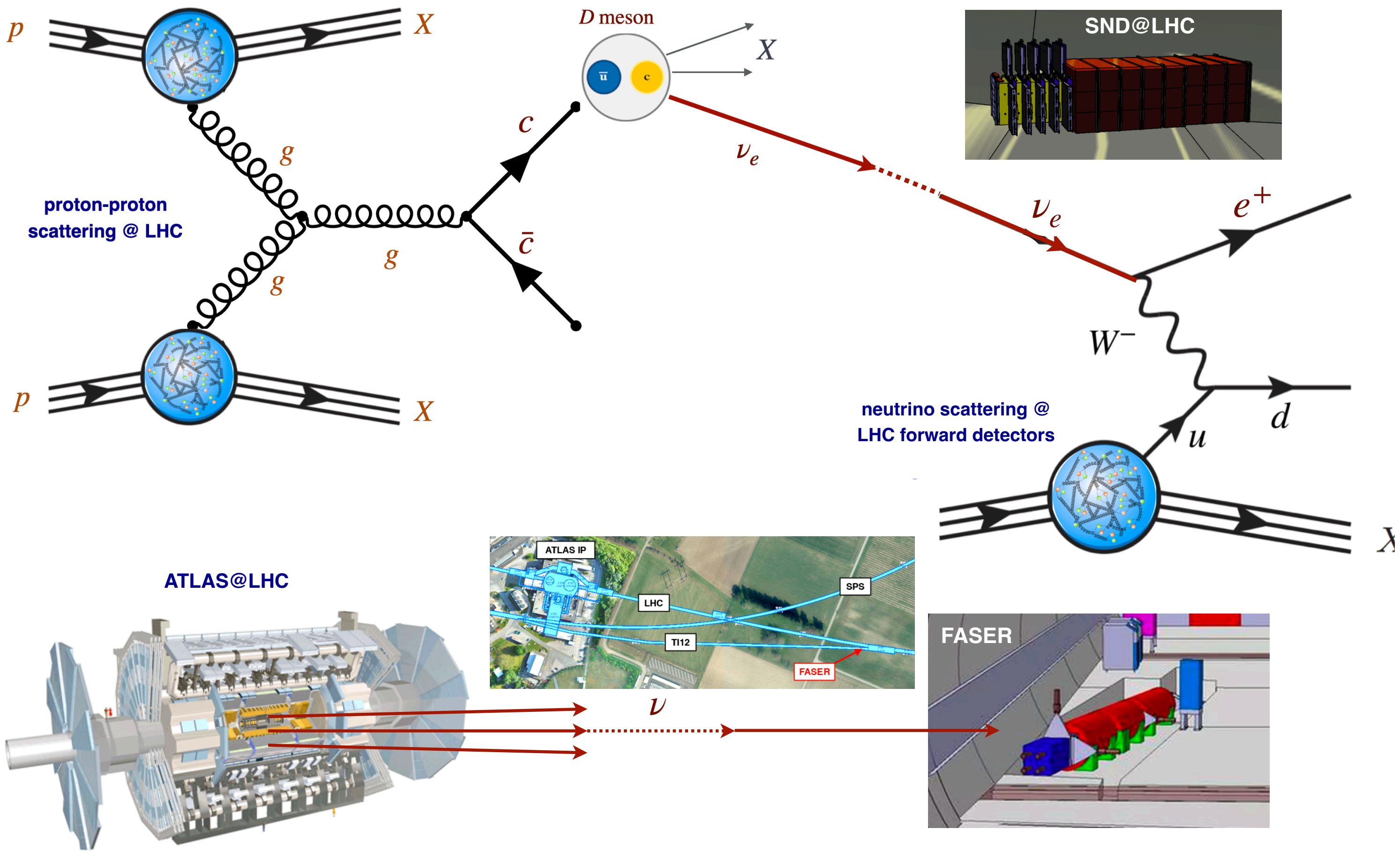
WG1: Neutrino Interactions and DIS

Juan Rojo, VU Amsterdam & Nikhef



CERN Forward Physics Facility Theory Workshop, CERN, 19.06.2023

WG1 Roadmap

Forward Physics Facility

Physics Working Group 1: Neutrino Interactions and Deep-Inelastic Scattering with High-Energy Neutrinos

Scientific Goals. This Working Group includes topics related to high-energy neutrino interactions at the FPF and using these high-energy neutrinos in the Deep-Inelastic Scattering process to constrain proton and nuclear structure. Topics include how well we can measure the neutrino cross-section at TeV energies and what we can learn from this, and how well we can constrain proton and nuclear DIS with the FPF neutrino beam. Also, we'd like to understand given the measurements of neutrino structure functions, how well the incoming neutrino flux can be constrained.

To begin with, we assume a perfectly known neutrino flux and a perfect detector (with finite acceptance) for our projections. Subsequently, we model detector simulation and the fact that the incoming neutrino flux carries large uncertainties.

This Working Group is closely related with WG2, in that measuring the incoming neutrino flux imposes constraints on charm meson and light hadron production in the far forward region at the LHC and in turn on the small-x and large-x PDFs of the colliding protons. We also plan to assess PDF sensitivity in "production" (as opposed to in "scattering") at some point in this WG studies.

In the following we indicate some possible **goals for this WG**. We consider three timescales: the FPF5 meeting, a February 2023 deadline (internal, FPF proponents have been asked to report on the progress by then), and the Conceptual Design Report (CDR) deadlines. These goals are not written in stone and can be discussed once the working group is formed.

FPF5 goals:

- Assemble a group of interested people and make an initial work plan.
- Collect the available tools and results and agree on which ones will be used.
- First estimate of how detector acceptance constraints (x,Q) range accessible.
- First discussion of key observables: inclusive structure functions, dimuon production, what else?
- First discussion of physics interest in neutrino cross-section measurement at TeV energies.
- Start an overleaf document summarizing our ideas, plans, and initial results.

February goals:

- Produce first set of FPF pseudo-data on neutrino inclusive and charm structure functions, including estimate of experimental uncertainties
- Assess impact on proton and nuclear PDFs using various fitting tools (e.g. xFitter, the open source NNPDF fitting code, the codes from other global (nuclear) PDF fitters, ….)
- First estimate of how well nuclear effects (shadowing, EMC effect) can be measured at the FPF.
- Study impact of detector size and acceptance, need of spectrometer, and how this modifies PDF constraints.
- Study possible interest for PDF studies of fixed target DIS using muon beams at the FPF, and repeat the pseudo-data exercise in this case
- State of the art predictions for neutrino structure functions that extend to the small-Q region and corresponding predictions of inclusive cross-sections in the FPF kinematics, and complete characterisation of the associated uncertainties.

CDR goals (partial overlap with **WG2**):

- Official sets of FPF neutrino DIS pseudo-data (and maybe also for muons?) in various scenarios for the experiments and detector, and study of their impact on proton and nuclear PDFs
- Official set of FPF pseudo-data on neutrino cross-section measurements, and study of its impact on e.g. anomalous neutrino interactions or EFT operators
- Official set of FPF predictions for neutrino fluxes, and quantitative study on the constraints that the flux measurement imposes on the charm production cross-section and on the small-x and large-x PDFs (in particular on the small-x gluon and the large-x intrinsic charm)
- Projections for the precision for which the FPF will measure: small-x gluon, large-x intrinsic charm, the strange PDFs, and the large-x quark flavor separation in protons and nuclei, among others. What else?
- Definition of key observables to extract the above information and how the projected uncertainty depends on experimental choices
- Detailed simulation pipeline translating the impact of theory choices (PDFs, charm production models, … etc) into the expected event rates at the FPF
- Study of the implication of FPF measurements for high-energy astrophysics: UHE neutrino cross-sections, prompt neutrino flux, cosmic ray interactions, what else?

Experimentally-related questions

- What should the detector be able to do for PDF measurements?
- Do we want to have different target materials? Impact on A-dependence of nPDFs?
- How crucial is the separation of neutrinos and antineutrinos (with an spectrometer) in order to constrain PDFs at the FPF?
- How large should be the rapidity acceptance to constrain the small-x PDFs?
- How large a detector should be to have sufficient statistics for neutrino DIS?
- How do experimental systematic uncertainties degrade the PDF sensitivity? Is there anything specific in which we should focus?

