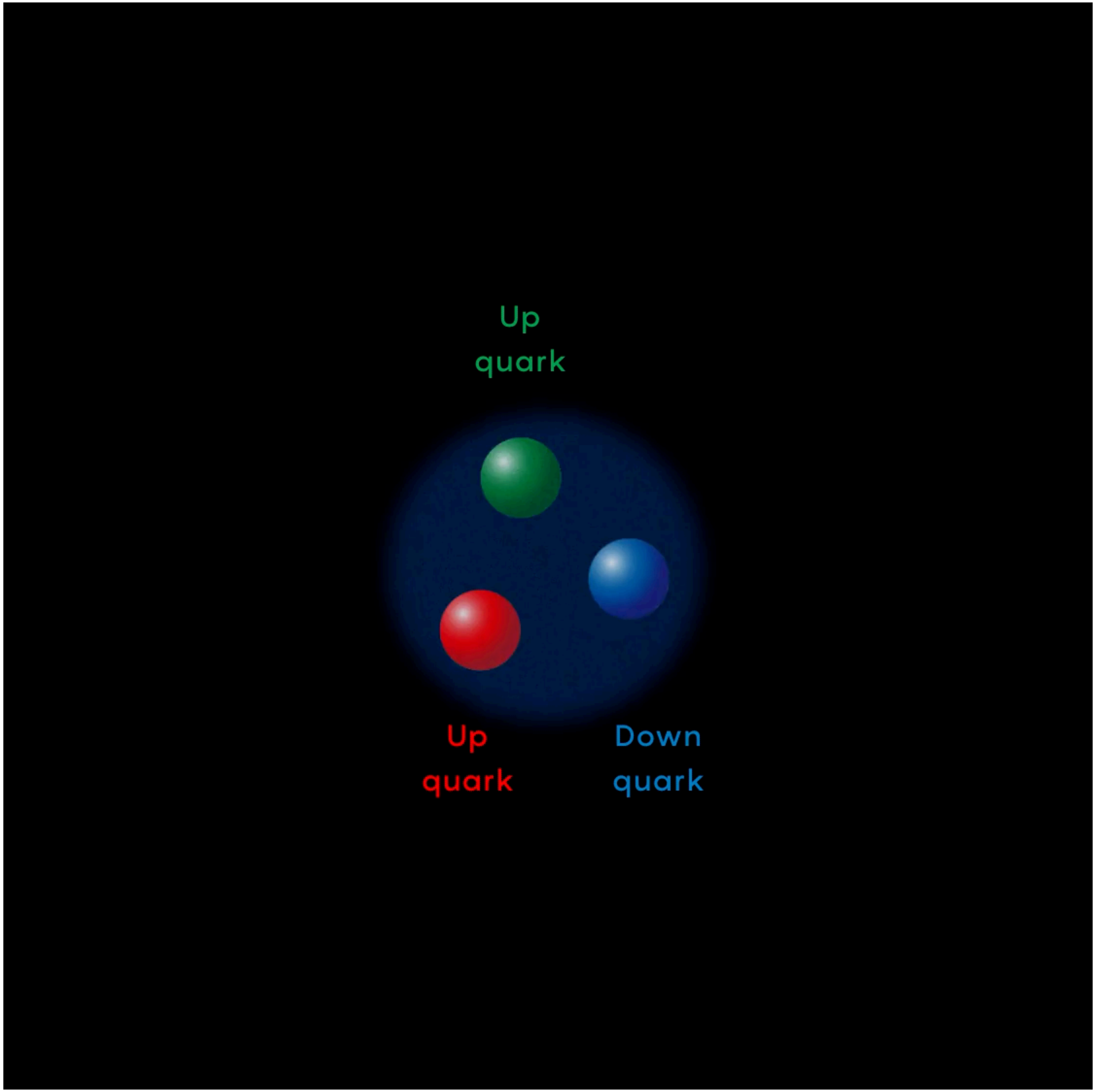
Intrinsic (3FNS) Charm

- Scale-independent
- PDF and MHO uncertainties

4FNS to 3FNS transformation

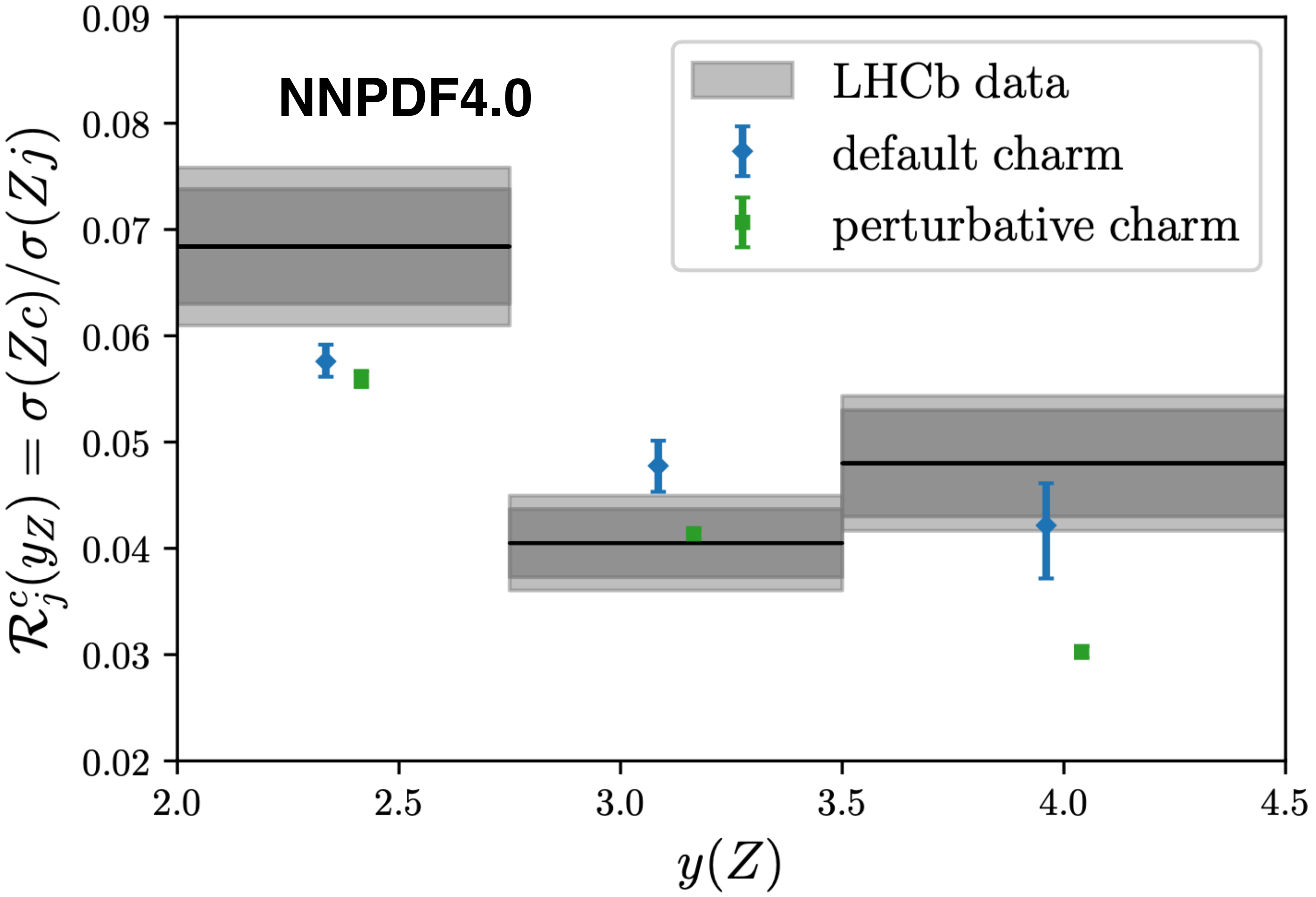


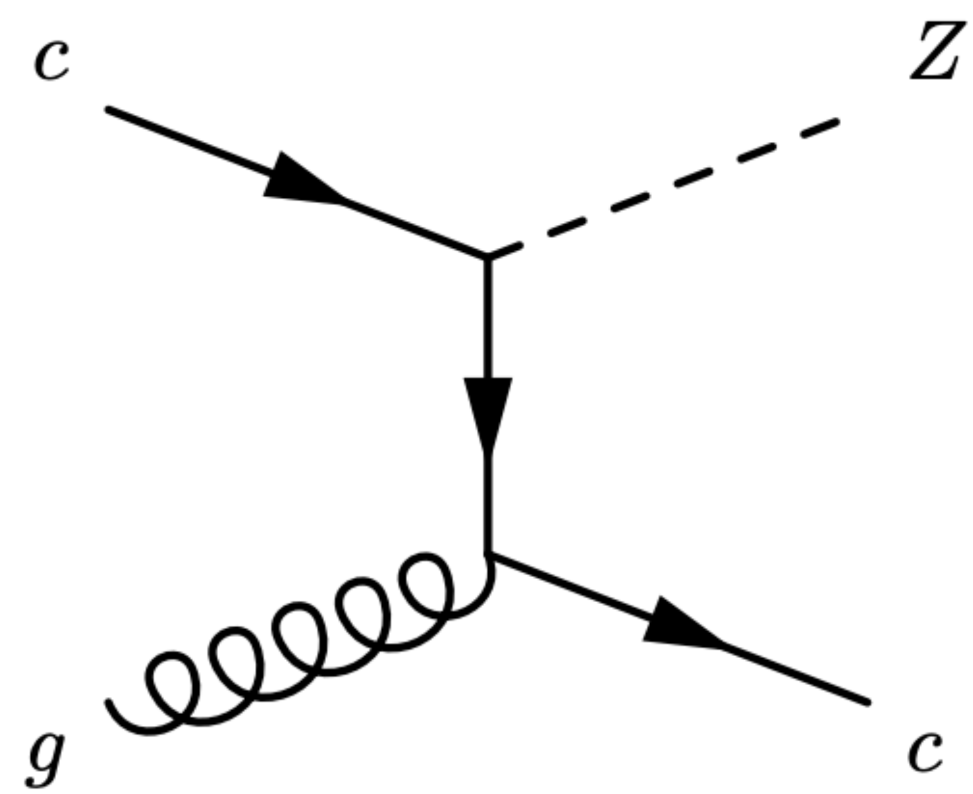
The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**



credits: https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

Z+charm @ LHCb





$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c \text{ tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

