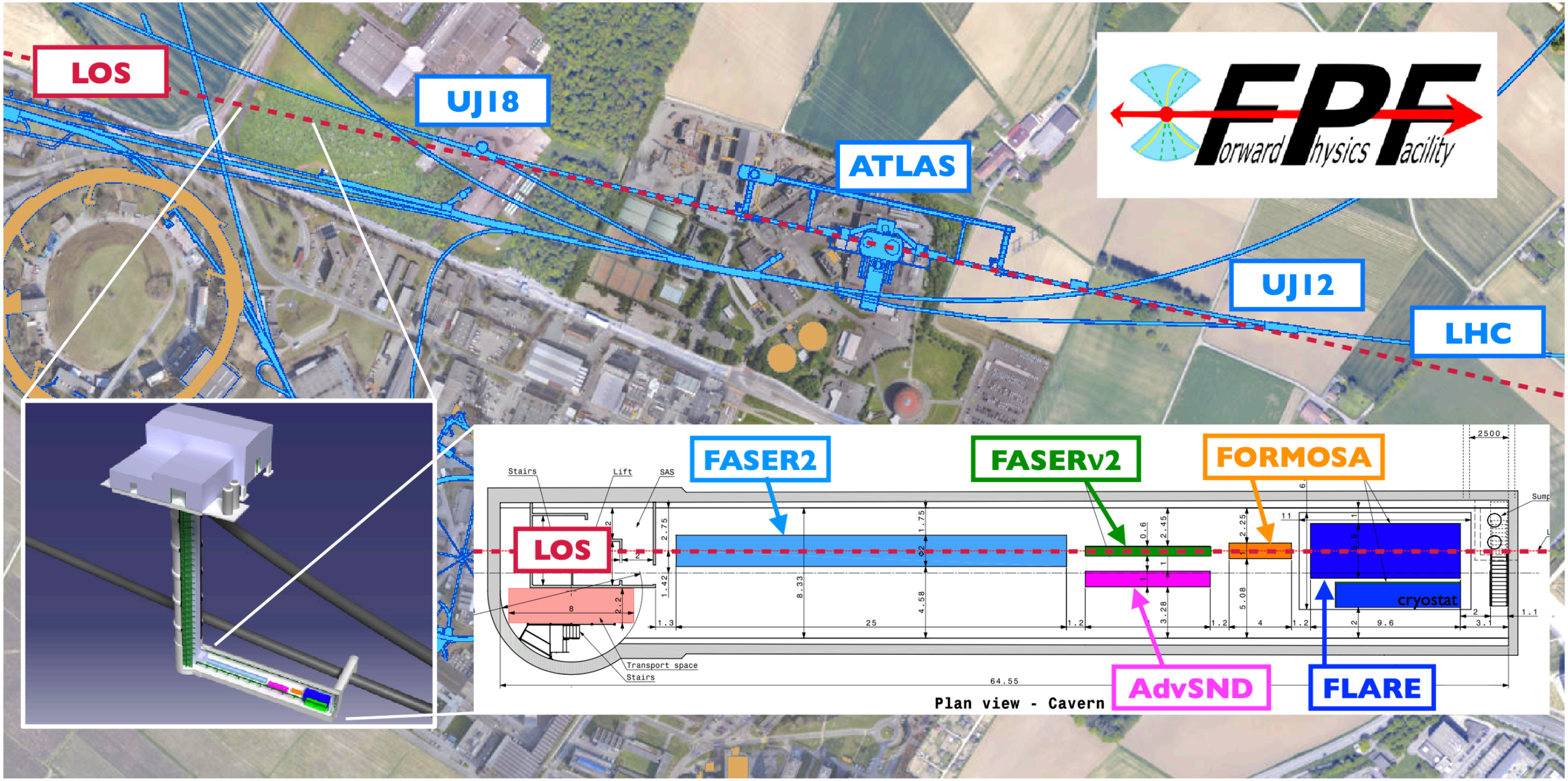
Deep-Inelastic Scattering with TeV Neutrinos at the Forward Physics Facility

Juan Rojo, VU Amsterdam & Nikhef

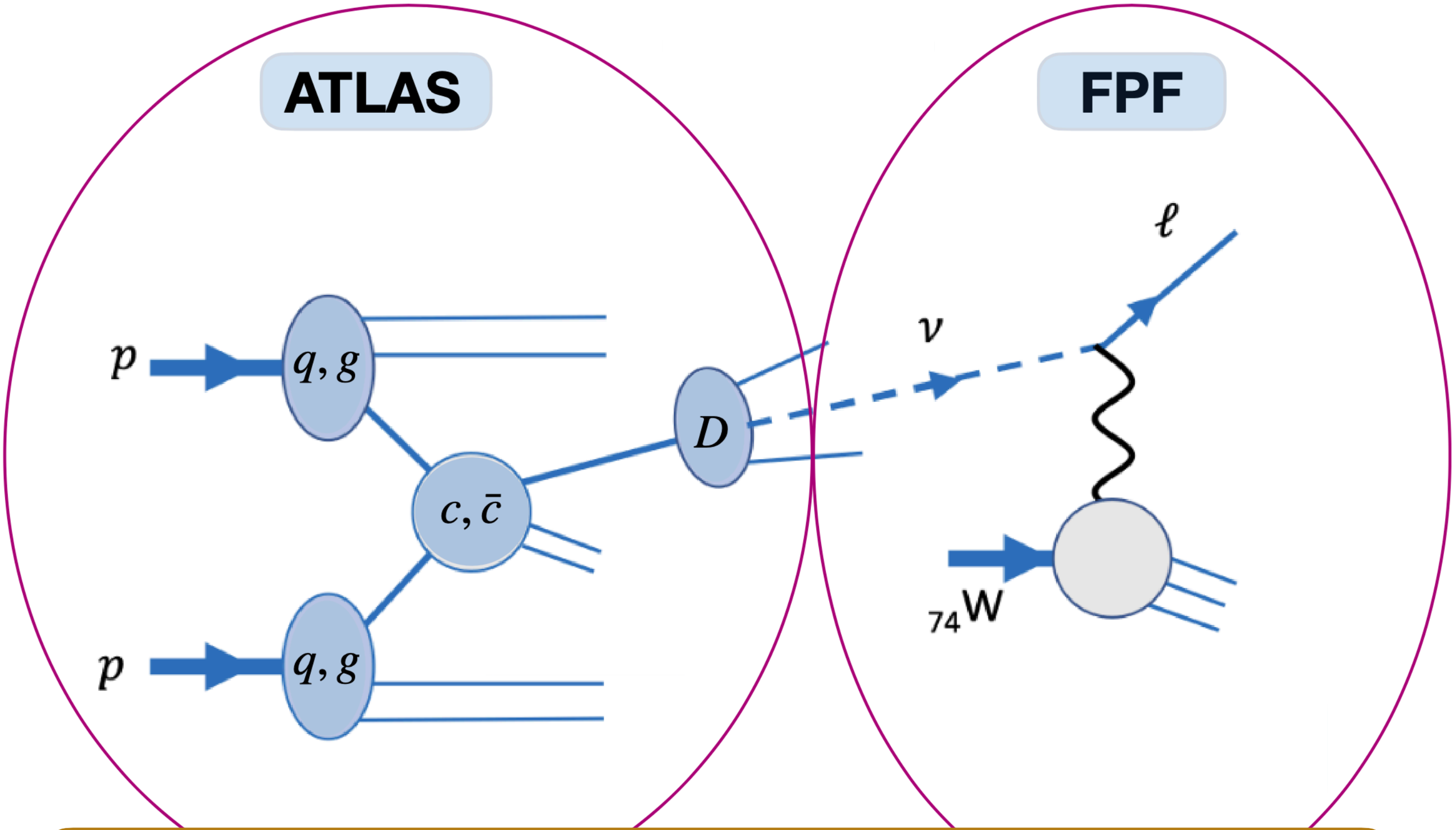
The Forward Physics Facility

A proposed 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 High-Luminosity LHC (ATLAS interaction point)



No modifications to the HL-LHC required!

The Forward Physics Facility



Huge **neutrino** fluxes produced in LHC collisions: **blind spot** of planned LHC operations!

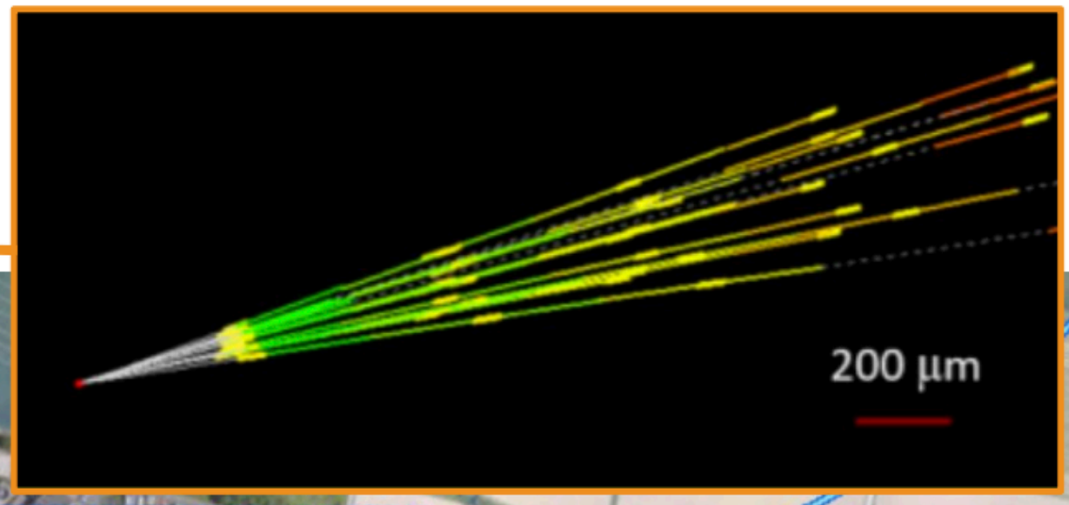
Neutrinos at the LHC

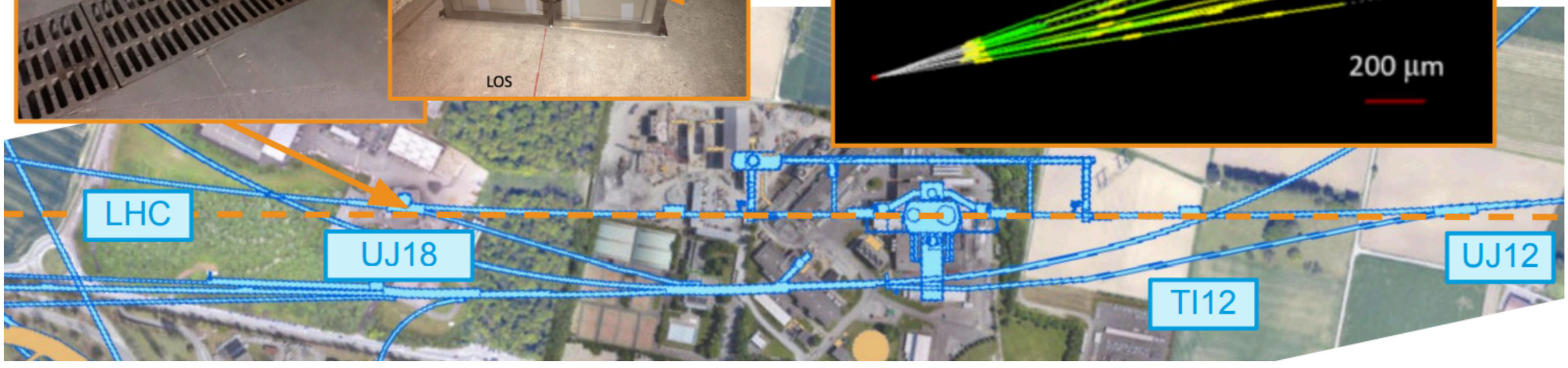
1984 — 2018 — 2022 — Felix Kling — 2028

In 2018, the FASER collaboration placed ~30 kg pilot emulsion detectors in TI18 for a few weeks. O(10) neutrino interactions expected

First neutrino interaction candidates were recently reported.

