Probing QCD and hadron structure at the Forward Physics Facility

Juan Rojo, VU Amsterdam & Nikhef

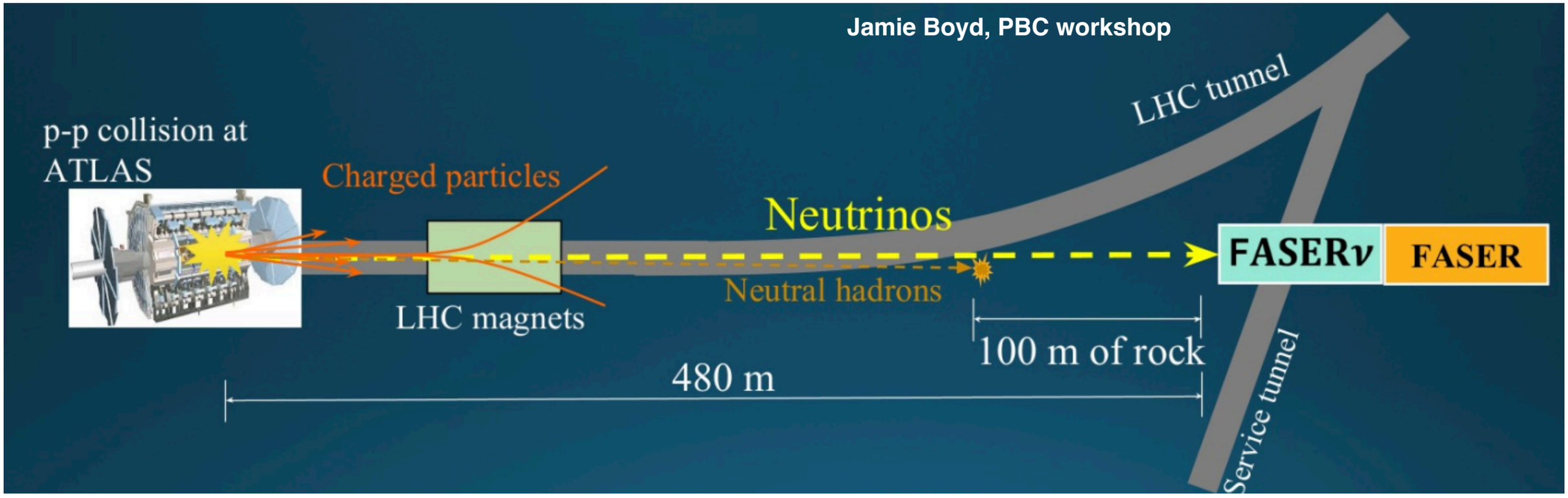
General Meeting of the LHC Forward Physics Working Group

14th December 2021

The Forward Physics Facility

A proposed new facility, located in the **very forward region** of the LHC collision point, suitable to detect **long-lived BSM particles** and **neutrinos** (everything else screened by rock)

Concept demonstrated by **FASER(ν)** and **SND@LHC** experiments (Run II + Run III)



Upscaling this exciting concept for the **HL-LHC era** demands a new suite of experiments (collectively denoted as **FPF**), to be located either in pre-existing alcoves or in a brand new cavern

The Forward Physics Facility

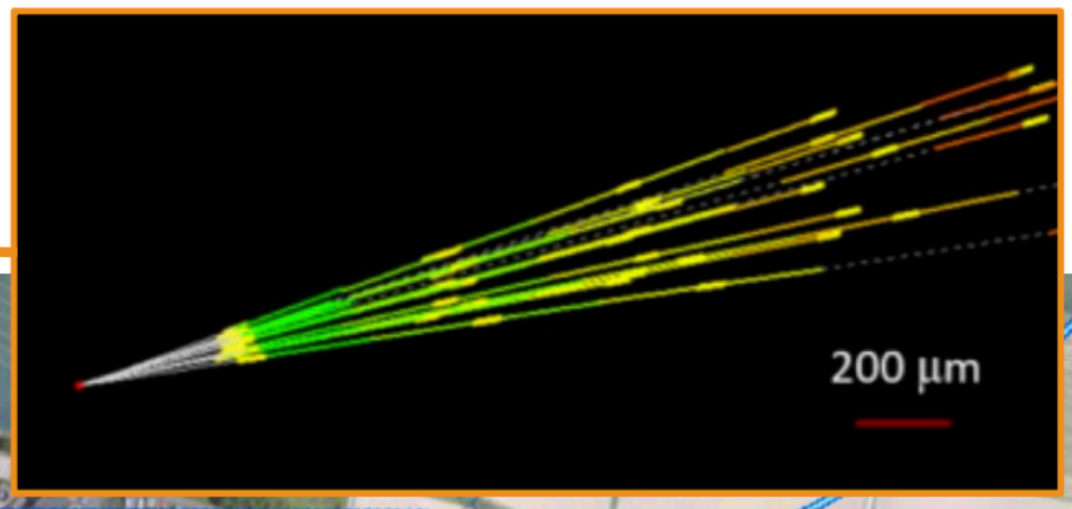
from Felix Kling

1984 | 2018 | 2022 | 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!

The Forward Physics Facility

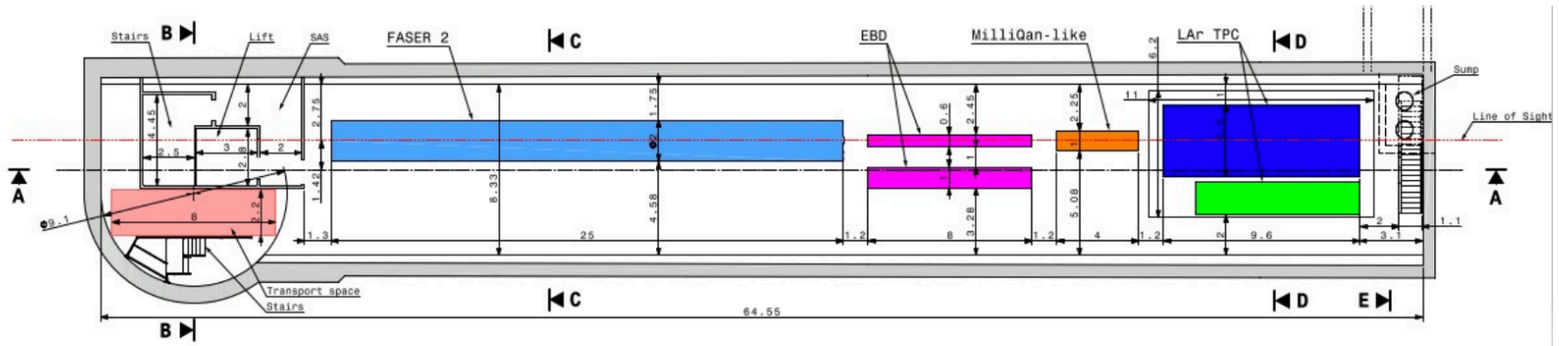
Jamie Boyd, PBC workshop

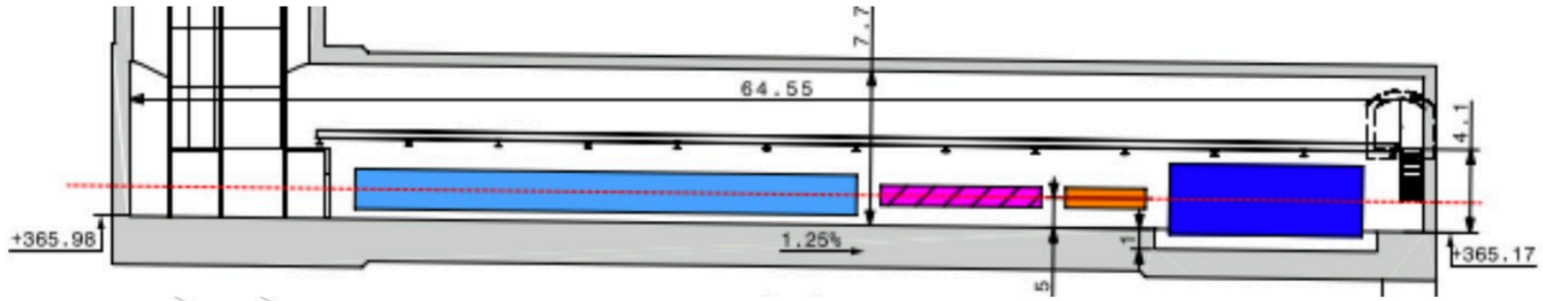
New cavern option:

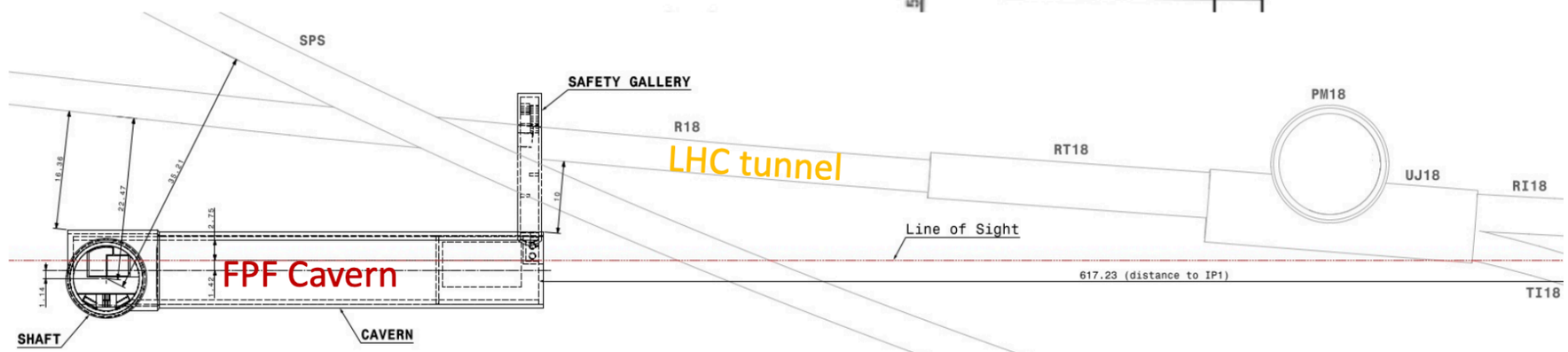
65m long, 8m wide/high cavern
Connected to surface through 88m high shaft (9.1m diameter): 612m from IP1.

New cavern >10m from LHC tunnel. Should mean that can access cavern during LHC operations (from RP point of view) – RP study ongoing.

Connection (safety gallery) from cavern to LHC for emergency evacuation.







610 m from ATLAS IP

Strong preference for new cavern option, greatly enhanced **physics reach** of the 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**

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☑ QCD, hadron structure, and astroparticle physics this talk!

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Physics potential

For the potential of the FPF for BSM and neutrino physics, and for more details about proposed **experimental facilities** and **civil engineering**, see the "short" FPF paper

The Forward Physics Facility: Sites, Experiments, and Physics Potential

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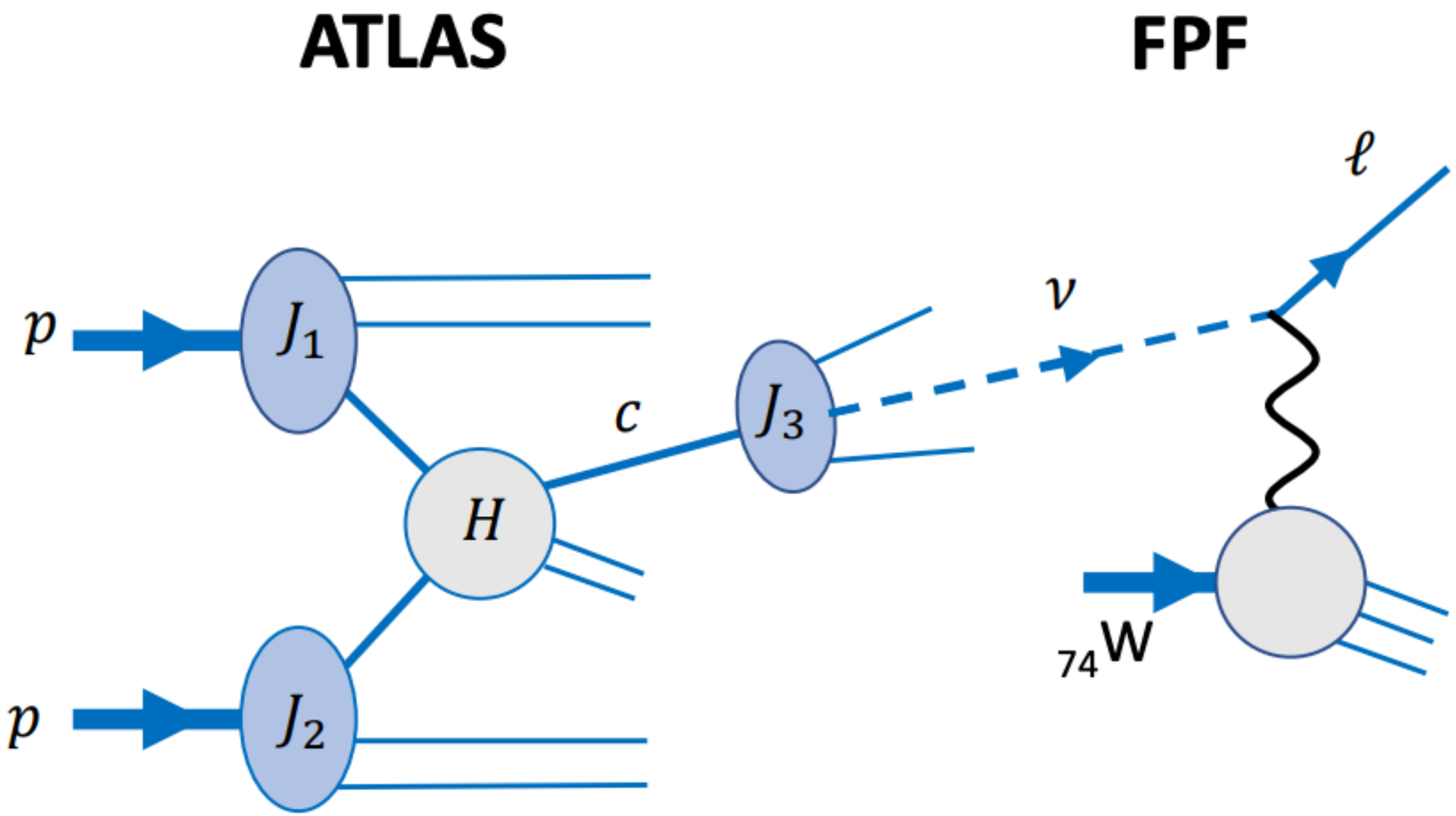
submitted to Physics Reports

CONTENTS

now working on an extended version for the FPF Snowmass White Paper, get in touch if you would like to contribute!
Editors: J. Feng (facilities), F. Kling (BSM), M. H. Reno (neutrinos), J. Rojo (QCD), D. Soldin (astroparticles),

