News from NNPDF: from aN^{3}LO PDFs to valence charm

Juan Rojo, VU Amsterdam & Nikhef

PDF4LHC Working Group meeting

CERN, 17th November 2023

NNPDF timescale

☑ Sep 2021: **NNPDF4.0 (paper & code)**

☑ Aug 2022: **Intrinsic charm**

☑ Sept 2022: **PDFs & BSM searches** (A_{FB} high-mass)

☑ Oct 2023: **IC valence**

☑ Q4 2023: **NNPDF4.0QED**

☑ Q4 2023: **NNPDF4.0 MHOUs**

☑ Q4 2023: **NNPDF4.0 aN^{3}LO**

☑ Q4 2023: **NNPDF4.0 LHC pheno study**

NNPDF timescale

☑ Sep 2021: **NNPDF4.0 (paper & code)**

☑ Aug 2022: **Intrinsic charm**

☑ Sept 2022: **PDFs & BSM searches** (A_{FB} high-mass)

☑ Oct 2023: **IC valence**

☑ Q4 2023: **NNPDF4.0QED**

☑ Q4 2023: **NNPDF4.0 aN^{3}LO**

☑ Q4 2023: **NNPDF4.0 MHOUs**

☑ Q4 2023: **NNPDF4.0 LHC pheno study**

- Determination of **neutrino structure functions**
- Combined **PDF & SMEFT fits**
- Projections for **LHC neutrino** experiments

NNPDF timescale

☑ Sep 2021: **NNPDF4.0 (paper & code)**

☑ Aug 2022: **Intrinsic charm**

☑ Sept 2022: **PDFs & BSM searches** (A_{FB} high-mass)

this talk

☑ Oct 2023: **IC valence**

☑ Q4 2023: **NNPDF4.0QED**

this talk

☑ Q4 2023: **NNPDF4.0 aN³LO**

this talk

☑ Q4 2023: **NNPDF4.0 MHOUs**

☑ Q4 2023: **NNPDF4.0 LHC pheno study**

Juan CM's talk

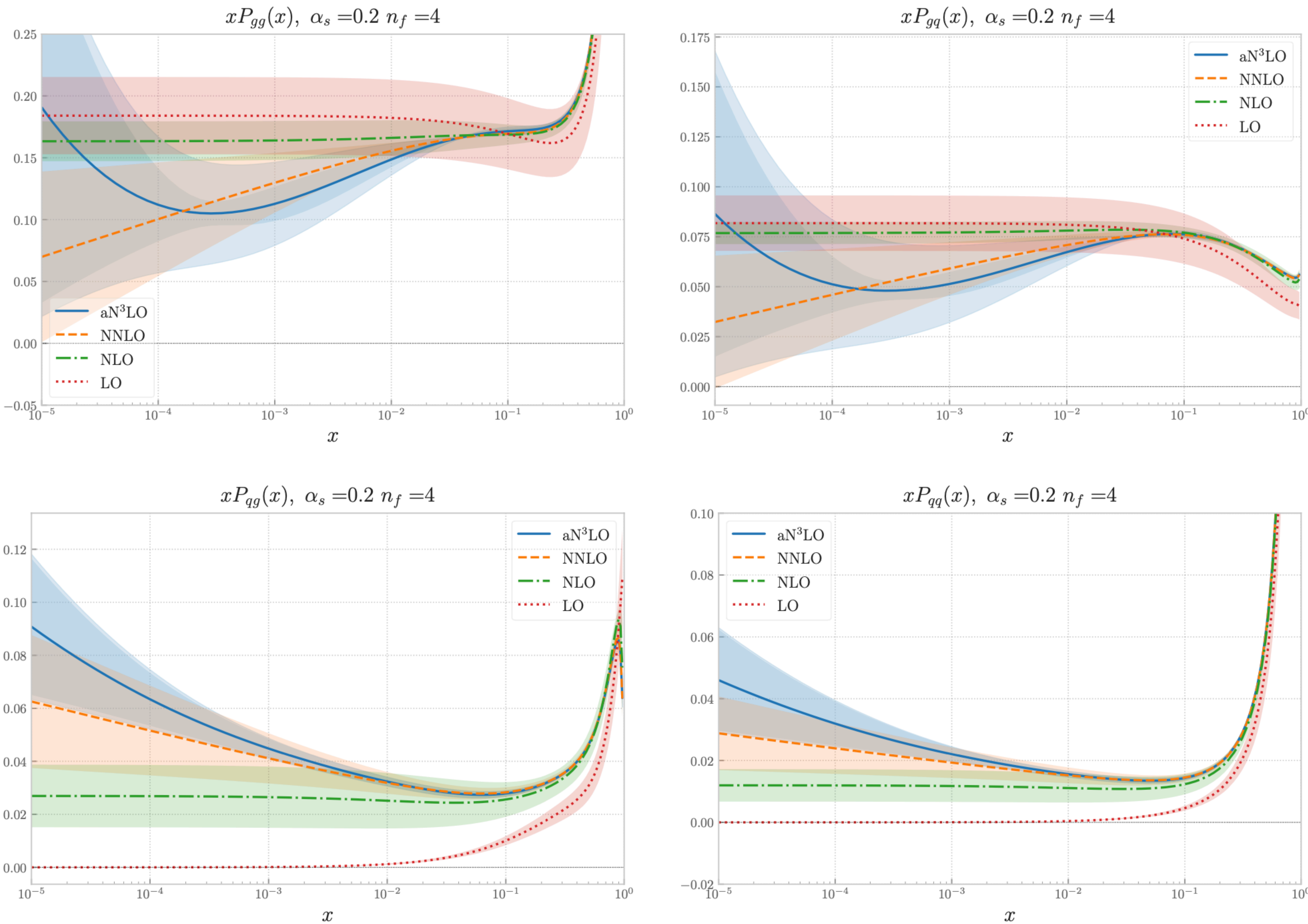
- Determination of **neutrino structure functions**
- Combined **PDF & SMEFT fits** *James' talk*
- Projections for **LHC neutrino** experiments *this talk*

The Path to PDFs at N^{3}LO

R. D. Ball, A. Barontini, A. Candido, S. Carrazza, J. Cruz-Martinez, L. Del Debbio, S. Forte, T. Giani, F. Hekhorn, Z. Kassabov, N. Laurenti, G. Magni, E. R. Nocera, T. R. Rabemananjara, J. Rojo, R. Stegeman, C. Schwan, and M. Ubiali, **to appear soon**

NNPDF4.0 at aN³LO

- Approximate parametrisation for the N³LO splitting functions satisfying known **exact results and limits**



LO, NLO, NNLO: **MHOU (μ_F)**

N³LO: **MHOU (μ_F) + IHOUs**

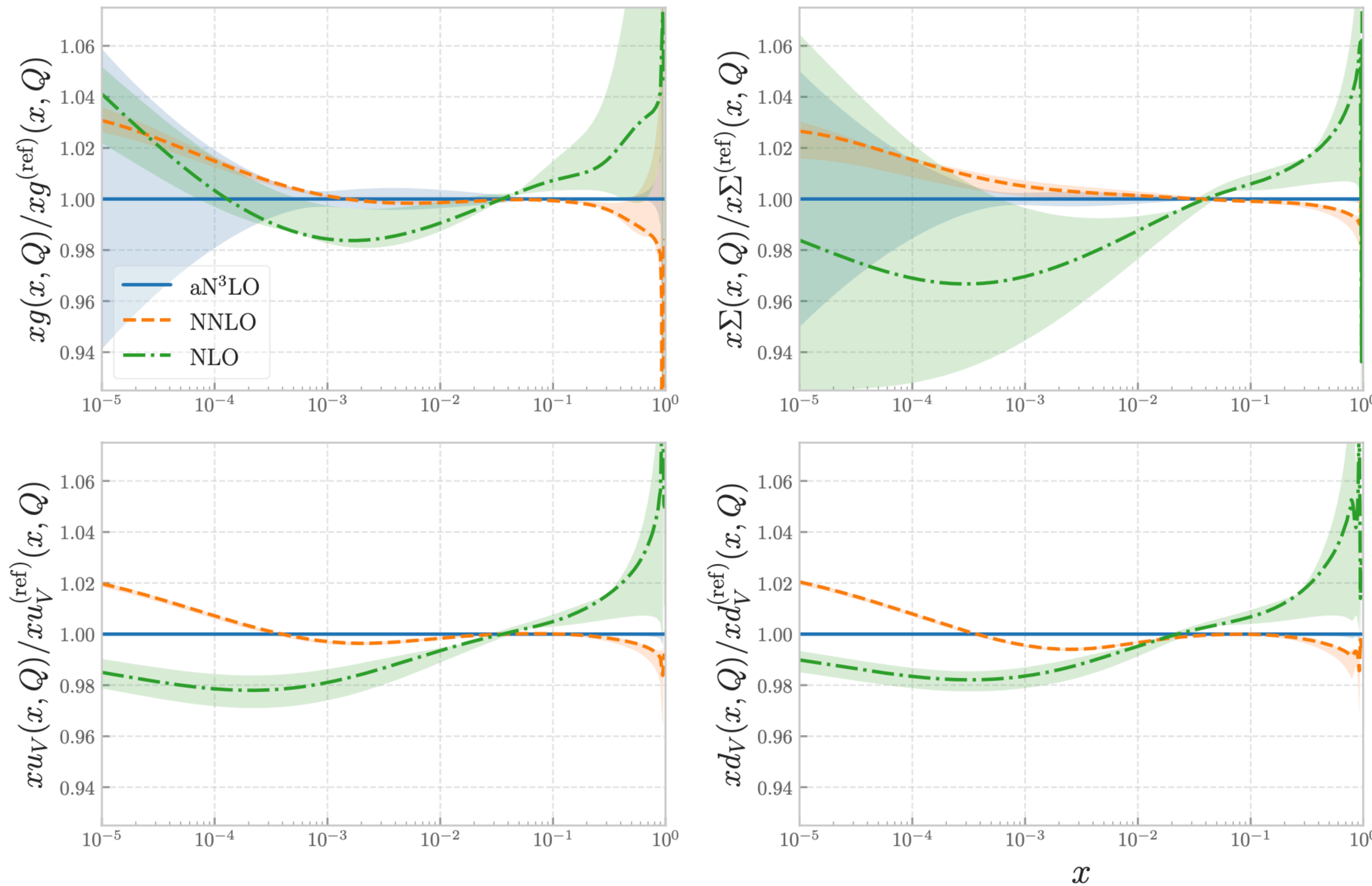
Estimate **Incomplete Higher Order Uncertainties** (IHOUs) by varying interpolating functions

Good perturbative consistency within uncertainties

NNPDF4.0 at aN^{3}LO

- Approximate parametrisation for the N^{3}LO splitting functions satisfying known **exact results and limits**

DGLAP evolution of NNPDF4.0 NNLO from $Q_0 = 1.65$ GeV to $Q = 100$ GeV



LO, NLO, NNLO: **MHOU (μ_F)**

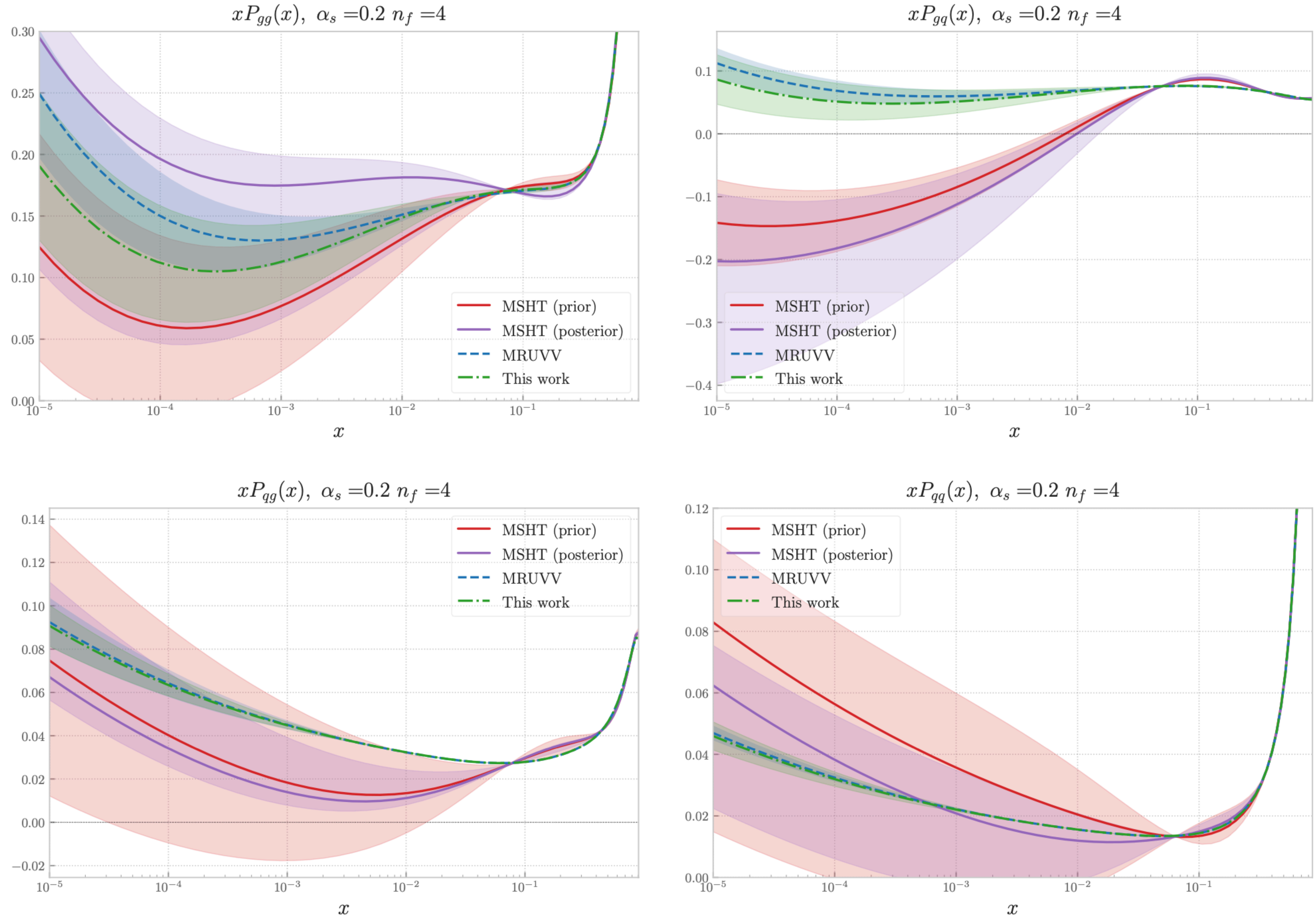
N^{3}LO: **MHOU (μ_F) + IHOUs**

Effects of N^{3}LO corrections to DGLAP evolution **< 1%** except at small-x

Theory uncertainties (MHOU + IHOU) at N^{3}LO are **negligible** except in small-x region

NNPDF4.0 at aN^{3}LO

- Approximate parametrisation for the N^{3}LO splitting functions satisfying known **exact results and limits**



NNPDF, MRUVV: **IHOUs (prior)**

MRUVV: Moch et al, arXiv:2310:05744

MSHT20: **IHOUs (prior & posterior)**

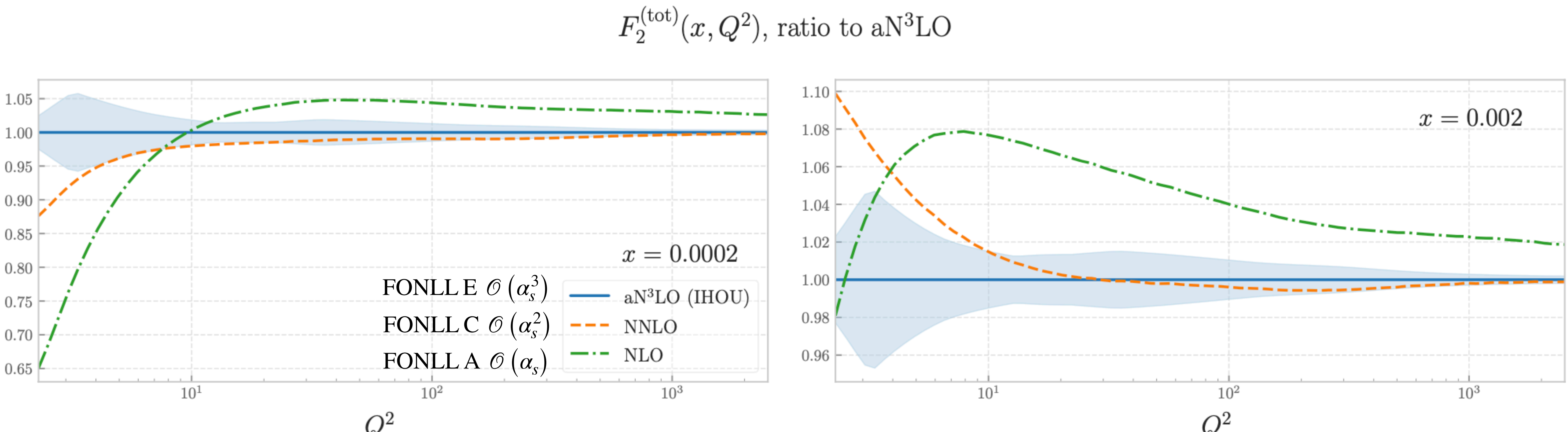
[IHOUs constrained from data via **nuisance parameters**]