[FASER, 2105.06197]





for the first time, **neutrino (candidates)** have been detected at the LHC!

Neutrinos at the LHC

Jonathan Feng

FASER Pilot Detector

Suitcase-size, 4 weeks
$0 (recycled parts)

6 candidate neutrinos

All previous
collider detectors

Building-size, decades
~10^9

0 candidate neutrinos

Huge **neutrino** fluxes produced in LHC collisions: **blind spot** of planned LHC operations!

FPF physics potential

Remarkably **broad** and **far-reaching potential** of the FPF experiments:

☑ 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 (3k 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

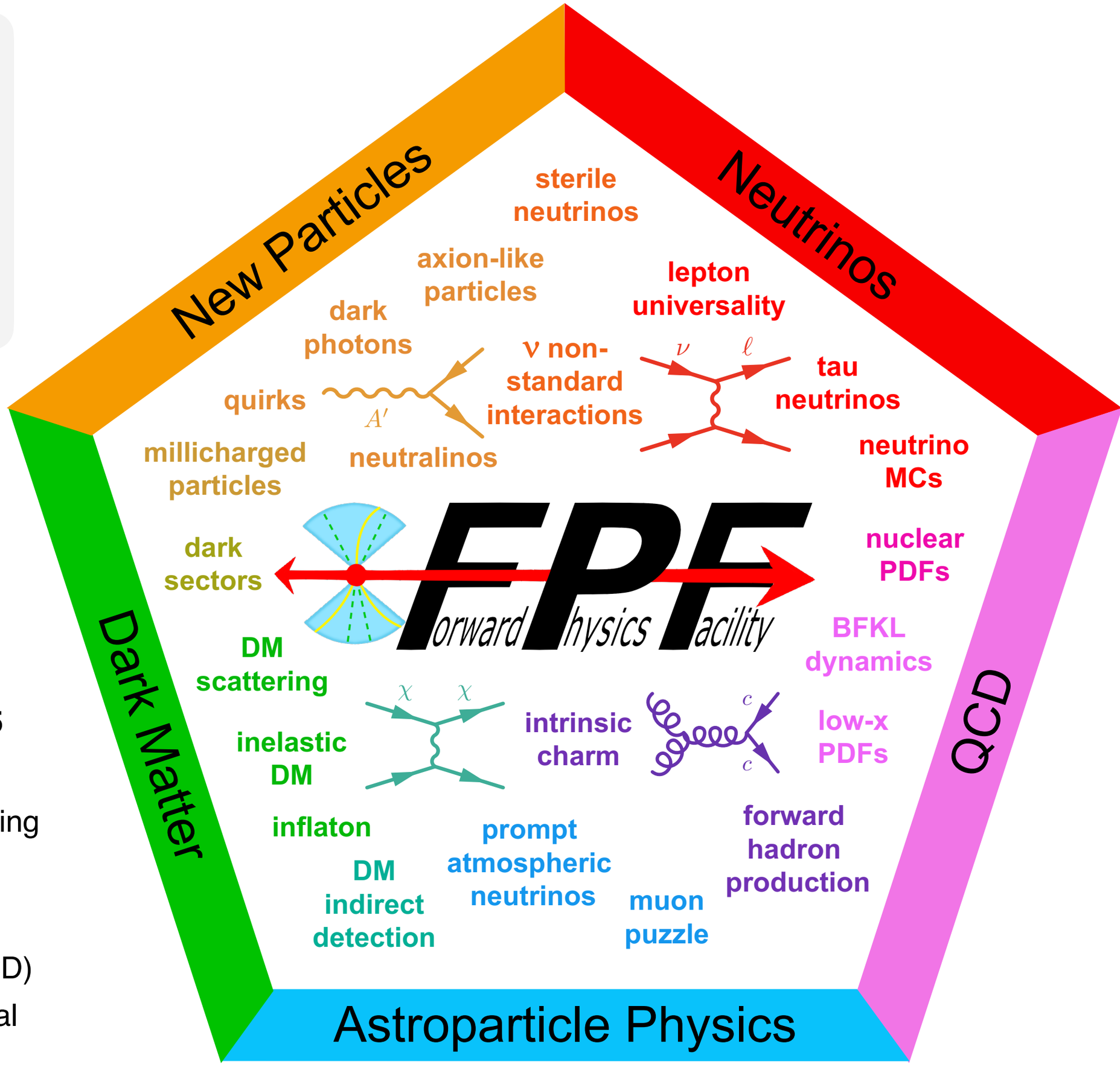
☑ QCD, hadron structure, and astroparticle physics

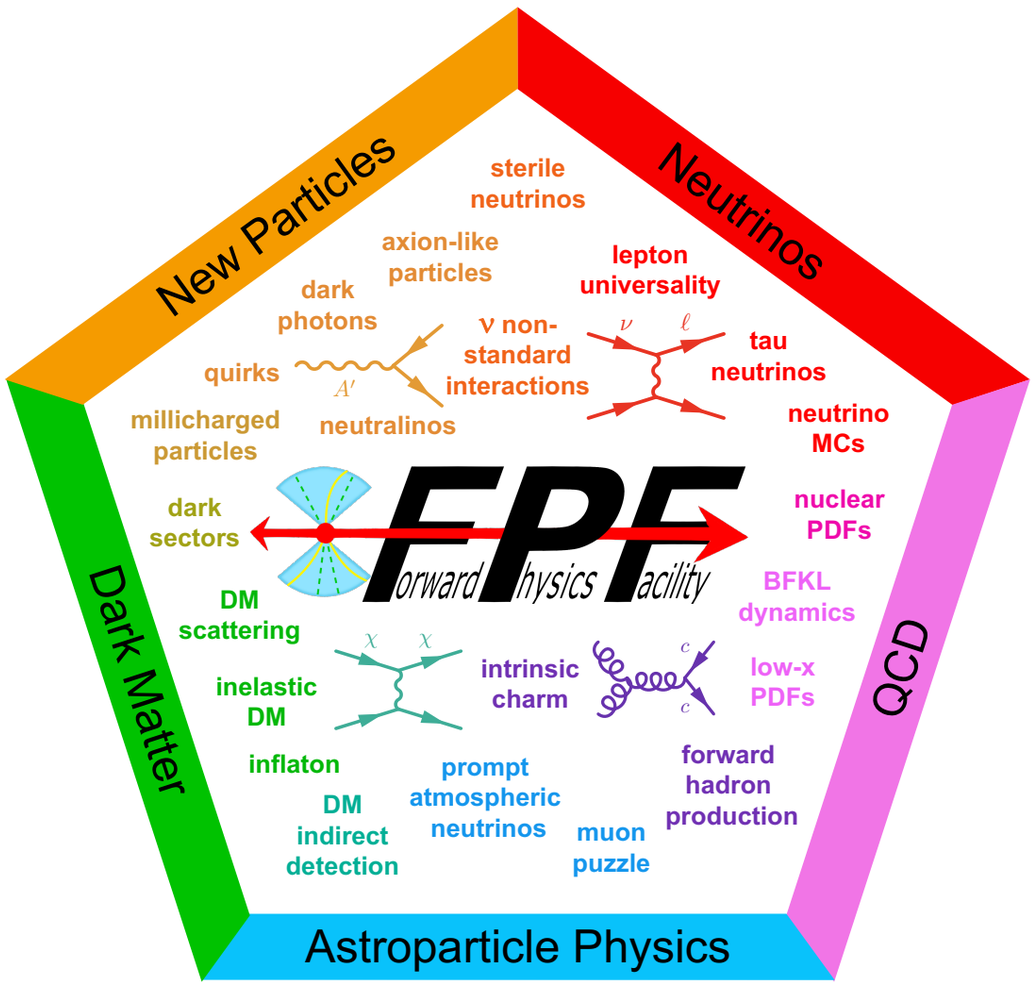
- **Neutrino cross section** measurements (energy region not covered by any other experiment)
- Neutrino DIS to constrain **proton and nuclear structure**
- Testing **BFKL dynamics** in LHC collisions, modelling charm, hadron production in forward region
- Key input for neutrino (IceCube, KM3NET) and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

Significant **extension of HL-LHC scientific potential** for moderate price tag!

Deep synergies also with the **Electron Ion Collider, cosmic rays, UHE neutrinos**

- **25 MCHF** construction **+ 15 MCCH services**
- Installation in **LS3**, data taking from **Run 4**
- Combination of guaranteed deliverables (neutrinos, QCD) and BSM discovery potential





- **430 pages** describing scientific case, infrastructure, detectors, and simulations
- Stepping stone for the FPF **Conceptual Design Report**

The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

Lead Conveners

Jonathan L. Feng[1*], Felix Kling[2], Mary Hall Reno[3], Juan Rojo[4,5], Dennis Soldin[6]

Topical Conveners

Luis A. Anchordoqui[7], Jamie Boyd[8], Ahmed Ismail[9], Lucian Harland-Lang[10,11], Kevin J. Kelly[12], Vishvas Pandey[13], Sebastian Trojanowski[14,15], Yu-Dai Tsai[1],

FPF physics potential

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- **Light BSM particles** produced in the very forward direction
- Decaying **dark sector long-lived particles** (dark photons, dark Higgs, heavy neutral leptons…)
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☑ QCD, hadron structure, and astroparticle physics

