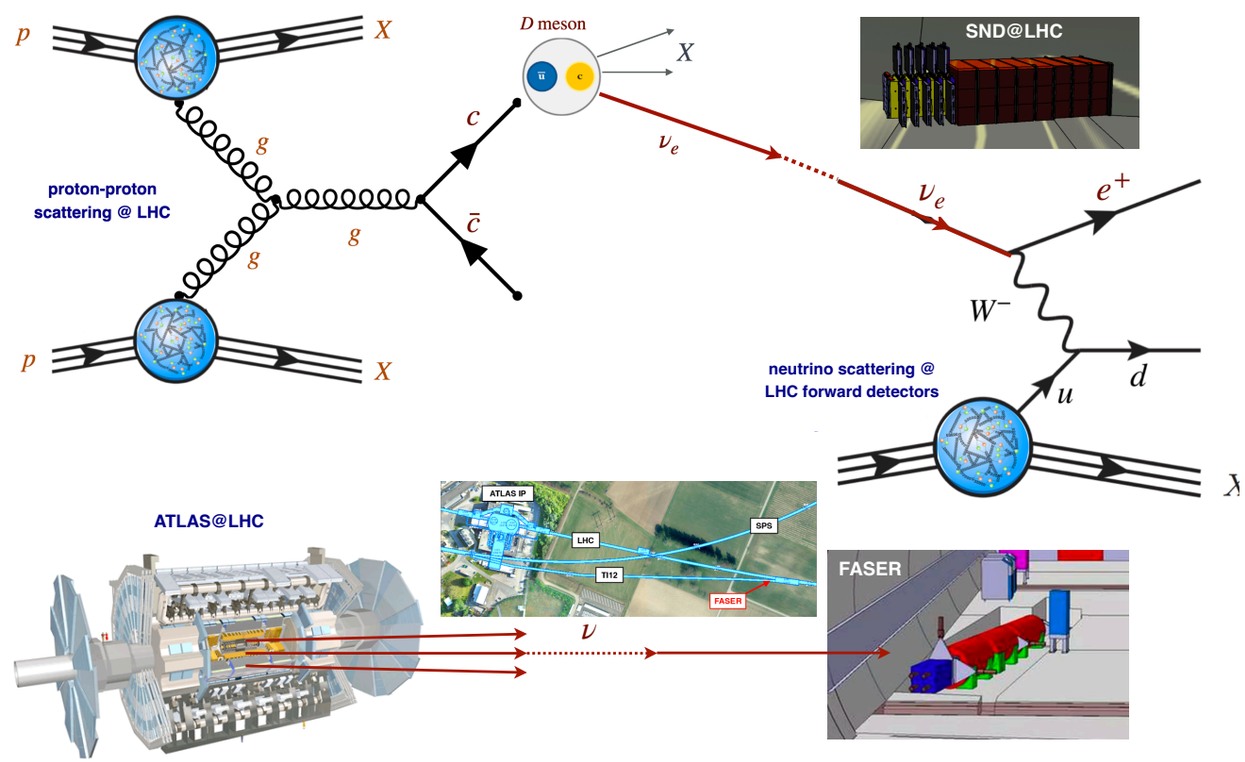
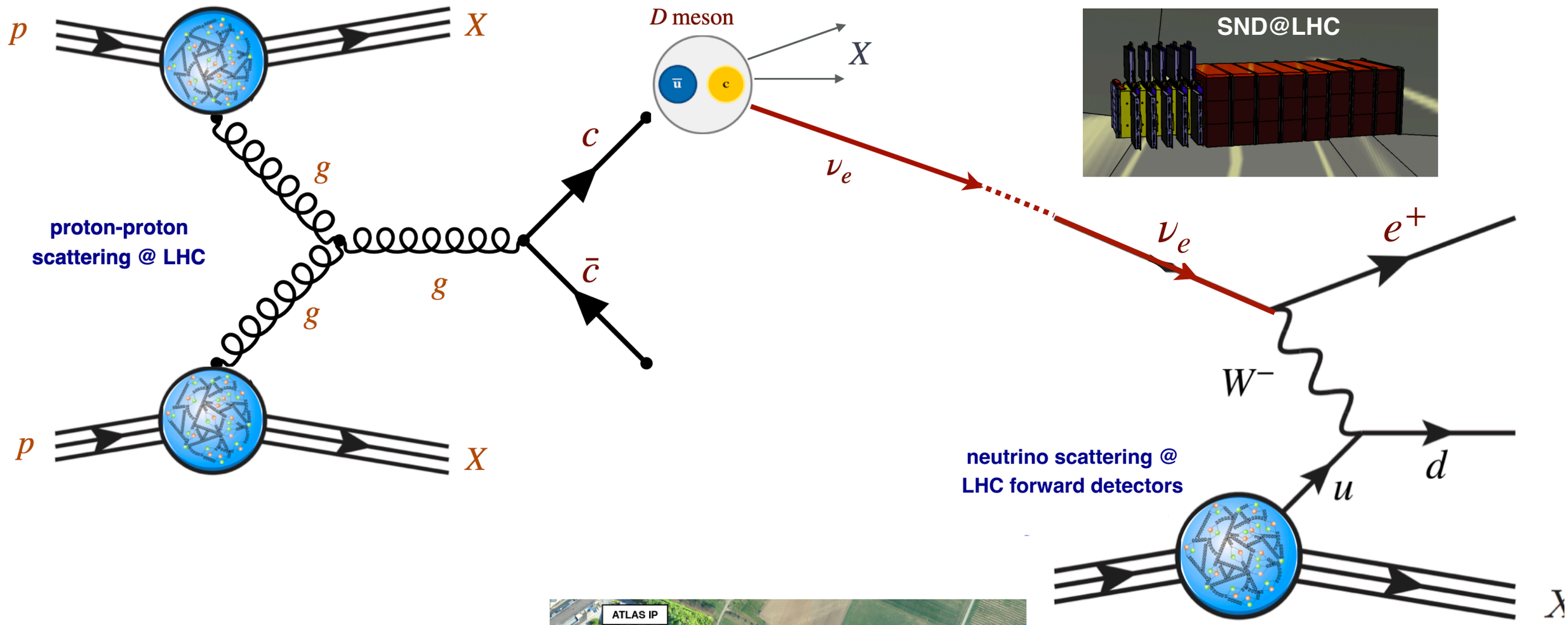
Hadron Structure under the Neutrino Femtoscope at FASER

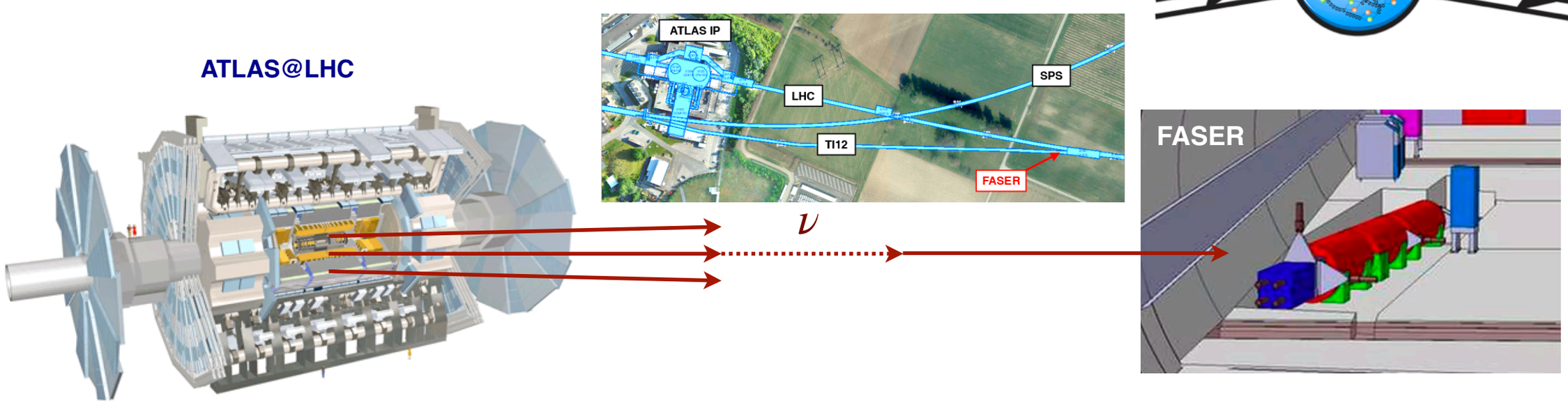
Juan Rojo, VU Amsterdam & Nikhef



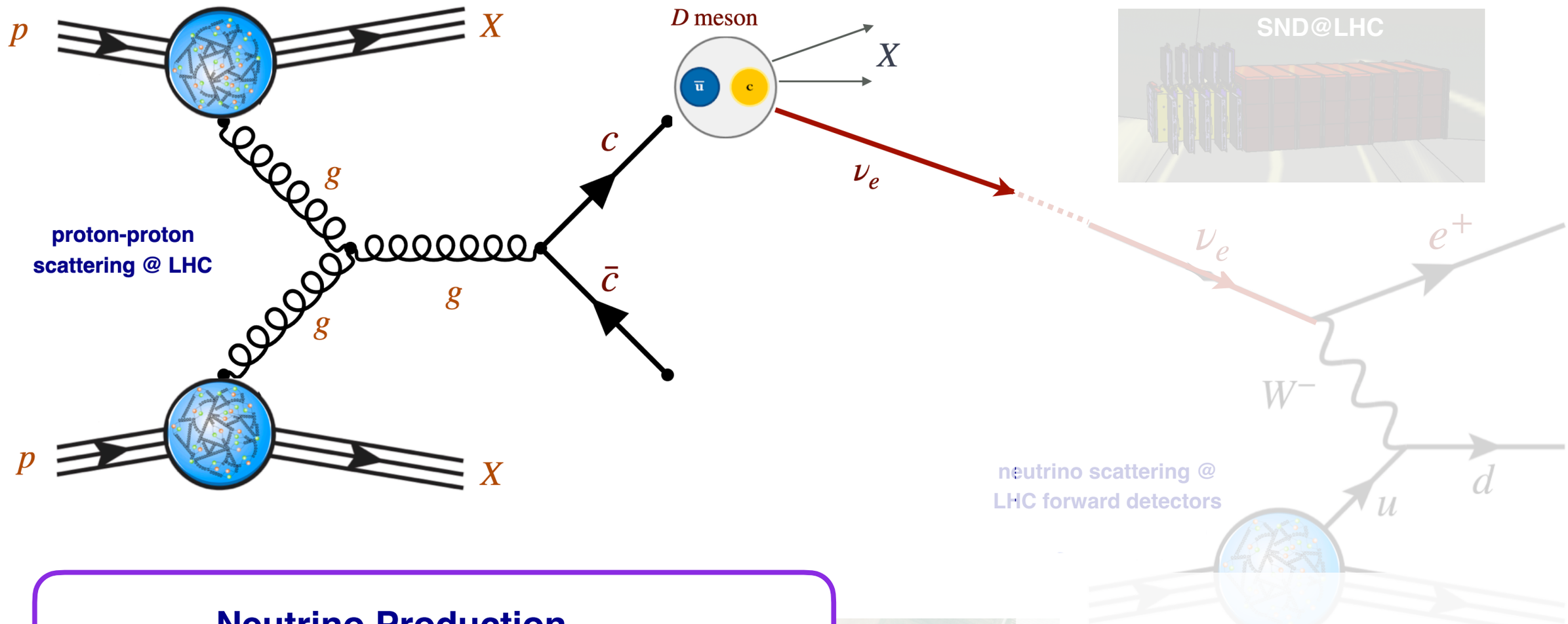
FASER Collaboration meeting, CERN, 07.06.2023

