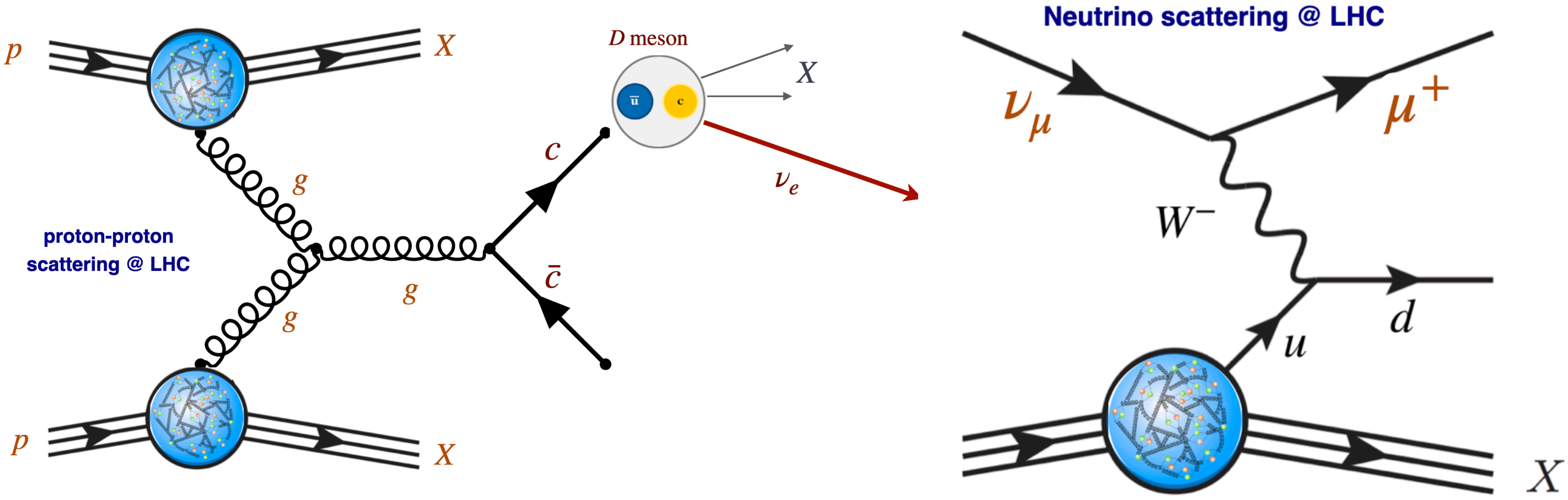
Physics with TeV Neutrinos at the LHC

Juan Rojo, VU Amsterdam & Nikhef



proton-proton scattering @ LHC

Neutrino scattering @ LHC

BNL HET Seminar

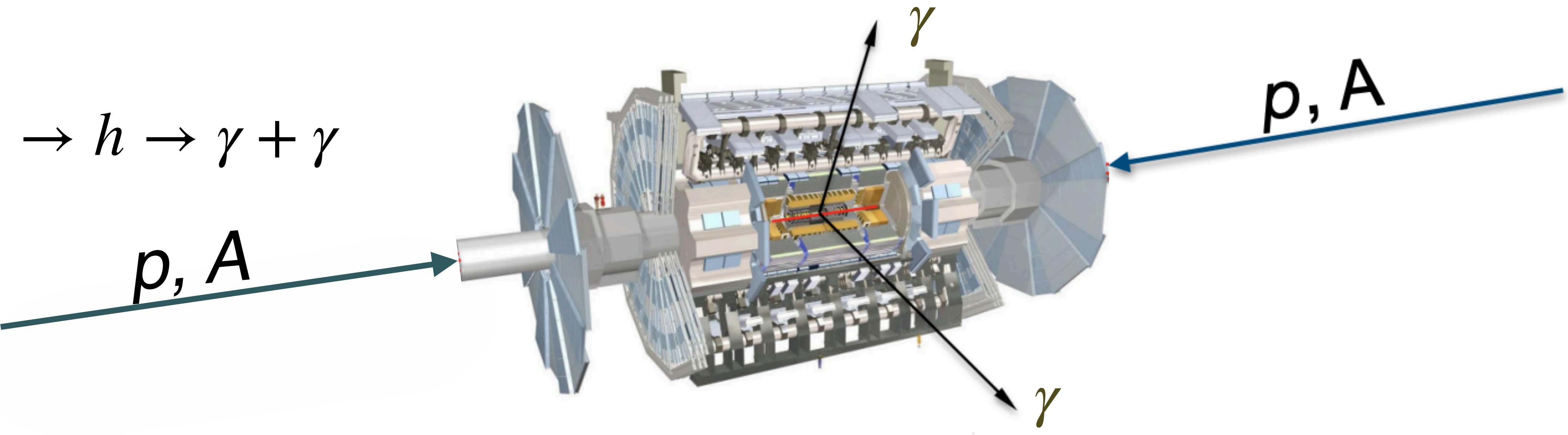
Zoom, 28 June 2023

Neutrinos at the LHC

Neutrinos at the LHC

- The ATLAS and CMS detectors were designed with a focus on **identifying weak-scale and heavier particles**, whose decay products lie in the **central rapidity** acceptance region

$$p + p \rightarrow h \rightarrow \gamma + \gamma$$



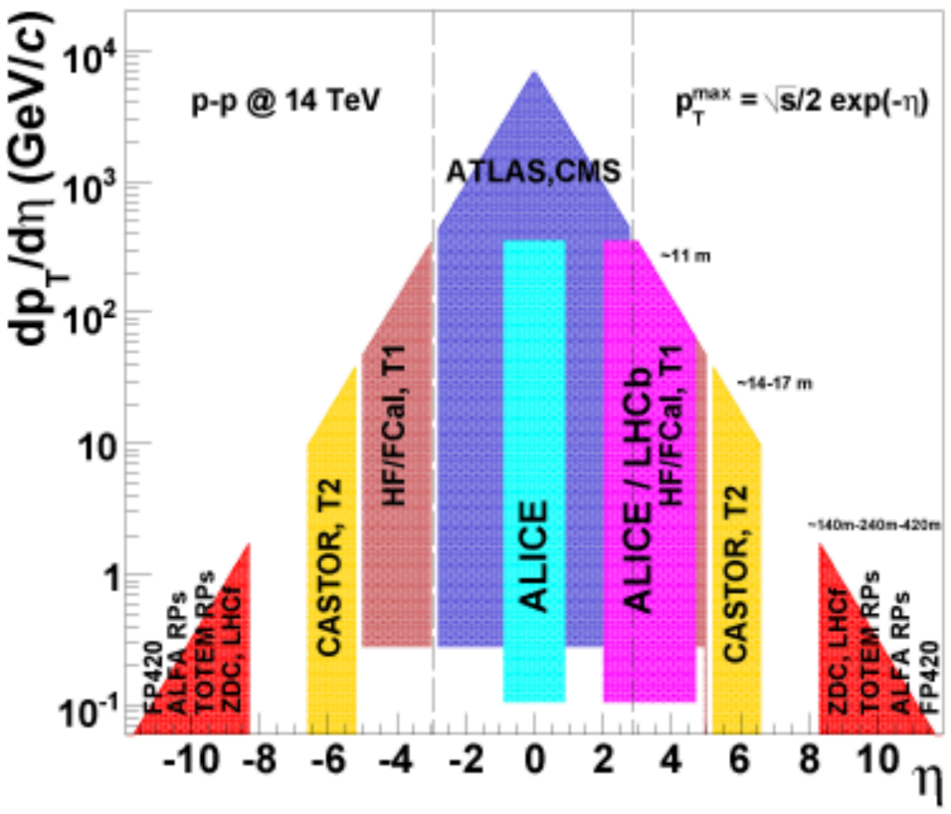
neglecting mass effects

$$y \simeq \eta = \log \tan(\theta/2)$$

scattering angle

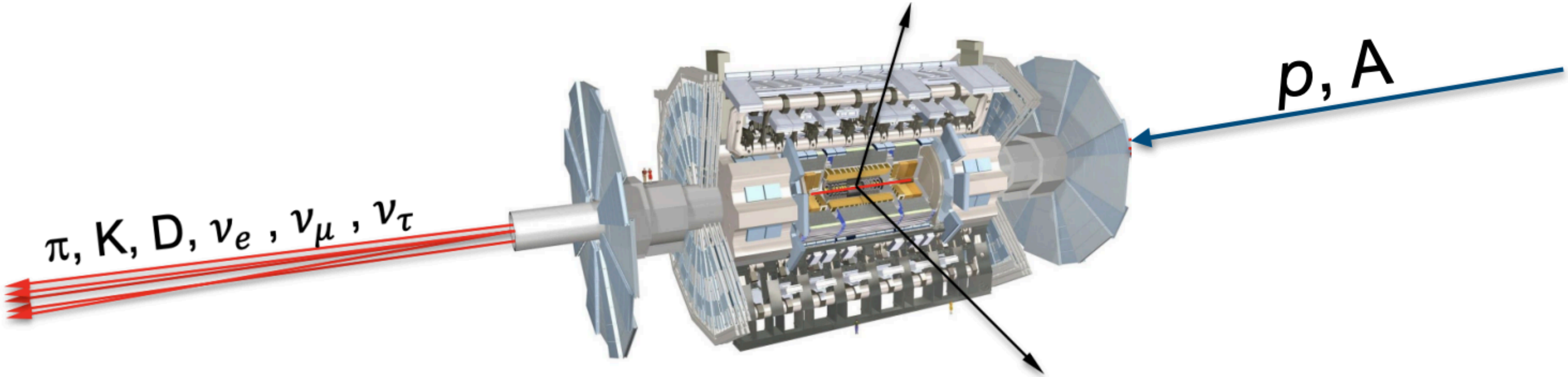
- Forward region for hard-scattering physics restricted to **LHCb** ($\eta < 4.5$) and in the future **ALICE-FoCal** ($\eta < 5.0$)

- **Far-forward region** essentially beyond access for current LHC detectors, except for *e.g.* total cross-section analyses

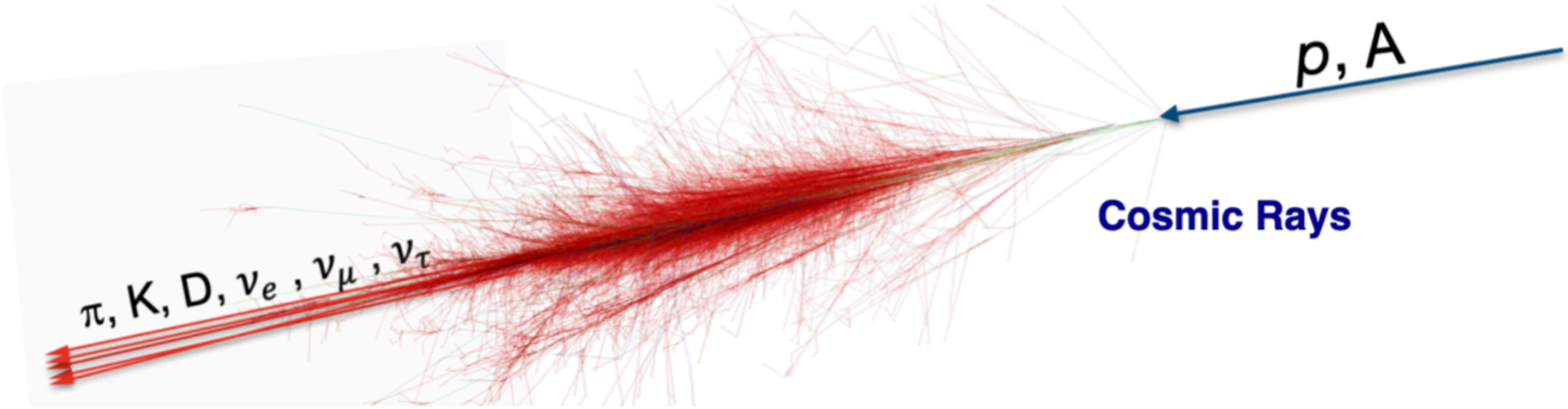


Neutrinos at the LHC

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

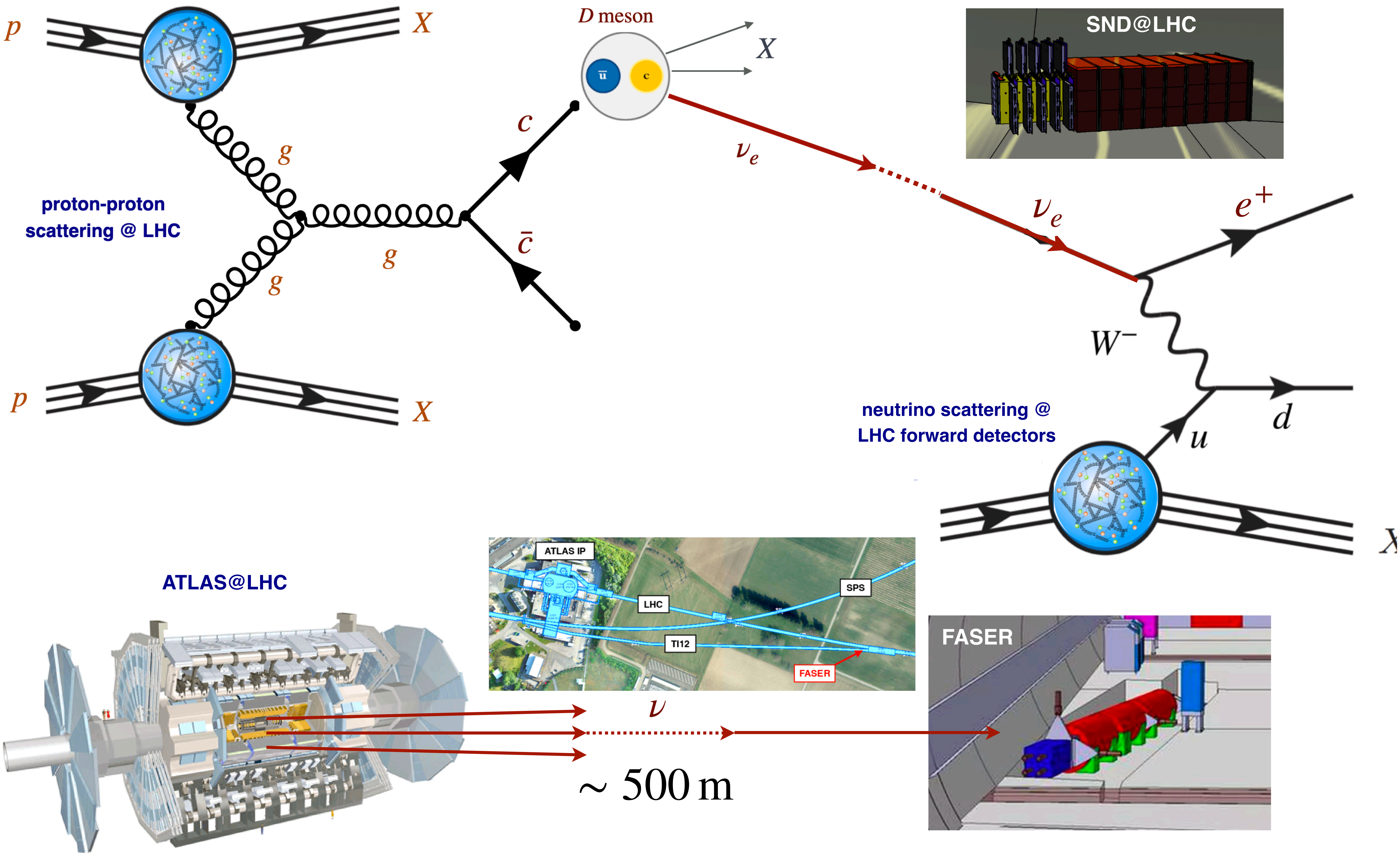


- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics



LHC neutrinos (CoM frame) ≈ Cosmic Rays and UHE neutrinos (lab frame)

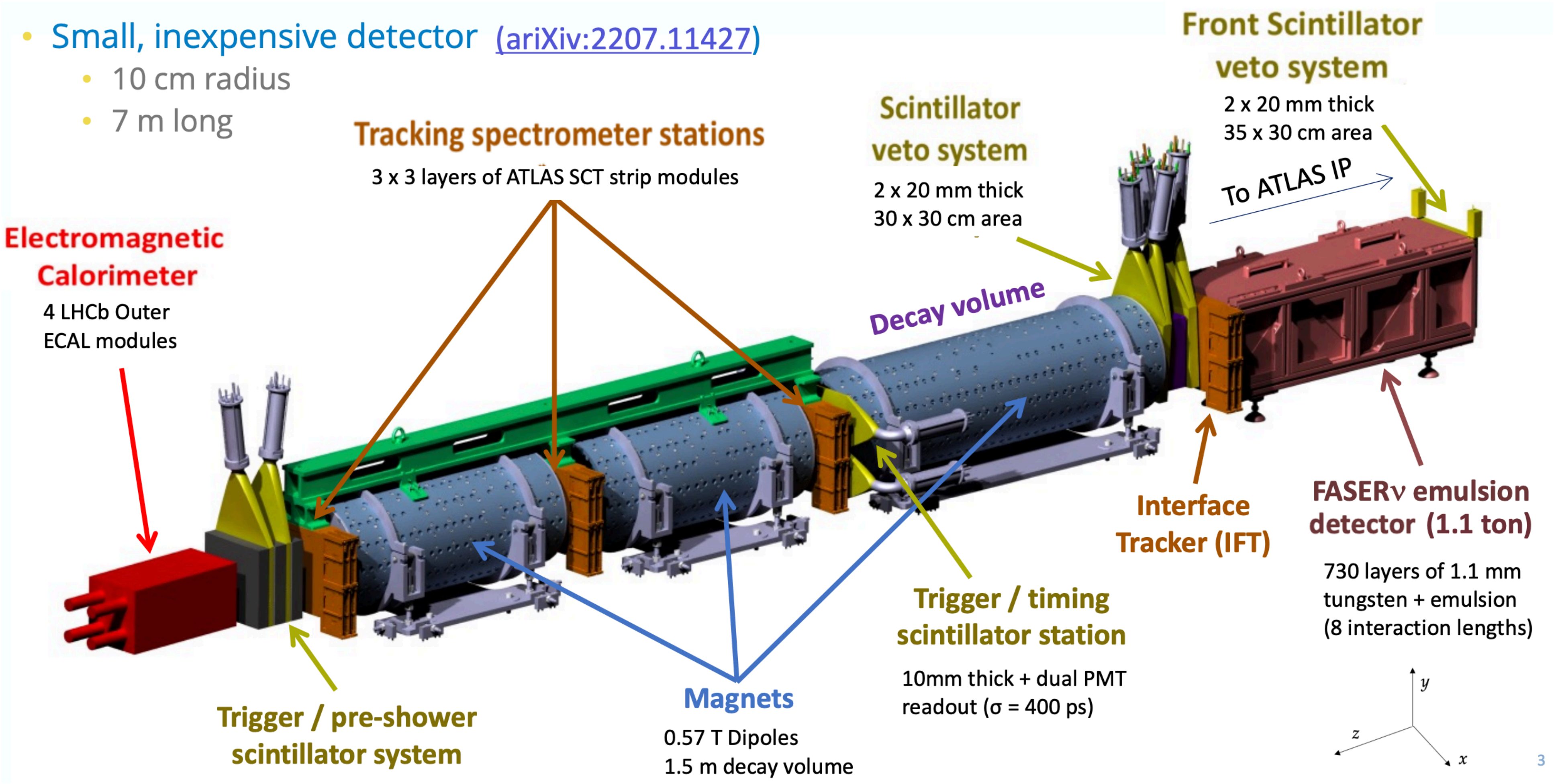
Neutrinos at the LHC



FASER & SND@LHC demonstrated how **far detectors** can be deployed to **identify collider neutrinos**

Neutrinos at the LHC: FASER

- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long



Tracking spectrometer stations
3 x 3 layers of ATLAS SCT strip modules

Electromagnetic Calorimeter
4 LHCb Outer ECAL modules

Scintillator veto system
2 x 20 mm thick
30 x 30 cm area

Front Scintillator veto system
2 x 20 mm thick
35 x 30 cm area

Decay volume

Interface Tracker (IFT)

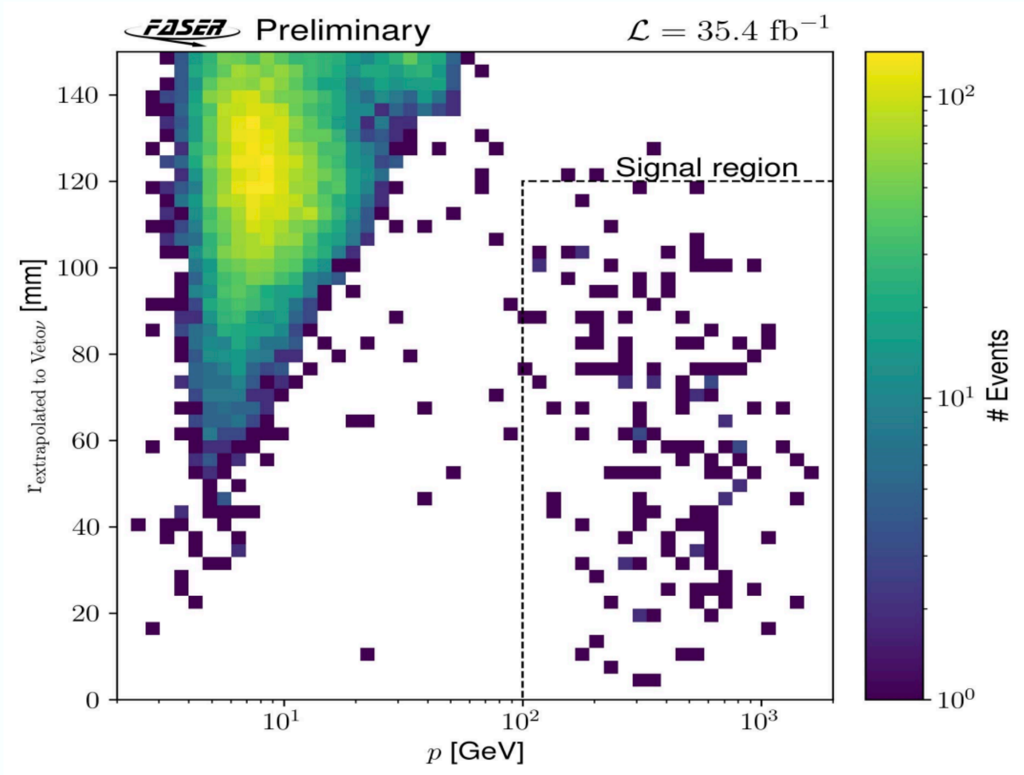
FASERν emulsion detector (1.1 ton)
730 layers of 1.1 mm tungsten + emulsion (8 interaction lengths)

