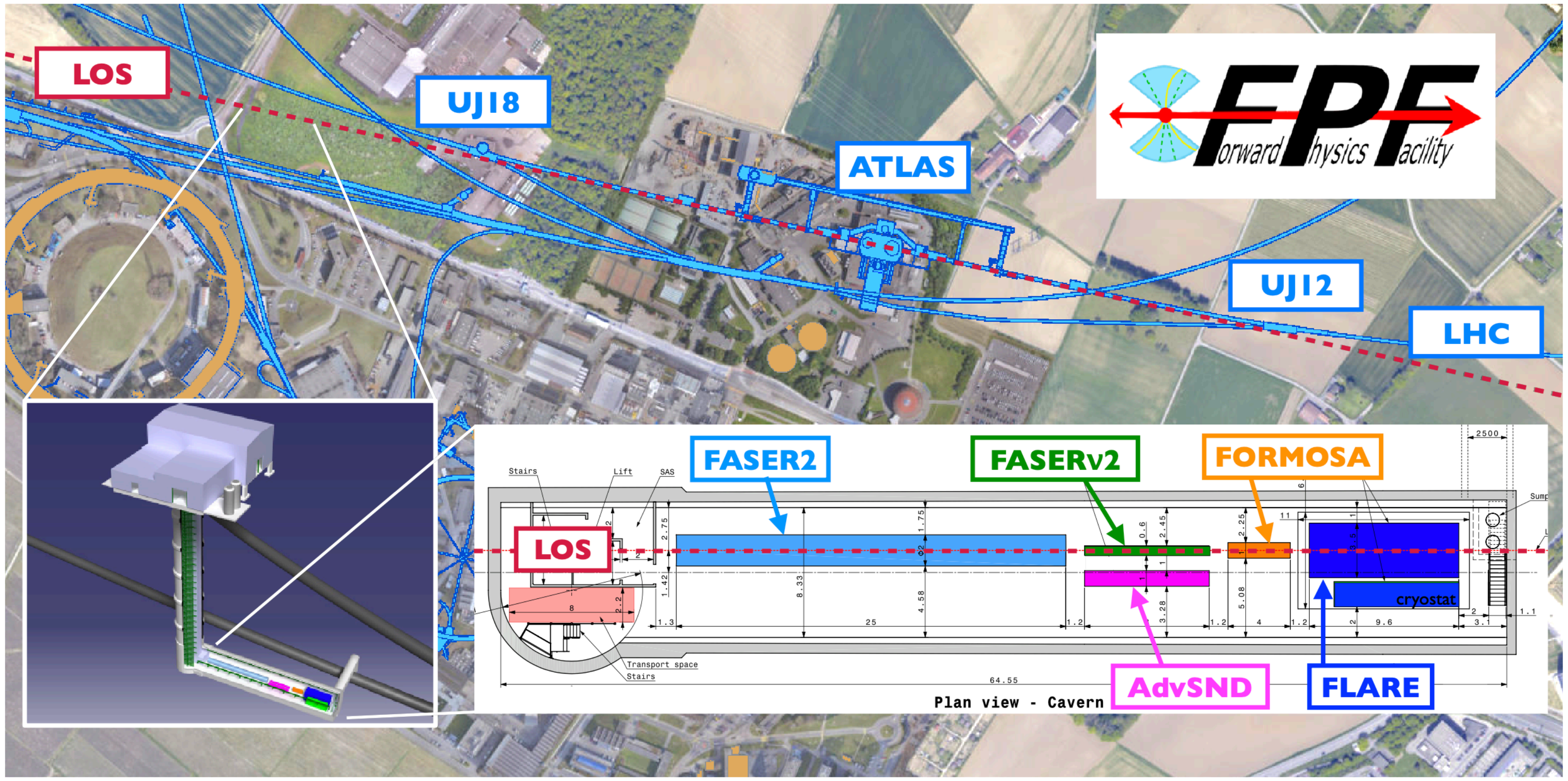
# QCD and neutrino physics at the FPF and the role of neutrino interaction modelling

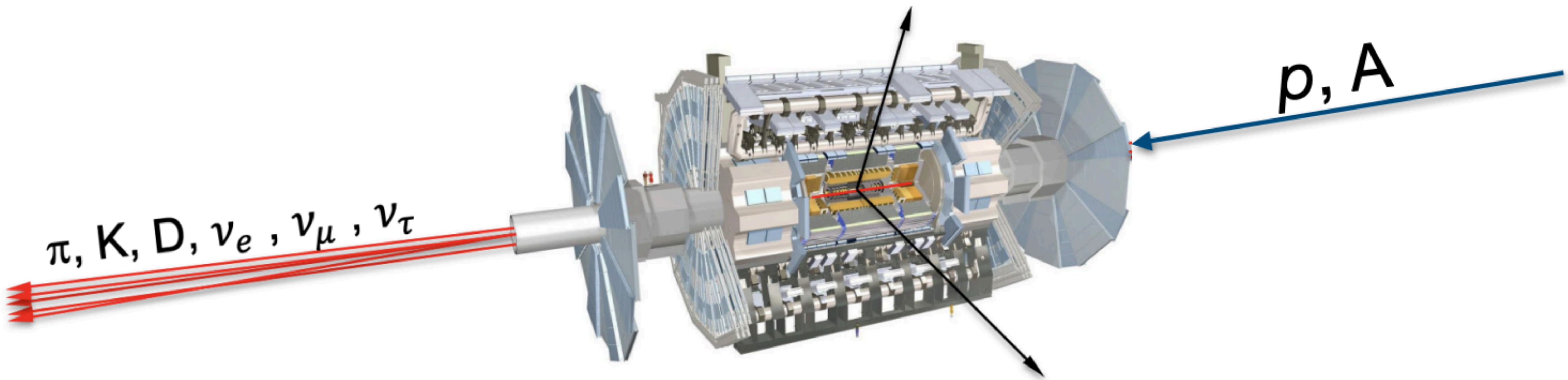
**Juan Rojo,** VU Amsterdam & Nikhef




**FLArE Far Forward Physics working group, 07.03.2023**

# The LHC as a neutrino factory

- 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

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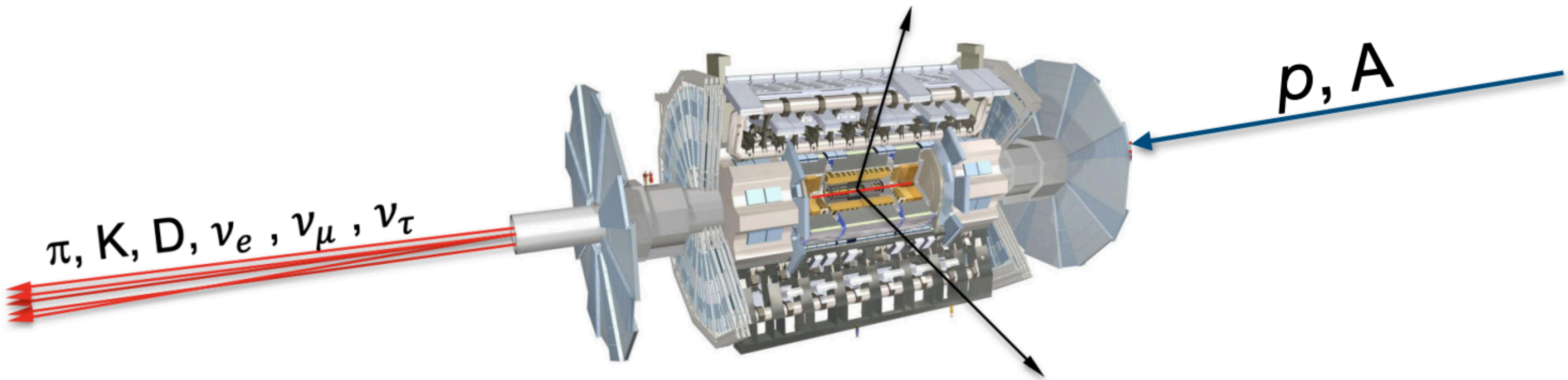


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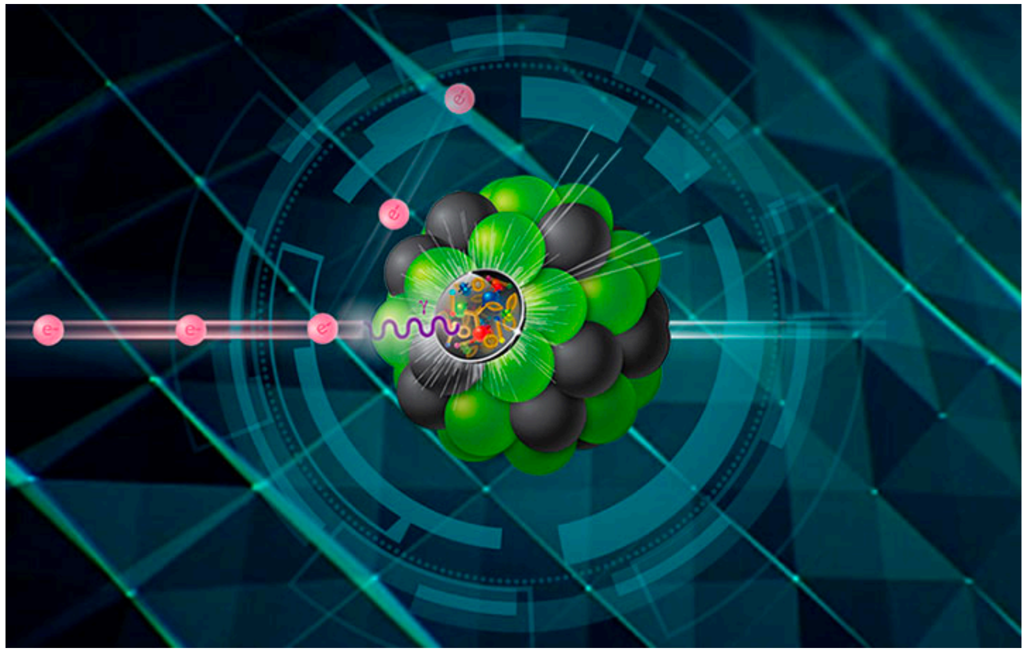
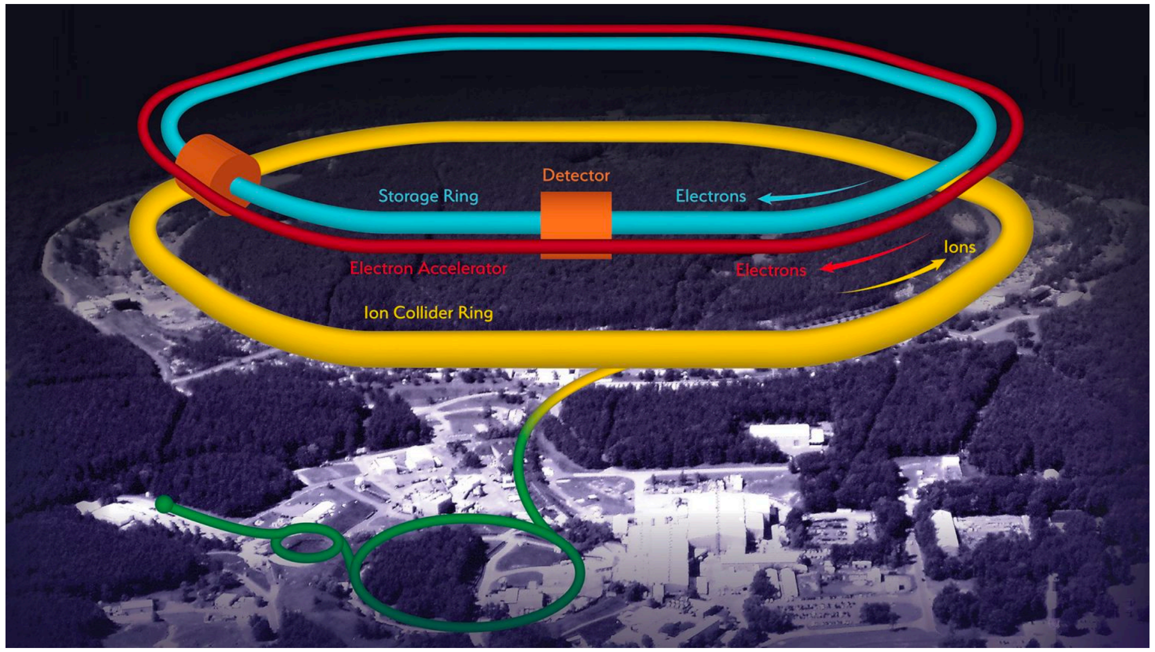
***TeV neutrino deep-inelastic scattering: charged-current counterpart of Electron Ion Collider***





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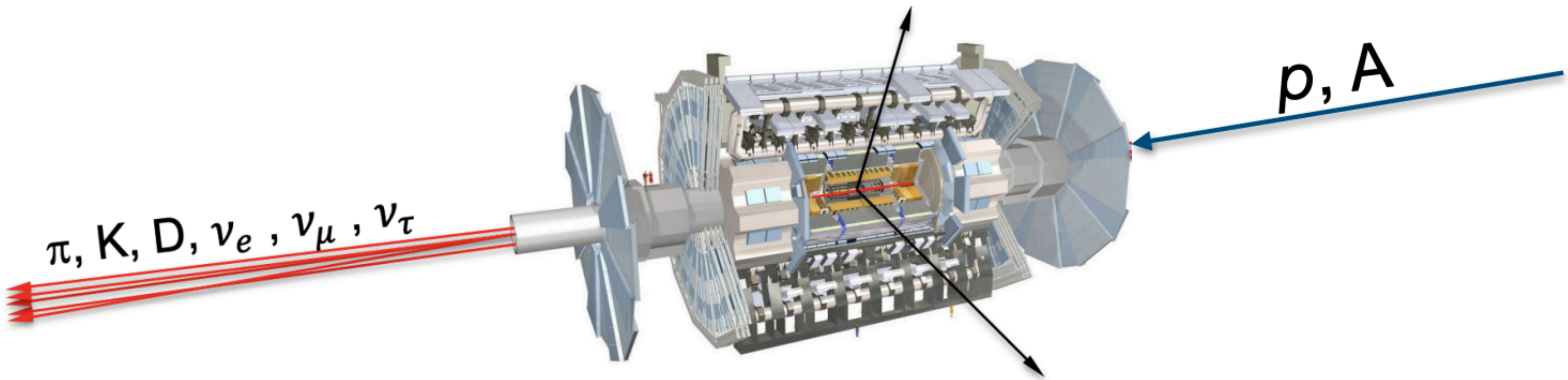


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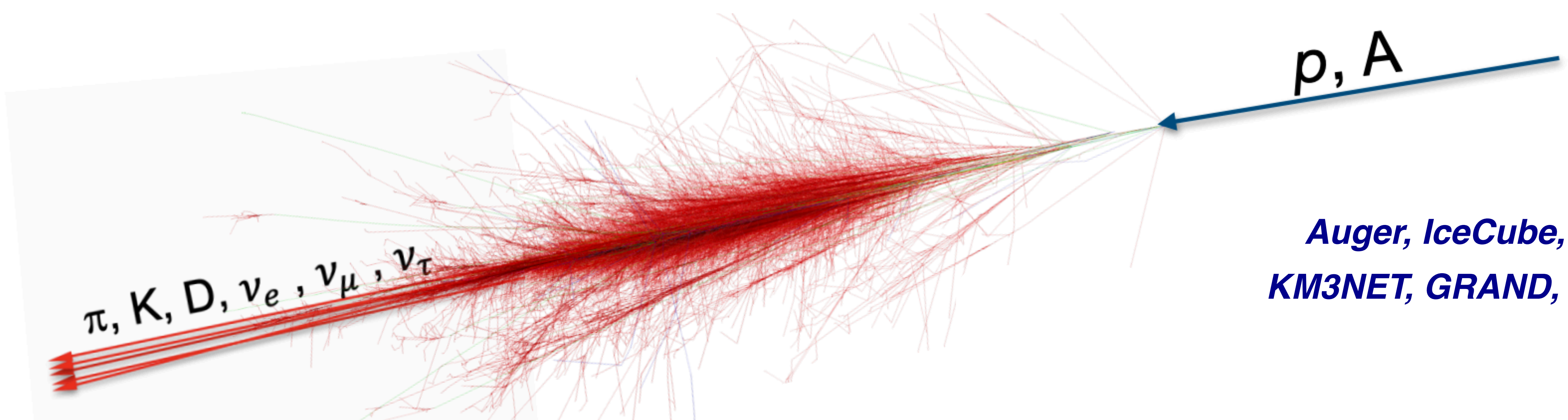
***Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux***




***Auger, IceCube, KM3NET, GRAND, …***

# The LHC as a neutrino factory

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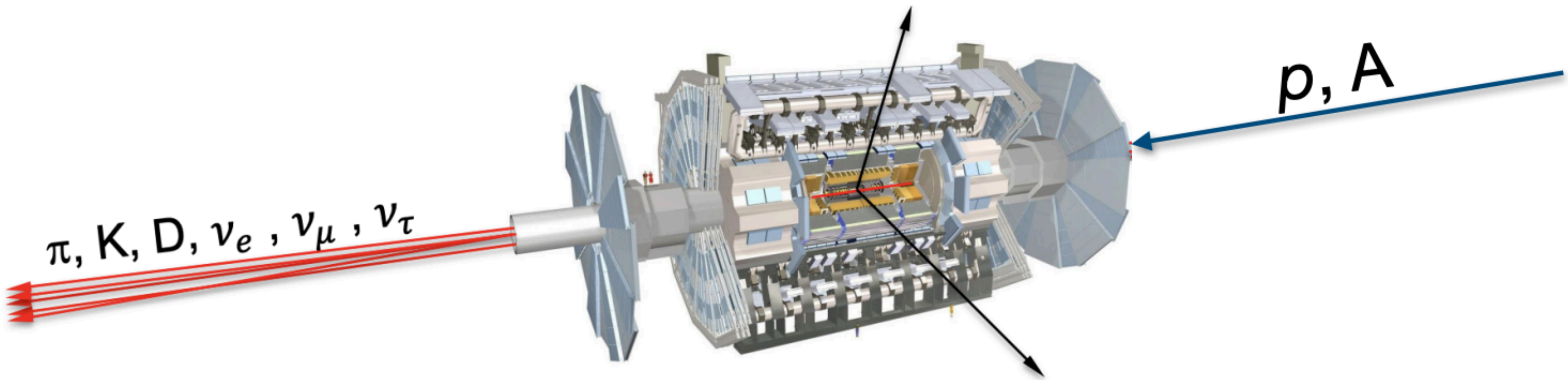
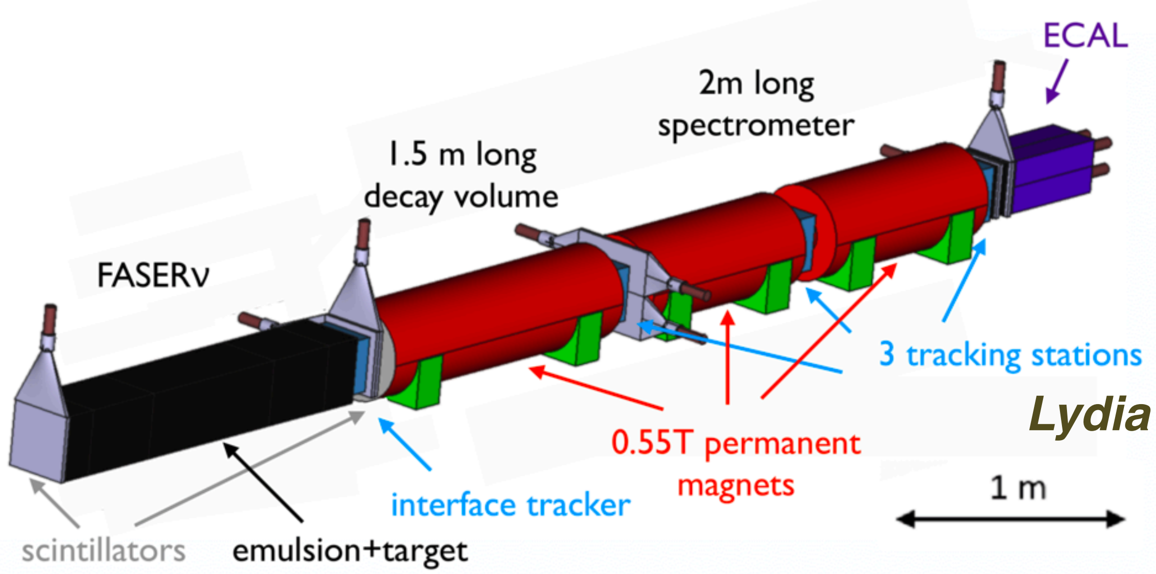