QCD and Neutrino Physics at FASER





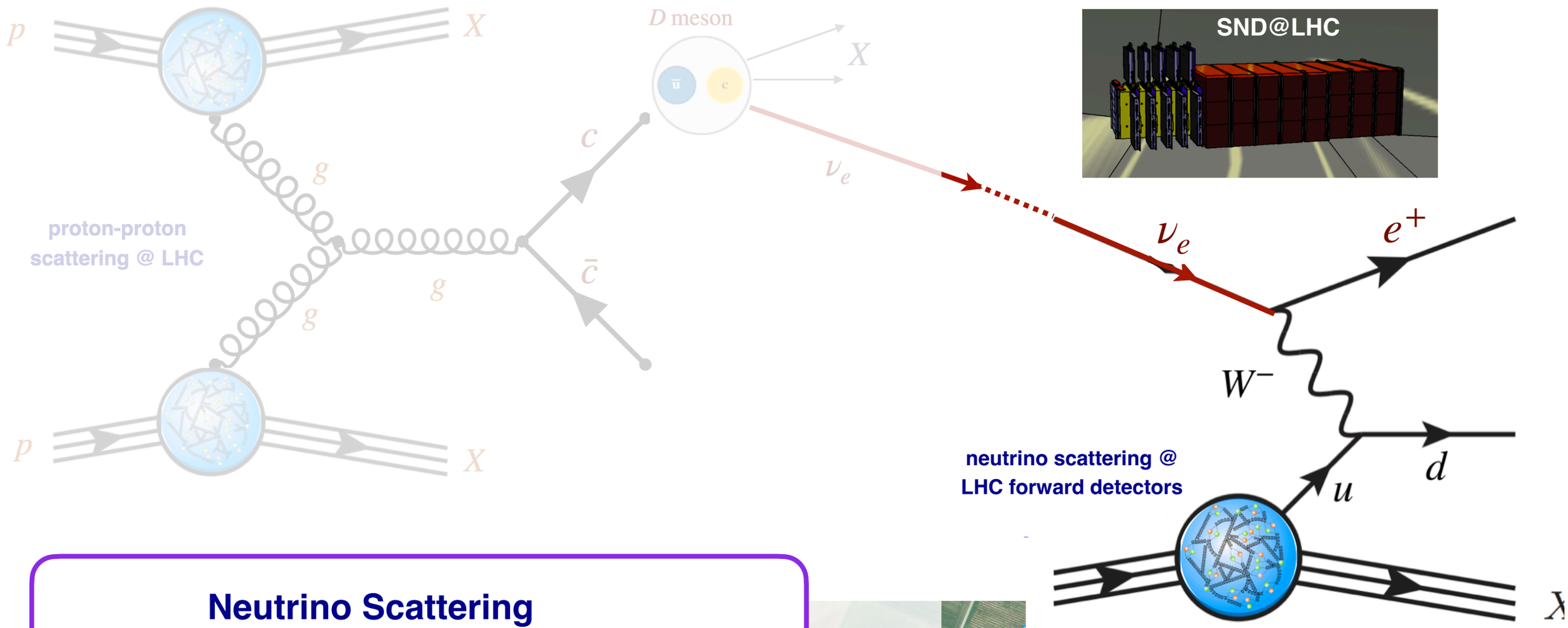
QCD and Neutrino Physics at FASER



Neutrino Production

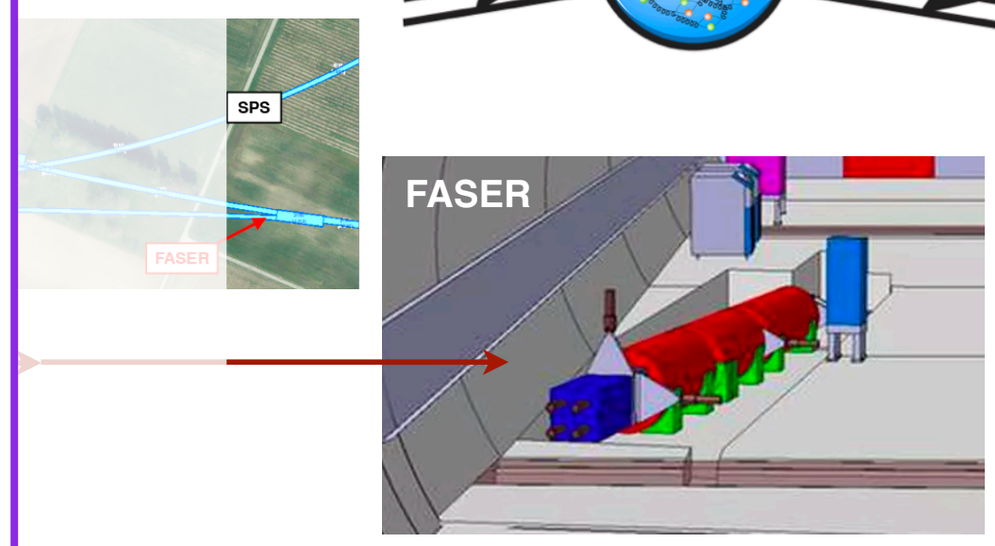
- Small-x gluon & large-x (intrinsic) charm
- *D*-meson fragmentation
- Cross-sections for UHE neutrinos (*e.g.* IceCube)
- Cosmic ray modelling, including muon puzzle

QCD and Neutrino Physics at FASER



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)



QCD and Neutrino Physics at FASER

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

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

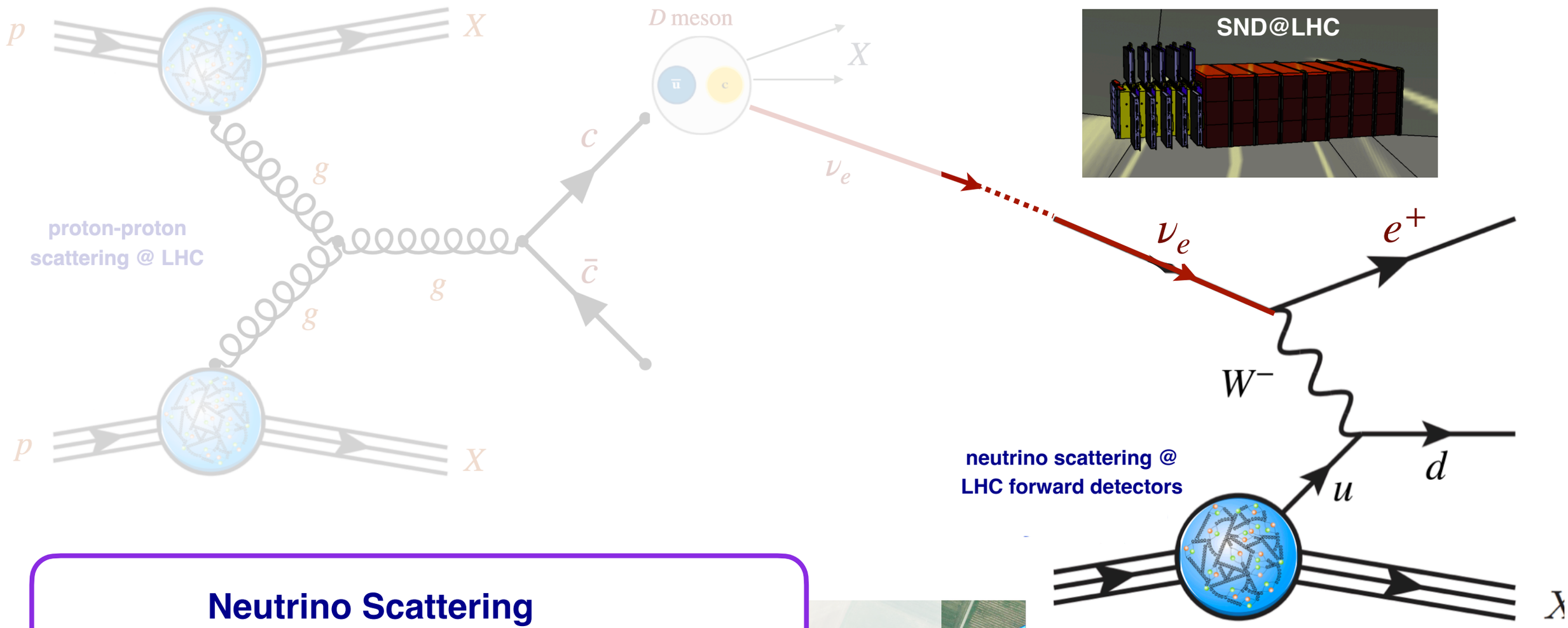
Neutrino Scattering

- 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)

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

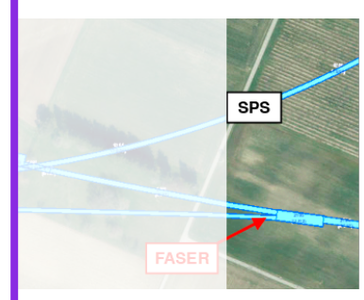
M. Fieg, T. Giani, P. Krack, G. Magni, T. Makela, T. Rabemananjara, J. Rojo, *work in progress from FPF Working Group 1*

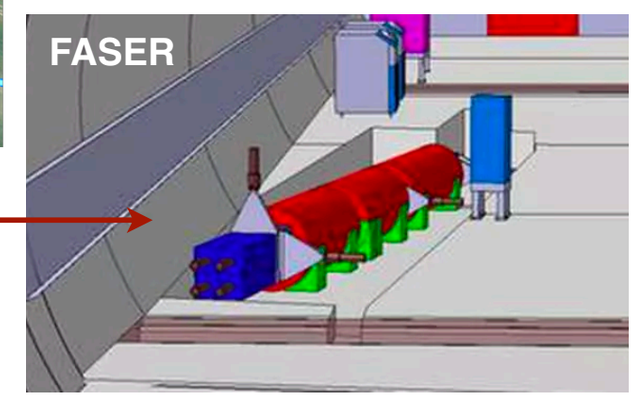
QCD and Neutrino Physics at FASER



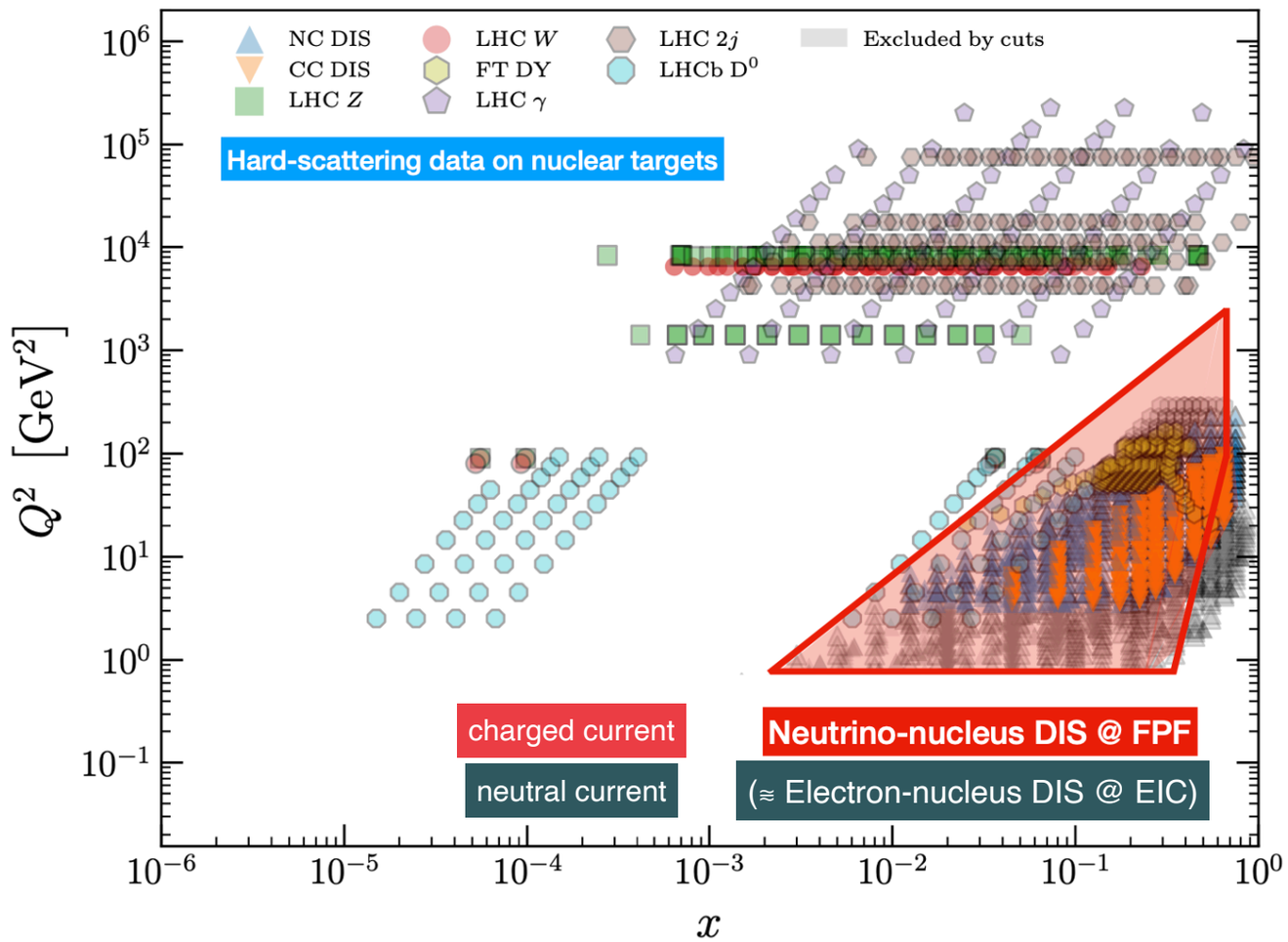
Neutrino Scattering

- **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)



