WG1: Neutrino Interactions and Hadronic Structure

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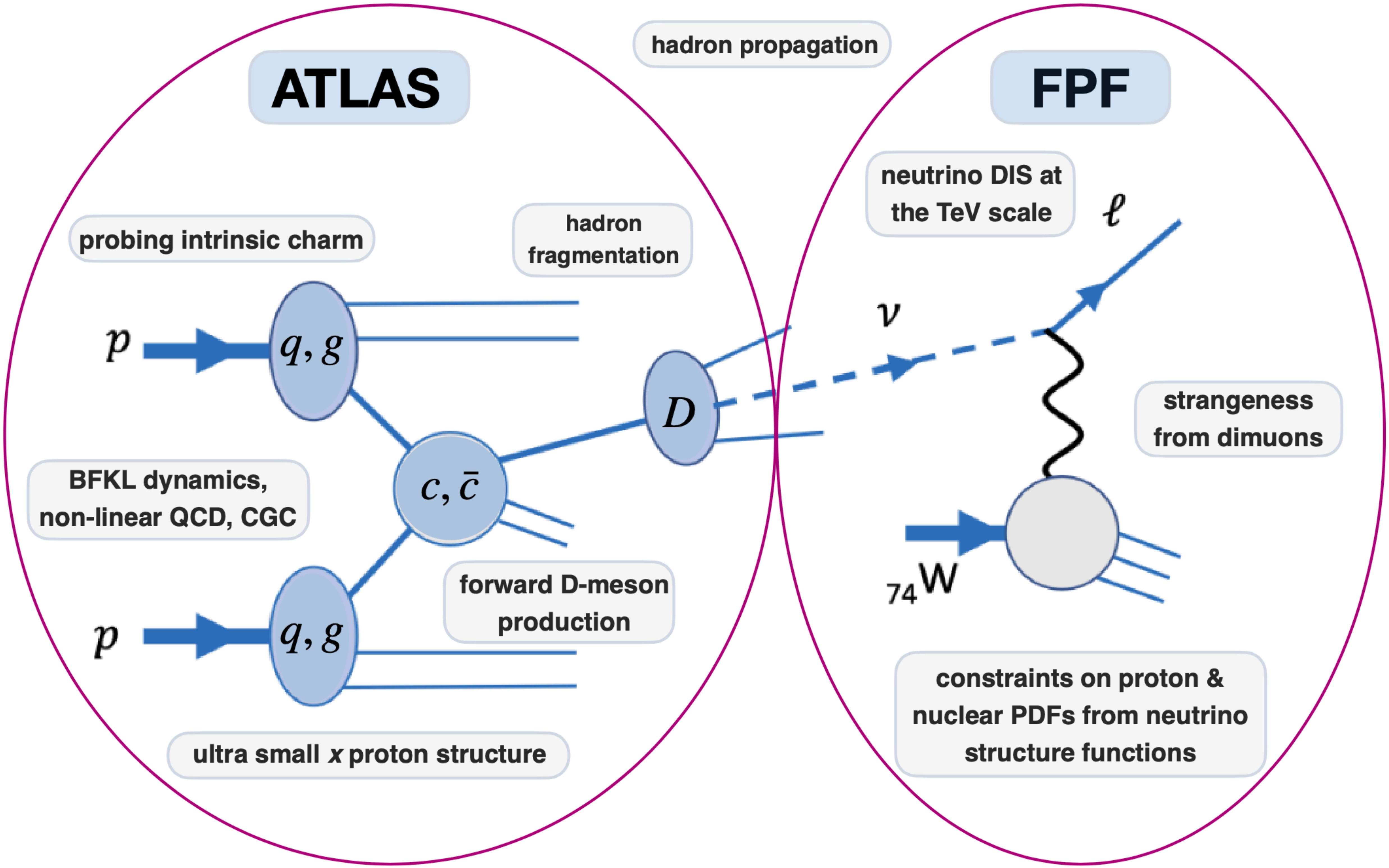