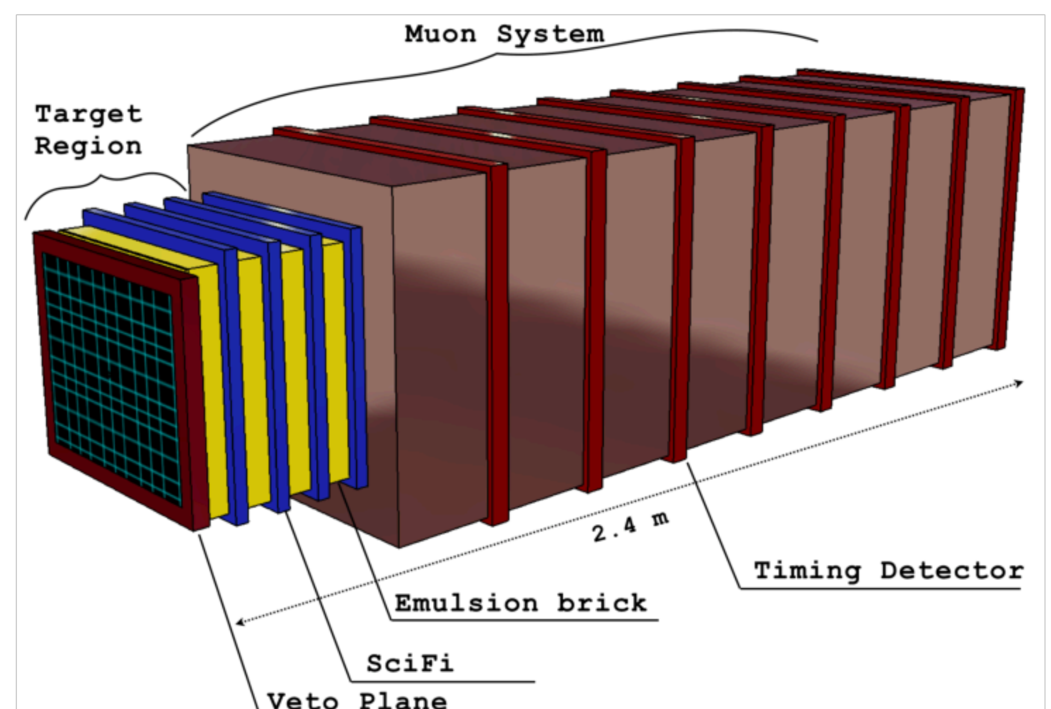

- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

***the feasibility of neutrino physics at the LHC already demonstrated by FaserNu and SND@LHC experiments***



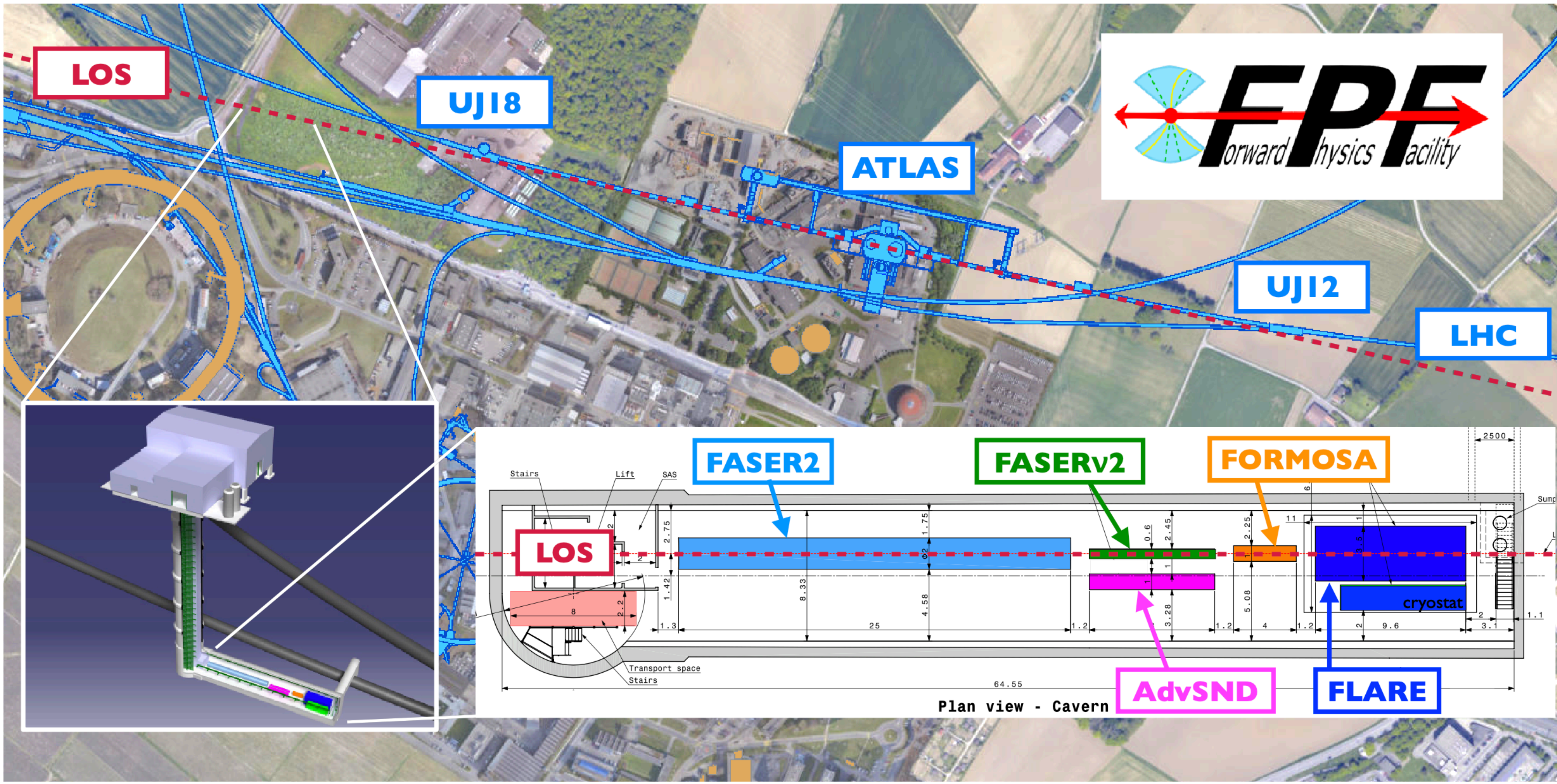

***Lydia's talk!***

***2021: first neutrino detection @ FaserNu***



# The Forward Physics Facility

A new facility in a tailor-made underground cavern hosting a suite of **far-forward experiments** suitable to detect **long-lived BSM particles** and **neutrinos** produced at the HL-LHC



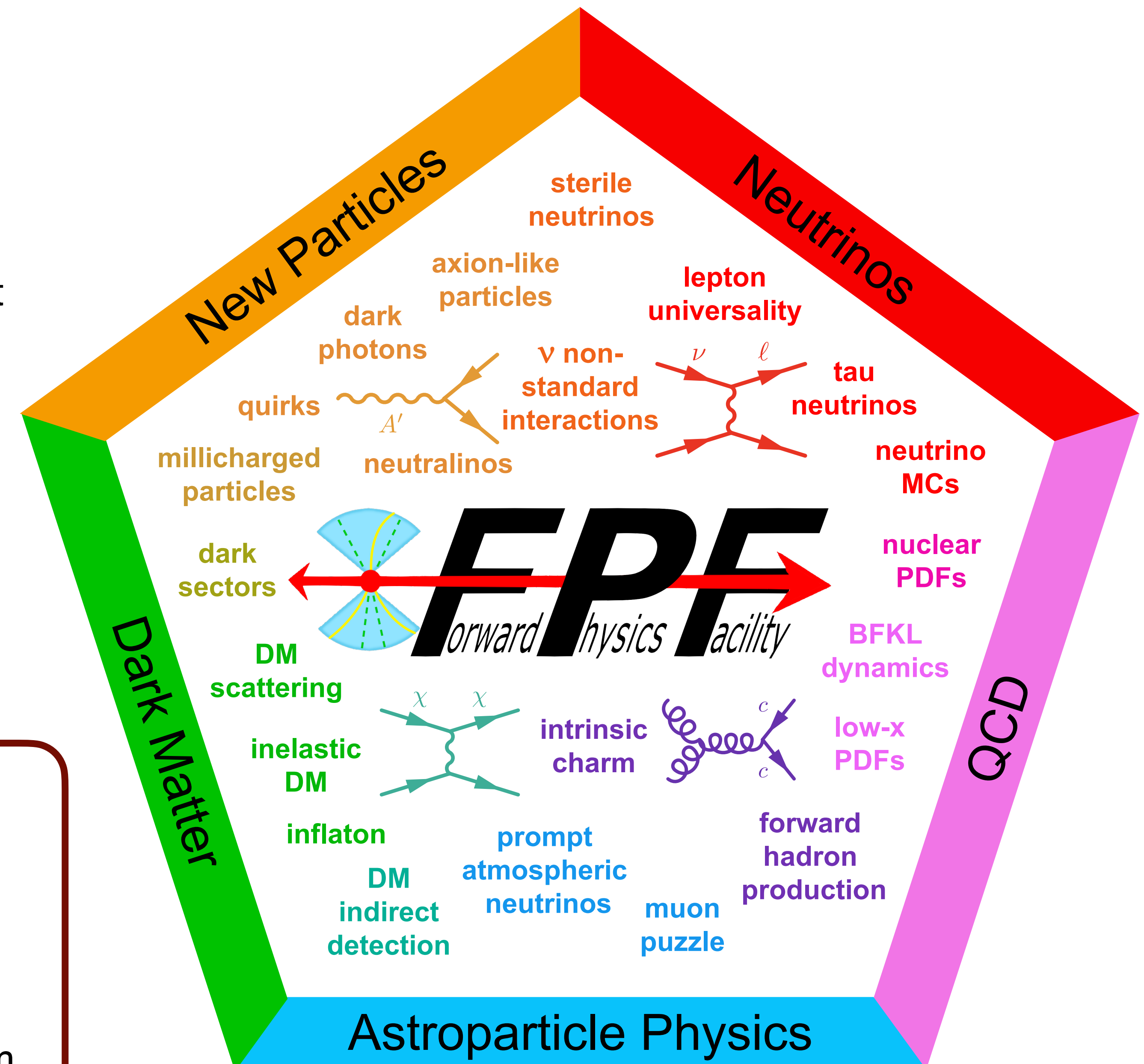

***no modifications to the HL-LHC infrastructure or operations required***

# FPF physics potential

- BSM searches
  - **Light BSM particles** produced in the very forward direction
  - Decaying **dark sector long-lived particles** (dark photons, dark Higgs, heavy neutral leptons…)
  - Milli-charged particles, dark matter scattering, …

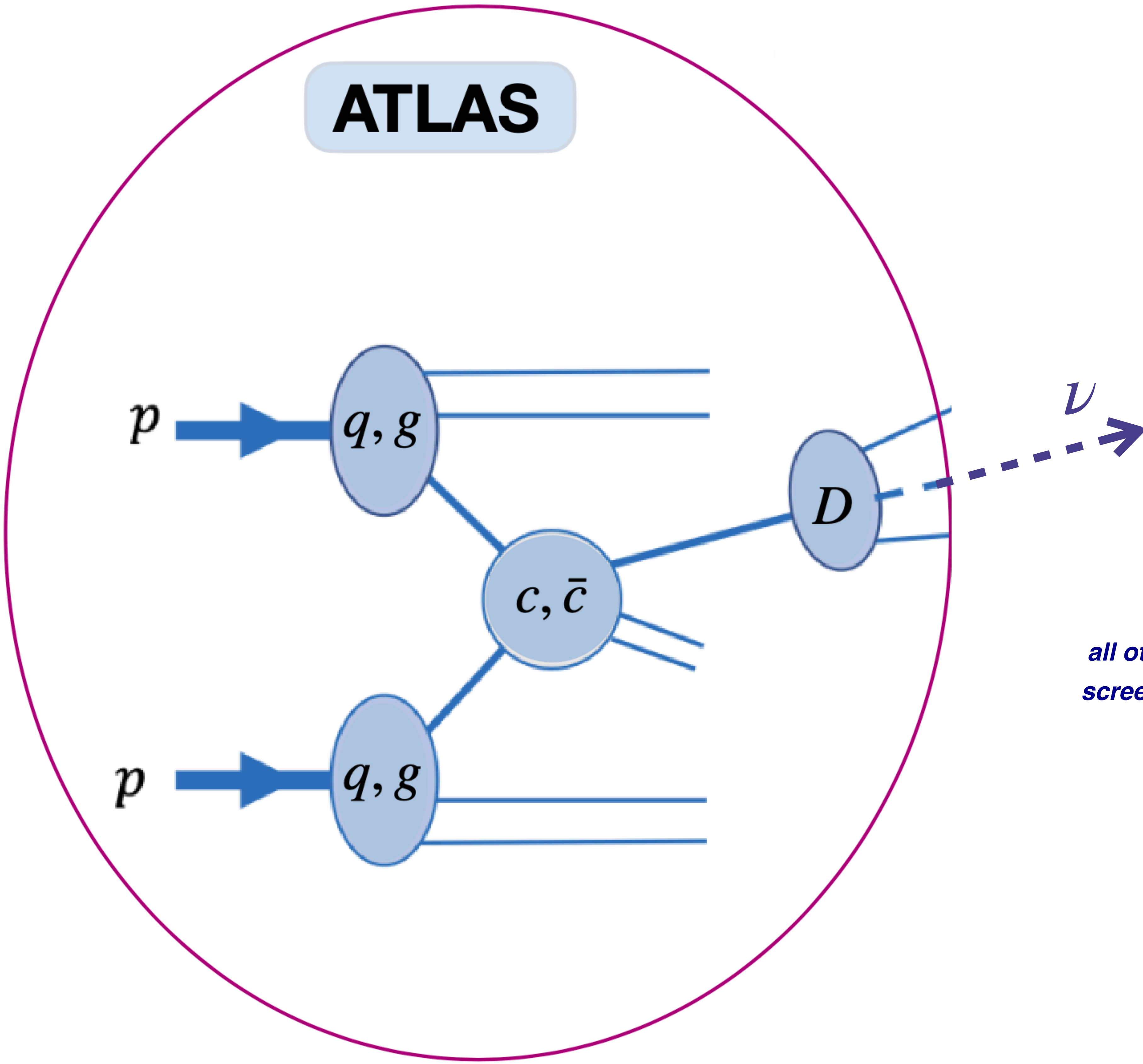
- Neutrino physics
  - **Tau neutrino** studies (10k tau neutrino interactions, current world sample <20)
  - Separation of tau neutrino / anti-neutrino, constrain tau neutrino EDM
  - Tau neutrino decays into heavy flavour (connection with **LHCb LFV anomalies**)
  - **EFT constraints** on neutrino interactions

- QCD, hadron structure, and astroparticle physics
  - **Neutrino cross section** measurements (energy region not covered by any other experiment)
  - Neutrino DIS to constrain **proton and nuclear structure**
  - Testing **BFKL dynamics** in LHC collisions, modelling charm hadron production in forward region
  - Key input for neutrino (IceCube, KM3NET) and cosmic ray **astroparticle experiments**



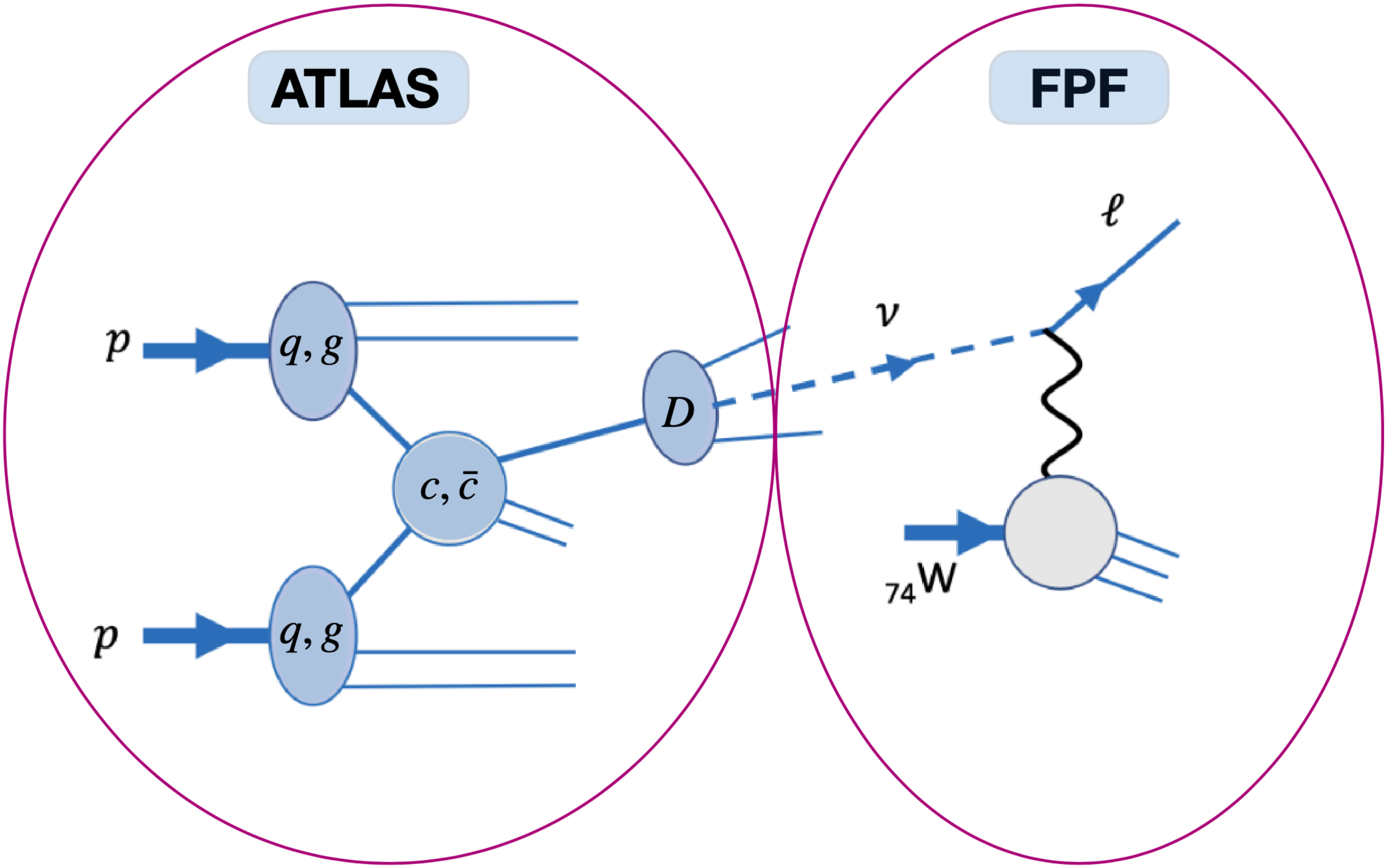
# QCD and Neutrino Interactions at the FPF

