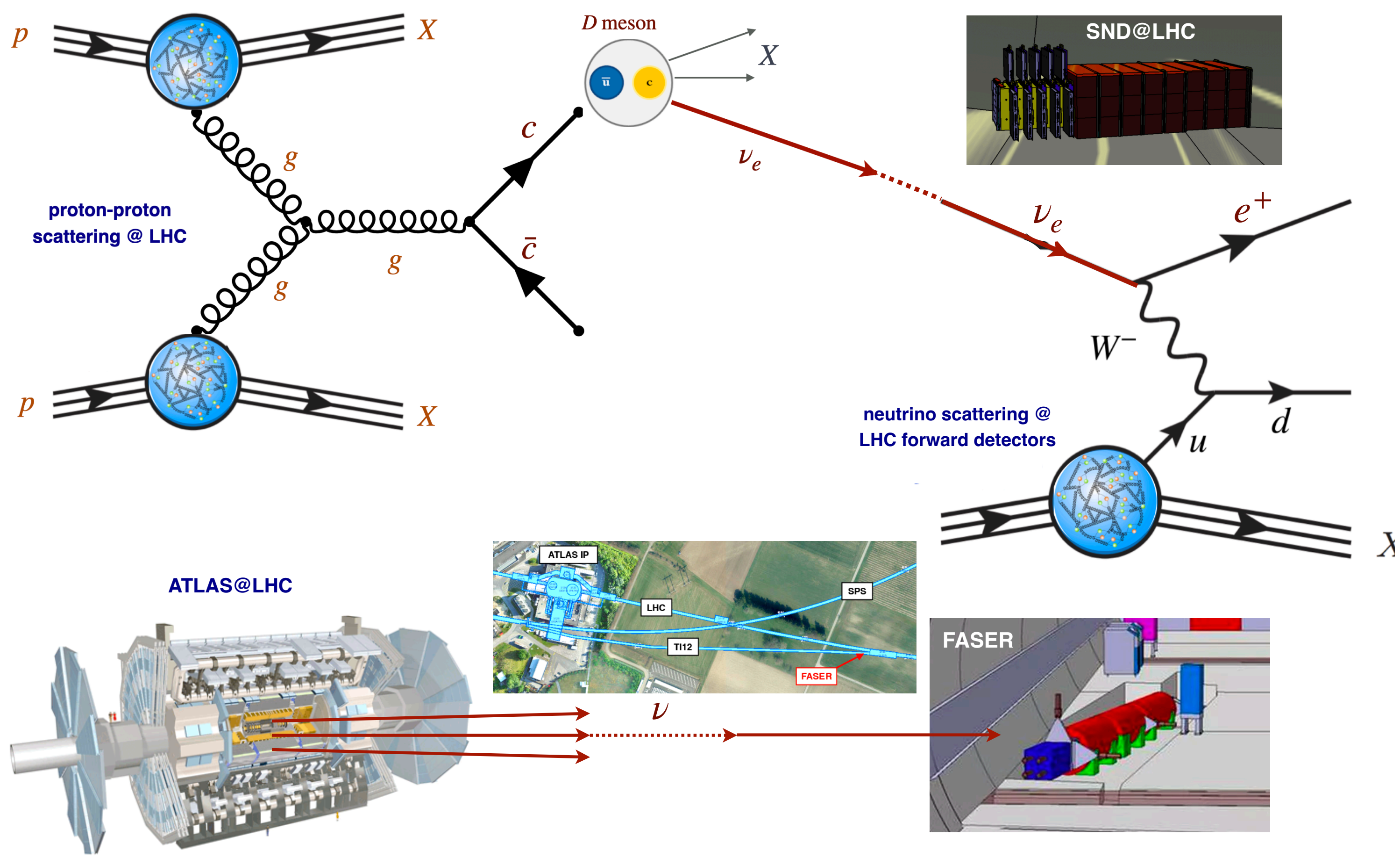
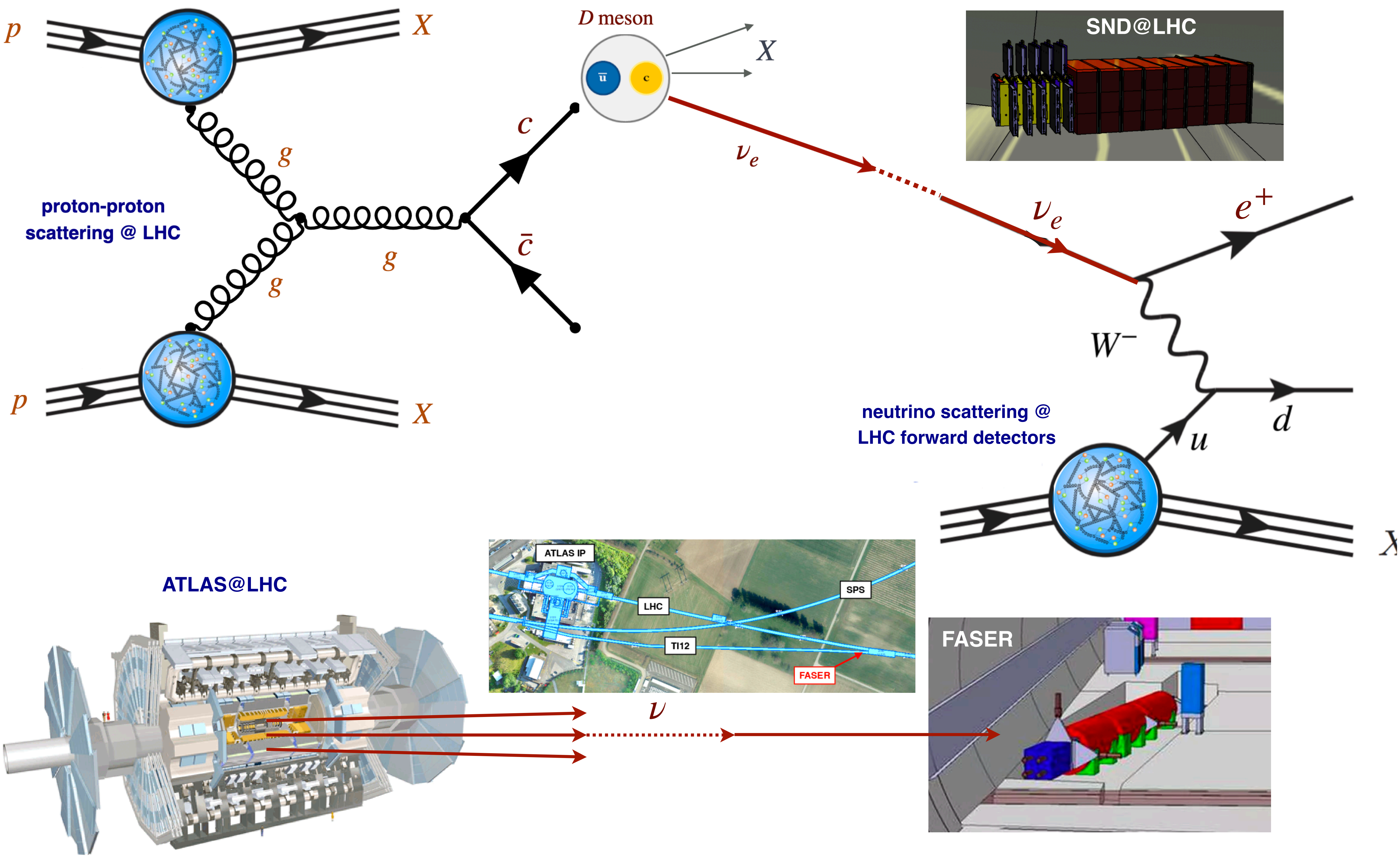
WG1: Neutrino Interactions and DIS

Juan Rojo, VU Amsterdam & Nikhef



6th Forward Physics Facility workshop, CERN, 09.06.2023

QCD and Neutrino Physics at FASER



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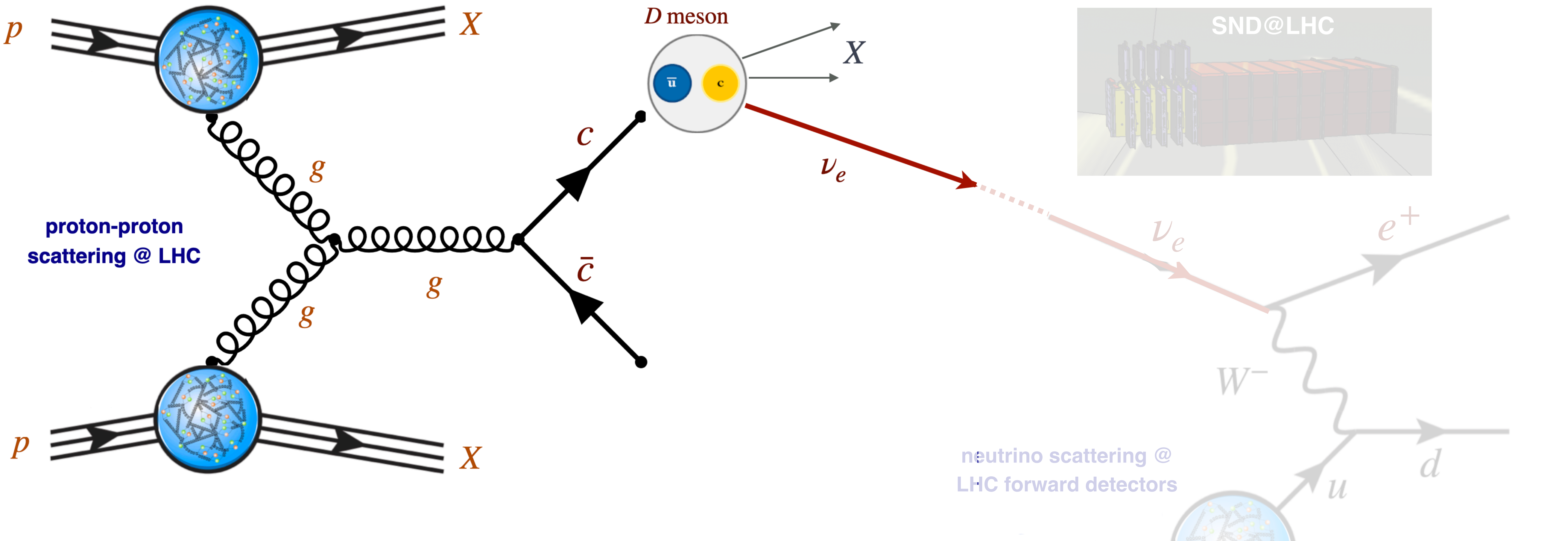

Neutrino Production

- Small-x gluon & large-x (intrinsic) charm
- *D*-meson fragmentation
- Cross-sections for UHE neutrinos (*e.g.* IceCube)
- Cosmic ray modelling, including muon puzzle

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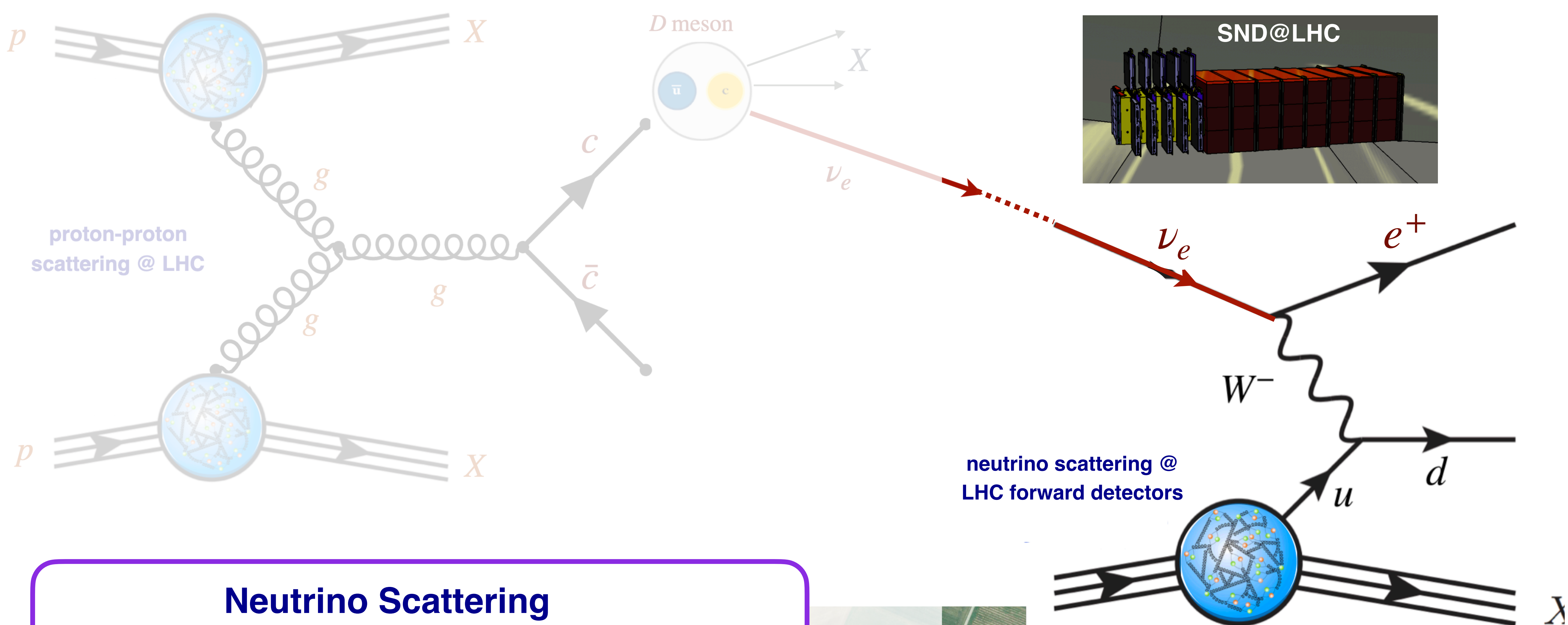

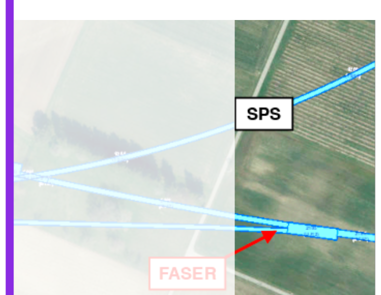

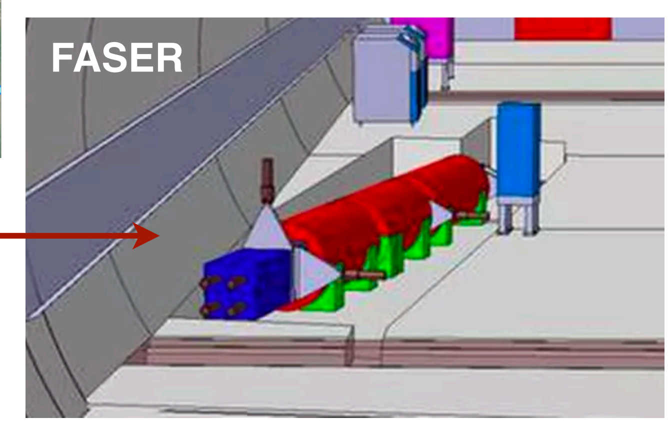

Neutrino Scattering

- DIS with TeV neutrinos (*Neutrino-Ion Collider*)
- Neutrino (effective) interactions at the TeV
- Cross-sections for atmospheric neutrinos
- Nuclear PDFs, strangeness from charm prod
- Neutrino flavor (non-)university (with tau neuts)

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- Neutrino Production and Scattering talk to each other via the **neutrino fluxes**
- Ultimately, **both ``production" and ``scattering"** need to be constrained by experimental data

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This talk

- Neutrino Production and Scattering talk to each other via the **neutrino fluxes**
- Ultimately, **both ``production'' and ``scattering''** need to be constrained by experimental data

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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?