The LHC as a Neutrino-Ion Collider

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Abstract

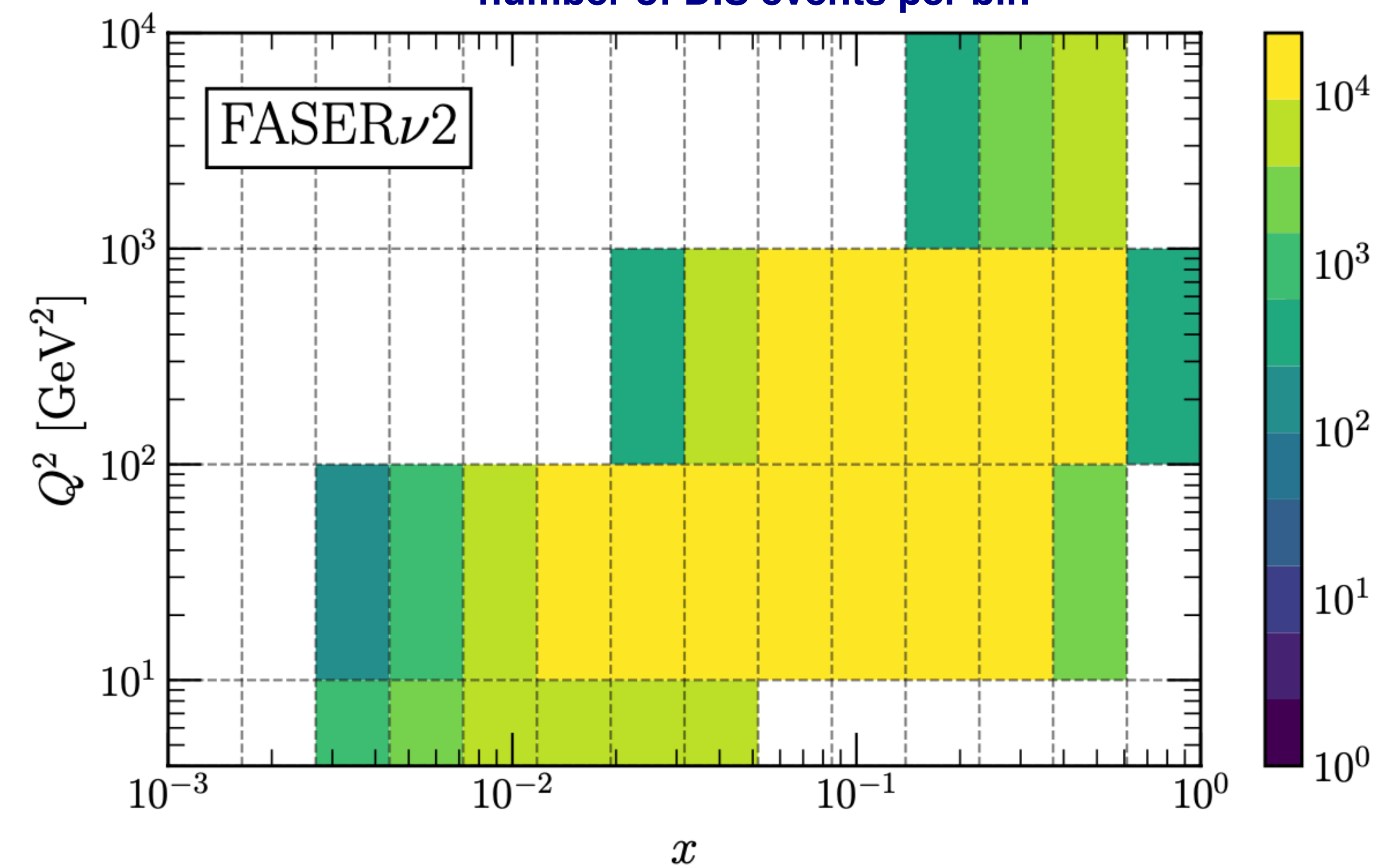
Proton-proton collisions at the LHC generate a high-intensity collimated beam of neutrinos in the forward (beam) direction, characterised by energies of up to several TeV. The recent observation of LHC neutrinos by FASERν and SND@LHC signals that this hitherto ignored particle beam is now available for scientific inquiry. Here we quantify the impact that neutrino deep-inelastic scattering (DIS) measurements at the LHC would have on the parton distributions (PDFs) of protons and heavy nuclei. We generate projections for DIS structure functions for FASERν and SND@LHC at Run III, as well as for the FASERν2, AdvSND, and FLArE experiments to be hosted at the proposed Forward Physics Facility (FPF) operating concurrently with the High-Luminosity LHC (HL-LHC). We determine that up to one million electron- and muon-neutrino DIS interactions within detector acceptance can be expected by the end of the HL-LHC, covering a kinematic region in x and Q^2 overlapping with that of the Electron-Ion Collider. Including these DIS projections into global (n)PDF analyses, specifically PDF4LHC21, NNPDF4.0, and EPPS21, reveals a significant reduction of PDF uncertainties, in particular for strangeness and the up and down valence PDFs. We show that LHC neutrino data enables improved theoretical predictions for core processes at the HL-LHC, such as Higgs and weak gauge boson production. Our analysis demonstrates that exploiting the LHC neutrino beam effectively provides CERN with a "Neutrino-Ion Collider" without requiring modifications in its accelerator infrastructure.

first FPF-WG1 publication!

Neutrino DIS 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**

number of DIS events per bin



Events per bin

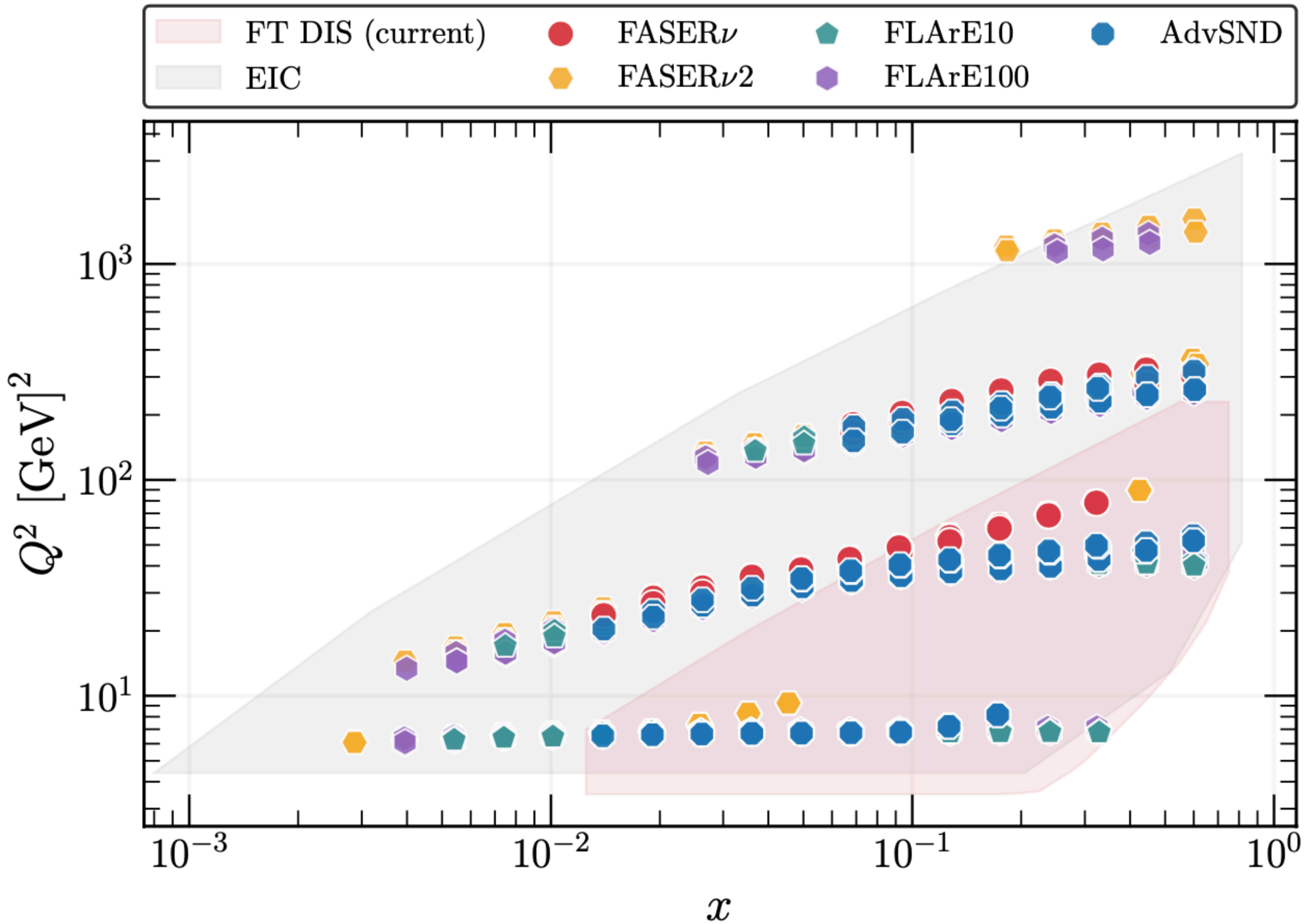
$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

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

Close collaboration between **theorists and experiments** crucial!

