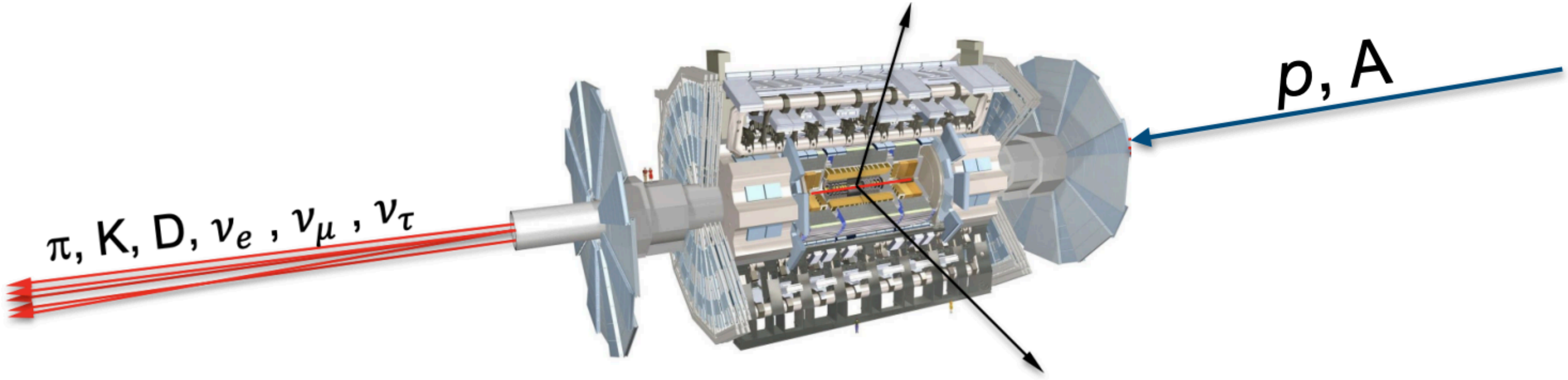
QCD, Neutrino, and BSM Physics at Far-Forward Experiments: from the LHC to the FCC-pp

Juan Rojo, VU Amsterdam & Nikhef



7th FCC Physics Workshop

Annecy, 1st February 2024

Neutrinos at the LHC

- New physics, if **light and feebly-interacting,** could already be copiously produced at the LHC, but fail to be detected due to the **blind spots** of existing LHC detectors in the **far-forward region**

- In addition, there are **guaranteed physics targets** to be reached should we instrument the forward region of the LHC, based on exploiting **the most energetic, high-intensity neutrino beam ever produced in a laboratory**

Neutrino and muon physics in the collider mode of future accelerators

A. De Rujula (CERN), R. Ruckl (CERN)
May, 1984

24 pages
Part of Proceedings, ECFA-CERN Workshop on large hadron collider in the LEP tunnel : Lausanne and Geneva, Switzerland, March 21-27 March, 1984, 571-596
Contribution to: CERN - ECFA Workshop on Feasibility of Hadron Colliders in the LEP Tunnel (2nd part of Lausanne mtg. of 3/21), 571-596, SSC Workshop: Superconducting Super Collider Fixed Target Physics
DOI: 10.5170/CERN-1984-010-V-2.571
Report number: CERN-TH-3892/84
View in: CERN Document Server, KEK scanned document

pdf cite claim reference search 14 citations

First proposal in 1984

Neutrinos at the LHC

- Two far-forward experiments, **FASER** and **SND@LHC**, have been instrumenting the LHC far-forward region since the begin of Run III and reported **evidence for LHC neutrinos** (March 2023)

PHYSICAL REVIEW LETTERS **131,** 031801 (2023)

Editors' Suggestion | Featured in Physics

First Direct Observation of Collider Neutrinos with FASER at the LHC

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of 35.4 fb^{-1} using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

DOI: 10.1103/PhysRevLett.131.031801

PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

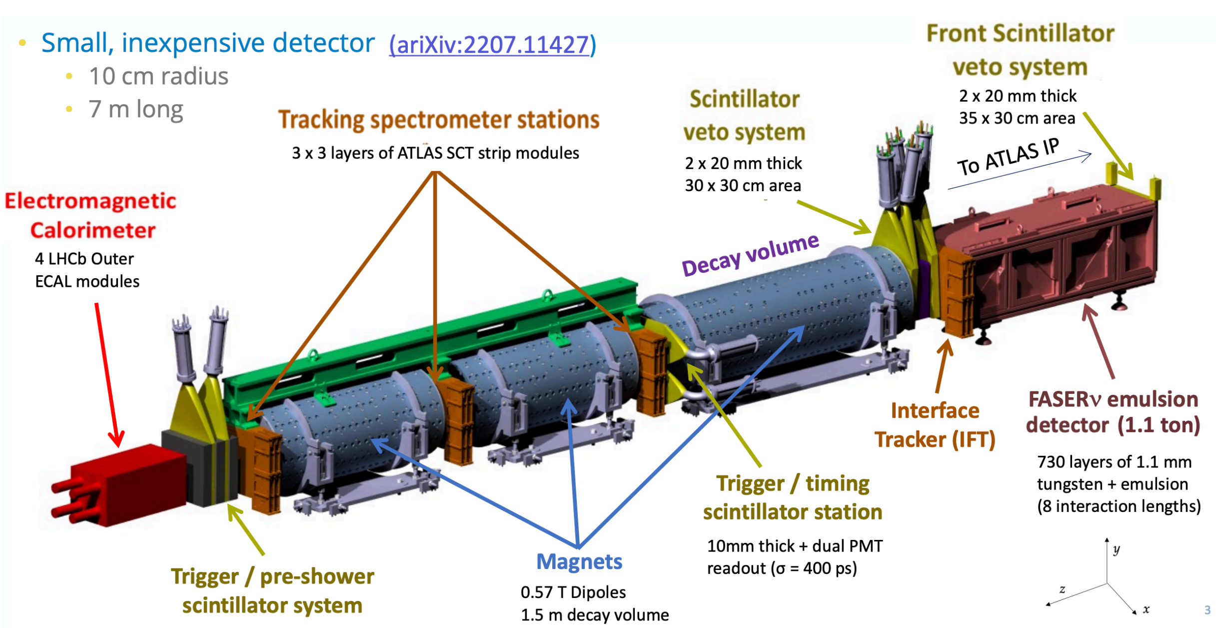
Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

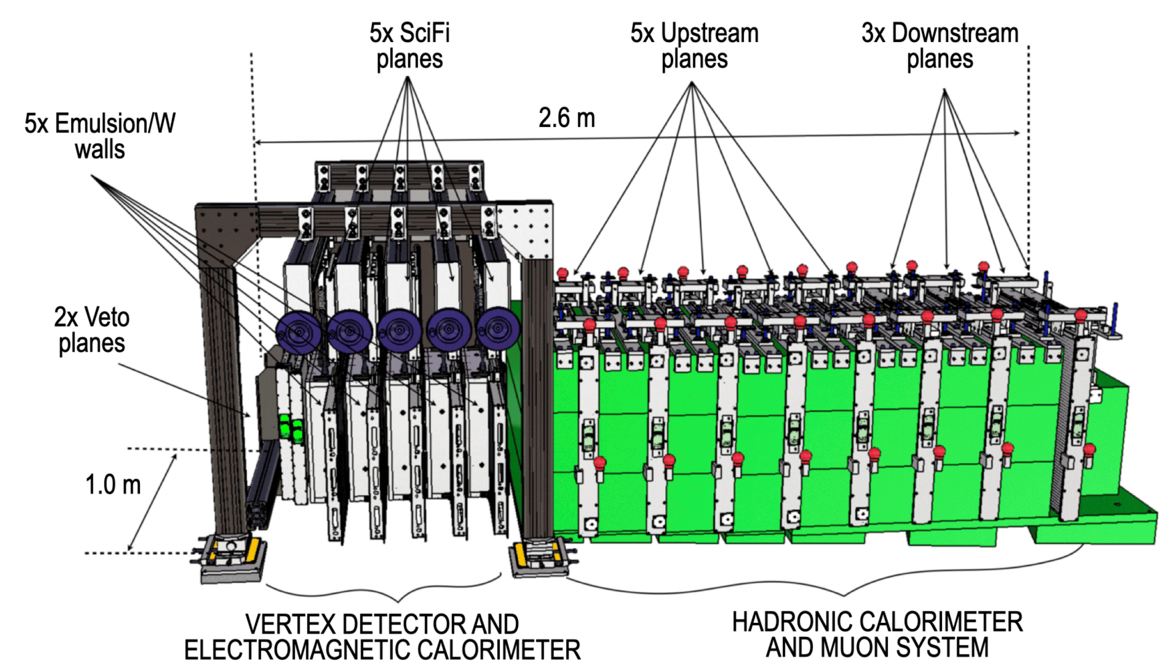
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_μ interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed ν_μ signal.