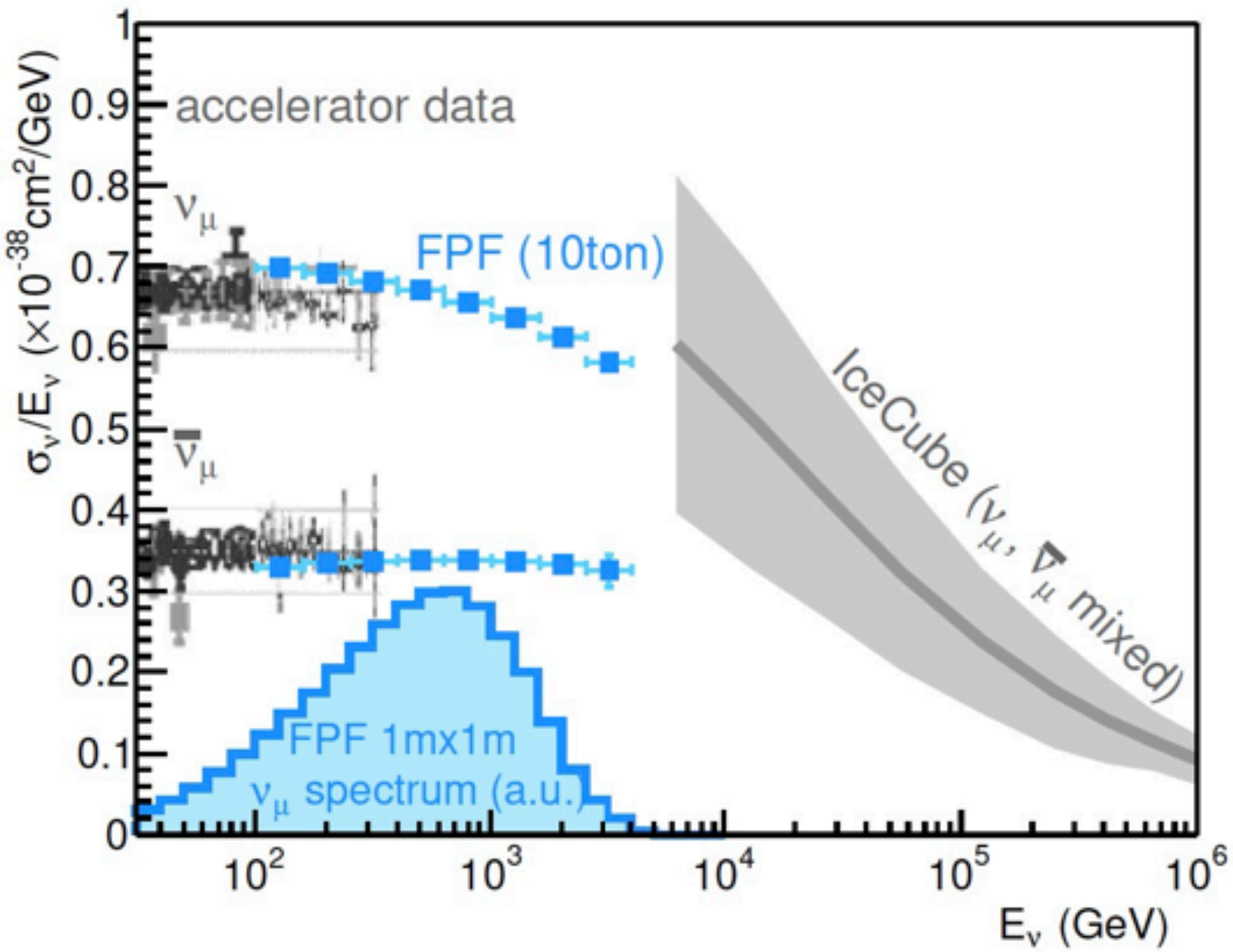
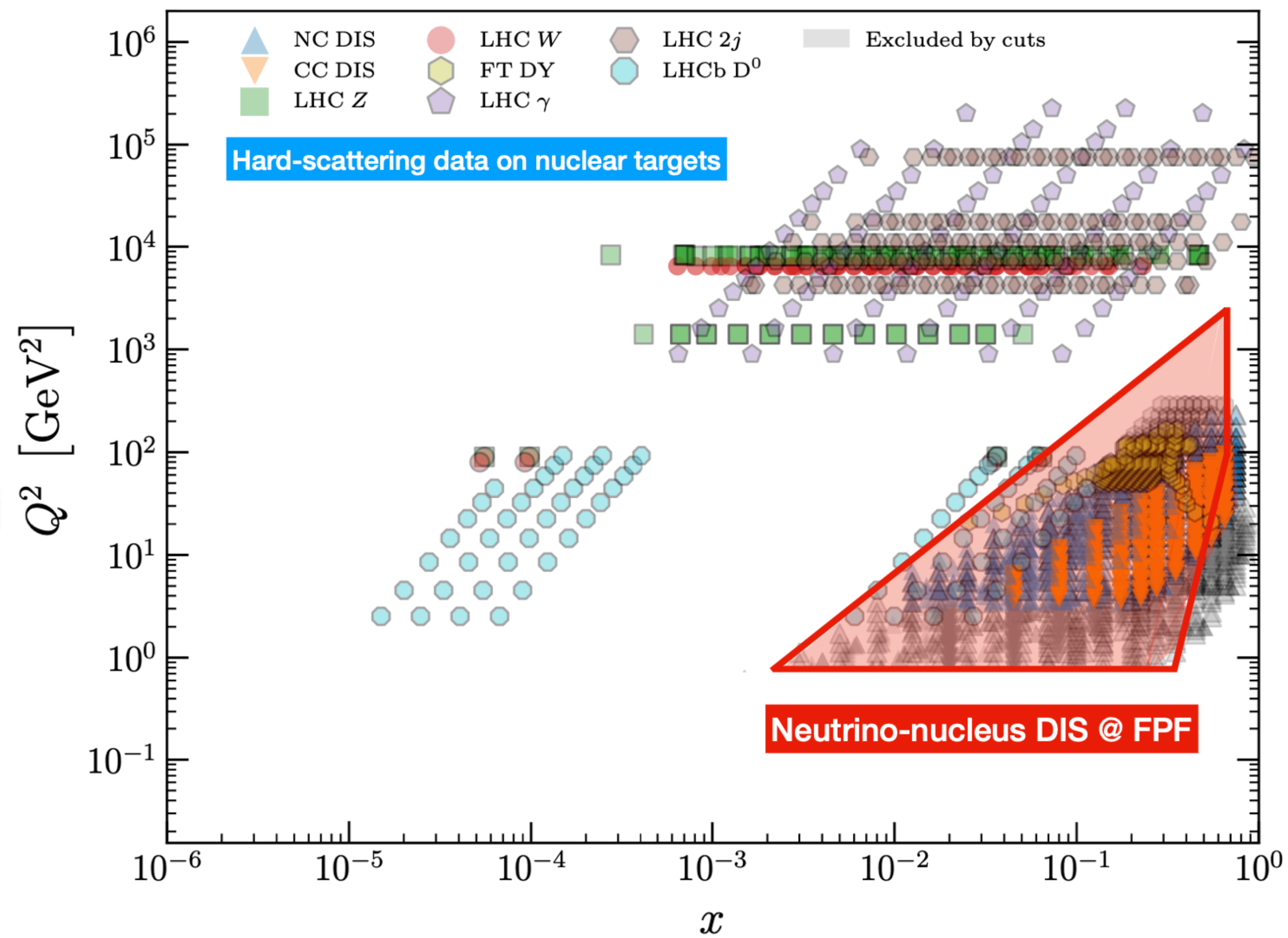
WG1 goals



