QCD at the Forward Physics Facility

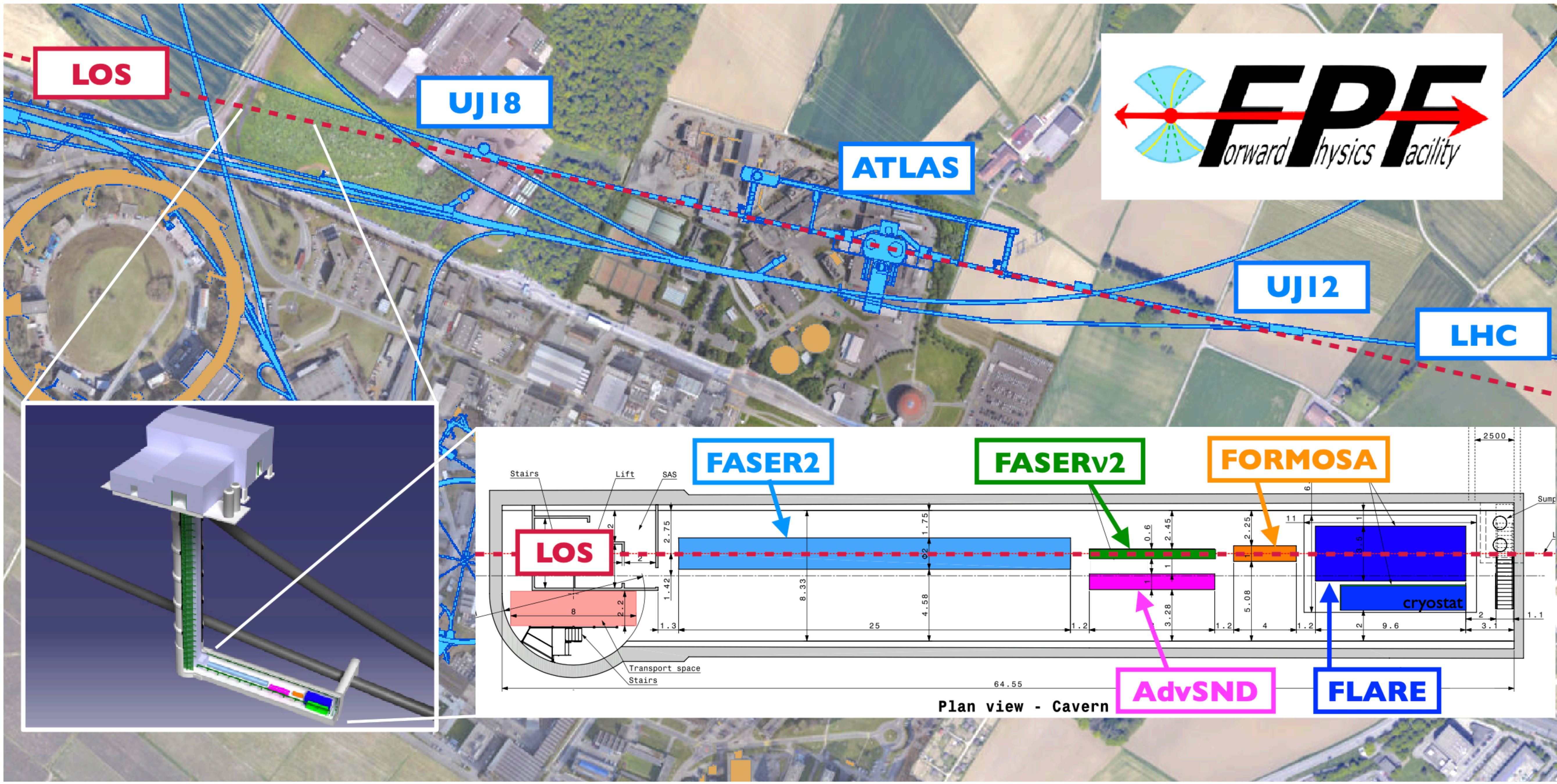
Juan Rojo, VU Amsterdam & Nikhef

Physics Beyond Colliders

QCD Working Group Spring Meeting, 11/05/2022

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)

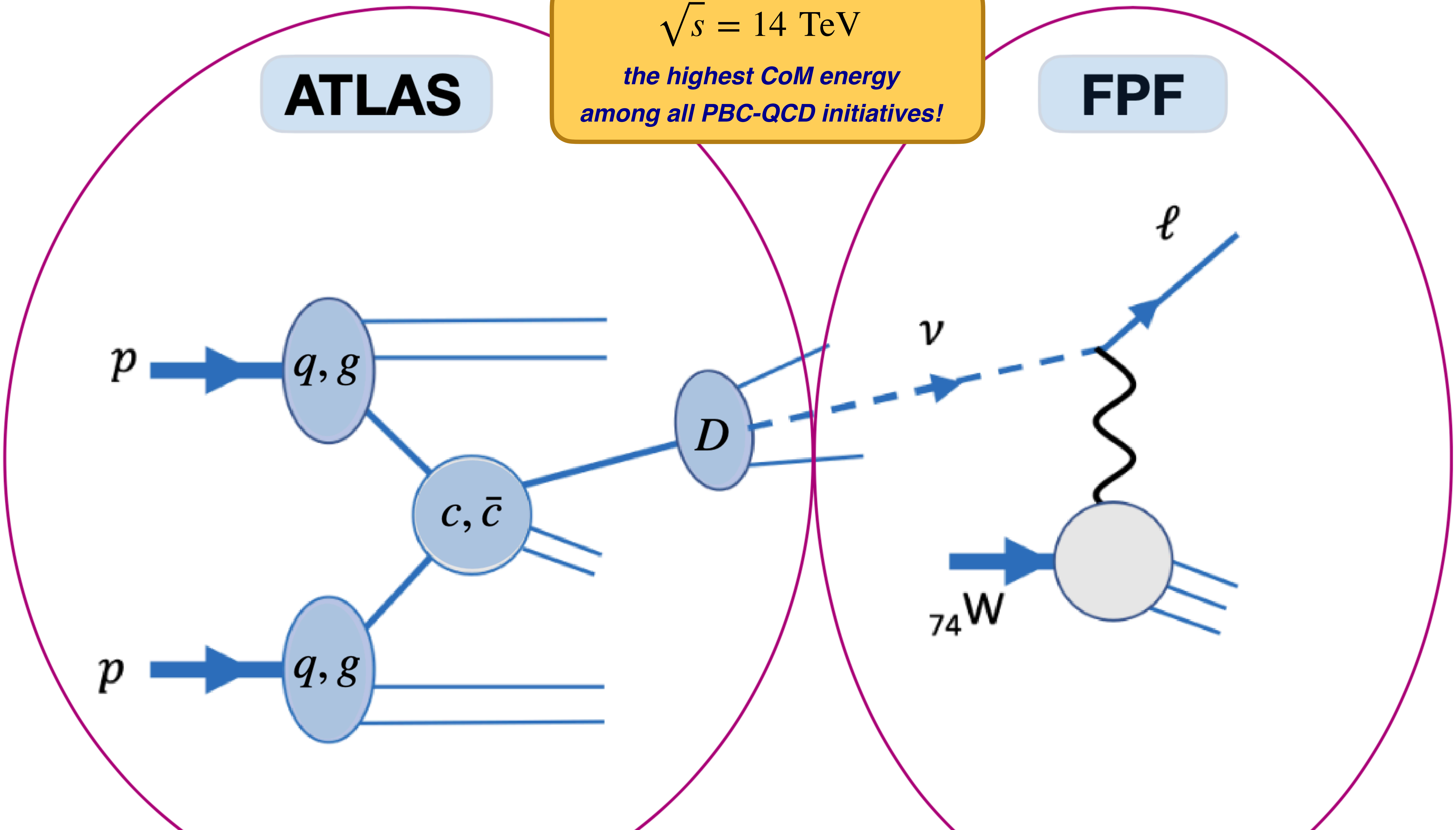


No modifications to the HL-LHC operations required!

Closing the neutrino gap at the LHC

$\sqrt{s} = 14$ TeV

the highest CoM energy among all PBC-QCD initiatives!



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

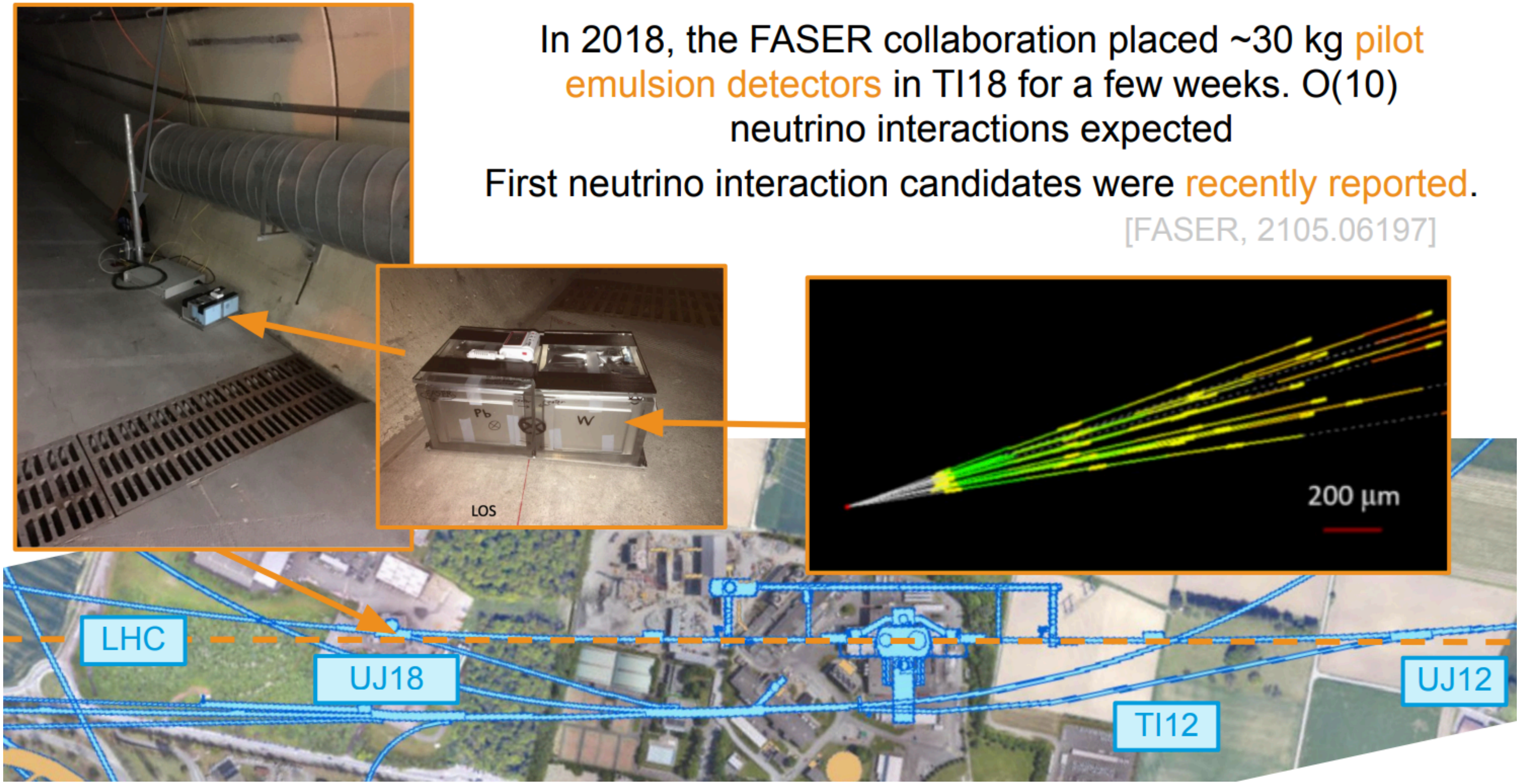
Closing the neutrino gap at the LHC

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!

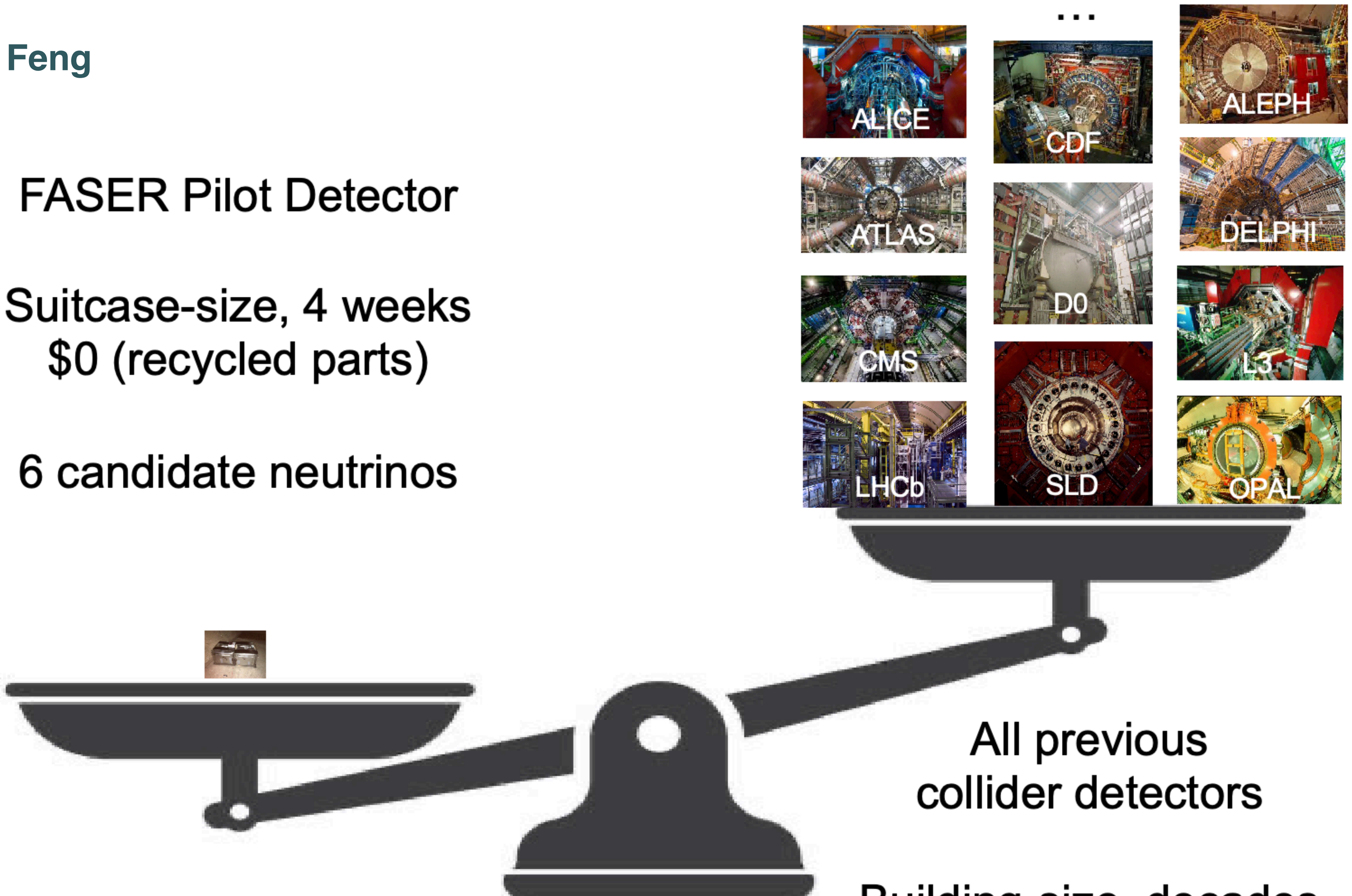
Closing the neutrino gap at the LHC

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 for QCD

Deploy the large flux of **far-forward, high-energy neutrinos** produced in pp collisions at 14 TeV as a unique probe of the **strong interactions** and **proton & nuclear structure**

extremely rich program at the cross-roads between **particle, nuclear**, and **astroparticle physics!**

- **Neutrino cross section** measurements (energy region not covered by any other experiment)
- Neutrino deep-inelastic scattering to constrain **proton and nuclear structure**
- Testing **BFKL dynamics** in LHC collisions, modelling charm, hadron production in forward region
- Novel QCD phenomena, e.g. **intrinsic charm,** parton saturation, nuclear shadowing
- Key input for neutrino (IceCube, KM3NET) and cosmic ray **astroparticle experiments**

also extensive program in **BSM** and **neutrino physics** (not covered here)

