Intrinsic charm in the proton

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Milan, Christmas meeting 2021

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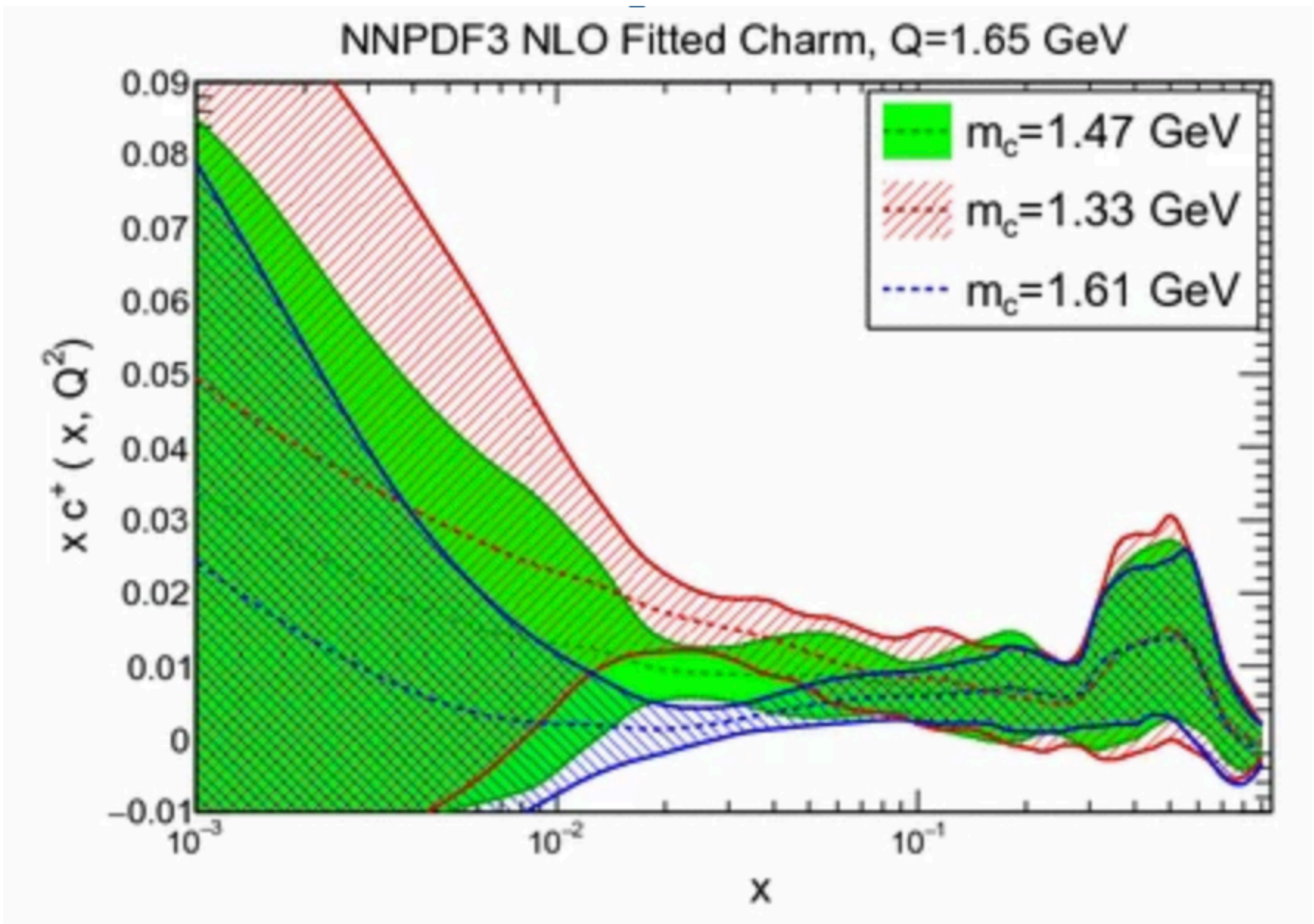
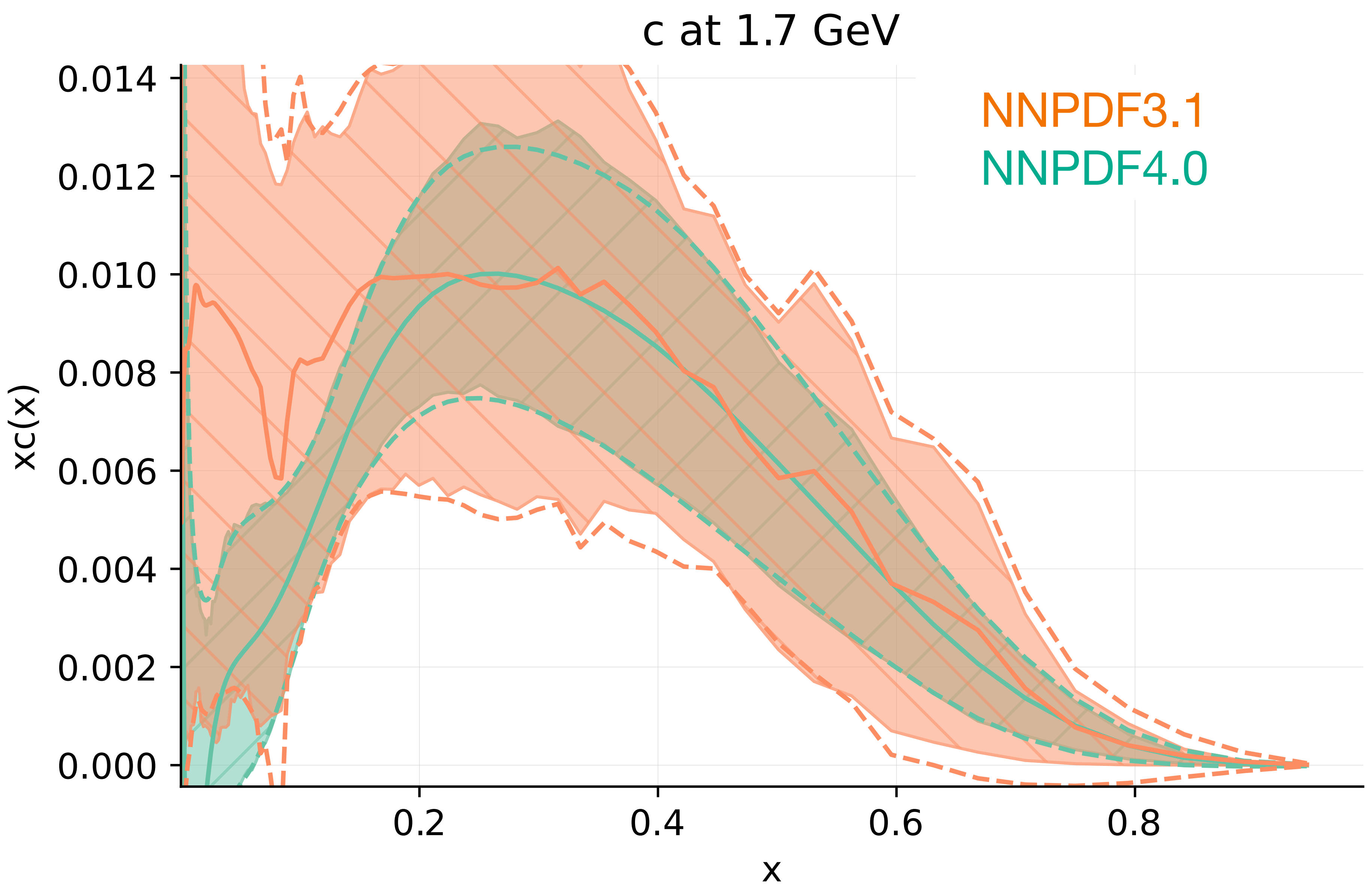
Introduction & Motivation

Do heavy quarks contribute to the proton wave function at low scales?

- Will focus on the charm PDF, as the *natural candite* to answer this question
- Will present results based on a work:
  NNDPF collaboration *"Charm in the proton"*
  (in preparation)
- Results are based on the *(recently released)* NNPDF4.0



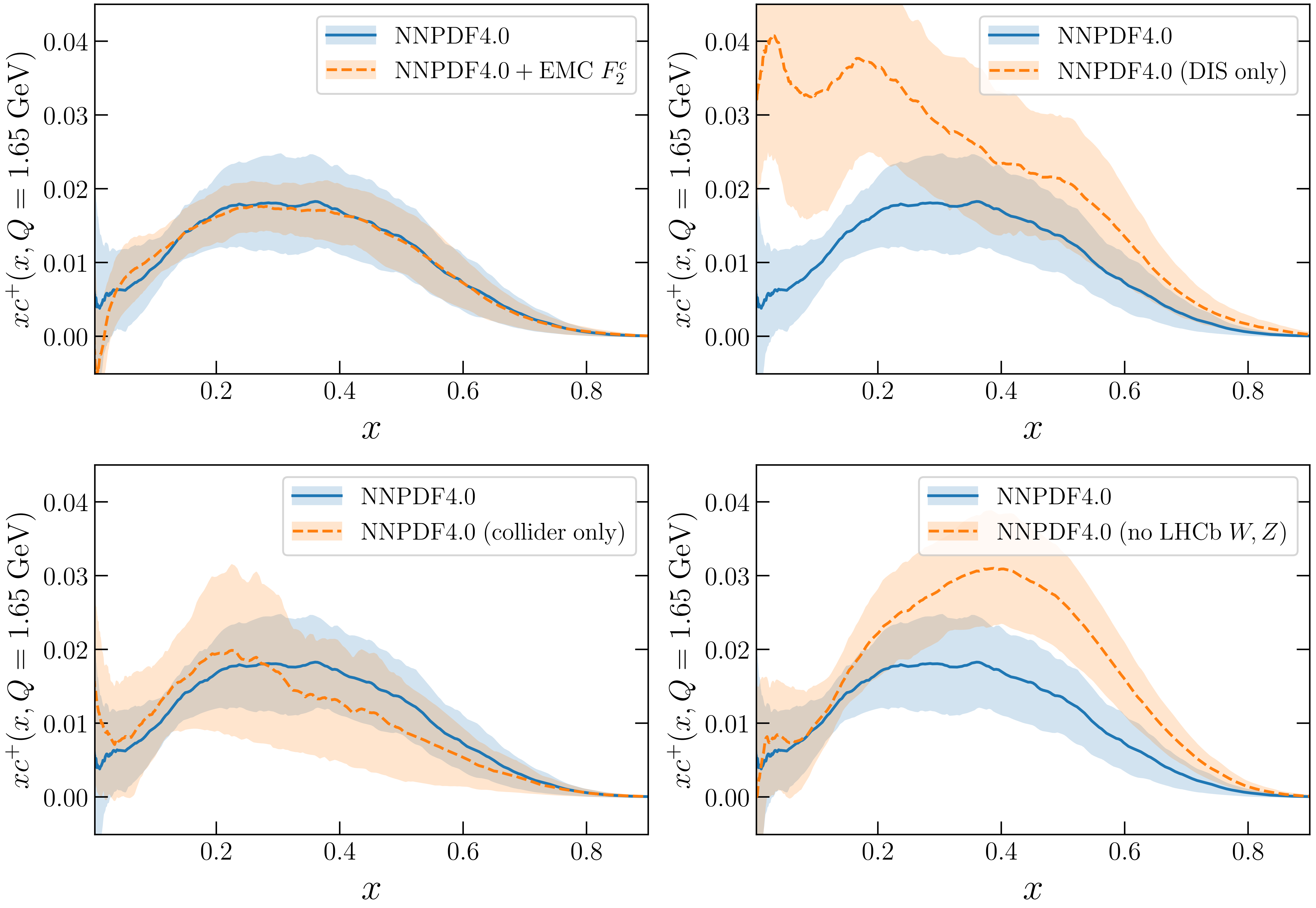


The charm pdf in 4 FNS

NNPDF 4.0 baseline

$$xc^{+}(x, Q_0, \Theta) = \left(x^{\alpha_\Sigma}(1-x)^{\beta_\Sigma} NN_\Sigma(x,\Theta) - x^{\alpha_{T15}}(1-x)^{\beta_{T15}} NN_{T_{15}(x,\Theta)}\right)/4$$

- The charm PDF is parametrised as an independent combination at scale $Q_0 = 1.65\ GeV$, and $n_f = 4$
- c^+ at the fitting scale exhibits a non vanishing peak in the *high x* region and vanishes at *low-x*
- $\bar{c} = c$
- Constrain are coming mainly from collider data
- NNPDF 4.0 is consistent with EMC data.



Why do we need intrinsic charm?

The fully perturbative scenario

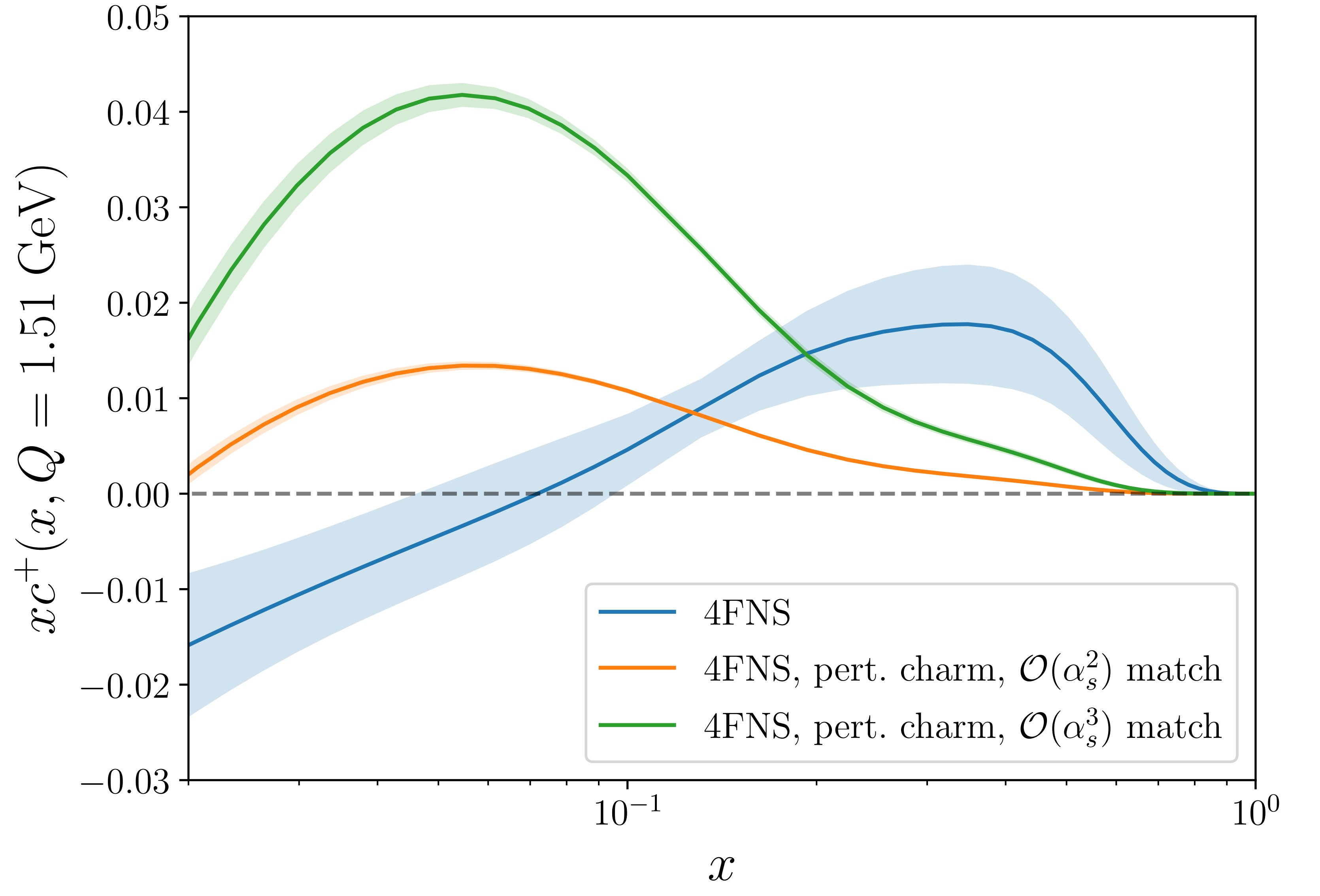
- **Perturbative charm** functional form is fully determined by the DGLAP evolution and the initial boundary conditions.