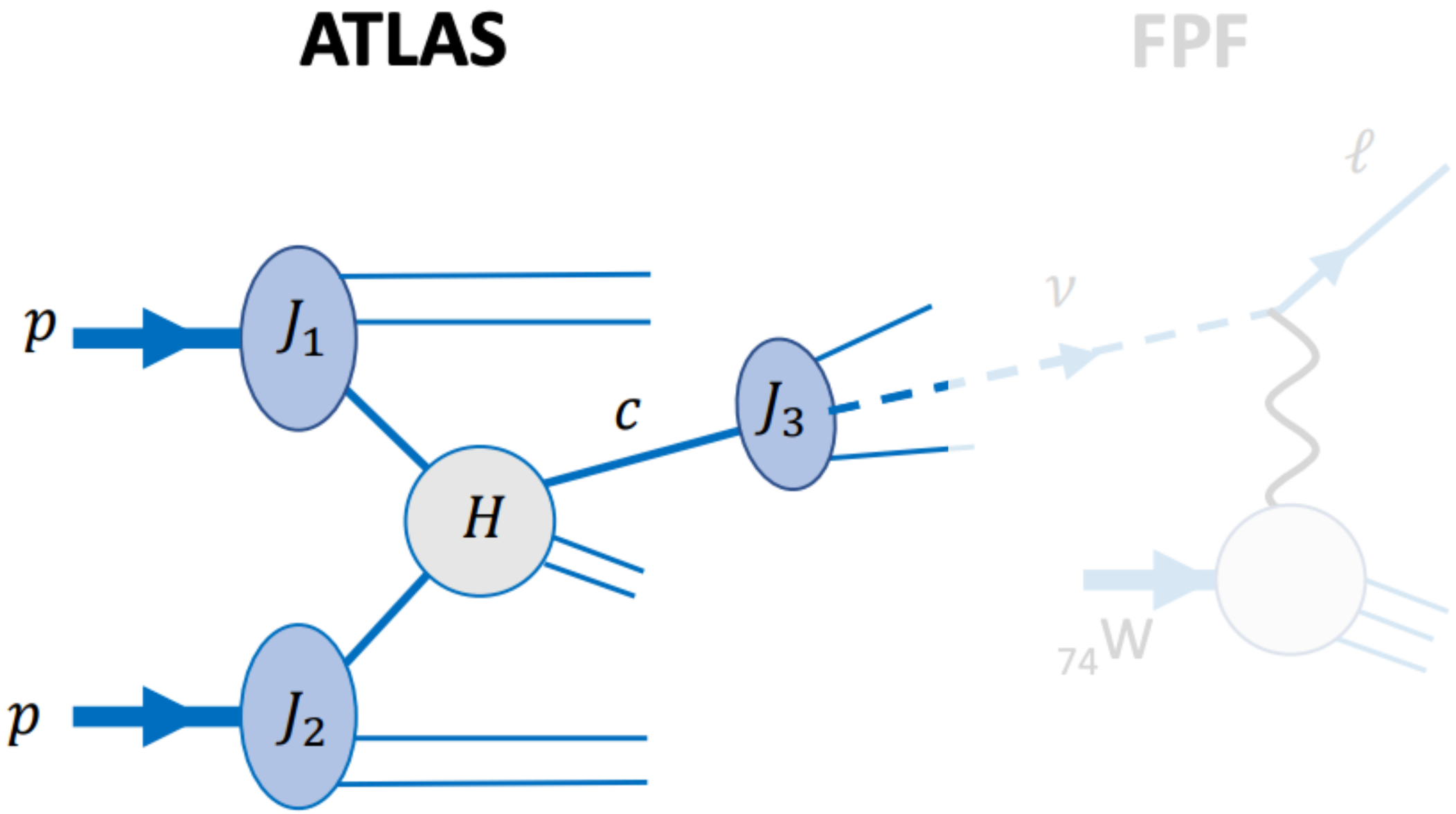
Neutrinos at the LHC



The LHC is a prodigious source of **high-energy neutrinos** from light hadron and charmed meson decays, which currently escape undetected

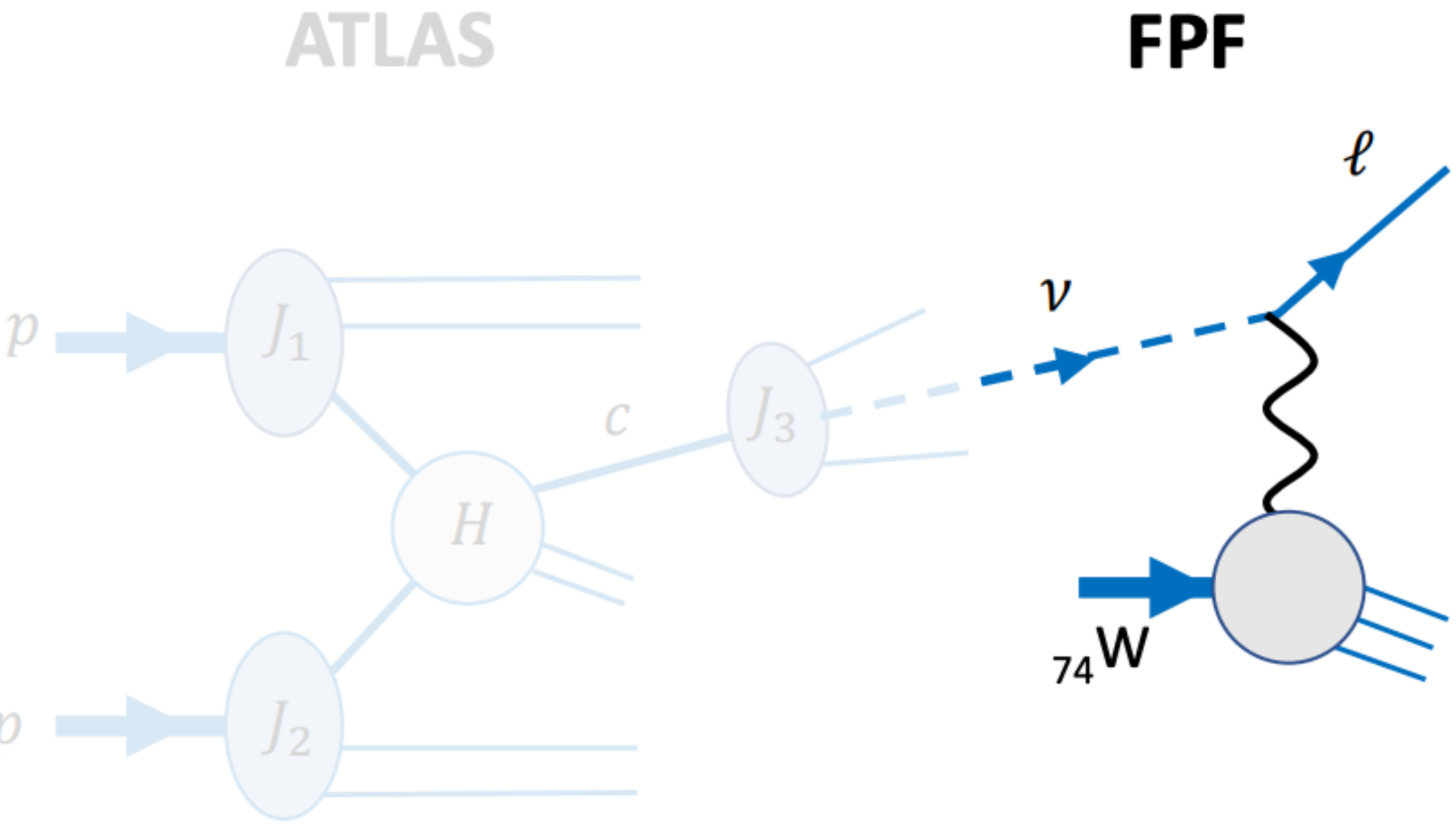
The FPF would detect these neutrinos by means of the **deep-inelastic scattering** processes on a nuclear target

Neutrinos at the LHC



- New window on **BFKL (small-x) dynamics** in LHC collisions from very forward particle production
- Modelling charm meson and light hadron production in the forward region (incl. **intrinsic charm**)
- Accessing **proton and nuclear structure** at extremely small values of momentum fraction
- Key input for **neutrino** (prompt fluxes) and **cosmic ray** astroparticle experiments

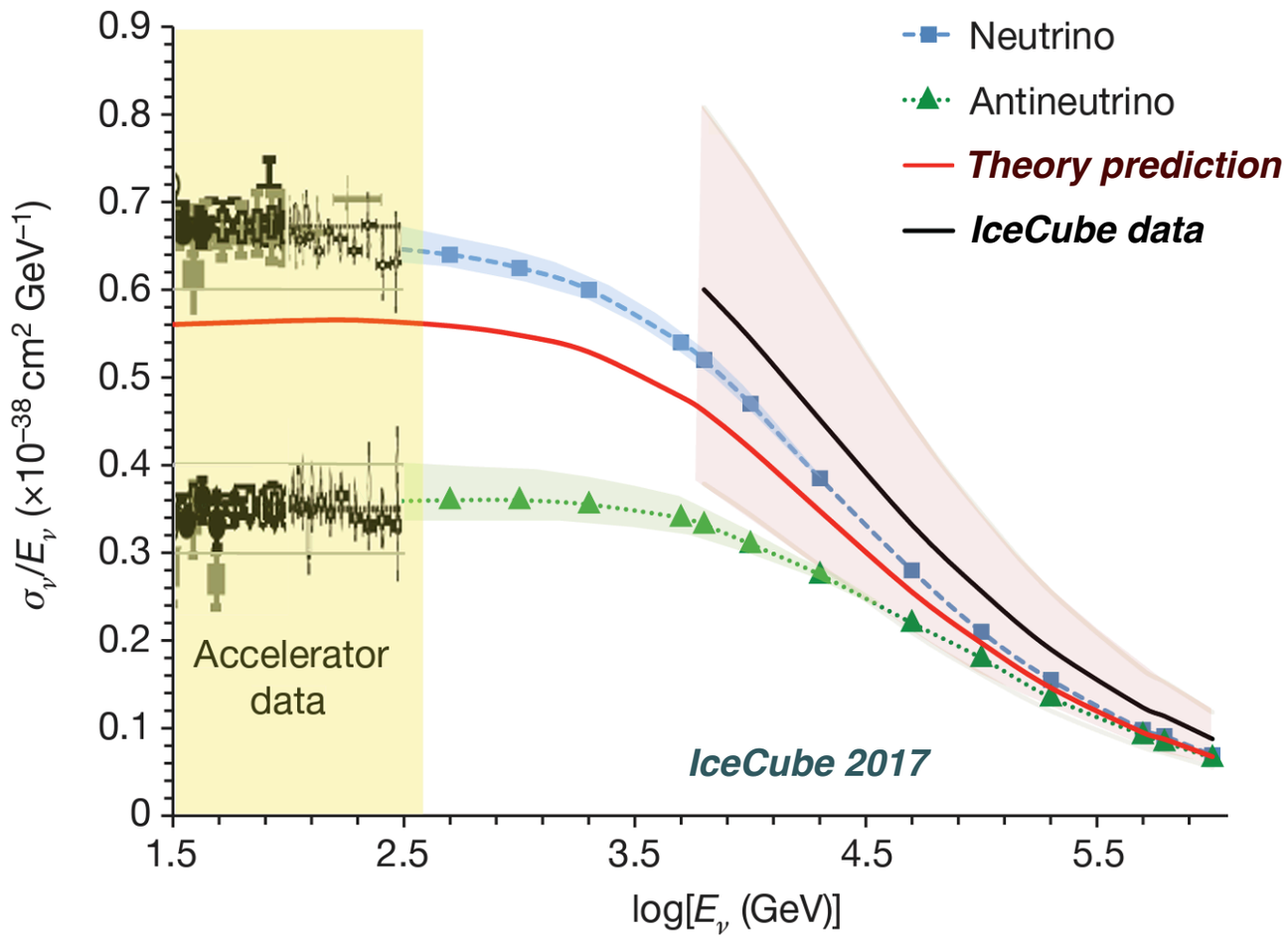
Neutrinos at the LHC

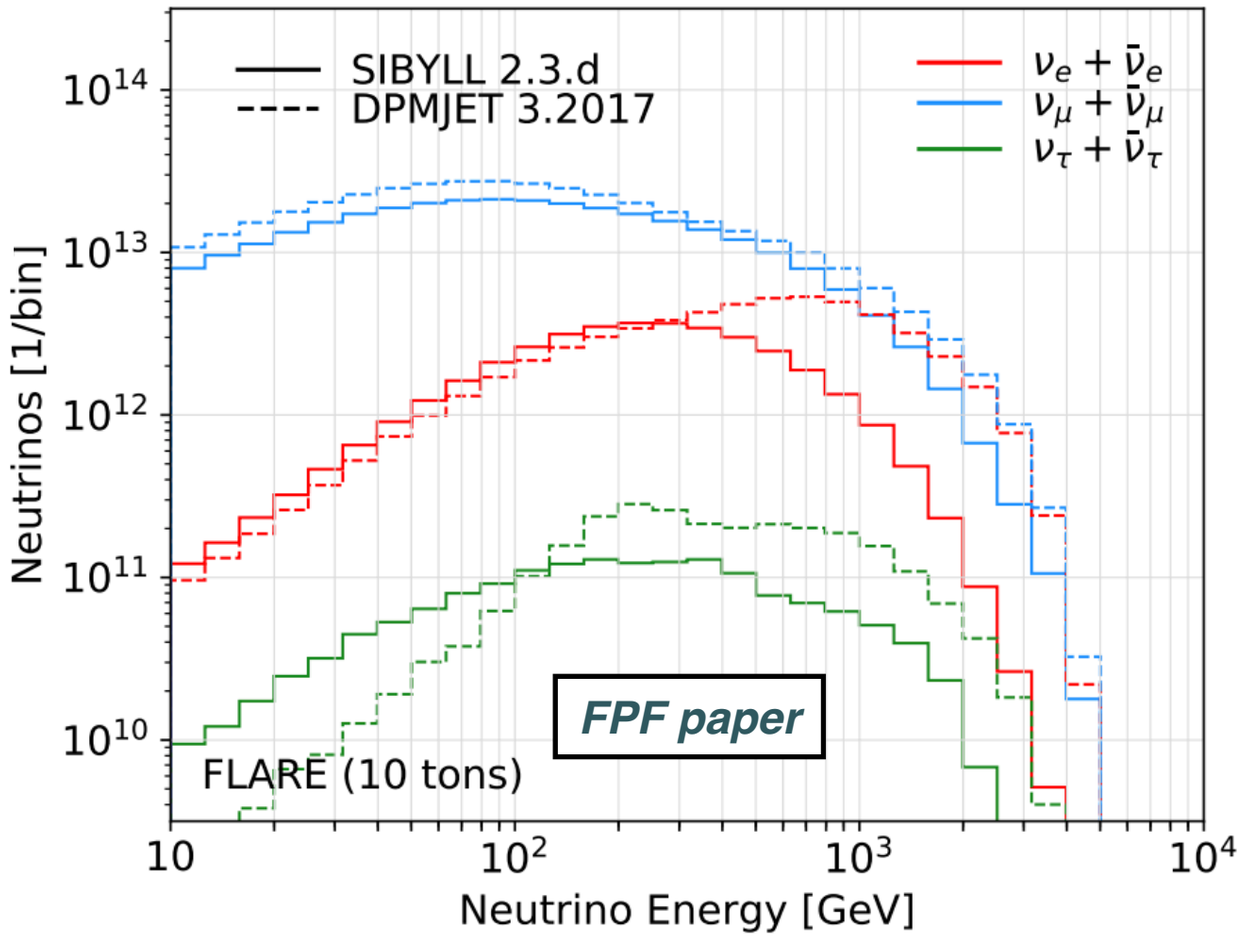


- **Neutrino cross-sections** in an uncharted energy range
- Neutrino DIS to access **proton and nuclear structure:** quark flavour separation, strangeness, charm
- Key input for **neutrino** (interaction event rates, UHE attenuation rates) astroparticle experiments
- (under discussion) using **muon beam** to realise **high-energy charged lepton DIS**

Neutrino-nucleus interactions

Neutrino cross-sections extensively studied for **energies up to 300 GeV** with accelerator neutrinos





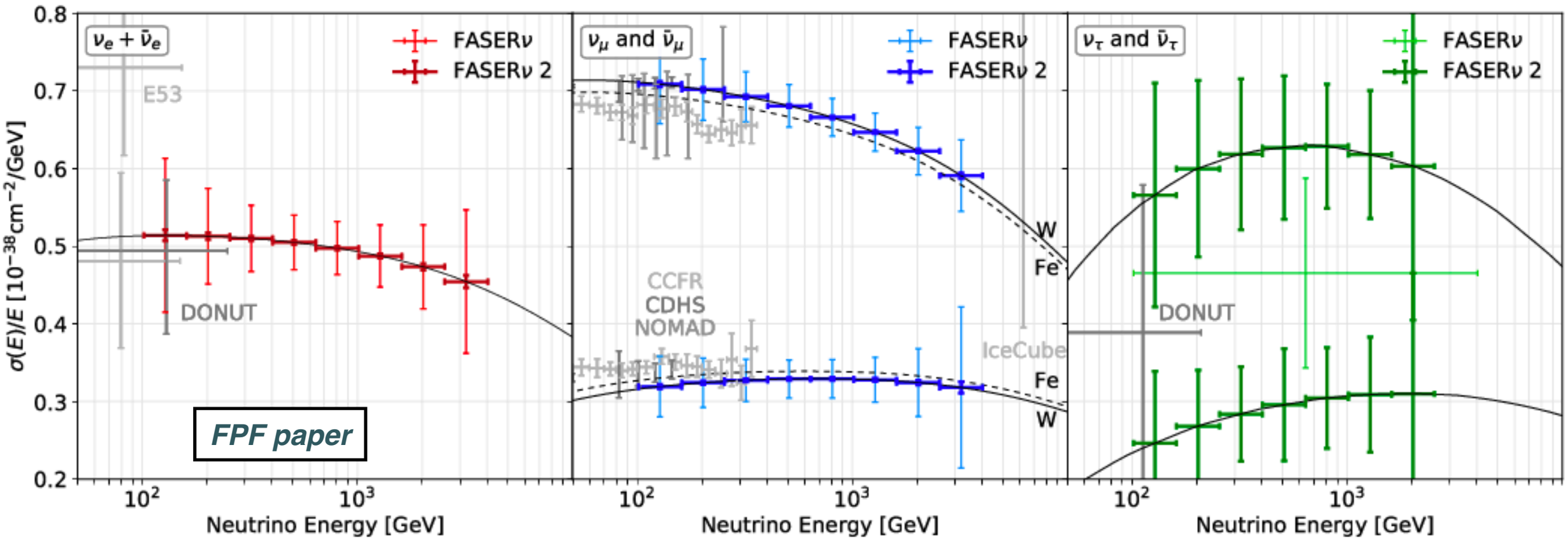
At higher energies, **IceCube** has measured cross-sections between 5 TeV and 10^4 TeV

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} = 90 GeV!