Good agreement with MRUVV reflects use of very similar **theory inputs** & parametrisation strategy

Differences with MSHT20 related to *i)* reduced set of **theory inputs** and *ii)* **constraining IHOUs from data**

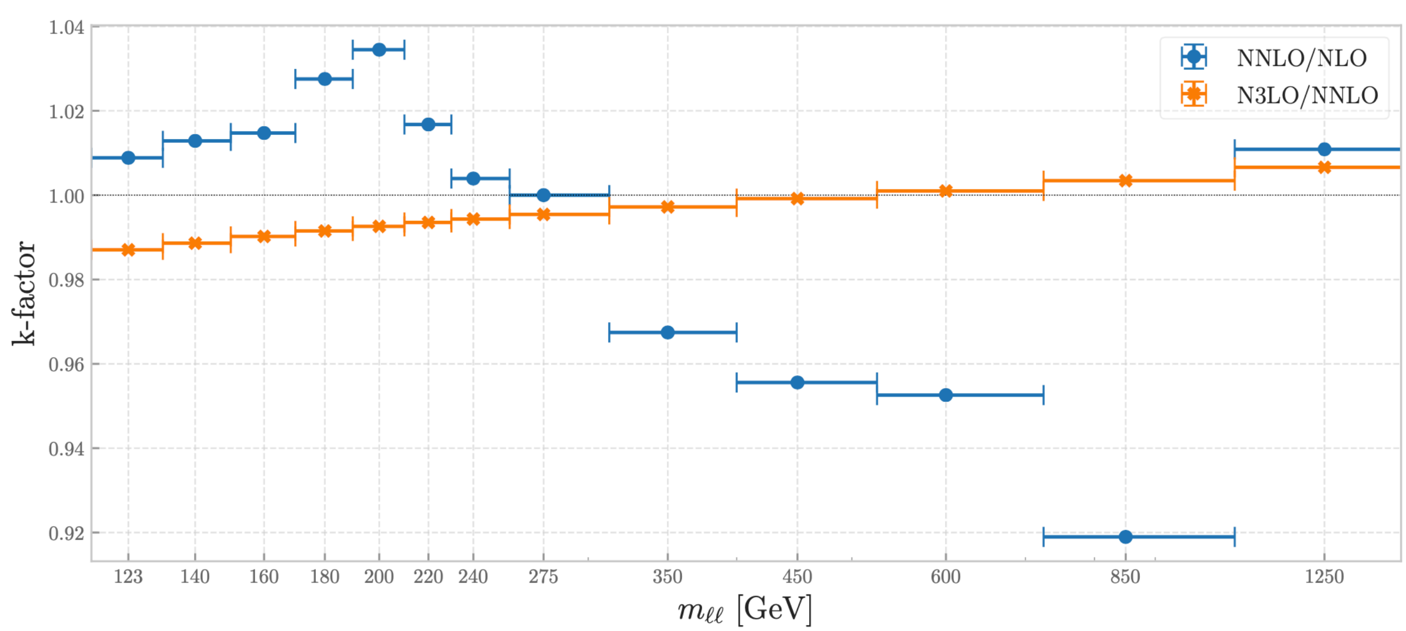
NNPDF4.0 at aN^{3}LO

- (Approximate) deep-inelastic coefficient functions at N^{3}LO accuracy
- Massless coefficients known, parametrisation of the massive coefficients reproducing known results, extension of the **FONLL general -mass scheme at N^{3}LO**



Large corrections close to **charm threshold**

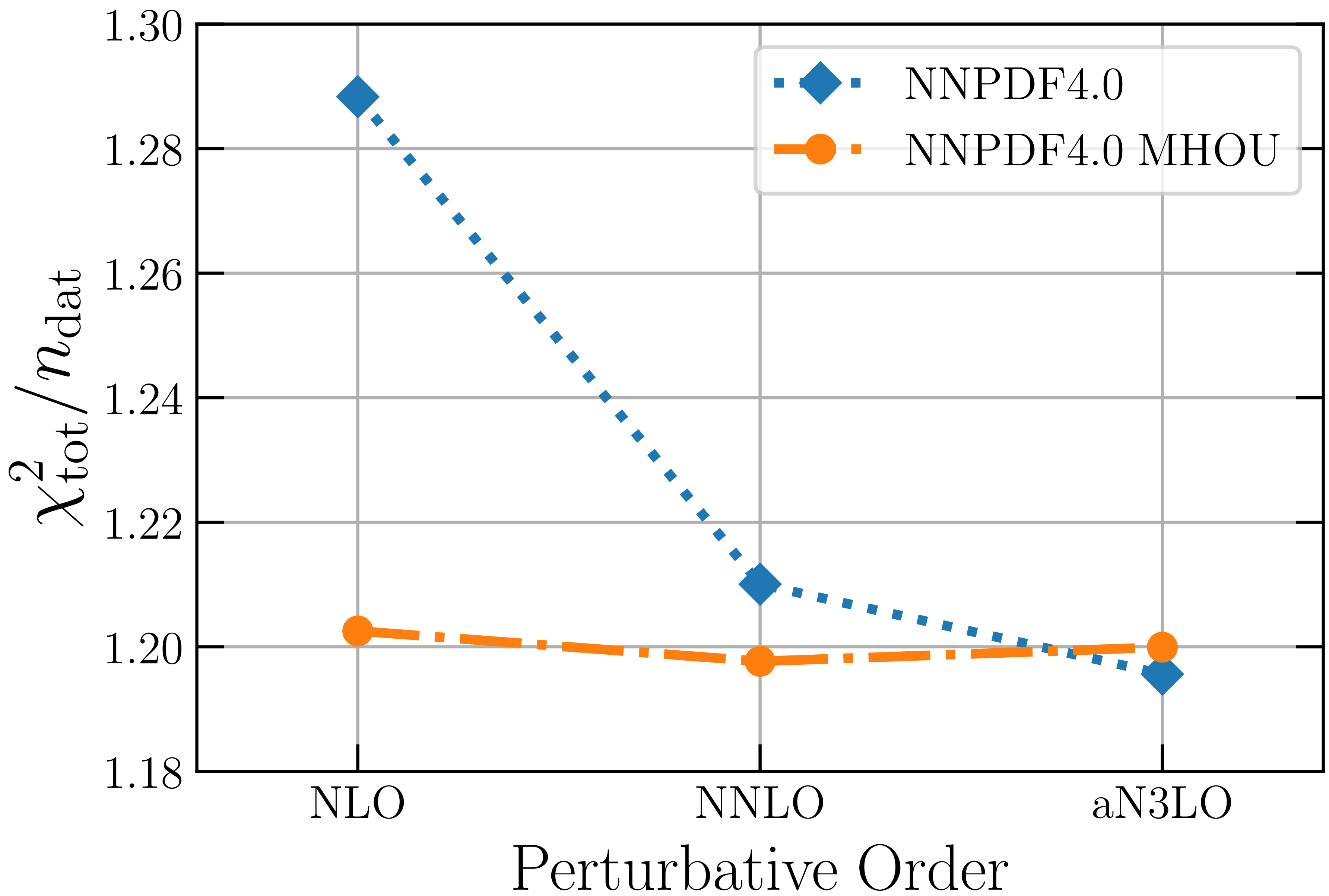
- MHOUs associated to **partonic cross-sections** for hadronic data via theory covariance matrix



- For a (small) subset of Drell-Yan data, **exact N^{3}LO calculations** are also available

not included in baseline fit

Results: Fit quality

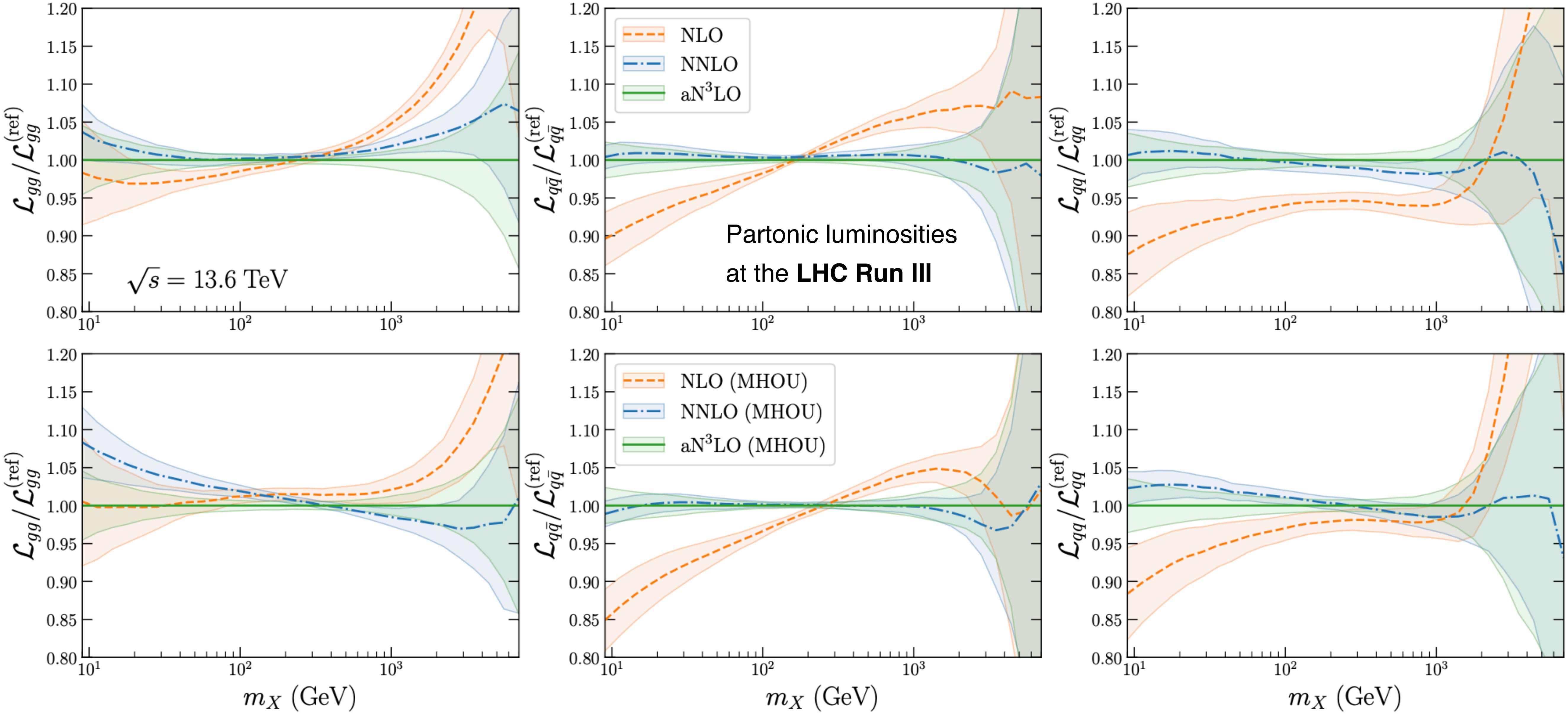


*Results shown **still preliminary**, final version to be released in O(weeks)*

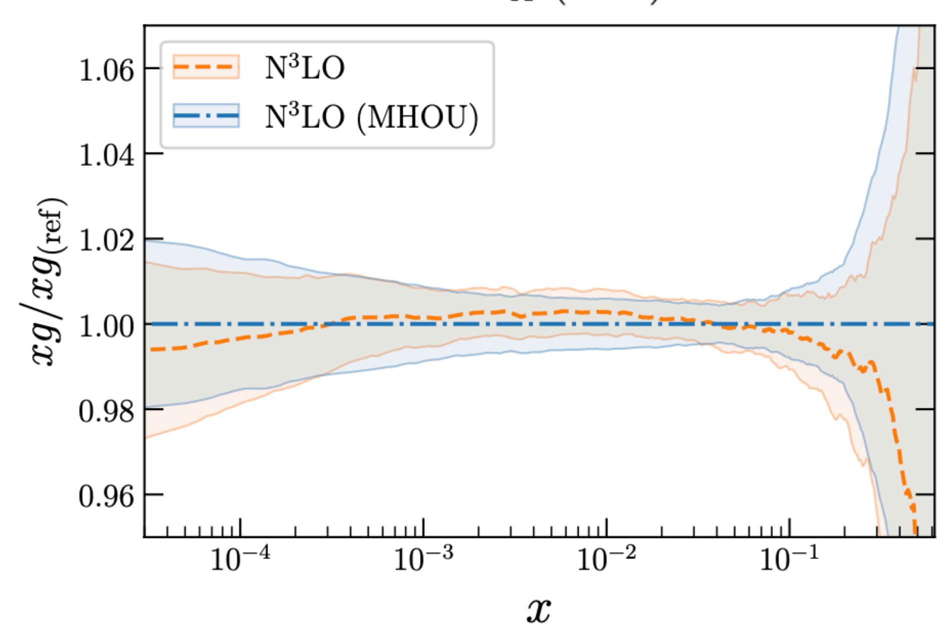
- Without MHOUs, the **χ^2 improves with the perturbative accuracy** of the PDF fit
- With MHOUs, the **χ^2** becomes **independent of perturbative accuracy**
- At aN3LO impact of MHOUs is small (also at PDF level)

N³LO corrections required for perturbative convergence at the PDF fit level

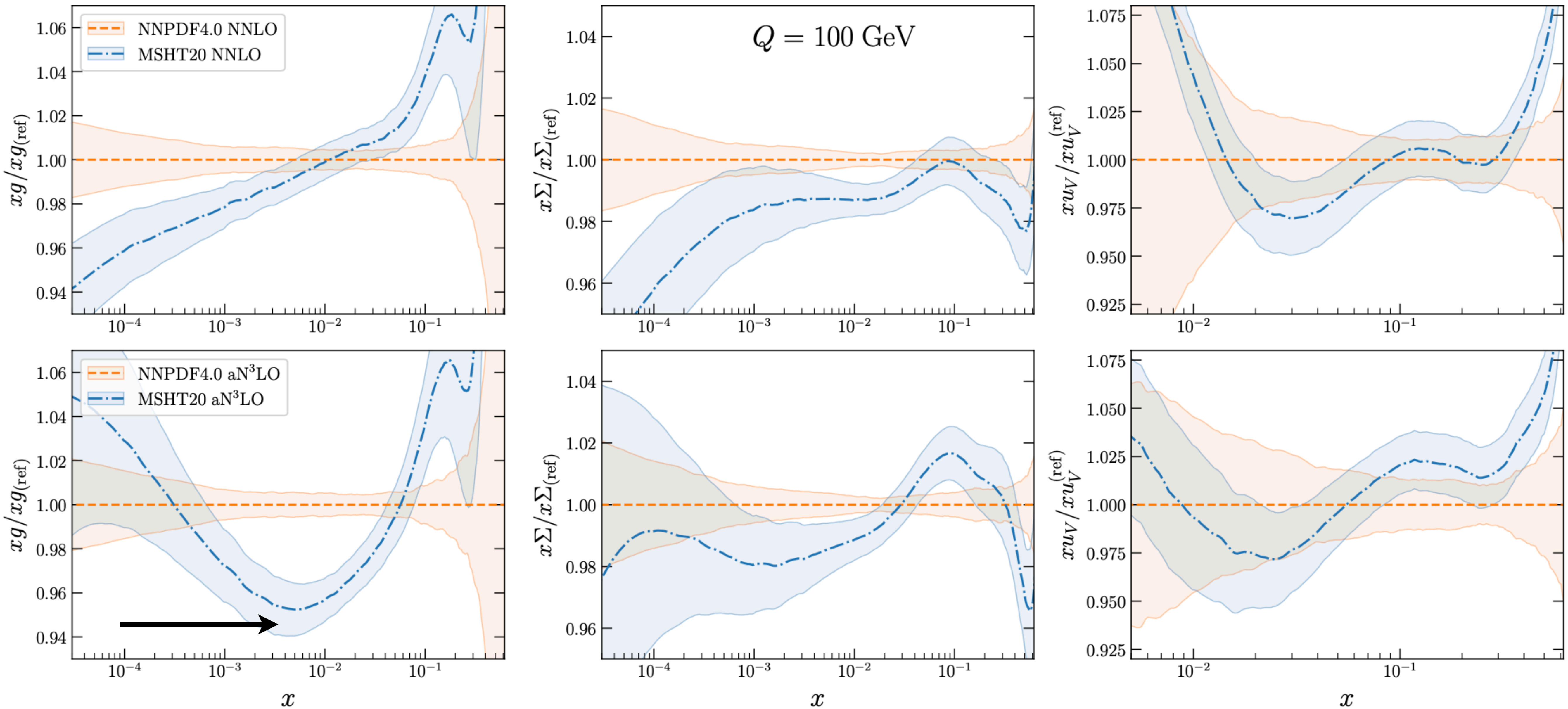
Results: perturbative stability



- N³LO corrections **moderate**, specially for quark luminosities
- Impact of **MHOUs negligible** at **N³LO**
- MHOUs at NNLO most relevant for the gluon, presumably due to the **deweighting of jet data**