DOI: 10.1103/PhysRevLett.131.031802

153 neutrinos detected, 151± 41 expected

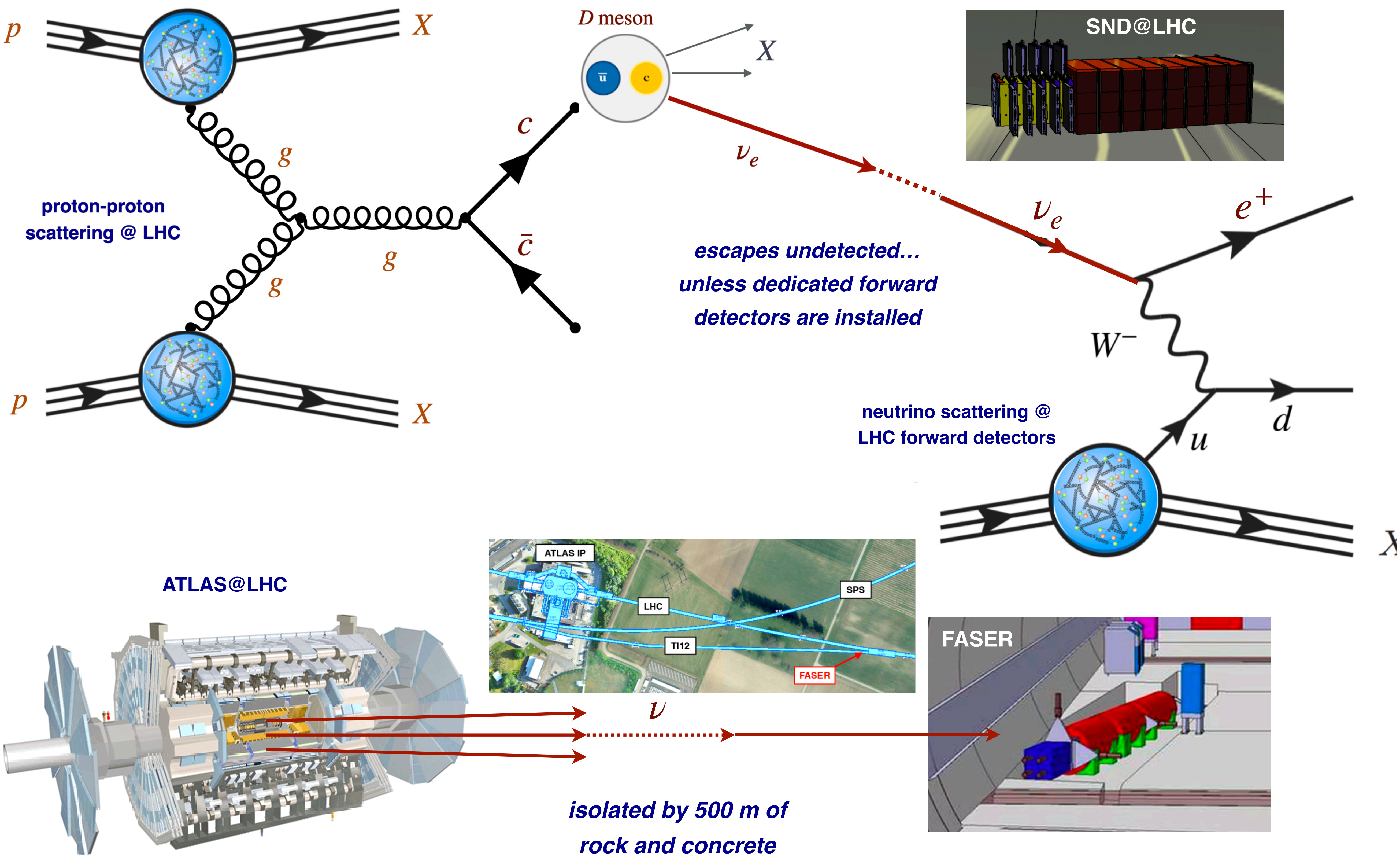


8 neutrinos detected, 4 expected

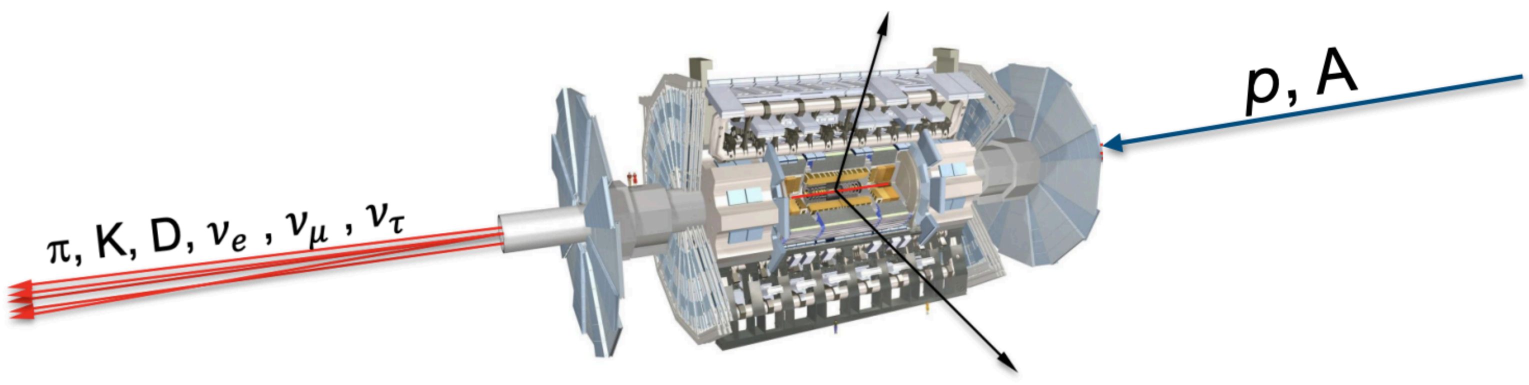


Now is the time to start exploiting their physics potential

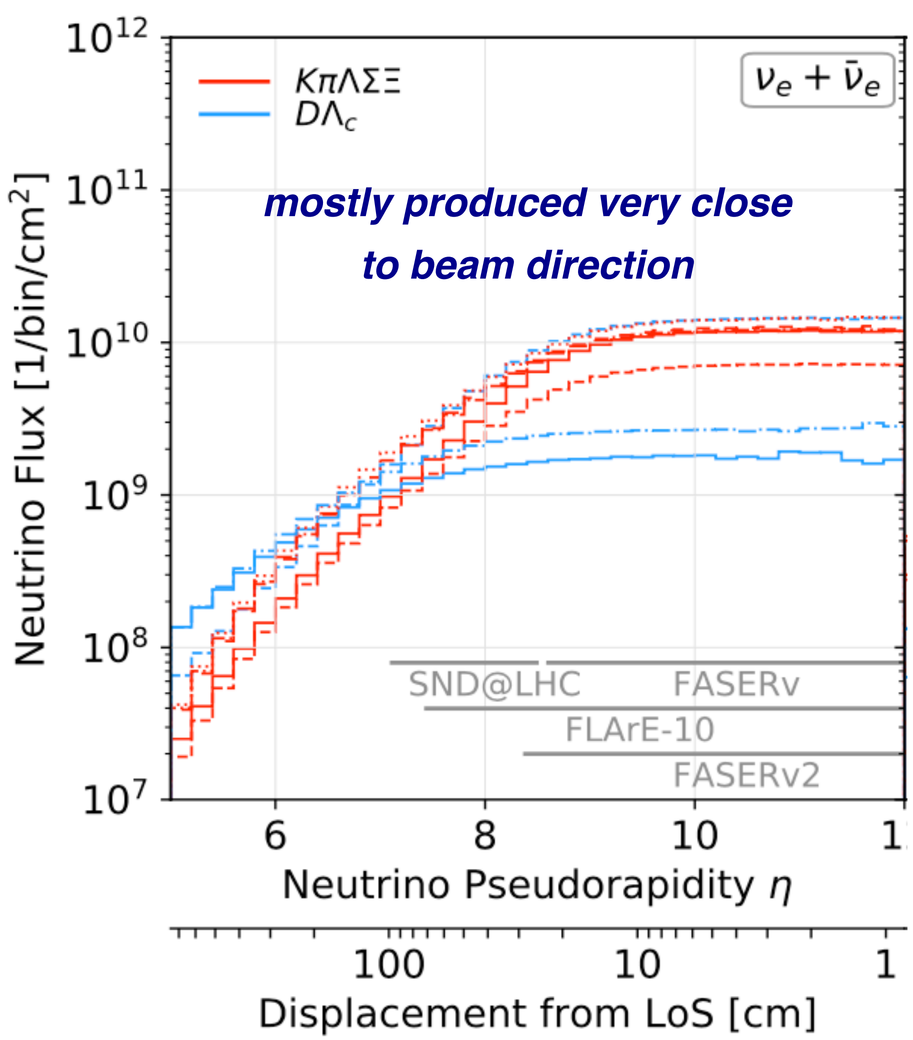
Neutrinos at the LHC

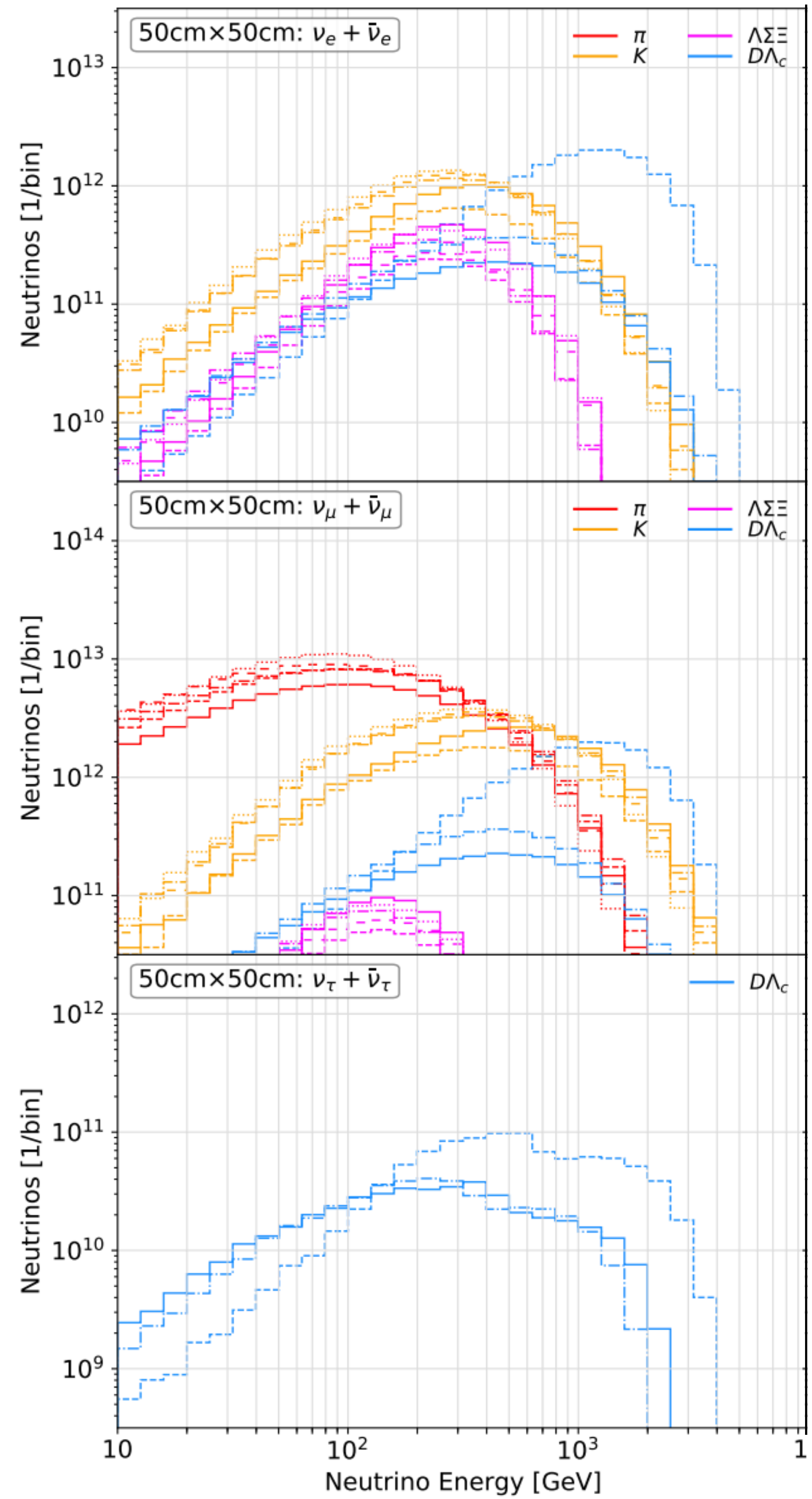


Neutrinos at the LHC



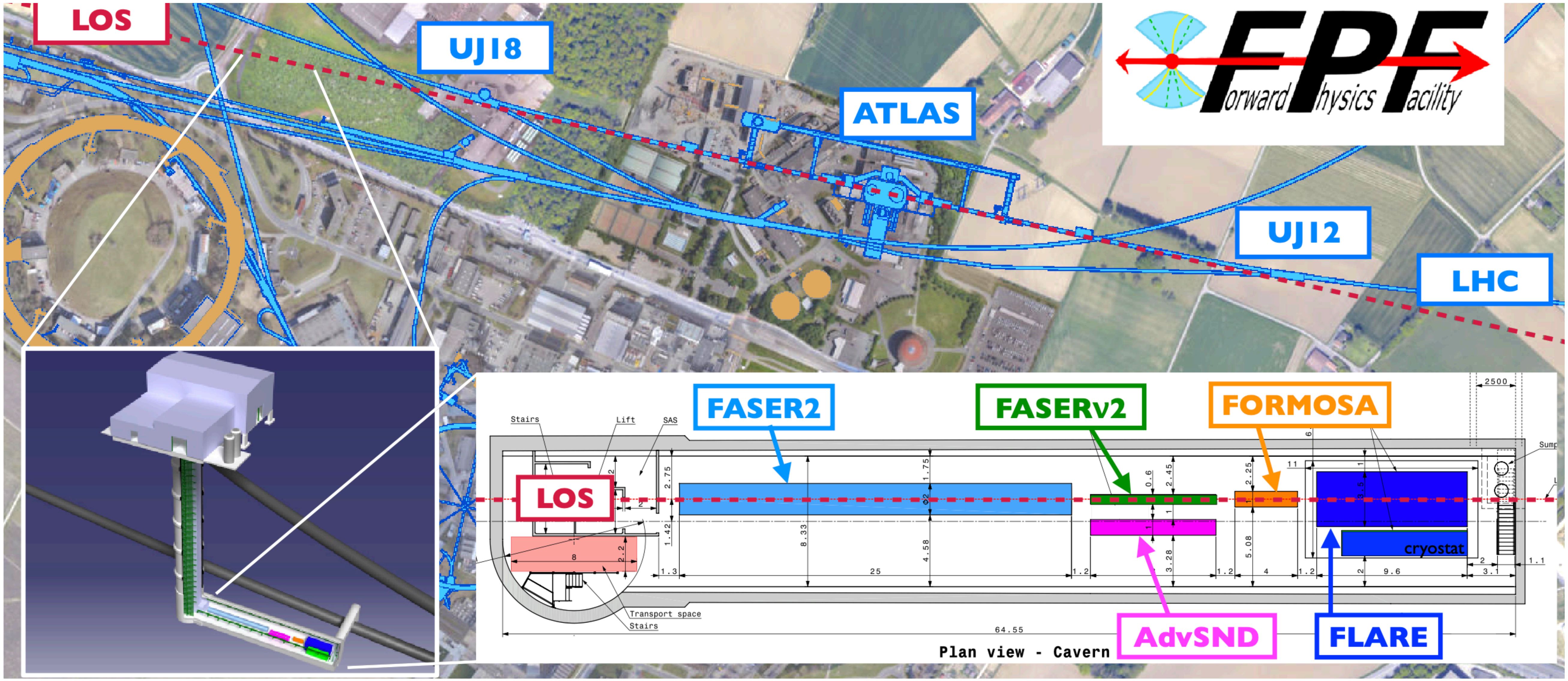
- **electron neutrinos** mostly from *D*-meson decays above 500 GeV, below it mostly from kaon decays
- **muon neutrino** flux dominated by pion & kaon decays
- **tau neutrinos** entirely from D-meson decays





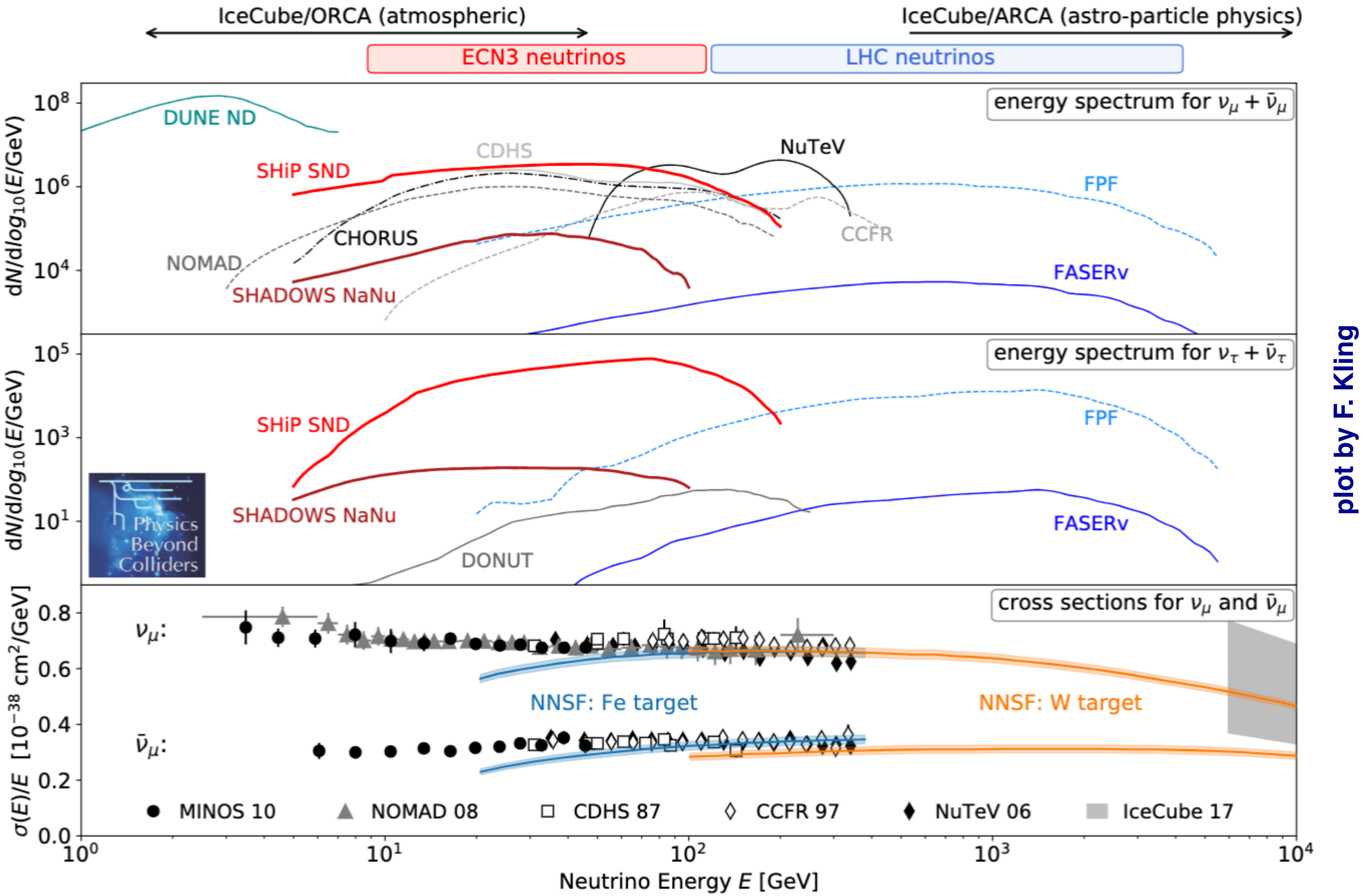
The Forward Physics Facility

A proposed new CERN facility to achieve the full potential of **LHC far-forward physics**



- Complementary suite of **far-forward experiments,** operating **concurrently with the HL-LHC**
- Start **civil engineering during LS3** or shortly thereafter, to maximise overlap with HL-LHC
- Positive outcome of **ongoing site investigation** studies (geological drill down to the cavern depth)