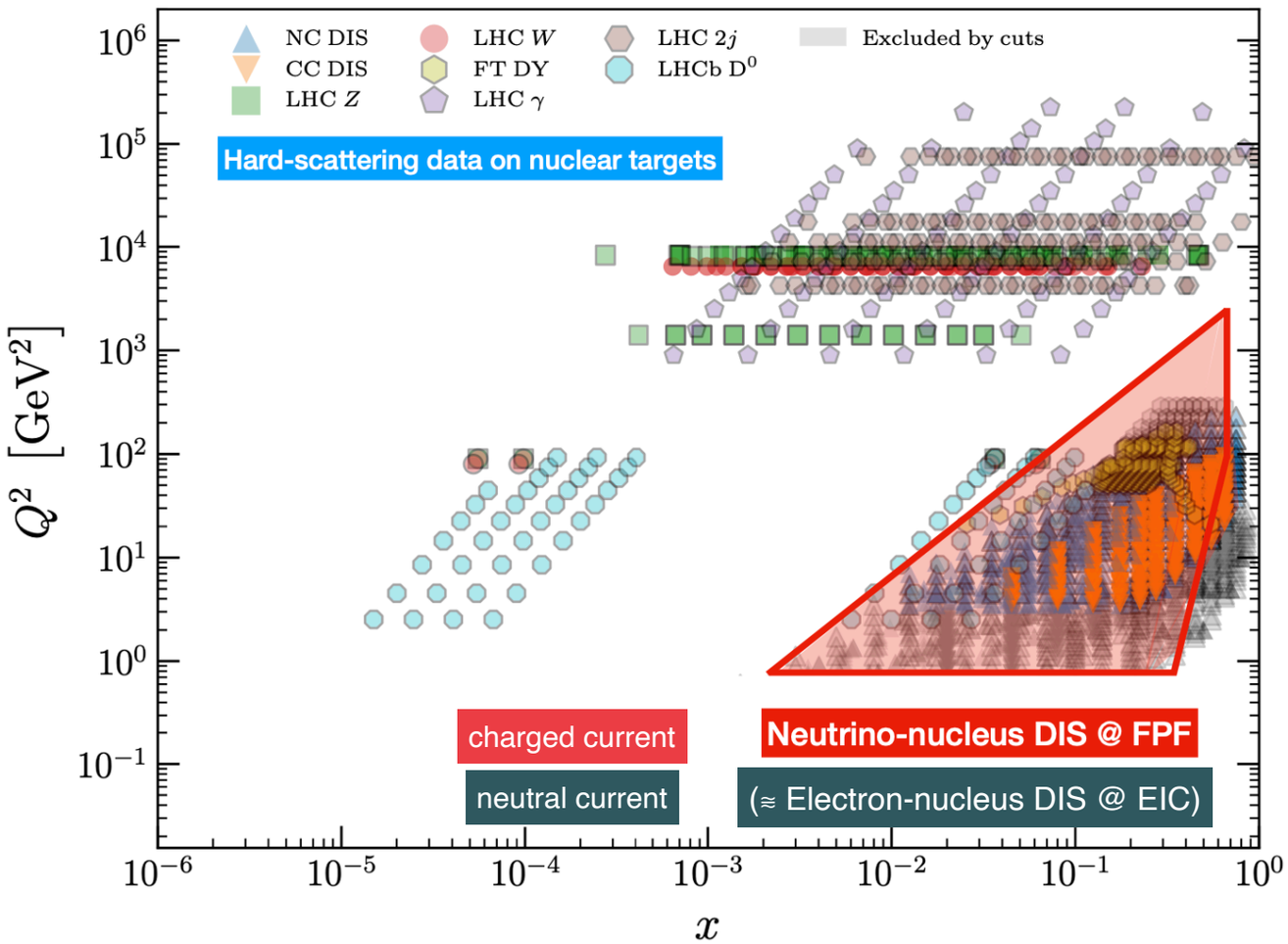


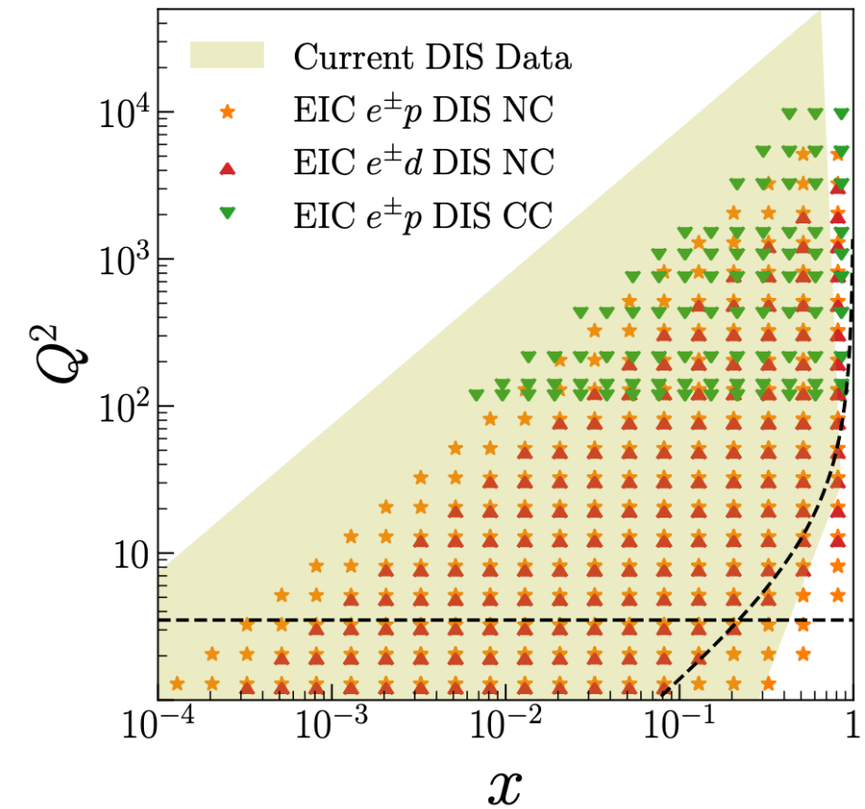
Deep-Inelastic Scattering at FASER

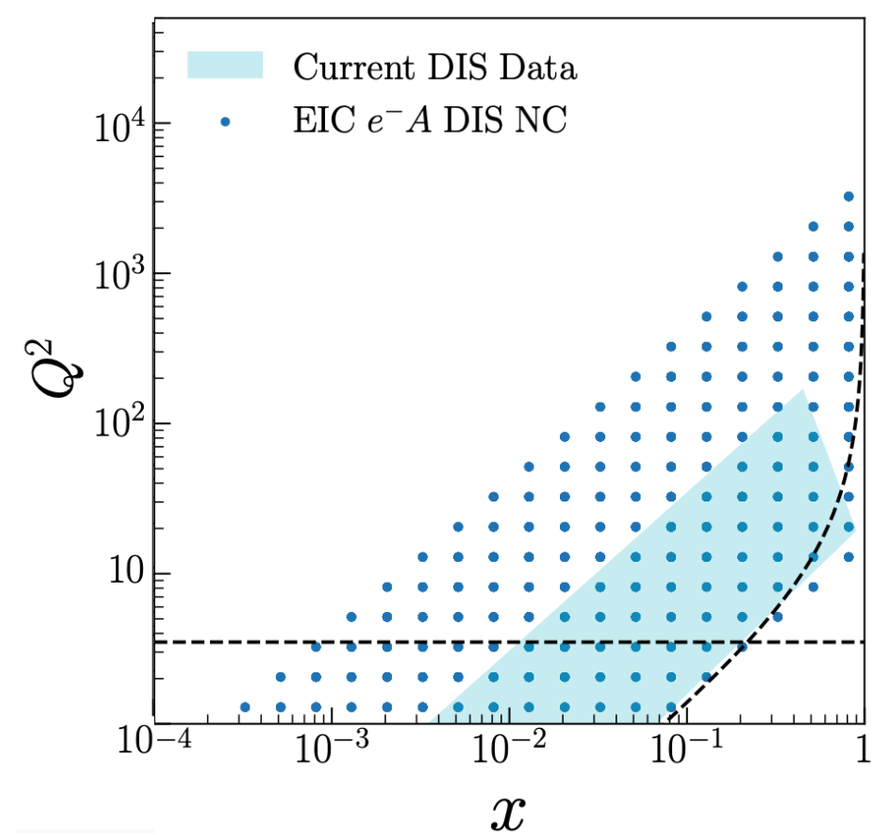


- **FASER:** deep-inelastic charged current scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN,** expand kinematic coverage of previous experiments both in x and Q
- Charged-current analog of the Electron-Ion Collider: the LHC as a **Neutrino-Ion Collider**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

Deep-Inelastic Scattering at FASER



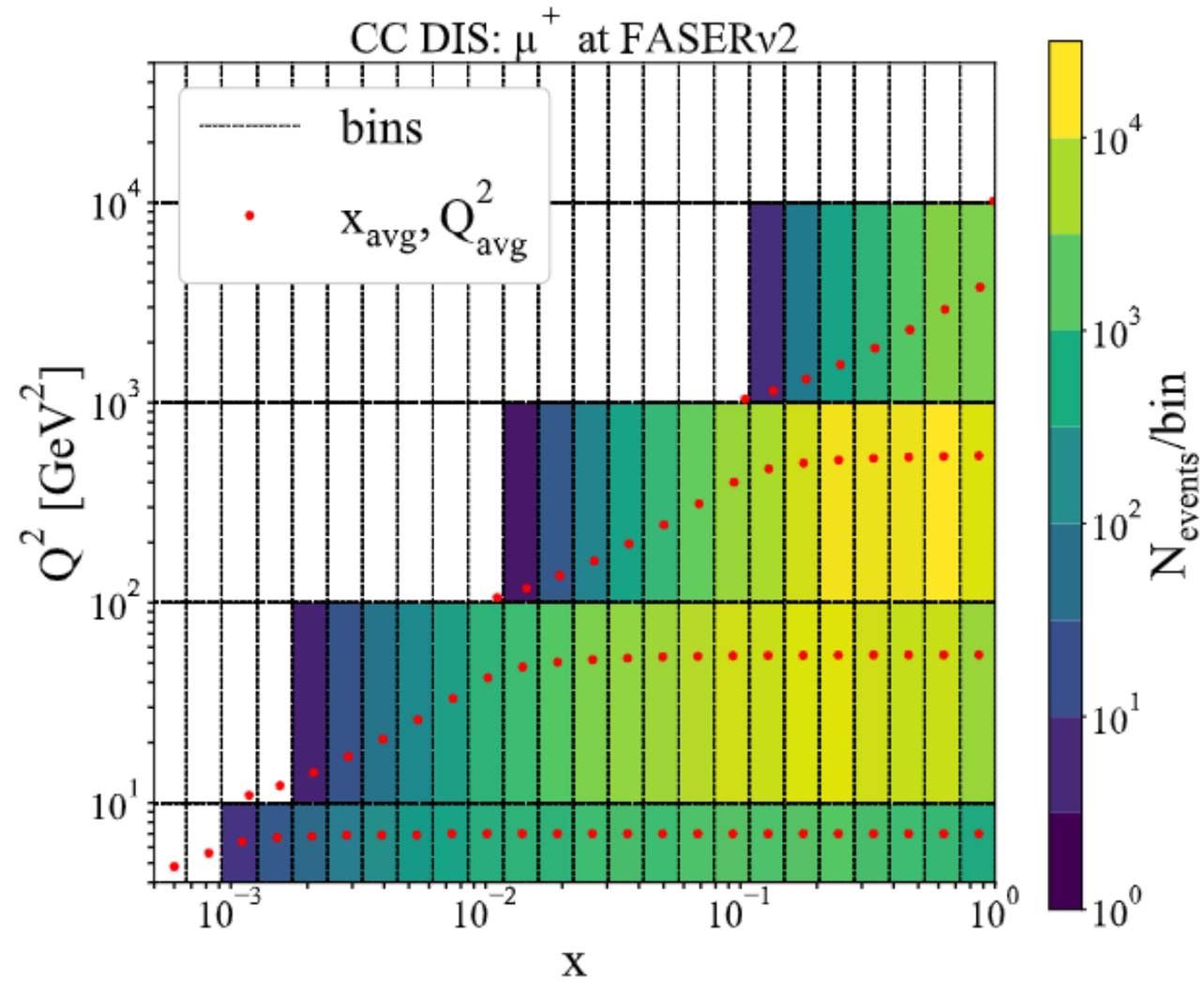




- Excellent complementarity between **EIC (neutral current)** and **FPF (charged current)** measurements of DIS structure function on proton and nuclear targets
- A **joint analysis of EIC+FPF data** markedly improves the (n)PDF reach of **individual experiments**

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

- 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

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

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

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

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

Impact projections

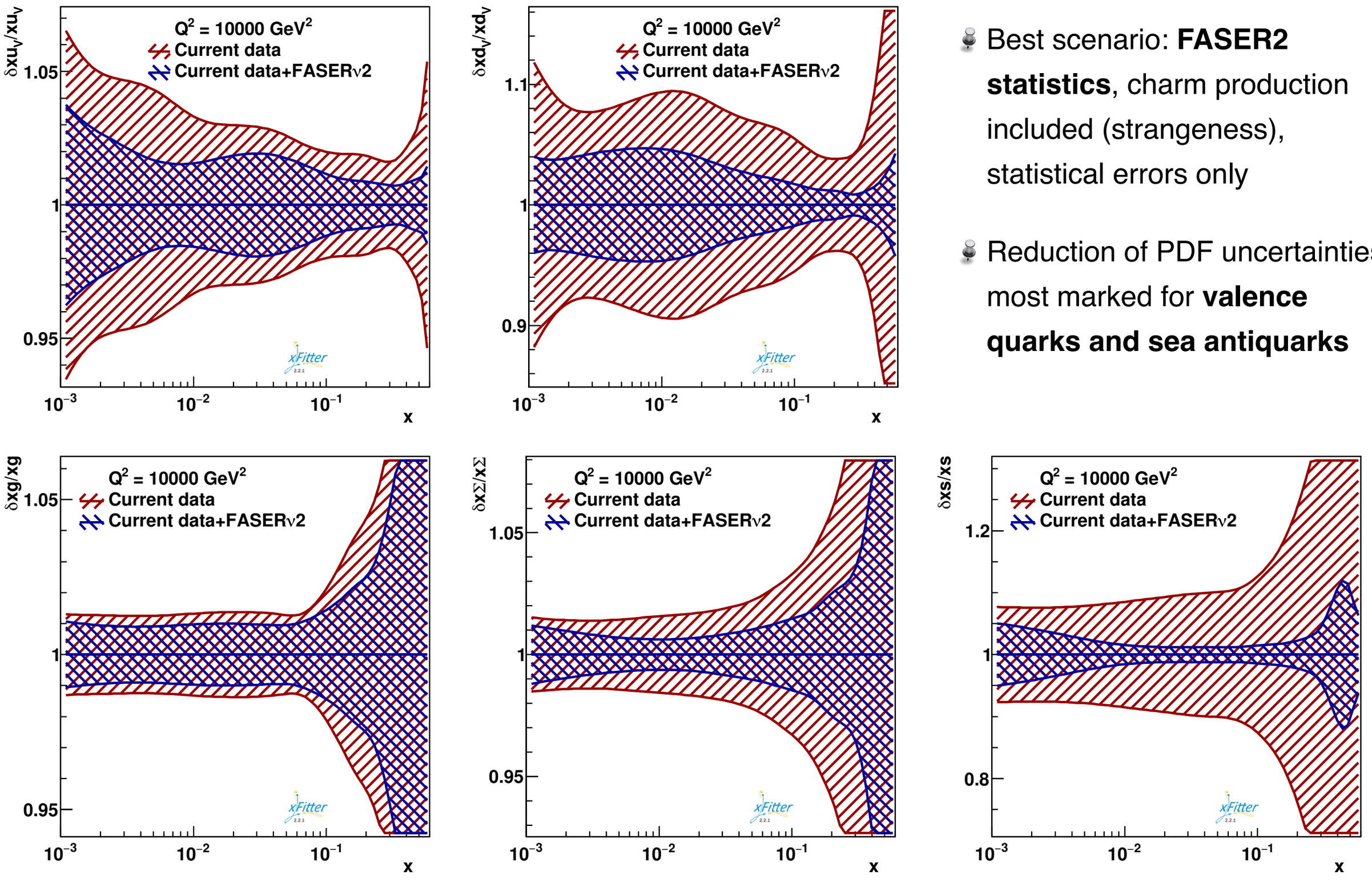
- Strategy: **xFitter** Hessian PDF profiling of **PDF4LHC21** (for proton PDF, neglect nuclear modifications) and **EPPS21** (for tungsten PDF)
- Cross-checked with independent inclusion in **NNPDF fitting code** (global dataset)
- Study relative sensitivity of the **different experiments**, role of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

