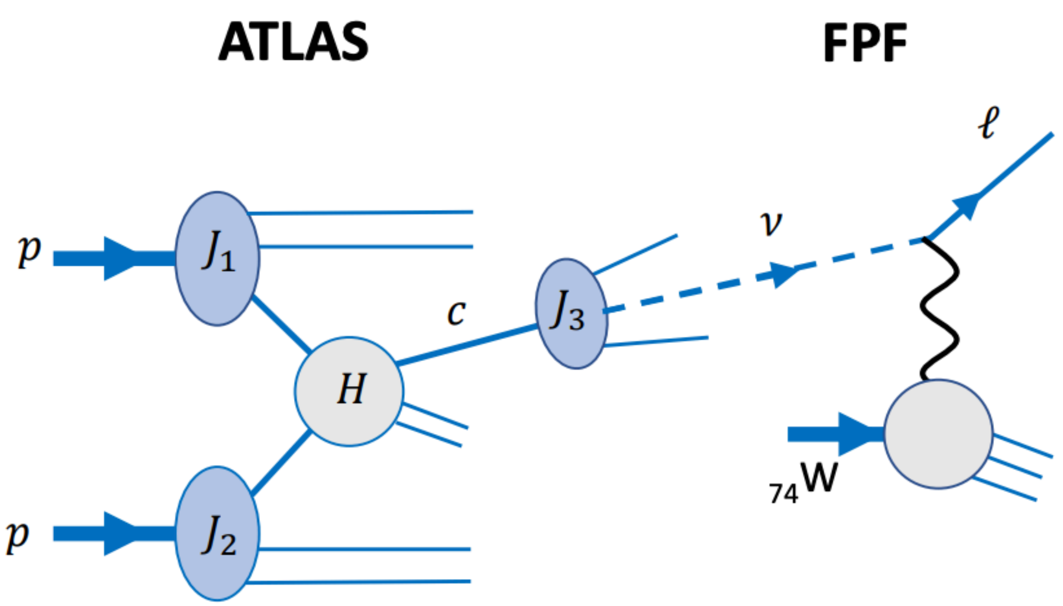
# Neutrino interactions at TeV energies and beyond



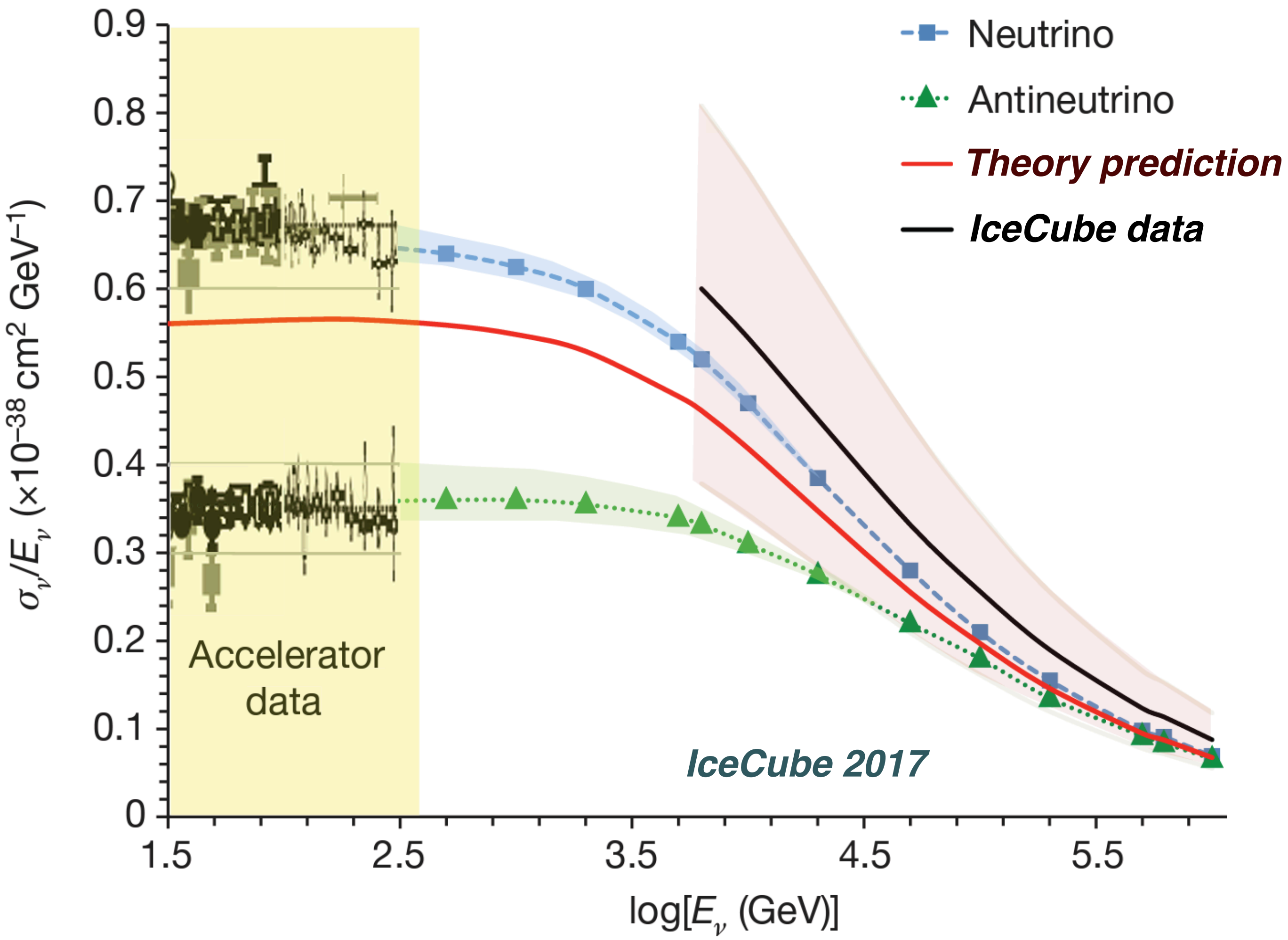

**Juan Rojo,** VU Amsterdam & Nikhef

**3rd Forward Physics Facility Meeting**

**26th October 2021**

# Neutrino-nucleus interactions

Neutrino cross-sections extensively studied for **energies up to 300 GeV** with accelerator neutrinos




At higher energies, **IceCube** has measured cross-sections between 5 TeV and $10^4$ TeV

***but with large uncertainties***

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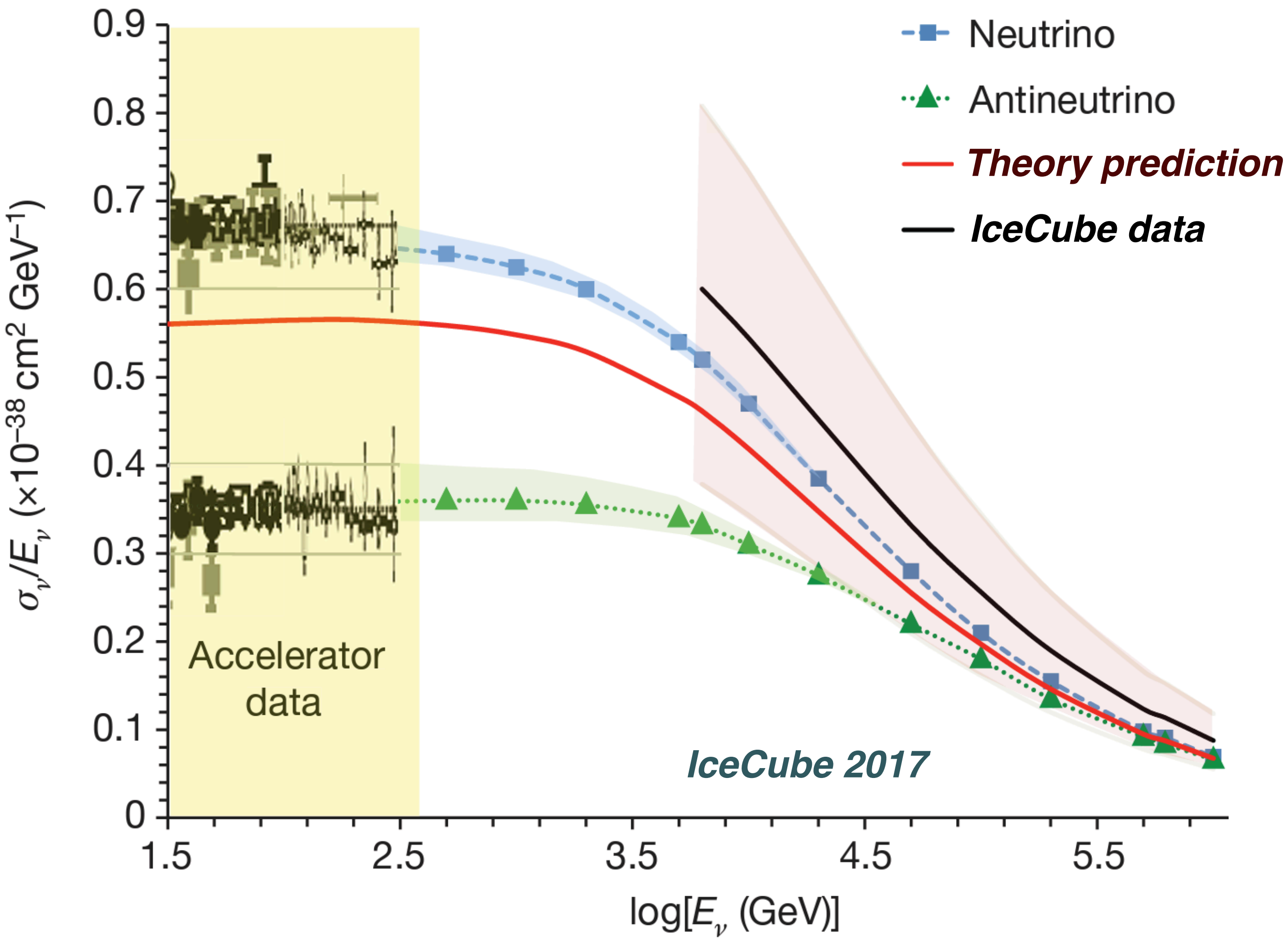
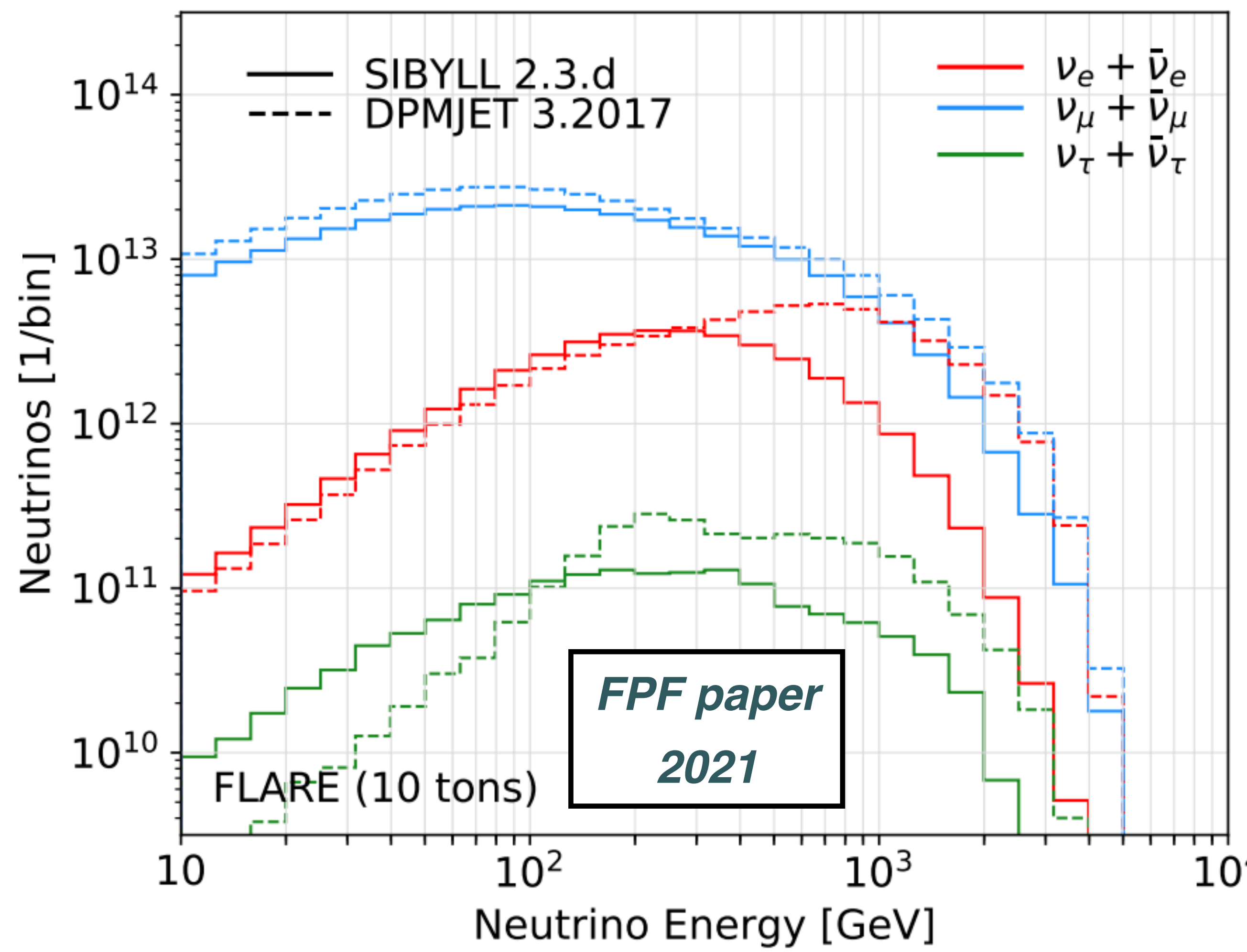


