



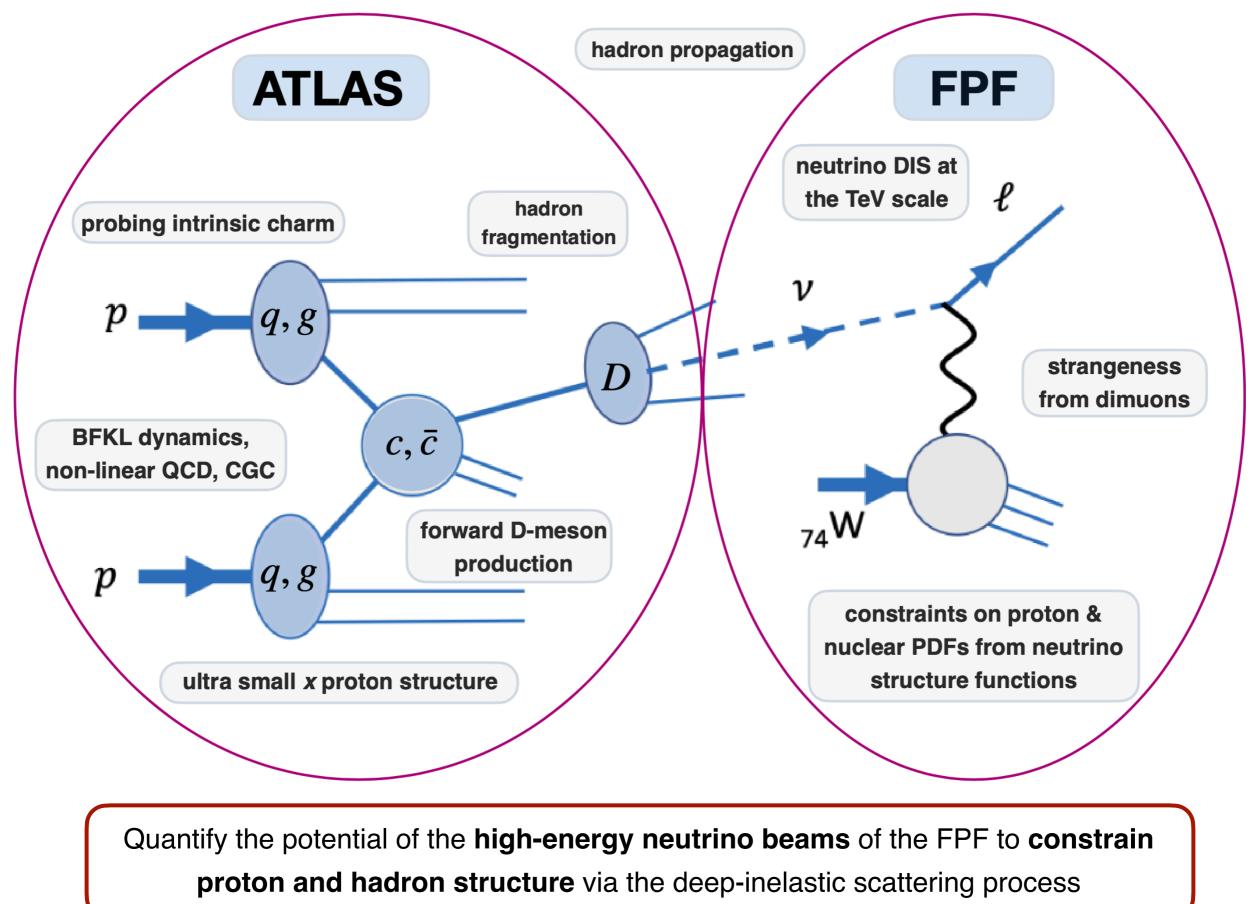
WG1: Neutrino Interactions and Hadronic Structure