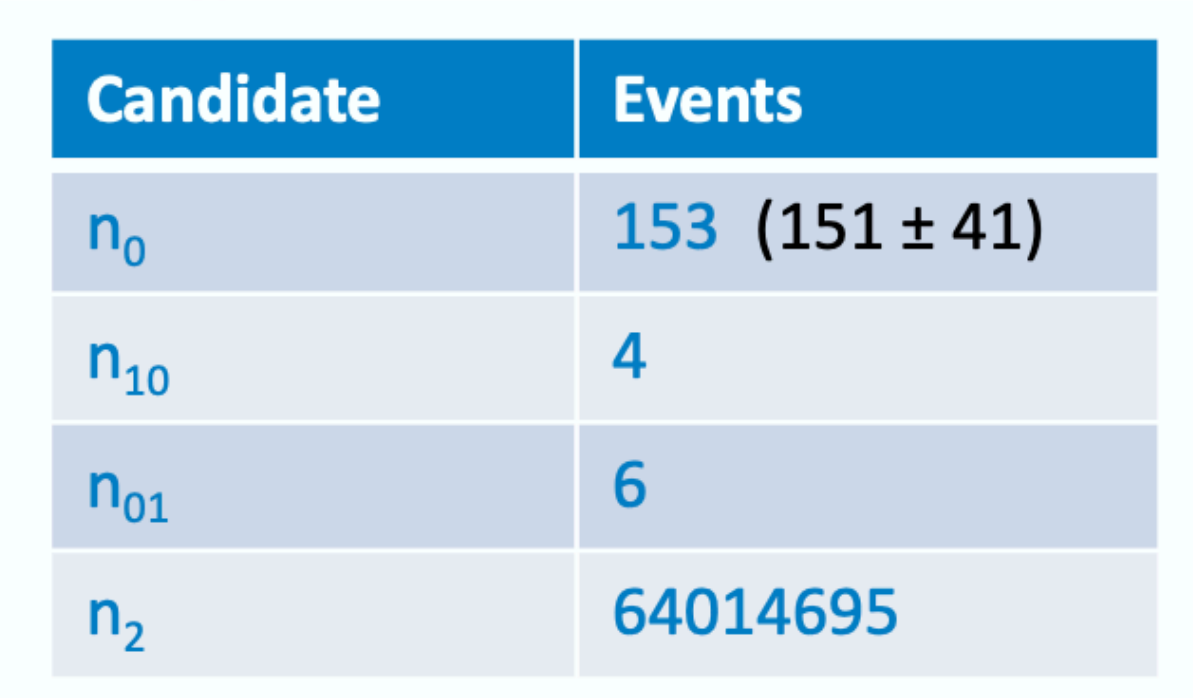
Trigger / timing scintillator station
10mm thick + dual PMT readout (σ = 400 ps)

Magnets
0.57 T Dipoles
1.5 m decay volume

Trigger / pre-shower scintillator system

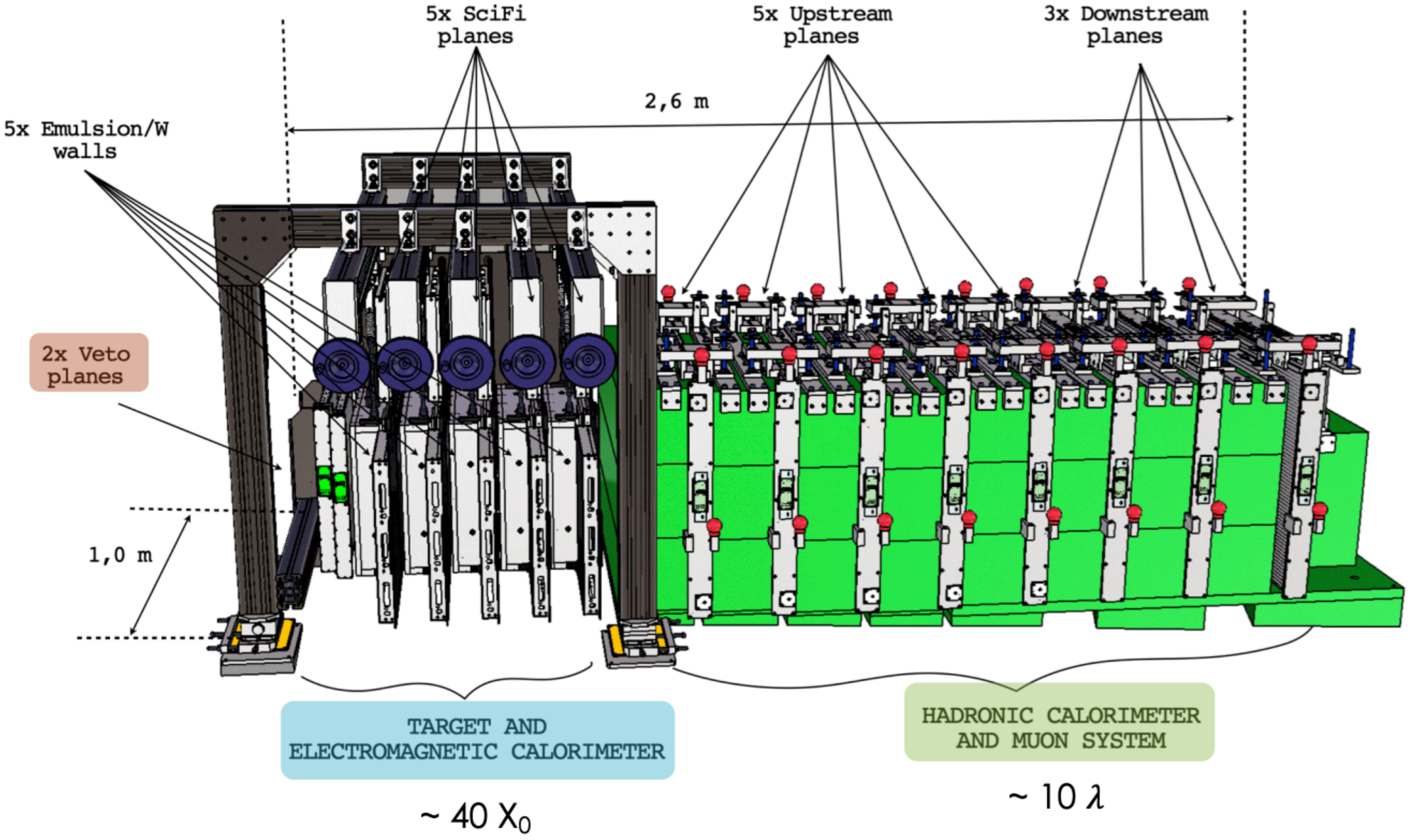
- 150 (muon) neutrino candidates over **basically no background**
- Large uncertainties in theory predictions from LHC **forward particle production**
- Expected **O(thousands) neutrinos** by end Run III

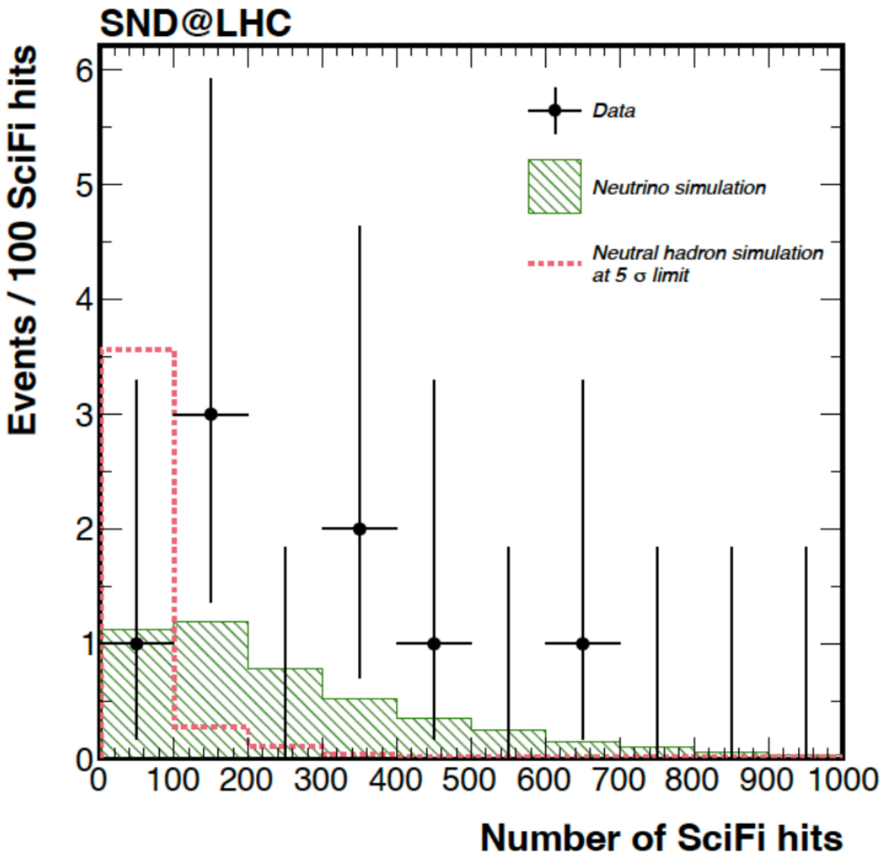




Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

Neutrinos at the LHC: SND@LHC





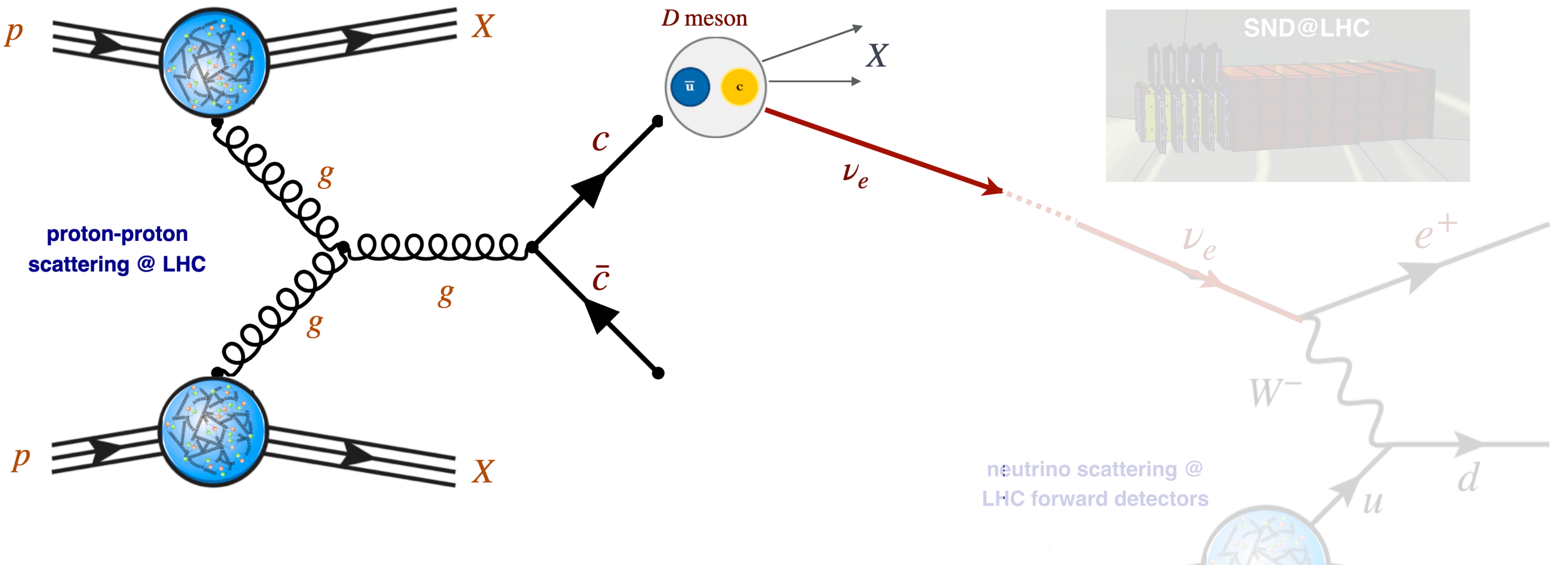
[arXiv:2305.09383]

Observed 8 ν_μ CC candidates with a significance of 7σ

(Expected from MC: 4.2 ν_μ)

- **8 neutrino candidates** (likely muon neutrinos)
- Different rapidity range from FASER (slightly off-axis): SND@LHC **covers $7.2 < y_\nu < 8.4$**

Neutrinos at the LHC



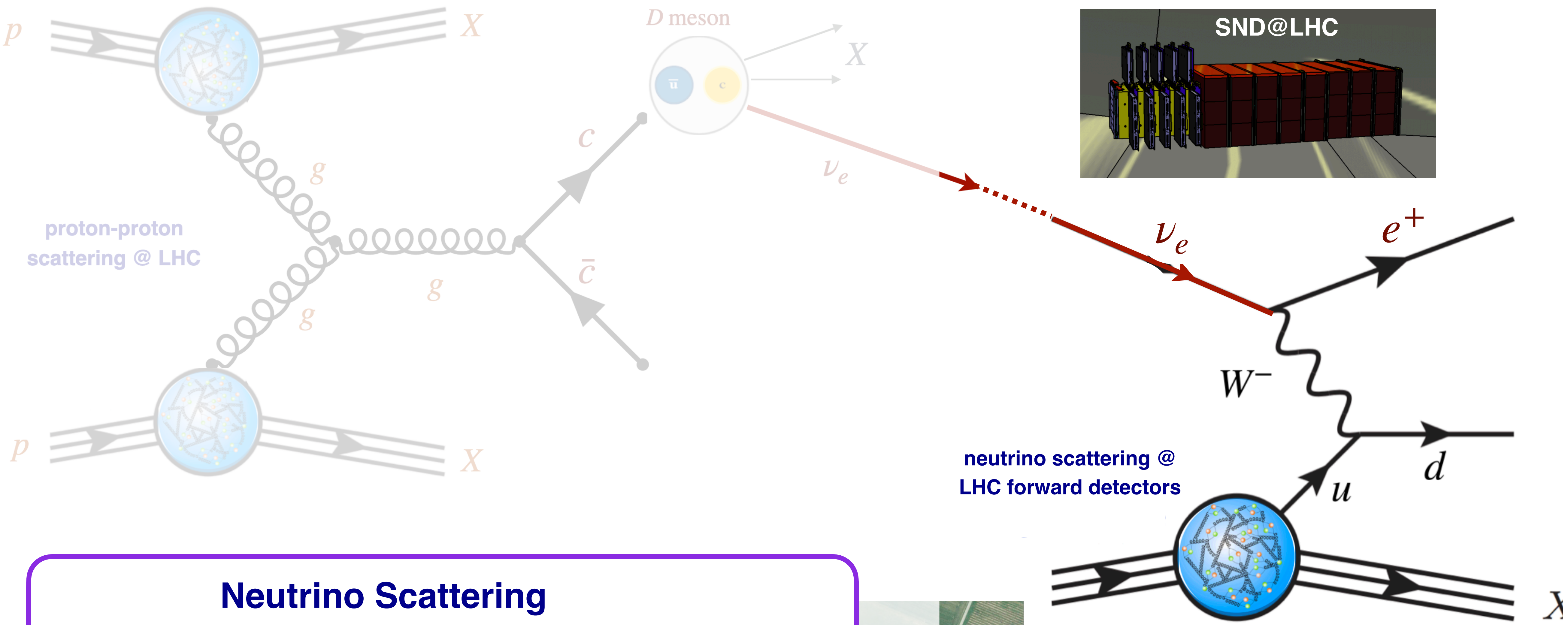
proton-proton scattering @ LHC

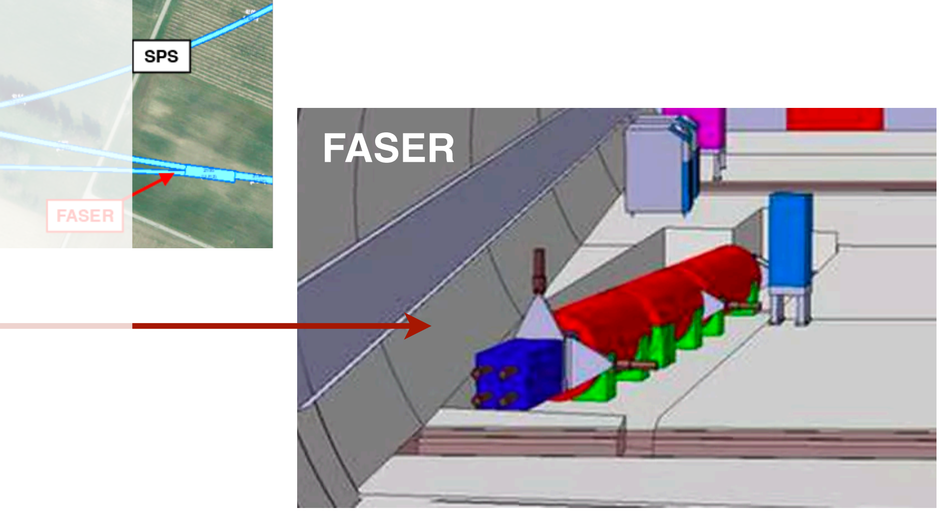
neutrino scattering @ LHC forward detectors

Neutrino Production

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

Neutrinos at the LHC

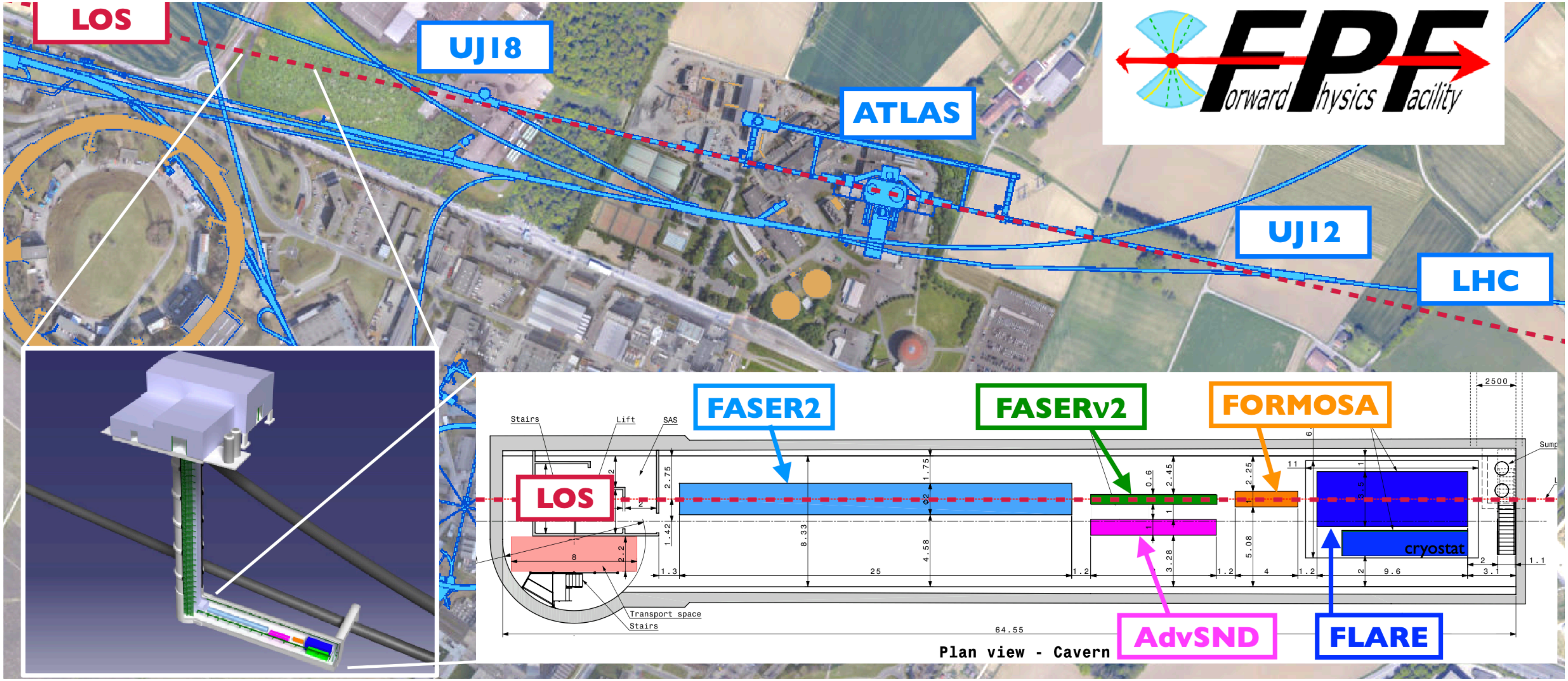




Neutrino Scattering

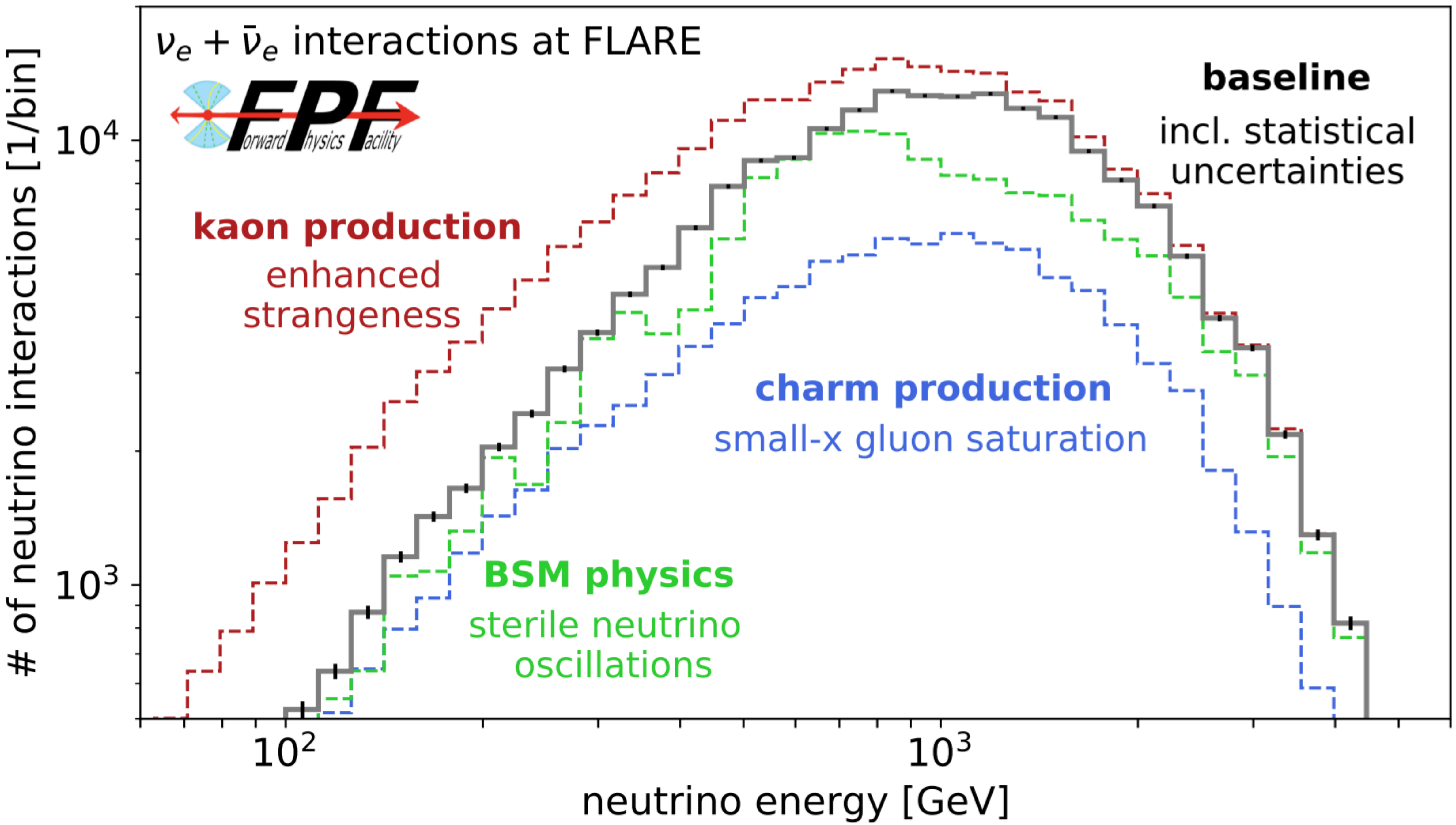
- **DIS with TeV neutrinos** (``Neutrino-Ion Collider'')
- Neutrino (EFT) interactions at the TeV
- **Cross-sections for atmospheric neutrinos**
- **Nuclear PDFs, strangeness** from charm
- Neutrino flavor (non-)university (with tau neutrinos)