Z+charm at forward rapidities (LHCb) sensitive to the **charm PDF up to *x*=0.5**

NNPDF4.0 predictions in agreement with LHCb Z+D data (not included in fit, independent validation)

The valence charm PDF

- No reason why intrinsic charm should be symmetric (it is not in most models)

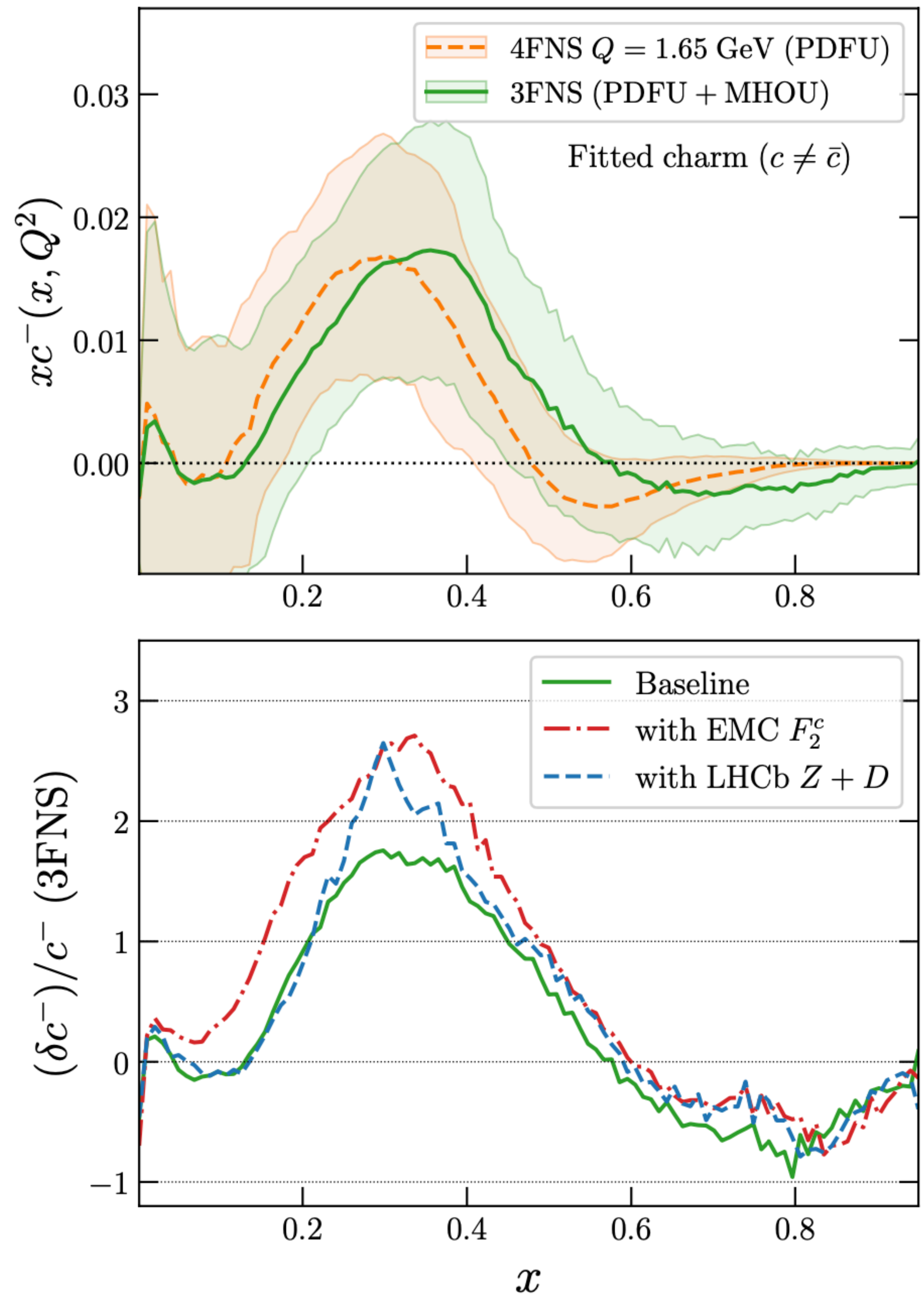
  i.e. up, down, and strange quark PDFs are asymmetric

- Extend the NNPDF4.0 analysis with an separate determination of charm and anti-charm PDFs