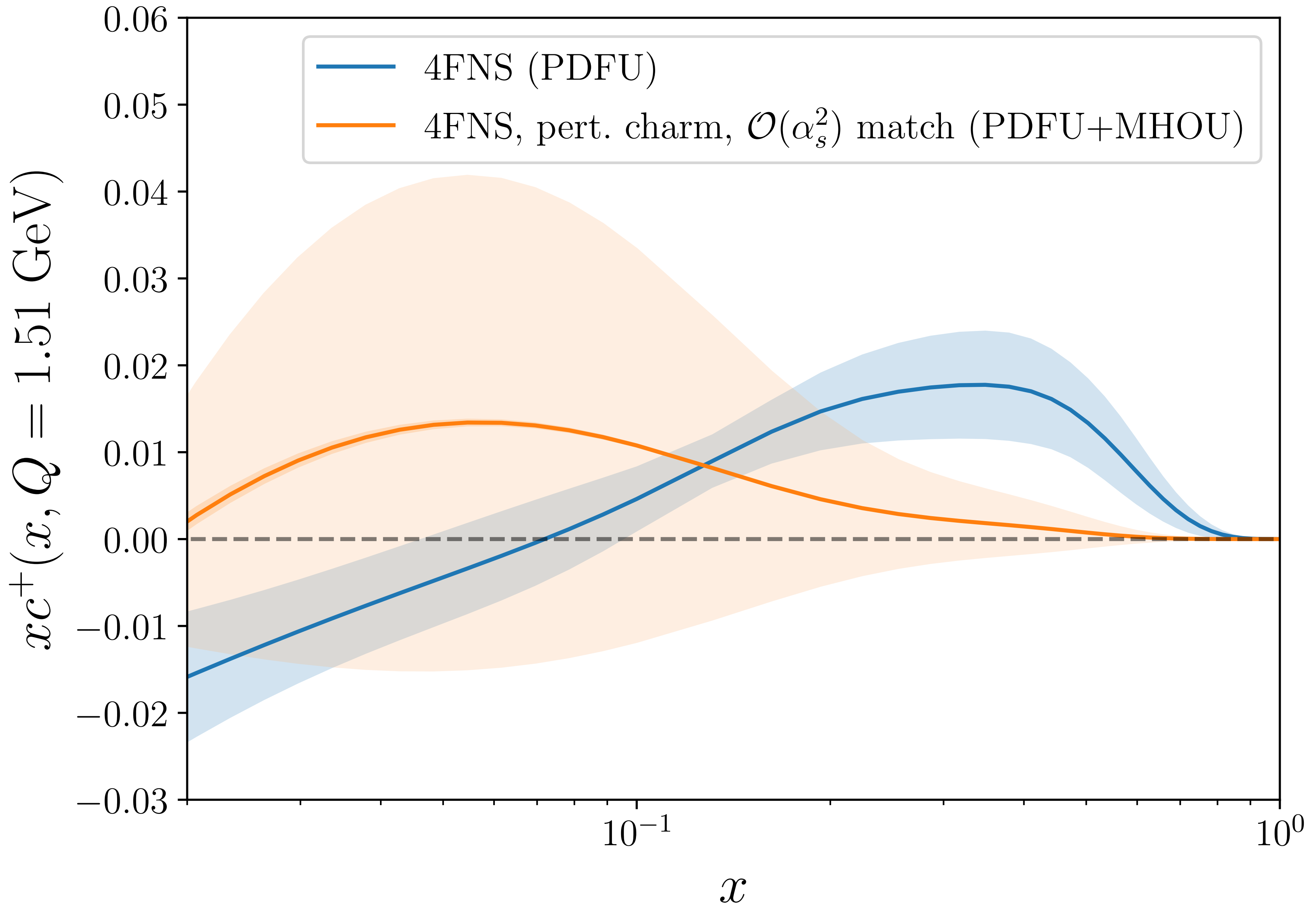
- In this case PDF uncertainties are clearly not the dominant source of uncertainties. Needs to estimate MHOU and mass dependence.

However…

- The post fit χ^2 favours a fitted charm scenario compared to a purely perturbative charm.

- Fully perturbative charm is not compatible with the fitted one.





Why do we need intrinsic charm?

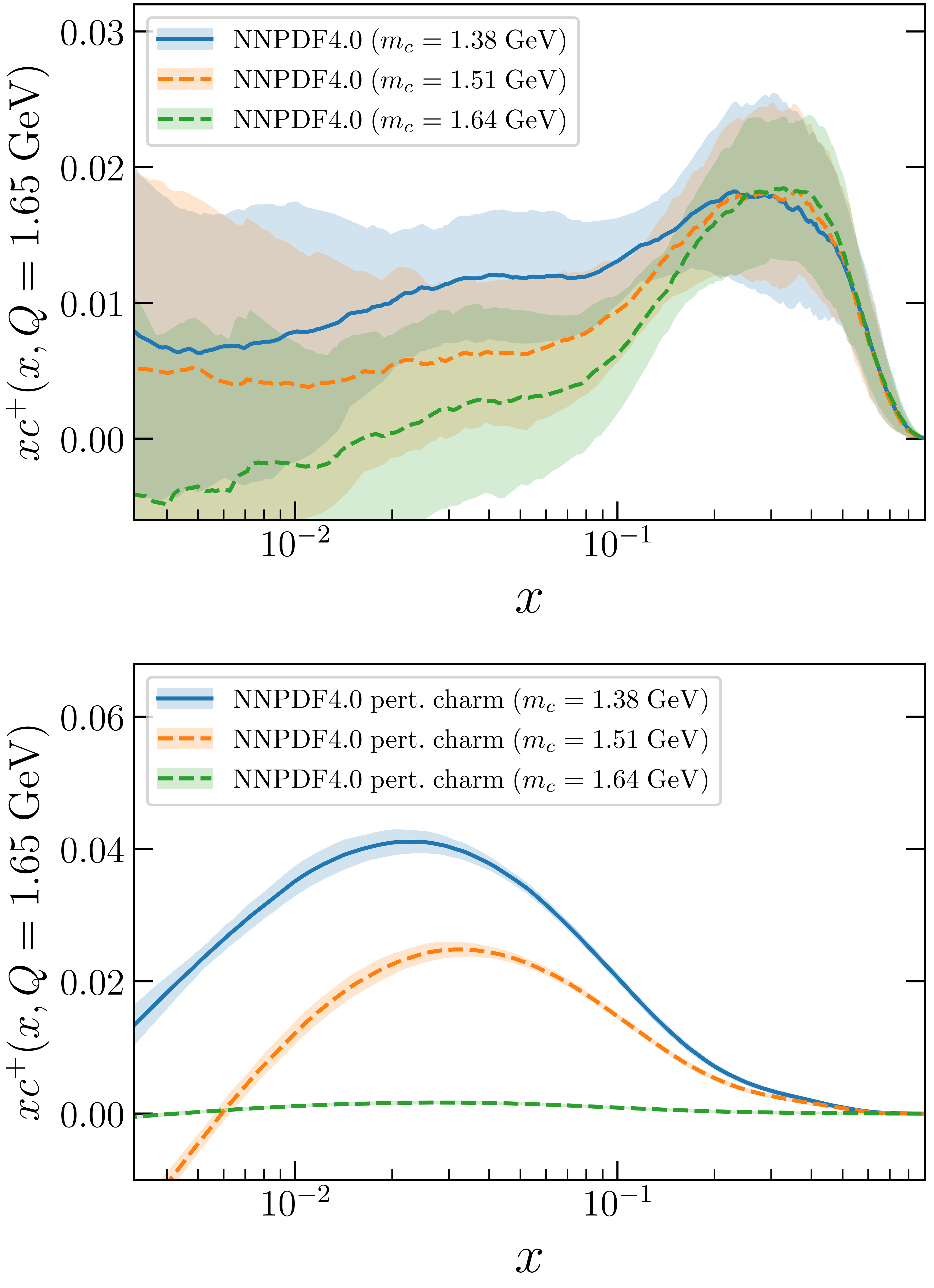
Mass dependence

- NNPDF4.0 fit is carried out using heavy quark pole mass

- Charm mass is varied in the range:

$$m_c = 1.51 \pm 0.13\ GeV$$

- The fitted charm is much more stable upon mass variation especially in the high x region compared to the perturbative one.



The Intrinsic charm scenario

Perturbative vs Fitted

- **Perturbative charm** functional form is fully determined by the DGLAP evolution and the initial boundary conditions.

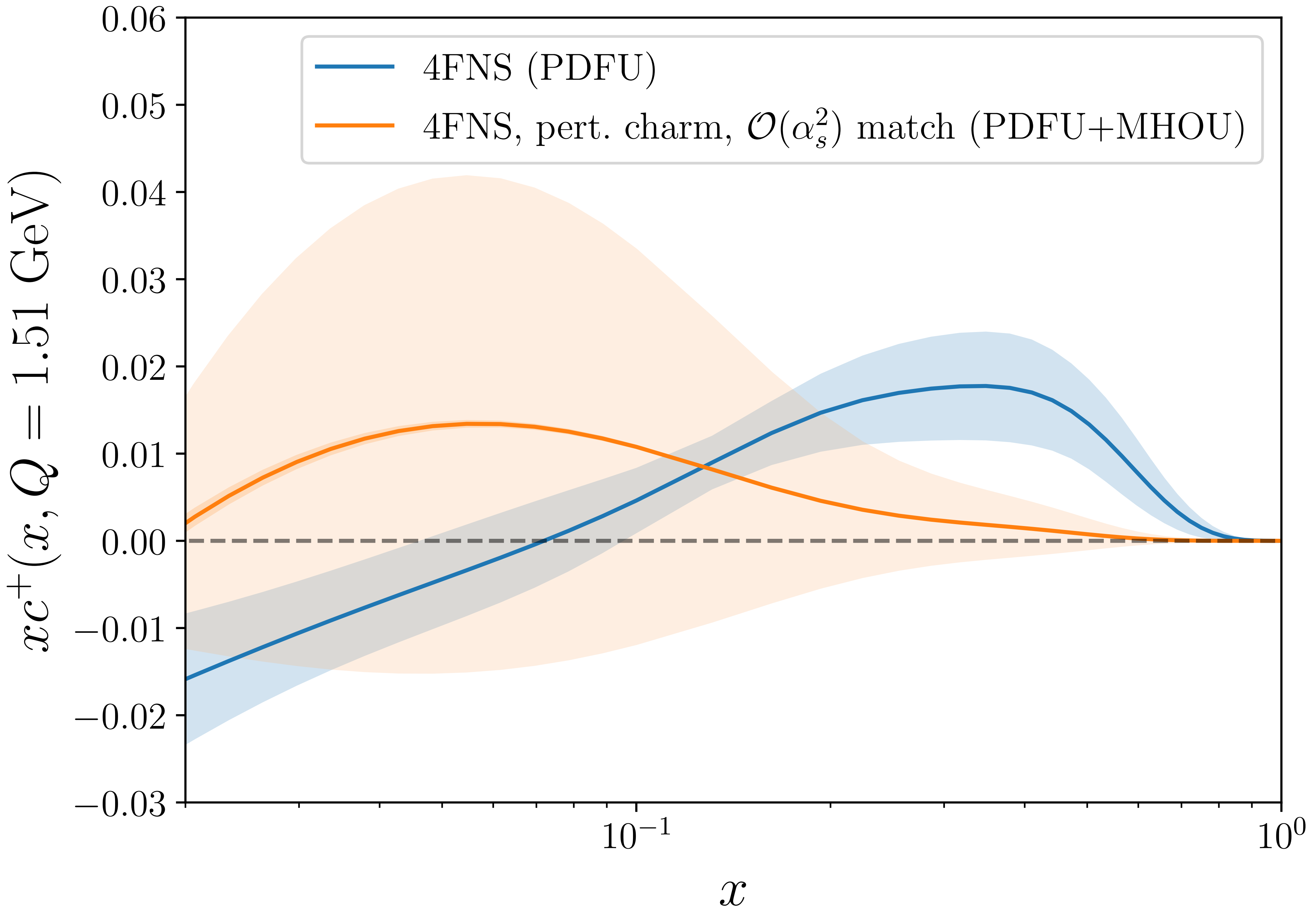
- Below the charm mass scale the perturbative charm is vanishing by definition

- **Fitted charm in** 4FNS contains both the intrinsic and the perturbative components.

how can we separate them?

↓

Need to work out the 3 FNS charm PDF



A brief digression on DGLAP

Solving DGLAP with EKO

Evolution Kernel Operators

$$\frac{d}{d\alpha_s}\tilde{\mathbf{f}}(\mu_F^2) = -\frac{\gamma(a_s)}{\beta(a_s)} \cdot \tilde{\mathbf{f}}(a_s)$$

- The formal solution of DGLAP can be written as in Mellin-space:

$$\tilde{\mathbf{f}}(a_s) = \tilde{\mathbf{E}}(a_s \leftarrow a_s^0) \cdot \tilde{\mathbf{f}}(a_s^0)$$

$$\tilde{\mathbf{E}}(a_s \leftarrow a_s^0) = \mathscr{P} \exp\left[-\int_{a_s^0}^{a_s} \frac{\gamma(a_s')}{\beta(a_s')} da_s'\right]$$

- In x-space:

$$\mathbf{f}(x_k, a_s) = \mathbf{E}_{k,j}(a_s \leftarrow a_s^0)\mathbf{f}(x_j, a_s^0)$$

The **EKO**, a rank 4 tensor

- Evolution is performed in **Intrinsic** Evolution basis: $span\{g, \Sigma, V, V_3, T_3, V_8, T_8, c^+, c^-, b^+, b^-, t^+, t^-)\}$

- Solution is available at: LO, NLO, NNLO

- EKO implements various solution methods: *Exact, Truncated, Expanded* ….
  see: documentation

From 4FNS to 3FNS

The matching conditions

At the heavy quark mass threshold the number of active flavour changes:

$$\tilde{\mathbf{f}}^{(n_f+1)}(Q_1^2) = \tilde{\mathbf{E}}^{(n_f+1)}(Q_1^2 \leftarrow \mu_h^2)\mathbf{R}^{(n_f)}\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)\tilde{\mathbf{E}}^{(n_f)}(\mu_h^2 \leftarrow Q_0^2)\tilde{\mathbf{f}}^{(n_f)}(Q_0^2)$$

Rotation from $intrisic^{(nf)}$ basis to $intrisic^{(nf+1)}$

The **Operator Matrix Elements:**

$$\begin{pmatrix} \tilde{V}_{(n_f)} \\ \tilde{h}^- \end{pmatrix}^{n_f+1} (\mu_h^2) = \tilde{\mathbf{A}}^{(n_f)}_{NS,h^-}(\mu_h^2) \begin{pmatrix} \tilde{V}_{(n_f)} \\ \tilde{h}^- \end{pmatrix}^{n_f} (\mu_h^2)$$

$$\begin{pmatrix} \tilde{g} \\ \tilde{\Sigma}_{(n_f)} \\ \tilde{h}^+ \end{pmatrix}^{n_f+1} (\mu_h^2) = \tilde{\mathbf{A}}^{(n_f)}_{S,h^+}(\mu_h^2) \begin{pmatrix} \tilde{g} \\ \tilde{\Sigma}_{(n_f)} \\ \tilde{h}^+ \end{pmatrix}^{n_f} (\mu_h^2)$$

