# Intrinsic Charm in the proton

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on behalf of NNDPF

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- **Heavy quark in PDF fits.**
- **The NNPDF4.0 Intrinsic Charm**
- **A possible IC charm asymmetry**

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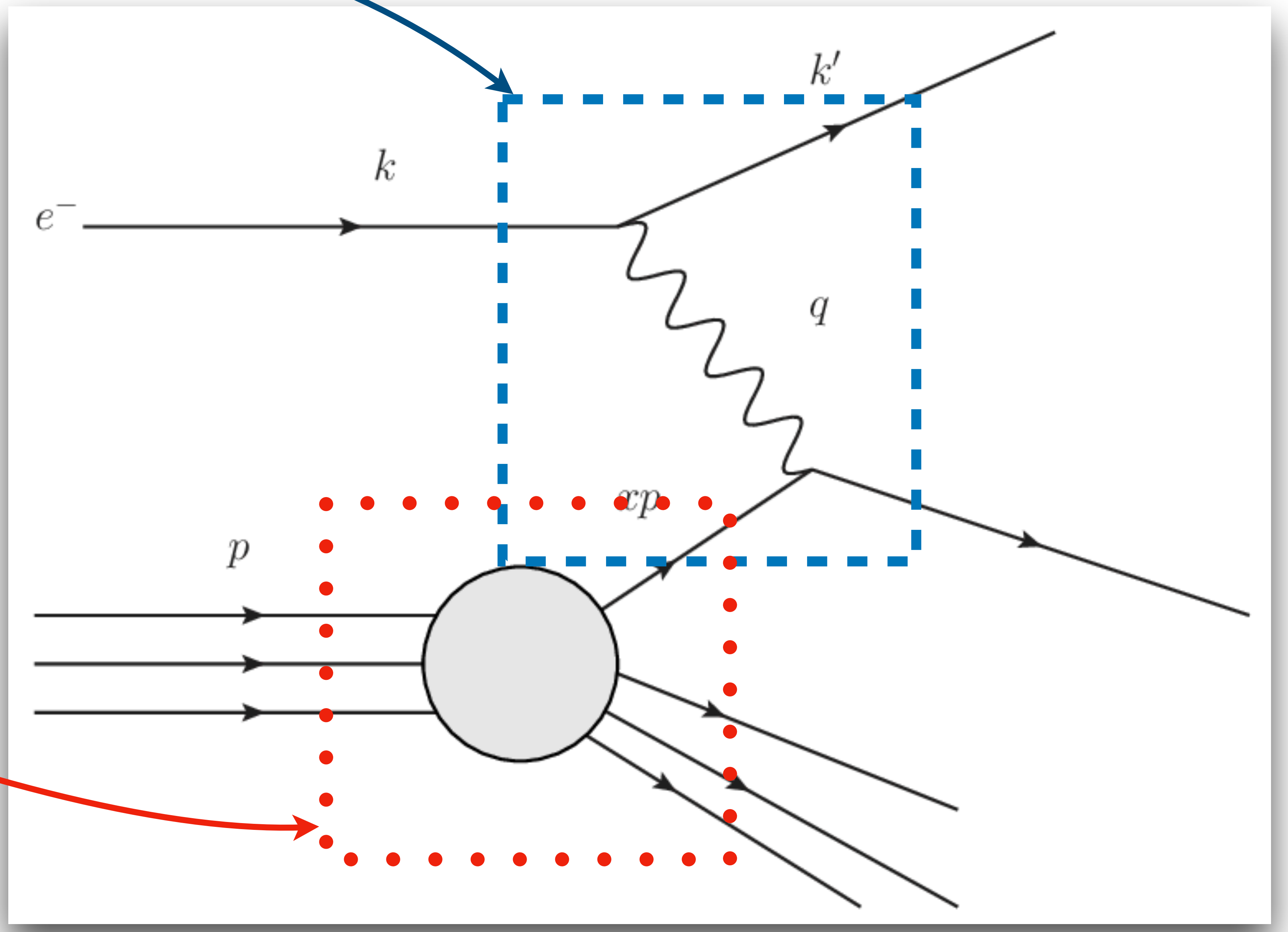
# Factorisation and PDFs

$$\sigma(x,Q^2) = \sum_i^{n_f} f_i(z,Q^2) \otimes \hat{\sigma}_i(\frac{x}{z},Q^2) + \mathcal{O}(\frac{\Lambda^2}{Q^2})$$




*A DIS process: $e\ p \to e + X$*

- **Factorsation theorem** allows us to separate the **Perturbative** component $\hat{\sigma}_i$ **(ME)**, from the **Non Perturbative $f_i$ (PDF)**.
- Partonic **ME** coefficient can be computed using pQCD.
- **PDFs** are universal and can be extracted from data.
- **PDFs are not directly observables** but are functional probability distribution and depend on the momentum fraction $x$ and on an energy scale $Q^2$.

# The role of Heavy Quarks PDFs

To account for heavy quark mass effect, a QCD **Variable Flavour scheme (VFNS)** is needed.

$Q^2 \gg m_h^2$ $\longrightarrow$ $Q^2 < m_h^2$

- Partonic ME can be computed in a **massless scheme** assuming that $Q^2 \gg m_h^2$
- All the collinear $\log(\frac{Q^2}{m_h^2})$ are reabsorbed inside the PDFs and resummed using DGLAP equations.
- **Heavy quark PDFs** can be treated as light flavour, and are **coupled** to other patrons (light quarks and gluons).

- **Mass effects** are retained inside the partonic ME. A smooth transition in the region $Q^2 \approx m_h^2$ is ensured with various prescriptions.
- **Heavy quark PDFs** are **now decoupled** from the others and become **scale independent**: $f_h^{(n_l+1)}(x, Q) \rightarrow f_h^{(n_l)}(x)$.
- Only light flavors are active in the DGLAP equations.

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- Only light flavors are active in the DGLAP equations.

***Are the heavy quark PDFs vanishing for scales $Q^2 < m_h^2$?***

# The Intrinsic Charm hypothesis

- The **charm** quark is the natural candidate to address this question as: $m_p = 0.938\ GeV \approx m_c = 1.51\ GeV$.

- The original idea of a non perturbative charm component of the proton trace back to 1980. *Brodsky, Hoyer, Peterson, Sakai* [Phys.Lett.B93451-455].

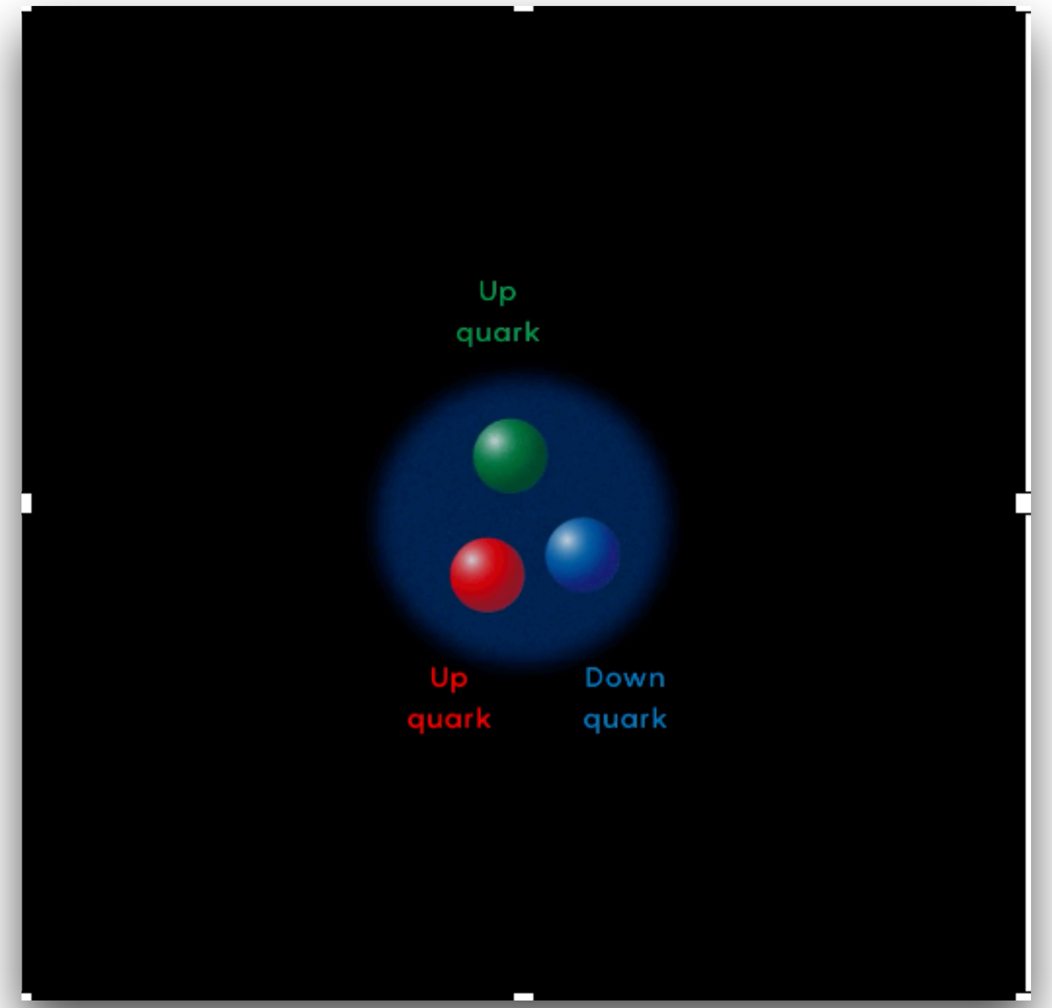
- We define the charm content of the proton for $Q < m_c$ in the $n_f = 3$ flavour scheme as **Intrinsic Charm (IC)**.

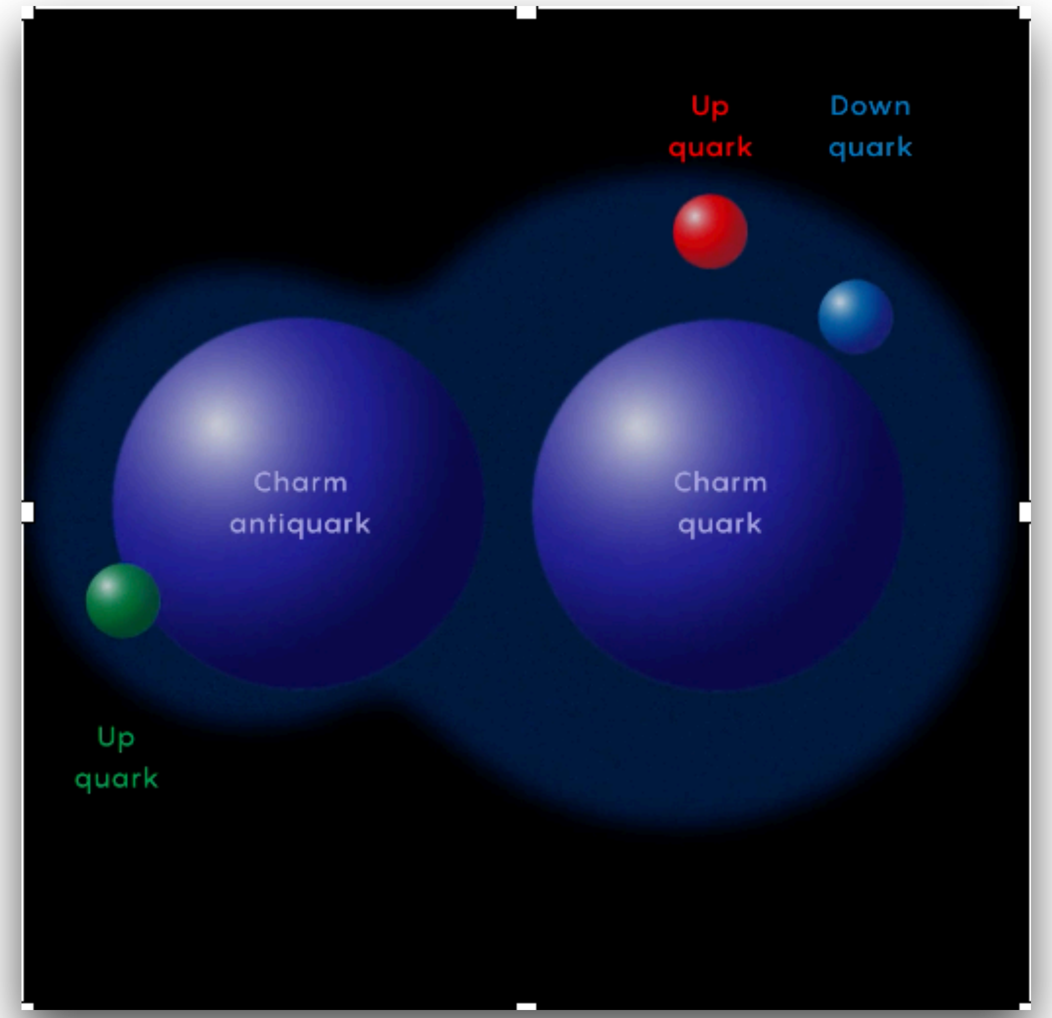
- To determine IC we will need to **separate the perturbative component** of the charm PDF. Results are based on:

*Evidence for intrinsic charm quarks in the proton*

*Nature 608 (2022) 7923, 483-487 [arxiv:2208.08372]*

*R. D. Ball , A. Candido , J.C. Martinez, S. Forte, T.Giani , F. Hekhorn, K. Kudashkin, GM and J.Rojo.*



# The Intrinsic Charm hypothesis

In a **purely perturbative** scenario the charm PDF is determined as:

$$f_c^{(3)} = 0 \;\rightarrow\; f_c^{(4)}(x, m_c^2) = \sum_{i=g,q} A_{c,i} \otimes f_i^{(3)}(x, m_c^2)$$

$A_{ij} = A_{ij}(x, \alpha_s, \frac{Q_h^2}{m_h^2})$ are the **matching conditions** available up to $\mathcal{O}(\alpha_s^3)$

[ Eur.Phys.J.C 1 (1998) 301-320, Phys.Lett.B 754 (2016) 49-58, Nucl.Phys.B 820 (2009) 417-482 et al.]

