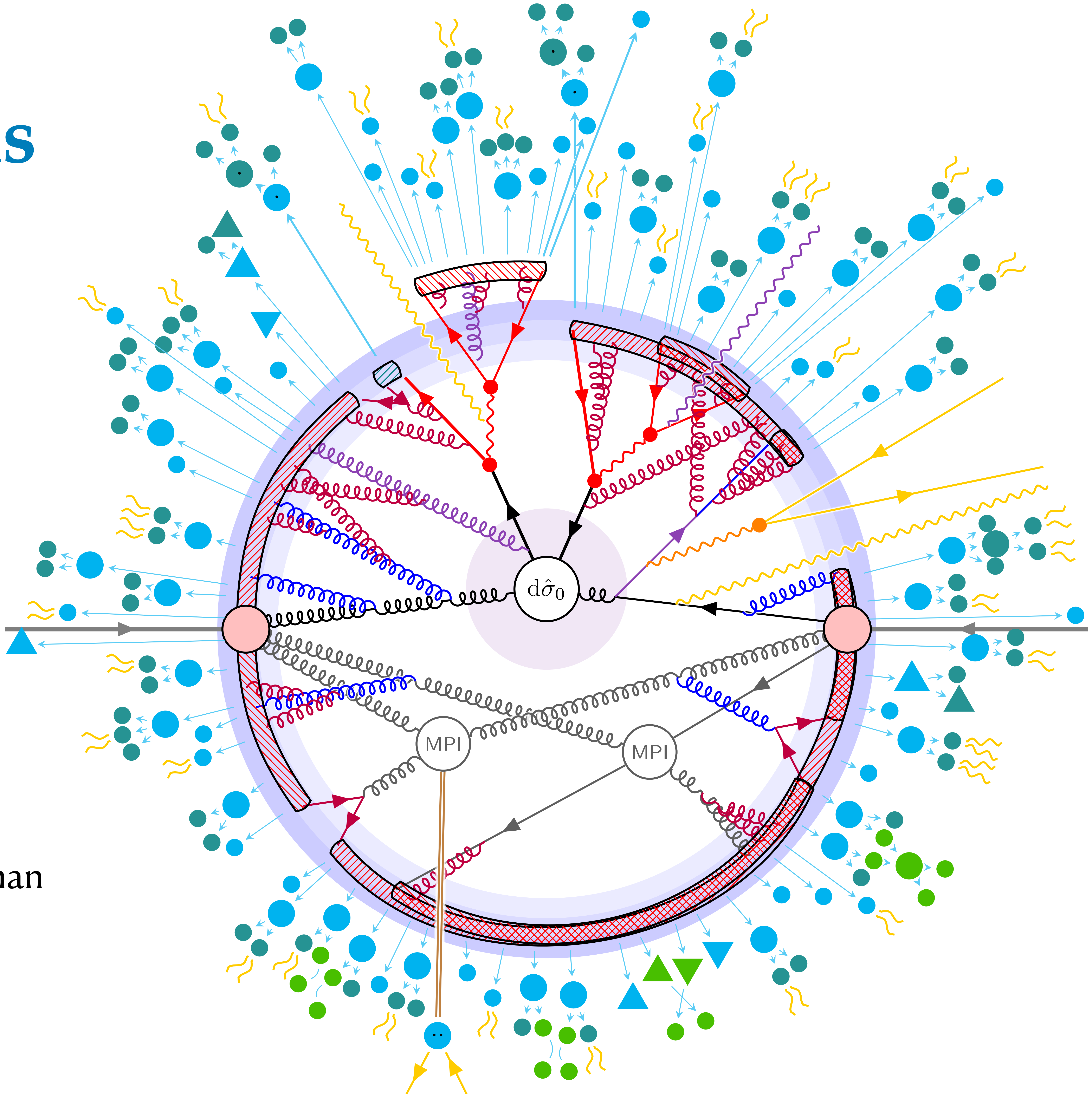
Neutrino Structure Functions from GeV to EeV Energies

VRIJE UNIVERSITEIT AMSTERDAM

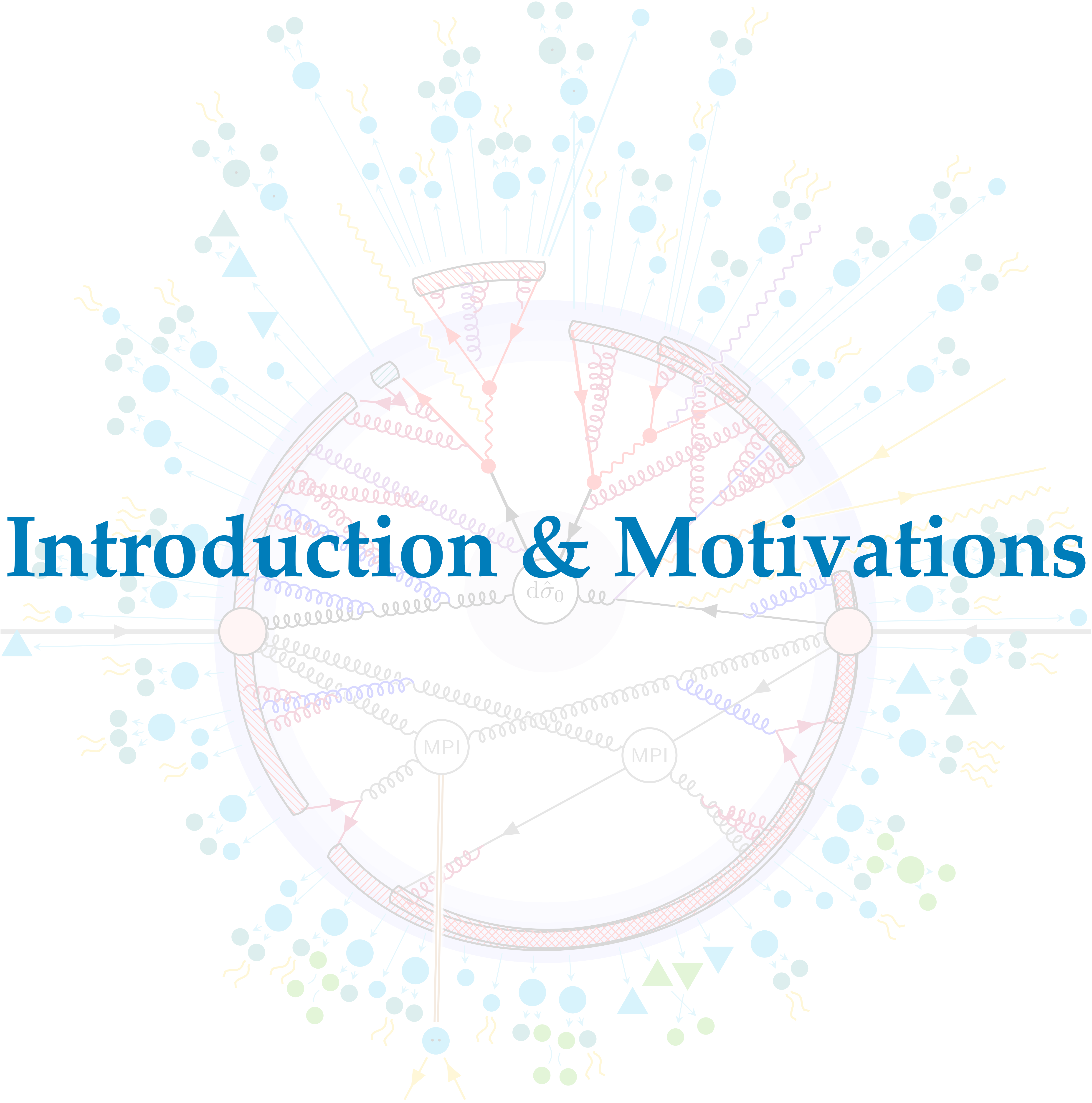
Nikhef



Tanjona R. Rabemananjara
In Collab. W/ A. Candido, A. Garcia, G. Magni, J. Rojo, R. Stegeman
FPF Theory Workshop - September 19, 2023
CERN, Geneva, Switzerland