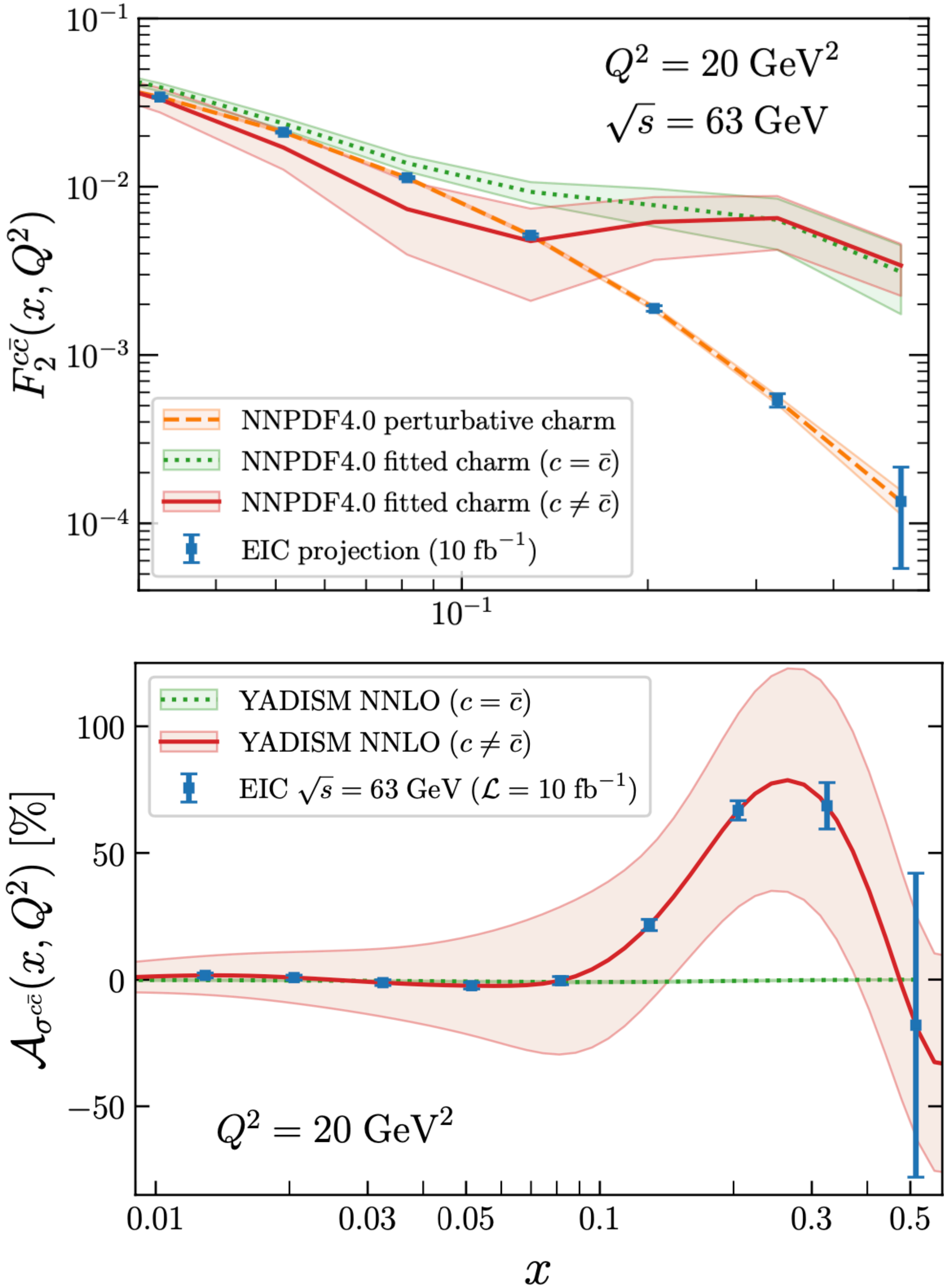
- PDF uncertainties are large, but preference for a **non-zero, positive IC asymmetry** around *x*=0.3

- Consistent with the independent constraints from **EMC F2c** and **LHCb Z+D**

- Can the EIC confirm or falsify these results?



Implications for the EIC



- Inclusive **F_2^c measurements at large-*x*** will clearly disentangle IC (factor 100 difference!)

- Measurements of the **asymmetry between final states with D and Dbar mesons** will pin down a non-vanishing charm valence PDF

$$\mathcal{A}_{\sigma^{c\bar{c}}}(x, Q^2) \equiv \frac{\sigma^{c}_{\rm red}(x, Q^2) - \sigma^{\bar{c}}_{\rm red}(x, Q^2)}{\sigma^{c\bar{c}}_{\rm red}(x, Q^2)}$$

- No perturbative mechanism can generate such asymmetry: **ultimate evidence for intrinsic charm**

Charm-tagged EIC projections: ***arXiv:****2107.05632*

Summary and outlook

- ☑ A robust modelling of **charm quark production** is a key ingredient of many scientific milestones at the EIC

- ☑ By extending the FONLL general-mass scheme to polarised DIS, we can consistently include **charm mass effects in a global analysis of polarised PDFs** aiming to pin down the polarised gluon at small-x

