INTRINSIC CHARM IN THE PROTON

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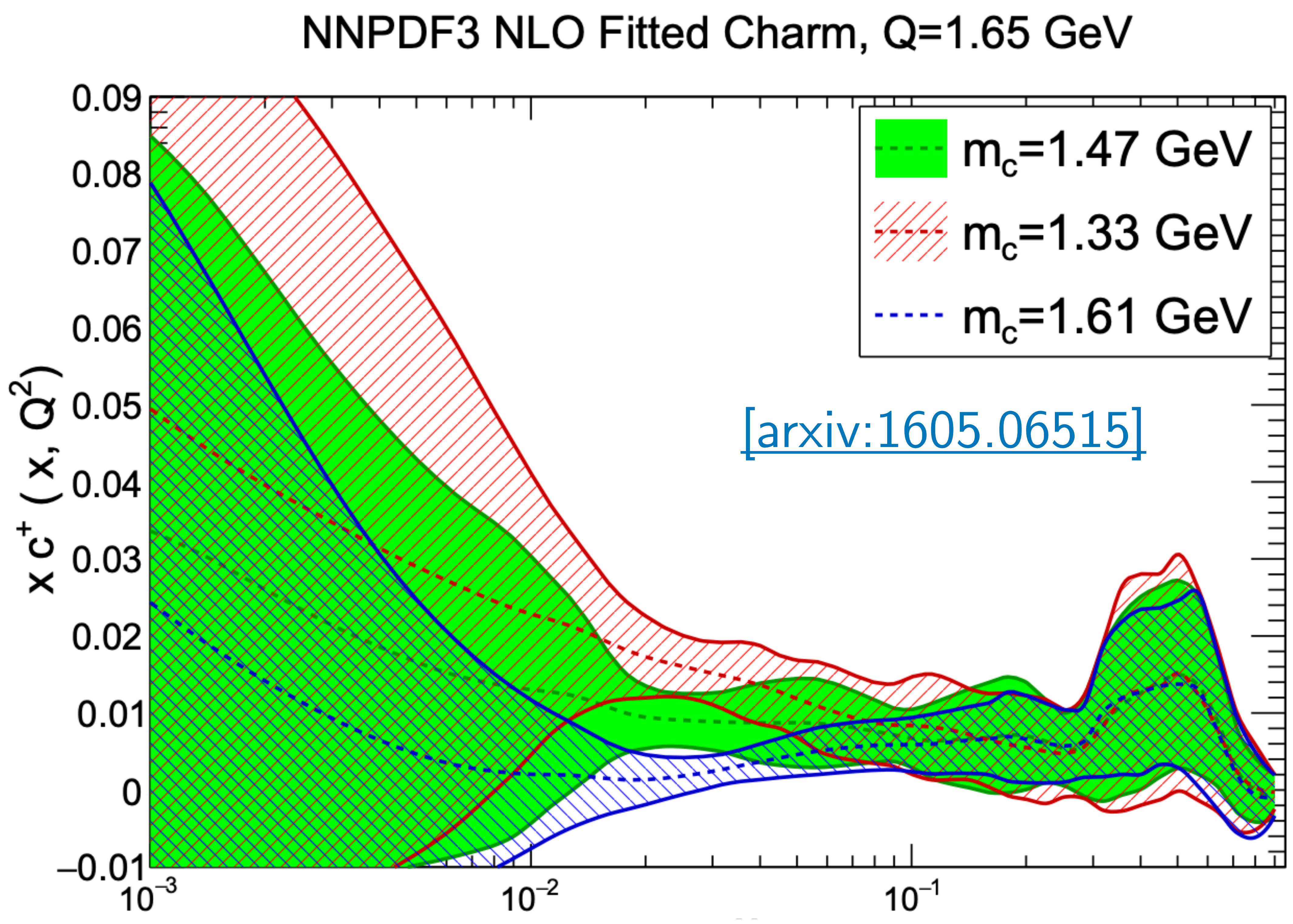
Introduction & Motivation

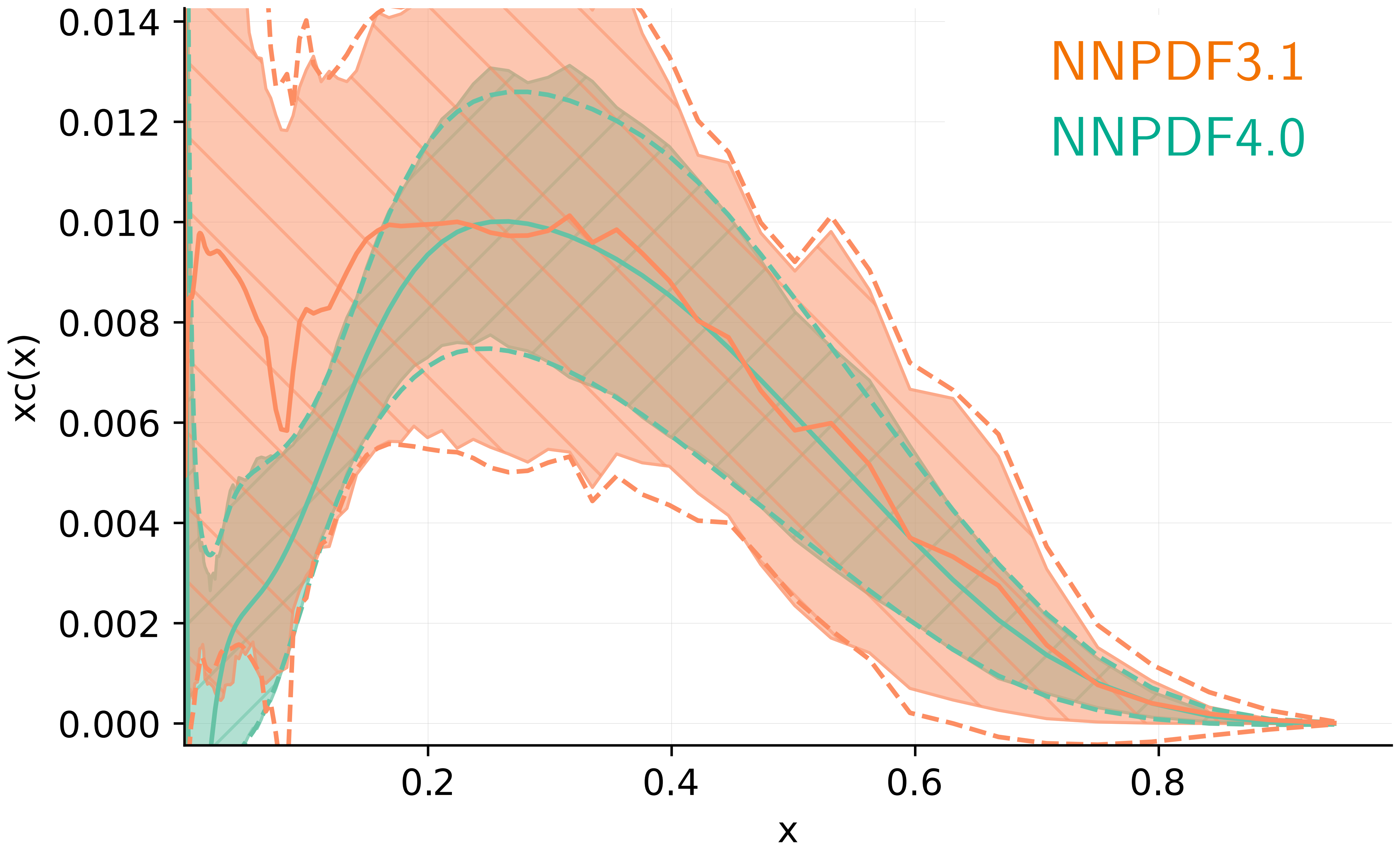
Do heavy quarks contribute to the proton PDFs at low scales?

- 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"
  [Ball, Candido, Cruz-Martinez, Forte, Giani, Hekhorn, Kudashkin, Magni, Rojo] *(in preparation)*

- Results are based on the NNPDF4.0 [arxiv:2109.02653]: great progress in the charm determination in the last years: both in the fitting framework and in number of included datapoints.



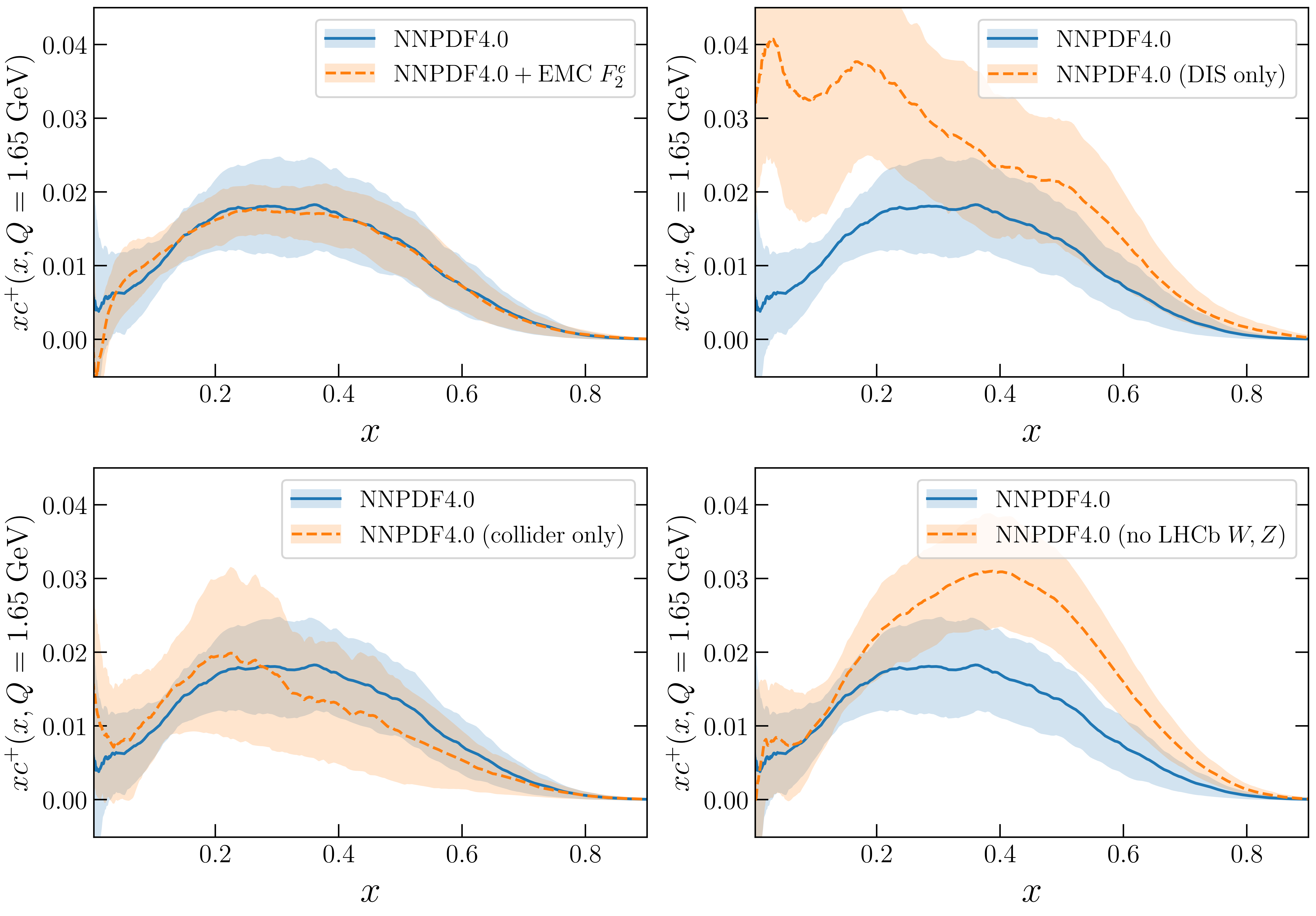


The charm PDF

NNPDF4.0 baseline

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

- The charm PDF is parametrised as an independent combination at scale $Q_0 = 1.65\ GeV$, and $n_f = 4$ *(4FNS)*
- 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
- NNPDF4.0 is consistent with EMC data.