Neutrino DIS @ LHC

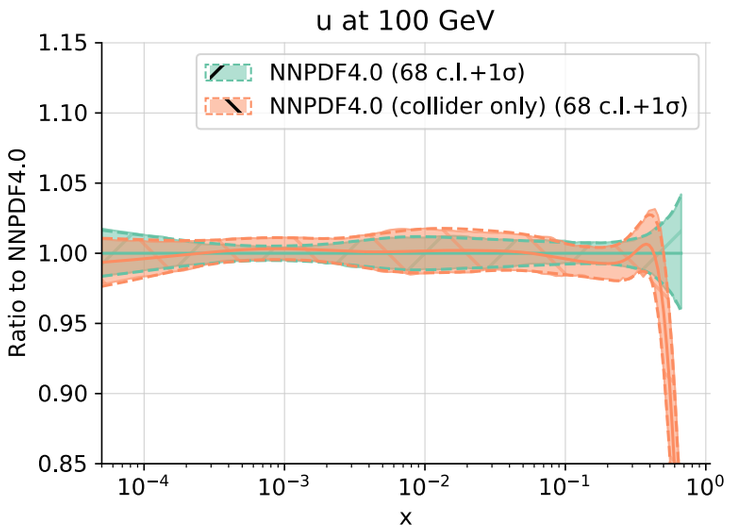


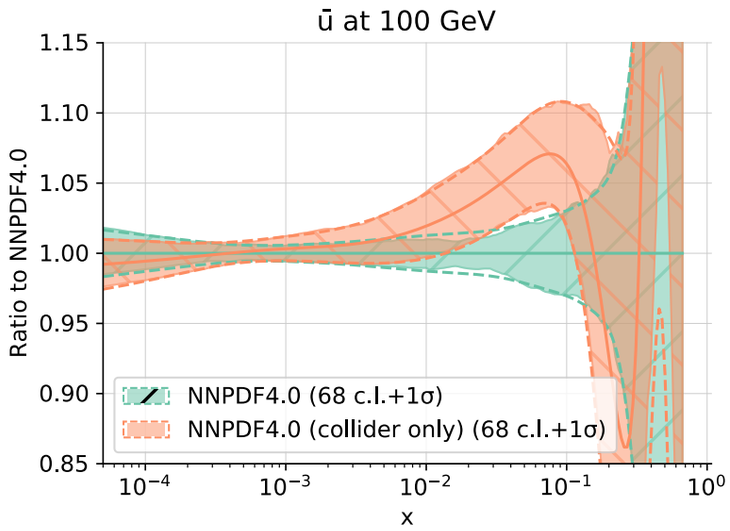
- Neutrino cross-sections and structure functions can be measured with **O(few %) statistical precision,** improving on available measurements

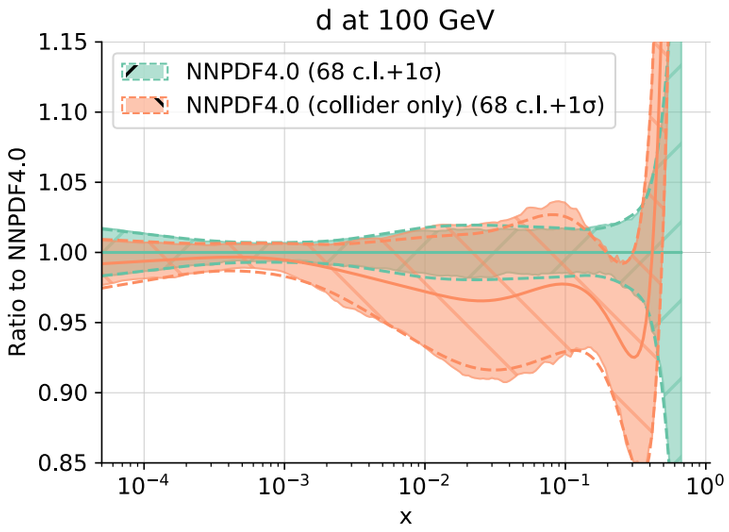
- Neutrino DIS provides access to the **quark flavour decomposition** in nucleons and nuclei: sea quark asymmetry, strangeness, charm

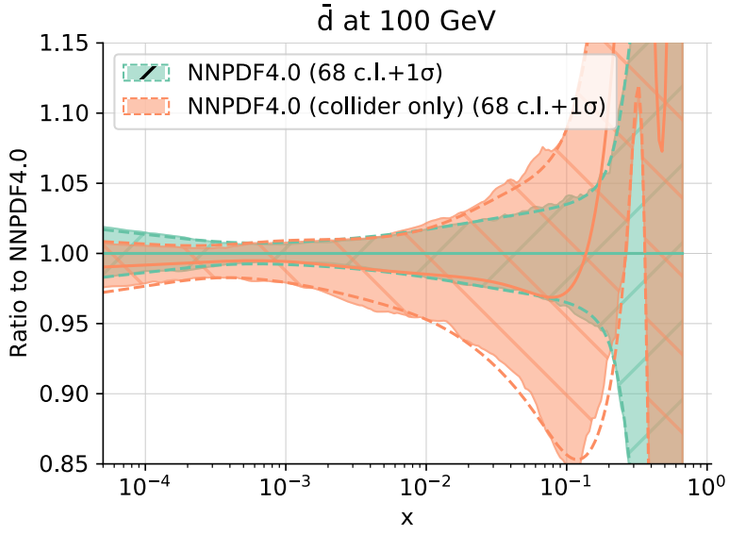
- Natural continuation of the extremely succesful **CERN programs on neutrino DIS**

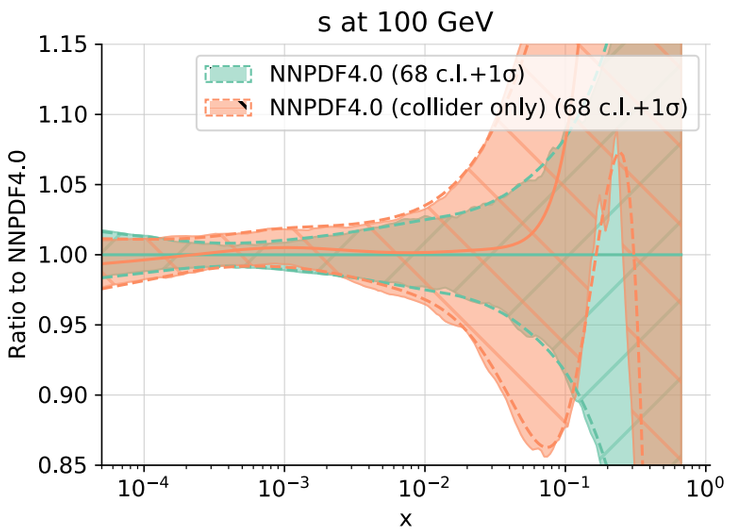
Neutrino DIS @ LHC

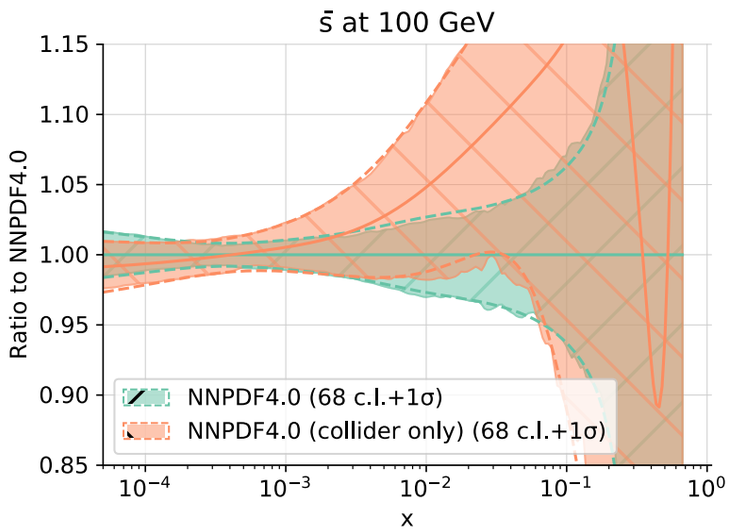










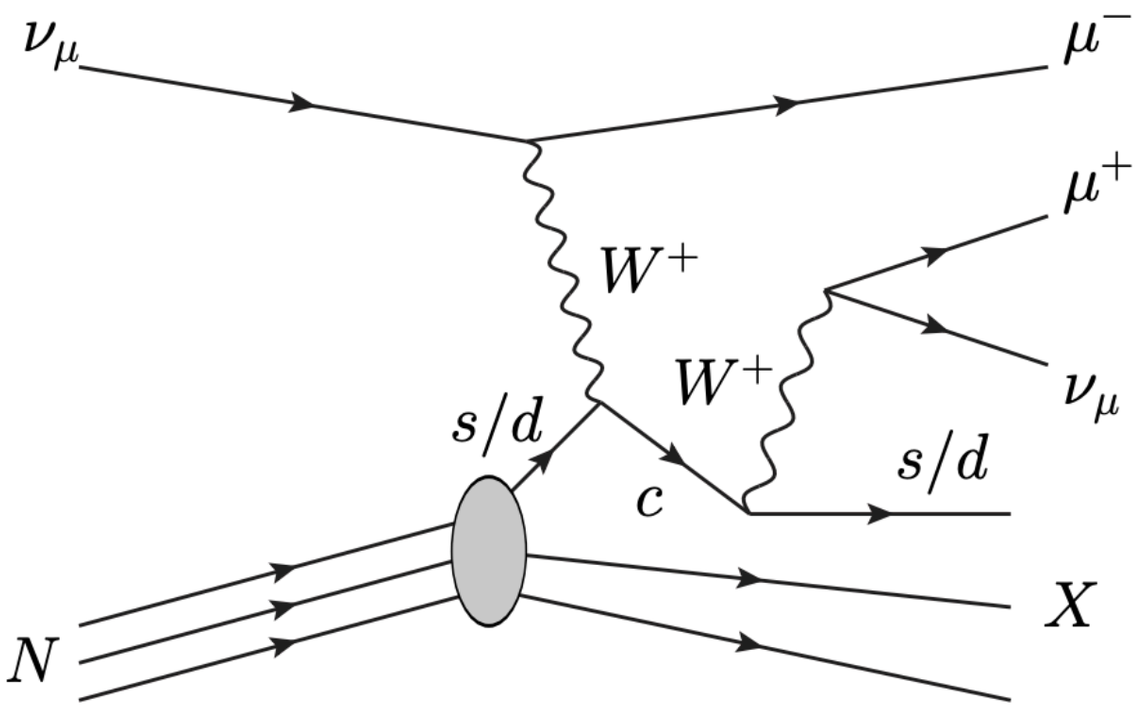


- **NC and CC fixed-target DIS** measurements still provide key constraints in global PDF fit

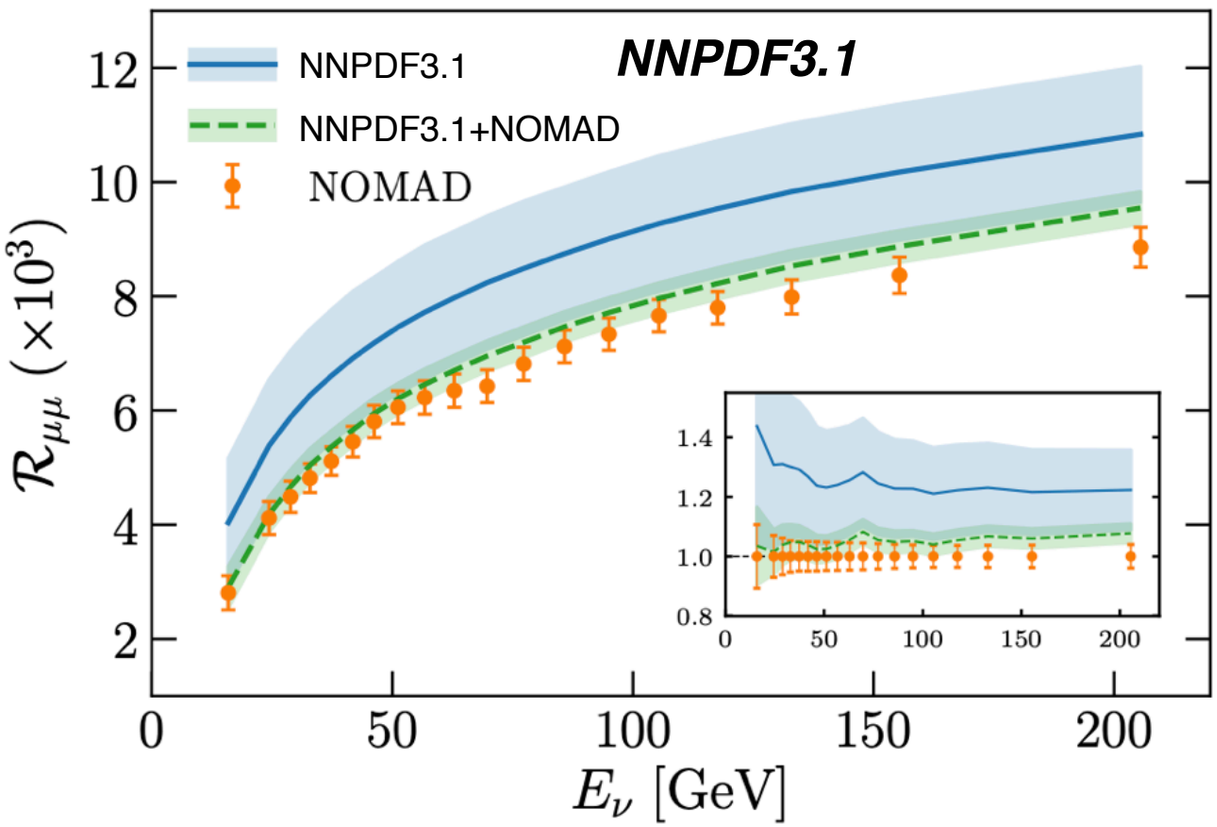
- In particular for ***x > 0.01***, a **collider-only PDF fit** affected by rather larger uncertainties