Forward Physics Facility



- Dedicated new cavern equipped with a suite of **far-forward experiments**
- Operating **concurrently with the HL-LHC**, exploit intense high-energy beam of forward particles
- Start **civil engineering during LS3** or shortly thereafter: positive outcome of ongoing site investigation studies (including drill down to the cavern depth)

Forward Physics Facility

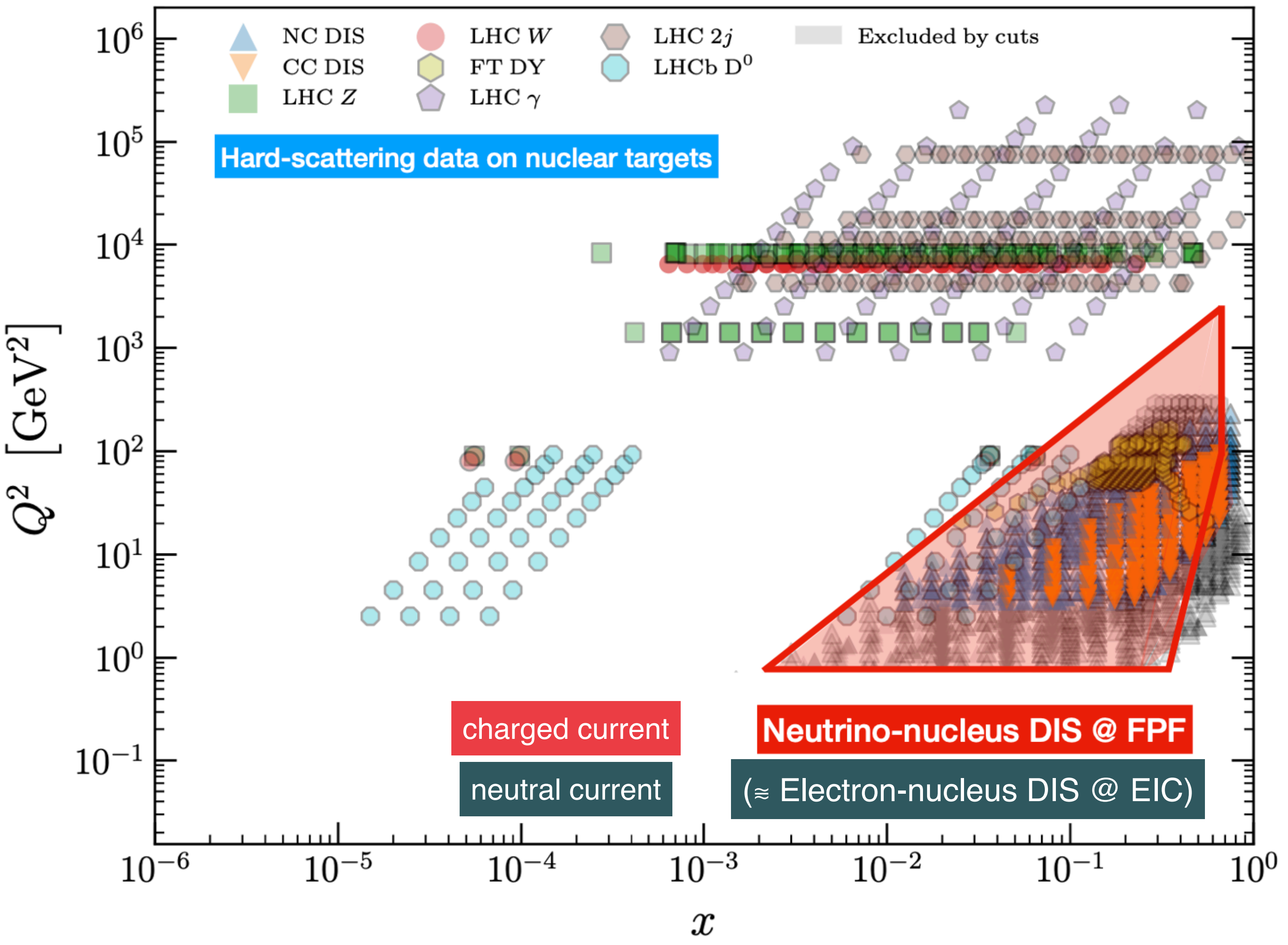


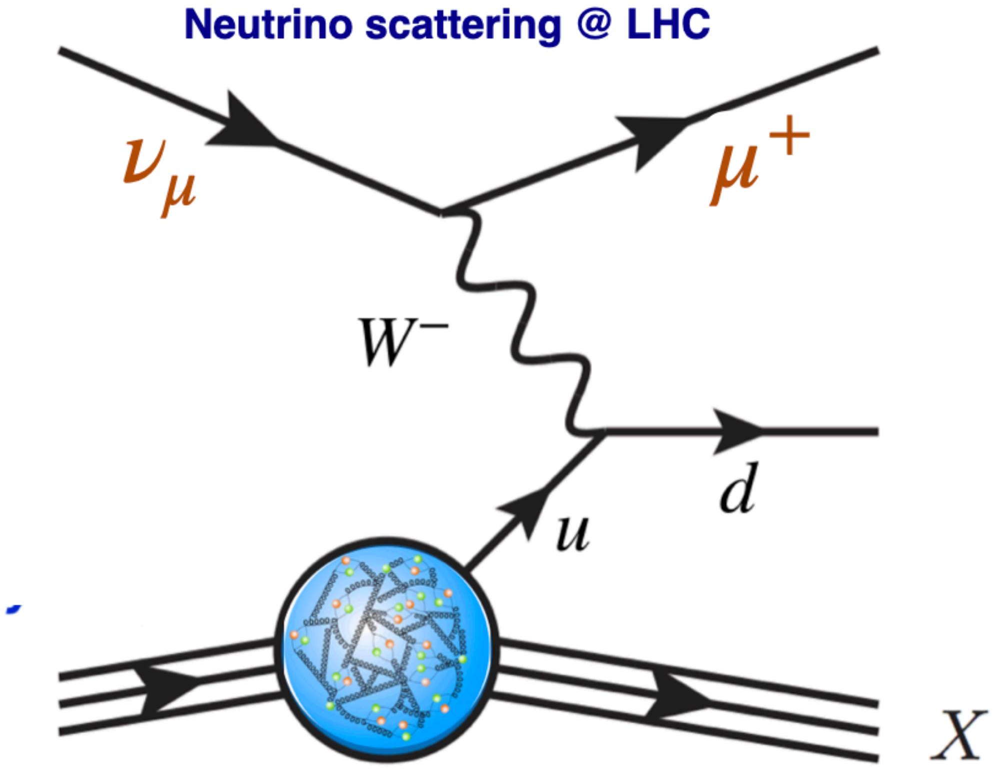
Broad, far-reaching program on **QCD** (small-x gluon, saturation), **cosmic rays** (muon puzzle), **neutrino BSM** (sterile neutrinos), hadronic structure, **UHE neutrinos**, **FCC-pp cross-sections** …

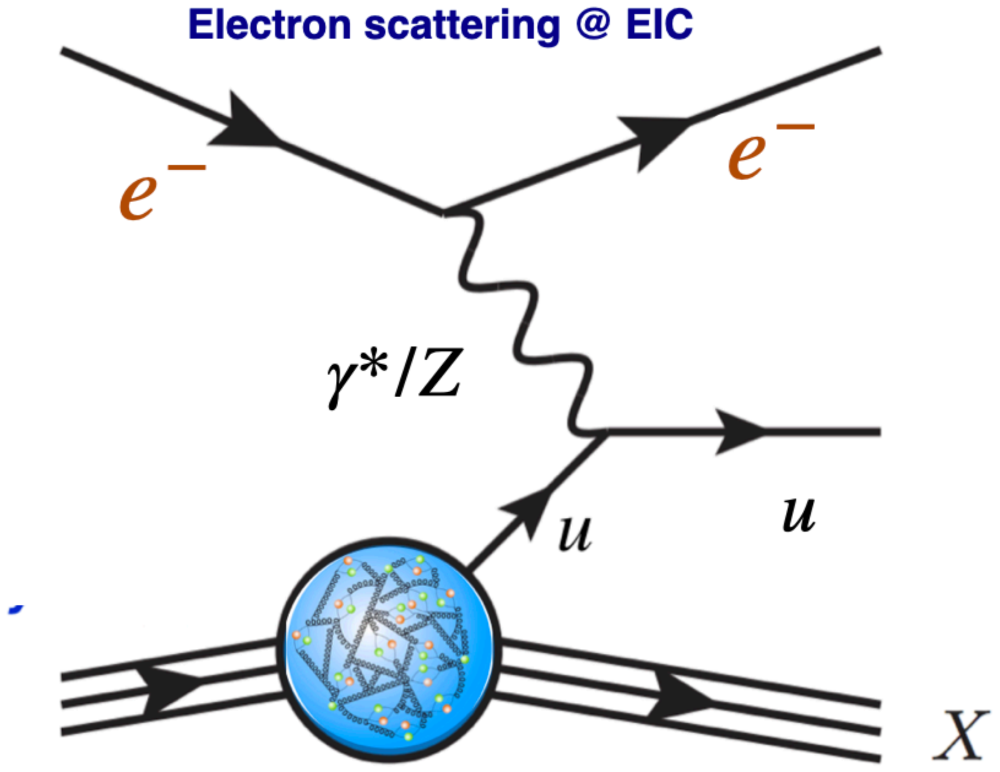
Proton and Nuclear Structure with TeV Neutrinos

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

Neutrino DIS at the LHC



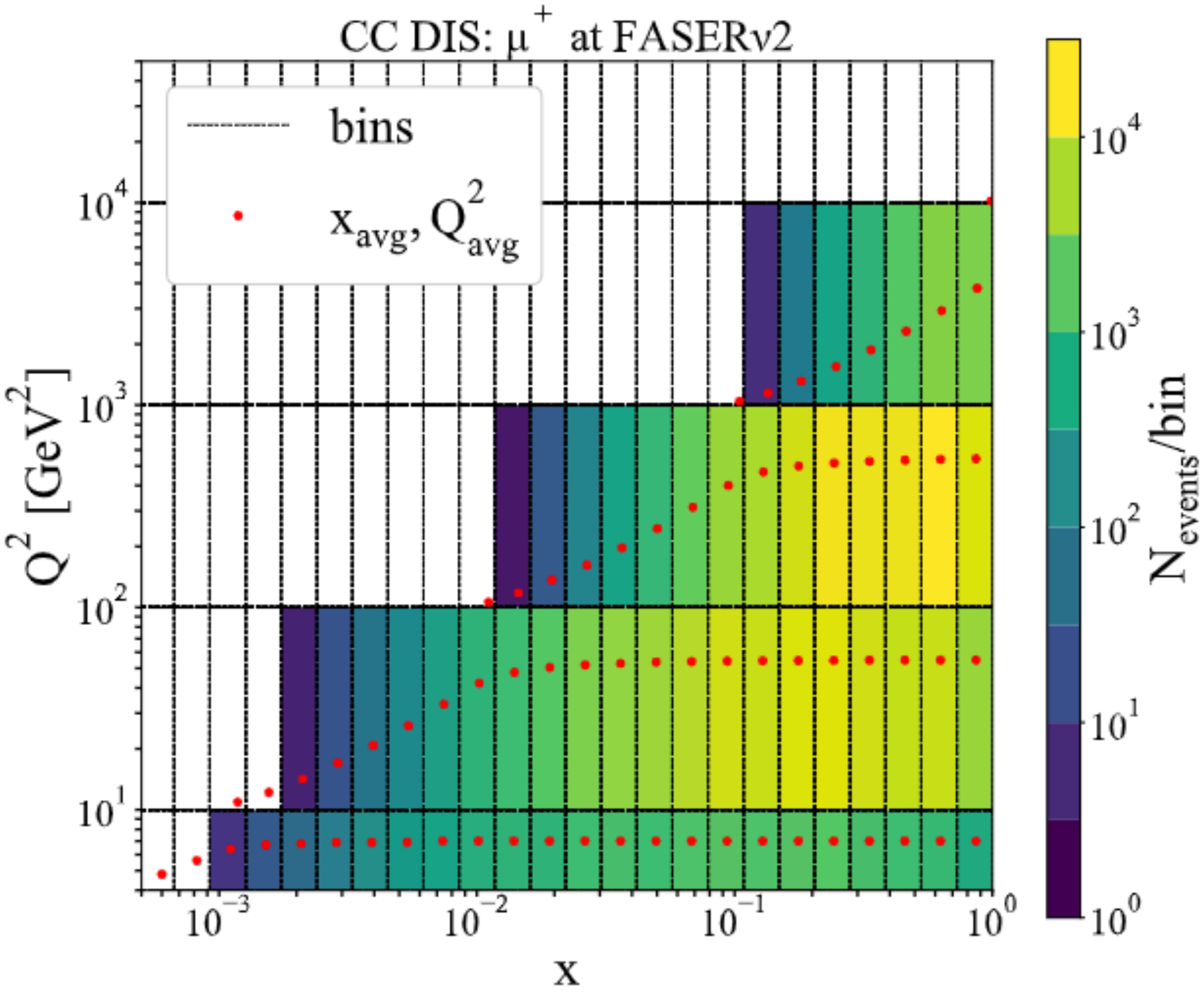




- **FASER / SND@LHC / FPF:** deep-inelastic charged current scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN &** expand kinematic coverage
- Charged-current analog of the Electron-Ion Collider: the LHC as a **Neutrino-Ion Collider**
- Constrain proton & nuclear **light (anti-)quark PDFs**

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



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

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

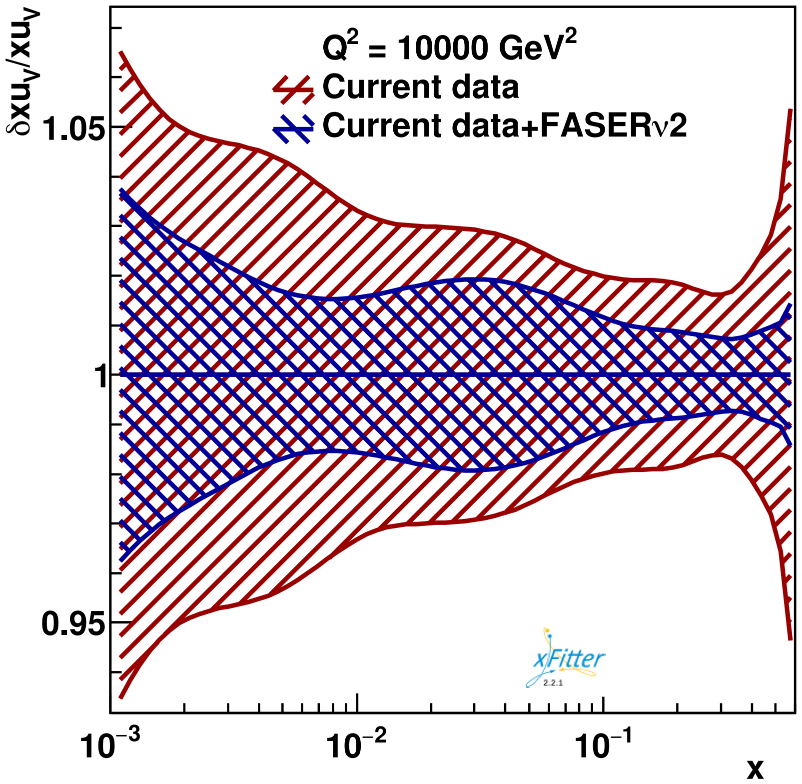
$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+F_2^{\nu A}(x,Q^2)-y^2F_L^{\nu A}(x,Q^2)+Y_-xF_3^{\nu A}(x,Q^2)\right]$$

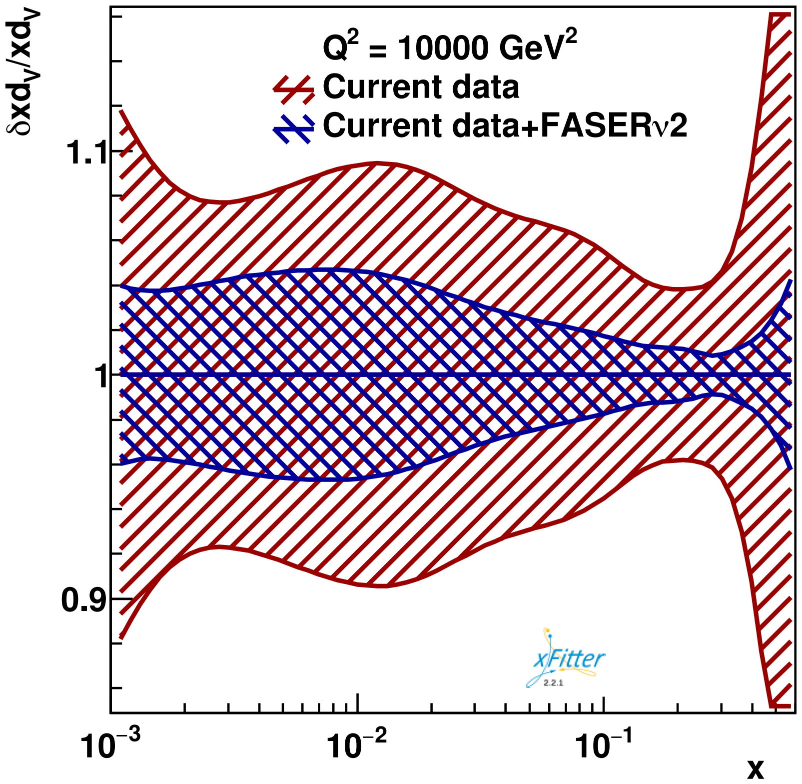
$$\frac{d^2\sigma^{\bar\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+F_2^{\bar\nu A}(x,Q^2)-y^2F_L^{\bar\nu A}(x,Q^2)-Y_-xF_3^{\bar\nu A}(x,Q^2)\right]$$

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

Results: proton PDFs

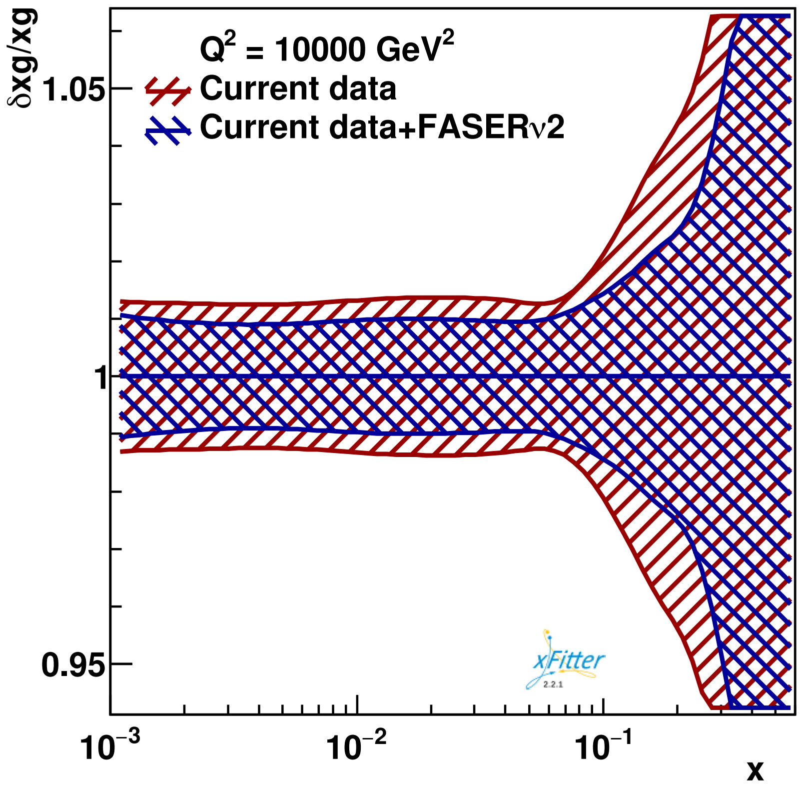
Statistical error only, inclusive + charm data