- In FFNS there are no difference between forward and backward evolution (just swap the integration bounds)
- The OME depends on $\alpha_s(\mu_h^2)$ and on $log(\mu_h^2/m_h^2)$
- OME are available up to N3LO (*NLO for heavy quark entries*)

$$\mathbf{A}^{(n_f)}(\mu_h^2) = \mathbf{I} + a_s^{(n_f)}(\mu_h^2)\mathbf{A}^{(n_f),(1)} + a_s^{(n_f),2}(\mu_h^2)\mathbf{A}^{(n_f),(2)} + a_s^{(n_f),3}(\mu_h^2)\mathbf{A}^{(n_f),(3)} + \mathcal{O}(\alpha_s^4)$$

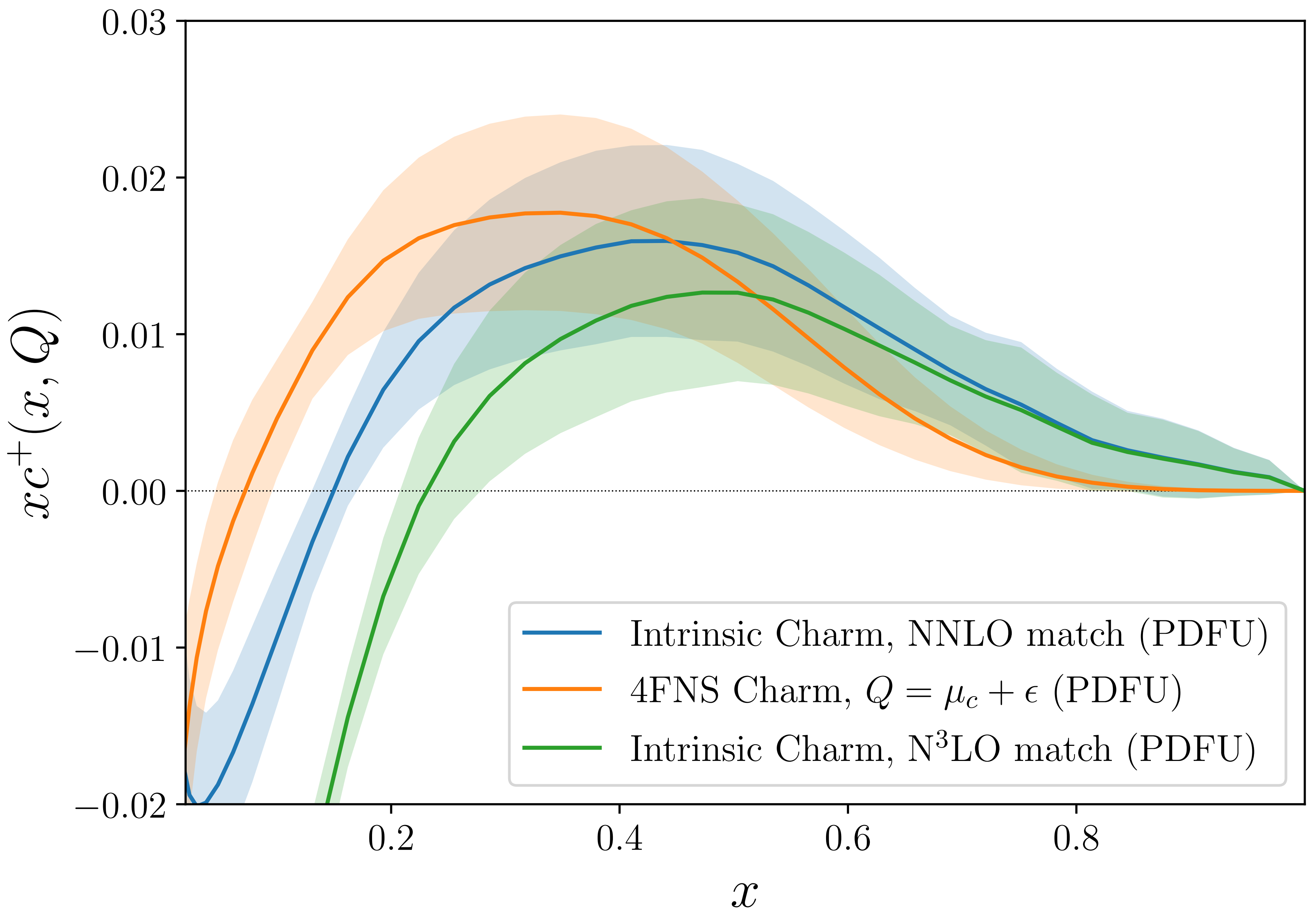
The Intrinsic charm

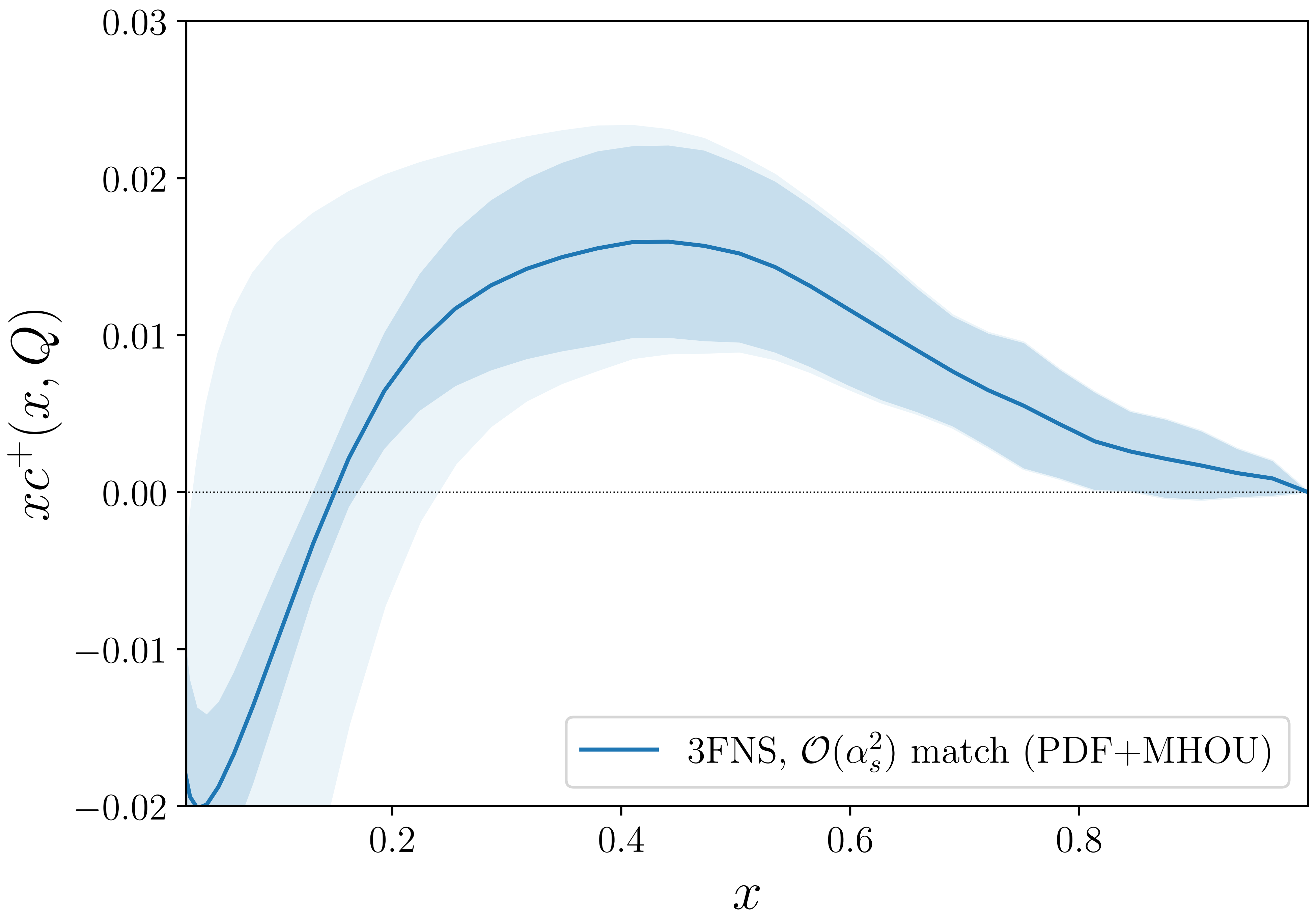
Charm in 3FNS

- Starting from the fitting scale we evolve the NNPDF4.0 baseline to $Q = m_c$.
- When passing the heavy quark threshold we need to apply the basis rotation and then invert the OMEs $\tilde{A}_{i,j}$.
- The remaining part of the charm pdf is the **Intrinsic component**, which is scale independent

In 3FNS:

- The *valence-like* peak is still present.
- For $x \leq 0.2$ the perturbative uncertainties are quite large
- The carried momentum fraction is within 1%