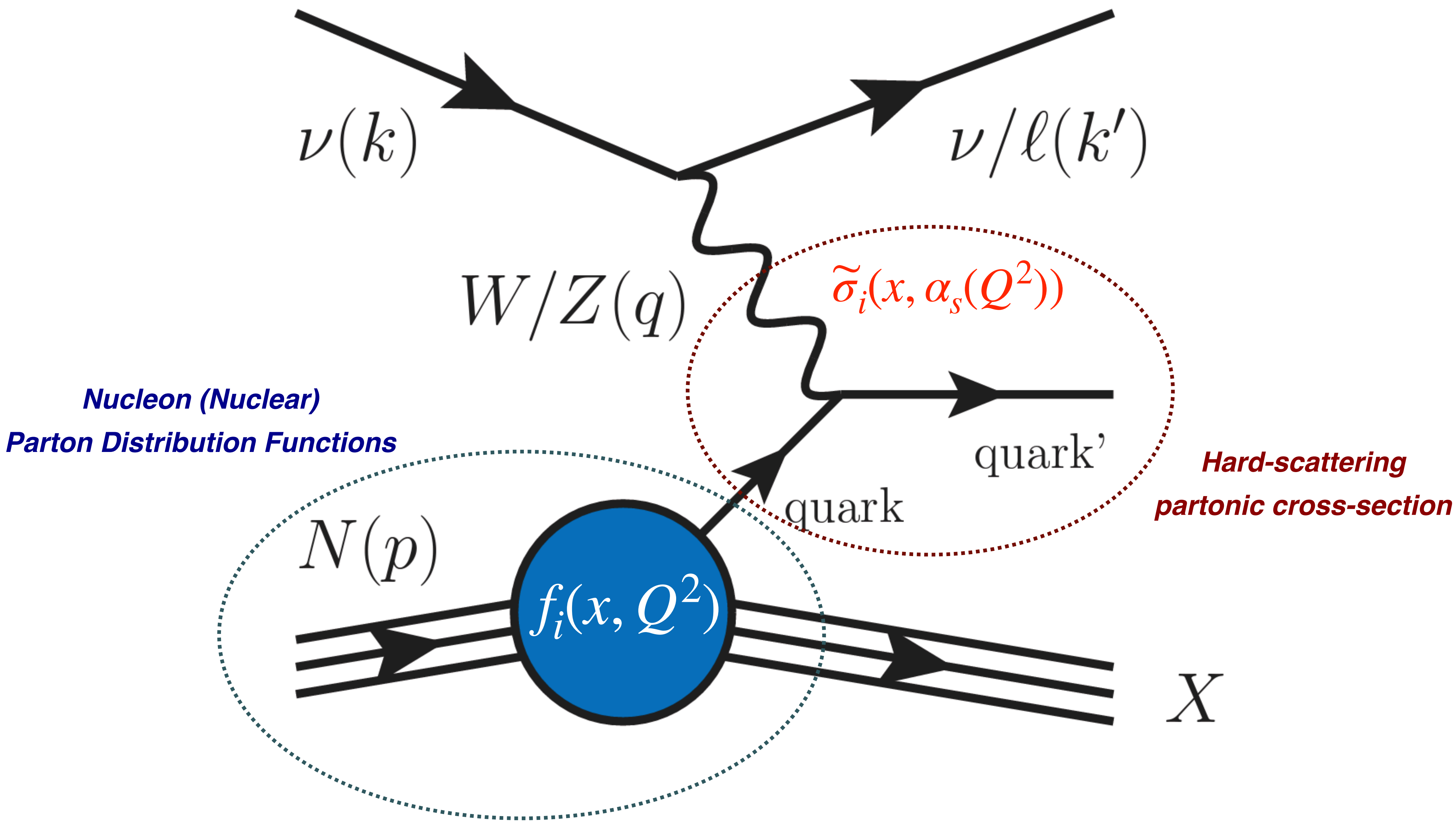

At higher energies, **IceCube** has measured cross-sections between 5 TeV and $10^4$ TeV

***but with large uncertainties***

Neutrinos arriving at the Forward Physics Facility have **energy distributions** peaking between **100 GeV and 10 TeV**. How well can we predict these cross-sections theoretically?

# Neutrino-nucleus interactions

For sufficiently large neutrino energies, their cross-sections can be reliably evaluated in **perturbative QCD** in terms of the scattering between partons and weak gauge bosons




$$\sigma(\nu + N \to \ell^{\pm}/\nu + X) \propto \sum_{i=u,d,g,...} \widetilde{\sigma}_i(x, \alpha_s(Q^2)) \otimes f_i(x, Q^2)$$

$$\widetilde{\sigma}_i(x, \alpha_s(Q^2)) = \sum_k \alpha_s^{k+n}(Q)\, \widetilde{\sigma}_i^{(k)}(x)$$

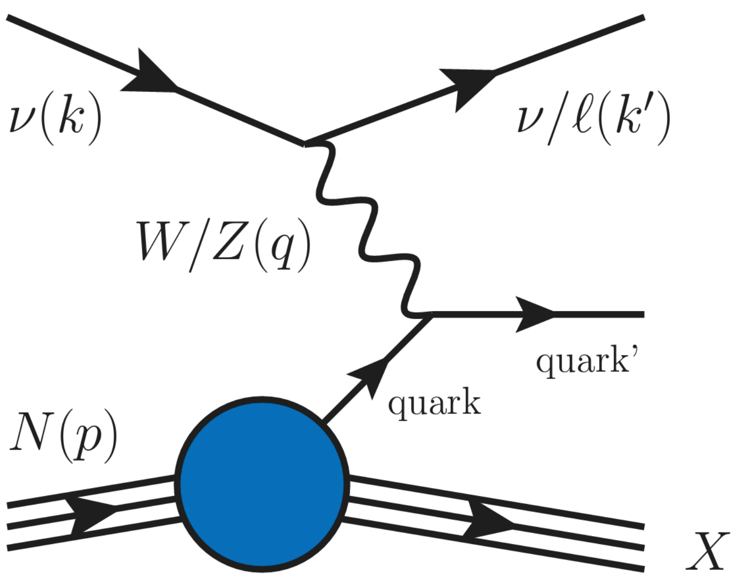
# Neutrino-nucleus interactions

Factoring out the purely electroweak scattering and accounting for Lorentz invariance, the double-differential neutrino-nucleus cross-section is expressed in terms of **structure functions**

$$\frac{\mathrm{d}^2\sigma^{\mathrm{CC}}_{\nu(\bar{\nu})N}(x,Q^2,E_\nu)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{4\pi x(Q^2+M_W^2)^2}$$

*similar expression for NC scattering*

$$\times\left(Y_+ F_{2,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2) \mp Y_- x F_{3,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2) - y^2 F_{L,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2)\right)$$




$$Q^2 = -q^2\,, \qquad y = \frac{q\cdot p}{k\cdot p} = 1 - \frac{E'}{E_\nu}\,, \qquad x = \frac{Q^2}{2\,q\cdot p} = \frac{Q^2}{2\,m_N y E_\nu}$$

In the domain of validity of **pQCD**, structure functions admin the usual factorised expression

$$F_i(x,Q^2) = \sum_{a=g,q}\int_x^1 \frac{\mathrm{d}z}{z} C_{i,a}\left(\frac{x}{z},Q^2\right) f_a\left(z,Q^2\right) \qquad Q^2 \gtrsim 1\ \mathrm{GeV}^2$$

For lower ***Q***, structure functions cannot be evaluated from first principles (at least perturbatively)

# Neutrino cross-sections at the TeV scale

A **precise** and **accurate** knowledge of **neutrino-nucleus cross-sections at the TeV scale** is instrumental to fully exploit the physics potential of the Forward Physics Facility

***What do we need to take into account to produce state-of-the-art predictions for TeV neutrino interactions?***

- Proton and nuclear **parton distributions** and their associated **uncertainties**
- **Higher-order QCD corrections** (to the PDFs and DIS coefficient functions)
- **Heavy quark** mass effects (charm and bottom)
- Contribution from **low-*Q* region** where pQCD is not applicable
- **Subleading channels**: coherent scattering, resonant DIS, neutrino-electron scattering ….