- **Light, feebly interacting BSM particles** produced in the forward direction
- Decaying **dark sector long-lived particles** (dark photons, dark Higgs, heavy neutral leptons…)
- Milli-charged particles, dark matter scattering
- **EFT constraints** on neutrino interactions

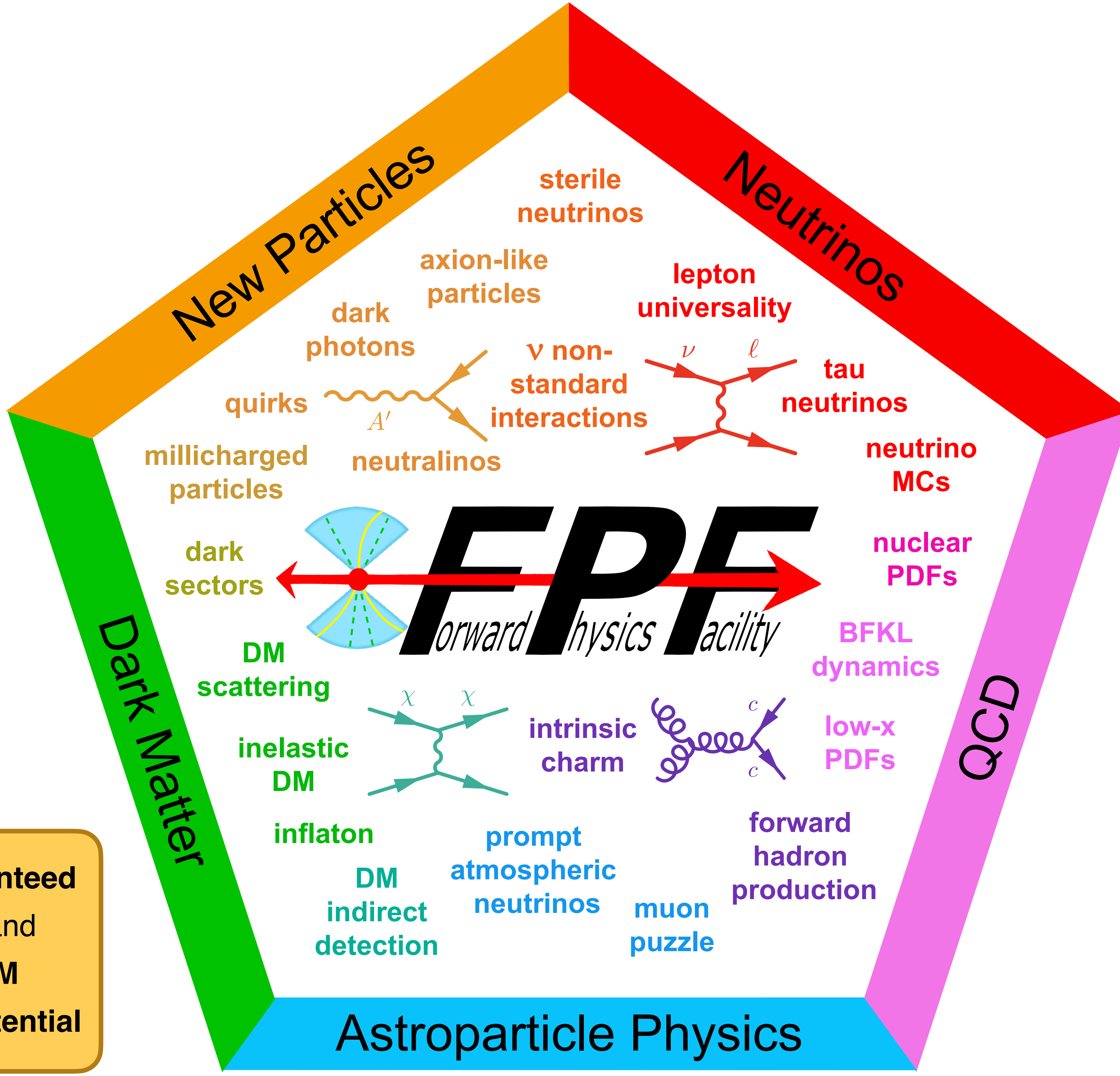
- **Tau neutrino** studies (**3k** tau neutrino interactions, current world sample <20)
- Separation of tau neutrino / anti-neutrino, constrain tau neutrino EDM
- Tau neutrino decays into heavy flavour (connection with **LHCb LFV anomalies**)

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

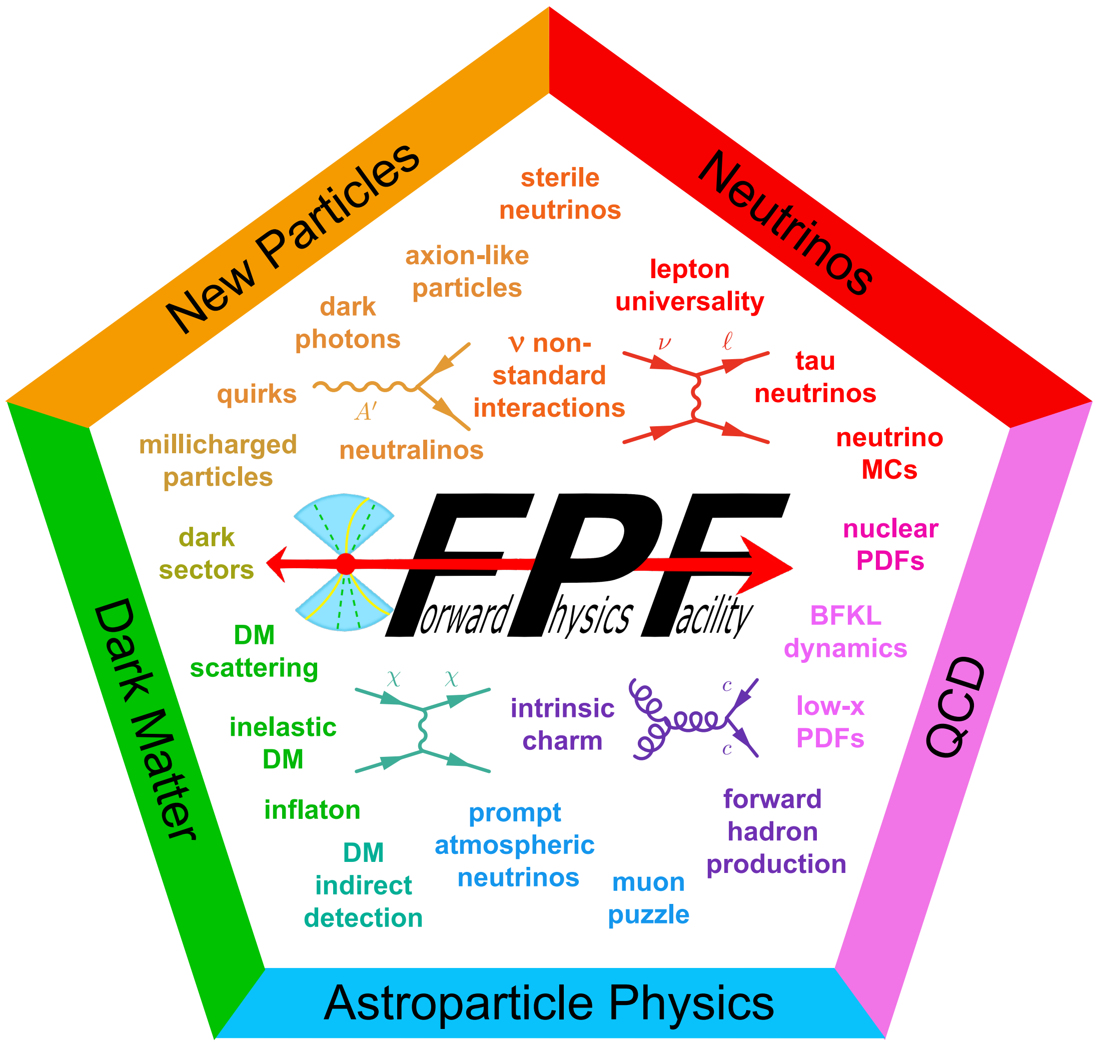
25 MCHF construction **+ 15 MCCH services**

Installation in **LS3**, data taking from **Run 4**

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



unique combination of **guaranteed physics targets** in QCD and neutrino physics and **BSM discovery & exploration 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

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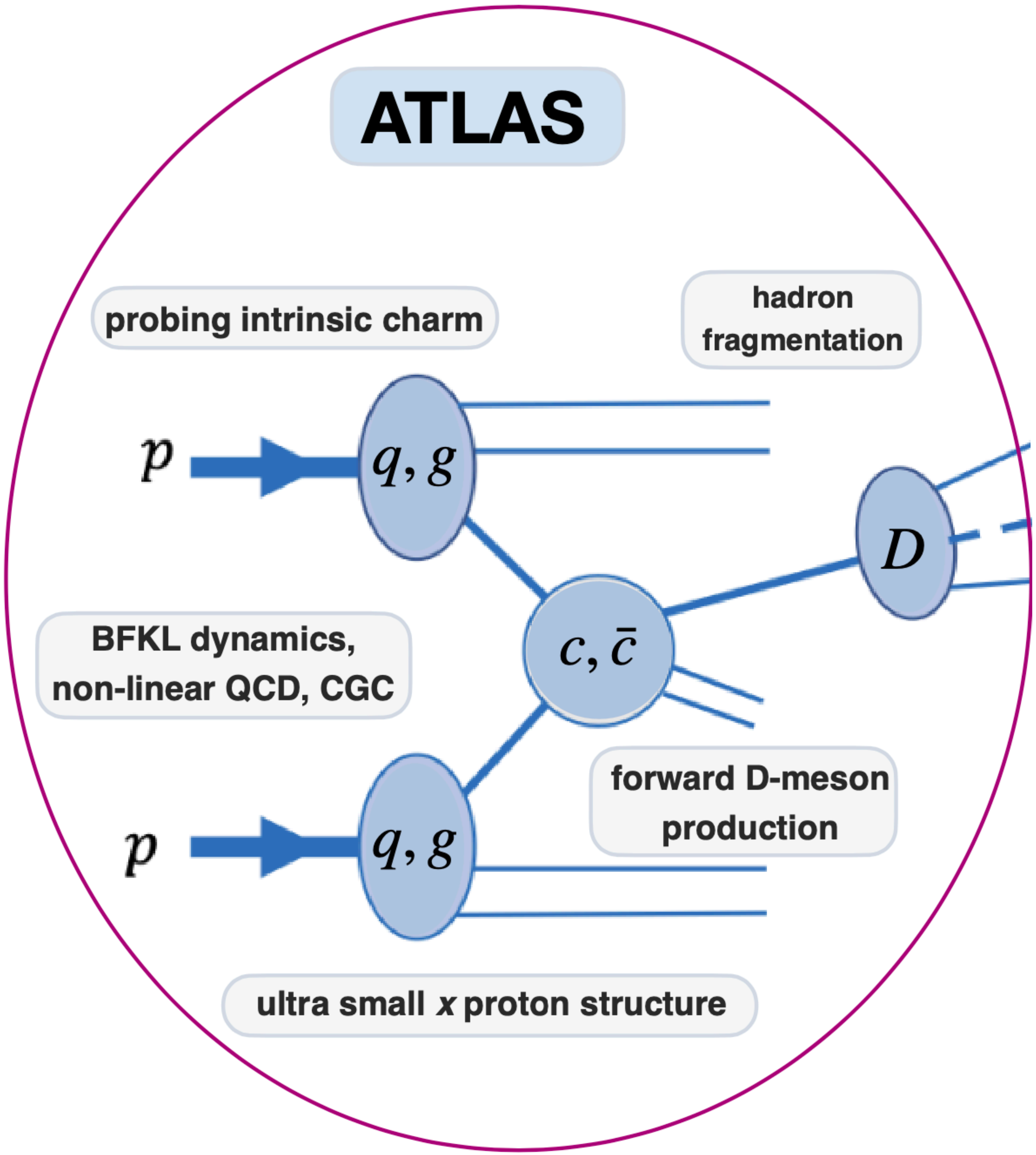
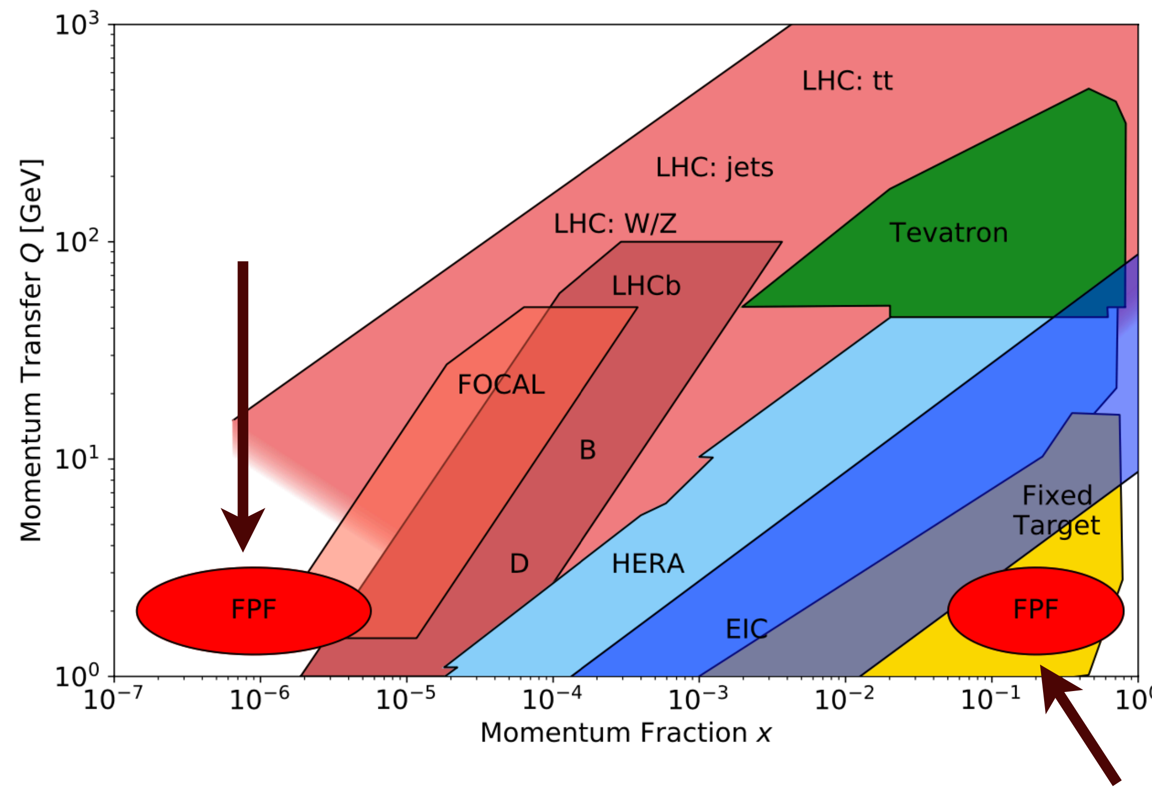
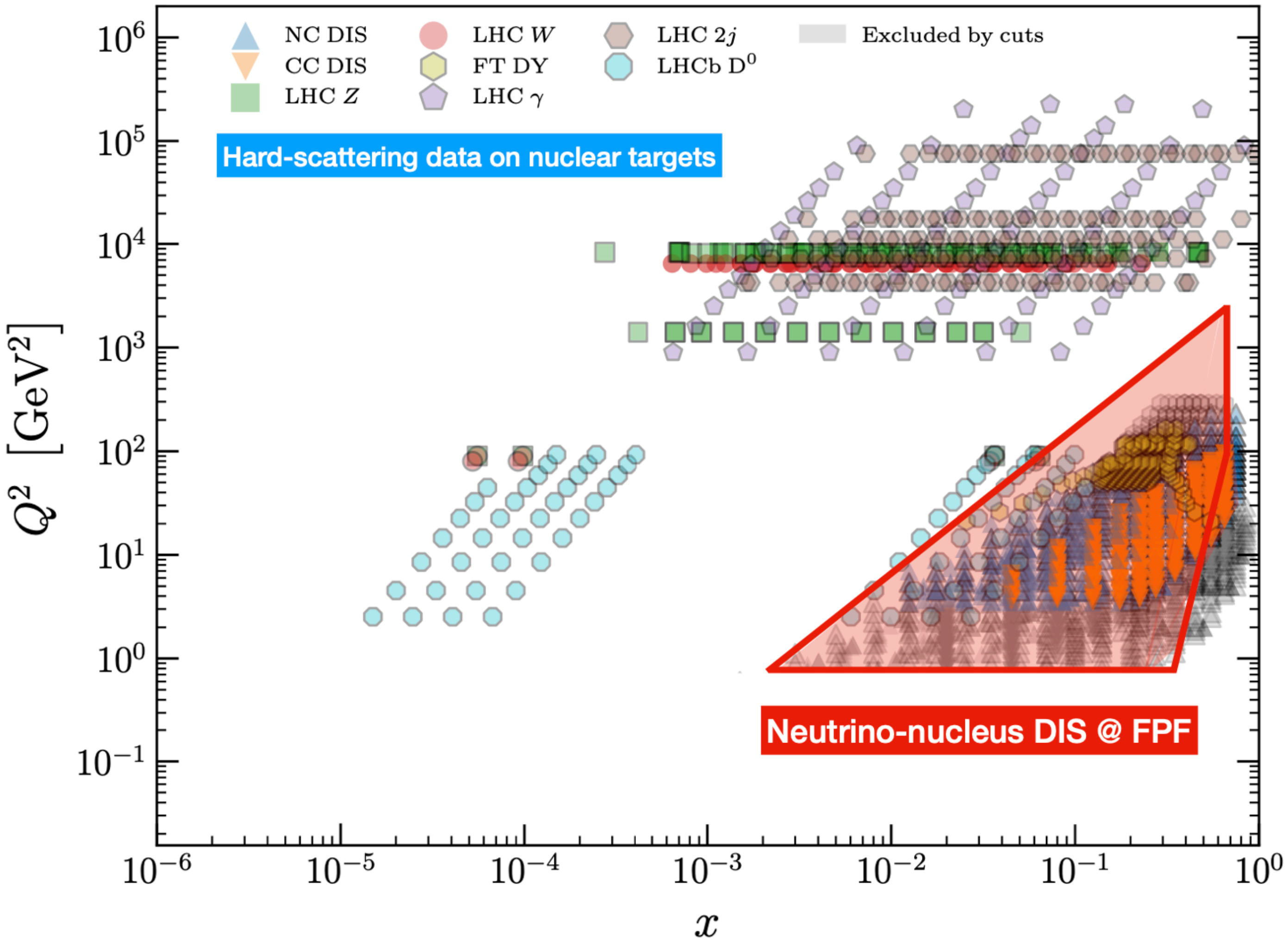
QCD at the FPF (neutrino production)