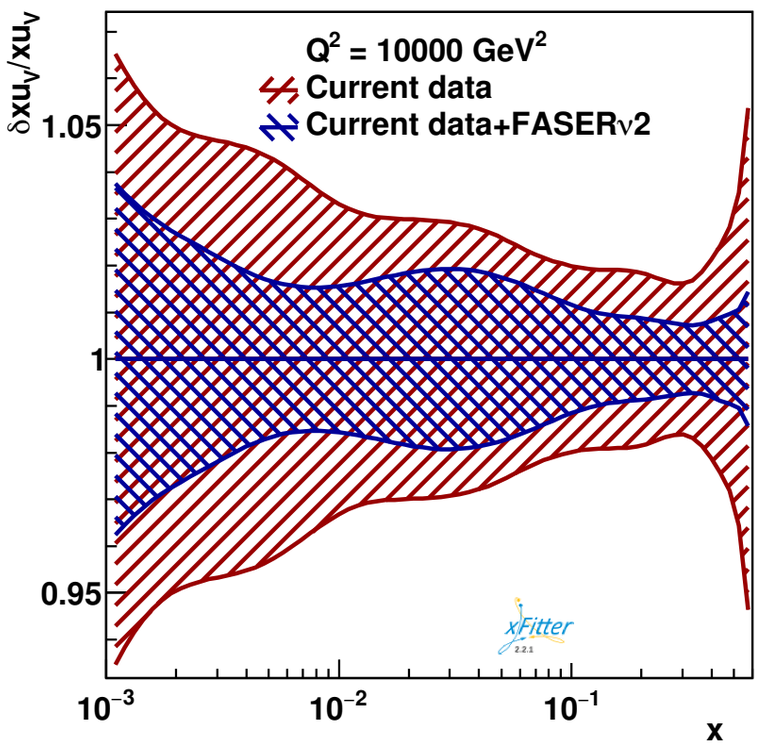
Statistical error only, inclusive + charm data

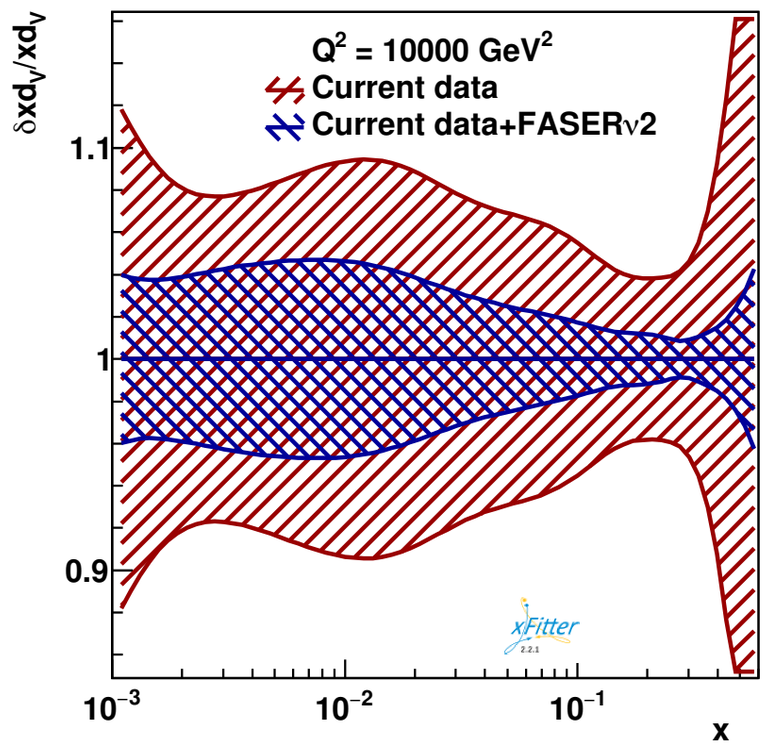


- Best scenario: **FASER2 statistics**, charm production included (strangeness), statistical errors only
- Reduction of PDF uncertainties most marked for **valence quarks and sea antiquarks**

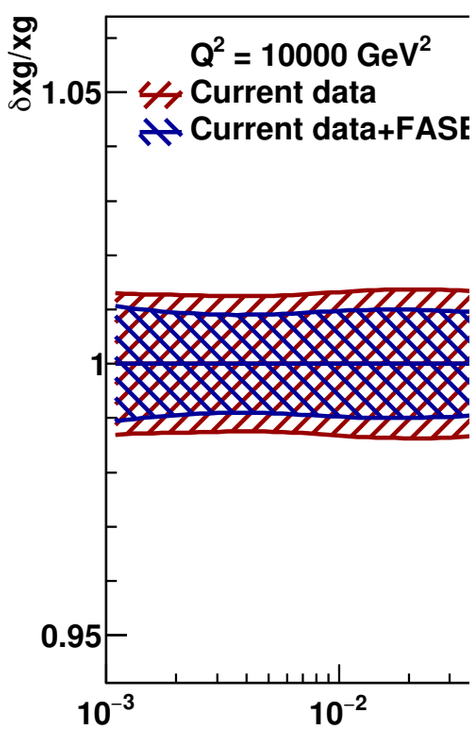
Results: proton PDFs

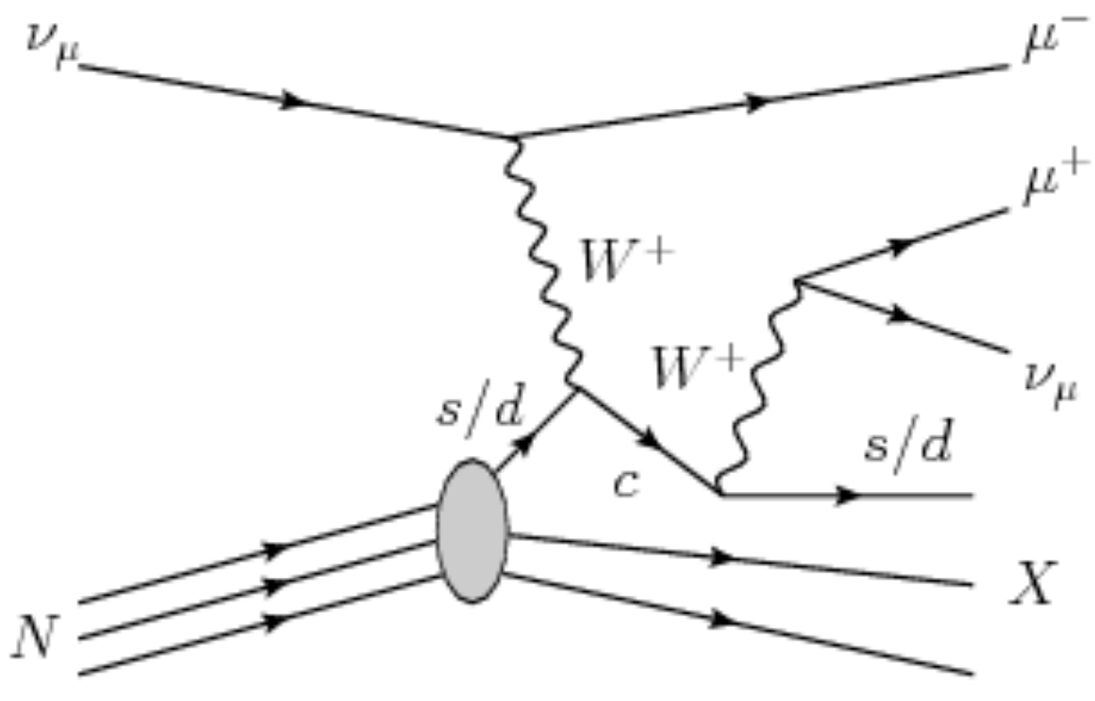
Statistical error only, inclusive + charm data

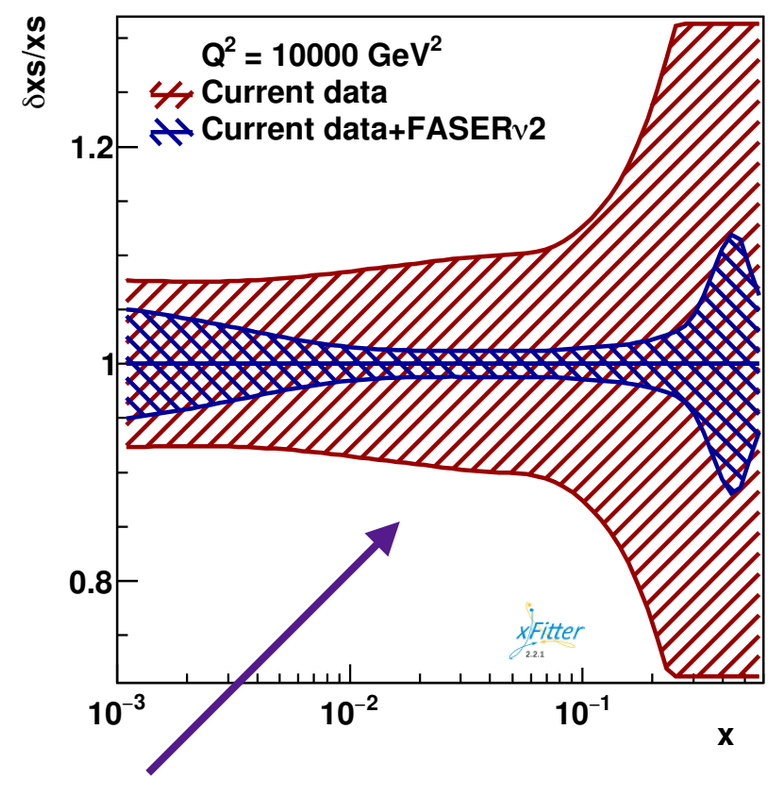




- Best scenario: **FASER2 statistics**, charm production included (strangeness), statistical errors only
- Reduction of PDF uncertainties most marked for **valence quarks and sea antiquarks**