*Bertone et al, JHEP 18*

JHEP
Published for SISSA by Springer
Received: *August 19, 2018*
Revised: *November 13, 2018*
Accepted: *January 3, 2019*
Published: *January 29, 2019*

**Neutrino telescopes as QCD microscopes**

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JHEP01(201



*Garcia et al, JCAP20*

Prepared for submission to JCAP

**Complete predictions for high-energy neutrino propagation in matter**

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**Abstract.** We present predictions for the interactions of energetic neutrinos with matter as they propagate through Earth towards large-volume detectors. Our results are based on state-

*many thanks to Alfonso Garcia for dedicated plots with HEDIS@GENIE*

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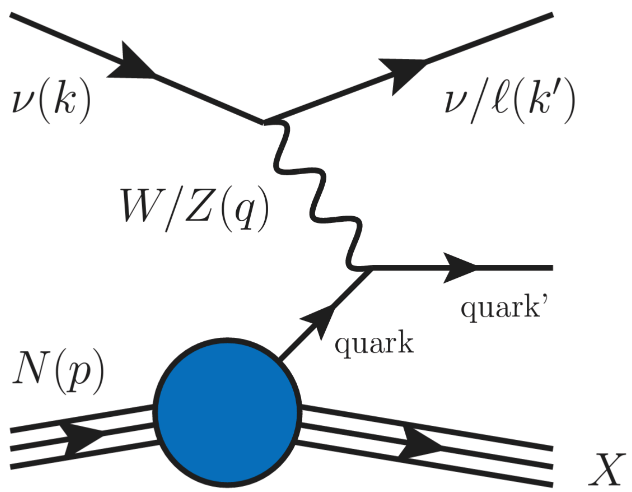
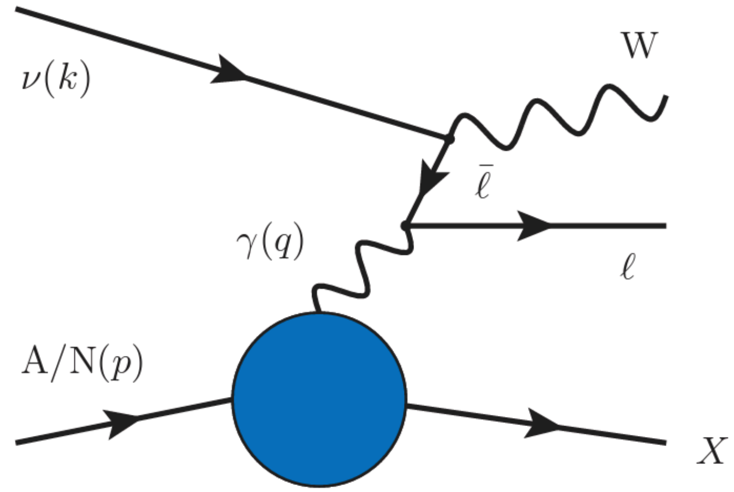
# Subleading processes

Beyond the dominant deep-inelastic scattering channel, several **sub-leading processes** contribute to the neutrino-nucleus interaction cross-section

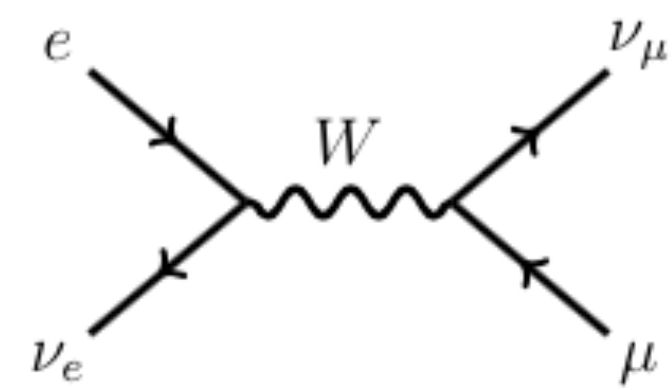



***DIS: hard scattering between quark/gluons and gauge bosons***

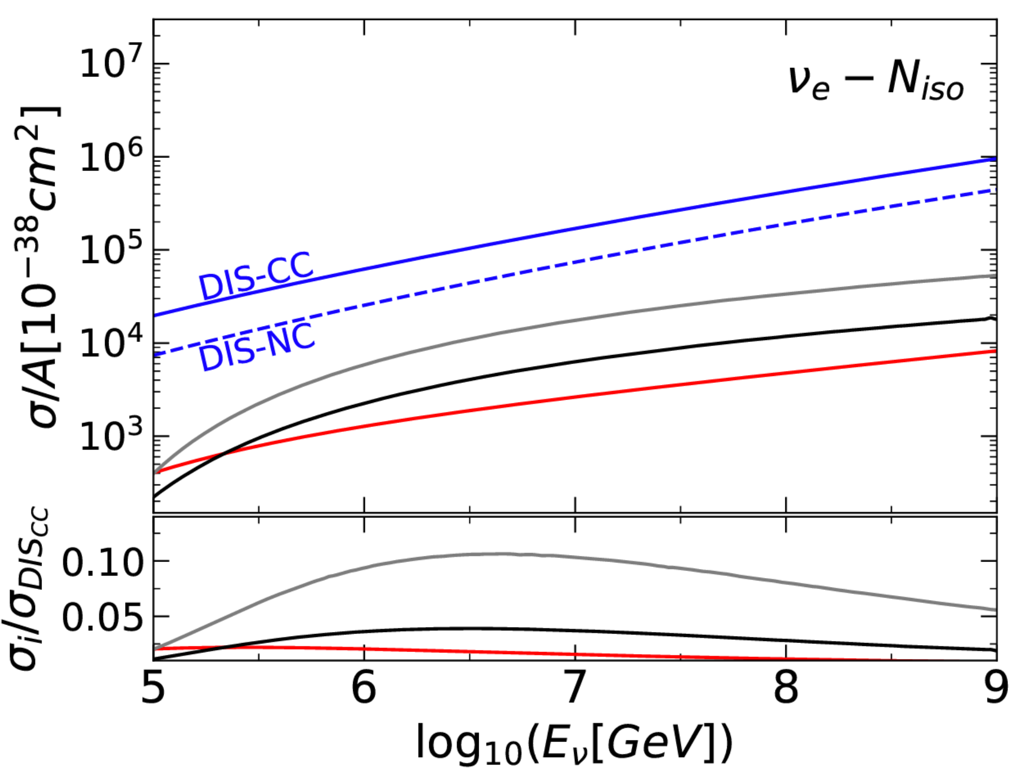



***Resonant DIS: scattering with nucleons photon field***

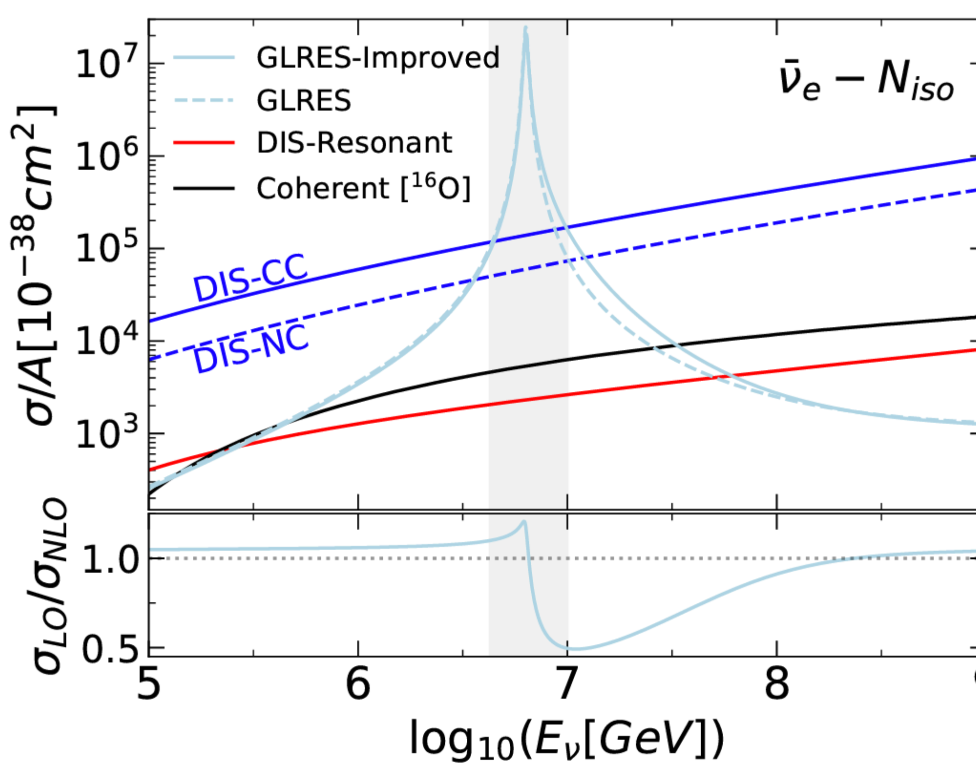
***& Coherent neutrino DIS with photon field of nucleus***




***Glashow resonance: electron-neutrino scattering at the W pole***




- For **$E_\nu$ >100 TeV**, sub-leading process add up to up to **15% of total cross-section** (+ Glashow)
- What about lower energies?



# Subleading processes

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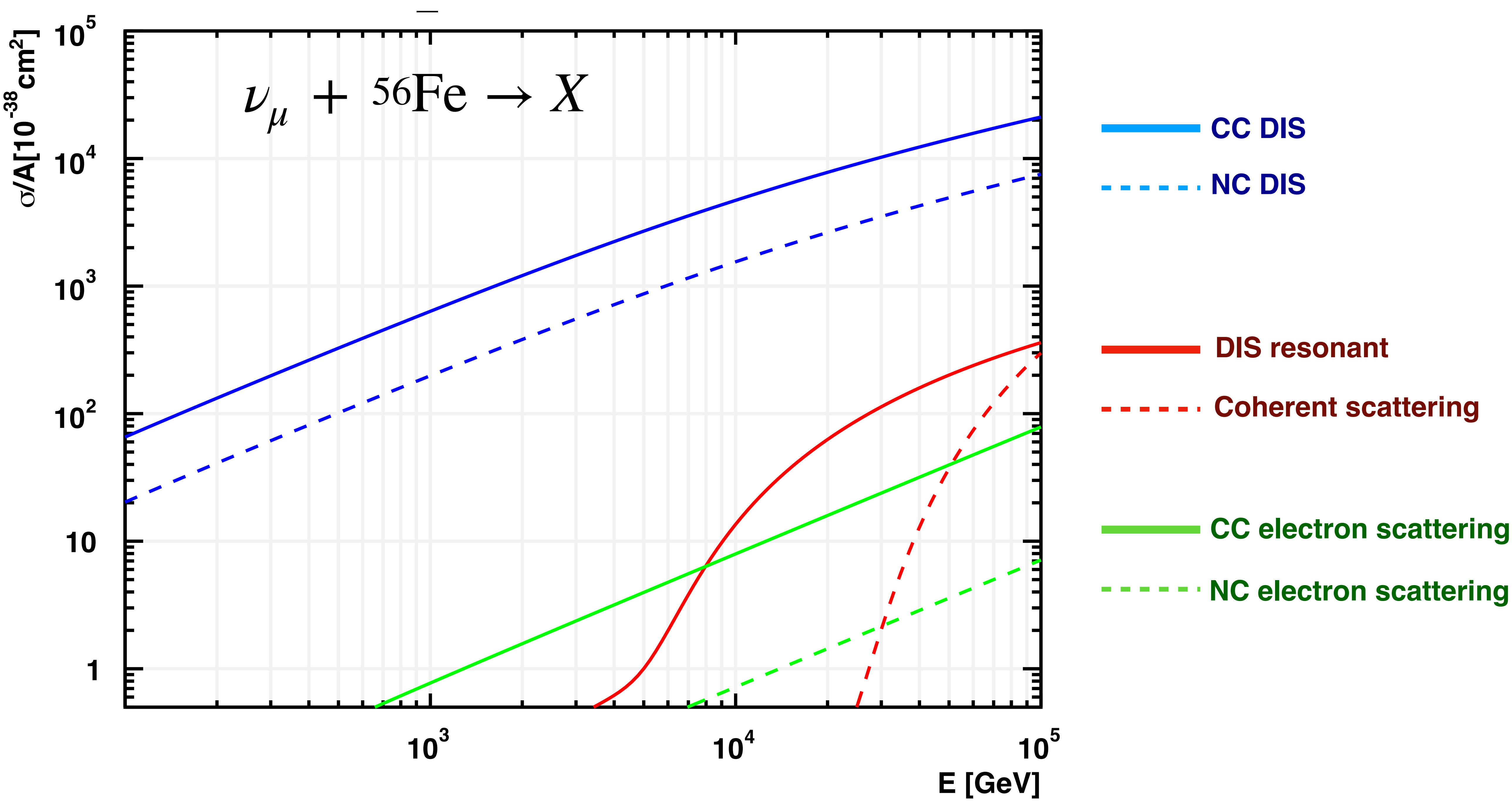