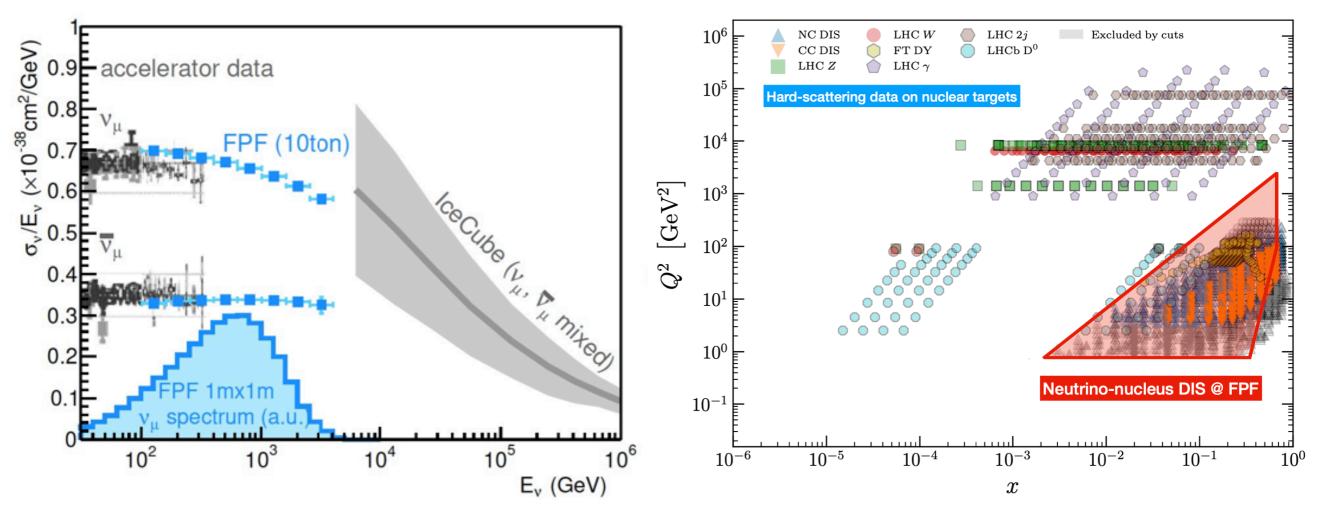
Juan Rojo, VU Amsterdam & Nikhef

5th Forward Physics Facility Meeting 16th November 2022

WG1 goals

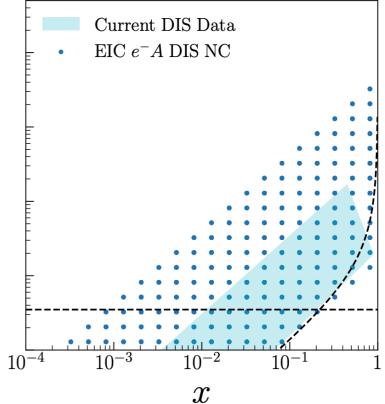


WG1 goals



- 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

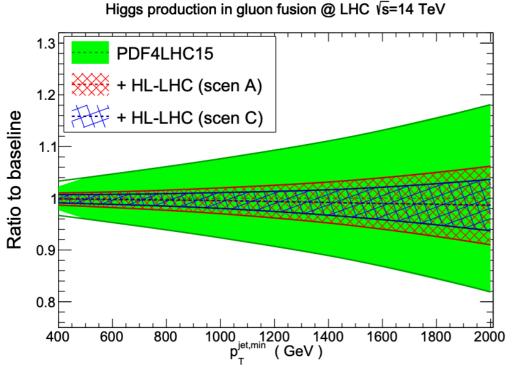


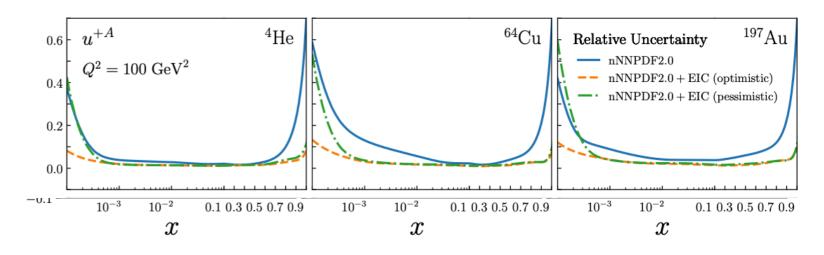
WG1 goals

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

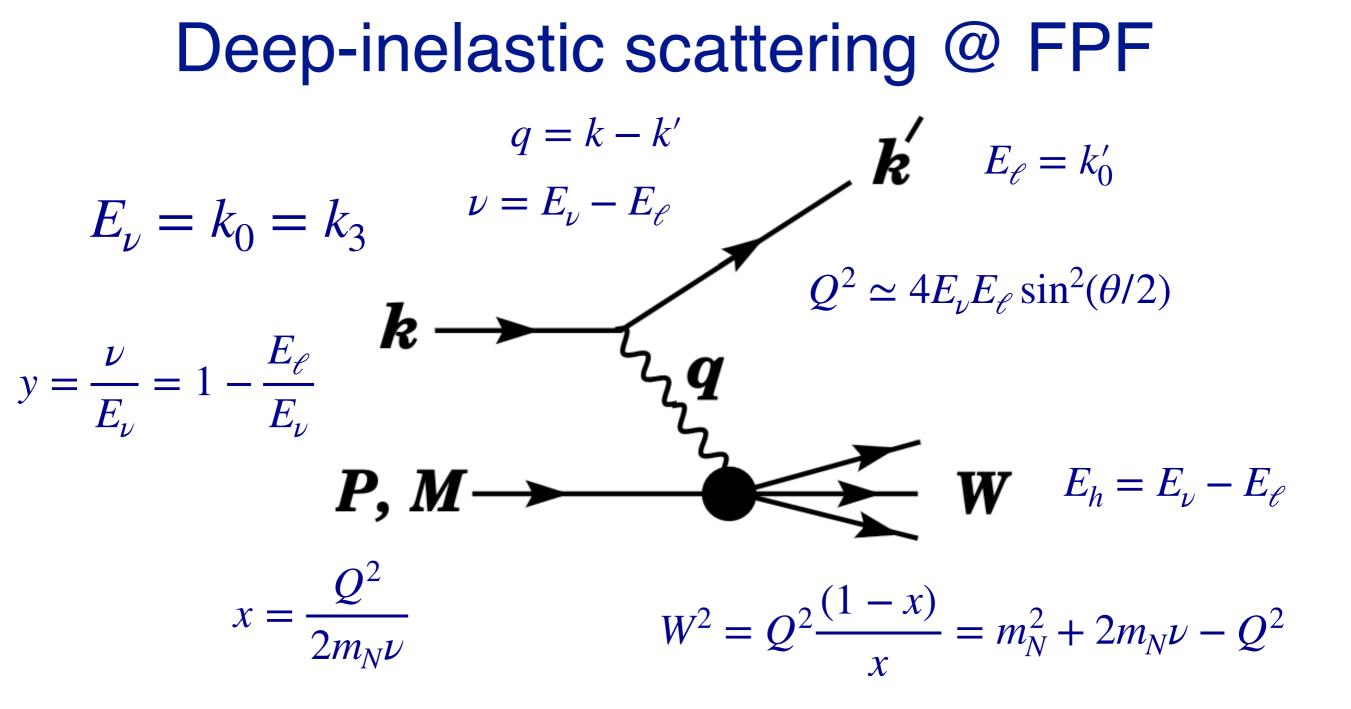
Quantify the potential of the high-energy neutrino beams of the FPF to constrain proton and hadron structure via the deep-inelastic scattering process