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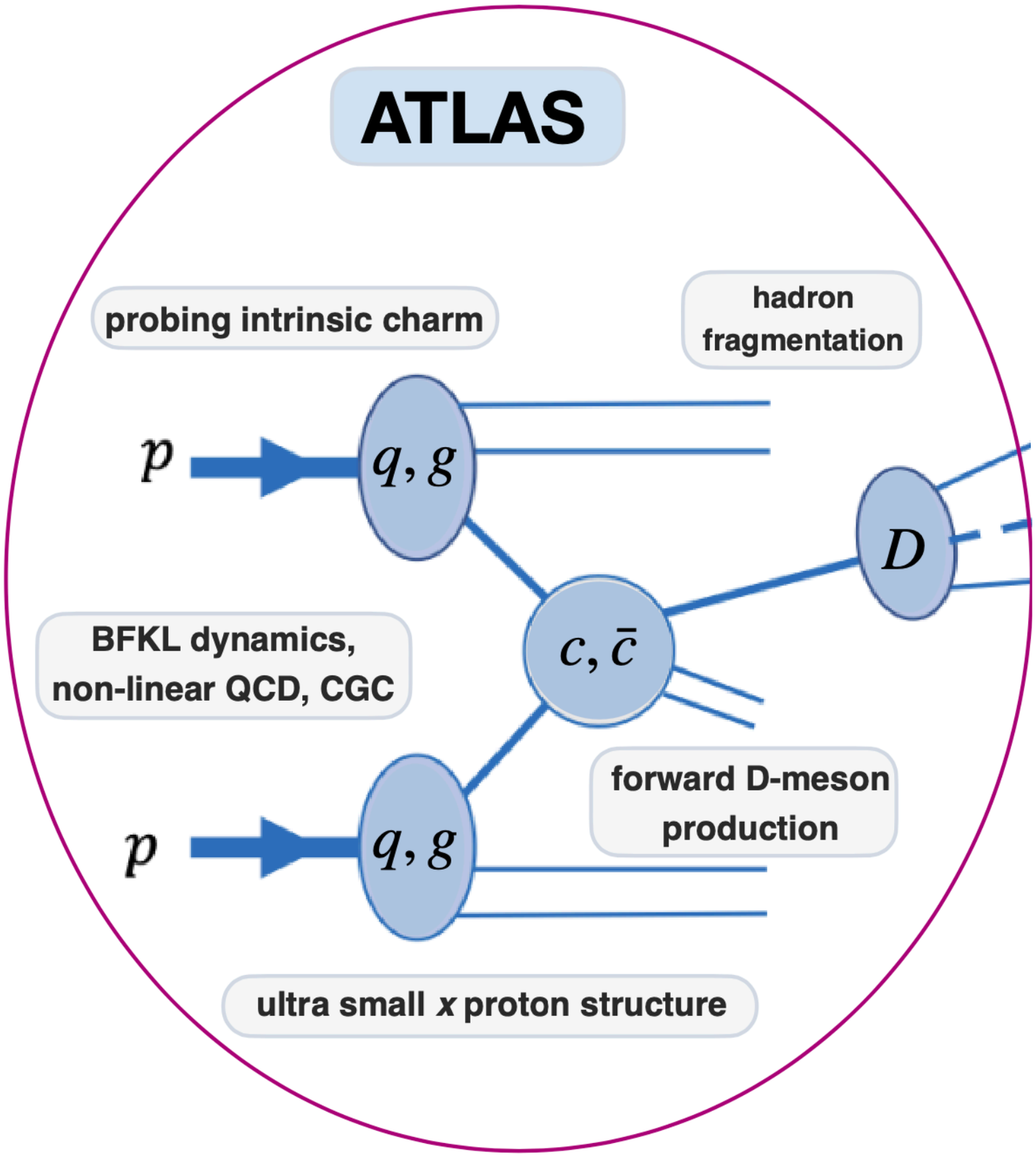
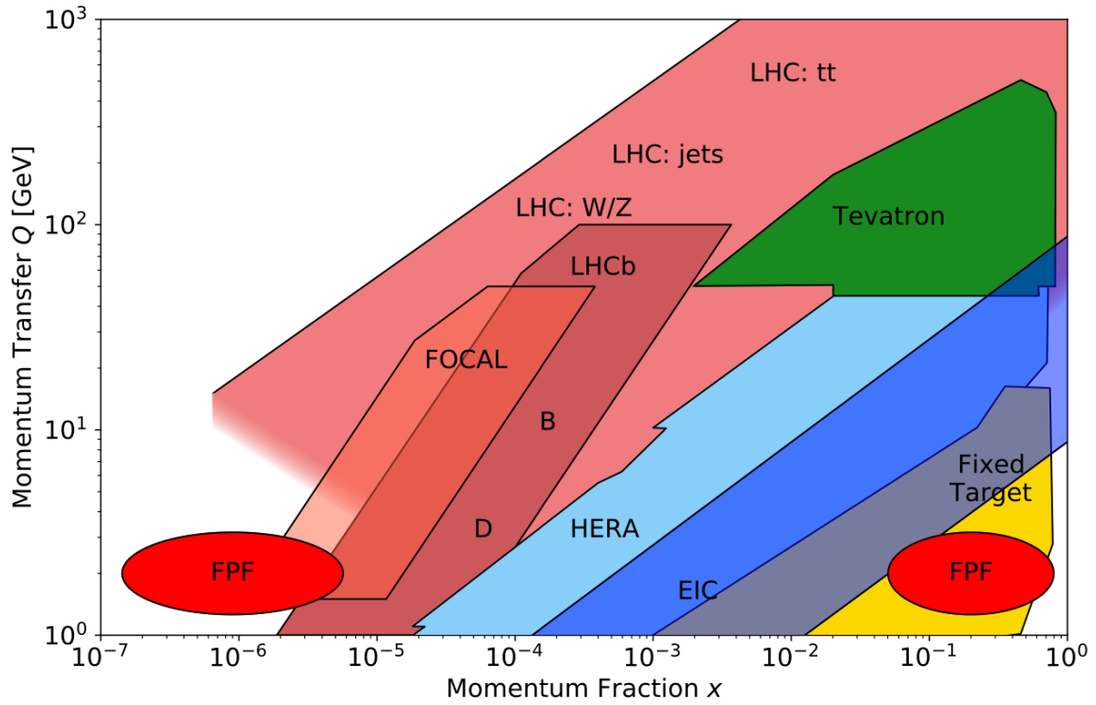
- Testing **BFKL dynamics** in LHC collisions, modelling charm, hadron production in forward region
- Key input for neutrino (IceCube, KM3NET) and cosmic ray **astroparticle experiments**