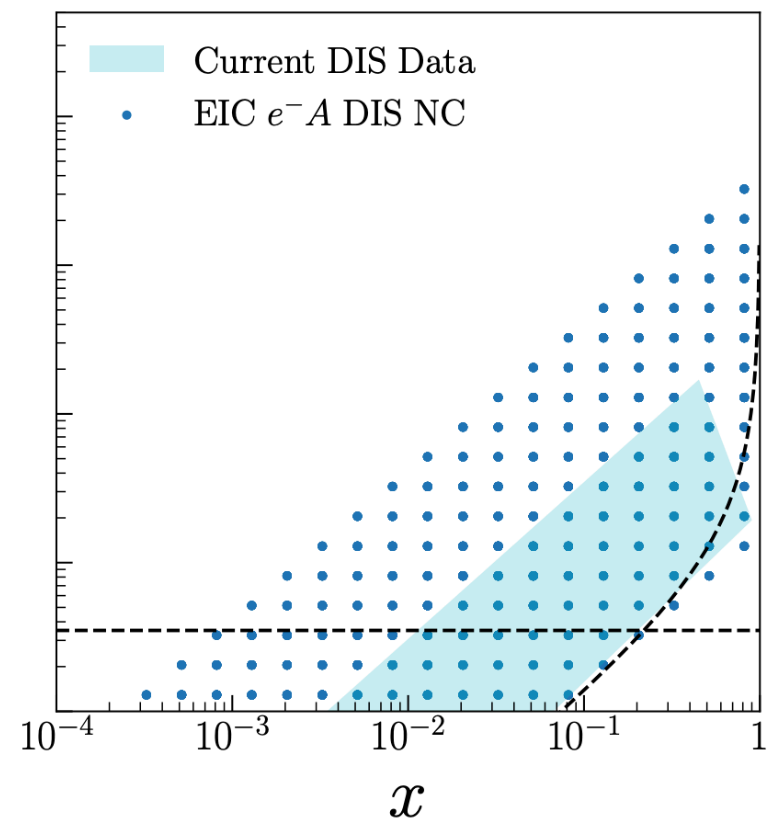
Quantify the potential of the **high-energy neutrino beams** of the FPF to **constrain proton and hadron structure** via the deep-inelastic scattering process