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

Neutrino DIS at the LHC



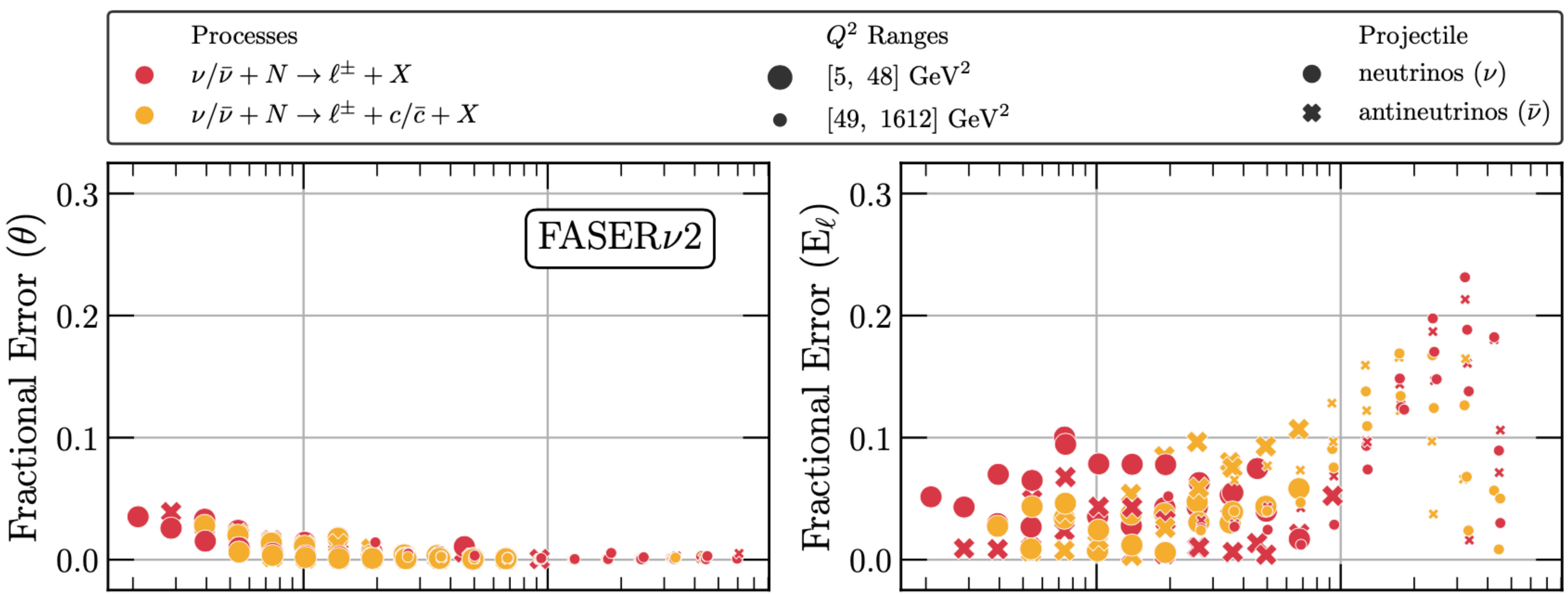
x: momentum fraction of quarks/gluons in the proton

***Q*²**: momentum transfer from incoming lepton

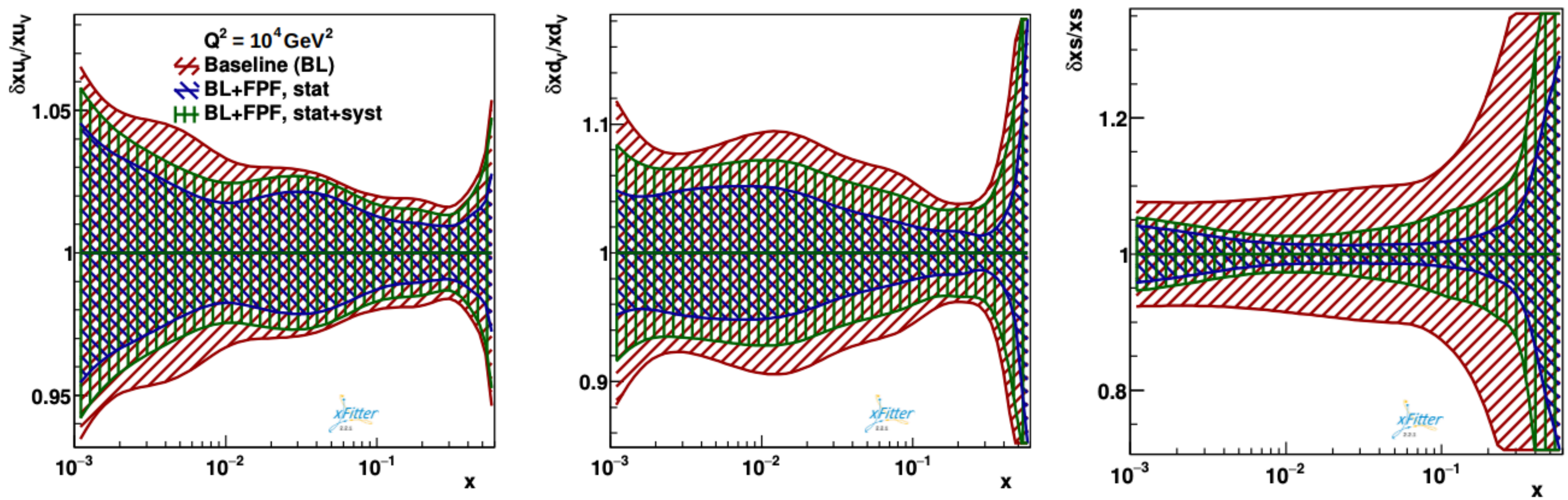
- Continue highly succesful program of neutrino **DIS experiments @ CERN,**
- **Expand kinematic coverage** of available experiments by an order of magnitude in x and Q^2
- Charged-current counterpart of the **Electron-Ion Collider** in a comparable region of phase space

Event yields, acceptance, systematics

Detector	before cuts	after DIS and acceptance cuts	acceptance efficiency
	$N_{\nu_e} + N_{\bar{\nu}_e},\ N_{\nu_\mu} + N_{\bar{\nu}_\mu}$	$N_{\nu_e} + N_{\bar{\nu}_e},\ N_{\nu_\mu} + N_{\bar{\nu}_\mu}$	$N_{\nu_e} + N_{\bar{\nu}_e},\ N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
FASERν	1.2k, 4.1k	610, 1.8k	51%, 44%
SND@LHC	280, 860	260, 700	92%, 81%
FASERν2	270k, 980k	170k, 510k	63%, 52%
AdvSND-far	19k, 66k	18k, 56k	95%, 85%
FLArE10	65k, 202k	64k, 110k	98%, 55%
FLArE100	427k, 1.3M	420k, 670k	98%, 52%