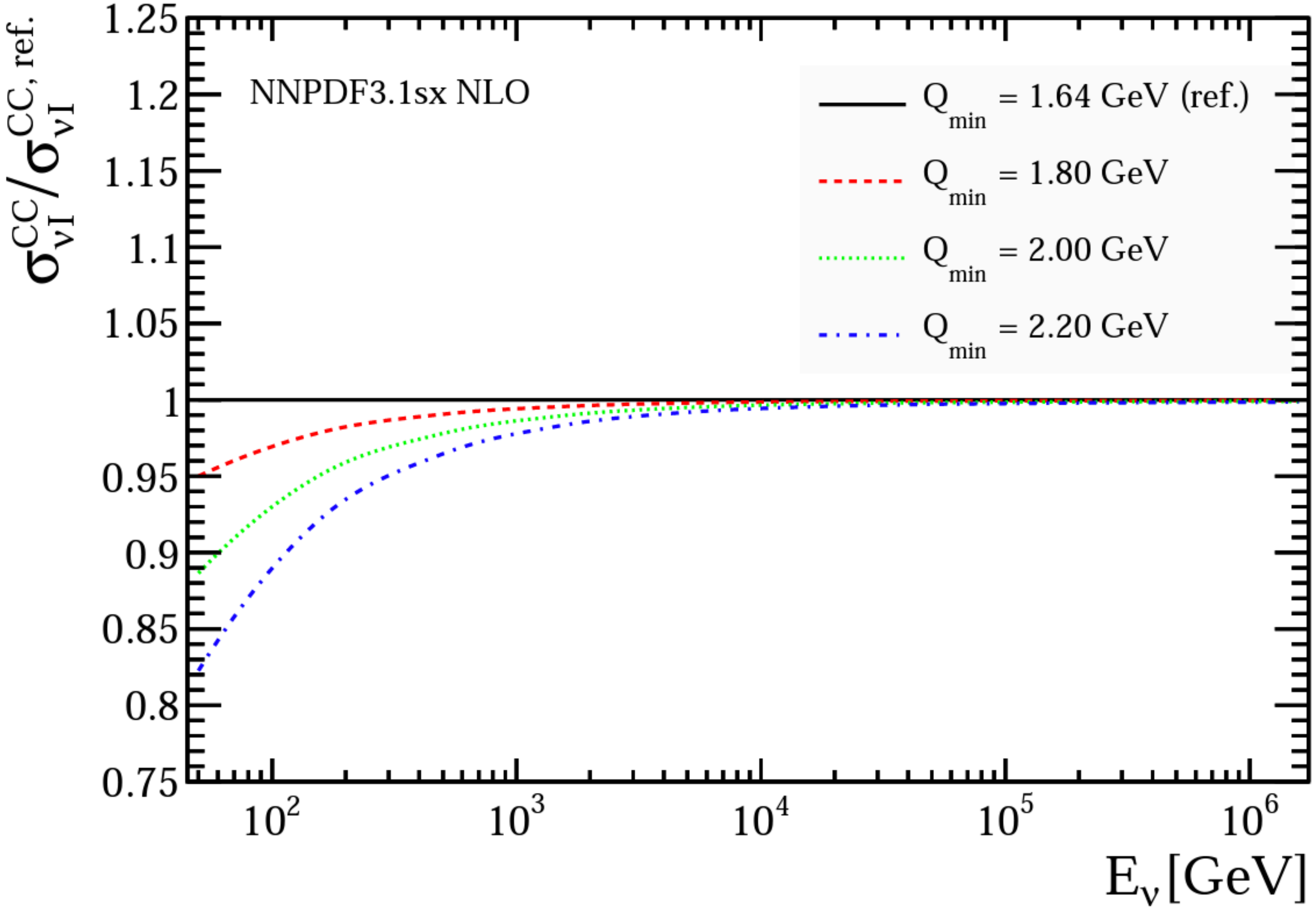

DIS dominates the total cross-section in the **FPF range**, sub-leading processes < 1%

# Impact of low-$Q$ region

Total cross-section obtained from **integrating the differential one** over fiducial phase space

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

***kinematically, $Q^2_{min}$ goes down to 0: vary its value to assess sensitivity to low-Q region***




- For **$E_\nu$ = 1 TeV**, low-$Q$ region weights up to **few %**
- For **$E_\nu$ = 100 GeV**, low-$Q$ region weights up to **15%**
- Weight of low-$Q$ region can be enhanced depending on **selection** and **acceptance** cuts

***How well we model neutrino interactions at low-Q?***

# Impact of low-$Q$ region

The **Bodek-Yang model** is usually adopted to describe **low-$Q$ neutrino DIS** structure functions

In the few GeV region, three types of neutrino-nucleon interaction:

- ***Deep-inelastic scattering*** (with large non-perturbative corrections)
- ***Resonance scattering***
- ***Quasi-elastic scattering***

The Bodek-Yang model uses **effective leading-order PDFs** to fit the charged lepton DIS data (**vector SFs**) which are then applied to predict neutrino DIS (**axial-vector SFs**)

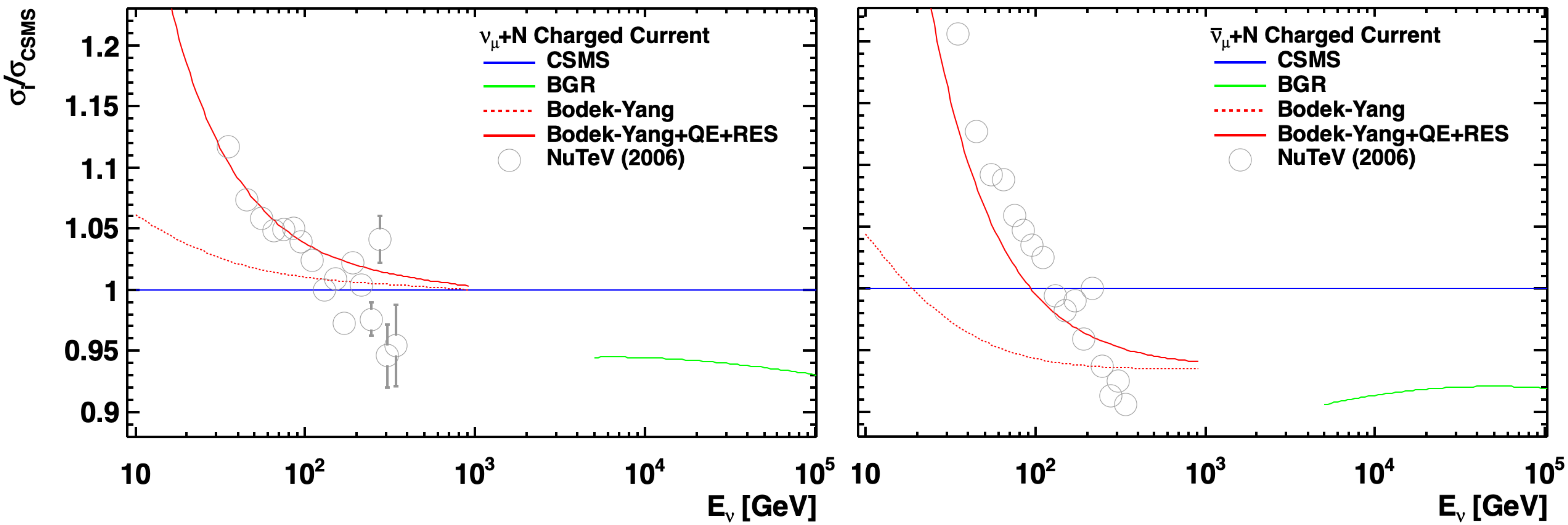
$$f_i^{\rm LO}(x,Q^2) \to f_i^{\rm LO,BY}(\xi,Q^2) \qquad \xi = \frac{2x(Q^2+m_f^2+B)}{Q^2\left[1+\sqrt{1+(2m_N x)^2/Q^2}\right]+2Ax}$$

This **phenomenological model** can then be extended to lower $Q$ than usual pQCD calculations, though both its accuracy and precision are unknown

***e.g. LO PDFs are known to be affected by extremely large perturbative uncertainties***

# Impact of low-$Q$ region

The Bodek-Yang model is usually taken to describe **low-$Q$ neutrino DIS** structure functions




*BGR18: Bertone at al 18*

*CSMS: Cooper-Sarkar et al 11*

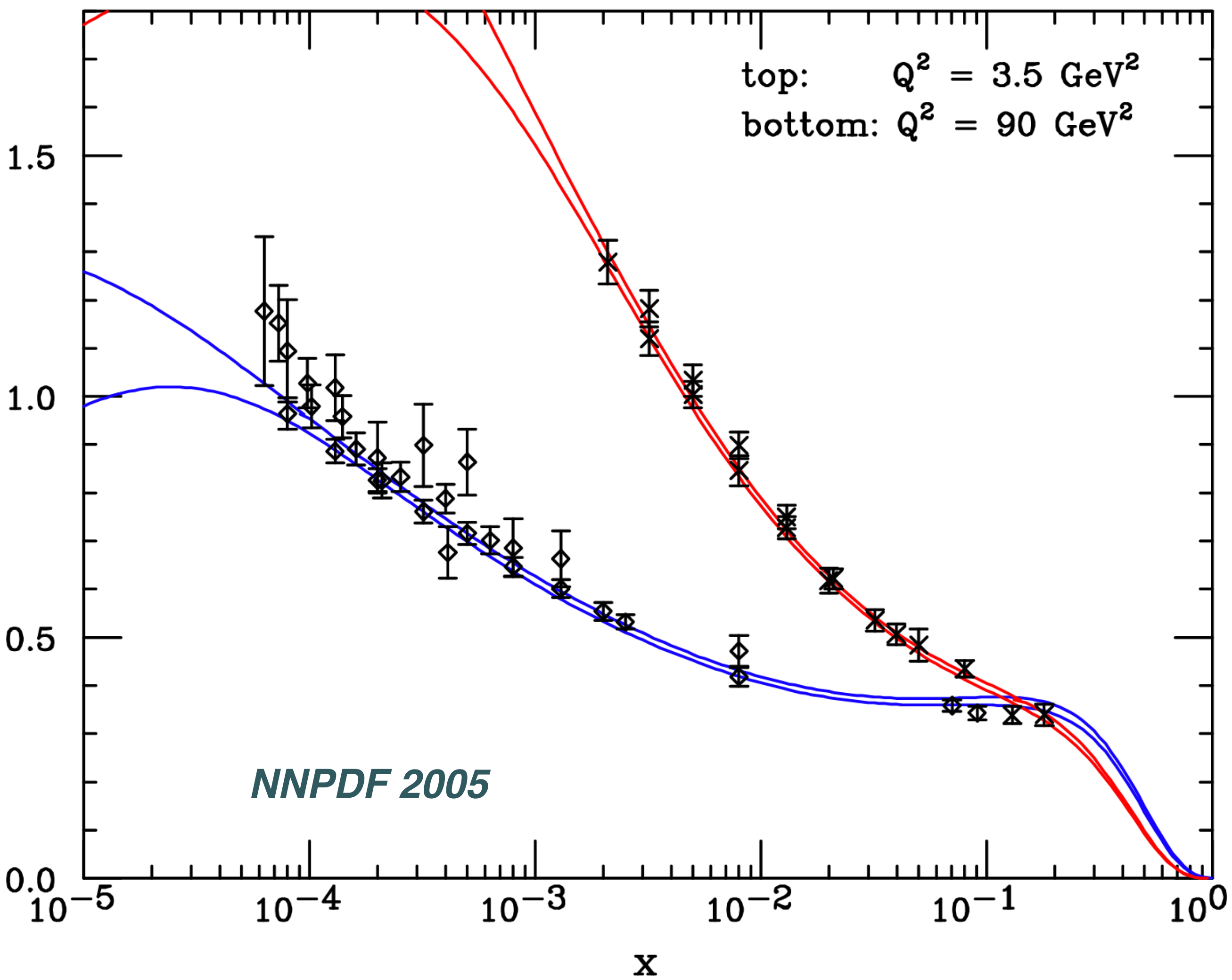
→ **pQCD calculations** of neutrino-nucleon cross-section