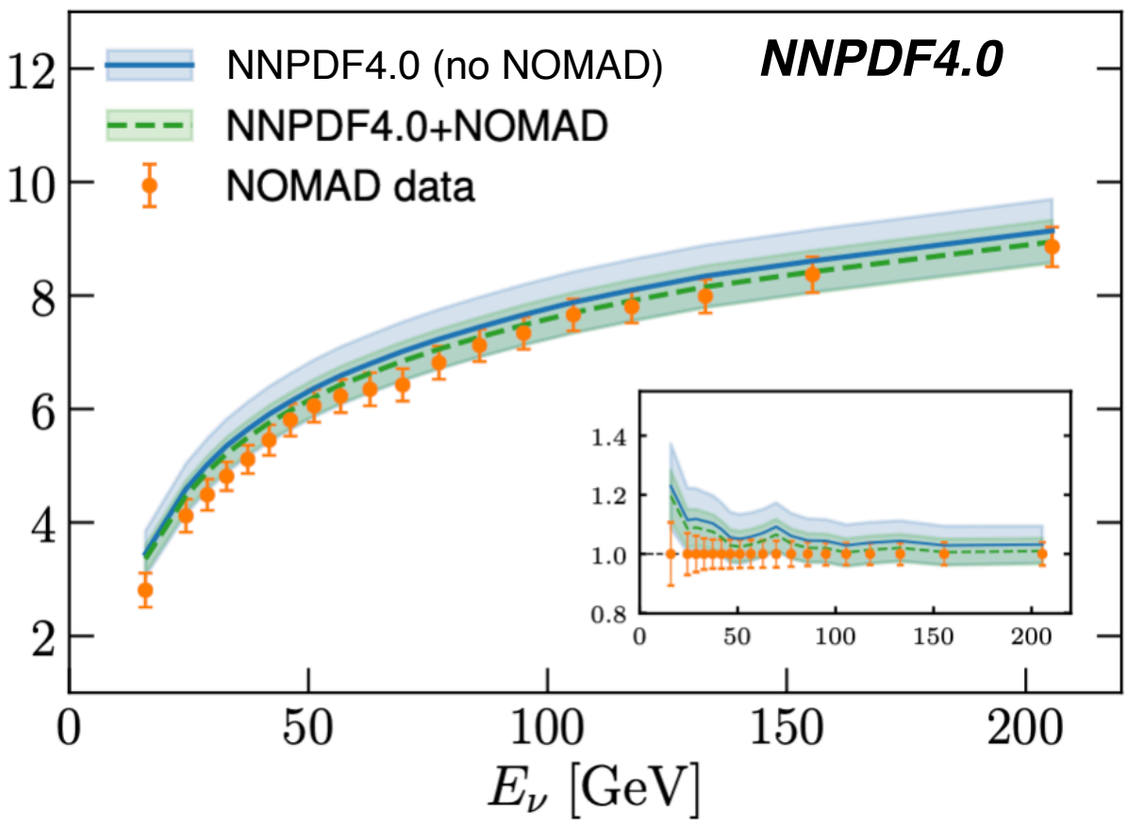
- FPF neutrino DIS measurements may **replace or complement existing data** and become one of the backbones of global fits

Neutrino DIS @ LHC



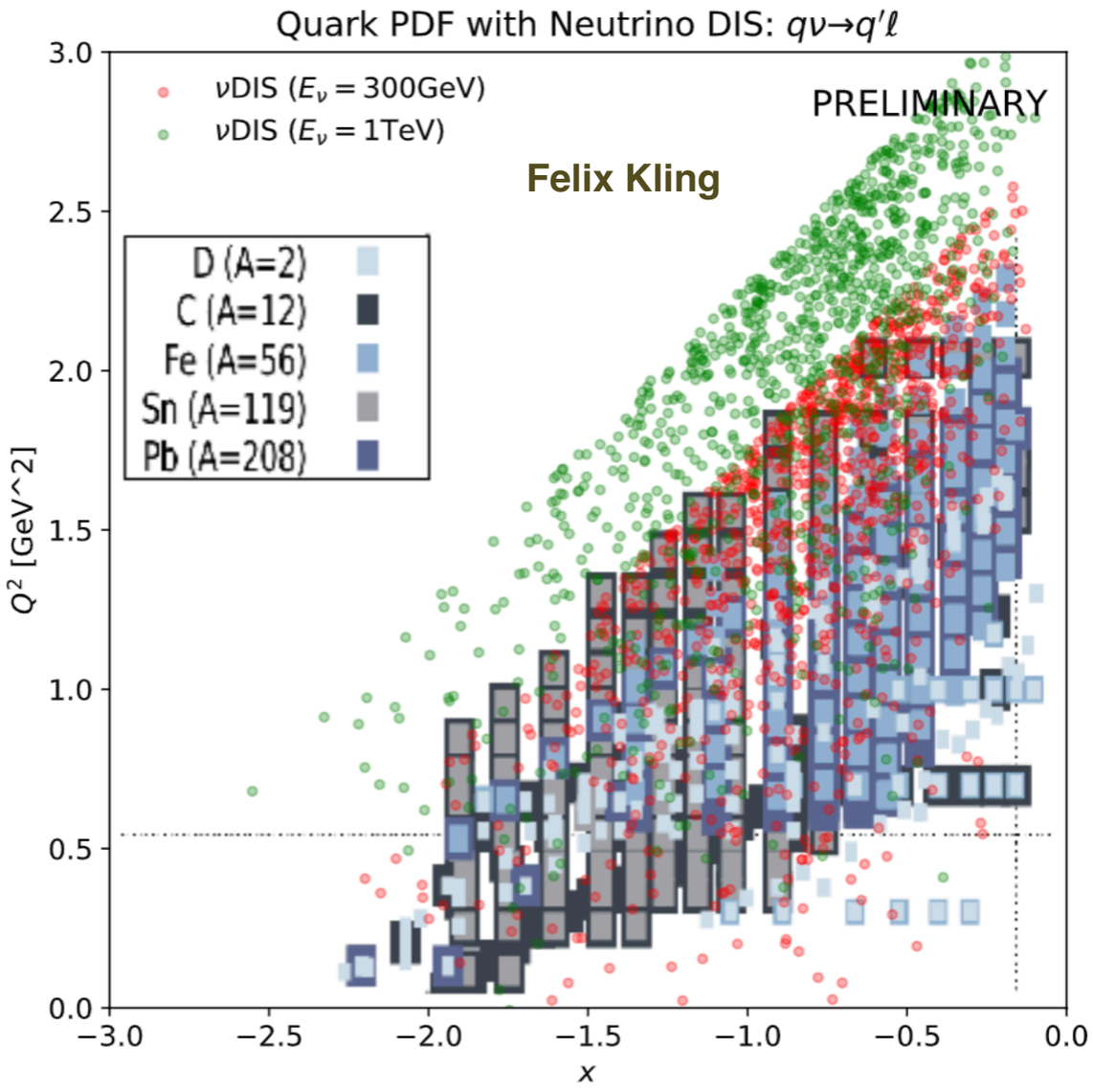
- ☑ Dimuon DIS data sensitive to **strangeness** via charged-current scattering
- ☑ Existing measurements (NuTeV, NOMAD) provide bulk of constraints on **strange PDF**
- ☑ Requires tagging the **dimuon final state**



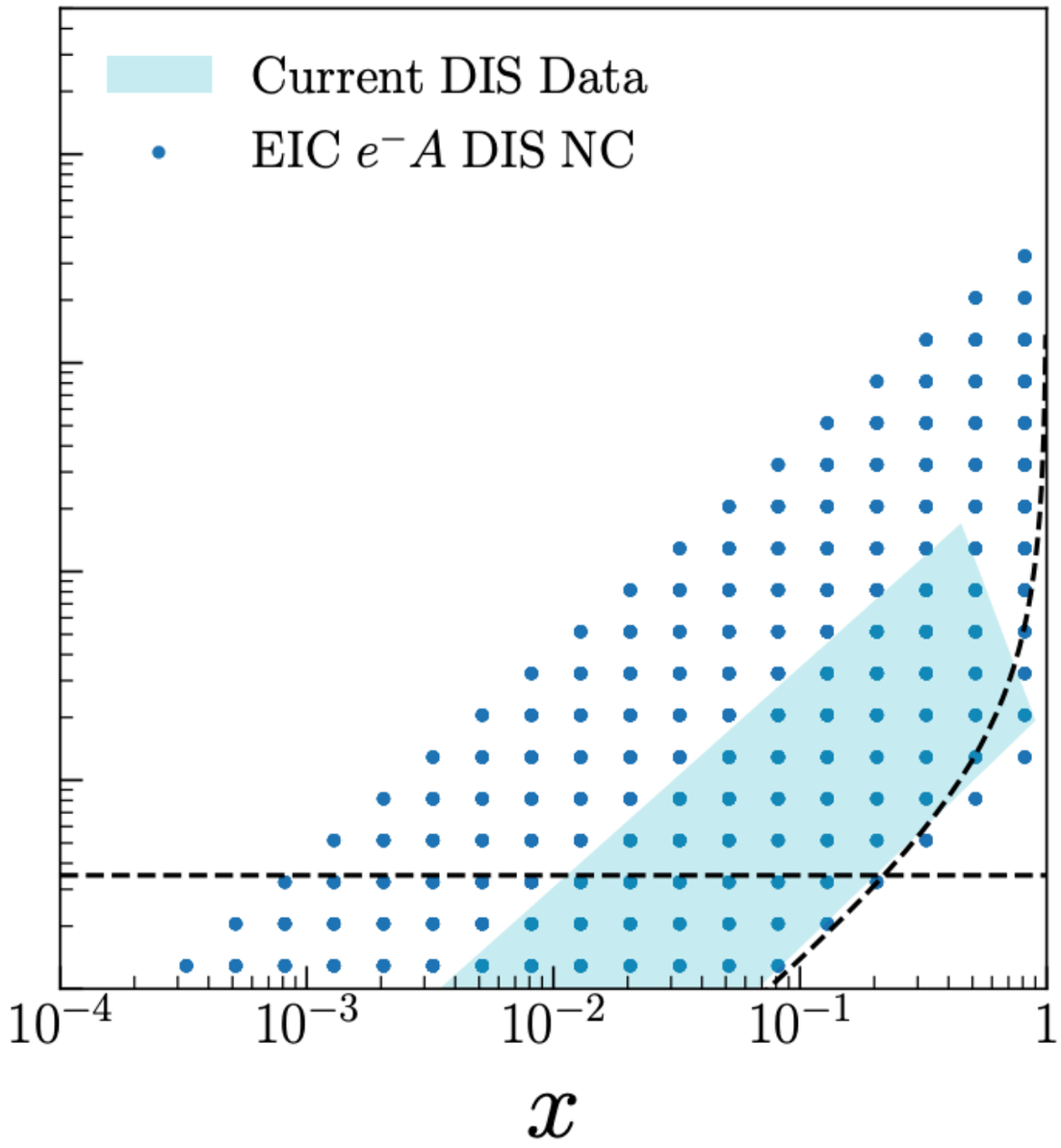


Neutrino DIS @ LHC

FPF coverage



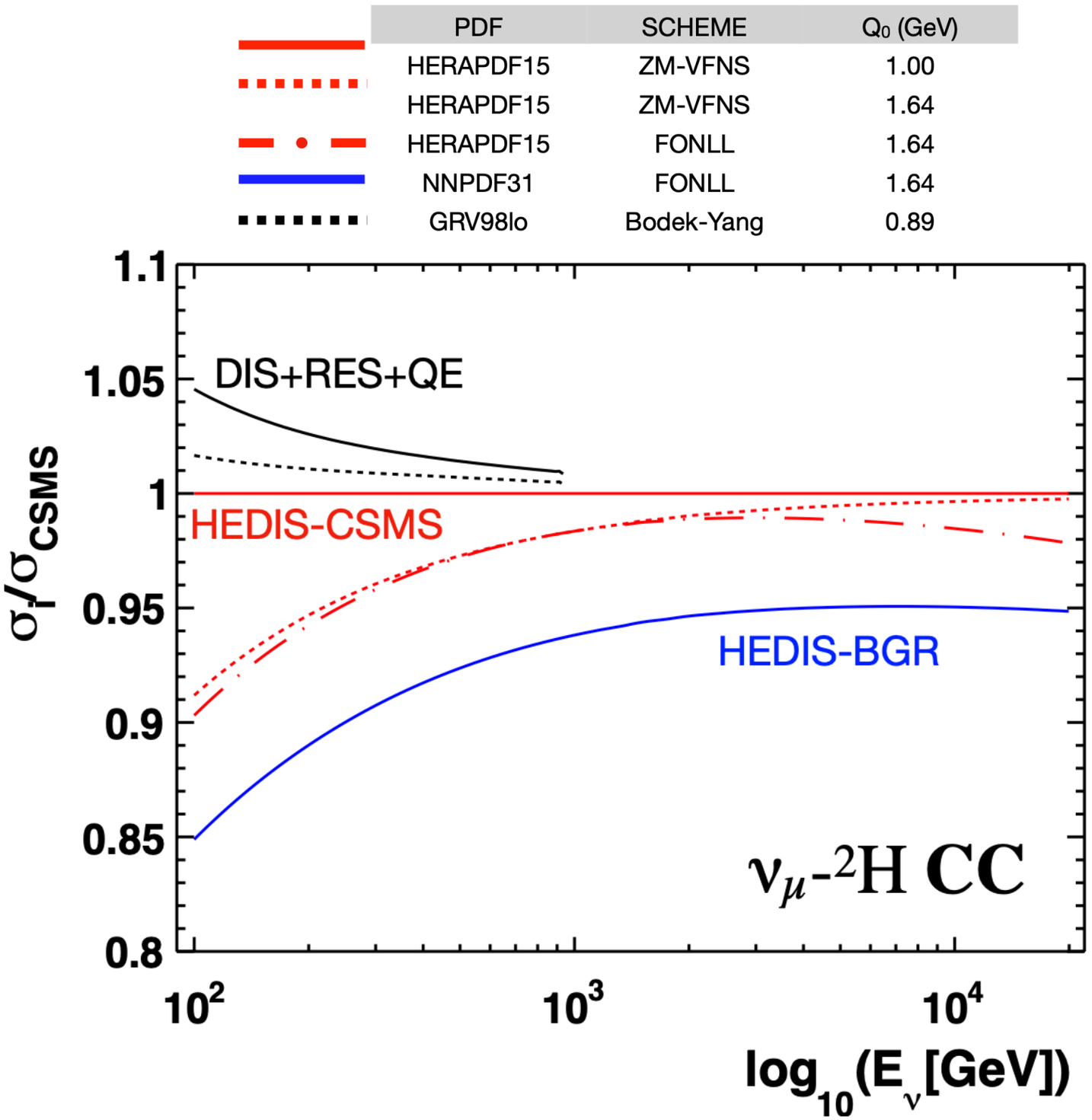
Electron-Ion Collider coverage



- The FPF coverage partially overlaps with the **EIC** for neutrino-nucleus scattering
- Complementarity for quark flavour separation: **neutral-current** (EIC) vs **charged-current** (FPF)
- Requires quantitative assessment of the impact of FPF measurements on nuclear PDFs

Neutrino DIS @ LHC

Before exploiting FPF neutrino-DIS measurements for **hadron structure studies**, need to improve calculations of **neutrino-nucleus scattering**, benefit for whole FPF physics program