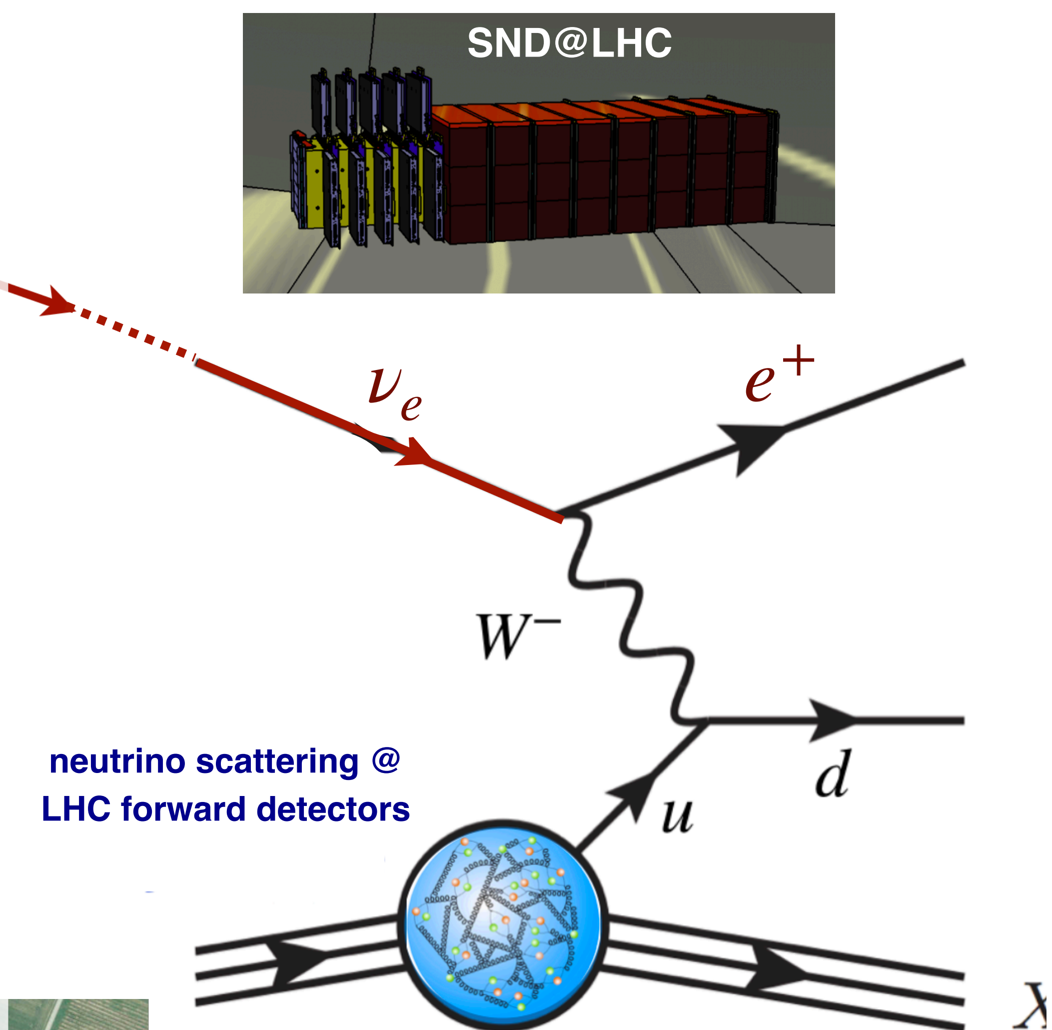
Experimentally-related questions

- 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?

Constraints on hadron structure with LHC neutrinos: deep-inelastic scattering

M. Fieg, T. Giani, P. Krack, G. Magni, T. Makela, T. Rabemananjara, J. Rojo, *paper in preparation*

QCD and Neutrino Physics at FASER



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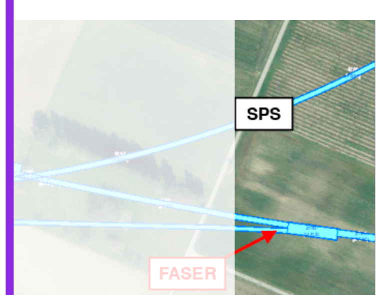
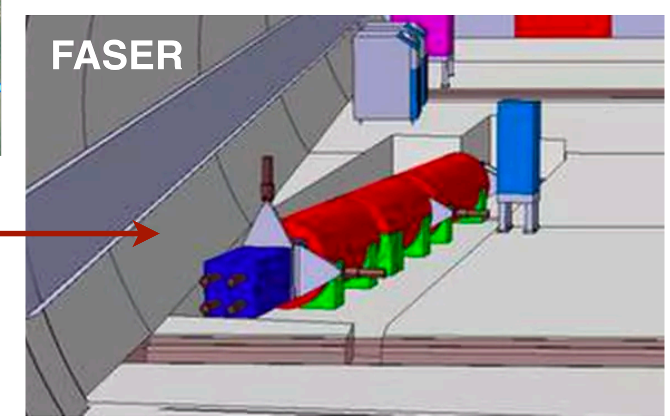
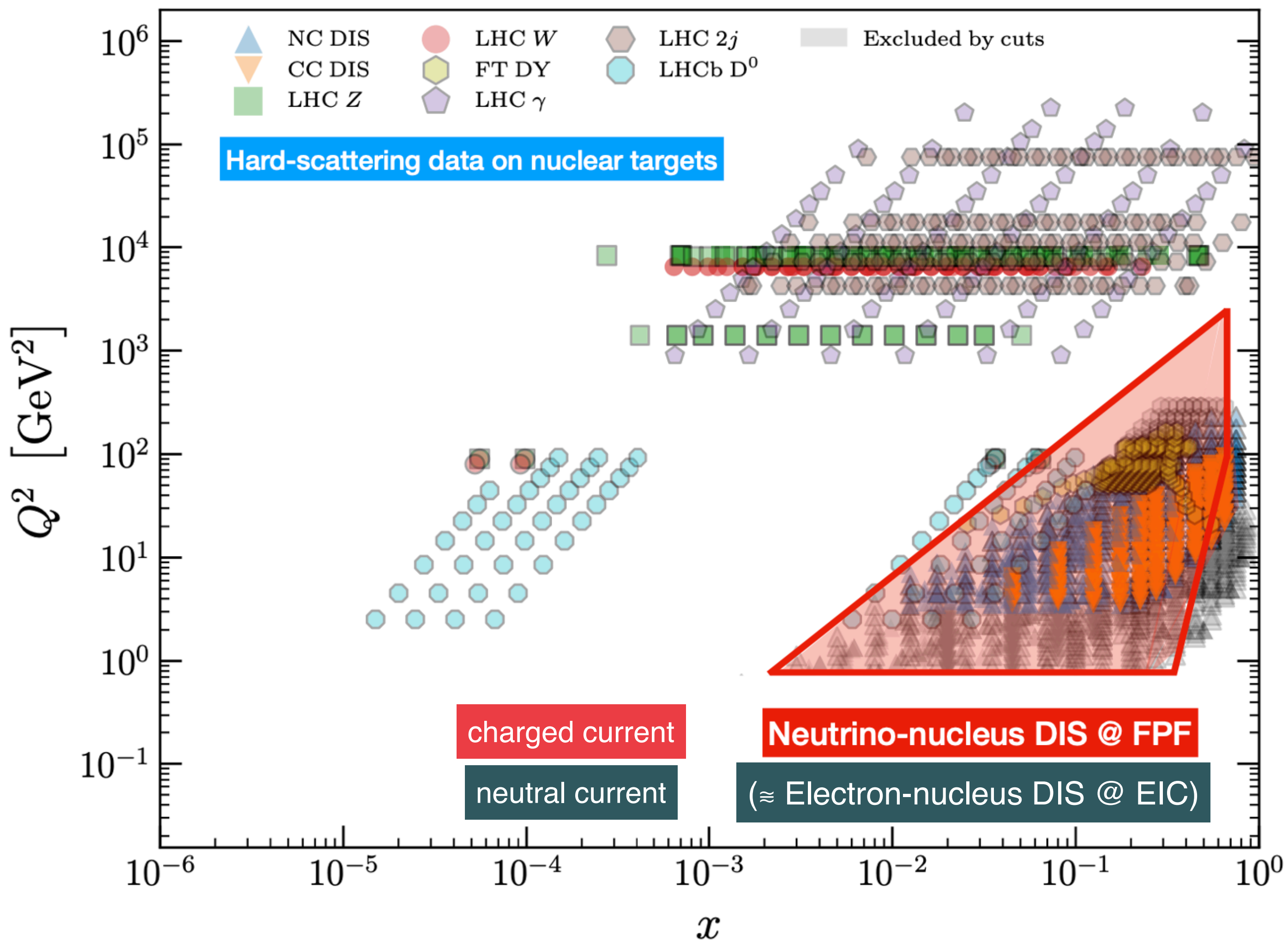




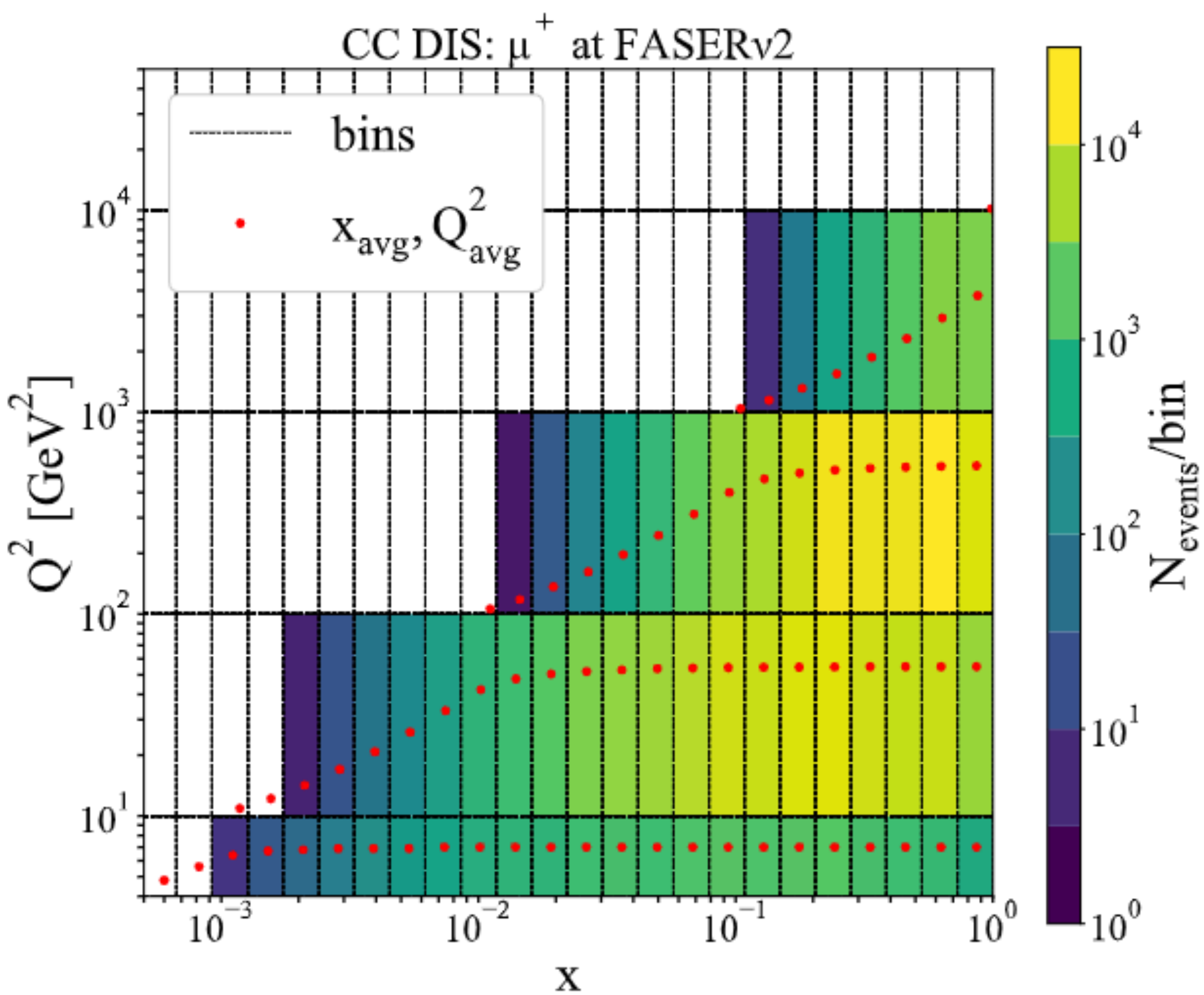
Deep-Inelastic Scattering at FASER



- **FASER:** deep-inelastic charged current scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN,** expand kinematic coverage of previous experiments both in x and Q
- Charged-current analog of the Electron-Ion Collider: the LHC as a **Neutrino-Ion Collider**
- Constrain proton & nuclear **light (anti-)quark PDFs,** including strangeness