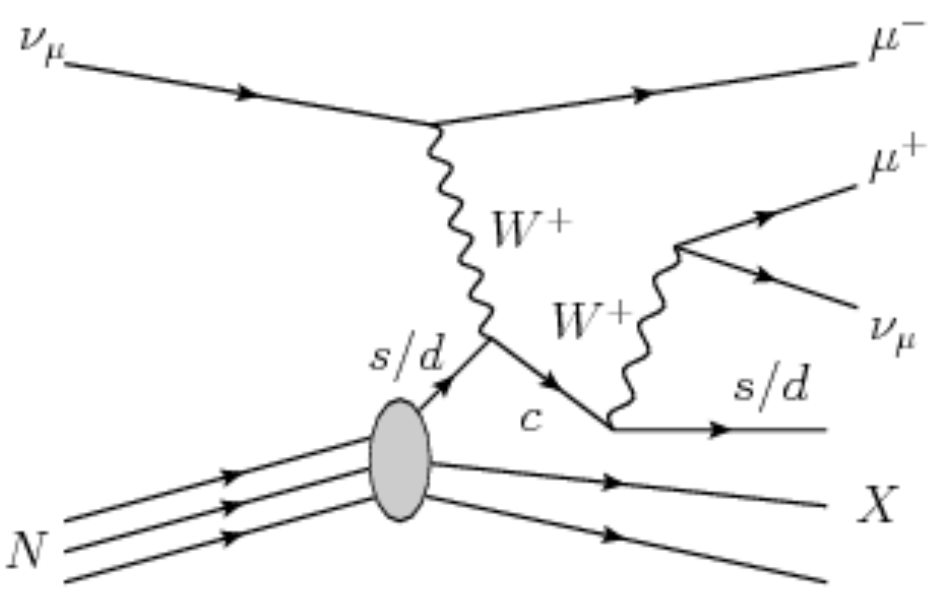


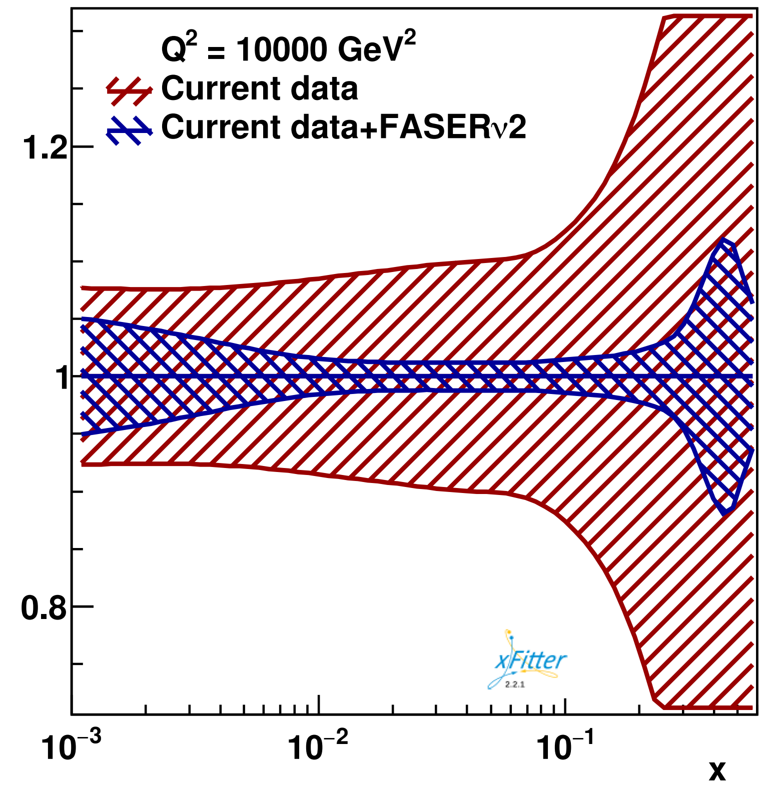


- Best scenario: **FASER2 statistics**, charm production included (strangeness), statistical errors only

- Reduction of PDF uncertainties most marked for **valence quarks and sea antiquarks**

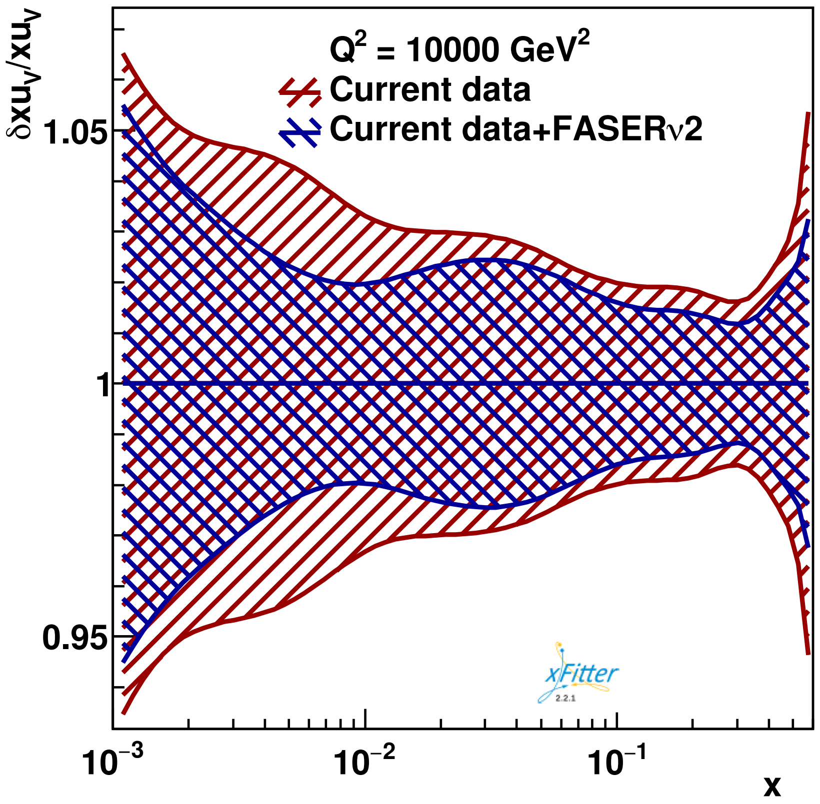


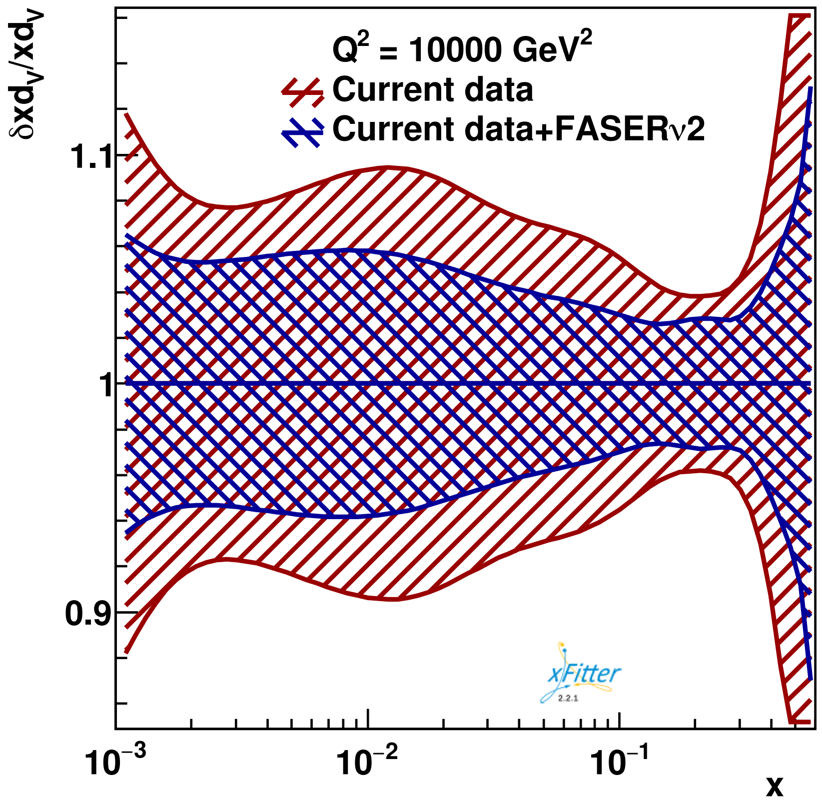




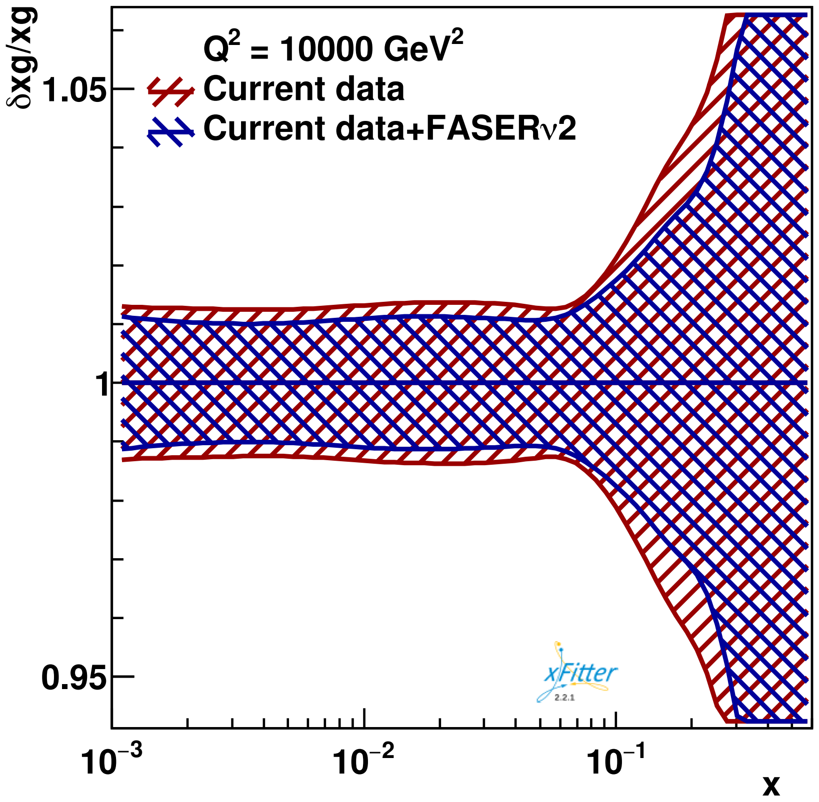
Results: proton PDFs

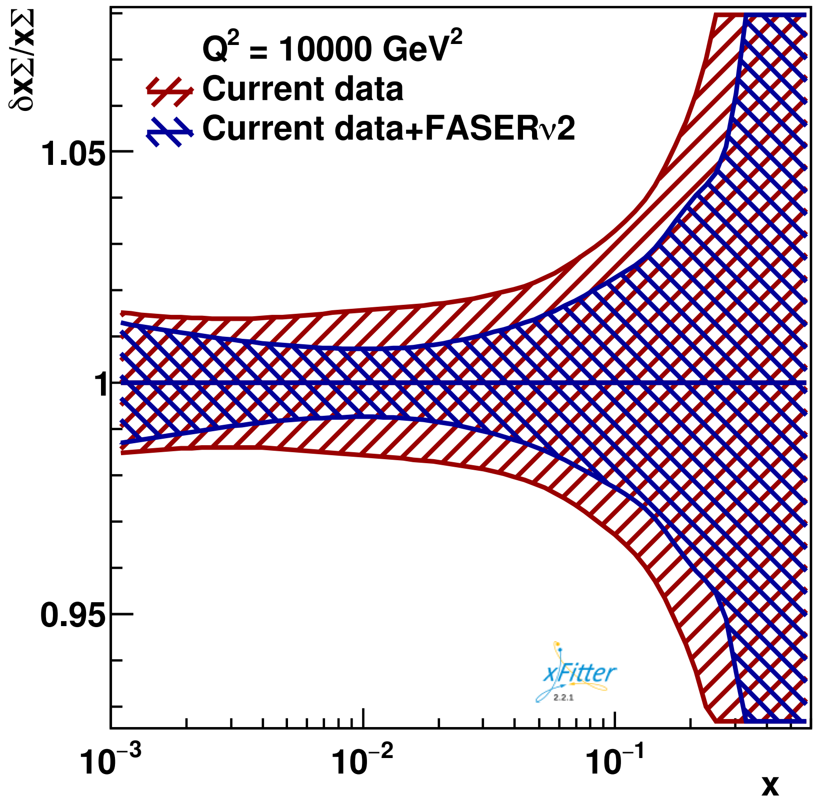
Statistical + Systematic errors only, inclusive + charm data

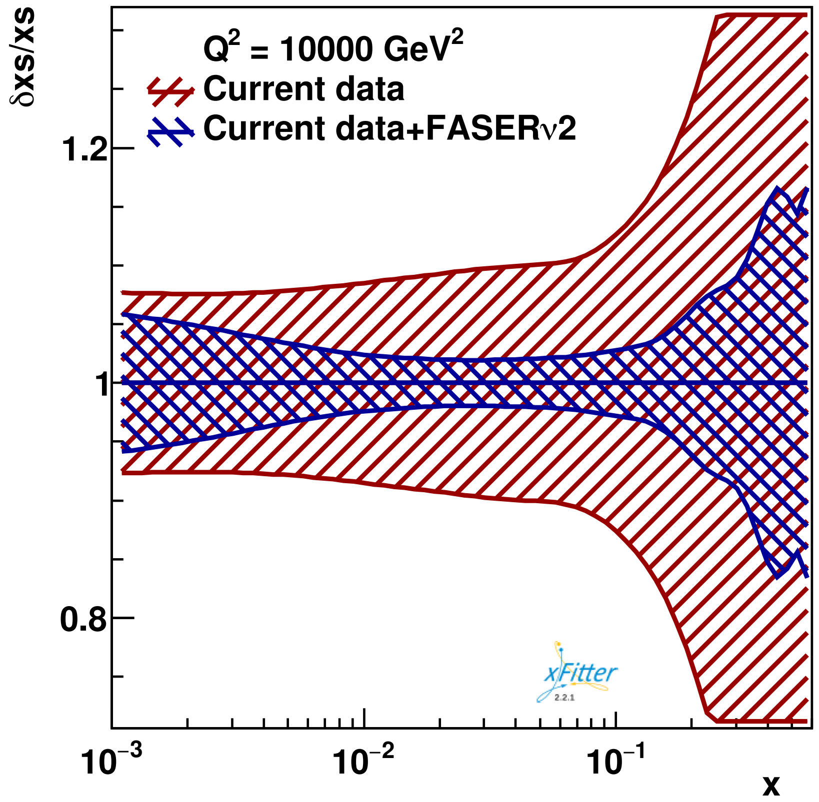




- Results are robust upon inclusion of **systematic errors**
- Depends on assumptions on **correlation model,** in particular bin-by-bin correlations
- Study of different scenarios in progress

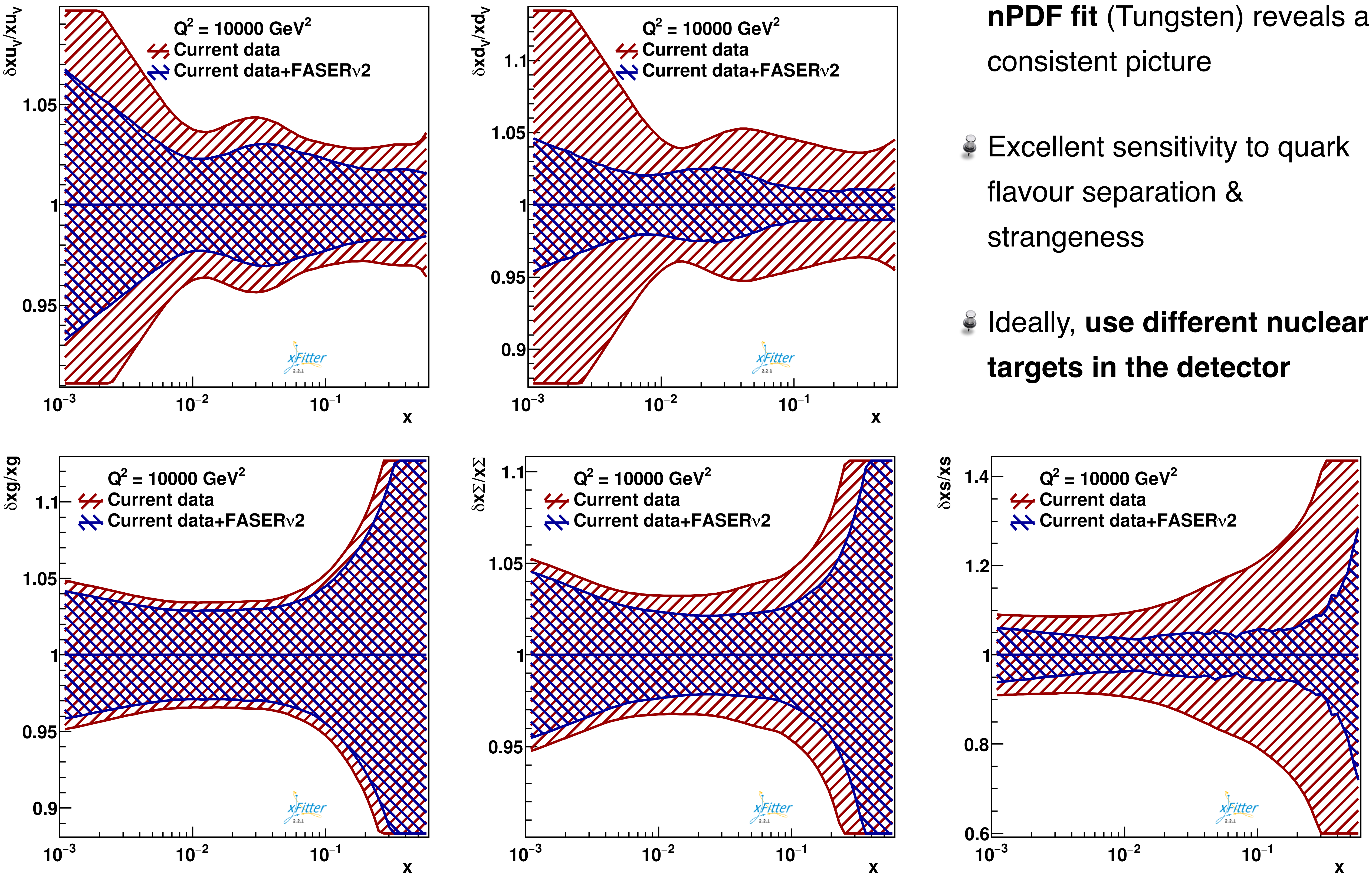






Results: nuclear PDFs

Statistical error only, inclusive + charm data

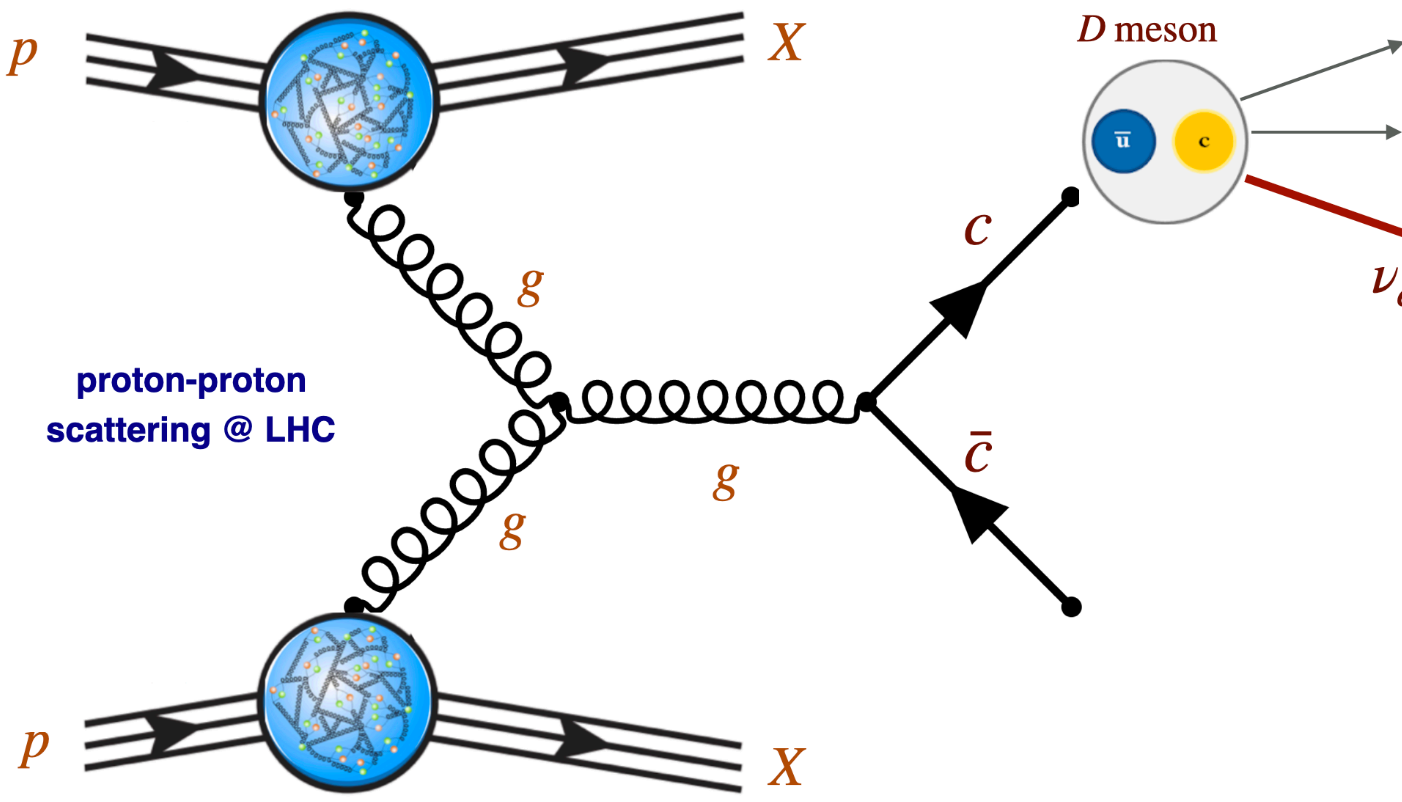


- Profiling of the **EPPS21 global nPDF fit** (Tungsten) reveals a consistent picture
- Excellent sensitivity to quark flavour separation & strangeness
- Ideally, **use different nuclear targets in the detector**