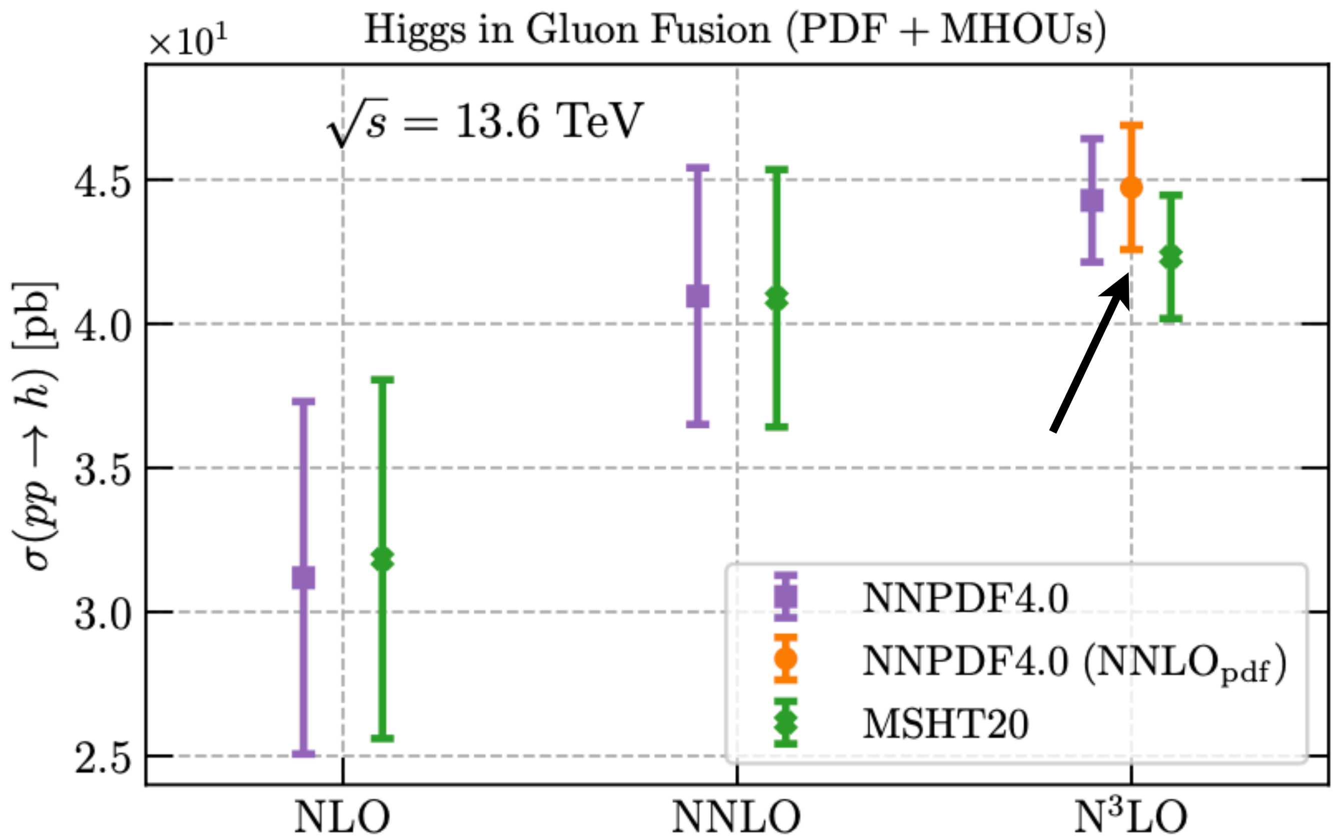


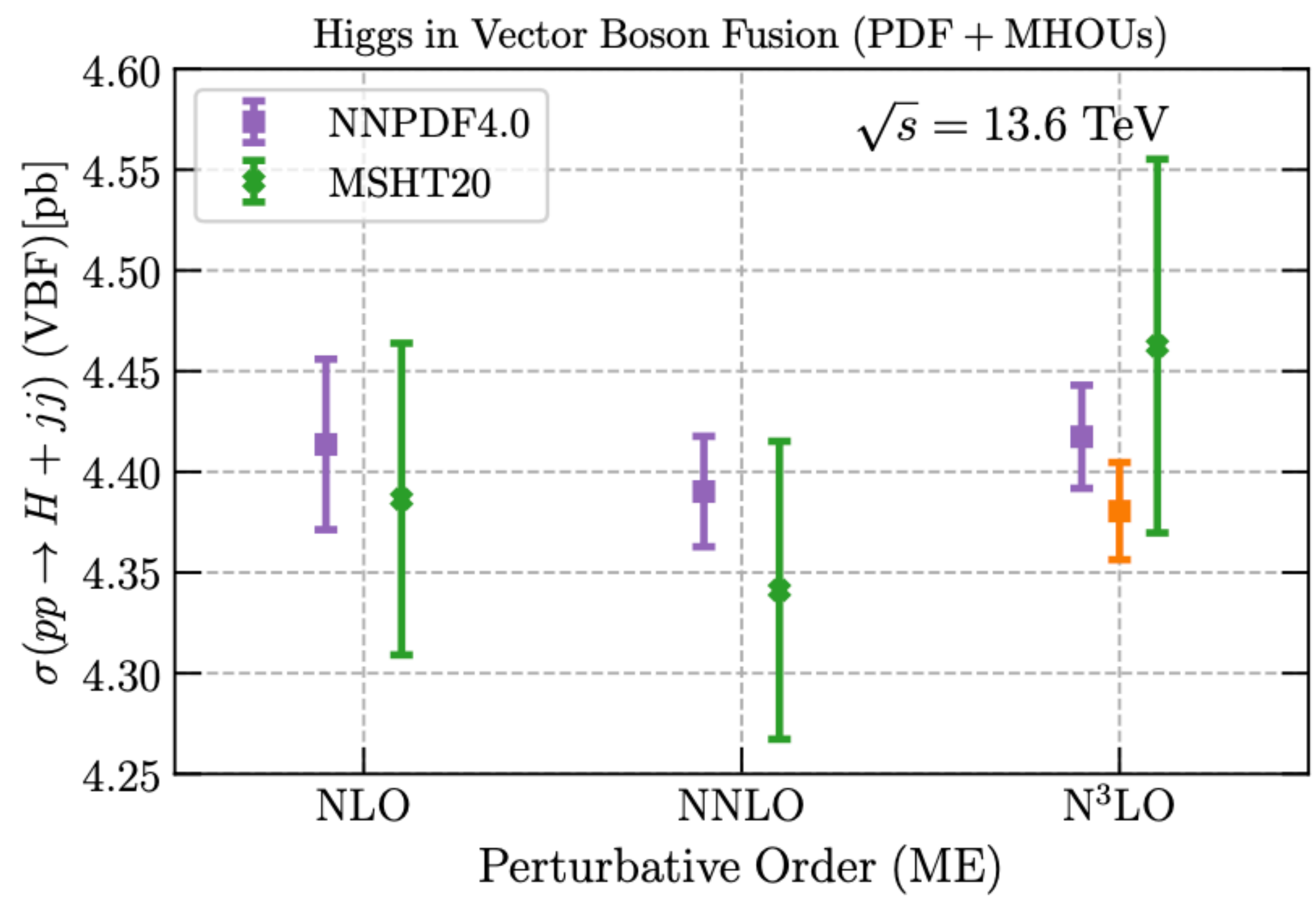
Results: comparison with MSHT20

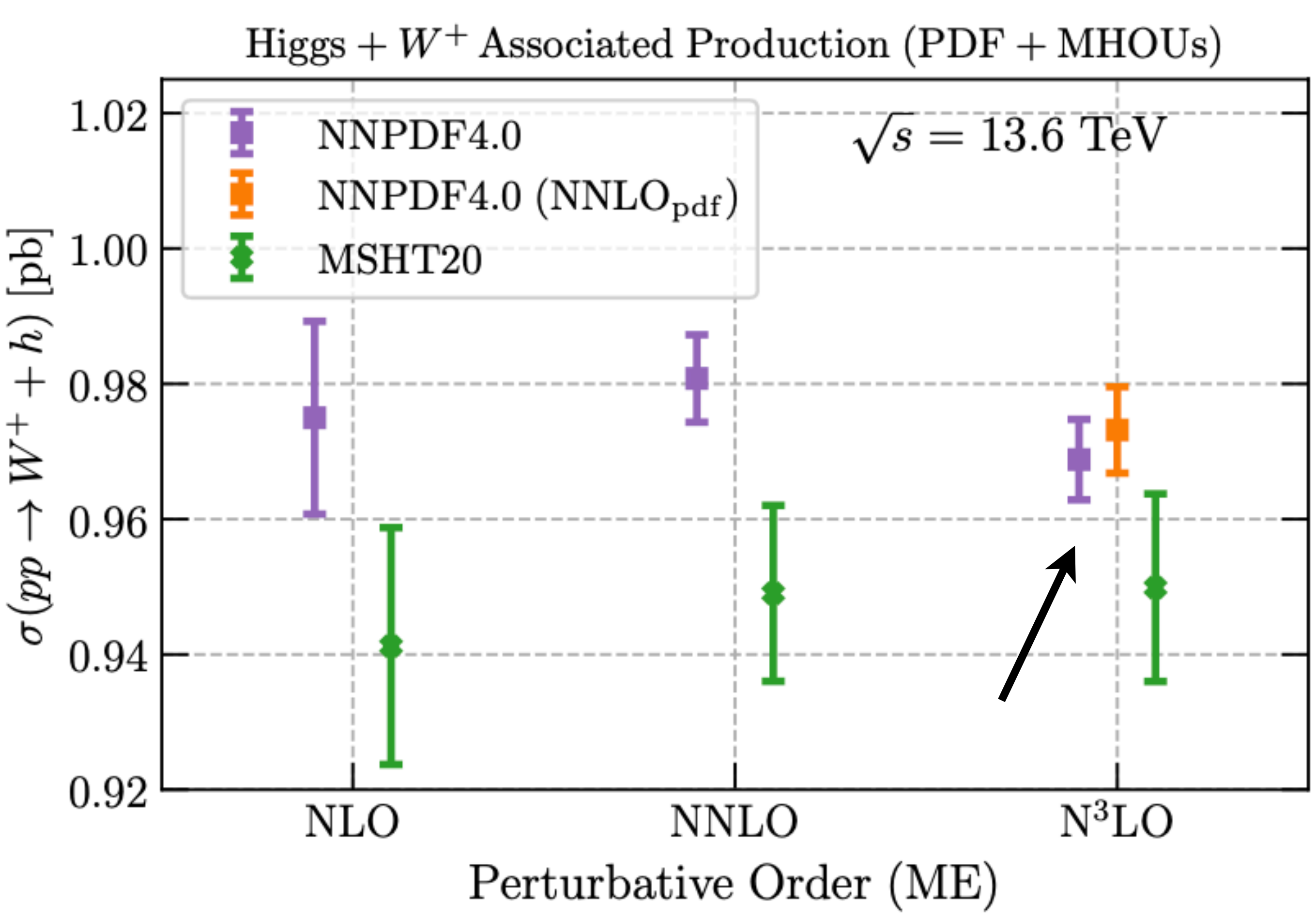


- As compared to existing results at NNLO, once the comparison is upgraded to N^{3}LO, main qualitative differences for the **gluon PDF**, quarks stable
- MSHT20 gluon PDF **suppressed by 5% at *x*=0.005** in comparison with NNPDF4.0, at small-x the agreement is improved with N^{3}LO corrections

LHC phenomenology: Higgs production







- N^{3}LO PDF corrections to **Higgs in gluon fusion small**, unlike MSHT20 prediction (with a 4% suppression)

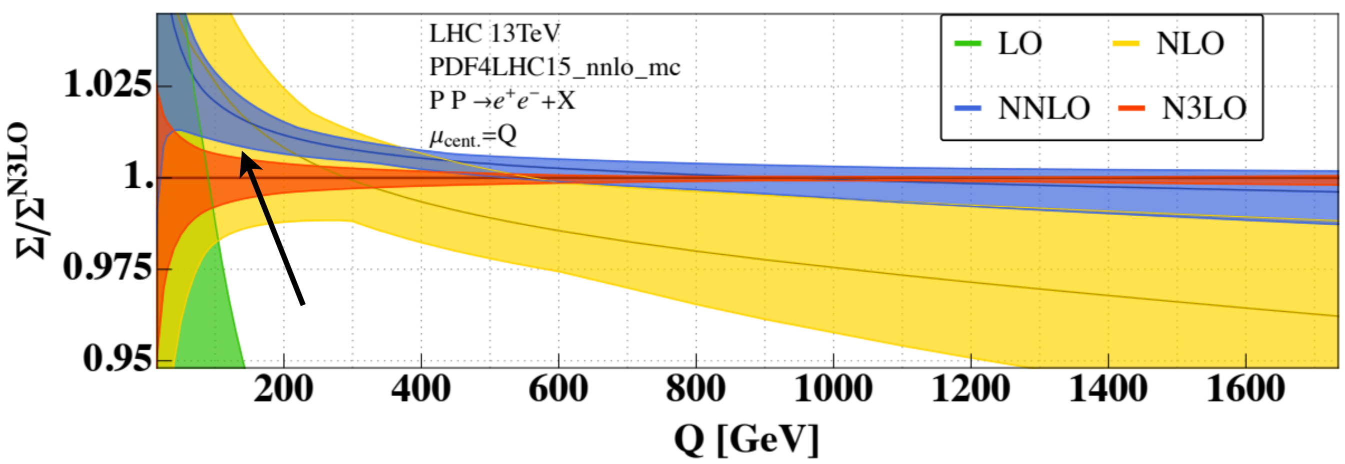
- N^{3}LO corrections improve agreement between NNPDF4.0 and MSHT20 for ***hW***

- **Higgs VBF** perturbatively stable

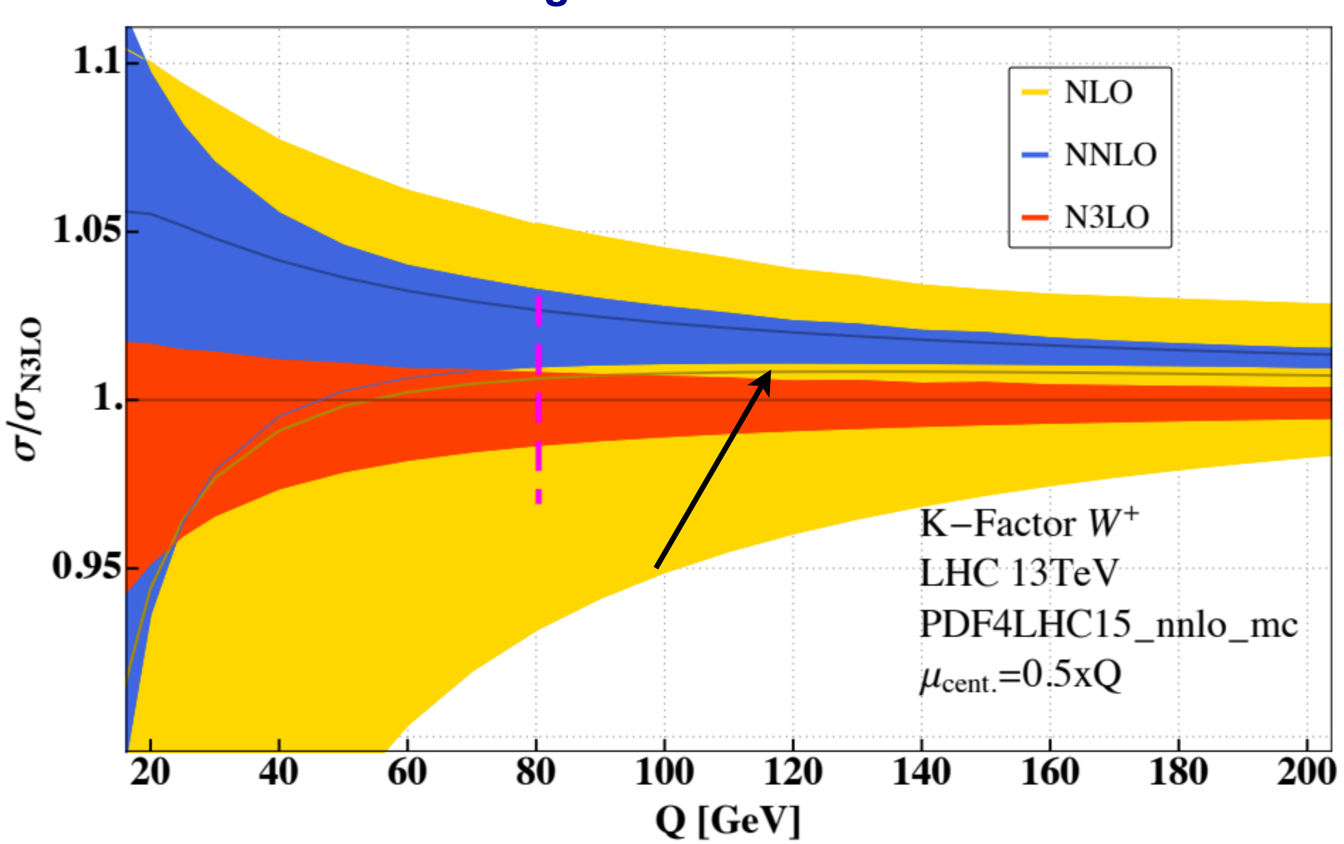
LHC phenomenology: Drell-Yan

Often predictions for N^3LO cross-sections are evaluated with NNLO PDFs. What happens when **aN^3LO PDFs are used**?