Impact projections

- Neutrino fluxes from **Kling-Nevay calculation**
- Focus on **muon neutrinos**: higher rates, dominated by light hadron production
- Generate **pseudo-data for DIS structure functions** for FASER, SND@LHC, and the proposed FPF experiments, both inclusive and charm production
- Assume outgoing **lepton charge separation**
- Model **systematic errors** based on the feedback provided by the experiments



$$N_{\rm ev}/{\rm bin} = n_T L_T \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} \int_{x_{\rm min}}^{x_{\rm max}} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \frac{d^2\sigma^{\nu A}(x,y,E_\nu)}{dxdy} dQ^2 dx dE_\nu$$

Geometry/Target

Binning

neutrino fluxes (include rapidity acceptance)

DIS differential cross-section

Both for inclusive production and for charm-tagged final states

Impact projections

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$$\begin{aligned} F_2^{\nu p}(x,Q^2) &= 2x\left(f_{\bar u} + f_d + f_s + f_{\bar c}\right)(x,Q^2)\,, \\ F_2^{\bar\nu p}(x,Q^2) &= 2x\left(f_u + f_{\bar d} + f_{\bar s} + f_c\right)(x,Q^2)\,, \\ xF_3^{\nu p}(x,Q^2) &= 2x\left(-f_{\bar u} + f_d + f_s - f_{\bar c}\right)(x,Q^2)\,, \\ xF_3^{\bar\nu p}(x,Q^2) &= 2x\left(f_u - f_{\bar d} - f_{\bar s} + f_c\right)(x,Q^2)\,, \end{aligned}$$

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- xF_3^{\nu A}(x,Q^2)\right]$$

$$\frac{d^2\sigma^{\bar\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+ F_2^{\bar\nu A}(x,Q^2) - y^2 F_L^{\bar\nu A}(x,Q^2) - Y_- xF_3^{\bar\nu A}(x,Q^2)\right]$$

Differential measurements with charge-separation key to achieve sensitivity to proton and nuclear structure

Impact projections

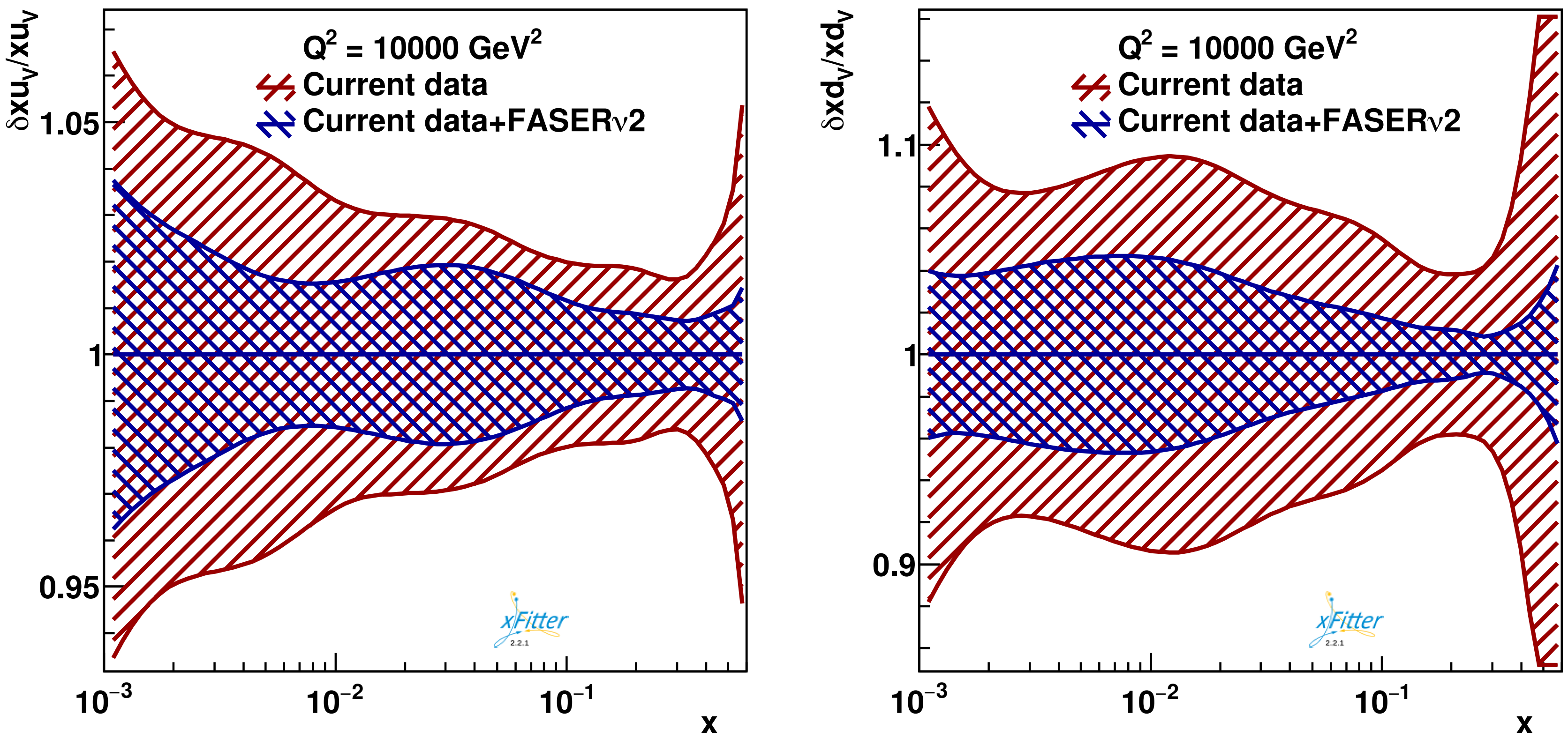
- Strategy: **xFitter** Hessian PDF profiling of **PDF4LHC21** (for proton PDF, neglect nuclear modifications) and **EPPS21** (for tungsten PDF)
- Cross-checked with independent inclusion in **NNPDF fitting code** (global dataset)
- Study relative sensitivity of the **different experiments**, role of lepton charge separation, impact of correlated systematics in different scenarios,…

Accurate modelling of systematic covariance matrix key for robust results: input from experiment needed!

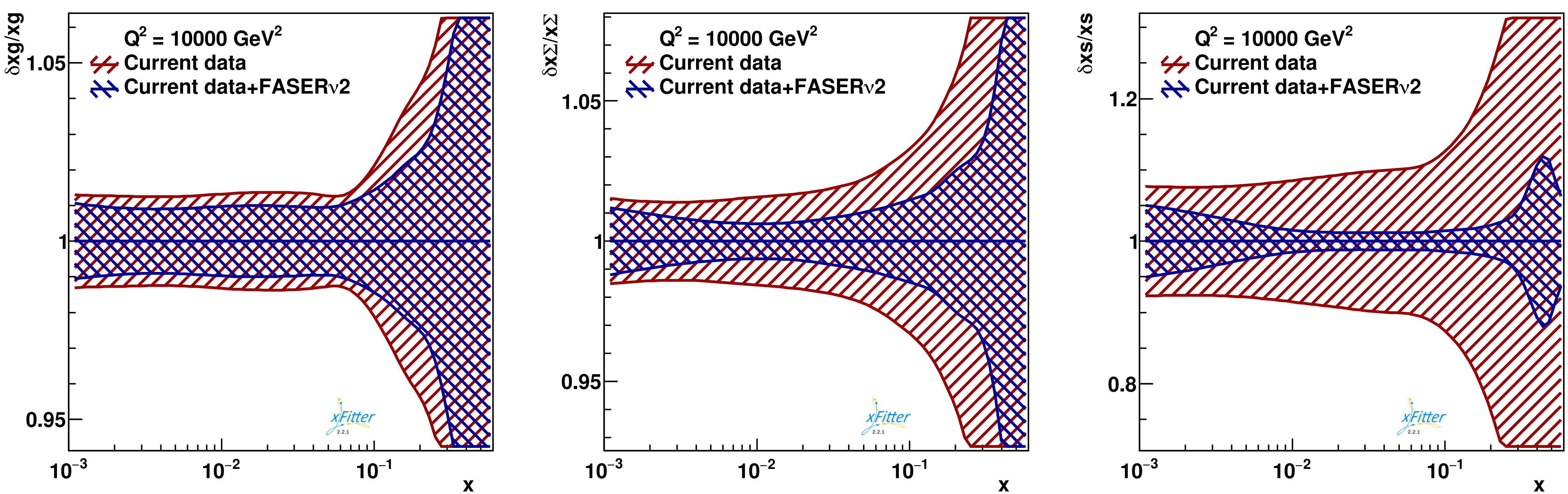
	lepton energy E_l	lepton angle θ	charged lepton sign	hadronic final state
FaserNu2	$E_l > 100$ GeV $\delta E_l = 30\%$	$\tan(\theta) < 0.5$ $\delta\theta = 1$ mrad	Yes, for muons	E_h accessible, charm ID possible, $\delta E_h = 30\text{-}50\%$
AdvSND@LHC	$E_l > 20$ GeV (muon)	$\theta < 0.15$ rad (muon) $\theta < 0.5$ rad (electron, tau)	Yes	E_h accessible
FLArE	$E_l < 1$ TeV, $\delta E_l =$ 5% (electron) $E_l < 2$ GeV (muon)	$\theta < 0.5$ rad, $\delta\theta =$ 15 mrad (electron) $\theta < 0.4$ rad (muon)	Maybe, for muons	E_h accessible, $\delta E_h = 30\%$

Results: proton PDFs

Statistical error only, inclusive + charm data



- Best scenario: **FASER2 statistics**, charm production included (strangeness), statistical errors only
- Reduction of PDF uncertainties most marked for **valence quarks and sea antiquarks**



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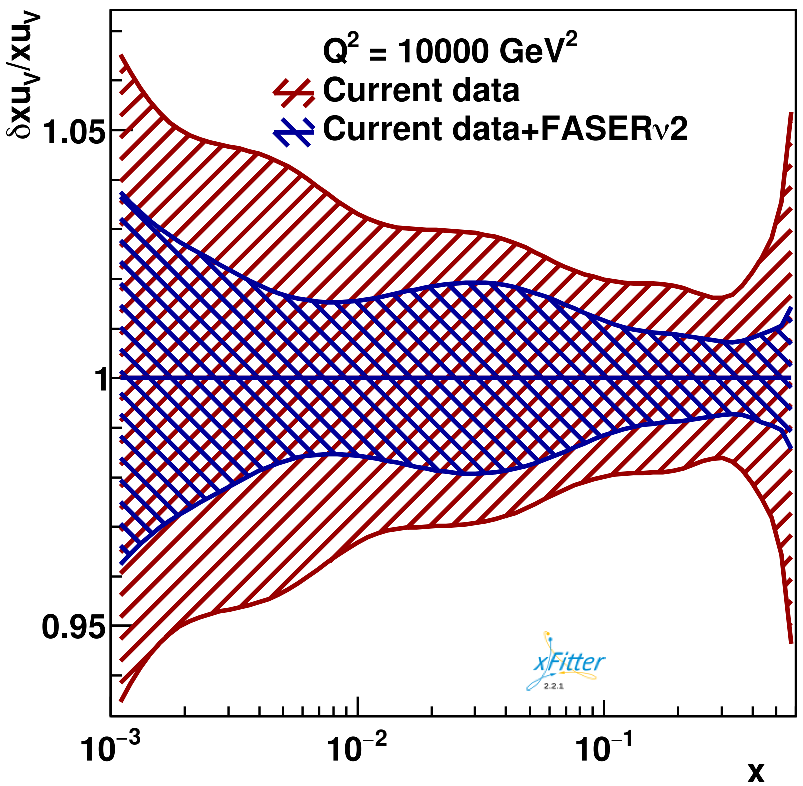