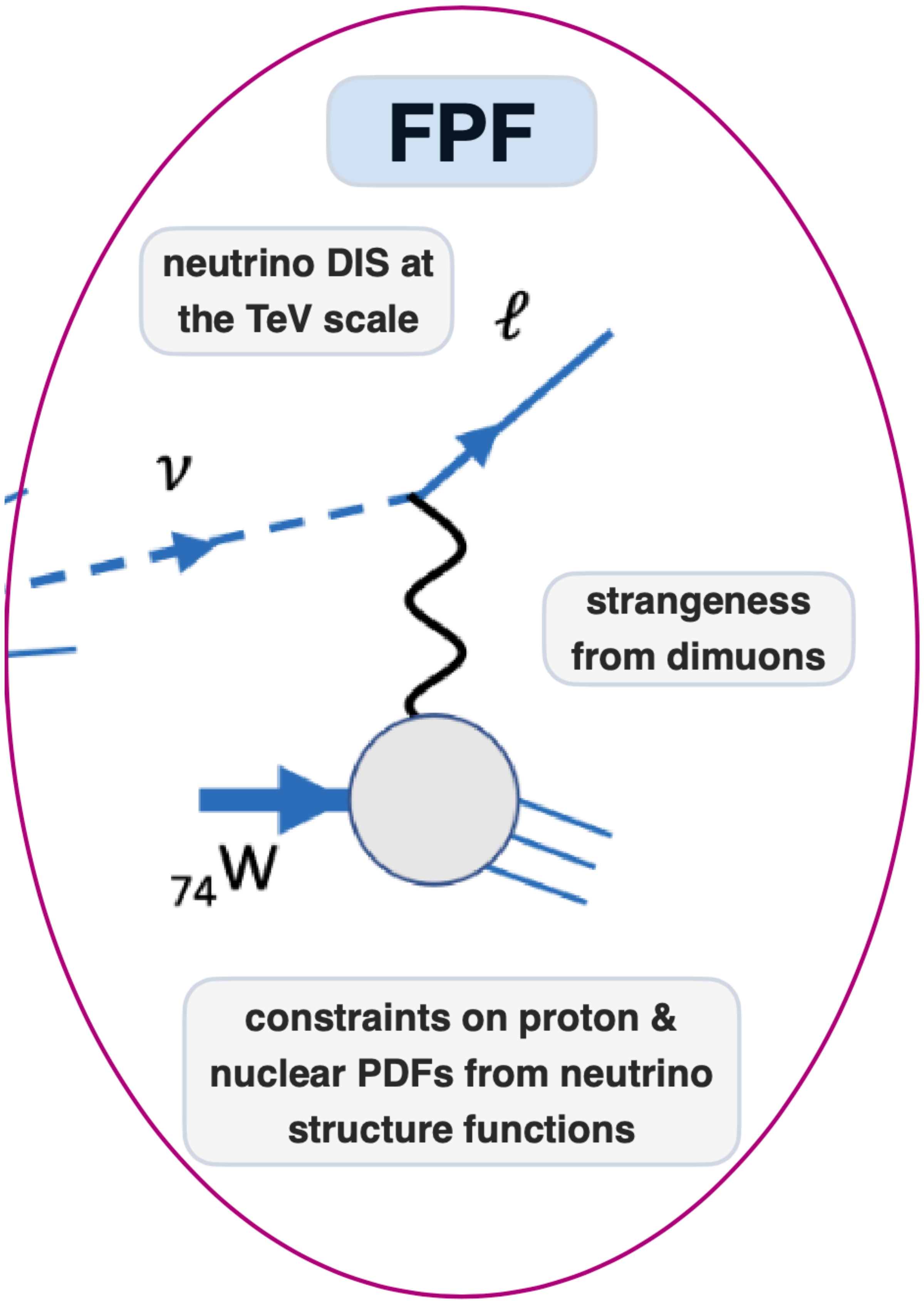




- **Forward particle production** (light hadrons & D-mesons) sensitive down to $\boldsymbol{x=10^{-7}}$
- Ultra small-x proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of forward hadron fragmentation (for e.g. cosmic rays)
- Constraints on **intrinsic charm** from large-x D-meson production

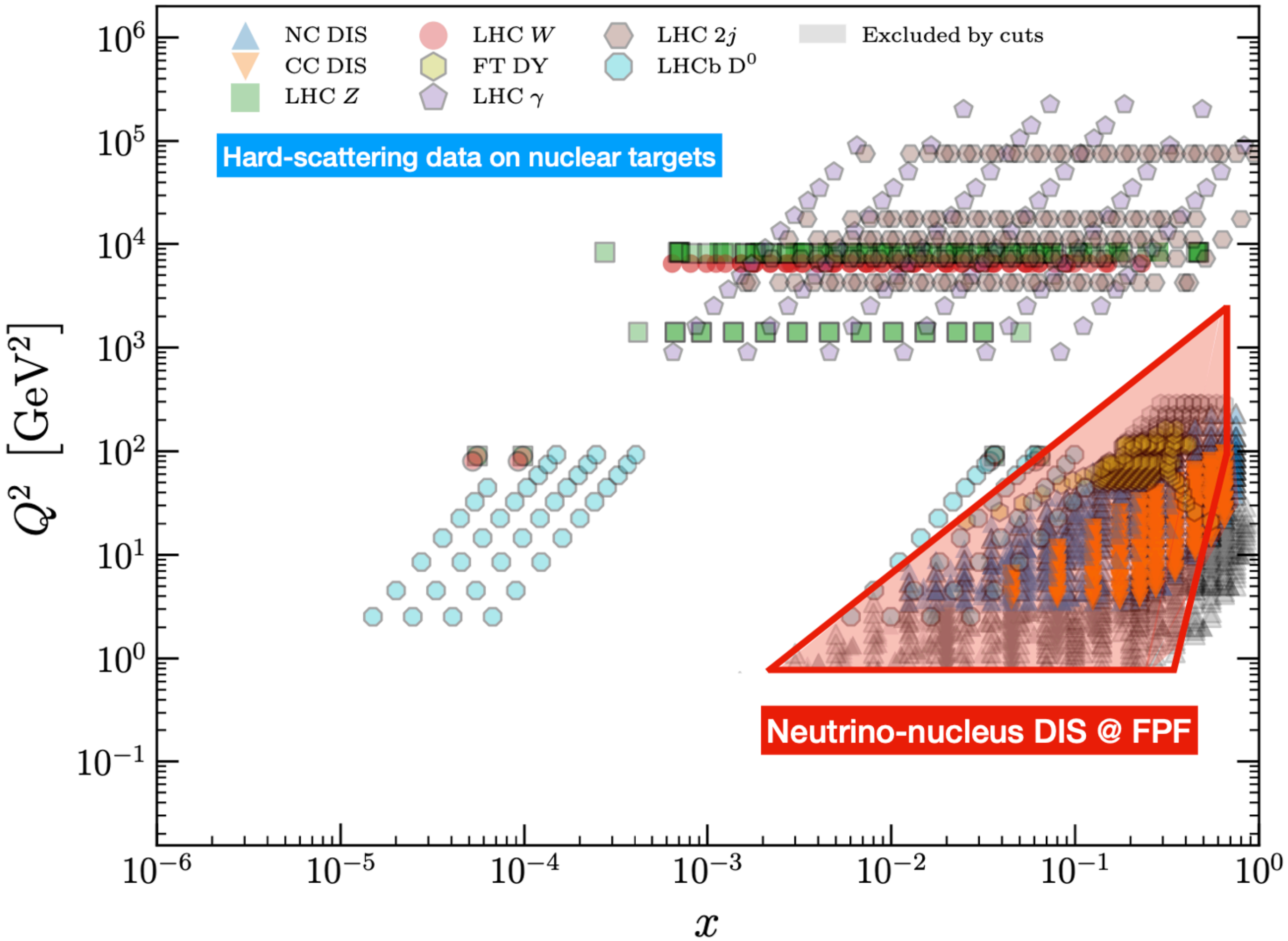
QCD at the FPF (neutrino interactions)

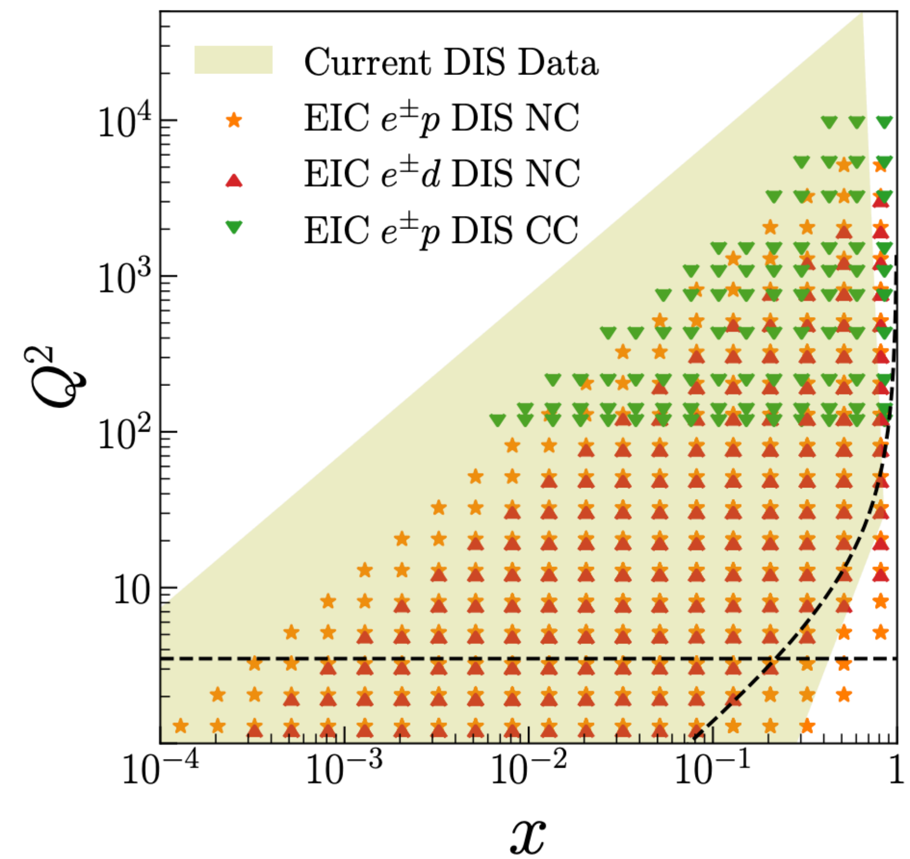


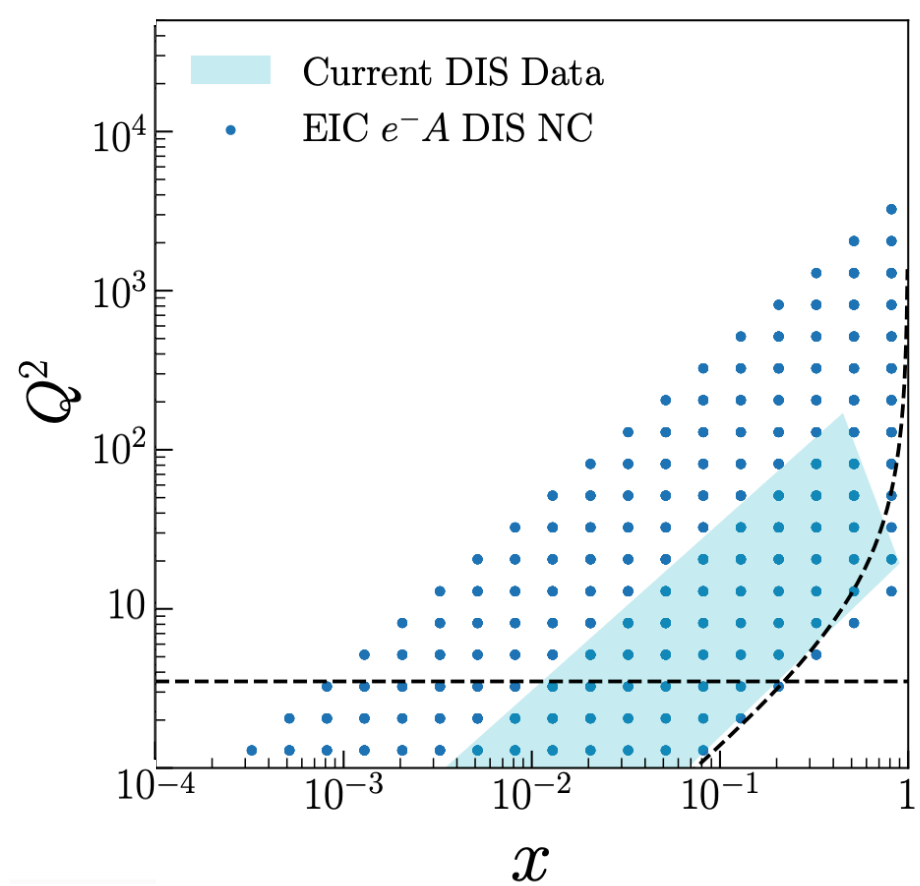


- Deep-inelastic CC scattering with **TeV neutrinos:** validate our understanding of neutrino cross-sections (relevant for oscillation experiments)
- Continue succesful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs** including strangeness

QCD at the FPF (neutrino interactions)