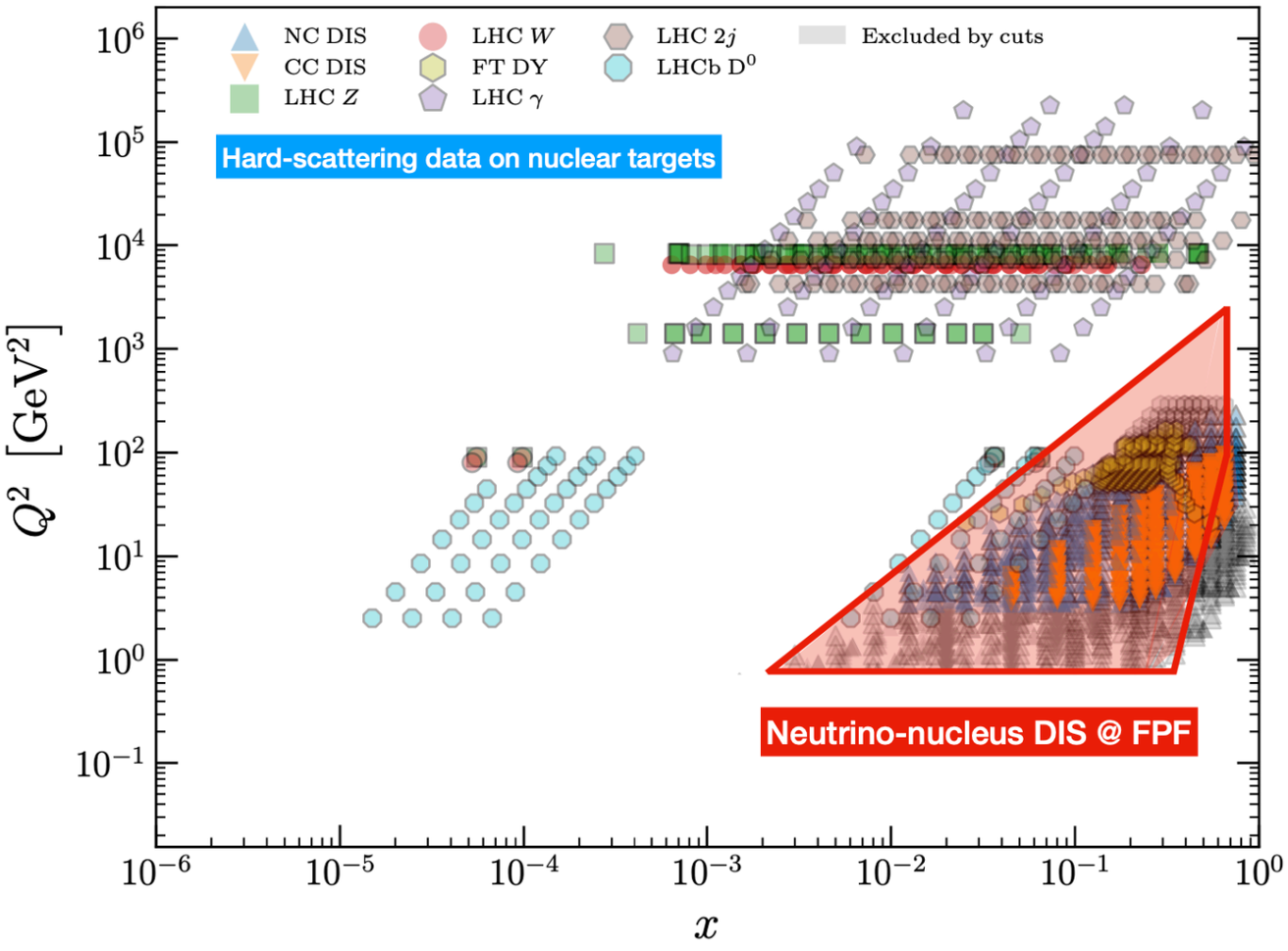
QCD at the FPF



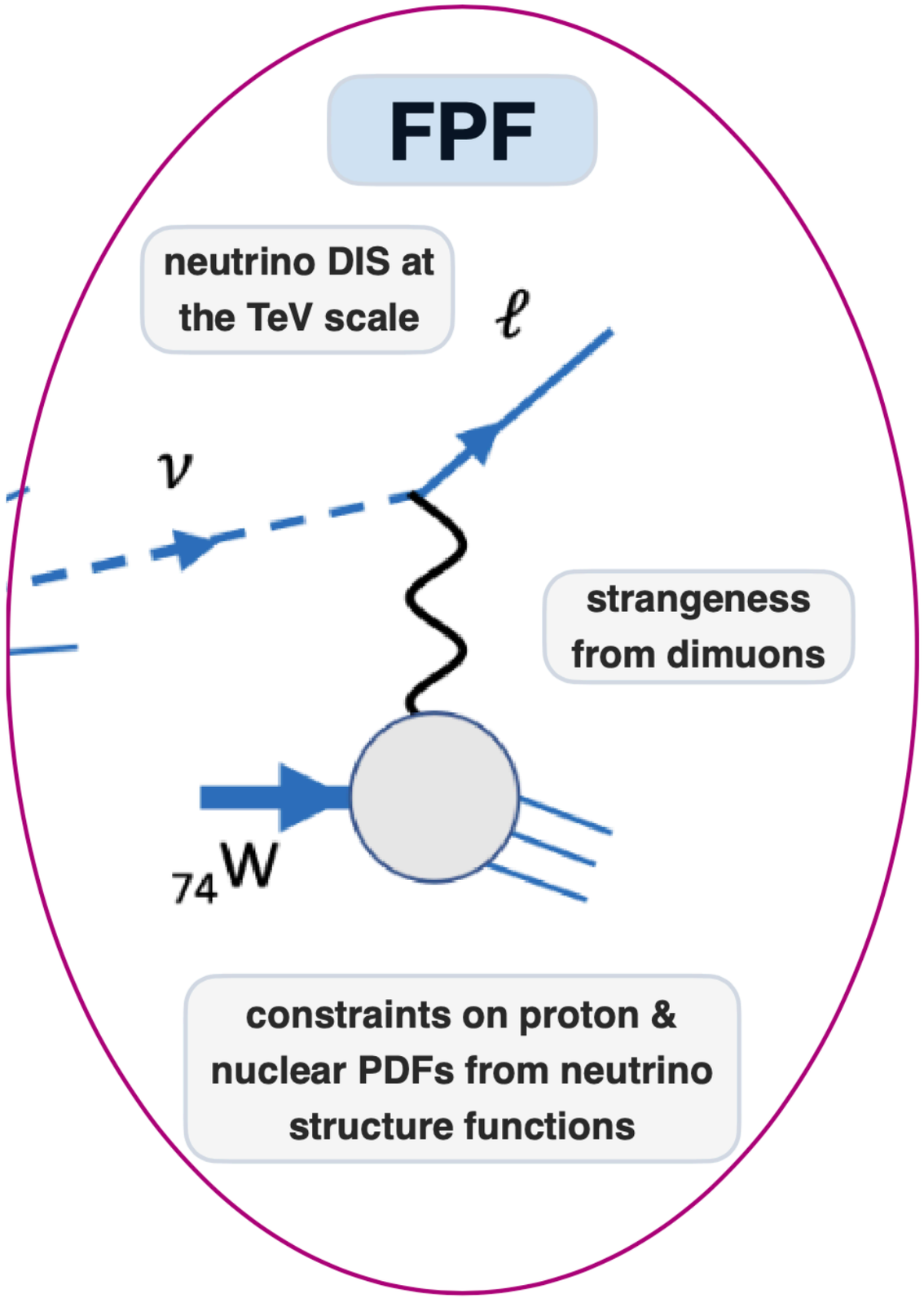


- **Forward particle production** (light hadrons & D-mesons) sensitive down to ***x*=10^{-7}**
- Ultra small-*x* proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of forward hadron fragmentation
- Constraints on **intrinsic charm**

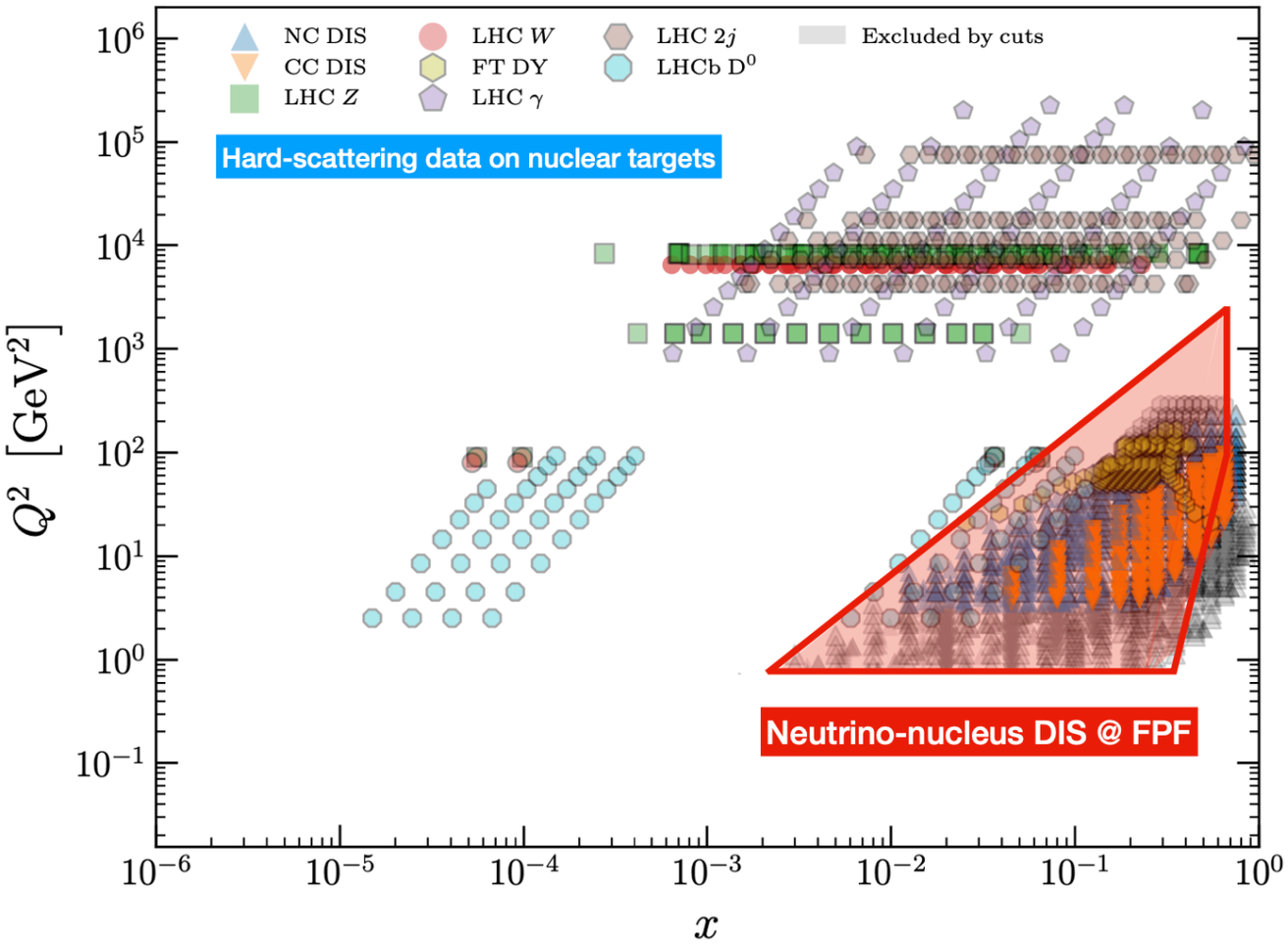
QCD at the FPF

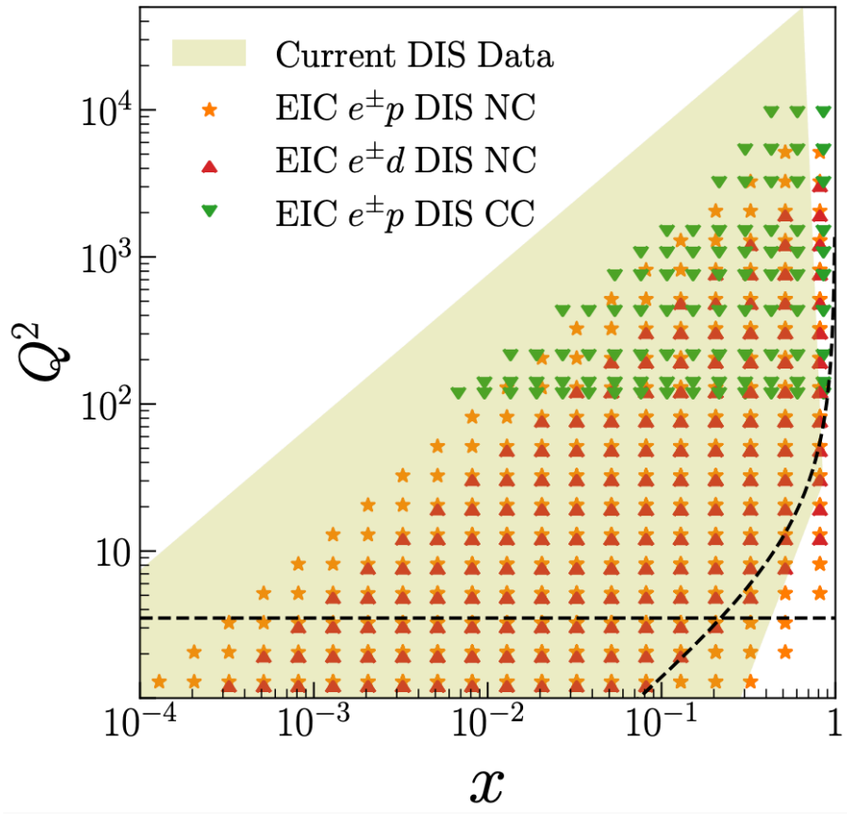


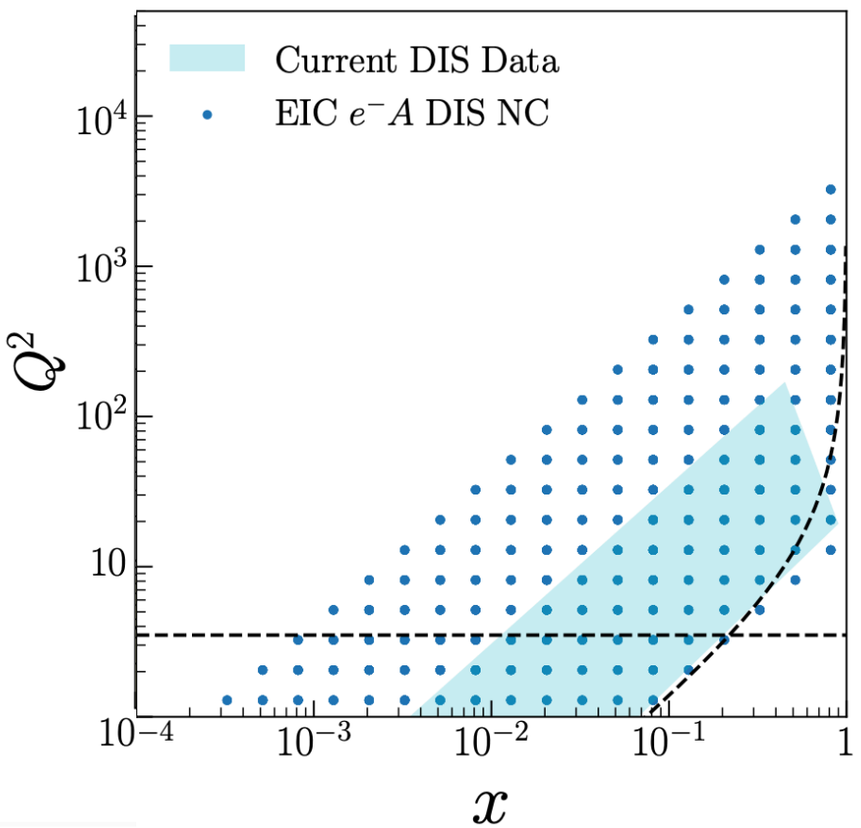
- Deep-inelastic CC scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs**