$f_c^{(4)}(x, Q)$ functional form is fully determined by the DGLAP evolution and the initial boundary conditions.

Allowing for **Intrinsic Charm** means:

$$f_c^{(3)}(x) \neq 0 \;\rightarrow\; f_c^{(4)}(x, m_c^2) = A_{cc} \otimes f_c^{(3)}(x) + \sum_{i=g,q} A_{c,i} \otimes f_i^{(3)}(x, m_c^2)$$

$f_c^{(4)}(x, Q)$ has to treated as the other light flavour and **fitted to the data**.

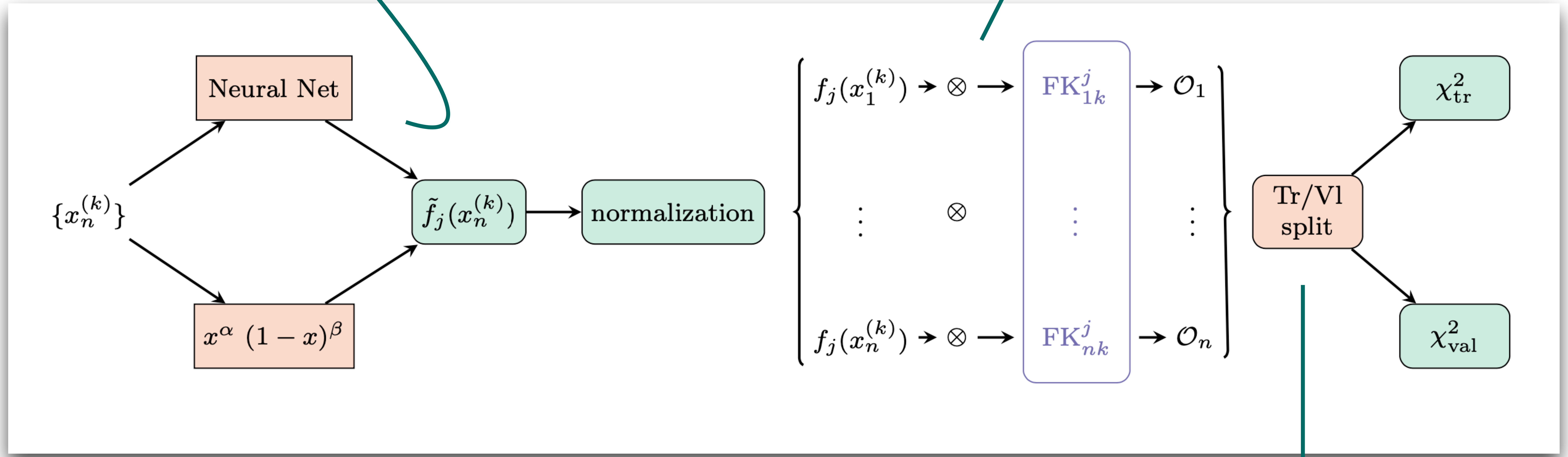
- Heavy quark in PDF fits.
- **The NNPDF4.0 Intrinsic Charm.**
- A possible IC charm asymmetry.

# The NNPDF4.0 methodology

1. PDFs are parametrised in $n_f = 4$, at $Q_0 = 1.65$ $GeV$ using a **neural net**:

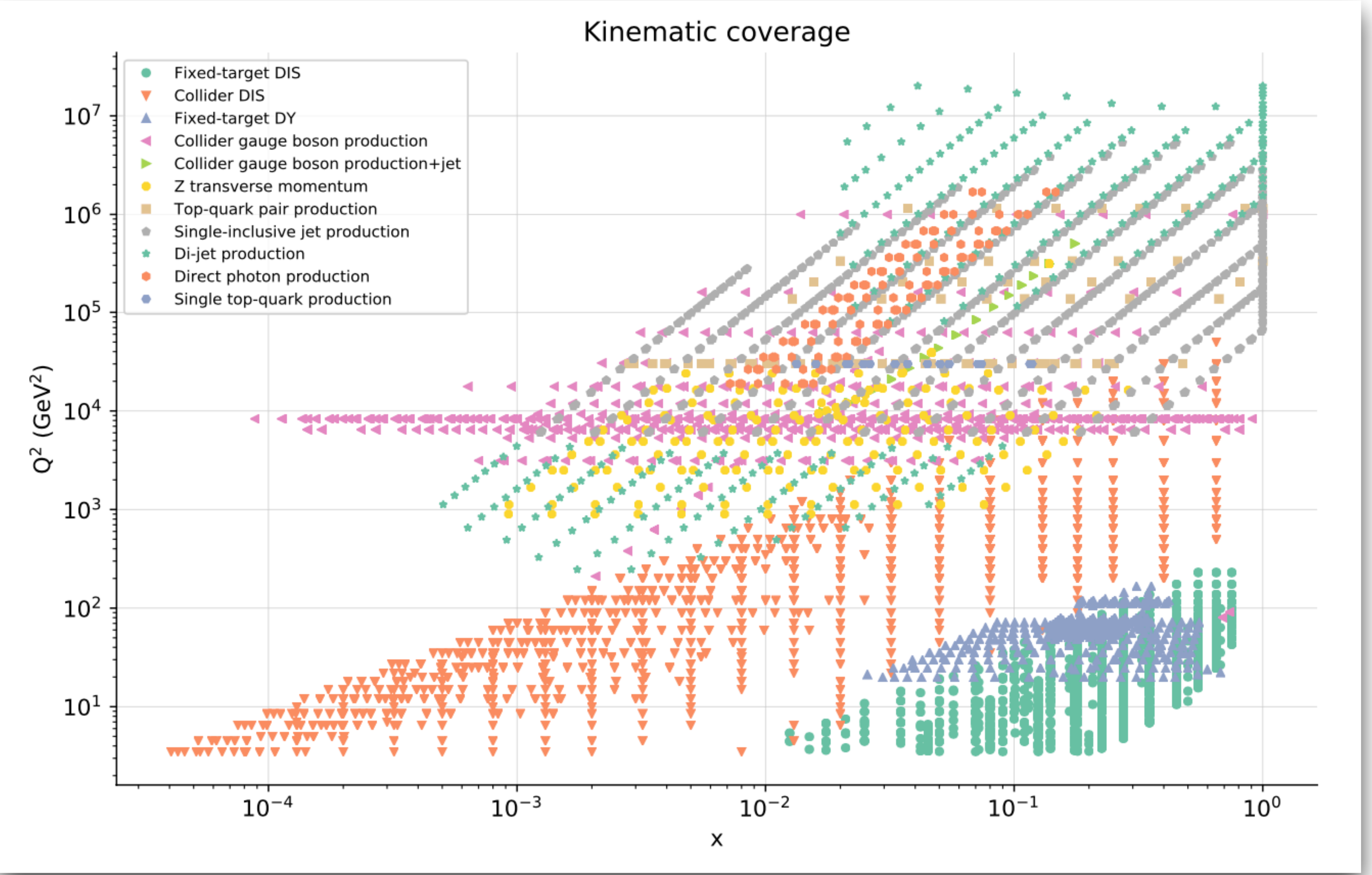
$$f_i(x) = x^{a_i}(1-x)^{b_i} NN(\theta, x, \log(x))_i$$

2. **Convolution** with partonic MEs.




3. Run the **minimisation** to compare with data and find the best fitting PDFs.

# The NNPDF4.0 methodology

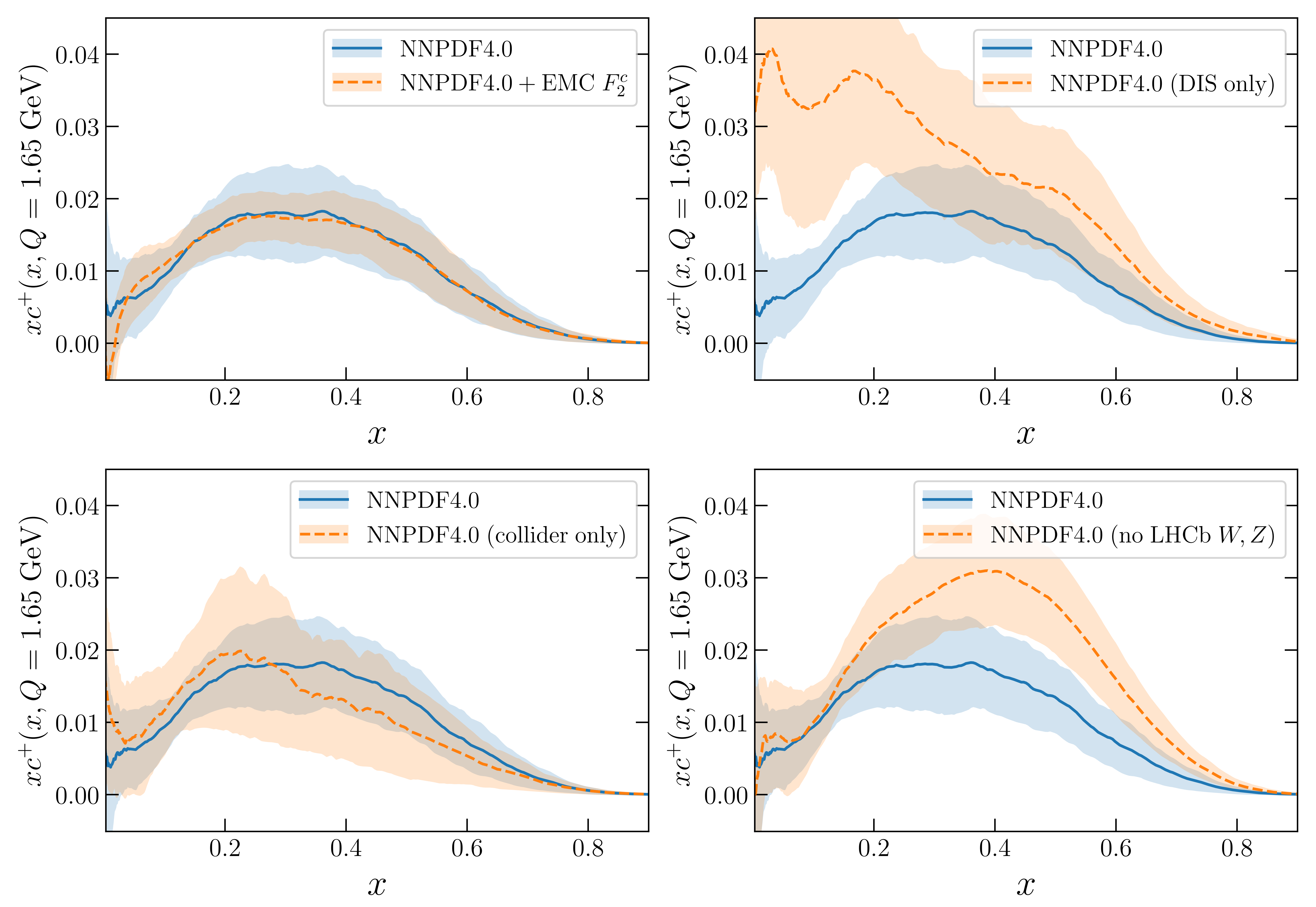



- More than 4000 datapoints, collected at various different experiments.
- Many (new) LHC process are included: $DY,\ W,\ t,\ t\bar{t}, jets$ .

# NNPDF4.0 Charm PDF

In **NNPDF 4.0** [arxiv:2109.02653]:

- $\bar{c} = c$, so we consider only the **total** $c^+$ combination.
- $c^+$ at the fitting scale exhibits a **non vanishing peak** in the **high-$x$** region and vanishes at low-$x$.
- Constrain are coming mainly from collider data.
- The charm PDF is consistent with EMC data.



# Probing Intrinsic Charm

- Starting from the fitting scale we **evolve** the NNPDF4.0 baseline **to** $Q^2 = m_c^2$.

- When passing the heavy quark threshold we need to **invert the matching conditions** $A_{ij}$.

- The **remaining part** of the charm PDF **is the intrinsic component**, which is scale independent for $Q^2 < m_c^2$.