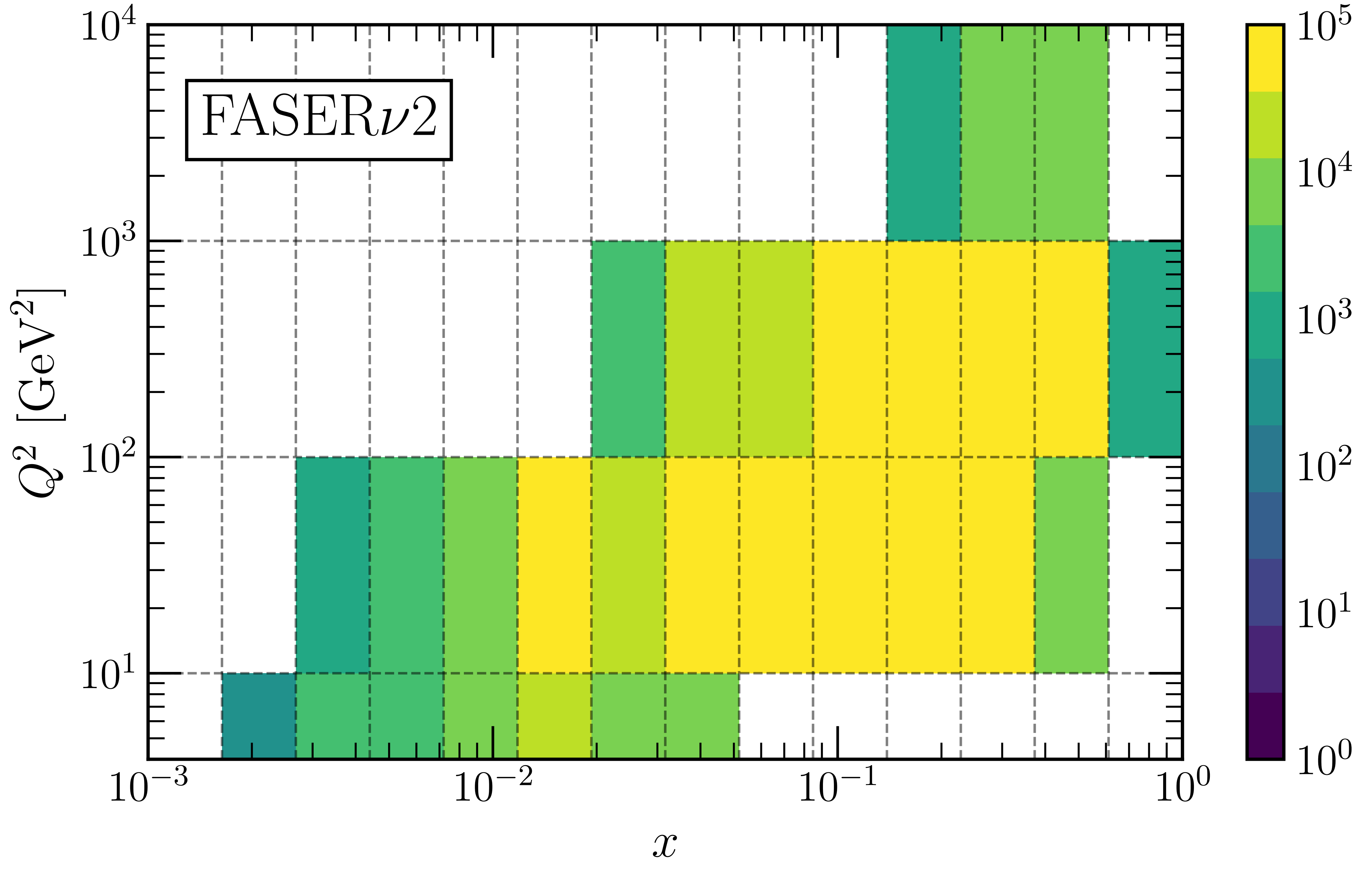
Based on arXiv:2302.08527

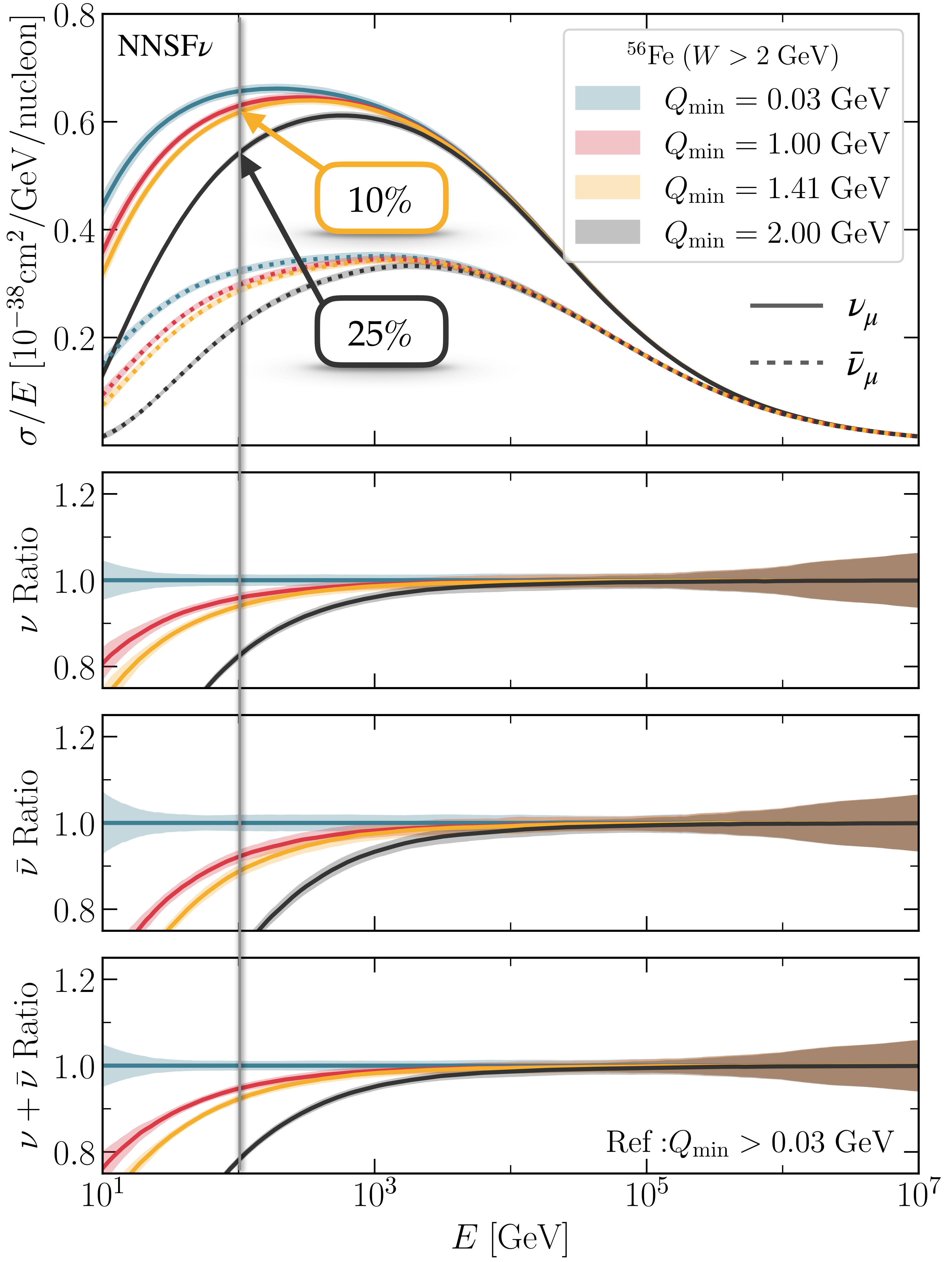
Introduction & Motivations



Introduction & Motivations

- **Interpretation** of present and future neutrino **experiments** requires **accurate theoretical predictions for neutrino-nucleon/nucleus scattering rates**
- Inclusive neutrino cross-section receives **sizeable contributions** from $Q < 2$ GeV where QCD calculations cannot be evaluated in the pQCD framework



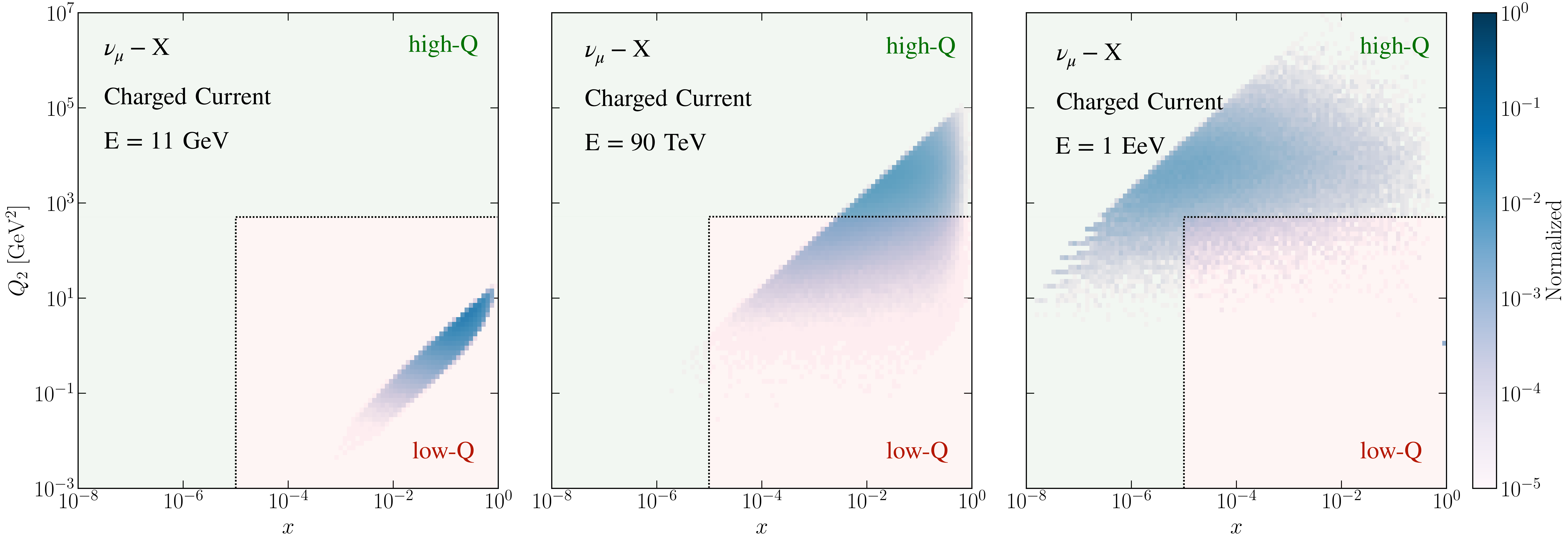


J. Cruz- Martinez, M. Fieg, T. Giani, P. Krack, T. Mäkelä, **TR**, J. Rojo, arXiv:230909581

Relevance of low-Q^2 Regions

In **muon-neutrino inelastic scattering**, at $E_\nu \sim \text{few GeV}$, the total cross-section is determined entirely by the **low-Q^2 regions:**

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



Model the low-Q^2: Bodek-Yang (BY)

BY is based on **Effective LO PDFs** (GRV98LO) with **modified scaling variables** and **K-factors** to approximate higher-order QCD corrections:

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

Shortcomings of the BY model:

- **Obsolete PDF parametrisation** that neglects constraints on proton & nuclear structure in the last 25 years
- **Neglect higher-order perturbative QCD calculations** (which can be significant)
- **Cannot be matched** to calculations of **high-energy neutrino scattering** based on modern PDF and higher-QCD calculations, introducing an unnecessary **separation between modelling of neutrino interactions** sensitive to **different energy regions**.
- **Lack** of **systematic estimate of the uncertainties** associated to the predictions $\Longleftrightarrow \nexists$ **degree of belief**