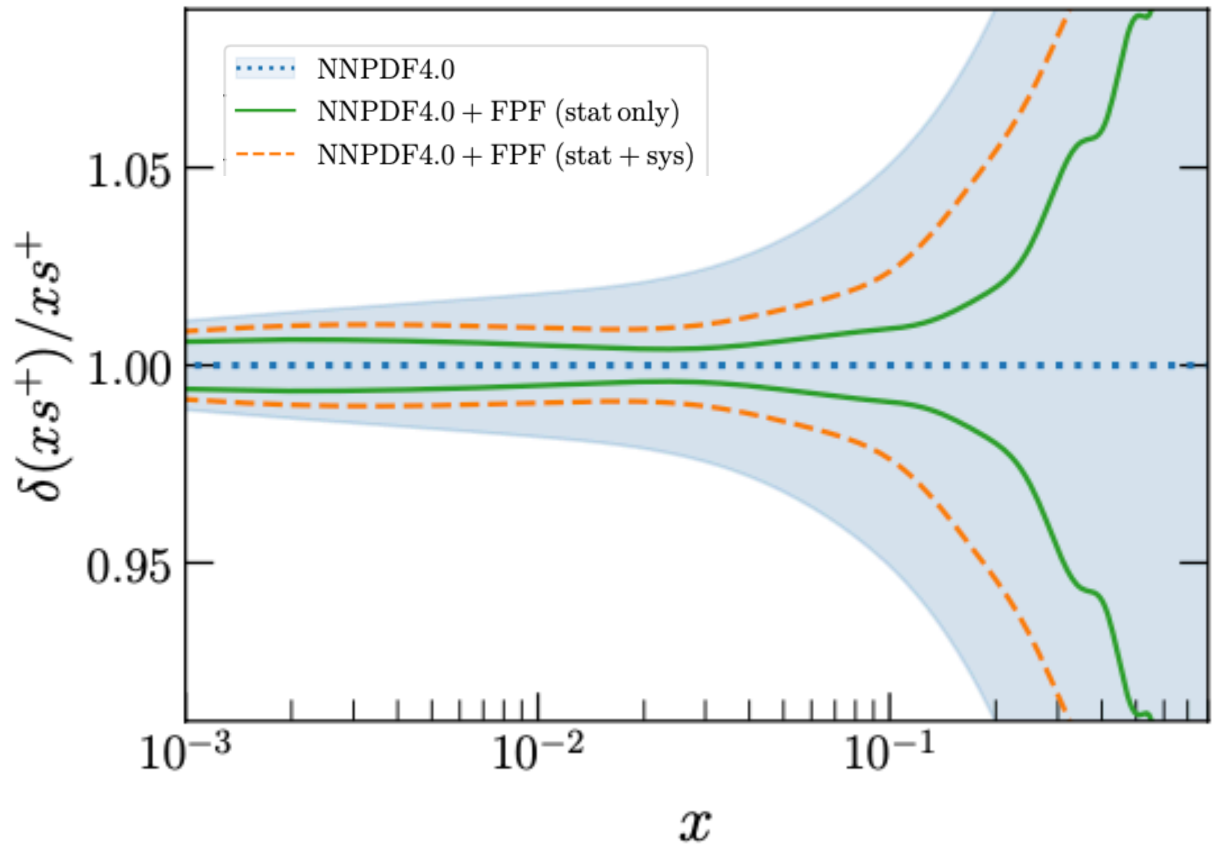


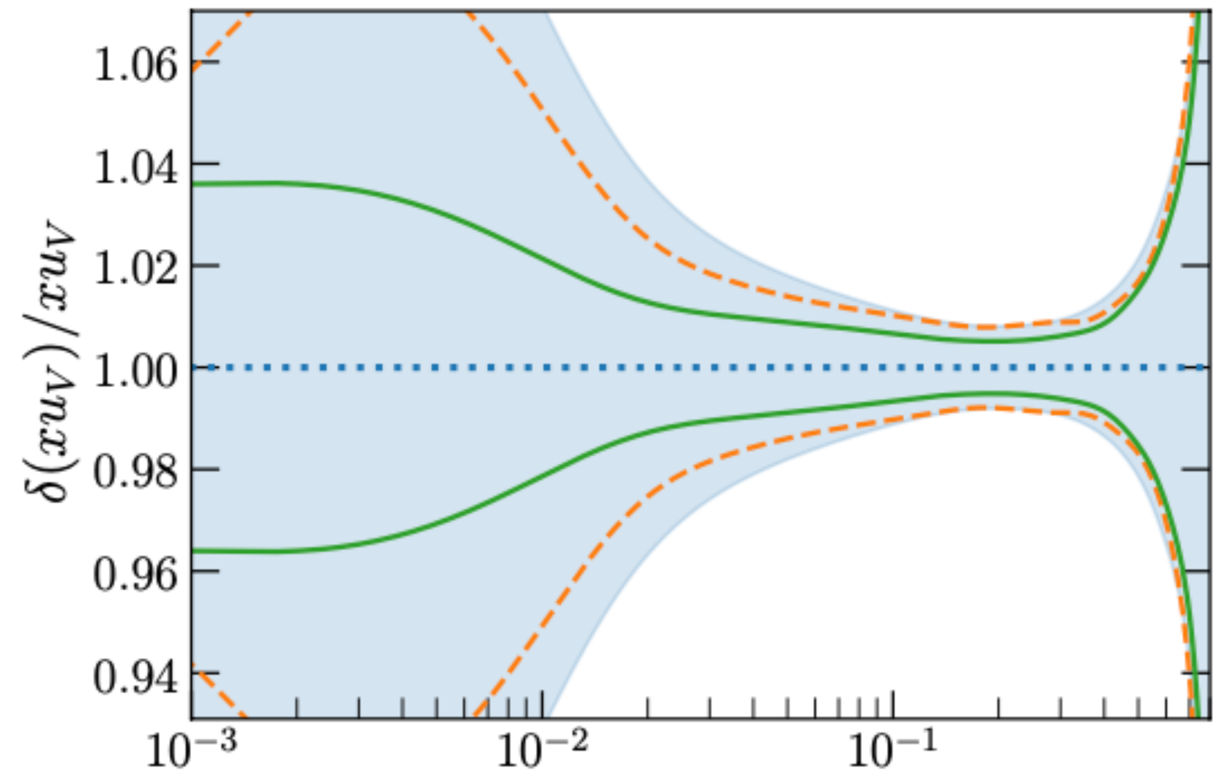
Impact on proton PDFs

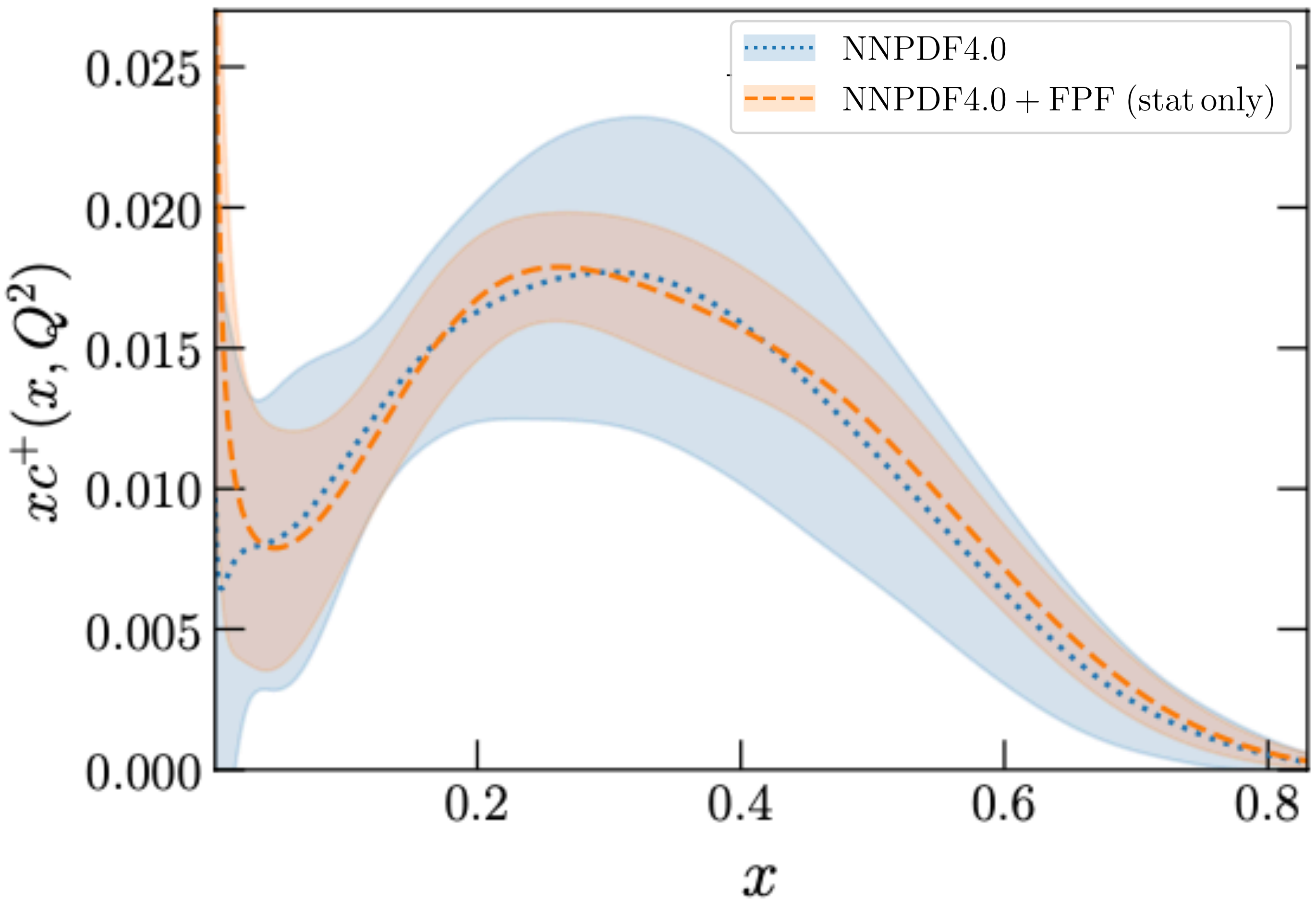


- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the **global NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics, but
- PDFs improved with LHC neutrino data **enhance precision HL-LHC measurements like *W* mass**

Impact on proton PDFs



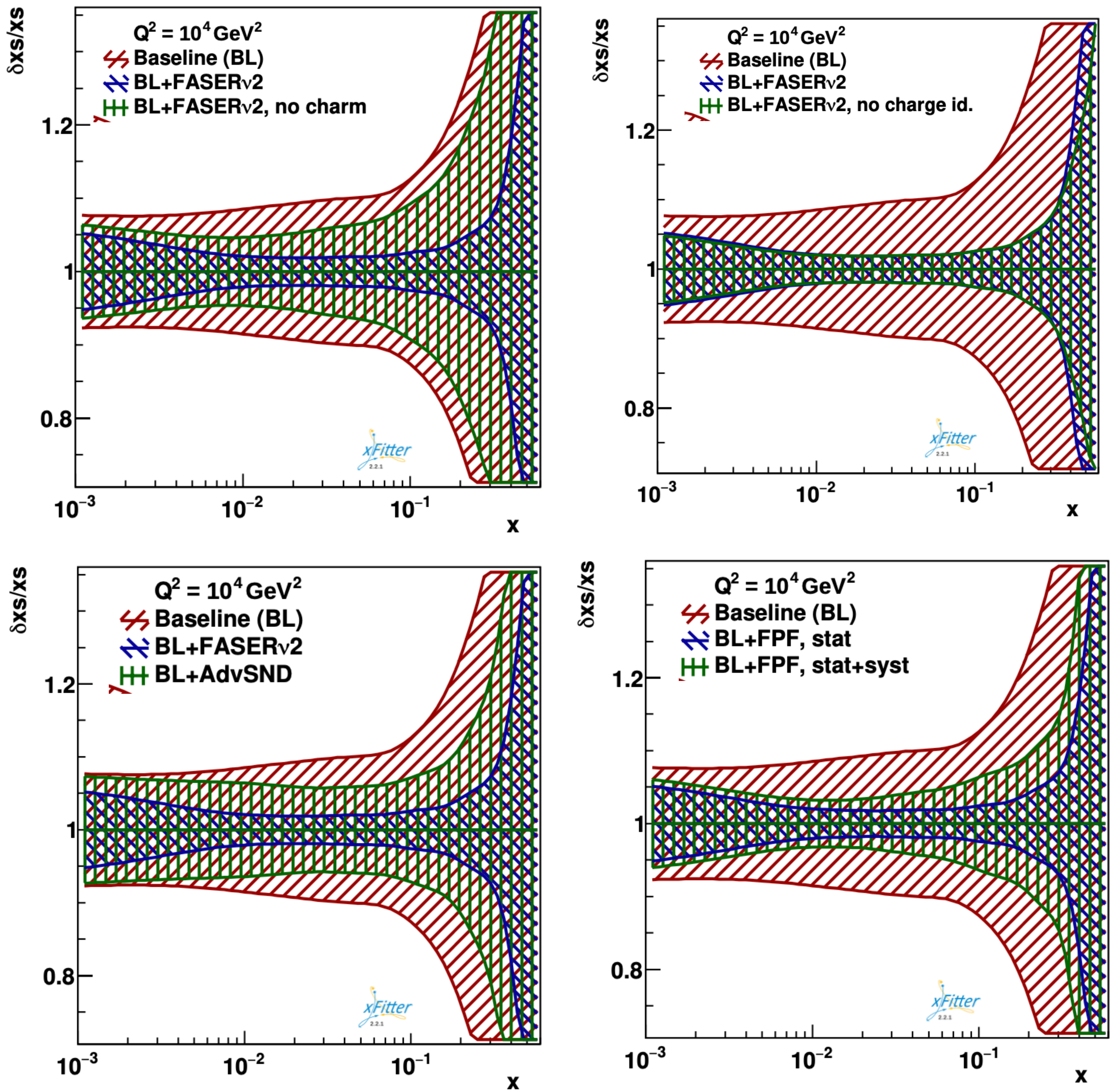




- Consistent results with two different methodologies (NNPDF fit & PDF4LHC21 profiling)
- Provides information on large-*x* charm PDF: a **new window to intrinsic charm**
- PDF reach **ultimately limited by systematics**