- 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



- 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

$$\left(E_{\ell},\ heta,\ W^2
ight)$$
 or $\left(E_{\ell},\ heta,\ E_h
ight)$

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

$$\left(x, \ Q^2, \ E_{
u}
ight)$$
 or $\left(x, \ Q^2, \ y
ight)$

by using the following equations

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

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

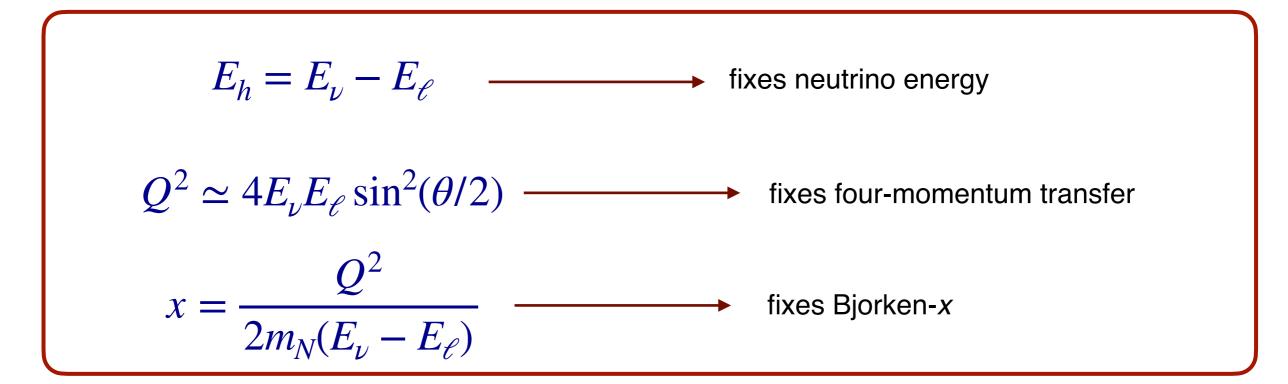
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Final sector of the sector of