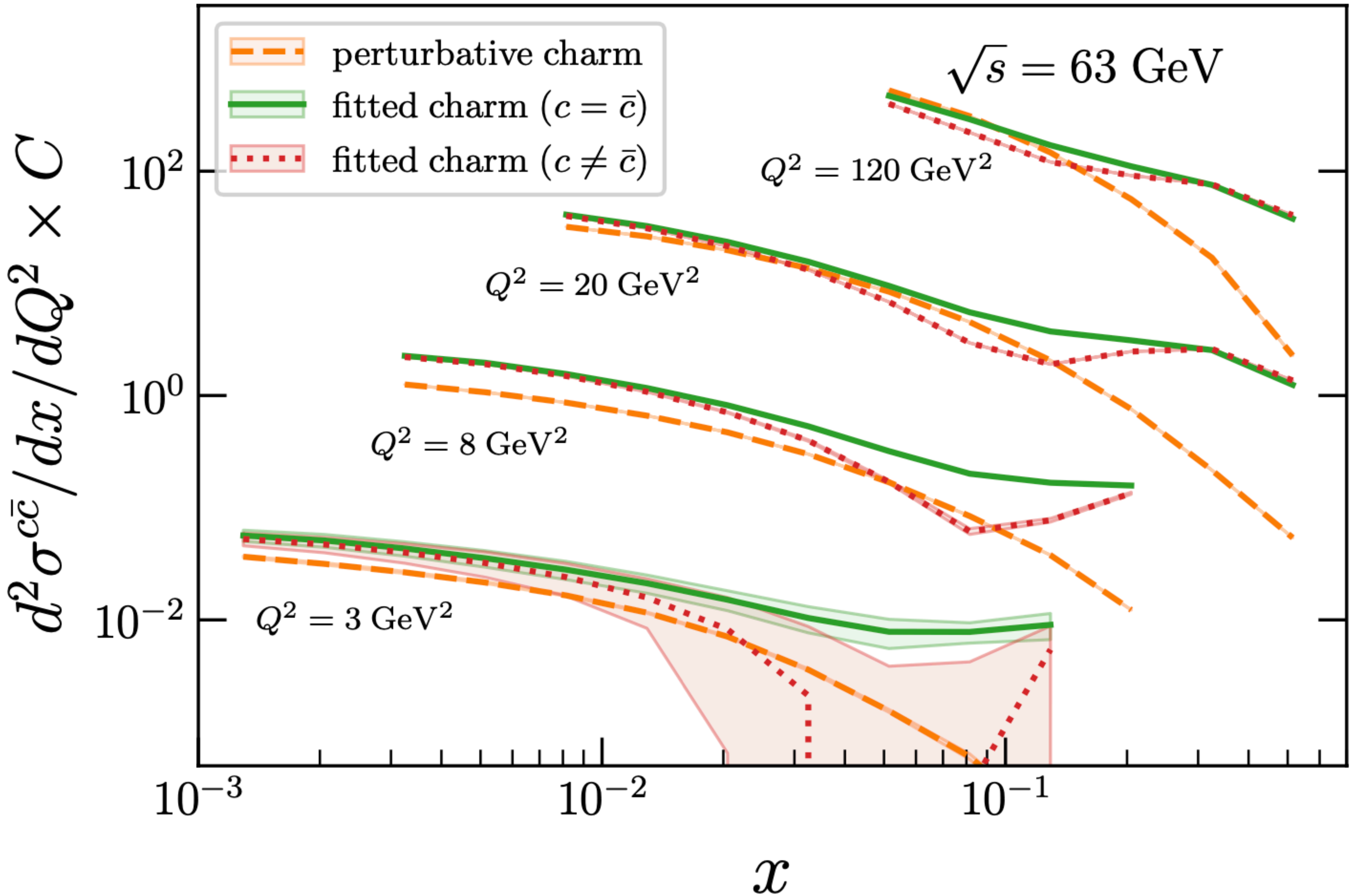
- ☑ Charm mass and higher-order QCD effects are found to be sizeable even for the **inclusive asymmetries,** in addition to charm structure functions themselves

- ☑ Charm production at large-x at the EIC will settle once and for all the **existence and characteristics of intrinsic charm** in the proton

- ☑ A non-zero asymmetry in charm production at the EIC cannot be generated by any perturbative mechanism, and hence it is the **ultimate smoking gun of IC**