# Neutrino production and detection

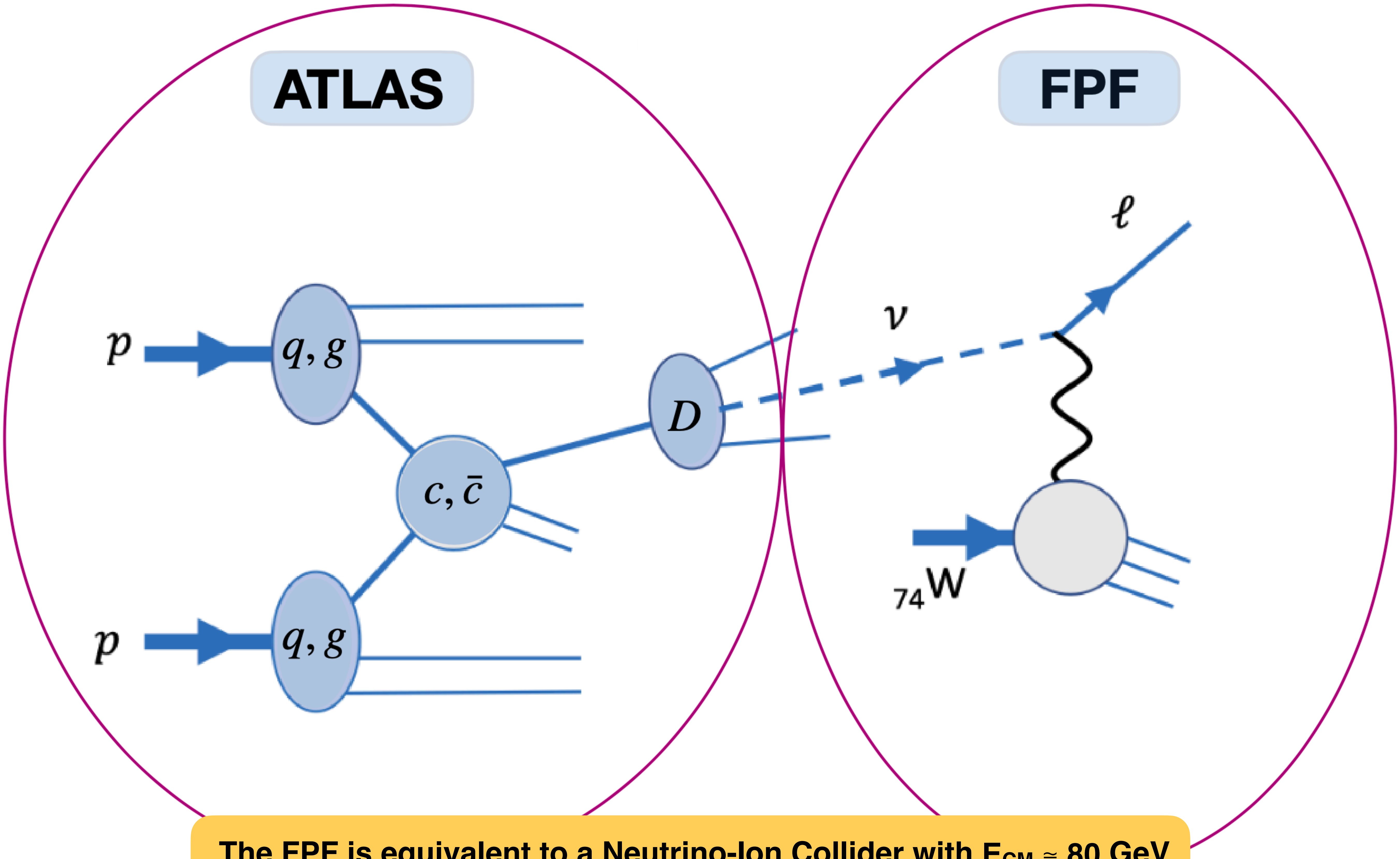



*all other SM particles (except muons)*
*screened by 1km of rock and concrete*

# Neutrino production and detection

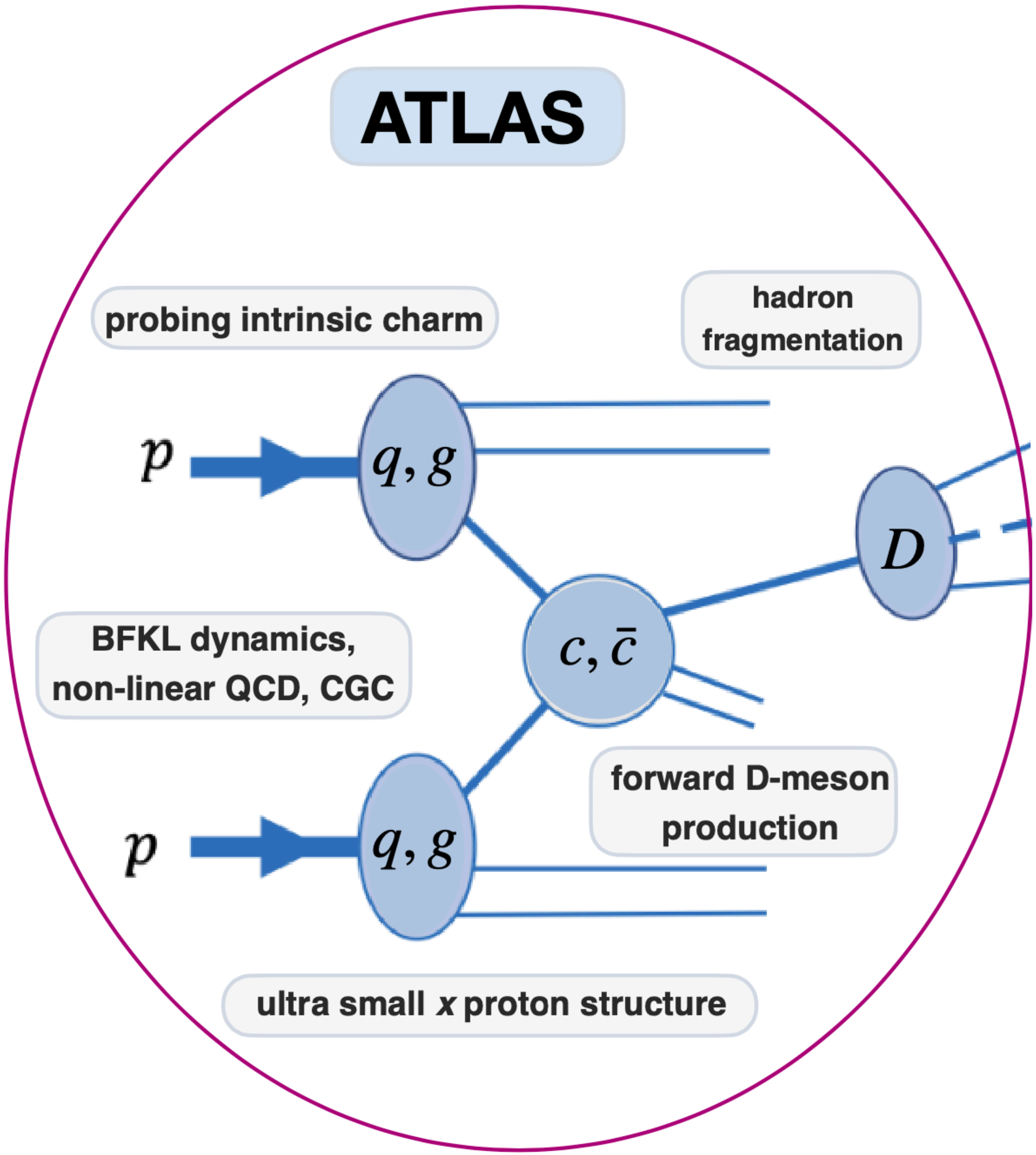


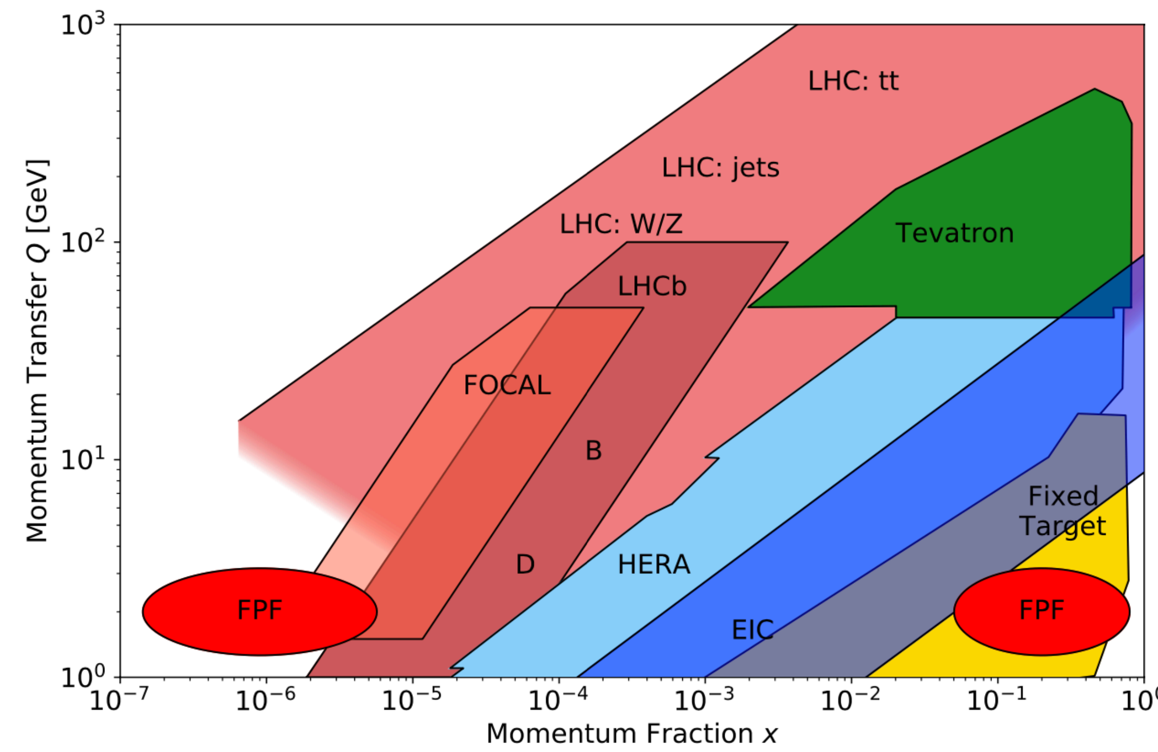
# Neutrino production and detection




The FPF is equivalent to a Neutrino-Ion Collider with $E_{CM} \approx 80$ GeV

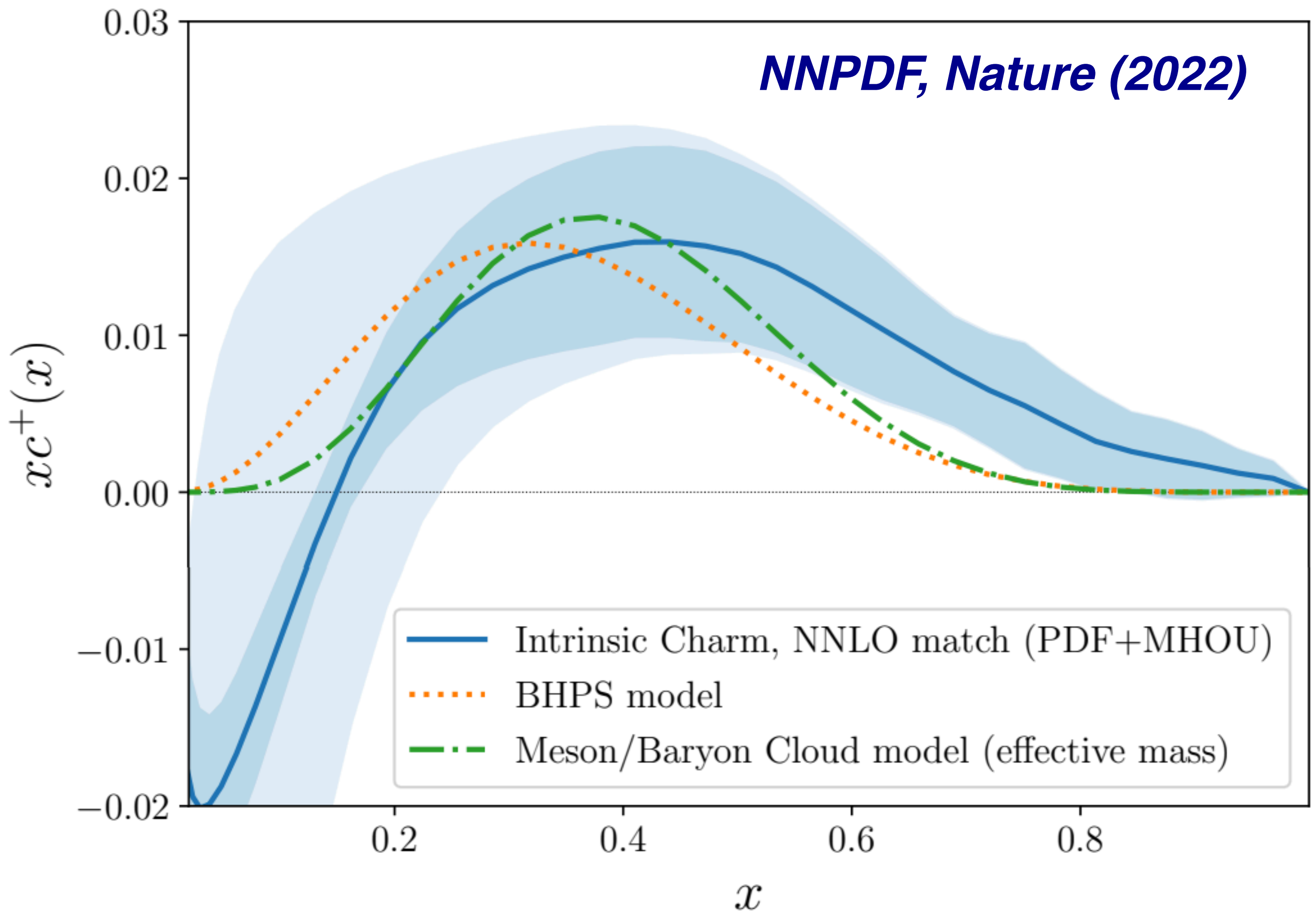
# QCD at the FPF

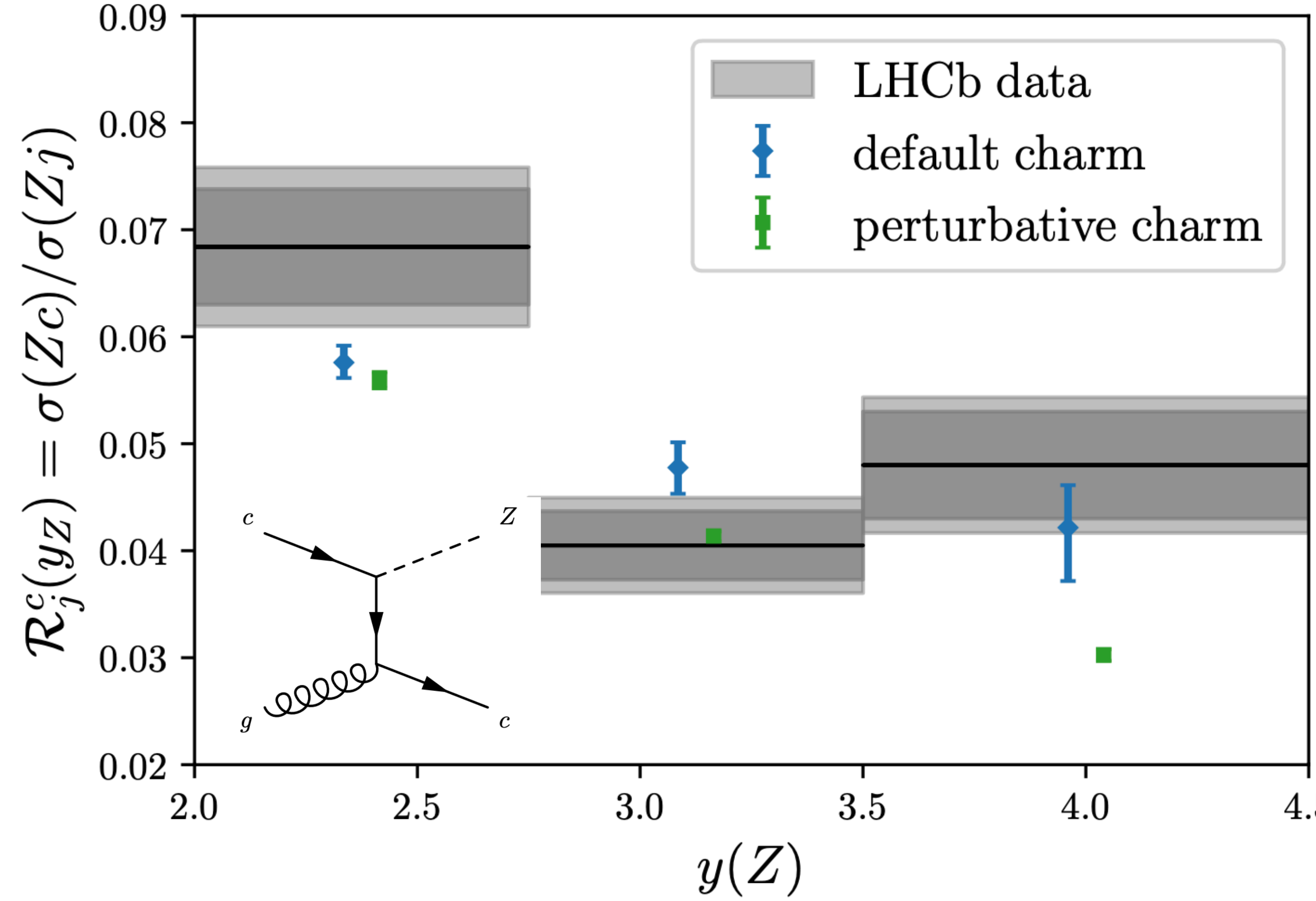


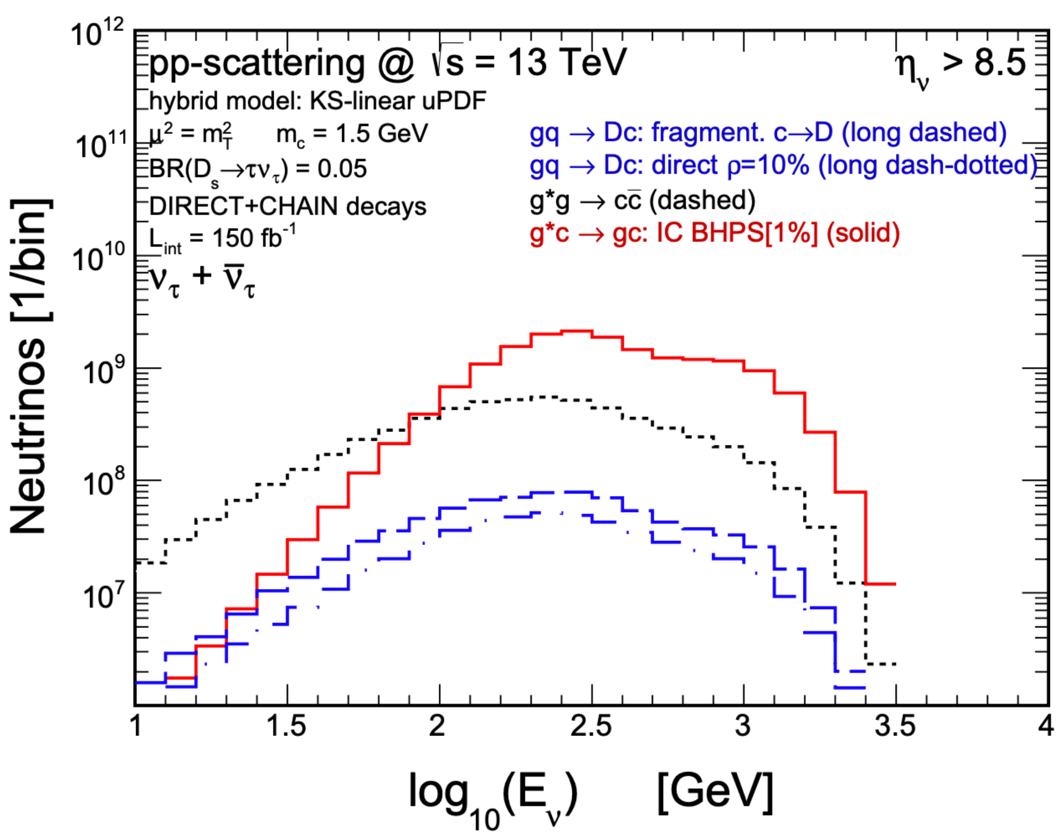




- **Forward particle production** (light hadrons & D-mesons) sensitive down to ***x*=10$^{-7}$**
- Ultra small-*x* proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of **forward hadron fragmentation**
- Constraints on **intrinsic charm**