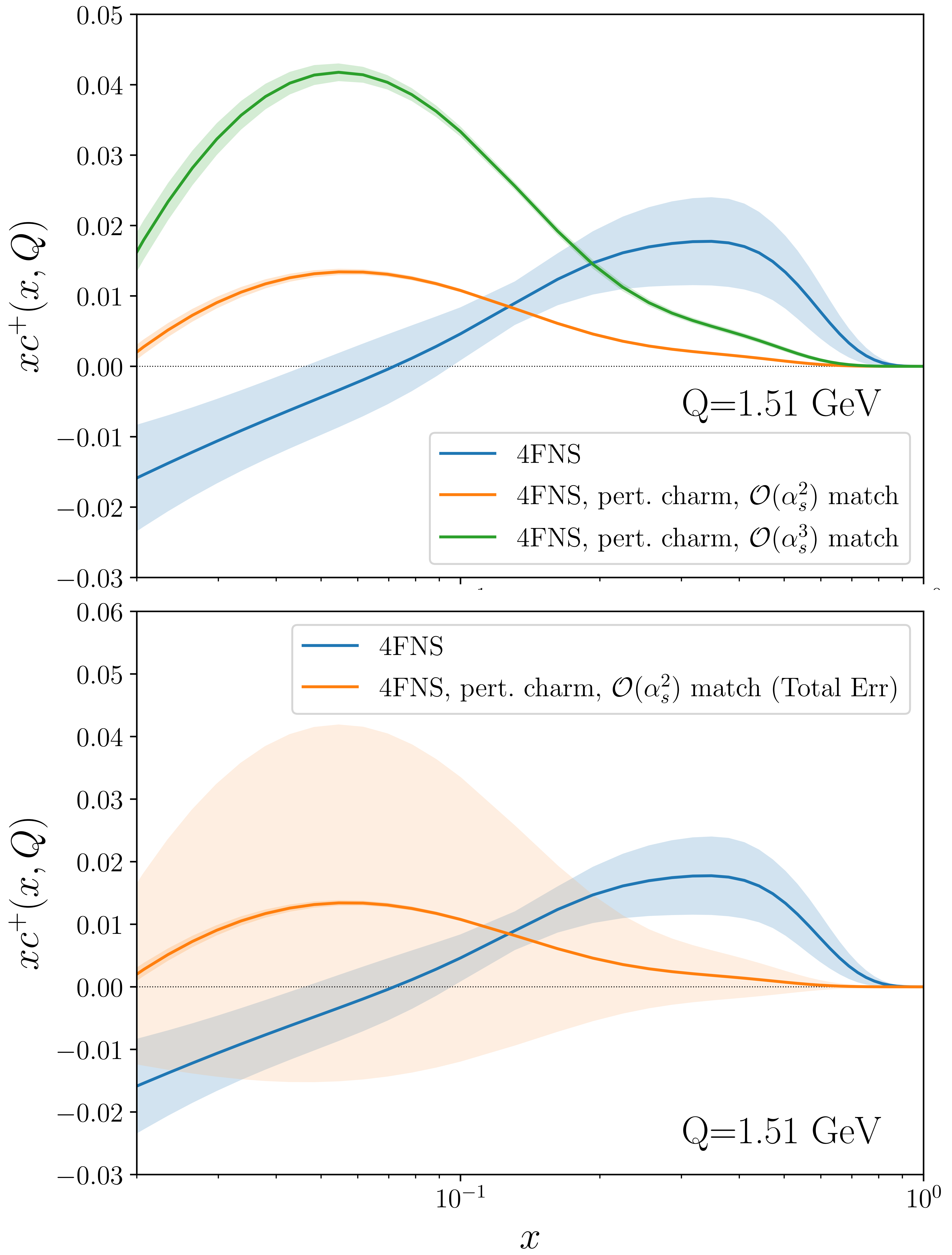
Why do we need fitted charm?

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...

- $\chi^2_{fitted\ ch.} = 1.17 \rightarrow \chi^2_{pert\ ch.} = 1.19$ mainly due to a worsening of the LHC W, Z and top pair data sets
- Fully perturbative charm is not compatible with the fitted one.



Why do we need fitted charm?

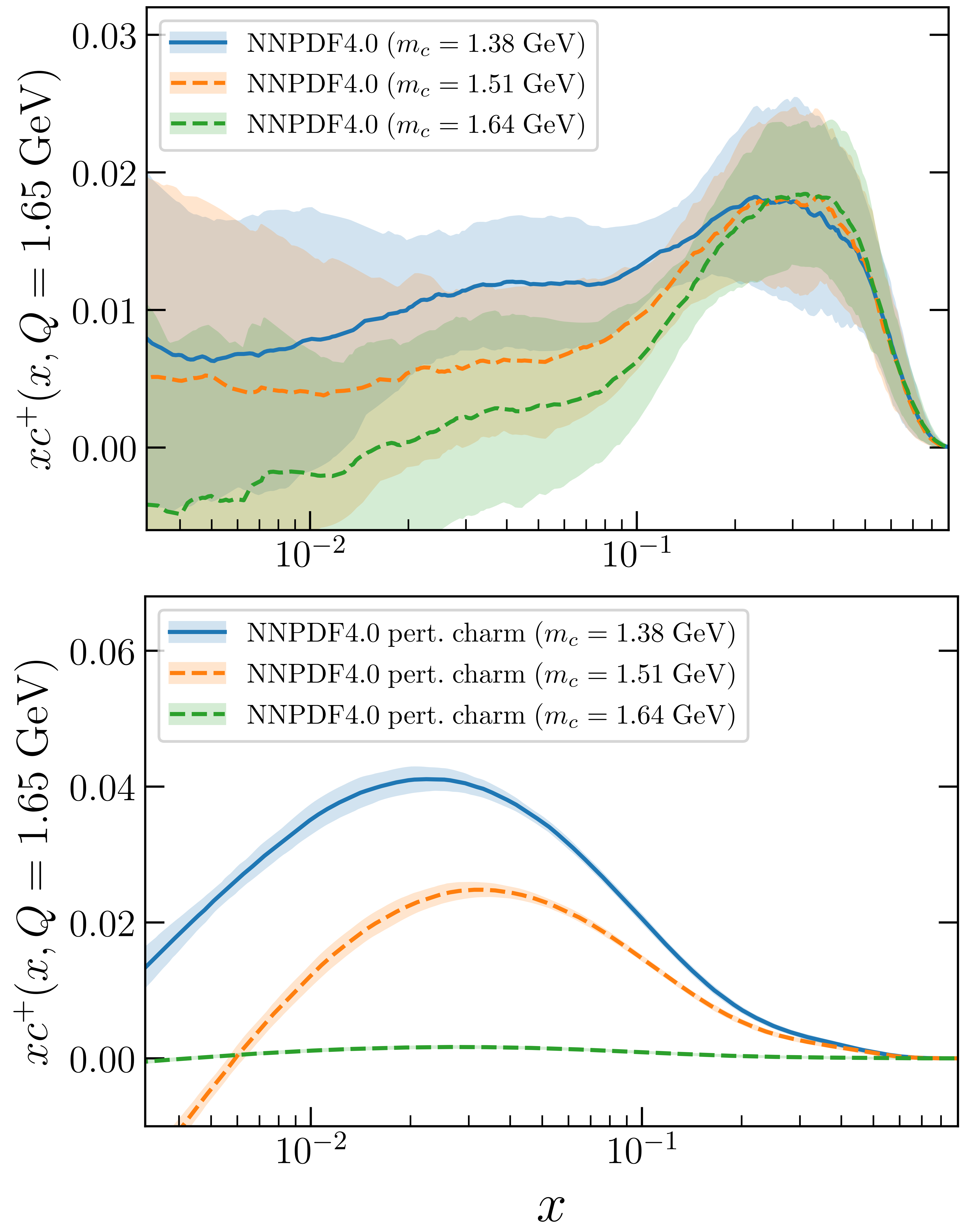
Mass dependence

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

- Charm mass is varied in the range:

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

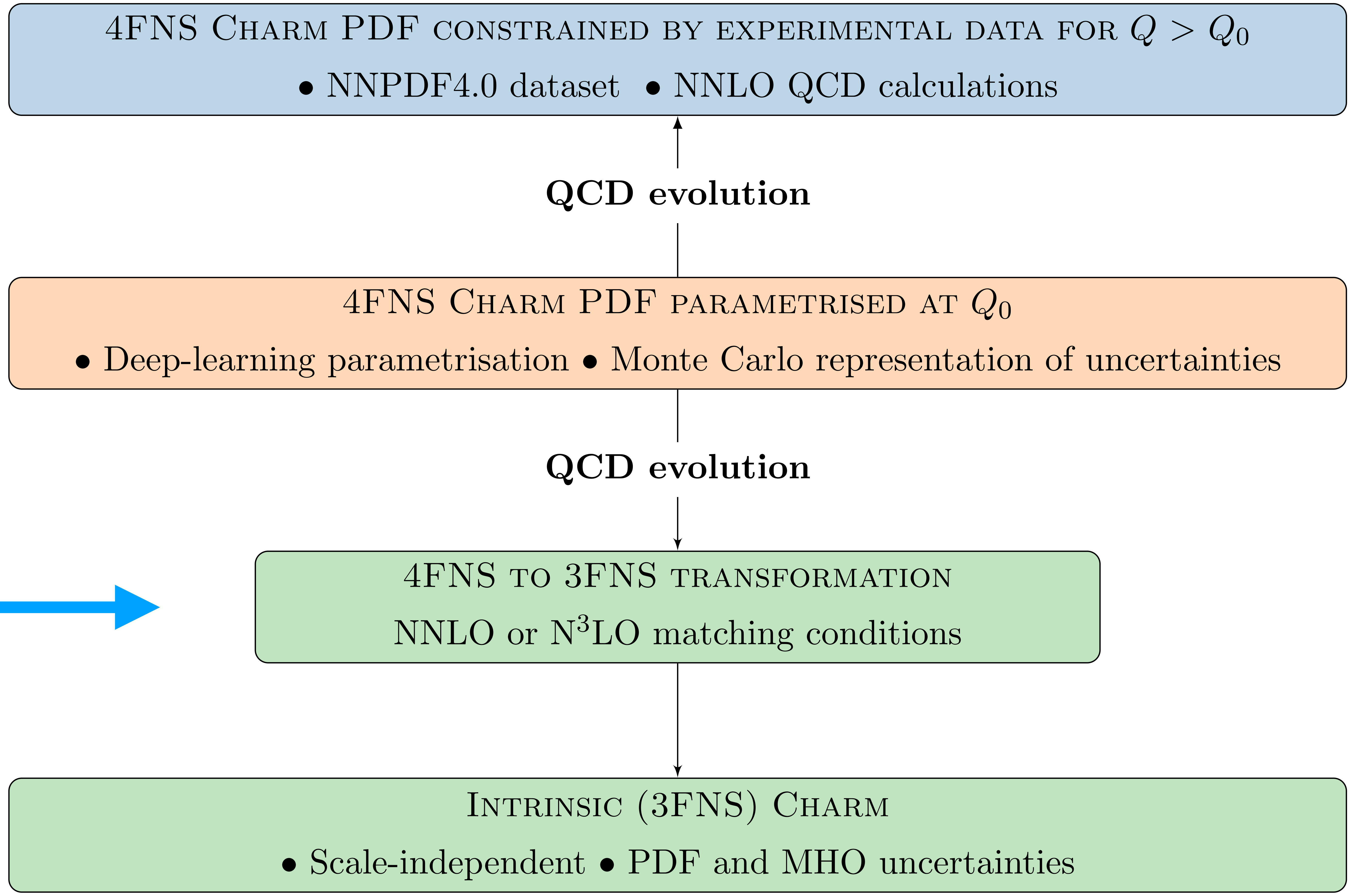
- The fitted charm is much more stable upon mass variation especially in the *high-x* region compared to the perturbative one.