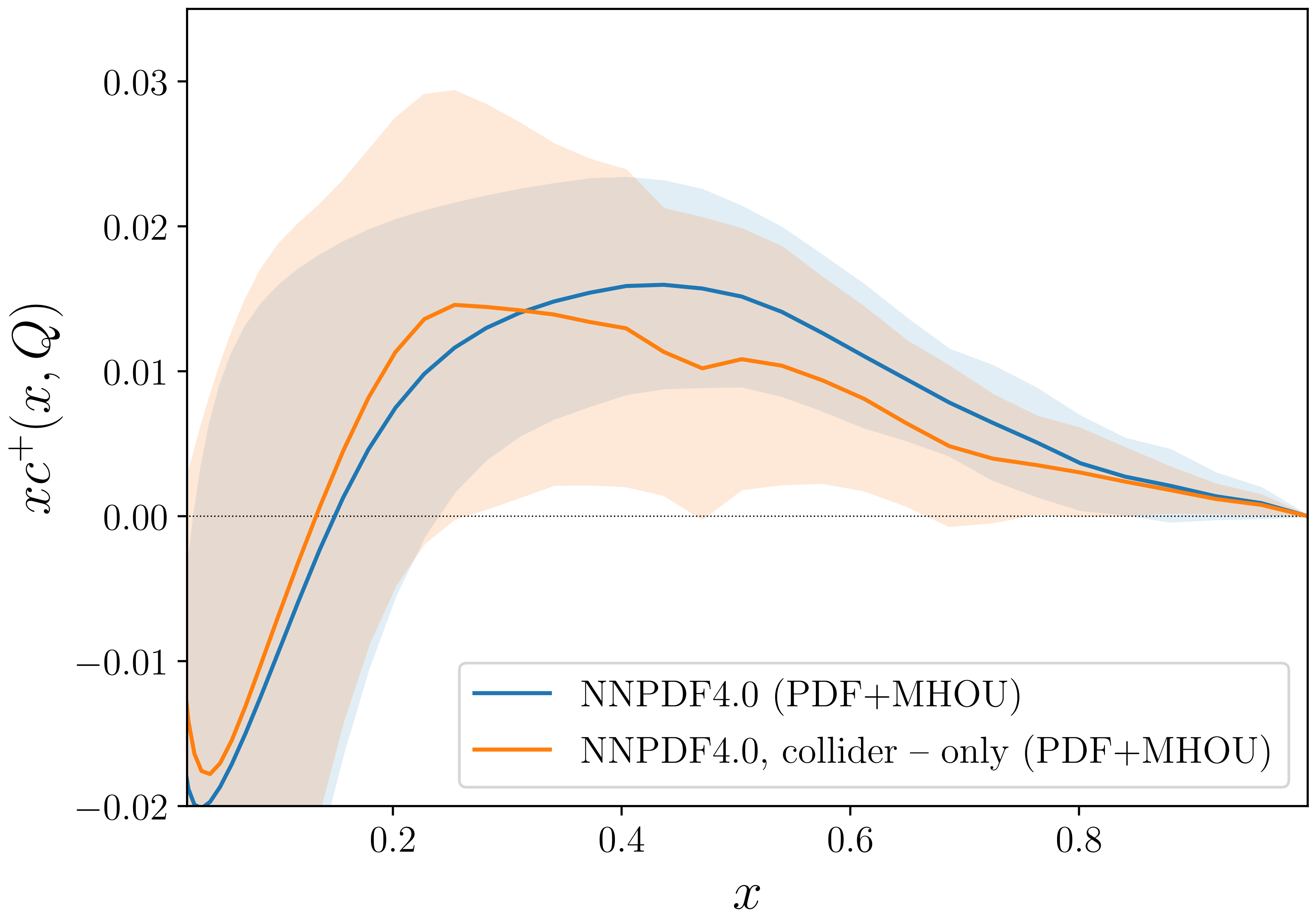


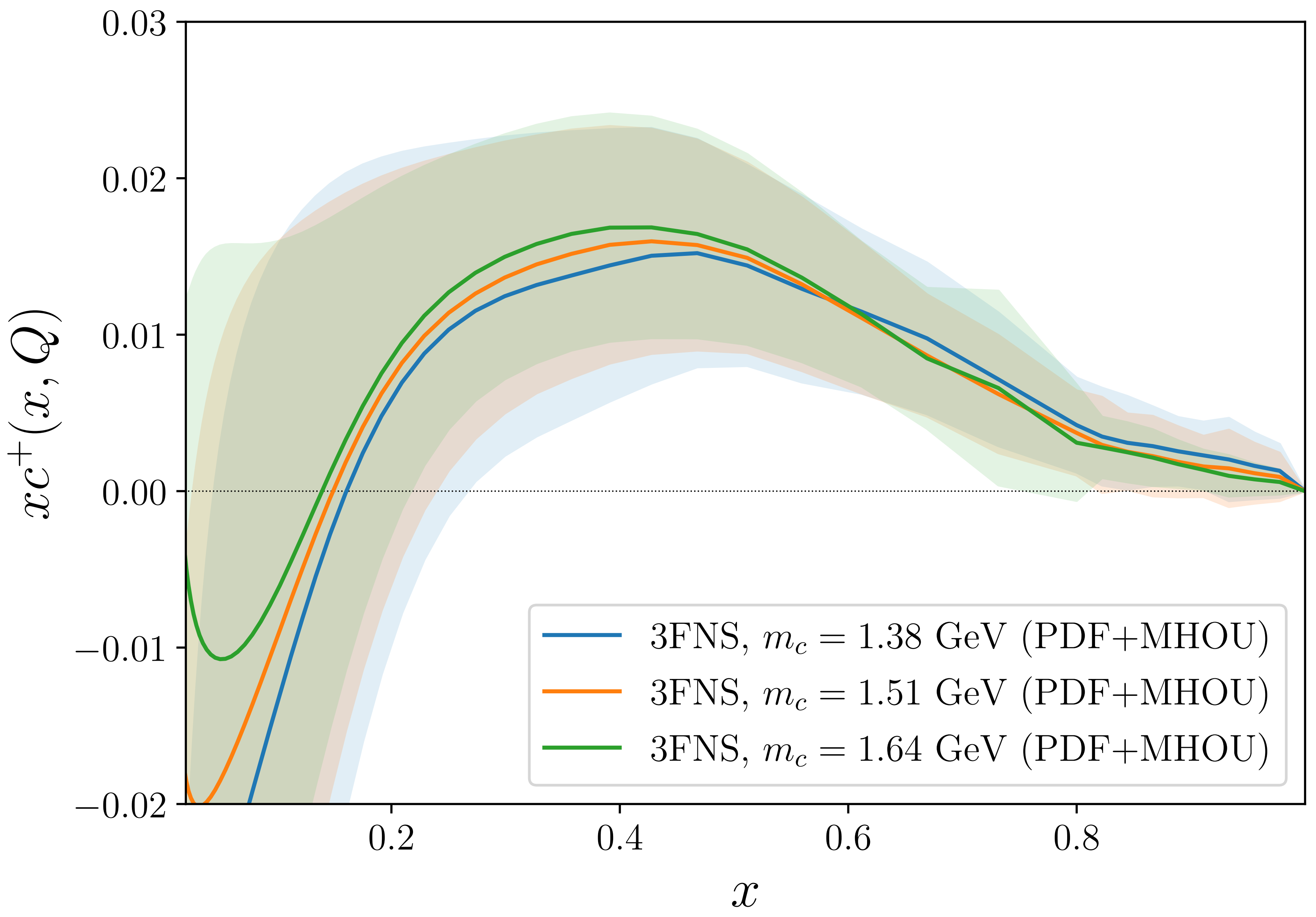


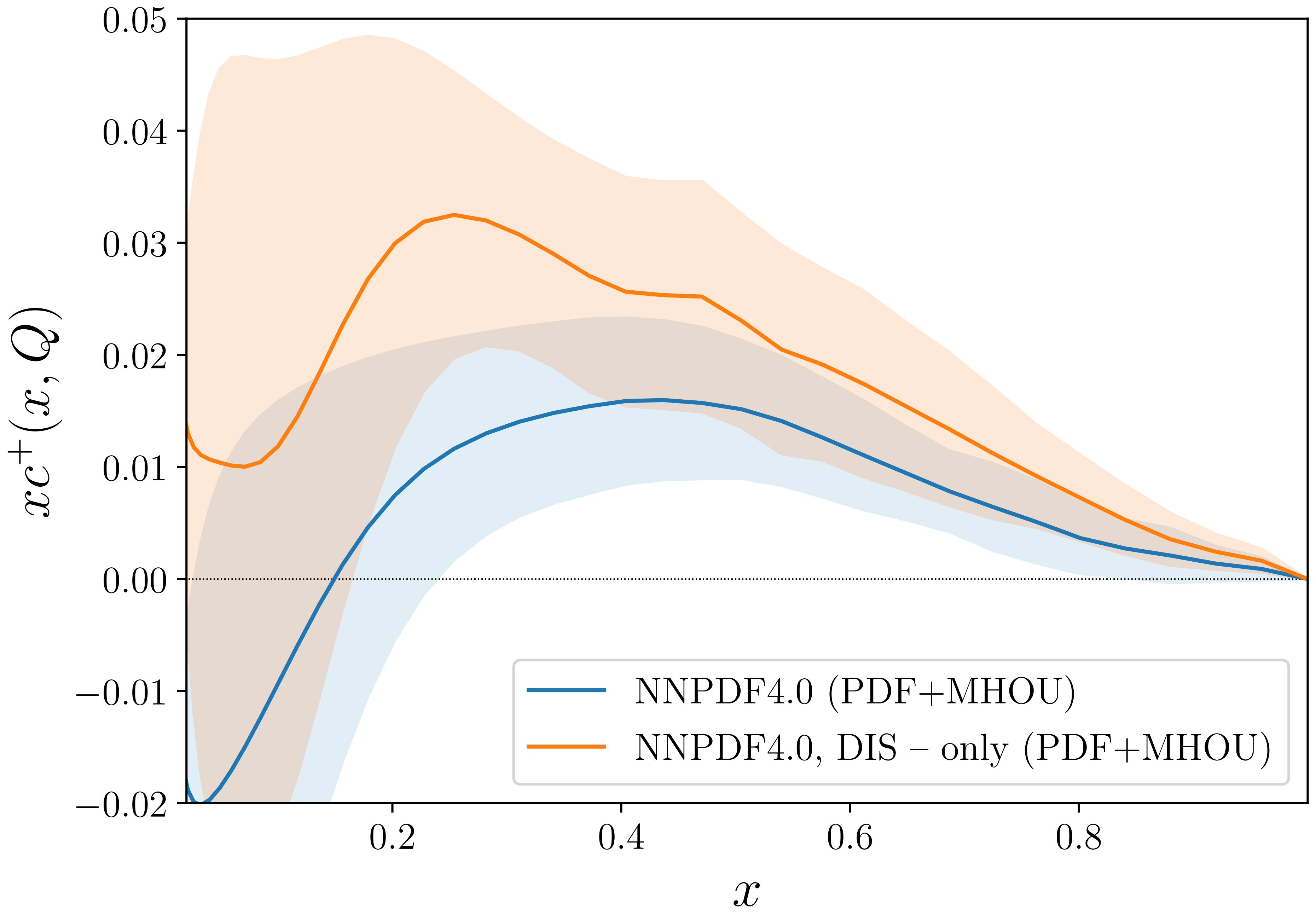
3FNS stability and accuracy

Mass dependence and dataset variation

- Intrinsic charm is stable upon mass variation
- Scale independecy
- Always vanishing for $x \leq 0.2$
- MHOU coming from NNLO-N3LO matching







The Intrinsic charm

Comparison with Models

- BHPS model: [Phy. Letter B (1980) 451-455]

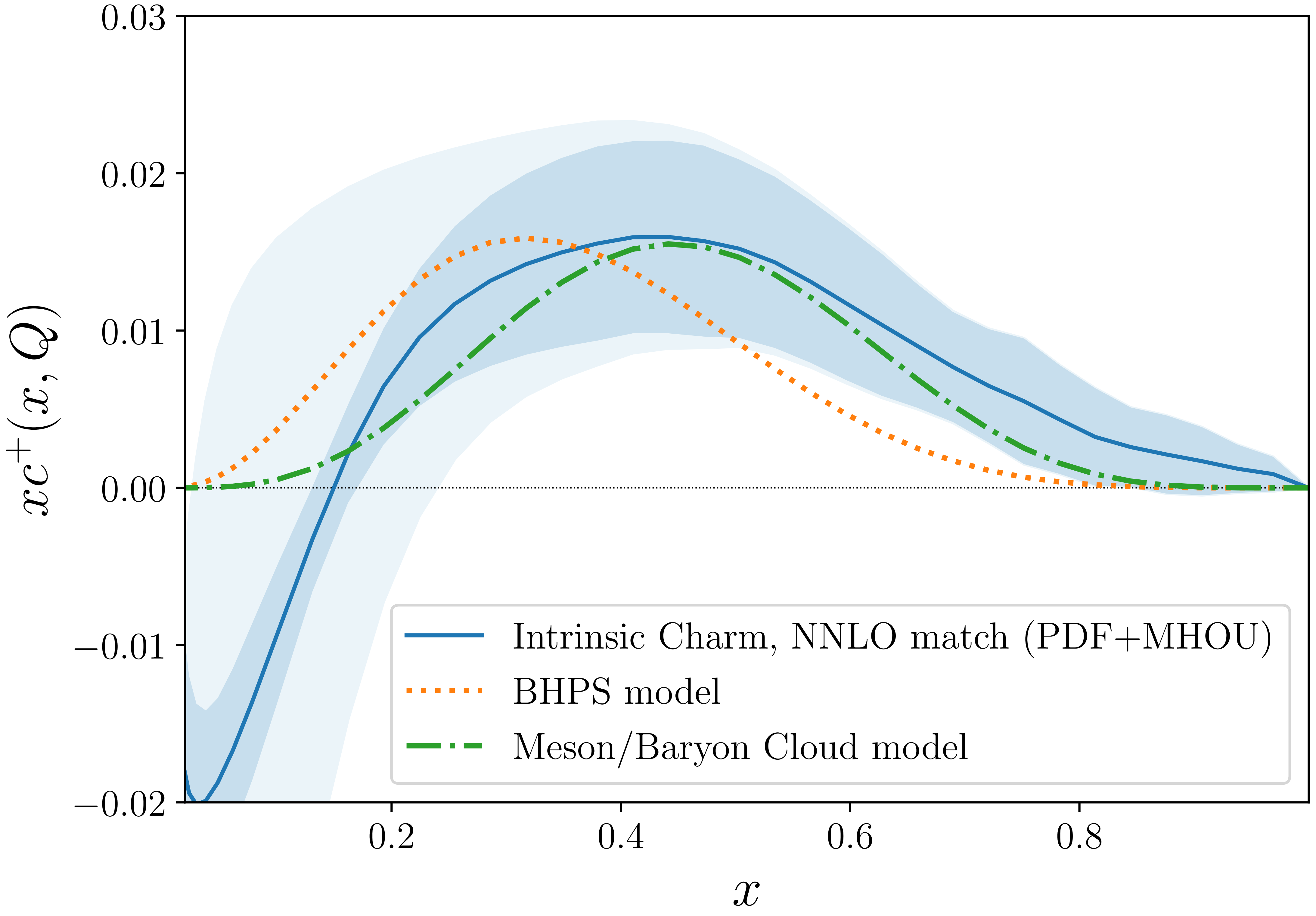
$$p \to uudc\bar{c}$$

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

- Meson Baryon model: [arxiv:1311.1578]

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

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



- $\bar{c} = c$ by assumption in BHPS, not true in M/B models.

- Work in the limit $m_c \gg m_p$

Impact on LHC observables

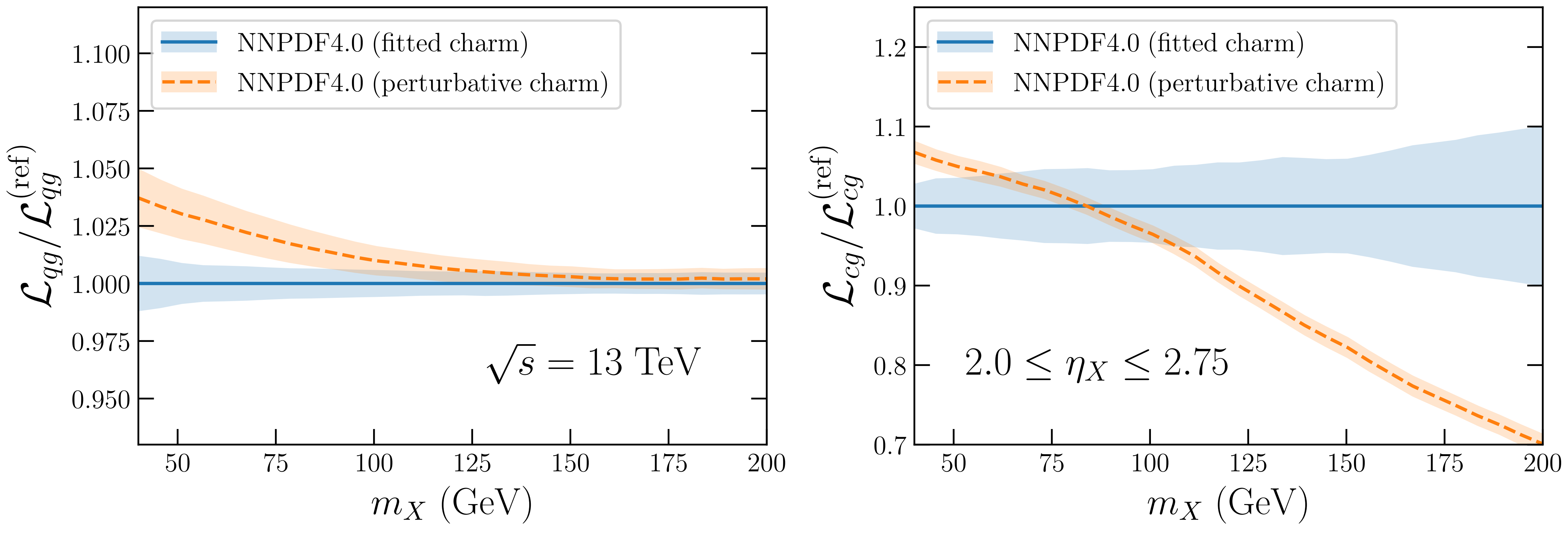
Partonic luminosities

To see where the differences between fitted and perturbative charm can be evident you can look at partonic lumi of: $pp \to X$

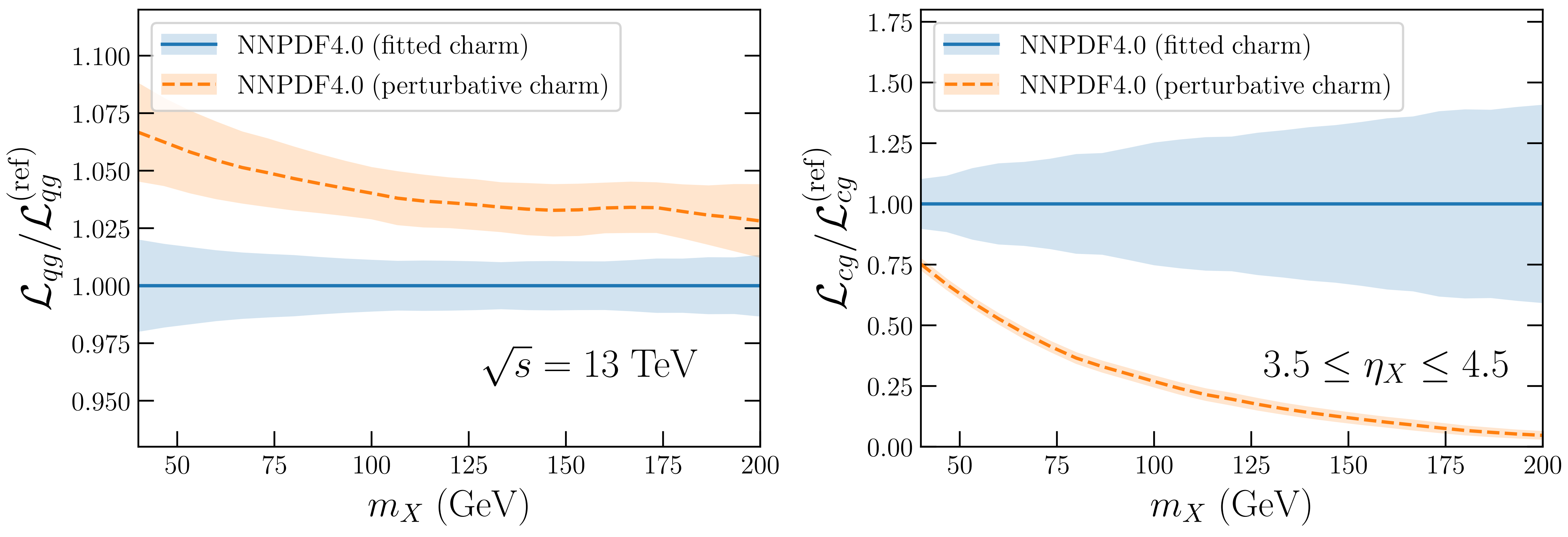
$$\mathscr{L}_{ab} = \frac{1}{s}\int_{\frac{m_X^2}{s}}^{1} \frac{dx}{x} f_a(x, m_X^2) f_b(x, m_X^2)\theta(y_X - y_{min})\theta(y_{max} - y_X)$$

$$\mathscr{L}_{cg} = \mathscr{L}_{cg} + \mathscr{L}_{\bar{c}g} \qquad \mathscr{L}_{qg} = \sum_{i=1}^{n_f} \mathscr{L}_{q_ig} + \mathscr{L}_{\bar{q}_ig}$$