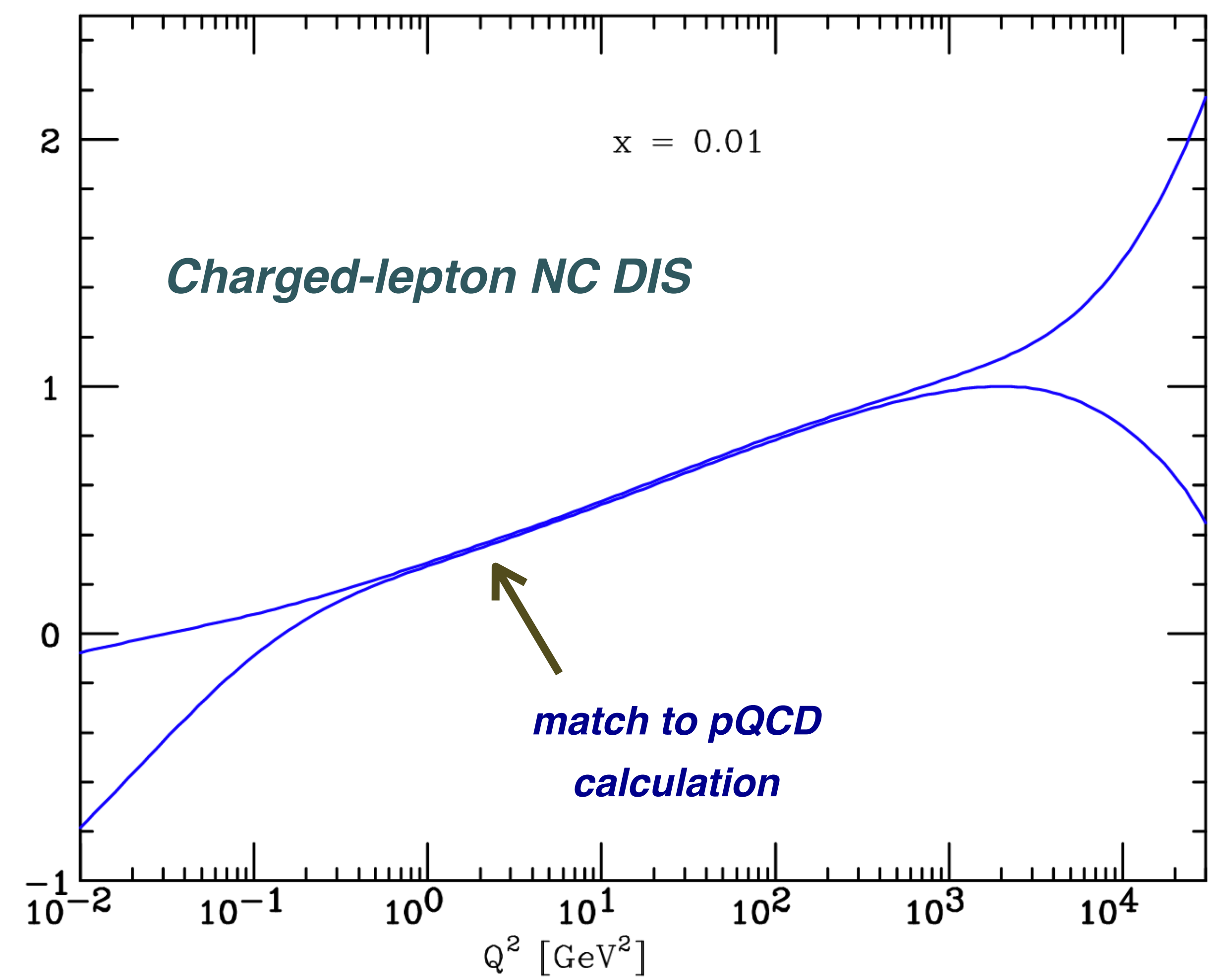
In the FPF kinematic region uncertainties related to **low-$Q$ scattering up to 15%**

Can we reduce model uncertainties and have fully controlled low-$Q$ structure function predictions?

# Impact of low-$Q$ region

possible solution: a deep-learning parametrisation of neutrino DIS structure functions at low-$Q$ which is then **smoothly matched** to the perturbative QCD calculation

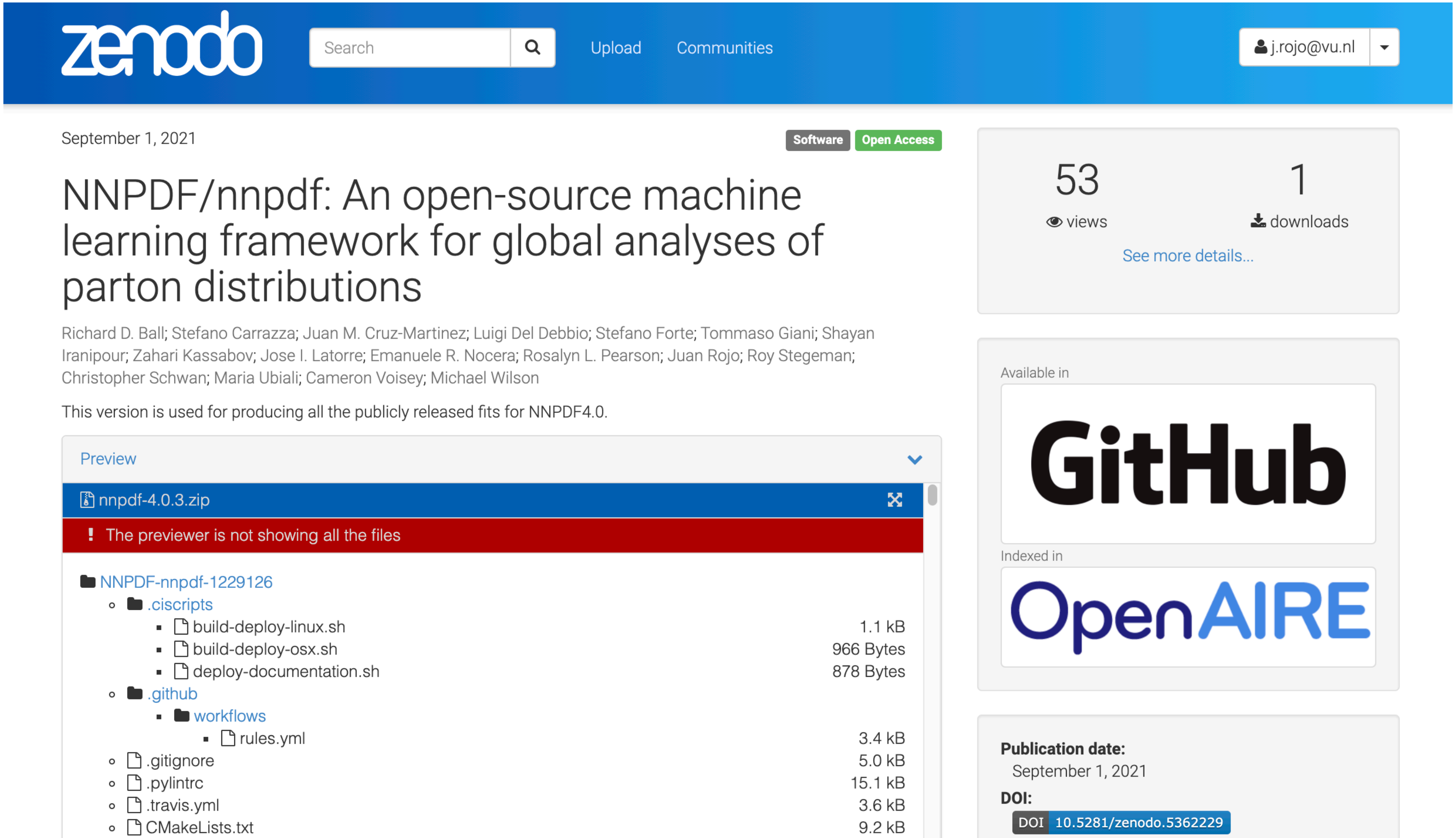



matching to pQCD can be implemented via Lagrange multipliers

$$\chi^2_{\rm tot} = \chi^2_{\rm dat} + \lambda \sum_i \left(F^{\rm NN}(x_i, Q^2_{\rm match}) - F^{\rm pQCD}(x_i, Q^2_{\rm match})\right)^2 / \left(\delta F_{\rm pQCD}(x_i, Q^2_{\rm match})\right)^2$$

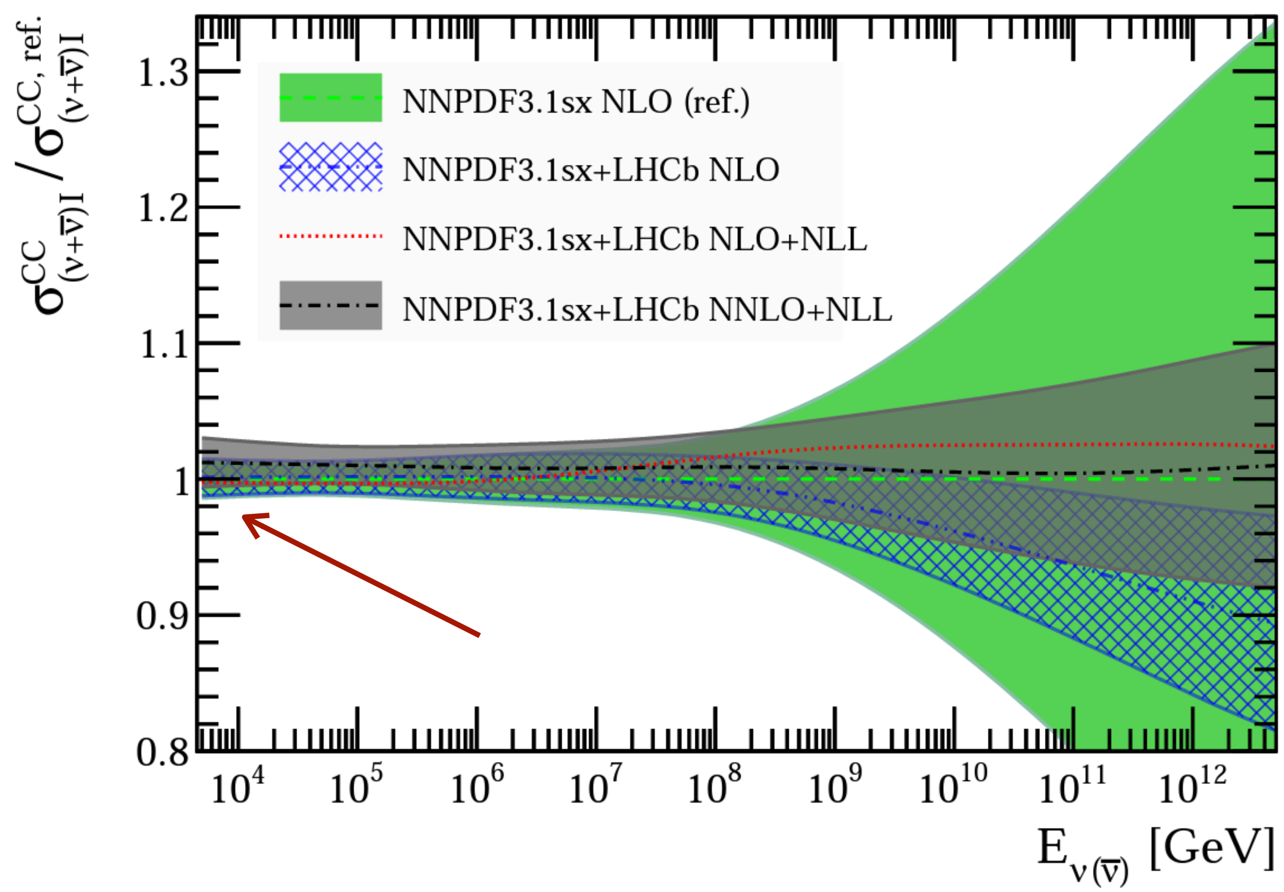
# A ML open-source QCD fitting framework