# QCD at the FPF

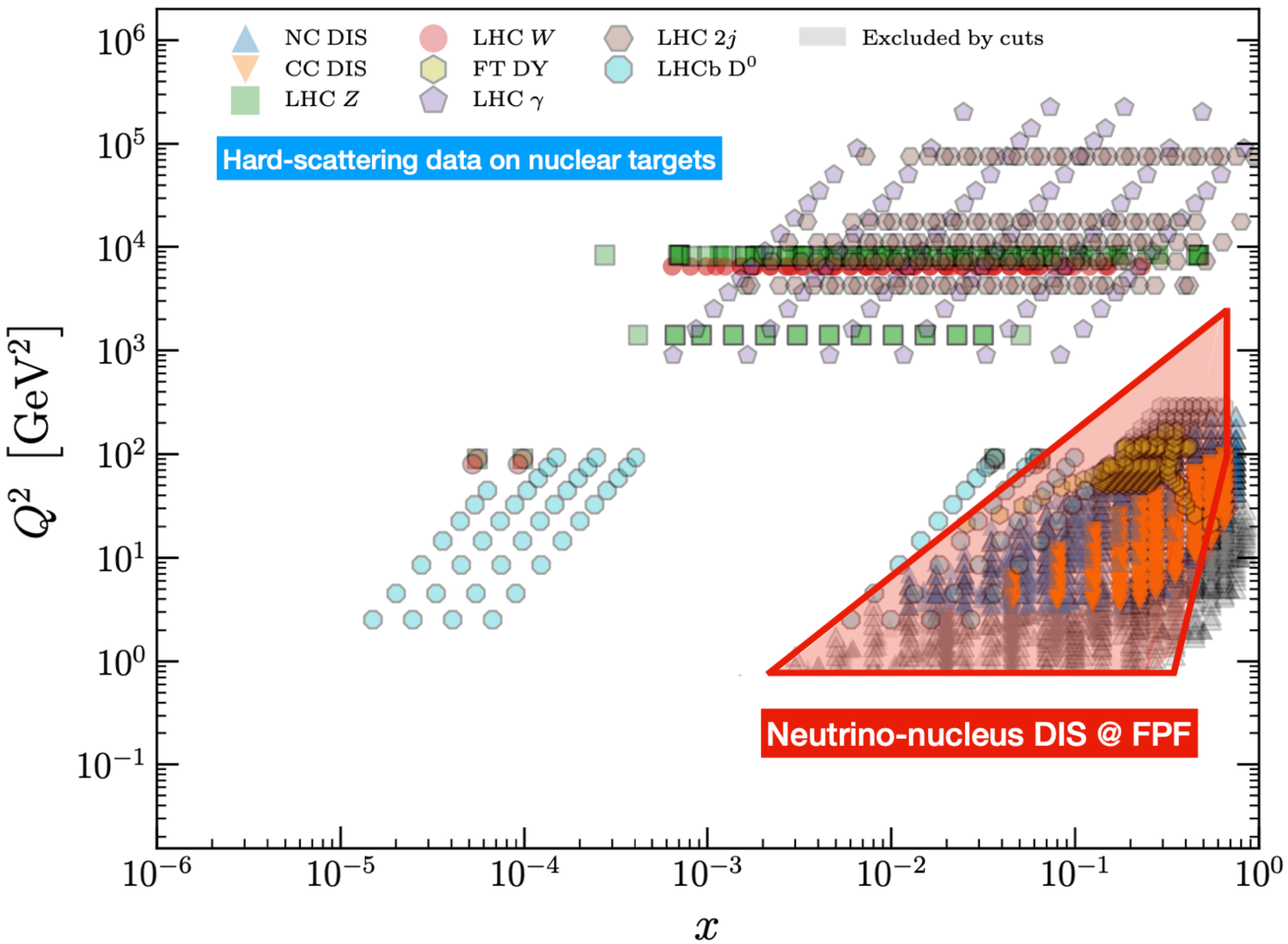


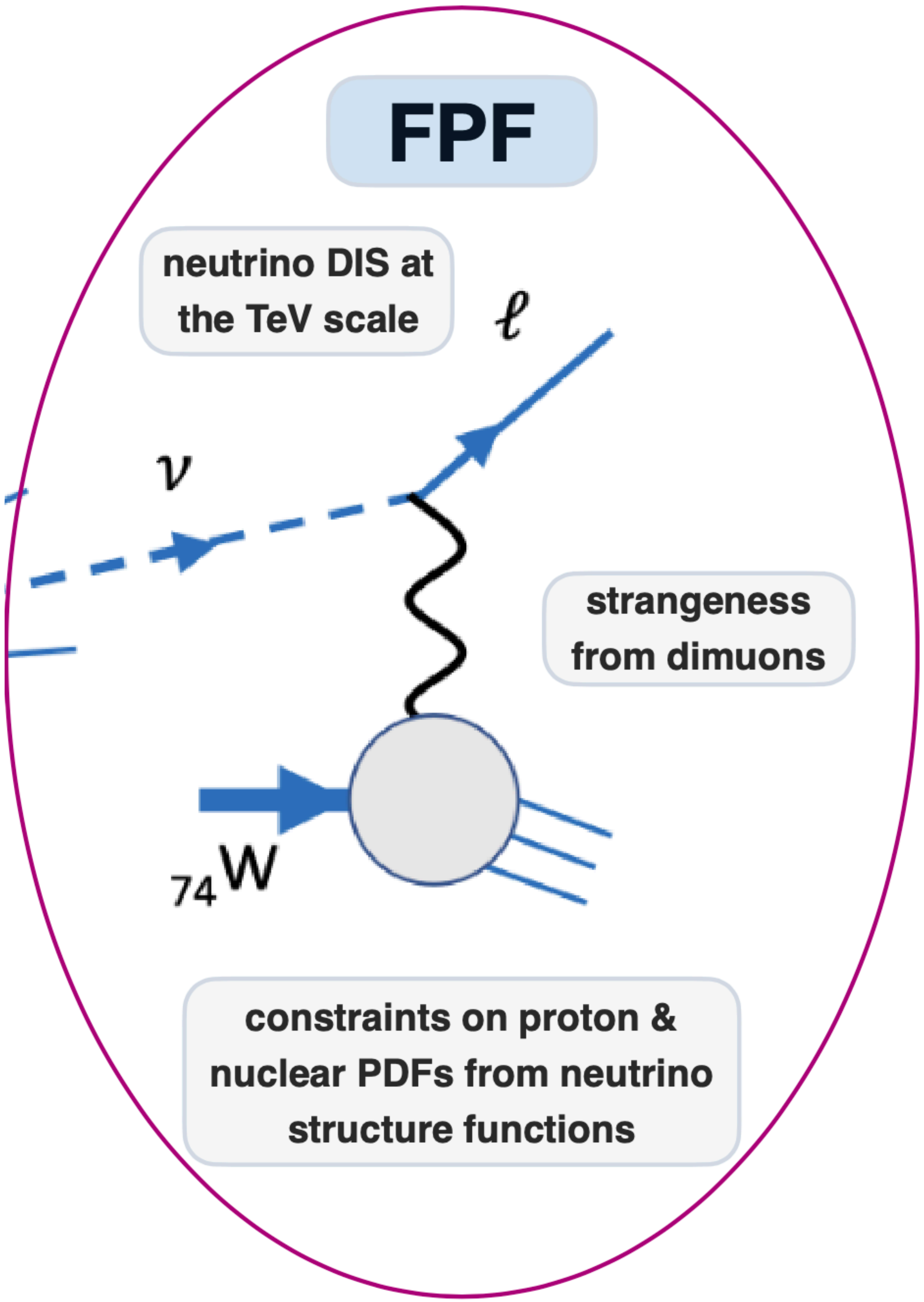




- Recent evidence for **intrinsic charm quarks** in the proton from global QCD analysis, validated by LHCb *Z+c* data
- IC enhances rates for **forward charm production** leading to e.g. factor 3 enhancement in **tau neutrino rates at FPF**
- FPF unique probe of intrinsic heavy quarks, key feedback for **prompt neutrino flux** calculations at IceCube/KM3NET

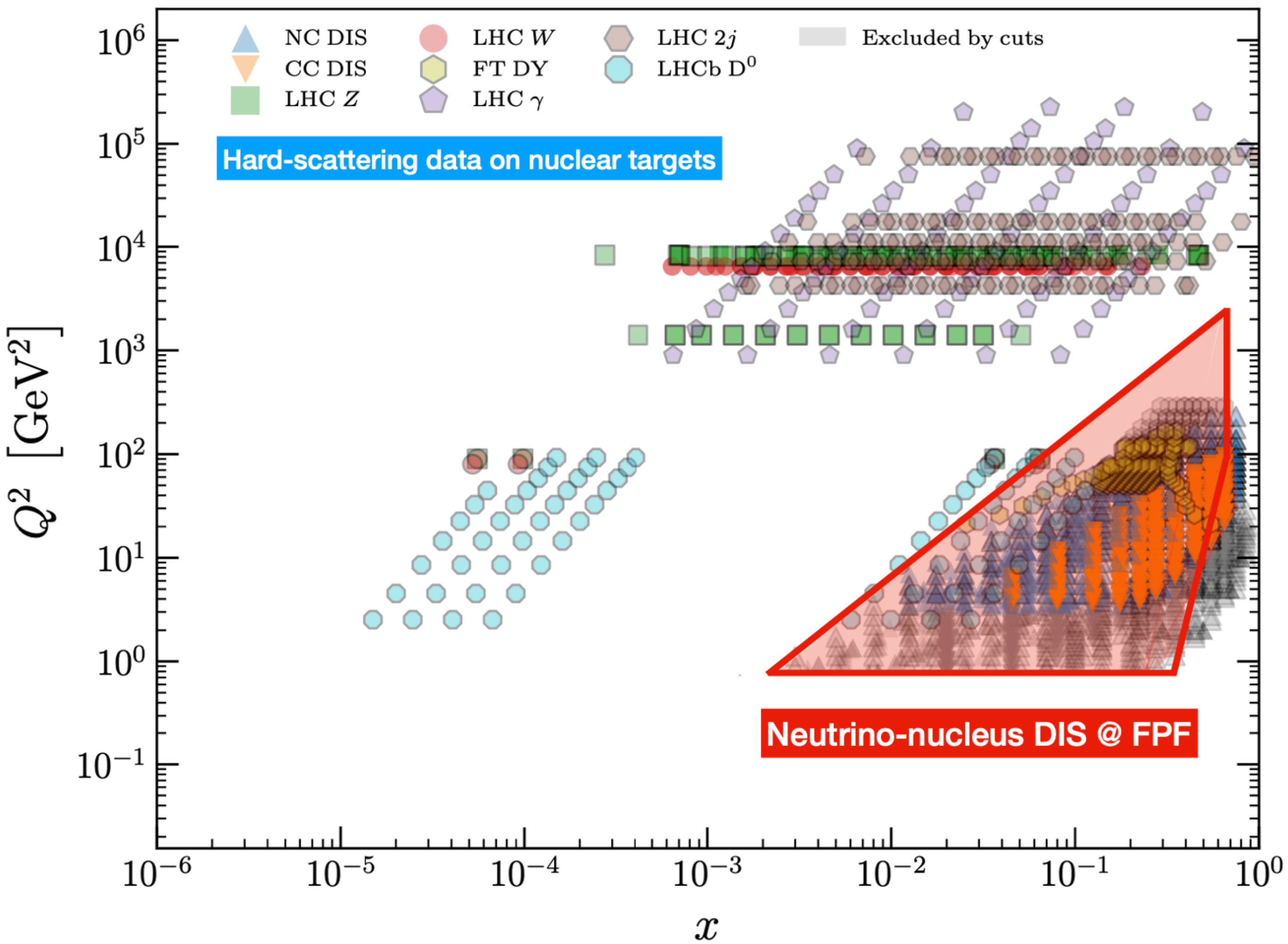
# QCD at the FPF

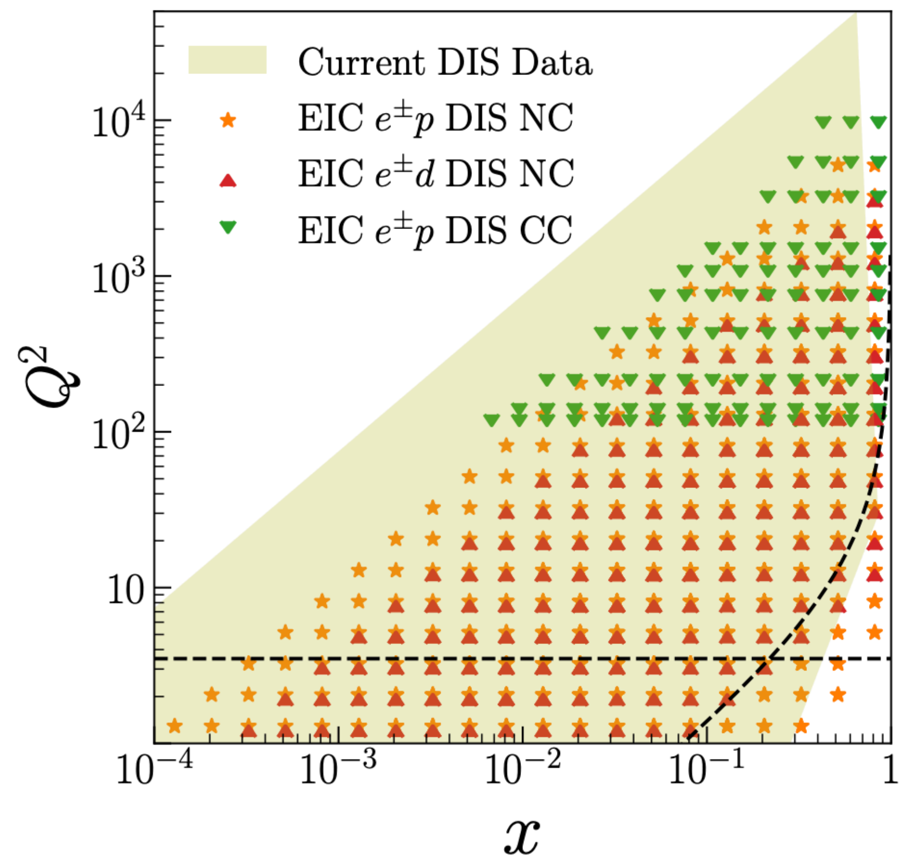


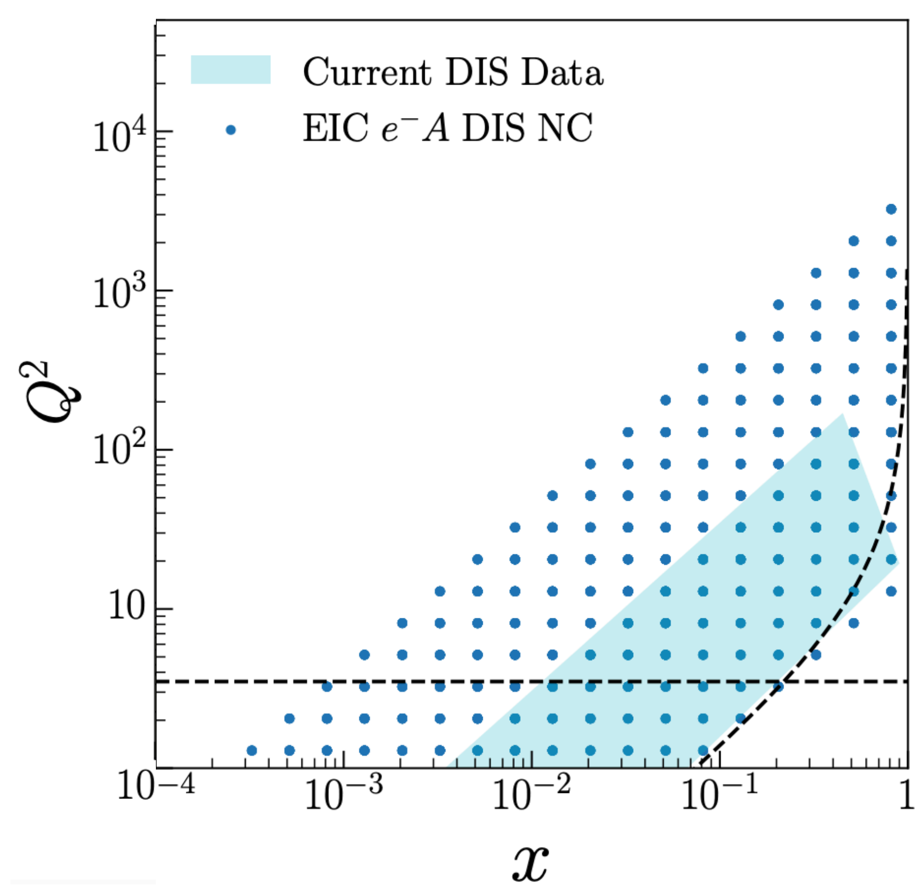




- Deep-inelastic CC scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs**

# QCD at the FPF




- 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**

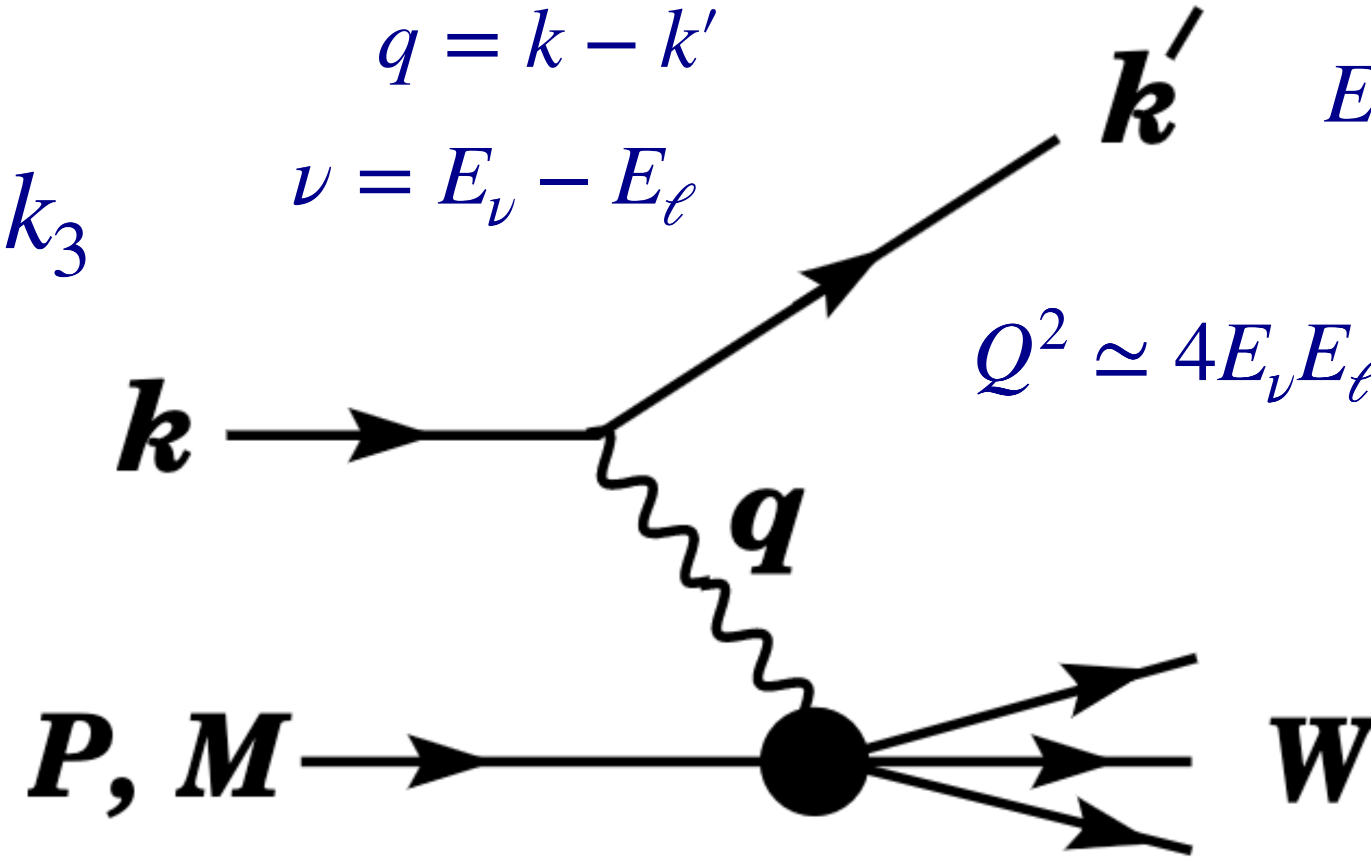
# Probing hadron structure @ FPF

$$q = k - k'$$

$$\nu = E_\nu - E_\ell$$

$$E_\ell = k'_0$$

$$E_\nu = k_0 = k_3$$




$$Q^2 \simeq 4E_\nu E_\ell \sin^2(\theta/2)$$

$$y = \frac{\nu}{E_\nu} = 1 - \frac{E_\ell}{E_\nu}$$

$$E_h = E_\nu - E_\ell$$

$$x = \frac{Q^2}{2m_N\nu}$$

$$W^2 = Q^2\frac{(1-x)}{x} = m_N^2 + 2m_N\nu - Q^2$$

- At the FPF the **flux and flavour of the incoming neutrinos depends on the energy**: we can either take it from existing calculation or constrain it from the data
- Focus on **charged-current inclusive scattering**, with a single charged lepton in final state. Extend to semi-inclusive processes (e.g. **dimuon production**) afterwards
- Model how each experiment measures final-state particles to **reconstruct the DIS kinematics**