Neutral-current Drell-Yan



Charged-current Drell-Yan

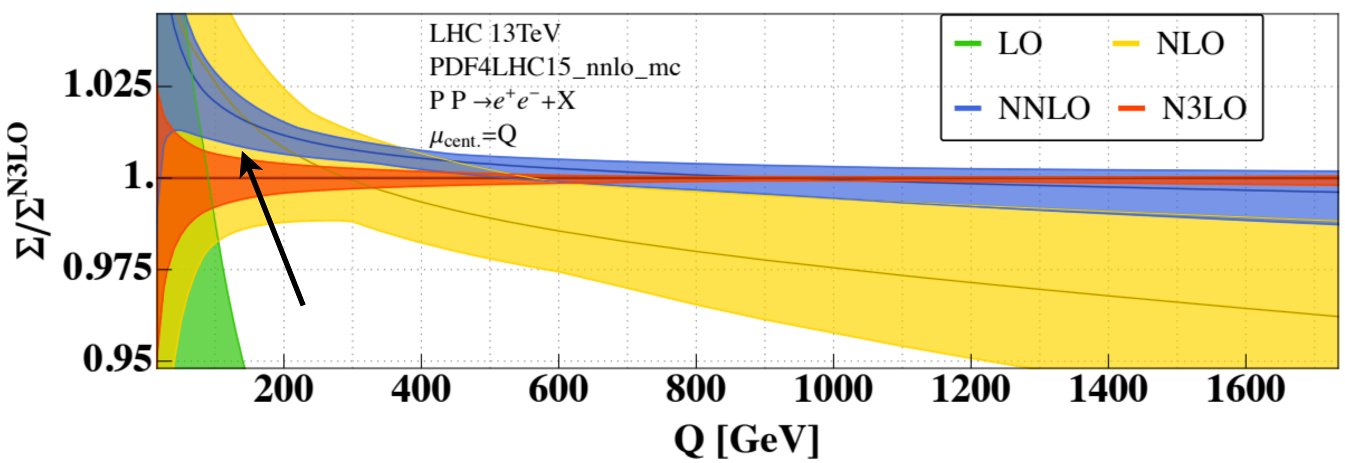


LHC phenomenology: Drell-Yan

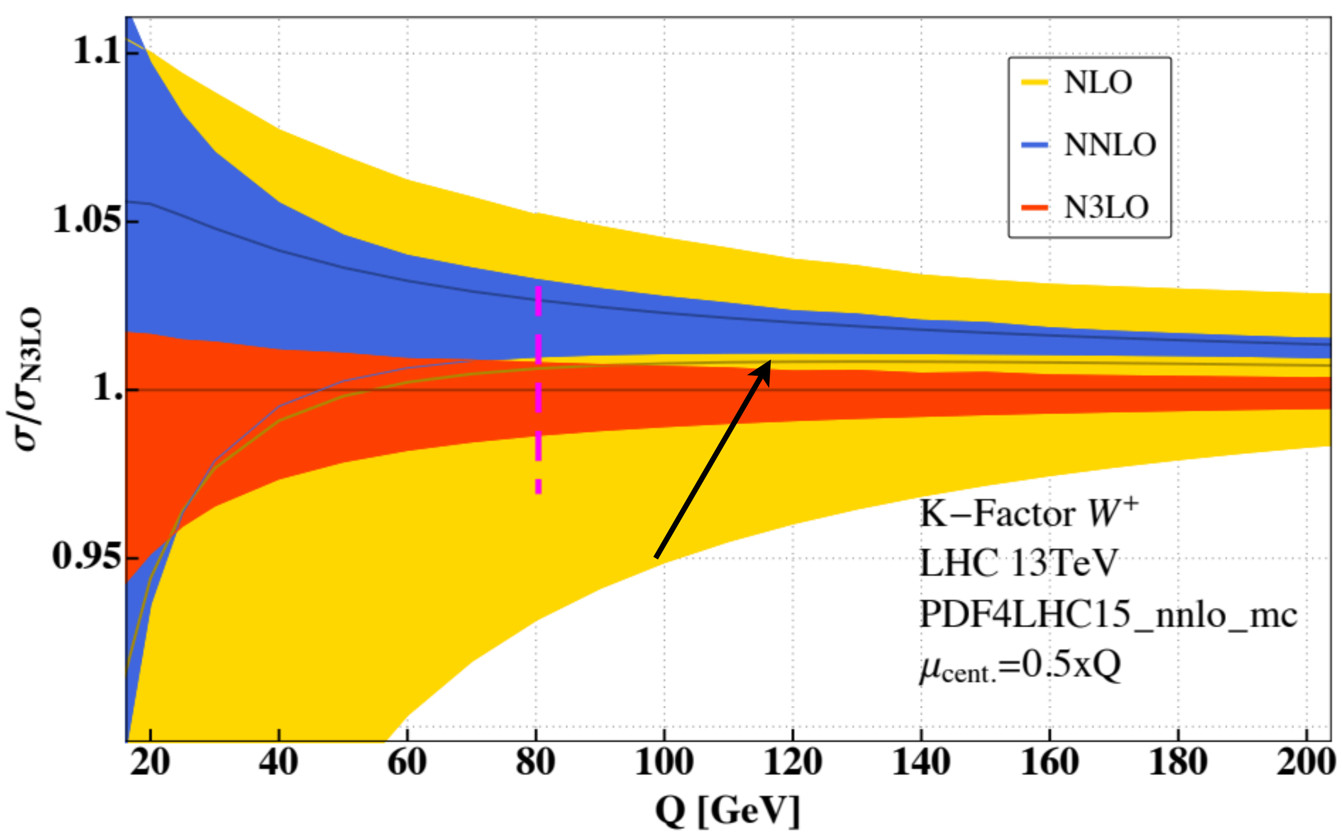
Often predictions for N³LO cross-sections are evaluated with NNLO PDFs. What happens when **aN³LO PDFs are used**?

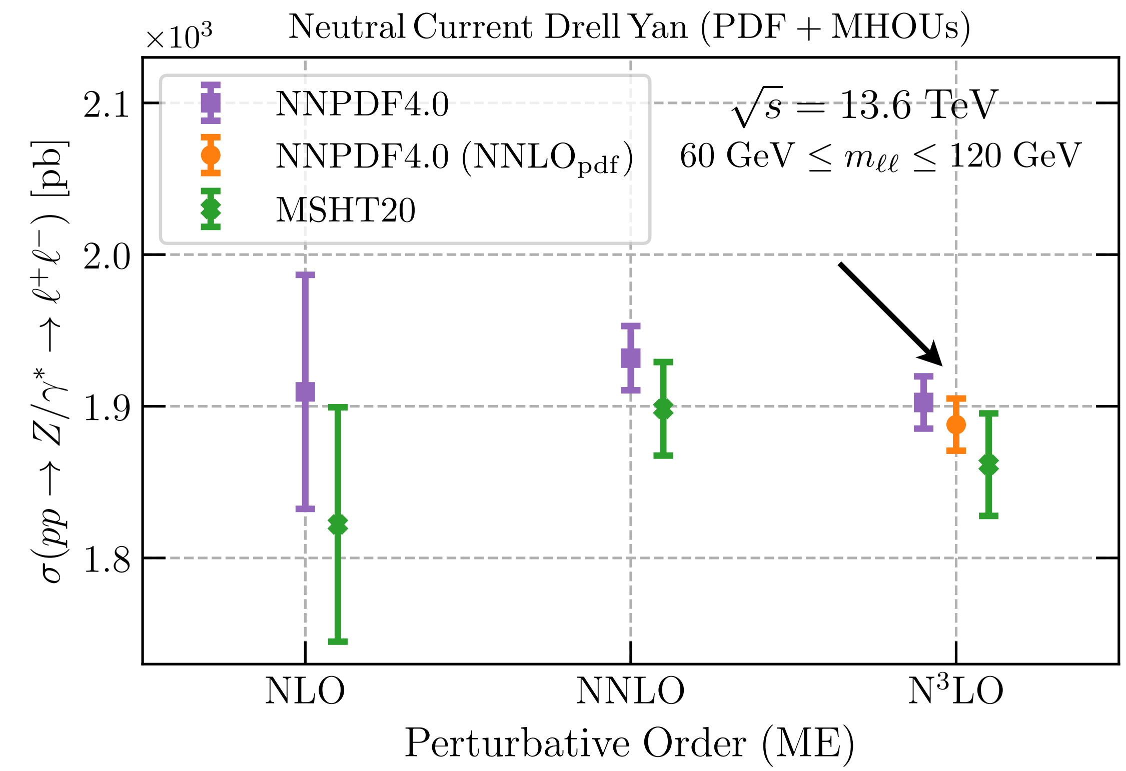
Consistent use of **aN³LO PDFs** with N³LO MEs improves **perturbative convergence**

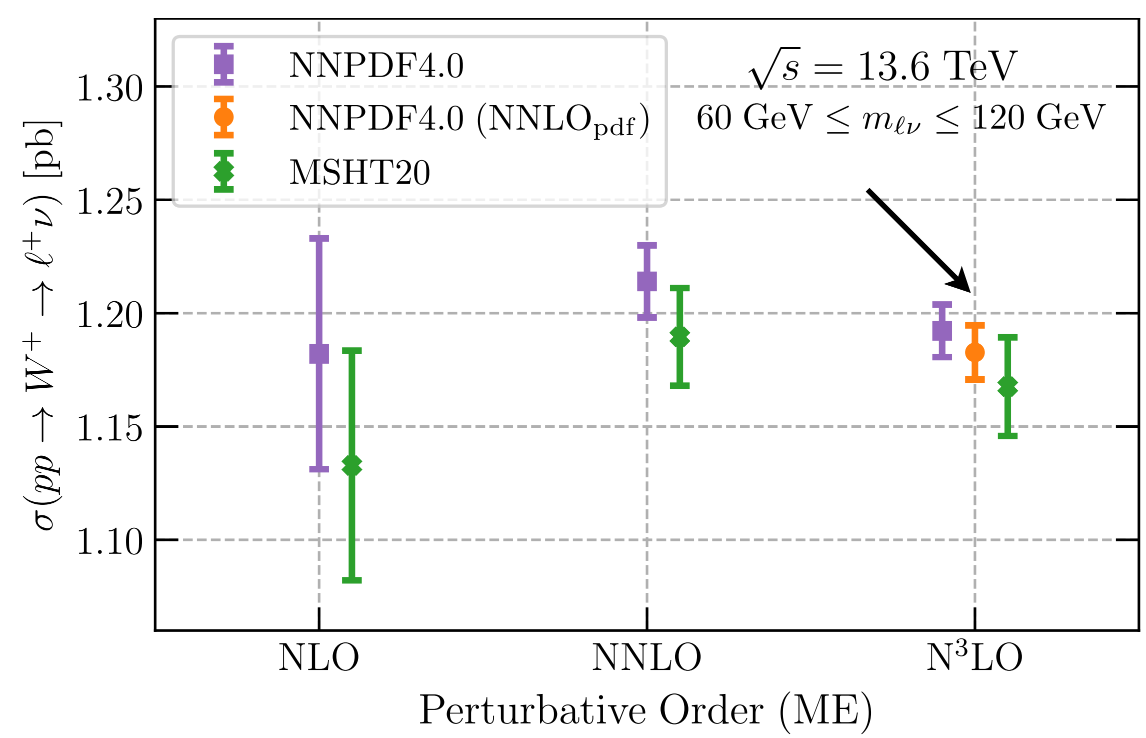
Neutral-current Drell-Yan



Charged-current Drell-Yan







The Valence Charm Content of the Proton

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, ***arXiv:2311:00743***

Disentangling intrinsic charm

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

Extracted phenomenologically from data

from pQCD evolution and matching

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

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

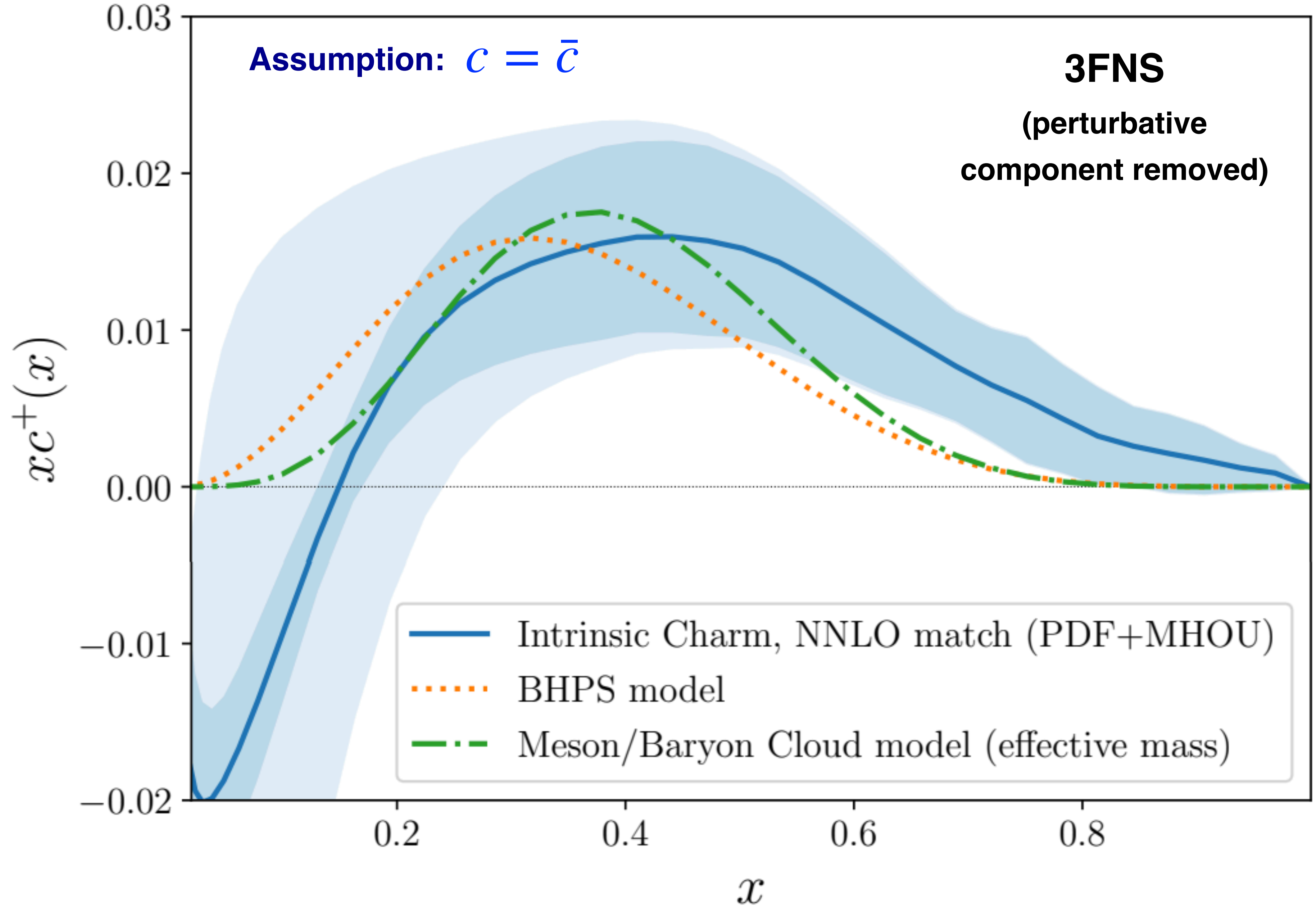
$$c^{(n_f=3)}(x,Q) = c_{(\mathrm{intr})}(x)$$