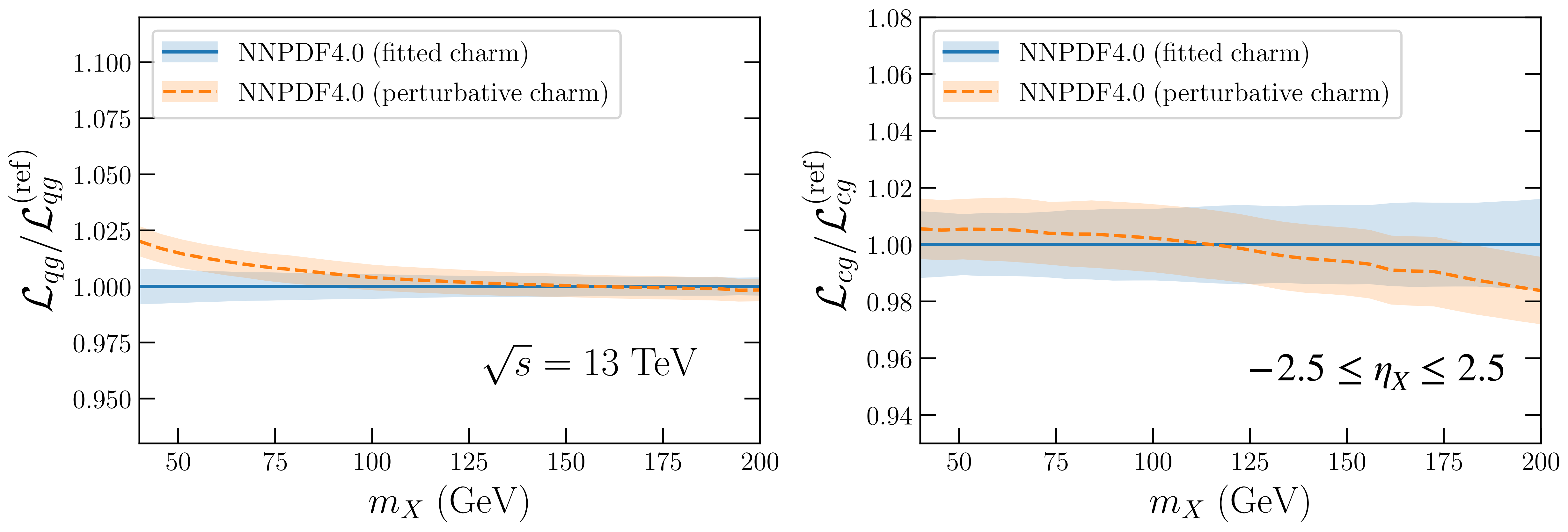
Central region LHCb



Forward region LHCb



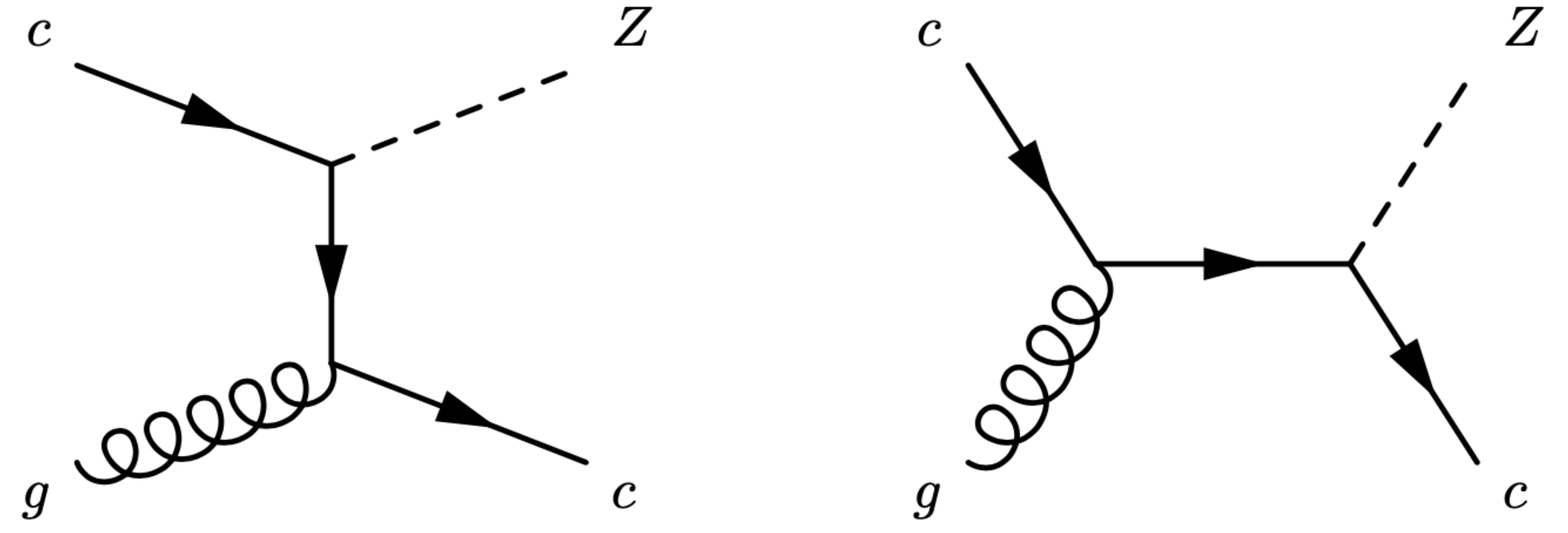
Central region ATLAS-CMS

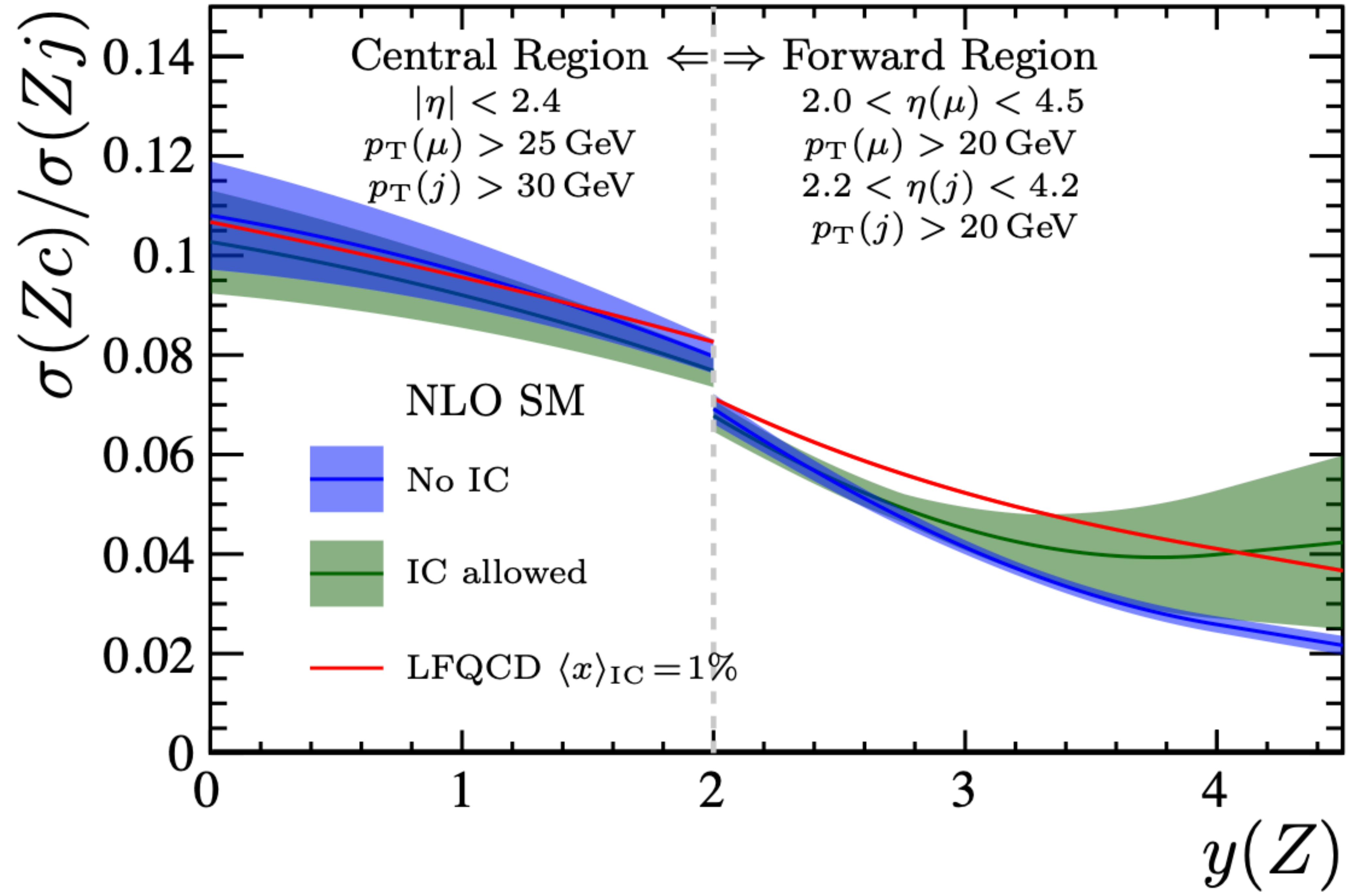


Impact on LHC observables

Z+charm production @ LHCb

We validate our observation of Intrinsic charm evaluating the prediction for:
$Z + c$ production at LHCb [arxiv:2109.08084]





$$R_j^c(y_Z) = \frac{\sigma_{Zc}}{\sigma_{Zj}}$$

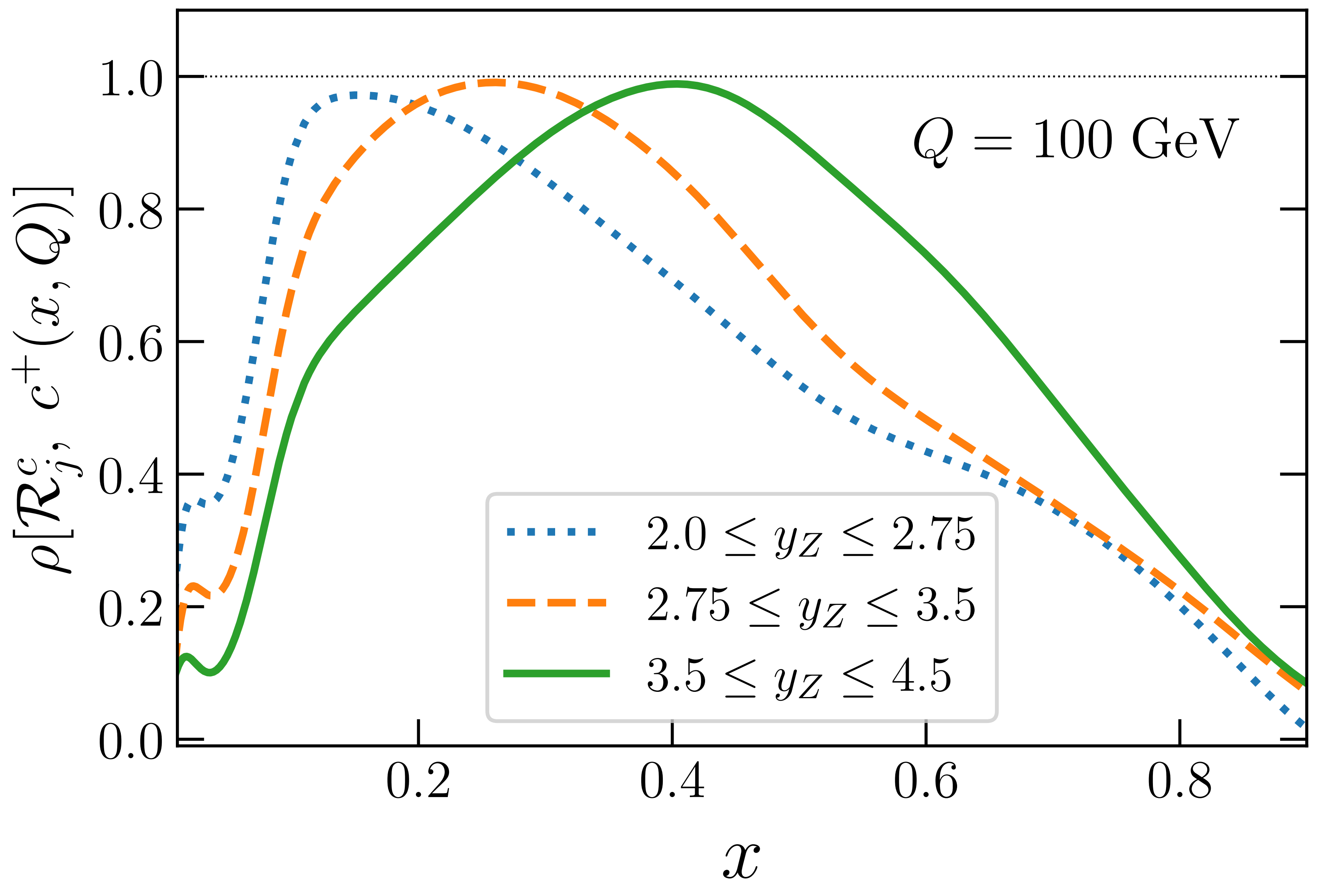
$y(Z)$	$\mathcal{R}_j^c$ (%)	Stat	Syst
2.00–2.75	6.84	± 0.54	± 0.51
2.75–3.50	4.05	± 0.32	± 0.31
3.50–4.50	4.80	± 0.50	± 0.39
2.00–4.50	4.98	± 0.25	± 0.35