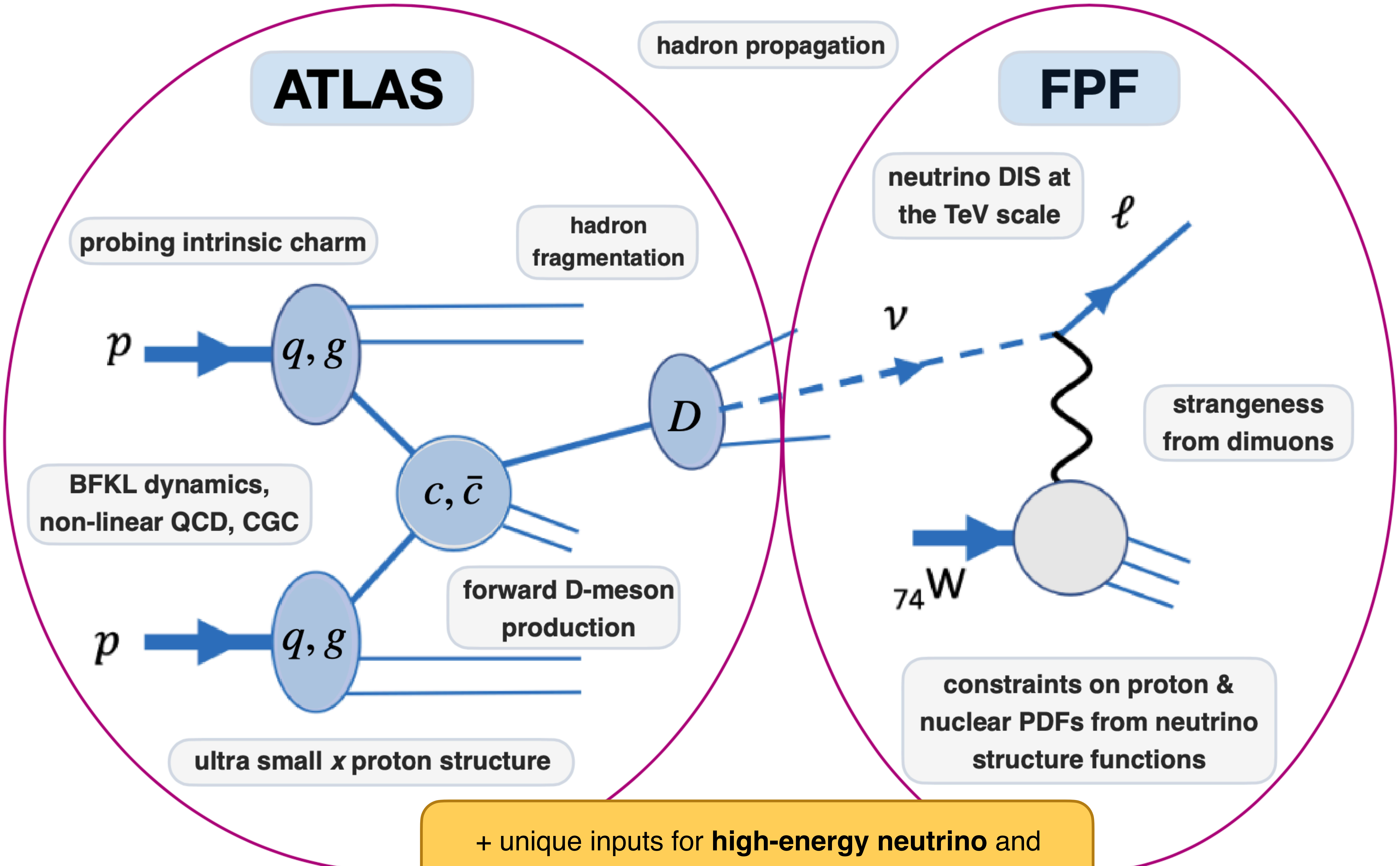




- Excellent complementarity between **EIC (neutral current)** and **FPF (charged current)** measurements of DIS structure function on proton and nuclear targets

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

QCD at the FPF

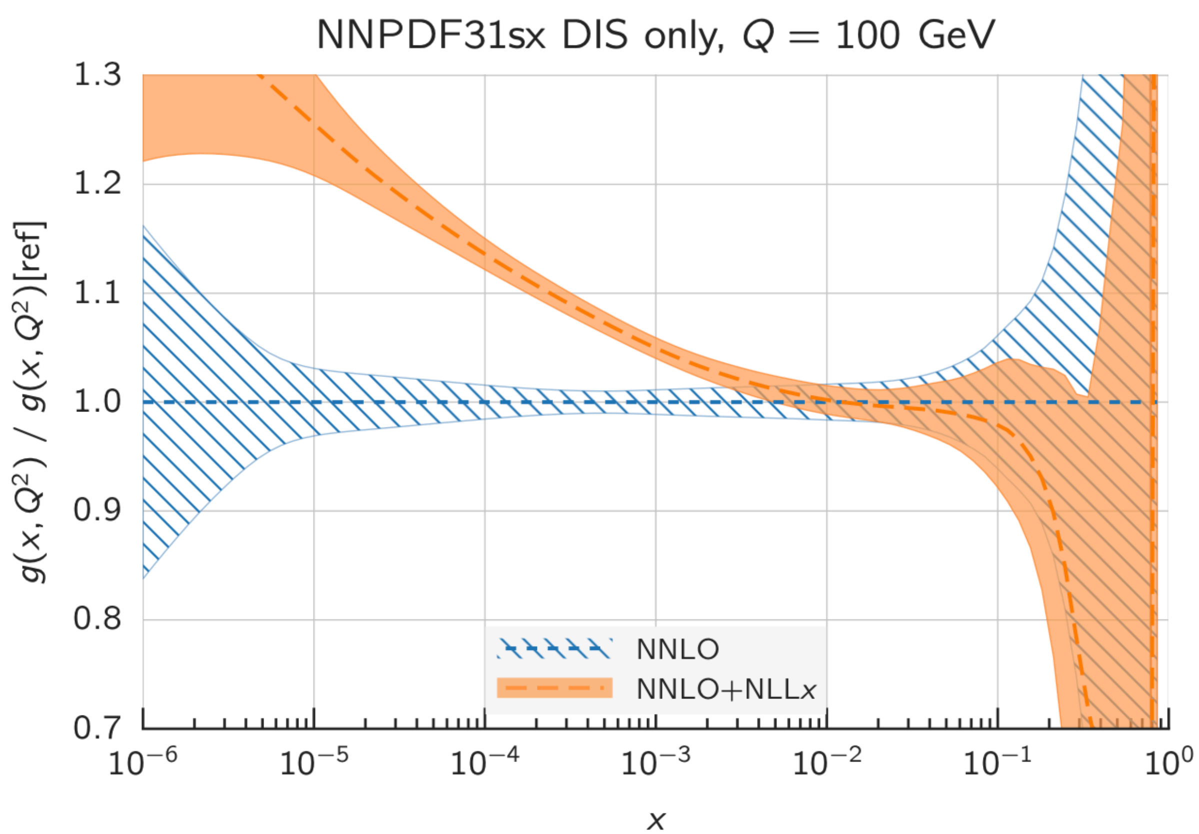


+ unique inputs for **high-energy neutrino** and **cosmic ray** astroparticle physics experiments

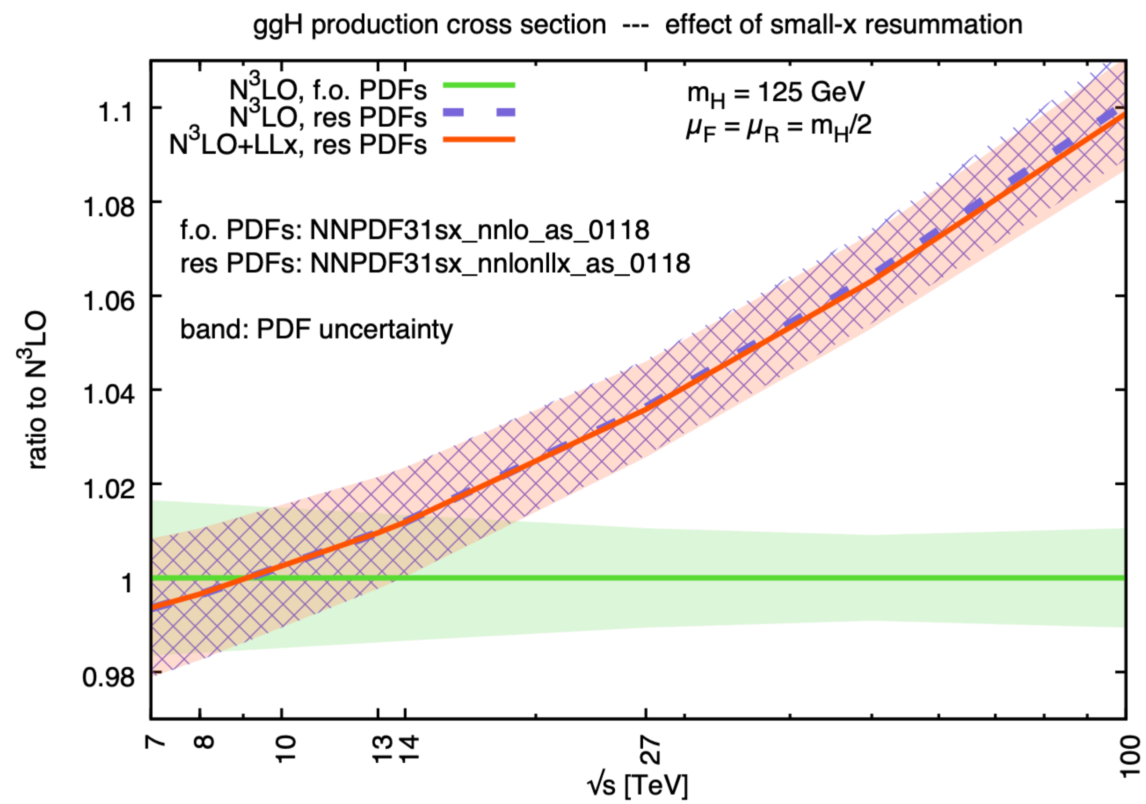
QCD at (ultra-)small *x*

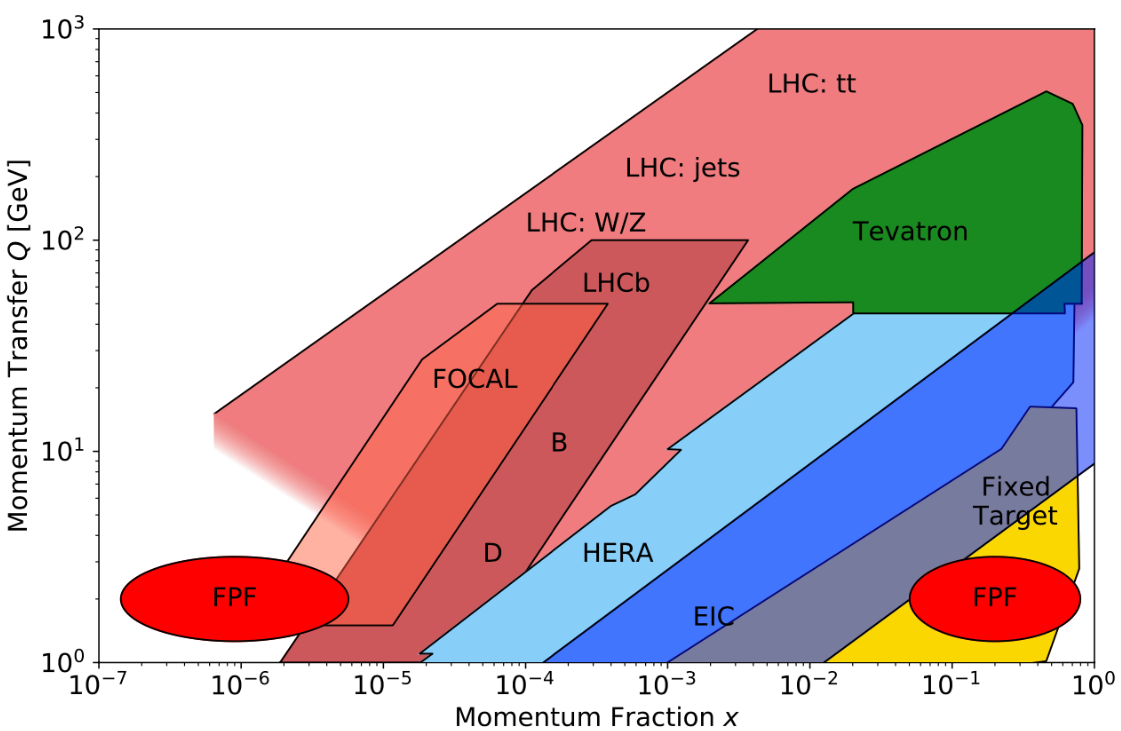
HERA data: at small-*x* fixed-order DGLAP is not sufficient, **BFKL small-*x* resummation** needed!