Physics with LHC neutrinos

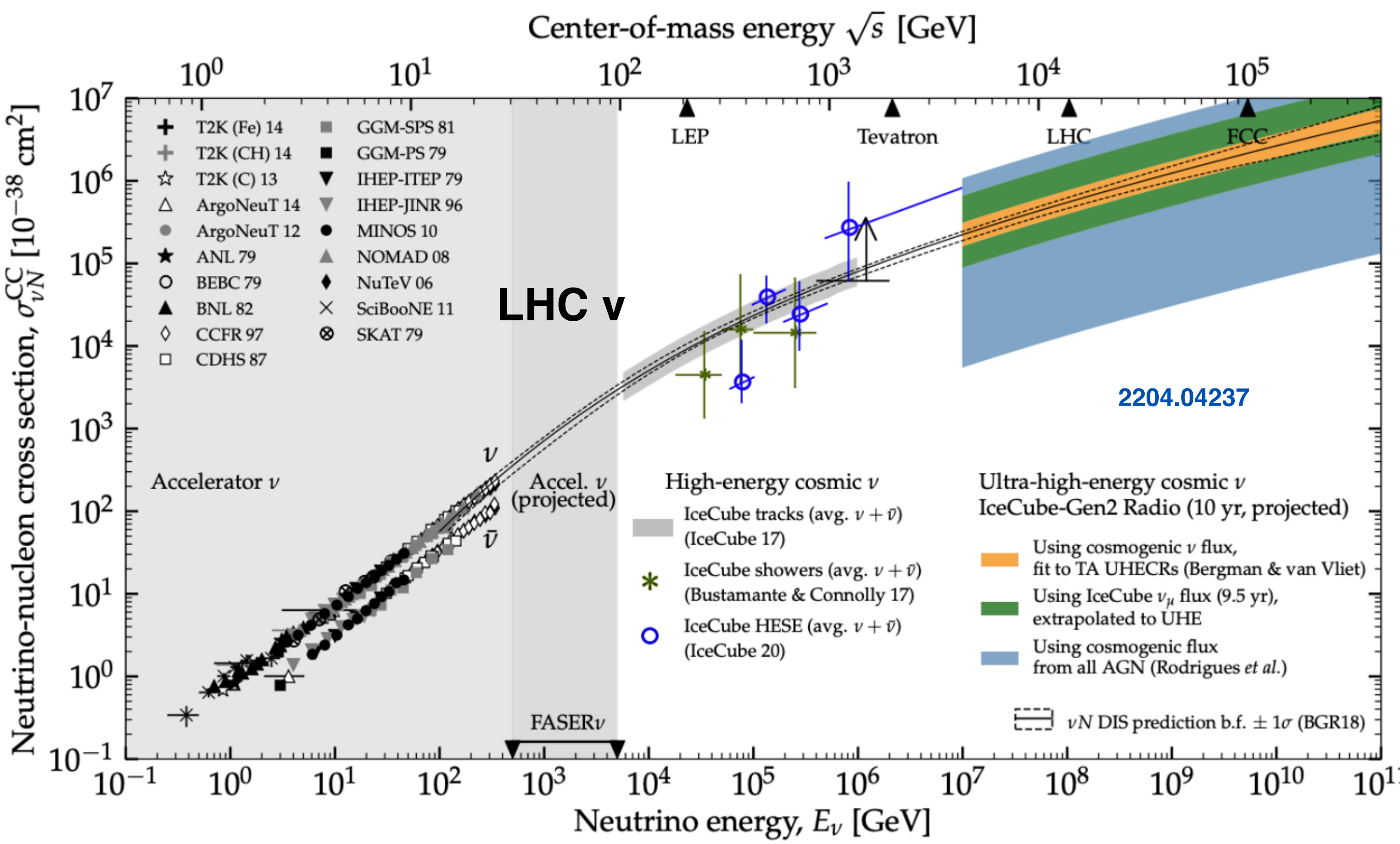


unique coverage of **TeV energy region**, high-statistics for **all three neutrino flavours**

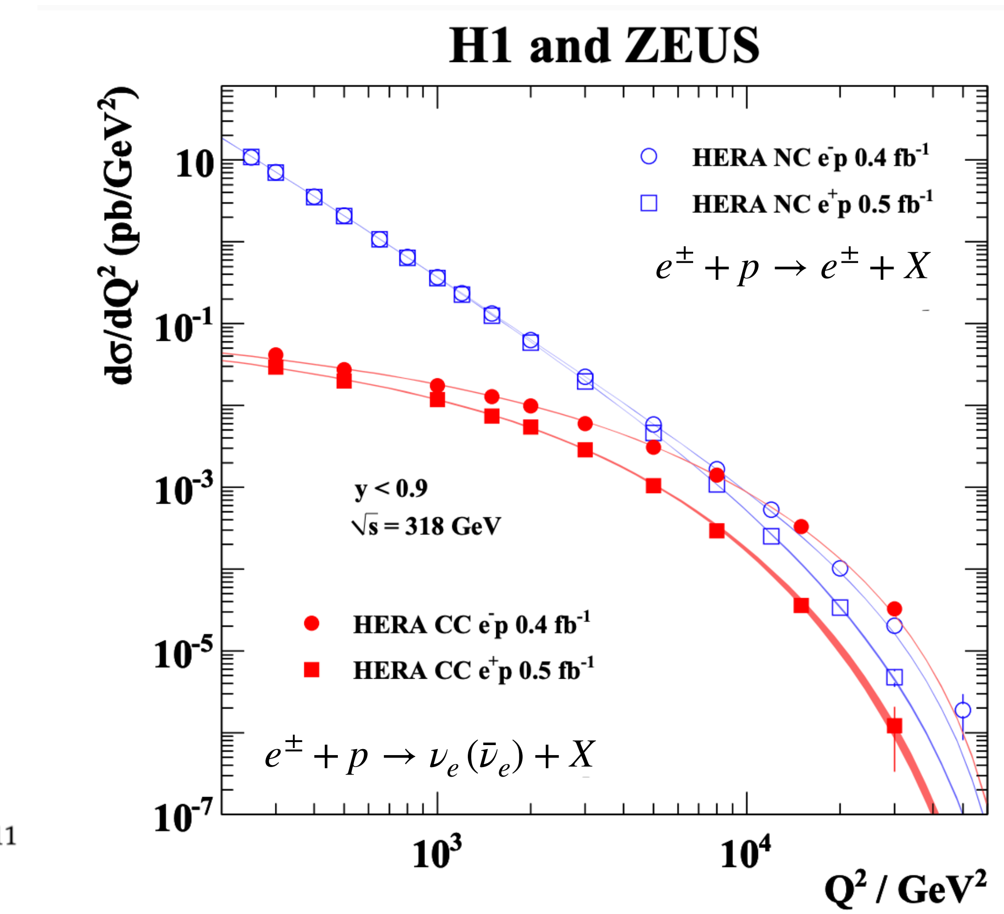
anomalous neutrino couplings, **lepton-flavour universality** tests with neutrinos

Physics with LHC neutrinos

- First measurement of **muon neutrino and tau neutrino cross-sections at the TeV**: test **lepton flavour universality,** search for anomalous interactions (*e.g.* in EFT framework)



LHC neutrinos cover unexplored gap in neutrino interactions



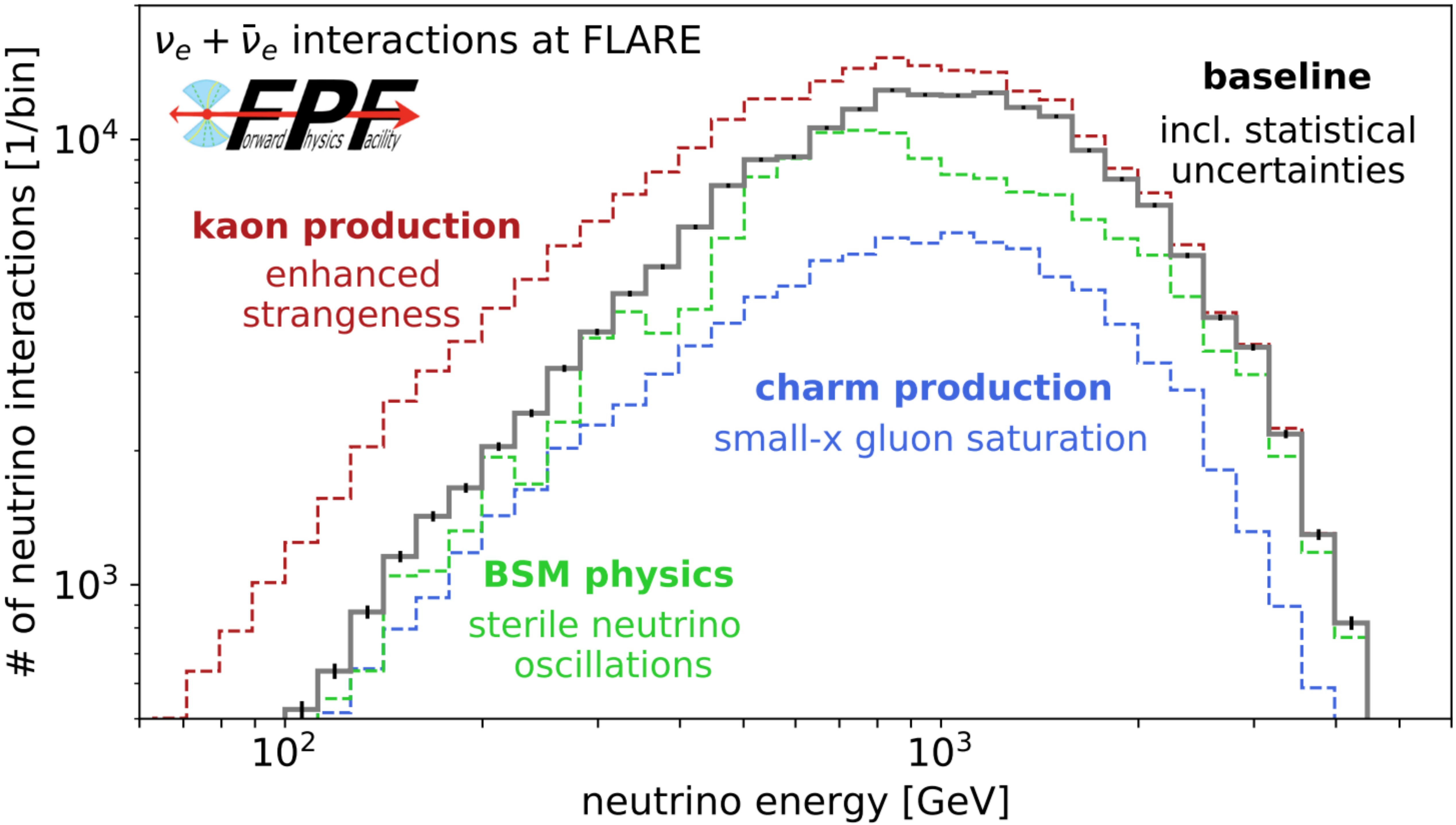
Indirect HERA constraints restricted to electron neutrinos, cross-sect measured at the 15% level at TeV energies

- **Largest sample of tau neutrinos**, explore with exquisite precision **worst known particle of the SM**

Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Thousands of tau neutrino events expected, current world sample being O(10)

Physics with LHC neutrinos



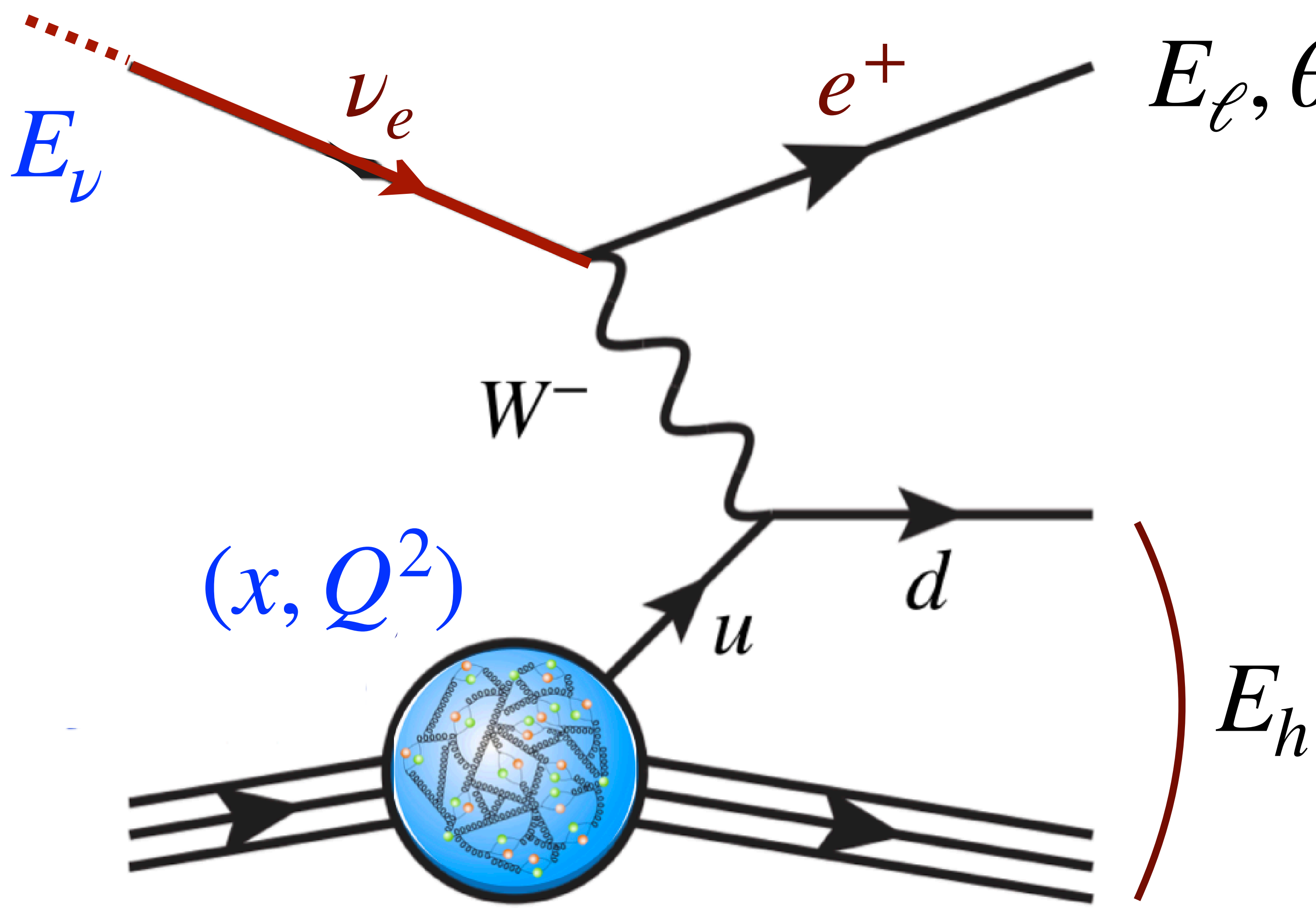
- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Provide a laboratory validation of **muon puzzle** predating **cosmic ray physics**
- New channels for **BSM searches** e.g. via sterile neutrino oscillations

The LHC as a Neutrino-Ion Collider

J. M. Cruz-Martinez, M. Fieg, T. Giani, P. Krack, T. Makela, T. Rabemananjara, and J. Rojo, ***arXiv:2309.09581***

Neutrino DIS at the LHC

- Neutrino **deep-inelastic scattering** is a powerful probe of the quark & gluon structure of hadrons