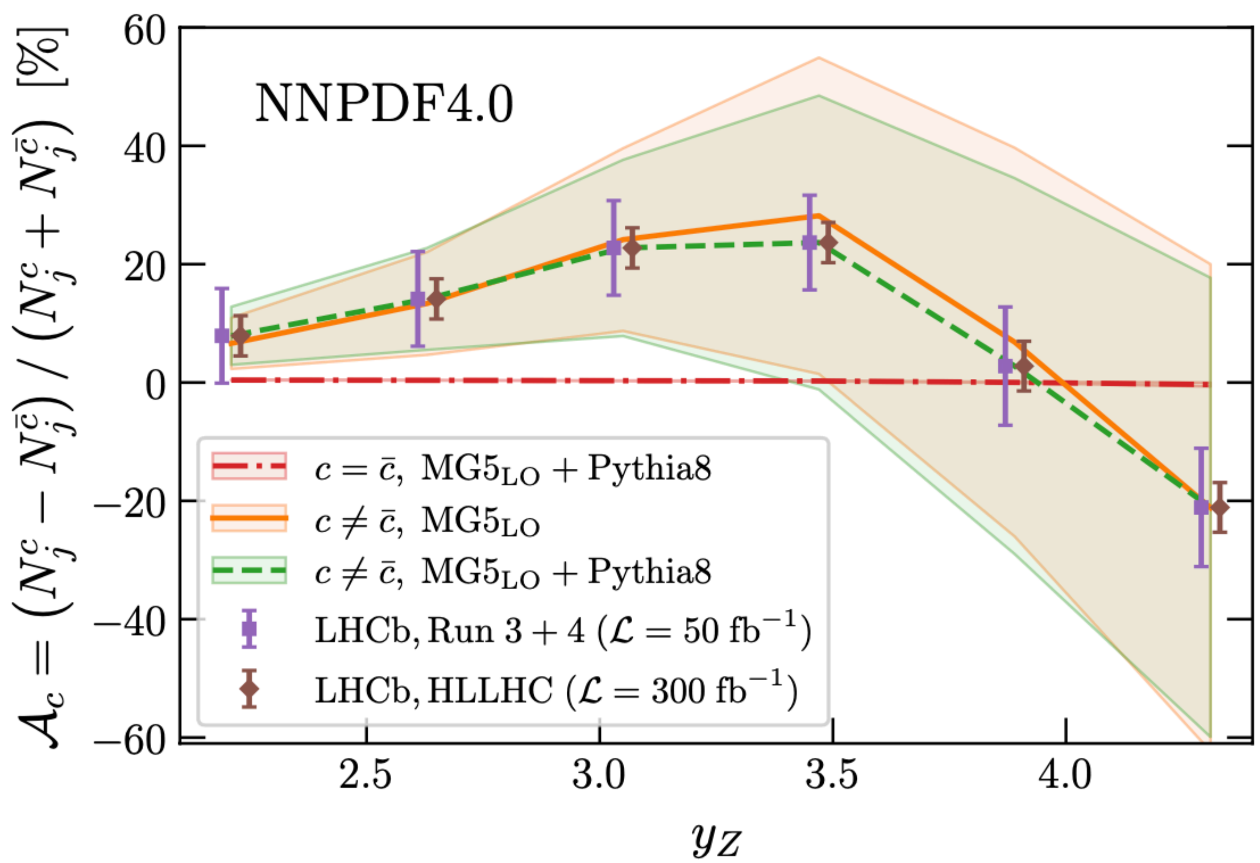
Extra Material

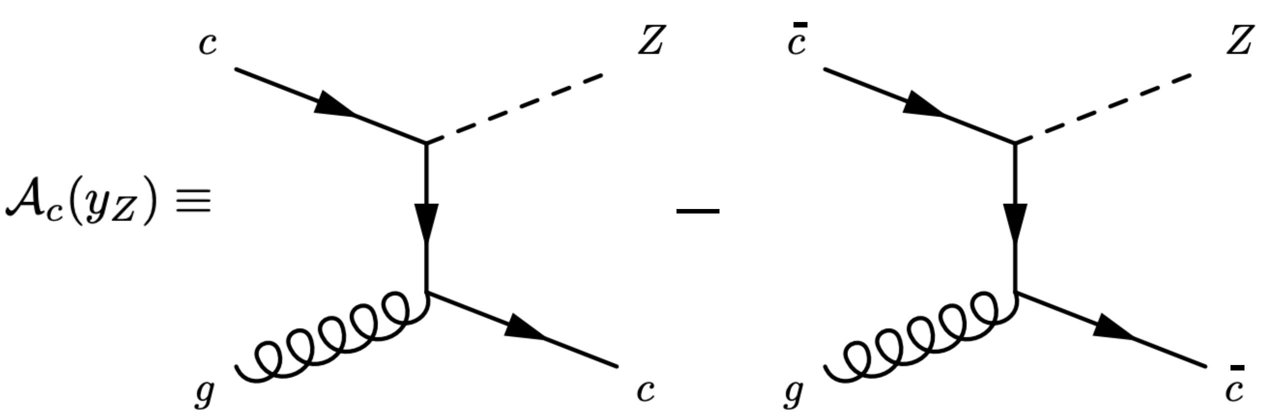
Implications for the EIC



Charm asymmetries at LHCb