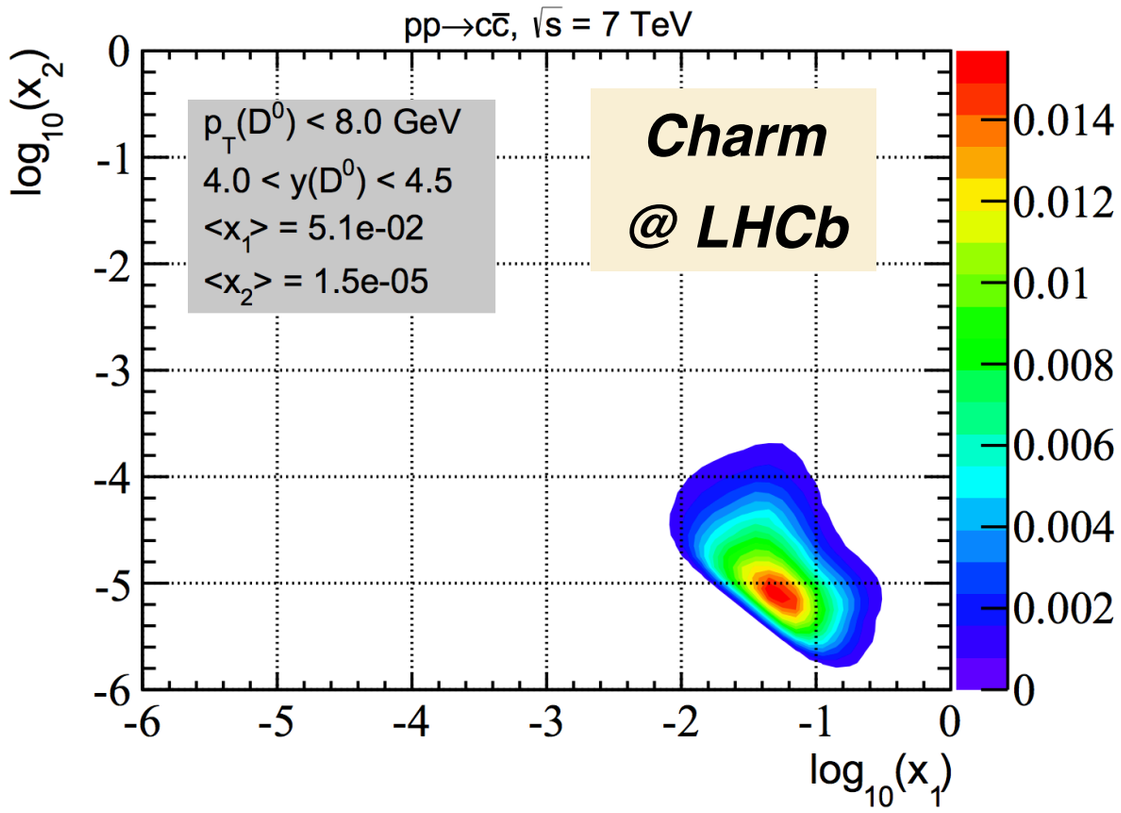


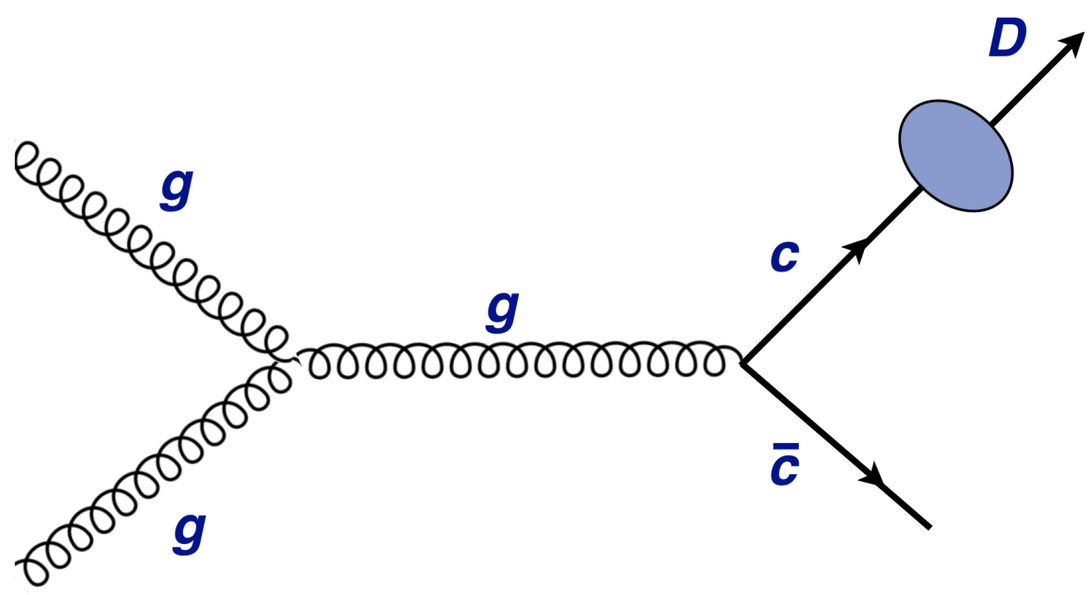
- pQCD calculations with NNLO QCD corrections and heavy quark mass effects
- State-of-the-art determinations of proton and nuclear PDFs
- Smooth, robust matching to the low-Q region (data-driven): current **limiting factor**
- Accounting for sub-leading scattering processes

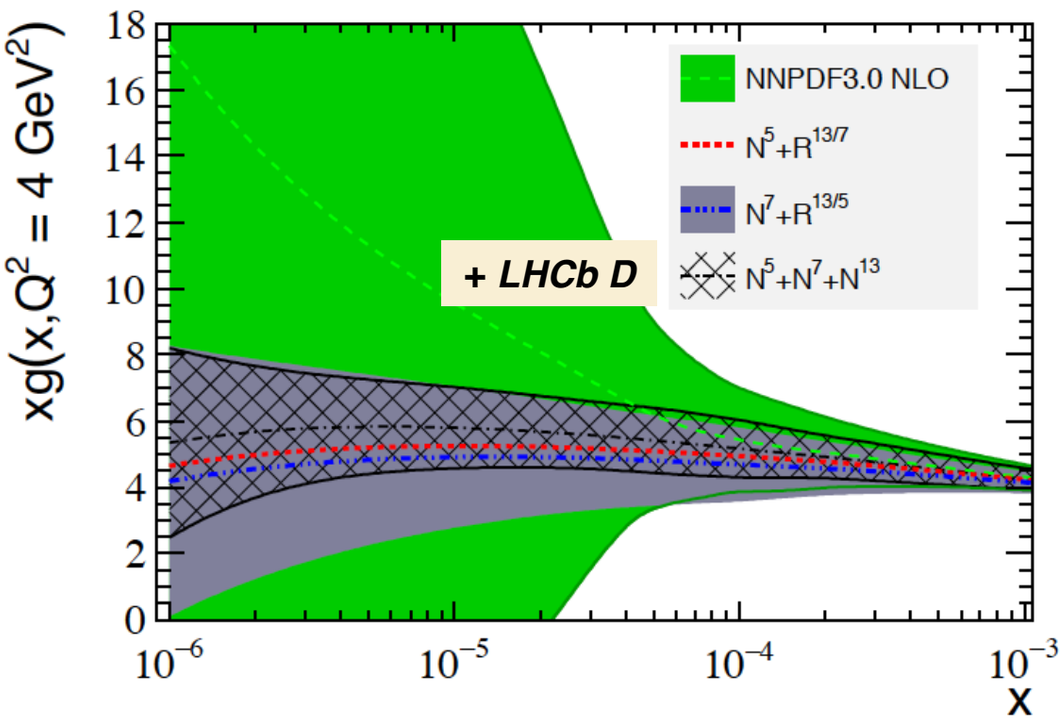
Goal: theory uncertainties down to **1% level** in full FPF kinematic range

Charm production in forward region

Measurements of ***D*-meson production** by LHCb provide unique constraints on **small-x PDFs**







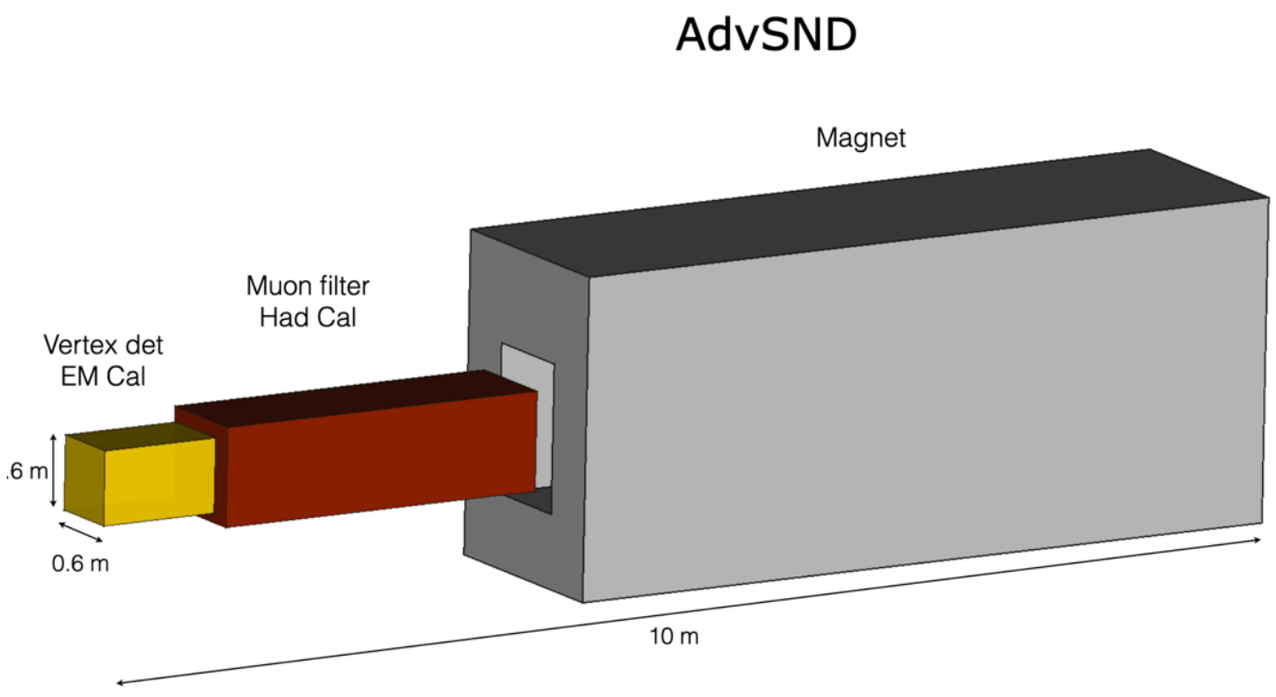
In turn, better small-*x* PDFs make possible improving predictions for the **prompt charm flux at neutrino telescopes**, which dominates the atmospheric background

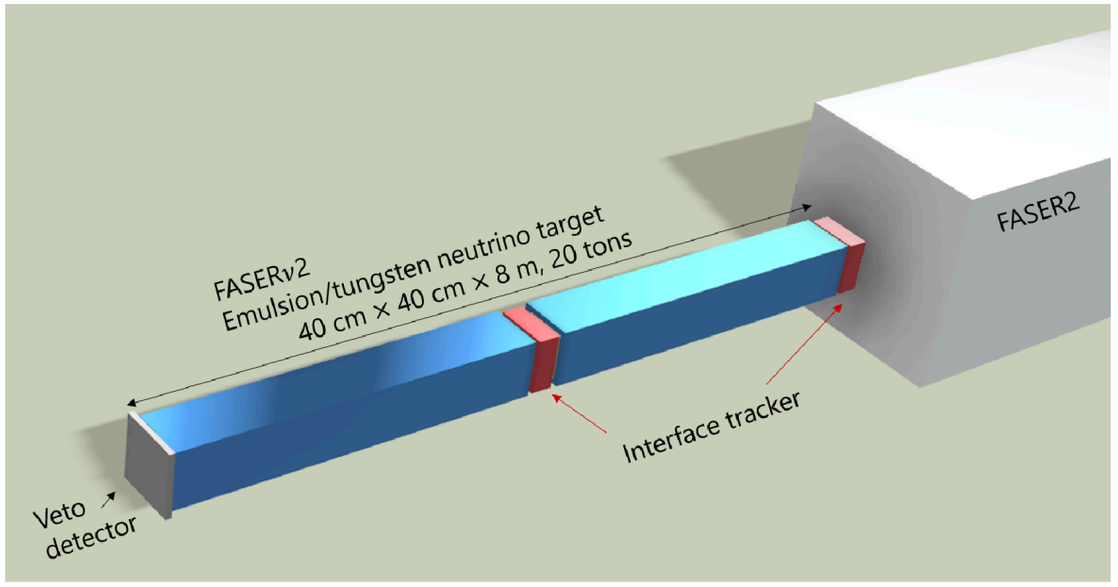
Also sensitive to higher-order QCD corrections, BFKL resummations, possible intrinsic charm in the proton

Charm production in forward region

The c**overage in rapidity** and the expected interaction rates depend on the detector(s) choice

Detector			Interactions at FPF			
Name	Mass	Coverage	CC $\nu_e+\bar{\nu}_e$	CC $\nu_\mu+\bar{\nu}_\mu$	CC $\nu_\tau+\bar{\nu}_\tau$	NC
FASERν2	20 tonnes	$\eta \gtrsim 8.5$	178k / 668k	943k / 1.4M	2.3k / 20k	408k / 857k
FLArE	10 tonnes	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k	89k / 157k
AdvSND1	2 tonnes	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754	17k / 29k
AdvSND2	2 tonnes	$\eta \sim 5$	29 / 14	48 / 29	2.6 / 0.9	32 / 17