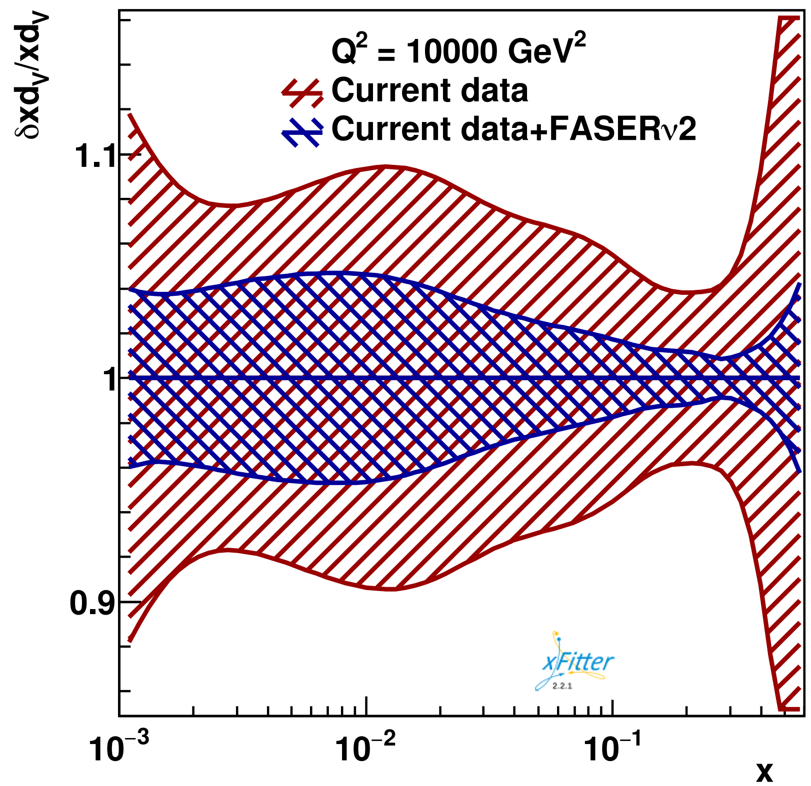

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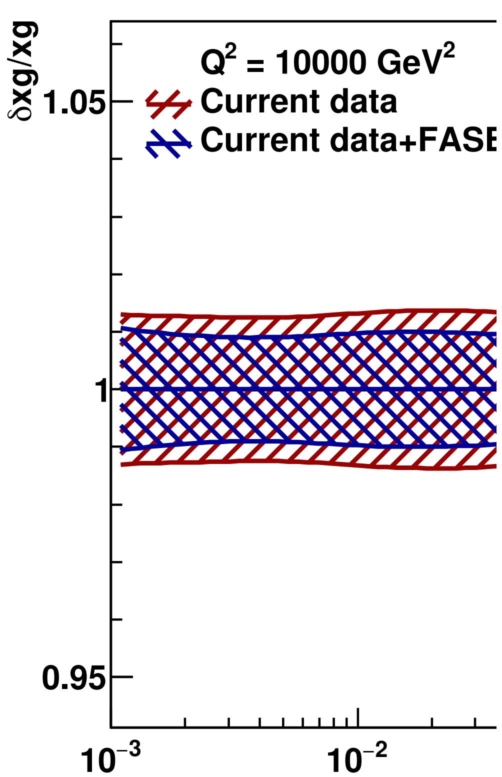
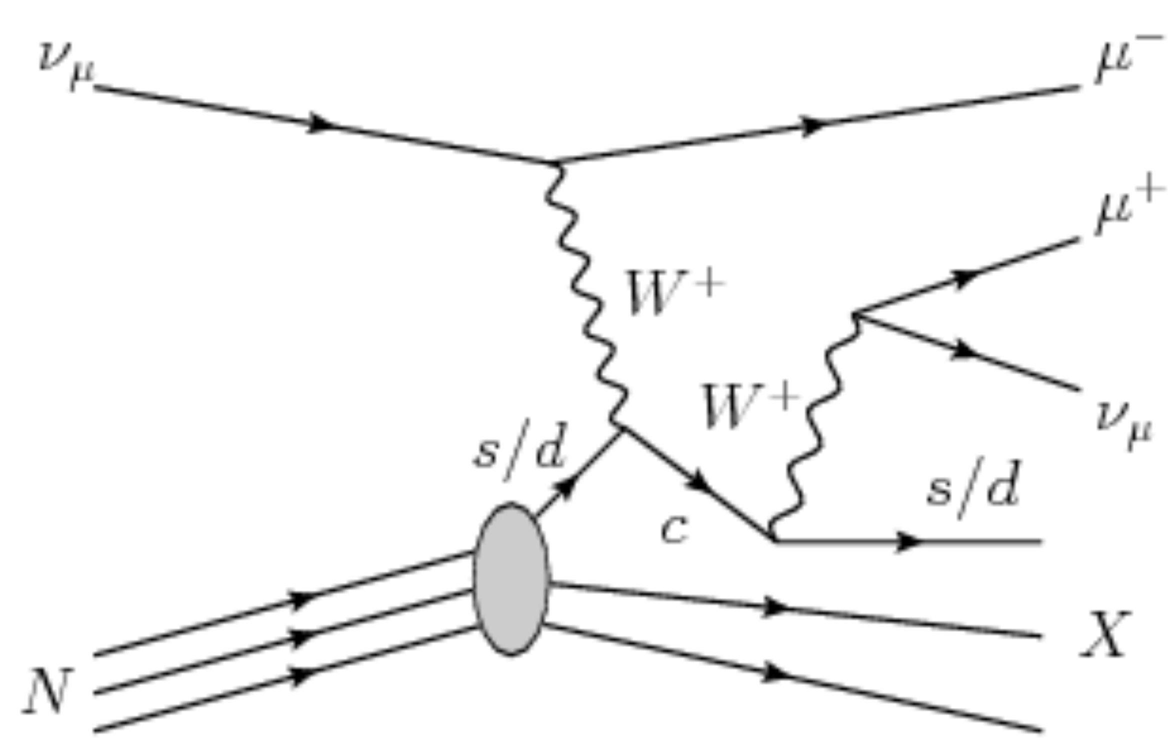
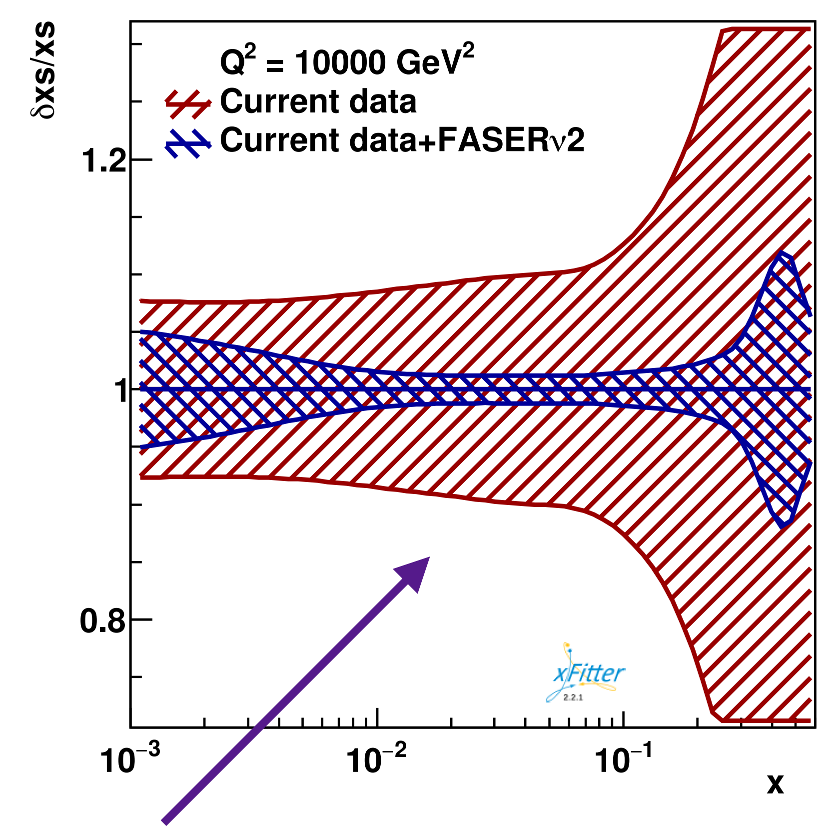
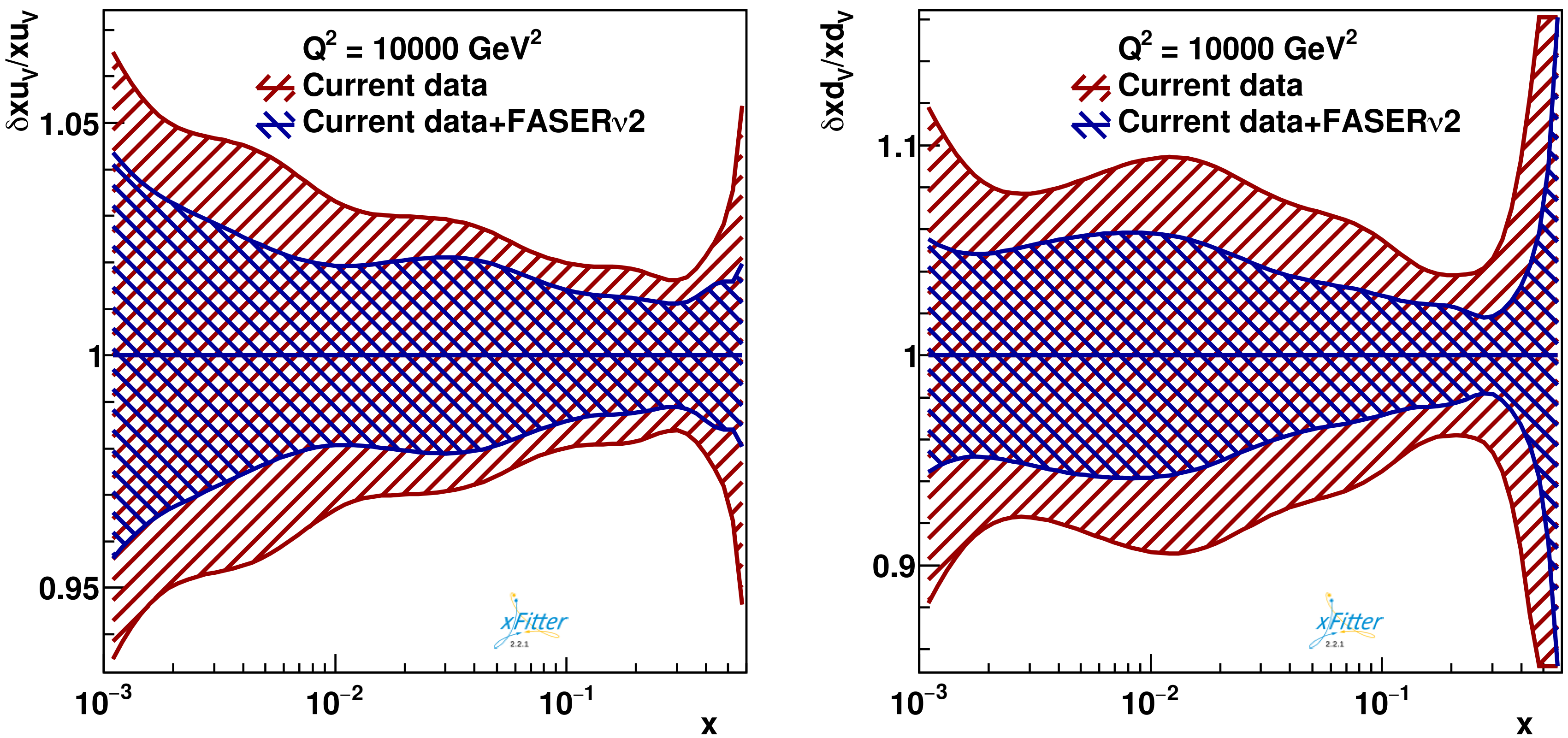




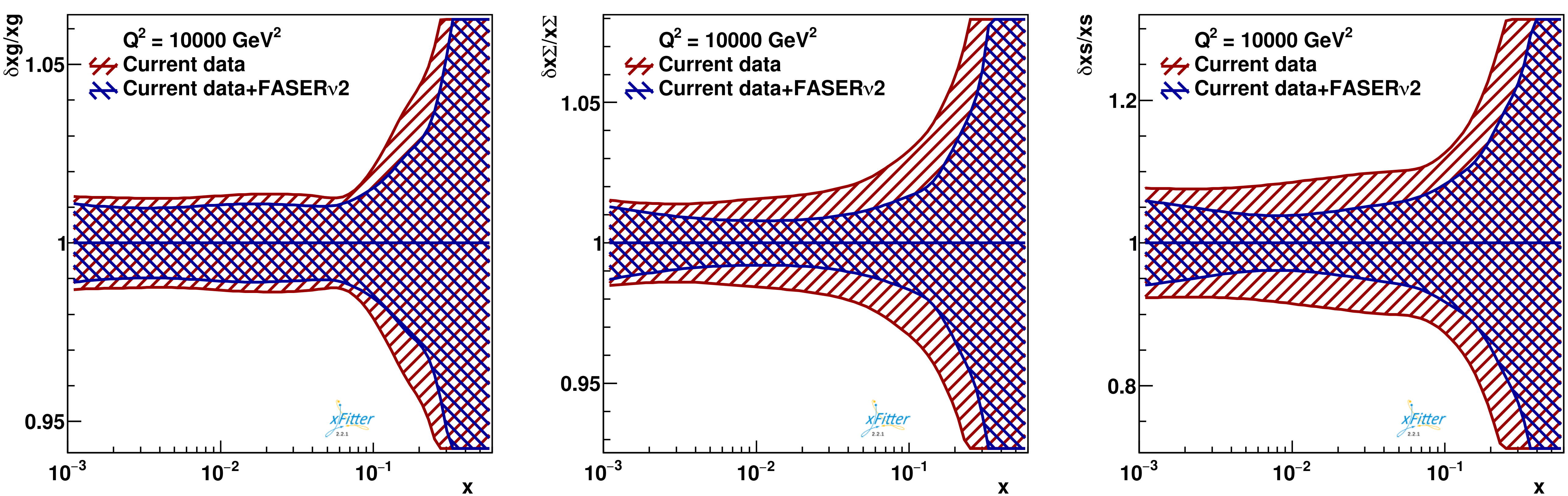


Results: proton PDFs

Statistical error only, inclusive data



- When **only inclusive data is considered**, reduction of constraints on strangeness and light quark see