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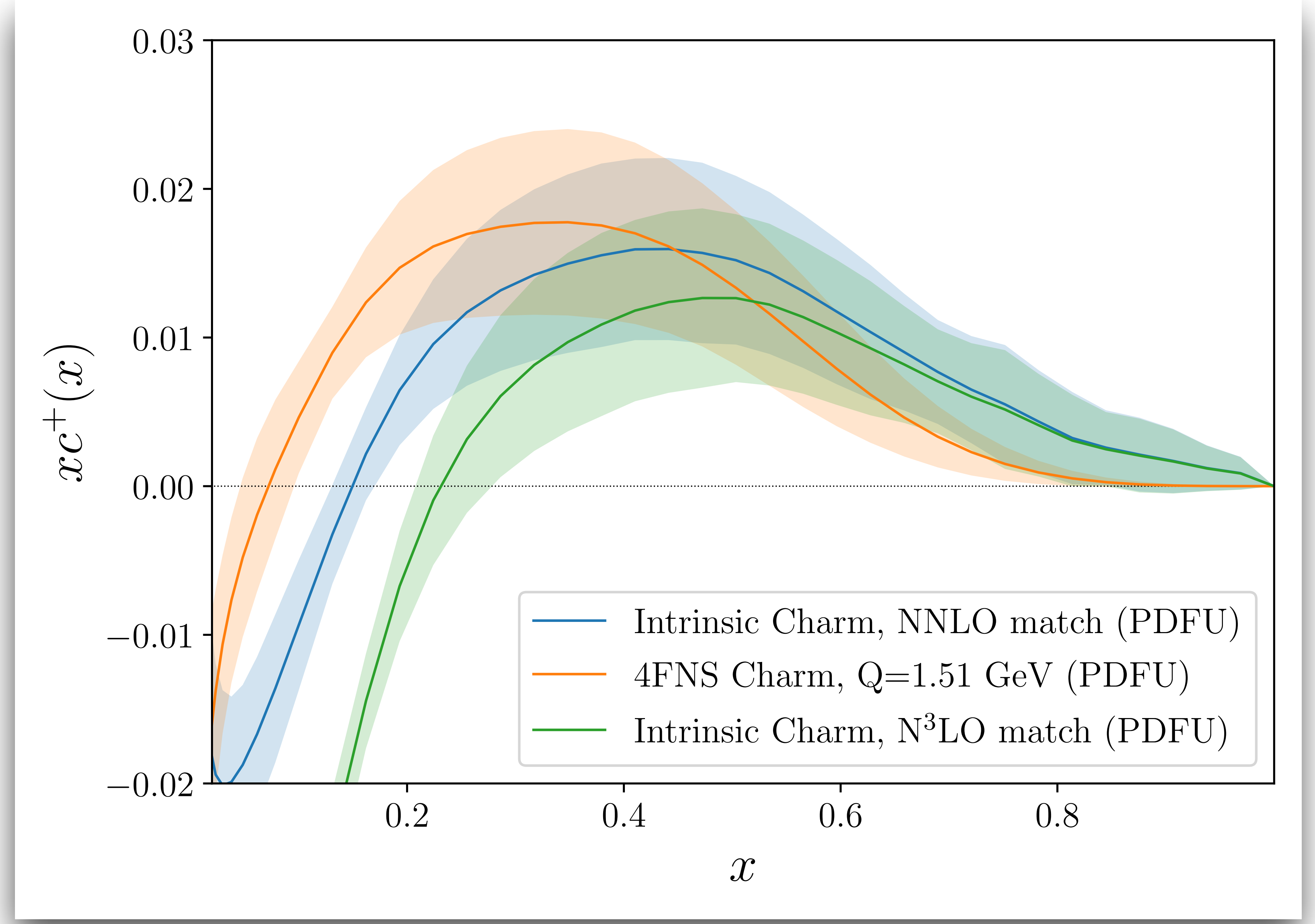
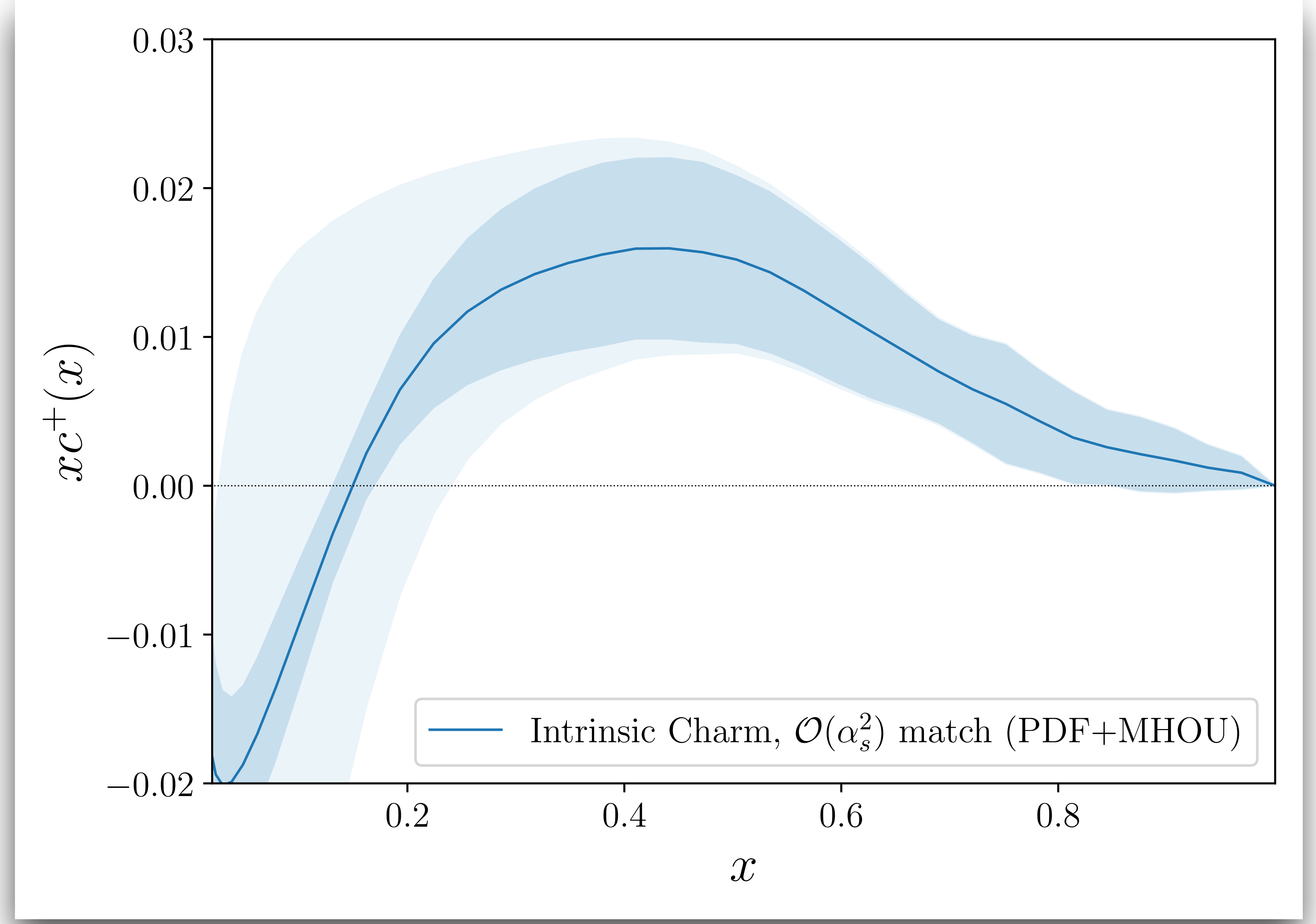
The resulting **IC** in the $n_f = 3$ scheme:

✓ Still contains ***valence-like*** peak.

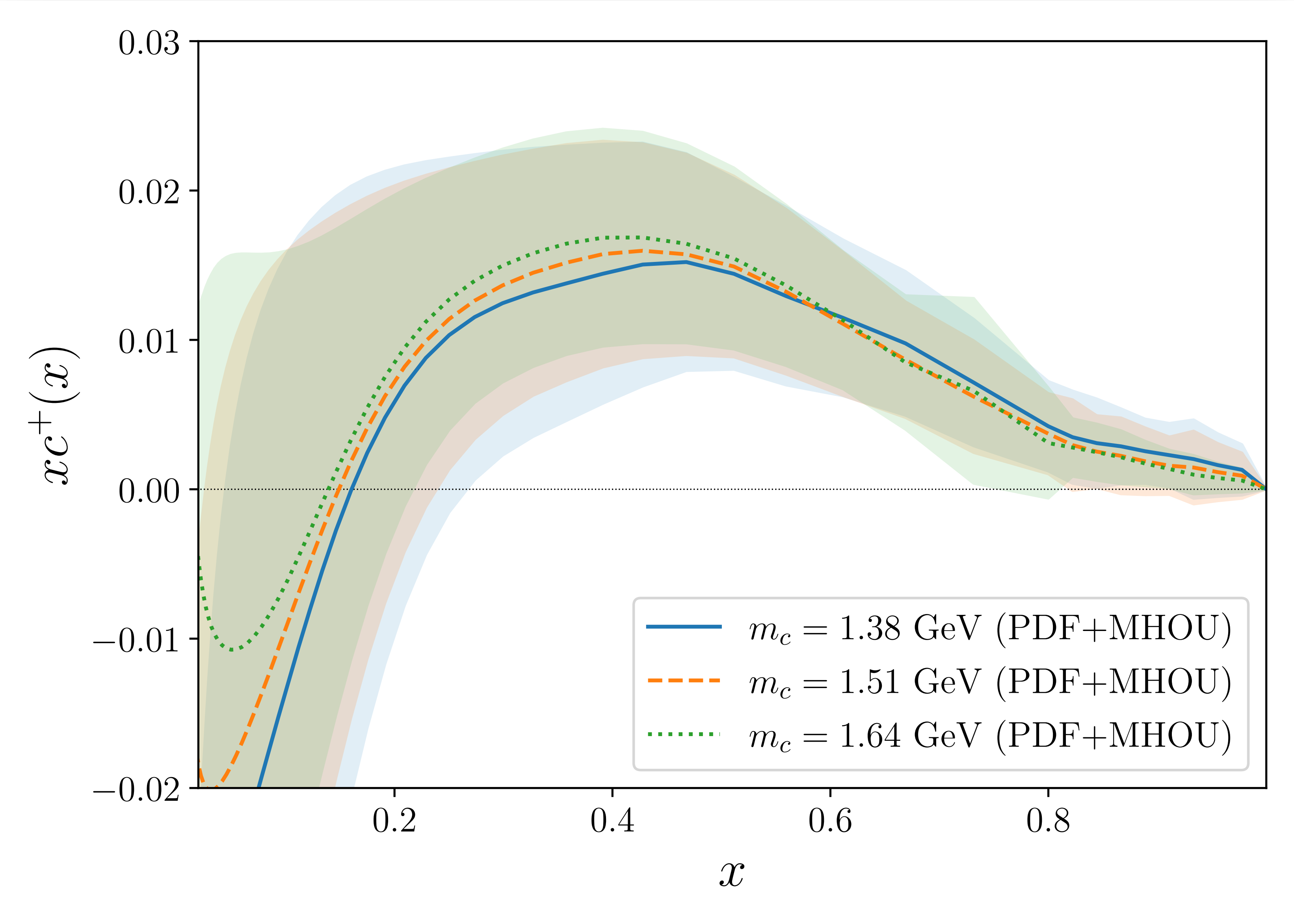
✓ For $x \leq 0.2$ the perturbative uncertainties are quite large.

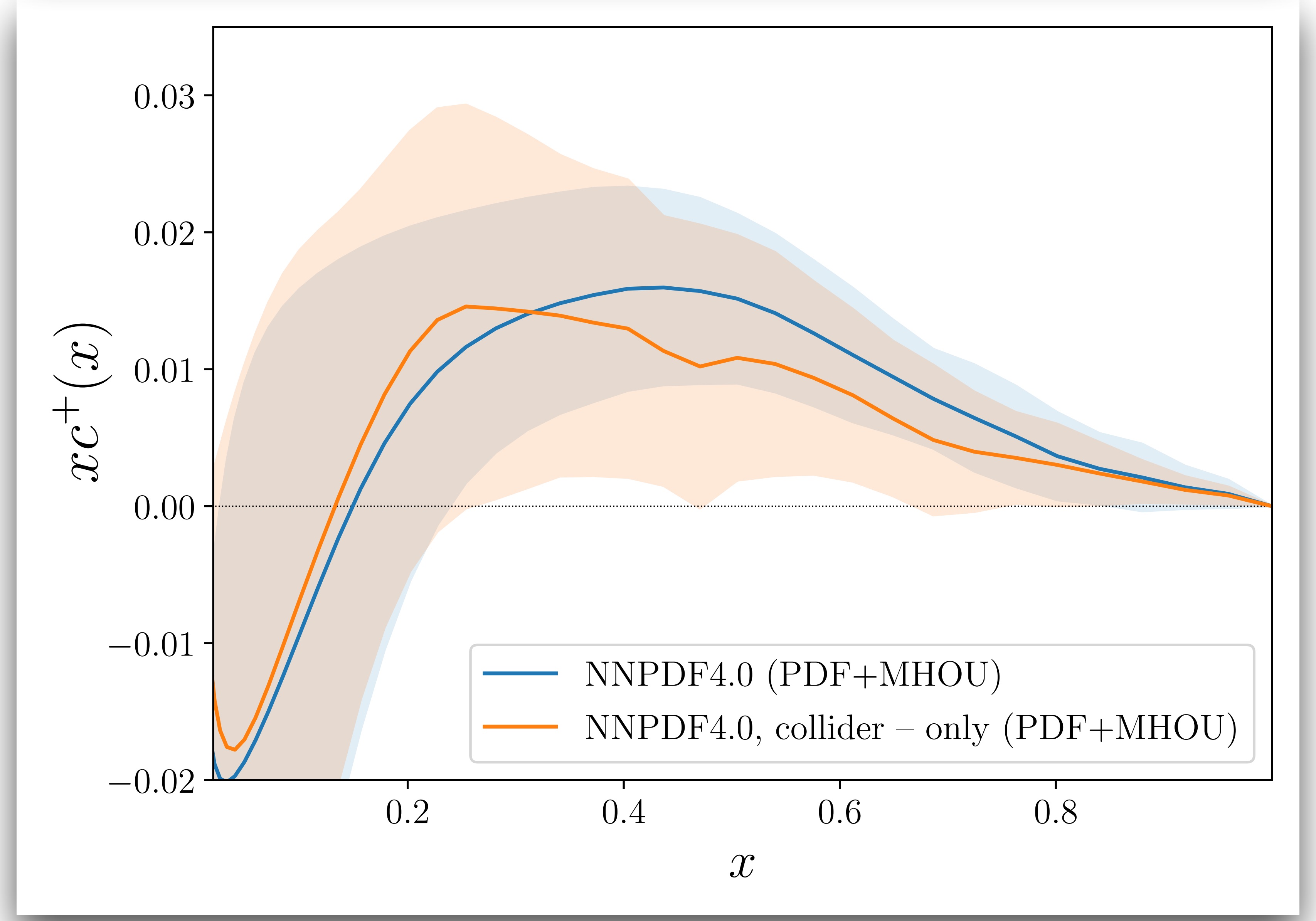
✓ The carried **momentum fraction** is within **1%.**