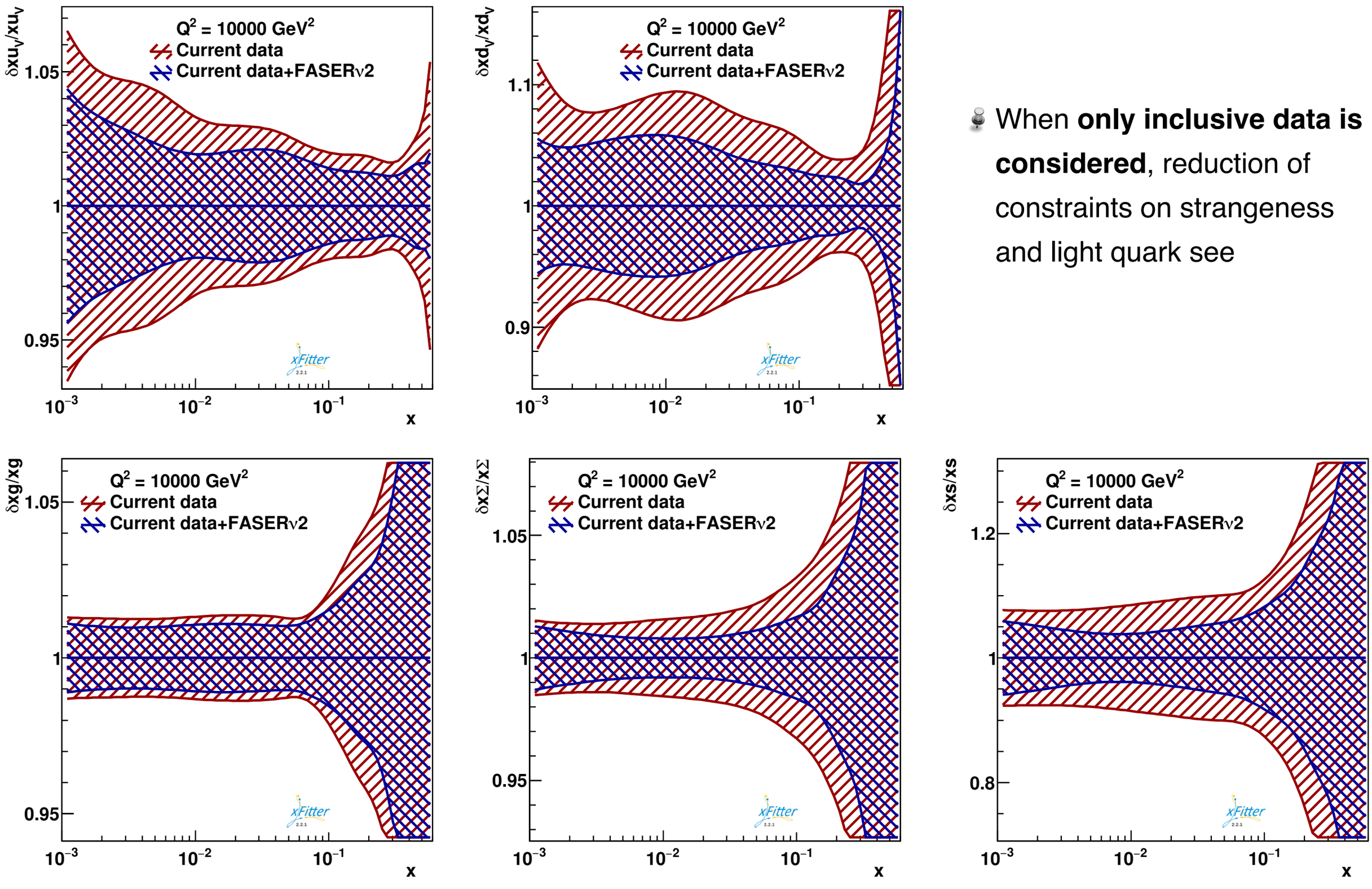






Results: proton PDFs

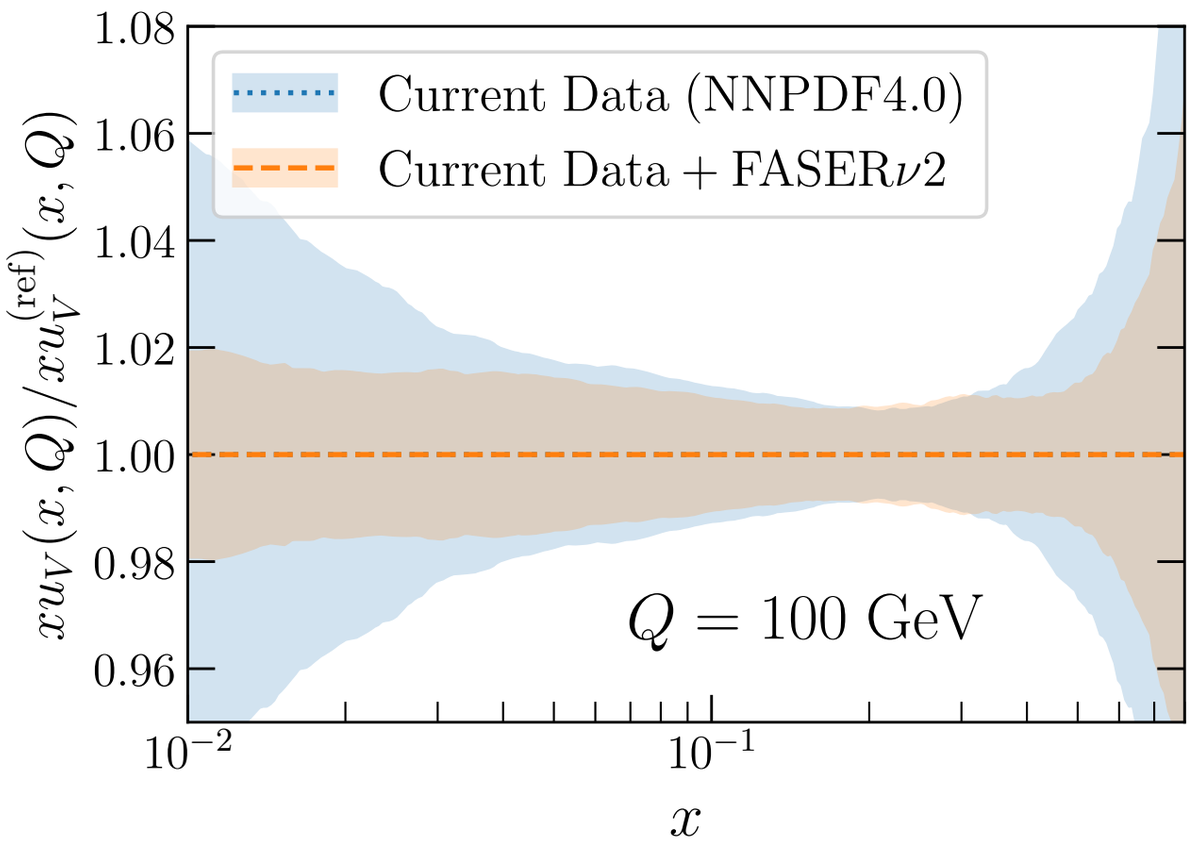
Statistical error only, inclusive data

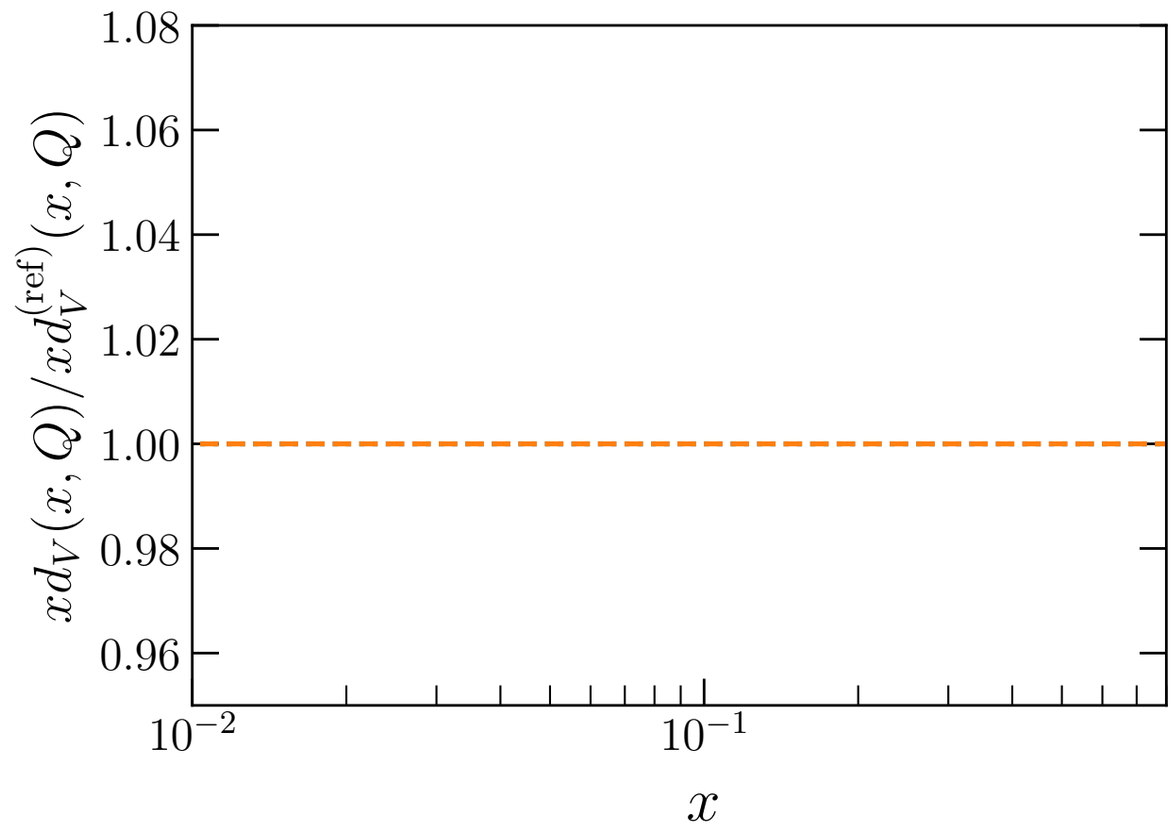


- When **only inclusive data is considered**, reduction of constraints on strangeness and light quark see

Results: proton PDFs

Statistical error only, inclusive data

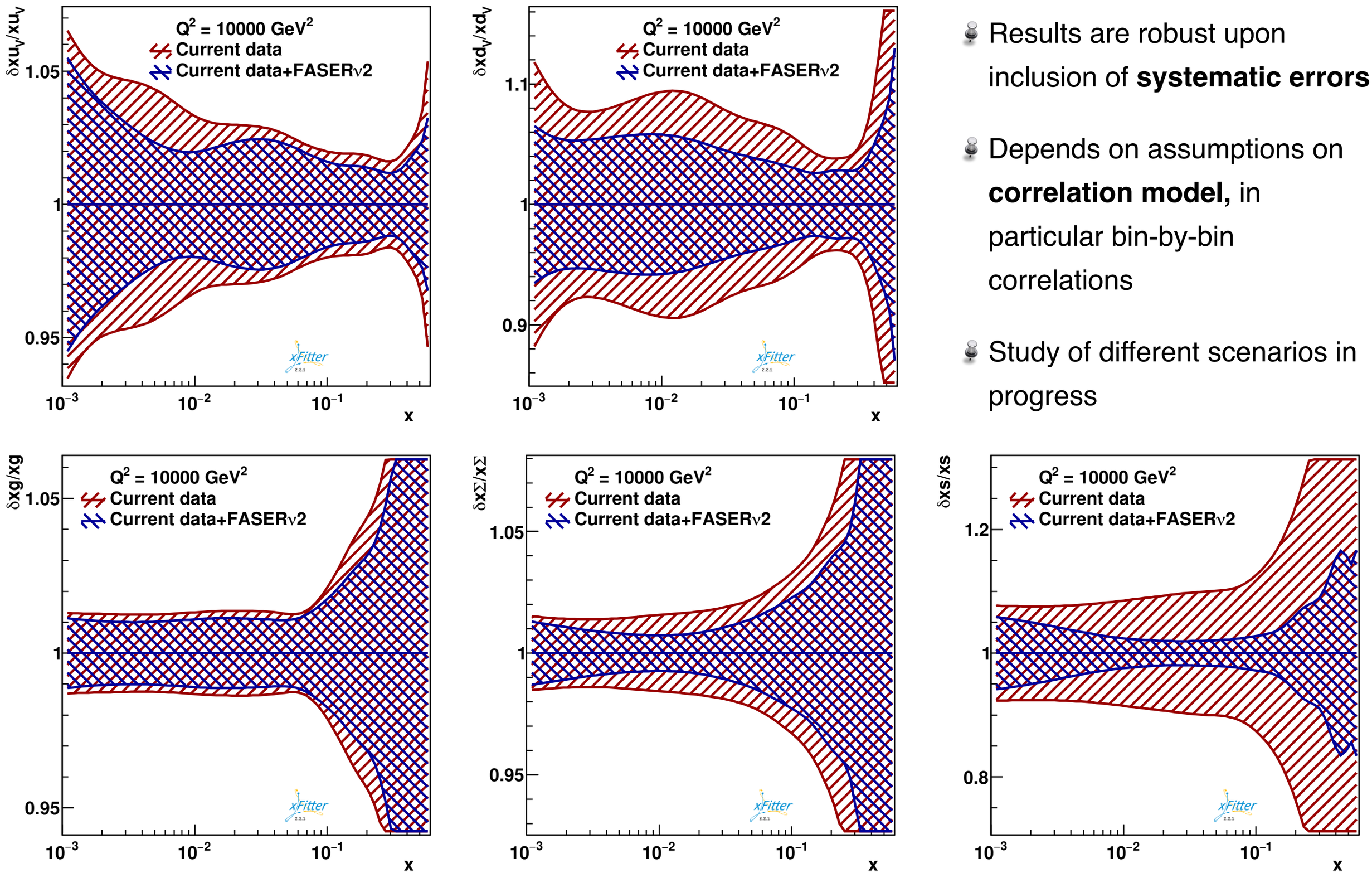




- Cross-checked with inclusion of FASER structure functions into **NNPDF global analysis framework**
- Again main impact on valence quark PDFs
- Study impact on **precision (High-Luminosity) LHC measurements** such as *W* mass