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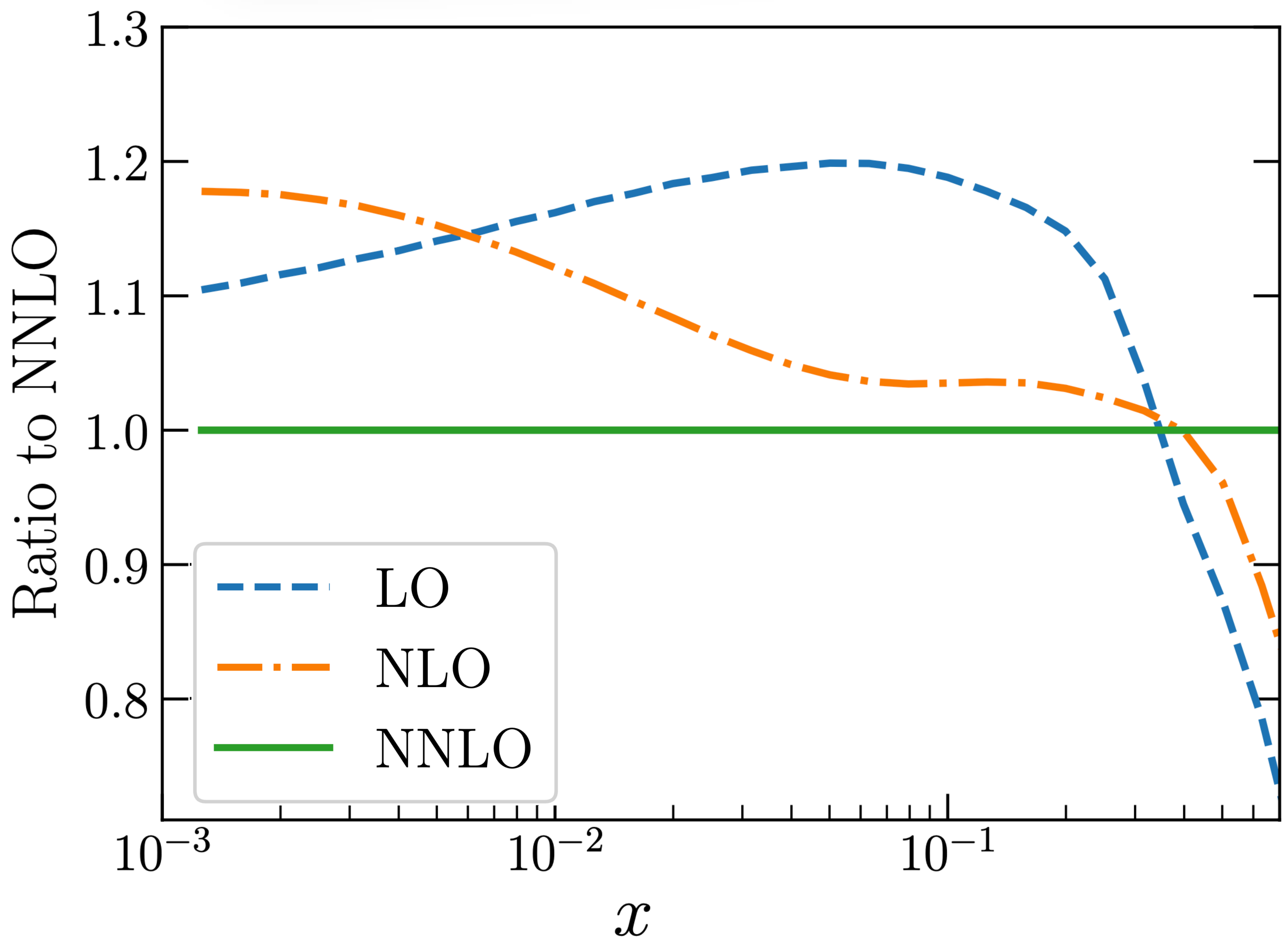
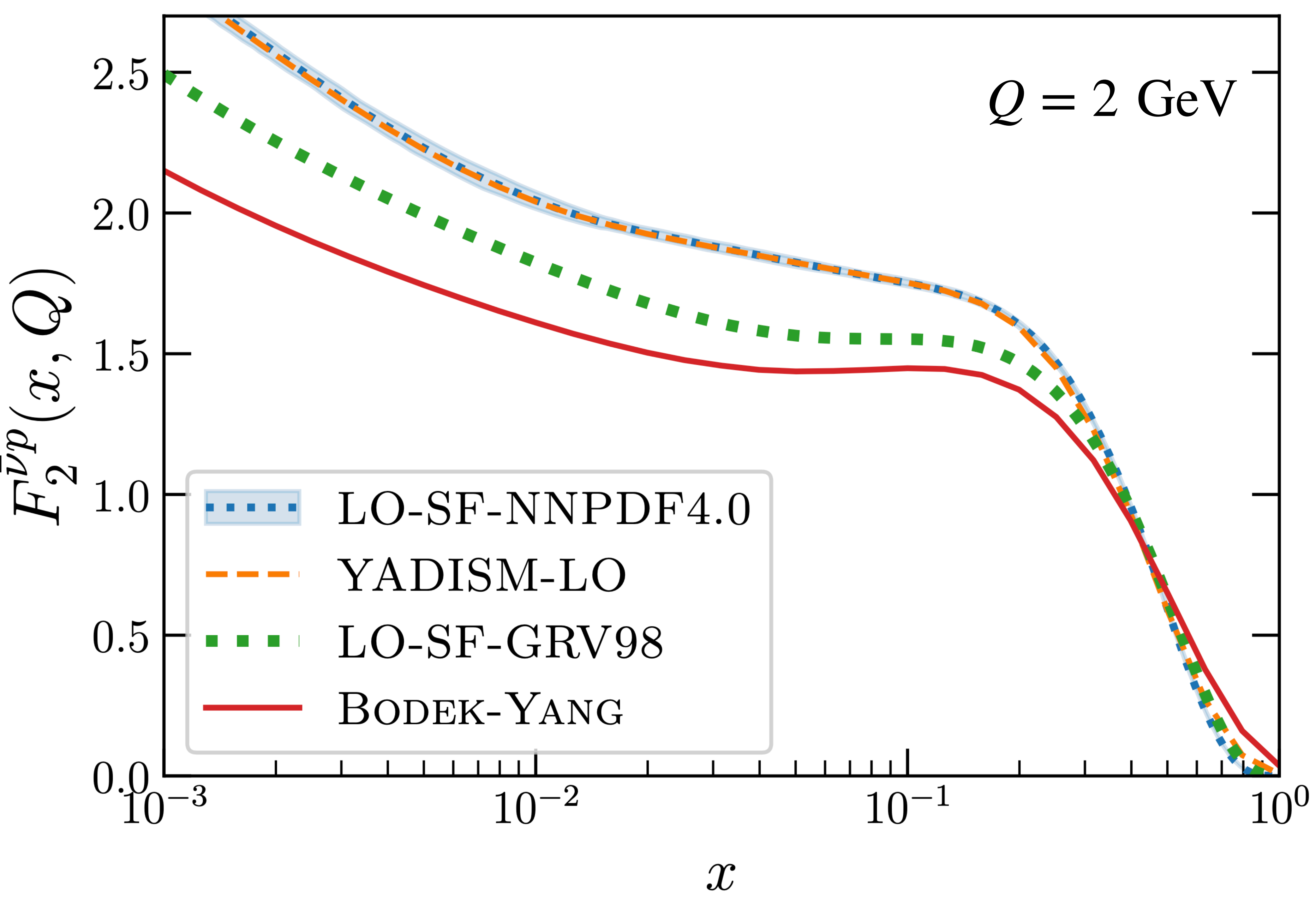
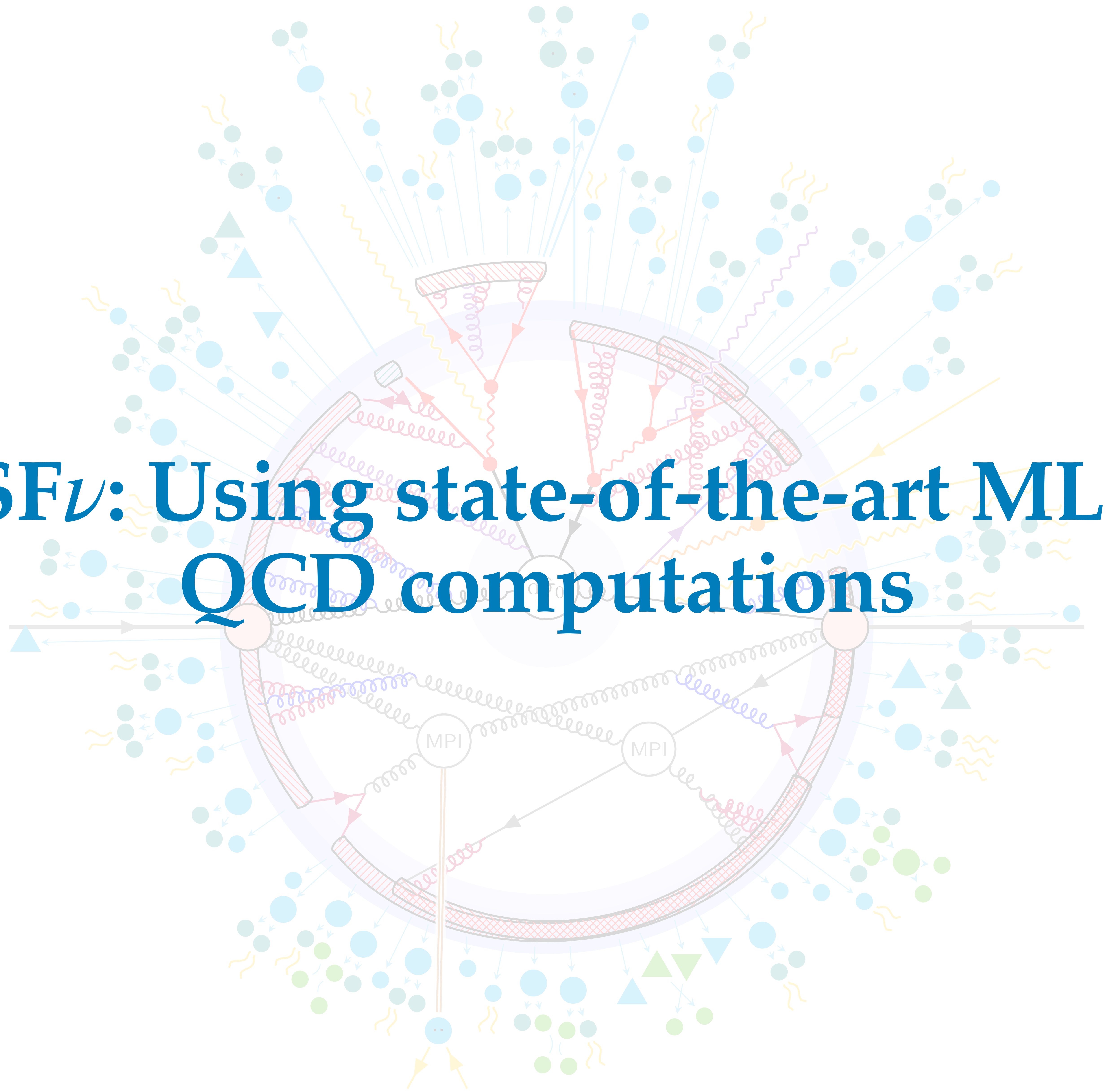




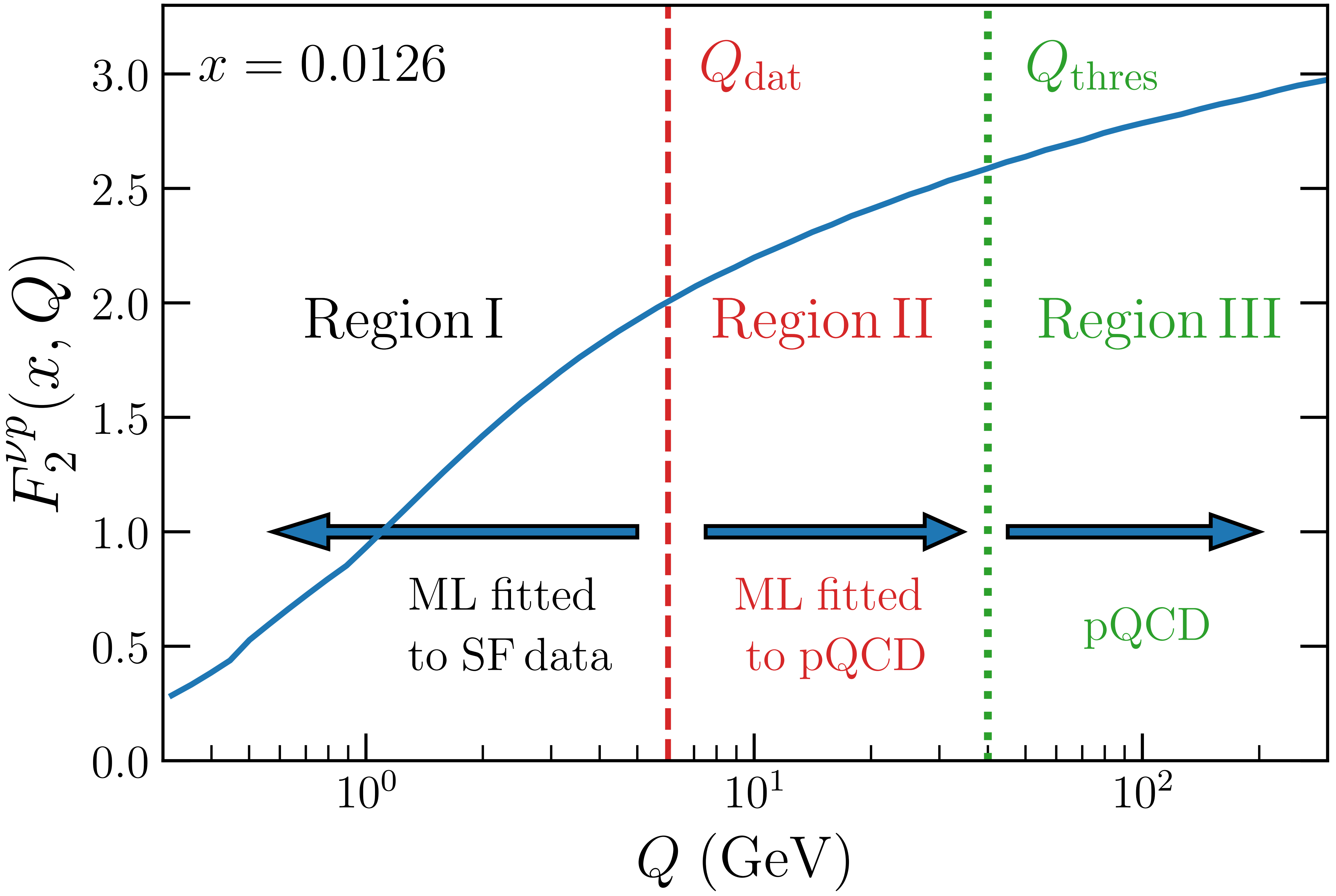
- **LO** predictions can be up to **25%** higher wrt NNLO
- **NLO** predictions can be up to **20%** higher wrt NNLO
- **BY** predictions depart from best QCD predictions even at moderate Q