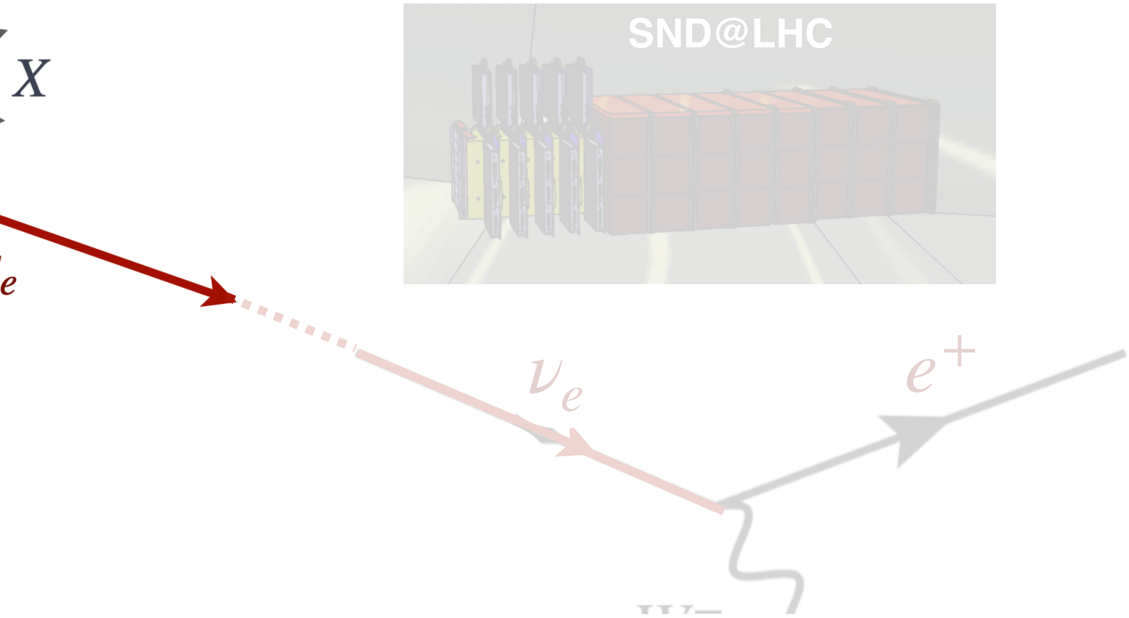
Pinning down ultra-small-x gluon with LHC neutrinos

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

Neutrinos at the LHC

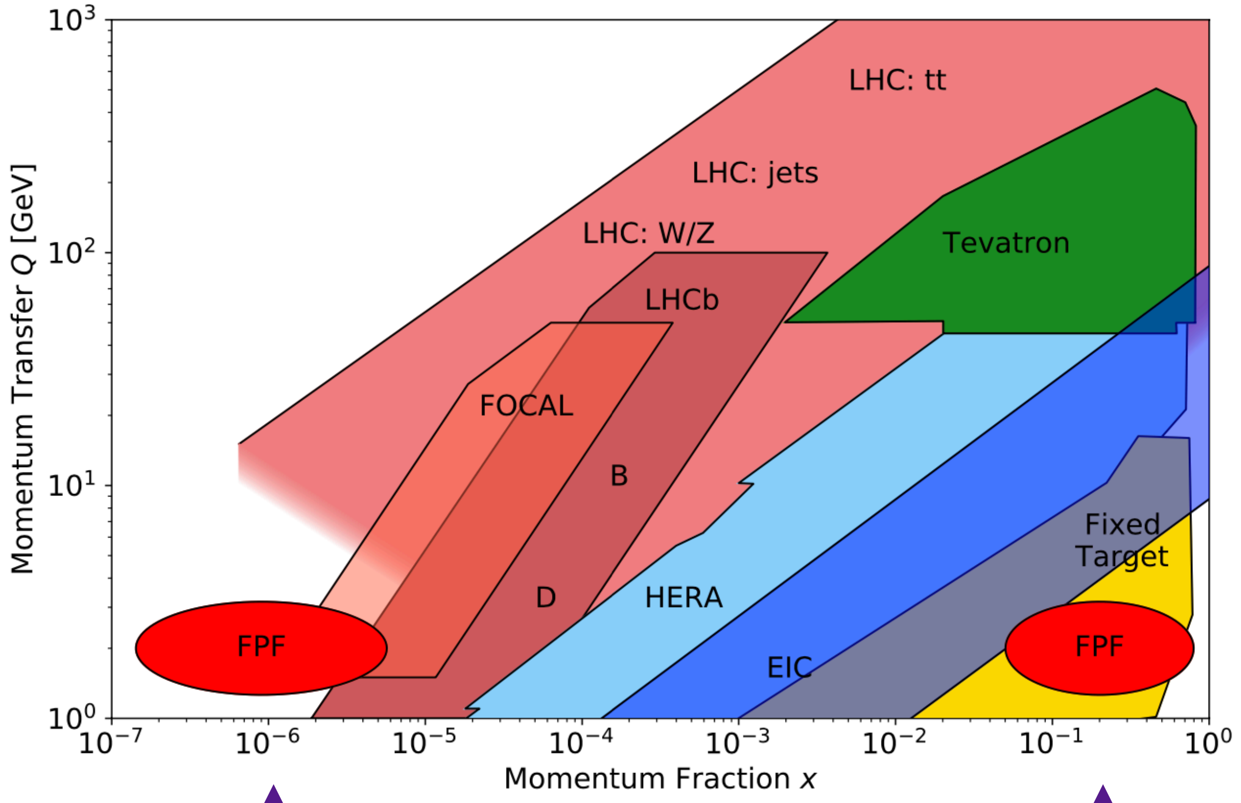


proton-proton scattering @ LHC



Neutrino Production

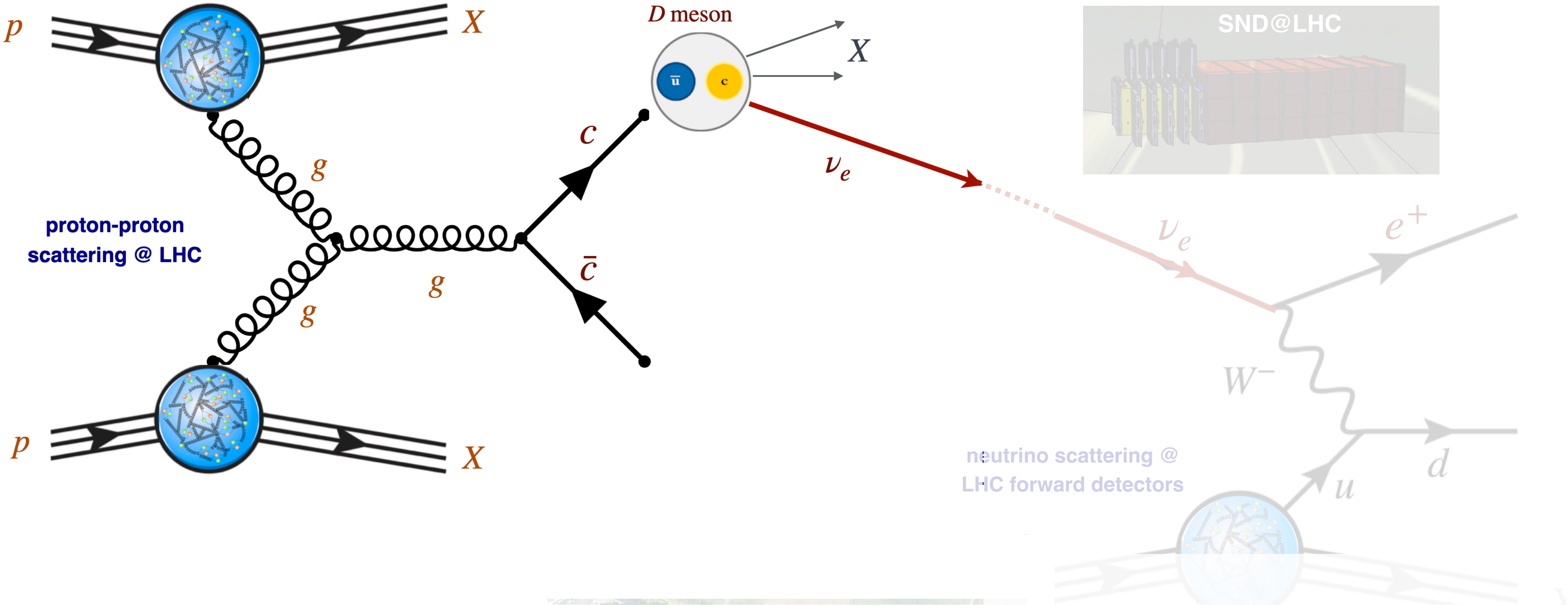
- **Small-x gluon & large-x (intrinsic) charm**
- *D*-meson fragmentation
- Cross-sections for UHE neutrinos (*e.g.* IceCube)
- Cosmic ray modelling, including muon puzzle



small-x gluon

large-x

Neutrinos at the LHC



proton-proton scattering @ LHC

neutrino scattering @ LHC forward detectors

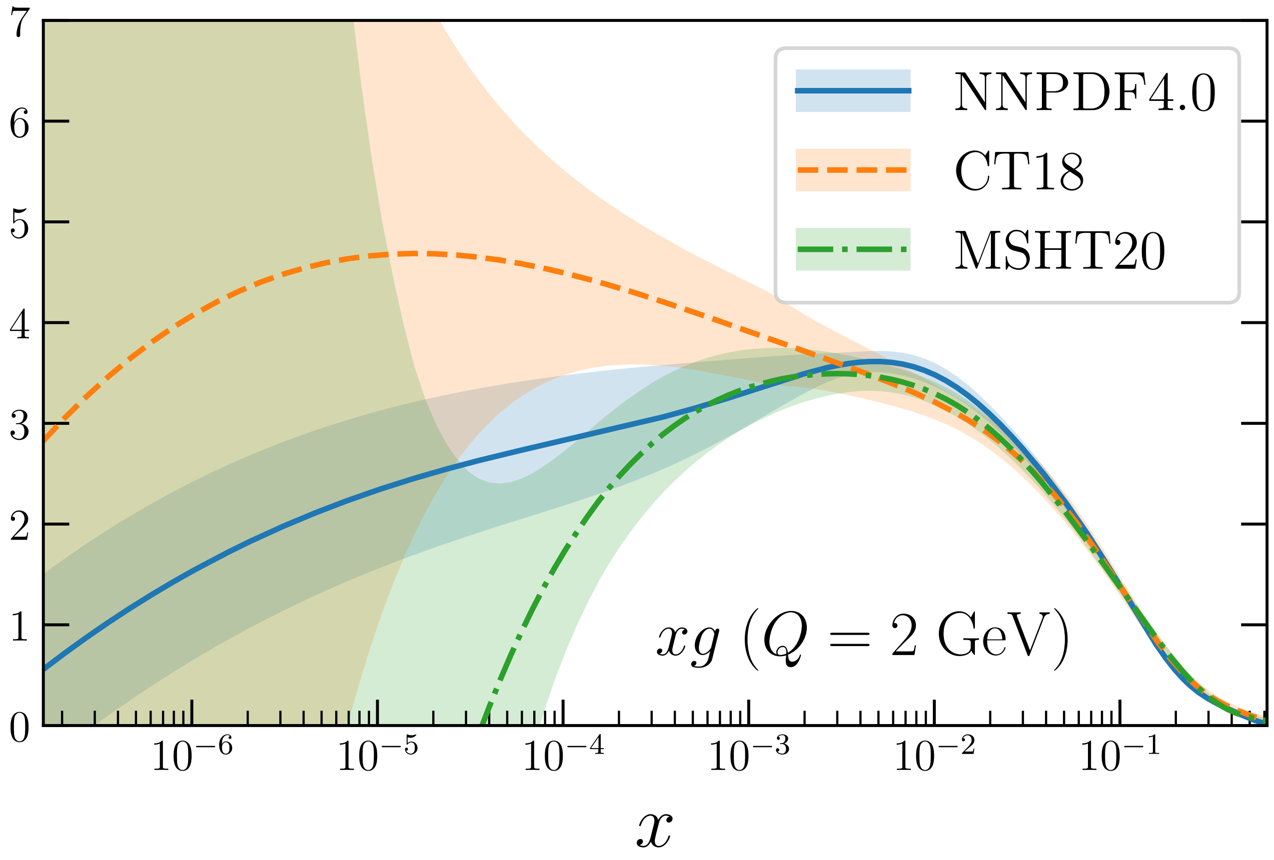
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\widehat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

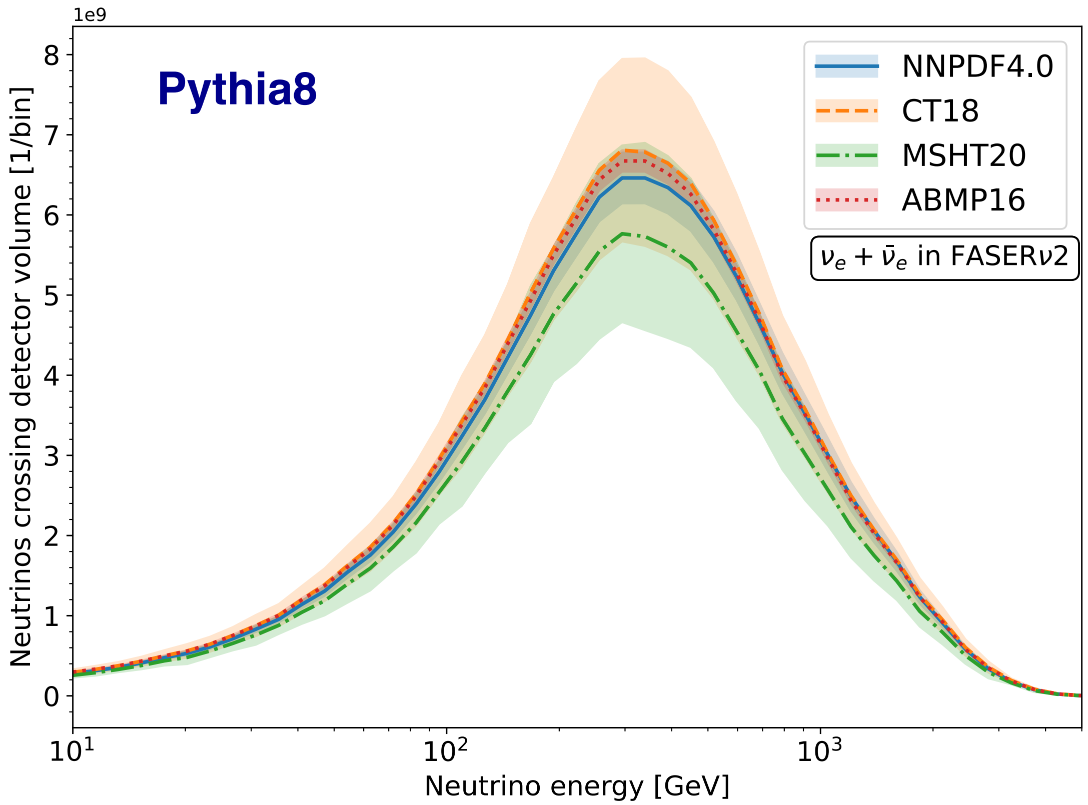
Extract from measured neutrino fluxes

Constrain from FASER/FPF data

QCD prediction: NLO + PS large theory uncertainties

Impact projections



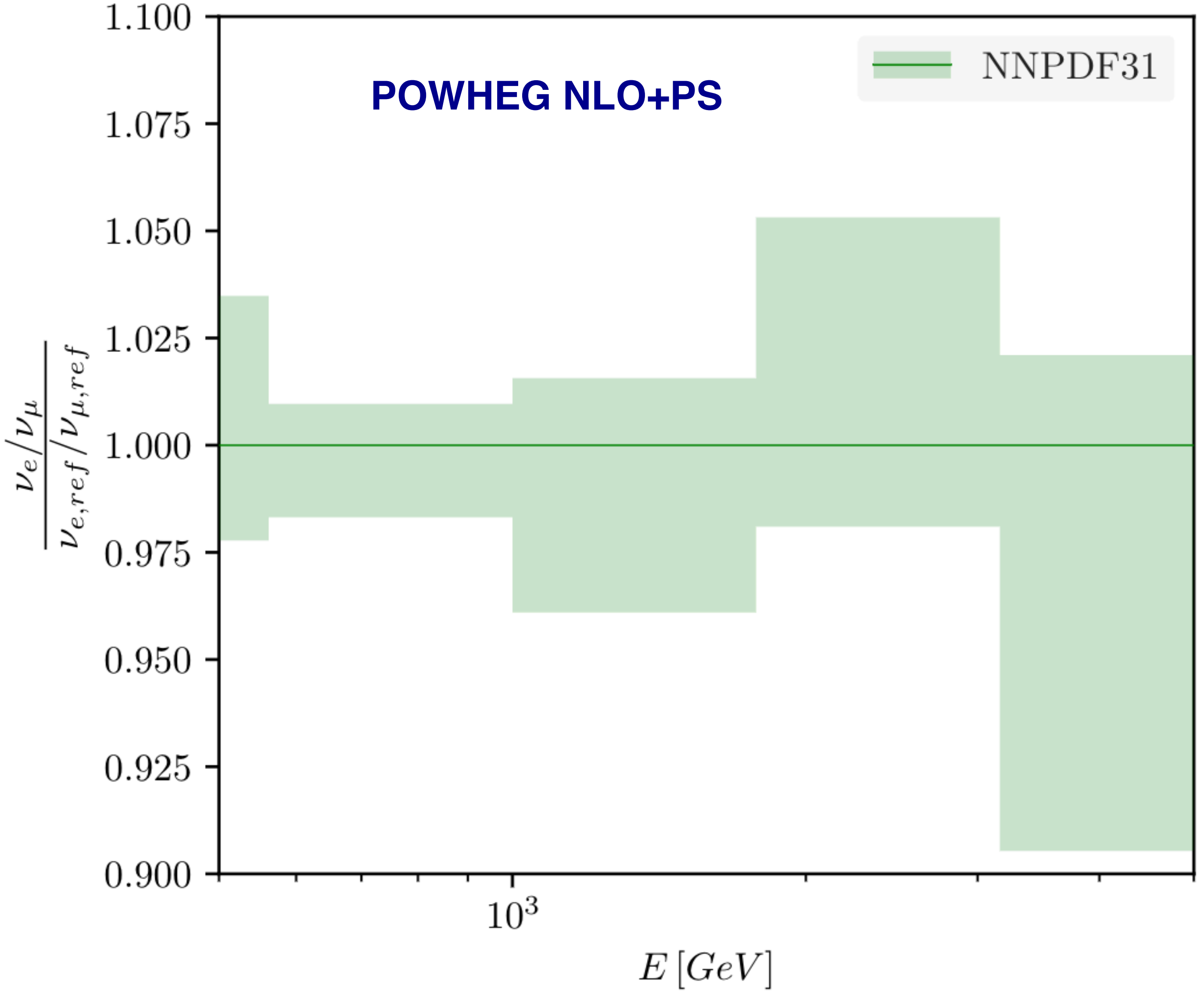


- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially)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



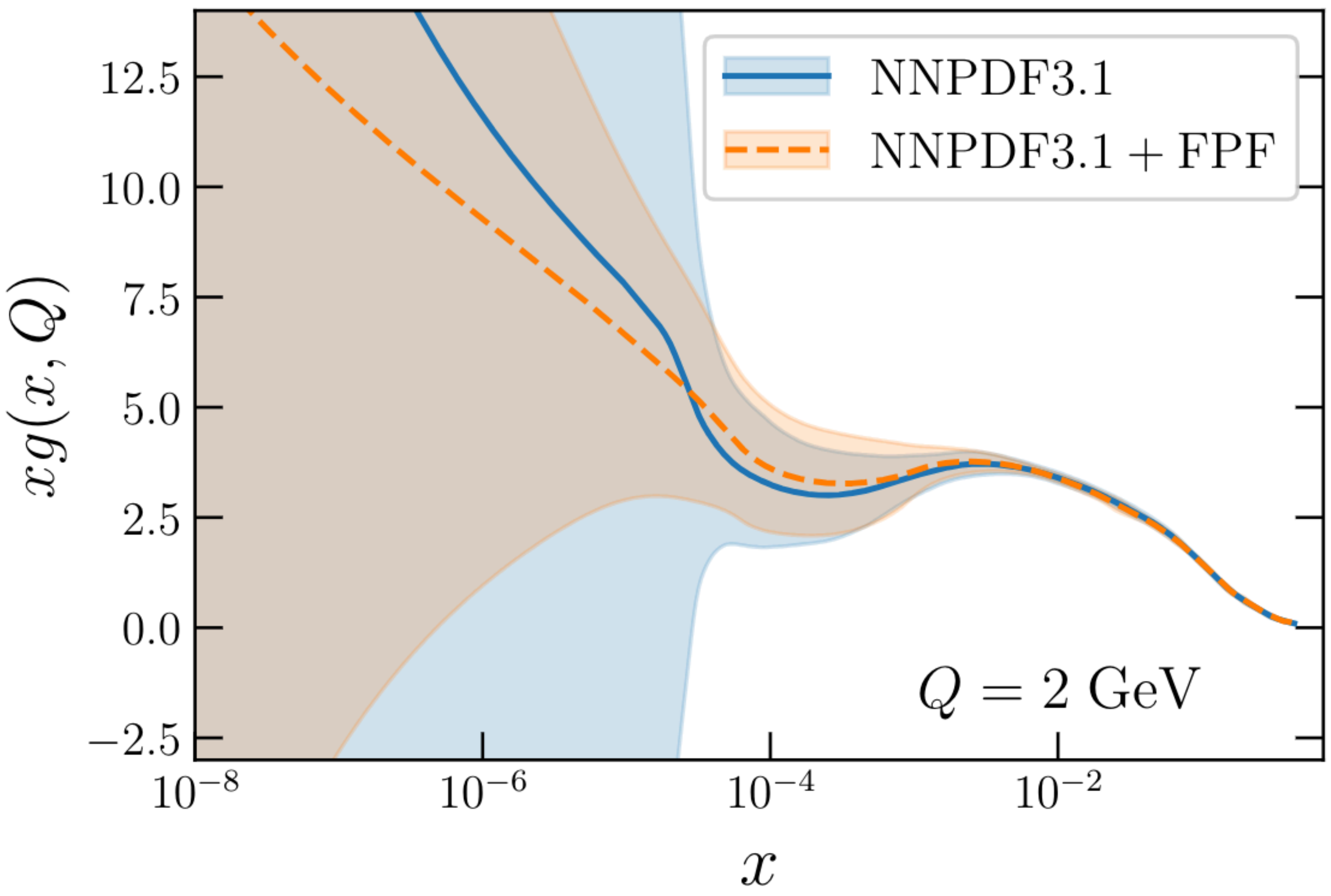
- When taking r**atios of event rates** (e.g. charm electron neutrinos vs charm muon neutrinos), QCD uncertainties reduced to O(few %)
- Strategy: assume a measurement of **inclusive event rates** as a function of neutrino energy with a given precision, quantify impact on PDFs via **Bayesian reweighting**