Results: proton PDFs

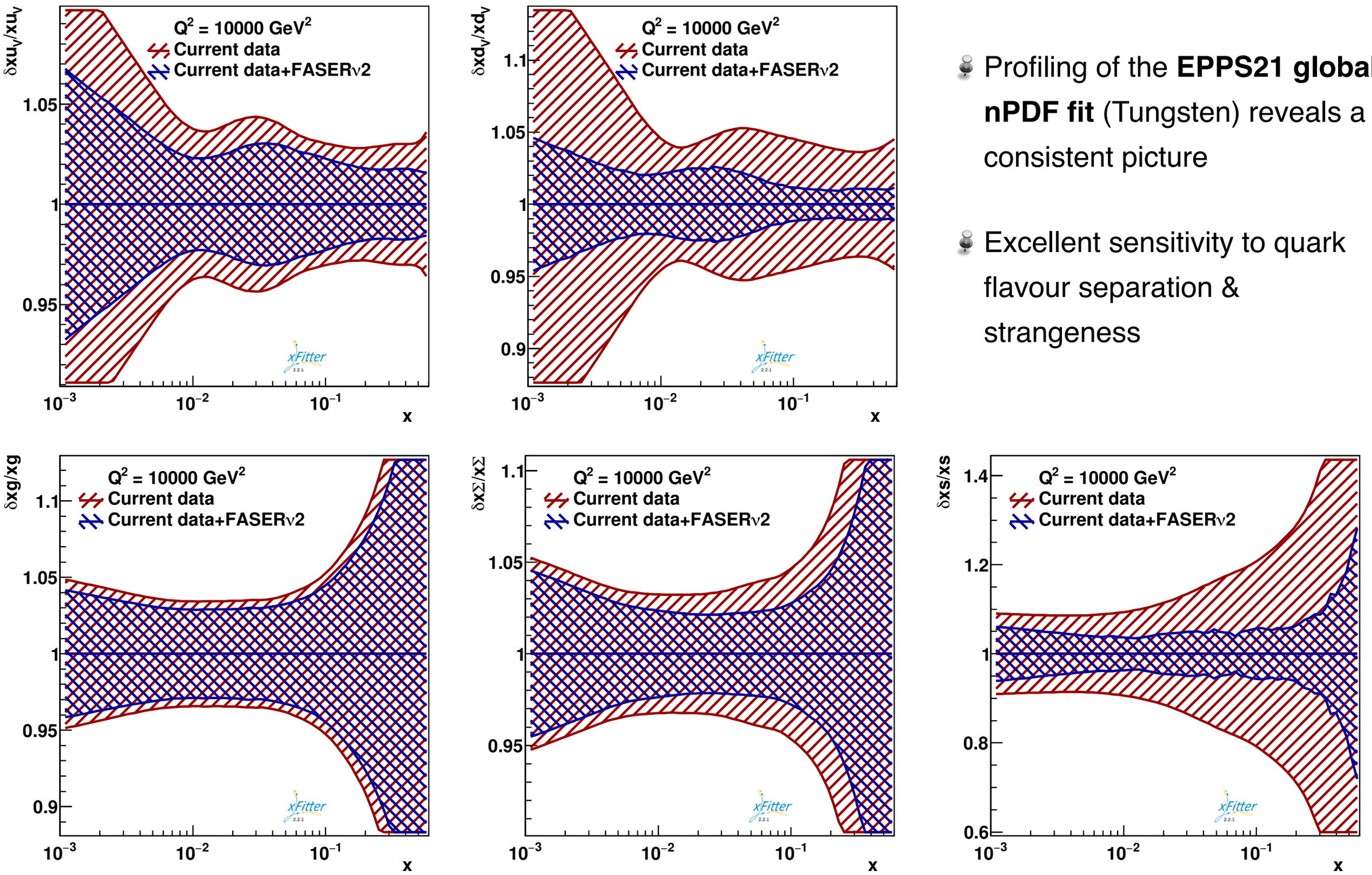
Statistical + Systematic errors only, inclusive + charm data



- 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

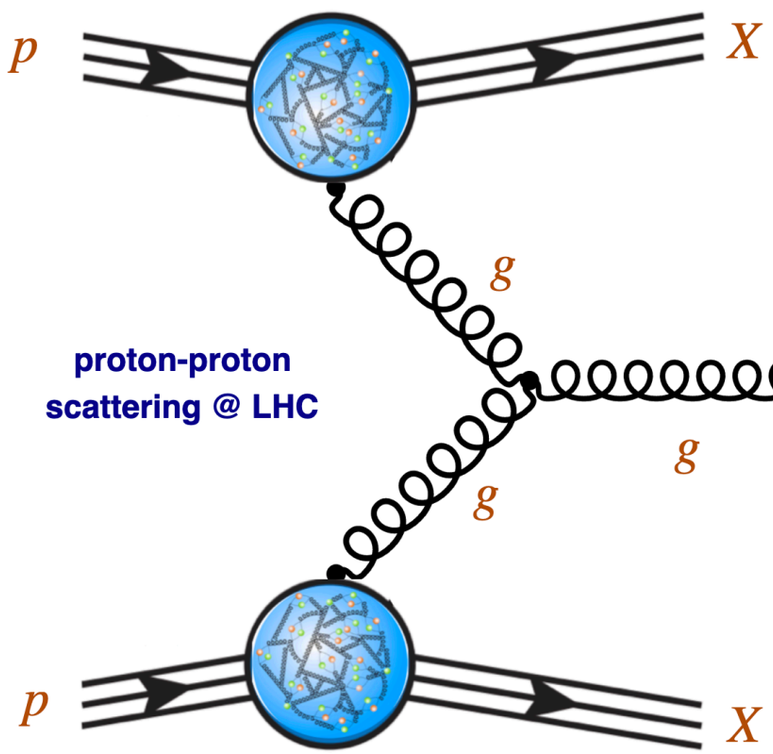


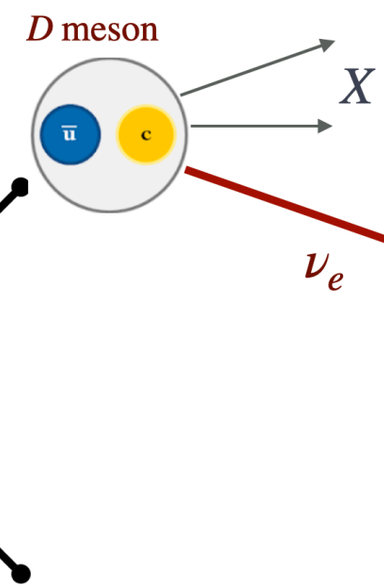
- Profiling of the **EPPS21 global nPDF fit** (Tungsten) reveals a consistent picture
- Excellent sensitivity to quark flavour separation & strangeness

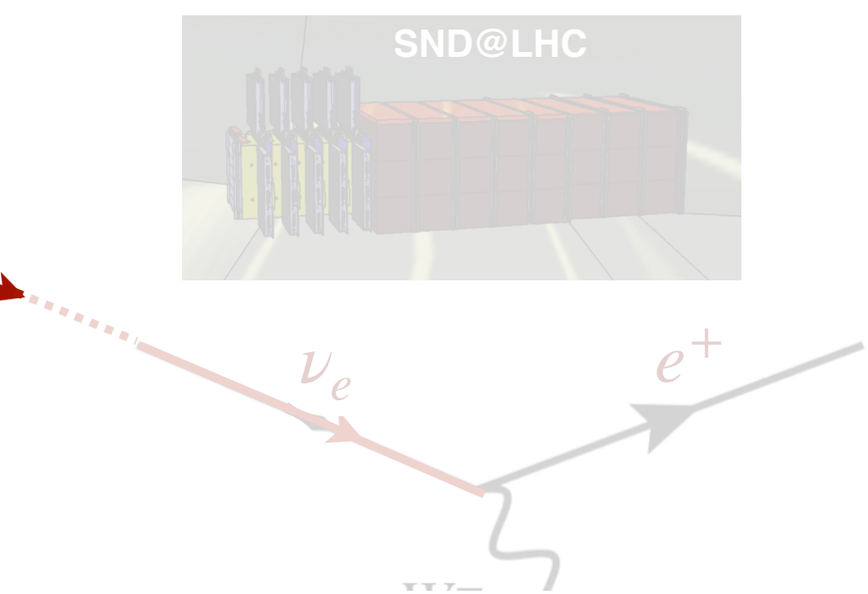
Constraints on hadron structure with LHC neutrinos: charm production

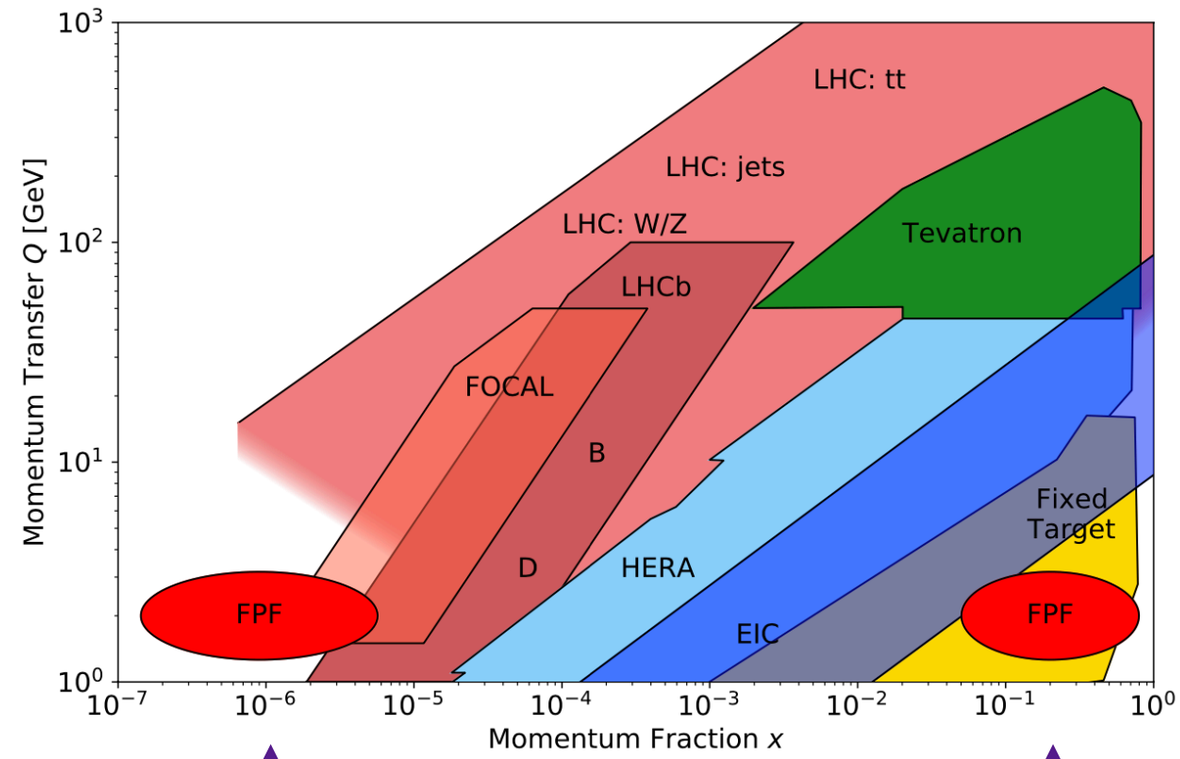
P. Krack, S. Niedenzu, J. Rojo,
J. Sola-Cava, *work in progress*