The Intrinsic charm scenario

From 4FNS to 3FNS

- Below the charm mass scale the perturbative charm is vanishing by definition
- Fitted charm in *4FNS* contains both the intrinsic and the perturbative components.
- Need to determine the *3FNS* charm PDF



A brief digression on DGLAP

DGLAP evolution with EKO

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

Evolution Kernel Operators

[arxiv:2202.02338]

- 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:

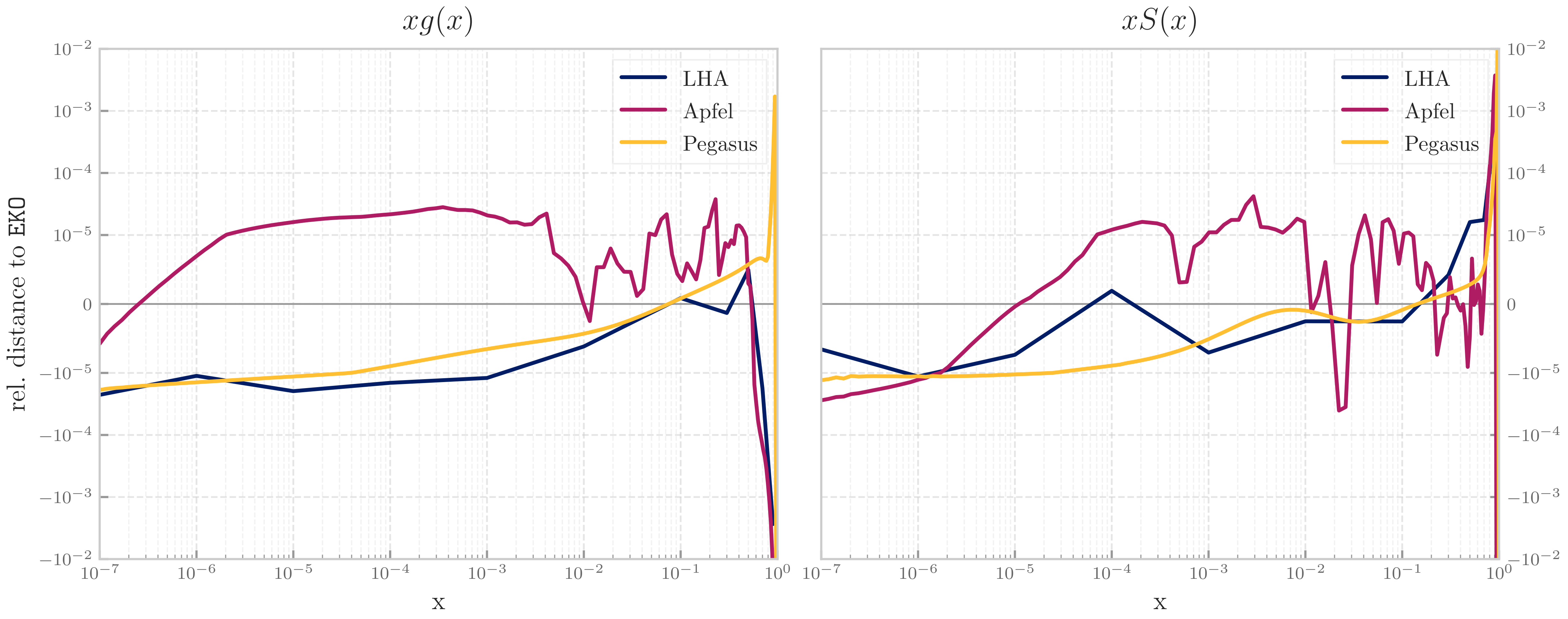
$$\mathbf{f}(x_k, a_s) = \mathbf{E}_{k,j}(a_s \leftarrow a_s^0)\mathbf{f}(x_j, a_s^0)$$

- 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 ....
  documentation

LHA Benchmark comparison



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*$^{(nf+1)}$

- In FFNS there are no difference between forward and backward evolution (just swap the integration bounds)
- The OME depends on $\alpha_s^{n_f+1}(\mu_h^2)$ and on $log(\mu_h^2/m_h^2)$
- OME are available up to N^{3}LO (*NLO for heavy quark entries*)

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

The **Operator Matrix Elements:**

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

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

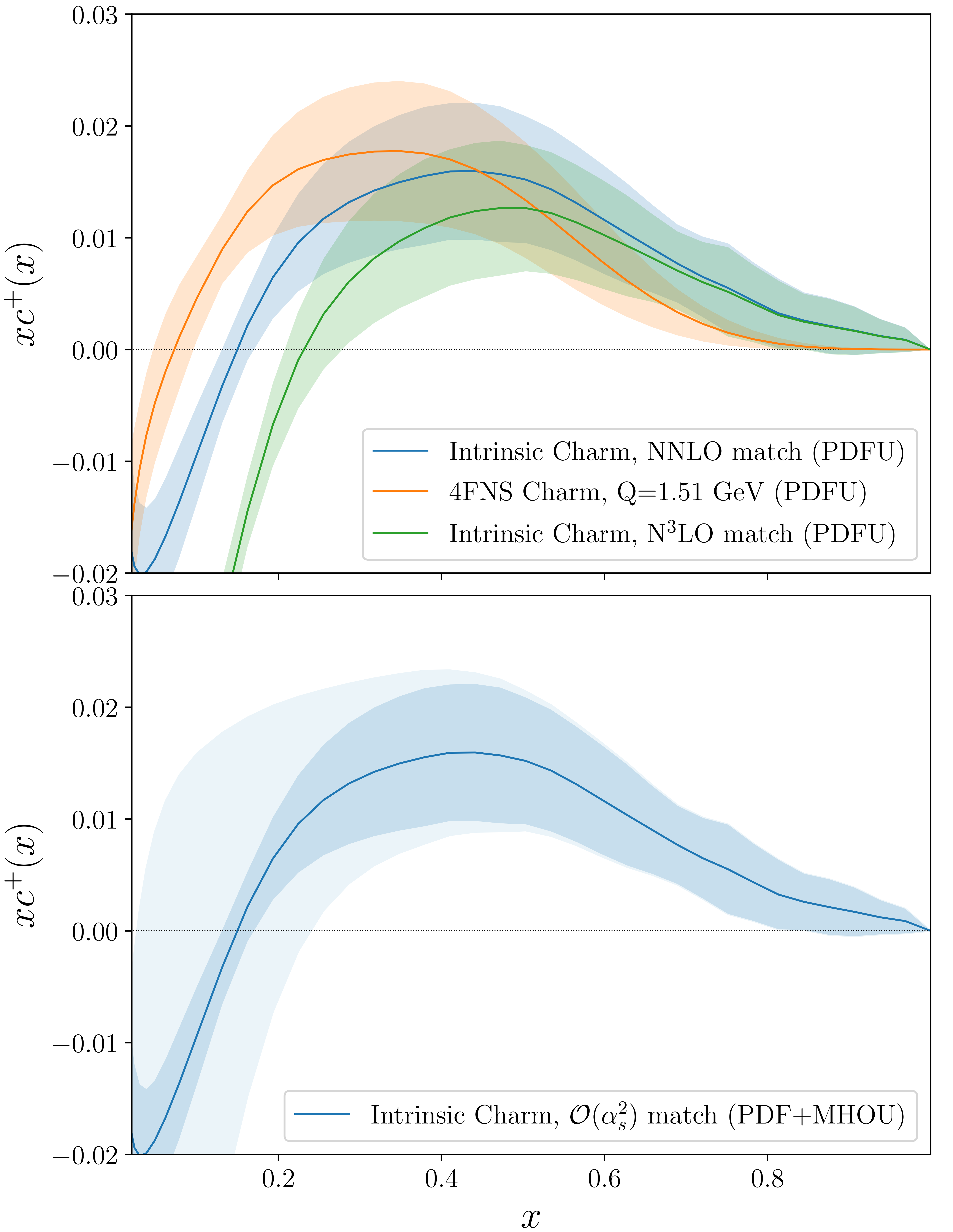
[Eur.Phys.J.C 1 (1998) 301-320,
Phys.Lett.B 754 (2016) 49-58,
Nucl.Phys.B 820 (2009) 417-482 et al.]

Intrinsic charm

- 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:**

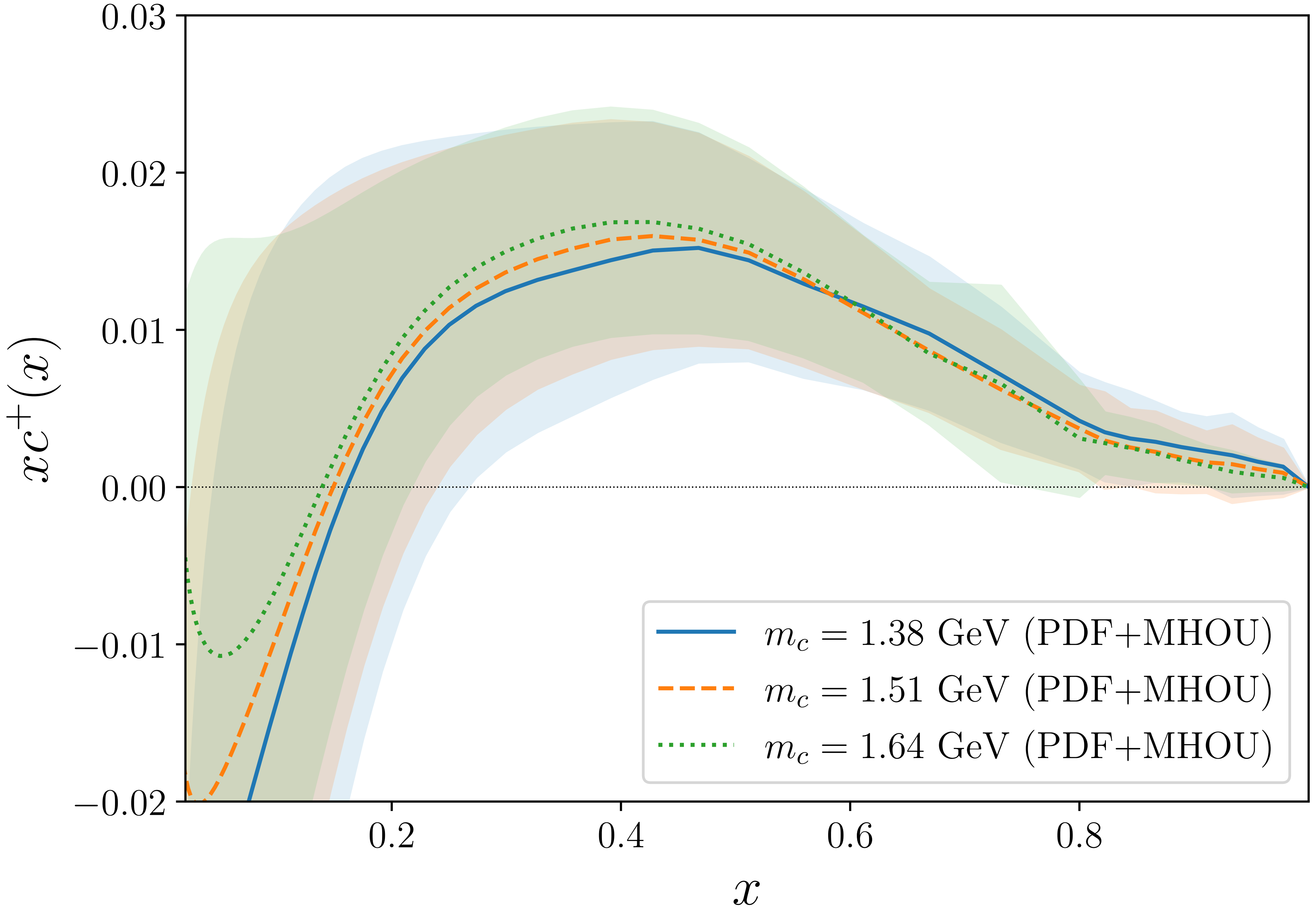
- The *valence-like* peak is still present.
- For $x \leq 0.2$ the perturbative uncertainties are quite large
- The carried momentum fraction is within 1%