BFKL physics already relevant at (HL-LHC) …



… and becoming dominant at higher-energy colliders

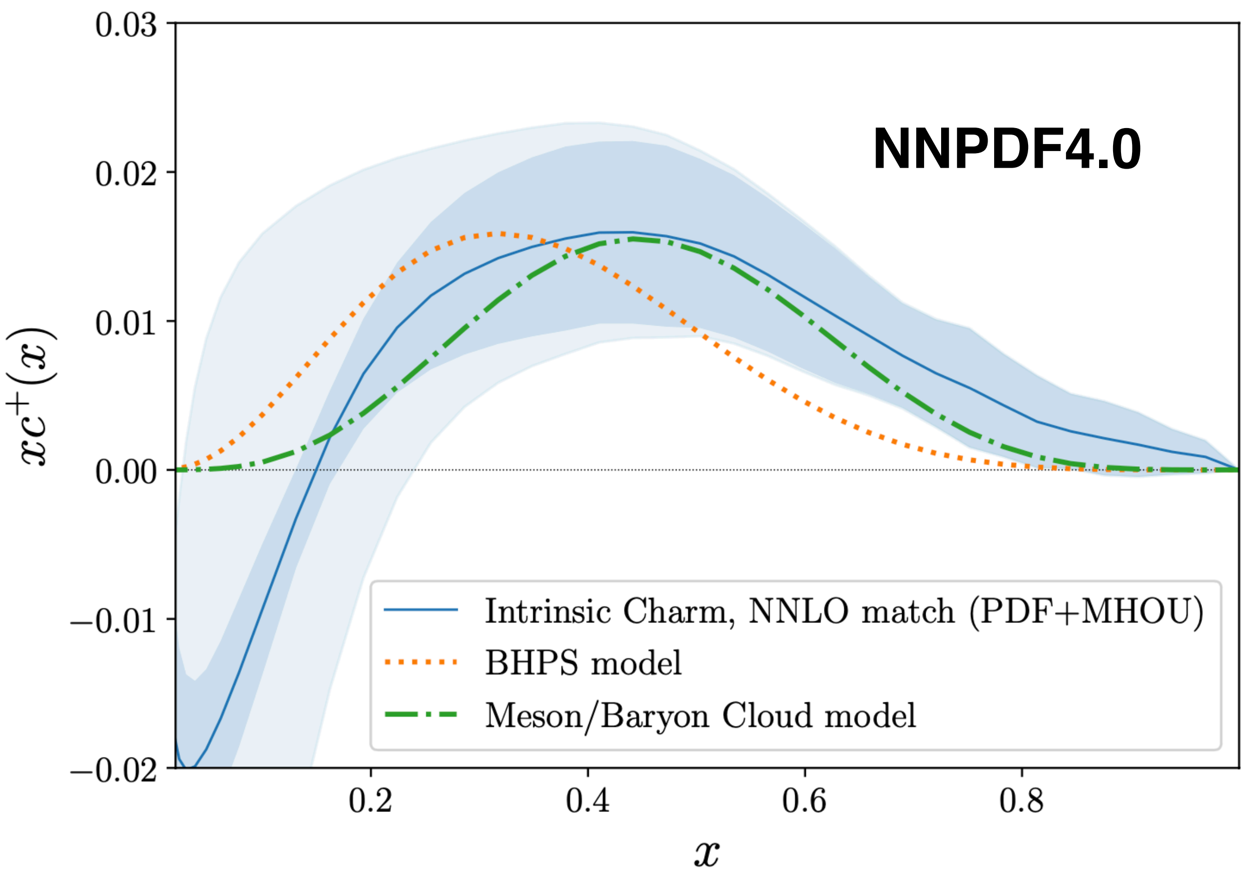




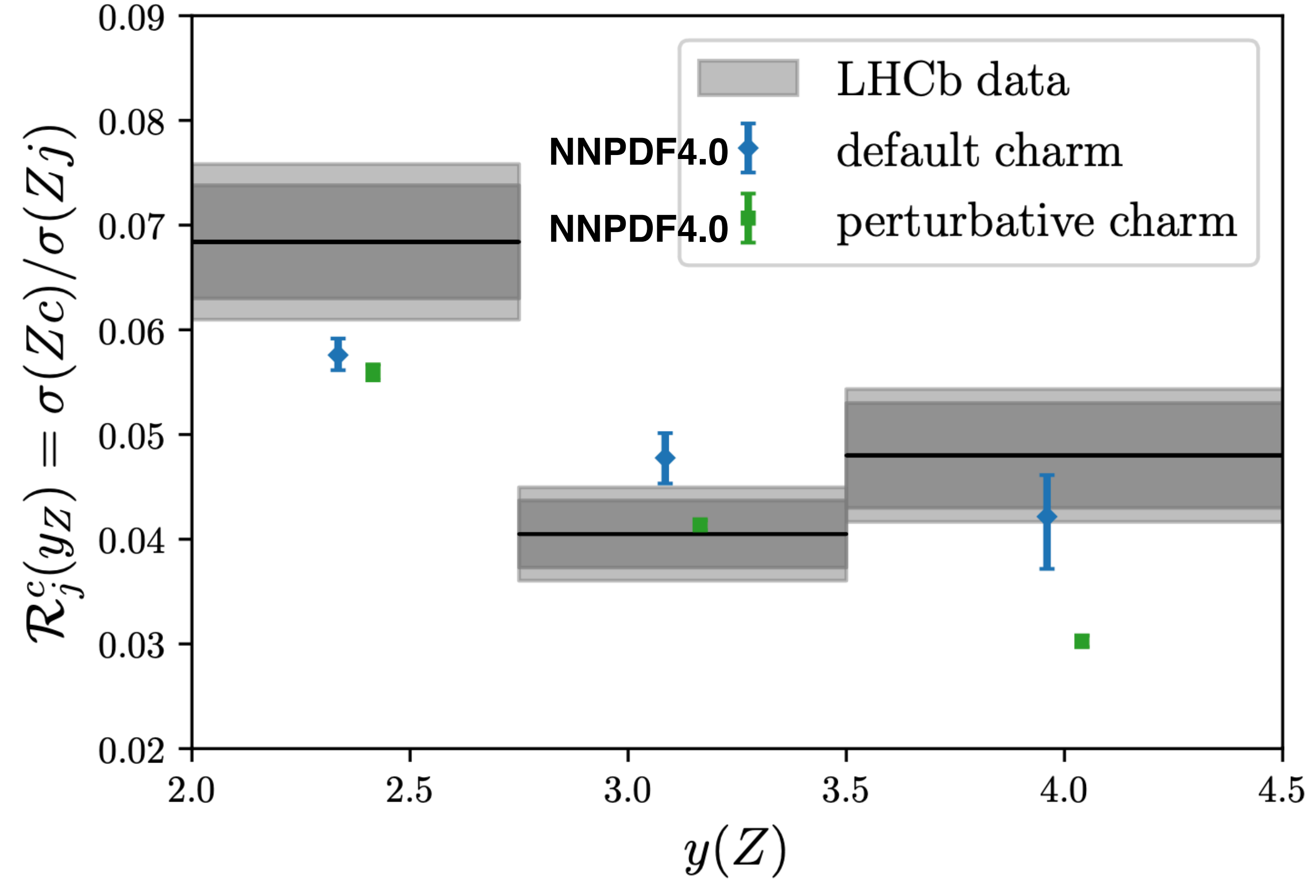
- At the FPF, direct access to **ultra-low-*x* QCD dynamics** via (perturbative) charm production
- Unexplored regime, **new phenomena** (e.g. saturation, non-linear QCD) may arise
- Proton PDFs essentially **unconstrained for $x < 10^{-6}$**, crucial inputs for QCD calculations and ultra-high-energy neutrino astronomy

Intrinsic Charm

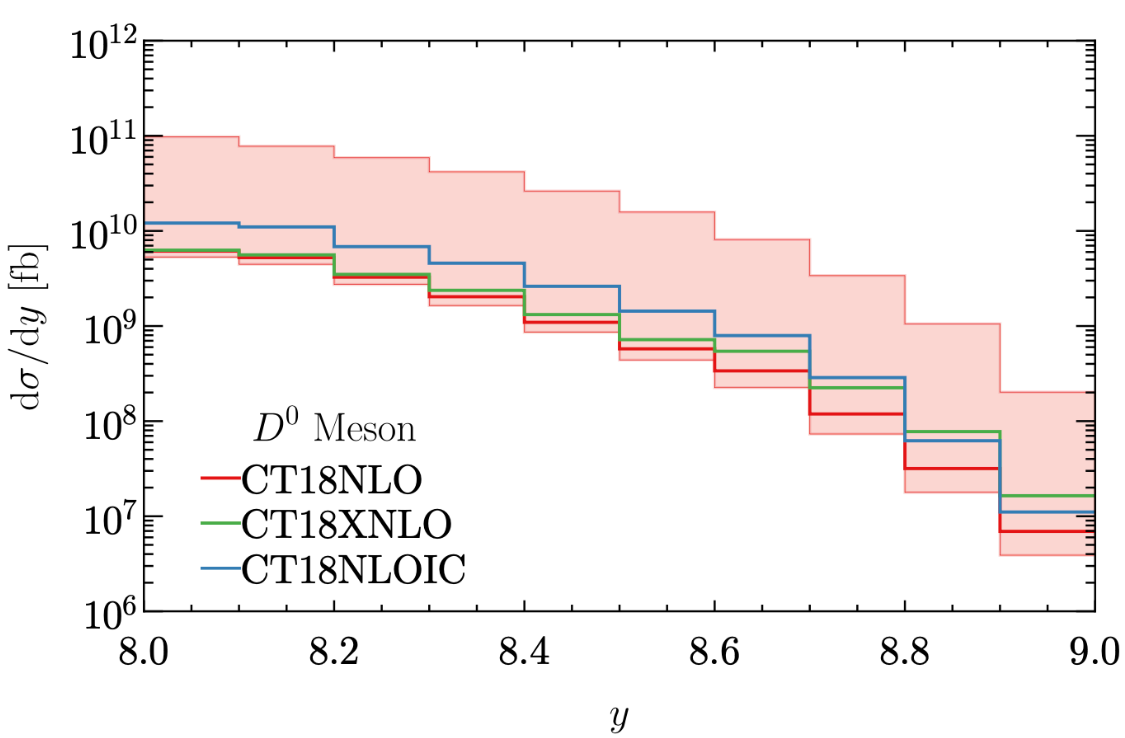
Growing evidence for **intrinsic charm in the proton**: consistent results from independent analyses



Intrinsic (3FNS) charm from NNPDF4.0 global analysis



LHCb Z+charm production (not included in NNPDF4.0)



- At the FPF, direct access to **large-*x* charm** via (perturbative) *D*-meson production
- Test **intrinsic charm calculations** in new kinematic regime
- Input for the calculation of **prompt neutrino fluxes** (from charm production in cosmic ray collisions)

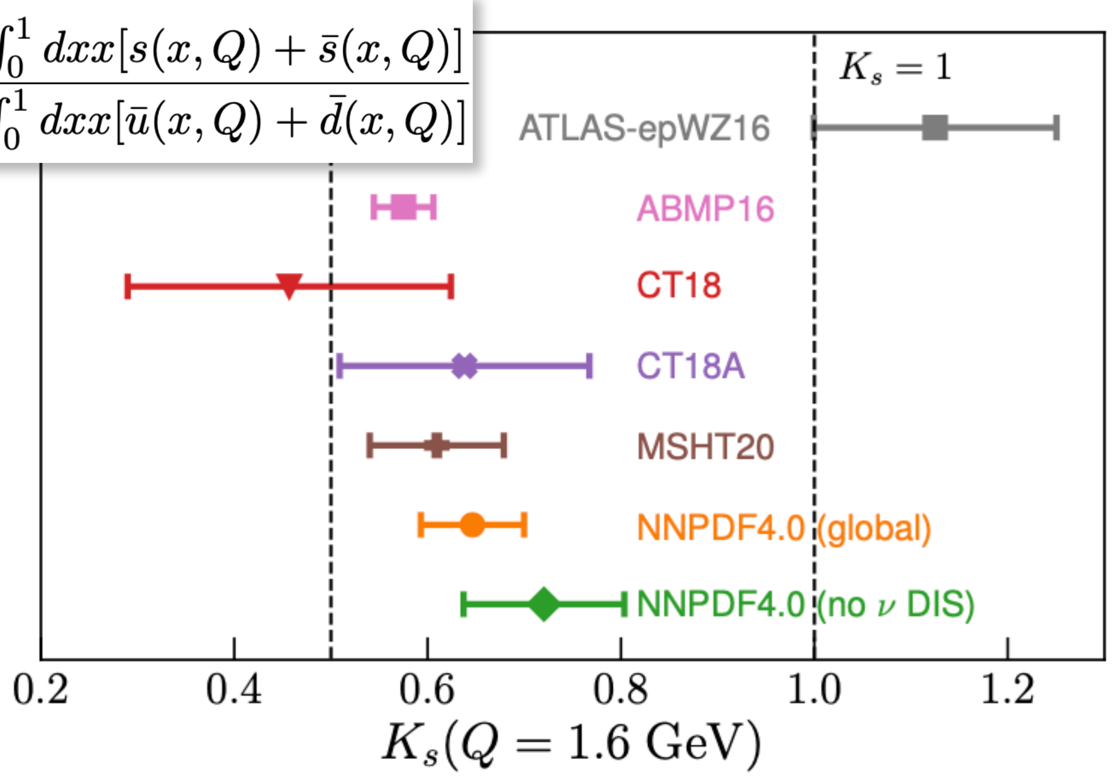
Neutrino DIS in (n)PDF fits

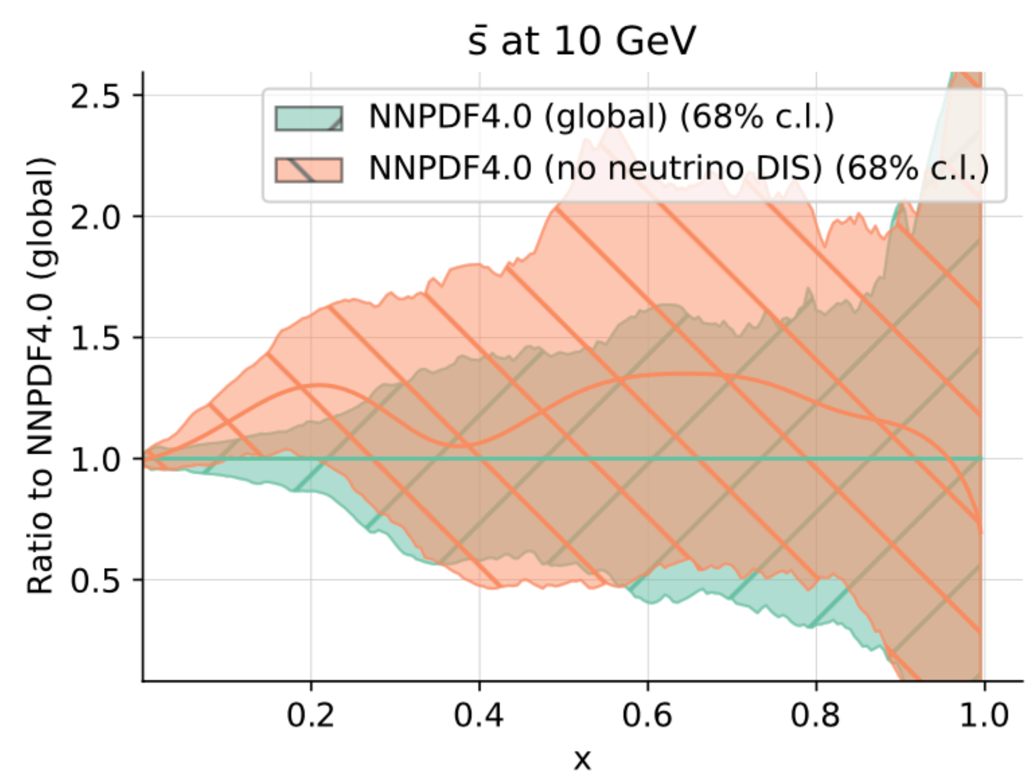
Neutrino DIS structure functions are a cornerstone of global nPDF fits

			Proton PDF sets				Nuclear PDF sets			
Data set		Ref.	ABMP16	CT18	MSHT20	NNPDF4.0	EPPS21	nCTEQ15	nNNPDF3.0	TUJU21
CHORUS $\sigma_{CC}^{\nu,\bar{\nu}}$	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 $\sigma_{CC}^{\nu,\bar{\nu}}$	Fe	[1196]	✓	✓	✓	✓	✗	✗	✓	✗
NuTeV F_2, F_3	Fe	[1194]	✗	✗	✓	✗	✗	✗	✗	✗