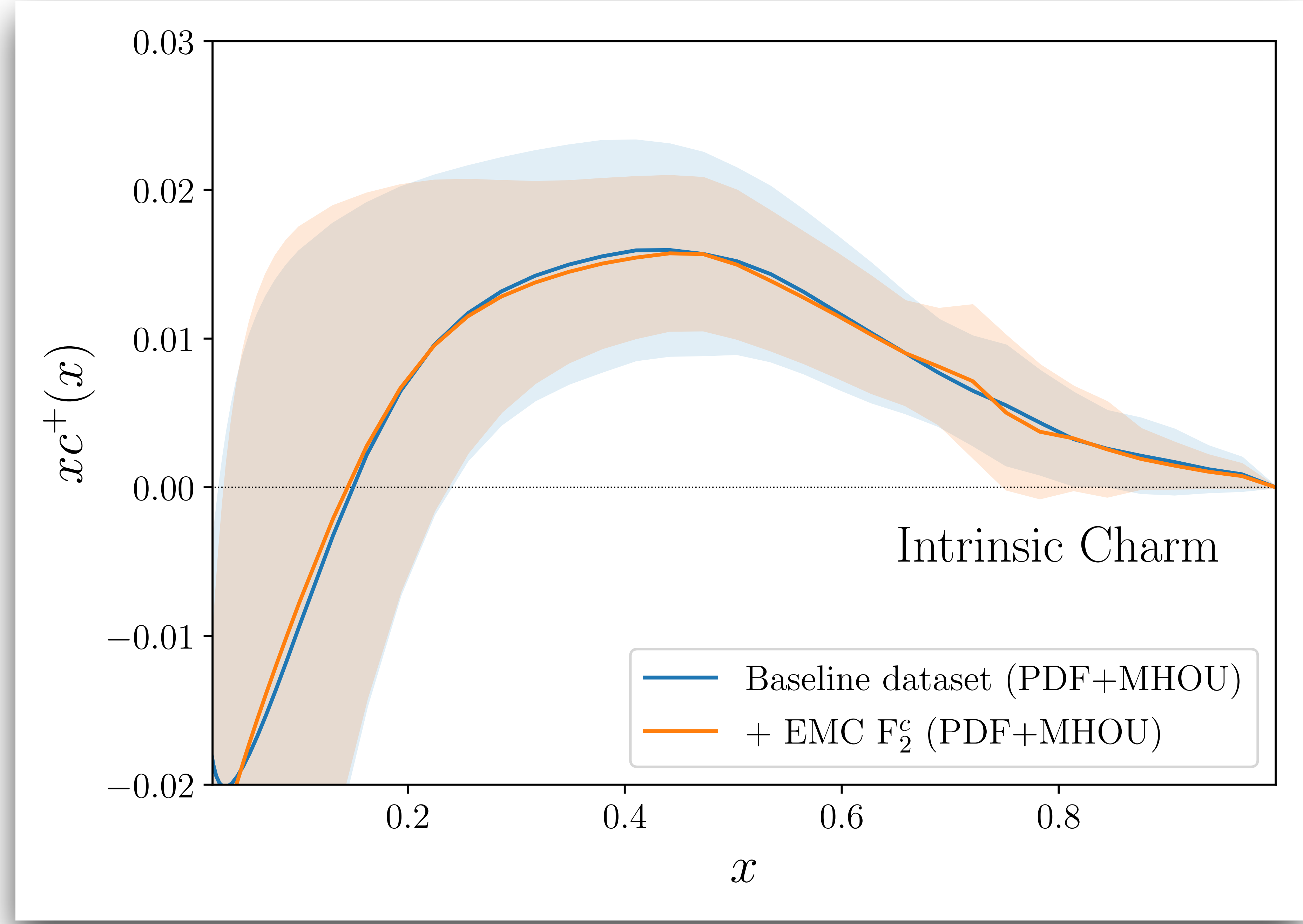



# Intrinsic Charm stability



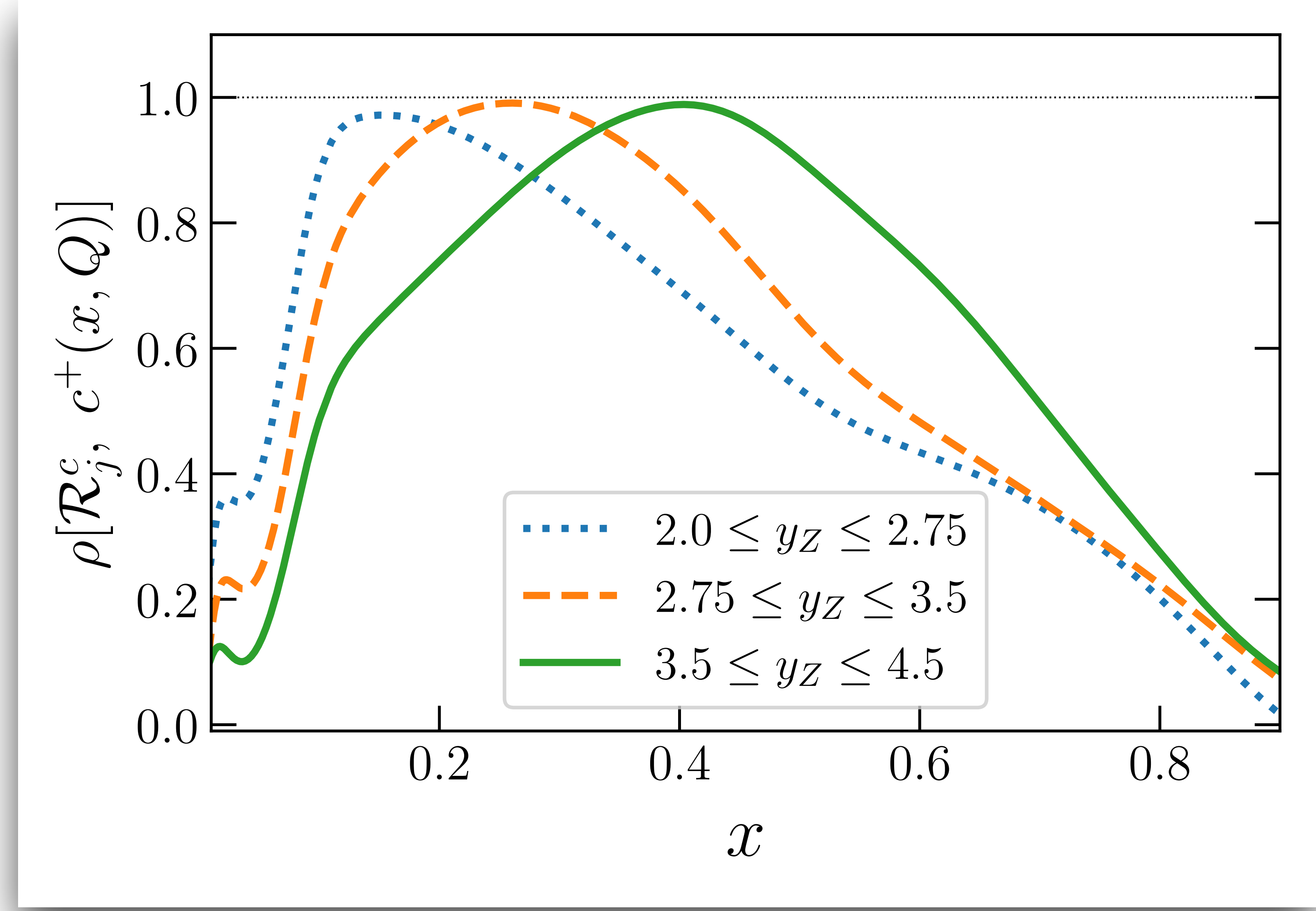

- The determined IC is **stable** upon **mass variations**.
- The determined IC is **stable** upon **datasets variations**.
- **EMC** DIS data (not included in the default) can constrain further the charm PDF, but don't shift the central value.

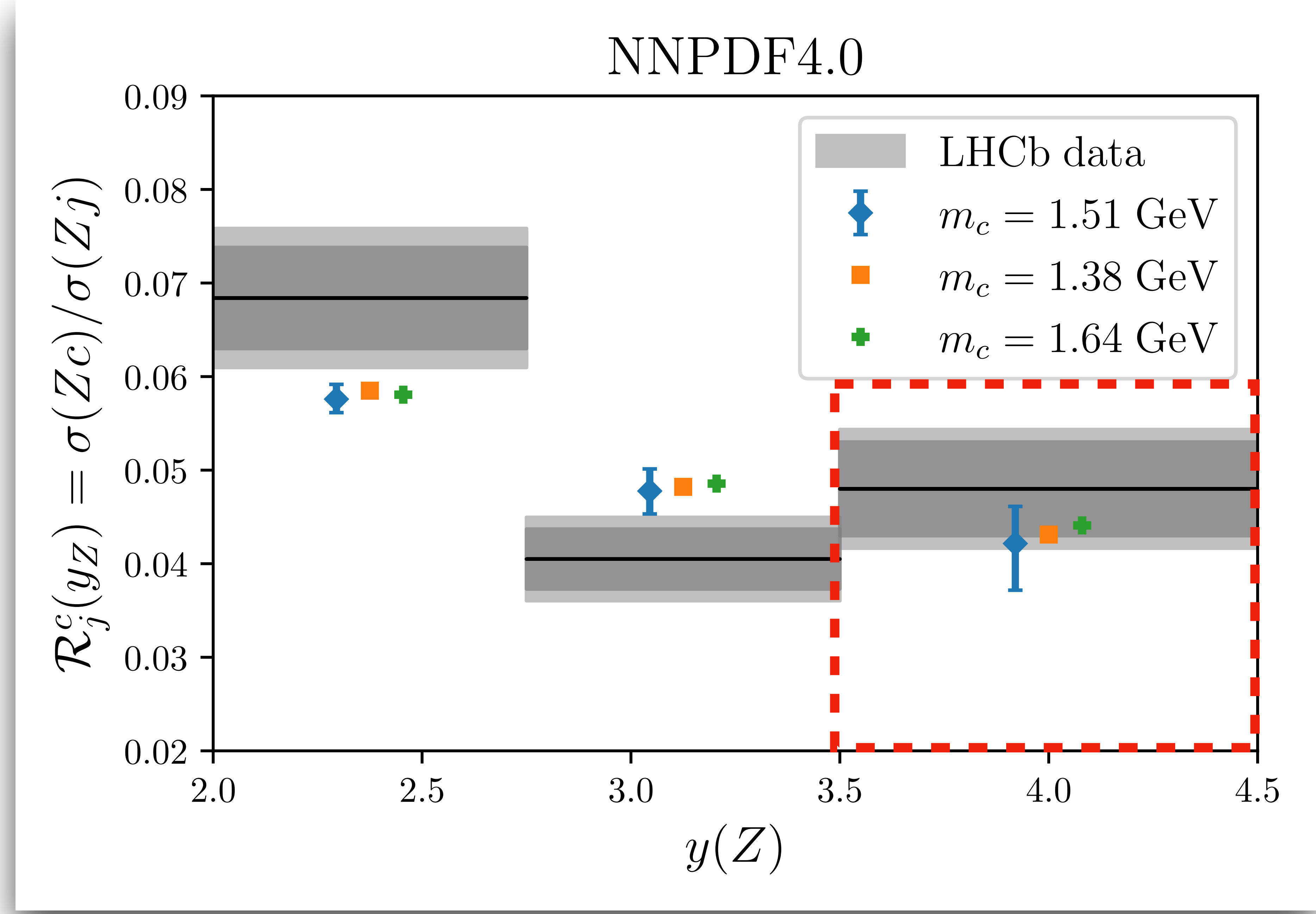


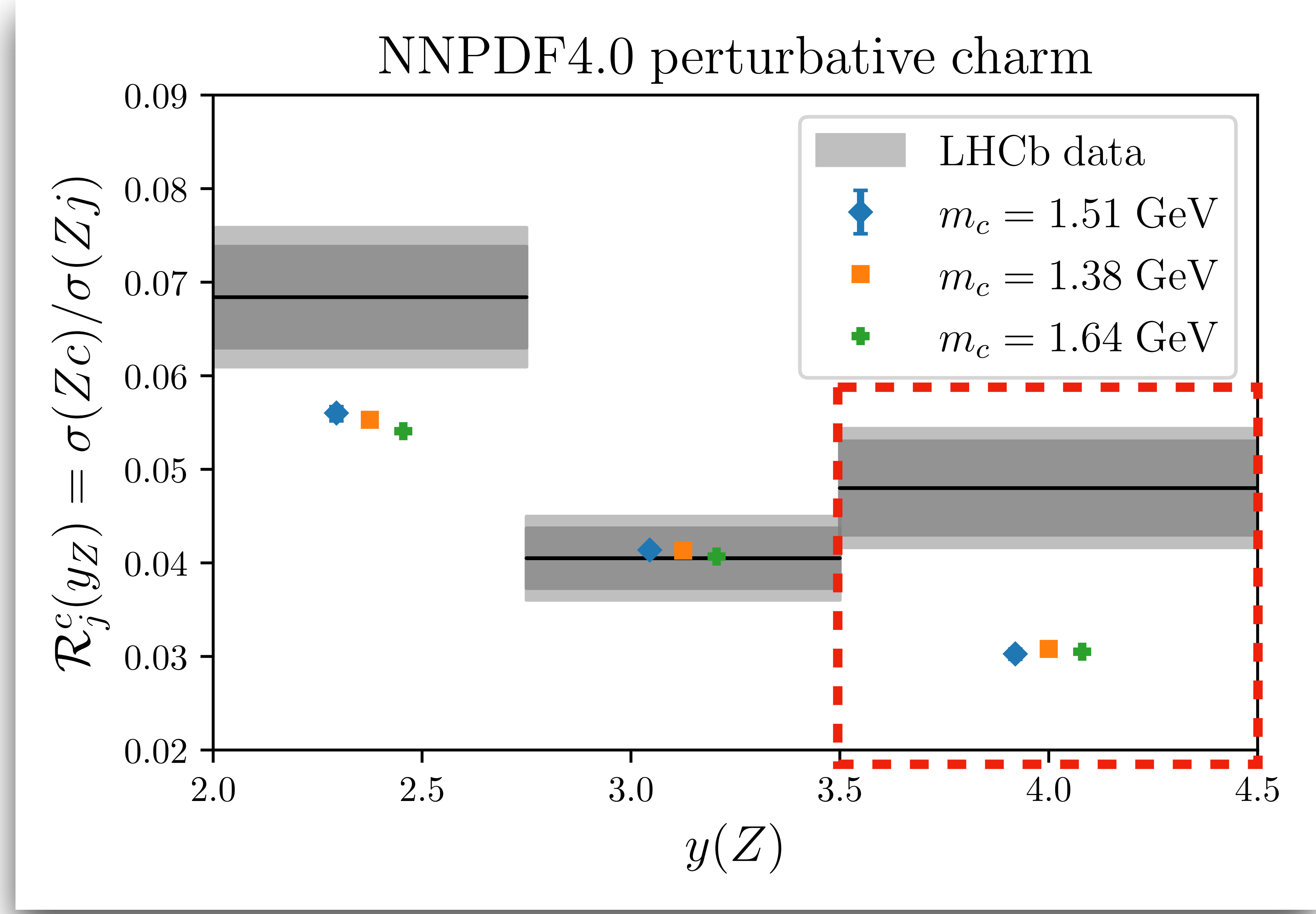
# Impact of IC at LHC

The evidence of **total $c^+$ IC** is validated comparing to **$Z + c$ production** at **LHCb** [arxiv:2109.08084]:

- Data vs theory comparison at **NLO+PS** [arxiv: 1009.5594]
- Better agreement is found once IC is allowed, especially in the **forward region**.
- **High correlation** with the **charm** PDF and **LHCb observable**:



- Heavy quark in PDF fits.
- The NNPDF4.0 intrinsic charm.
- **A possible IC charm asymmetry.**

# Models for Intrinsic Charm

- **BHPS** model: *Brodsky, Hoyer, Peterson, Sakai* [Phys.Lett.B93451-455]

  $p \to uudc\bar{c}$

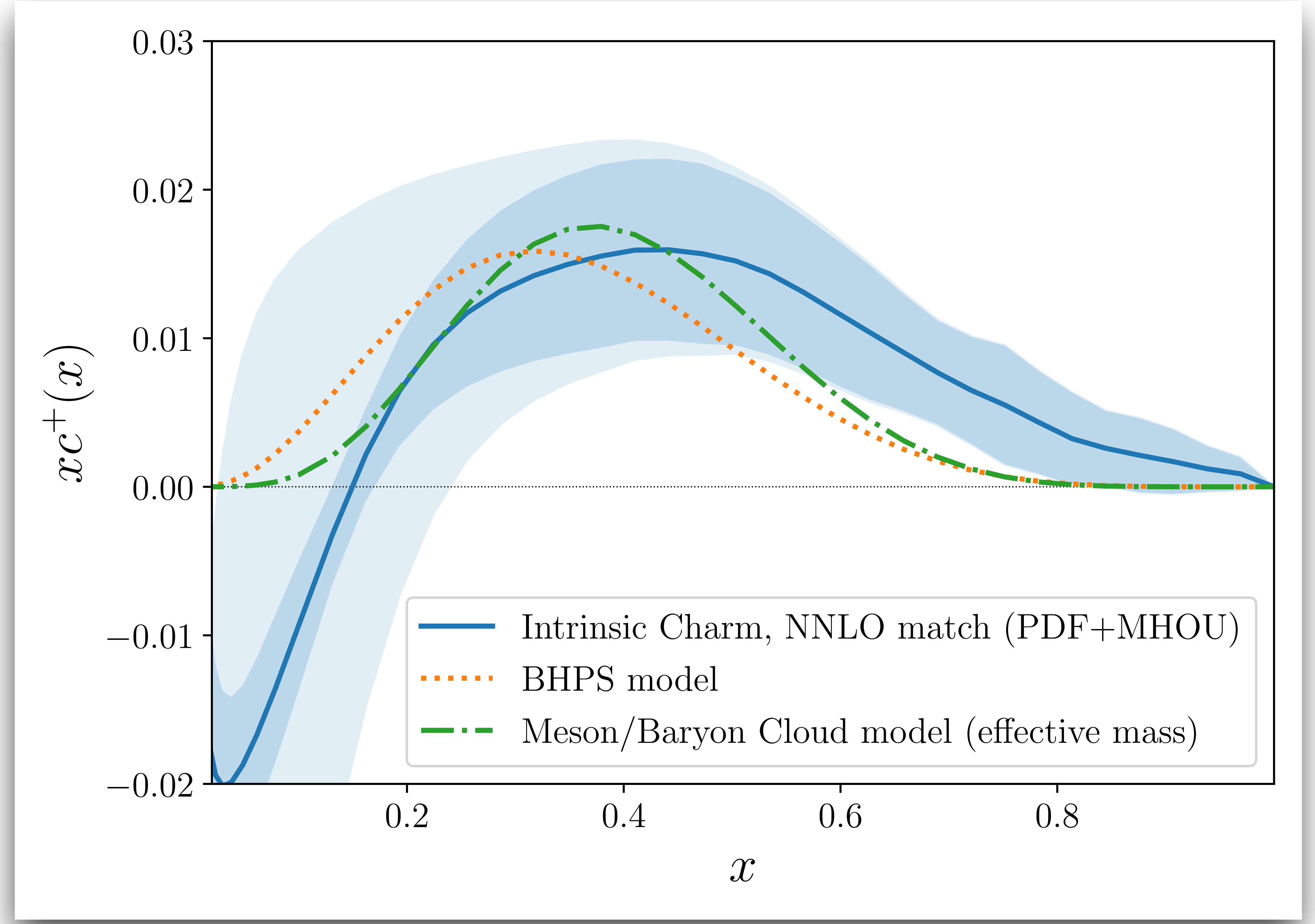
$$xc^{+} = \frac{1}{2}Nx^{3}[\frac{1}{3}(1-x)(1+10x+x^{2}) + 2x(1+x^{2})\ln(x)]$$

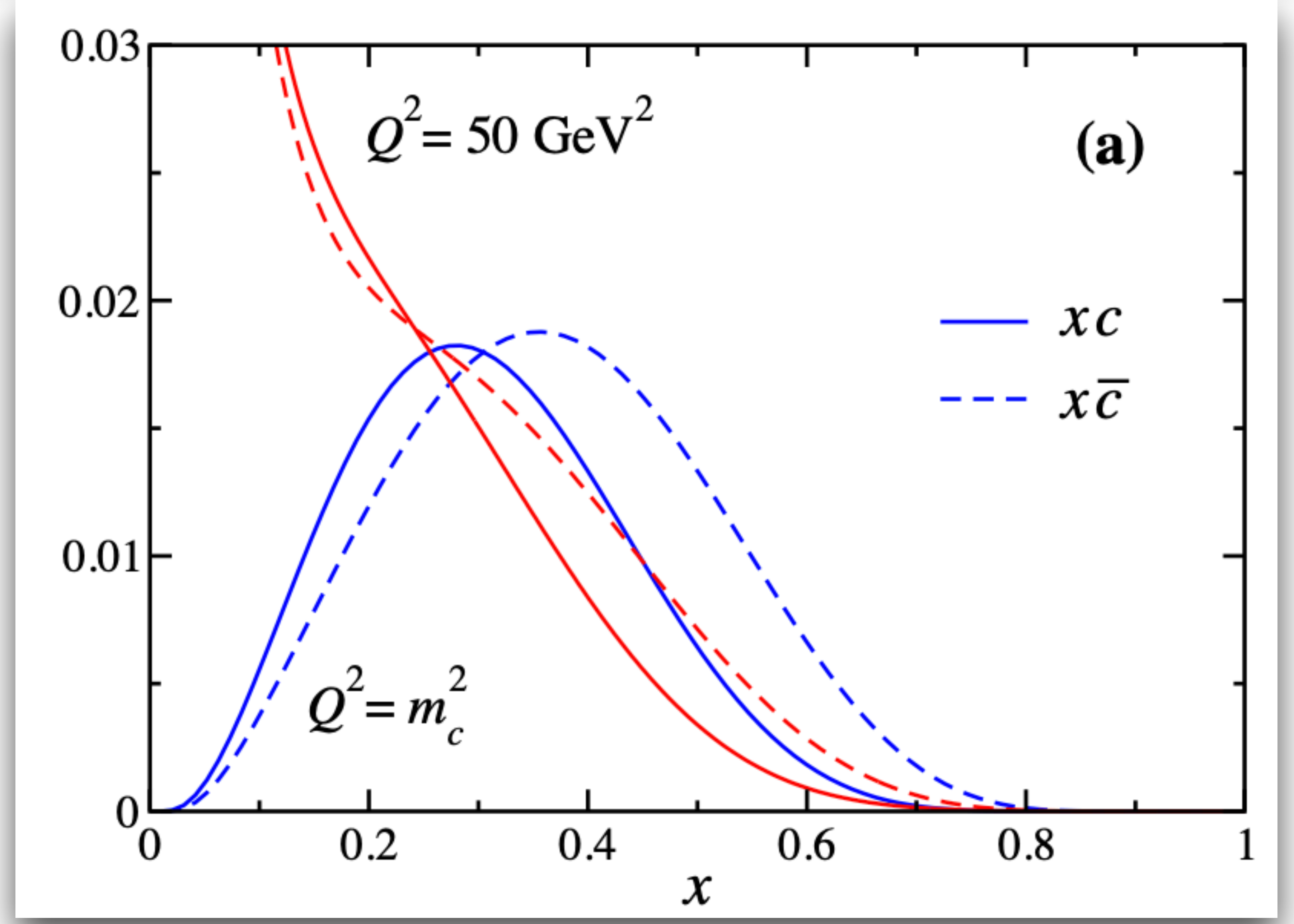
- **Meson Baryon** model: *Hobbs, Londergan, Melnitchouk* [arxiv:1311.1578]

  $p \to \Lambda_c^{+} + \bar{D}_0$

$$xc^{+} = \frac{N}{B(\alpha+2,\beta+1)}x^{(1+\alpha)}(1-x)^{\beta}$$

- Overall PDF normalisation non given by the model.
- BHPS assumes $\bar{c} = c$, not true in M/B models.
- Work in the limit $m_c \gg m_p$.



# The charm asymmetry: $c^- \neq 0$ ?

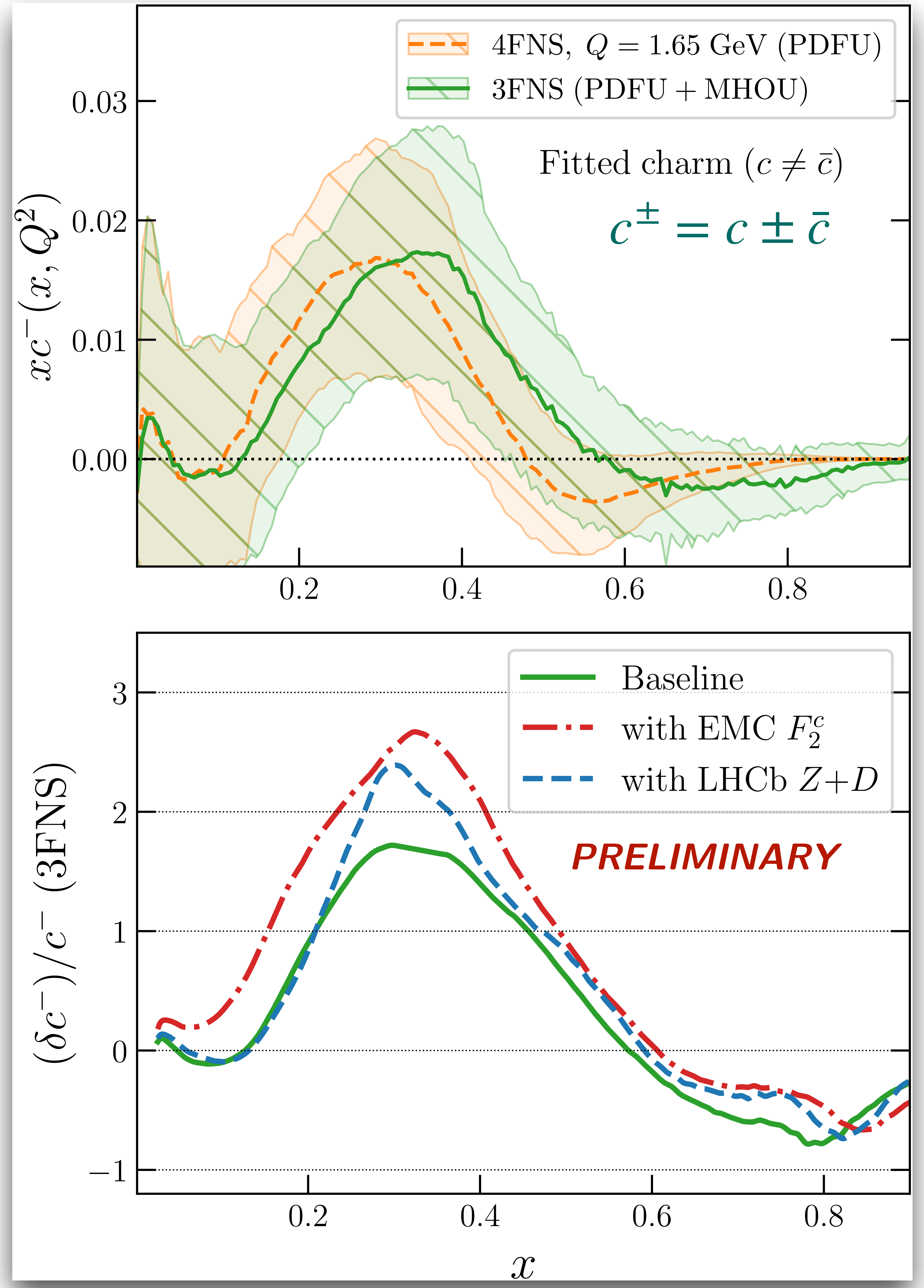
- The ultimate test to probe a possible IC would be to find a **charm asymmetry $c \neq \bar{c}$ also in $n_f = 3$ scheme.**
- pQCD can also generate an heavy quark asymmetry, but only through higher order corrections $\mathcal{O}(\alpha_s^2)$.
- Such asymmetry will be **small** and with a **vanishing integral**, but can be probed.