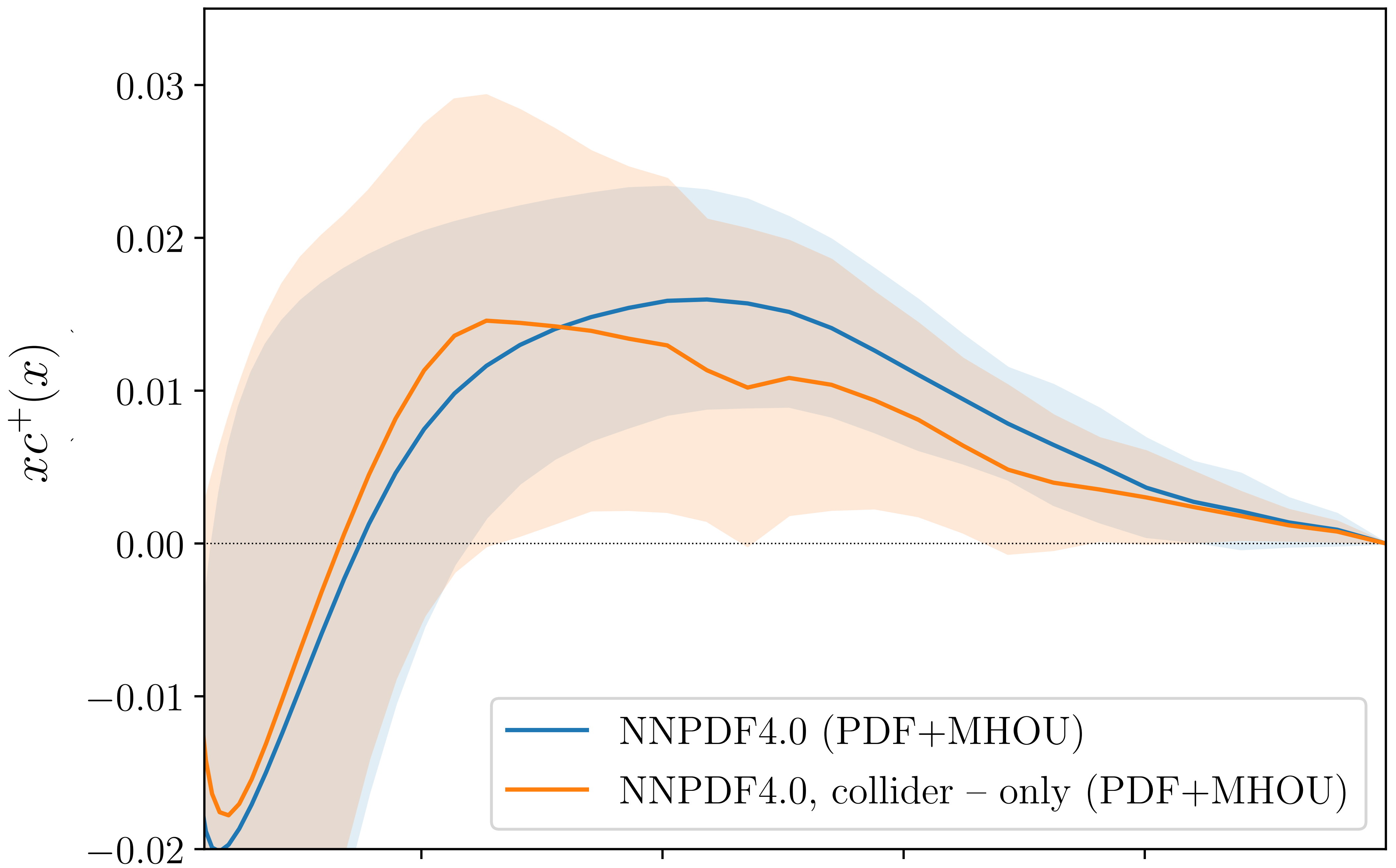


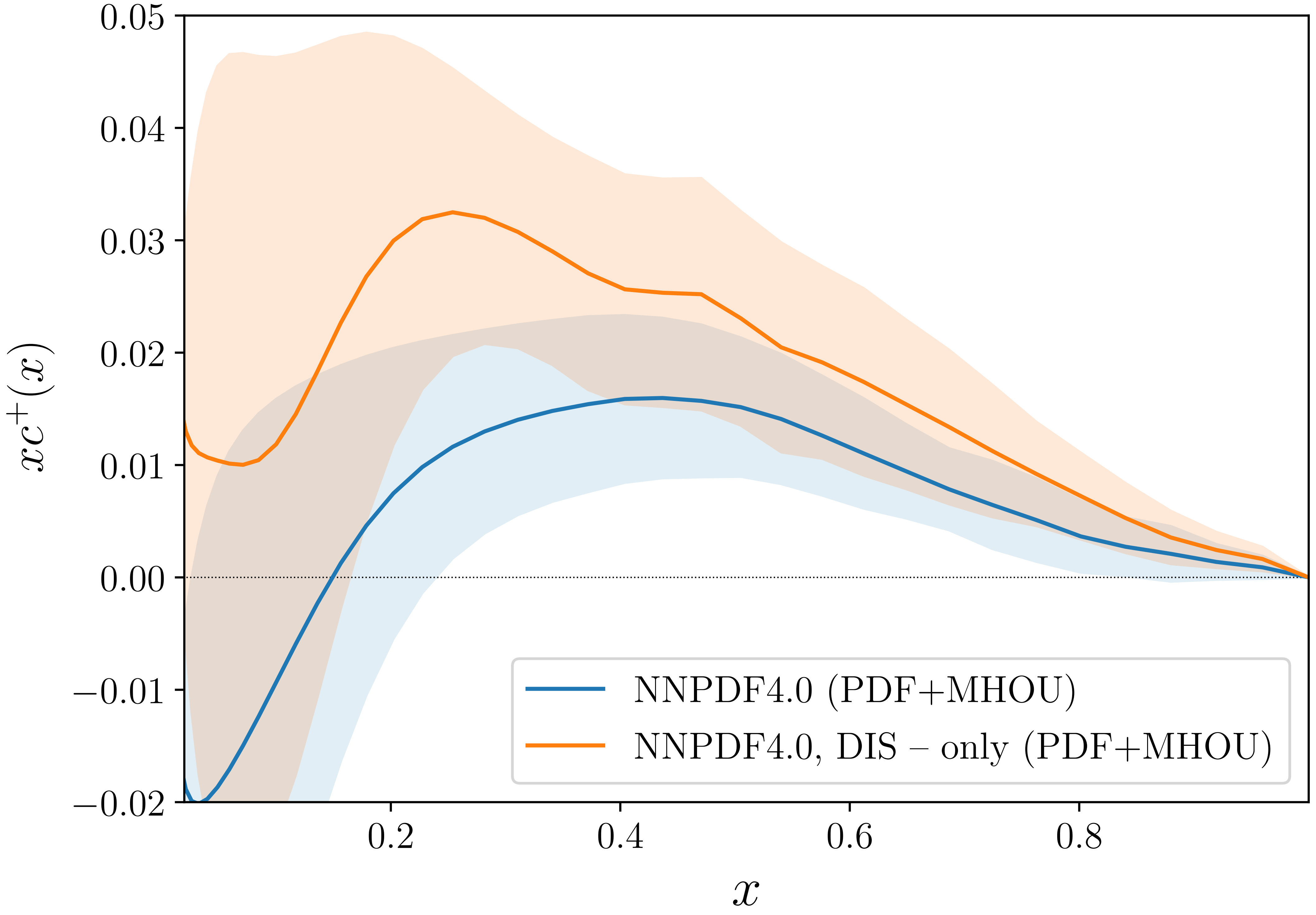
Intrinsic charm stability and accuracy

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-N^{3}LO matching







The Intrinsic charm

Comparison with Models

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

  $p \to uudc\bar{c}$

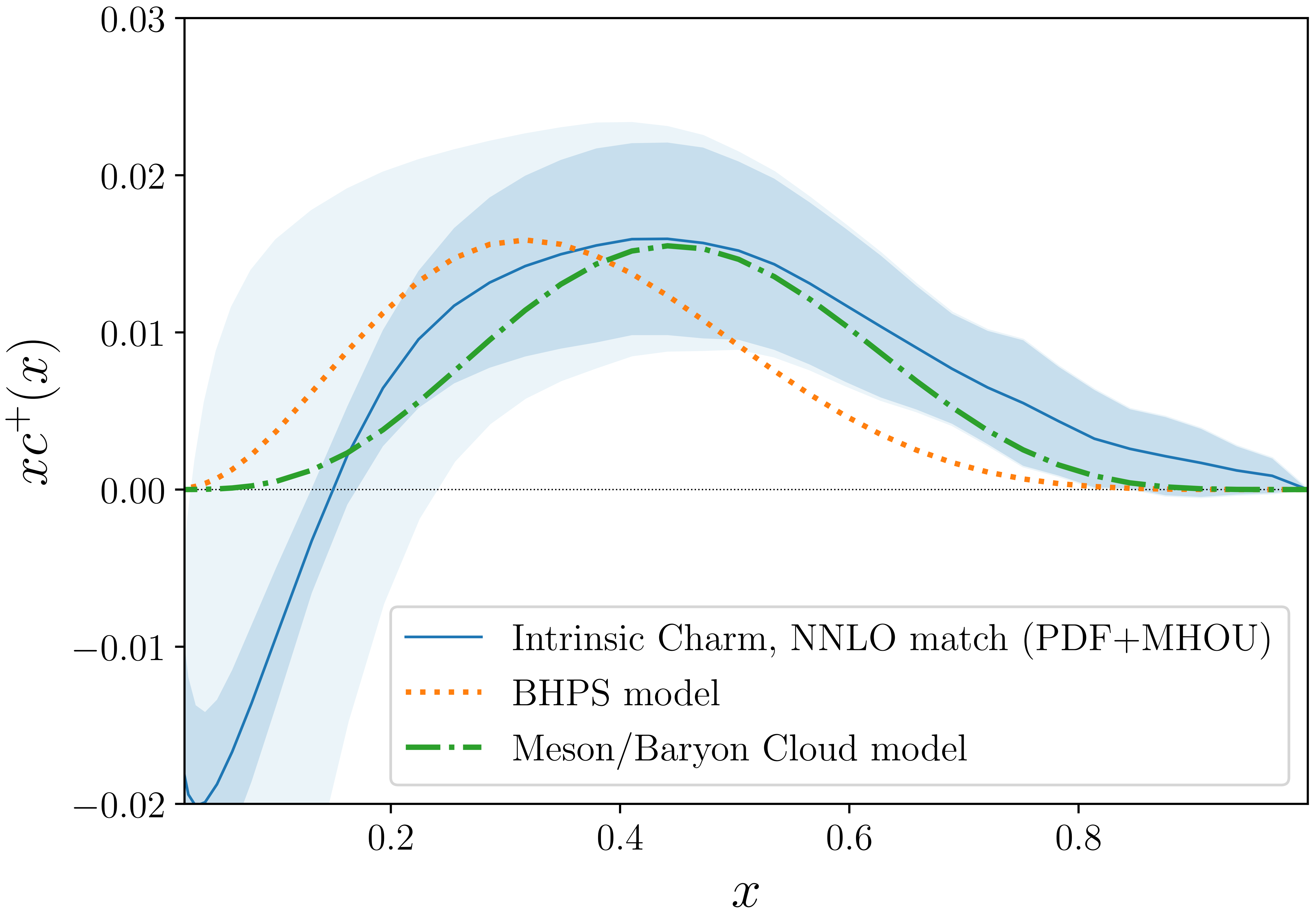
  $$xc^+ = \frac{1}{2}Nx^3[\frac{1}{3}(1-x)(1+10x+x^2)+2x(1+x^2)\ln(x)]$$

- **Meson Baryon** model: [arxiv:1311.1578]

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

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

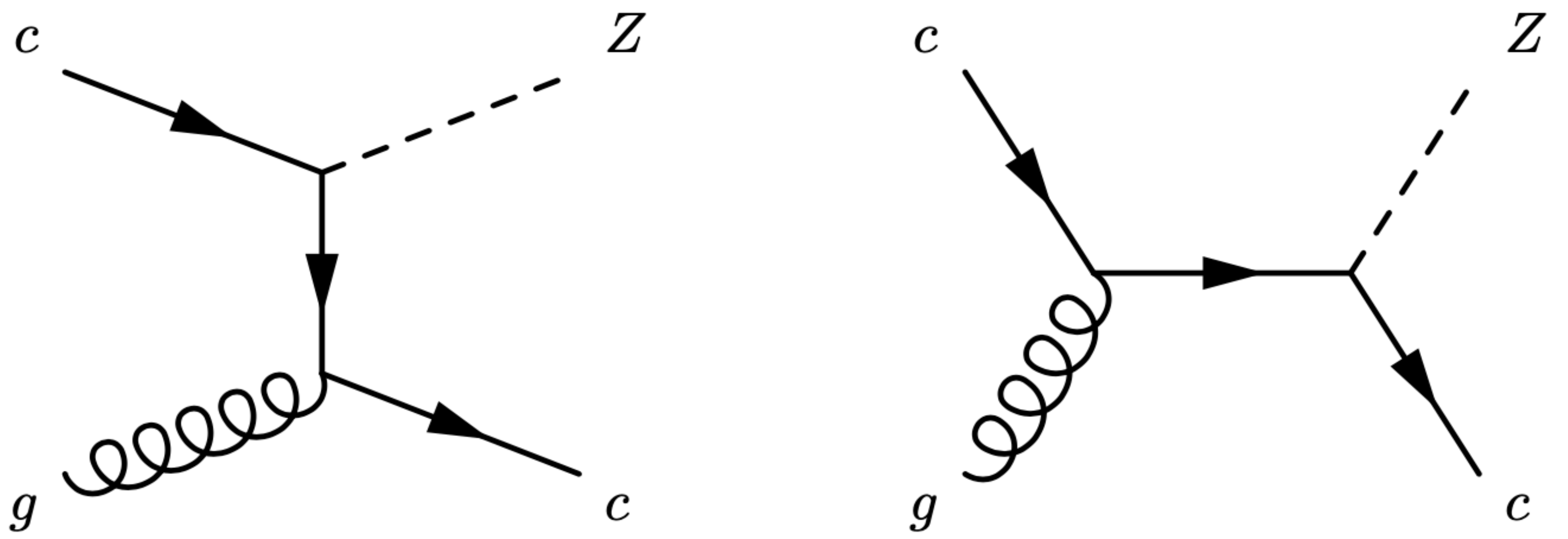
- $\bar{c} = c$ by assumption in BHPS, not true in M/B models.
- Work in the limit $m_c \gg m_p$