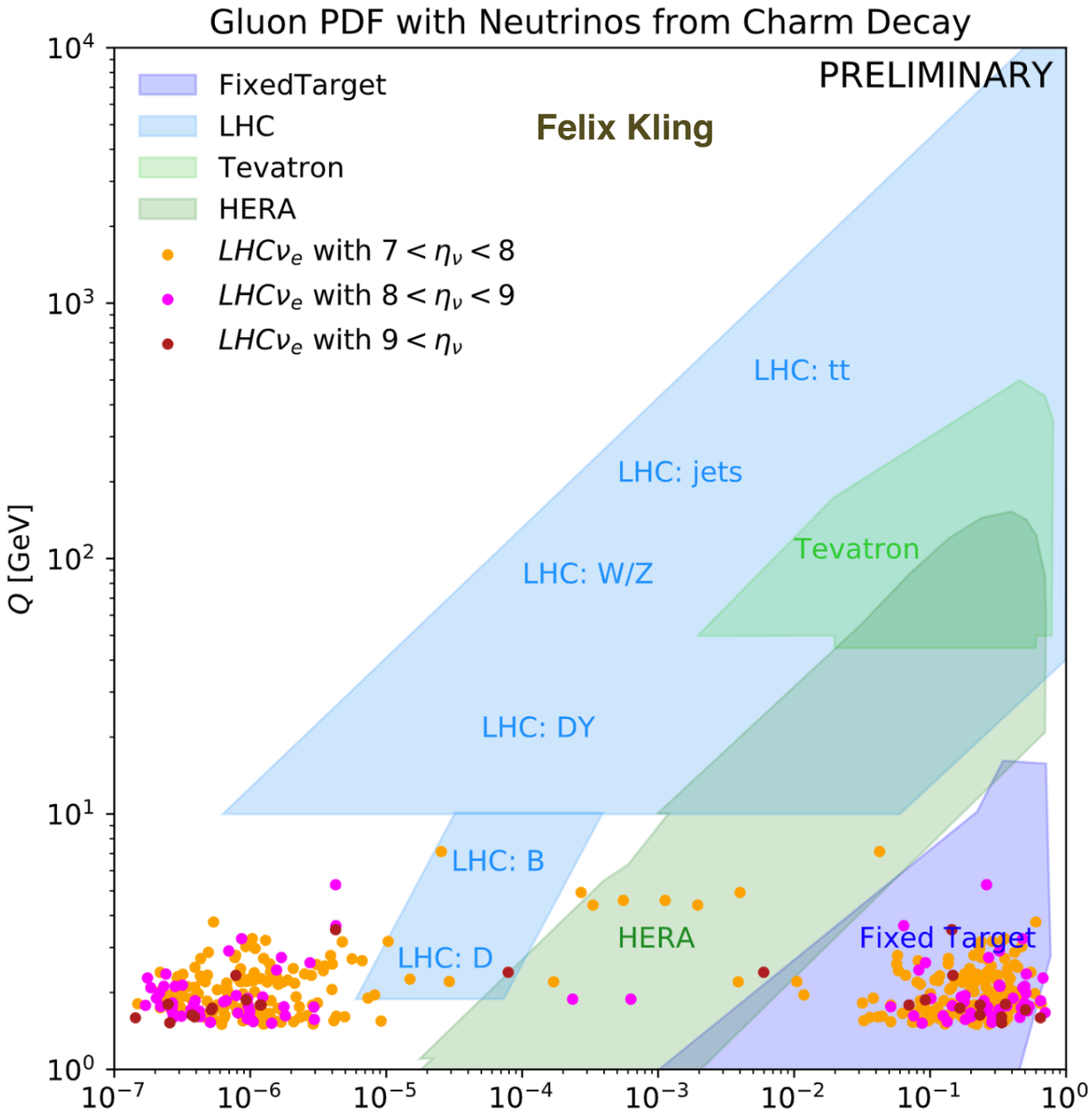




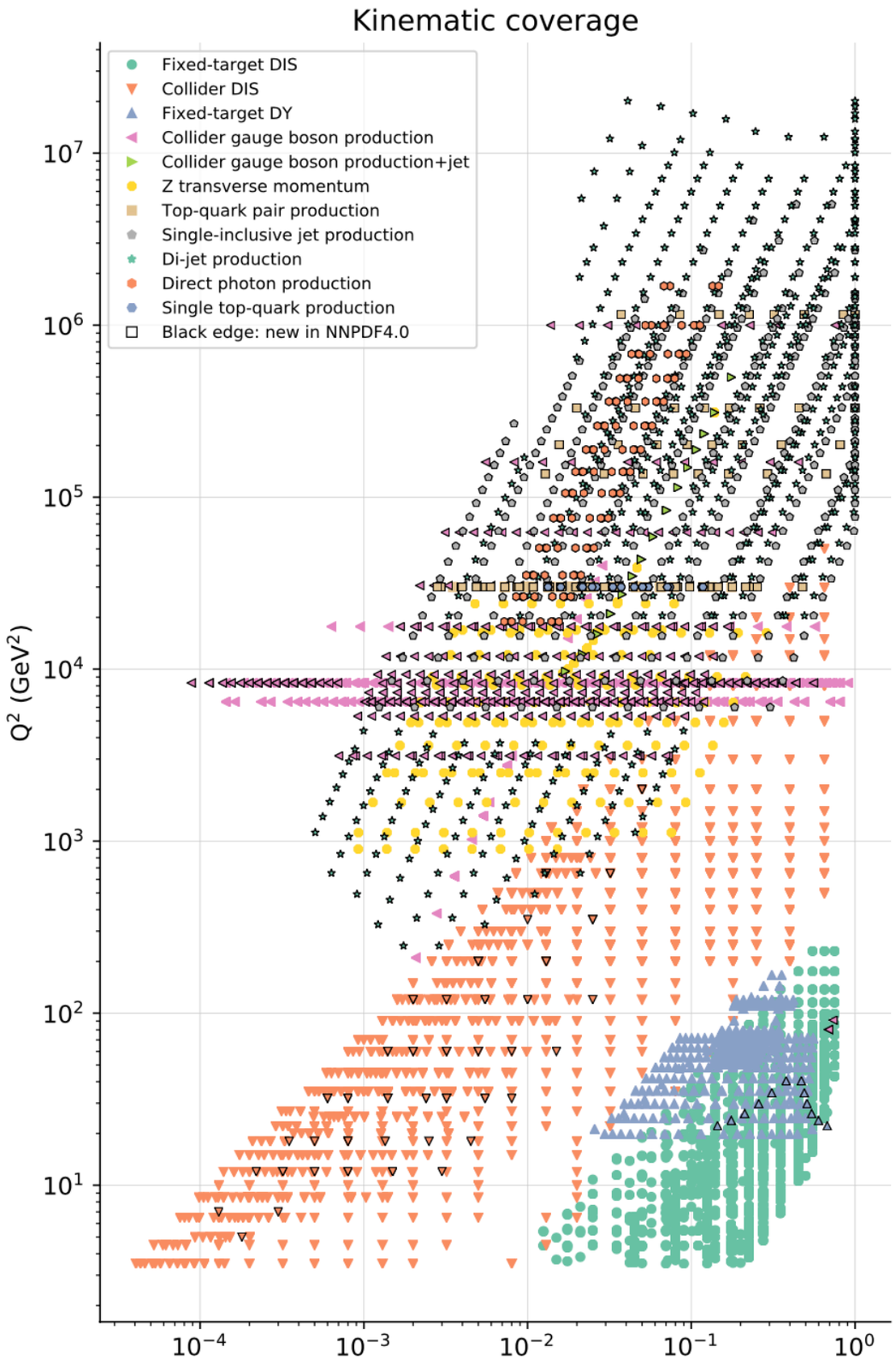
A larger detector makes possible the **high-stats** required for QCD measurements

Charm production in forward region

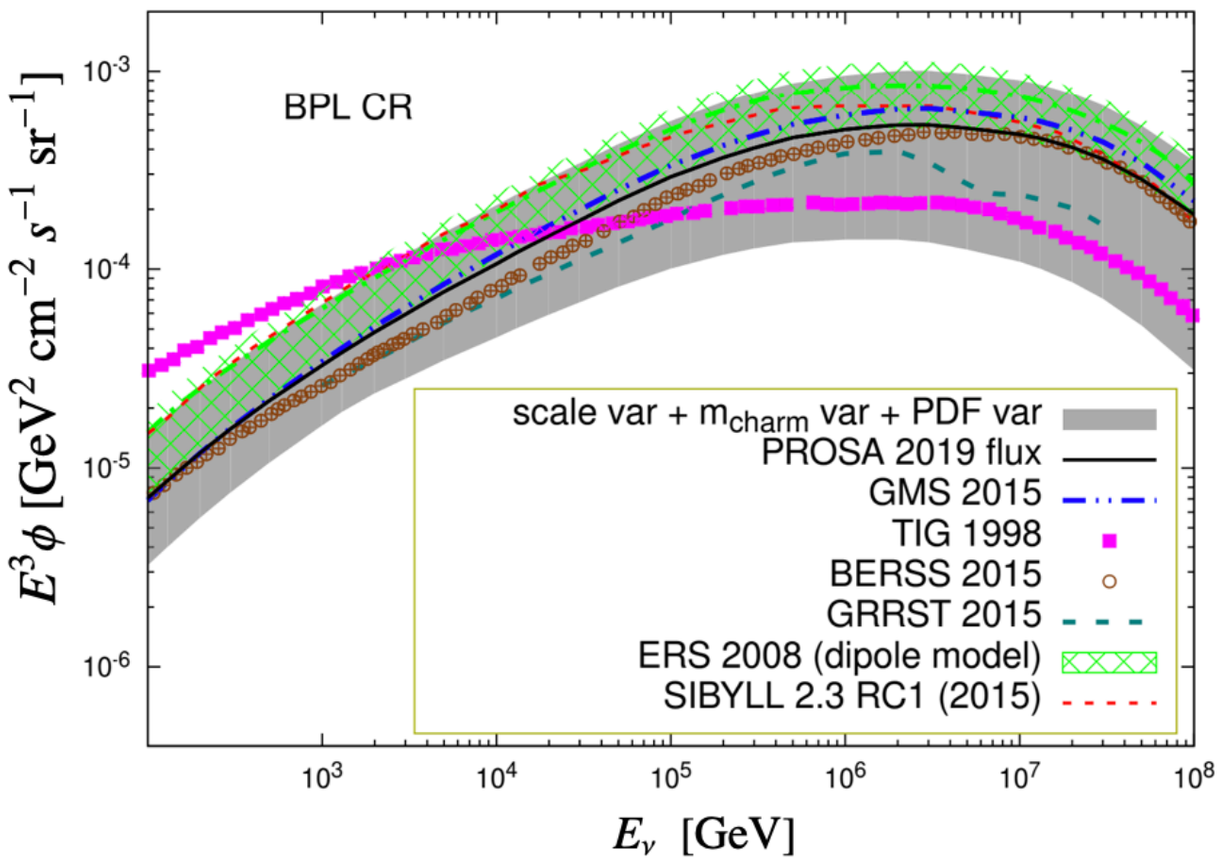
Significant extension in the small-x coverage of proton PDFs compared to current fits

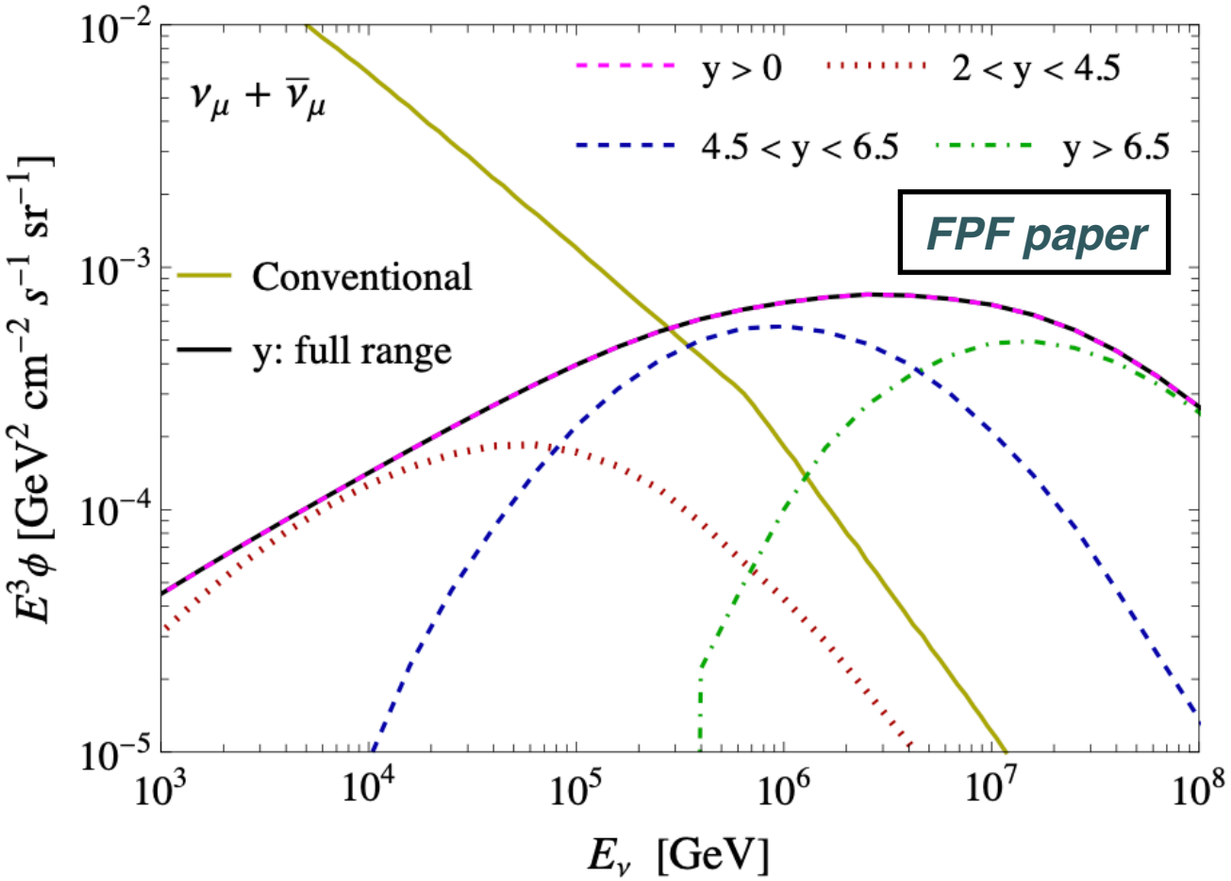


even more powerful for data-taking in p+Pb collisions



Charm production in forward region





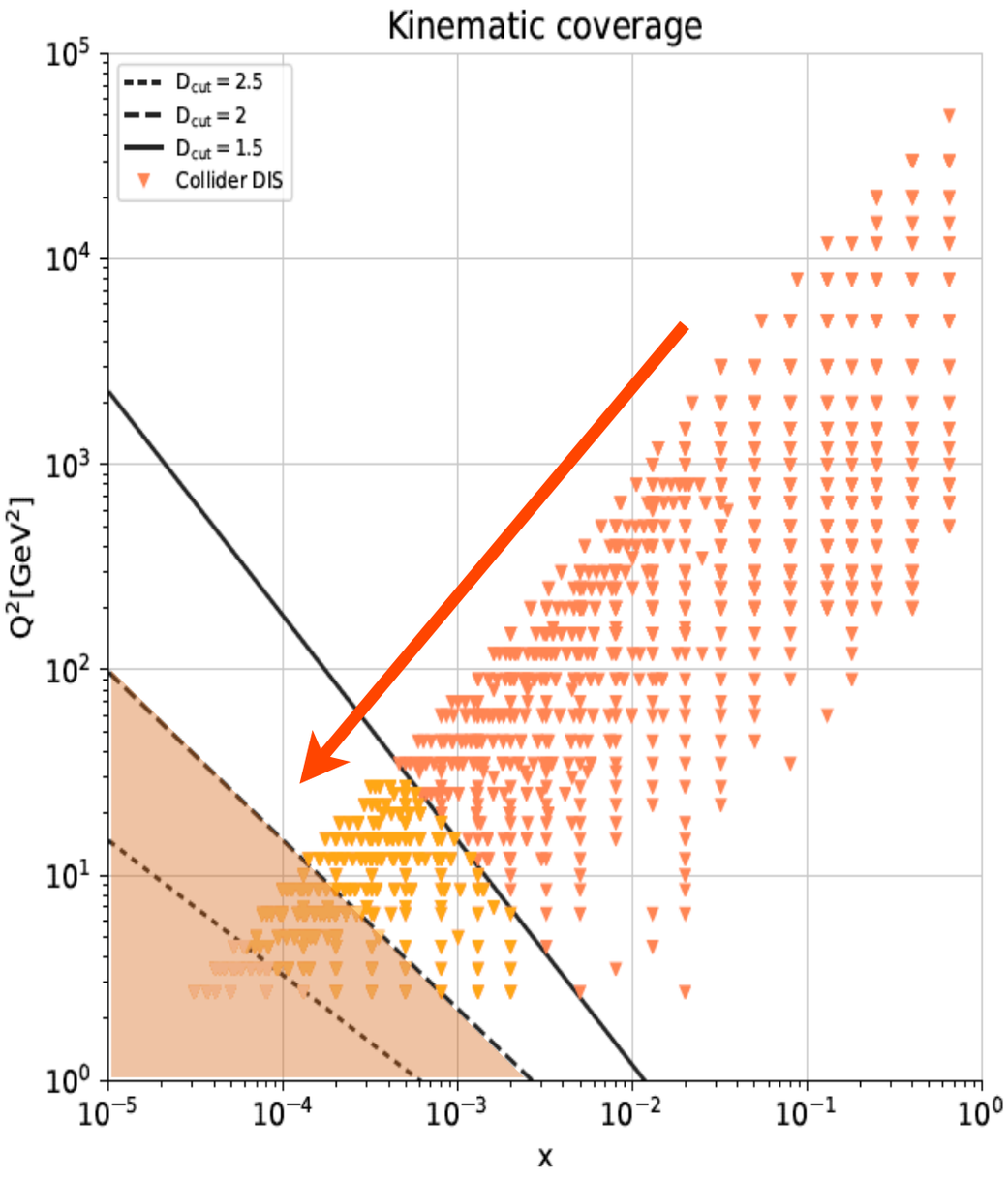
- Most existing calculations of prompt neutrino fluxes already account for information from **LHCb D-meson** cross-sections

- The very forward region **outside the LHCb acceptance (*y > 4.5*)** is particularly important in the evaluation of the prompt neutrino fluxes

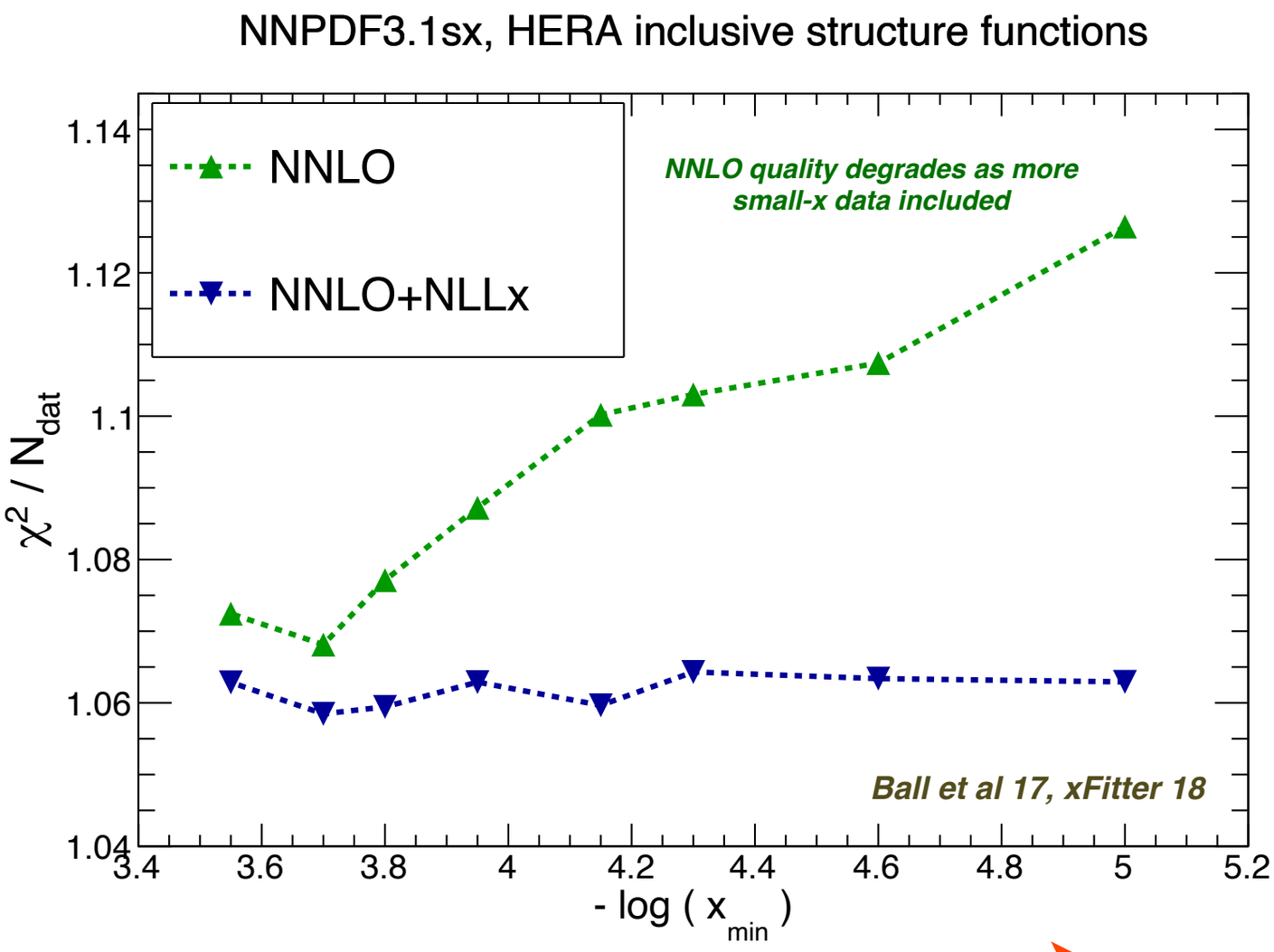
- Unique opportunity to test production models and **QCD in the high-energy regime**