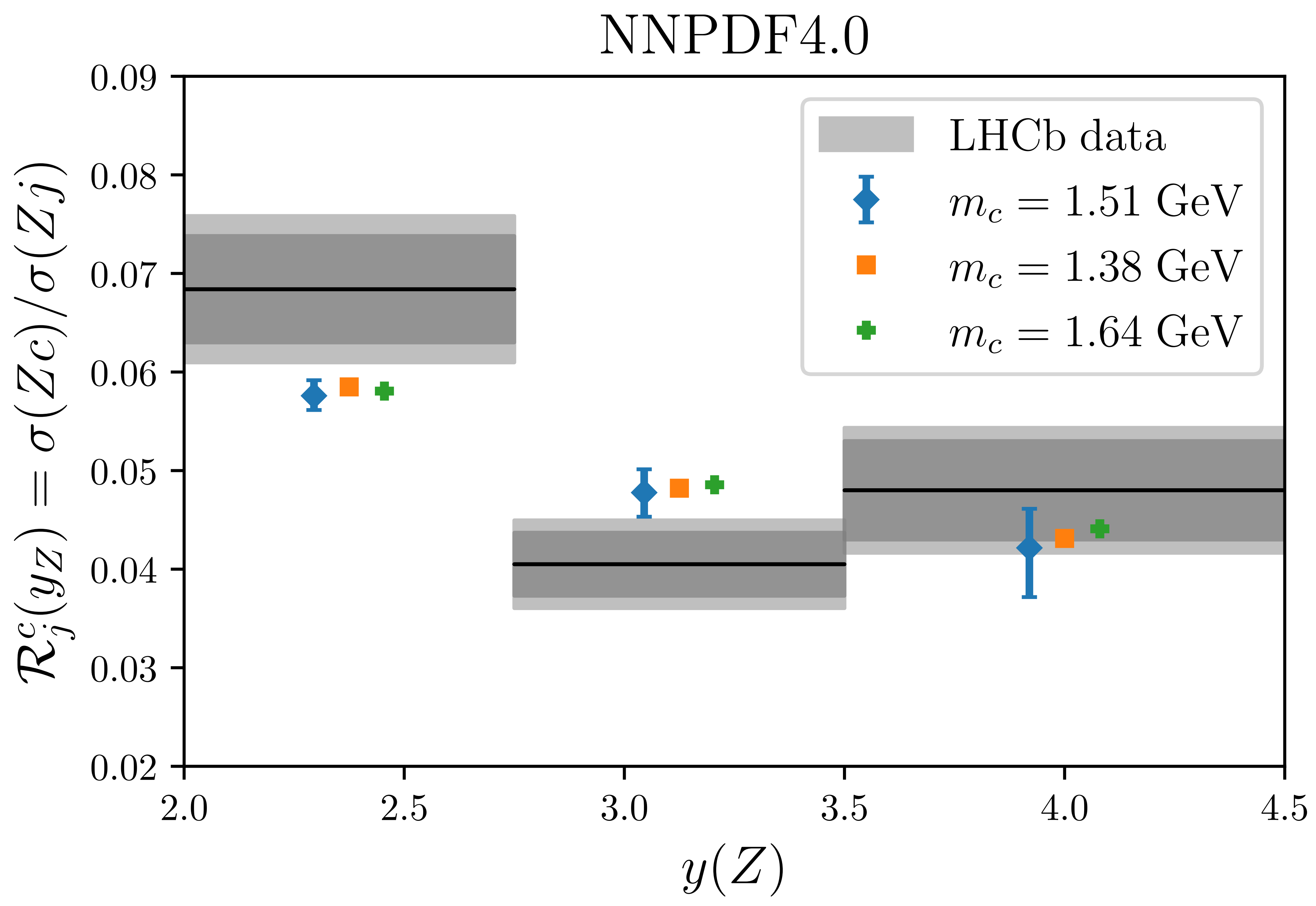
Impact on LHC observables

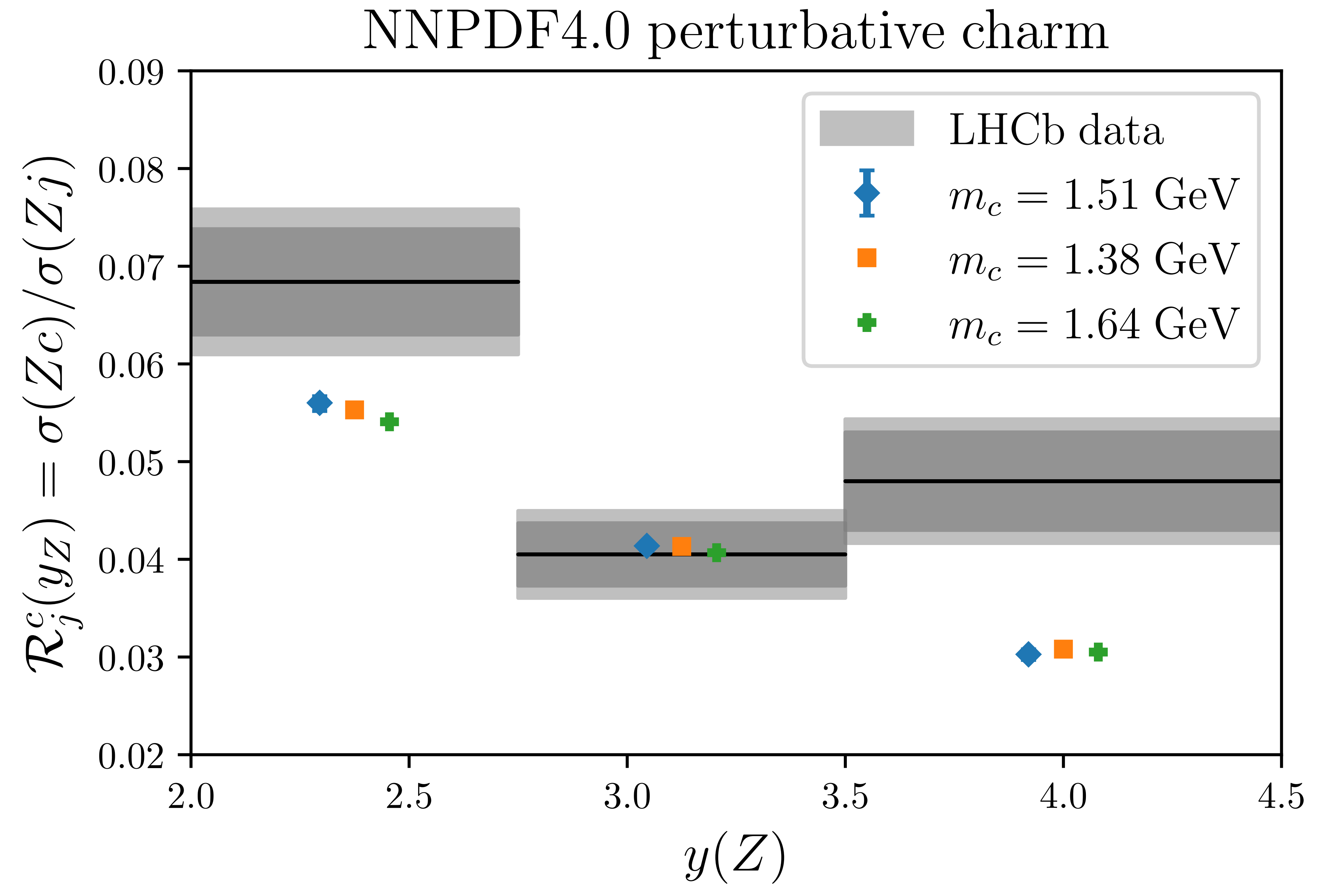
Z+charm production @ LHCb

Our in-house prediction, with *Powheg* @ NLO+PS [arxiv: 1009.5594]

- Better agreement is found with the NNPDF4.0 baseline especially in the forward region
- Predictions are also stable upon charm mass variation
- NNLO corrections not taken into account yet
- High correlation with the charm PDF and LHCb observable:







The Intrinsic charm

Our current best estimation

To achieve the best sensitivity on the intrinsic charm, we add the LHCb results to the NNPDF4.0 baseline.

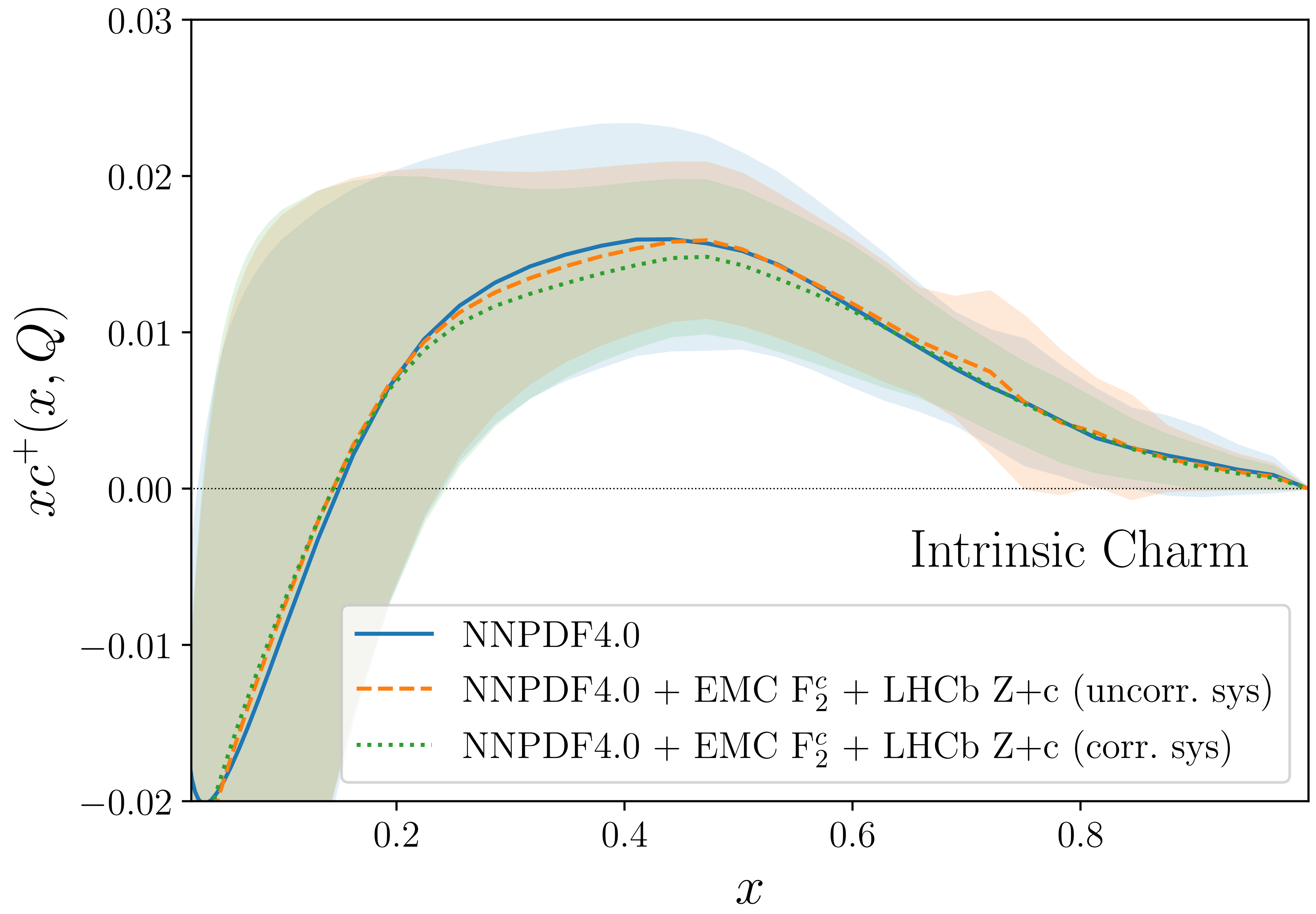
We compute:

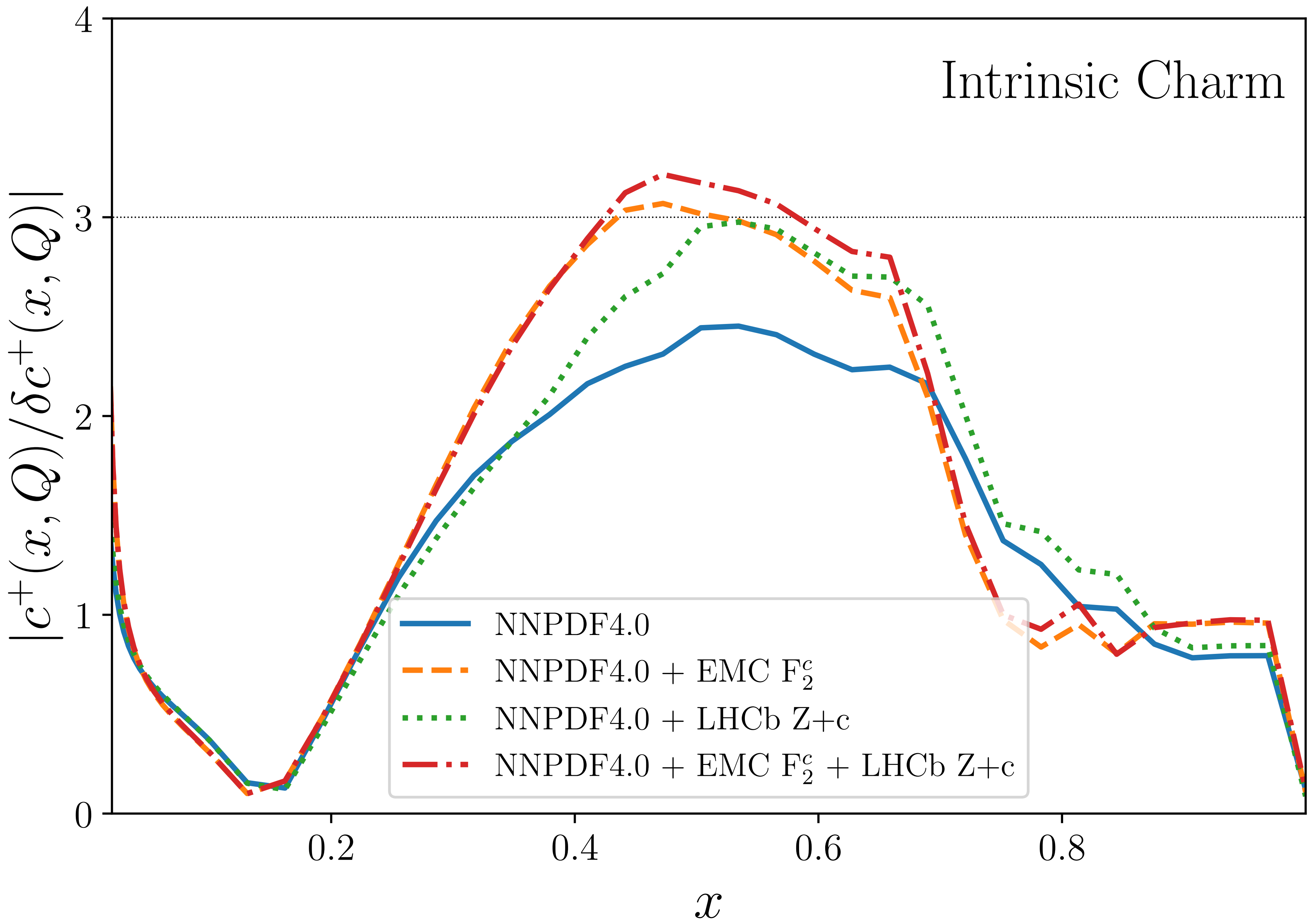
- **local significance:**

- **momentum fraction**:

$$[c] = \int_0^1 xc^+(x, Q^2)dx$$

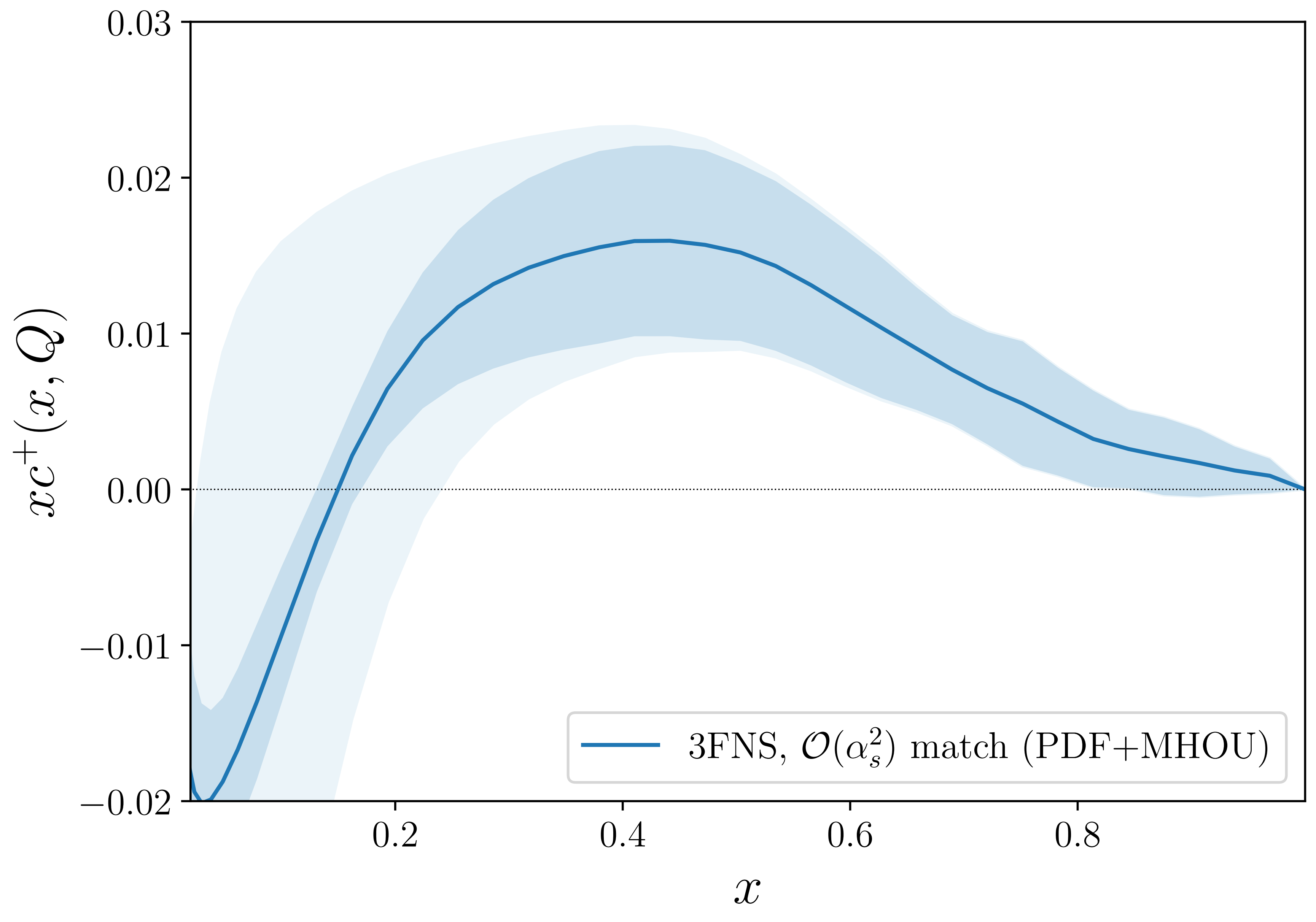
m_c	Dataset	$[c]\,(Q)$ (%)
1.51 GeV	Baseline	$0.62 \pm 0.28_{\rm pdf} \pm 0.54_{\rm mhou}$
1.51 GeV	Baseline+EMC	$0.60 \pm 0.18_{\rm pdf} \pm 0.54_{\rm mhou}$
1.51 GeV	Baseline+EMC+LHBCb Zc	$0.60 \pm 0.17_{\rm pdf} \pm 0.59_{\rm mhou}$
1.38 GeV	Baseline	$0.47 \pm 0.27_{\rm pdf} \pm 0.62_{\rm mhou}$
1.64 GeV	Baseline	$0.77 \pm 0.28_{\rm pdf} \pm 0.48_{\rm mhou}$