WG1 goals





- FPF provides **most energetic human-made neutrino beam ever produced:** unprecedented probe of nucleon and nuclear structure
- Deep-inelastic scattering with TeV neutrinos **constrains proton & nuclear (anti-)quark PDFs** (including strangeness & charm) complementary to **Electron Ion Collider and HL-LHC** data
- Key information also for precision LHC measurements e.g. ***W* mass**

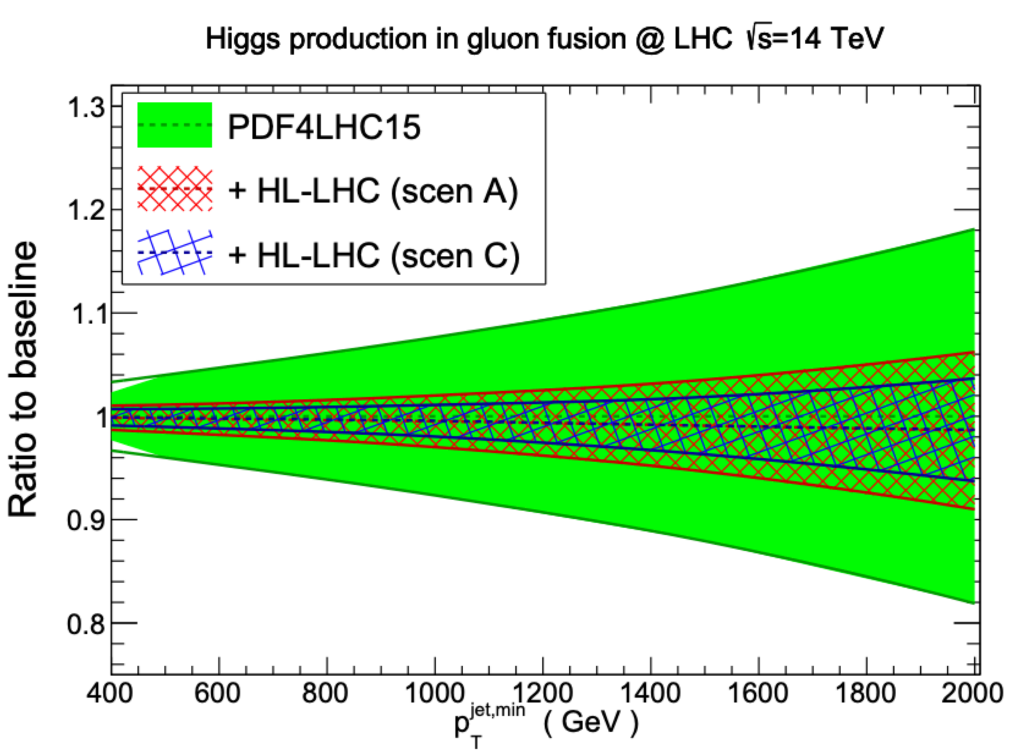


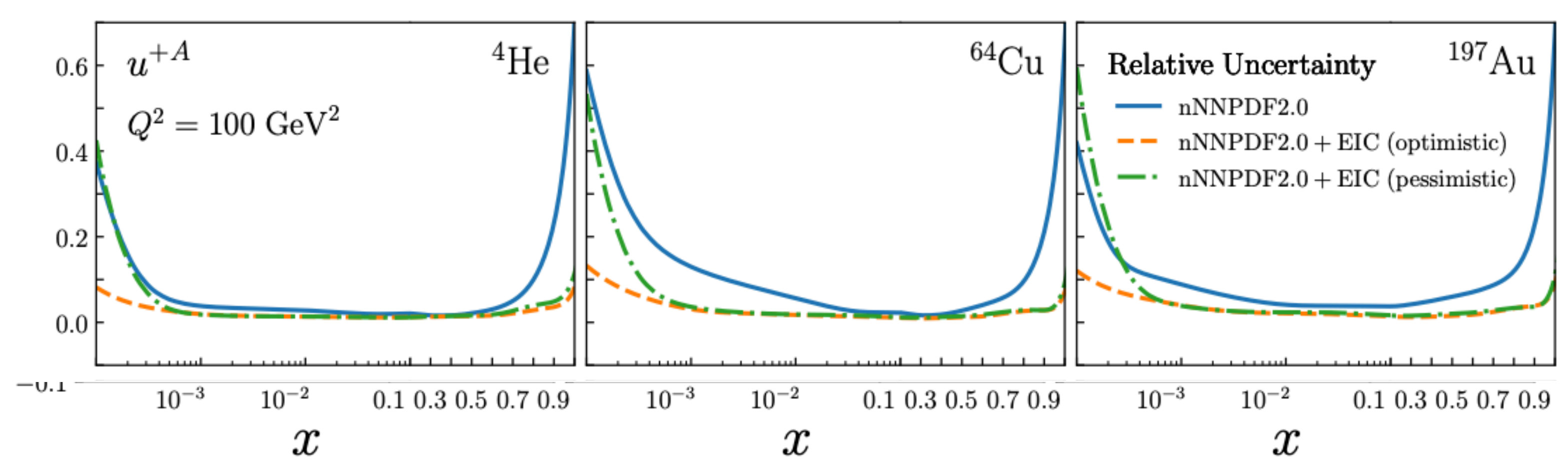
WG1 goals

WG1 goal is to move from **qualitative to quantitative** estimates of the impact of neutrino DIS at the FPF of proton and nuclear parton distributions

Quantify the potential of the **high-energy neutrino beams** of the FPF to **constrain proton and hadron structure** via the deep-inelastic scattering process