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

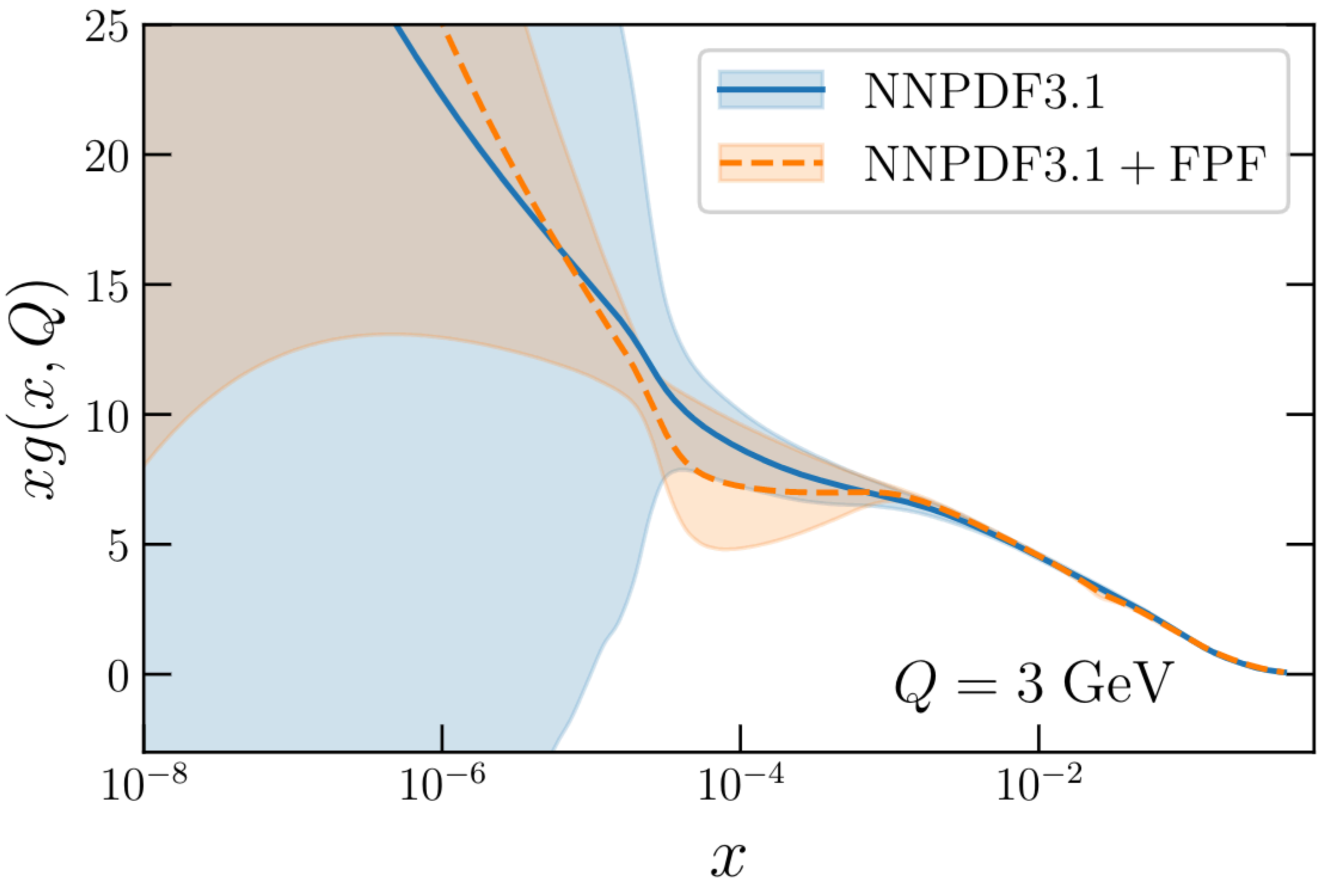
Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

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)

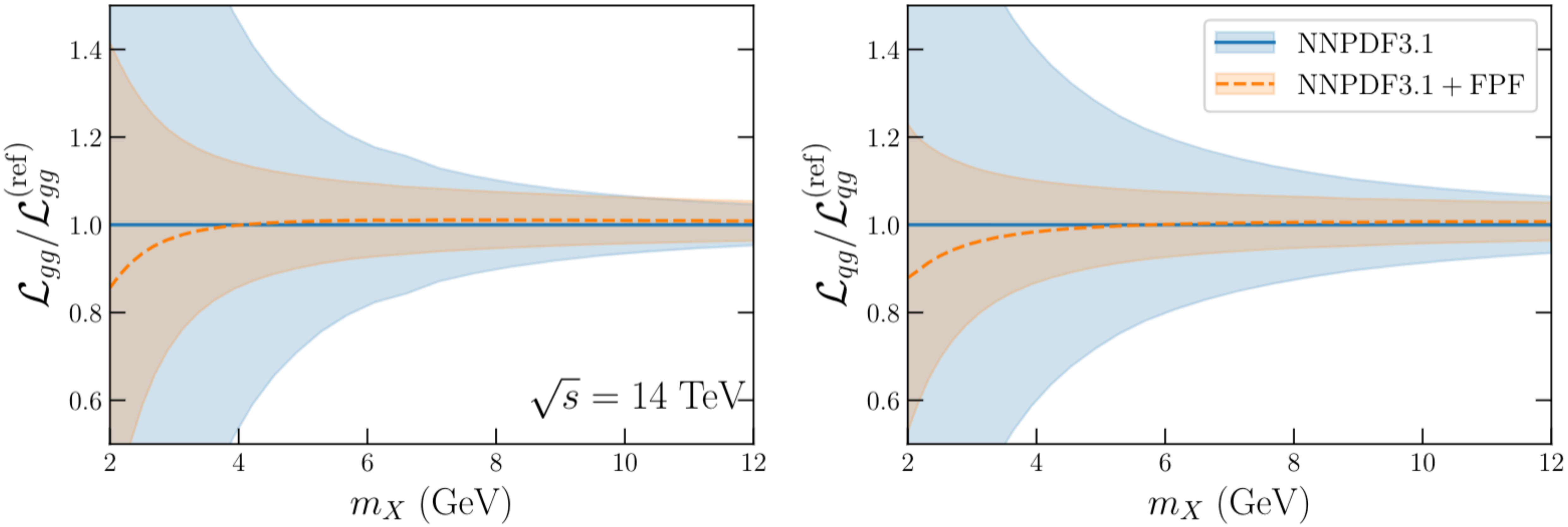
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_u < 9.0)} \qquad R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_u < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_u < 9.0)}$$

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

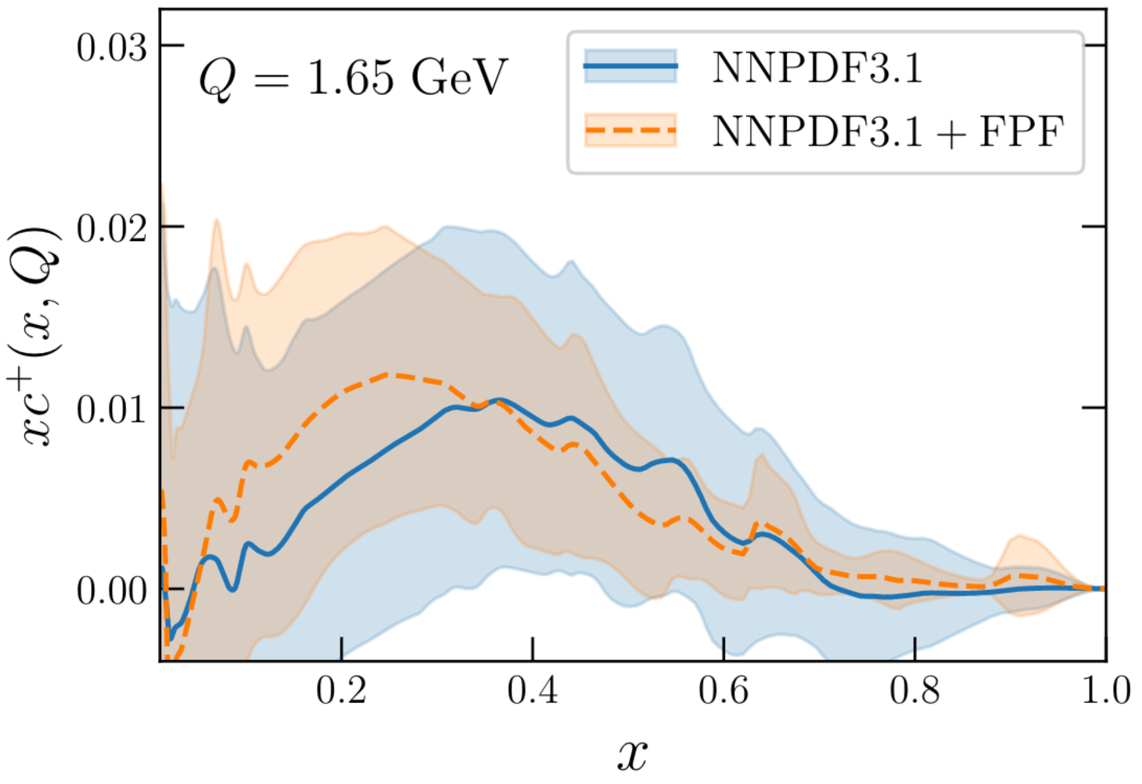
- Study impact of different observables, QCD errors, and the precision of measurement

Results

Electron neutrinos, 2% uncertainty in inclusive event rates



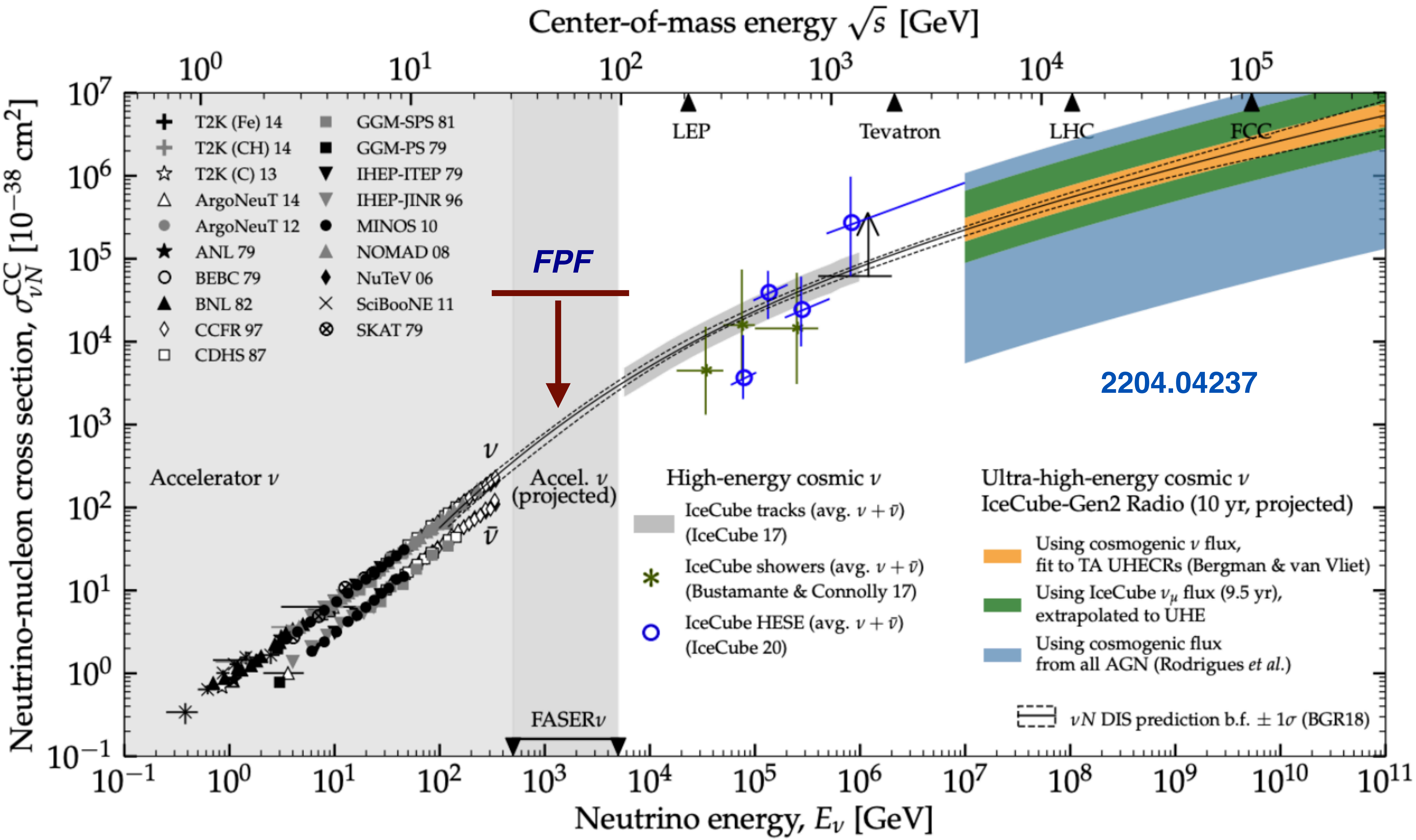
- General improvements of **low-mass gluon-initiated** processes at the LHC
- Constraints also on the **charm PDF** via the gluon-charm initial state
- Run III data on LHC neutrinos may provide first measurement of the **gluon content of the proton at x=10^{-7}**



Neutrino Structure Functions from GeV to EeV Energies

A. Candido, A. Garcia, G. Magni, T. Rabemananjara, J. Rojo, R. Stegeman, JHEP 23

The neutrino cross-section landscape

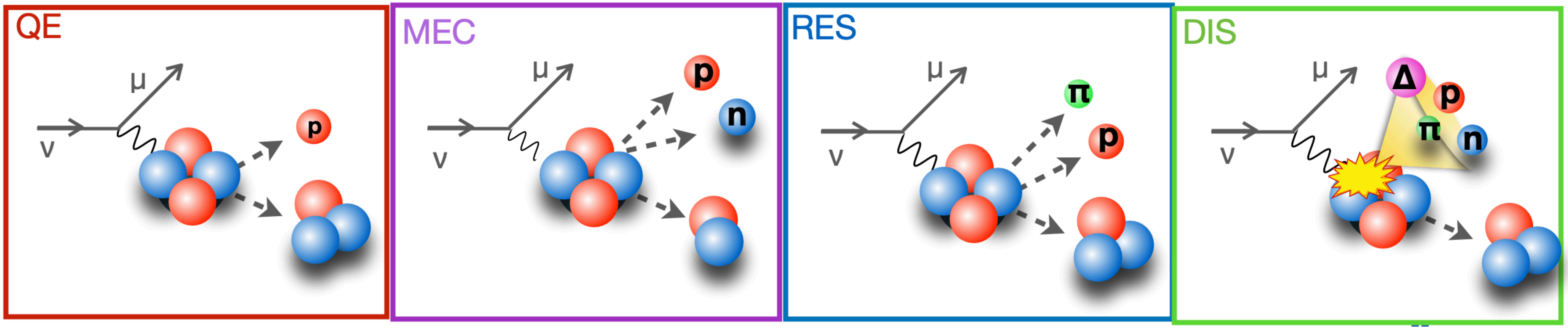


2204.04237

Depending on the neutrino energy, **different interaction mechanisms** dominate the neutrino-nucleus cross-section

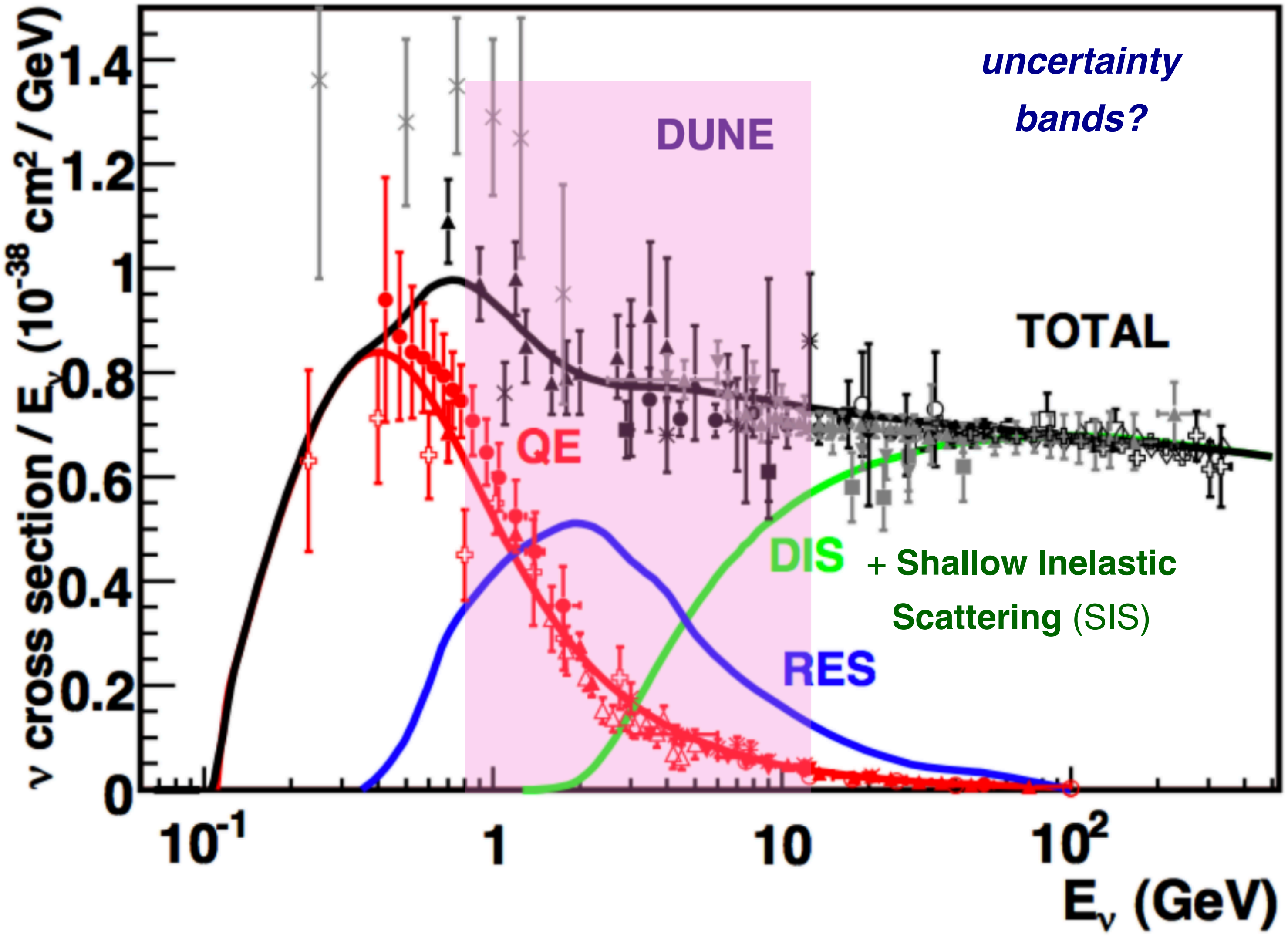
``collider neutrinos'' (FASER, SND@LHC, FPF) cover uncharted range

The neutrino cross-section landscape

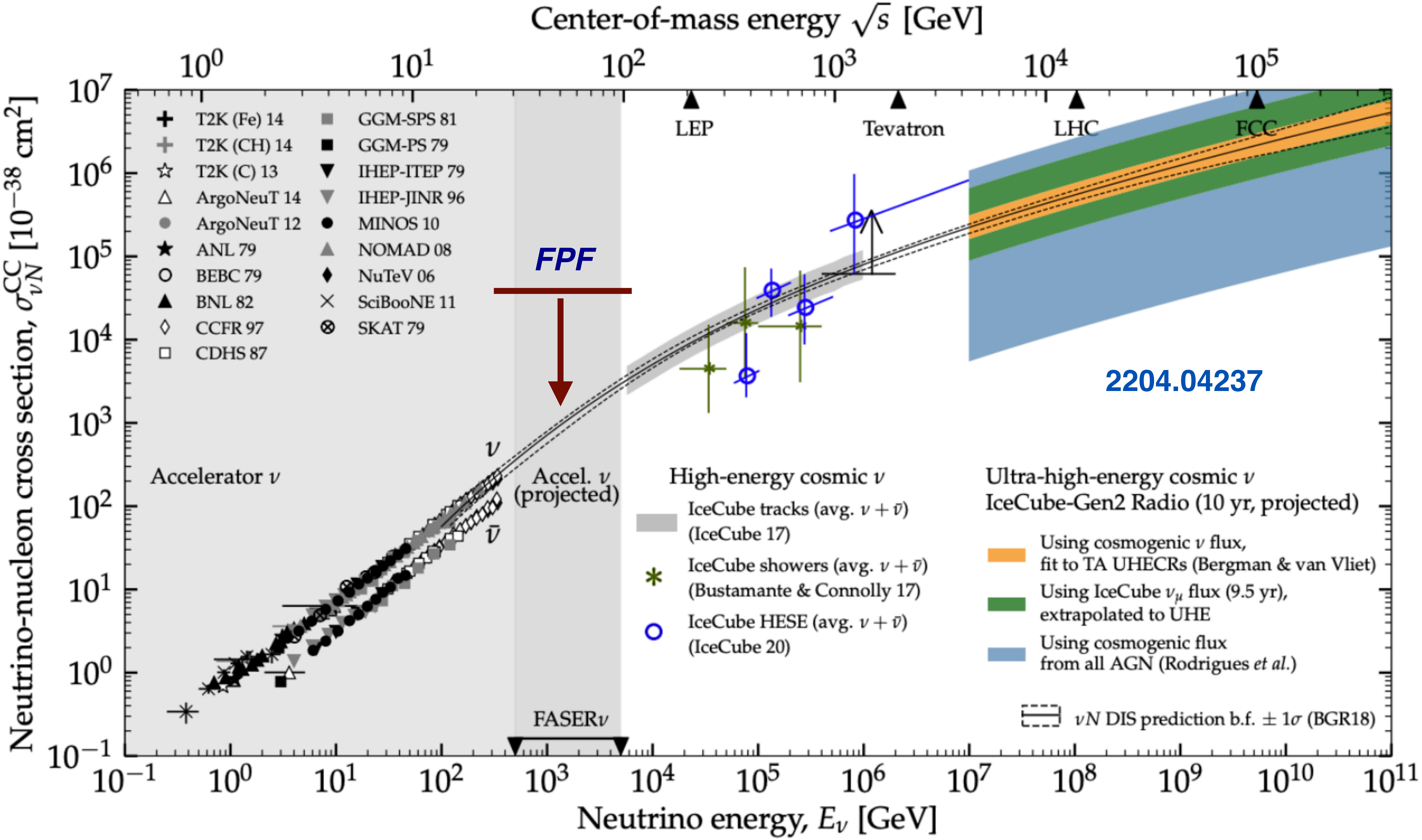


- For energies > 5 GeV, **inelastic scattering** dominates the inclusive cross-section
- Common misconception: inelastic scattering does **not** coincide with **deep-inelastic scattering** (DIS) where pQCD can be applied!
- How robust is our **theoretical understanding** of neutrino inelastic scattering interactions?