Measuring outgoing **charged lepton** and **hadronic energy** specifies initial state of the collision

$$
\begin{aligned}
E_\nu &= E_h + E_\ell\,, \\
Q^2 &= 4(E_h + E_\ell)E_\ell \sin^2(\theta_\ell/2)\,, \\
x &= \frac{4(E_h + E_\ell)E_\ell \sin^2(\theta_\ell/2)}{2m_N E_h}
\end{aligned}
$$

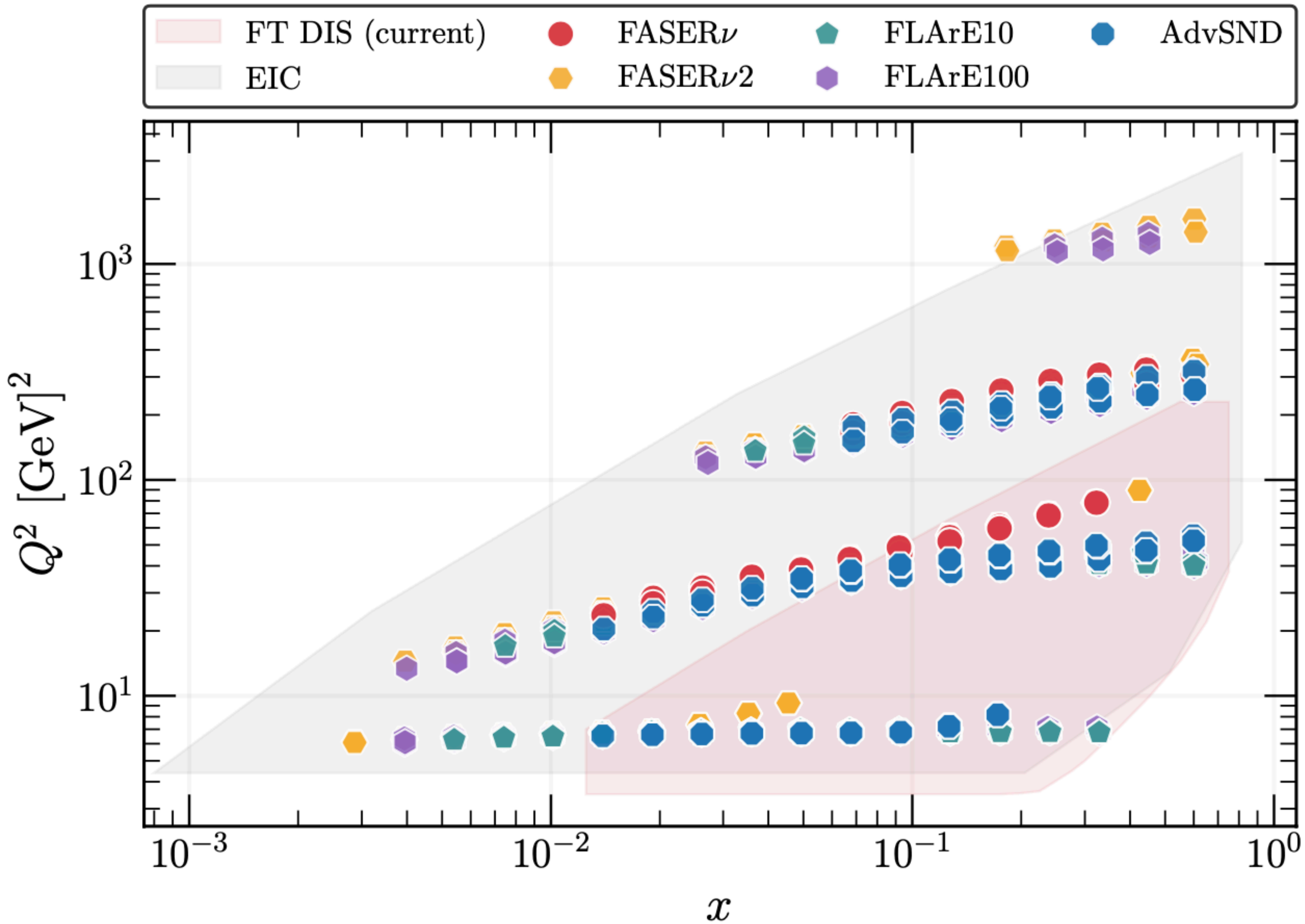
$$\sigma_{\nu p \to e^+ X}(E_\nu) = \tilde{\sigma}_{\nu u \to d} \otimes u(x, Q^2)$$

- $\sigma_{\nu p \to e^+ X}(E_\nu)$ → neutrino-proton scattering rate
- $\tilde{\sigma}_{\nu u \to d}$ → partonic cross-section
- $u(x, Q^2)$ → up-quark content int the proton

Unique information on **quark & antiquark flavour separation**

key for core LHC theory predictions

Neutrino DIS at the LHC



x: momentum fraction of quarks/gluons in the proton

Q²: momentum transfer from incoming lepton

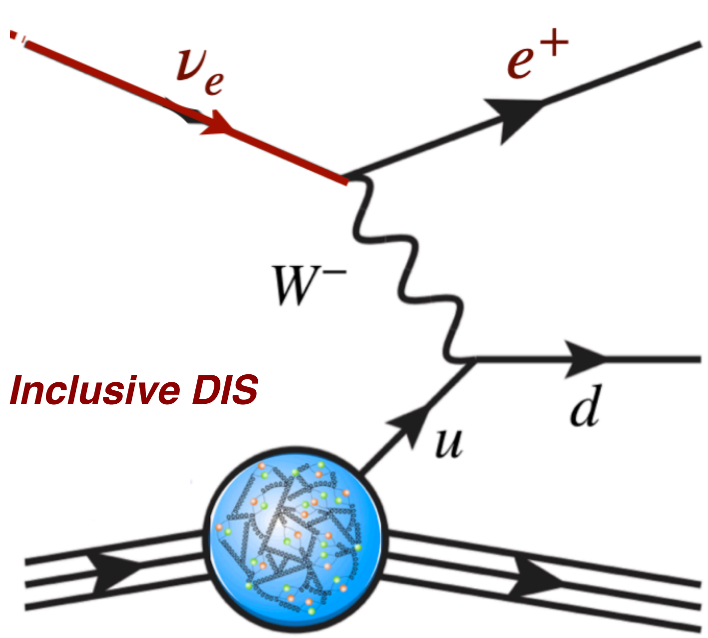
- Continue highly succesful program of neutrino **DIS experiments @ CERN**
- **Expand kinematic coverage** of available experiments by an order of magnitude in *x* and *Q²*
- Charged-current counterpart of the **Electron-Ion Collider** covering same region of phase space

Extend CERN infrastructure with an (effective) Neutrino-Ion Collider by ``recycling'' an otherwise discarded beam

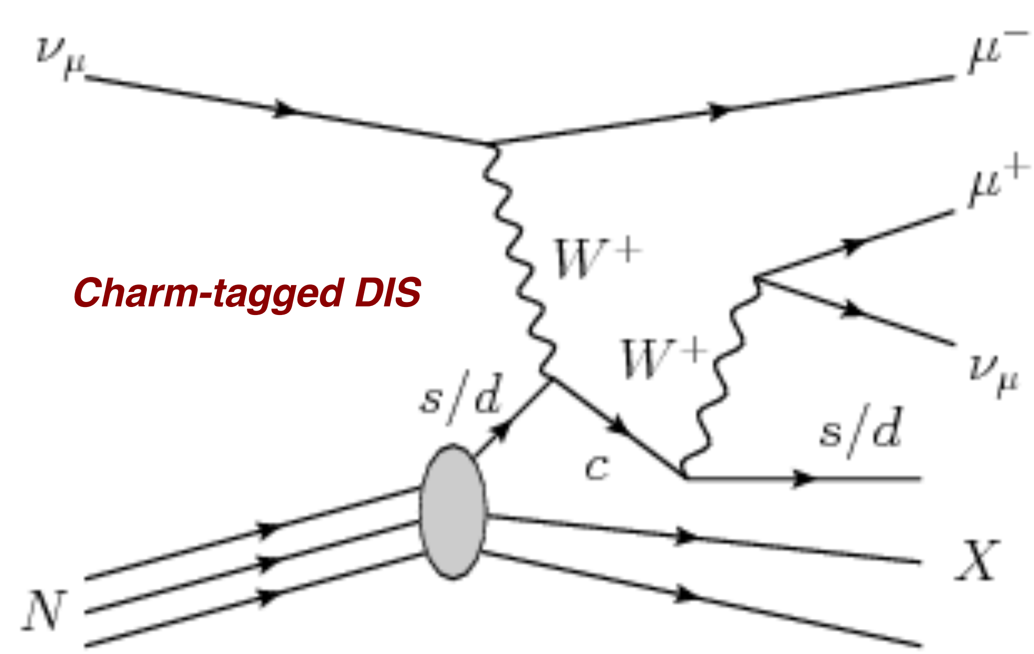
Neutrino DIS at the LHC

Integrated event rates for DIS kinematics for **inclusive (charm-tagged)** production

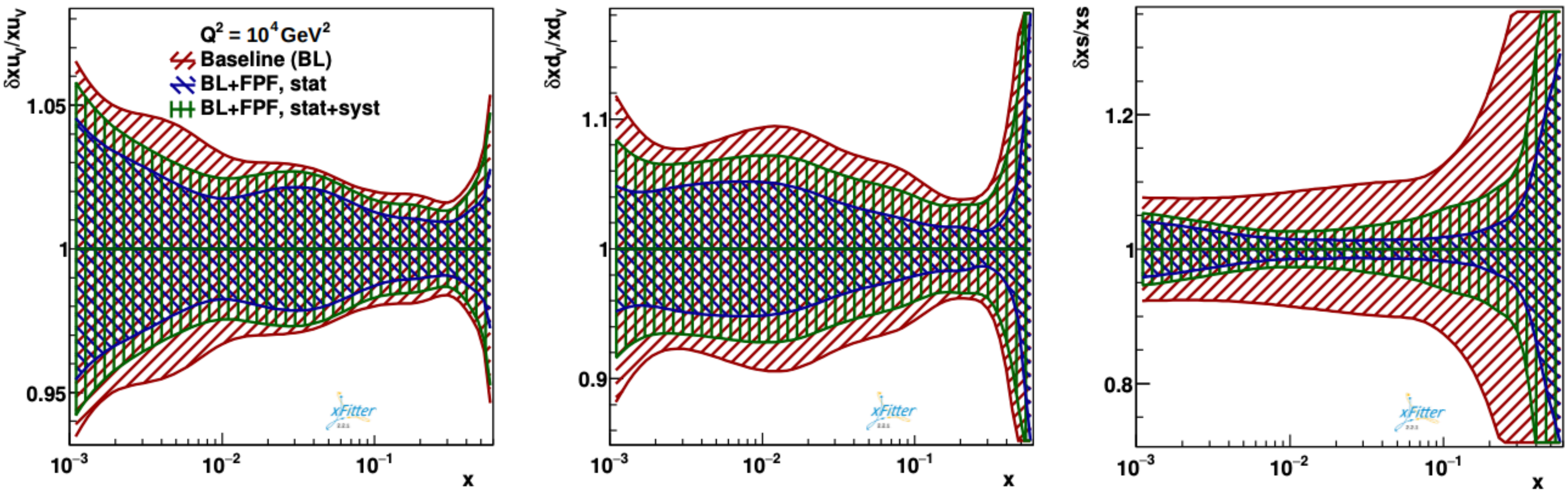
Detector	N_{ν_e}	$N_{\bar{\nu}_e}$	$N_{\nu_e}+N_{\bar{\nu}_e}$	N_{ν_μ}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu}+N_{\bar{\nu}_\mu}$
FASERν	400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	180 (22)	76 (11)	260 (32)	510 (59)	190 (25)	700 (83)
FASERν2	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)	133k (23k)	510k (76k)
AdvSND-far	12k (1.5k)	5.5k (0.82k)	18k (2.3k)	40k (4.8k)	16k (2.2k)	56k (7k)
FLArE10	44k (5.5k)	20k (3.0k)	64k (8.5k)	76k (10k)	38k (5.0k)	110k (15k)
FLArE100	290k (35k)	130k (19k)	420k (54k)	440k (60k)	232k (30k)	670k (90k)



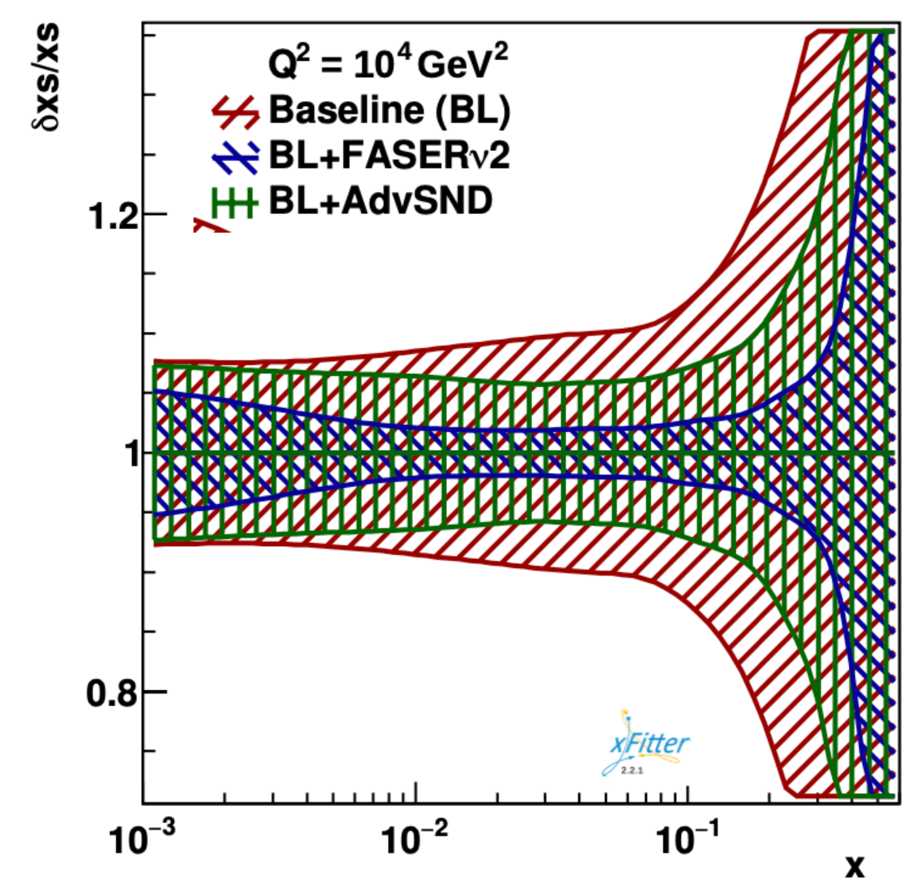
- Muon-neutrinos: **larger event rates, smaller production uncertainties**
- Current experiments limited by statistics, FPF **by systematics**
- Ultimate reach achieved by **combining all experiments**