- For each FPF experiment, determine **acceptance and coverage in *(x,Q)* plane**
- Estimate the number of **expected DIS events** for each bin in the *(x,Q)* plane (statistical errors)
- Estimate **systematic errors** from expected detector response
- Generate **DIS pseudo-data** using state-of-the-art pQCD calculations and include in *i)* proton and *ii)* nuclear PDF fits using **public** (e.g. xFitter, NNPDF, reweighting/profiling) and **private fitting tools**





building upon past expertise on related HL-LHC & EIC projections

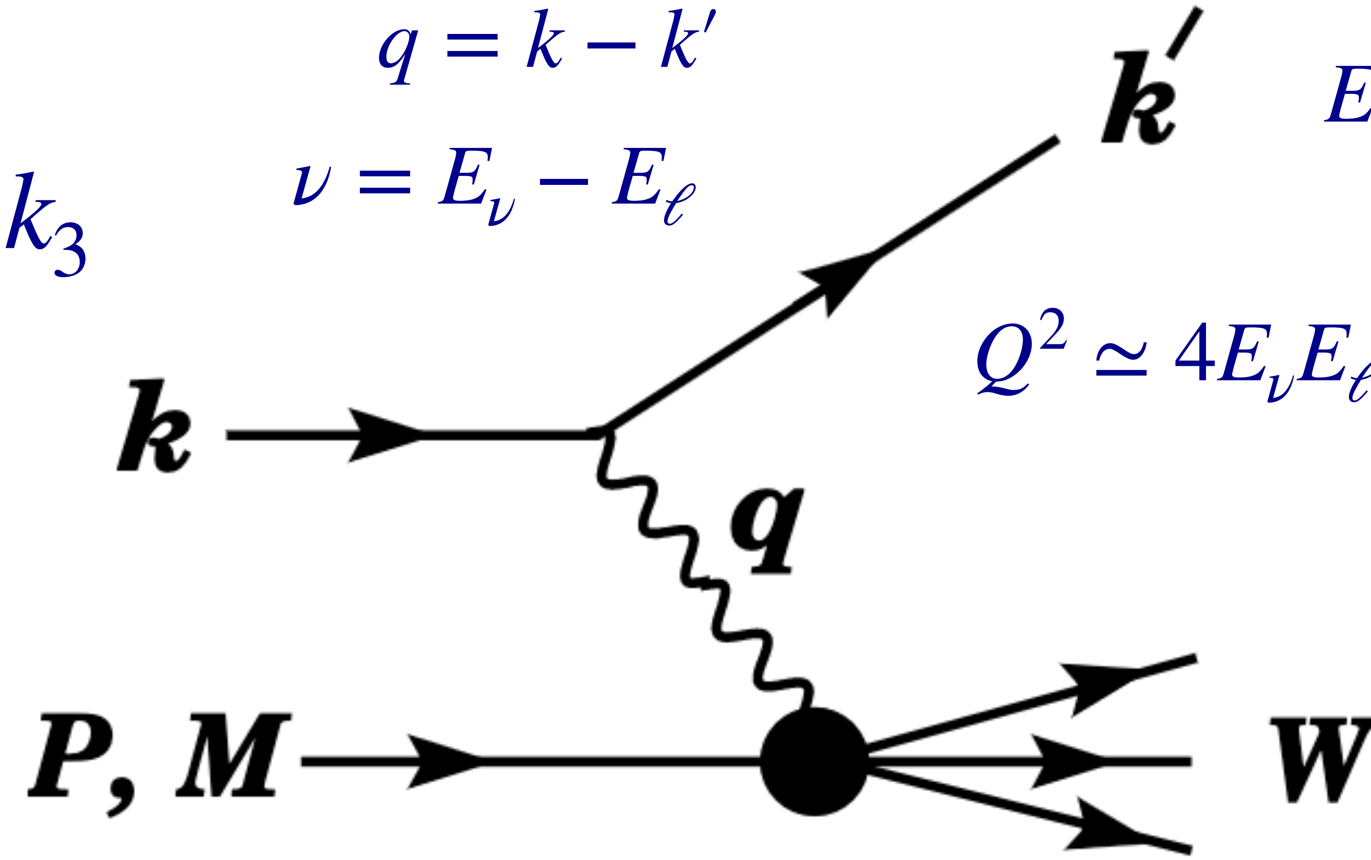
Deep-inelastic scattering @ FPF

$$q = k - k'$$

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

$$E_\ell = k'_0$$

$$E_\nu = k_0 = k_3$$



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

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

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

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

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

- 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**

Deep-inelastic scattering @ 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