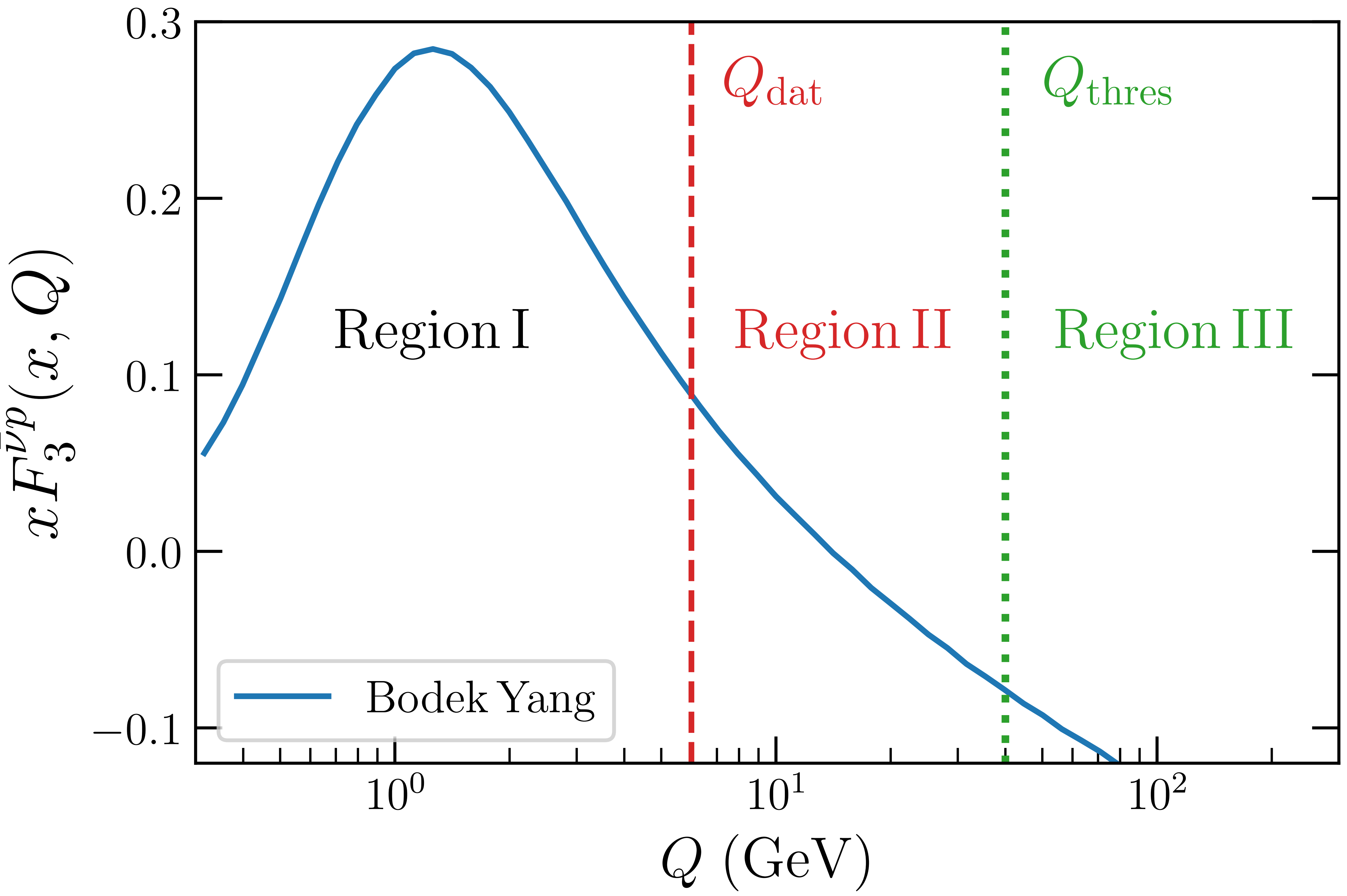
NNSFν: Using state-of-the-art ML and QCD computations



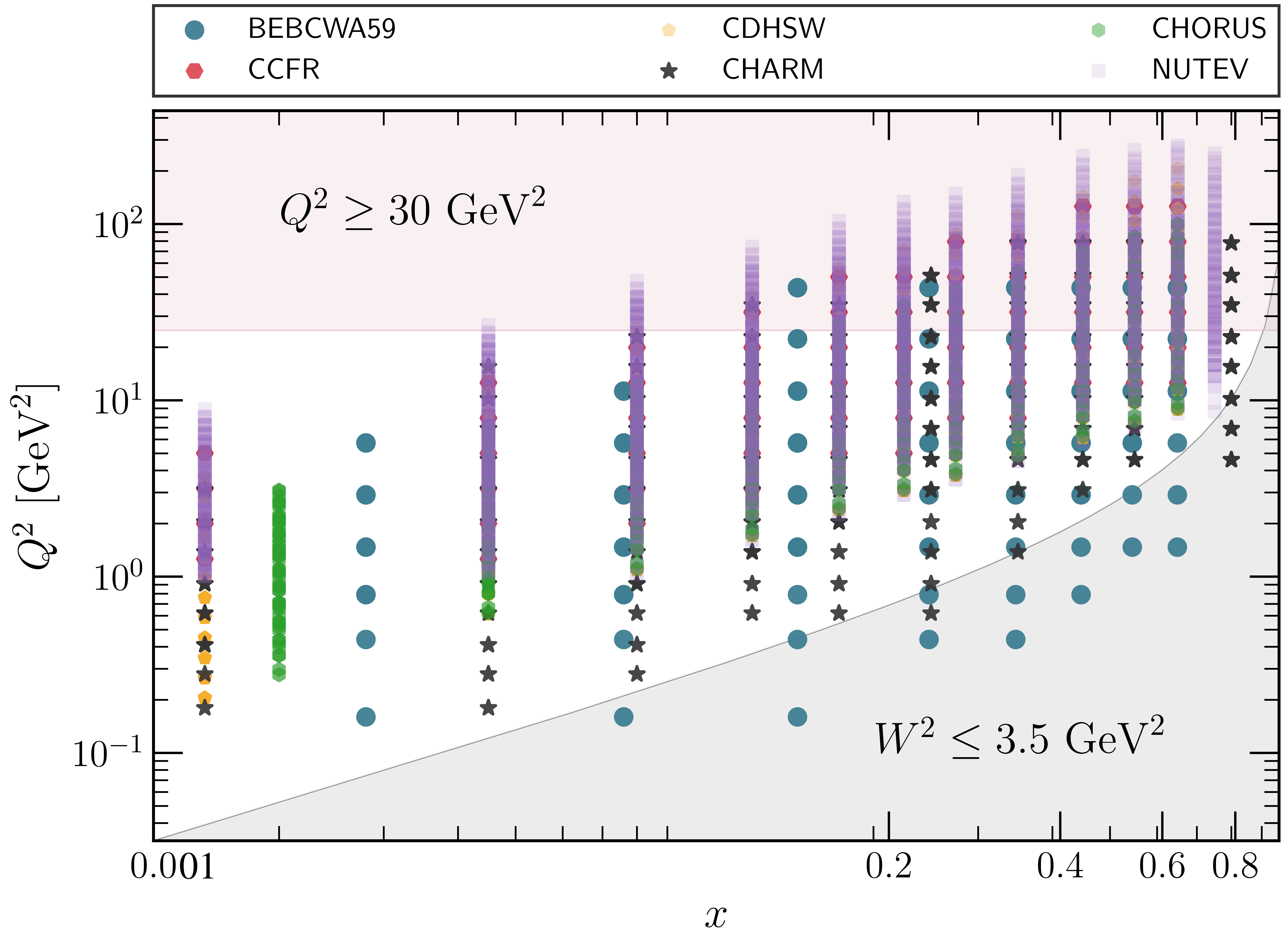
NNSFν: The Approach

- Use available **data** on neutrino-nucleus scattering to **parametrise and determine the inelastic structure functions** using a NN as an unbiased interpolant
- The parametrisation is done in such a way that it **converges to the pQCD calculations at large enough Q^2**
- In the region where neutrino energy is sensitive to **large-Q^2**, the parametrisation is **replaced by pQCD calculations**