QCD and Neutrino Physics at FASER









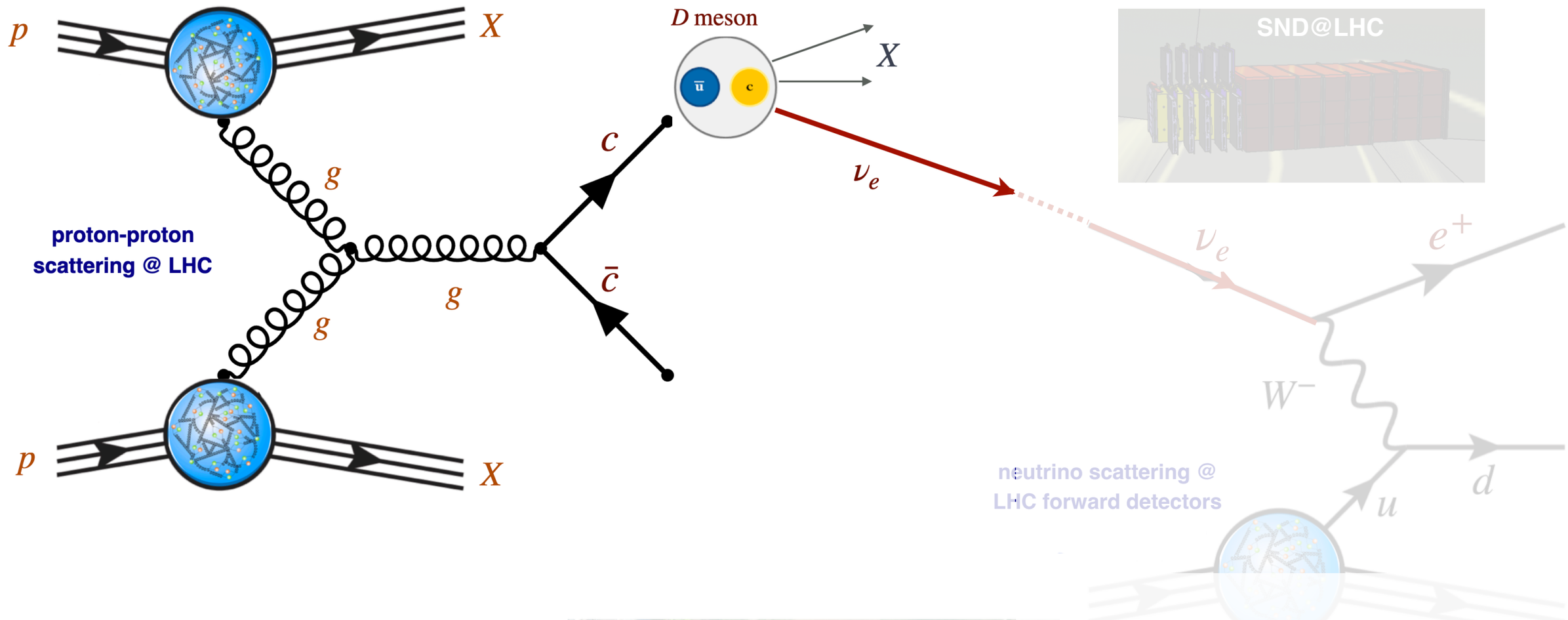
small-x gluon

large-x

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

QCD and Neutrino Physics at FASER



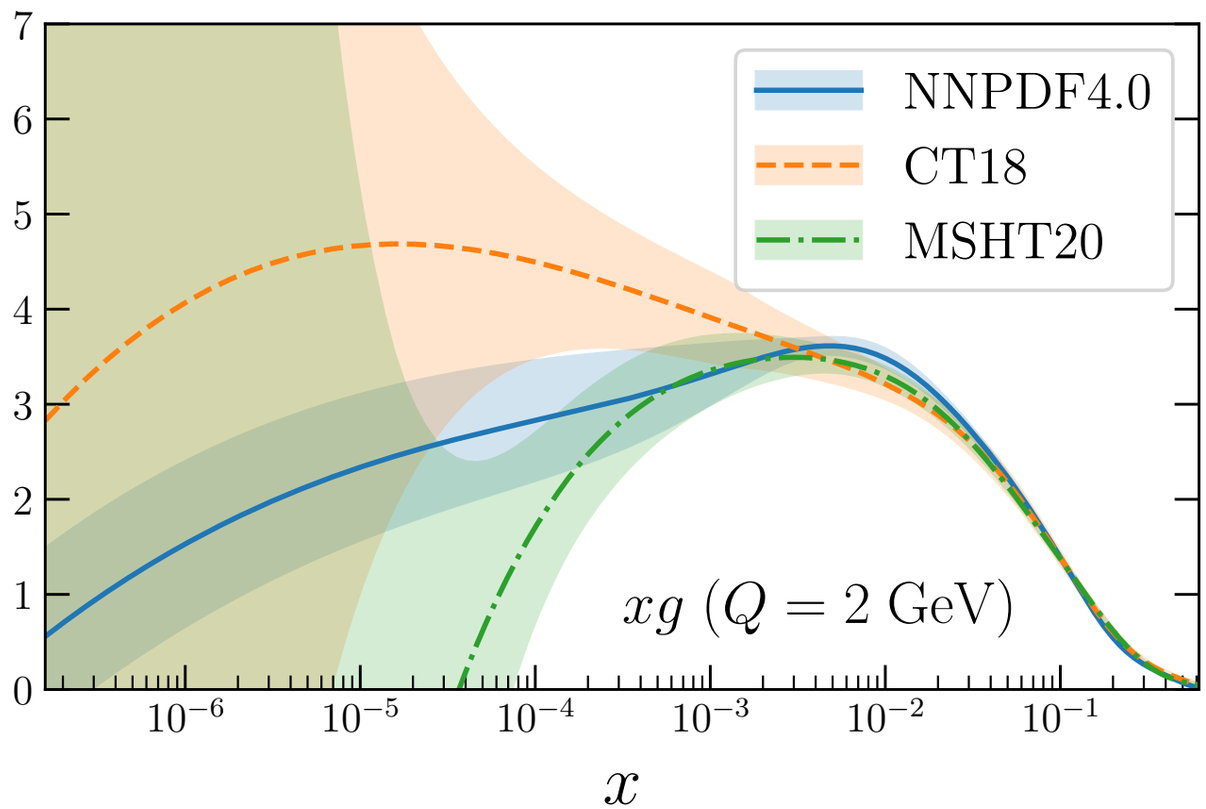
$$\frac{d^2\sigma(\mathrm{pp} \to D(\to \nu) + X)}{p_T^{\nu} y_{\nu}} \propto f_g(x_1, Q^2) \otimes f_g(x_2, Q^2) \otimes \frac{d^2\hat{\sigma}(gg \to c\bar{c})}{p_T^{c} y_c} \otimes D_{c\to D}(z, Q^2) \otimes \mathrm{BR}(D \to \nu + X)$$

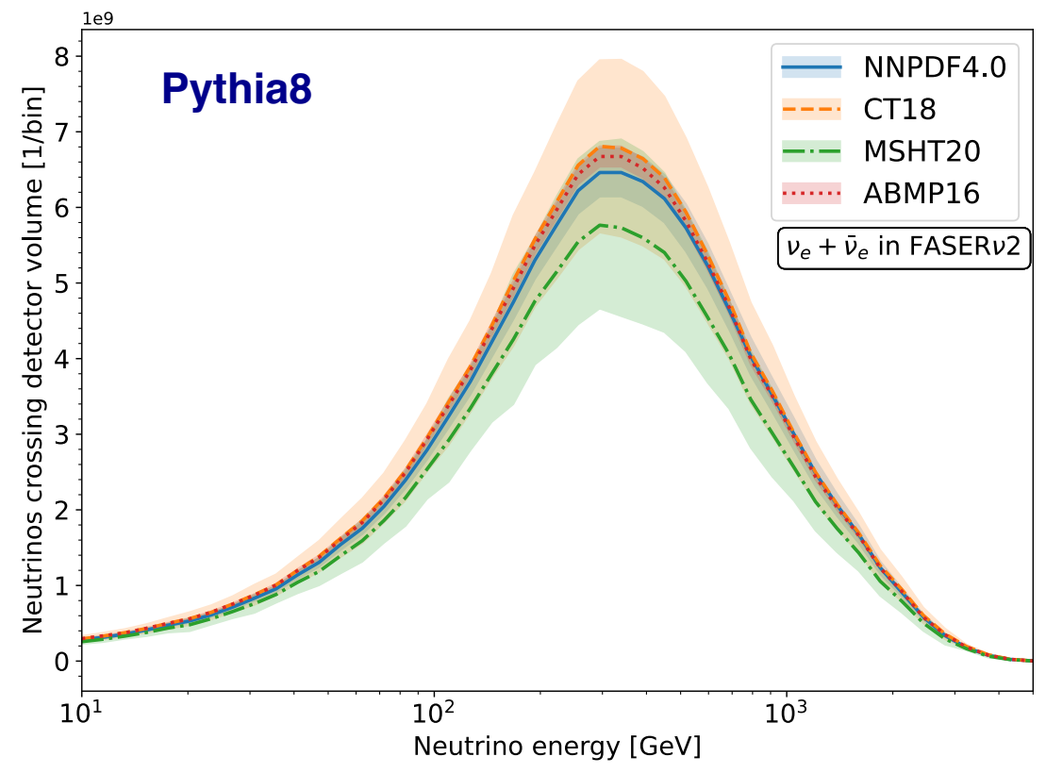
Extract from measured neutrino fluxes

Constrain from FASER/FPF data

QCD prediction: NLO + PS large theory uncertainties

Impact projections



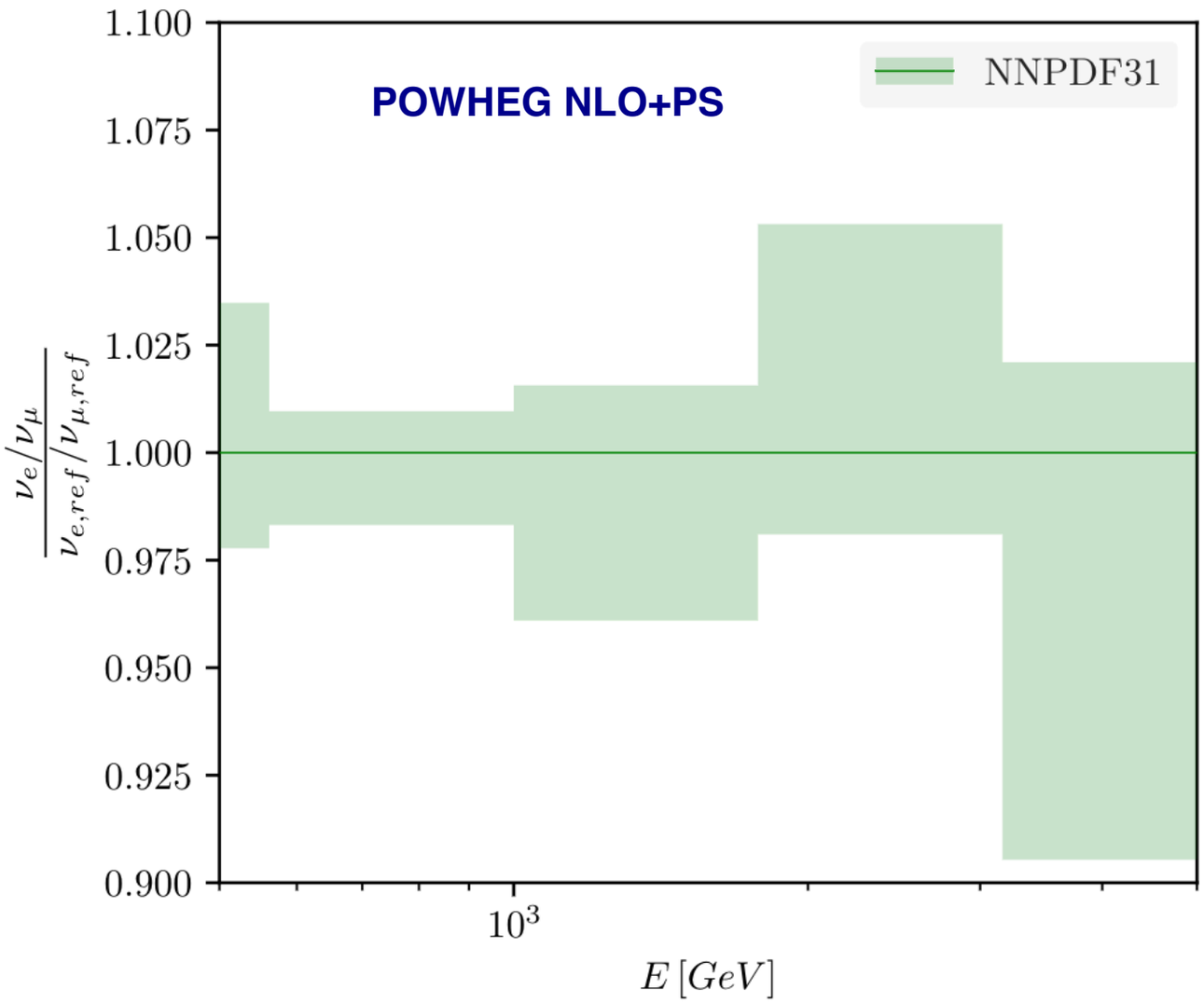


- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially)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

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

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

Impact projections



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

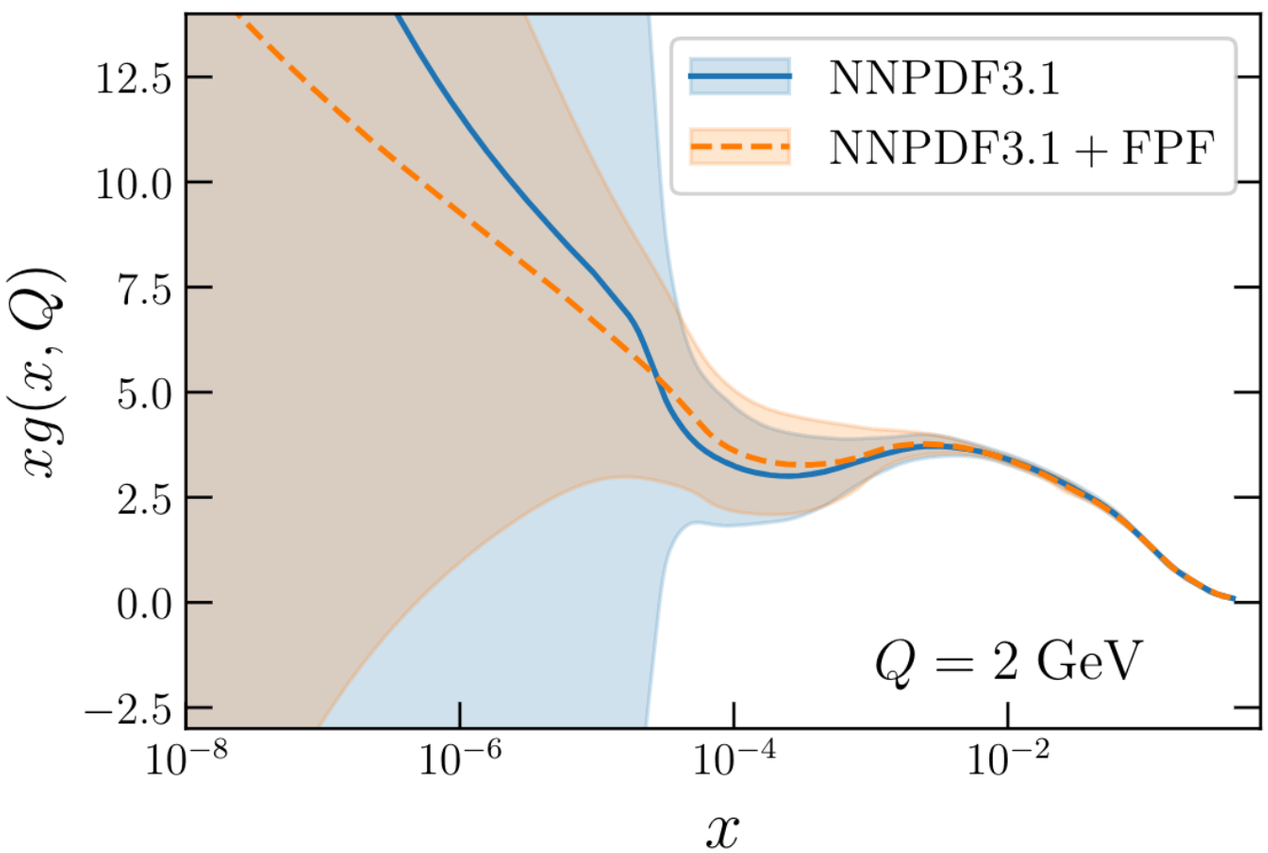
- Strategy: assume a measurement of **inclusive event rates** as a function of neutrino energy with a given precision, quantify impact on PDFs via **Bayesian reweighting**