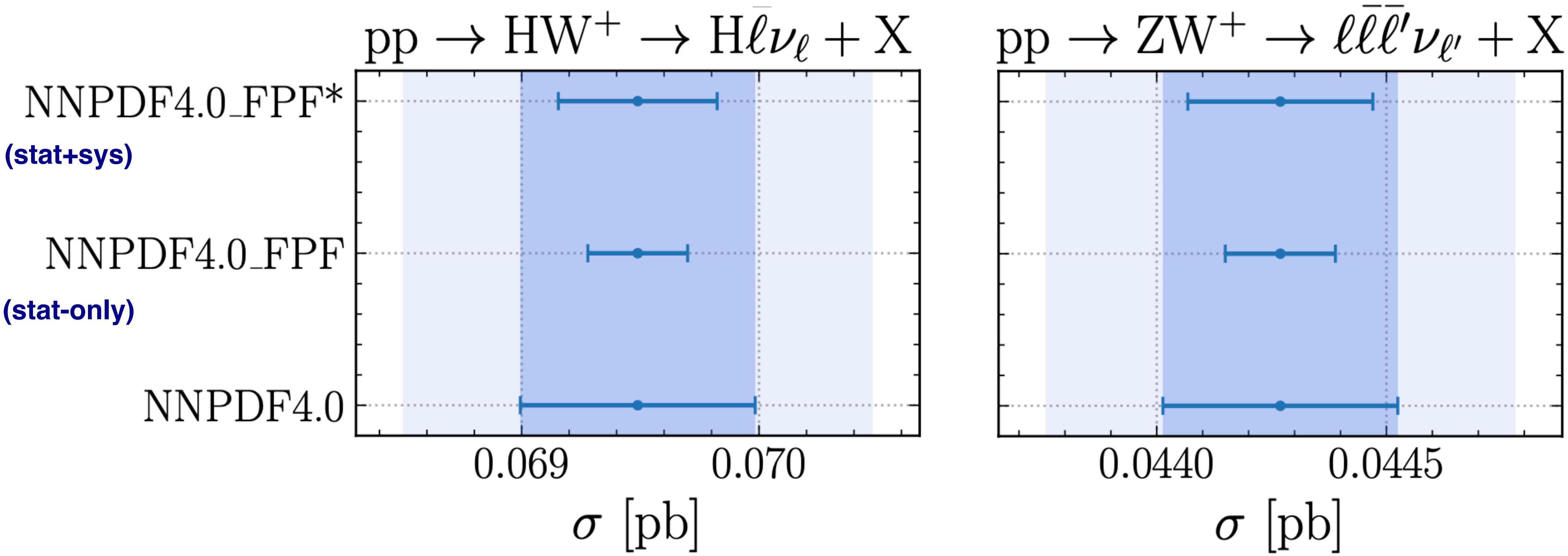
but we are only theorists, can we do bettter?

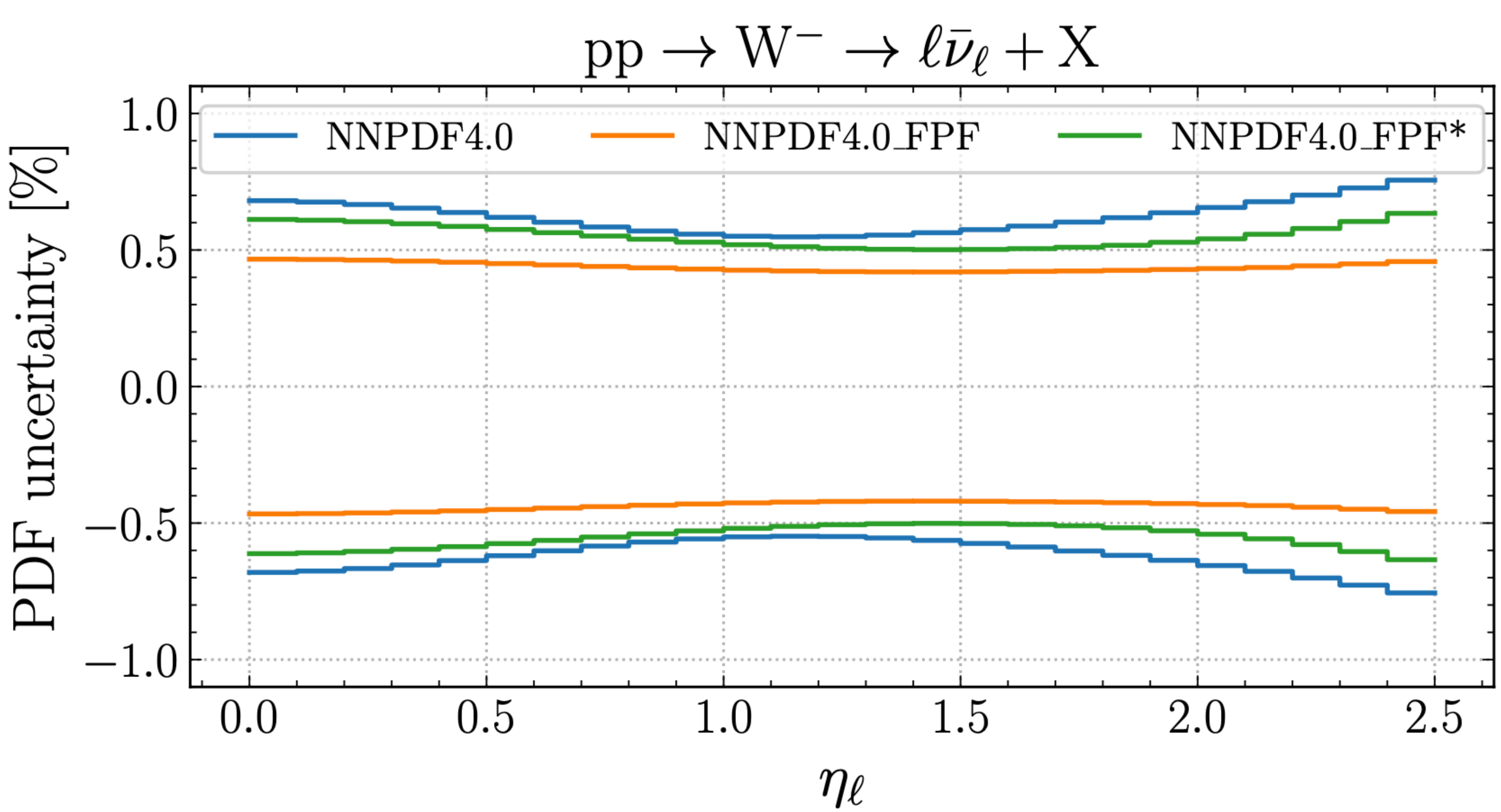
Stability



- **Charm-tagged data** is crucial for hadron structure studies
- Little impact of **charged-lepton ID** (magnet): isoscalar target
- FASERν2 dominates the PDF sensitivity (**higher statistics**)
- **Combination of all FPF experiments** (ignore cross-correlations) yields a result close to the FASERν2-only analysis