# Probing hadron structure @ FPF

- Assume that we can access the **outgoing charged lepton energy**, the **lepton scattering angle**, and the **total hadronic energy or invariant mass of the hadronic final state**

$$\left(E_\ell,\ \theta,\ W^2\right) \quad \text{or} \quad \left(E_\ell,\ \theta,\ E_h\right)$$

- Then we can reconstruct **Bjorken-*x*, momentum transfer square**, and **incoming neutrino energy**

$$\left(x,\ Q^2,\ E_\nu\right) \quad \text{or} \quad \left(x,\ Q^2,\ y\right)$$

by using the following equations

$$E_h = E_\nu - E_\ell \longrightarrow \text{fixes neutrino energy}$$

$$Q^2 \simeq 4E_\nu E_\ell \sin^2(\theta/2) \longrightarrow \text{fixes four-momentum transfer}$$

$$x = \frac{Q^2}{2m_N(E_\nu - E_\ell)} \longrightarrow \text{fixes Bjorken-}x$$

***nb ideally we'd like to over-constrain the kinematics by measuring more variables than unknowns***

# Probing hadron structure @ FPF

- Given the DIS kinematics of an event, the interaction probability will be proportional to the **double-differential DIS cross-section**

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/2\pi}{\left(1+Q^2/m_W^2\right)^2}\left[(1-y)F_2^{\nu A}(x,Q^2) + y^2 x F_1^{\nu A}(x,Q^2) + y\left(1-\frac{y}{2}\right) x F_3^{\nu A}(x,Q^2)\right]$$

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

- Traditionally neutrino measurements are presented at the level of individual structure functions, but this requires extra assumptions: cleaner to measure directly the **reduced cross-section**

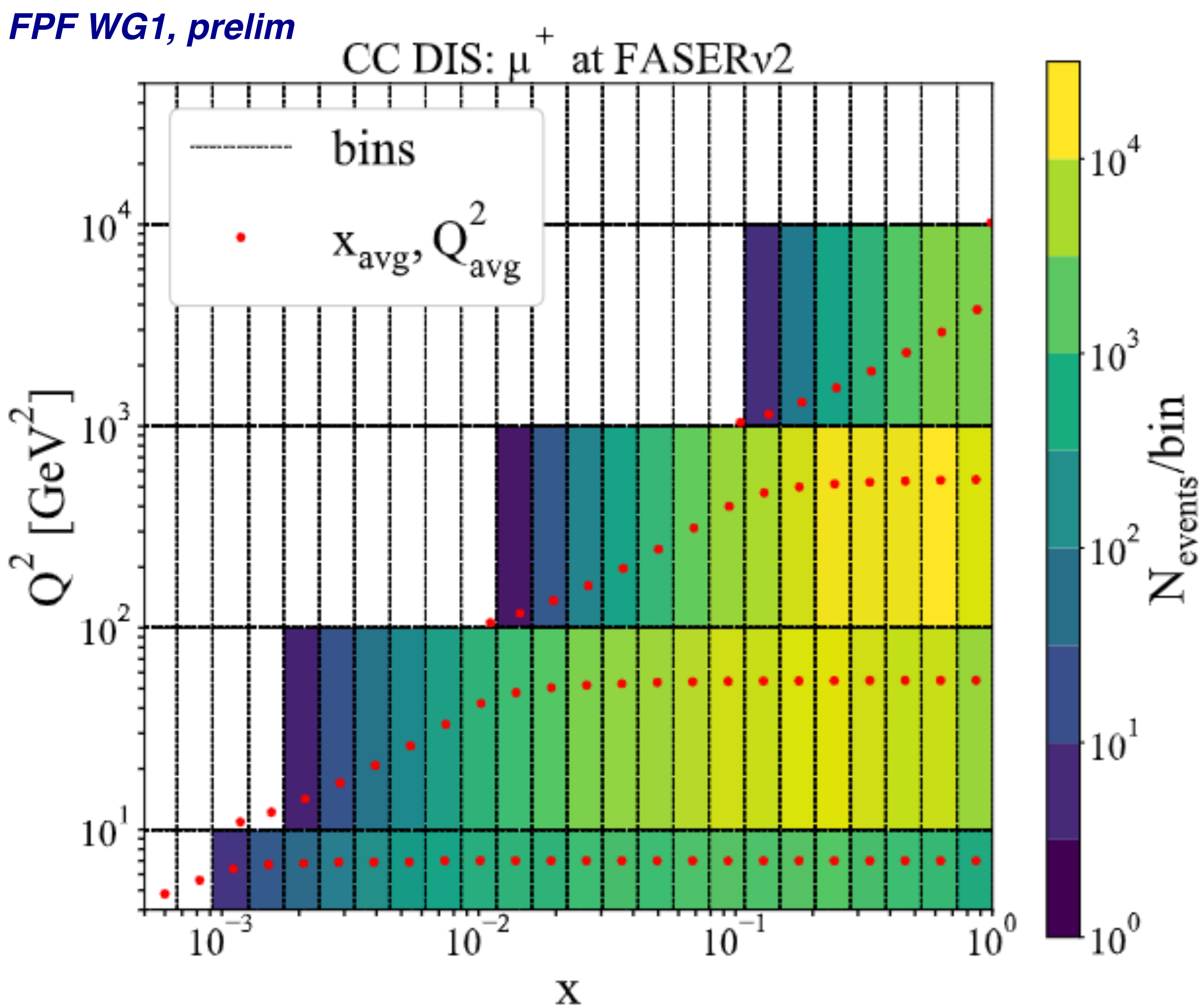
- The number of events in a given bin will be given by

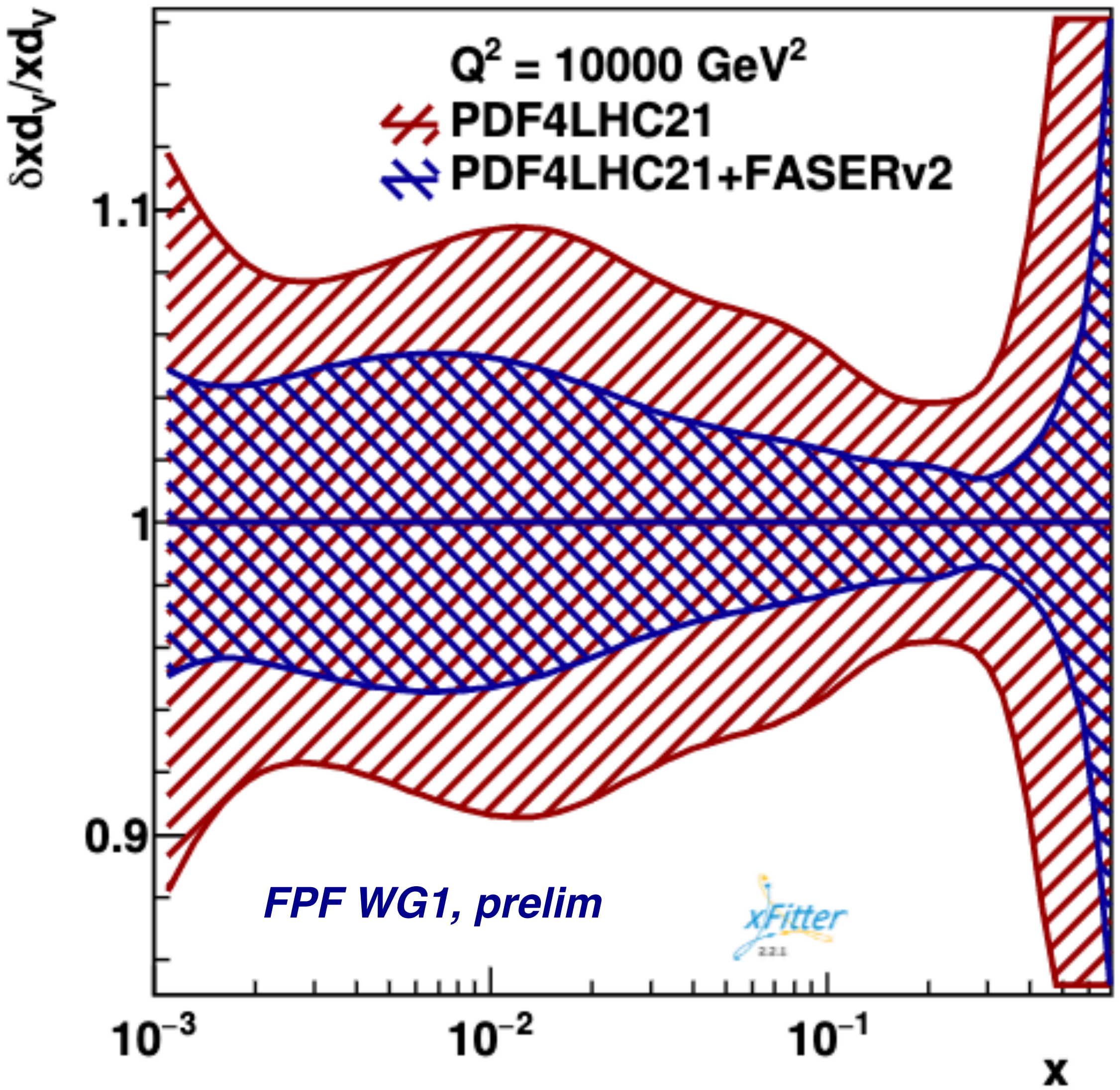
$$N_{\rm ev}(x\in[x_{\rm min},x_{\rm max}], Q^2\in[Q^2_{\rm min},Q^2_{\rm max}, E_\nu\in[E_{\nu,\rm min},E_{\nu,\rm max}]) \propto \int_{x_{\rm min}}^{x_{\rm max}} dx \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} dQ^2 \int_{E_{\nu,\rm min}}^{E_{\nu,\rm max}} dE_\nu \frac{d^2\sigma(x,Q^2,E_\nu)}{dxdy} f(E_\nu)$$

***experiment-dependent factor*** ***scattering cross-section*** ***incoming neutrino flux***

- We have produced **dedicated sets of FPF pseudo-data** for each of the proposed experiments and for different systematic correlation models: used as input in **NNPDF and xFitter PDF projections**

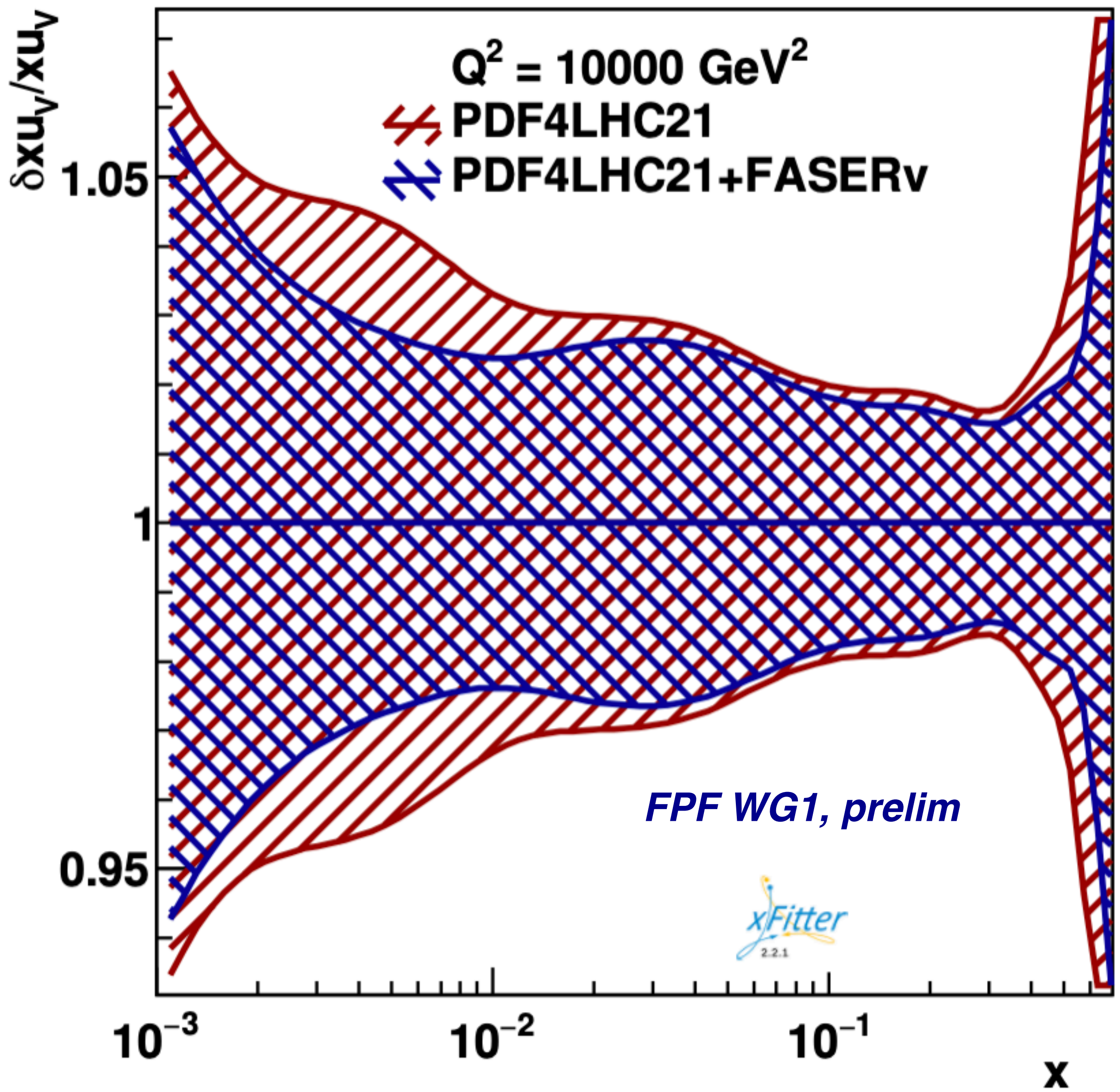
# Probing hadron structure @ FPF

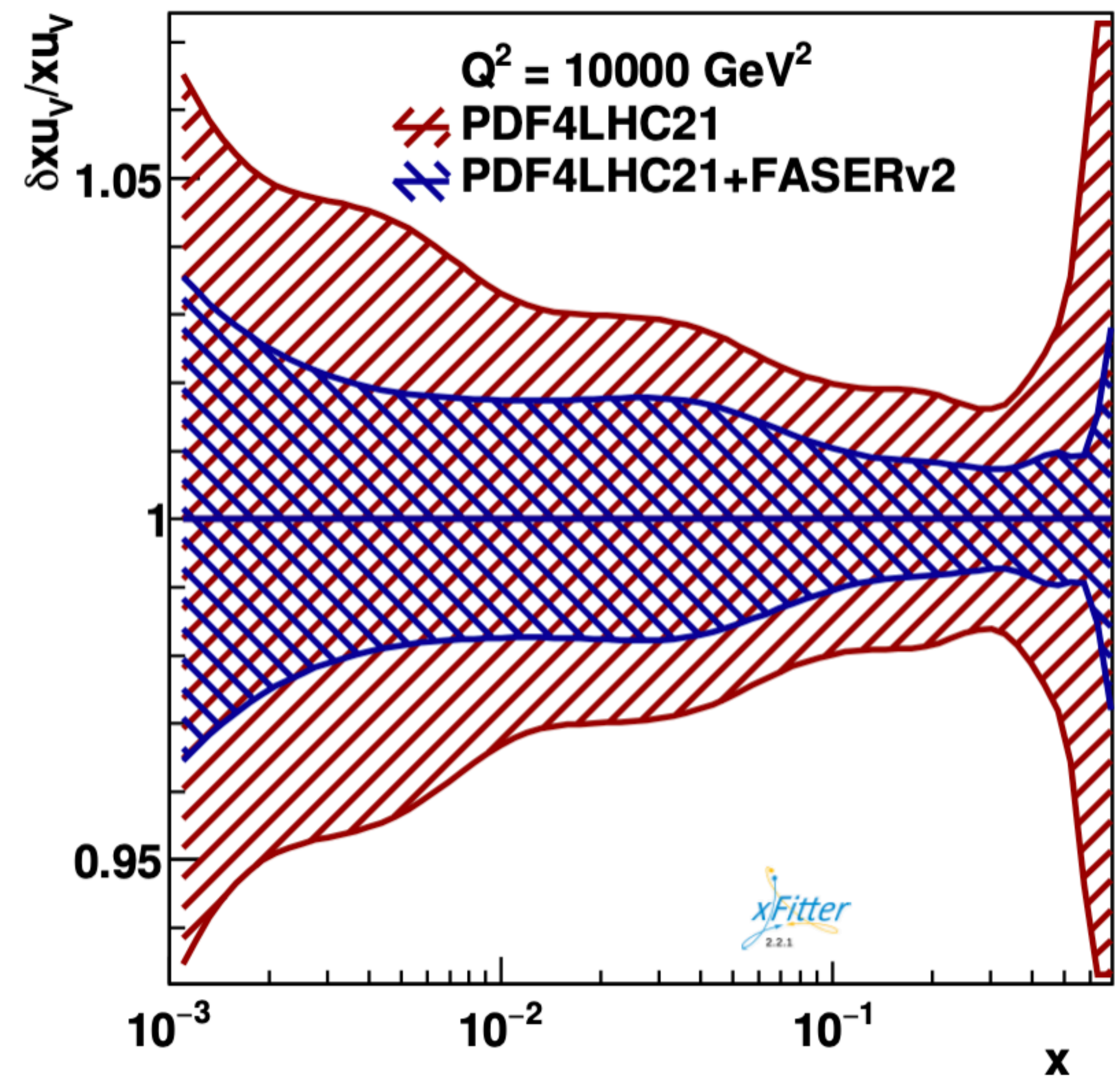



- Large statistics for **inclusive DIS**, with uncertainties at the **few % level** for most of the bins
- When added to PDF4LHC21 via PDF profiling, large impact specially in **up and down valence PDFs**
- Full FPF statistics crucial: PDF impact much reduced e.g. for FASERnu pseudo-data
- Work in progress: implement **realistic systematic correlation models**

# Probing hadron structure @ FPF

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# Probing hadron structure @ FPF