The **NNPDF machine learning fitting framework** has been publicly released open source**,** together with extensive documentation and user-friendly examples. Many opportunities for new studies within the **FPF community**

# higher-order QCD and PDF uncertainties

Higher-order QCD corrections to neutrino DIS are small: **good perturbative stability**

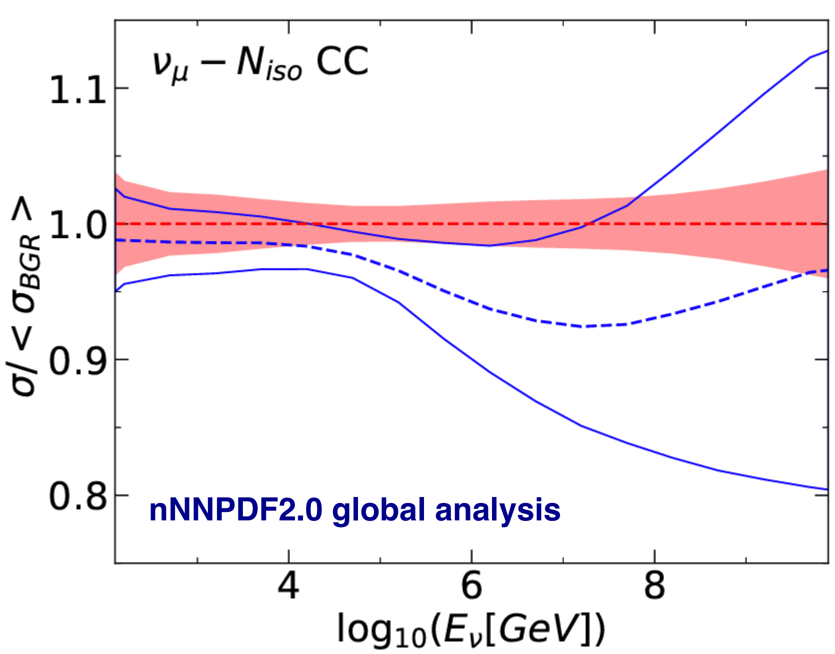


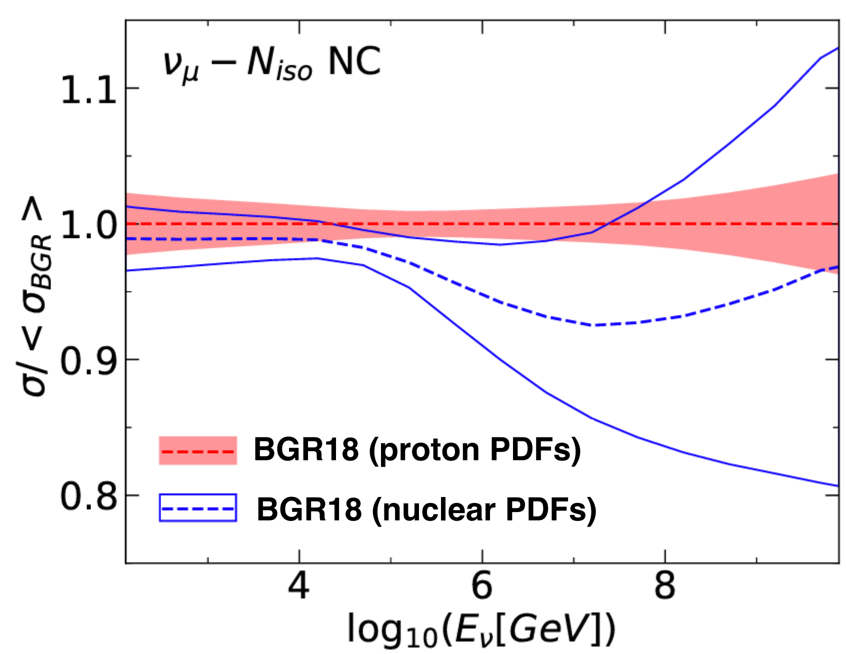

MHOUs estimated from shift between NLO and NNLO: **< 2% in FPF region**

Large perturbative corrections from small-x physics arise only for **$E_\nu$ >$10^5$ TeV** and need to be resumed (BFKL)

**Proton PDF uncertainties** also moderate (few %) in FPF region

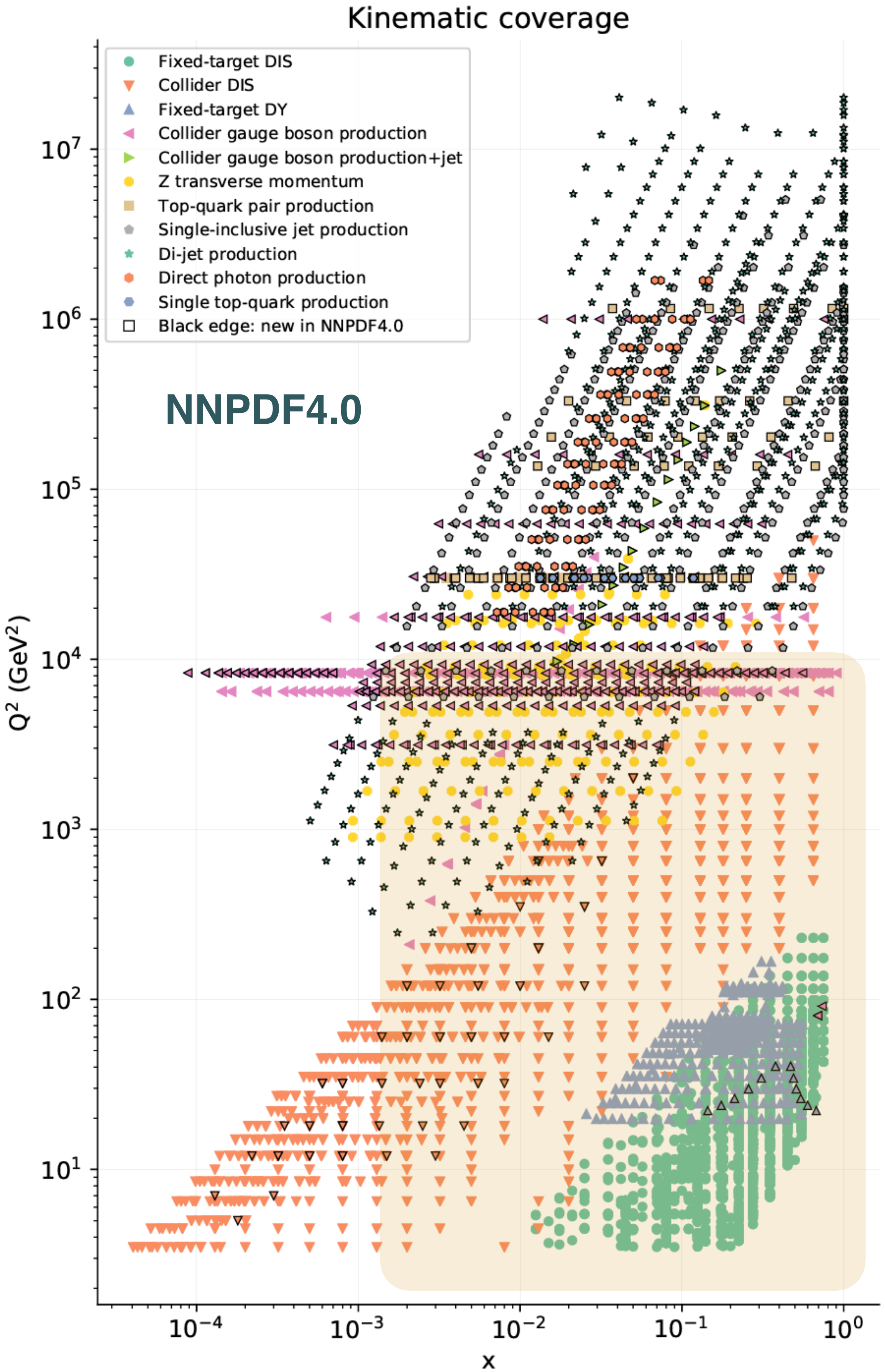
What about **nuclear PDF uncertainties**? FPF neutrinos scatter on a heavy nuclear target