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

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



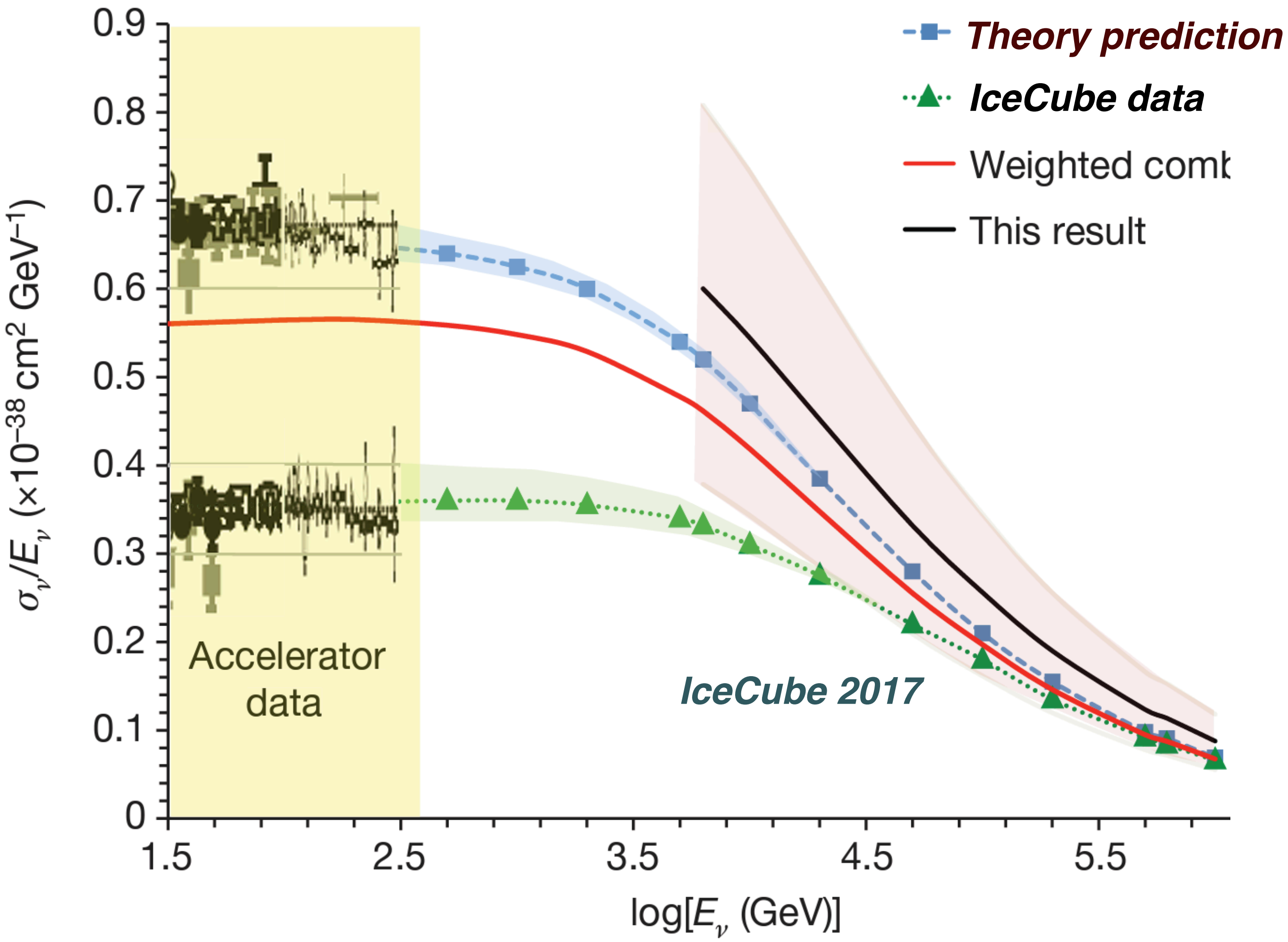


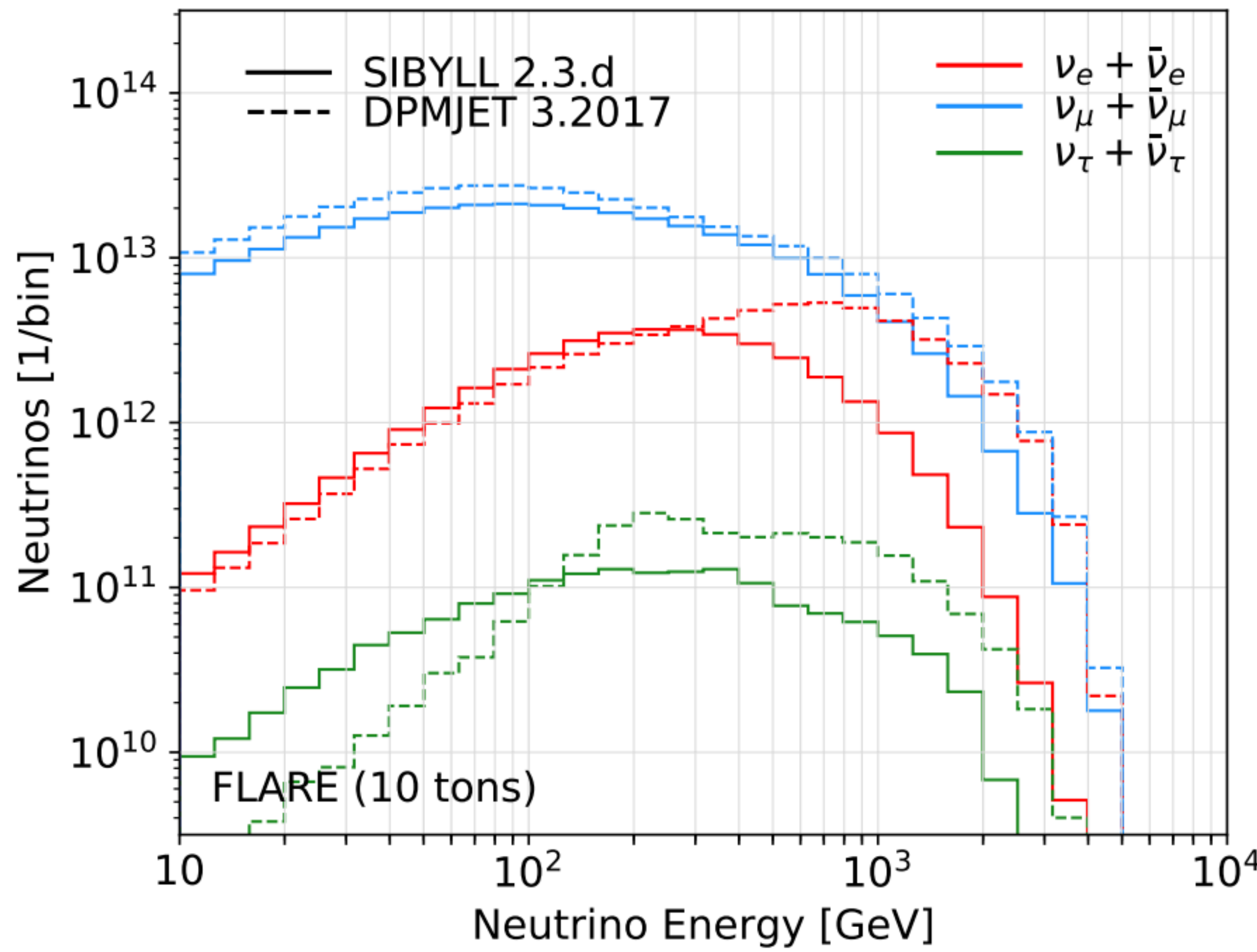
Neutrino DIS at the FPF

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



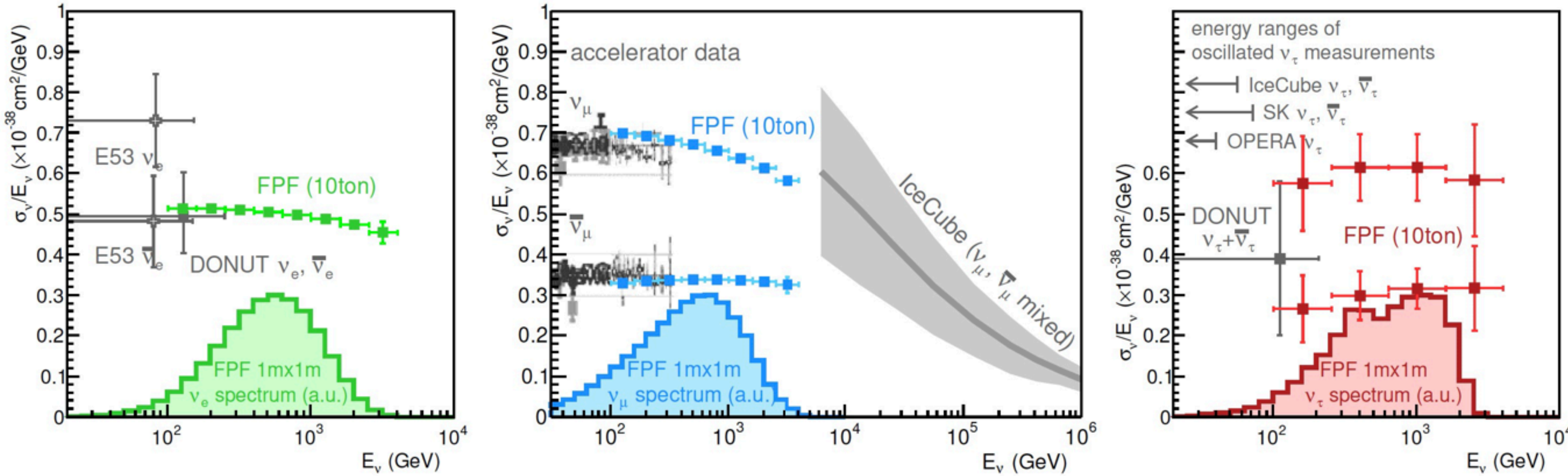


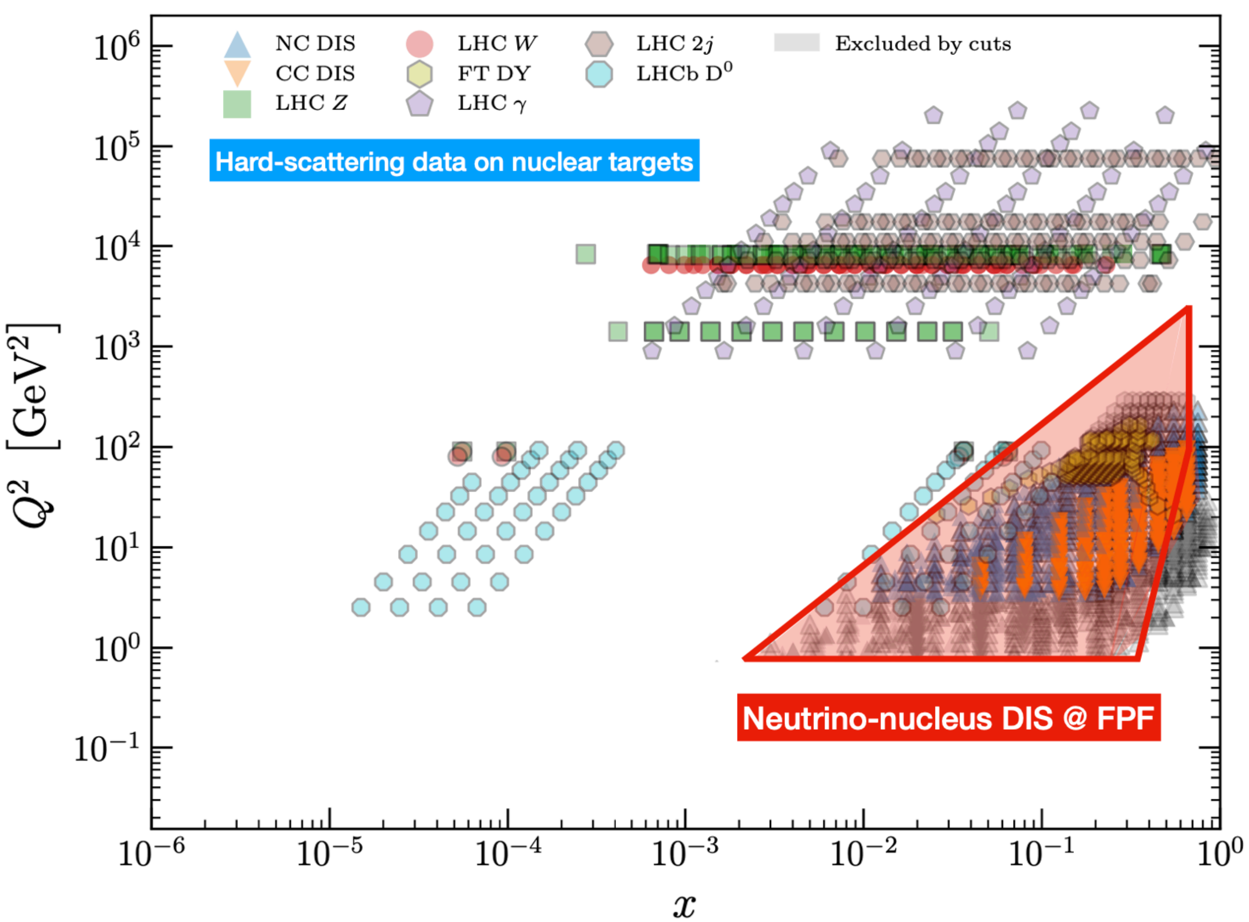
Neutrinos arriving at the Forward Physics Facility have **energy distributions** peaking between **100 GeV and 10 TeV**. Unique opportunity to test neutrino interactions and QCD cross-sections!

The FPF is effectively a **Neutrino-Ion fixed-target DIS experiment** with $E_{CM} \approx 100$ GeV!

Neutrino DIS at the FPF

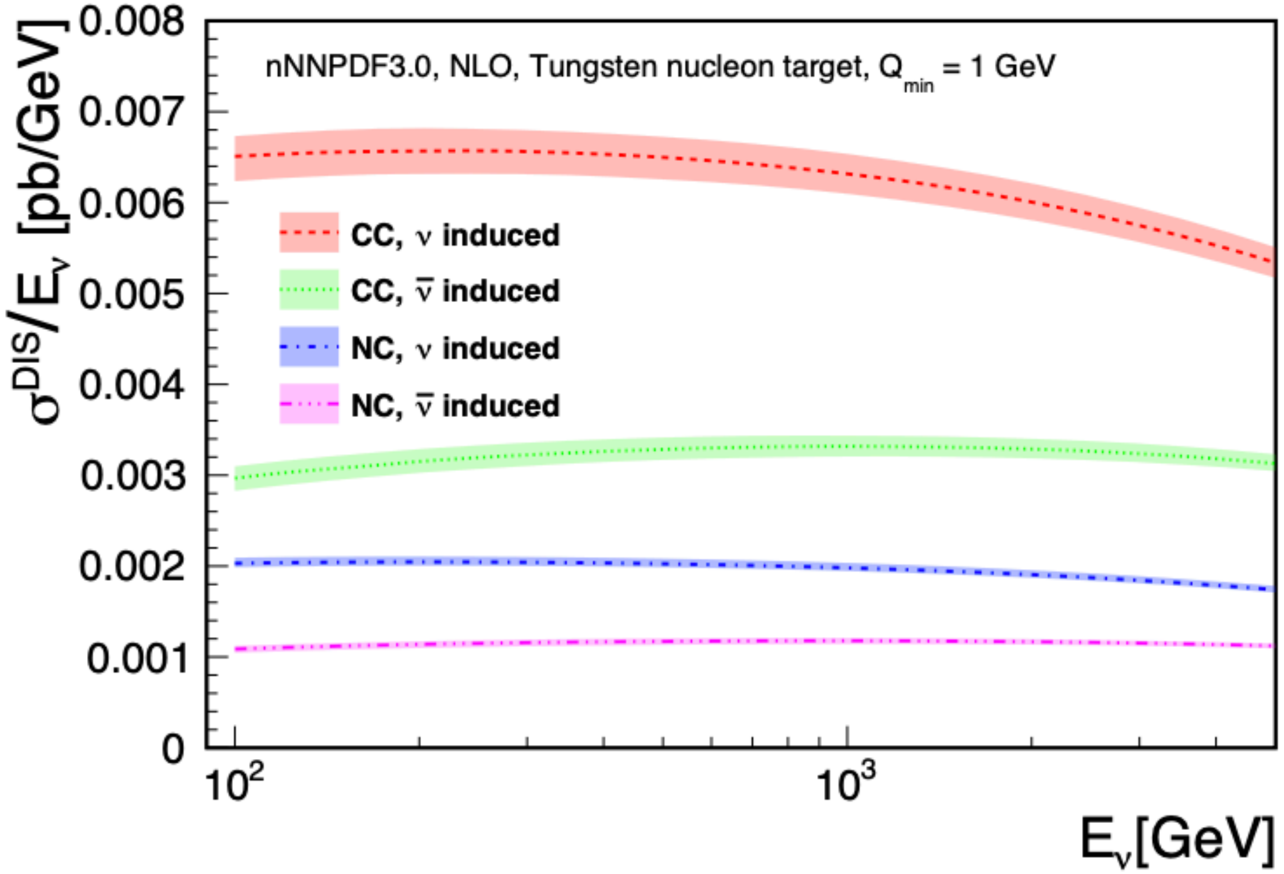
FPF neutrinos: bridging the gap between **accelerator data** and **cosmic neutrinos**