**Let's repeat our analysis now dropping the assumption $c \neq \bar{c}$.**

**The intrinsic charm valence in the proton**

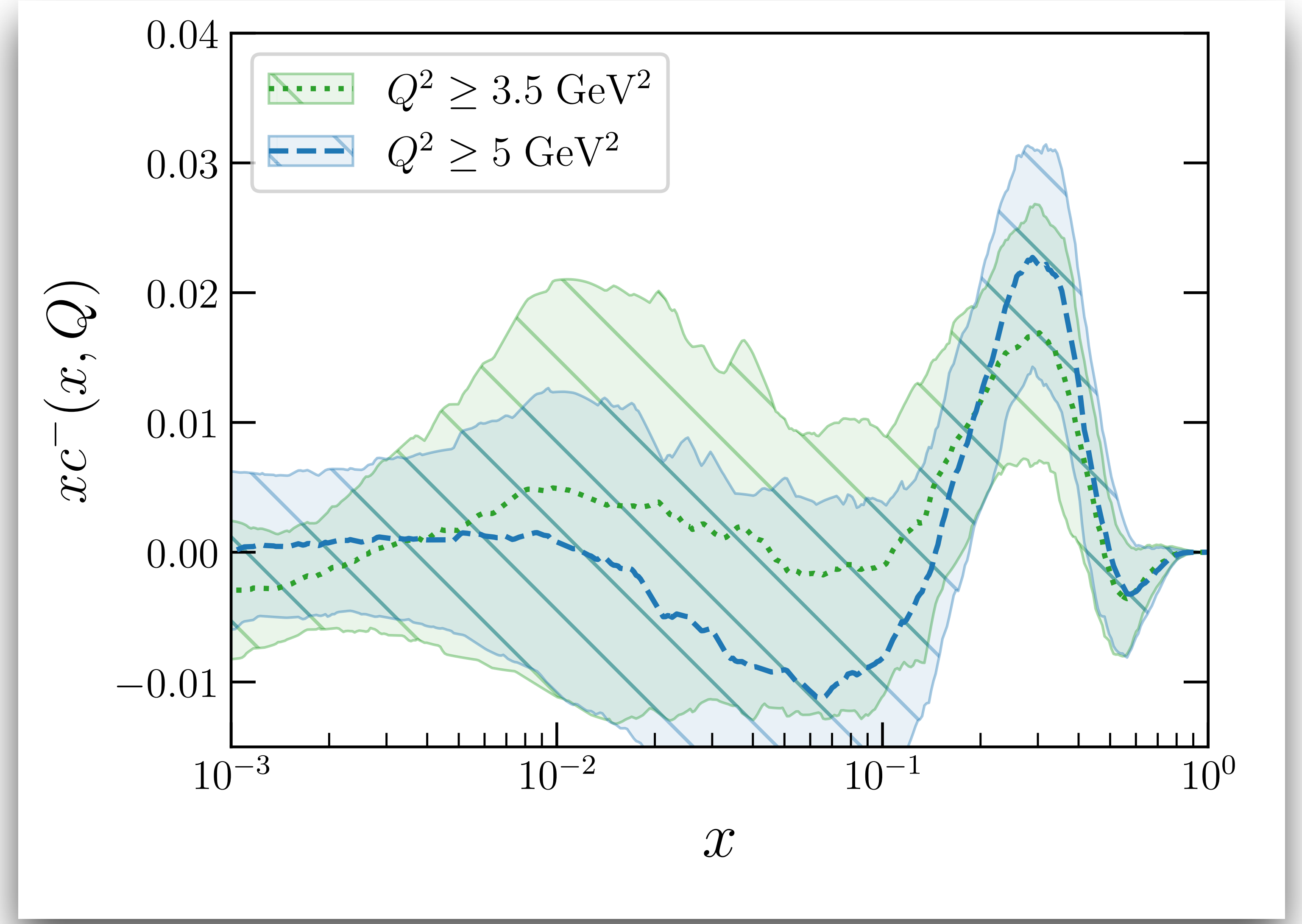
***[in preparation]***

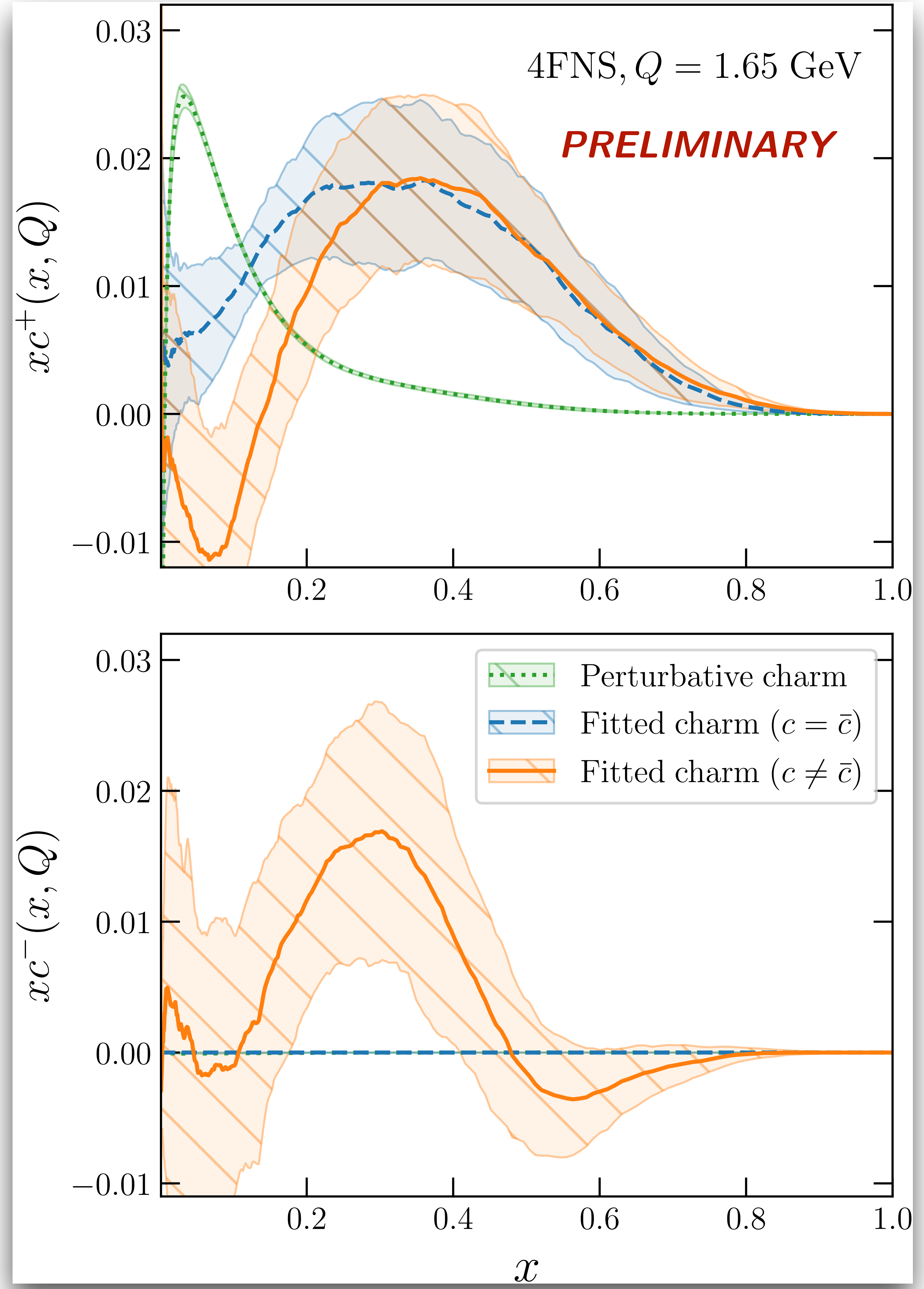
*Ball, Candido ,Cruz-Martinez, Forte, Giani , Hekhorn, GM , Nocera, Rojo, Stegeman.*



# The charm asymmetry: $c^- \neq 0$ ?

- Total charm $c^+$ is **not changing** drastically once fitted $c^-$ is allowed. Better overall agreement with the experimental data.
- **Stability** upon **charm mass variation** is verified.
- Low $Q^2$ data play a mild role. Collider data favour a larger charm asymmetry.




**The intrinsic charm valence in the proton**

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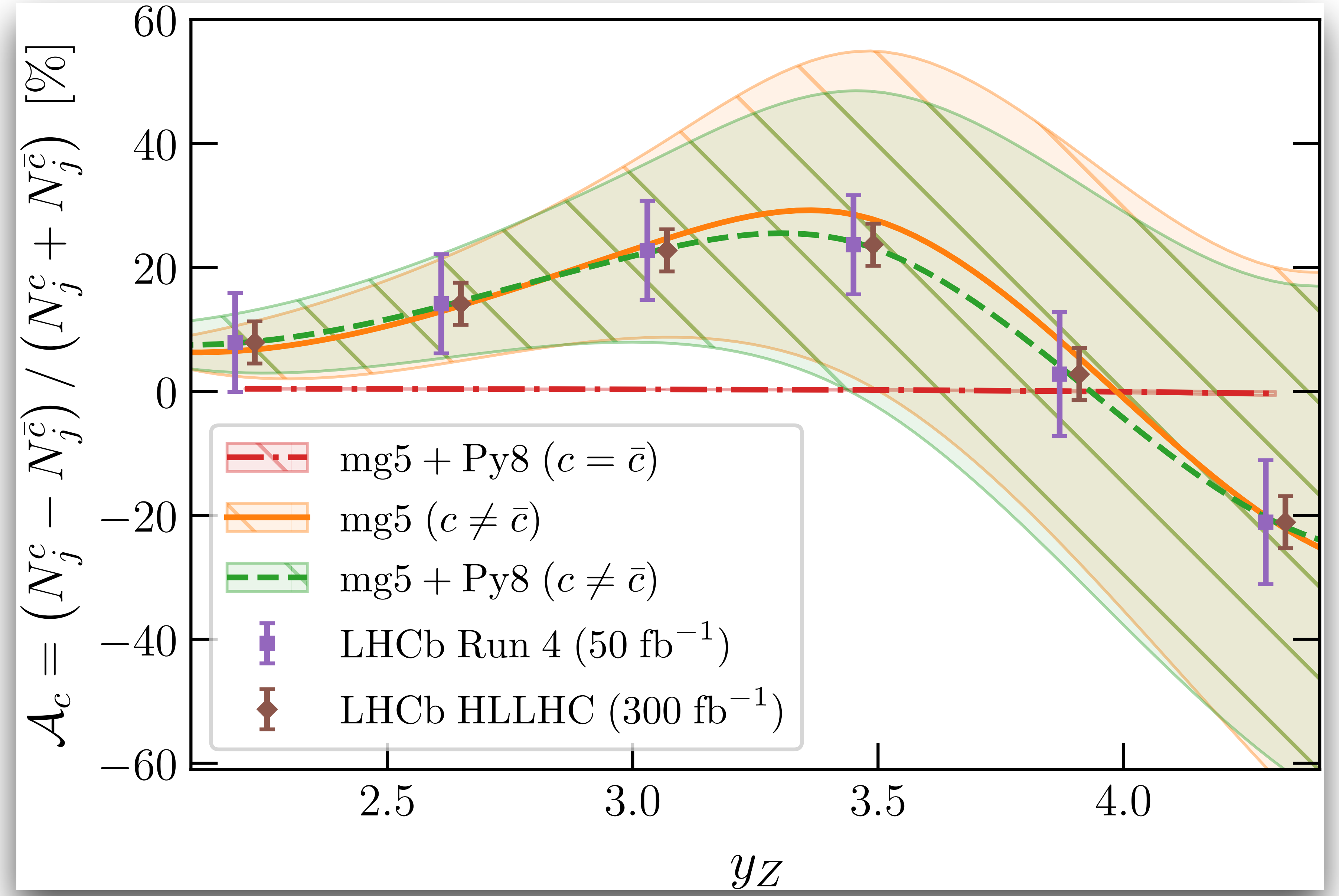
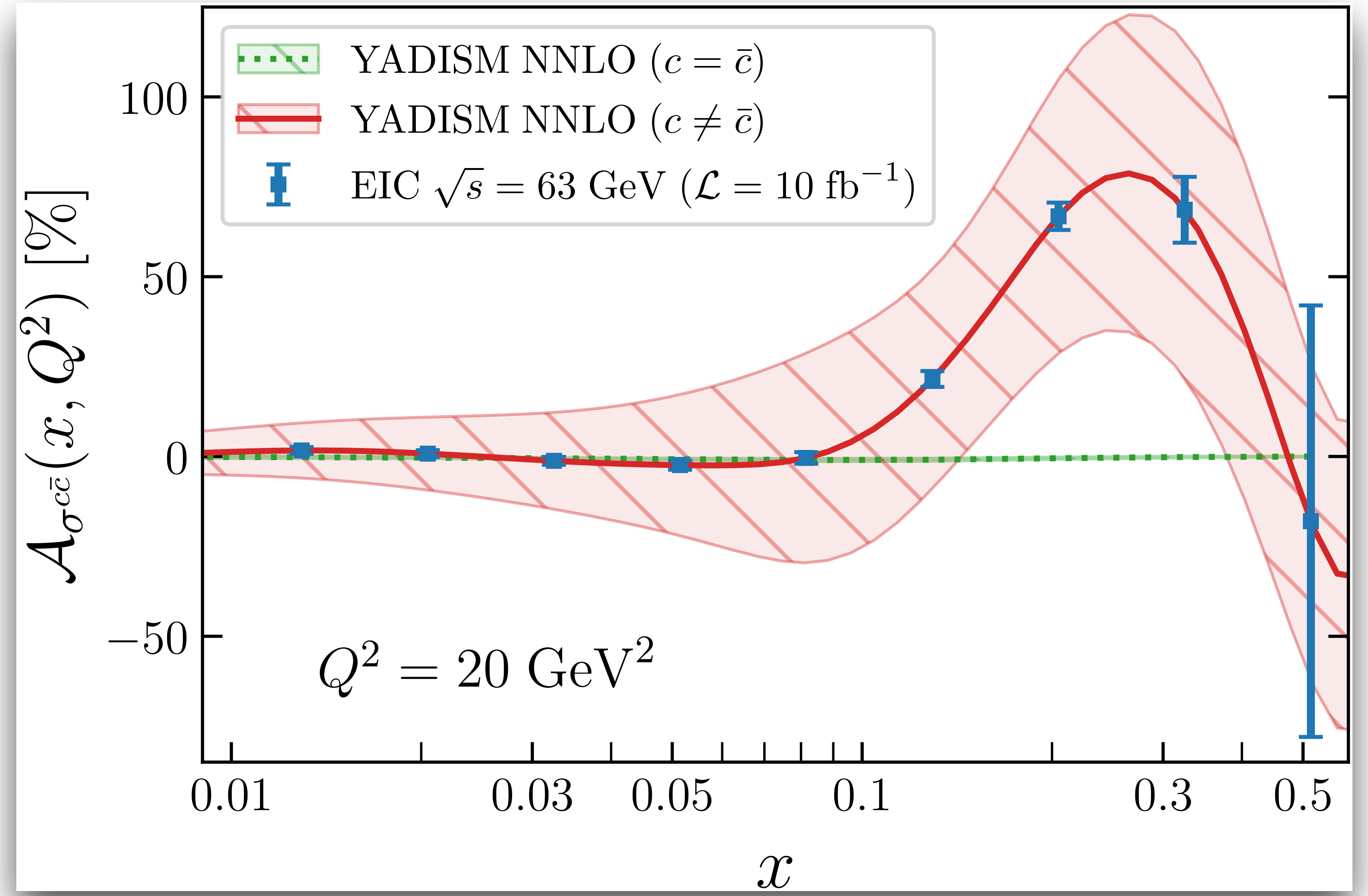
# Future experimental tests on IC