QCD at the FPF



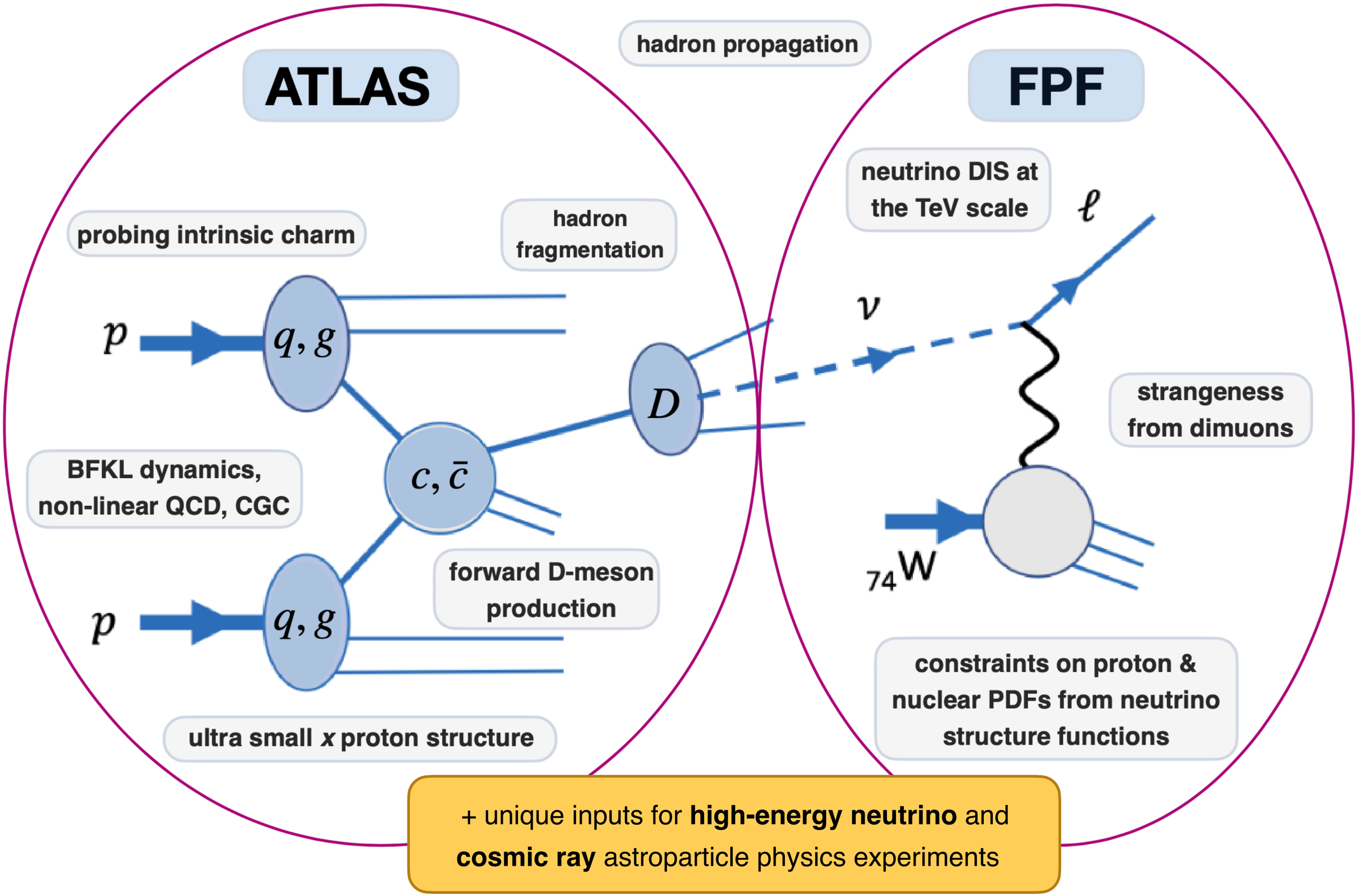




- Excellent complementarity between **EIC (neutral current)** and **FPF (charged current)** measurements of DIS structure function on proton and nuclear targets

- A **joint analysis of EIC+FPF data** markedly improves the (n)PDF reach of **individual experiments**

QCD at the FPF



+ unique inputs for **high-energy neutrino** and **cosmic ray** astroparticle physics experiments

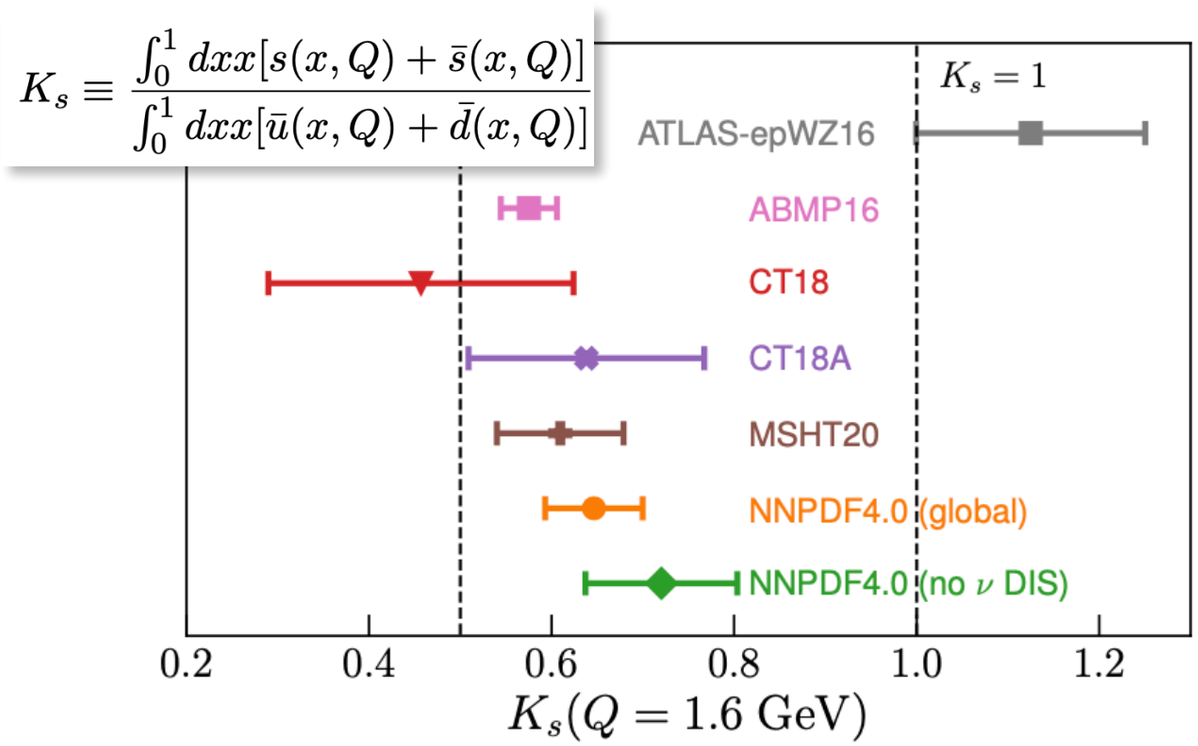
Neutrino DIS in (n)PDF fits

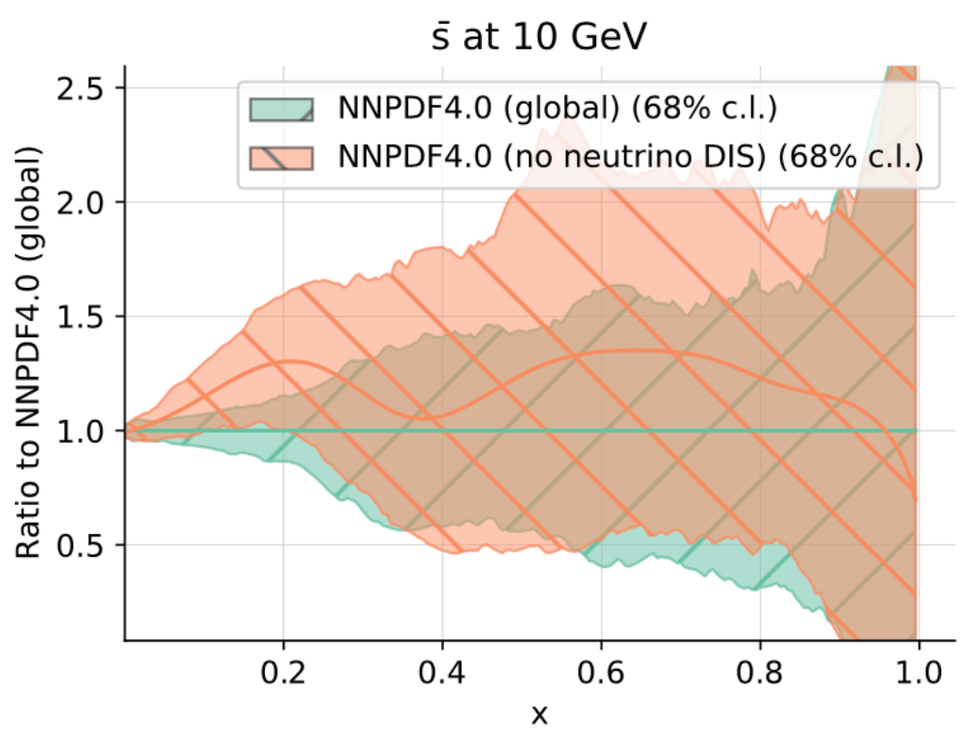
Neutrino DIS structure functions are a cornerstone of global nPDF fits

			Proton PDF sets				Nuclear PDF sets			
Data set		Ref.	ABMP16	CT18	MSHT20	NNPDF4.0	EPPS21	nCTEQ15	nNNPDF3.0	TUJU21
CHORUS $\sigma^{\nu,\bar{\nu}}_{CC}$	Pb	[1238]	✗	✗	✓	✓	✓	✗	✓	✓
CHORUS	Pb	[1239]	✓	✗	✗	✗	✗	✗	✗	✗
NOMAD $\mathcal{R}_{\mu\mu}$	Fe	[1195]	✓	✗	✗	(✓)	✗	✗	✗	✗
CCFR xF_3^p	Fe	[1240]	✗	✓	✗	✗	✗	✗	✗	✗
CCFR F_2^p	Fe	[1241]	✗	✓	✗	✗	✗	✗	✗	✗
CDSHW F_2^p, xF_3^p	Fe	[1242]	✗	✓	✗	✗	✗	✗	✗	✓
NuTeV $\sigma^{\nu,\bar{\nu}}_{CC}$	Fe	[1196]	✓	✓	✓	✓	✗	✗	✓	✗
NuTeV F_2, F_3	Fe	[1194]	✗	✗	✓	✗	✗	✗	✗	✗

Despite constraints on **quark flavour separation** from LHC, **neutrino DIS** still provides key information