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

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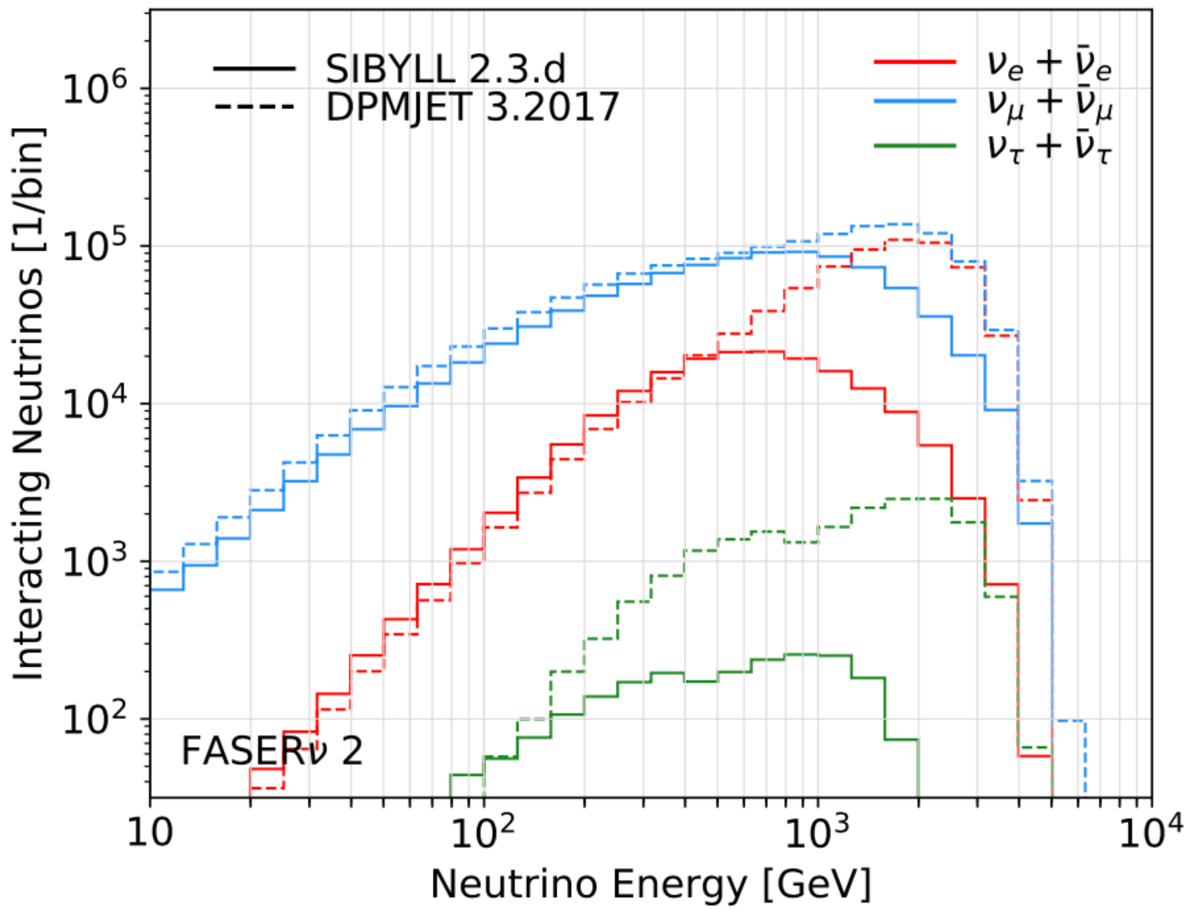
# Neutrino Structure Functions from GeV to EeV energies

arXiv:2302.08527

# The role of the low-$Q$ region

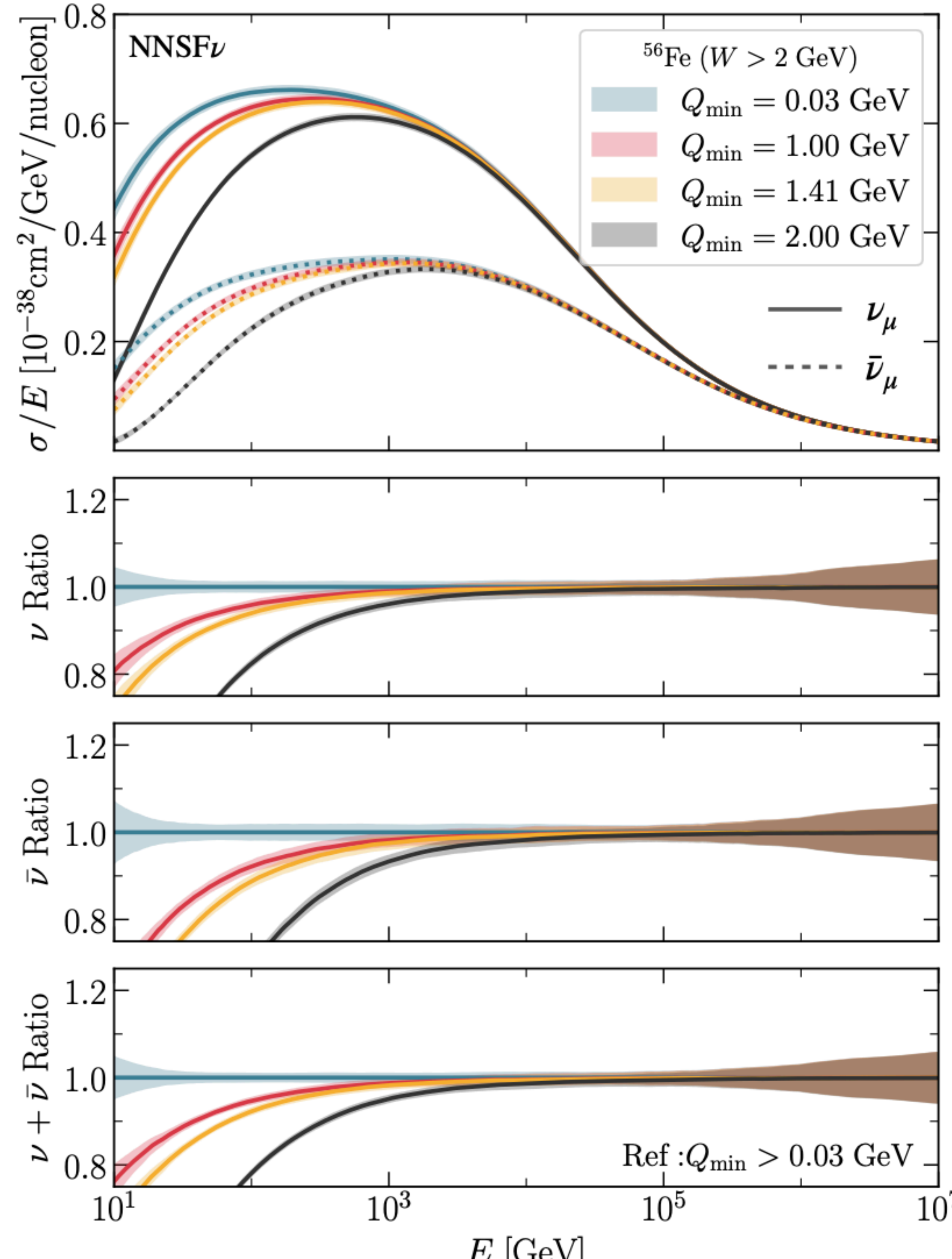
FPF neutrinos have **energy distributions** dominated by region **[100 GeV , 5 TeV]**.

How reliably can we predict their cross-sections and event rates?




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

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



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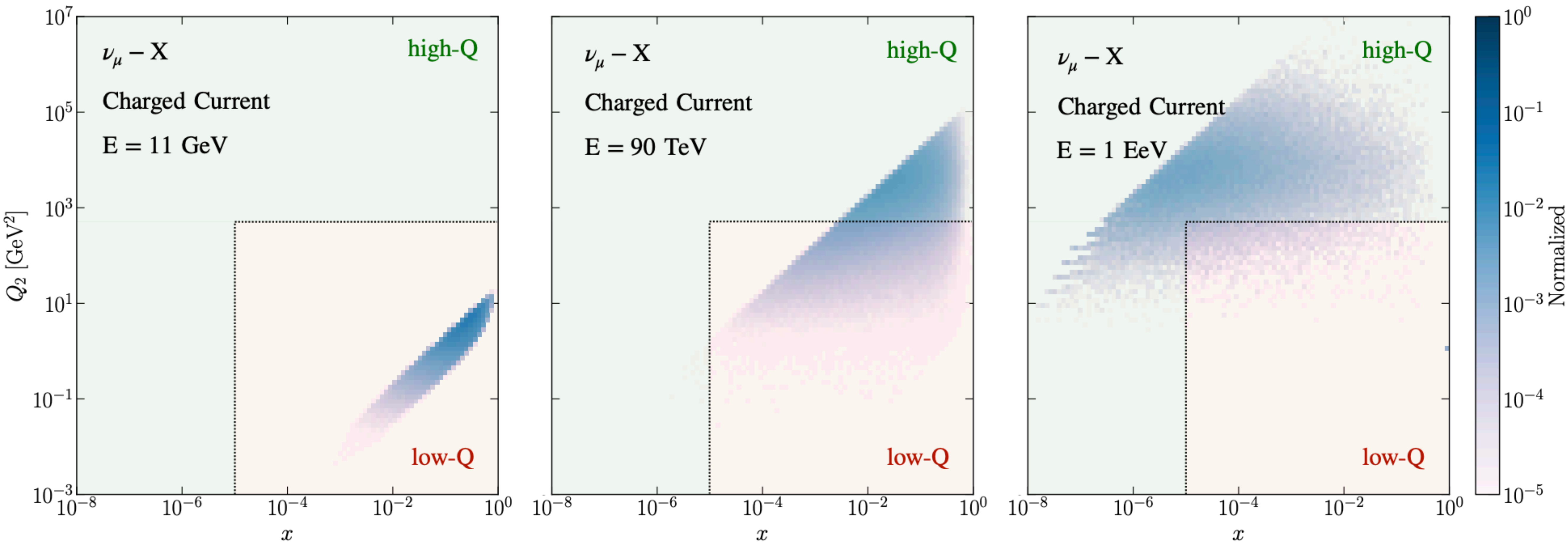


$$\sigma(E_\nu) = \int_{Q^2_{\min}}^{2m_N E_\nu} dQ^2 \left[ \int_{Q^2/(2m_N y E_\nu)}^{1} dx \, \frac{d^2\sigma}{dx dQ^2}(x, Q^2, E_\nu) \right]$$

# State of the art

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

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

**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%)
- Does not provide **uncertainty estimate**, difficult to assess its accuracy and precision
- Cannot be systematically improvable e.g. by new data

# State of the art

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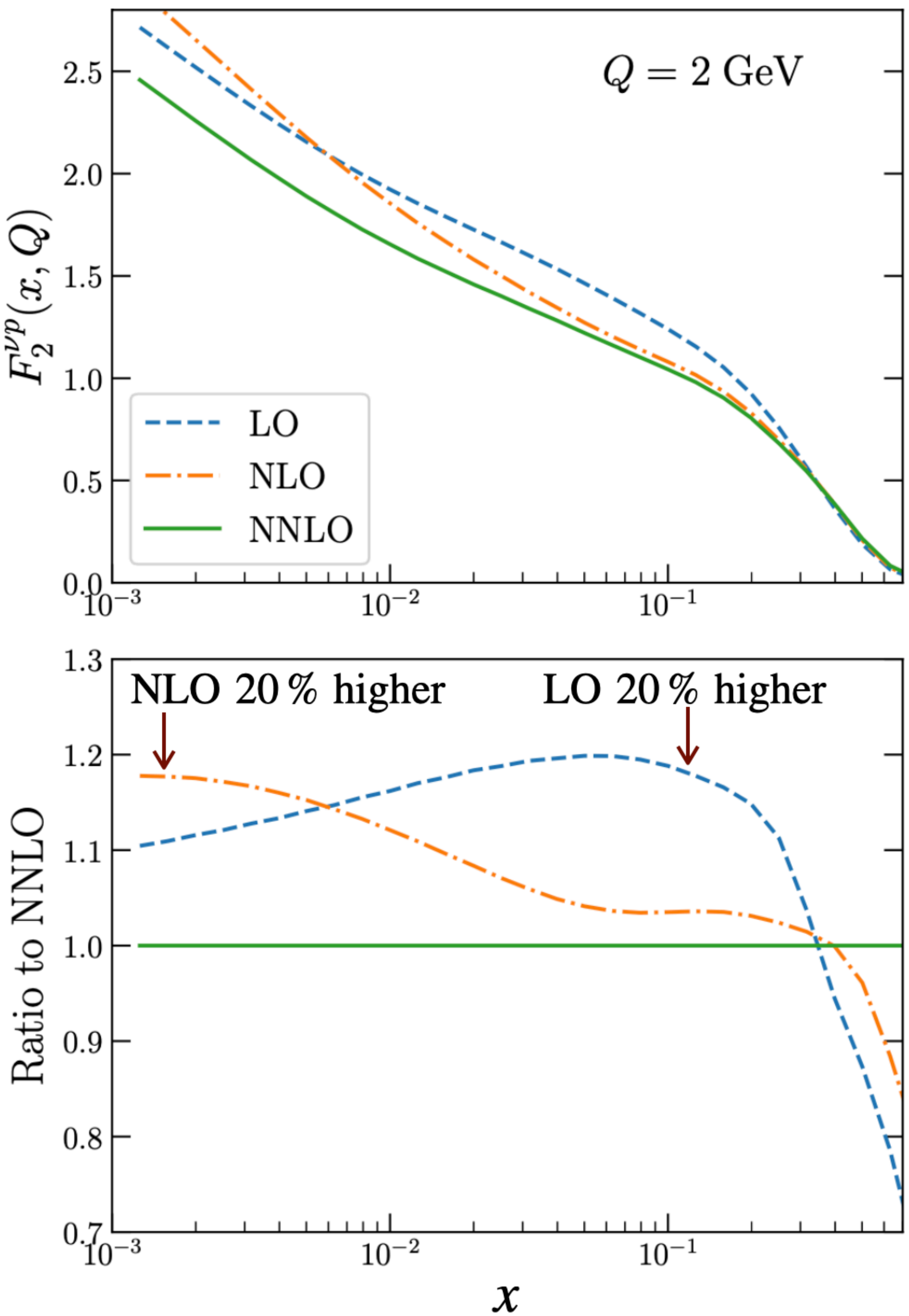
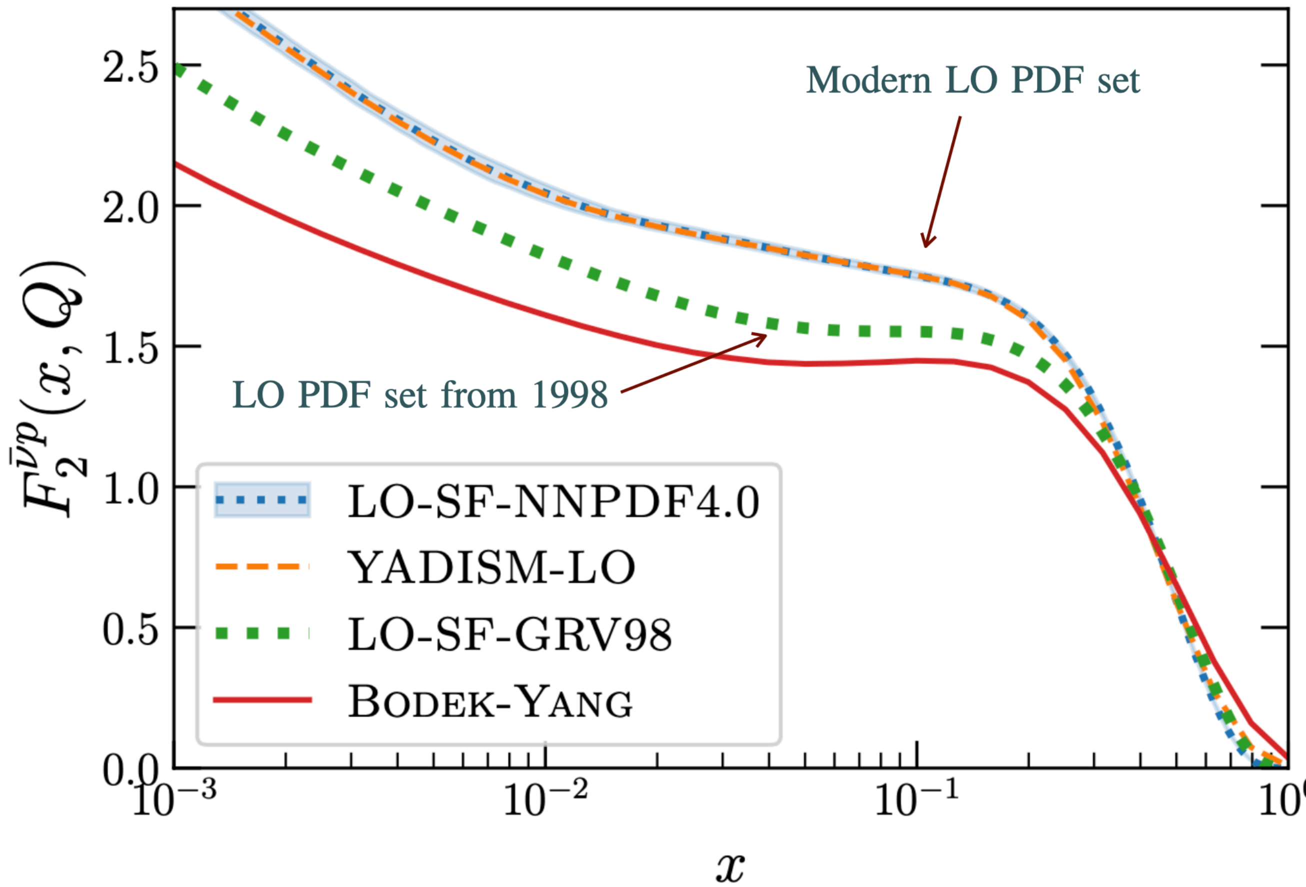
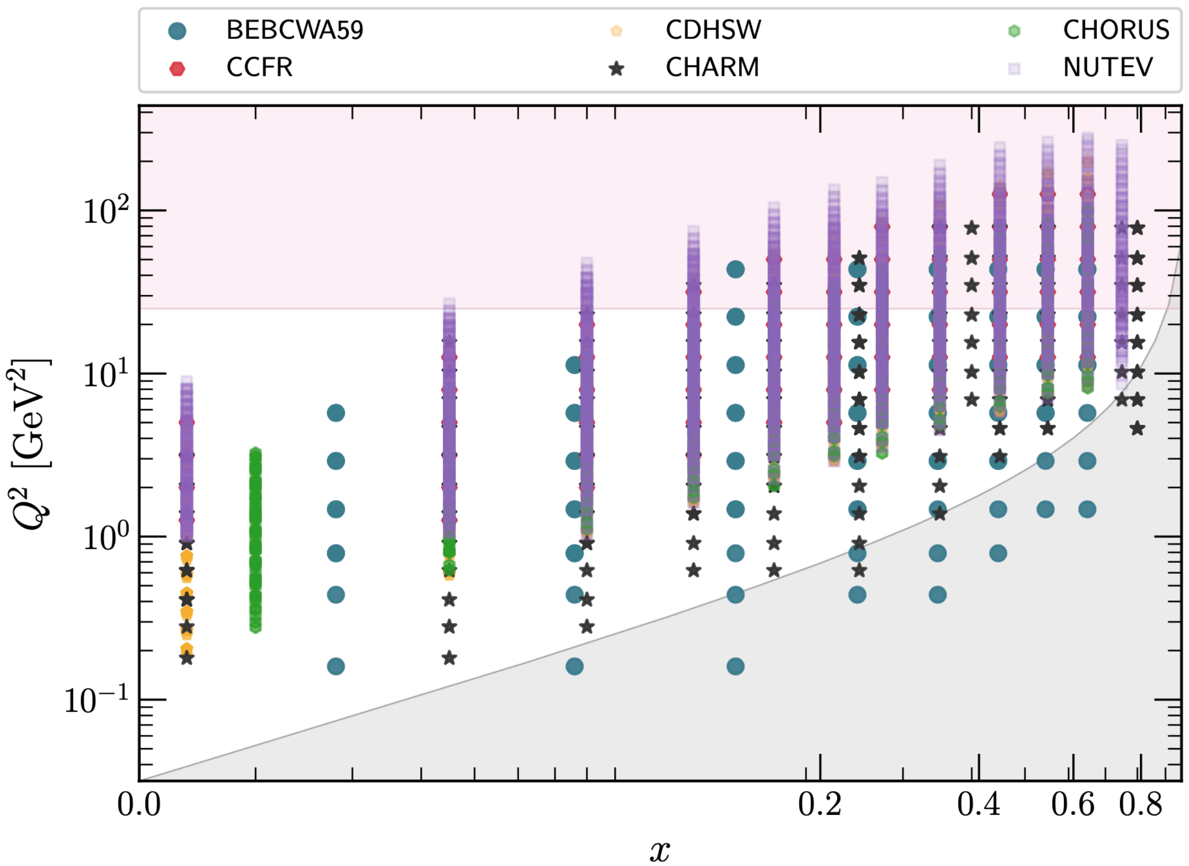