Results: proton PDFs

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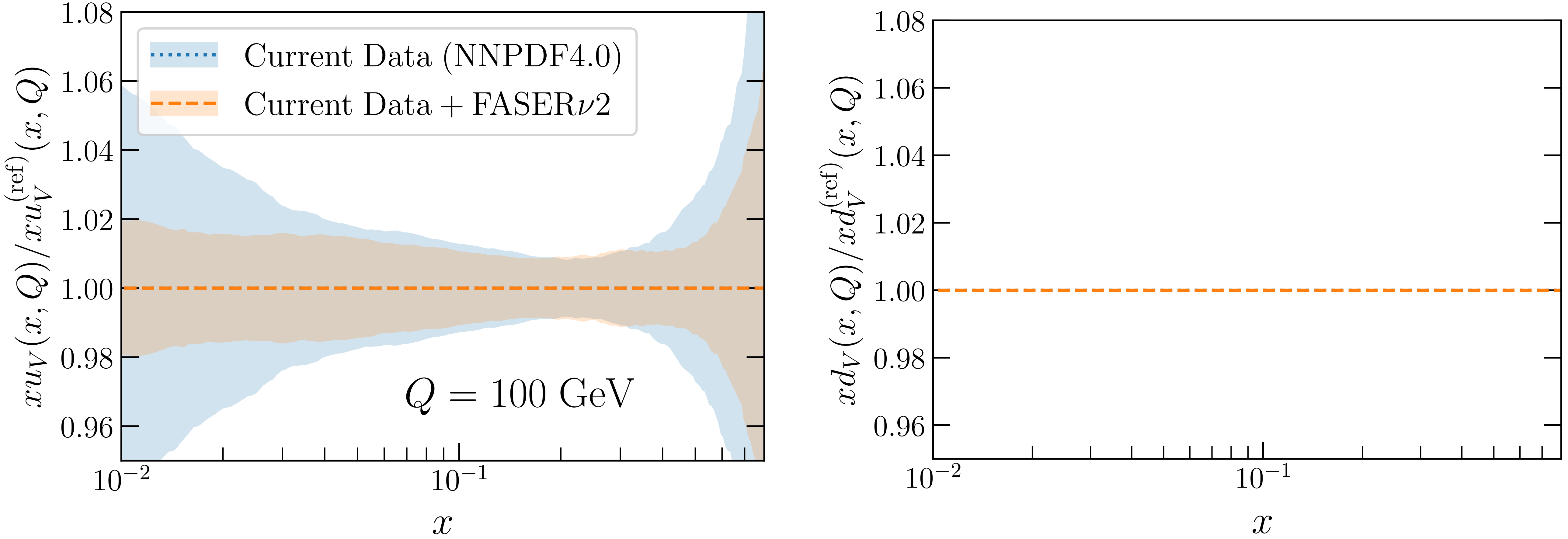
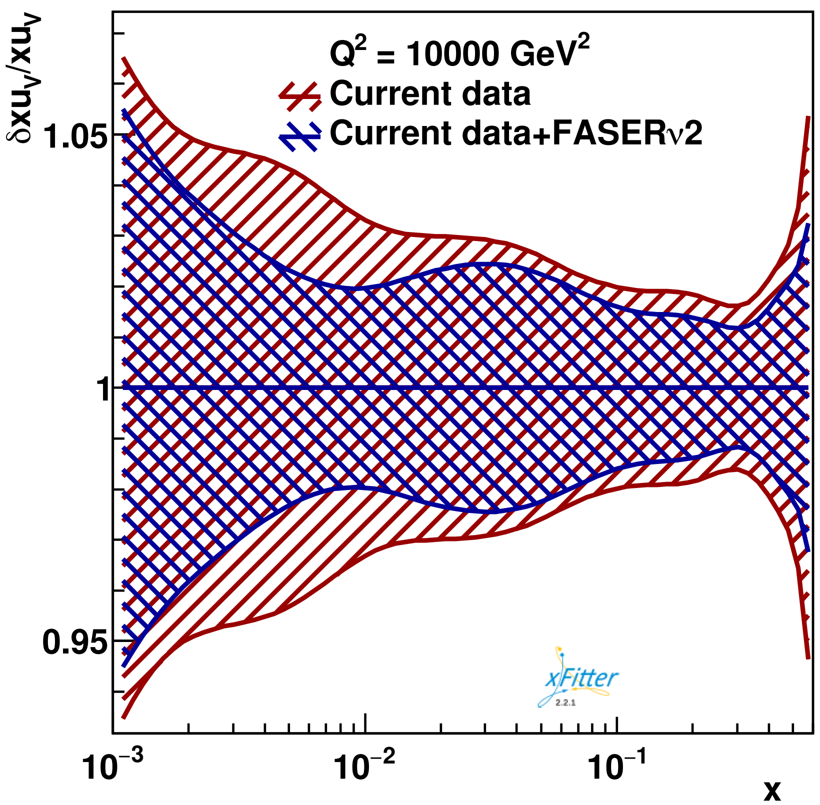
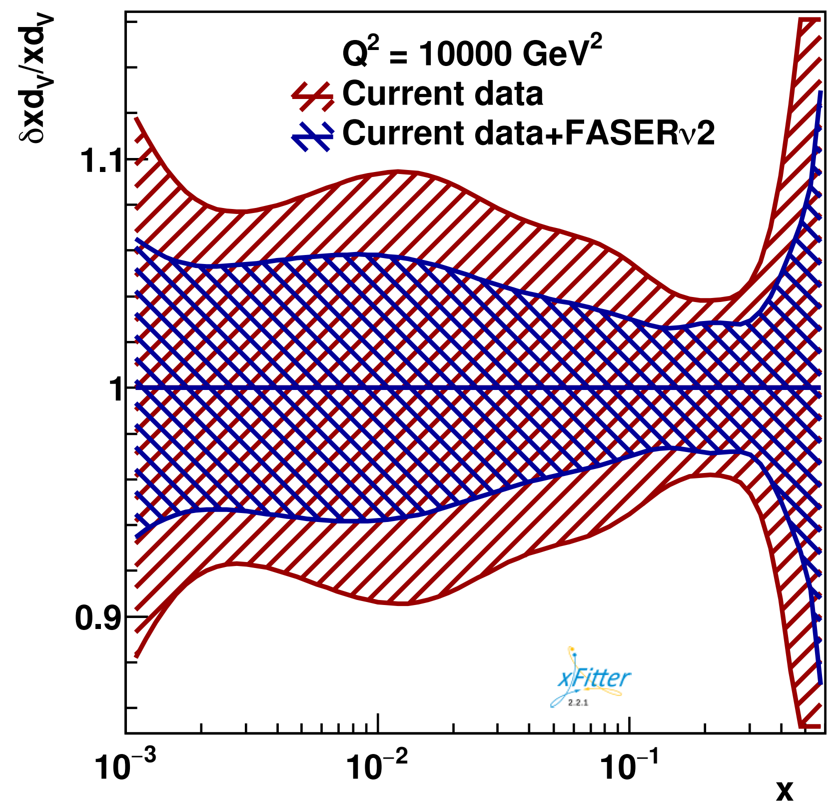


- Cross-checked with inclusion of FASER structure functions into **NNPDF global analysis framework**
- Again main impact on valence quark PDFs
- Study impact on **precision (High-Luminosity) LHC measurements** such as *W* mass

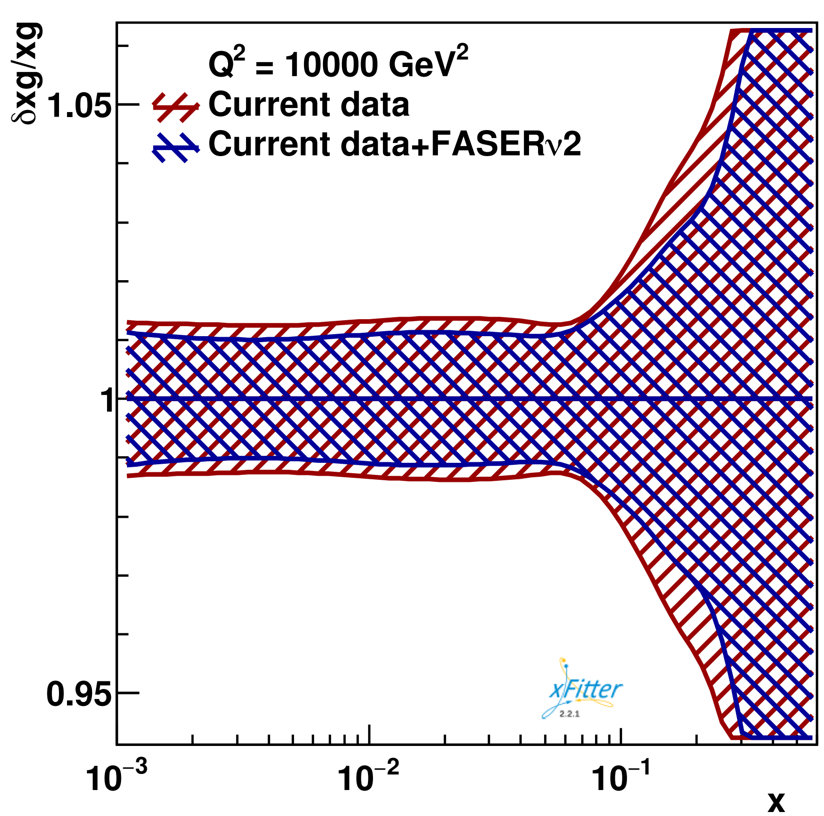
Results: proton PDFs

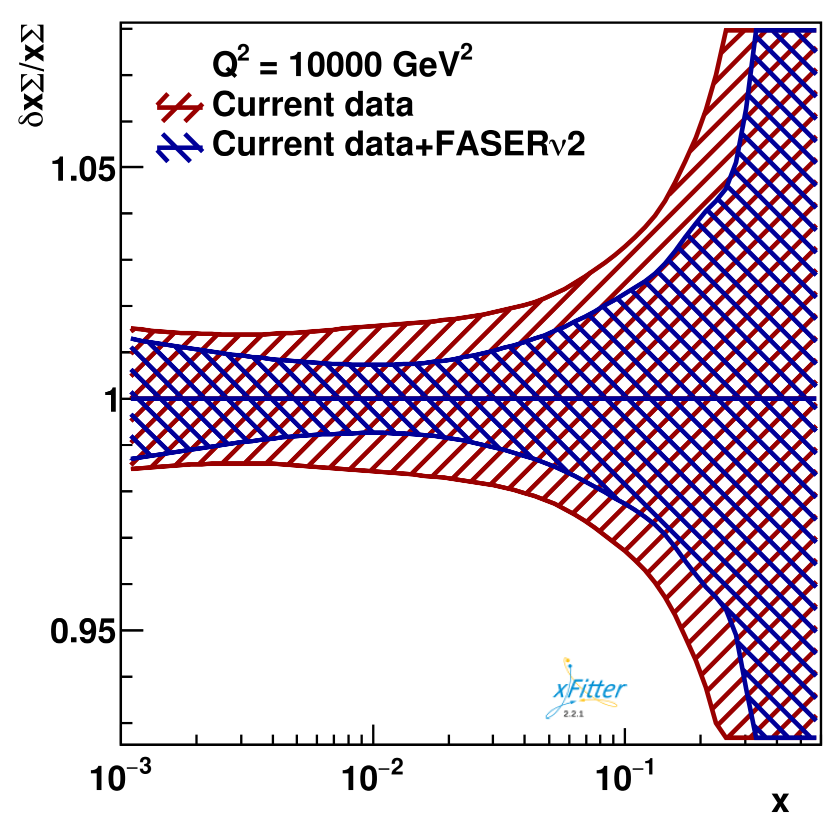
Statistical + Systematic errors only, inclusive + charm data

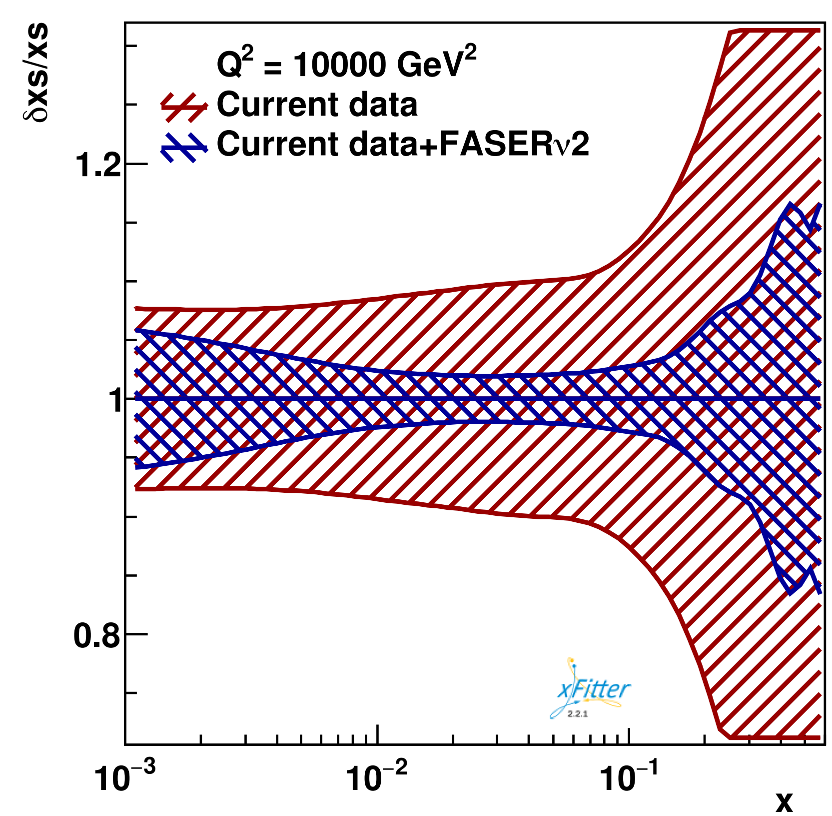




- Results are robust upon inclusion of **systematic errors**
- Depends on assumptions on **correlation model,** in particular bin-by-bin correlations
- Study of different scenarios in progress