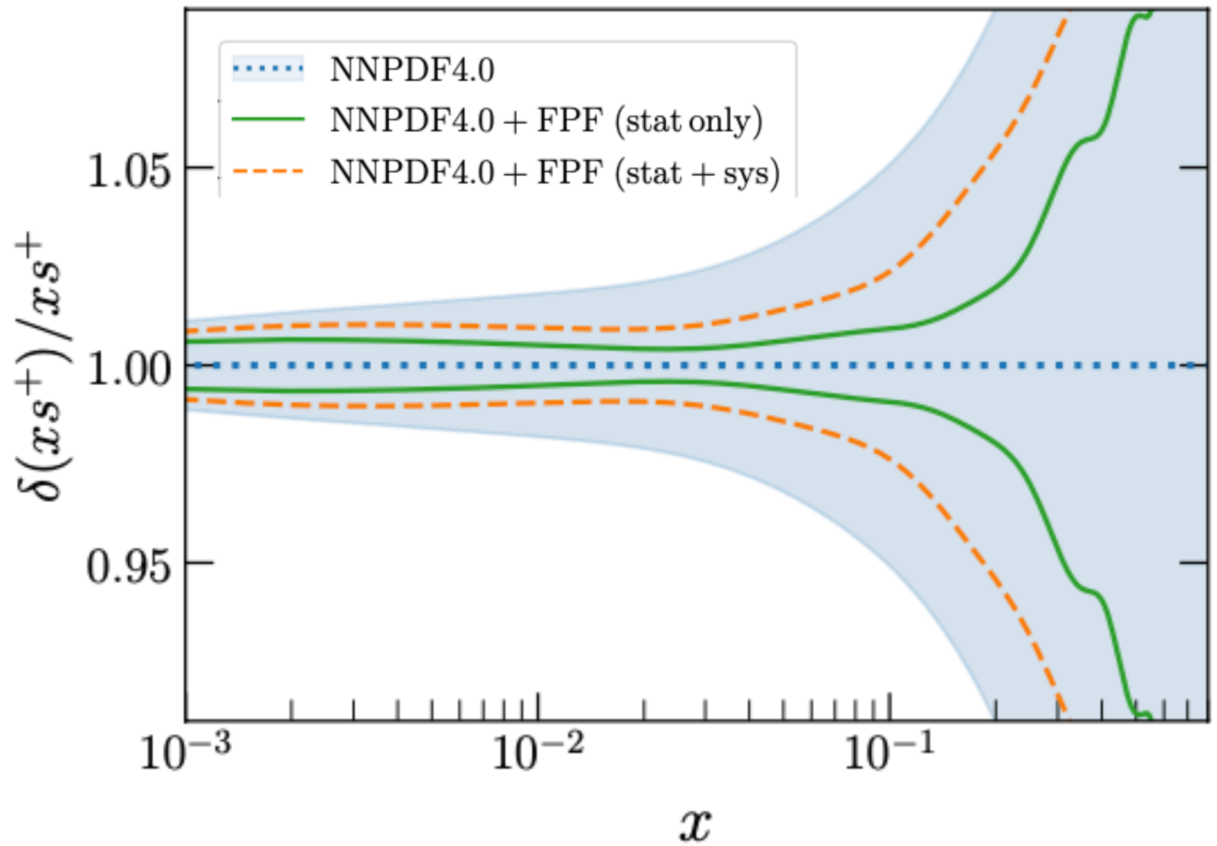
$$\mathcal{A}_c(y_Z) \equiv \frac{N_j^c(y_Z) - N_j^{\bar{c}}(y_Z)}{N_j^c(y_Z) + N_j^{\bar{c}}(y_Z)}$$