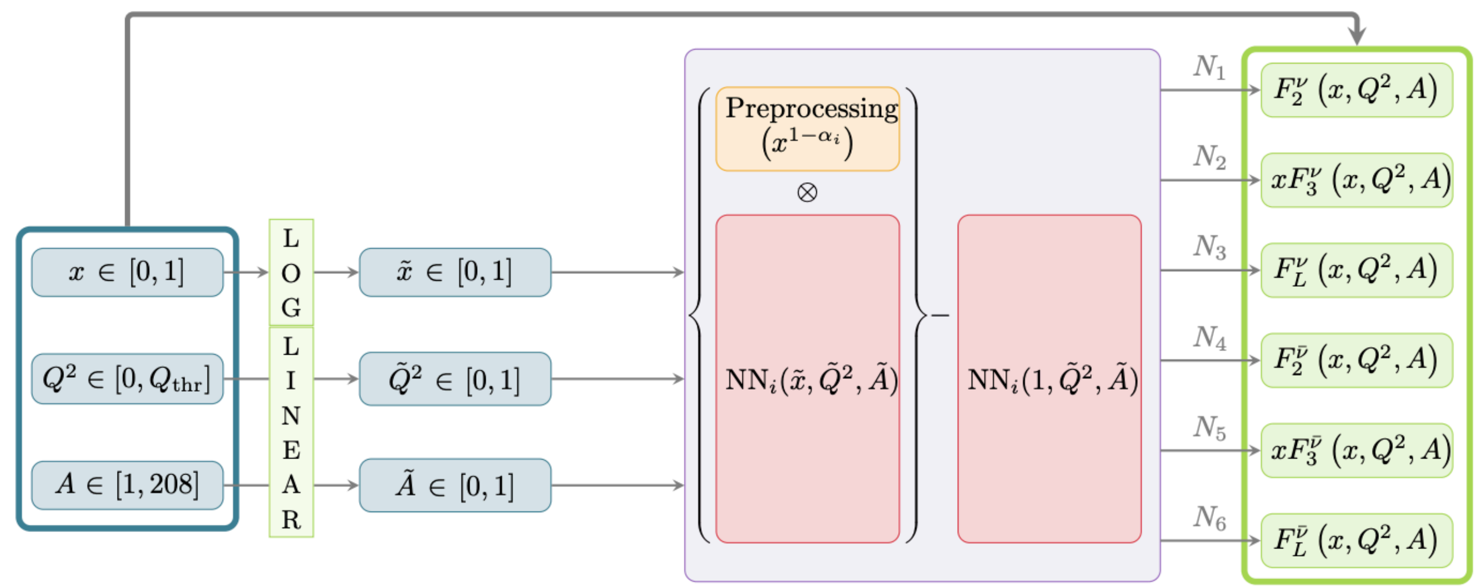




**Improved** models of neutrino-nucleon interactions essential for FPF physics (as well as IceCube, KM3NET, …)

# The NNSFν approach

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



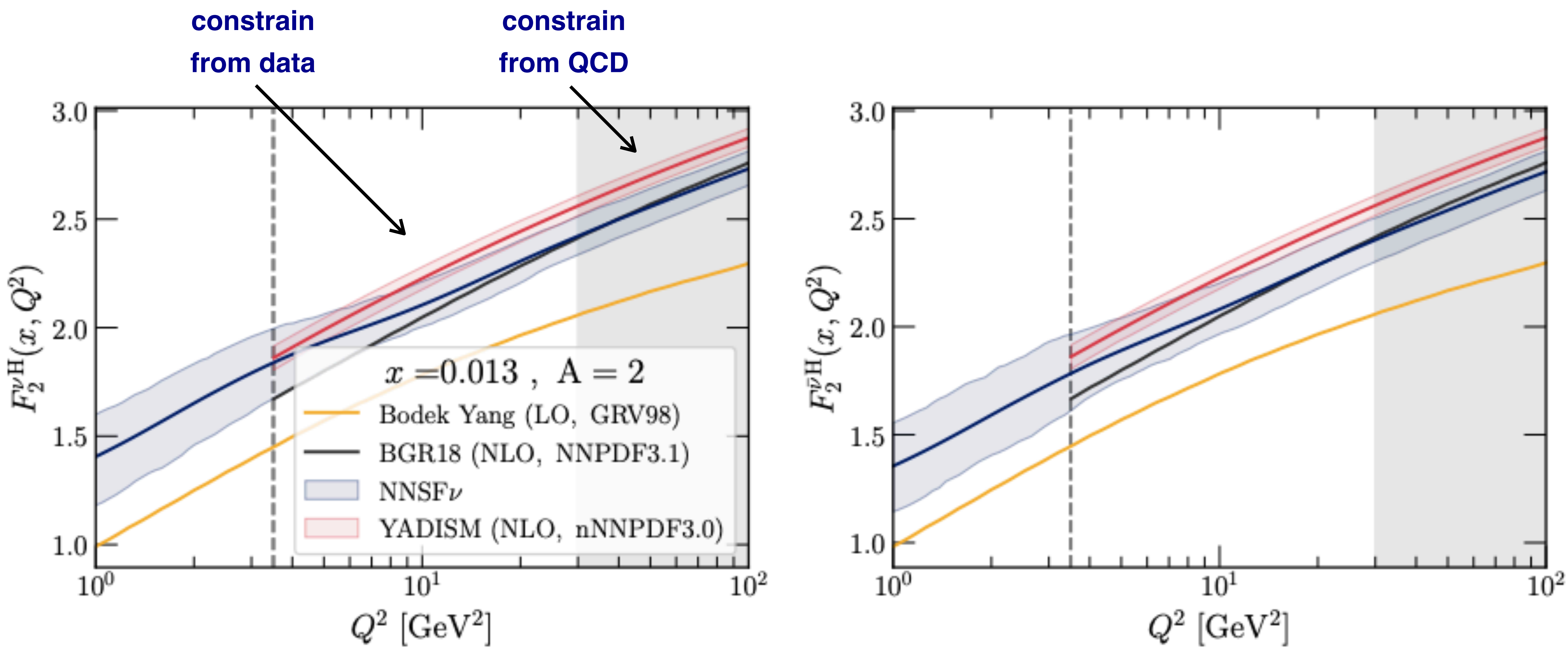




- This data-driven parametrisation is made to **converge to the pQCD calculation** for large enough $Q^2$ values as implemented with Lagrange multipliers

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

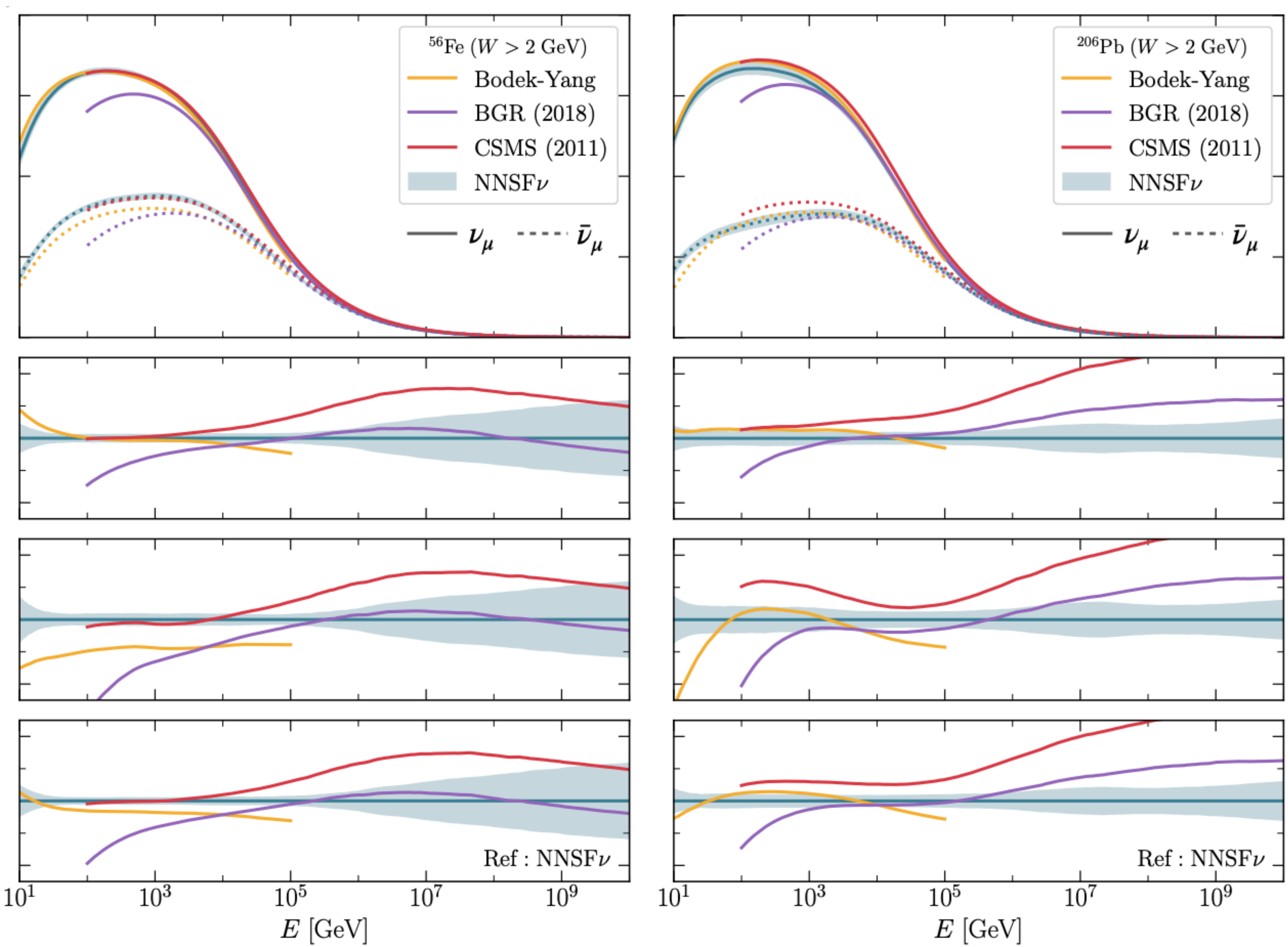
consistent determination of neutrino structure functions valid **for 12 orders of magnitude** from $E_{nu}$ = few GeV up to $E_{nu}=10^{12}$ GeV

# The NNSFv results

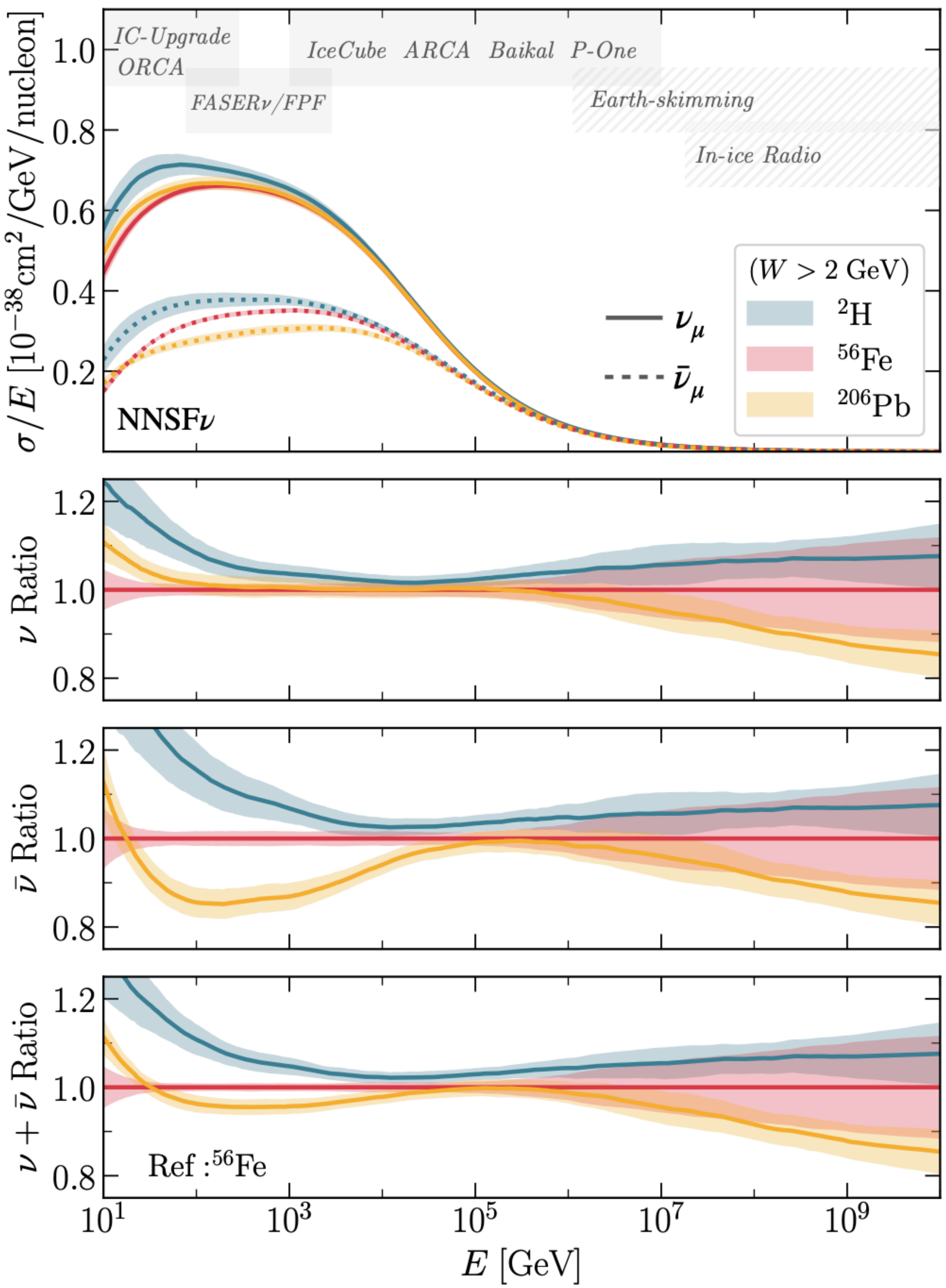


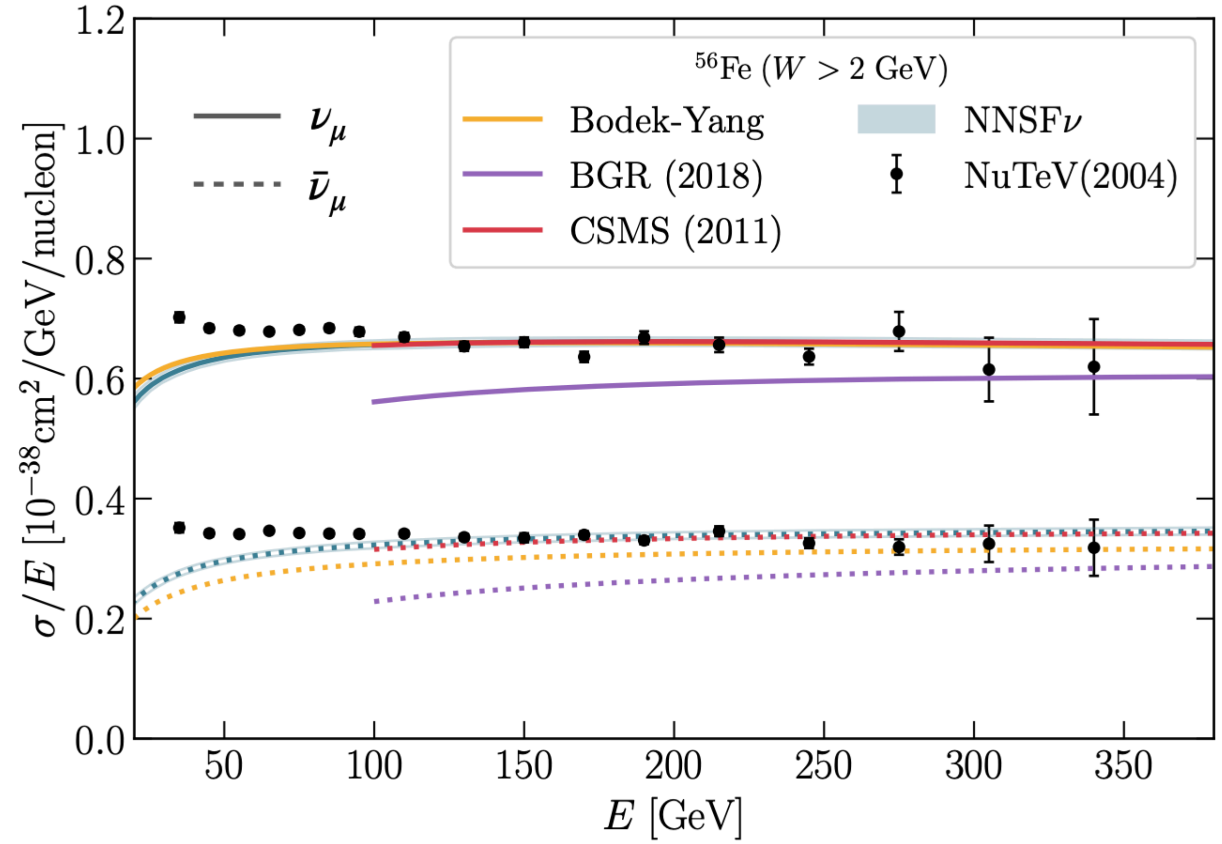

- **Smooth matching** between data-driven and pQCD regions, uncertainty estimate in whole energy range
- Structure functions and integrated cross-sections available via **user-friendly LHAPDF grids**
- For the first time, a **unique theory prediction** for neutrino inelastic scattering suitable for neutrinos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

# The NNSFν results



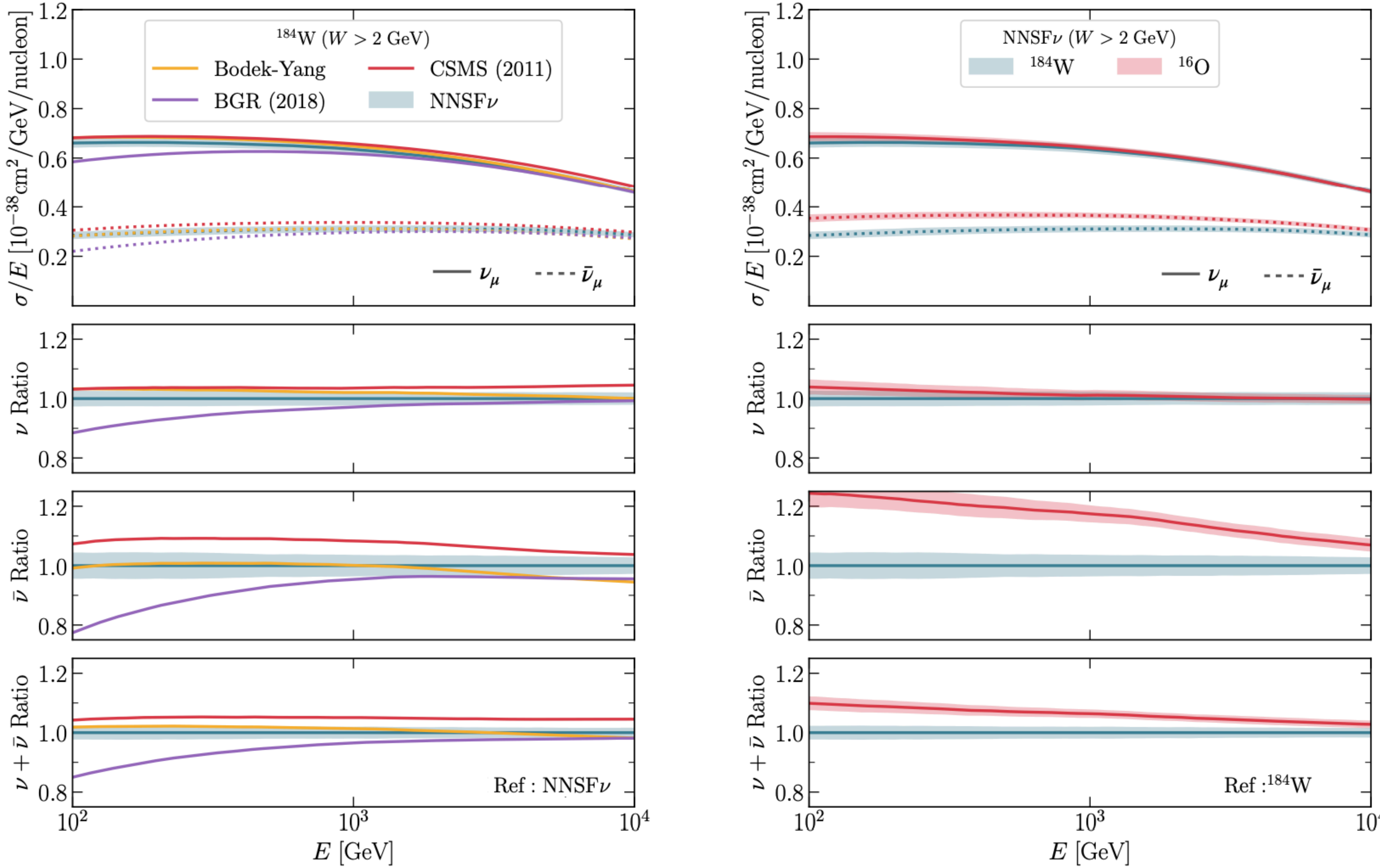
# The NNSFν results




- Good agreement with available neutrino structure function and **cross-section data**
- Robust estimate of all relevant sources of experimental and theory **uncertainties**
- Model-independent determination of **nuclear corrections** to free-nucleon scattering