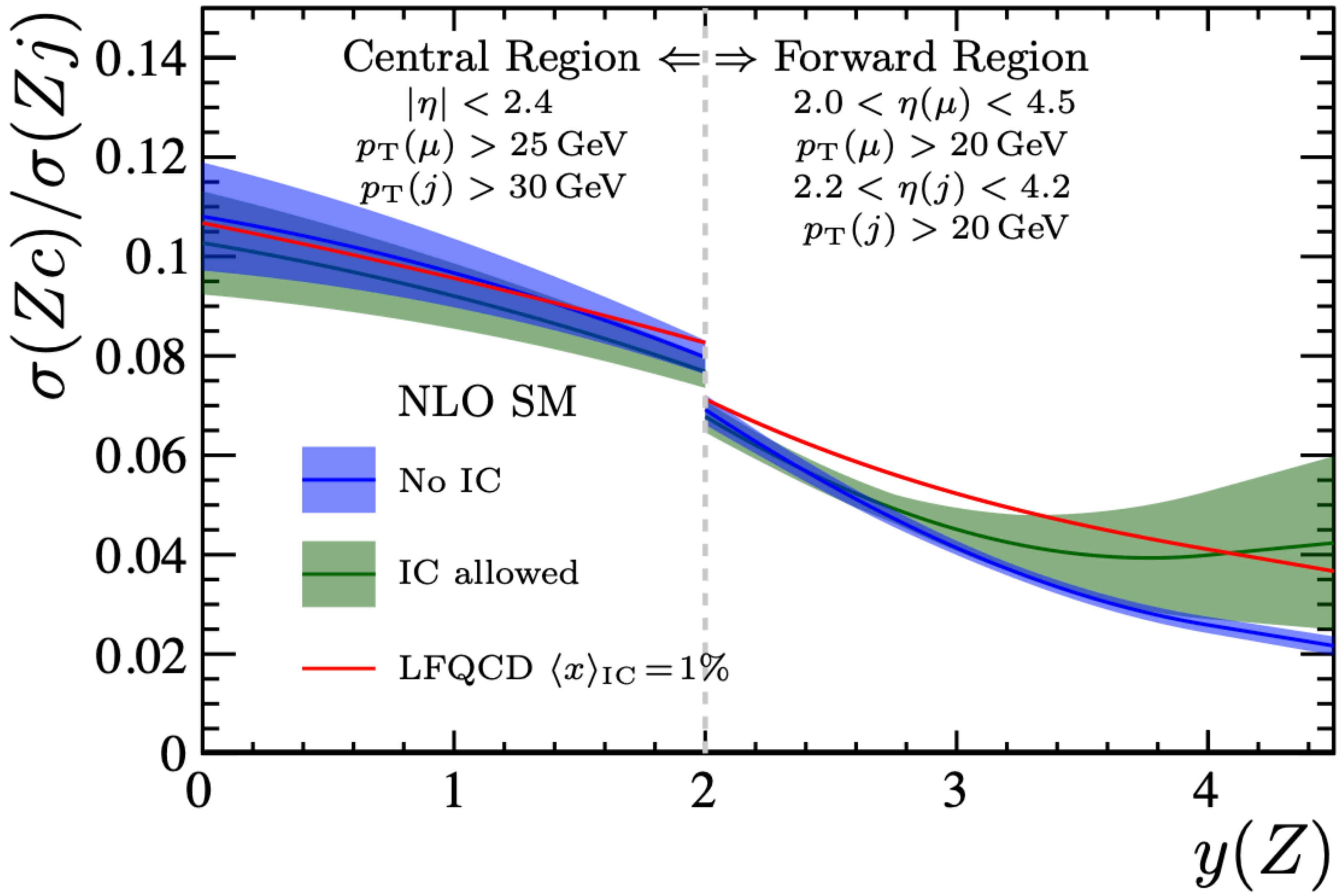
Impact on LHC observables

Z+charm production @ LHCb

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



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



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

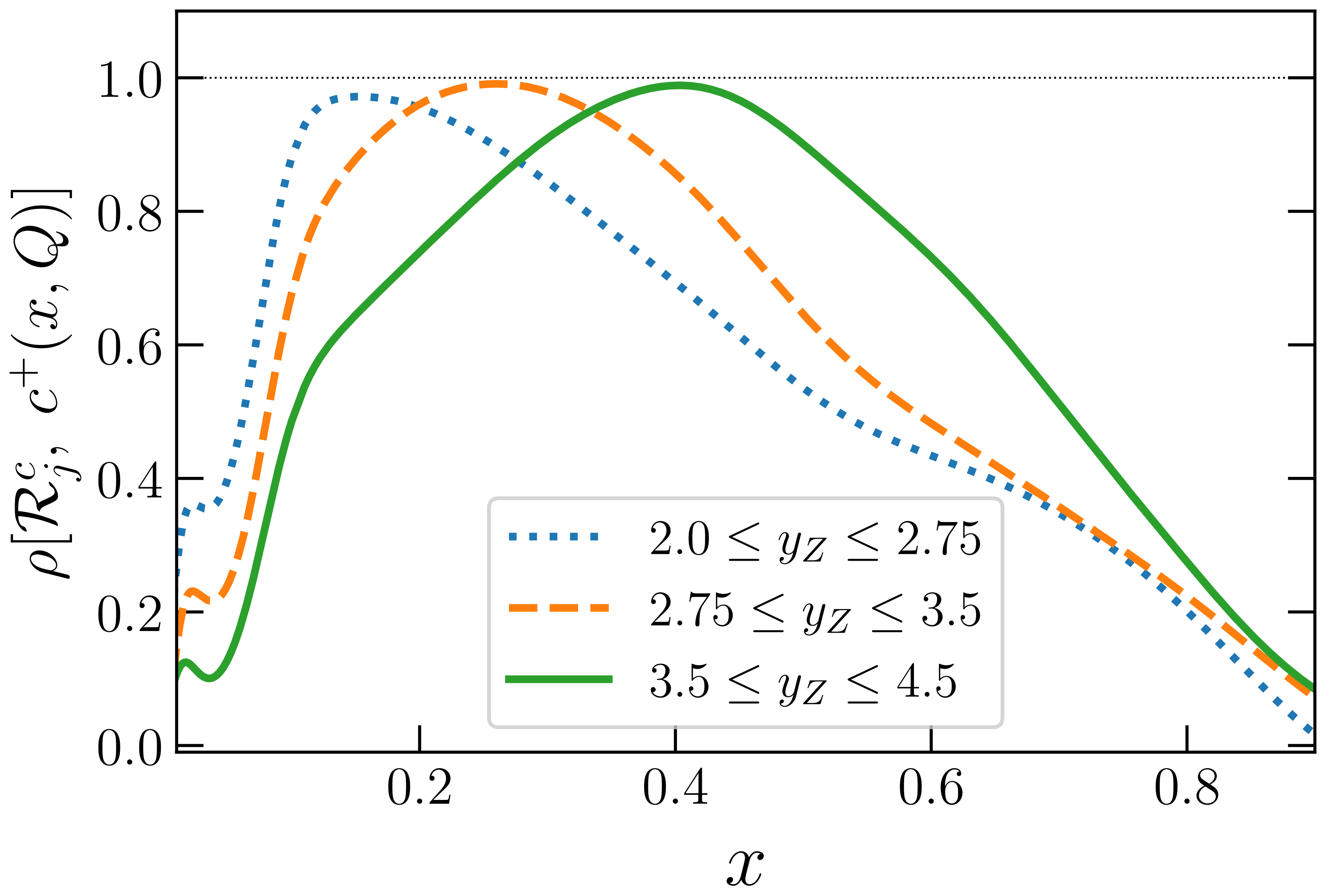
Stat Syst

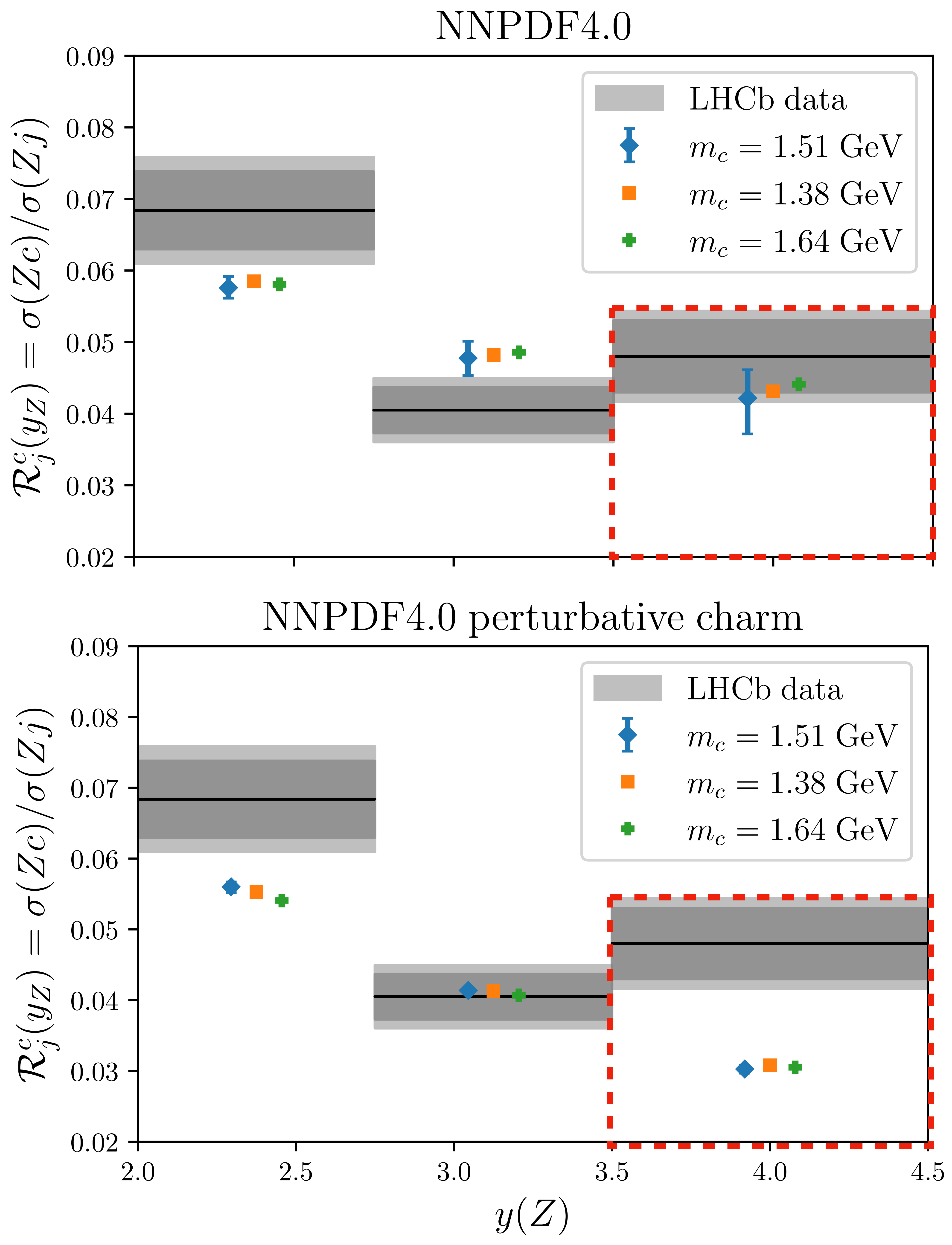
Impact on LHC observables

Z+charm production @ LHCb

Compare data to *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

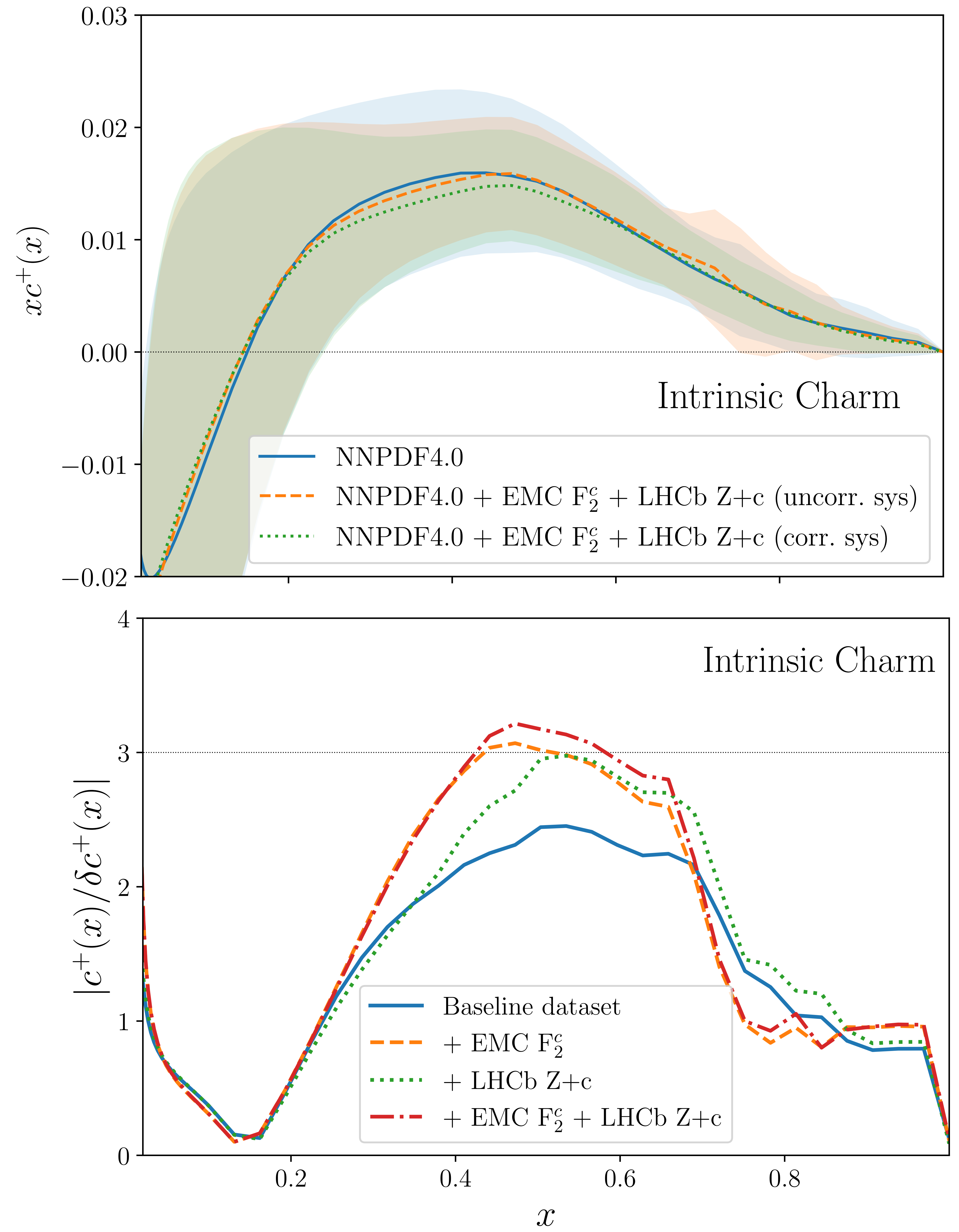
Our current best estimation

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

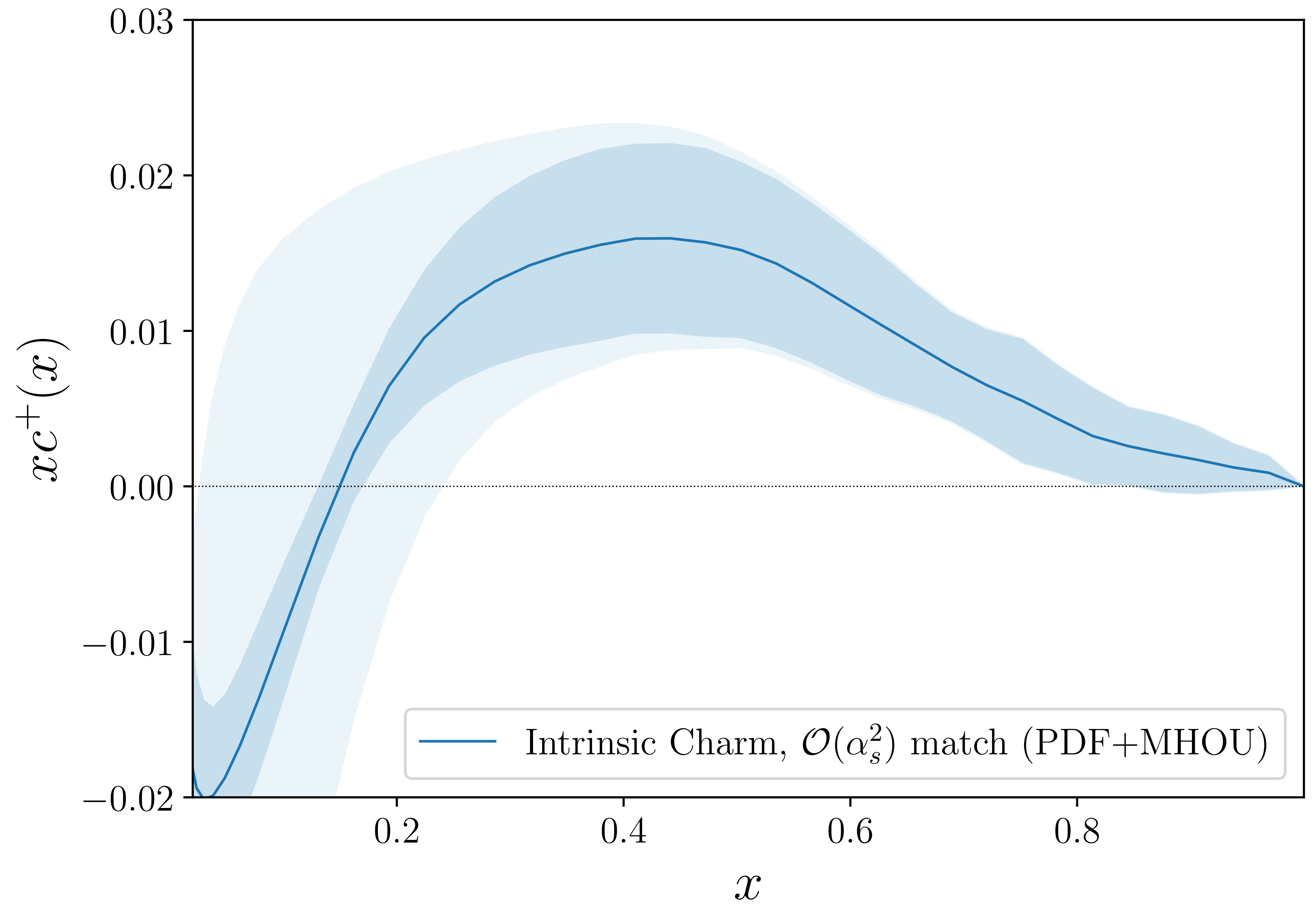
m_c	Dataset	$[c]\,(Q)\ \ (\%)$