Implications for the HL-LHC

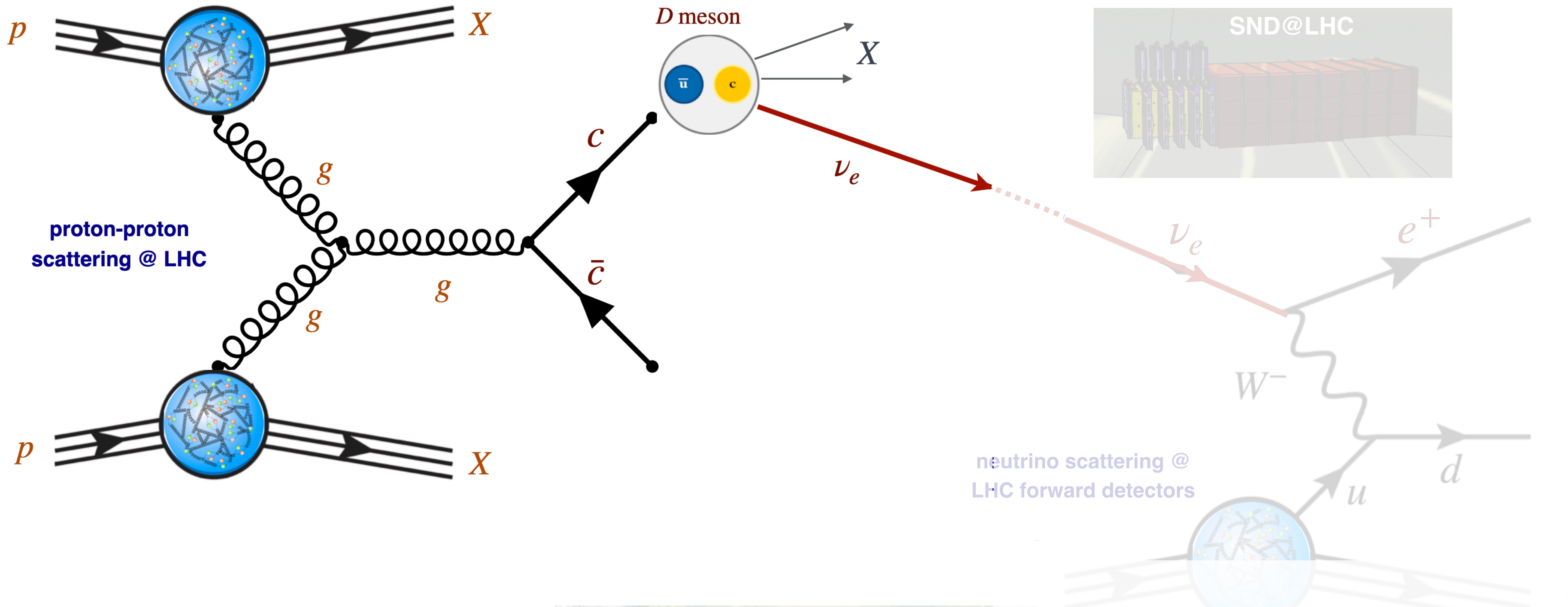




- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)

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

Constraints on small-*x* PDFs



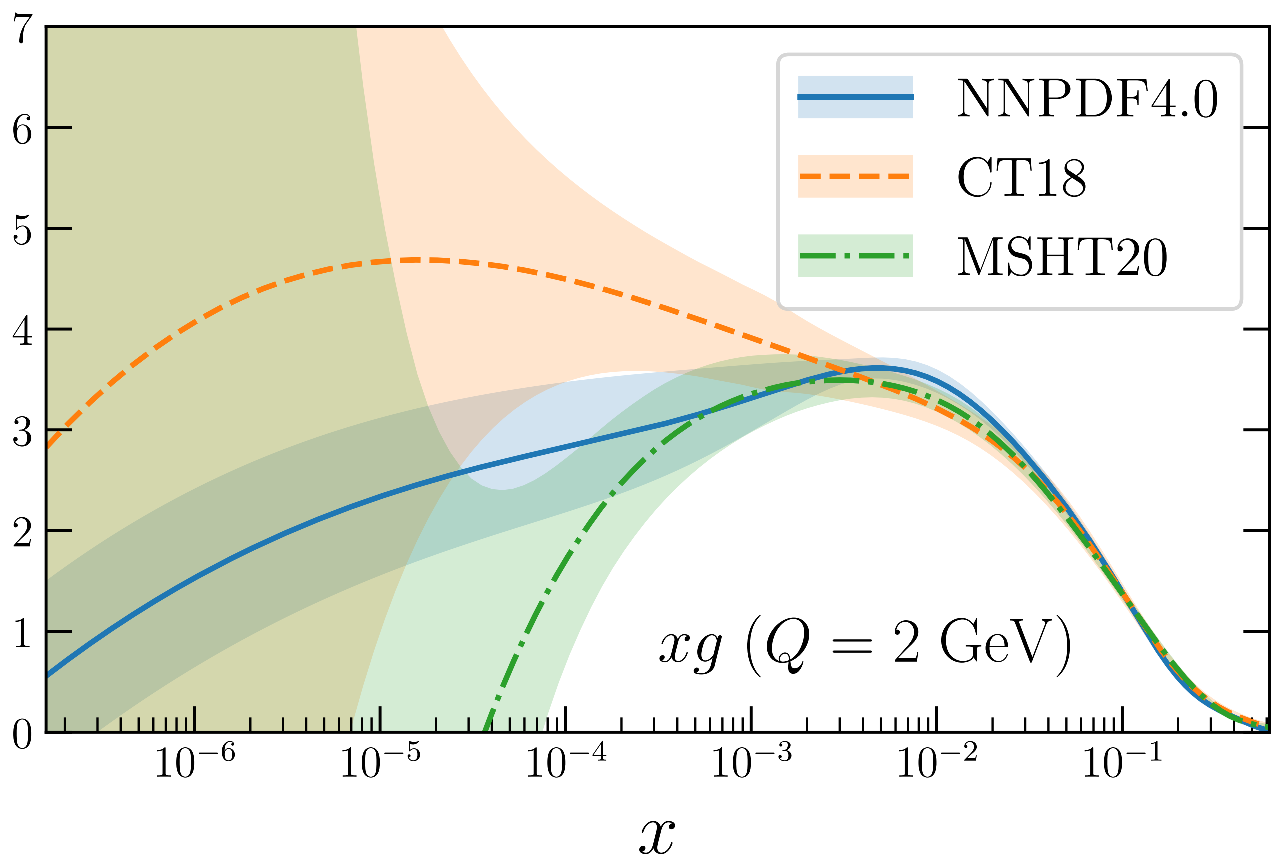
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to \nu)+X)}{p_T^{\nu} y_{\nu}} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\widehat{\sigma}(gg\to c\bar{c})}{p_T^{c} y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to \nu+X)$$