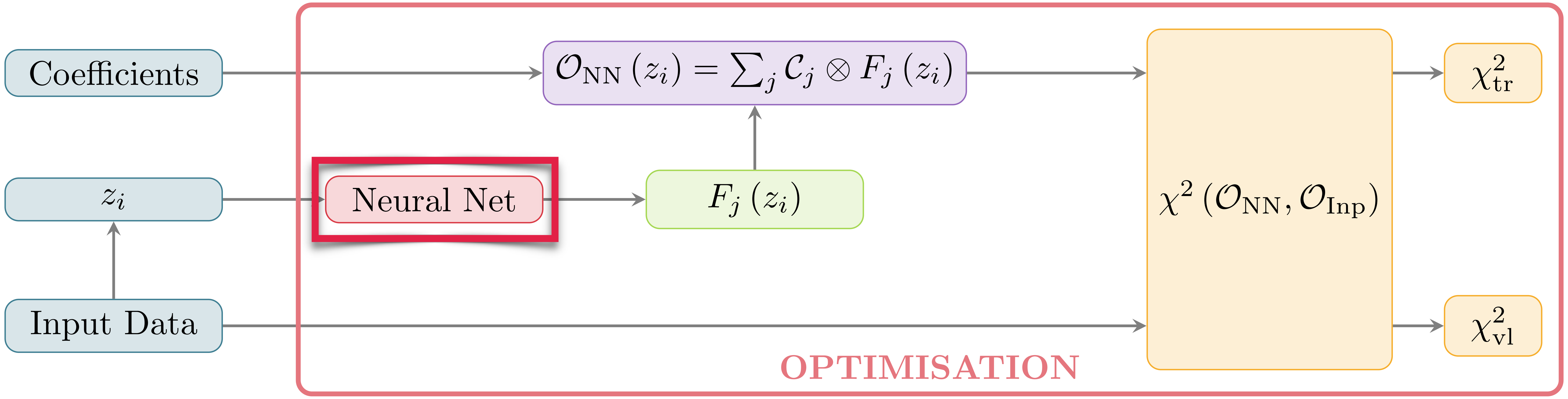


NNSFν: Experimental Inputs



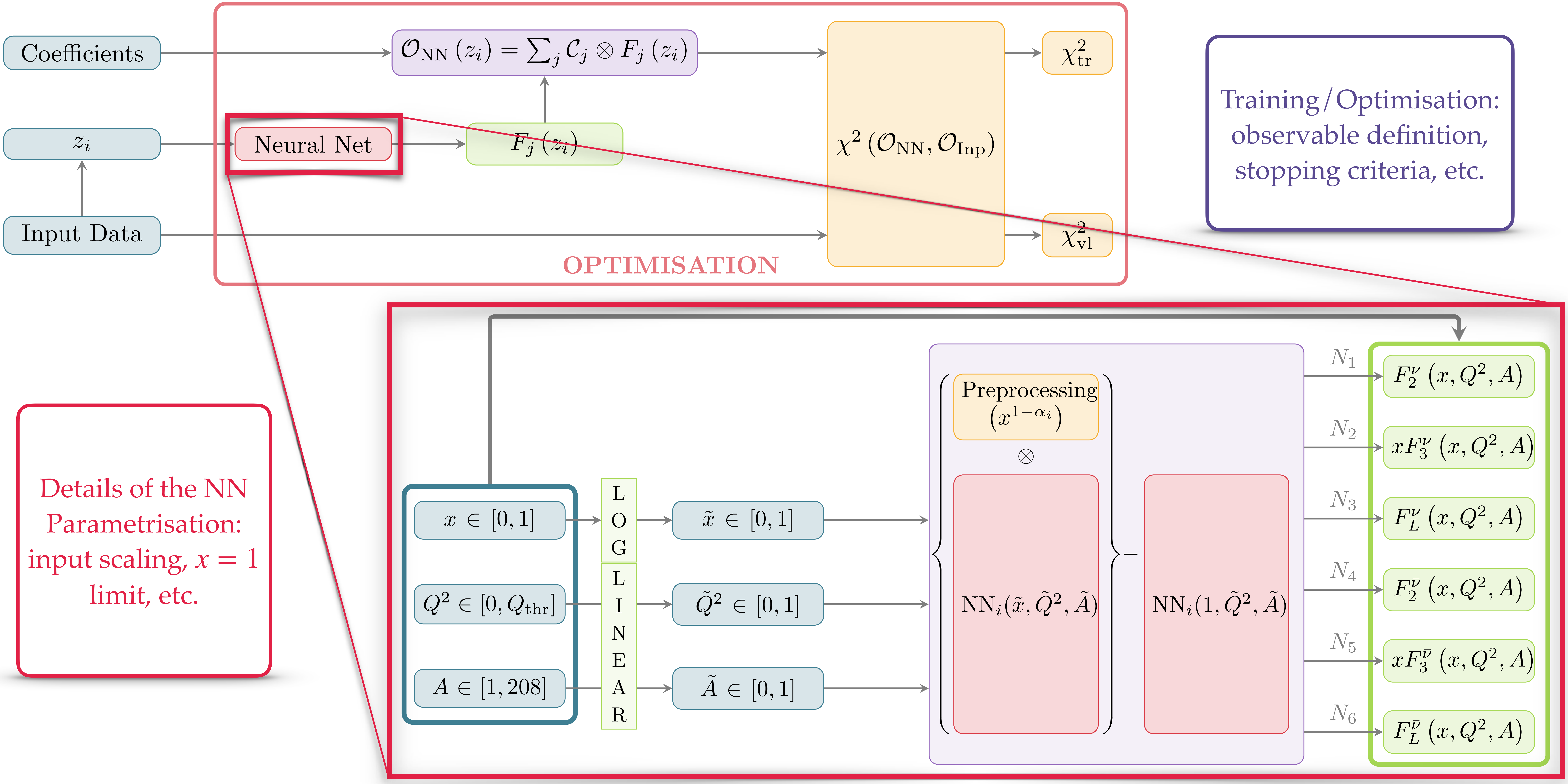
- The datasets include various **observables**, **scattering target**, and **final state** that amounts to 6224 (4184) before (after) the cut
- The datasets span a **wide range of kinematics**. Two different types of **cuts** are applied to the experimental datasets: W^2 and $Q^2_{\rm max}$
- The resulting **determination** of neutrino inelastic structure functions are **valid for ~12 orders of magnitude in E_ν**, from ~few GeV to 10^{12} GeV

NNSFν: Methodology



Training / Optimisation: observable definition, stopping criteria, etc.

NNSFν: Methodology

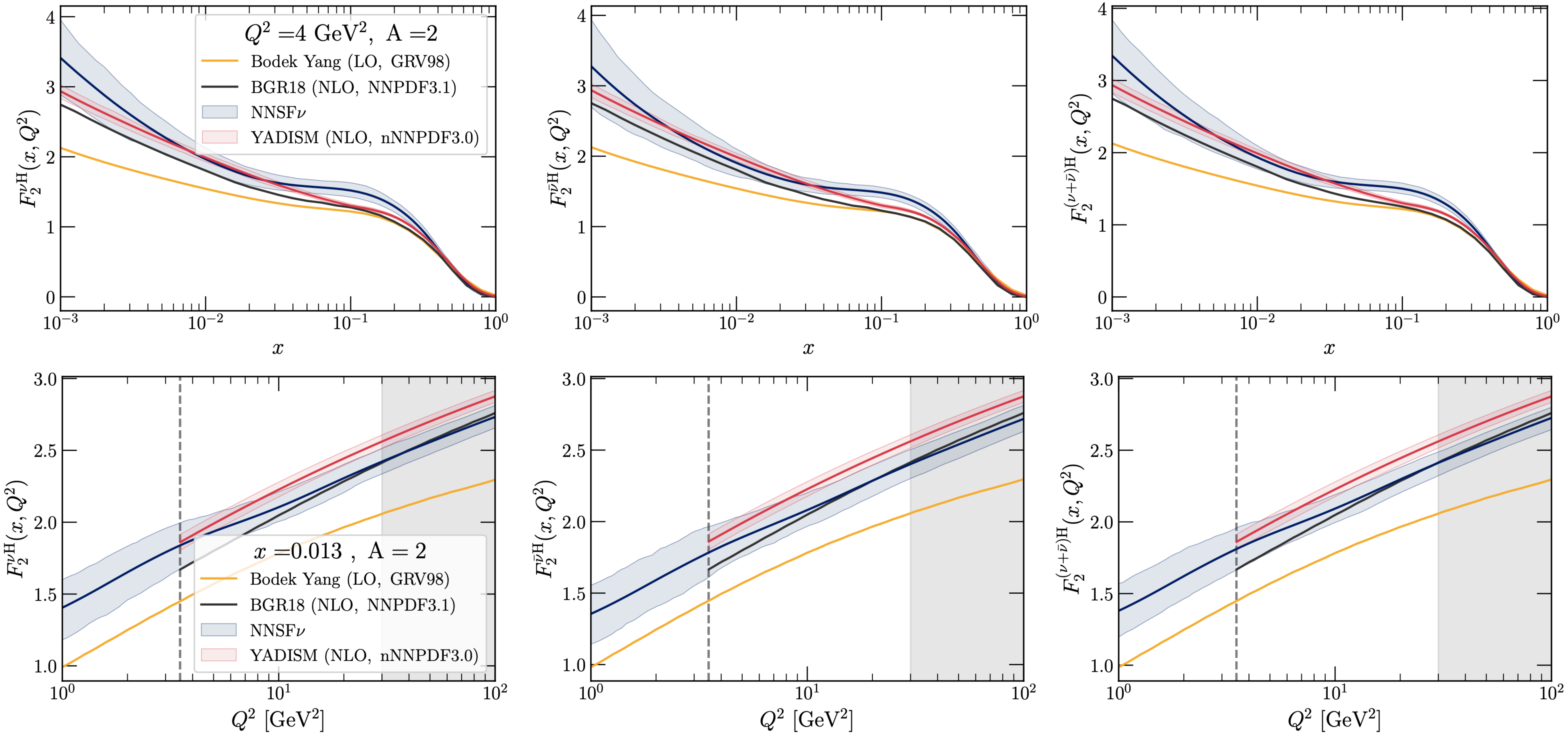


Training / Optimisation: observable definition, stopping criteria, etc.

Details of the NN Parametrisation: input scaling, $x = 1$ limit, etc.

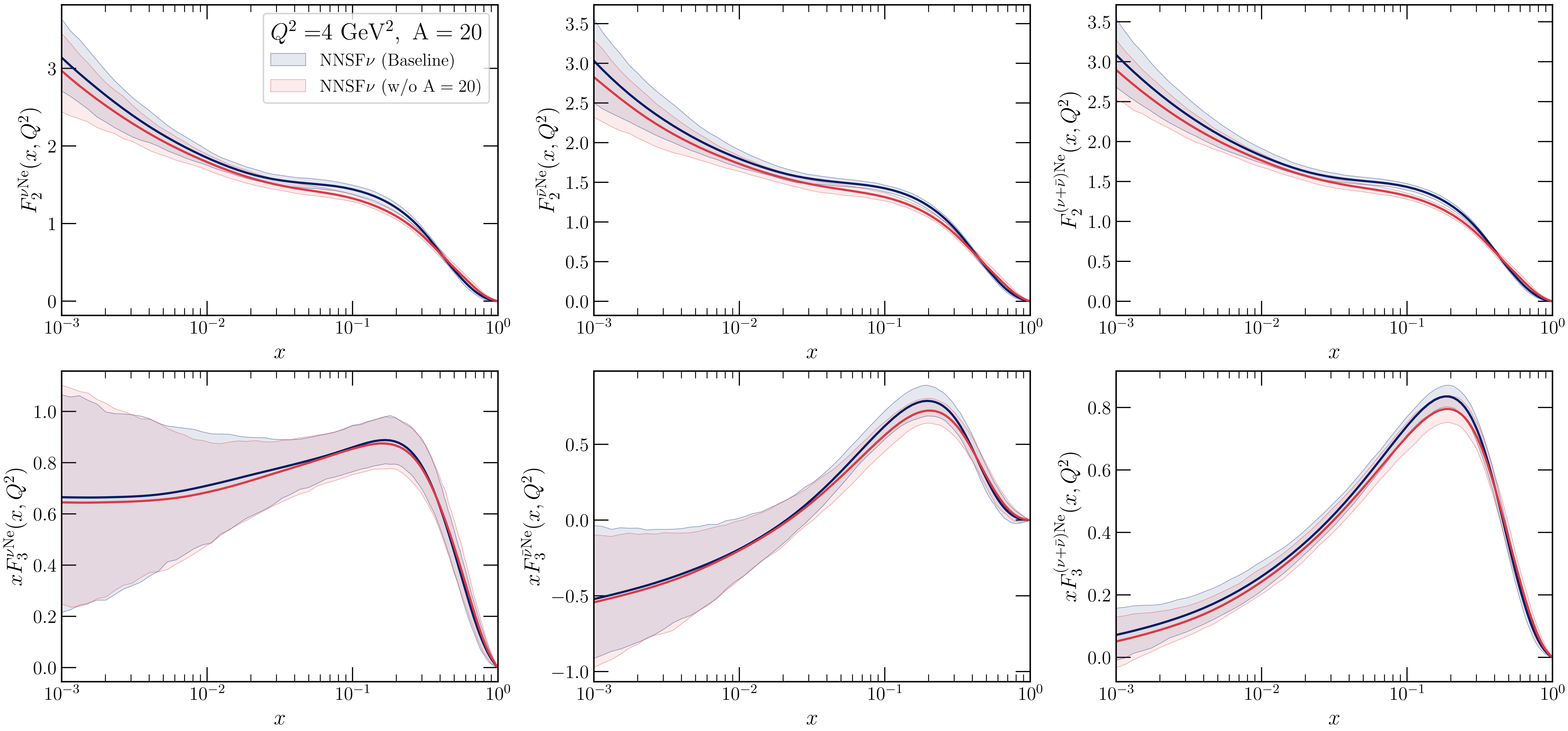
NNSFν: Neutrino Structure Function Predictions

Smooth transition between data-driven & pQCD computations with proper uncertainty estimate in whole Q range