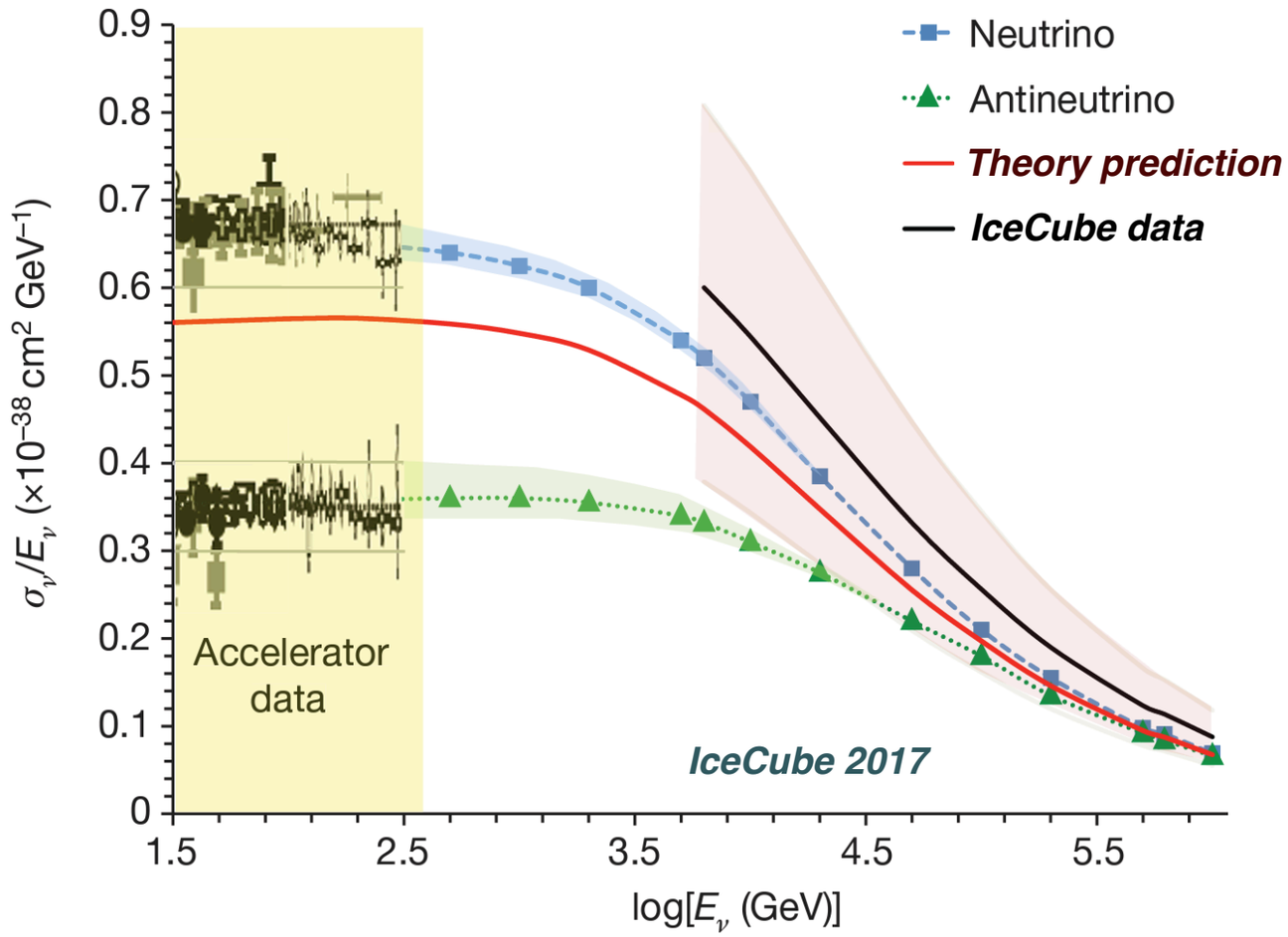
$$K_s \equiv \frac{\int_0^1 dx x[s(x,Q)+\bar{s}(x,Q)]}{\int_0^1 dx x[\bar{u}(x,Q)+\bar{d}(x,Q)]}$$

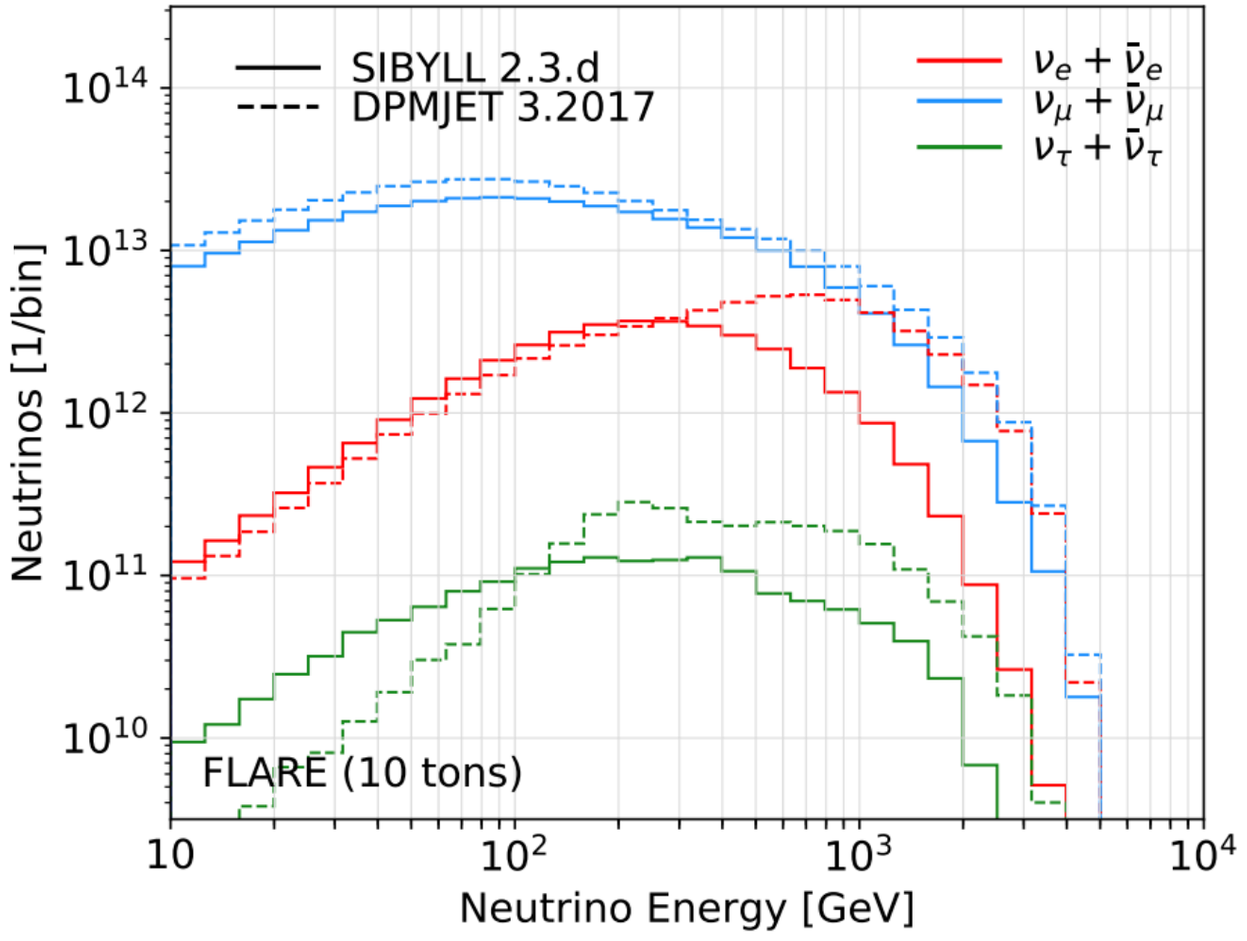




Neutrino DIS at the LHC

Neutrino cross-sections 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

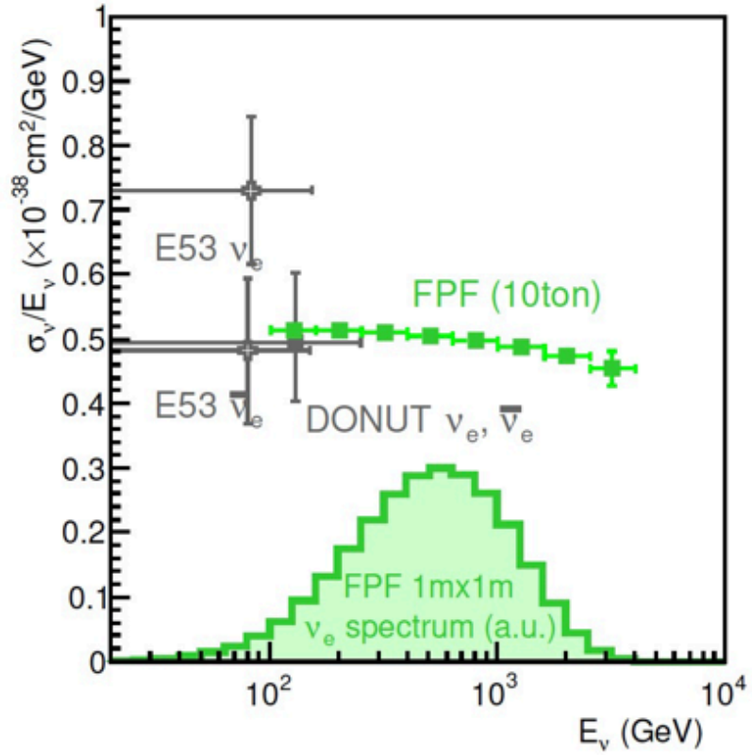
but with large uncertainties

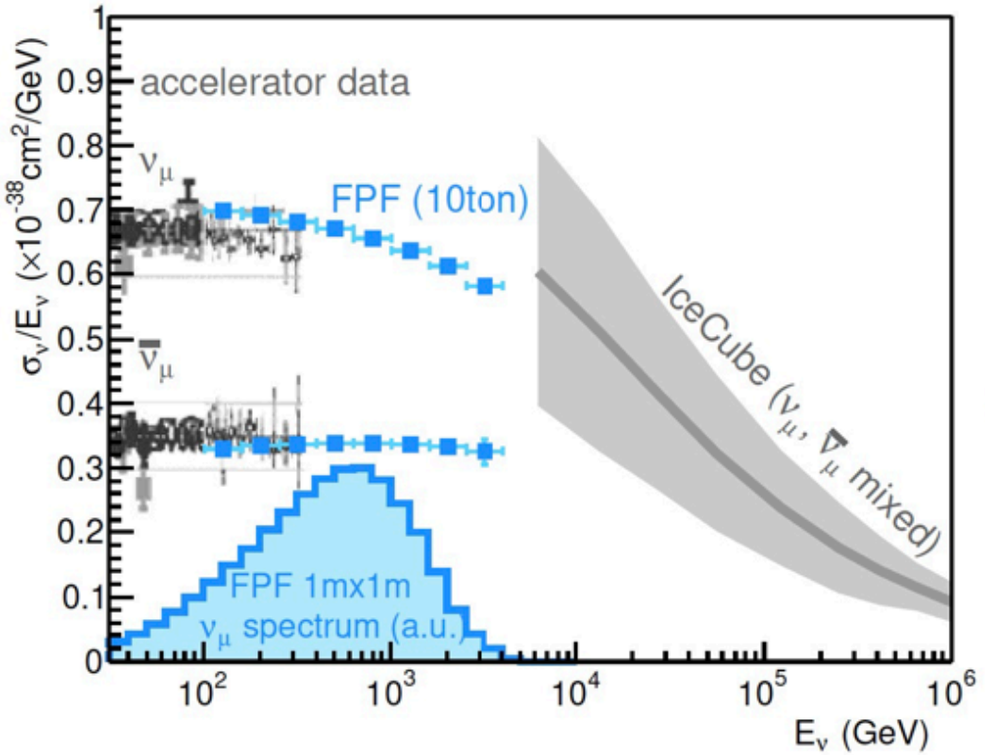
Neutrinos arriving at the Forward Physics Facility have **energy distributions** peaking between **100 GeV and 10 TeV**. Unique opportunity to test neutrino interactions