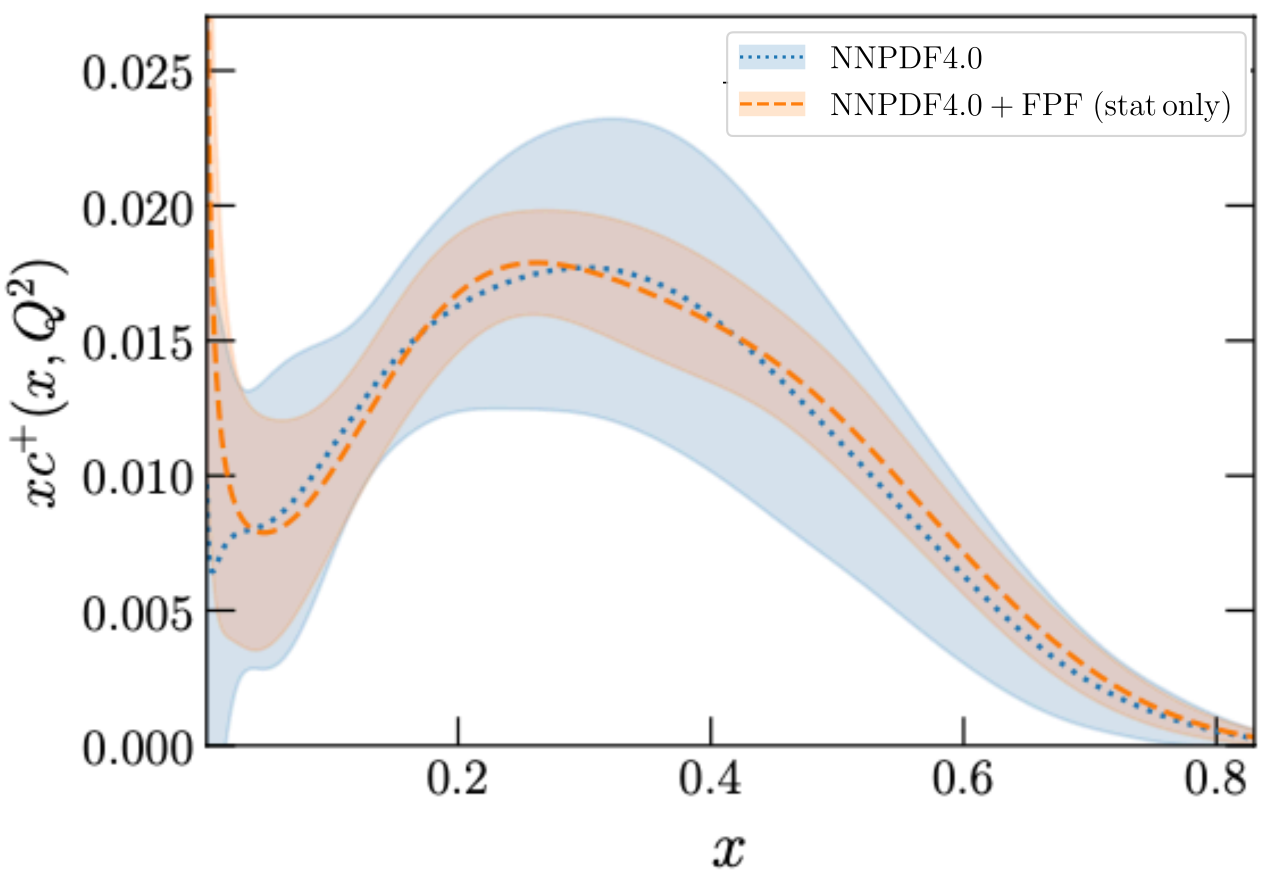




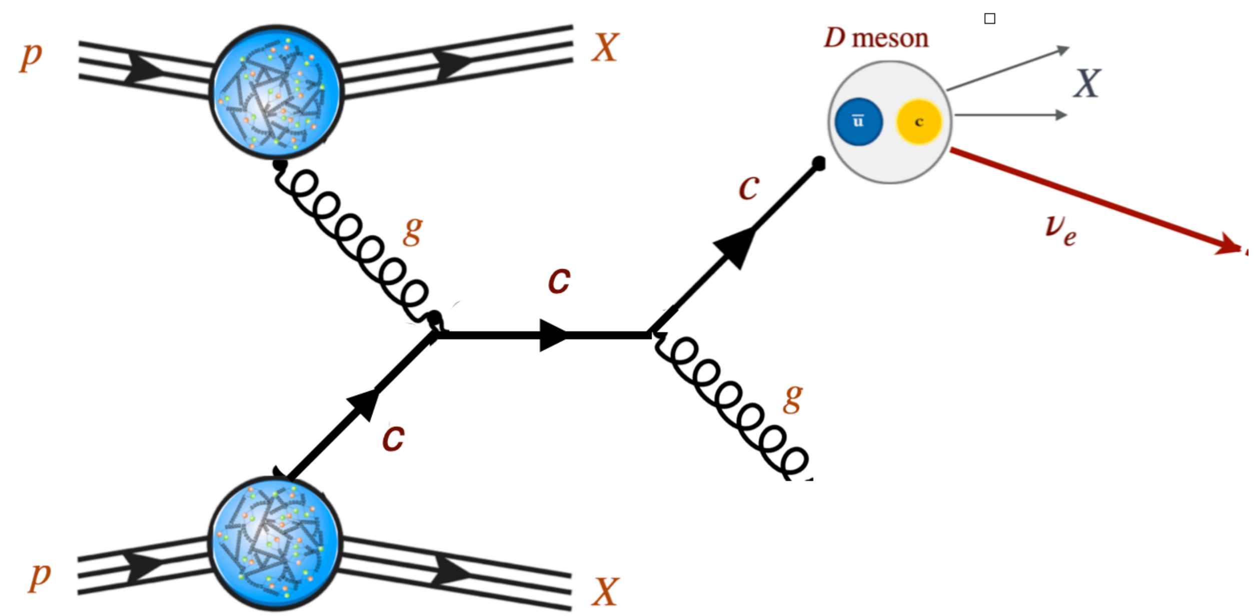
- Projections for LHCb *Z+D* measurements, constructing an **asymmetry between final states with D and Dbar mesons** will pin down a non-vanishing charm valence PDF
- Data from **upcoming LHC runs** will confirm or falsify a non-zero charm asymmetry in the proton
- Ideally the measurement should be carry out in terms of **IRC-safe flavour jets,** to reduce sensitivity to charm fragmentation model

IC and LHC neutrinos





- Projections for LHC neutrino DIS within the **NNPDF4.0 global fit** consistent with the PDF4LHC21 profiling
- Sensitivity to the charm PDF via the **gluon-charm initial state ....**



- …as well as via **neutrino scattering off charm quarks** in the target

WIP: study implications of initial state charm asymmetry on **LHC neutrino observables**