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

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

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

If we only have access to the charged lepton kinematics, we **cannot reconstruct the neutrino energy** and it needs to be taken from external calculation

Deep-inelastic scattering @ 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

Deep-inelastic scattering @ FPF

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

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/2\pi}{\left(1+Q^2/m_W^2\right)^2}\left[(1-y)F_2^{\nu A}(x,Q^2) + y^2 x F_1^{\nu A}(x,Q^2) + y\left(1-\frac{y}{2}\right)xF_3^{\nu A}(x,Q^2)\right]$$

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

- 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

depends on experiment

$$N_{\rm ev}(x \in [x_{\rm min}, x_{\rm max}], Q^2 \in [Q^2_{\rm min}, Q^2_{\rm max}, E_\nu \in [E_{\nu,{\rm min}}, E_{\nu,{\rm max}}]) \propto$$

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

scattering cross-section ***incoming neutrino flux***

Generating FPF pseudo-data

- To quantify the **impact of nuDIS data from the FPF** on global fits of proton and nuclear PDFs, need to generate pseudo-data with an estimate of experimental uncertainties and realistic acceptances.
- Start assuming **perfect detector**, then at second step smear kinematics based on some estimate of the expected systematic error of the measurements
- For each of the FPF experiments, we need to know:
  - Their **acceptance in the outgoing charged lepton** (scattering angle and energy)
  - Whether we can access information on the **sign of the charged lepton**
  - Whether the **hadronic final state** can be reconstructed
  - Initial estimate of the **systematic errors** on $\left(E_\ell,\ \theta,\ E_h\right)$
- The calculation of double-differential DIS cross-sections based on **state-of-the-art pQCD calculations** and proton/nuclear PDF sets will be carried out using YADISM

https://yadism.readthedocs.io/en/latest/

https://github.com/NNPDF/yadism

- Start with **muon neutrino scattering,** the most relevant for DIS (higher event rates, smaller charm contribution which has large uncertainties)

Input from experiments

	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, $\delta E_h = 30\%$

caveat: initial approximate estimates!

thanks to Antonia, Tomoko, Aki, Steven, and Wenjie for the information

exploit complementary of FPF experiments for hadron structure studies & provide input for experiment design at the light of **DIS & PDF requirements**

Progress so far

- Generated **DIS predictions** using PDF4LHC21 as input PDF set (proton target) and YADISM for a fine grid of ***(x,Q,y)* values**

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

- Interfaced this calculation to the **muon neutrino flux predictions** from Felix and Laurie

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

incoming neutrino flux

- Determined **acceptance in *(x,Q)* plane** for each experiment for DIS

Work in progress

- Determine the expected event rates for different **choices of binning in *(x,Q)* plane**
- Generate pseudo-data with statistical & systematic errors and **include them in proton PDF fit**
- Then extend to **nuclear PDF determinations**, **semi-inclusive processes**, & other observables

ETA: first proton PDF fit with FPF pseudo-data before the end of the year using both xFitter and NNPDF

This is just the beginning …

- We are only now starting to scratch the surface of the physics reach of the FPF for QCD, neutrino, and astroparticle physics science: unique opportunity!
- The DIS pseudo-data that we generate could also be used to constrain **EFT effects and non-standard neutrino interactions** as well as models of the neutrino cross-section in poorly known regions like low-Q
- Close collaboration between **theory and experiment**, as well as among different theory groups, is essential to provide robust quantitative projections of the FPF reach for the CDR
- A lot of exciting work to do, please join the team if you are interested (Slack & GitHub)!