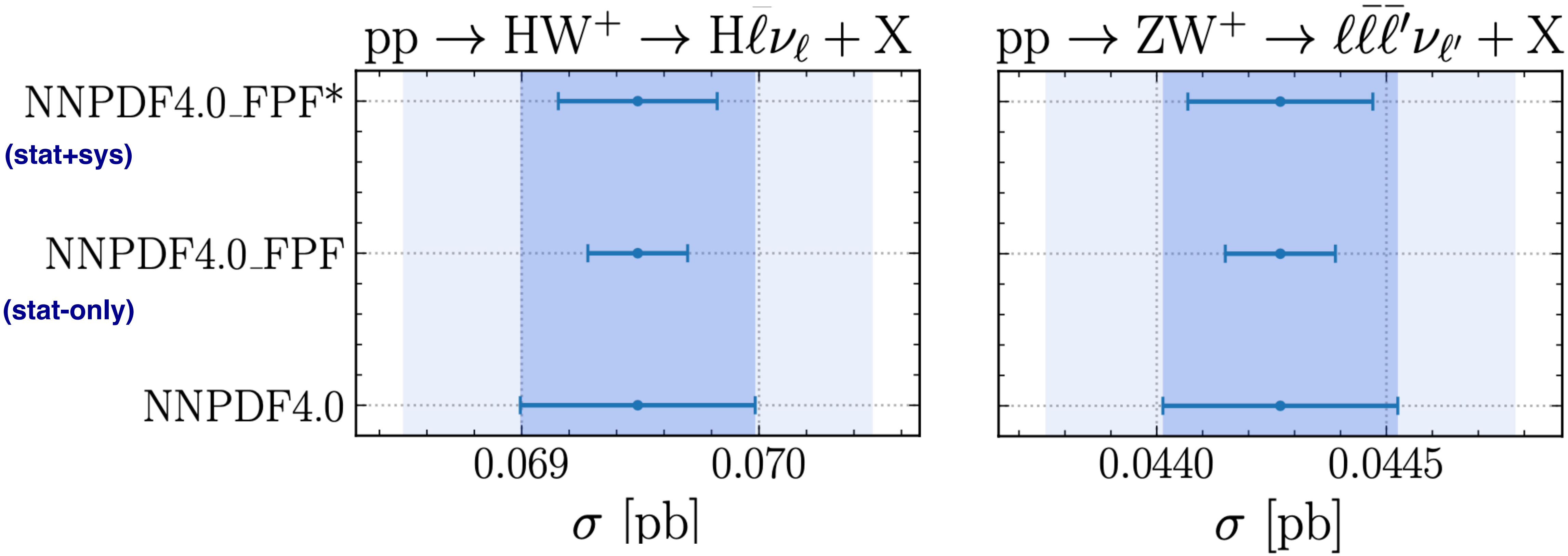
PDF constraints from LHC neutrinos

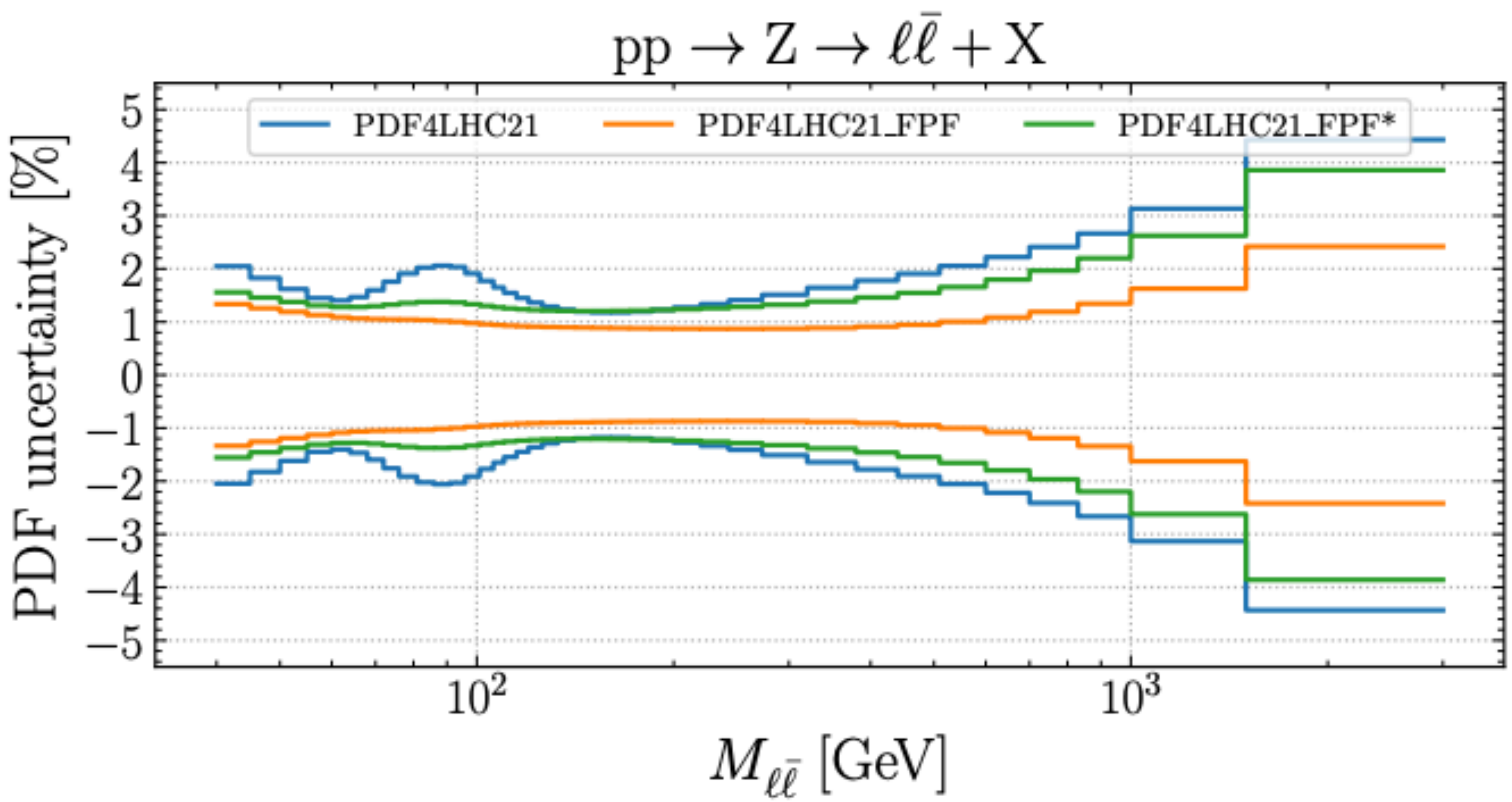


- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics
- Quantitative analysis **guiding detector design** for the FPF, highlighting complementarity between experiments



Impact at the HL-LHC





- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)

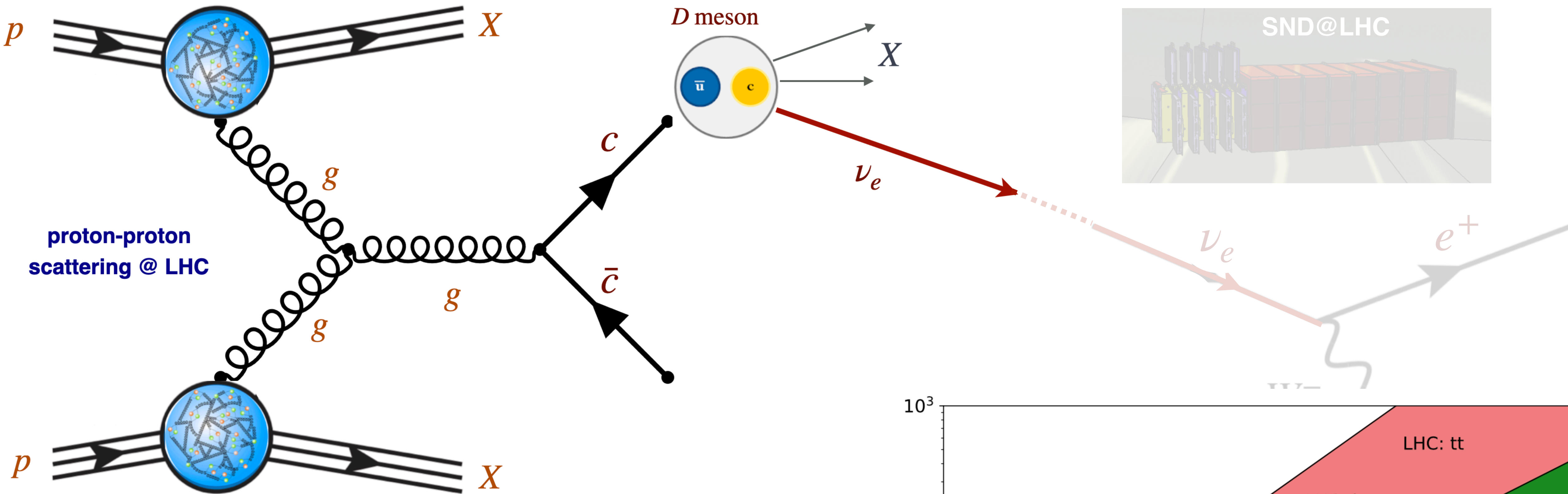
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

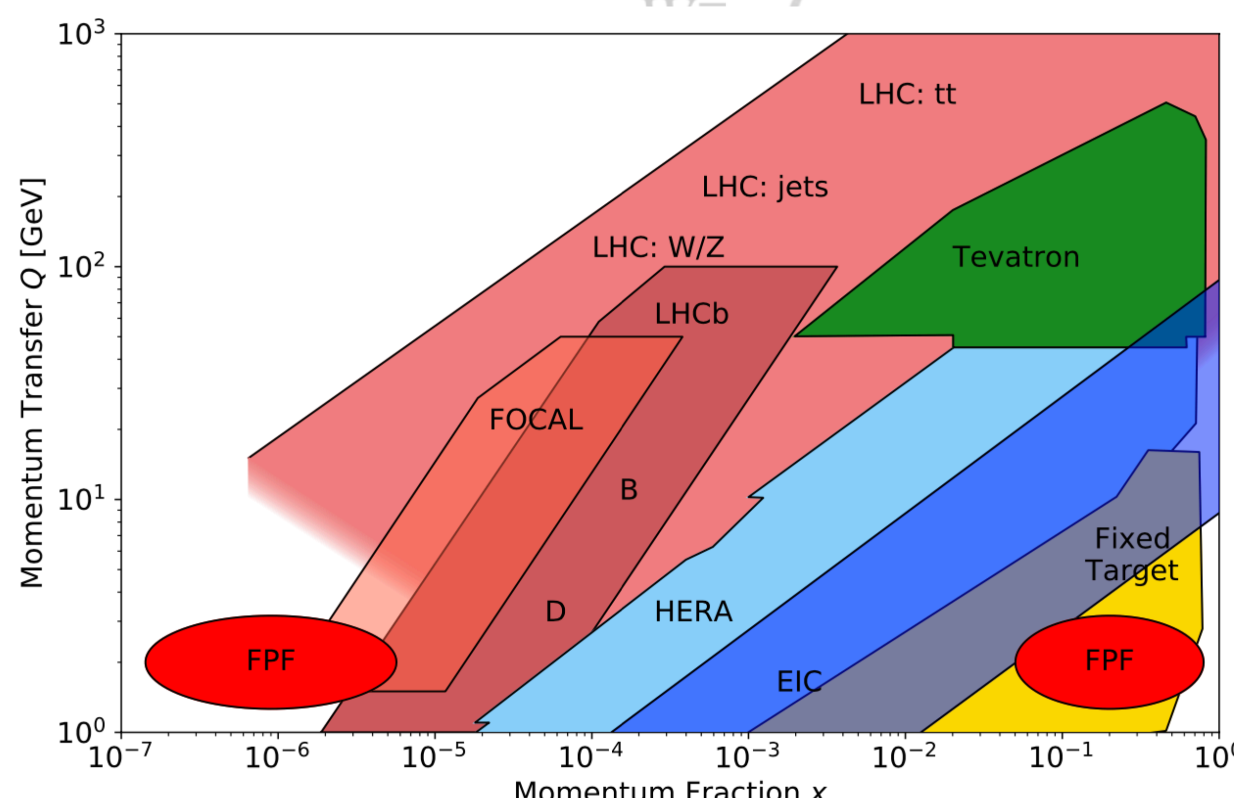
e.g. high-mass dilepton resonances

Fully independent constraints on proton structure, crucial to disentangle possible BSM signatures in high p_T data

Probing small-x QCD with far-forward neutrinos

LHC neutrinos and small-x QCD





small-x gluon

large-x

QCD in Neutrino Production

- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
- Forward light hadron production & cosmic ray modelling

Relevant for **FCC-pp, UHE neutrinos, cosmic rays**

LHC neutrinos and small-x QCD

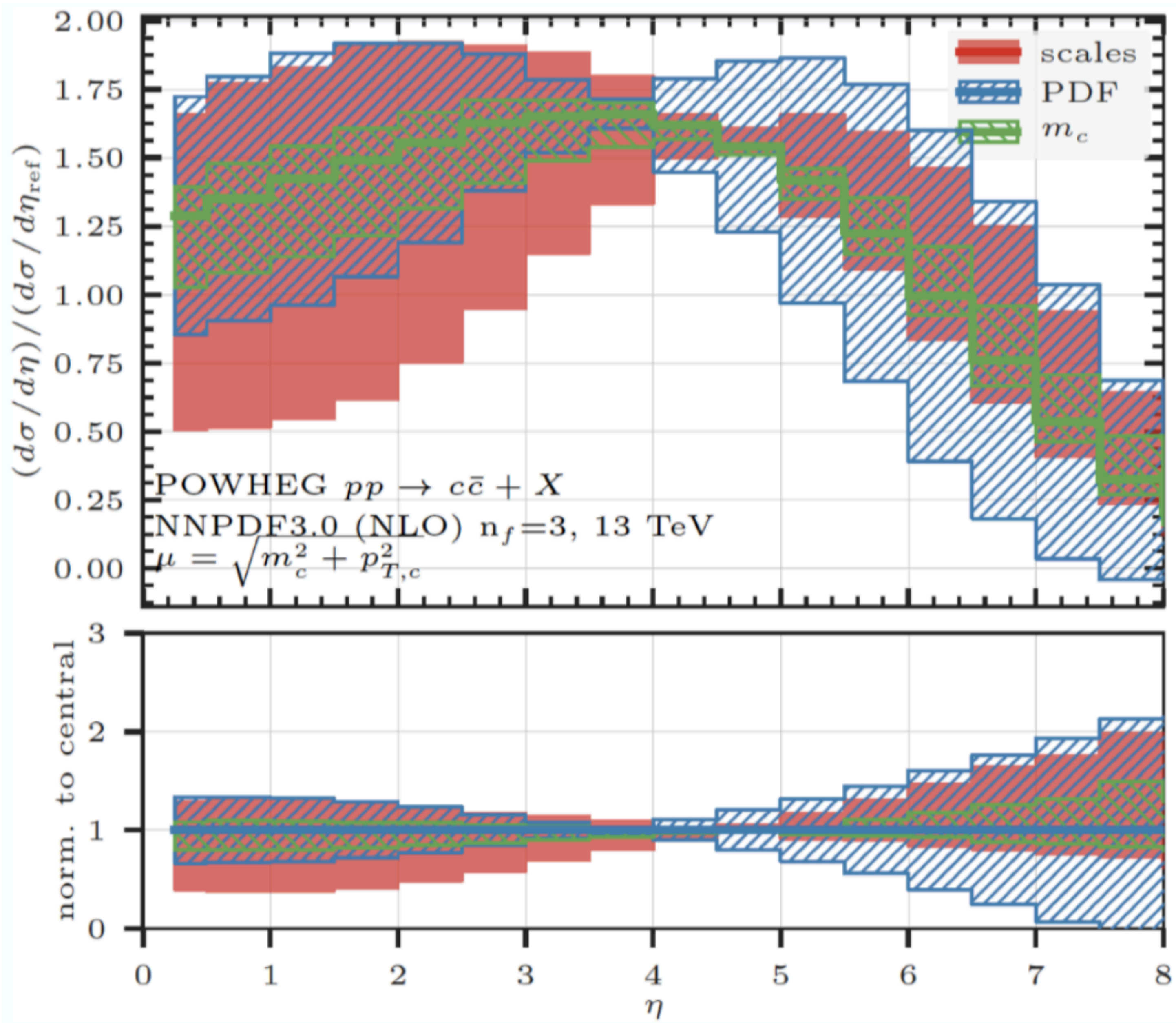
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\hat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