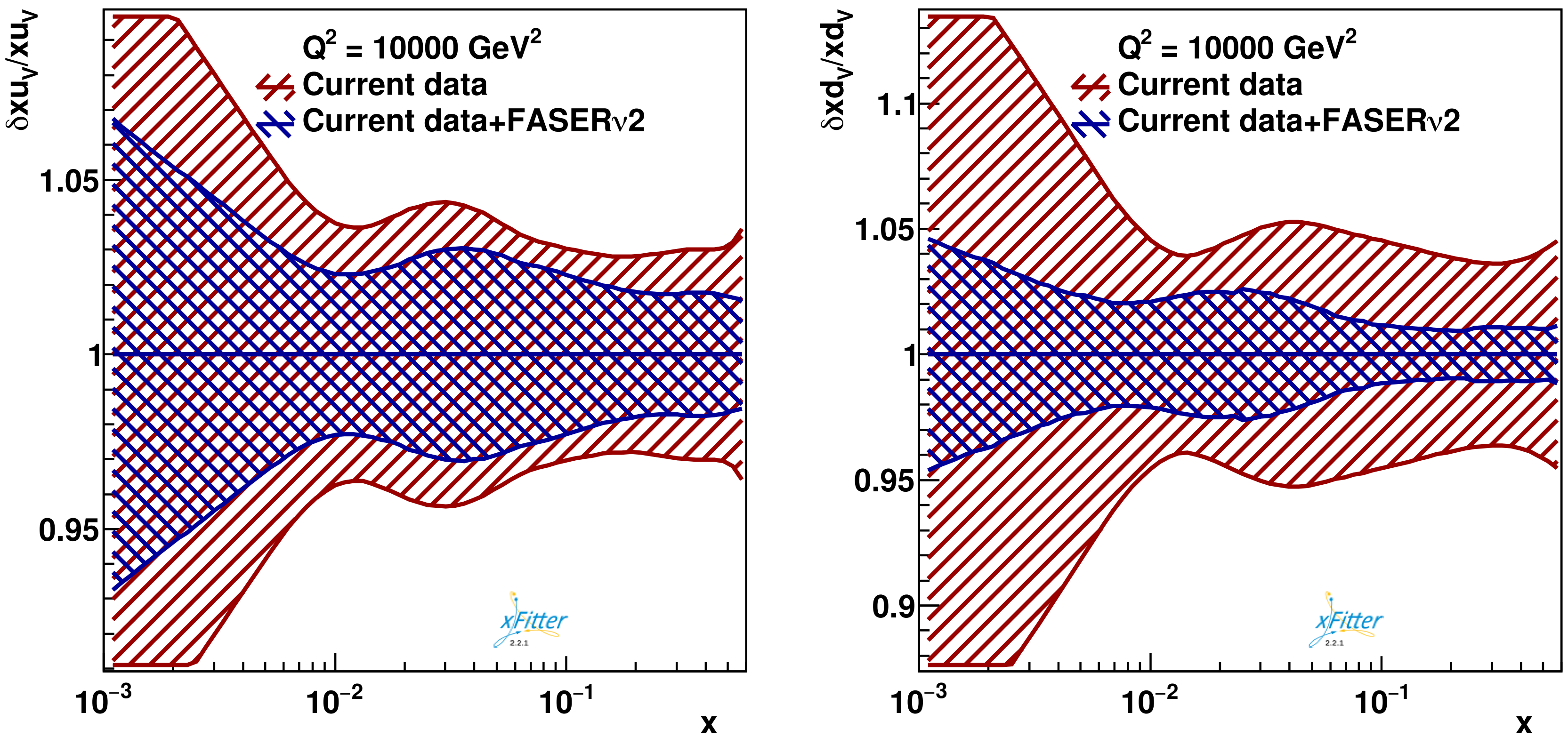




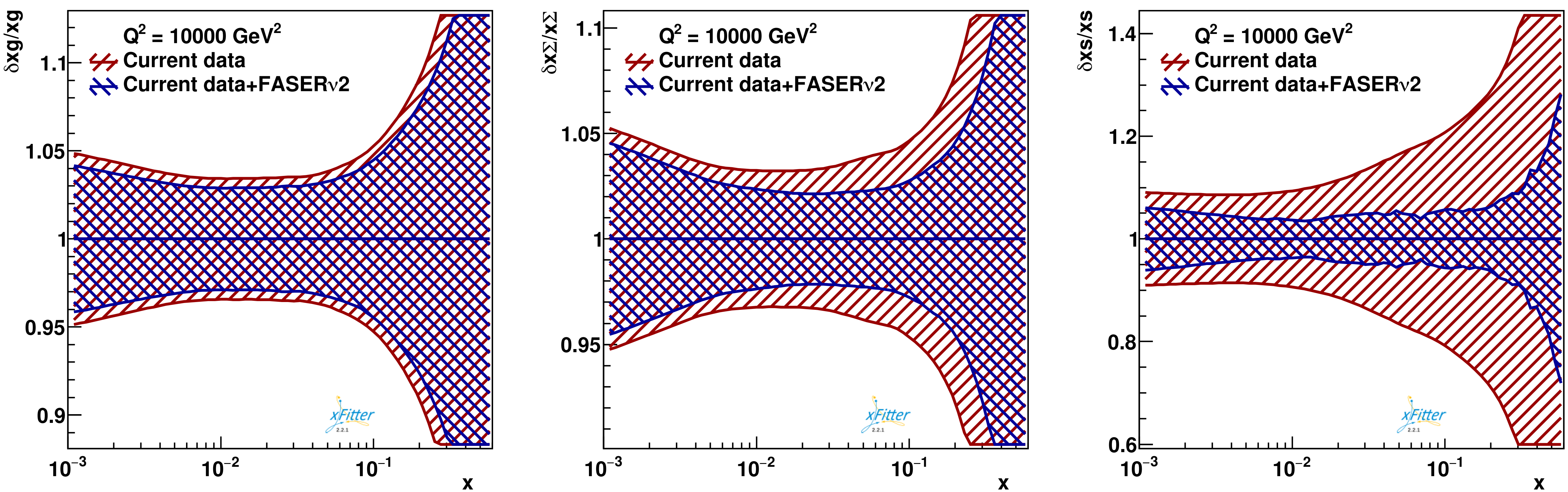


Results: nuclear PDFs

Statistical error only, inclusive + charm data



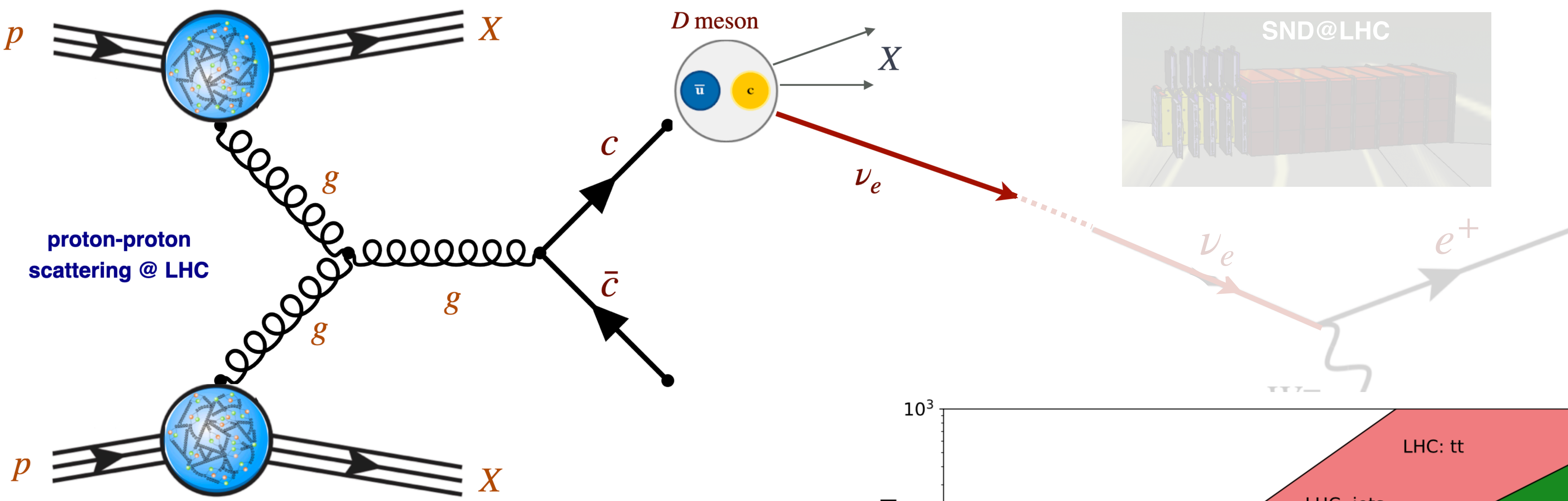
- Profiling of the **EPPS21 global nPDF fit** (Tungsten) reveals a consistent picture
- Excellent sensitivity to quark flavour separation & strangeness



Constraints on hadron structure with LHC neutrinos: charm production

P. Krack, S. Niedenzu, J. Rojo,
J. Sola-Cava, *work in progress*

QCD and Neutrino Physics at FASER



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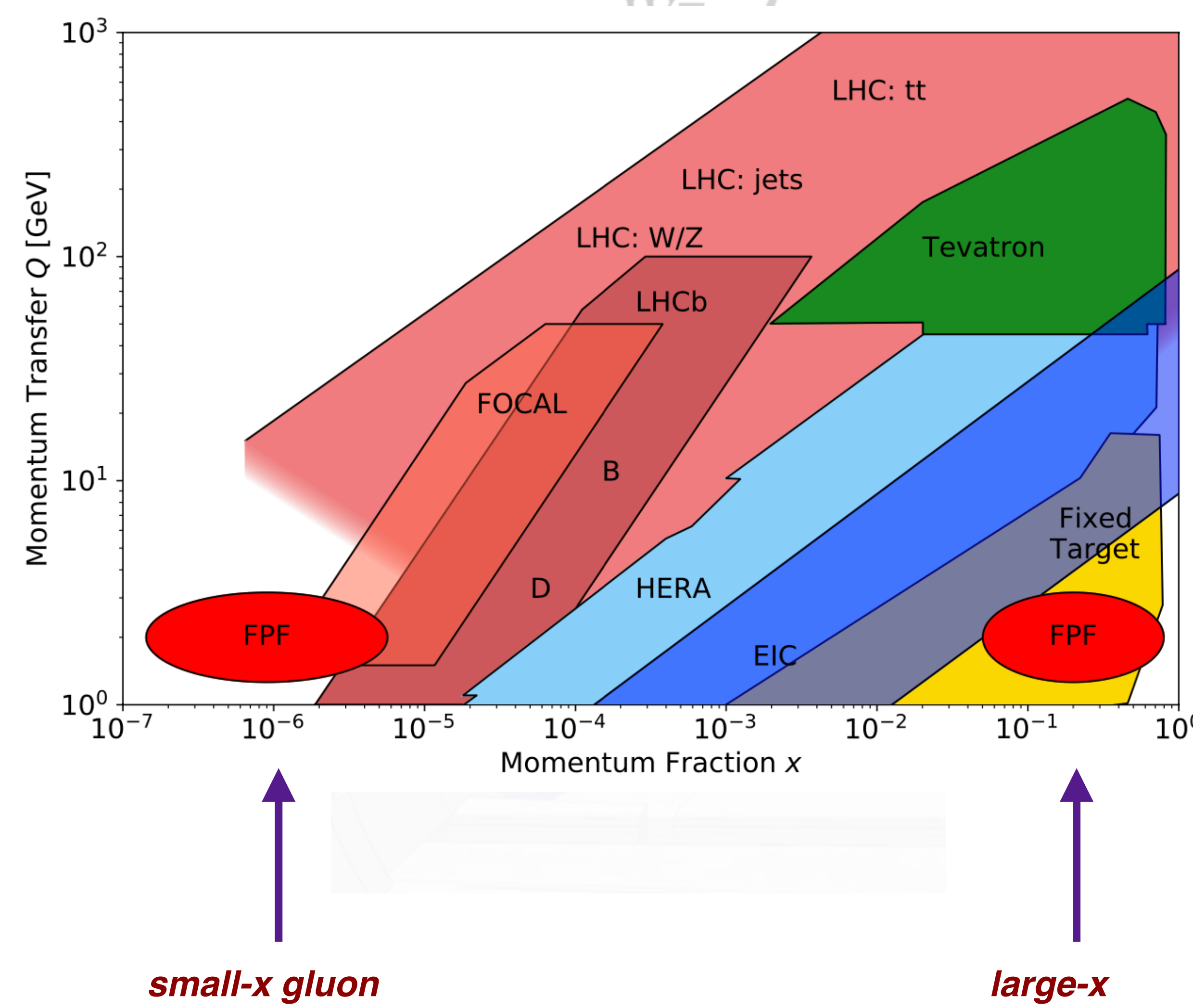

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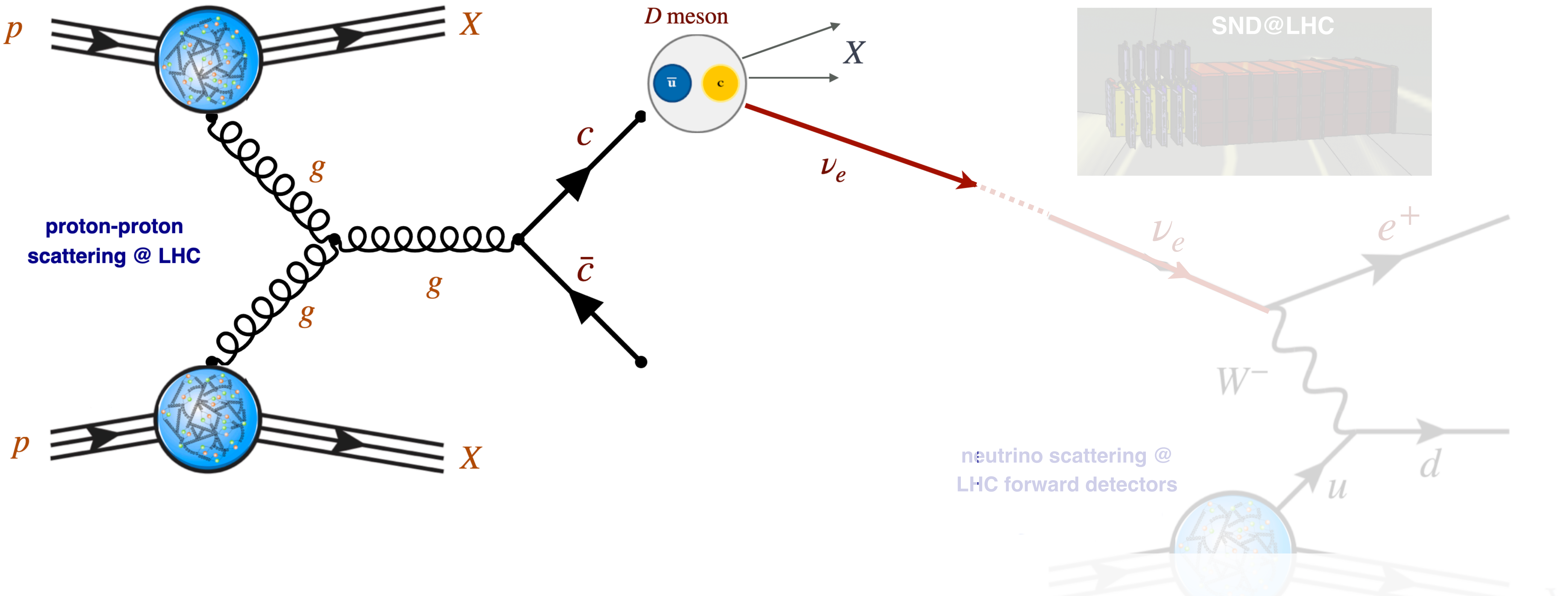