✐ J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



The neutrino cross-section landscape



Inelastic scattering (SIS + DIS)

Deep-inelastic scattering (>95%)

sizable kinematic region where **Shallow Inelastic Scattering** (SIS) cannot be neglected

The role of the low-Q region

inclusive neutrino cross-sections receives **sizeable contributions from $Q < 2$ GeV region**, where structure functions cannot be evaluated in the pQCD framework

$$\boxed{\sigma(E_\nu) = \int_{Q^2_{\rm min}}^{2m_N E_\nu} dQ^2 \left[\int_{Q^2/(2m_N y E_\nu)}^{1} dx \, \frac{d^2\sigma}{dx dQ^2}(x, Q^2, E_\nu) \right]}$$

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2)\right]$$

Deep-Inelastic Scattering

$$F_i^{\nu A}(x,Q^2) = \sum_{j=q,\bar{q},g} \int_x^1 \frac{dz}{z} C_{i,j}^{\nu N}(z, \alpha_s(Q^2)) f_j^{(A)}\left(\frac{x}{z}, Q^2\right)$$

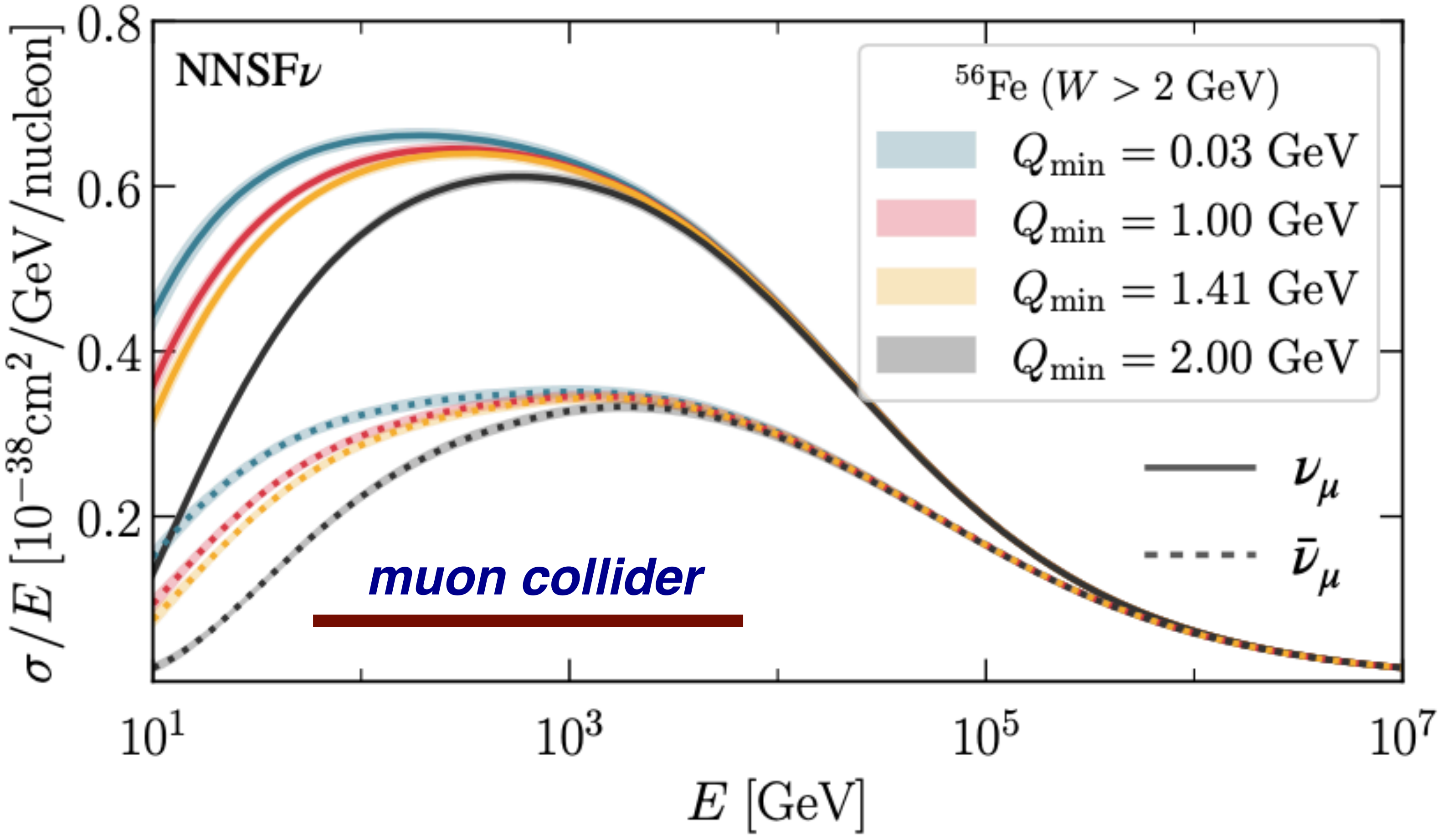
Shallow-Inelastic Scattering

$$F_i^{\nu A}(x,Q^2) = \quad ?$$

The role of the low-Q region

inclusive neutrino cross-sections receives **sizeable contributions from $Q < 2$ GeV region**, where structure functions cannot be evaluated in the pQCD framework

$$\sigma(E_\nu) = \int_{Q^2_{\rm min}}^{2m_N E_\nu} dQ^2 \left[\int_{Q^2/(2m_N y E_\nu)}^{1} dx \, \frac{d^2\sigma}{dx dQ^2}(x, Q^2, E_\nu) \right]$$



- Even for neutrino energies of hundreds of GeV, **sizeable contribution from low-Q region**
- Perturbative QCD not reliable, what to do?
- So far, most calculations used in phenomenology rely on **phenomenological models**

The Bodek-Yang model

The **Bodek-Yang model** is popular to describe **inelastic neutrino DIS** structure functions

based on **effective leading-order PDFs** (GRV98LO) supplemented to phenomenological scaling variables and *K*-factors to improve agreement with data

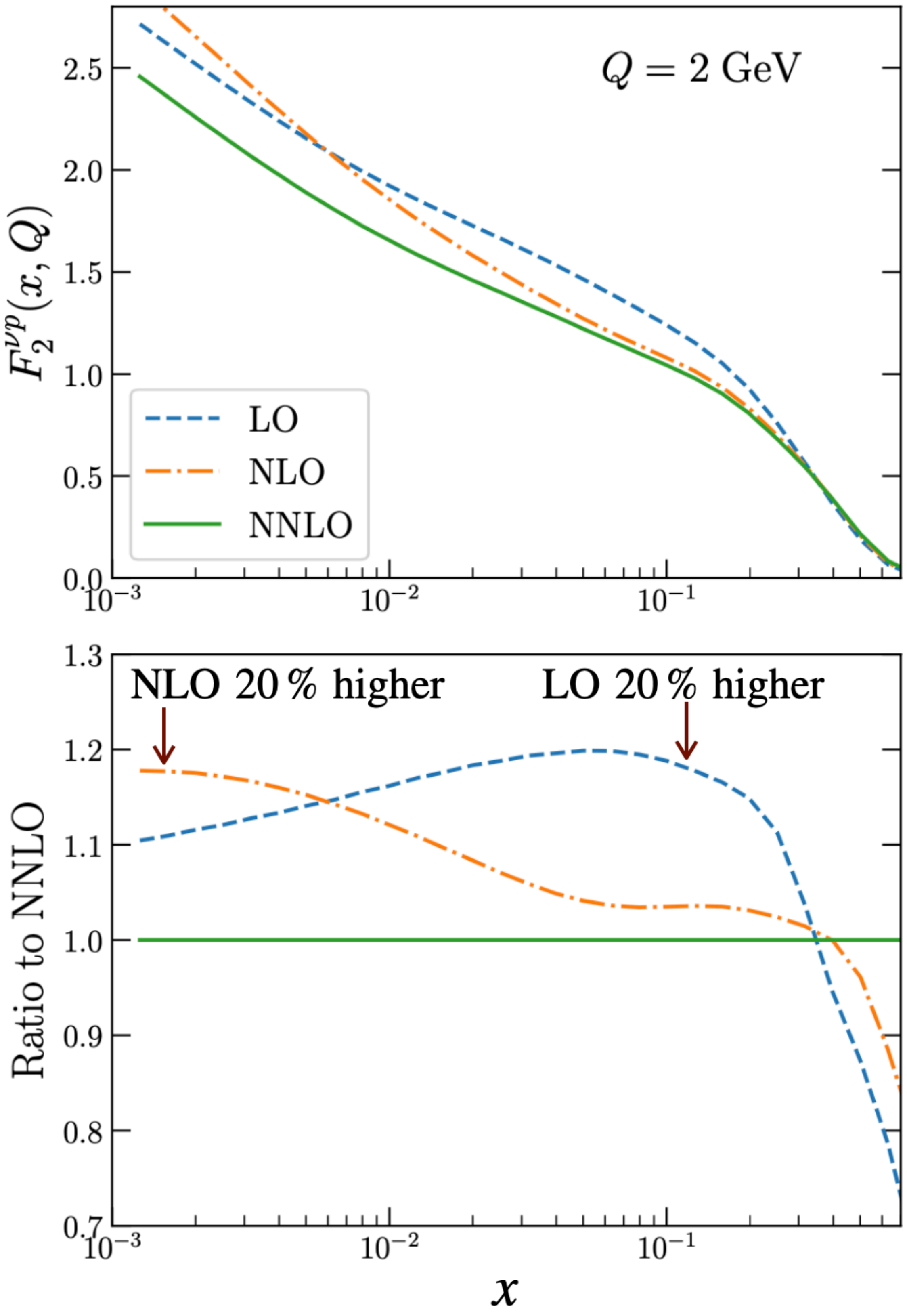
$$f_i^{\mathrm{LO}}(x, Q^2) \to f_i^{\mathrm{LO,BY}}(\xi, Q^2) \qquad \xi = \frac{2x(Q^2 + m_f^2 + B)}{Q^2\left[1 + \sqrt{1 + (2m_N x)^2/Q^2}\right] + 2Ax}$$

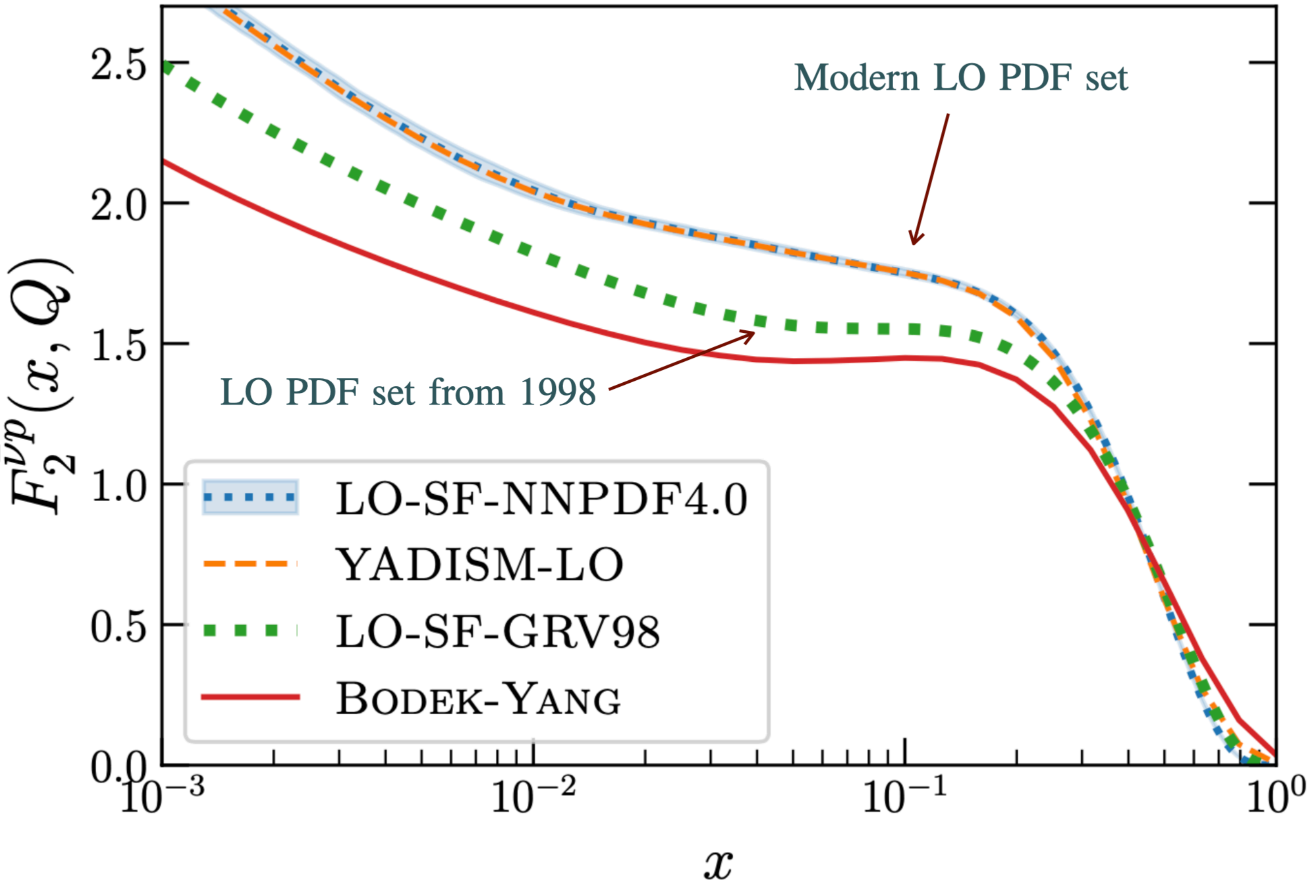
Limitations of the BY model of neutrino structure functions:

- Obsolete PDF parametrisation that **ignores constraints from the last 25 years**
- Neglects **higher-order QCD corrections** (can be up to 100%)
- Cannot be used above 100 TeV: **not an option for UHE neutrinos**
- Does not provide **uncertainty estimate**, difficult to assess its accuracy and precision
- Cannot be systematically improvable e.g. by new data

The Bodek-Yang model

The **Bodek-Yang model** is popular to describe **inelastic neutrino DIS** structure functions

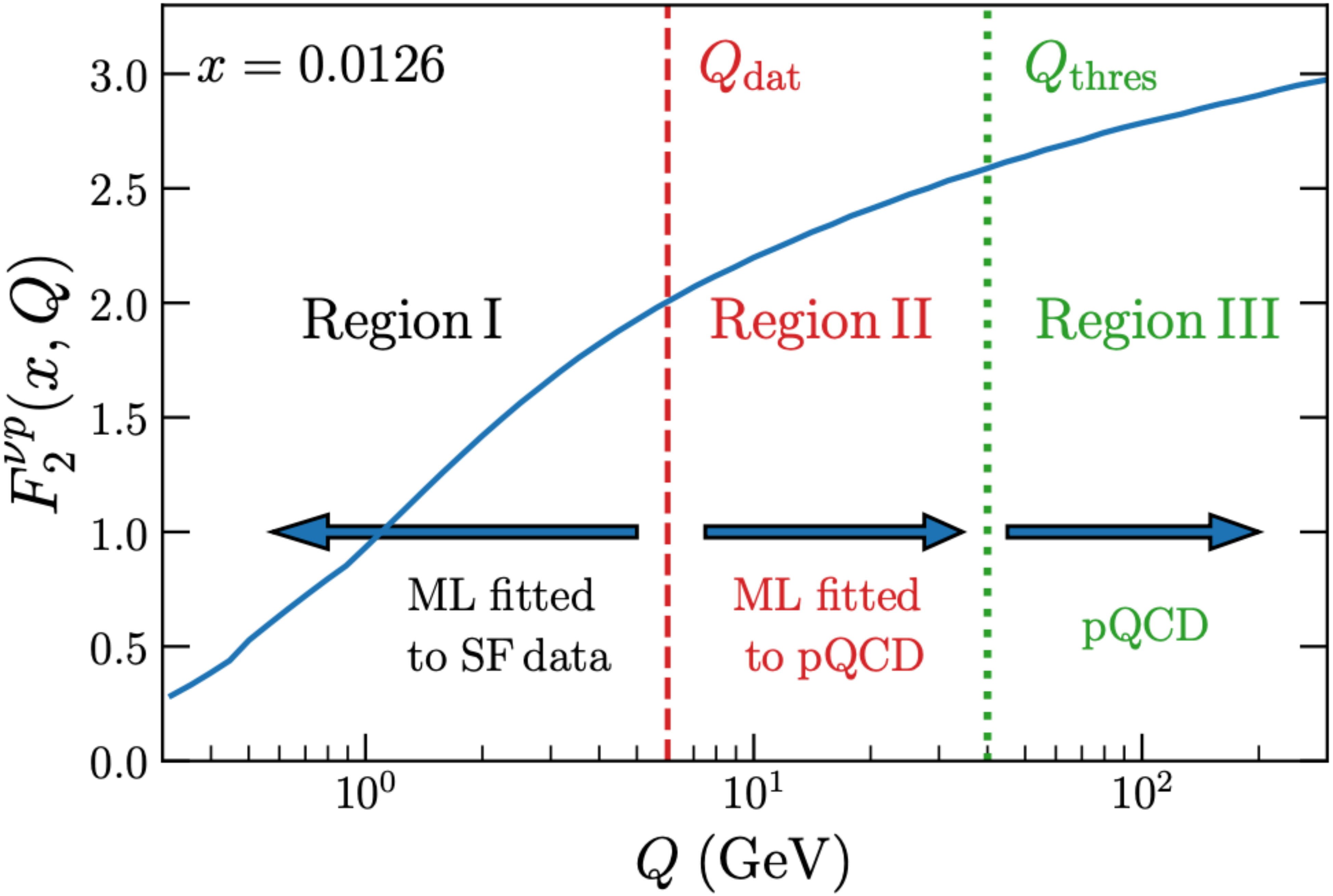




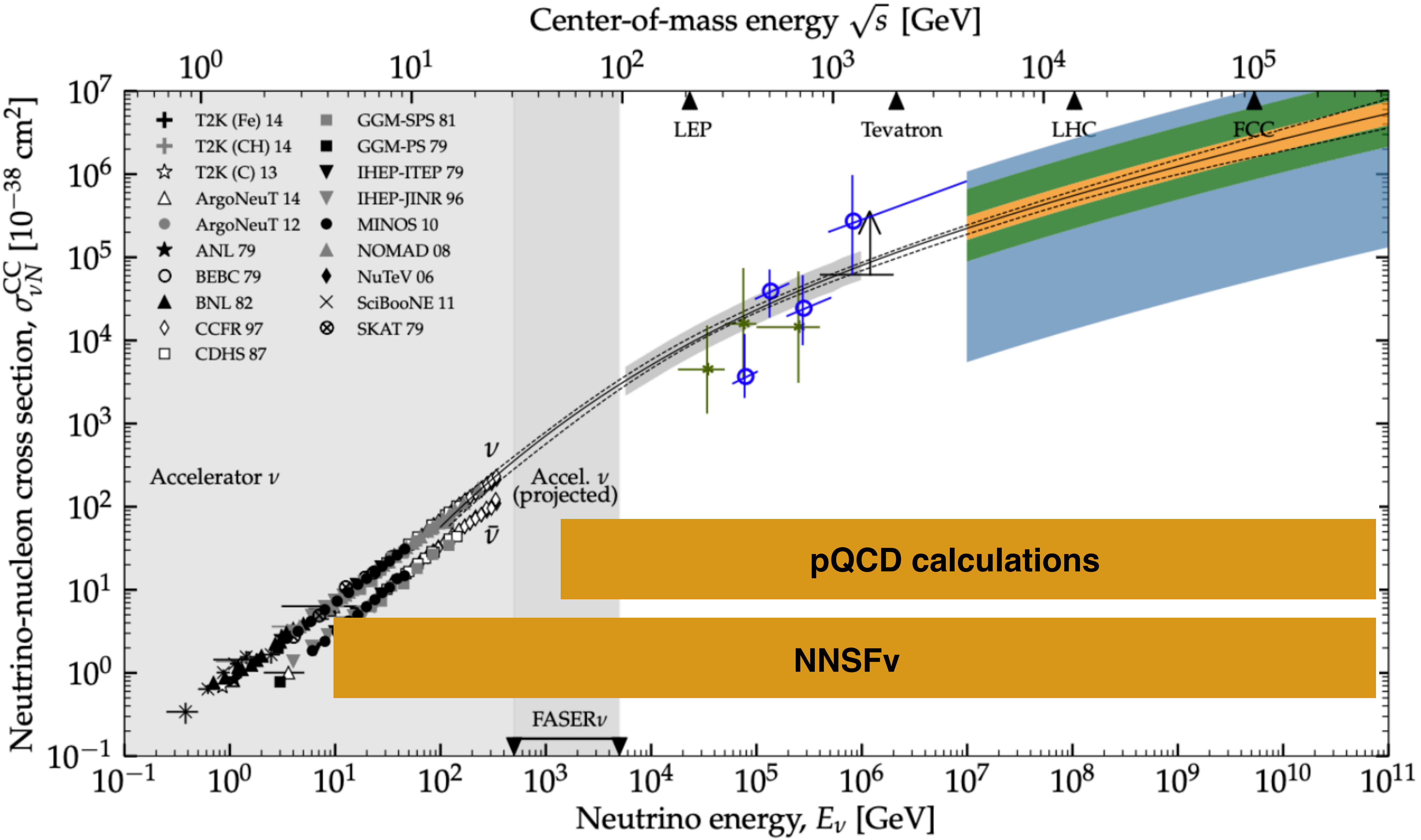
Improved models of neutrino-nucleon interactions essential for **LHC neutrino physics** as well as IceCube, KM3NET, …