Intrinsic (3FNS) Charm

- Scale-independent
- PDF and MHO uncertainties

EKO Evolution Kernel Operators

3FNS charm



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

The valence charm PDF

- No reason why i**ntrinsic 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

- No perturbative mechanism generates a (sizeable) charm valence PDF: best **evidence for IC**

The valence charm PDF

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

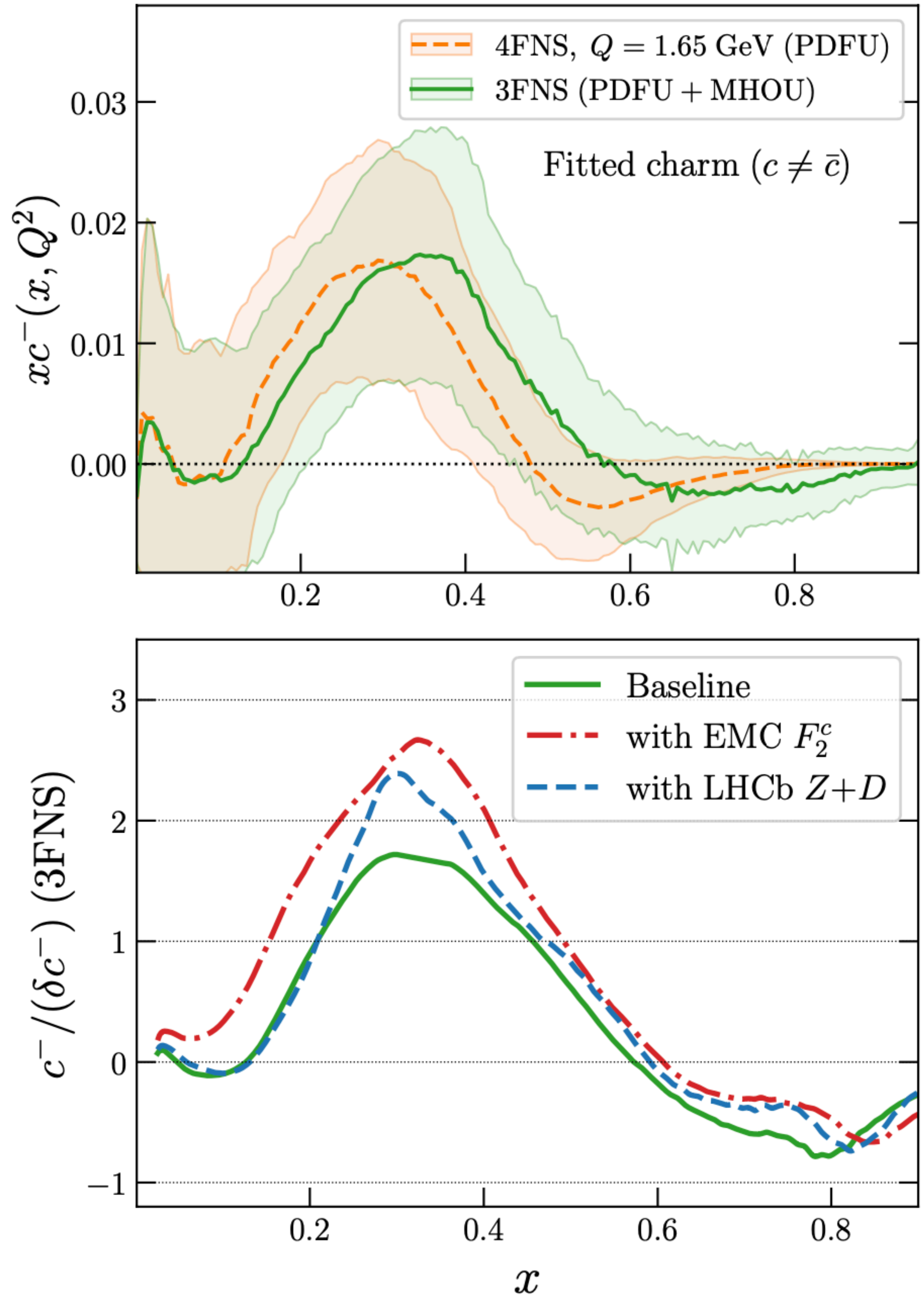
  i.e. up, down, and strange quark PDFs are asymmetric

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

- No perturbative mechanism generates a (sizeable) charm valence PDF: best **evidence for IC**

> - Preference for a **non-zero, positive IC asymmetry** around *x*=0.3
> - Consistent with the independent constraints from **EMC F_2^c** and **LHCb Z+D**

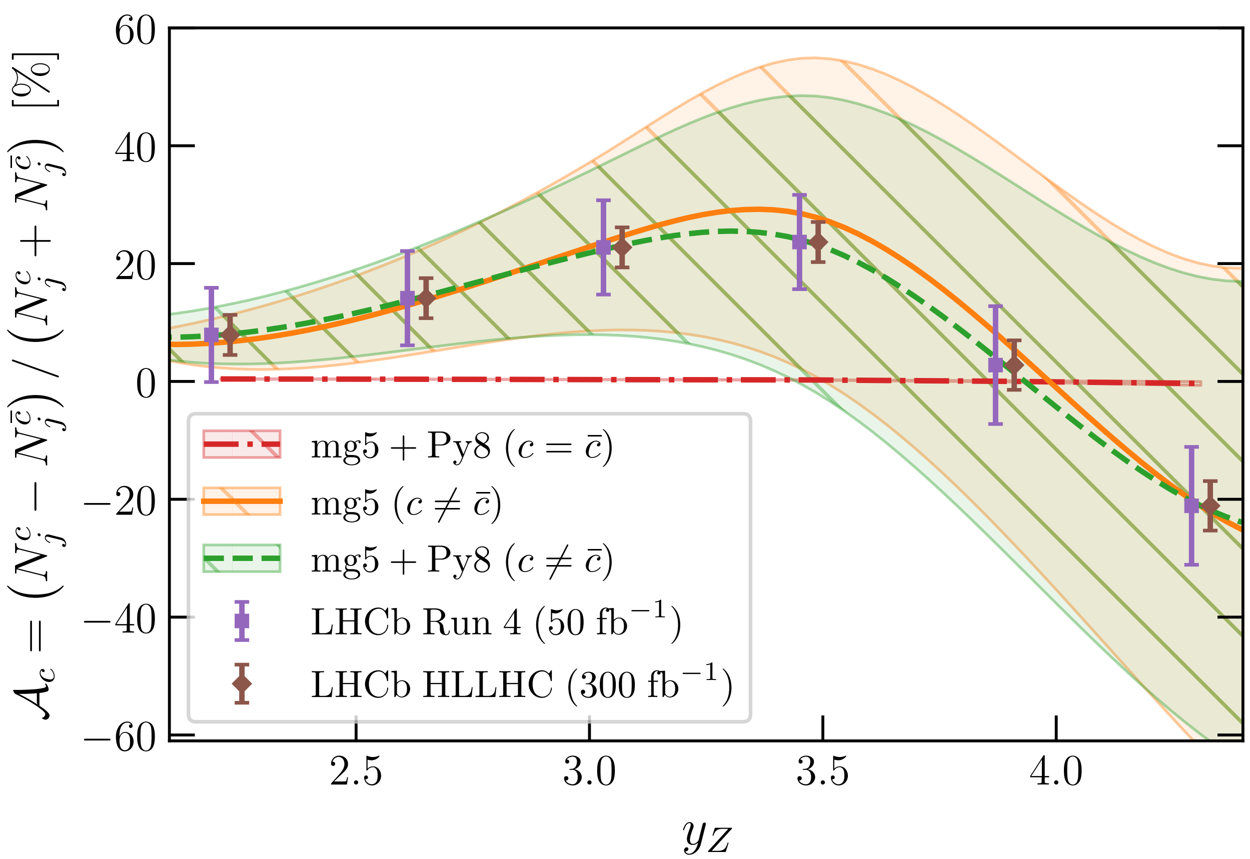
Total charm PDF (4FNS & 3FNS) essentially unaffected

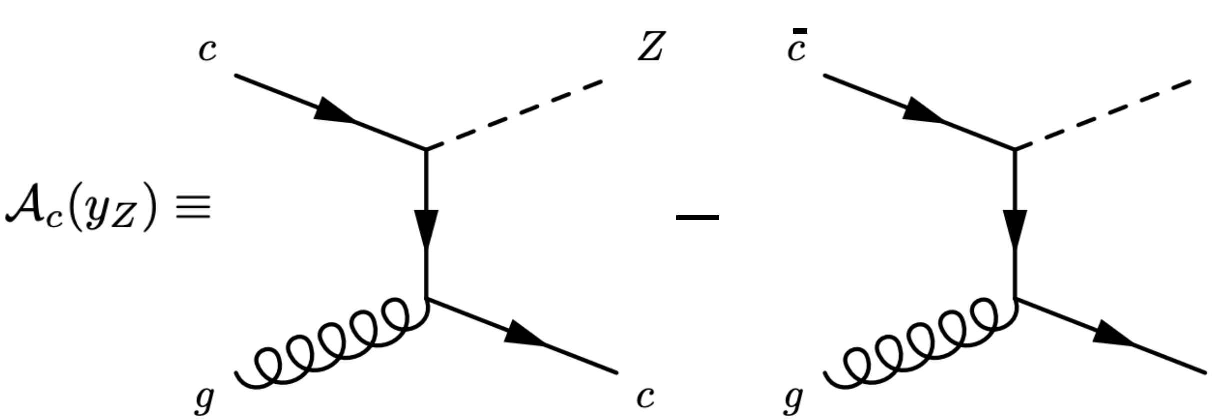


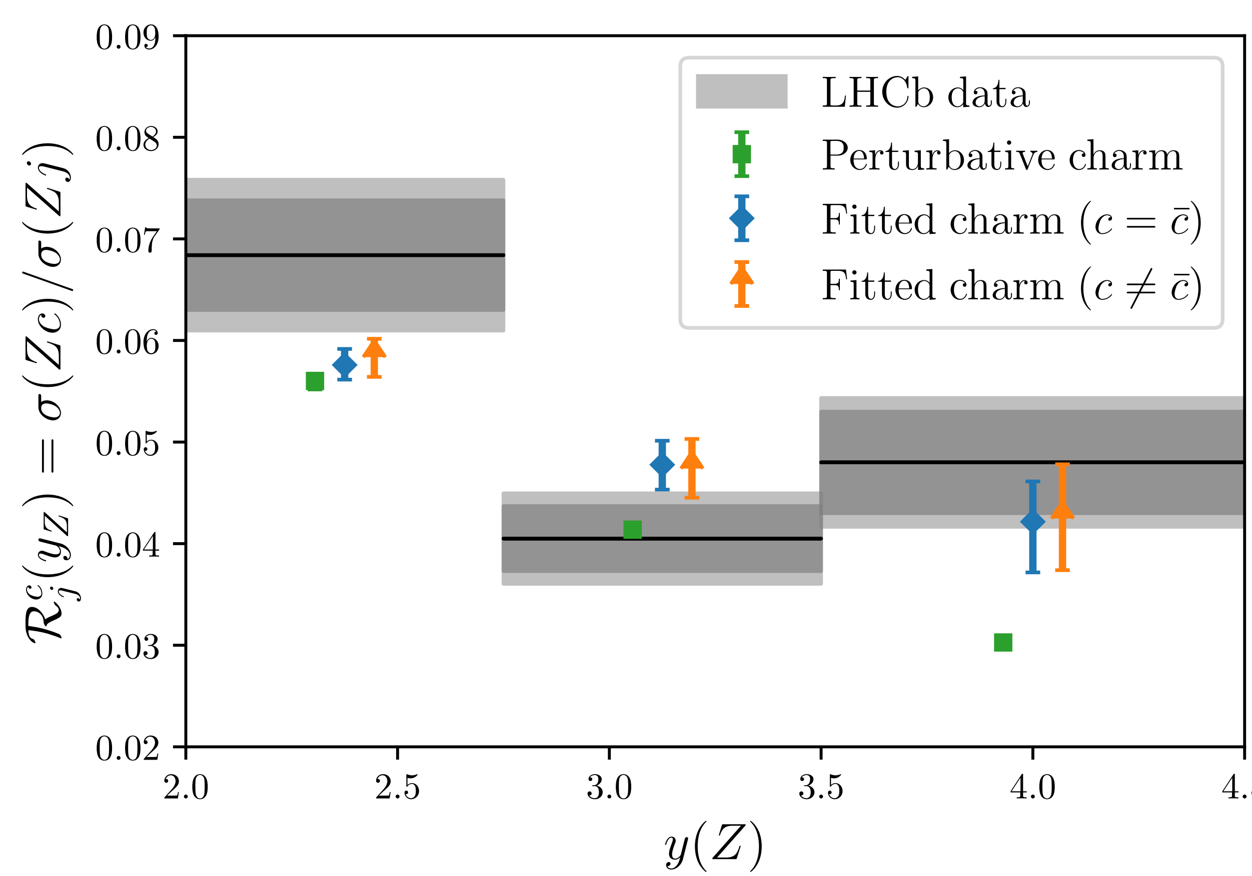
Charm asymmetries at LHCb

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

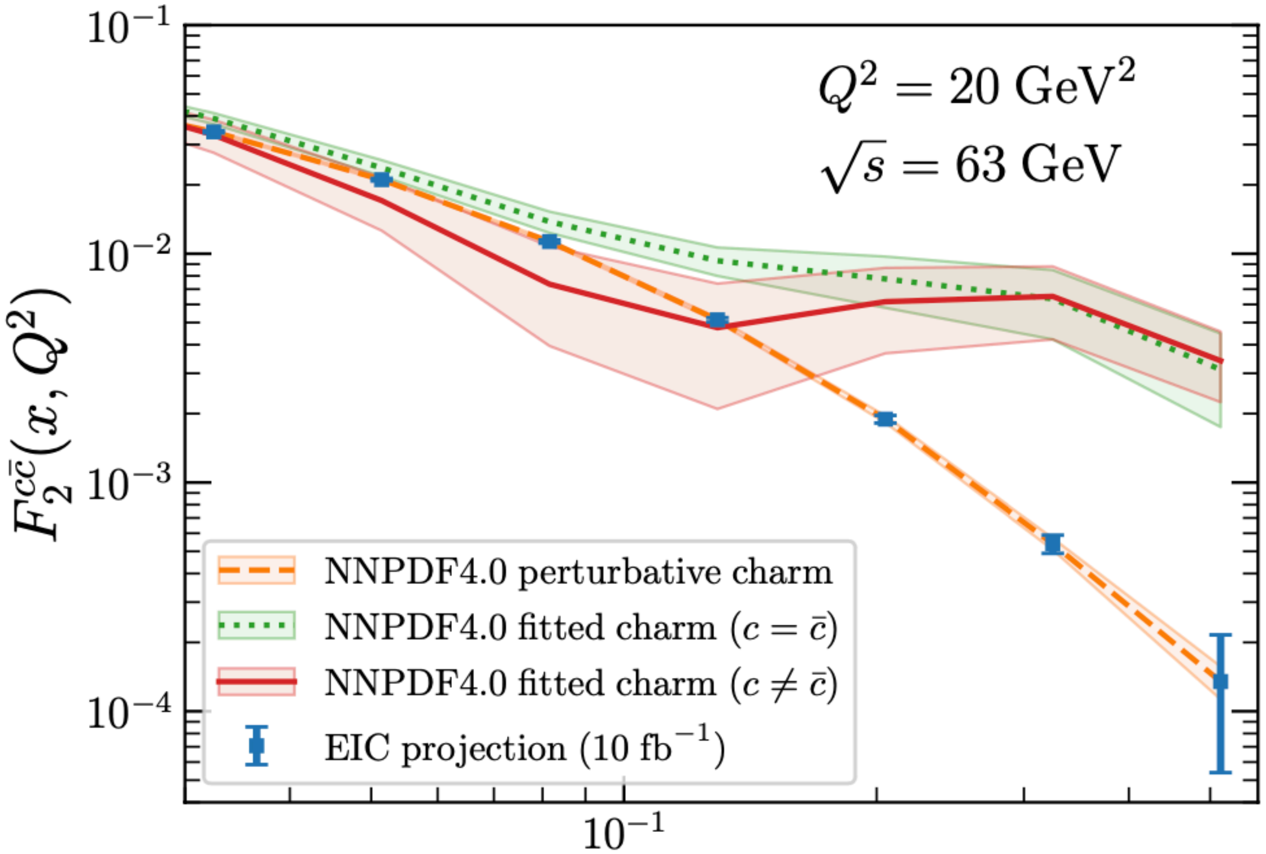
- Projections for LHCb *Z+D* measurements, constructing an **asymmetry between final states with D and Dbar mesons**
- Data from **upcoming LHC runs** will confirm or falsify a non-zero charm valence in the proton
- Ideally the measurement should be carry out in terms of **IRC-safe flavour jets,** to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