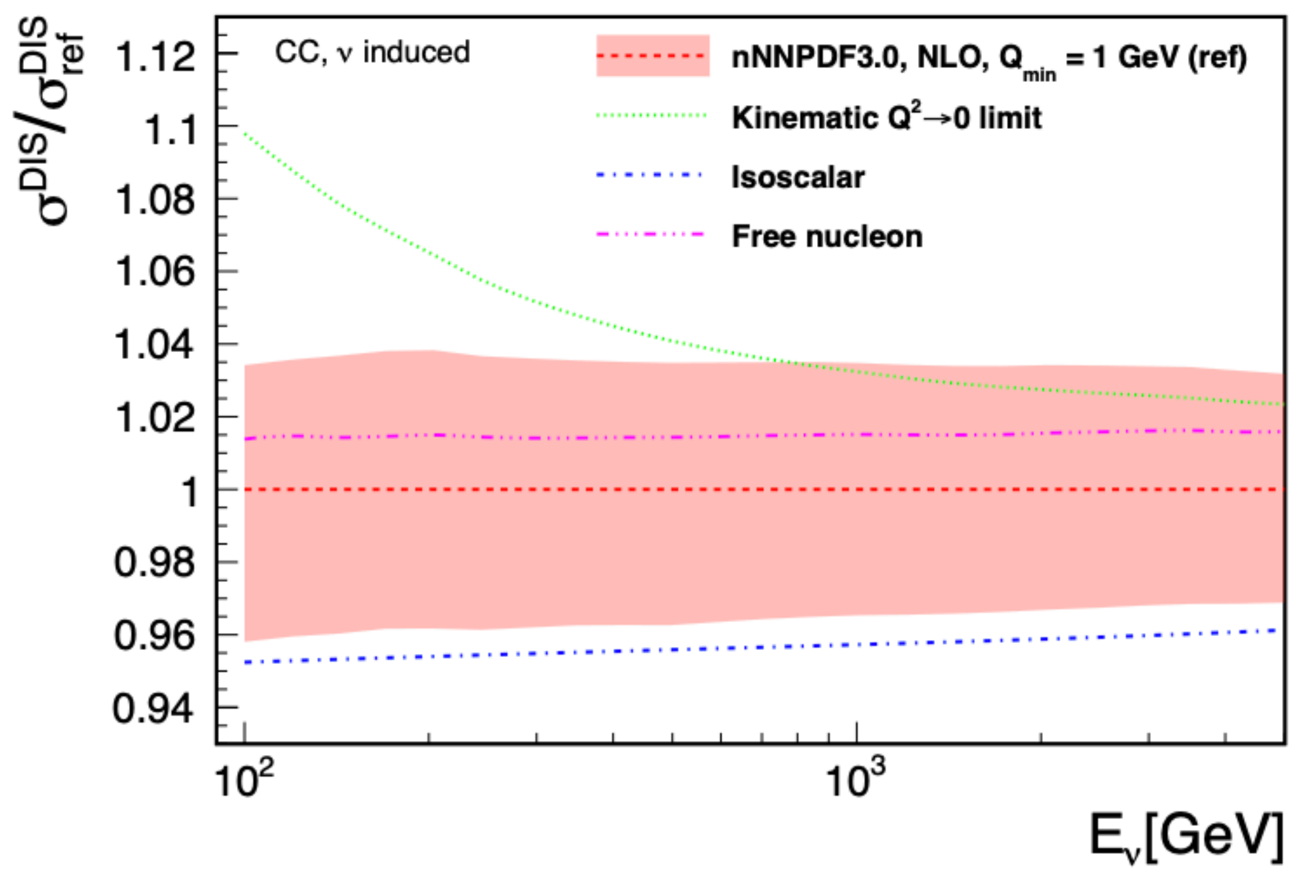




- Neutrino structure functions can be measured with **O(%) statistical precision,** improving on available measurements
- Neutrino DIS provides access to the **quark flavour decomposition** in nucleons and nuclei: sea quark asymmetry, strangeness, charm, …
- Natural continuation of the extremely succesful **CERN programs on neutrino DIS**

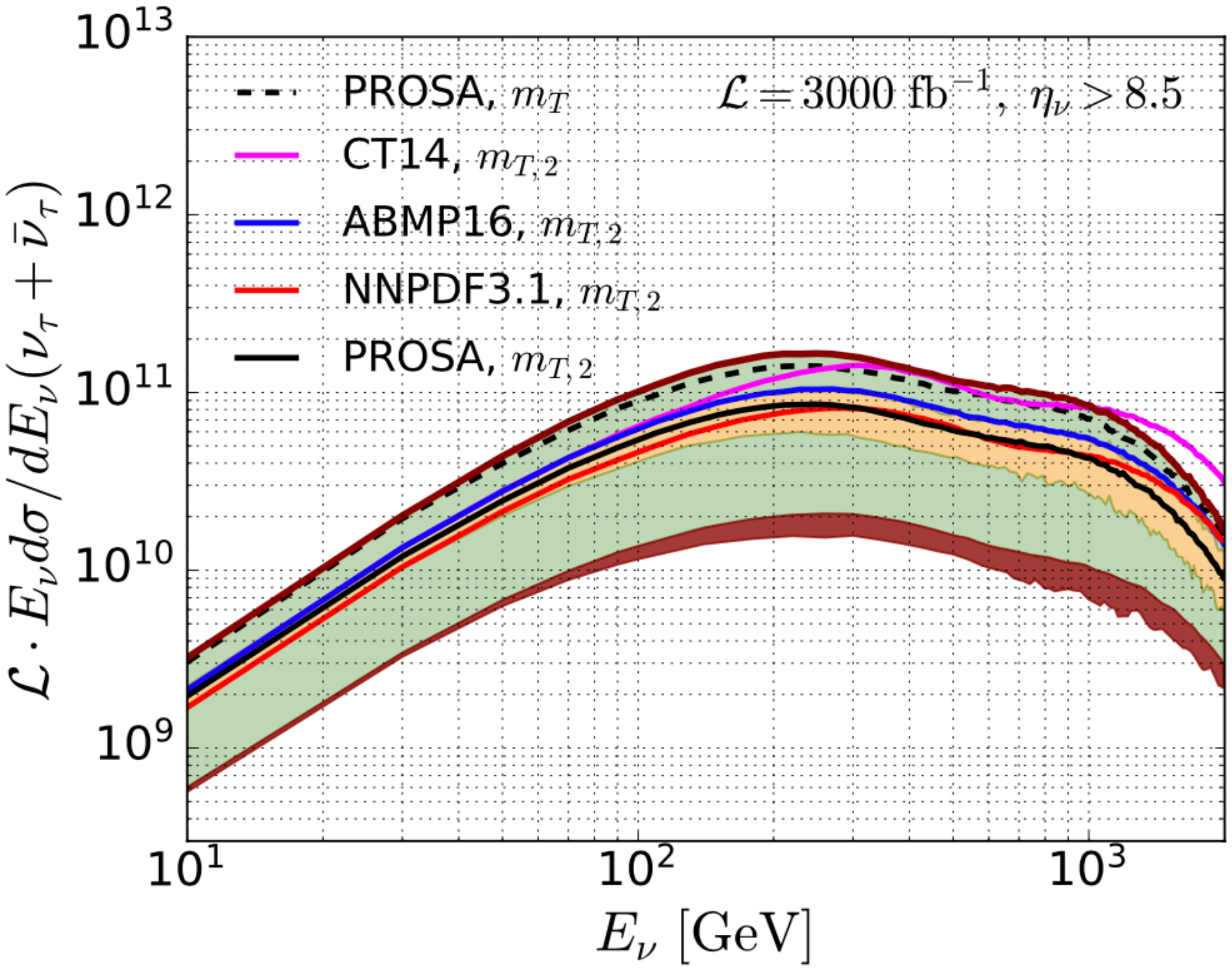
Neutrino DIS at the FPF

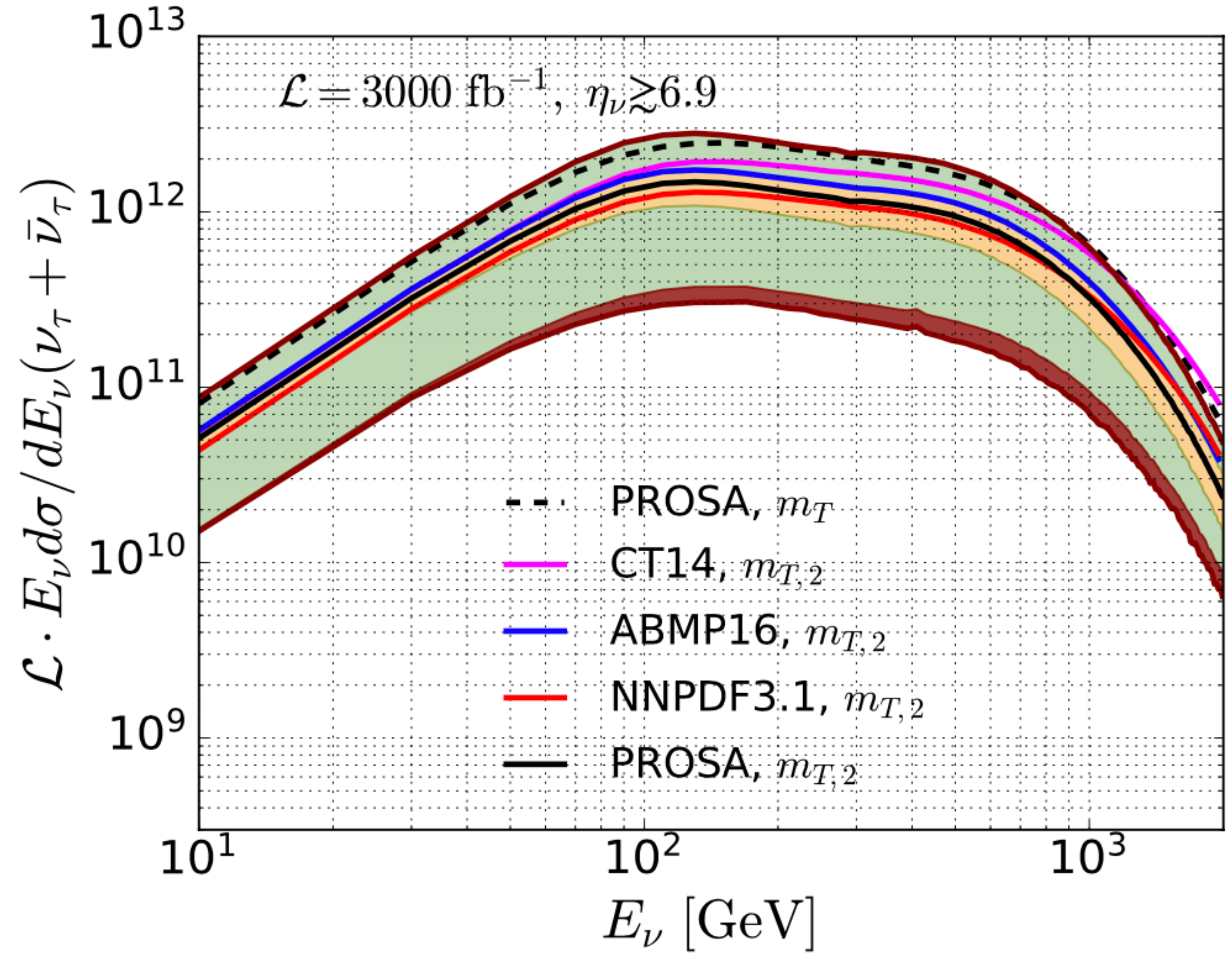




- Measurements of neutrino DIS structure functions will **constrain quark flavour separation**
- Inclusive cross-section measurements sensitive to **low-*Q* region** beyond validity of perturbative QCD, novel approaches there required to bypass model-dependence
- Nuclear corrections on tungsten targets relatively small in the region covered by FPF: strong potential to **constrain the free-nucleon PDFs**

Neutrino fluxes





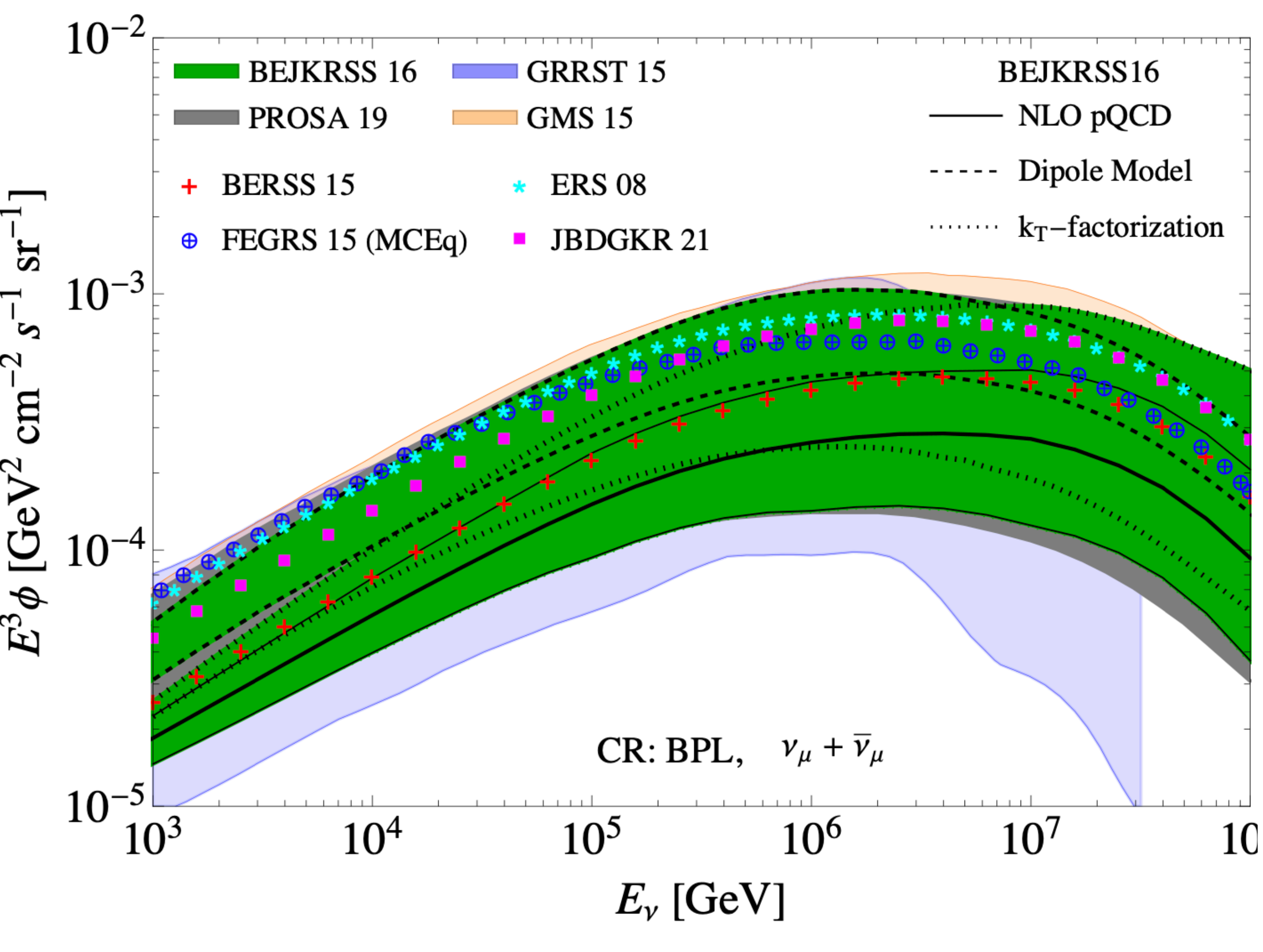
- One challenge for the interpretation of the FPF data will be the **large theory uncertainties** associated to the incoming neutrino flux e.g. large MHOUs to *D*-meson production

- Design observables where **flux uncertainties cancel out** to maximise QCD sensitivity

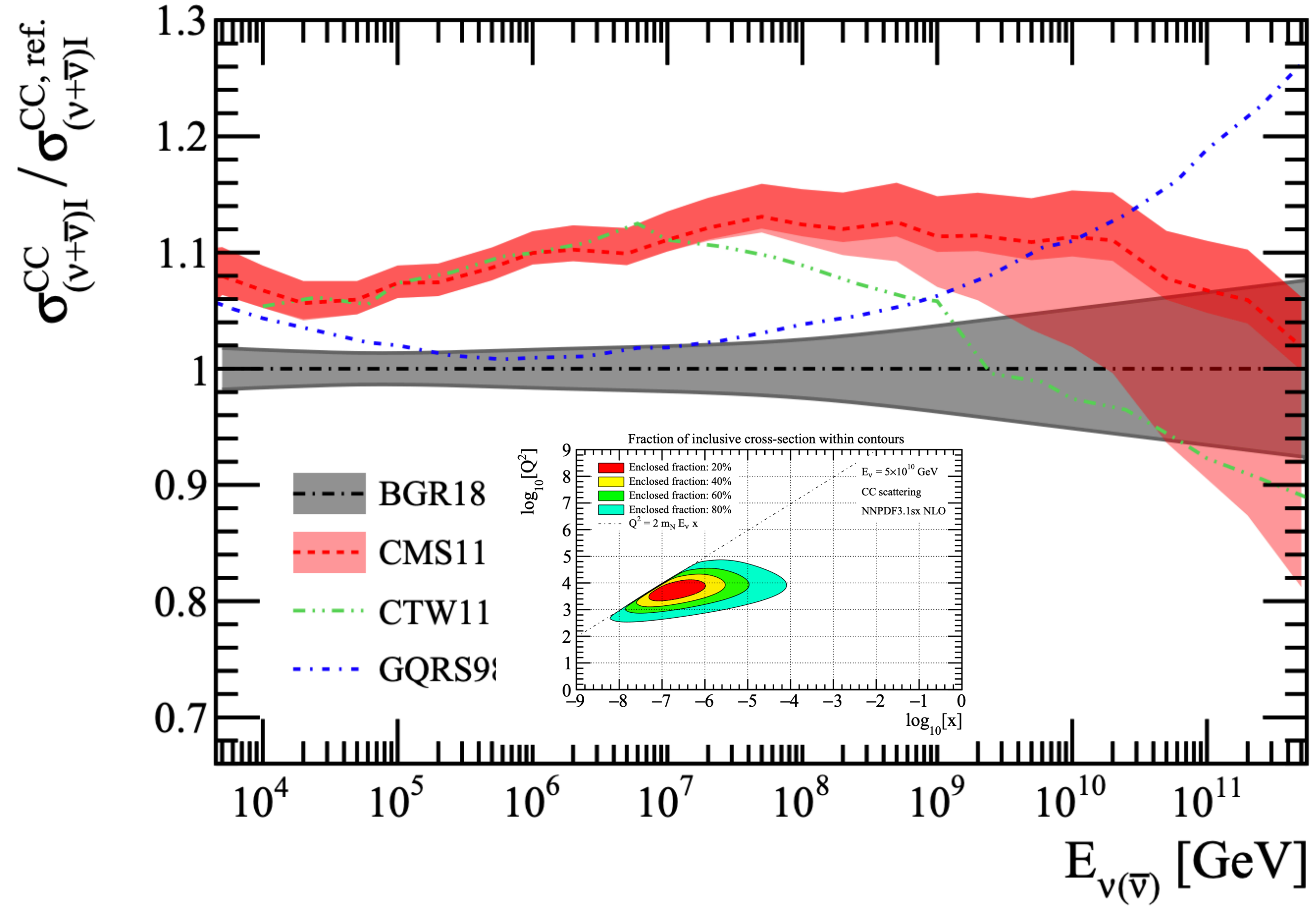
- Progress in **NNLO QCD** (+ parton shower matching) required to reduce absolute MHOUs