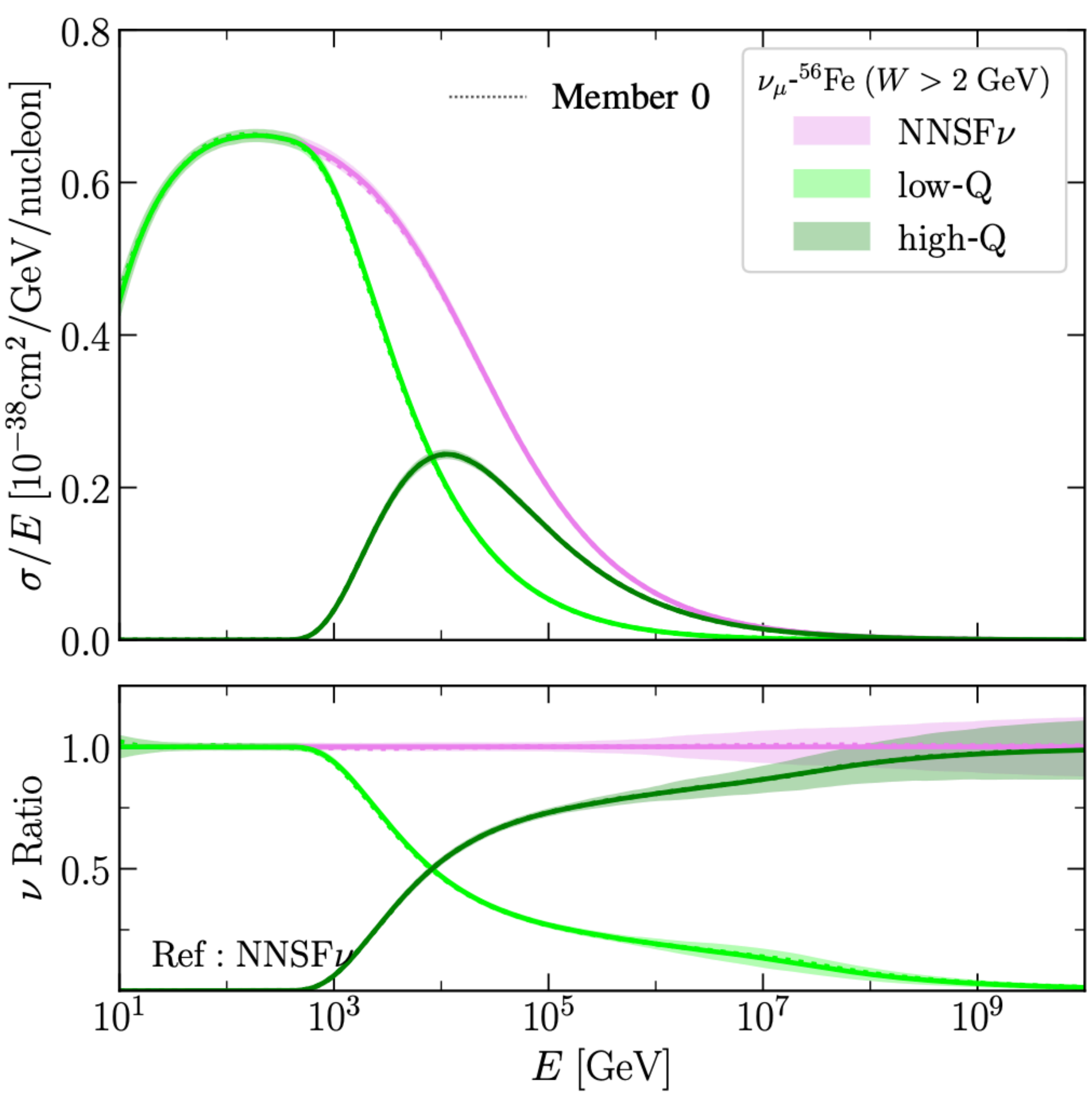
# NNSFν cross-sections for FPF simulations




- Reliable state-of-the-art predictions for **differential neutrino cross-sections** at FPF energies

# Using NNSFν for neutrino simulations

- The NNSFν structure functions are provided in terms of **fast LHAPDF interpolation grids**
- They can be readily used in **GENIE** by means of the **HEDIS** package (**official GENIE release)**
- Same GENIE/HEDIS interface: access other cross-section models like Bodek-Yang and BGR18
- Implementation in other neutrino event generators straightforward: no reason not to **adopt NNSFν in your neutrino scattering simulations!**

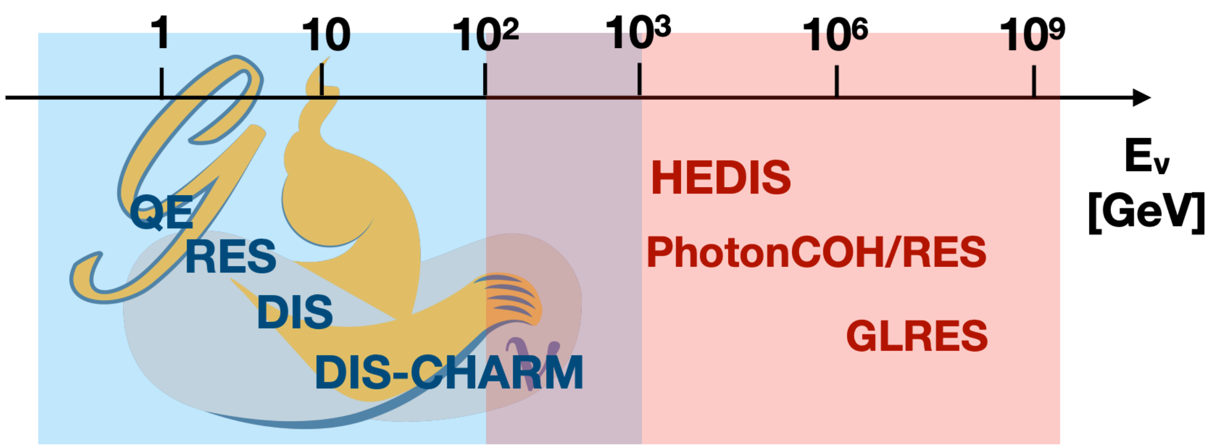



| $(Z, A)$ [target] | low-$Q$ grid | high-$Q$ grid |
|---|---|---|
| $(1, 2)$ [D] | NNSFnu_D_lowQ | NNSFnu_D_highQ |
| $(2, 4)$ [He] | NNSFnu_He_lowQ | NNSFnu_He_highQ |
| $(3, 6)$ [Li] | NNSFnu_Li_lowQ | NNSFnu_Li_highQ |
| $(4, 9)$ [Be] | NNSFnu_Be_lowQ | NNSFnu_Be_highQ |
| $(6, 12)$ [C] | NNSFnu_C_lowQ | NNSFnu_C_highQ |
| $(7, 14)$ [N] | NNSFnu_N_lowQ | NNSFnu_N_highQ |
| $(8, 16)$ [O] | NNSFnu_O_lowQ | NNSFnu_O_highQ |
| $(13, 27)$ [Al] | NNSFnu_Al_lowQ | NNSFnu_Al_highQ |
| $(15, 31)$ [Ea] | NNSFnu_Ea_lowQ | NNSFnu_Ea_highQ |
| $(20, 40)$ [Ca] | NNSFnu_Ca_lowQ | NNSFnu_Ca_highQ |
| $(26, 56)$ [Fe] | NNSFnu_Fe_lowQ | NNSFnu_Fe_highQ |
| $(29, 64)$ [Cu] | NNSFnu_Cu_lowQ | NNSFnu_Cu_highQ |
| $(47, 108)$ [Ag] | NNSFnu_Ag_lowQ | NNSFnu_Ag_highQ |
| $(50, 119)$ [Sn] | NNSFnu_Sn_lowQ | NNSFnu_Sn_highQ |
| $(54, 131)$ [Xe] | NNSFnu_Xe_lowQ | NNSFnu_Xe_highQ |
| $(74, 184)$ [W] | NNSFnu_W_lowQ | NNSFnu_W_highQ |
| $(79, 197)$ [Au] | NNSFnu_Au_lowQ | NNSFnu_Au_highQ |
| $(82, 208)$ [Pb] | NNSFnu_Pb_lowQ | NNSFnu_Pb_highQ |

# The HEDIS package

- Lead developer: **Alfonso Garcia Soto** (MIT & IFIC)
- Original goal was to extend coverage of GENIE to **neutrino energies above 1 TeV**
- Current implementation, when combined with NNSFν, allows calculations of **inelastic scattering for all energies** from a few GeV to the multi-EeV regime

- Current status of GENIE in the high energy regime:
  - DIS based on Bodek-Yang model -> optimised for low $Q^2$.
  - Structure Function = $C_{ij}$ LO⊗PDF LO (GRV98 $Q^2[0.8, 2\cdot10^6]$).
  - Contributions from heavy quarks are not included.



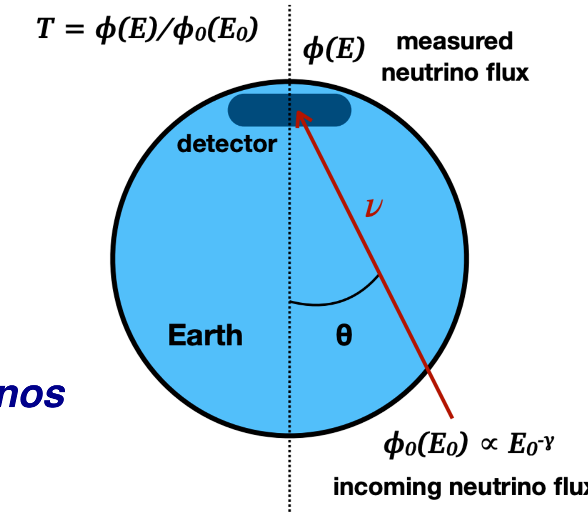

- New extension allows UHE interaction -> HEDIS
  - Newer PDFs with broader $Q^2$ phase space.
  - Structure Functions = $C_{ij}$ NLO⊗PDF NLO.
  - Account for the heavy quark contributions.

## Targeted experiments

- KM3NeT:
  - Already using GENIE (both DIS and HEDIS) in its simulation framework (gSeaGen).
- IceCube(-Gen2):
  - Uses HEDIS as an auxiliary tool to crosscheck their simulation framework at HE.
- Neutrino facilities at LHC:
  - Data in 2021-2023 (FASERnu).
  - Overlapping region between DIS & HEDIS (~0.1-1TeV).
  - Not sure what simulation package they are using so far.
- Others: GVD-Baikal, P-ONE, GRAND, etc.

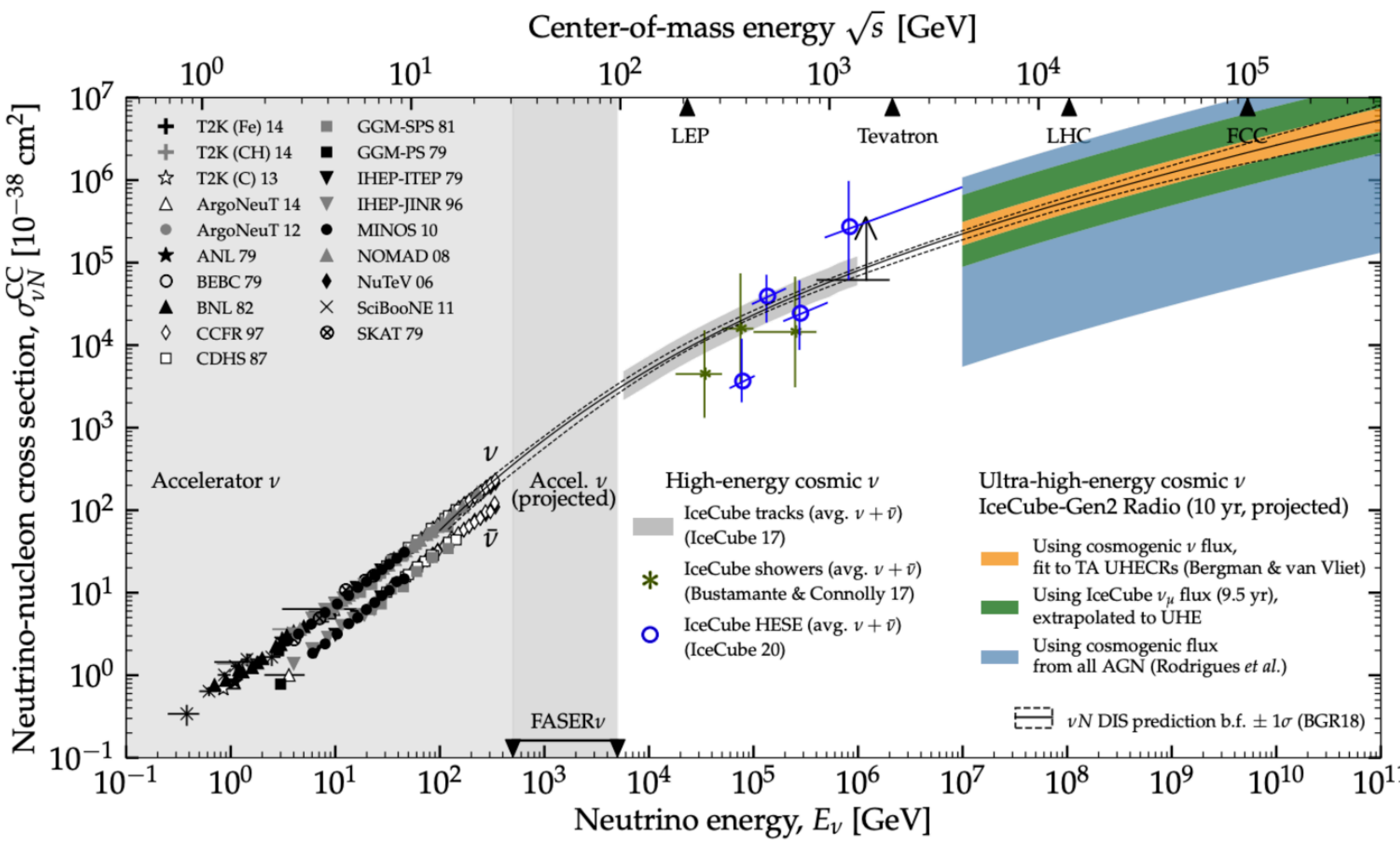
*Alfonso Garcia Soto, GENIE Users Meeting, Dec 2021*

# The HEDIS package




- Successfully deployed for many **phenomenological neutrino applications**

***Forecasts for UHE cross-section measurement***

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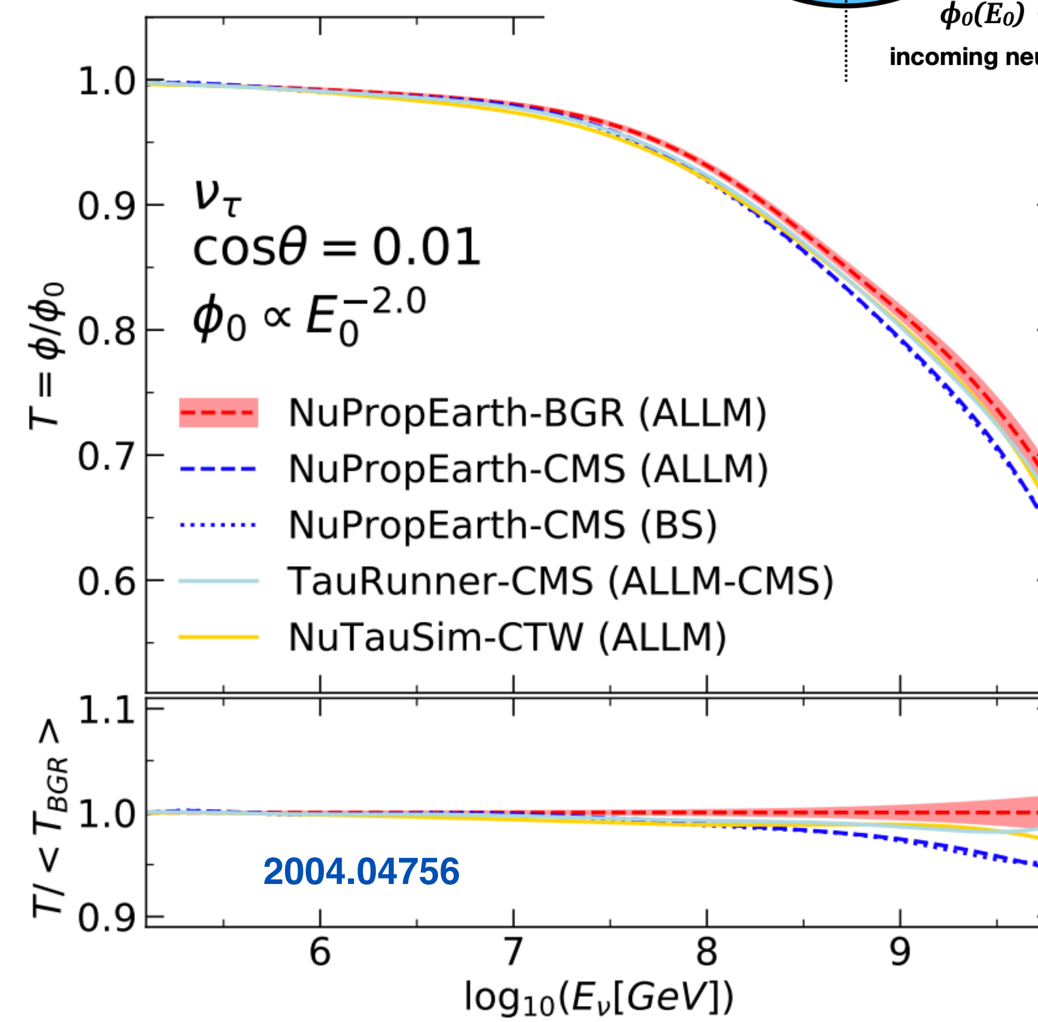
***Attenuation rates of UHE neutrinos***




- And ready to become the go-to tool for the **modelling of neutrino interactions in the FPF era**

- Next milestone: **exclusive event generation for high-energy neutrino-nucleus interactions** at (N)NLO QCD matched to parton showers!

# Summary and outlook

- The FPF would 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

- The FPF would continue the long tradition of neutrino DIS @ CERN **now with TeV beams**

- **High-energy neutrino DIS** would open a new probe to proton and nuclear structure: a charged-current counterpart of the Electron Ion Collider

- Ongoing studies demonstrate the quantitative reach of FPF measurements to **constrain proton and nuclear structure**, in particular quark & antiquark flavour separation

- Precision QCD and neutrino physics at the FPF requires **state-of-the-art modelling of neutrino inelastic structure functions** and cross-sections,

- The **NNSFν calculation of neutrino structure functions** and cross-sections, valid for all energies of phenomenological relevance, is **available via the HEDIS module of GENIE**