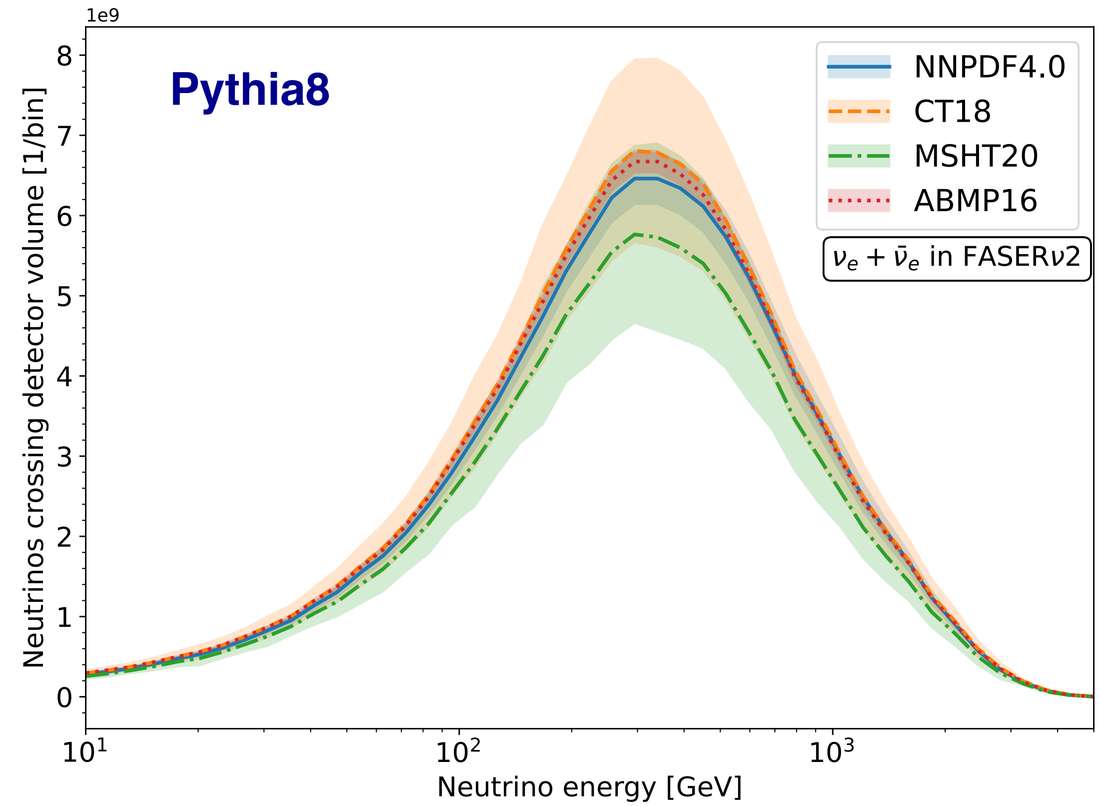
Extract from measured neutrino fluxes

Constrain from FASER/FPF data

QCD prediction: NLO + PS large theory uncertainties

Impact projections



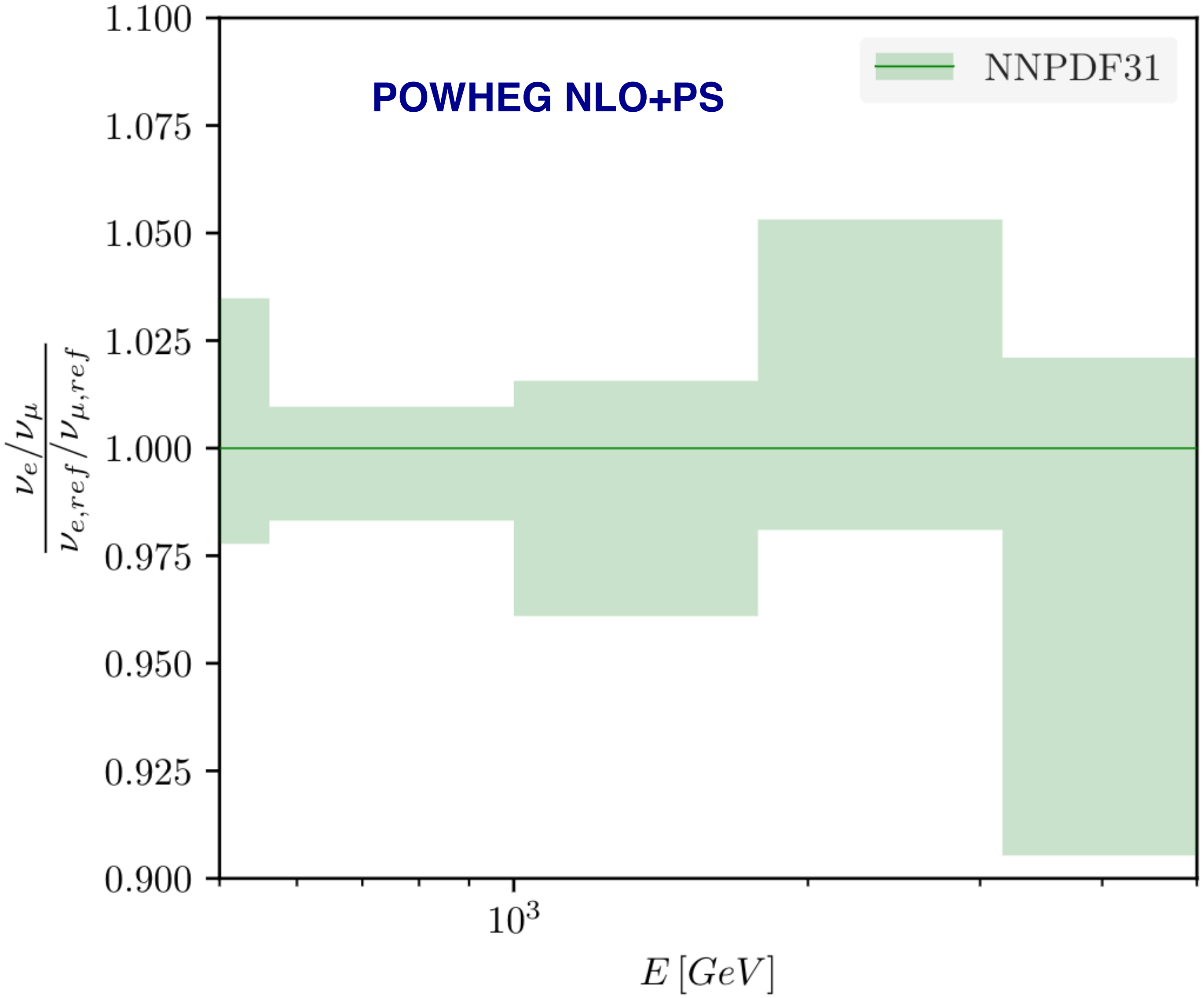


- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially) cancel out

$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)}, \qquad R^{\nu_e}_{\rm exp}(E_\nu) = \frac{N_{\rm FASER\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\rm SND@LHC}(\nu_e + \bar{\nu}_e; E_\nu)}$$

Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

Impact projections



- When taking **ratios of event rates** (e.g. charm electron neutrinos vs charm muon neutrinos), QCD uncertainties reduced to O(few %)

- Strategy: assume a measurement of **inclusive event rates** as a function of neutrino energy with a given precision, quantify impact on PDFs via **Bayesian reweighting**

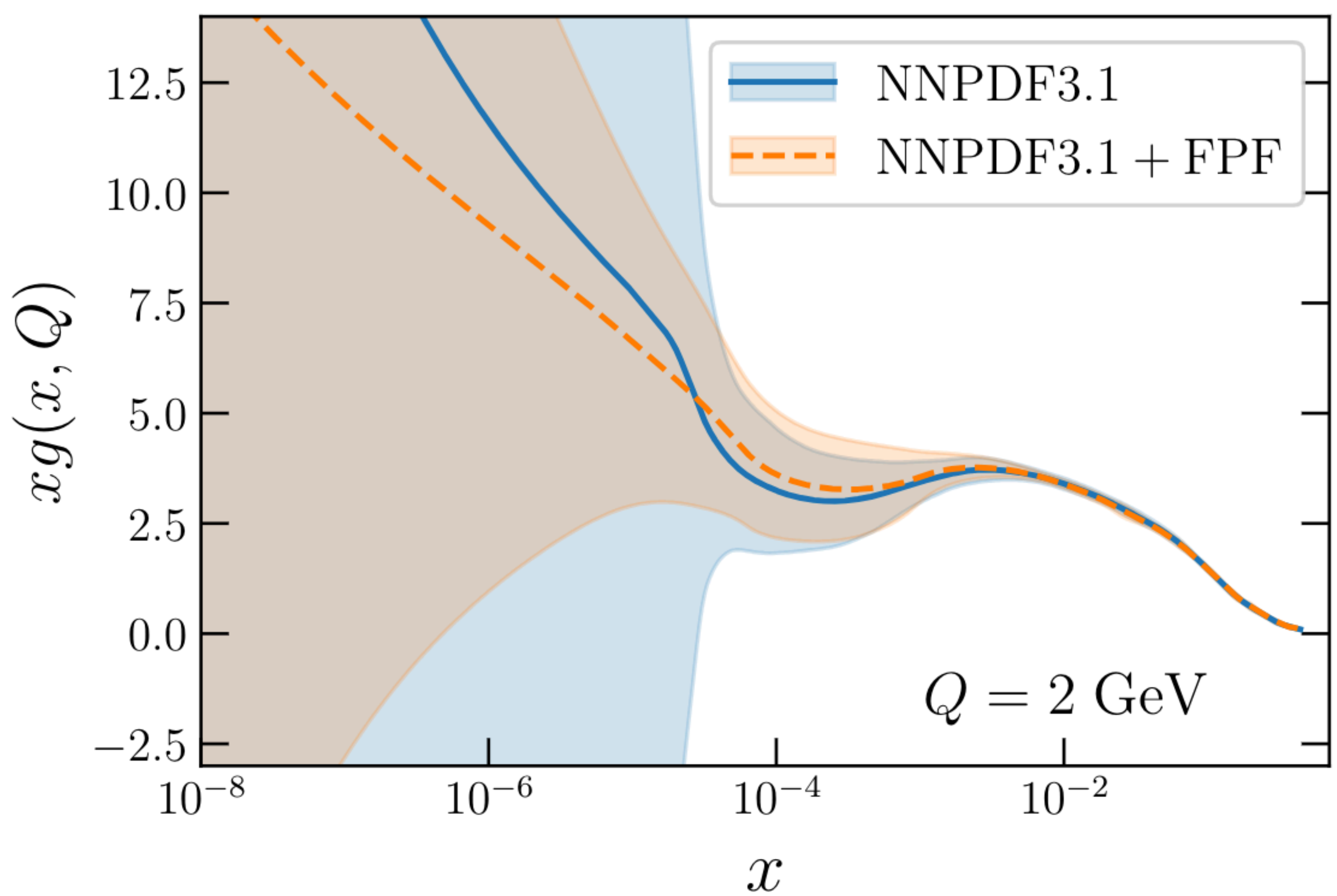
$$w_k \propto \mathcal{P}(f_k|\chi_k) \propto \chi_k^{n-1} e^{-\frac{1}{2}\chi_k^2}$$

$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)}, \qquad R_{\rm exp}^{\nu_e}(E_\nu) = \frac{N_{{\rm FASER}\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\rm SND@LHC}(\nu_e + \bar{\nu}_e; E_\nu)}$$

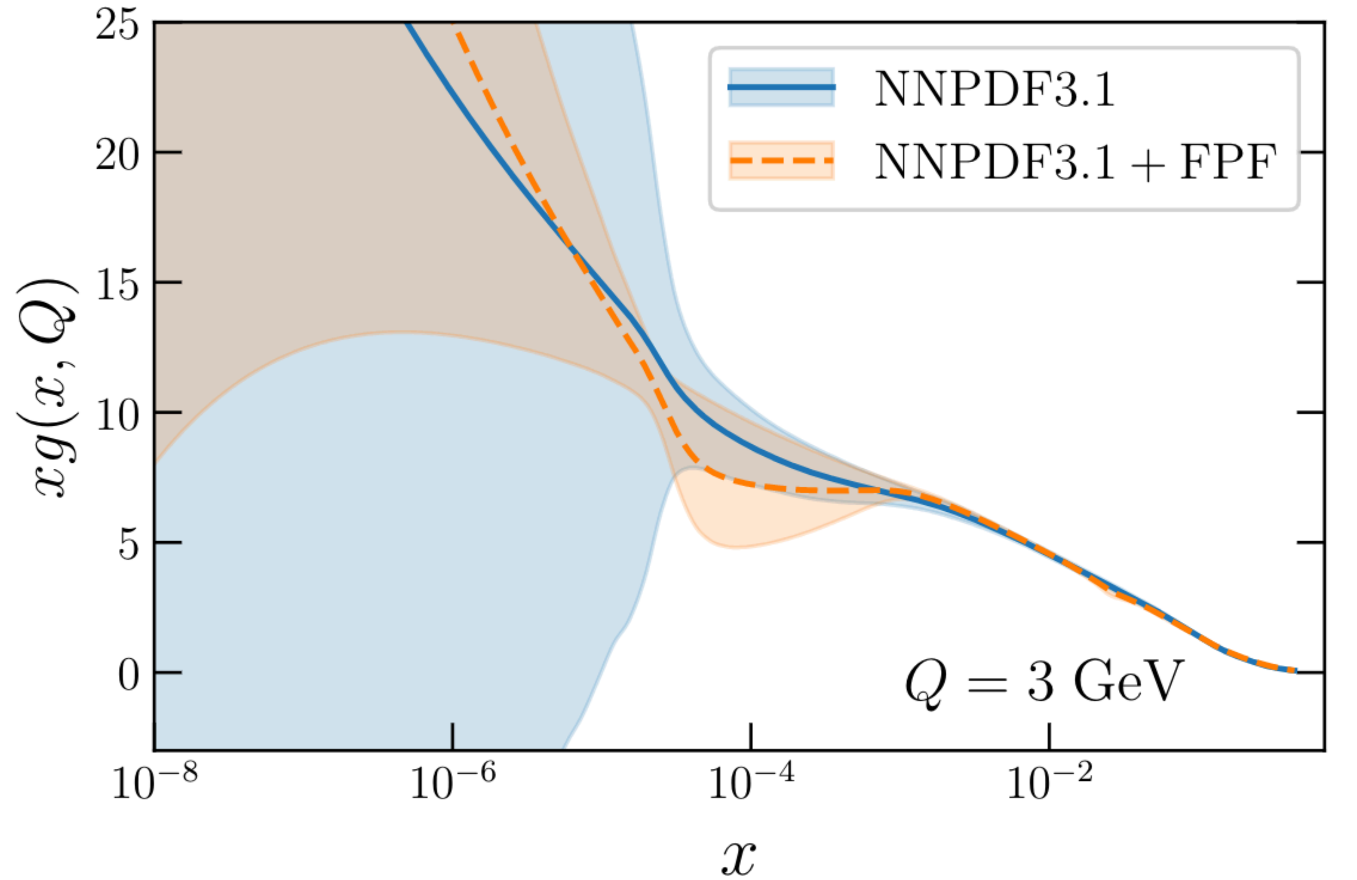
Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