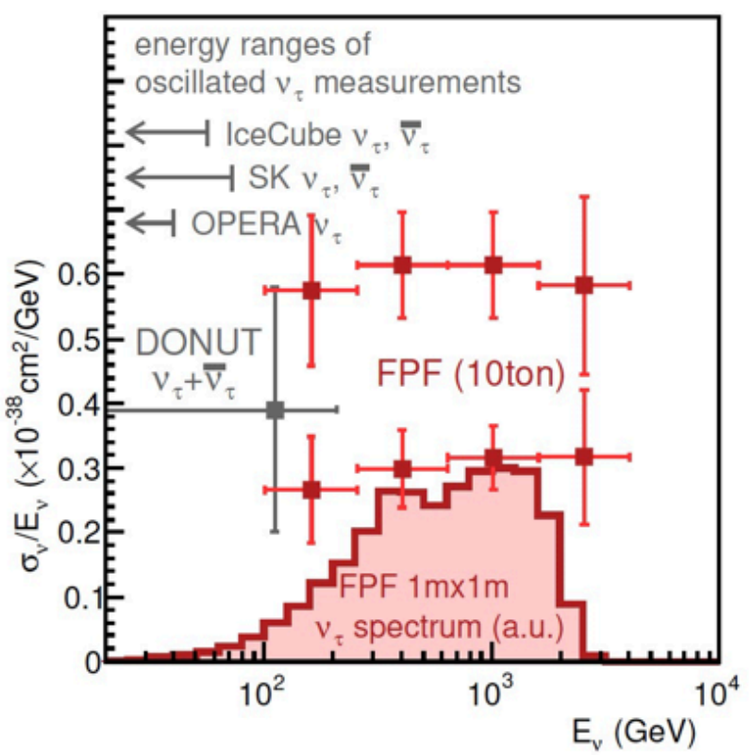
The FPF is effectively a Neutrino-Ion Collider with $E_{CM} \approx$ 100 GeV!

Neutrino DIS at the LHC

FPF neutrinos: bridging the gap between **accelerator data** and **cosmic neutrinos**





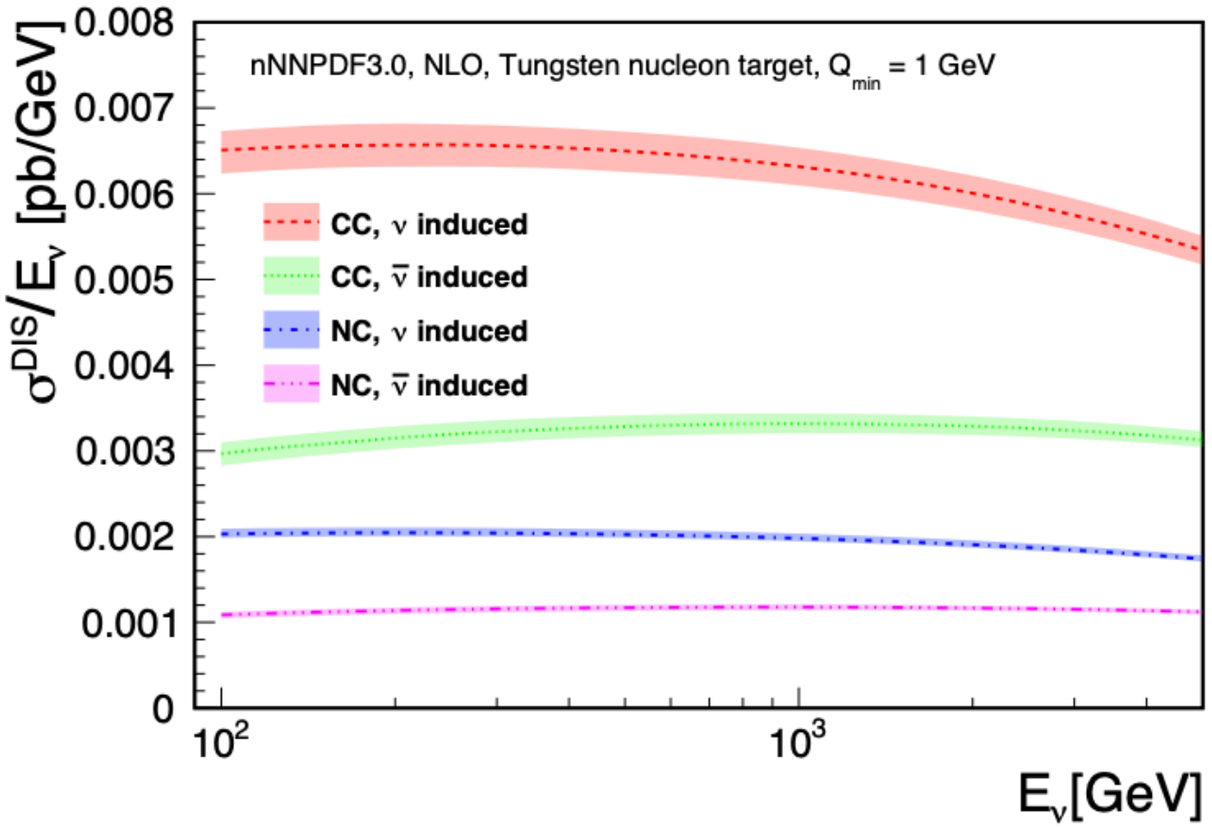


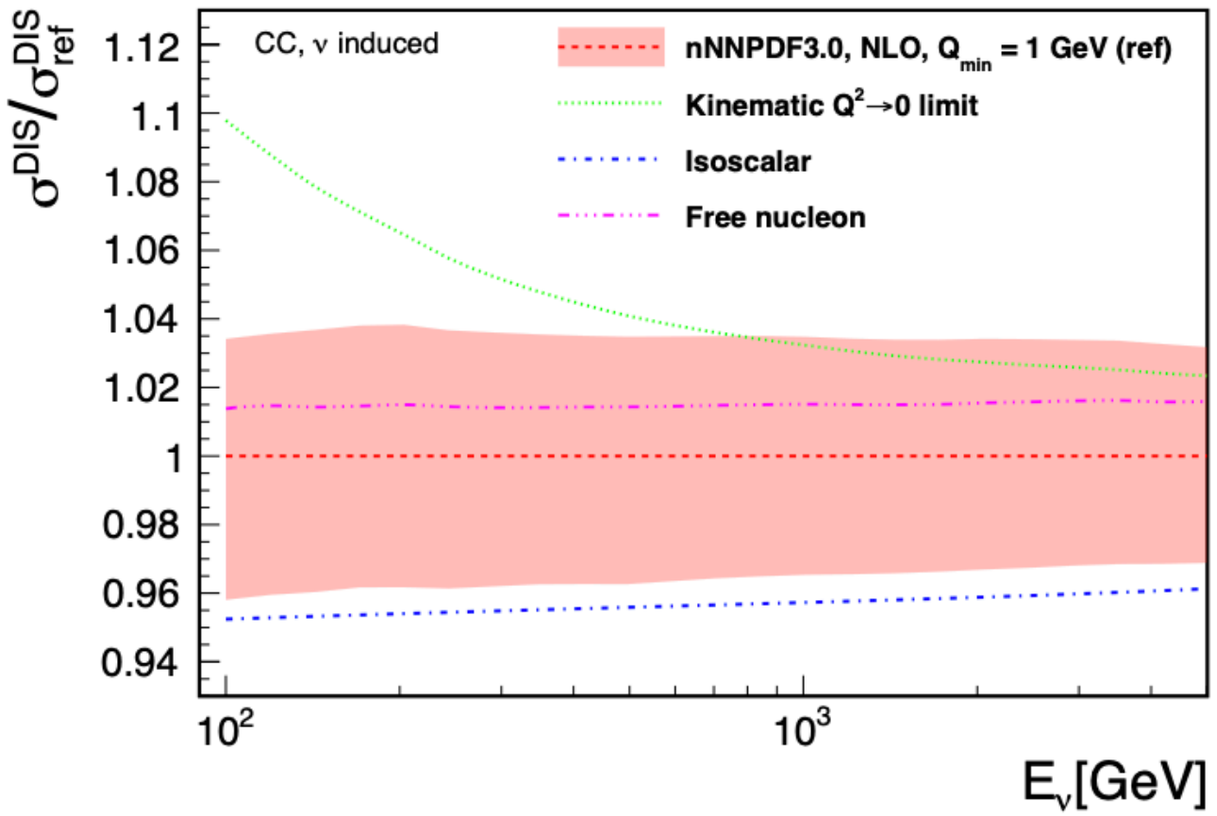
- Neutrino cross-sections and structure functions can be measured with **O(few %) statistical precision,** improving on available measurements specially with **muon neutrinos**

- Neutrino DIS provides access to the **quark flavour decomposition** in nucleons and nuclei: sea quark asymmetry, strangeness, charm

- Natural continuation of the extremely succesful **CERN programs on neutrino DIS**