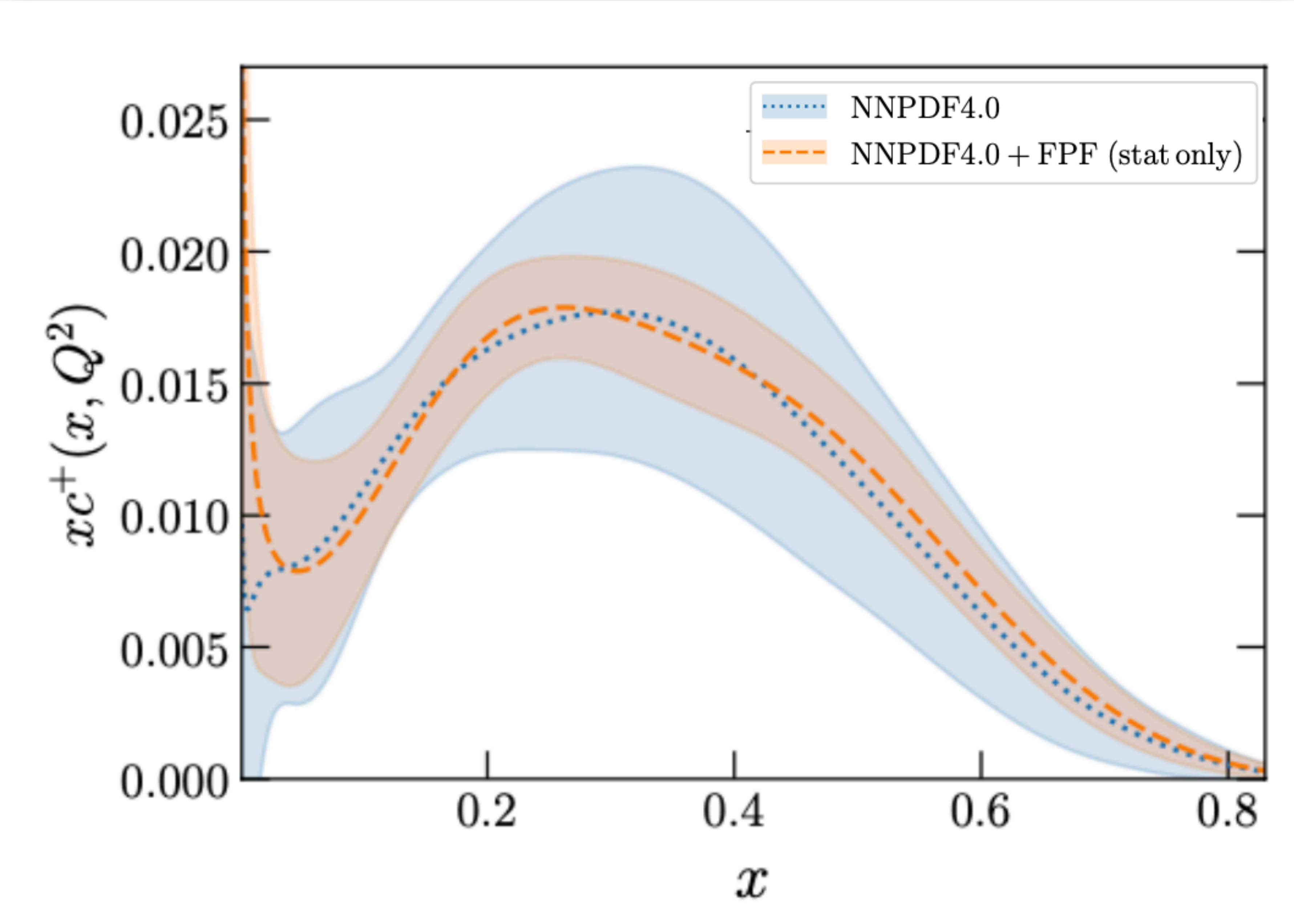



1. At **LHC Run3** and **HL-LHC**:
   - Measuring $W^{\pm} + b$ and $Z + c$ in the forward region can constrain better the total $c^+$ **IC**.
   - **Flavour/anti-flavour tagging** of the final **jet** can be used to construct an asymmetry.
   - This can be a sensible probe to a non vanishing $c^- \neq 0$ **IC**.

2. At **EIC (Neutral currents DIS)**:
   - Measuring a **charm** reduced cross section can constrain the total $c^+$ **IC**.
   - **Flavour/anti-flavour tagging** of the final **jets** can be used to construct an asymmetry.
   - Measuring the parity violating structure function $xF_3$ can also probe $c^- \neq 0$ **IC**.