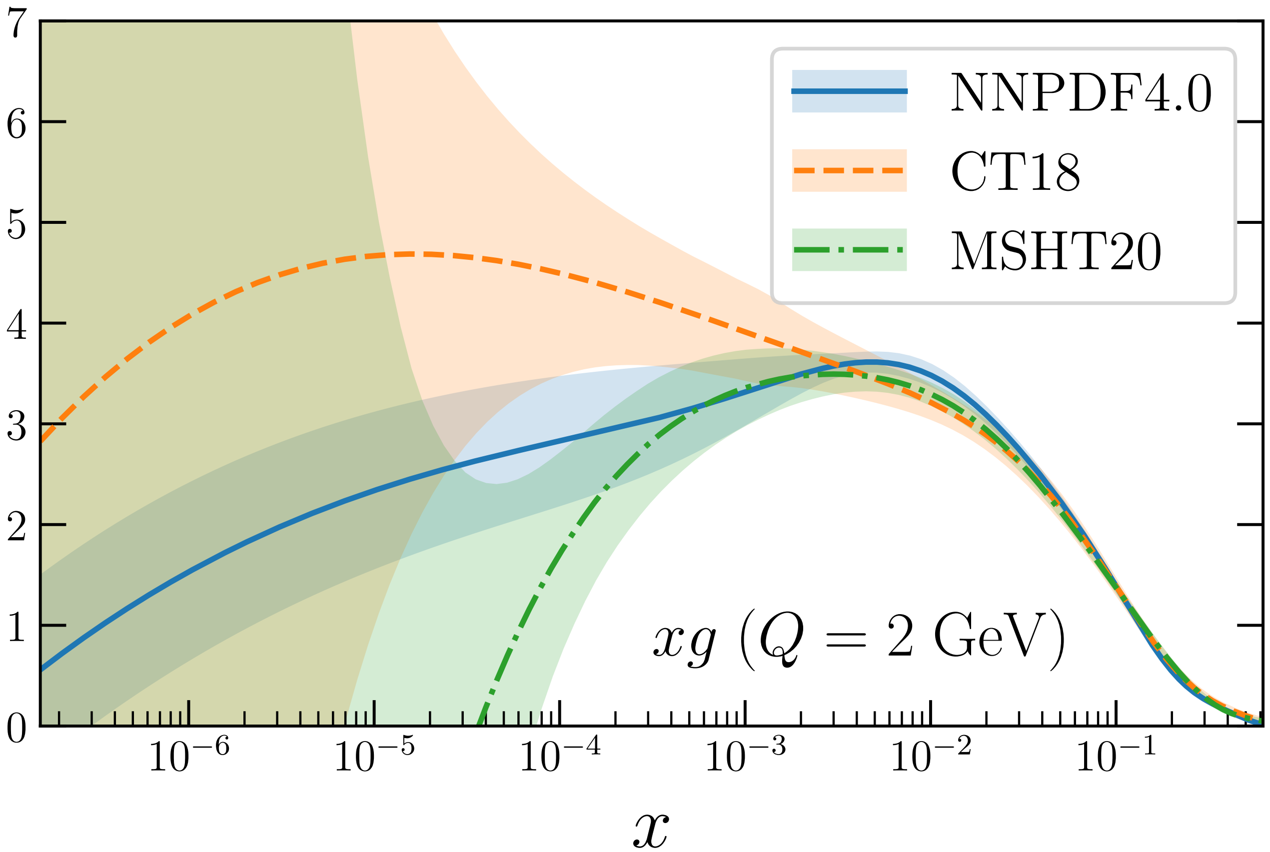
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\widehat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

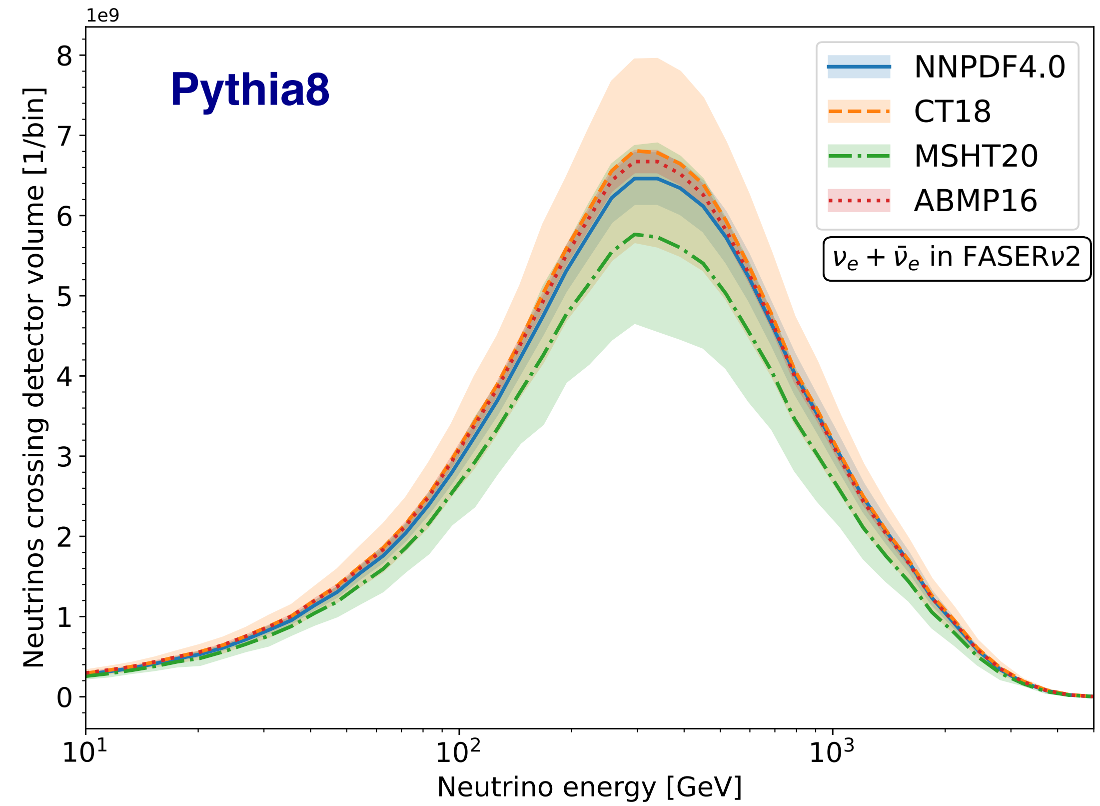
Extract from measured neutrino fluxes

Constrain from FASER/FPF data

QCD prediction: NLO + PS large theory uncertainties

Impact projections



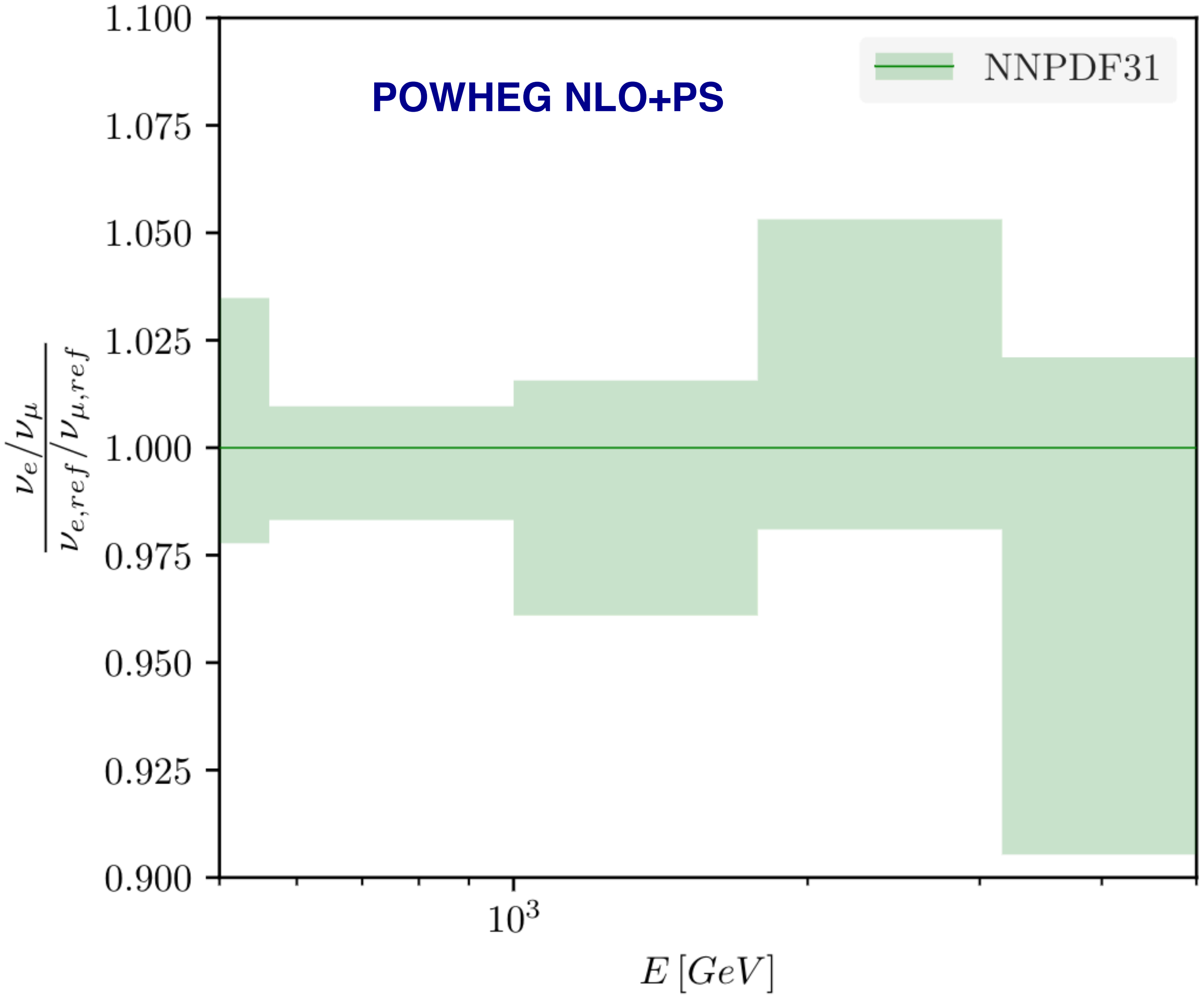


- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially)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

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

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

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**

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

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

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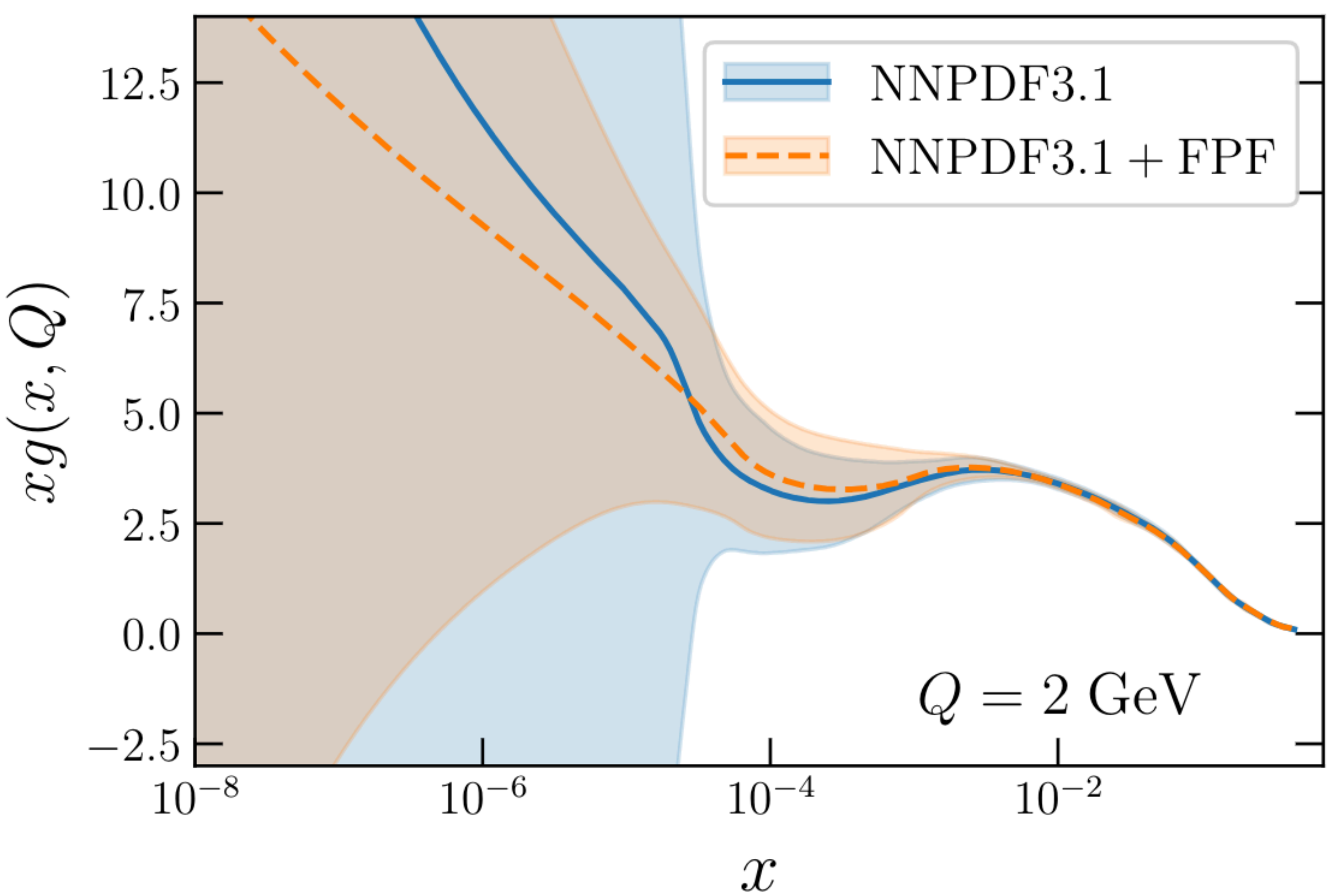
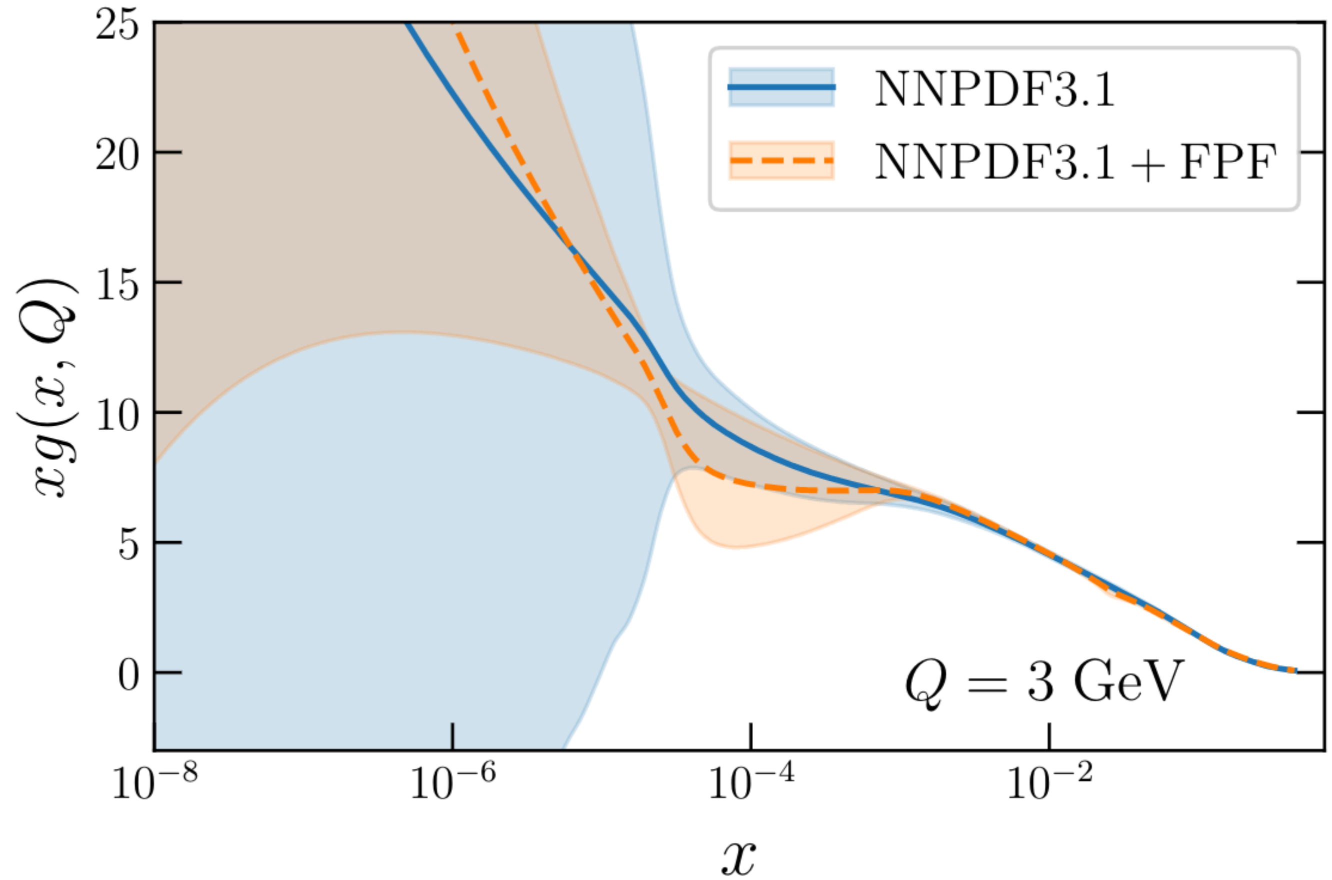
Results