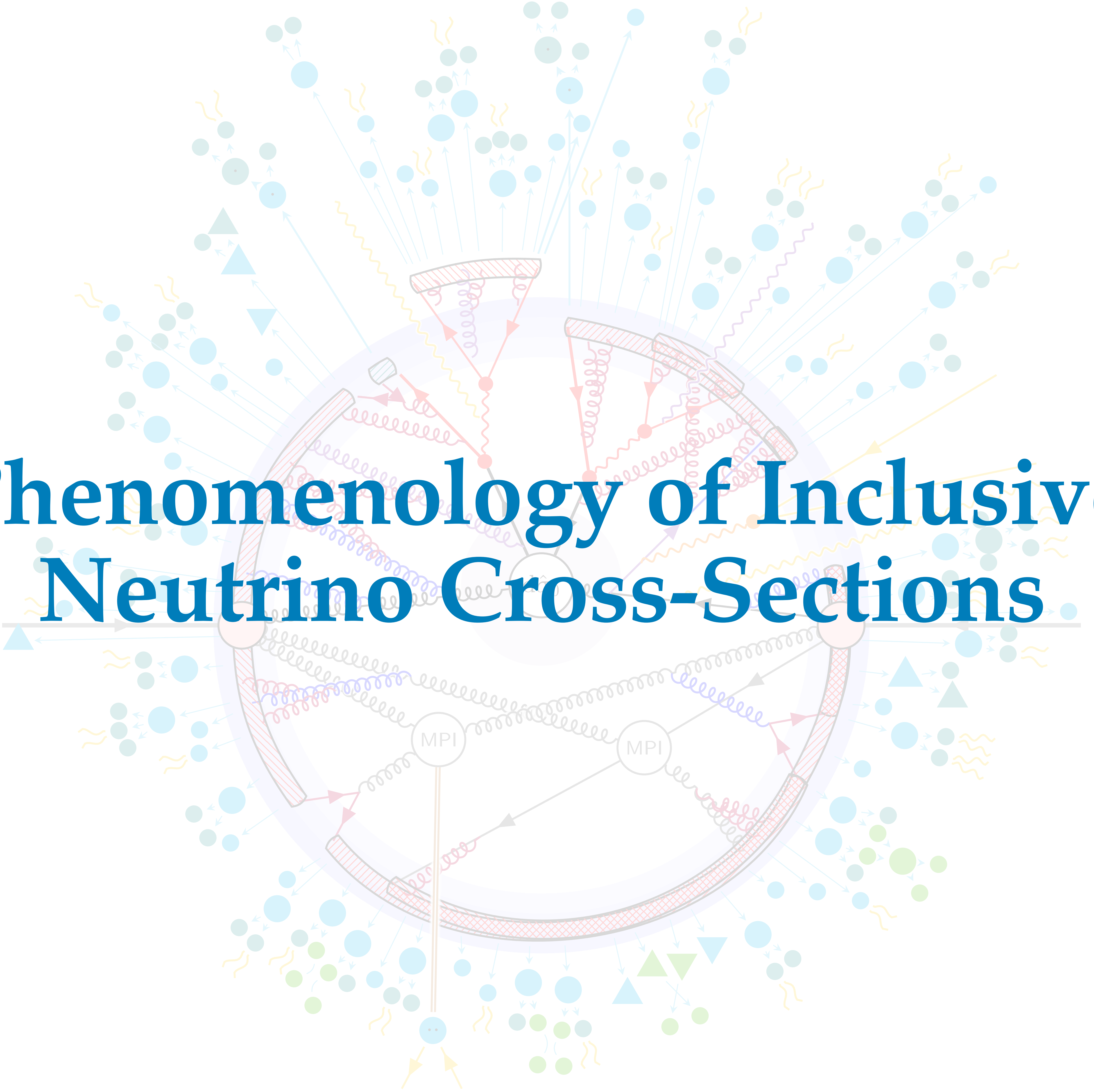


NNSFν: Interpolation along A

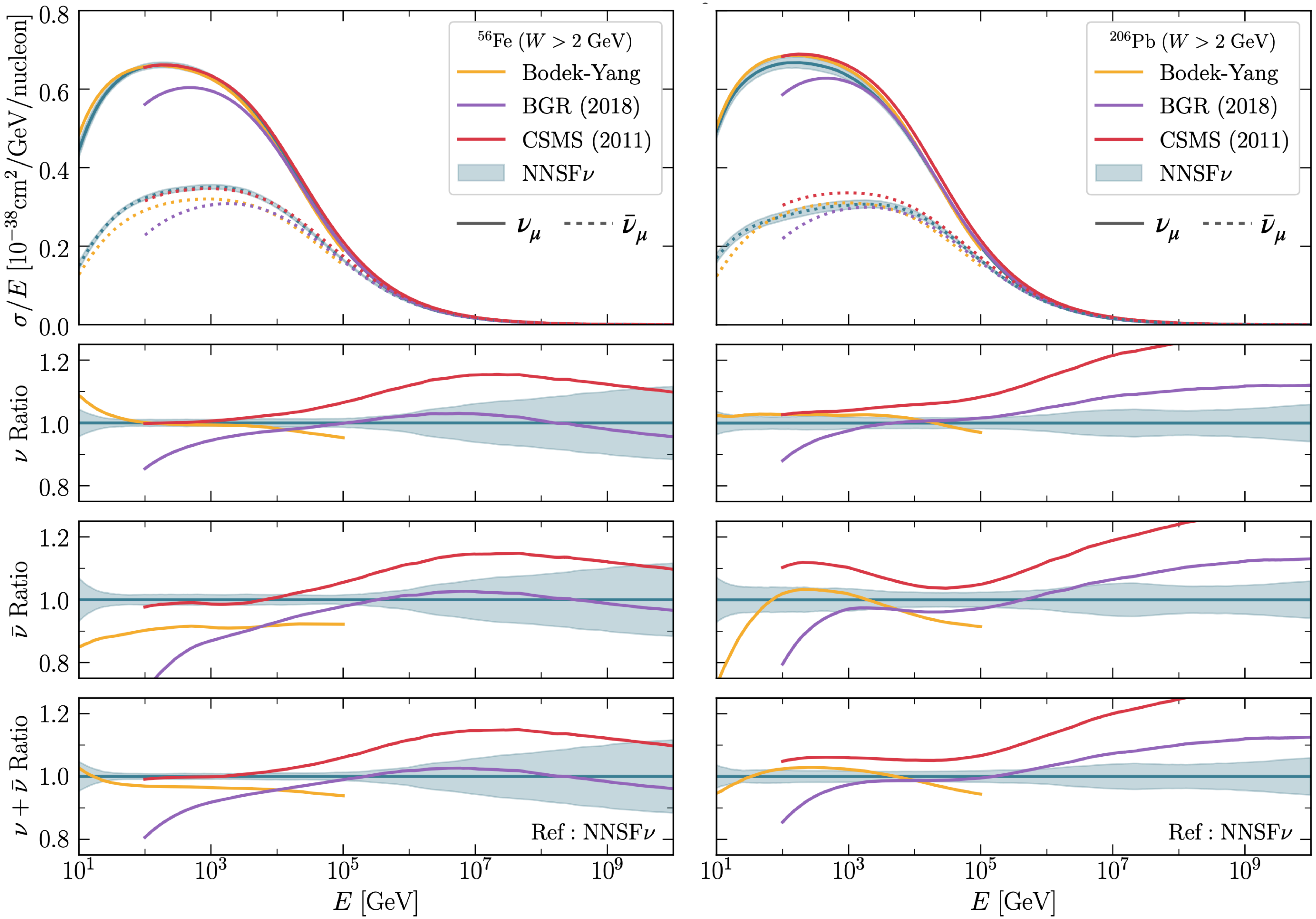
The advantage of parametrising A is that one can generate predictions for nuclei for which direct experimental measurements are not available. To illustrate this we compare two fits in which $A = 20$ is removed in one.