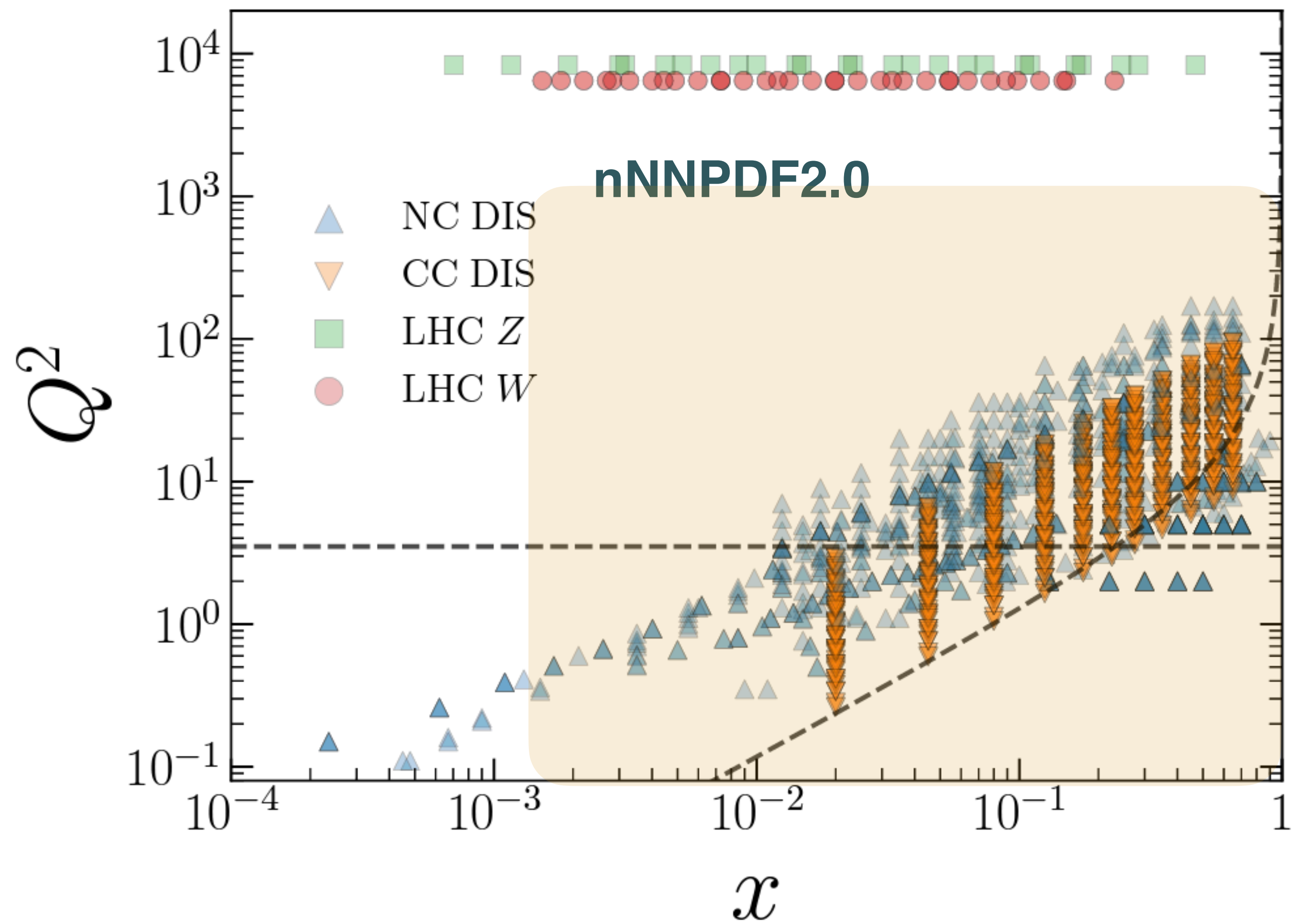



**Nuclear PDF errors** also in few % ballpark

# higher-order QCD and PDF uncertainties

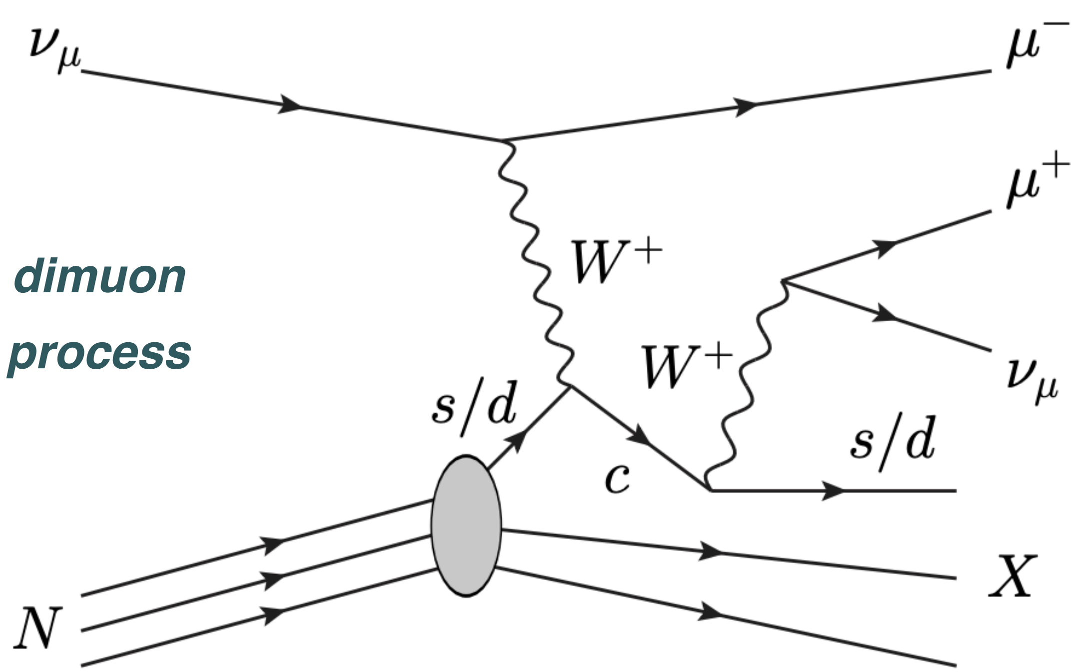


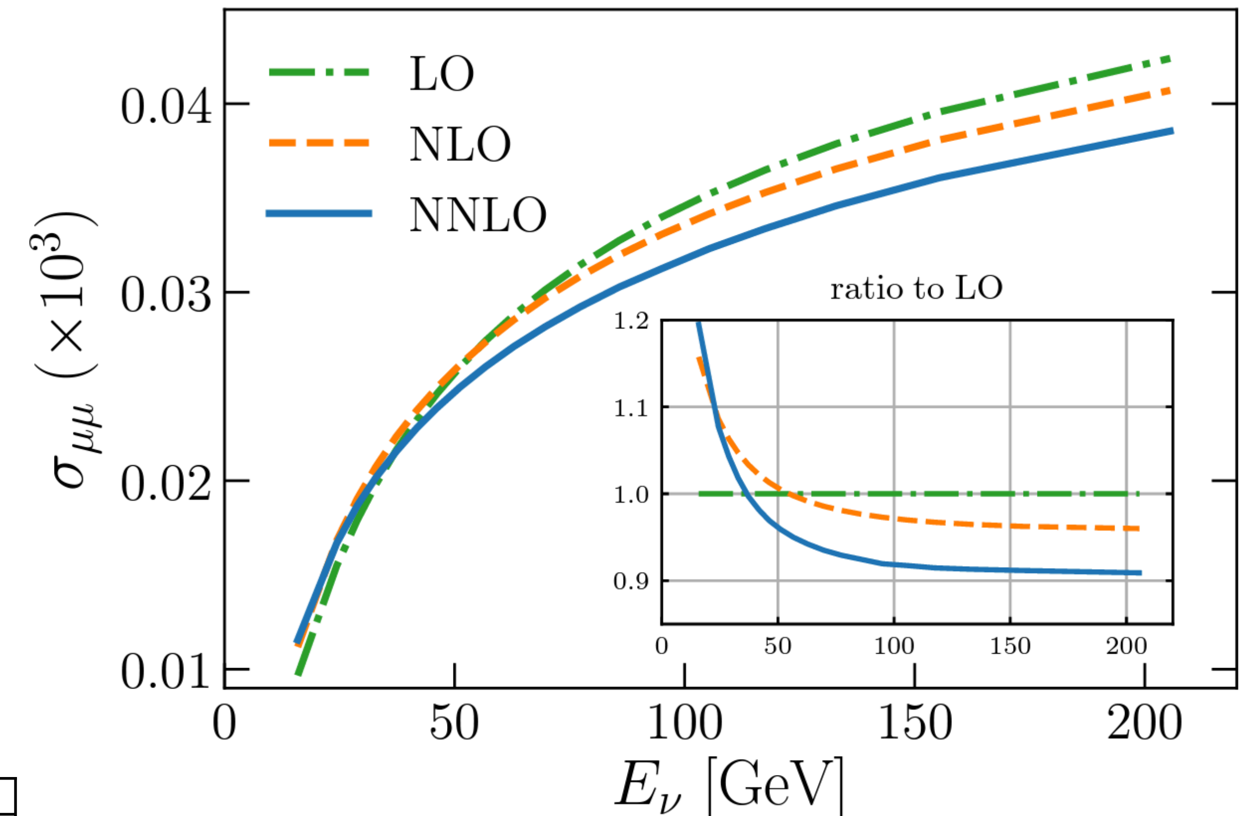



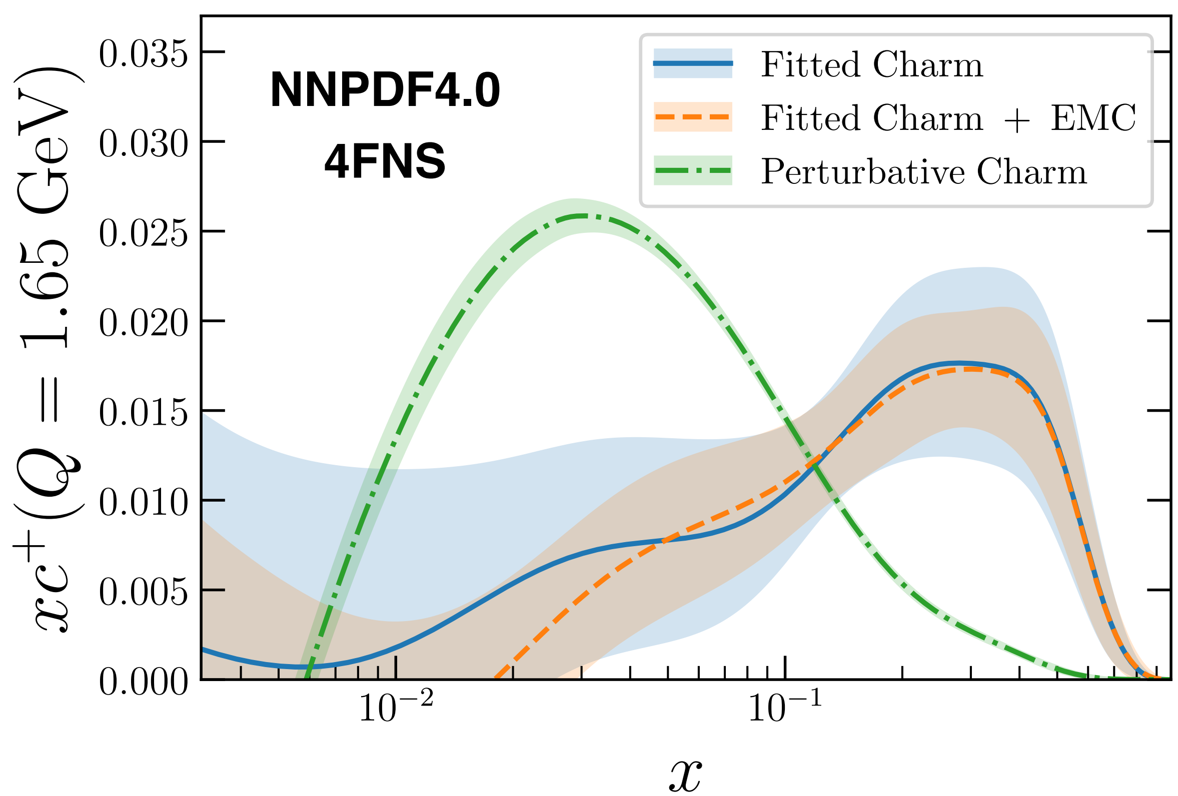

The kinematic region in **(*x*,*Q*) plane** relevant for neutrino scattering at FPF is **well-covered** in fits of proton and nuclear PDFs

# Heavy quark mass effects

Mass corrections to ***s -> c & c -> s* transitions** are important to describe **heavy quark structure functions** in CC neutrino DIS. Computed up to NNLO QCD