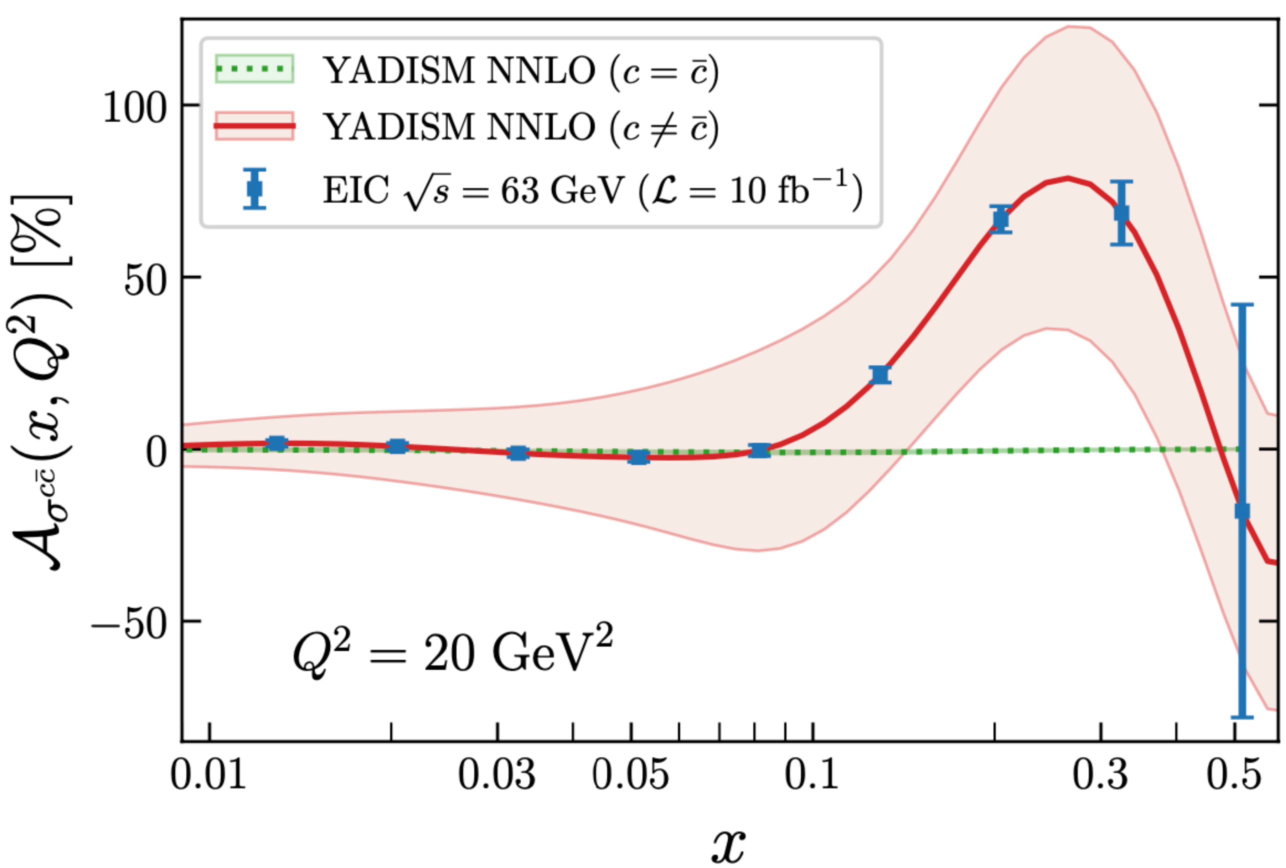






Charm asymmetries at the EIC





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

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

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

Charm-tagged EIC projections: arXiv:2107.05632

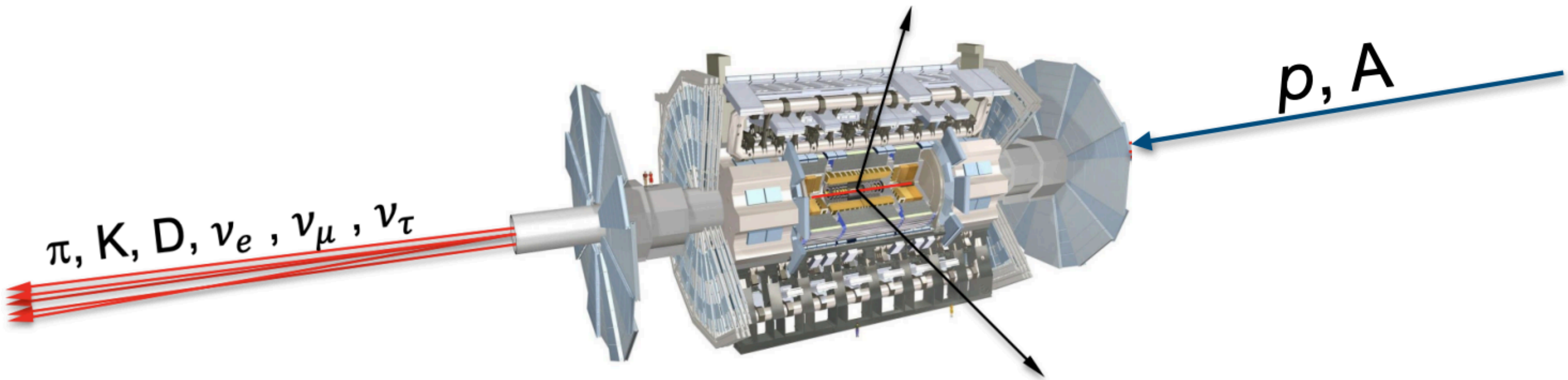
- Even at low luminosities, EIC will **cleanly identify the charm valence PDF** if non-zero

The LHC as a Neutrino-Ion Collider

J. M. Cruz-Martinez, M. Fieg, T. Giani, P. Krack, T. Makela, T. Rabemananjara, and J. Rojo***, arXiv:2309.09581***

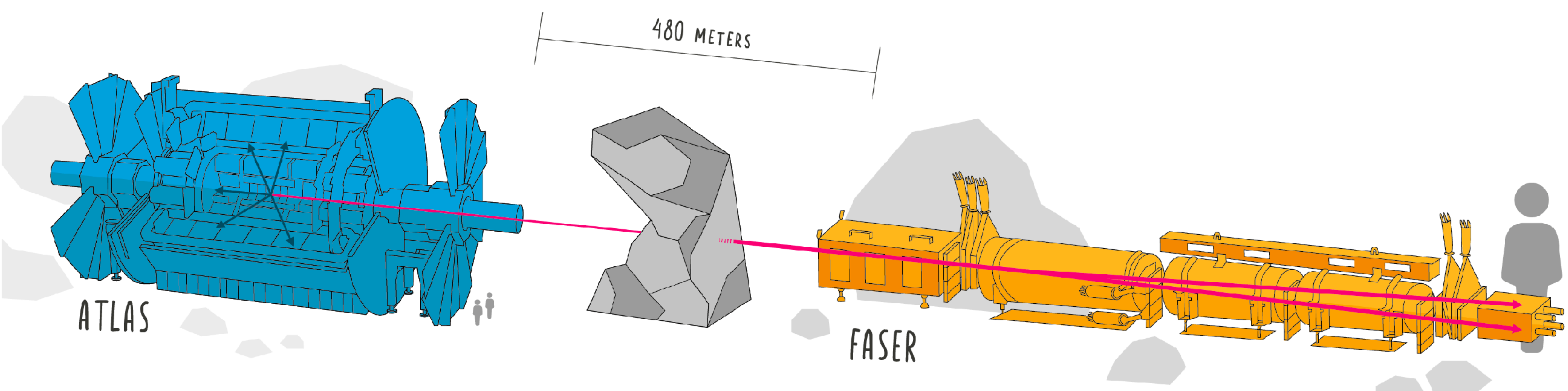
Neutrinos at the LHC

- LHC collisions result into a **large flux of energetic neutrinos** which escape the detectors unobserved: **major blind spot of the LHC**



- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

solution: install **far-forward detectors** instrumenting an hitherto uncharted region



The dawn of the LHC neutrino era

- Two far-forward experiments, **FASER** and **SND@LHC**, have been instrumenting the LHC far-forward region since the begin of Run III and reported **evidence for LHC neutrinos** (March 2023)

PHYSICAL REVIEW LETTERS **131,** 031801 (2023)

Editors' Suggestion | Featured in Physics

First Direct Observation of Collider Neutrinos with FASER at the LHC

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of 35.4 fb^{-1} using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

DOI: 10.1103/PhysRevLett.131.031801

PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

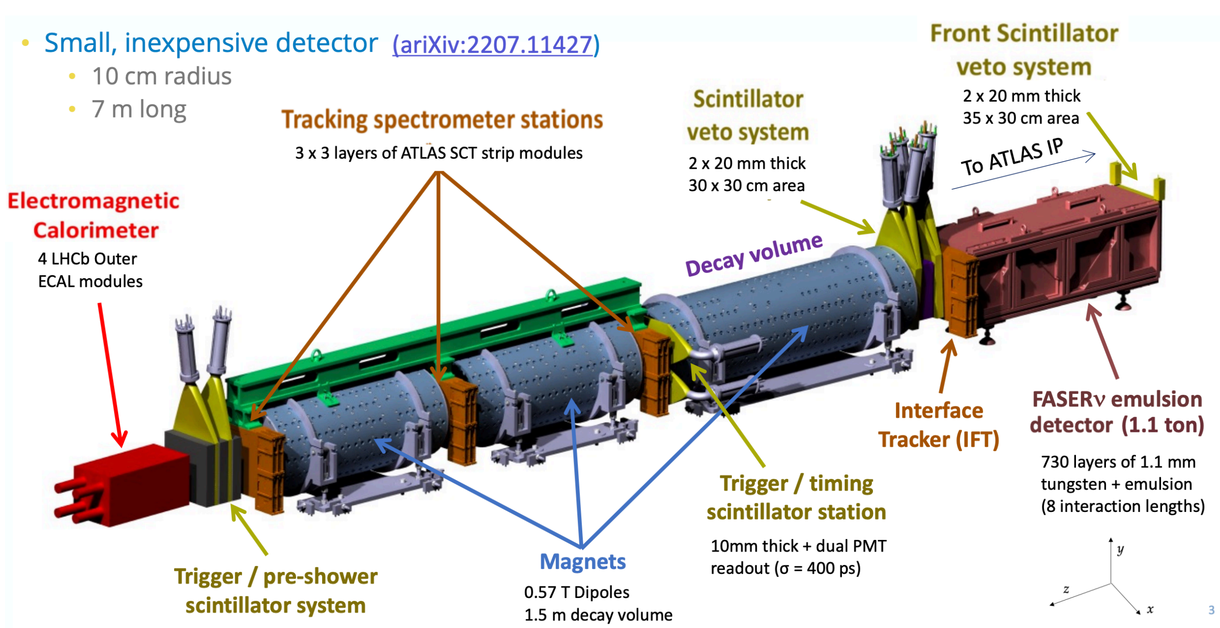
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

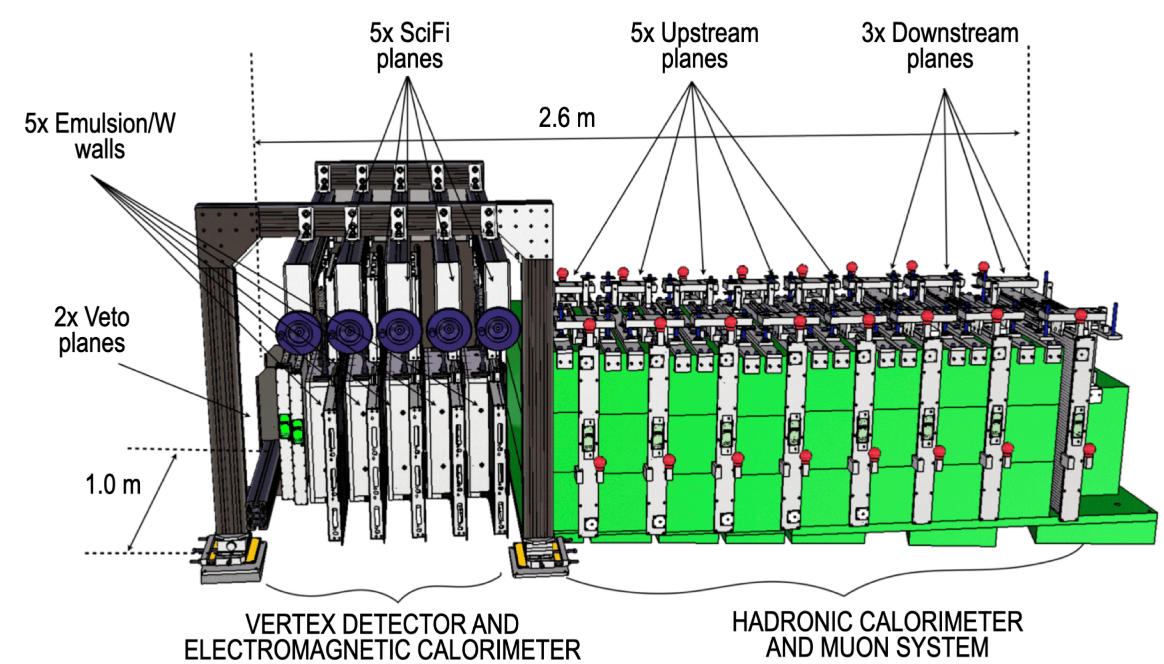
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_μ interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed ν_μ signal.