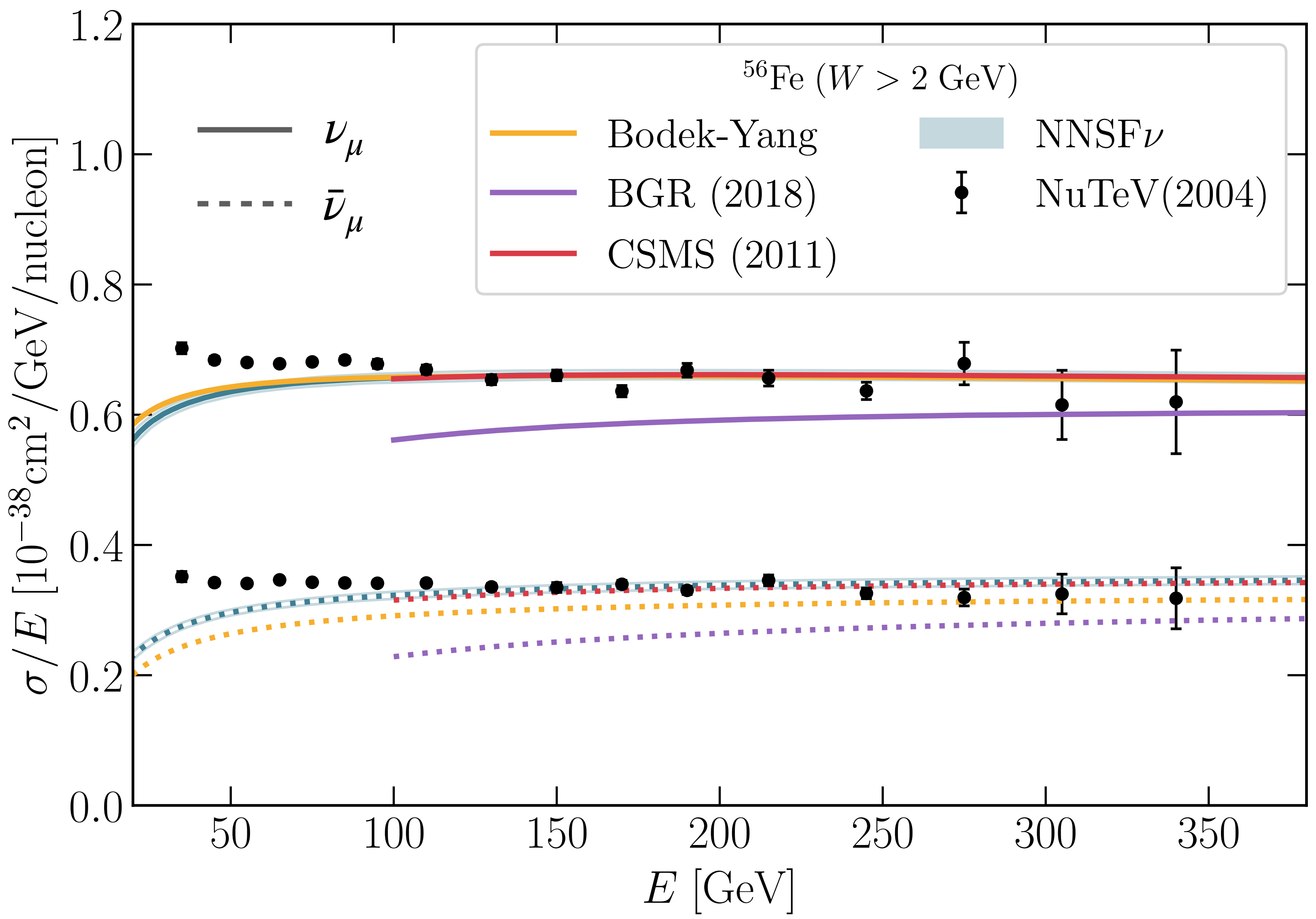


Phenomenology of Inclusive Neutrino Cross-Sections



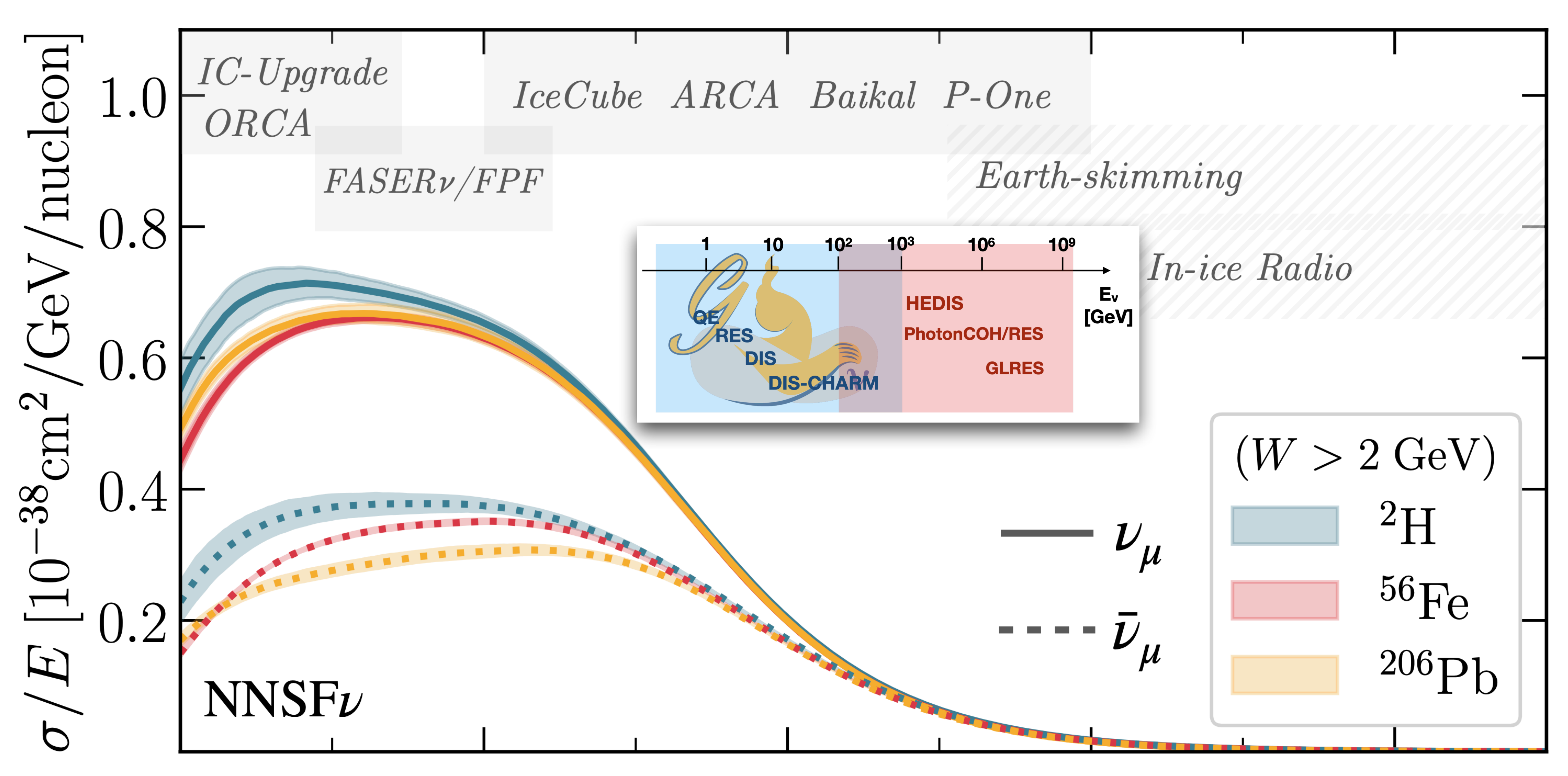
NNSFν: Inclusive Neutrino-Nucleus Cross-Sections



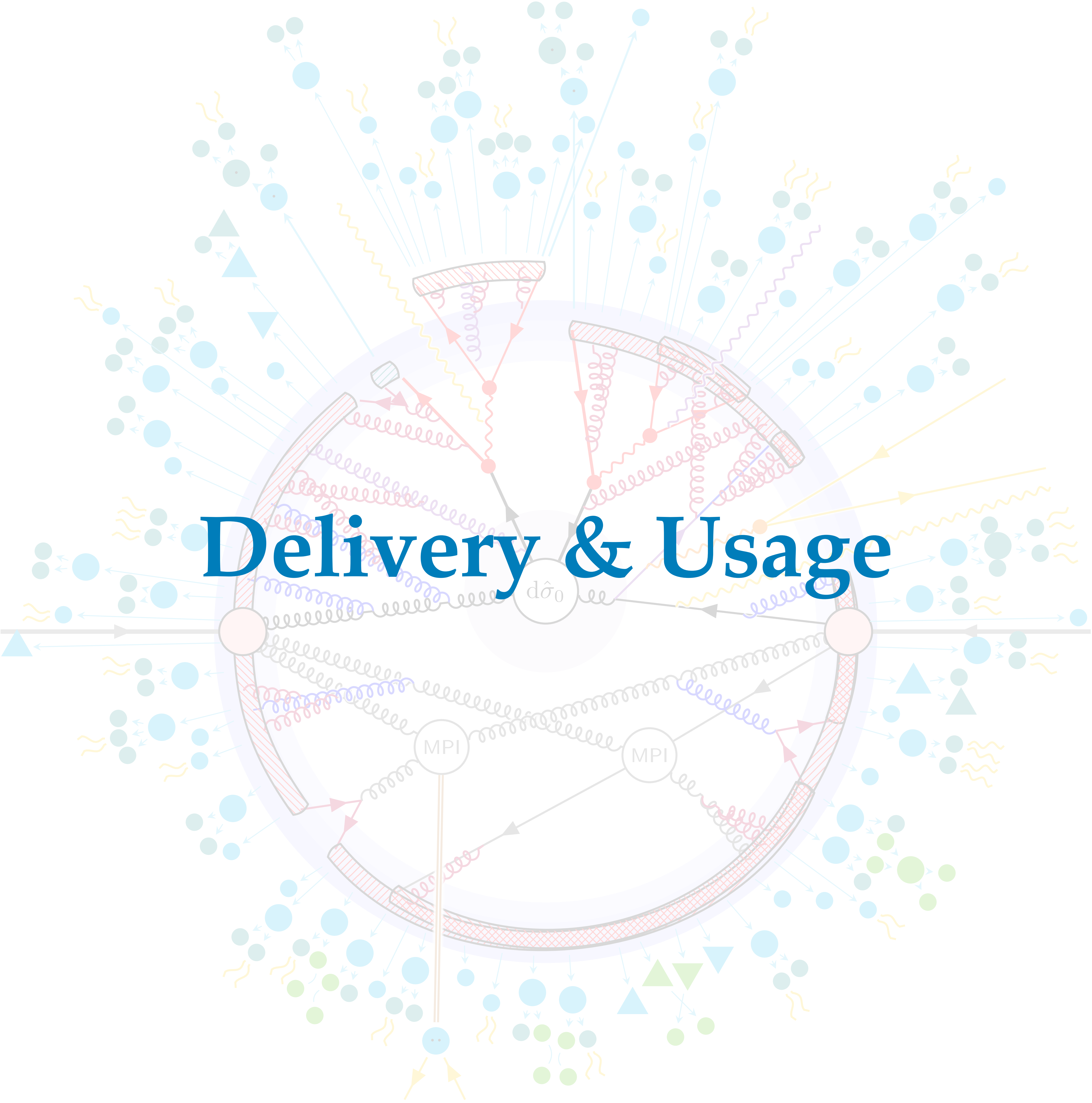


- NNSFν: only predictions **valid for all E_ν** with **uncertainty estimate**
- Reliable state-of-the-art predictions for neutrino inclusive cross-sections at **FPF energies**
- Very Good **agreement** between neutrino inelastic structure functions and cross-sections and **experimental measurements**

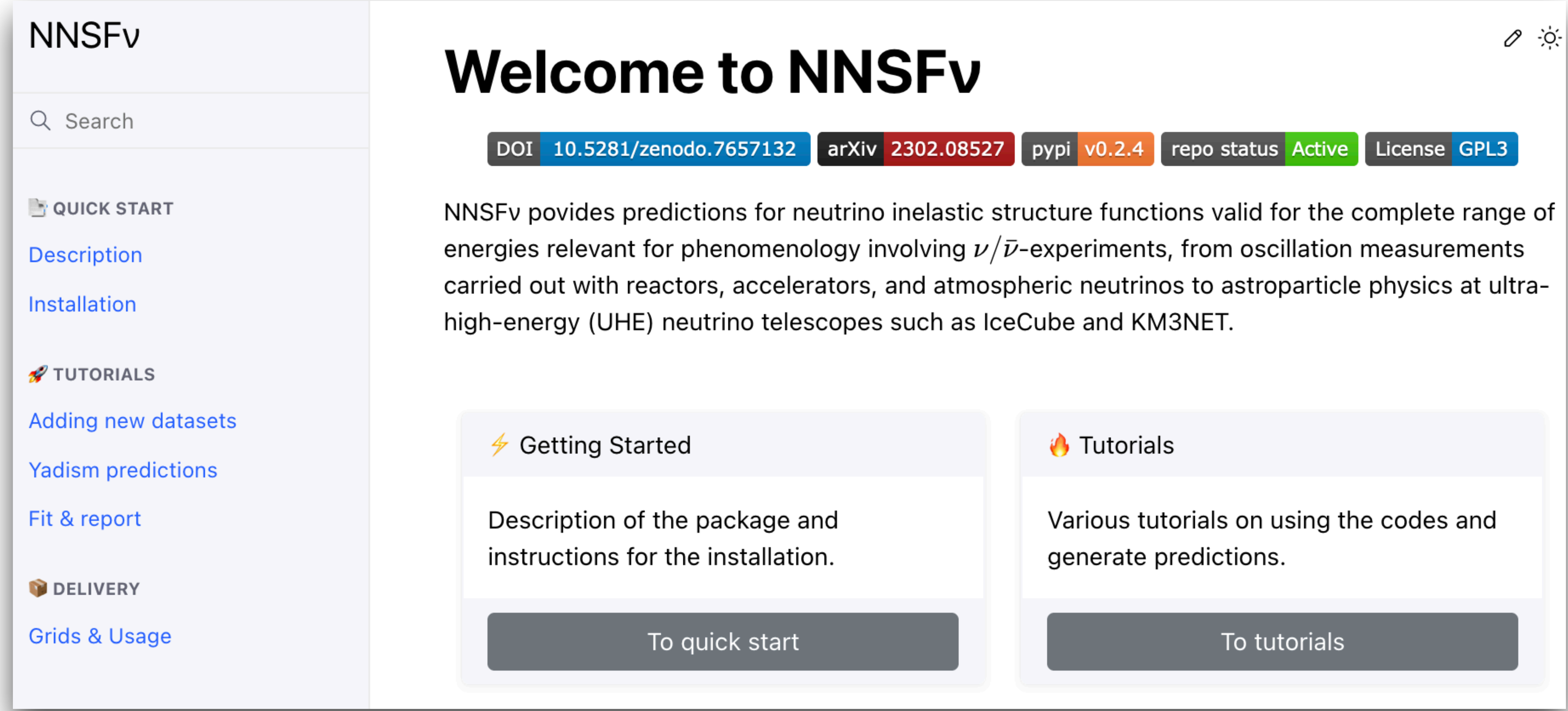
NNSFν: Inclusive Neutrino-Nucleus Cross-Sections