1.51 GeV	Baseline	$0.62 \pm 0.28_{\mathrm{pdf}} \pm 0.54_{\mathrm{mhou}}$
1.51 GeV	Baseline+EMC	$0.60 \pm 0.18_{\mathrm{pdf}} \pm 0.54_{\mathrm{mhou}}$
1.51 GeV	Baseline+EMC+LHBCb Zc	$0.60 \pm 0.17_{\mathrm{pdf}} \pm 0.59_{\mathrm{mhou}}$
1.38 GeV	Baseline	$0.47 \pm 0.27_{\mathrm{pdf}}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

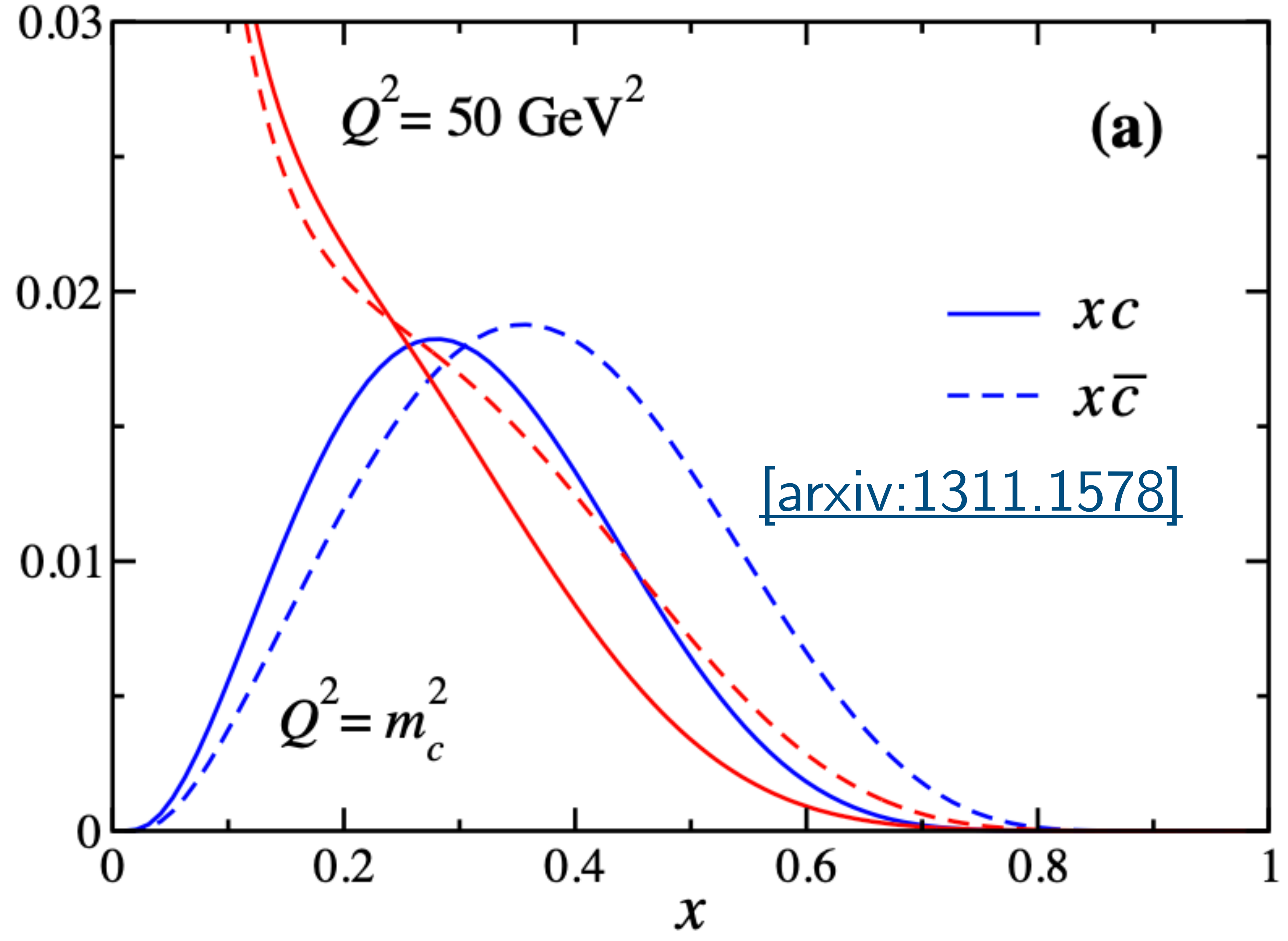


Summary and outlook

- 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 N^{3}LO matching conditions is relevant.
  Need to proper quantify MHOU and possibly move towards N^{3}LO pdf fit.
- Try a fit with independent c^- parametrisation
  as suggested by the Meson/Baryon models.
- Possible validation by an independent PDFs study.

Thank you for the attention!