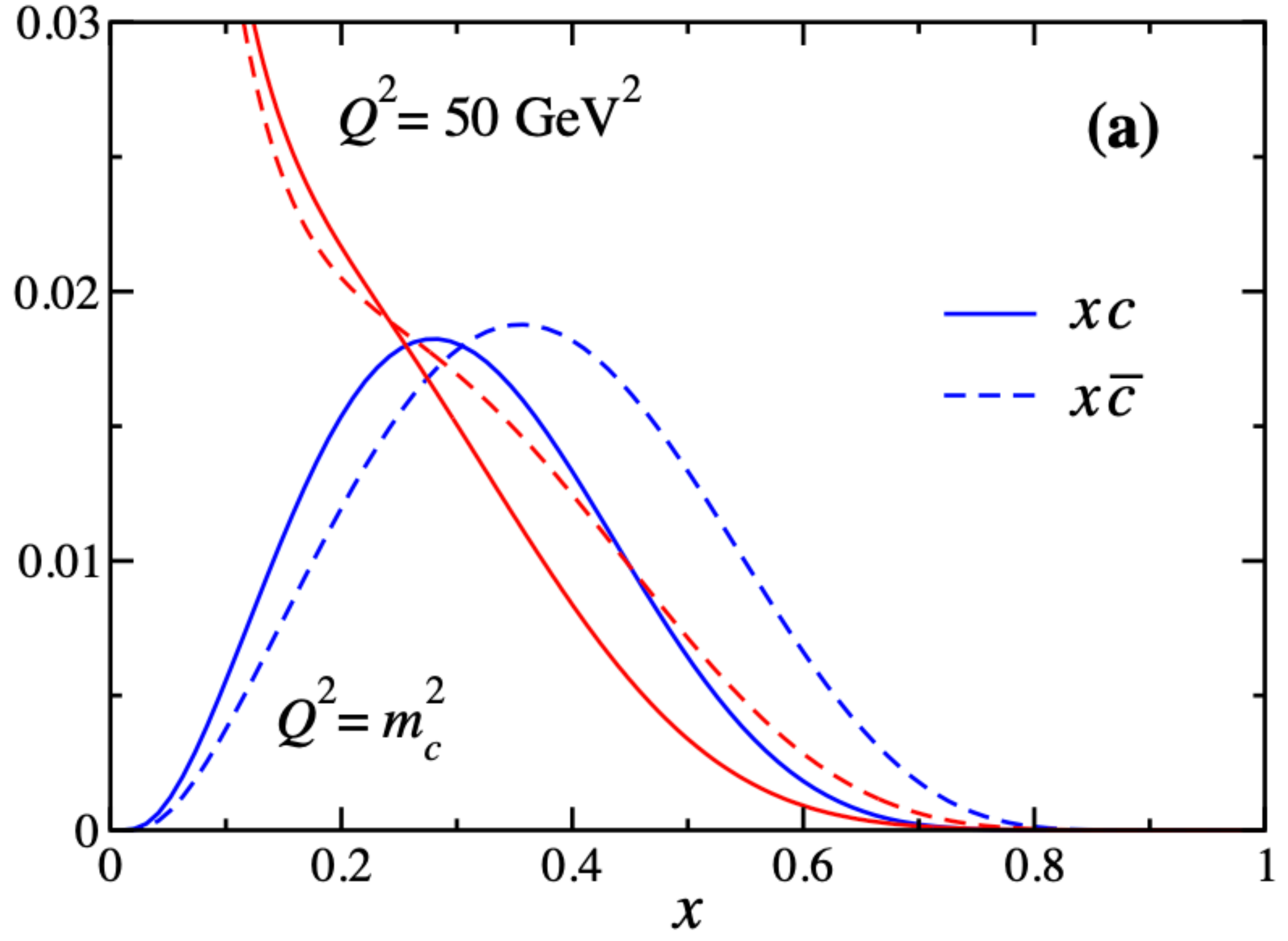




Summary and outlook

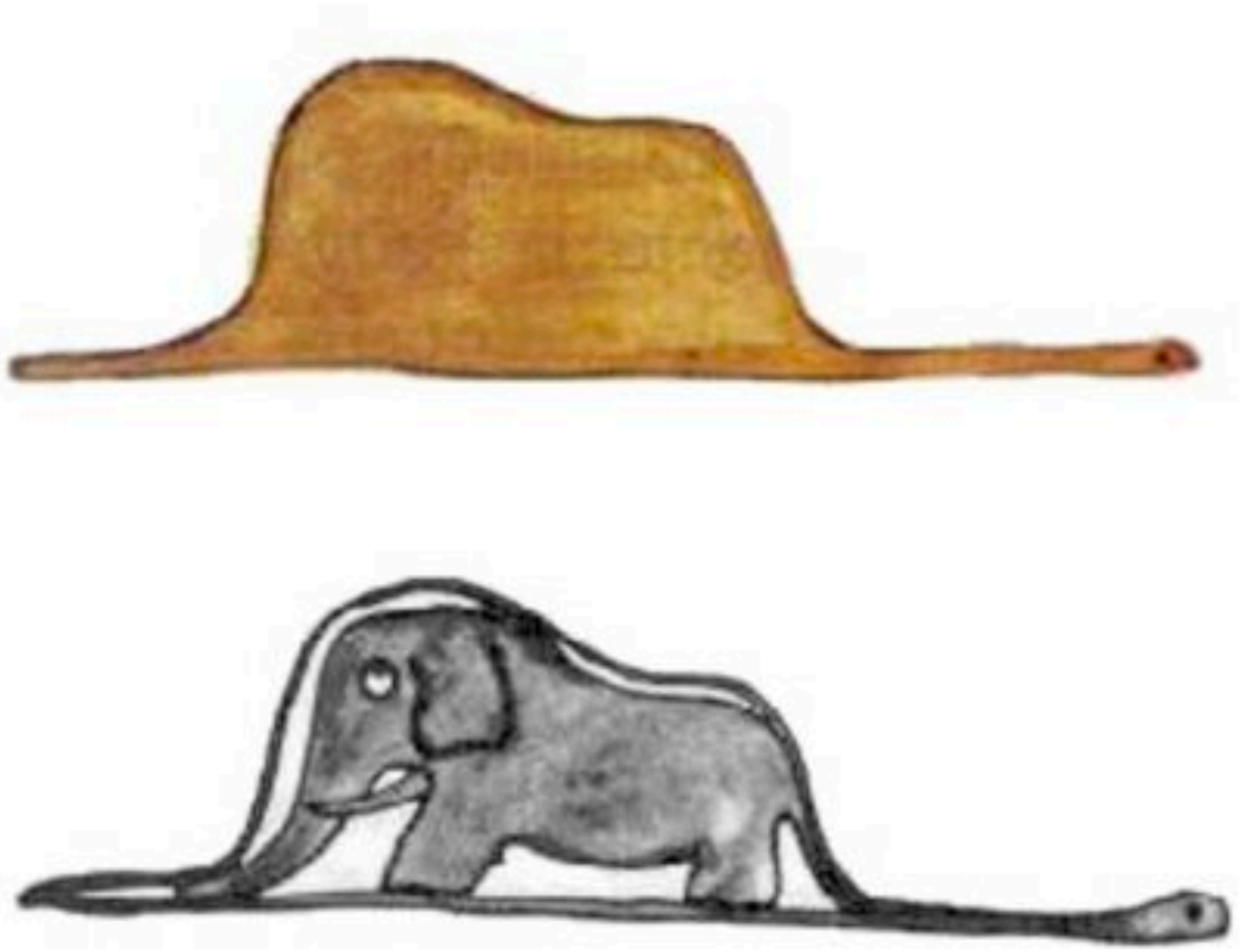
- Evidence of a non zero intrinsic charm c^+ in $n_f = 3$, carrying a momentum fraction total within 1%.
- Our intrinsic charm is in agreement with most recent LHC results.
- Impact of the N3LO matching conditions is relevant. Need to proper quantify MHOU and possibly move towards N3LO pdf fit.
- Is it worth to try a fit with independent c^- parametrisation as suggested by the Meson/Baryon models?





From [arxiv:1311.1578]

“My drawing was not a picture of a hat. It was a picture of a boa constrictor digesting an elephant.”



Thank you!

Backup slides

From 4FNS to 3FNS

The matching conditions

$$\mathbf{A}^{(n_f)}(\mu_h^2) = \mathbf{I} + a_s^{(n_f)}(\mu_h^2)\mathbf{A}^{(n_f),(1)} + a_s^{(n_f),2}(\mu_h^2)\mathbf{A}^{(n_f),(2)} + a_s^{(n_f),3}(\mu_h^2)\mathbf{A}^{(n_f),(3)} + \mathcal{O}(\alpha_s^4)$$

NLO

$$\mathbf{A}^{(n_f),(1)}_{S,h^+} = \begin{pmatrix} A^{S,(1)}_{gg,H} & 0 & A^{S,(1)}_{gH} \\ 0 & 0 & 0 \\ A^{S,(1)}_{Hg} & 0 & A^{(1)}_{HH} \end{pmatrix}$$

$$\mathbf{A}^{(n_f),(1)}_{nsv,h^-} = \begin{pmatrix} 0 & 0 \\ 0 & A^{(1)}_{HH} \end{pmatrix}$$

NNLO

$$\mathbf{A}^{(n_f),(2)}_{S,h^+} = \begin{pmatrix} A^{S,(2)}_{gg,H} & A^{S,(2)}_{gq,H} & 0 \\ 0 & A^{ns,(2)}_{qq,H} & 0 \\ A^{S,(2)}_{Hg} & A^{ps,(2)}_{Hq} & 0 \end{pmatrix}$$

$$\mathbf{A}^{(n_f),(2)}_{nsv,h^-} = \begin{pmatrix} A^{ns,(2)}_{qq,H} & 0 \\ 0 & 0 \end{pmatrix}$$

N3LO

$$\mathbf{A}^{(n_f),(3)}_{S,h^+} = \begin{pmatrix} A^{S,(3)}_{gg,H} & A^{S,(3)}_{gq,H} & 0 \\ A^{S,(3)}_{qg,H} & A^{ns,(3)}_{qq,H} + A^{ps,(3)}_{qq,H} & 0 \\ A^{S,(3)}_{Hg} & A^{ps,(3)}_{Hq} & 0 \end{pmatrix}$$

$$\mathbf{A}^{(n_f),(3)}_{nsv,h^-} = \begin{pmatrix} A^{ns,(3)}_{qq,H} & 0 \\ 0 & 0 \end{pmatrix}$$

Inversion can be computed exactly or expanding in α_s:

$$\mathbf{A}^{-1}_{exp}(\mu_h^2) = \mathbf{I} - a_s(\mu_h^2)\mathbf{A}^{(1)} + a_s^2(\mu_h^2)\left[\mathbf{A}^{(2)} - \left(\mathbf{A}^{(1)}\right)^2\right] + a_s^3(\mu_h^2)\left[-\mathbf{A}^{(3)} + 2\mathbf{A}^{(1)}\mathbf{A}^{(2)} - \left(\mathbf{A}^{(1)}\right)^3\right] + O(a_s^4)$$

3FNS stability and accuracy

The EKO closure test

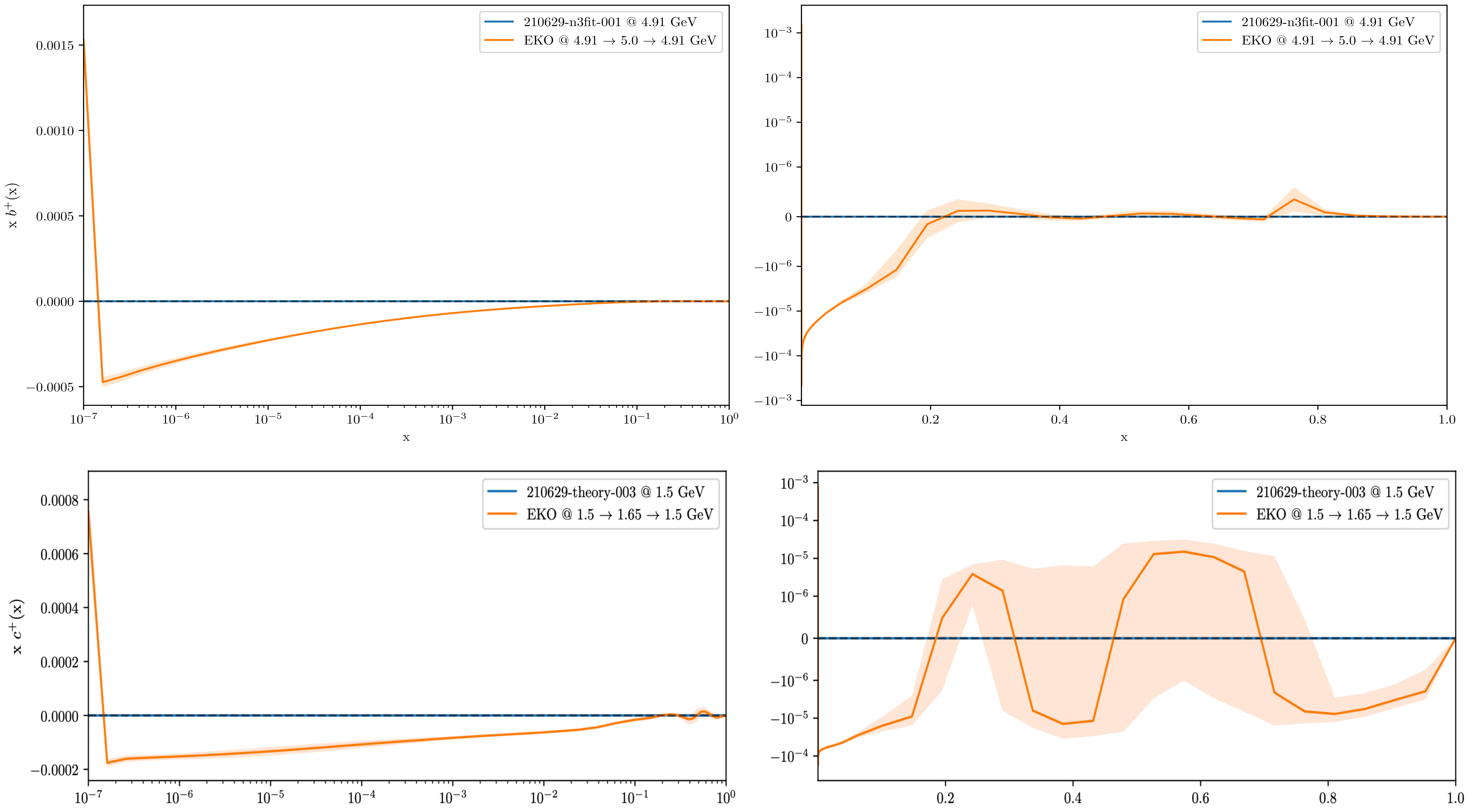
$$\tilde{\mathbf{f}}(Q^0) = \tilde{\mathbf{E}}(Q^0 \leftarrow Q) \cdot \tilde{\mathbf{E}}(Q \leftarrow Q^0) \cdot \tilde{\mathbf{f}}(Q^0) \ ??$$