Charm production in forward region

BFKL dynamics stablished in HERA data: crucial for description of **low-*x* physics at LHC / FPF**



Monitor the fit quality in small-*x* region

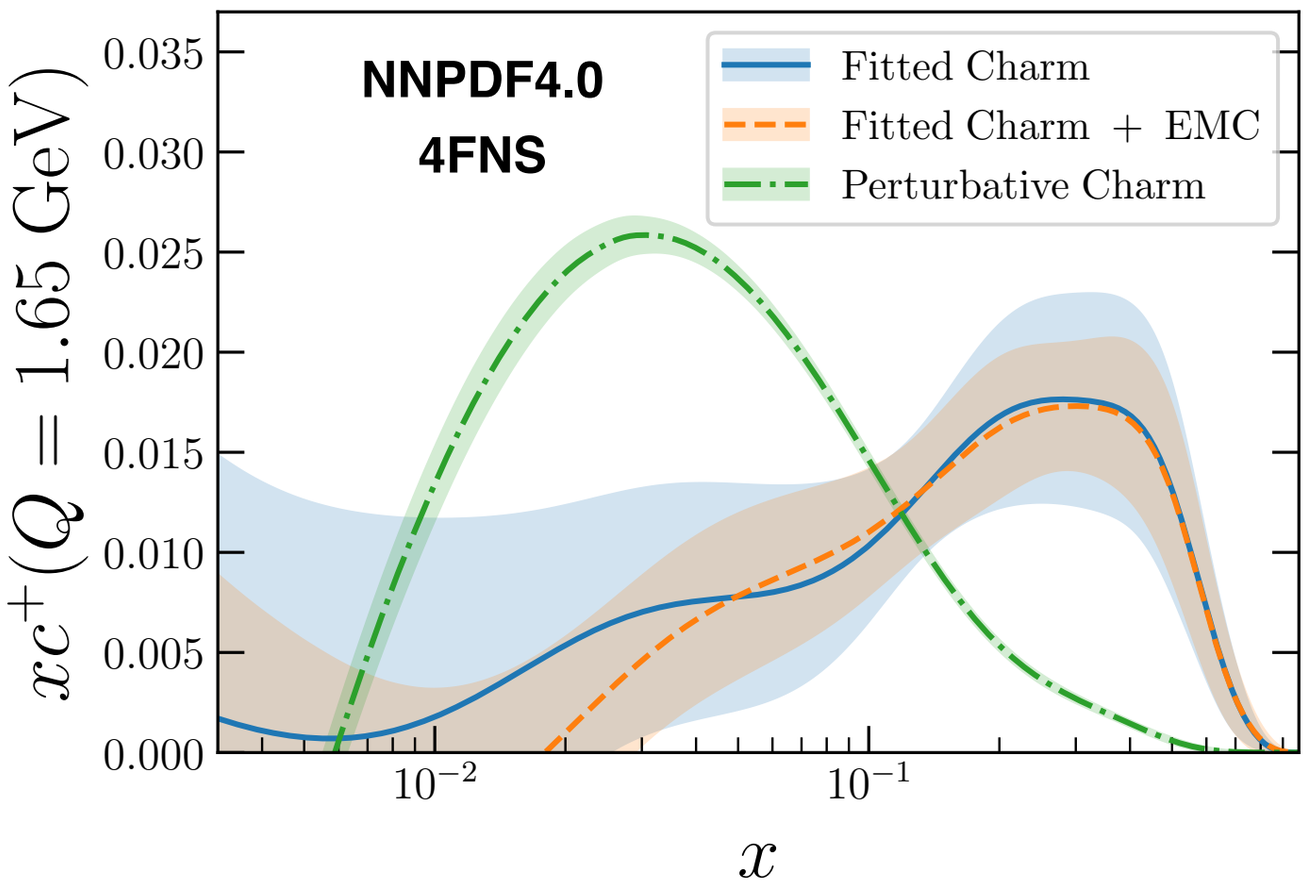


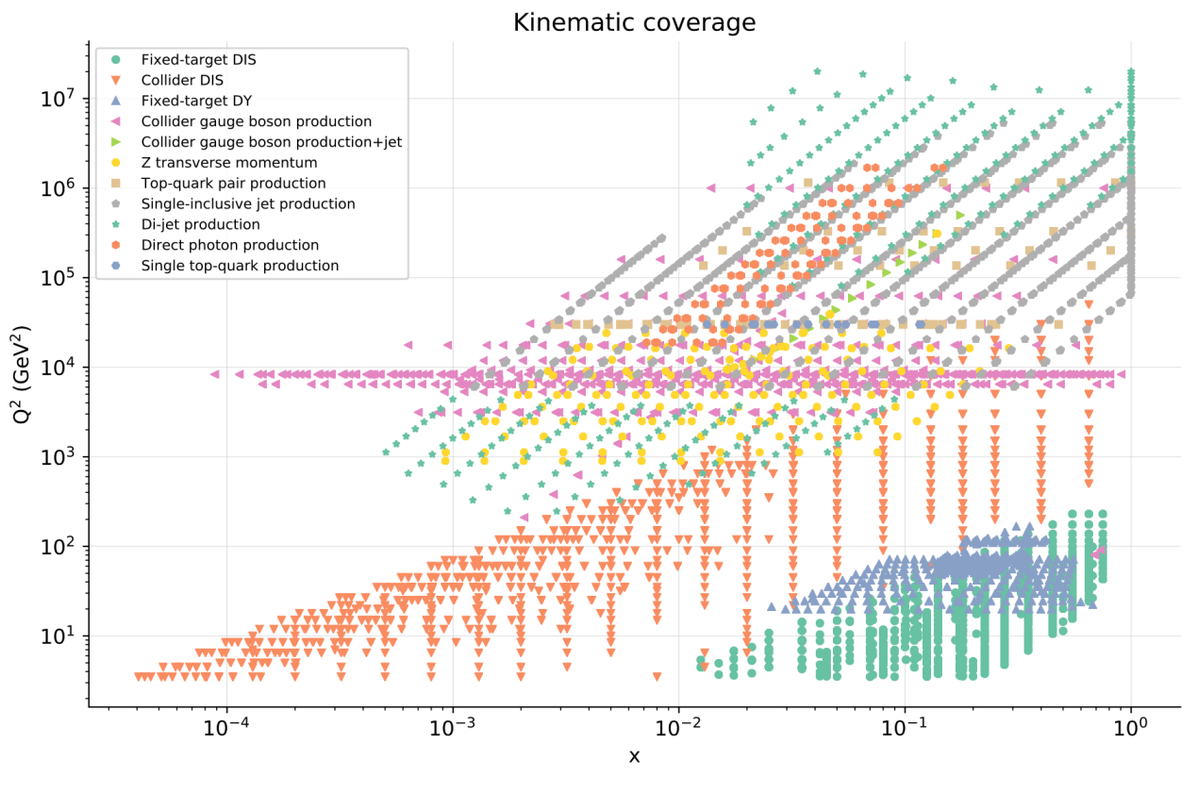
Best description of **small-*x* HERA data:**

BFKL resummation

motivates program for BFKL-resummed calculations of LHC processes

Intrinsic charm at the FPF





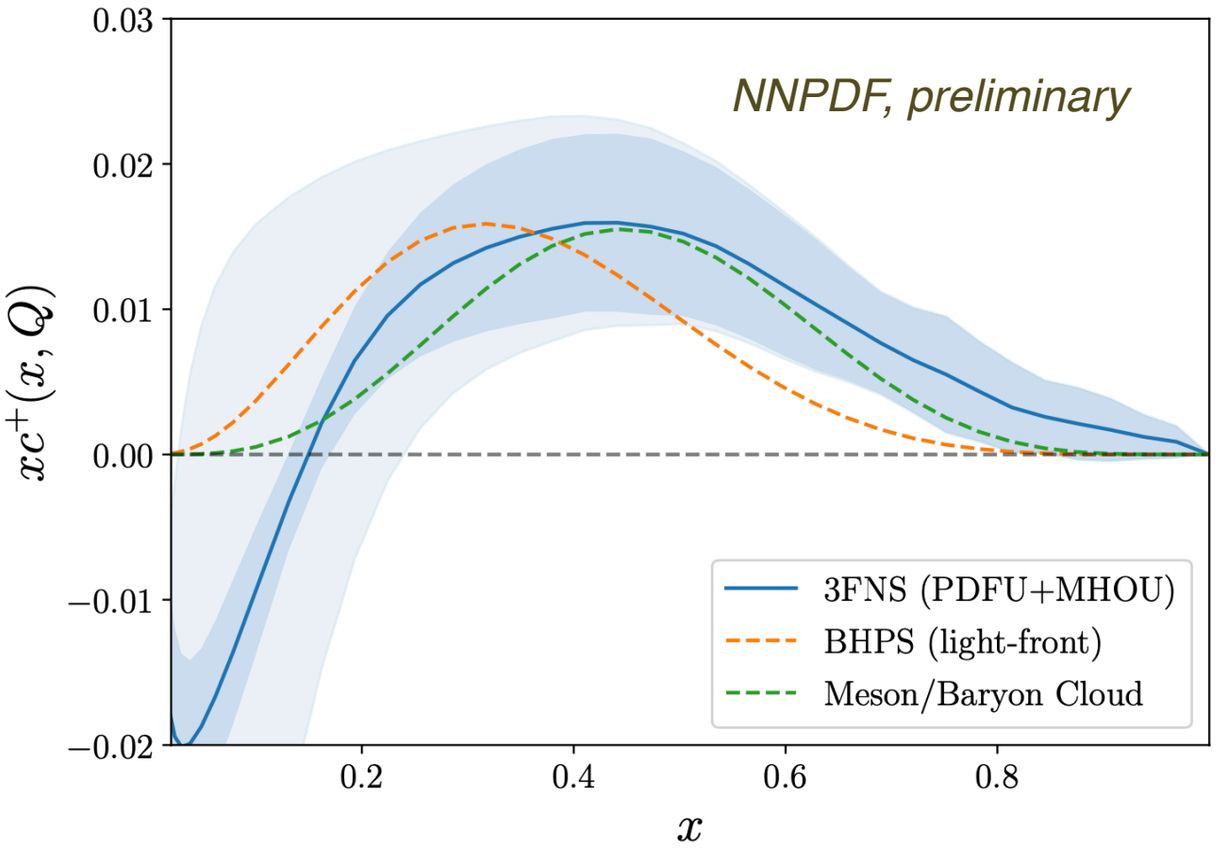
- ☑ Increasing evidence for **non-perturbative charm component** within the proton, robust upon conversion to the **3FNS** via backwards evolution and matching conditions

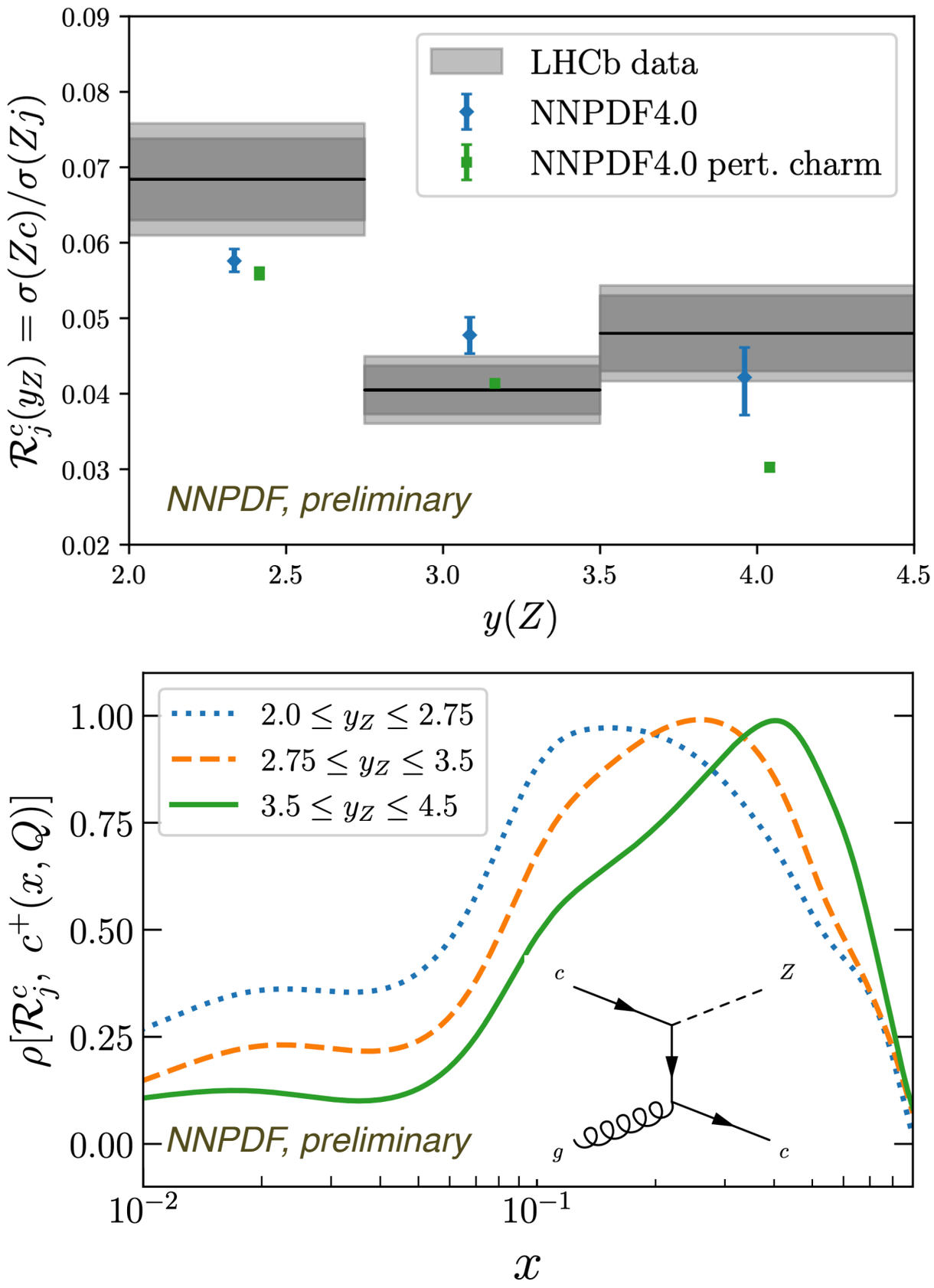
- ☑ Bulk of constraints provided by new **precision LHC data**, complemented by fixed-target DIS

- ☑ As opposed to previous studies, impact of the **EMC charm measurements** mild now

- ☑ An enhanced **large-*x* charm PDF** will modify *D*-meson production at forward rapidities