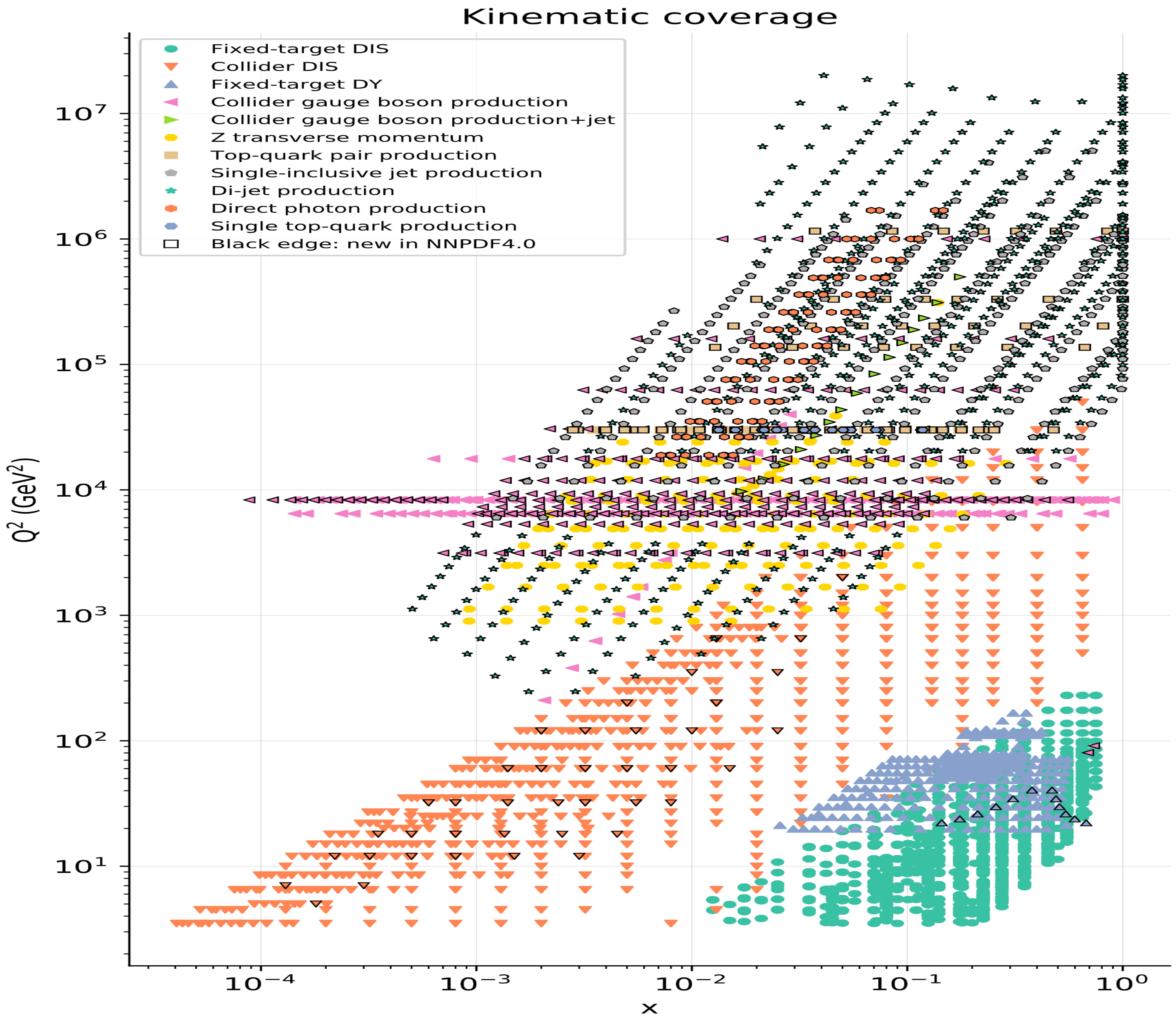




[arxiv:1311.1578]

Backup slides

NNPDF4.0 [arxiv:2109.02653]



From Emanuele R. Nocera

- Theoretical framework [EPJ C79 (2019) 282; EPJ C81 (2021) 37; EPJC80 (2020) 1168]
  → nuclear uncertainties for both deuteron and heavy nuclei included by default
  → NNLO charm-quark massive corrections implemented
  → EW corrections not included to ensure consistency with data, but carefully checked

- Implementation of PDF properties [JHEP 11 (2020) 129]
  → extended positivity constraints for light quark/antiquark and gluon PDFs
  → extended integrability constraints of non-singlet light quark PDF combinations

- PDF parametrisation and optimisation [EPJ C79 (2019) 676]
  → single neural network to parametrise eight independent PDF combinations
  → check of the independence of the results from the chosen parametrisation basis
  → new optimisation strategy based on gradient descent rather than genetic algorithms
  → scan of the hyperparameter space to find the optimal minimisation settings

- Statistical validation of PDF uncertainties [Acta Phys.Polon. B52 (2021) 243]
  → (multi-)closure tests to validate PDF uncertainties in the data region
  → future tests to check the sensibleness of PDF uncertainties in extrapolation regions

From 4FNS to 3FNS

The matching conditions

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

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

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

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

N^{3}LO

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

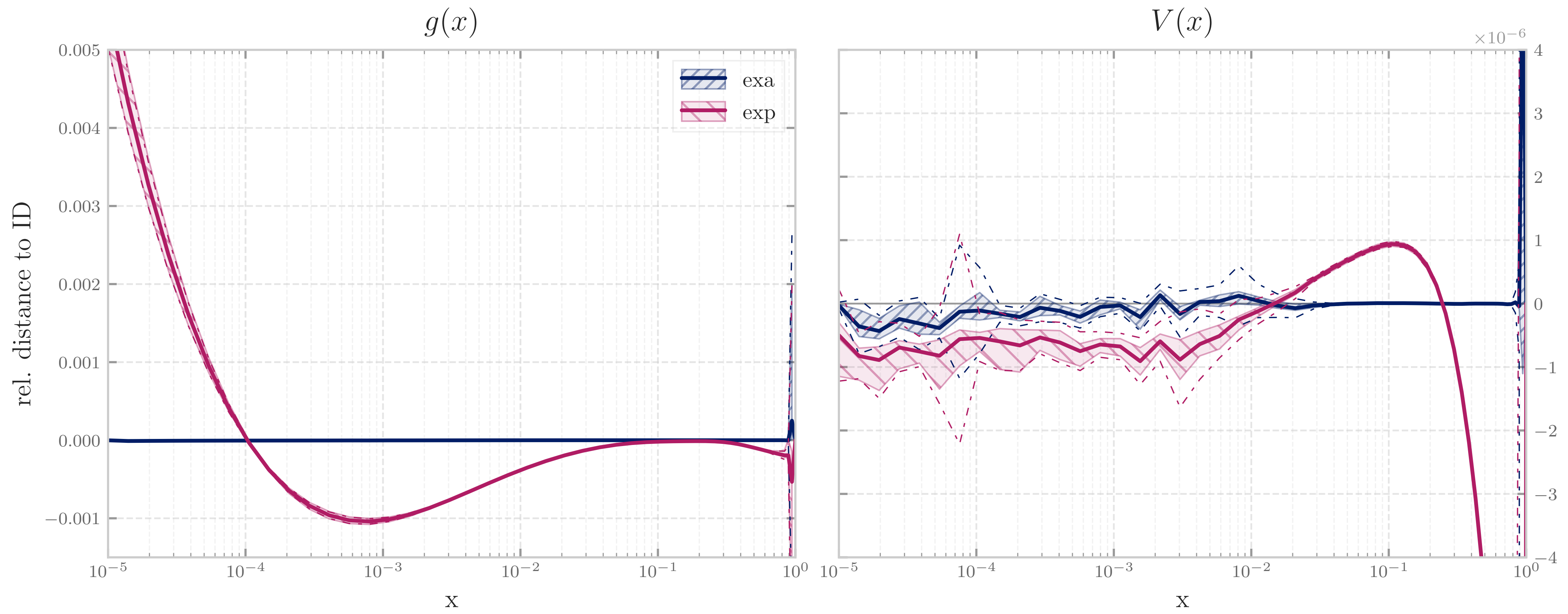
$$\mathbf{A}^{(n_f),(3)}_{nsv,h^-} = \begin{pmatrix} A^{ns,(3)}_{qq,H} & 0 \\ 0 & 0 \end{pmatrix}$$

[Eur.Phys.J.C 1 (1998) 301-320, Phys.Lett.B 754 (2016) 49-58]

[Nucl.Phys.B 820 (2009) 417-482 et al.]

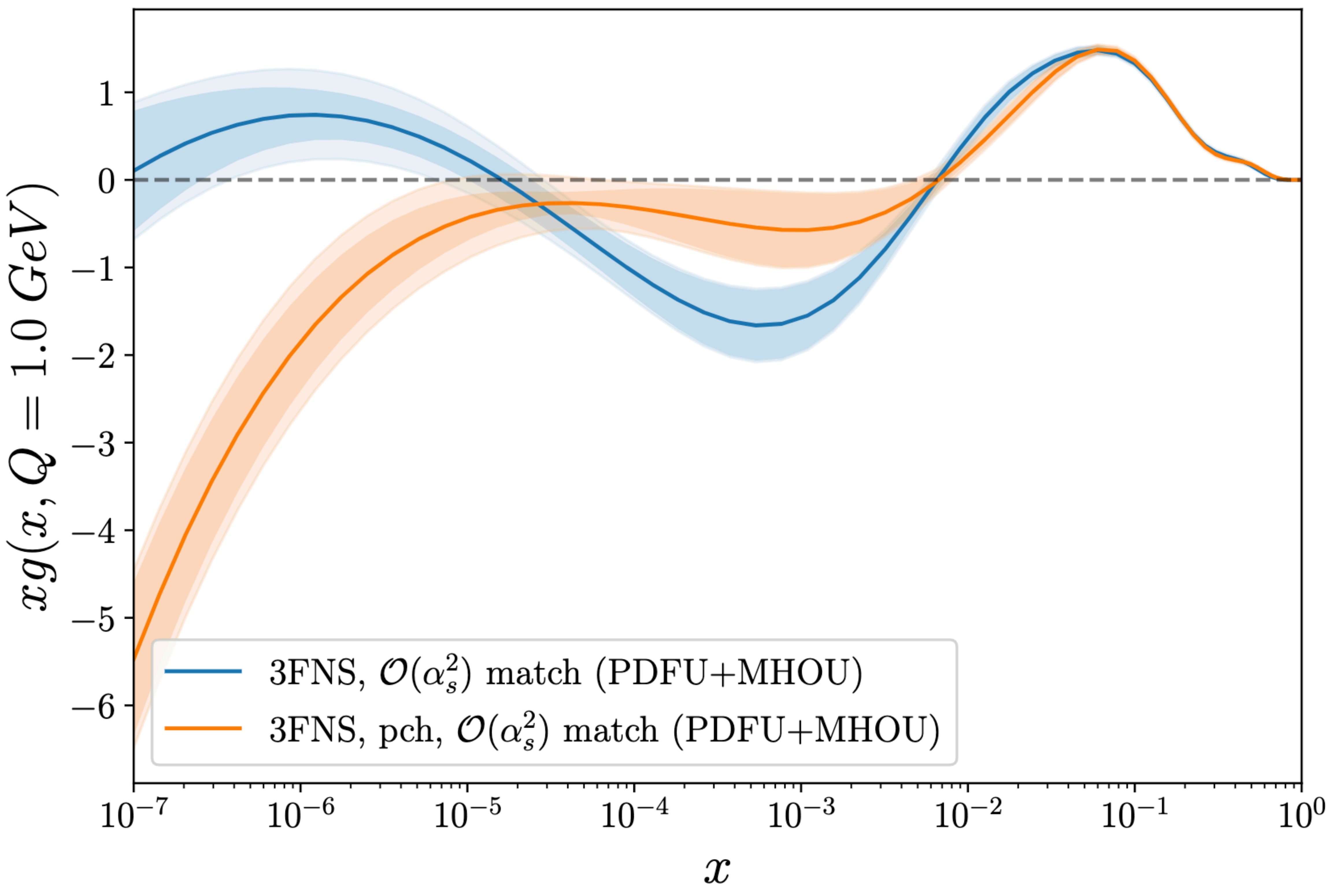
Inversion can be computed exactly or expanding in α_s:

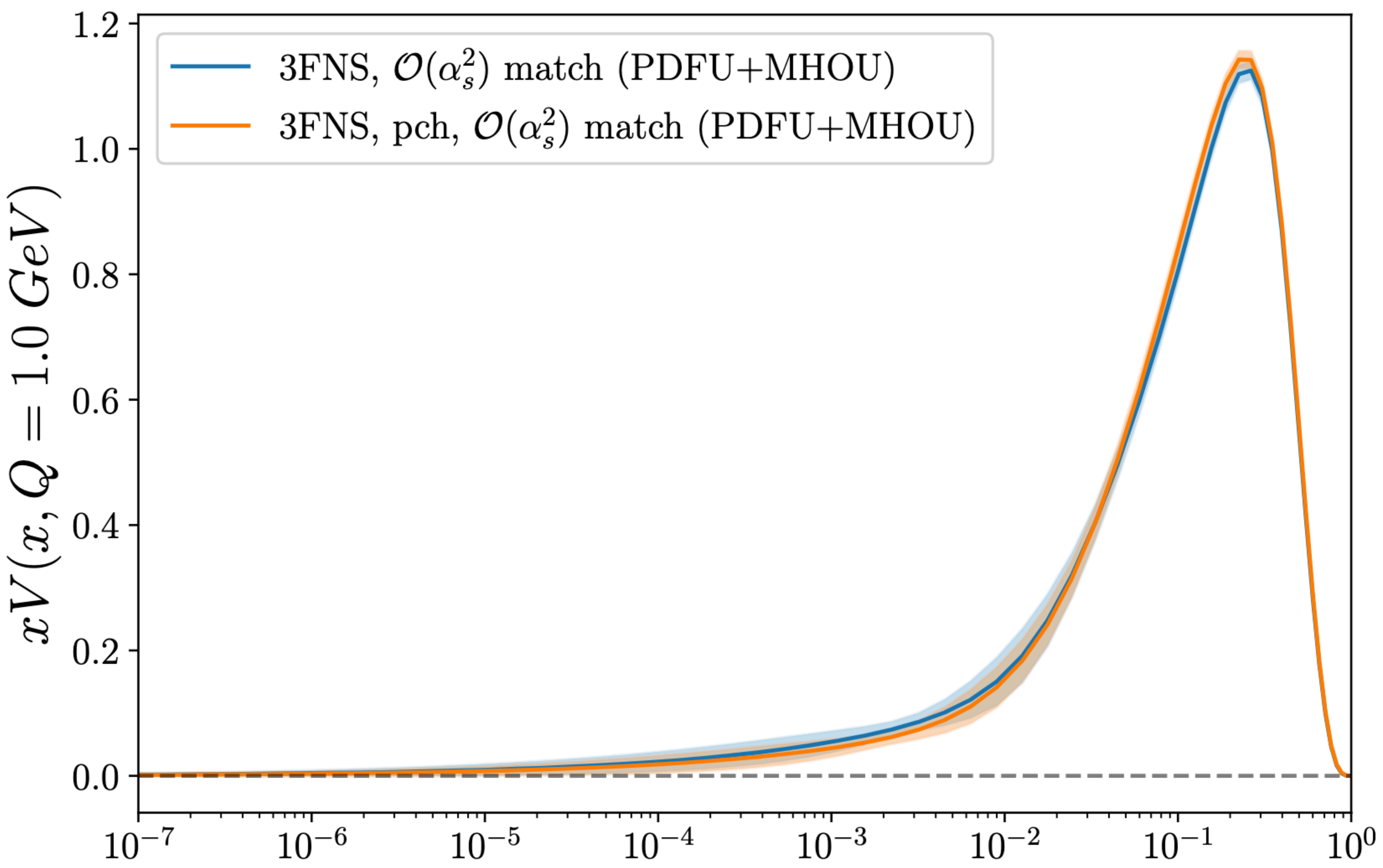
$$\mathbf{A}^{-1}_{exp}(\mu_h^2) = \mathbf{I} - a_s(\mu_h^2)\mathbf{A}^{(1)} + a_s^2(\mu_h^2)\left[\mathbf{A}^{(2)} - \left(\mathbf{A}^{(1)}\right)^2\right] + a_s^3(\mu_h^2)\left[-\mathbf{A}^{(3)} + 2\mathbf{A}^{(1)}\mathbf{A}^{(2)} - \left(\mathbf{A}^{(1)}\right)^3\right] + O(a_s^4)$$

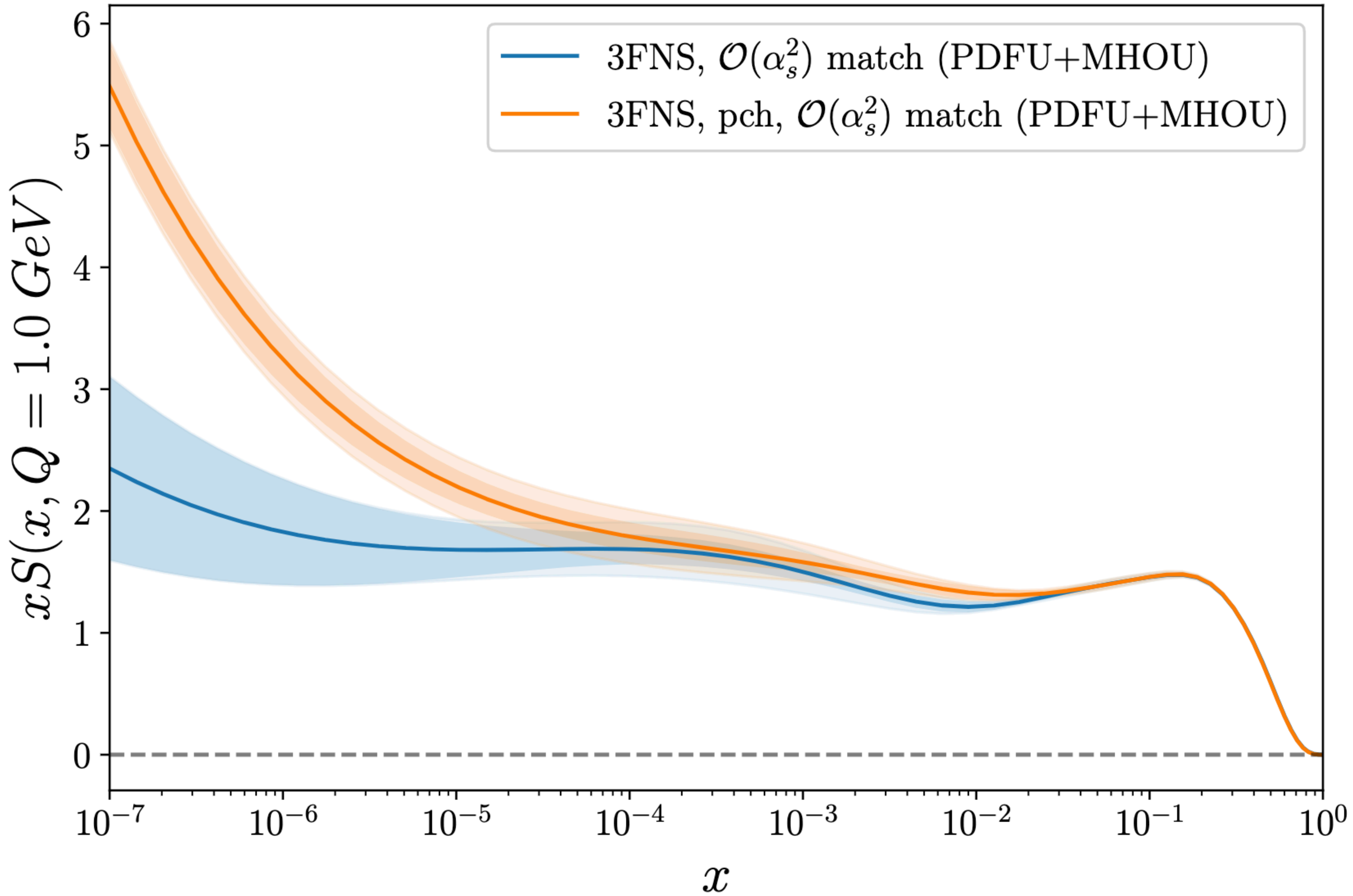


PDFs in 3FNS

- Evolution range: $Q = 1.65\ GeV \rightarrow 1.0\ GeV$
- MHOU estimated from different matching order







Impact on LHC observables

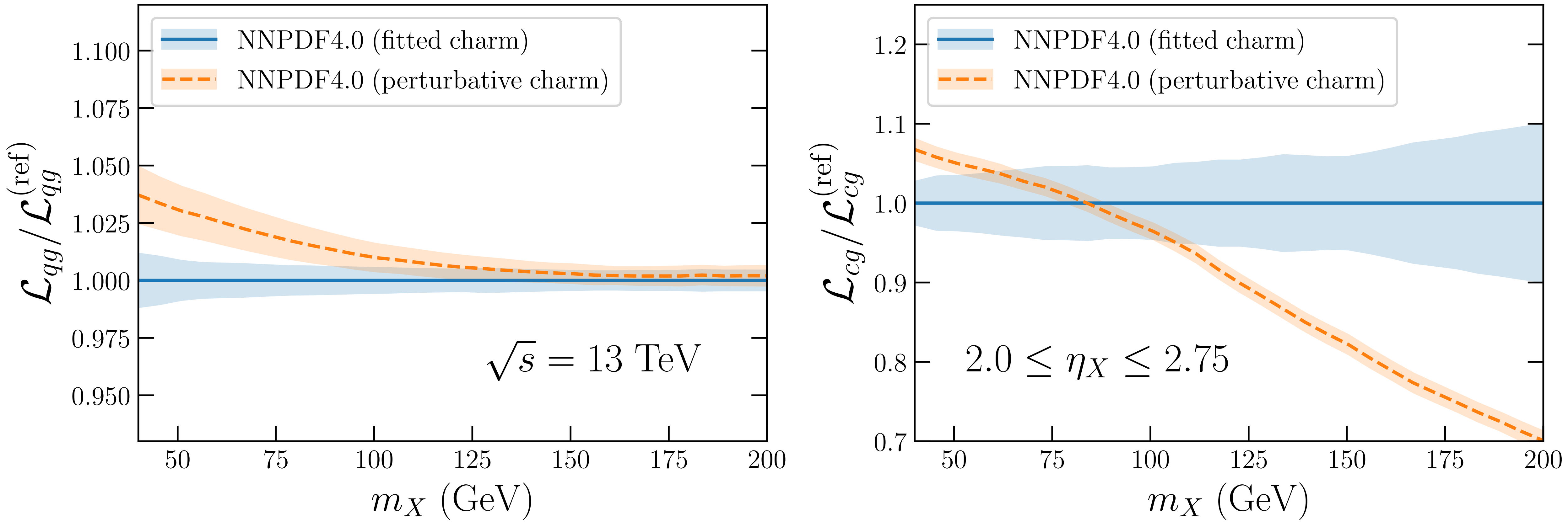
Partonic luminosities

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

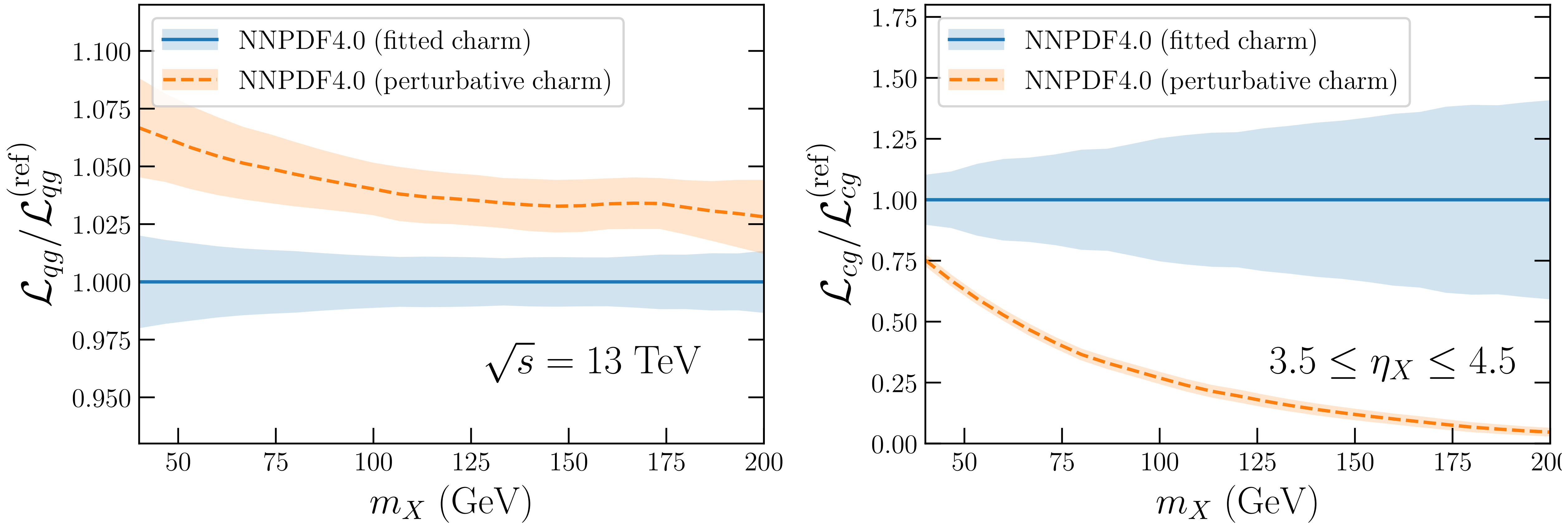
$$\mathscr{L}_{ab} = \frac{1}{s}\int_{\frac{m_X^2}{s}}^{1} \frac{dx}{x} f_a(x, m_X^2) f_b(x, m_X^2)\theta(y_X - y_{min})\theta(y_{max} - y_X)$$

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

Central region LHCb



Forward region LHCb



Central region ATLAS-CMS