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

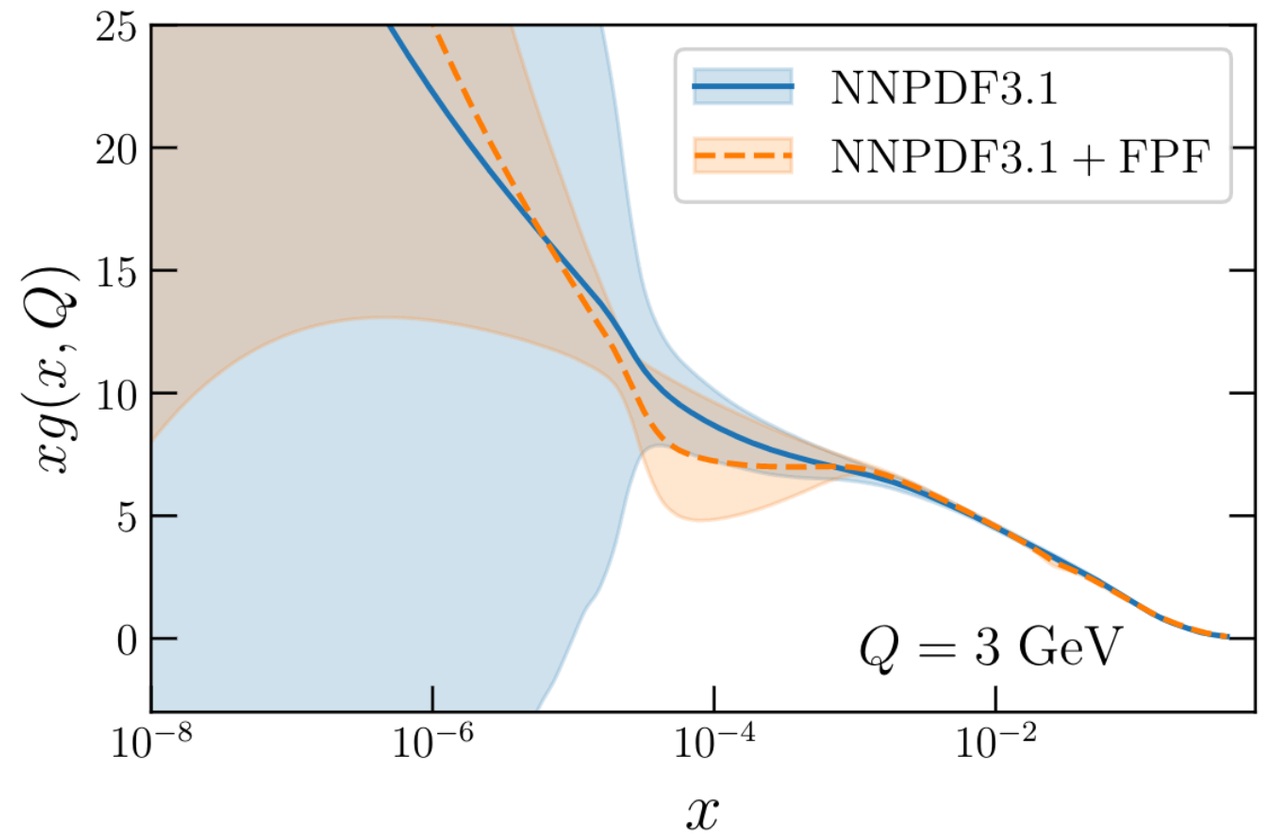
Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

Results

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates



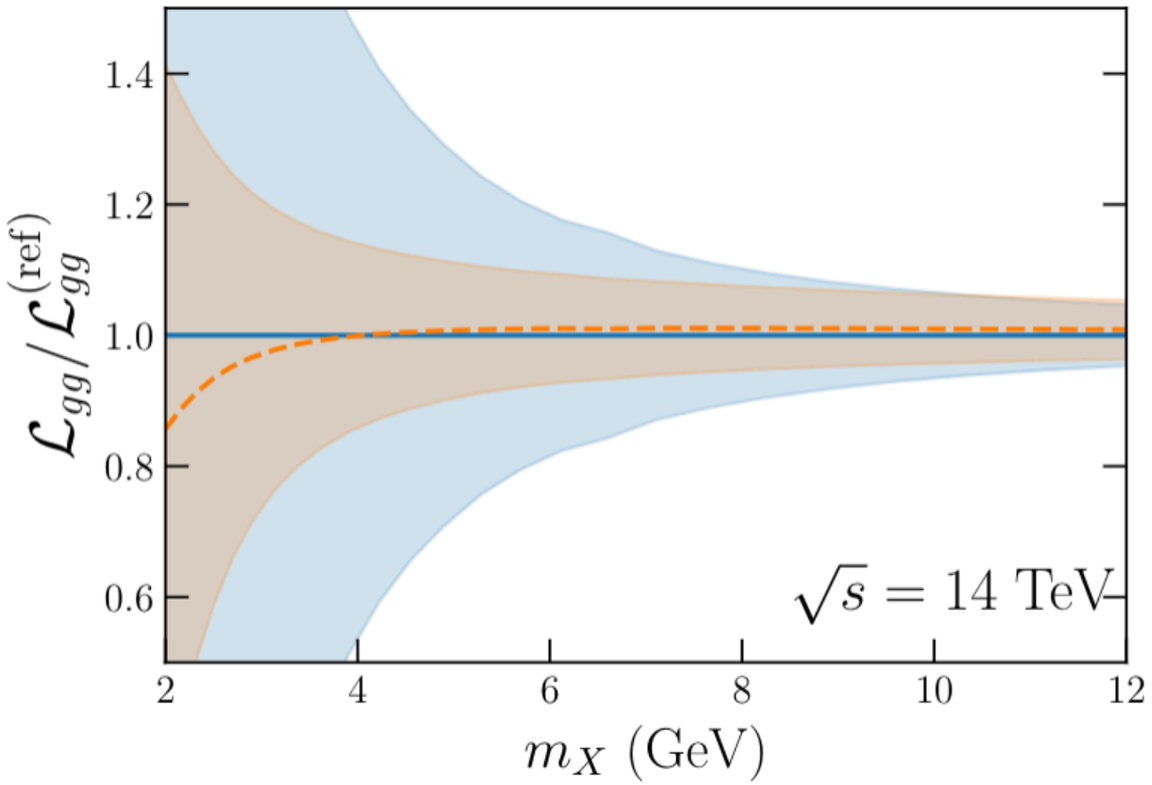
- Results based on pseudo-data for a **measurement of the rapidity ratio** (proxy for experiment ratio)

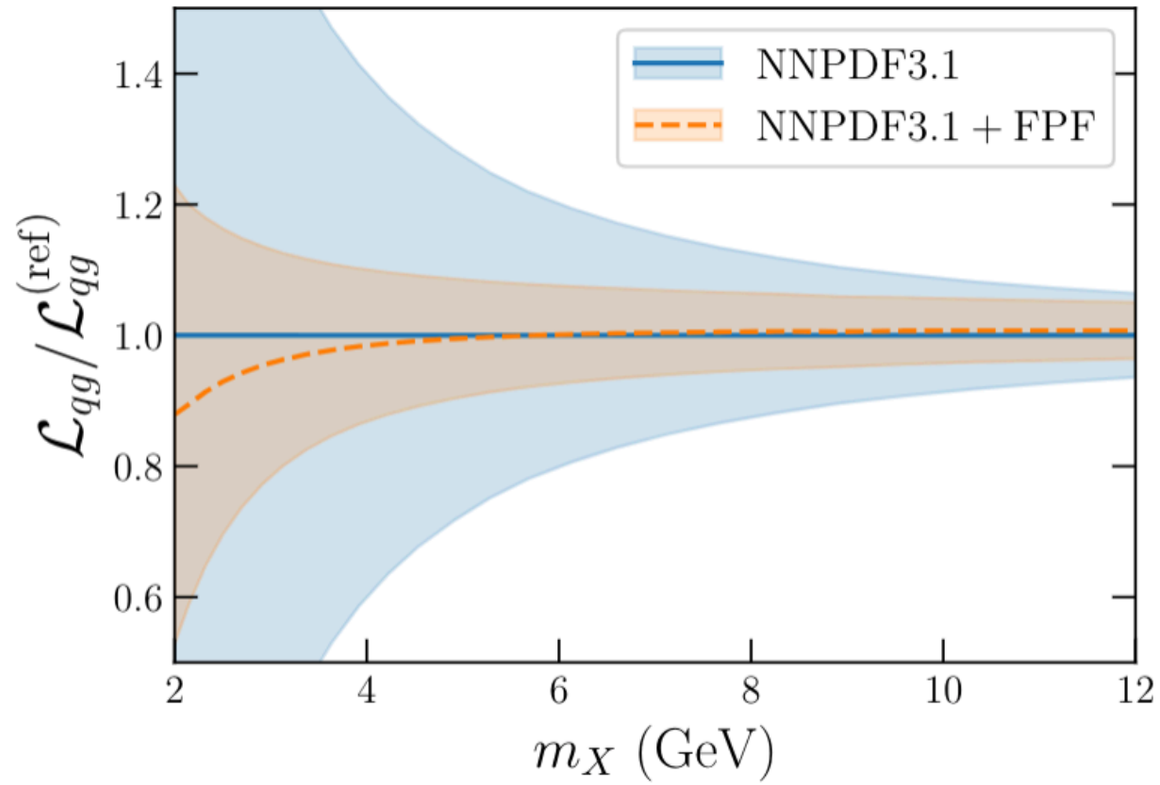
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_u < 9.0)} \qquad R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_u < 9.0)}$$

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

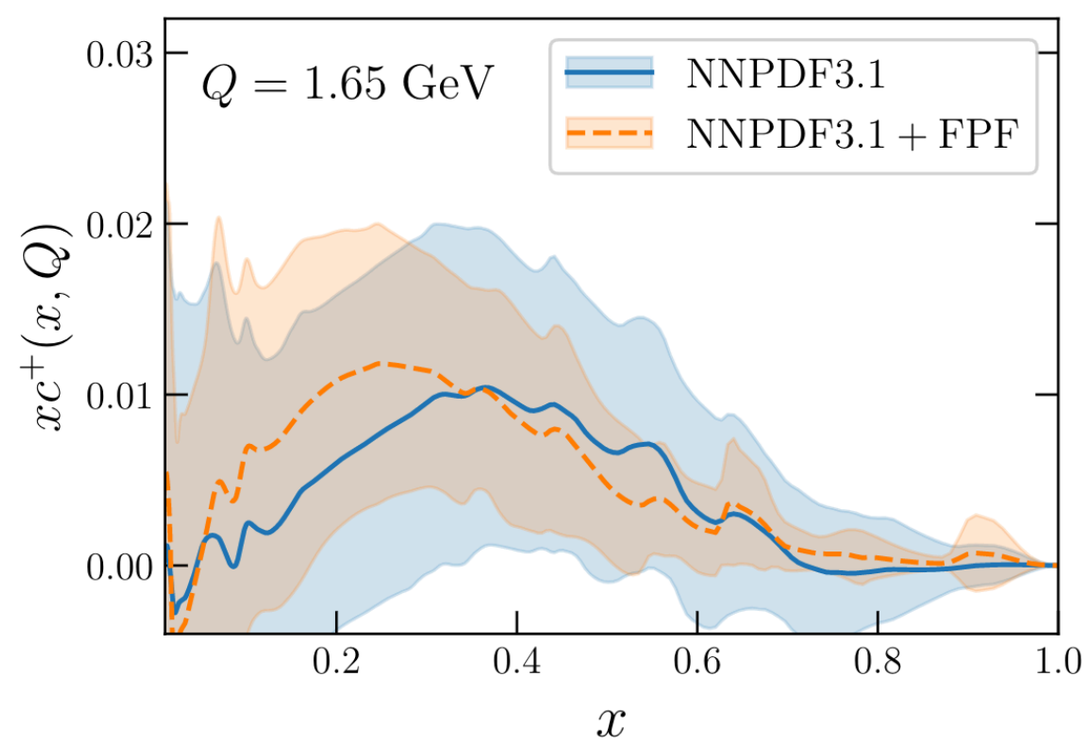
Results

Electron neutrinos, 2% uncertainty in inclusive event rates





- General improvements of **low-mass gluon-initiated** processes at the LHC
- Constraints also on the **charm PDF** via the gluon-charm initial state
- FASER Run III data should be able to provide the first measurement of the **gluon content of the proton at x=10^{-7}**



Summary and outlook

- LHC neutrinos realise an exciting program in a broad range of topics from **BSM and long-lived particles** to **neutrinos, QCD, and hadron structure**, with connections to astroparticle physics

- Measurements of **muon neutrino DIS structure functions** at FASER (FPF) open a new probe to proton and nuclear structure: a charged-current counterpart of the Electron Ion Collider

- Measurements of **electron and tau neutrino event rates** at FASER (FPF) can constrain the small-x gluon and large-x cham in unexplored regions by using **dedicated observables** where QCD errors cancel out