Extract from measured neutrino fluxes

Constrain from LHC neutrino data

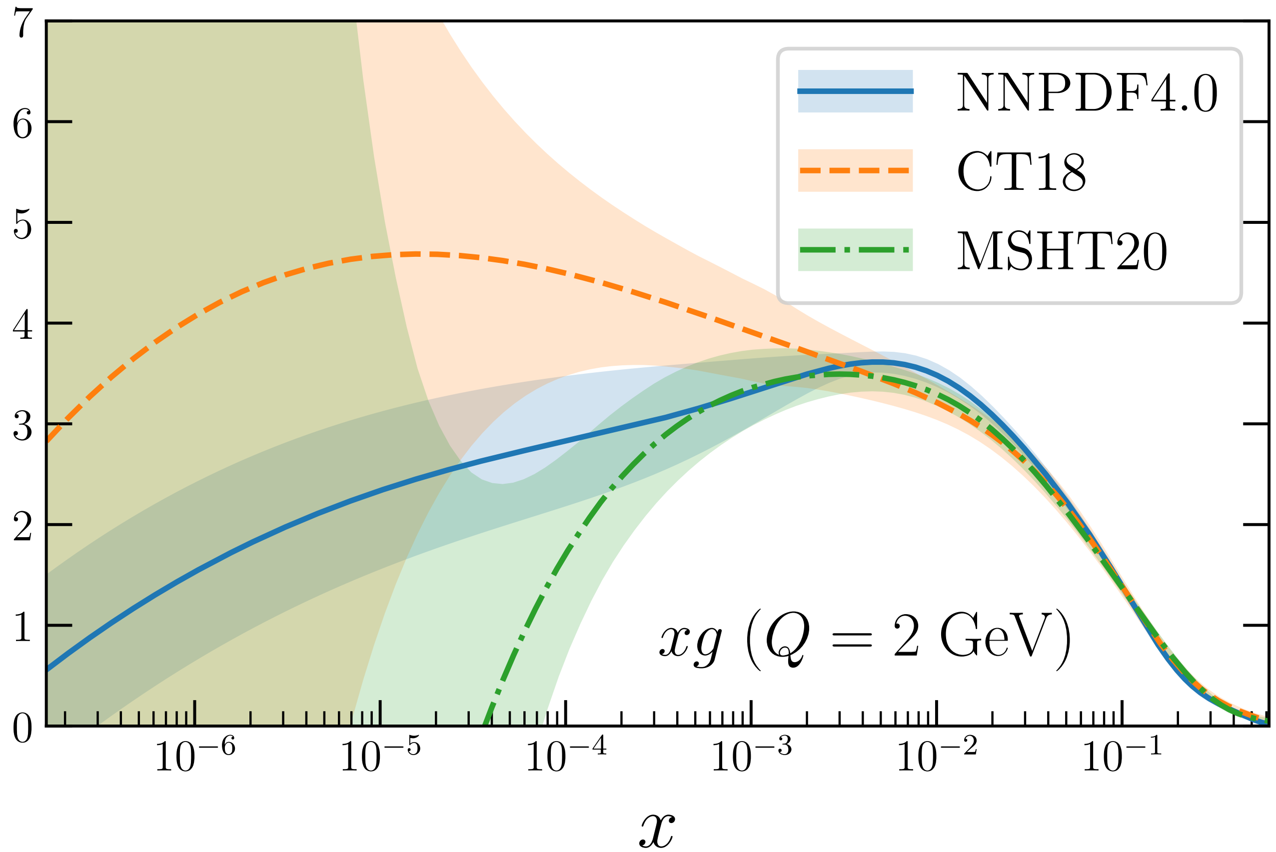
QCD prediction: NLO + PS large theory uncertainties

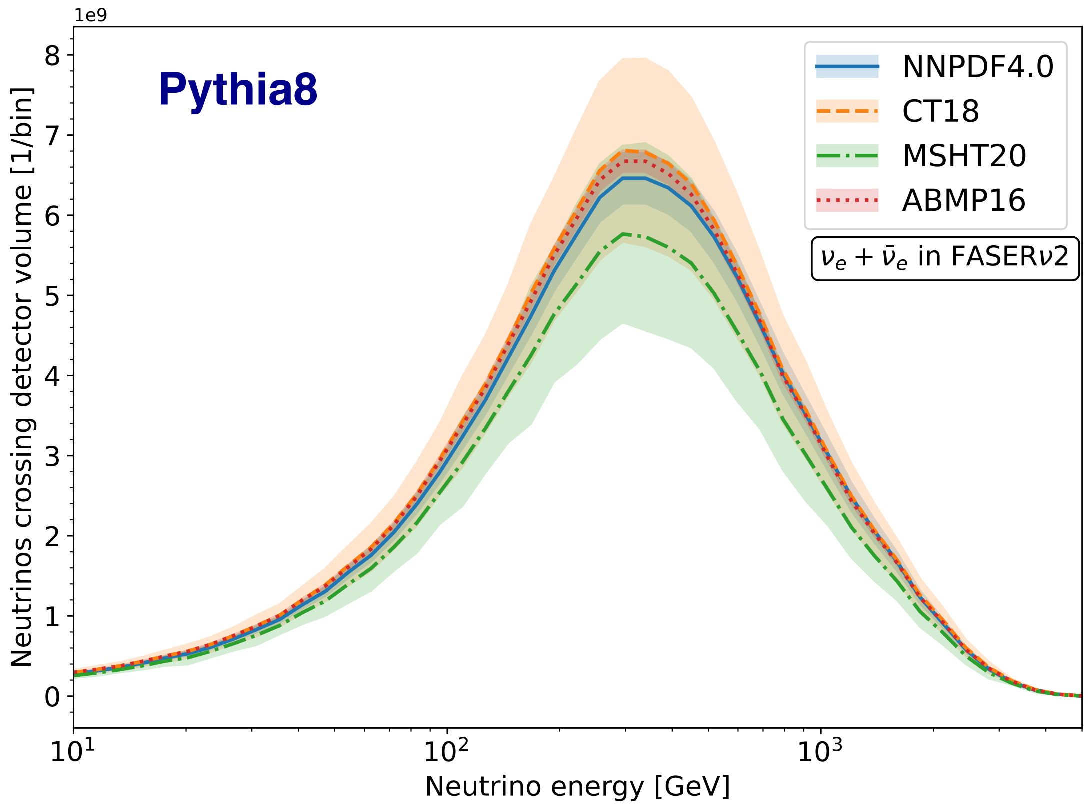
QCD prediction/models + non-perturbative physics



- **Only laboratory experiment** which can inform both UHE neutrino interactions, cosmic ray collisions, and FCC-pp cross-sections
- Challenges in **modelling forward charm production**: QCD corrections, fragmentation, interaction with beam remnants ….
- Requires designing observables where **theory systematics cancel out**
  - ☑ Ratios to reference rapidity bin
  - ☑ Ratios between CoM energy
  - ☑ Ratios between correlated observables

LHC neutrinos and small-x QCD





- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially) cancel out

$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)},$$

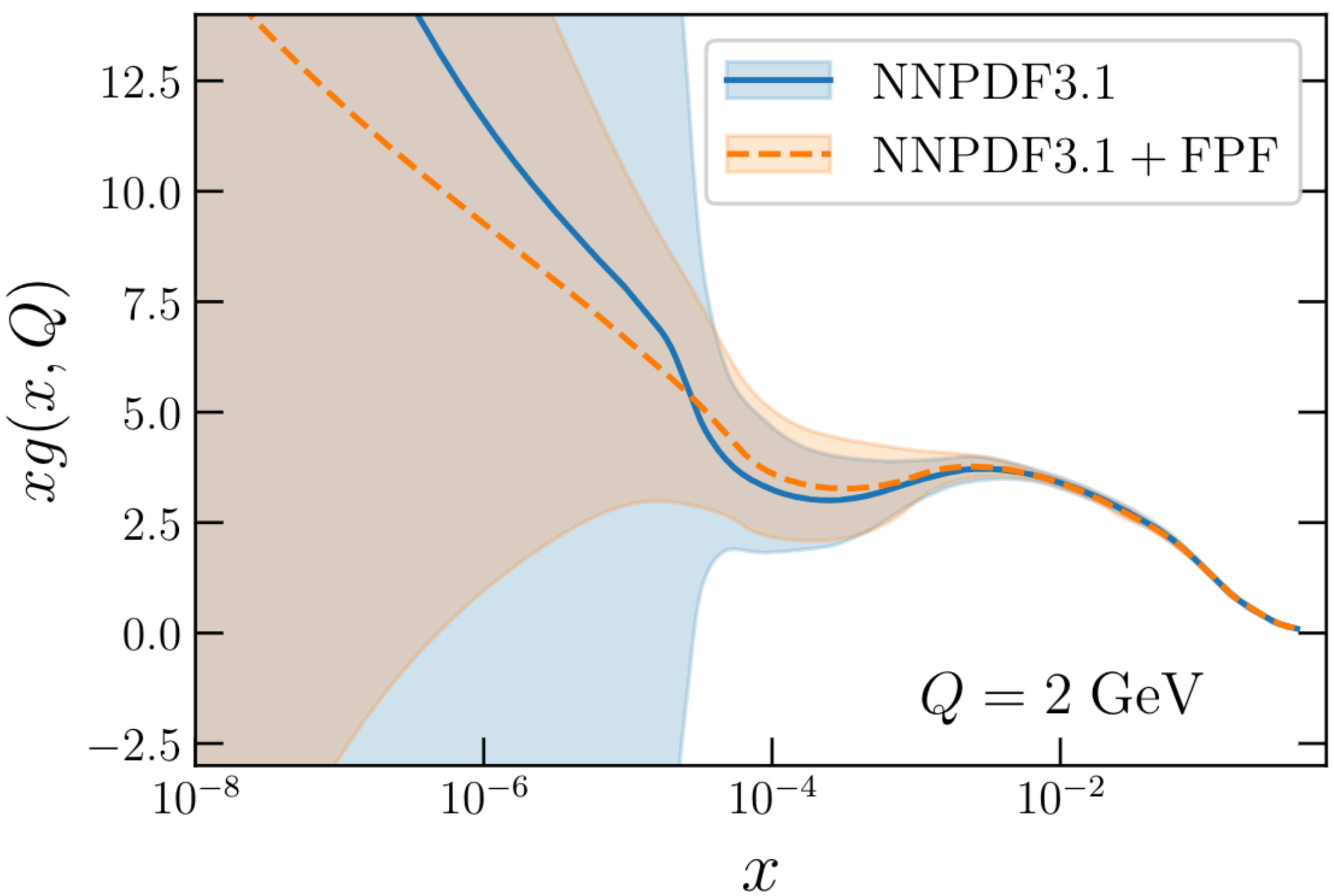
$$R^{\nu_e}_{\mathrm{exp}}(E_\nu) = \frac{N_{\mathrm{FASER}\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\mathrm{SND@LHC}}(\nu_e + \bar{\nu}_e; E_\nu)}$$

Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

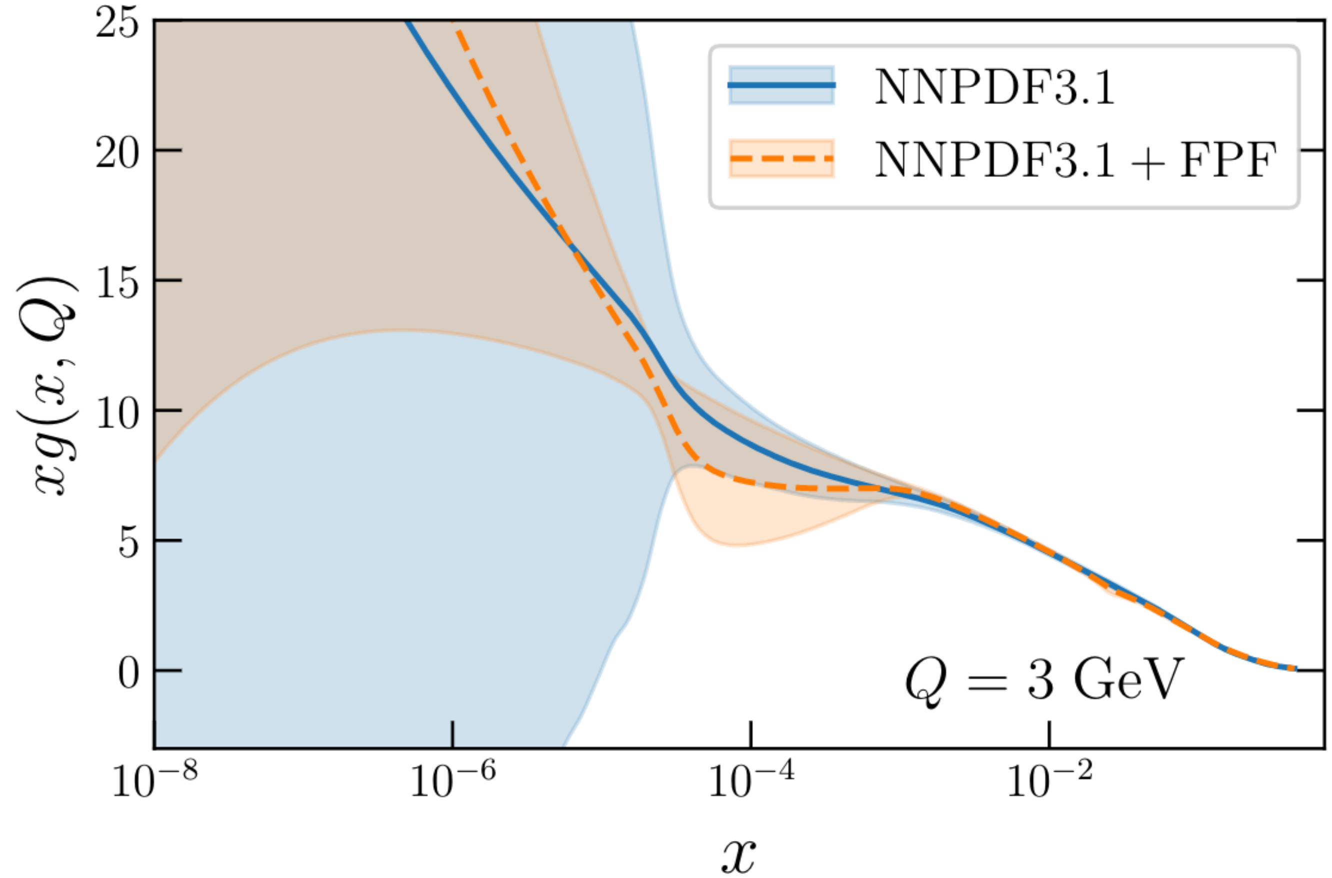
Proxy for 2D xsec differential in (energy, rapidity)