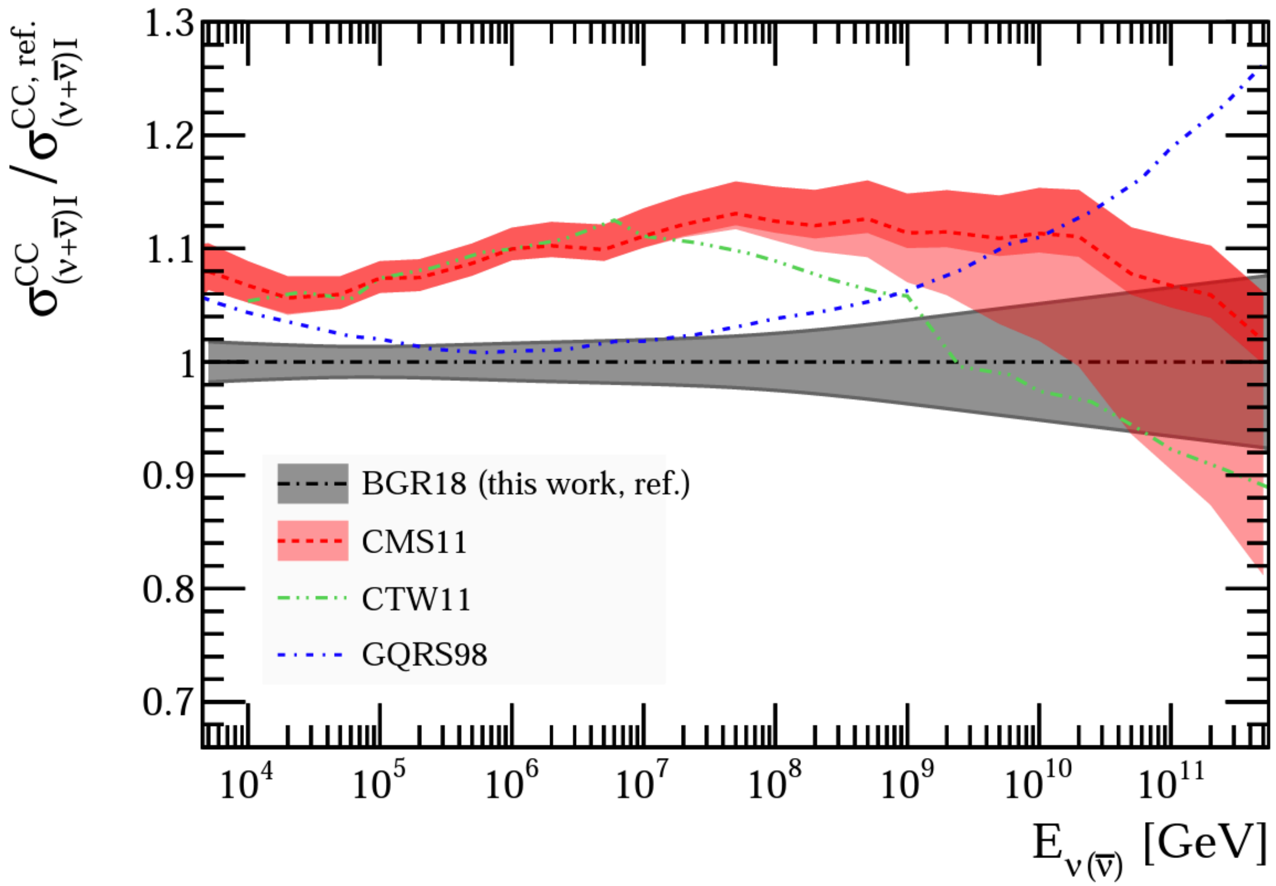



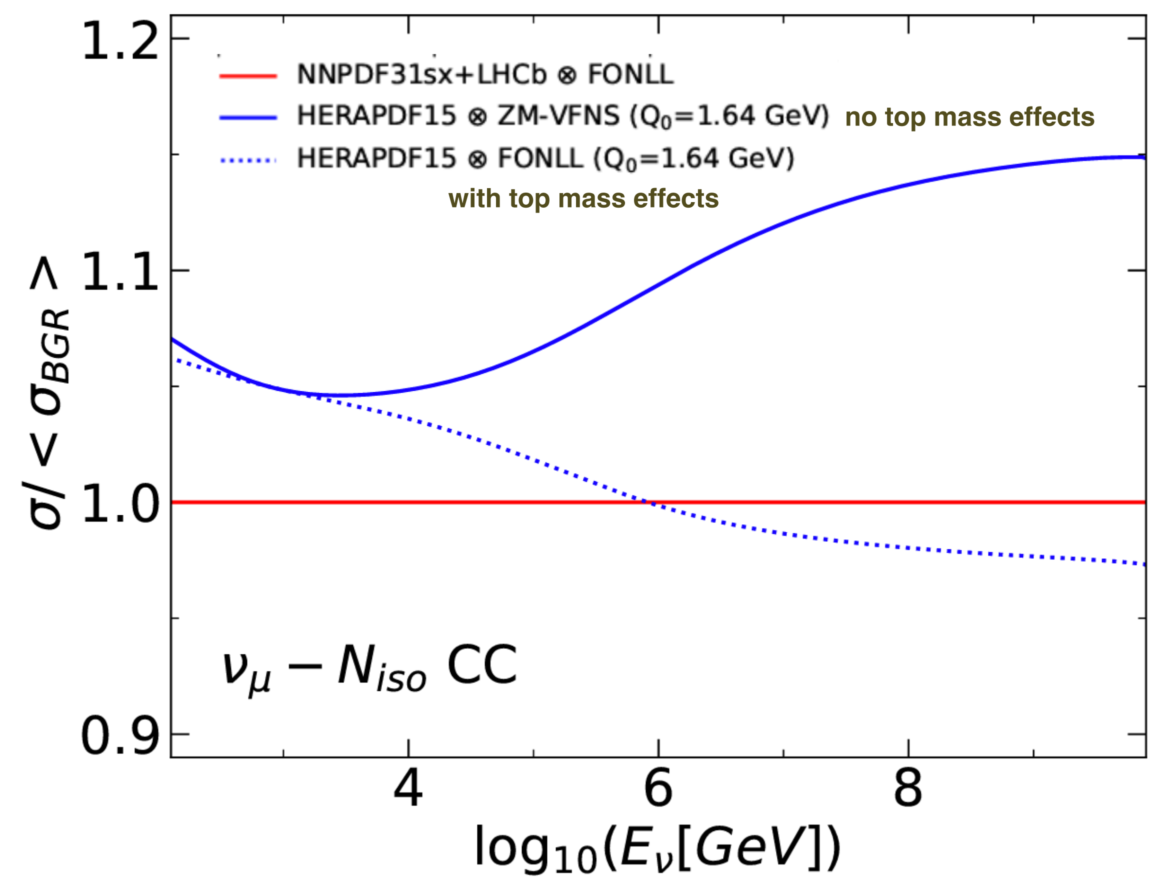



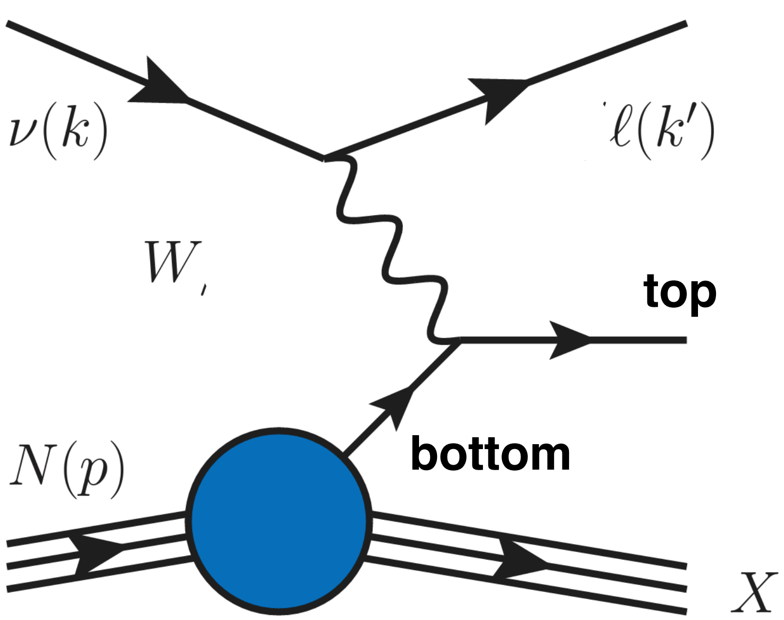

Charm-initiated processes will be enhanced for a **non-zero intrinsic charm** component, as favoured by global NNPDF4.0 analysis and **LHCb Z+charm data**

# Heavy quark mass effects

top quark mass effects associated to the ***b -> t*** transition become important for **$E_\nu$ >10 TeV**



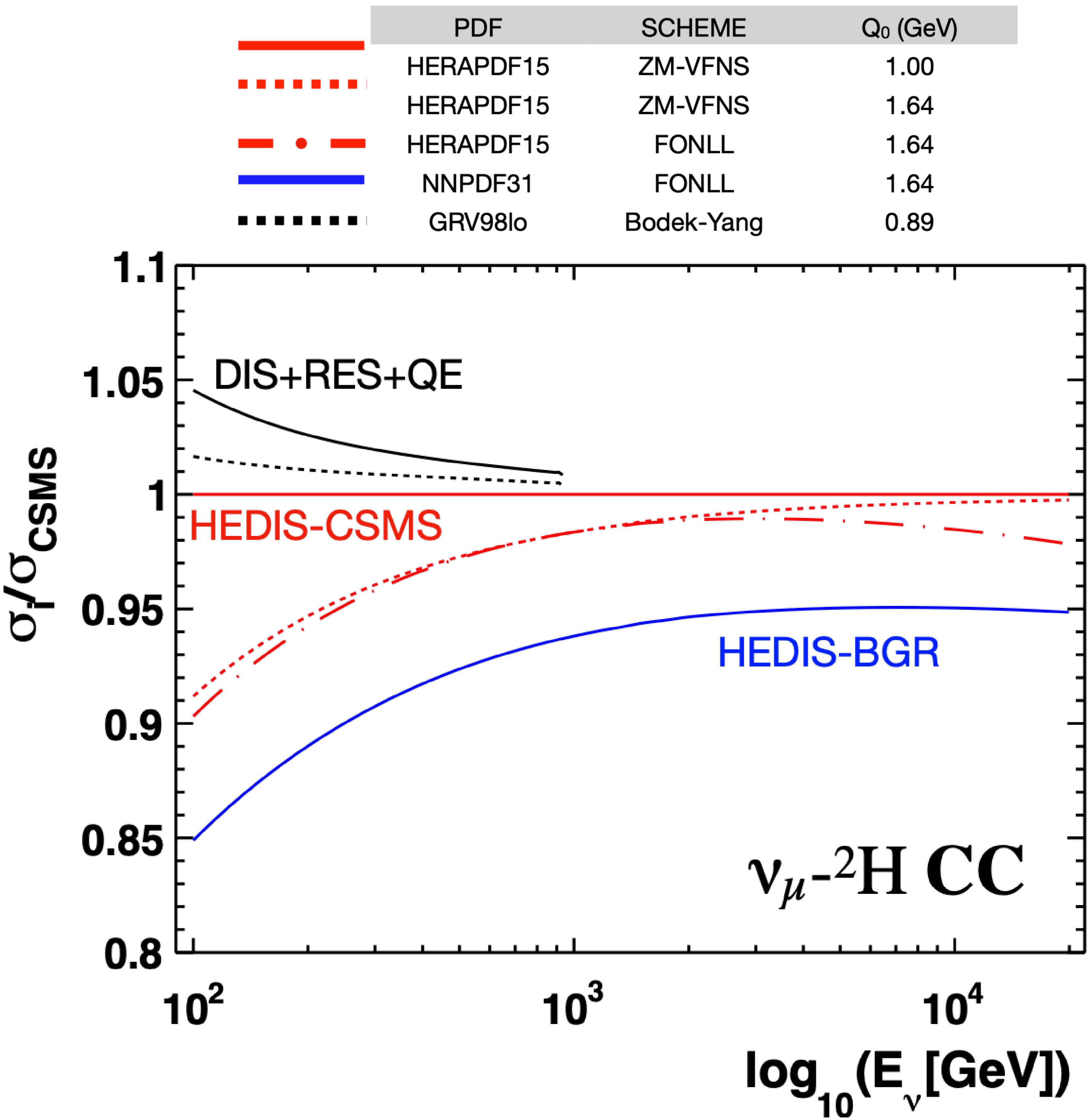




Bulk of the differences between CMS11 and BGR18 traced back to **ZM-VFN vs GM-VFN treatment** of the ***b -> t*** transition respectively (up to 20% effect at high-E)

Small effects for FPF kinematics

# Neutrino cross-sections @ FPF




Calculations of **FPF neutrino cross-sections** require:

- pQCD calculations with NNLO QCD corrections and heavy quark mass effects
- State-of-the-art determinations of proton and nuclear PDFs
- Smooth, robust matching to the low-$Q$ region (data-driven): current **limiting factor**
- Accounting for sub-leading scattering processes

Goal: theory uncertainties down to **few % level** in full FPF kinematic range

# Summary and outlook

- Neutrino interactions at the Forward Physics Facility **probe a new range of scattering energies**, intermediate between current accelerator data and neutrino telescopes

- Theoretical predictions in this energy range must take into account several factors, from **proton and nuclear structure** to **higher order QCD** and **heavy quark mass corrections**, as well as the contribution from subleading scattering channels

- Dominant source of uncertainty is **modelling of low-*Q* region**, where data-driven parametrisation matched to pQCD could be deployed to enhanced precision and accuracy

***relevant also for many other neutrino experiments!***