The NNSFν approach

Motivation: realise the first determination of neutrino structure functions **valid from photoproduction $Q = 0$ all the way to $Q = 100$ TeV**, enabling calculation of inclusive inelastic cross-sections **for neutrinos from 5 GeV to 10^{12} GeV energies**



The NNSFν approach

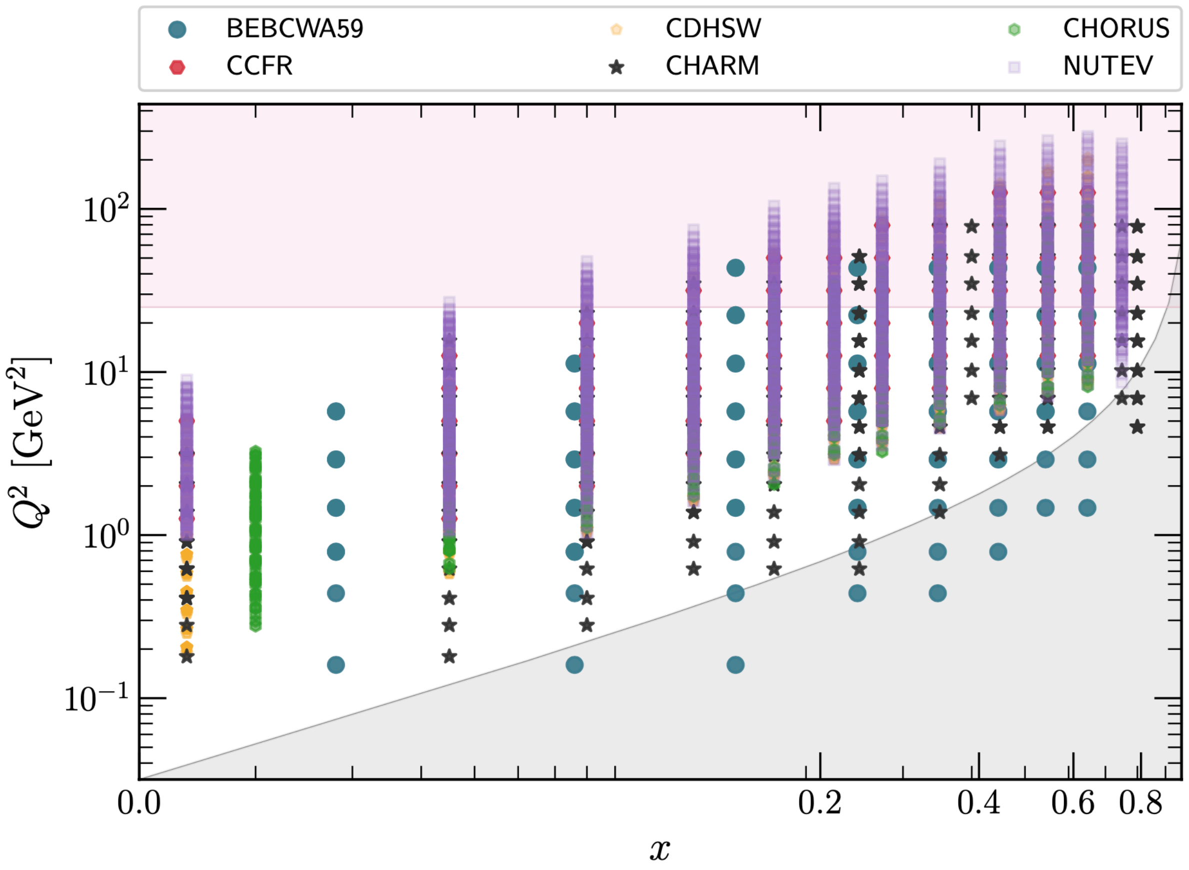


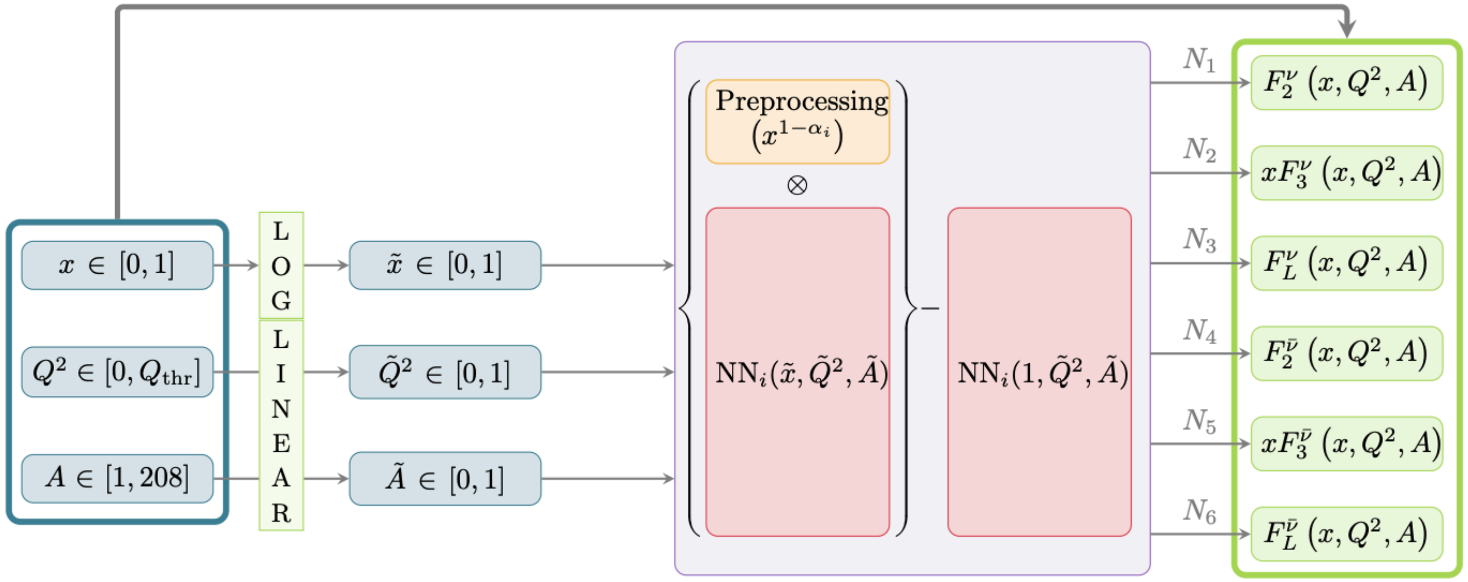
pQCD calculations

NNSFν

The neutrino cross-section landscape

- Use available data on neutrino-nucleus scattering to **parametrise and determine inelastic structure functions** by means of the NNPDF fitting methodology



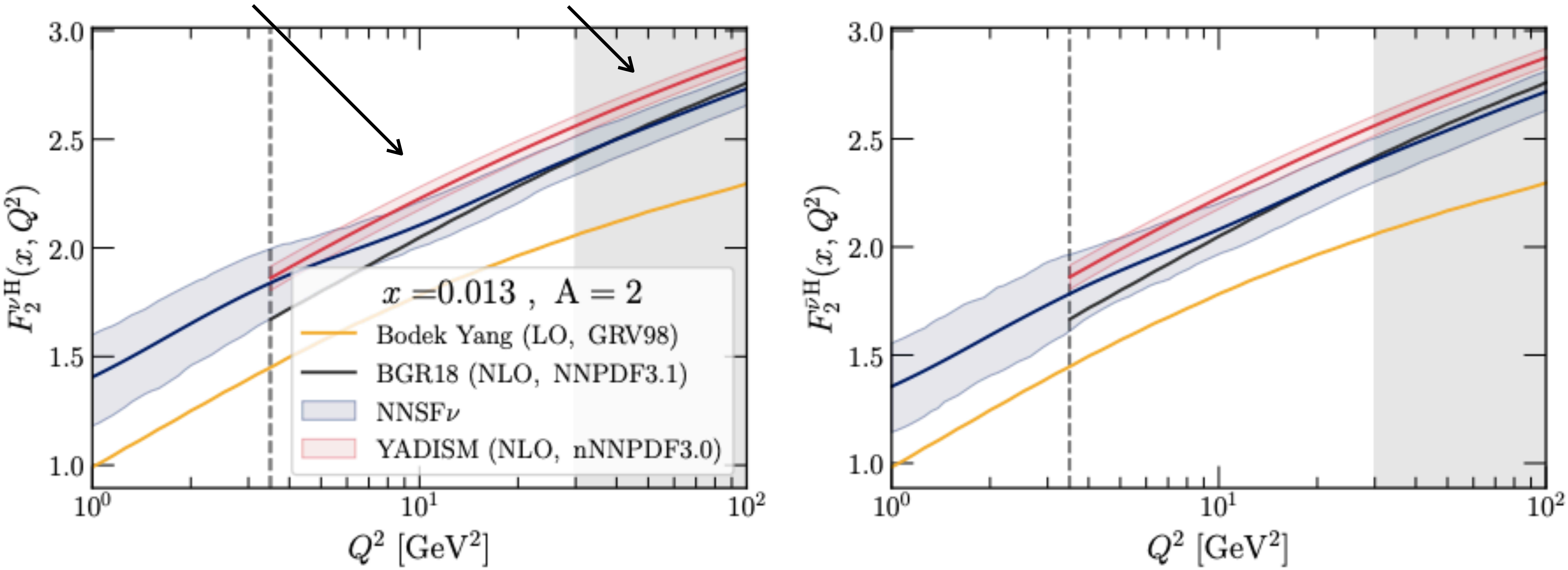


- This data-driven parametrisation is made to **converge to the pQCD calculation** for large enough Q^2 values as implemented with Lagrange multipliers

- In the neutrino energy region sensitive only to $Q >$ few GeV, **replace by pQCD calculation**

consistent determination of neutrino structure functions valid **for 12 orders of magnitude** from E_{nu} = few GeV up to $E_{nu}=10^{12}$ GeV

The NNSFν results

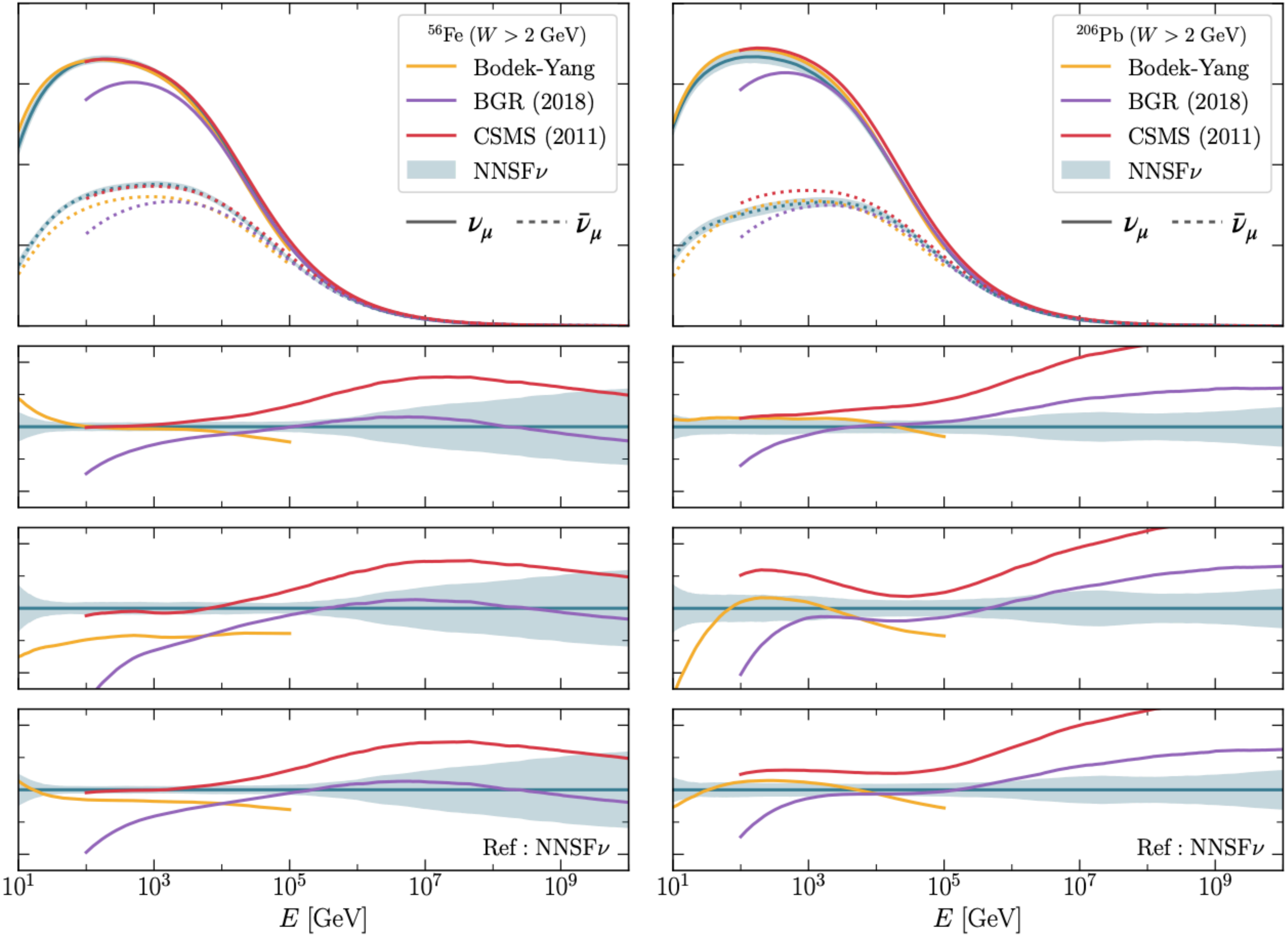


constrain from data

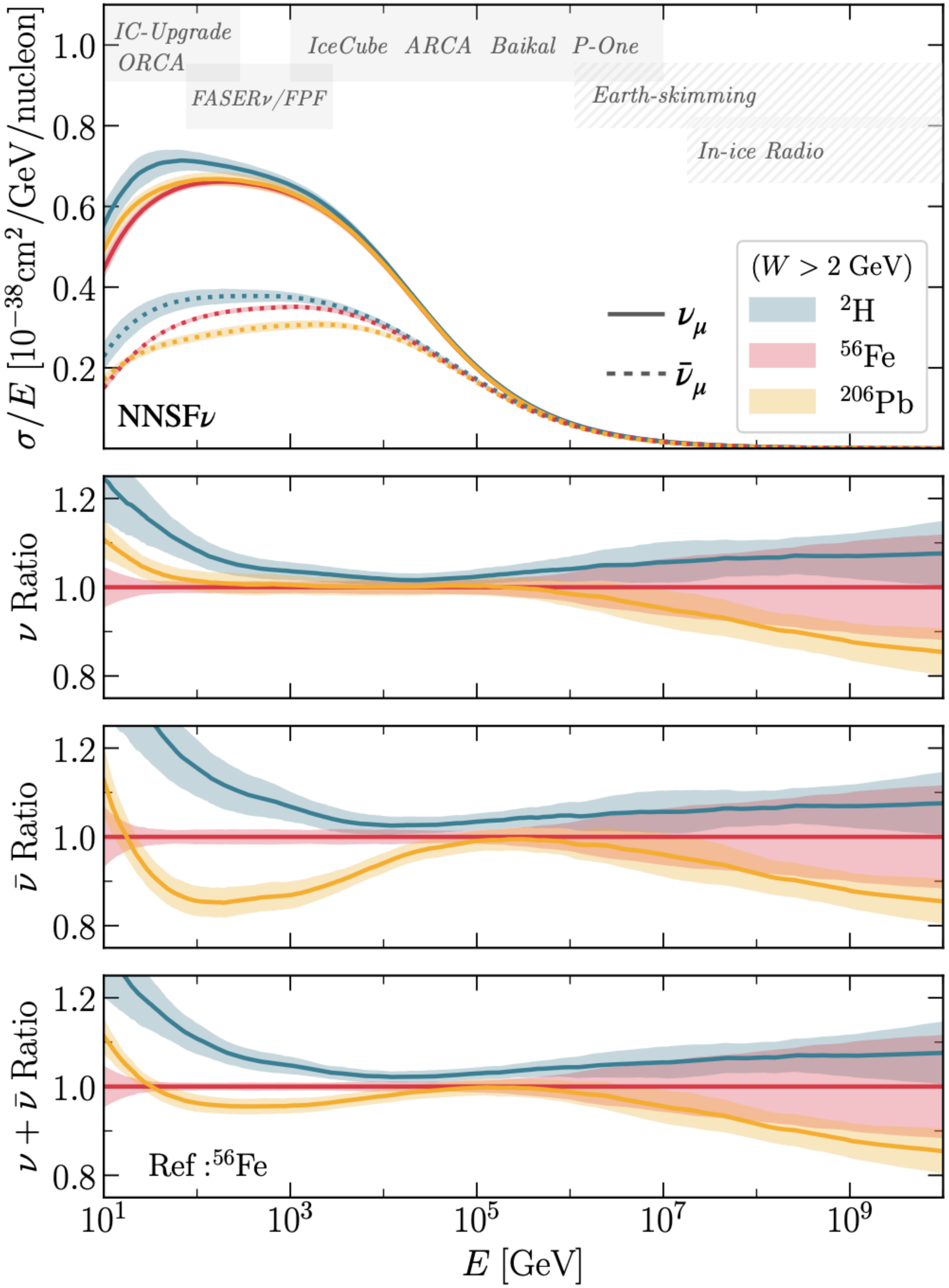
constrain from QCD

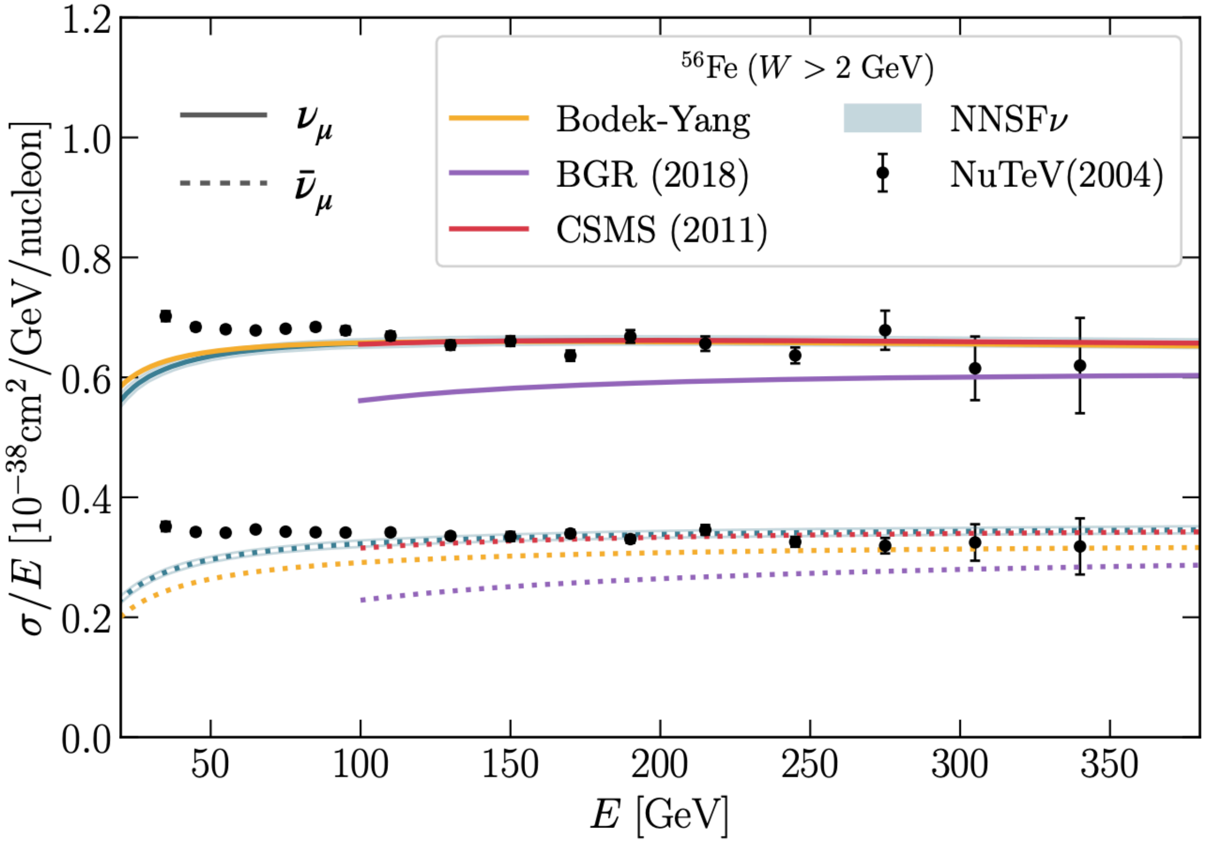
- **Smooth matching** between data-driven and pQCD regions, uncertainty estimate in whole energy range
- Structure functions and integrated cross-sections available via **user-friendly LHAPDF grids**
- For the first time, a **unique theory prediction** for neutrino inelastic scattering suitable for neutrinos with energies from a few GeV up to the multi-EeV region

The NNSFν results



The NNSFν results





- Agreement with available neutrino structure function and **cross-section data**
- Estimate experimental & theory **uncertainties**
- Model-independent determination of **nuclear corrections**

Implemented in GENIE: ready to be used in your neutrino simulations!

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 the LHC 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 the LHC can constrain the small-x gluon in unexplored regions by using **dedicated observables** where QCD errors cancel out

- An improved modelling of the **low-Q region in inelastic scattering** required for many neutrino experiments and will be precisely tested with LHC neutrinos