LHC neutrinos and small-x QCD

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates

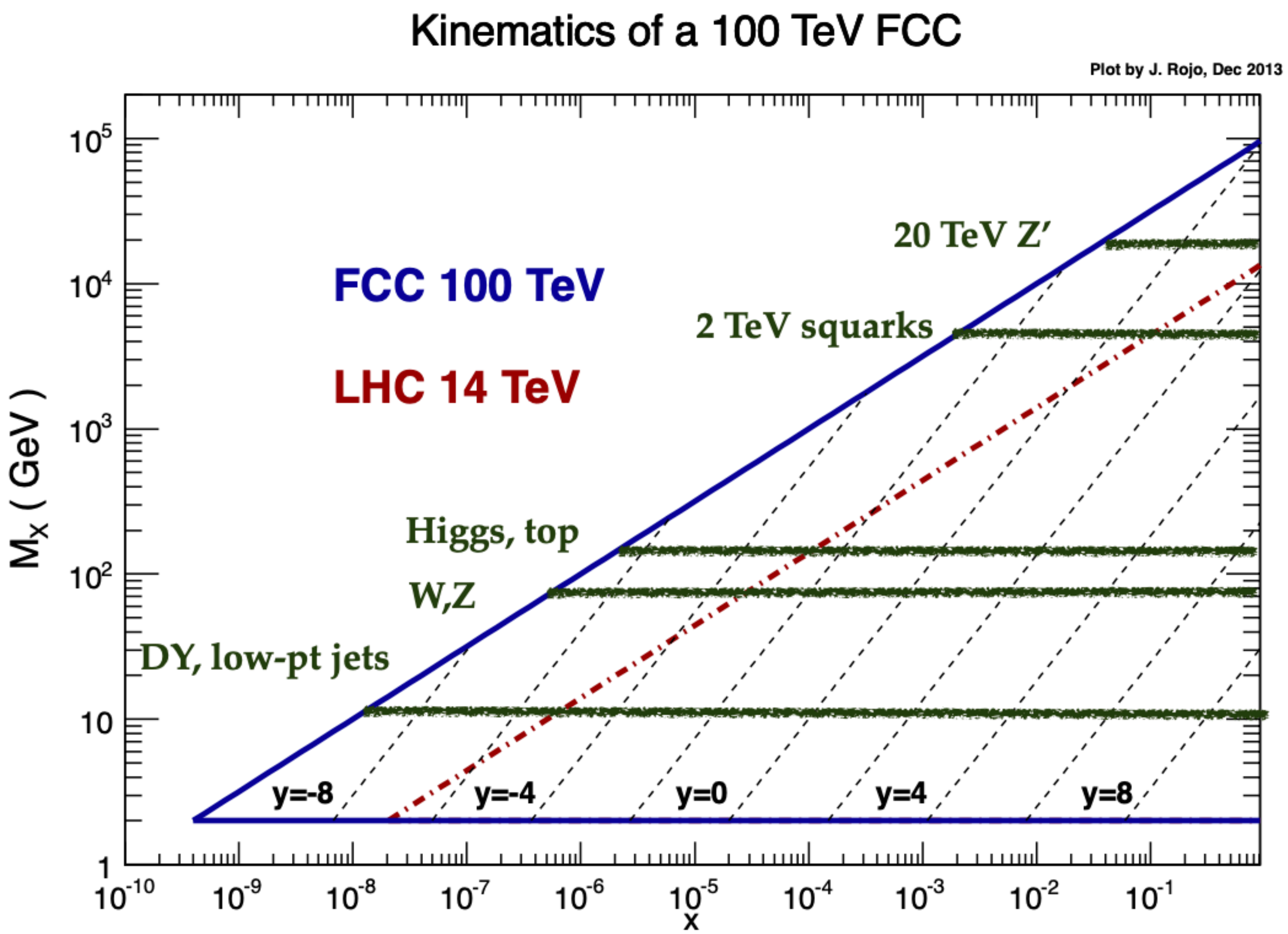


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

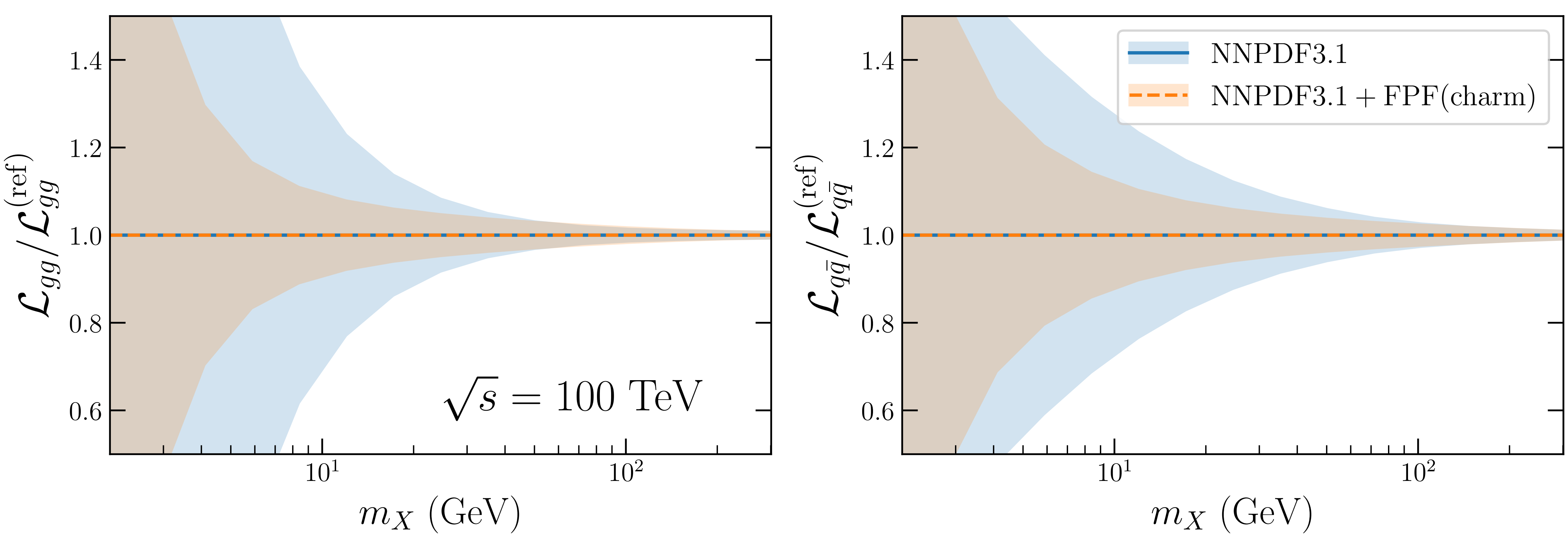
$$R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment
- These initial projections are now being extended to full-fledged simulations with state-of-the-art QCD
- Quantify impact for **UHE neutrinos** and for cross-sections at a 100 TeV proton collider

Implications for the FCC-pp



- FCC-pp would be a **small-*x* machine,** even Higgs and EWK sensitive to small-*x* QCD
- LHC neutrinos: laboratory to test **small-x QCD** for **dedicated FCC-pp physics** and simulations
- Current projections show a marked PDF error reduction on **FCC-pp cross-sections** thanks to constraints from LHC neutrinos



QCD, Neutrino, and BSM Physics Opportunities with Far-Forward Experiments at a 100 TeV Proton Collider

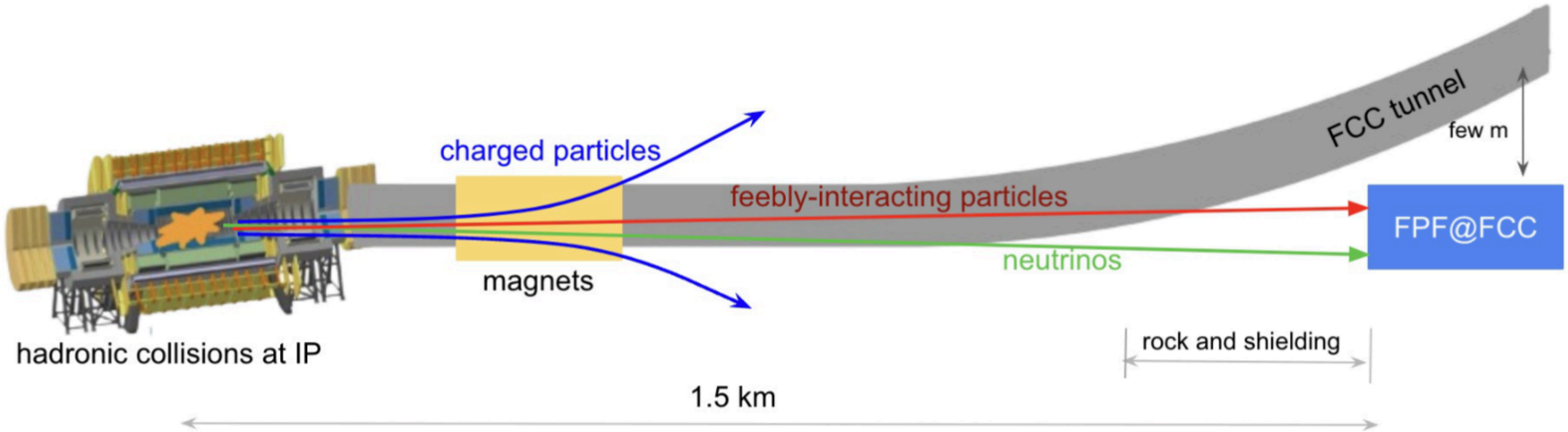
Roshan Abraham, Jyotismita Adhikary, Jonathan Feng, Max Fieg, Felix Kling, Juan Rojo, and Sebastian Trojanowski**, WIP**

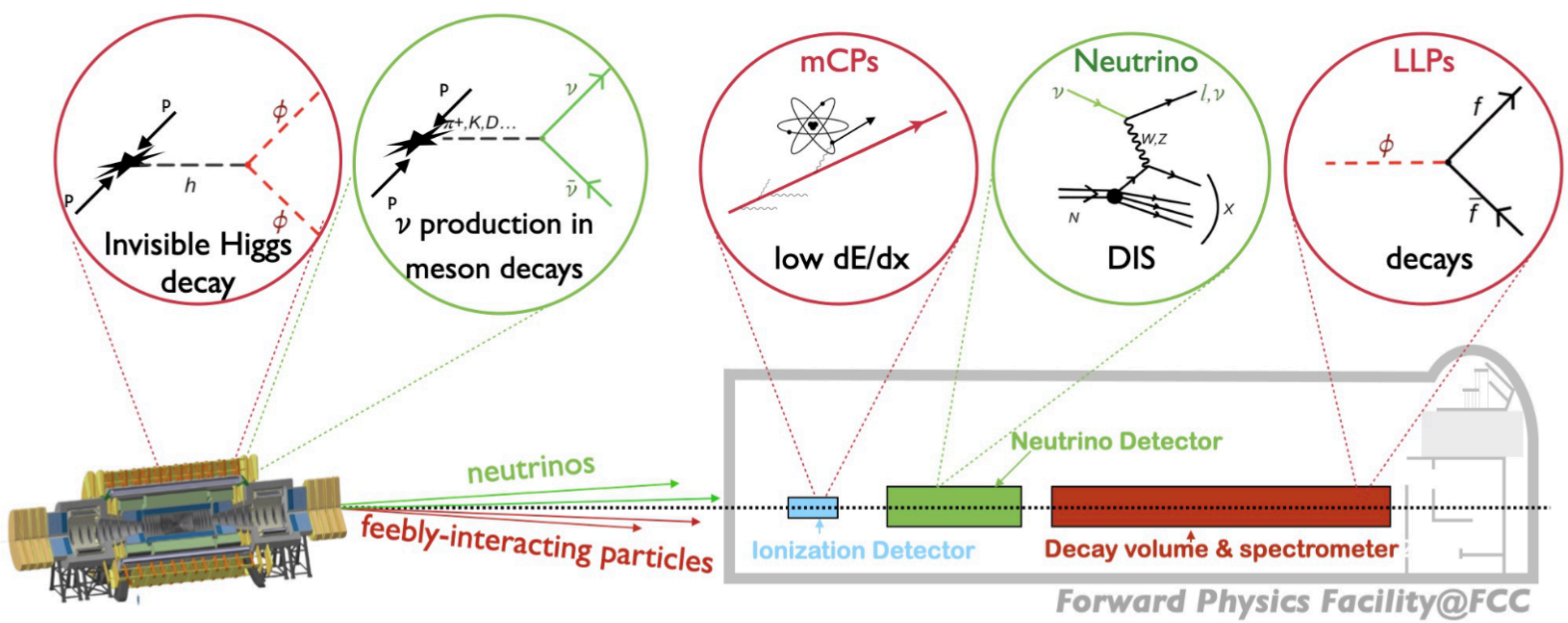
see also **Sebastian's talk** at the parallel session on Wednesday

see also **Felix Kling's talk** at the FCC BSM Physics Programme Workshop in March 2022