DOI: 10.1103/PhysRevLett.131.031802

153 neutrinos detected, 151± 41 expected

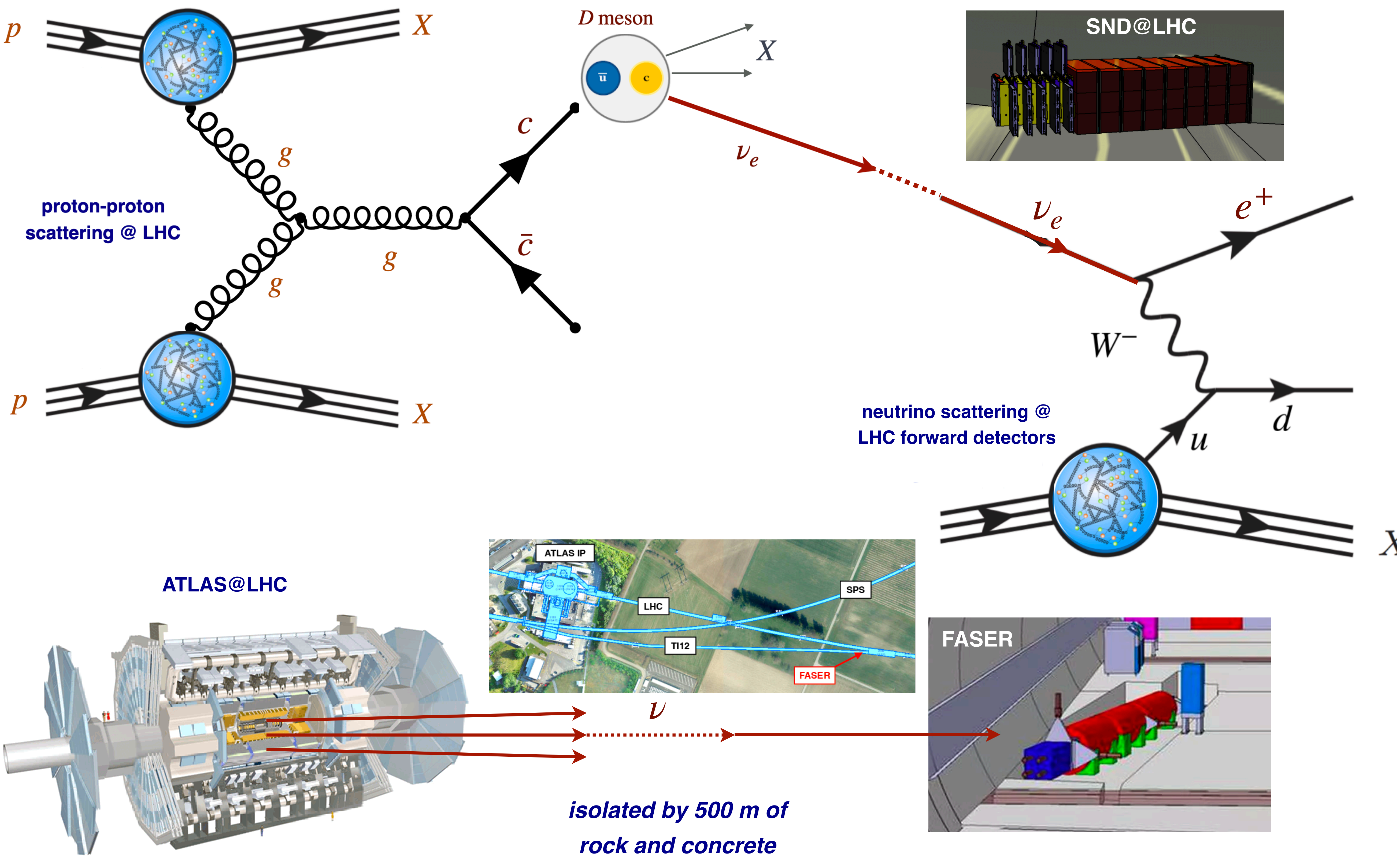
8 neutrinos detected, 4 expected



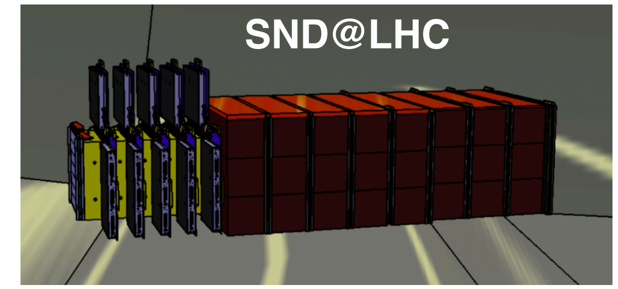


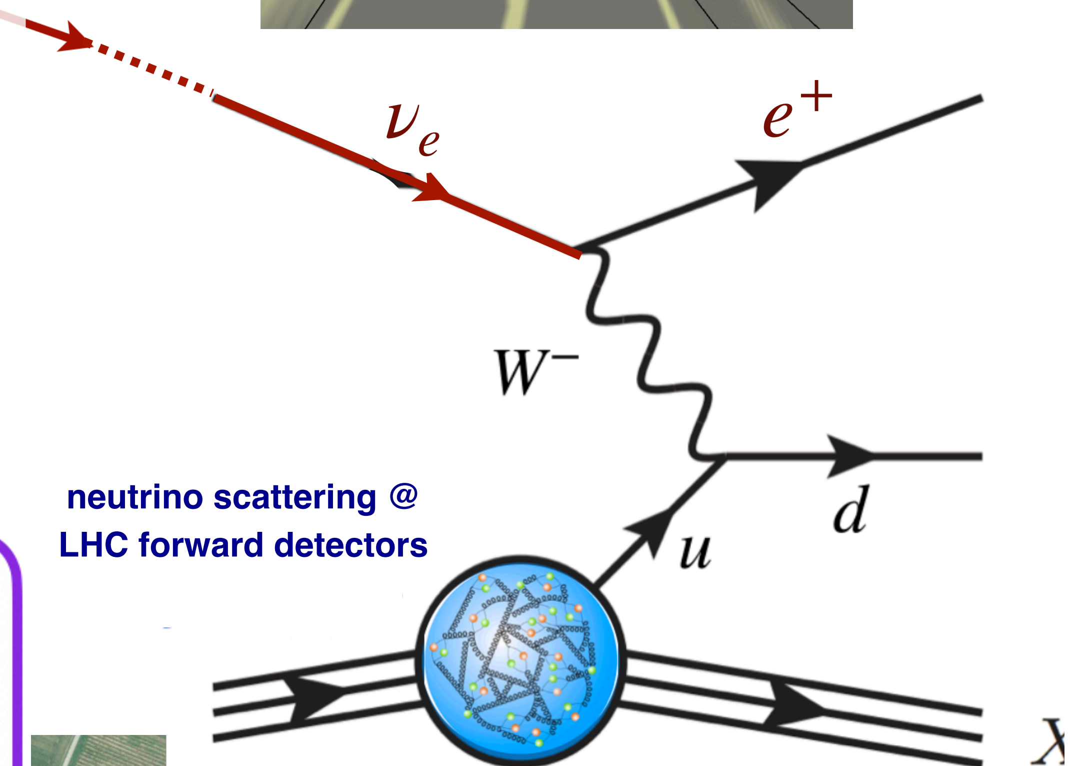
Now is the time to start exploiting their physics potential

Neutrinos at the LHC



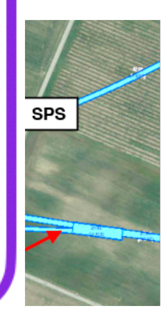
Neutrinos at the LHC

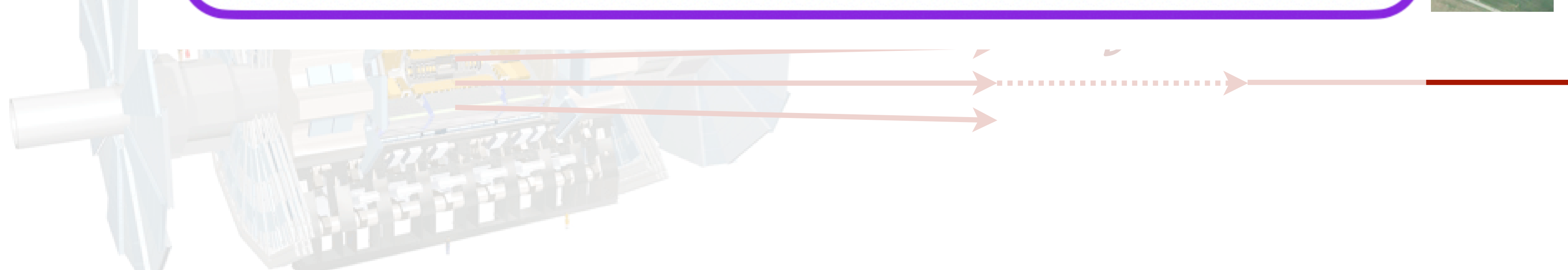


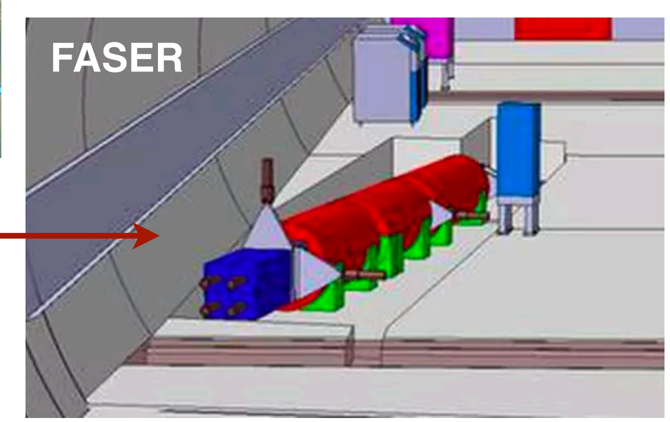


QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's

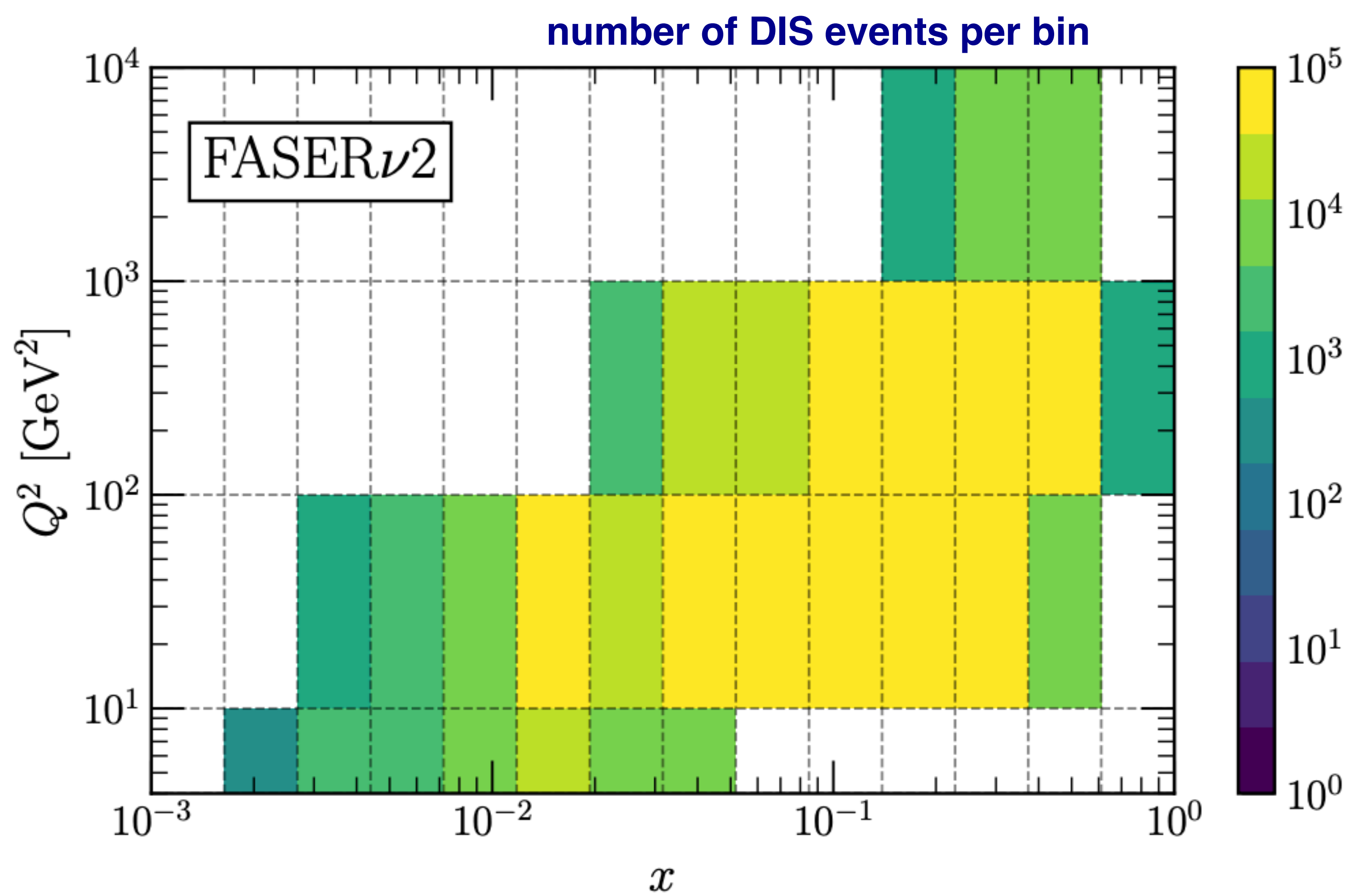






Neutrinos at the LHC

- Generate **DIS pseudo-data** at current and proposed LHC neutrino experiments
- Fully differential calculation based on **state-of-the-art QCD** calculations
- Model **systematic errors** based on the expected performance of the experiments
- Consider both inclusive and **charm-production DIS**



Events per bin

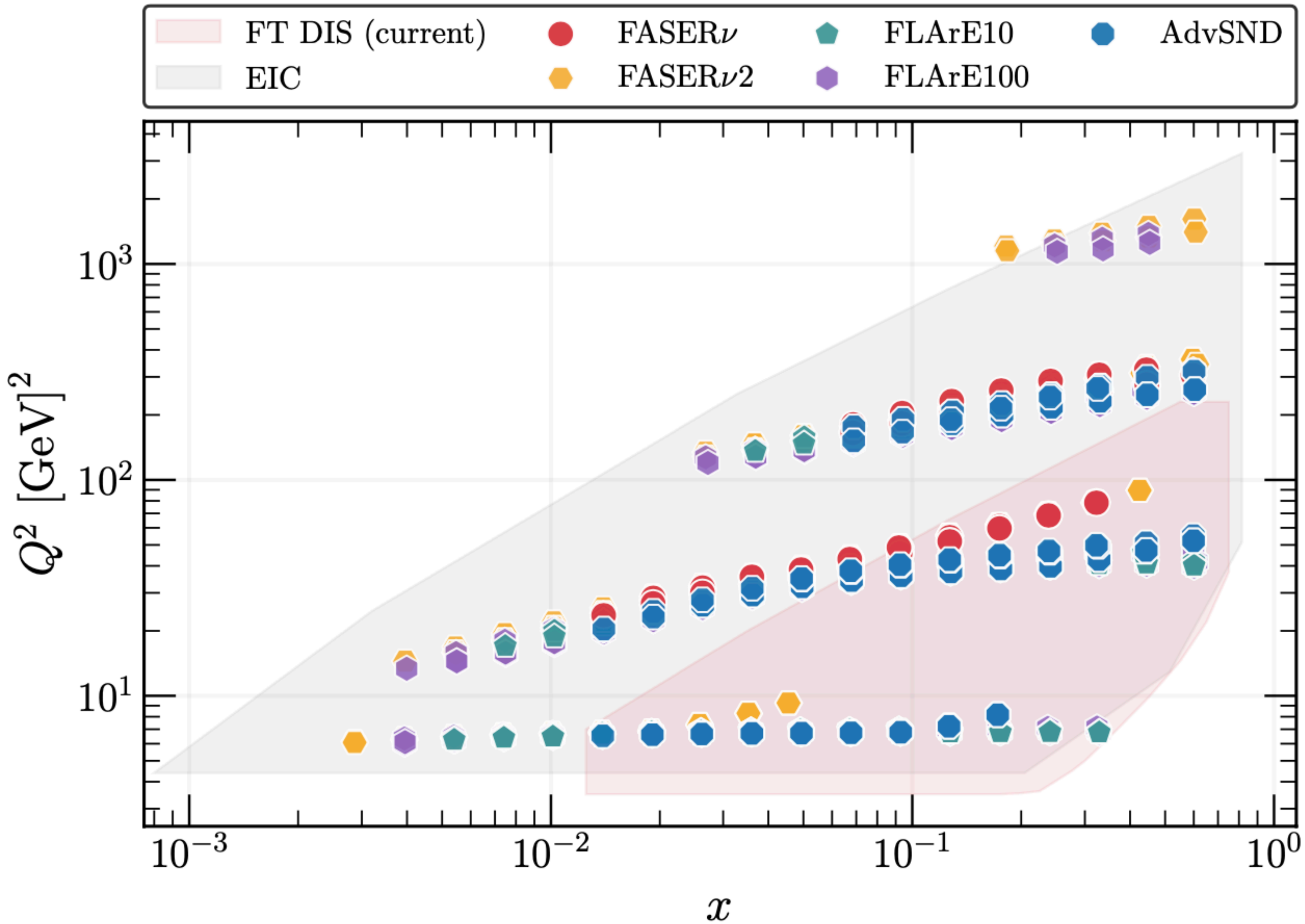
$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

Geometry — *Binning* — *neutrino fluxes (include rapidity acceptance)* — *DIS differential cross-section* — *Acceptance*

Based on **current designs**, may be different in final experiments

$$\begin{aligned} E_\nu &= E_h + E_\ell \,, \\ Q^2 &= 4(E_h + E_\ell) E_\ell \sin^2(\theta_\ell/2) \\ x &= \frac{4(E_h + E_\ell) E_\ell \sin^2(\theta_\ell/2)}{2 m_N E_h} \end{aligned}$$