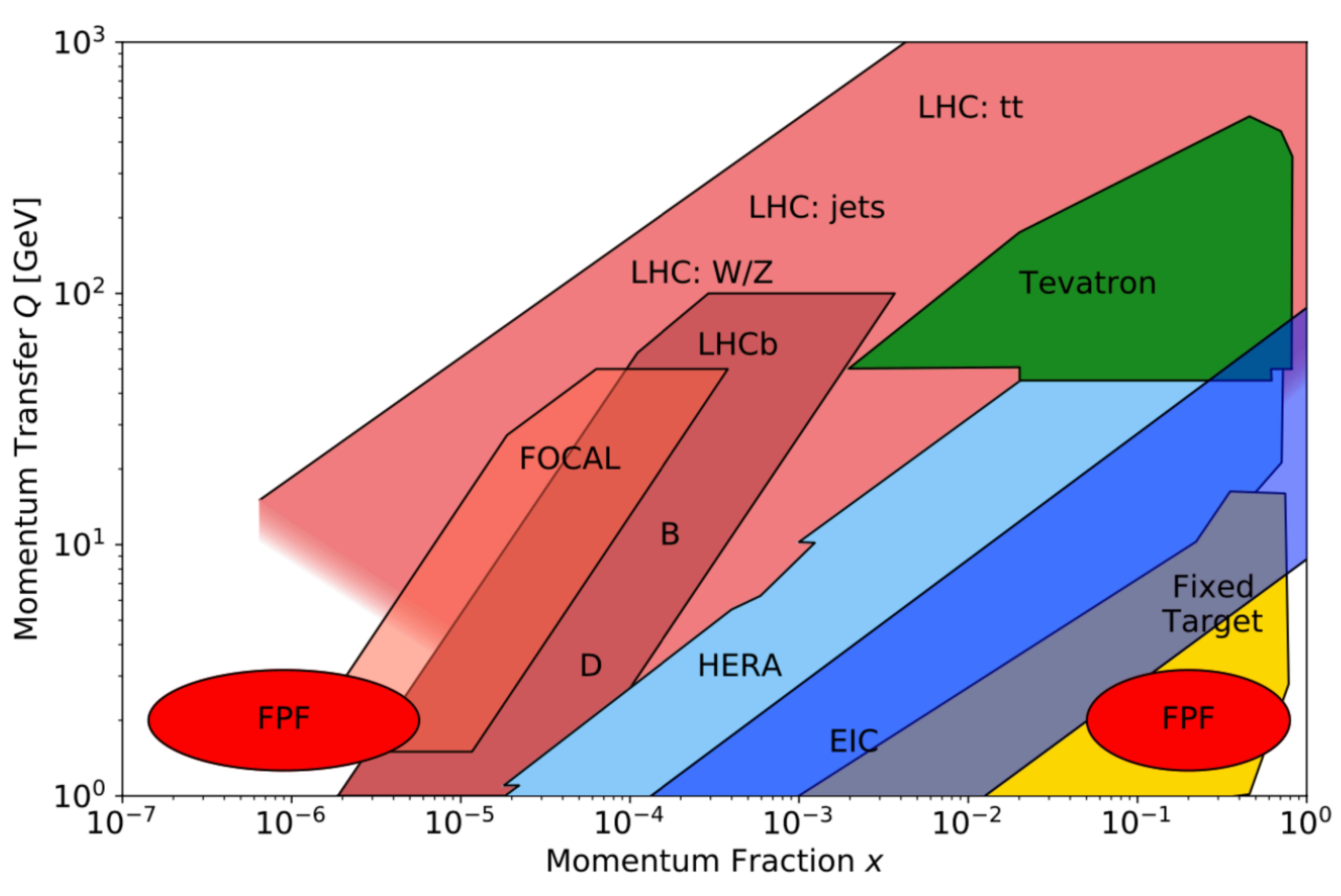


# Future experimental tests on IC



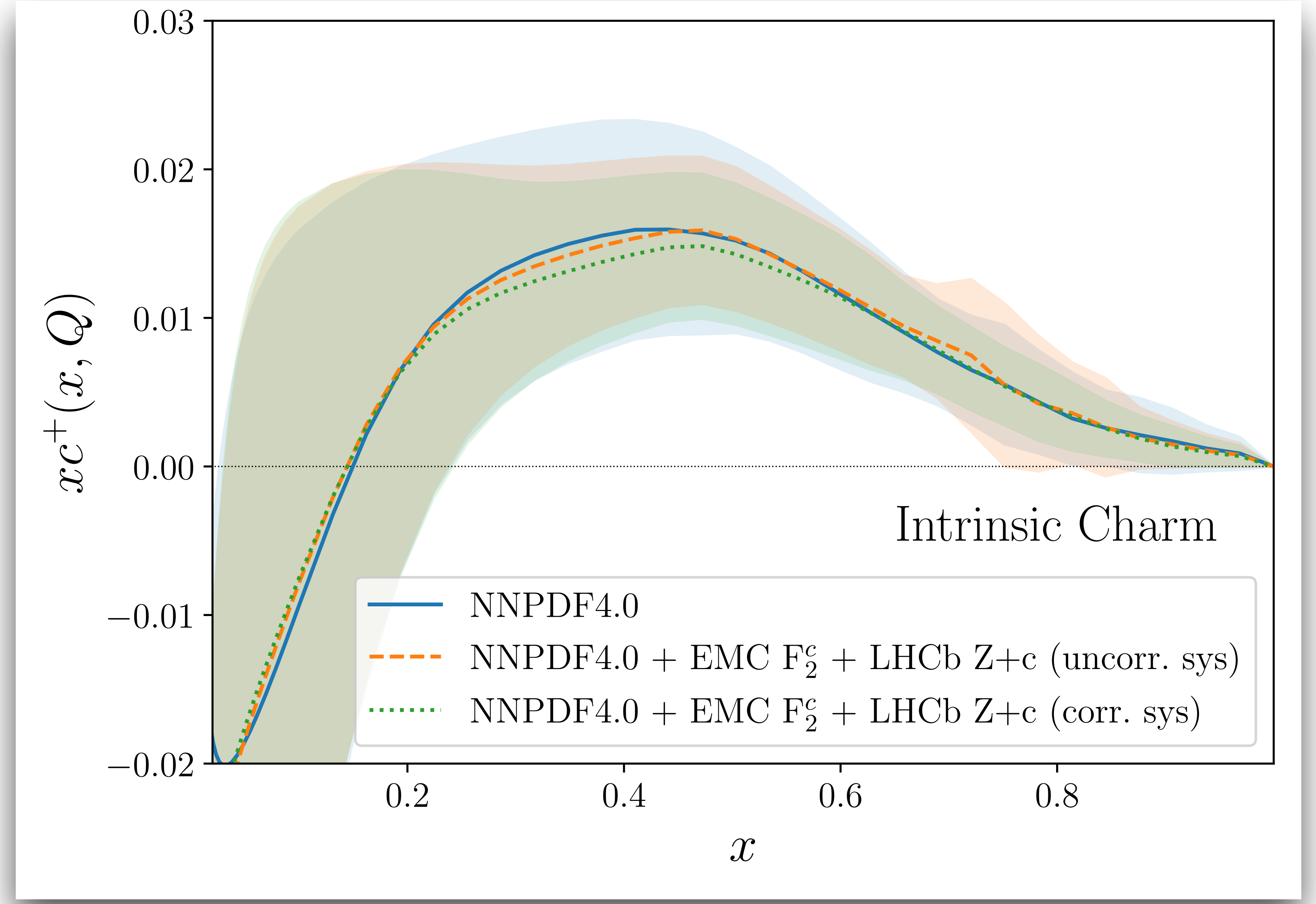

3. At **LHC FASER2 (FPF)**:

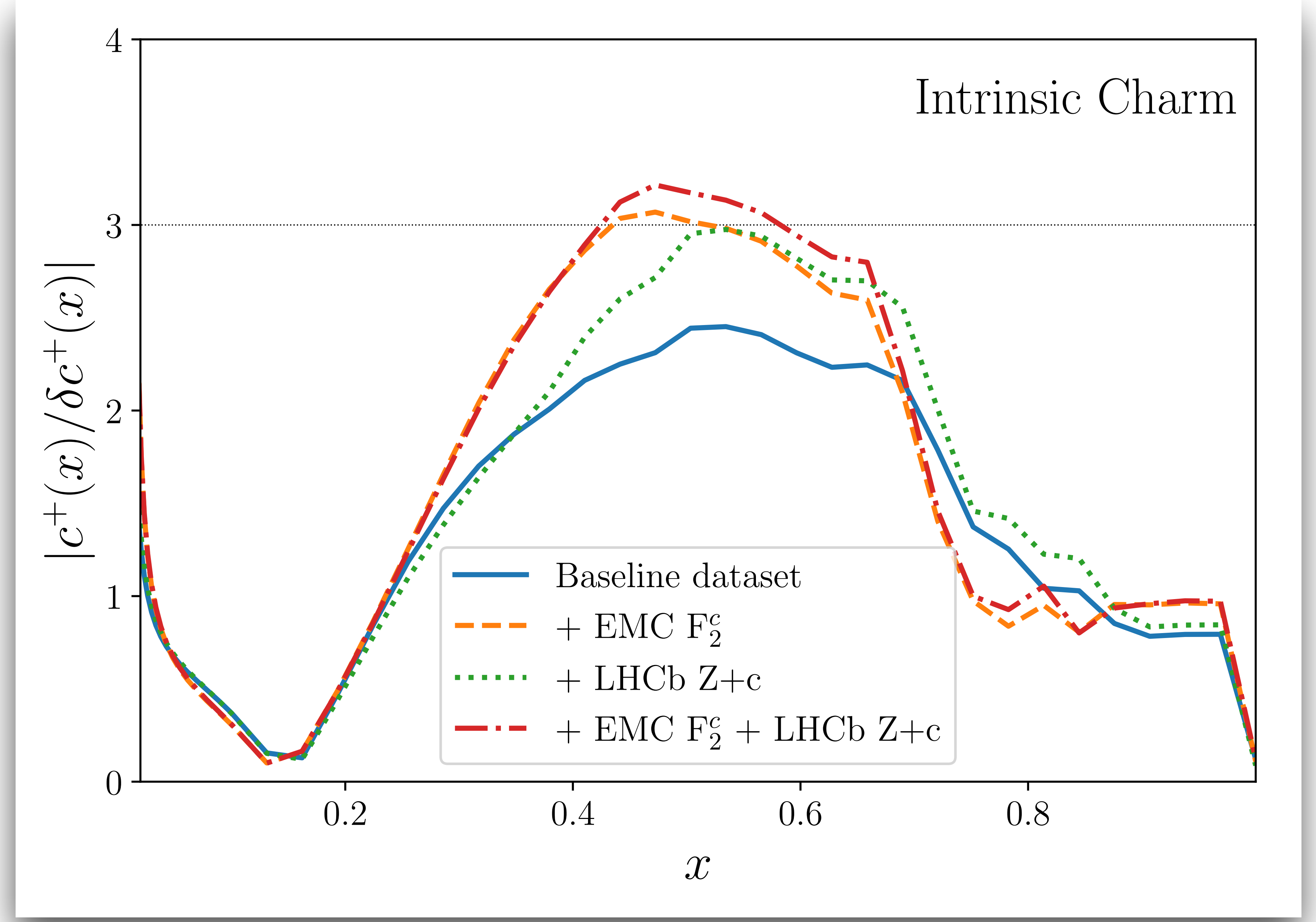
- Neutrino DIS can be a direct probe of a flavour asymmetry in the target. ( $F^{\nu}_{2,charm} - F^{\bar{\nu}}_{2,charm} \propto c^-$ at LO).
- Neutrino beams coming from LHC $pp$ collisions can be sensitive to IC.
- Good kinematic coverage: probing small-$x$ gluon and **large-$x$ quark PDFs.**



# Summary

# First evidence of IC



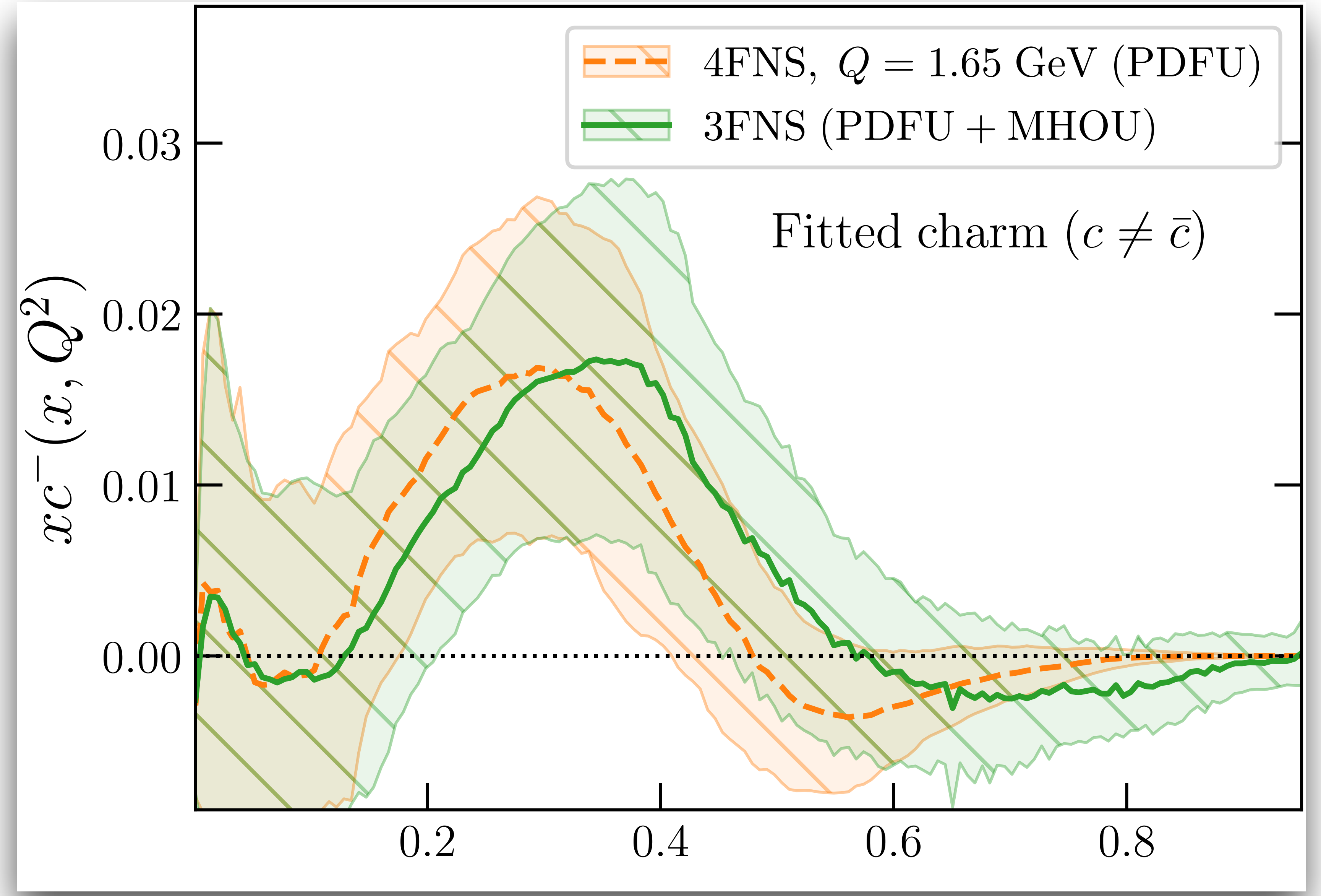



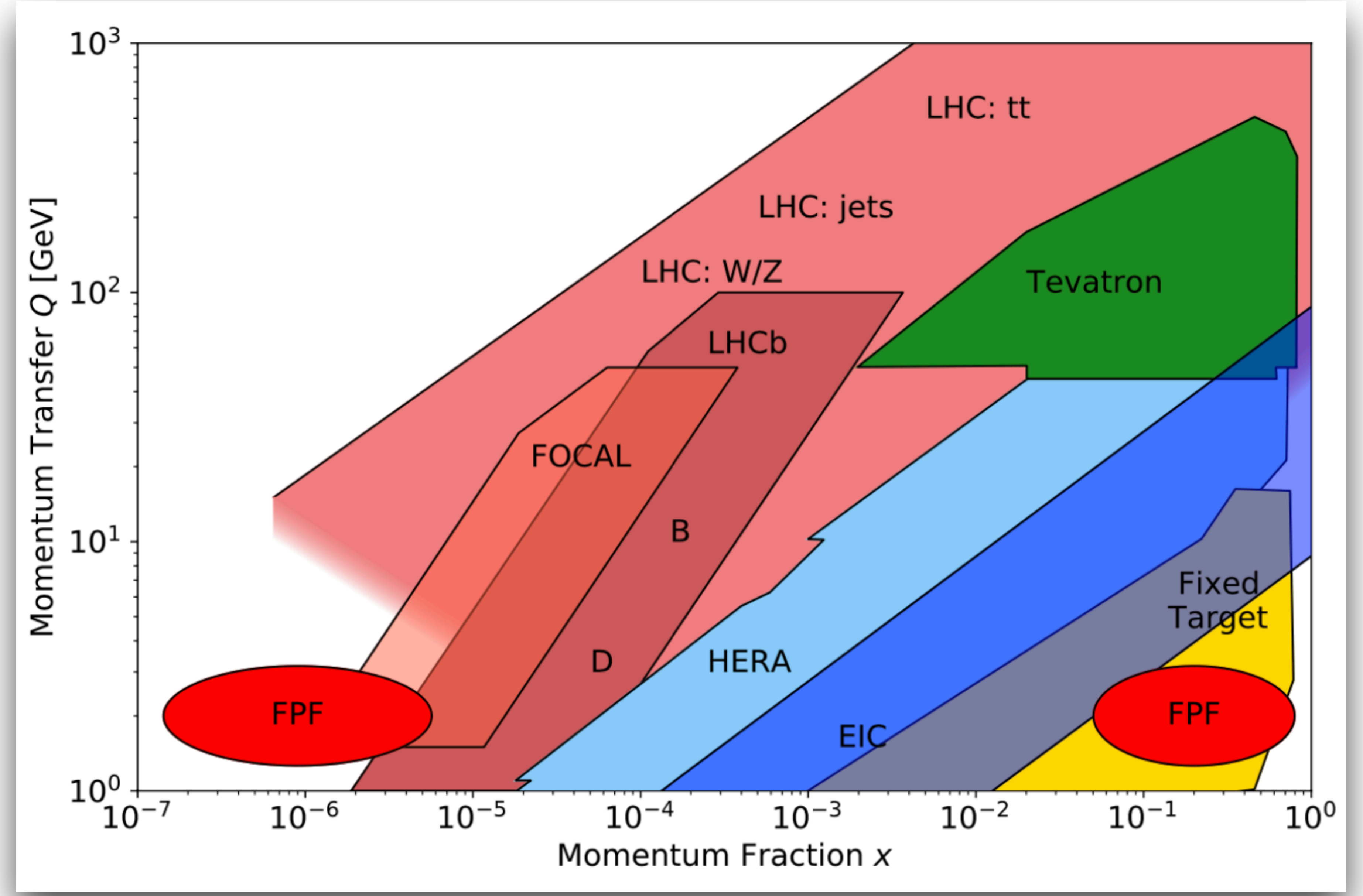

- Heavy quark PDFs have a non negligible impact in the current global PDF fits.
- The NNPDF releases allow both for perturbative and fitted charm.
- We have found a first evidence of a **non zero intrinsic charm $c^+$ in $n_f = 3$**, carrying a momentum fraction total within 1%.
- IC is relevant in the **large-$x$** region and display a **valence-like** structure.
- IC is in **agreement** with most recent **LHCb results** and stable upon inputs variations.

# Future tests on IC

**Ongoing work:**

- A first attempt to **fit $c^-$** indicates that the **IC asymmetry** can be non vanishing. ***The intrinsic charm valence in the proton [in preparation]***
- Impact of the N3LO pQCD corrections might be relevant. Need to include properly **Theory uncertainties** in PDF fits.




**Future colliders:**

- In the *(near)* future we will be able to test and **constrain** further both the **total charm PDF** and its possible **asymmetry**.
- This will require dedicated experimental analysis and accurate **flavour jet tagging**.