Delivery & Usage



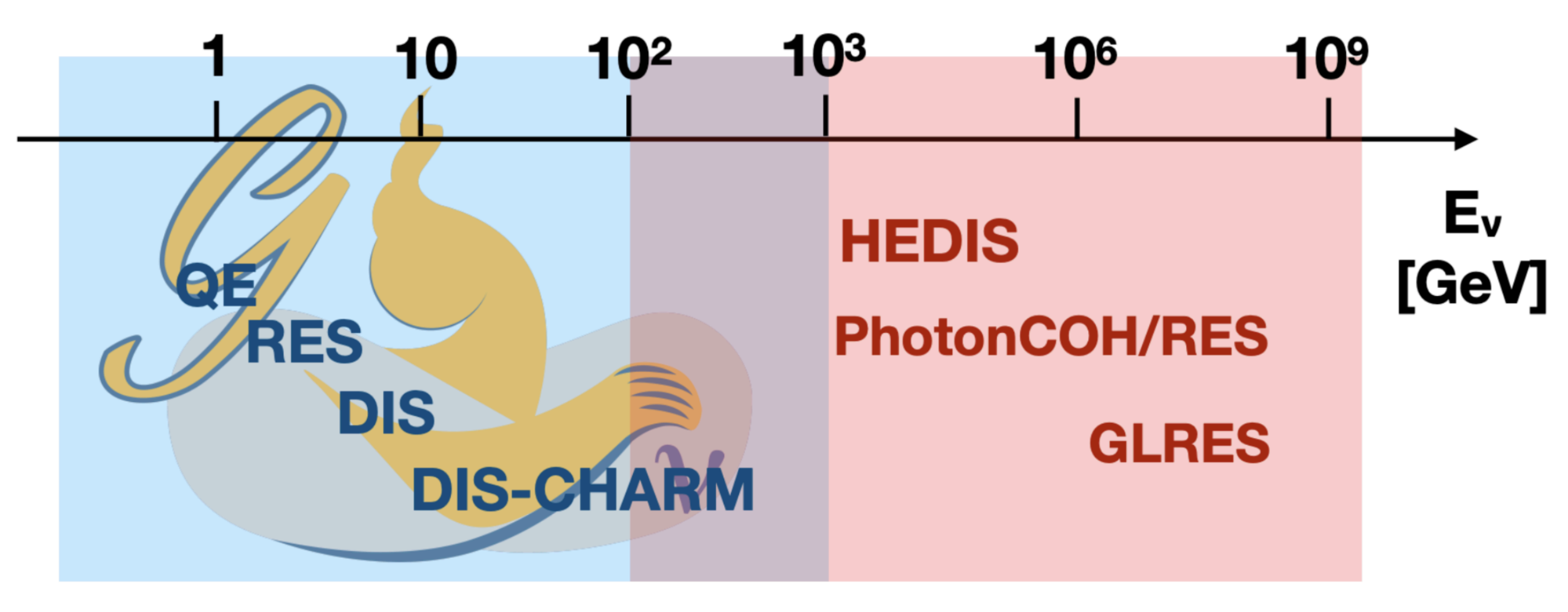
Adopting FOSS Philosophy



The code is publicly available at the following link:
https://github.com/NNPDF/nnusf
Documentation along with tutorials are available at:
https://nnpdf.github.io/nnusf/

NNSFν is interfaced with the GENIE MC Generator:
http://genie-mc.org/

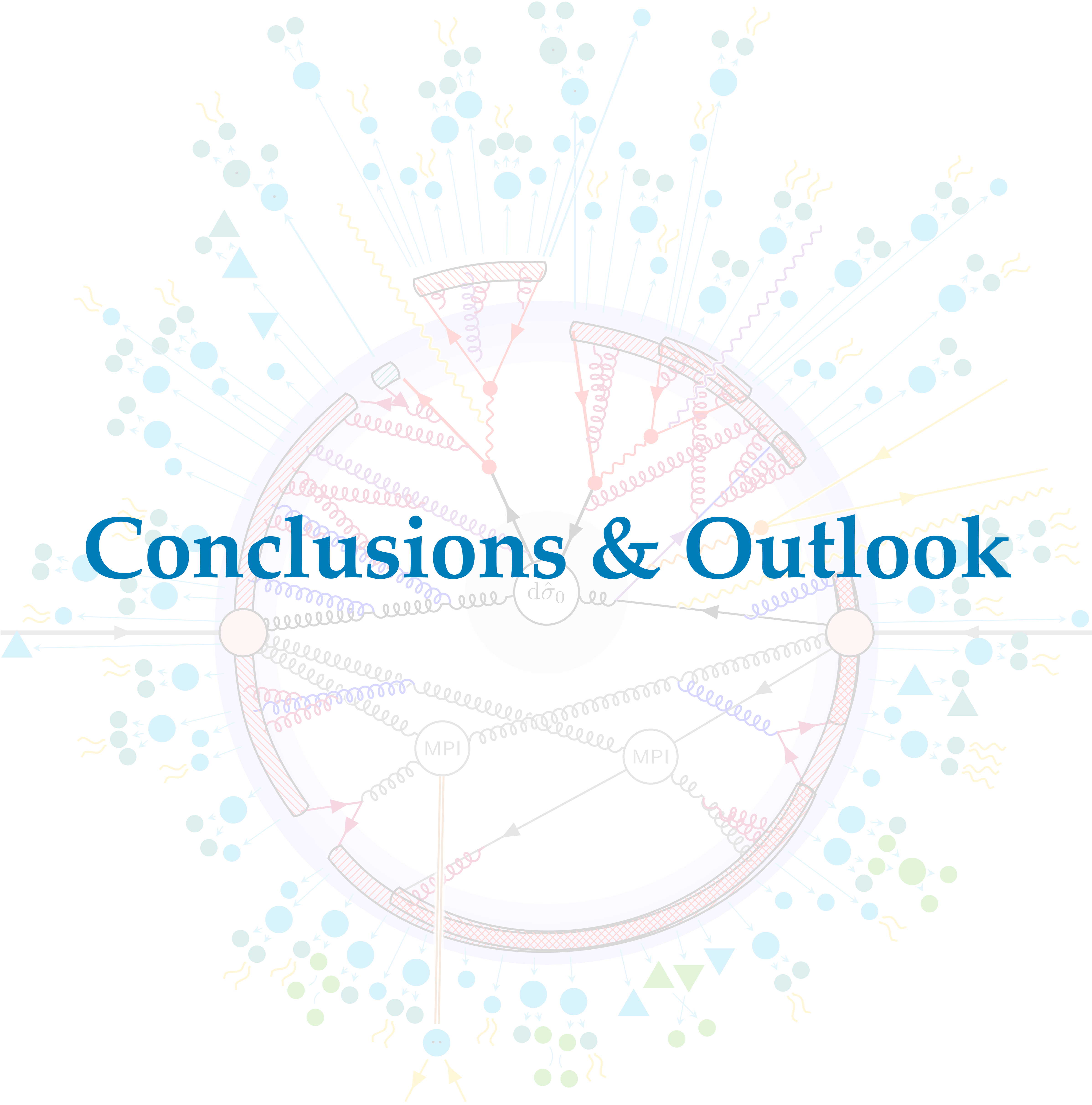
NNSFν grids are tabulated in the LHAPDF format:
https://lhapdf.hepforge.org/index.html



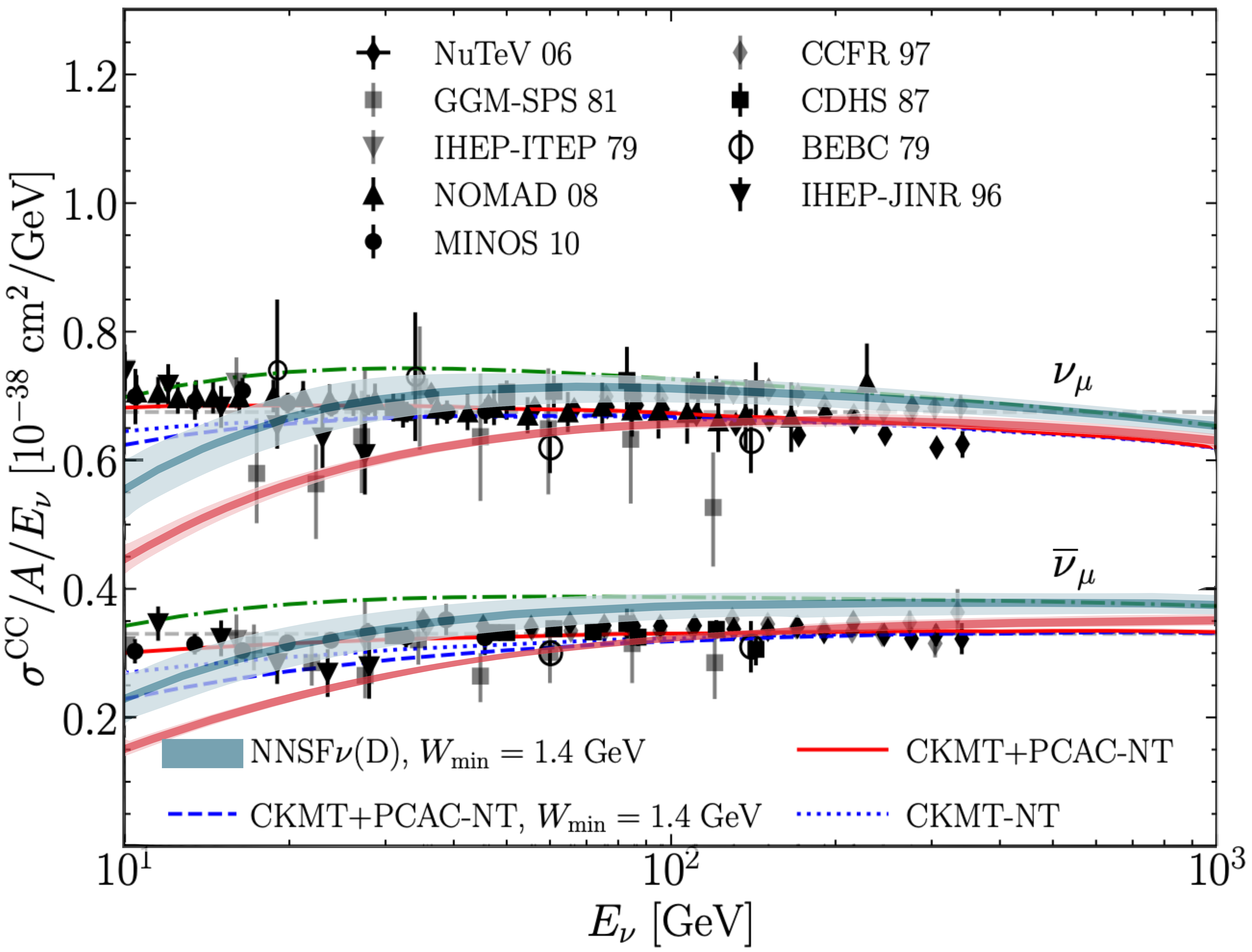
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

(Z, A) [target]	Low-Q Grid	High-Q Grid
$(1, 2)$	NNSFnu_D_lowQ	NNSFnu_D_highQ
$(2, 4)$	NNSFnu_He_lowQ	NNSFnu_He_highQ
$(3, 6)$	NNSFnu_Li_lowQ	NNSFnu_Li_highQ
$(4, 9)$	NNSFnu_Be_lowQ	NNSFnu_Be_highQ
$(6, 12)$	NNSFnu_C_lowQ	NNSFnu_C_highQ
$(7, 14)$	NNSFnu_N_lowQ	NNSFnu_N_highQ
$(8, 16)$	NNSFnu_O_lowQ	NNSFnu_O_highQ
$(13, 27)$	NNSFnu_Al_lowQ	NNSFnu_Al_highQ
$(15, 31)$	NNSFnu_Ea_lowQ	NNSFnu_Ea_highQ
$(20, 40)$	NNSFnu_Ca_lowQ	NNSFnu_Ca_highQ
$(26, 56)$	NNSFnu_Fe_lowQ	NNSFnu_Fe_highQ
$(29, 64)$	NNSFnu_Cu_lowQ	NNSFnu_Cu_highQ
$(47, 108)$	NNSFnu_Ag_lowQ	NNSFnu_Ag_highQ
$(50, 119)$	NNSFnu_Sn_lowQ	NNSFnu_Sn_highQ
$(54, 131)$	NNSFnu_Xe_lowQ	NNSFnu_Xe_highQ
$(74, 184)$	NNSFnu_W_lowQ	NNSFnu_W_highQ
$(79, 197)$	NNSFnu_Au_lowQ	NNSFnu_Au_highQ
$(82, 208)$	NNSFnu_Pb_lowQ	NNSFnu_Pb_highQ

Conclusions & Outlook



NNSFν: Inclusive Neutrino-Nucleus Cross-Sections



See Yu Seon Jeong's Talk

- The **low-Q^2** regions **contribute to a significant degree** to the inclusive neutrino inelastic cross-sections
- State-of-the-art methods relying on Machine Learning provide an **unbiased** and **better predictions** for neutrino physics
- **NNSFν** predictions for inelastic neutrino structure functions and cross-sections are **valid for all energies** relevant for neutrino phenomenology and are **available as interpolation grids** in the LHAPDF format & as an **interface with GENIE**
- **Precision QCD** and neutrino physics at **FPF** will benefit from **precision** neutrino structure functions