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)

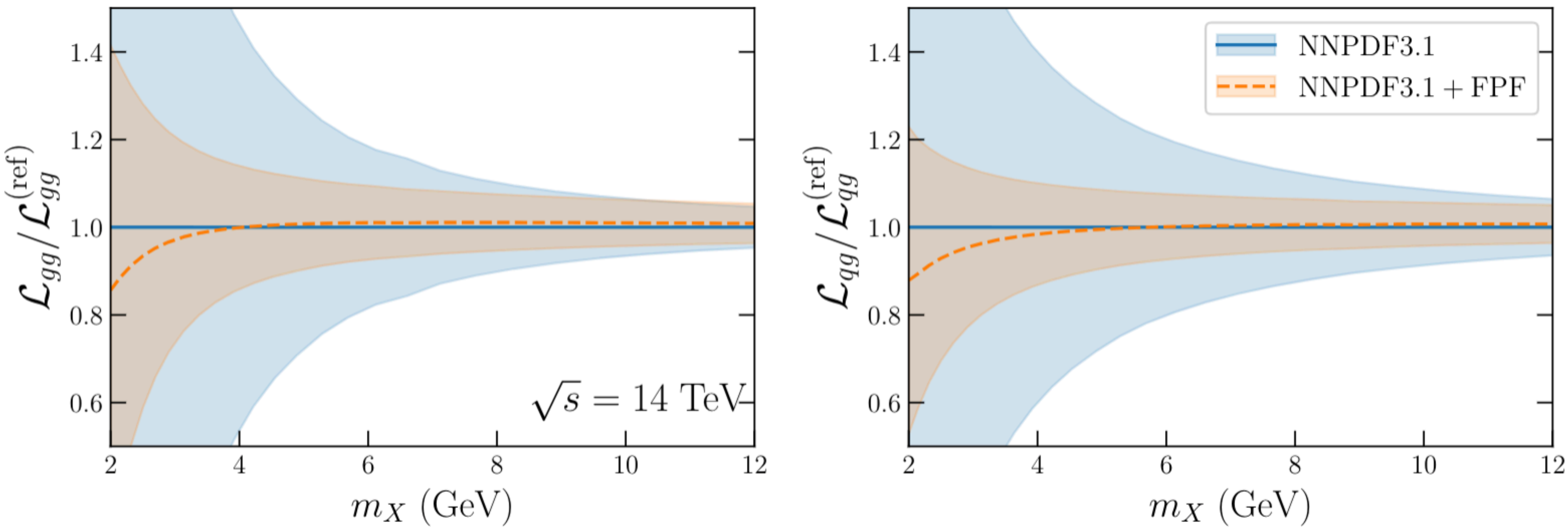
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_u < 9.0)}$$

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

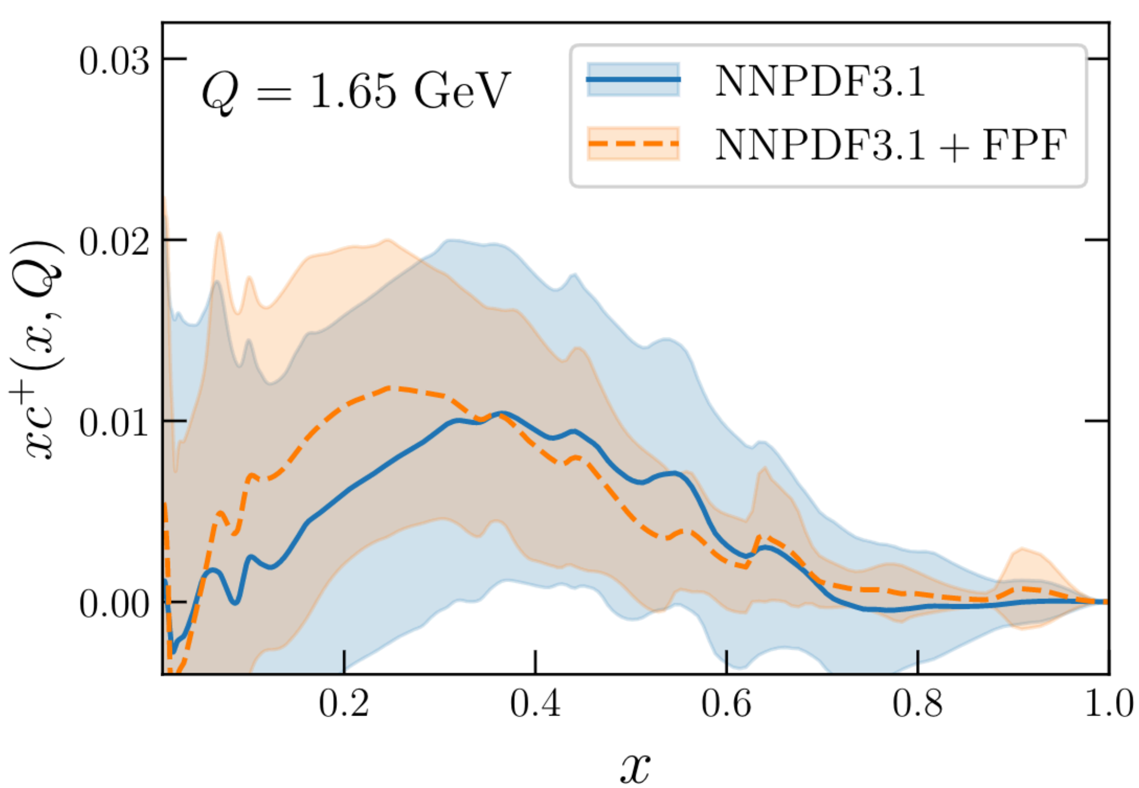
- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment
- Study impact of different observables, QCD errors, and the precision of measurement

Results

Electron neutrinos, 2% uncertainty in inclusive event rates



- General improvements of **low-mass gluon-initiated** processes at the LHC
- 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 $x=10^{-7}$**

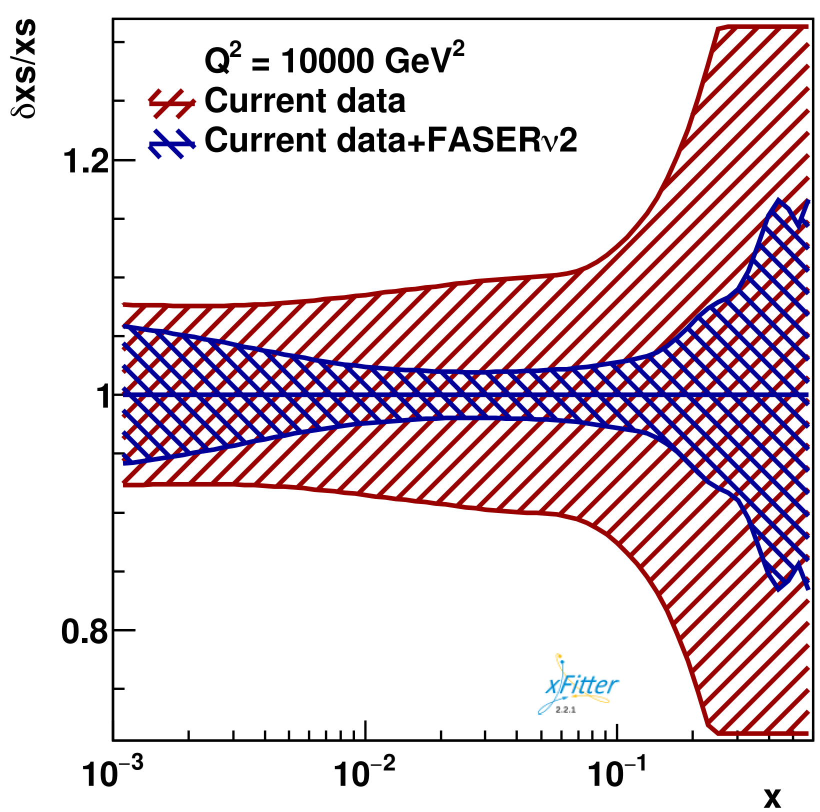


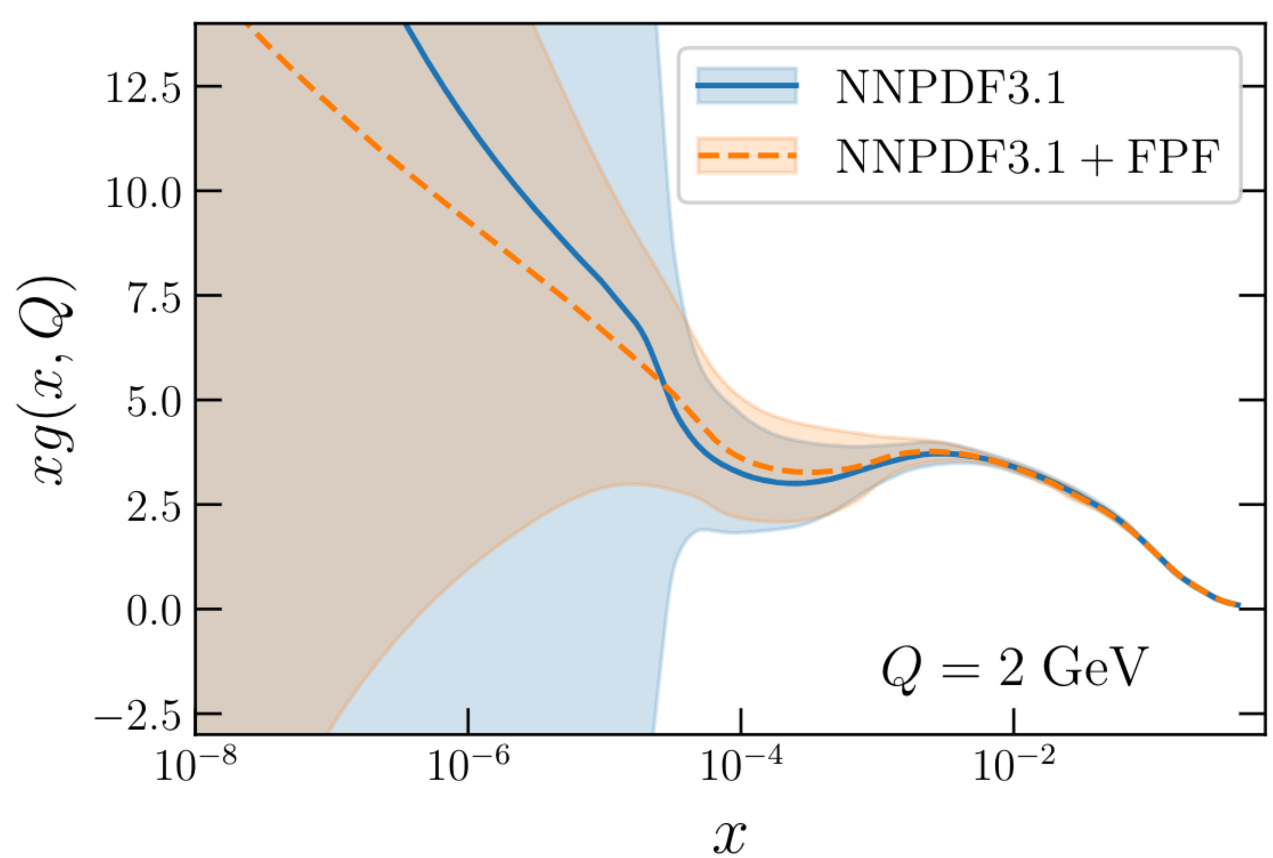
Summary and outlook

- Steady progress from WG1 aimed to **quantify the FPF potential** on hadronic structure and neutrino DIS

- Demonstrated reach of neutrino DIS at the FPF to **constrain proton and nuclear PDFs**. Paper in preparation, with dedicated set of projections for **FPF neutrino structure functions** as bonus

- Measurements of **electron and tau neutrino event rates** at the FPF constrain the small-x gluon and large-x charm in unexplored regions by using **dedicated observables**





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.

together with WG2!

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?

On track to meet our (pre-)CDR targets

WG1 welcomes any colleagues that want to join these studies!