$$\left(x, \ Q^2, \ E_{
u}
ight)$$
 or $\left(x, \ Q^2, \ y
ight)$

by using the following equations



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 doubledifferential DIS cross-section

$$\begin{aligned} \frac{d^2 \sigma^{\nu A}(x,Q^2,y)}{dxdy} &= \frac{G_F^2 s/2\pi}{\left(1+Q^2/m_W^2\right)^2} \left[(1-y) F_2^{\nu A}(x,Q^2) + y^2 x F_1^{\nu A}(x,Q^2) + y \left(1-\frac{y}{2}\right) x F_3^{\nu A}(x,Q^2) \right] \\ \frac{d^2 \sigma^{\nu A}(x,Q^2,y)}{dxdy} &= \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2} \left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2) \right] \end{aligned}$$

- 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
- Final Formation Formation

depends on experiment

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

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

$$scattering incoming i$$

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:
 - Freir 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
 - \mathbf{P} Initial estimate of the **systematic errors** on $\left(E_{\mathcal{C}}, \theta, E_{h}\right)$
- 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	lepton angle θ	charged lepton sign	hadronic final state
FaserNu2	E _l > 100 GeV δE _l = 30%	tan(θ) < 0.5 δθ = 1 mrad	Yes, for muons	E_h accessible, charm ID possible, $\delta E_h = 30-50\%$
AdvSND@LHC	E _I > 20 GeV (muon)	θ < 0.15 rad (muon) θ < 0.5 rad (electron, tau)	Yes	E _h accessible
FLArE	E _l < 1 TeV, δE _l = 5% (electron) E _l < 2 GeV (muon)	$\theta < 0.5 \text{ rad, } \delta\theta =$ 15 mrad (electron) $\theta < 0.4 \text{ rad (muon)}$	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

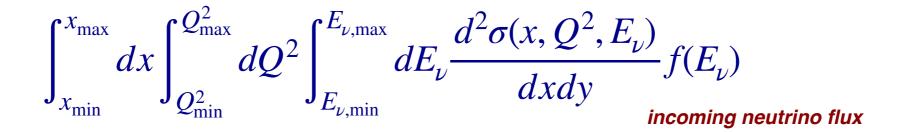
exploit complementary of FPF experiments for hadron structure studies & provide input for experiment design at the light of **DIS & PDF requirements**

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



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
- From 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 nonstandard 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)!

Forward Physics F 👻 🕜	# wg1_neutrino_interactions > Physics WG: Neutrino Interactions at TeV energies						
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 ④ Threads ⑥ Direct messages ◎ Mentions & reactions 	Tanjona Rabemananjara 10:07 AM Hi @Juan Rojo, the slides look good to me. I could try to provide by U. Monday, Nov (x, Q2)-plane. I will do so after various meetings. (edited)	<> Code	🕑 Actions 🖽 Projects 🖽 Wiki 🙂 Sect	zurity 🗠 Insights 영	3 Settings		
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i More	Tanjona Rabemananjara 10:11 AM Perfect. I will send you the plots as soon as I have them.			a18438f 8 days ago	Working Group 1 "N	Working Group 1 "Neutrino interactions and hadron structure" of the Forward	
 Channels 	Steven Linden 1:31 PM					Physics Facility	
合 fpf_conveners	@Juan Rojo These look good. One note is that we have been talking about using t course we could tag the charge of through-going muons. So perhaps in the table o	igrids	Add kinematic input file and results		10 days ago	 □ Readme ☆ 0 stars ⊙ 3 watching ౪ 0 forks 	
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<pre># wg4_bsm_physics # wg5 faser2</pre>	@Juan Rojo The slides look great. Just one comment: I think we can (in principle) n W^2. The last one, W^2, is perhaps the least thought of one from the experimenta						
# wg6_fasernu2	would like to have it measured well too. (edited)	C README.md	Fix minor typos in documentation		10 days ago		
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