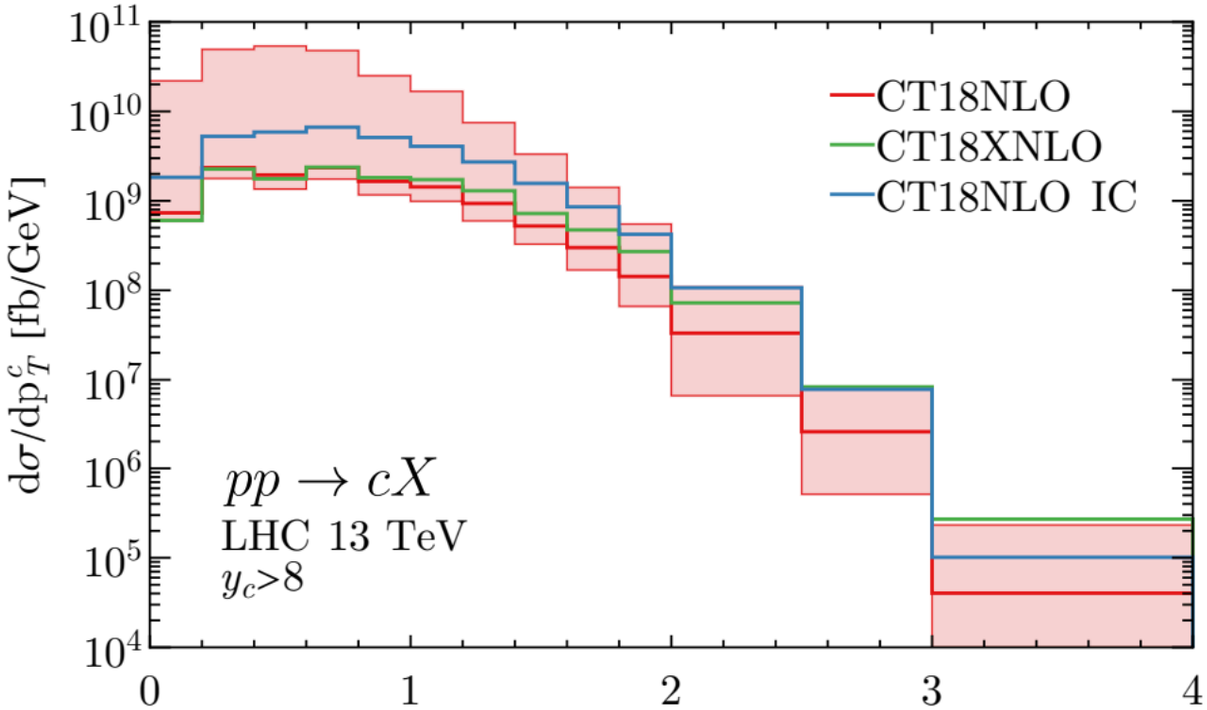
Intrinsic charm at the FPF

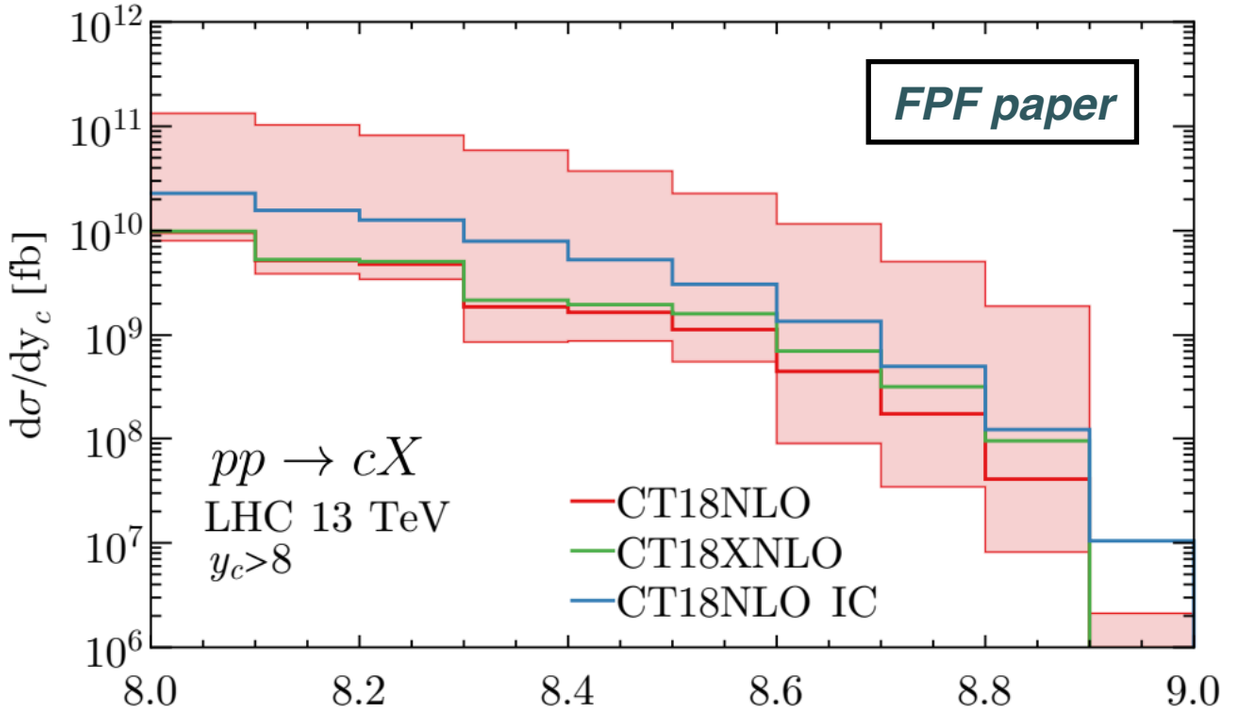


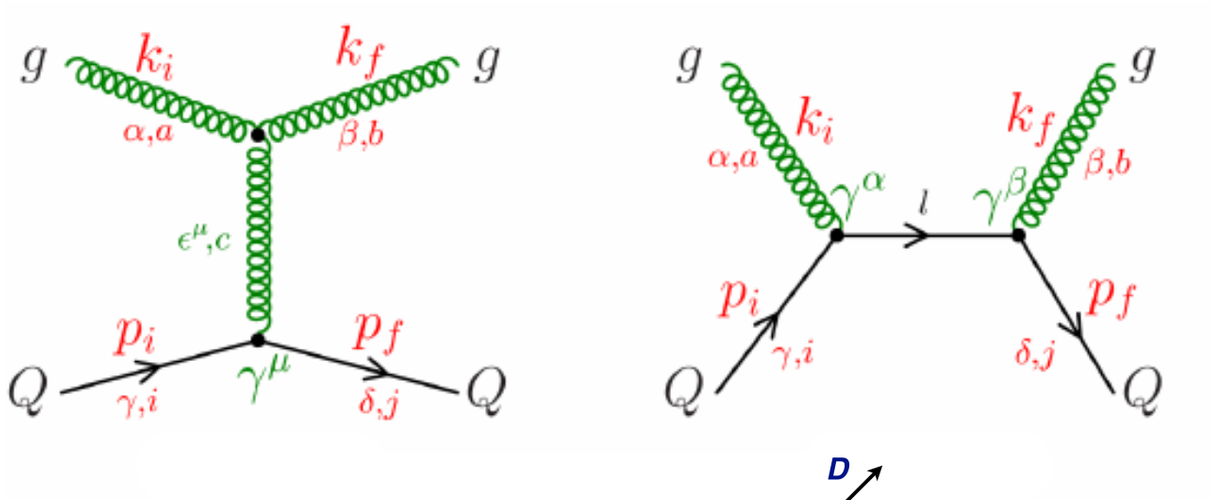


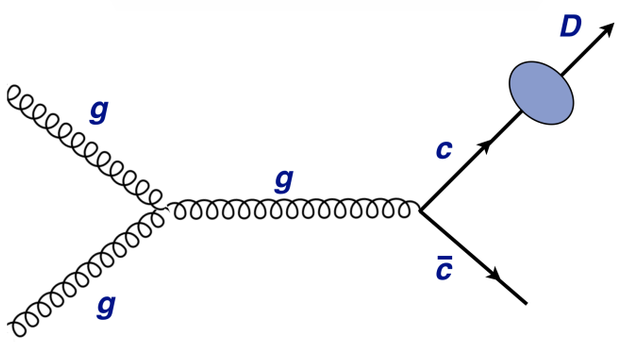
- ☑ Good agreement of the 3FNS (intrinsic) charm PDF with **non-perturbative models**
- ☑ Independent validation with recent LHCb measurements of **Z+charm:** consistency of indirect and direct constraints
- ☑ Motivates dedicated studies at the FPF!

Intrinsic charm at the FPF









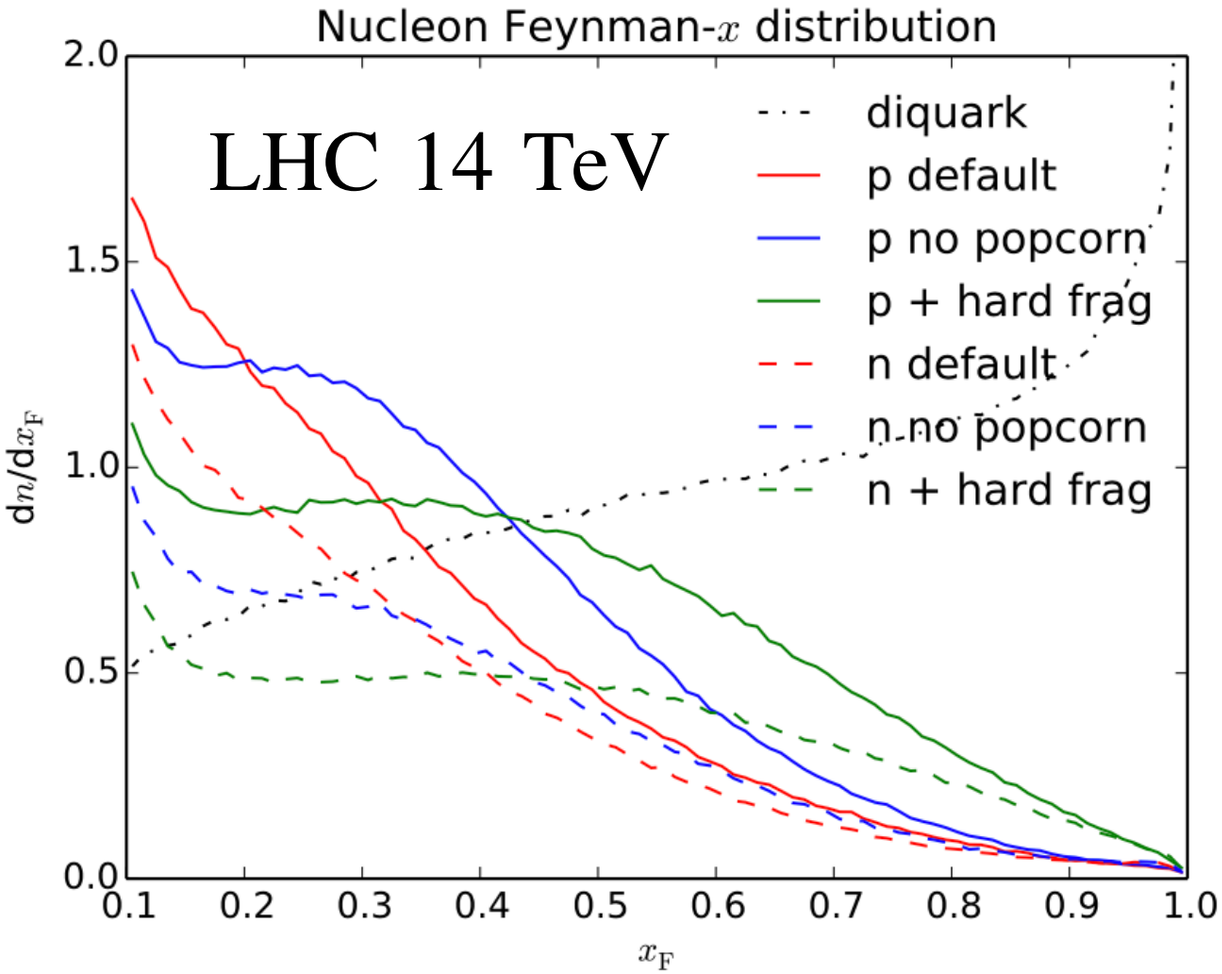
- Charm production in the FPF acceptance: sensitive to both **BFKL dynamics** and **intrinsic charm**

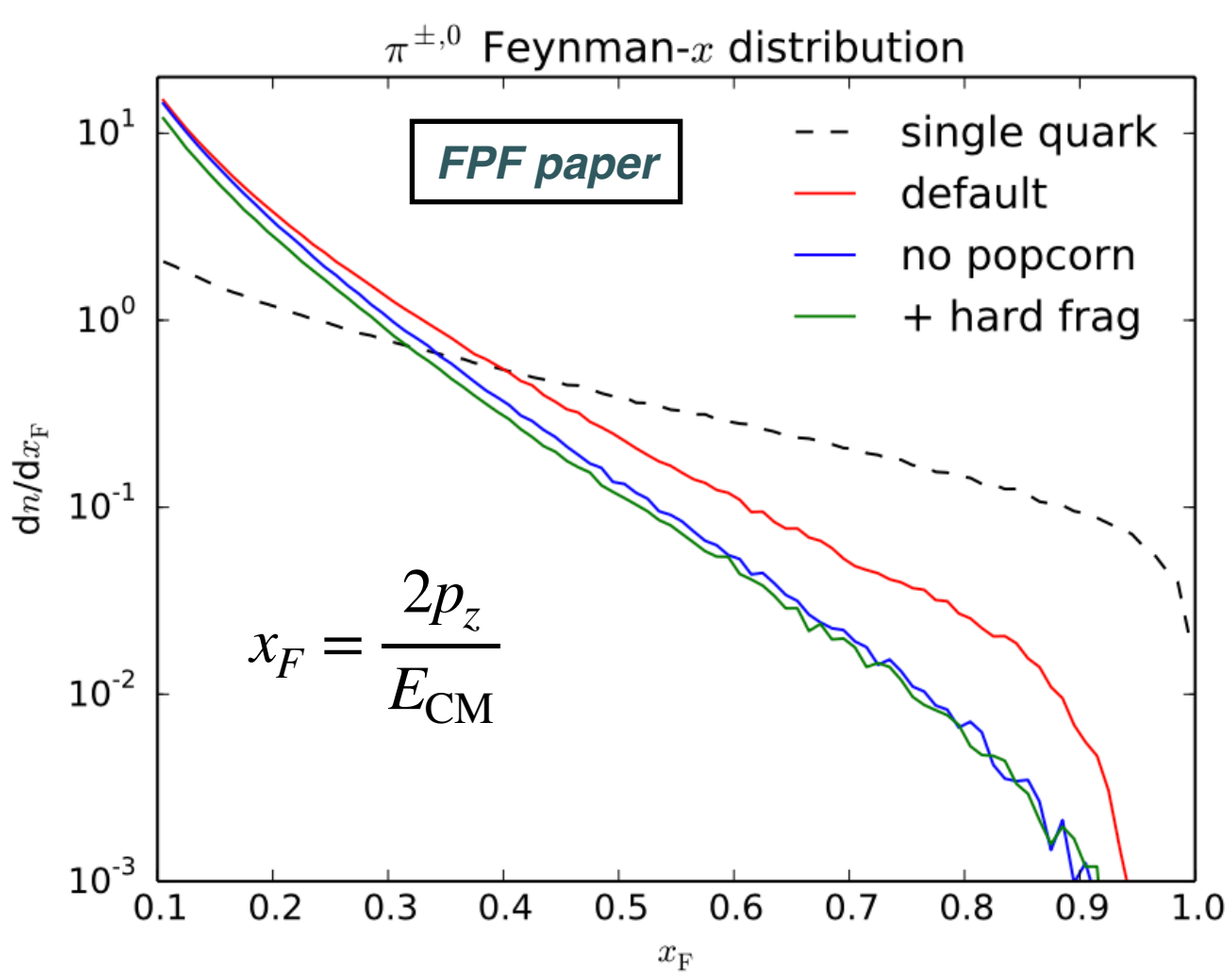
  also non-linear effects, subleading fragmentation

- **Charm-gluon scattering** dominates at large rapidities over gluon-gluon in the presence of IC

- Related opportunities in forward hadron production

Forward hadron production at the FPF





- Improving models for forward light hadron production is crucial for **cosmic ray measurements**
- Large uncertainties in models of l**ight hadron production and fragmentation**, which dominate the uncertainties on the expected neutrino fluxes at the FPF
- Deconvolution analysis will be required to disentangle **neutrino production** (from forward hadrons) from the subsequent **neutrino interactions**

Summary and outlook

- The Forward Physics Facility would realise an exciting program in a broad range of topics from **BSM and long-lived particles** to **neutrinos, QCD, and hadron structure**, with deep connections to astroparticle physics

- **High-energy neutrino DIS** would open a new probe to proton and nuclear structure, complementing existing and future experiments (e.g. CC DIS is challenging at 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!