Results

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates



- Results based on pseudo-data for a **measurement of the rapidity ratio** (proxy for experiment ratio)

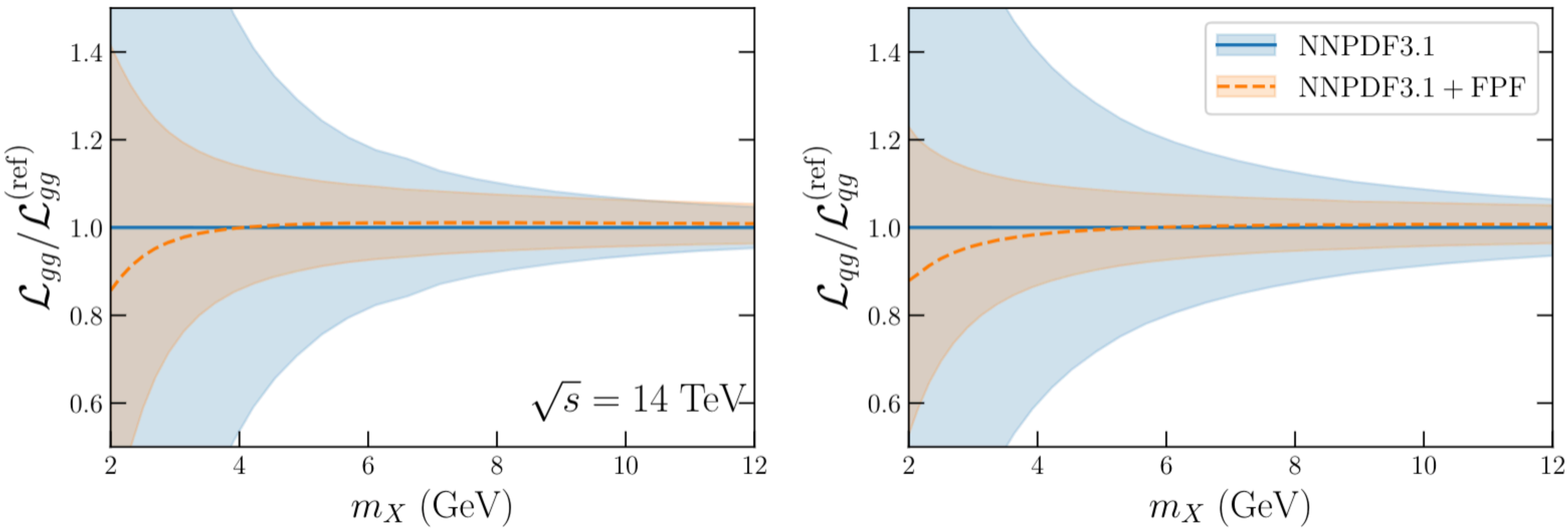
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_u < 9.0)} \qquad R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_u < 9.0)}$$

- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment

- Study impact of different observables, QCD errors, and the precision of measurement

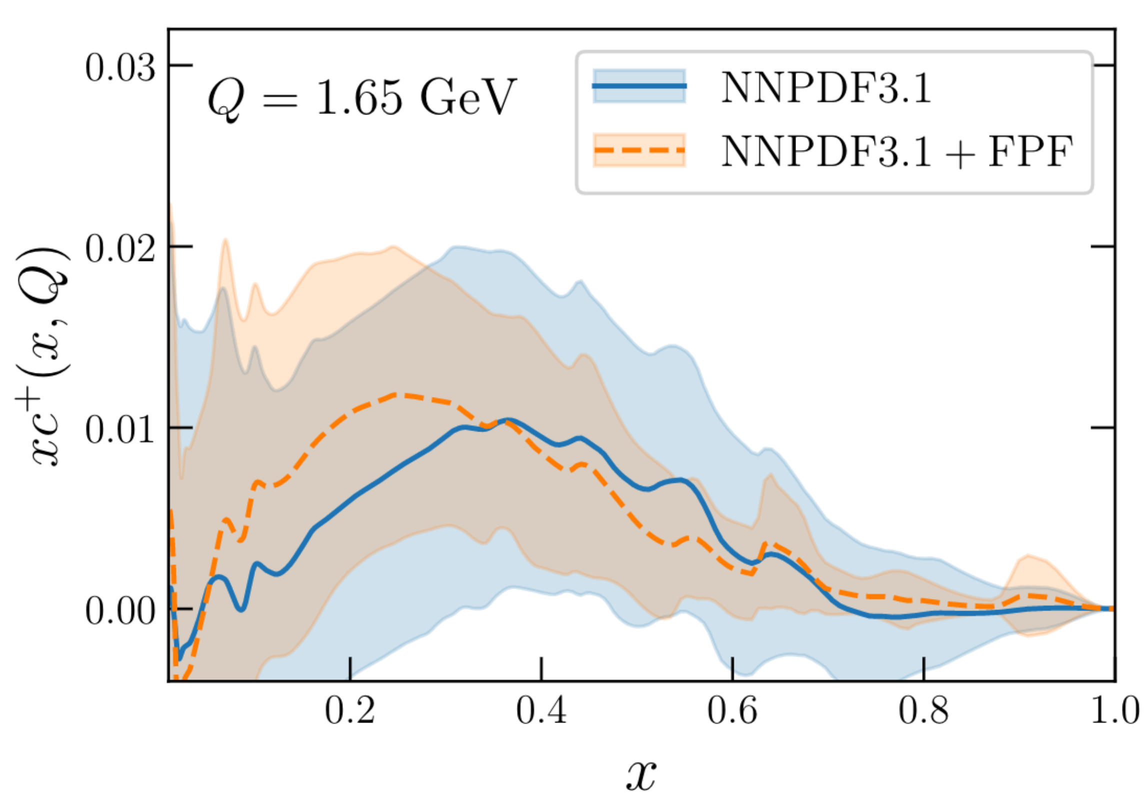
Results

Electron neutrinos, 2% uncertainty in inclusive event rates



- Constraints also on the **charm PDF** via the gluon-charm initial state
- Run III data may be able to provide the first measurement of the **gluon content of the proton at x=10^{-7}**

WIP: generate FPF pseudo-data for event rates including systematic uncertainties



WG1 Roadmap

CDR goals (partial overlap with **WG2**):

- Official sets of FPF neutrino DIS pseudo-data (and maybe also for muons?) in various scenarios for the experiments and detector, and study of their impact on proton and nuclear PDFs — ***Done for electron & muon neutrinos, missing tau neutrinos***
- Official set of FPF pseudo-data on neutrino cross-section measurements, and study of its impact on e.g. anomalous neutrino interactions or EFT operators — ***Good progress!***
- Official set of FPF predictions for neutrino fluxes, and quantitative study on the constraints that the flux measurement imposes on the charm production cross-section and on the small-x and large-x PDFs (in particular on the small-x gluon and the large-x intrinsic charm) — ***work in progress***
- Projections for the precision for which the FPF will measure: small-x gluon, large-x intrinsic charm, the strange PDFs, and the large-x quark flavor separation in protons and nuclei, among others. What else? — ***Done for PDFs from neutrino DIS, WIP for PDFs from pp collisions***
- Definition of key observables to extract the above information and how the projected uncertainty depends on experimental choices
- Detailed simulation pipeline translating the impact of theory choices (PDFs, charm production models, … etc) into the expected event rates at the FPF — ***WIP together with other FPF WGs***
- Study of the implication of FPF measurements for high-energy astrophysics: UHE neutrino cross-sections, prompt neutrino flux, cosmic ray interactions, what else?

On track to meet our (pre-)CDR targets!

WG1 welcomes any colleagues that want to join these studies!