Neutrino DIS at the LHC



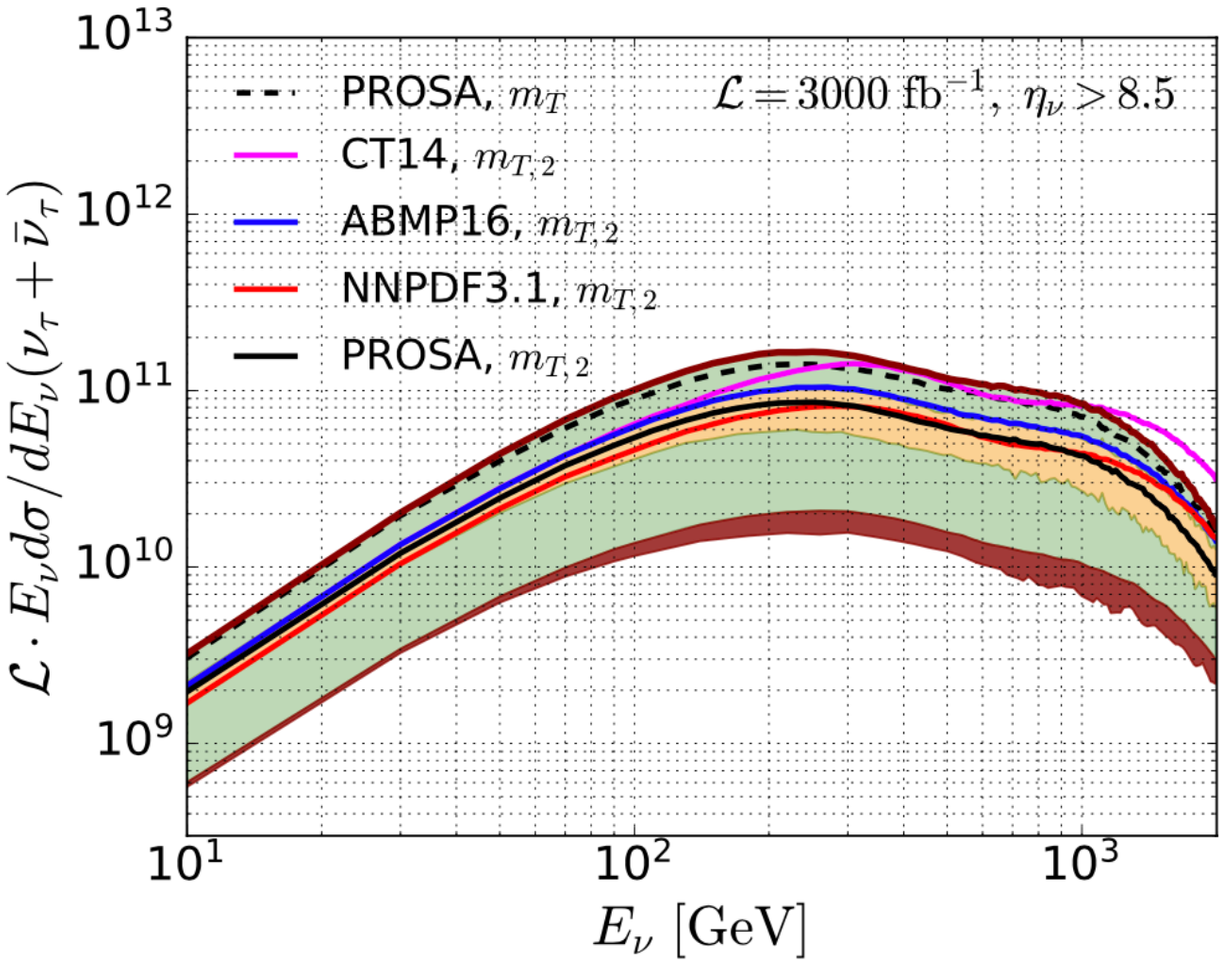


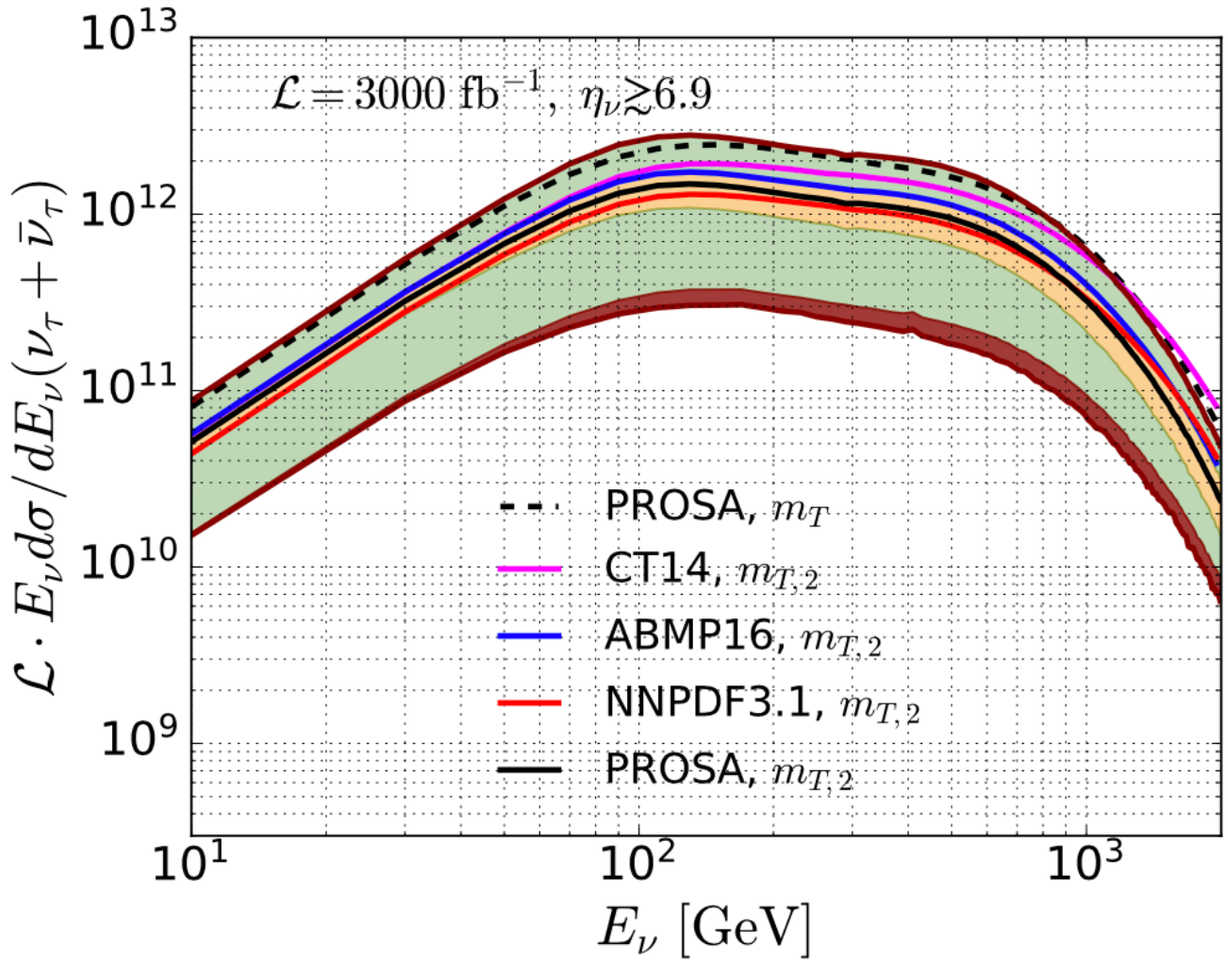
- Measurements of neutrino DIS structure functions will **constrain quark flavour separation**

- Inclusive cross-section measurements sensitive to **low-*Q* region** beyond validity of perturbative QCD, novel approaches there required to bypass model-dependence

- Nuclear corrections on tungsten targets relatively small in the region covered by FPF: strong potential to **constrain the free-nucleon PDFs**

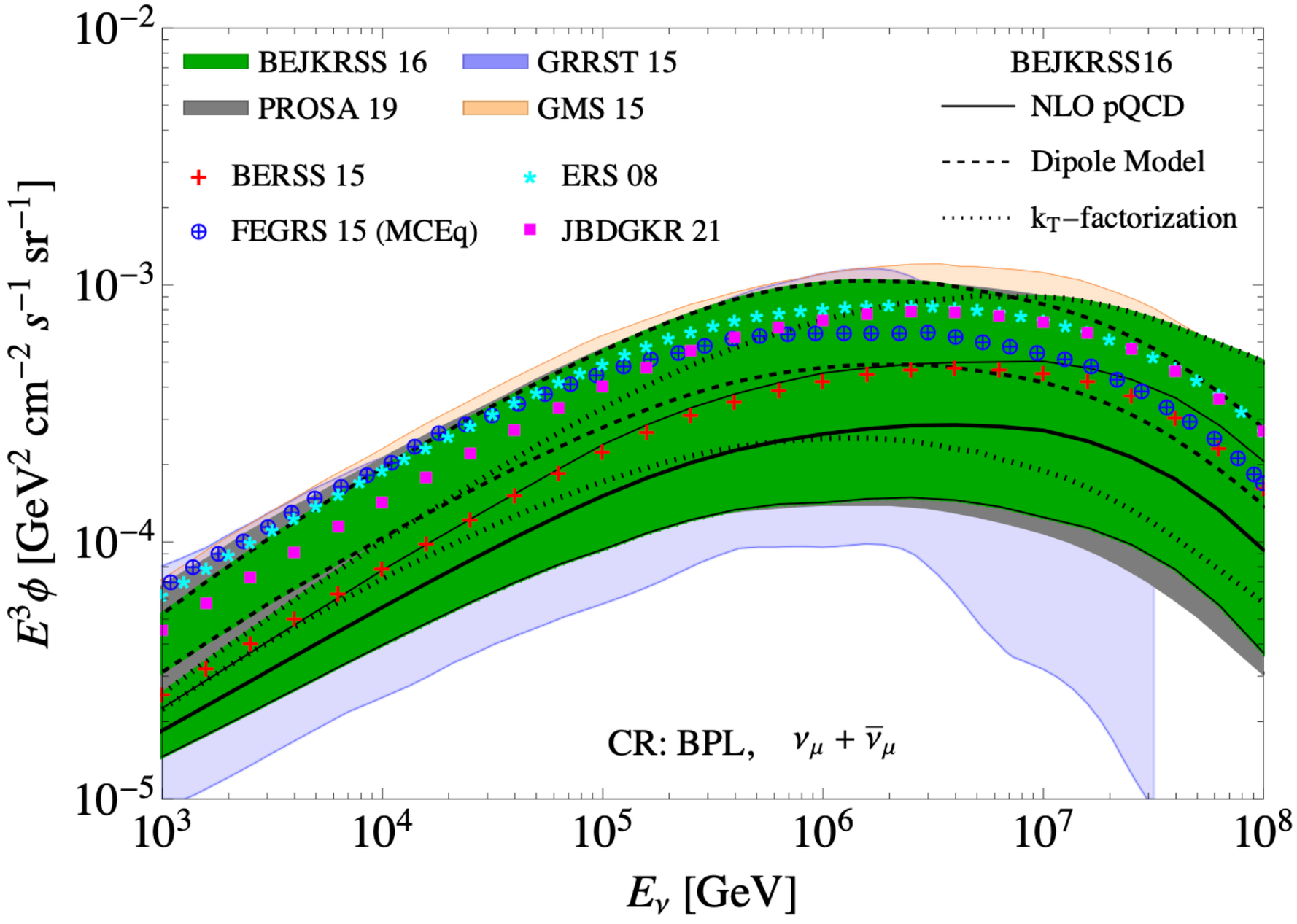
Neutrino fluxes





- One challenge for the interpretation of the FPF data will be the **large theory uncertainties** associated to the incoming neutrino flux e.g. large MHOUs to *D*-meson production
- Design observables where **flux uncertainties cancel out** to maximise QCD sensitivity
- Progress in **NNLO QCD** (+ parton shower matching) required to reduce absolute MHOUs

The cosmic connection



- FPF will constrain **small-*x* proton structure** and validate **calculations of low-*x* QCD processes**
- In turn this will benefit **predictions for key astroparticle physics processes**, such as the flux of prompt neutrinos (main background to UHE cosmic neutrinos)

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, complementing existing and future experiments, e.g. CC DIS complements the **EIC**

- Charm meson and light hadron production in the forward region represent a **testbed for QCD calculations**: higher-orders, BFKL, fragmentation, non-linear effects, small-*x* PDFs, …

- Production (ATLAS) and interaction (FPF) processes **intertwined**: *e.g.* intrinsic charm enhances *D*-meson production which in turn leads to a **larger neutrino flux**

- Ideas and contributions to **further strengthen the FPF potential** more than welcome!