Low x

High x

$Q_0 = m_b$

$Q_0 = m_c$



Numerical accuracy is:

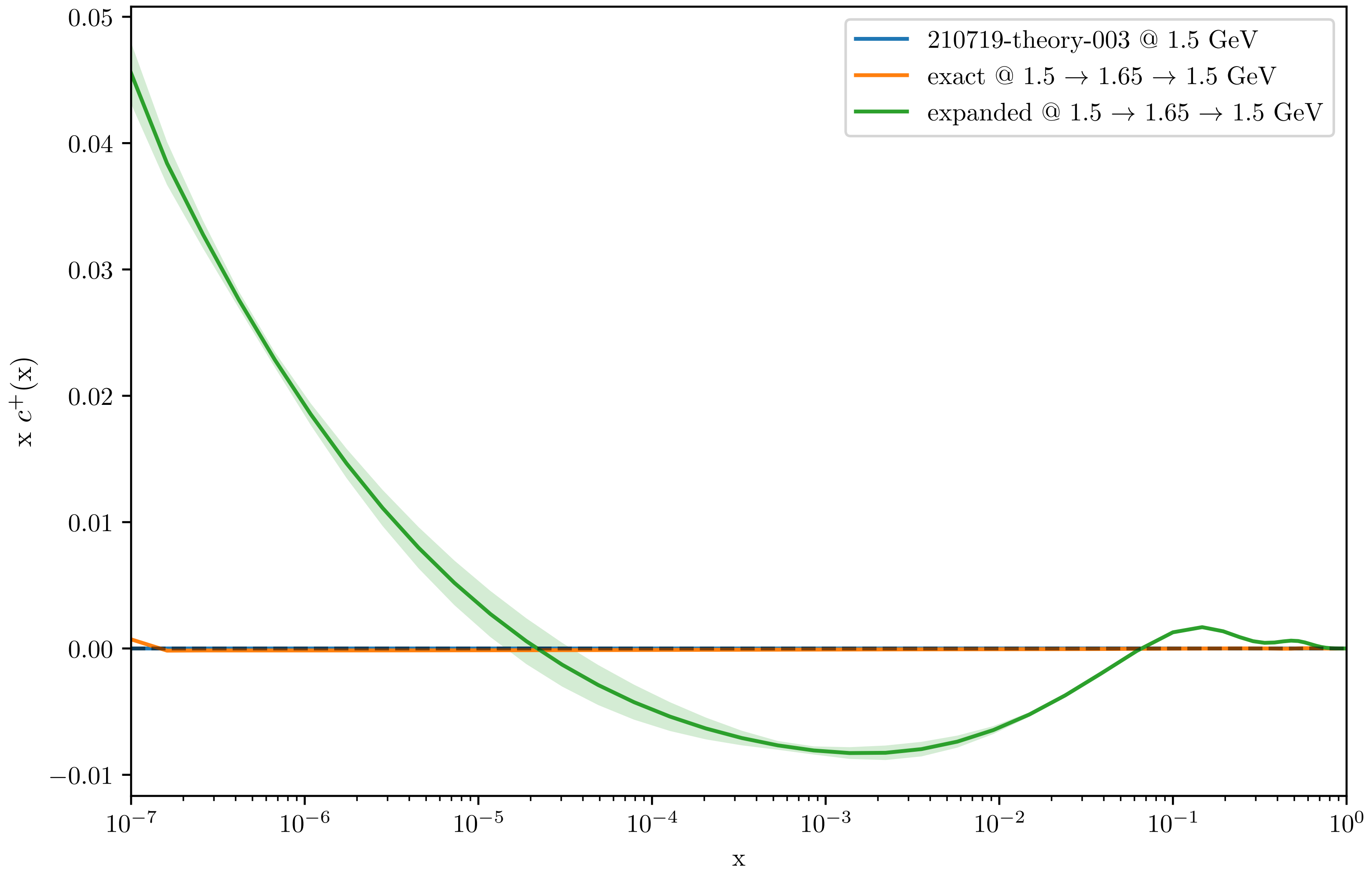
$\approx 2 \cdot 10^{-4}$ at *low x*

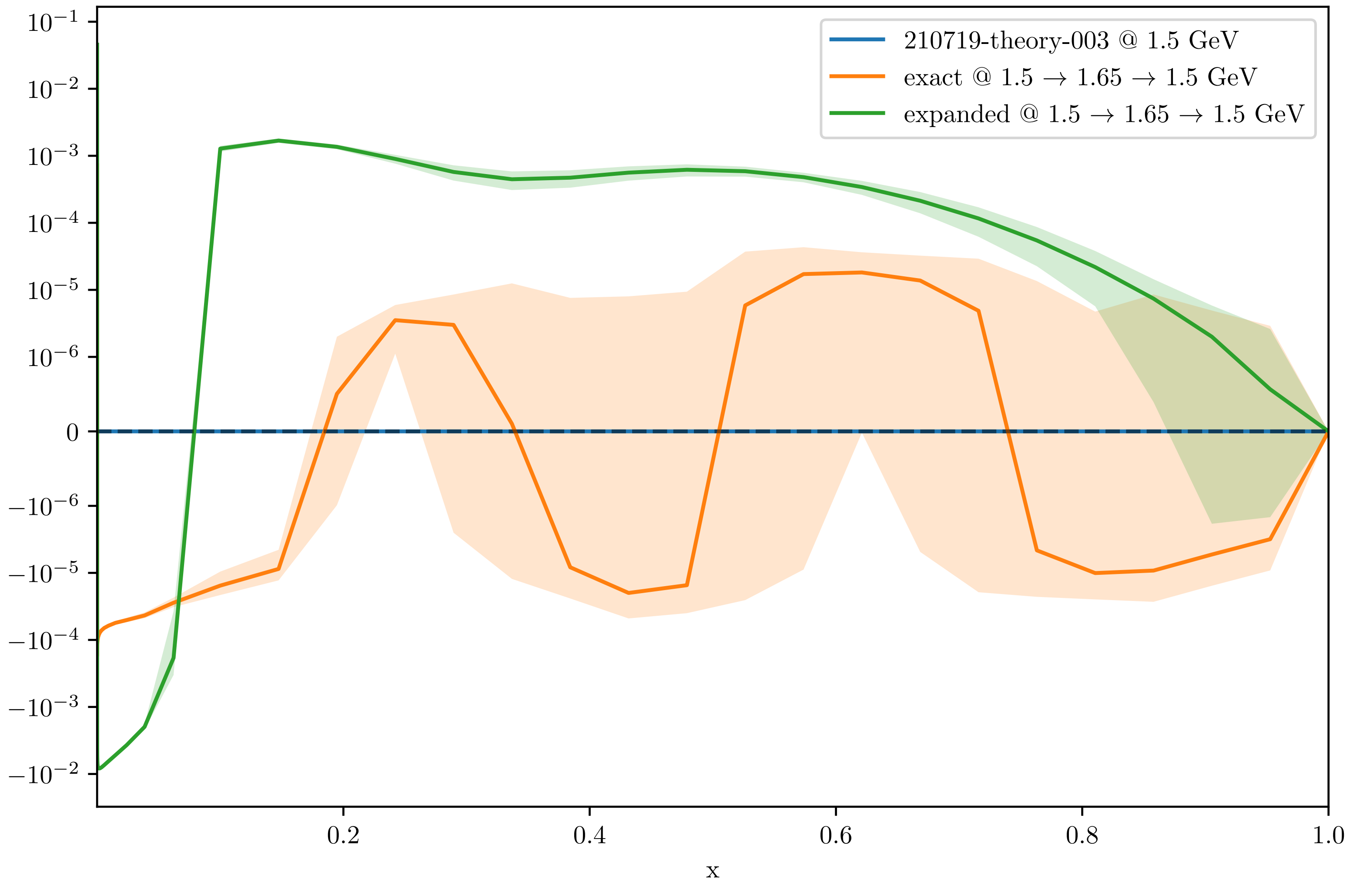
$\approx 10^{-5}$ for *high x* region

3FNS stability and accuracy

Exact vs Expanded inversion

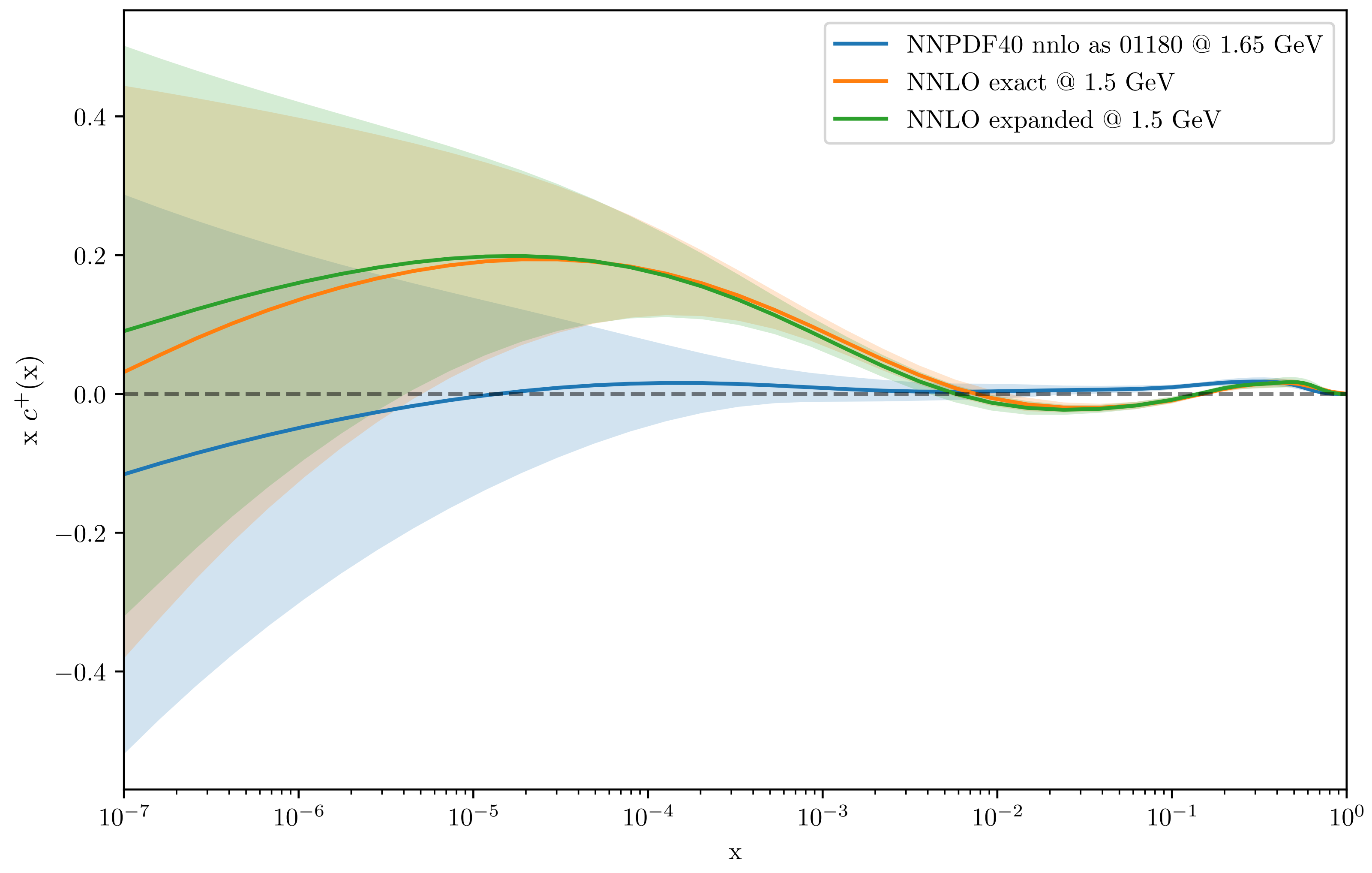
- [210719-theory-003]() = NNPDF4.0 pch

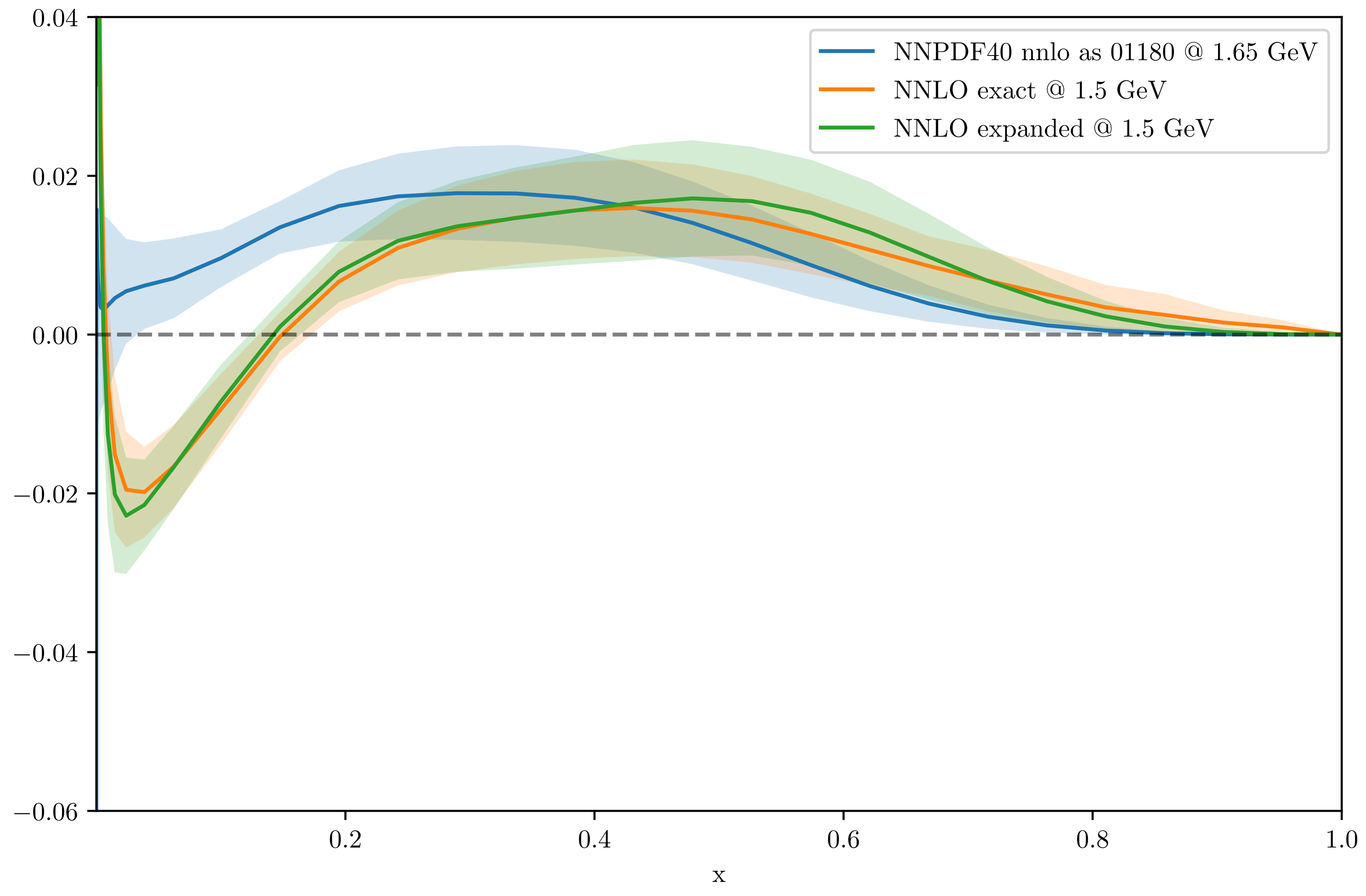




Low x

High x





- **Exact**: the matching matrices are inverted exactly in N-space, and then integrated entry by entry

- **Expanded**: the matching matrices are inverted through a perturbative expansion in α_s before the Mellin inversion:

The Intrinsic charm

Low x