The cosmic connection

- FPF will constrain **small-*x* proton structure** and validate **calculations of low-*x* QCD processes**
- Benefit **predictions for key astroparticle physics processes**, such as the flux of prompt neutrinos (main background to UHE cosmic neutrinos), UHE neutrino interactions and attenuation rates



Prompt neutrino fluxes



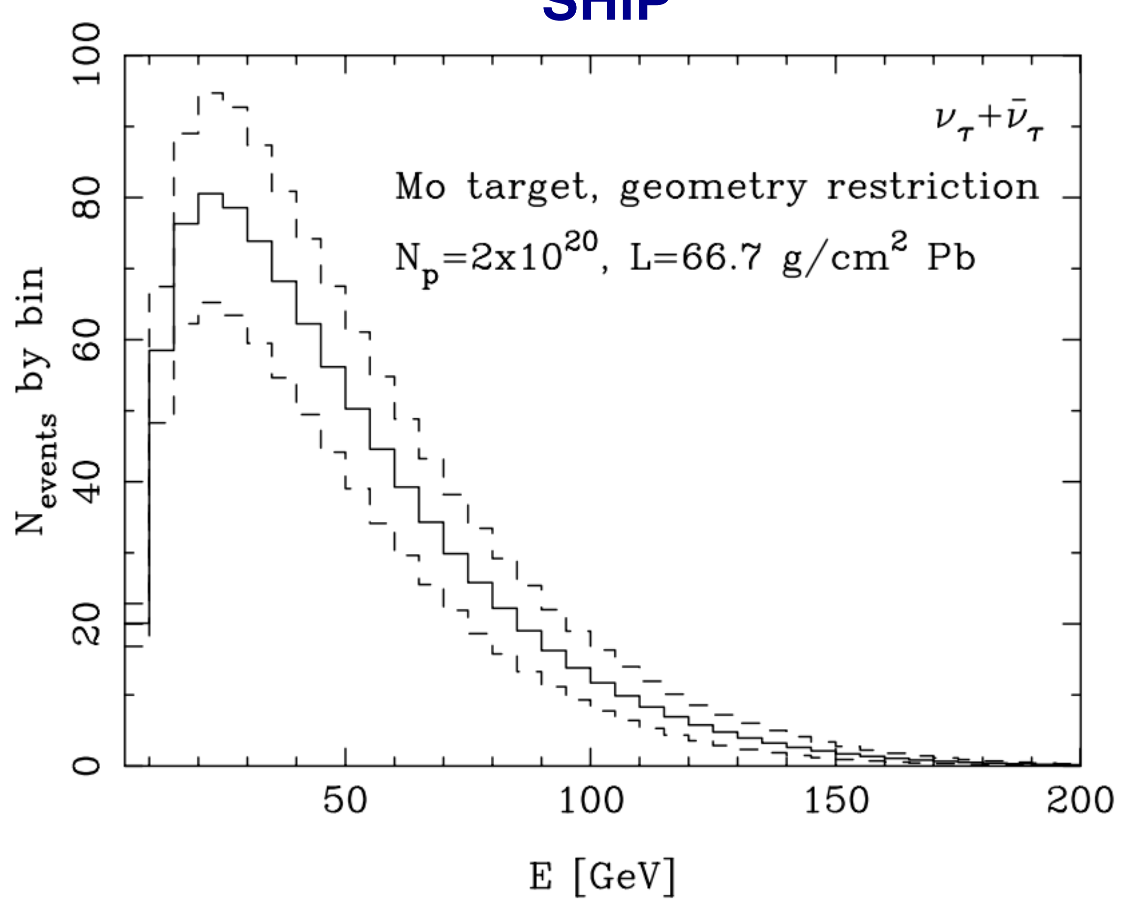
UHE neutrino cross-sections

The FPF provides key inputs for a wide range of **next-generation astroparticle physics experiments**

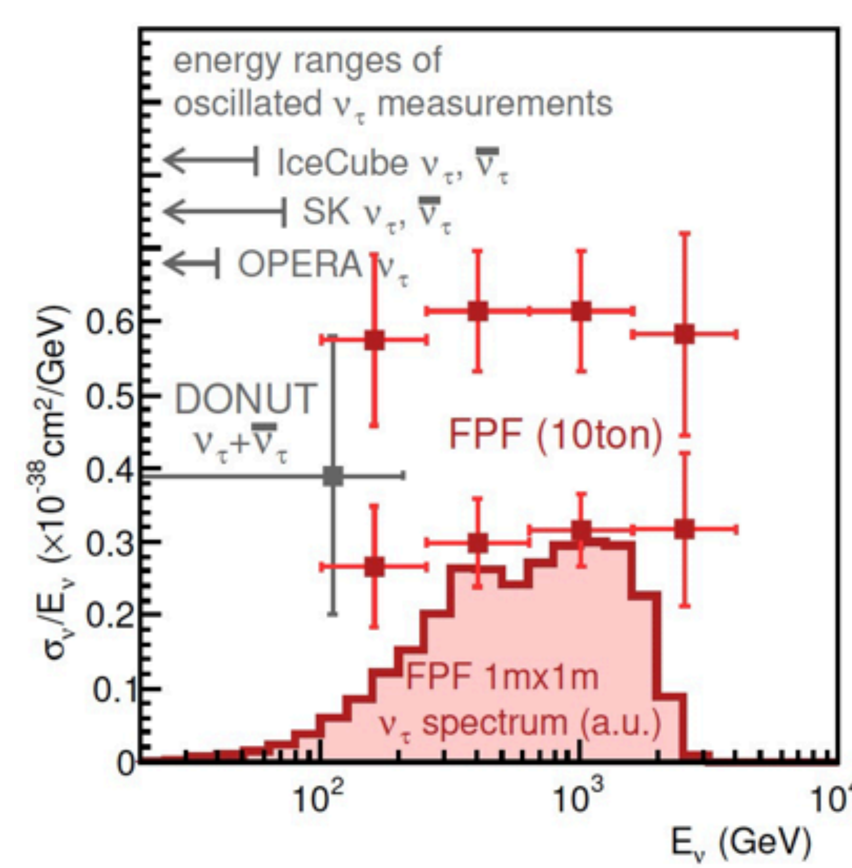
Relation with other PBC (QCD) initiatives

- From the QCD point of view, the main difference between proposed PBC-QCD initiatives and the **FPF** is the **much higher CoM energy** of the primary collisions in the latter: e.g $\boldsymbol{E_{CM}}$**=27 GeV** (SHiP) vs $\boldsymbol{E_{CM}}$**=14 TeV** (FPF)
- This implies that the FPF can reach **smaller values of *x*** in the primary pp collision (BFKL, non-linear QCD, APP connection), **higher neutrino energies** from light hadron & *D*-meson decays, and a substantially **wider *(x,Q)* coverage** in the subsequent DIS neutrino scattering

SHiP



FPF



SHiP **neutrino fluxes** peak at 20 GeV, the FPF ones at 1 TeV

Relation with other PBC (QCD) initiatives

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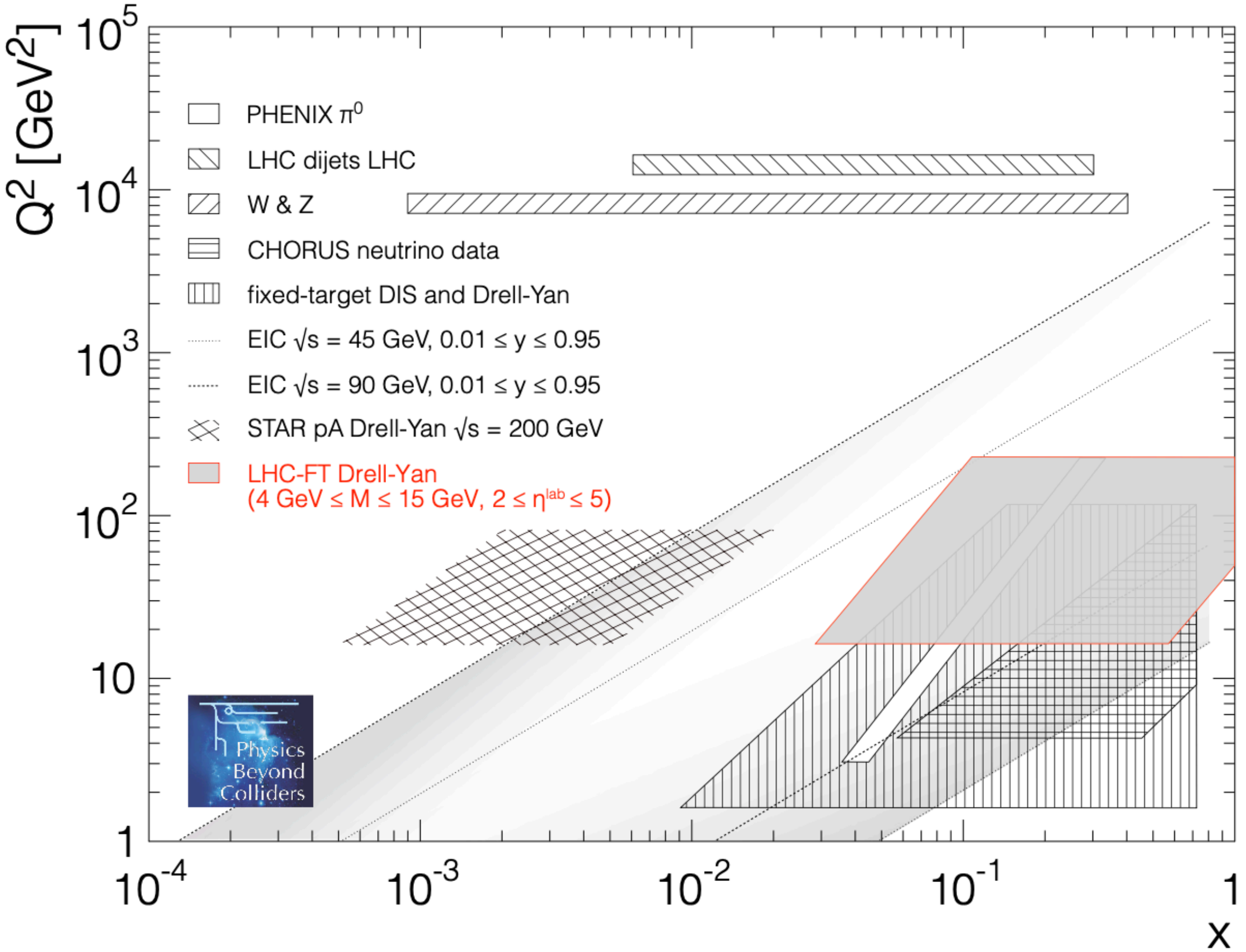
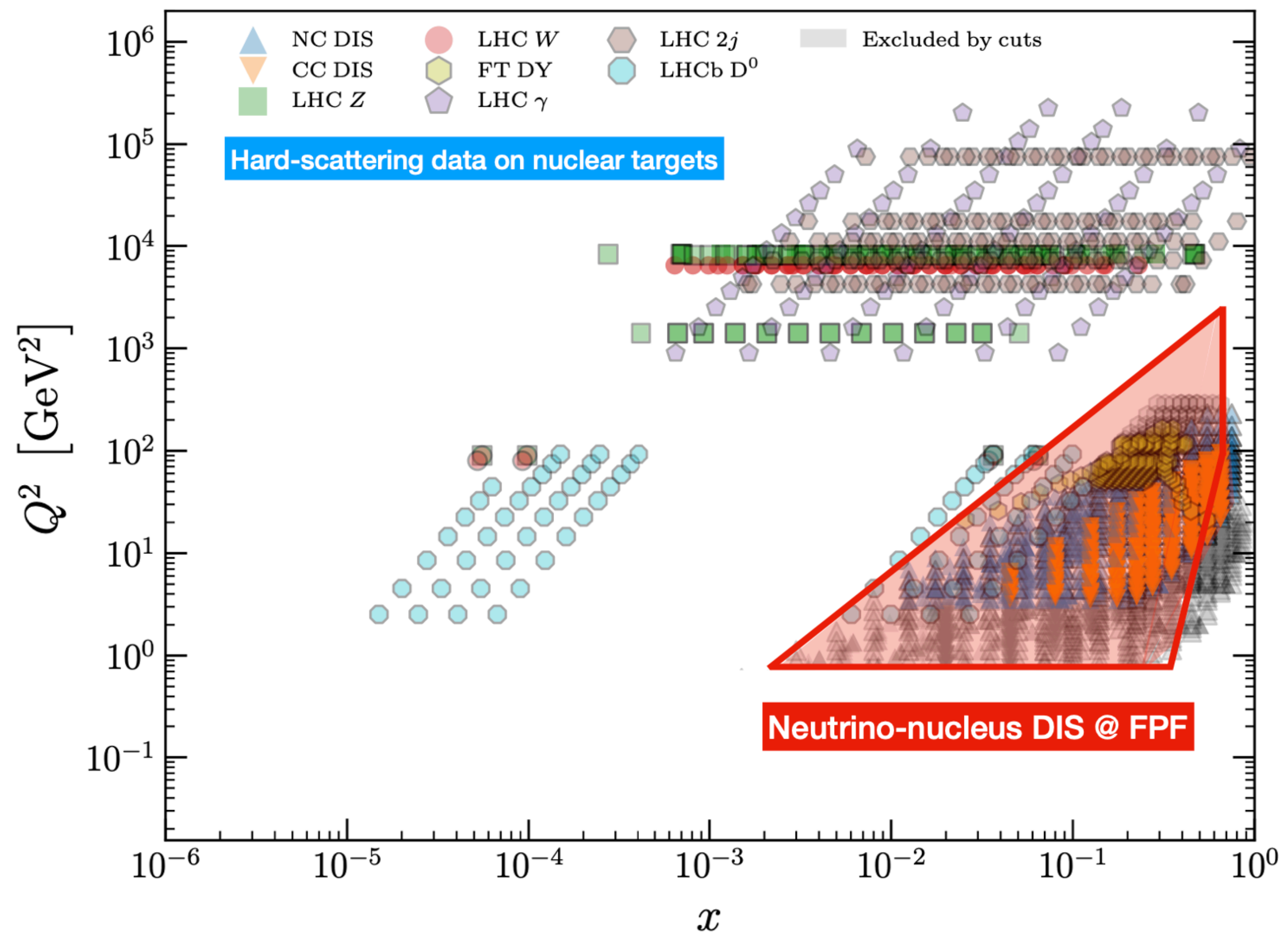


Coverage of **Drell-Yan on nuclear targets** at LHC-FT



Coverage of **DIS on nuclear targets** at FPF

none of the proposed PBC-QCD initiatives is sensitive to **small-*x* QCD** and **proton structure,** hence most of the crucial connection with astroparticle experiments is unique to the FPF

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!