Neutrinos at the LHC

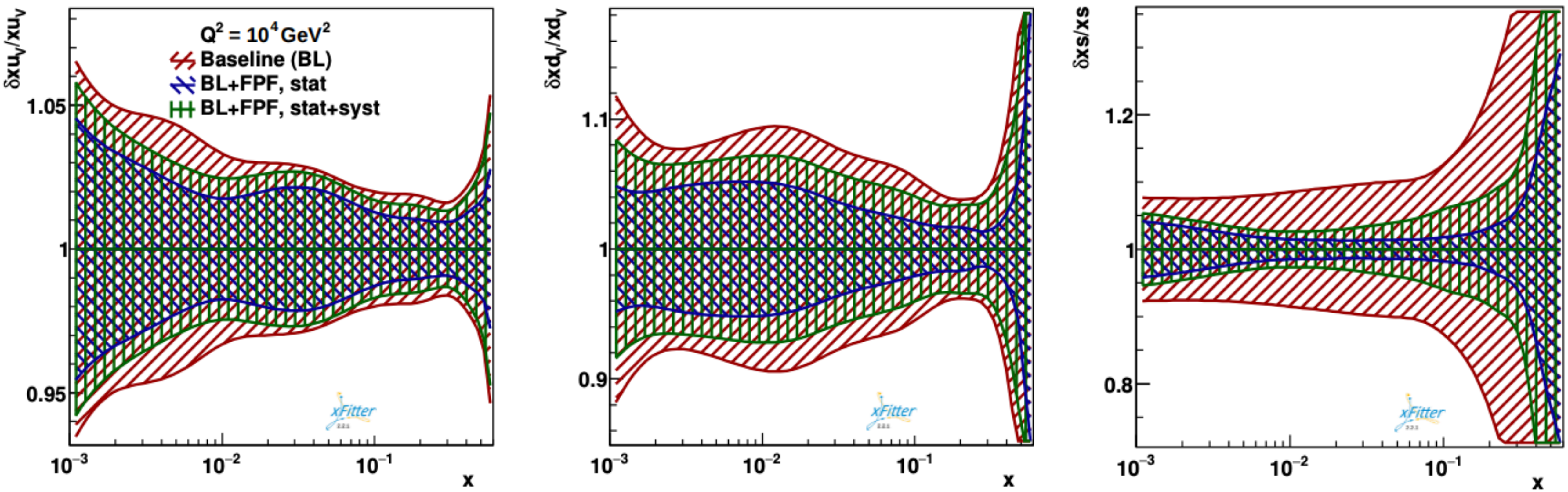


x: momentum fraction of quarks/gluons in the proton

Q²: momentum transfer from incoming lepton

- Continue highly succesful program of neutrino **DIS experiments @ CERN,**
- **Expand kinematic coverage** of available experiments by an order of magnitude in *x* and *Q²*
- Charged-current counterpart of the **Electron-Ion Collider** in a comparable region of phase space

PDF constraints from LHC neutrinos



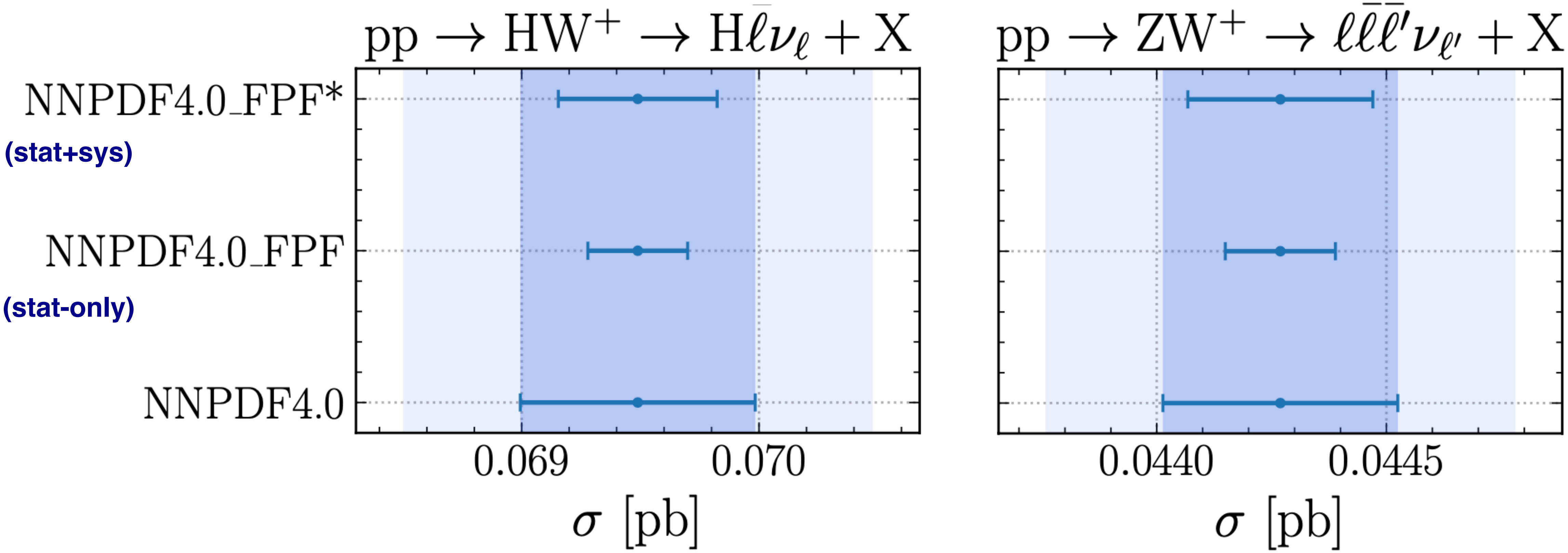
- Impact on proton PDFs quantified by both the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**

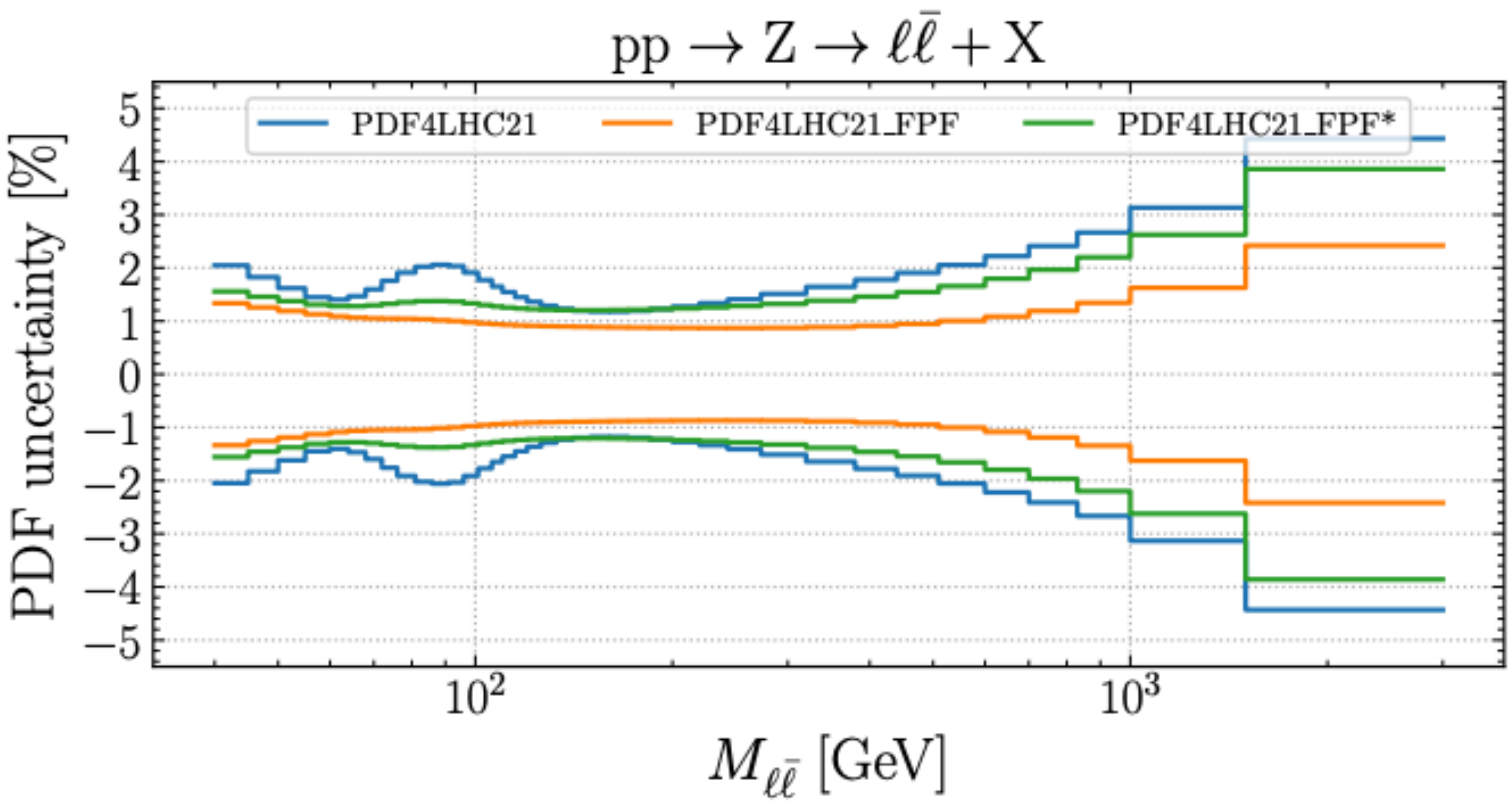
new: PineAPPL interface to xFitter!
enables use of YADISM, MATRIX, aMC@NLO calculations

- Impact on **up/down valence quarks** as well as in **strangeness,** ultimately limited by systematics

Far-forward neutrino detectors effectively extend CERN with a **Neutrino-Ion Collider** by ``recycling'' an otherwise discarded beam (with the highest energies ever achieved in a lab!)

PDF constraints from LHC neutrinos





- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)

- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

e.g. high-mass dilepton resonances

Summary and outlook

- ☑ Crucial ingredients to **LHC phenomenology at 1% precision** are N^{3}LO PDFs which account for all sources of theory uncertainties

- ☑ The new aN^{3}LO NNPDF4.0 enable **consistent N^{3}LO calculations** of LHC cross-sections

- ☑ Preliminary assessment: **stability of the gluon-fusion Higgs** cross-section, improved perturbative convergence of **Drell-Yan production**

- ☑ Extended NNPDF methodology to **constrain charm valence PDF from data**, finding preference for a non-zero, positive result peaking around x=0.3

- ☑ S non-zero valence charm PDF cannot be generated perturbatively: measurements of charm asymmetries at the EIC and the LHC **represent the ultimate smoking gun of IC**

- ☑ The high-intensity, high-energy neutrino beam produced at the LHC enables unique opportunities for QCD studies, realising a **charged-current analog of the EIC**

Summary and outlook

- Crucial ingredients to **LHC phenomenology at 1% precision** are N^3LO PDFs which account for all sources of theory uncertainties

- The new aN^3LO NNPDF4.0 enable **consistent N^3LO calculations**

- Preliminary assessment: **stability of the gluo** urbative convergence of **Drell-Yan productio**

- Extended NNPD **harm valence PDF from data**, finding preferen ult peaking around x=0.3

- S valence charm PDF cannot be generated perturbatively, measurements of c asymmetries at the EIC and the LHC **represent the ultimate smoking gun of IC**

- The high-intensity, high-energy neutrino beam produced at the LHC enables unique opportunities for QCD studies, realising a **charged-current analog of the EIC**

Thanks for your attention

Extra Material

Fit settings

Fit	kinematic cuts	IHOUs	MHOU (DIS)	MHOU (hadronic)
NNPDF4.0 aN^{3}LO (baseline)	$Q^2 \geq 3.5$ GeV^2	Yes	No	3-point (μ_R variations)
NNPDF4.0 aN^{3}LO MHOU	$Q^2 \geq 13.96$ GeV^2	Yes	7-point (μ_R, μ_F variations)	7-point (μ_R, μ_F variations)
NNPDF4.0 aN^{3}LO MHOUcuts	$Q^2 \geq 13.96$ GeV^2	Yes	No	3-point (μ_R variations)

Theory covariance matrix for DIS data

$$\mathrm{cov}_{\mathrm{th},ij} = \mathrm{cov}_{\gamma_{\mathrm{IHOU}},ij} + \mathrm{cov}_{\mathrm{MHOU},ij} + \mathrm{cov}_{C_{\mathrm{IHOU}},ij} + \mathrm{cov}_{\mathrm{nucl},ij}$$

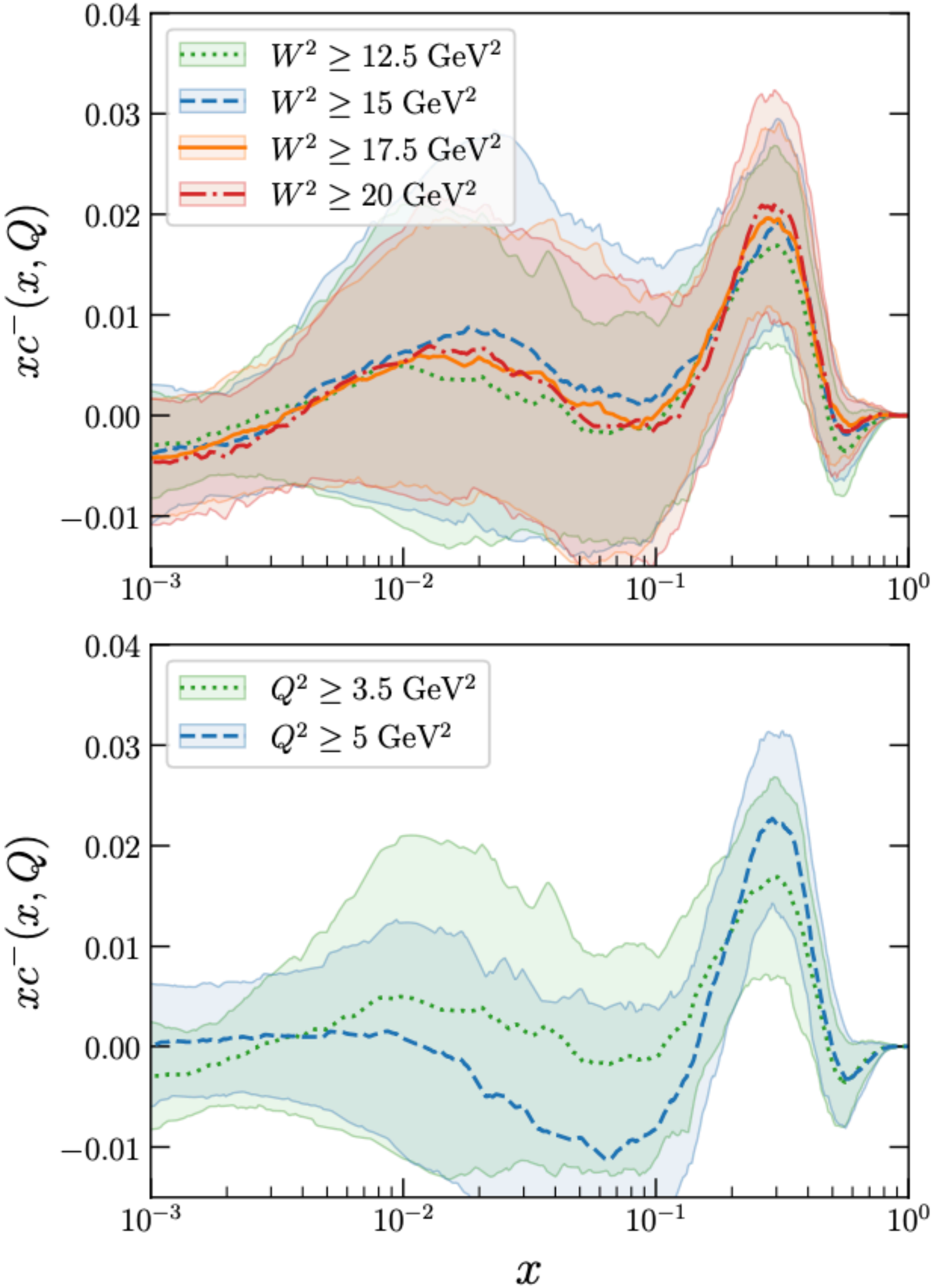
Theory covariance matrix for hadronic data

$$\mathrm{cov}_{\mathrm{th},ij} = \mathrm{cov}_{\gamma_{\mathrm{IHOU}},ij} + \mathrm{cov}_{\mathrm{MHOU},ij} + \mathrm{cov}_{\mathrm{nucl},ij}$$

- Based on the **new theory pipeline** underlying the NNPDF global analysis framework (EKO, YADISM, PineAPPL, pineko, …) arXiv:2302:12124
- Same dataset as in NNPDF4.0, same fitting methodology

Charm valence stability

kinematic cuts & higher twists



dataset & charm mass