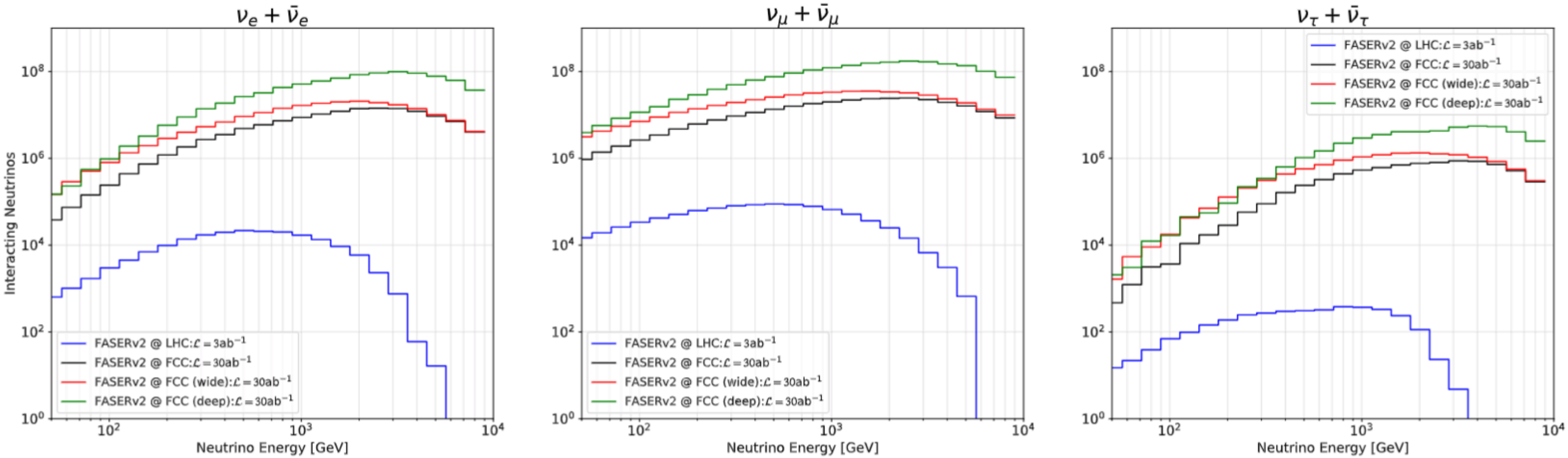
FPF@FCC

- An FPF-like suite of far-forward experiments could be **integrated in FCC design** from day one
- Benefit from *i)* higher CoM energy, *ii)* higher luminosity, *iii)* larger/better detectors & technology





Event rates

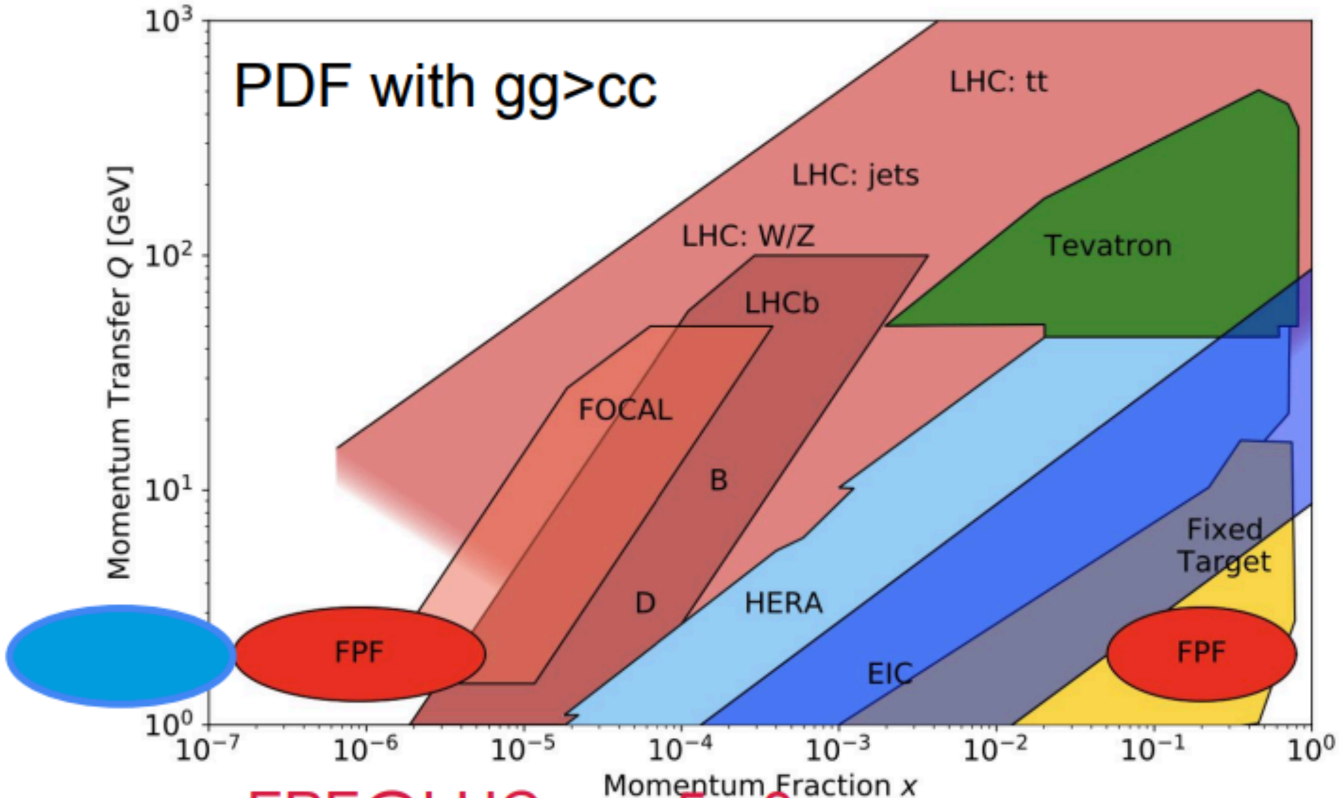


Detector	$\sqrt{s}$	$\mathcal{L}_{\text{int}}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$	$N_{\nu_\tau} + N_{\bar{\nu}_\tau}$
FASERν	13.6 TeV	150 fb^{-1}	610 (100)	1.8k (290)	
FASERν2	14 TeV	3 ab^{-1}	170k (27k)	510k (76k)	
FASERν2	100 TeV	30 ab^{-1}	145M	308M	8.7M
FASERν2-deep	100 TeV	30 ab^{-1}	976M	2100M	54M
FASERν2-wide	100 TeV	30 ab^{-1}	216M	488M	14M

- For the same FASERv2 detector: **factor O(10^3) increase** due to **higher lumi** (x 10) and **higher CoM energy** (x 100)
- Deeper (x 10) and wider (x 10) detectors can also be considered
- Up to **2 billion (!) muon neutrino** scattering events**,** up to **O(50M) tau neutrino** events

Access **neutrino cross-sections at multi-TeV energies**, test **Lepton Flavour Universality for the three neutrino generations,** and search for anomalous interactions with **permille precision**

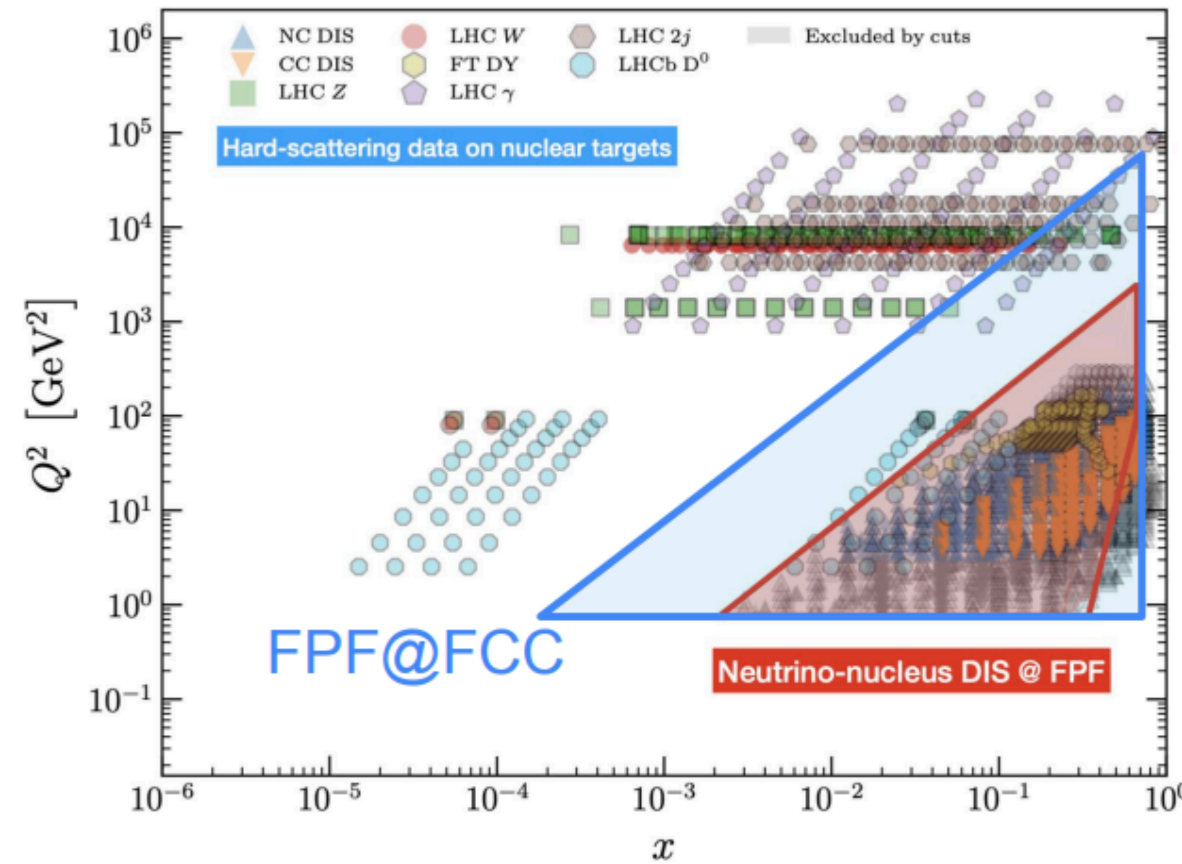
Proton Structure & Small-x QCD



FPF@LHC: x > 5e-8

FPF@FCC: x > 9e-10

PDF via ν-scattering: x ~ 1/Eν



- Access proton structure and **ultra-small-x QCD** in uncharted regimes

  input for UHE astroparticle physics

- Improved understanding of **small-x BFKL QCD** (& even **non-linear QCD**!) will be instrumental for core FCC-pp program

- Large statistics & extended kinematic coverage enable **multi-differential measurements** (e.g. proton 3D structure)

  Which novel features of proton 3D structure can be revealed by a neutrino probe?

- Would need dedicated ``**general-purpose**" **detector** to extract all physics potential

  hermeticity, particle ID, jet reconstruction ….

New SM Opportunities

Polarised DIS with neutrinos: **spin mapping**


RM3-TH/00-20

Polarized Parton Distributions
from Charged–Current Deep-Inelastic Scattering
and Future Neutrino Factories

Stefano Forte†

INFN, Sezione di Roma III
Via della Vasca Navale 84, I-00146 Rome, Italy

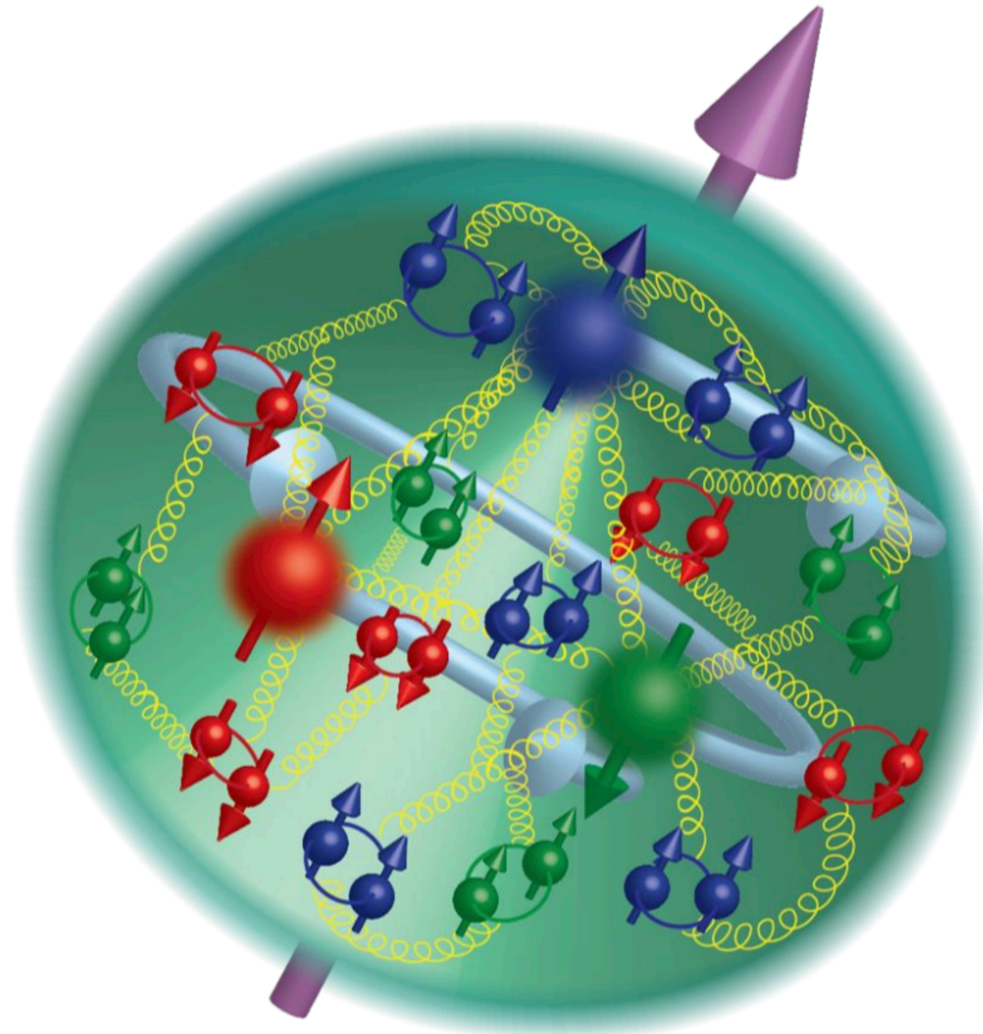
Michelangelo L. Mangano and Giovanni Ridolfi*

Theory Division, CERN
CH-1211 Geneva 23, Switzerland

arXiv:hep-ph/0101192v2 14 Mar 2001

Abstract

We discuss the determination of polarized parton distributions from charged–current deep–inelastic scattering experiments. We summarize the next-to-leading order treatment of charged–current polarized structure functions, their relation to polarized parton distributions and scale dependence, and discuss their description by means of a next-to-leading order evolution code. We discuss current theoretical expectations and positivity constraints on the unmeasured C–odd combinations $\Delta q - \Delta\bar{q}$ of polarized quark distributions, and their determination in charged–current deep–inelastic scattering experiments. We give estimates of the expected errors on charged–current structure functions at a future neutrino factory, and perform a study of the accuracy in the determination of polarized parton distributions that would be possible at such a facility. We show that these measurements have the potential to distinguish between different theoretical scenarios for the proton spin structure.

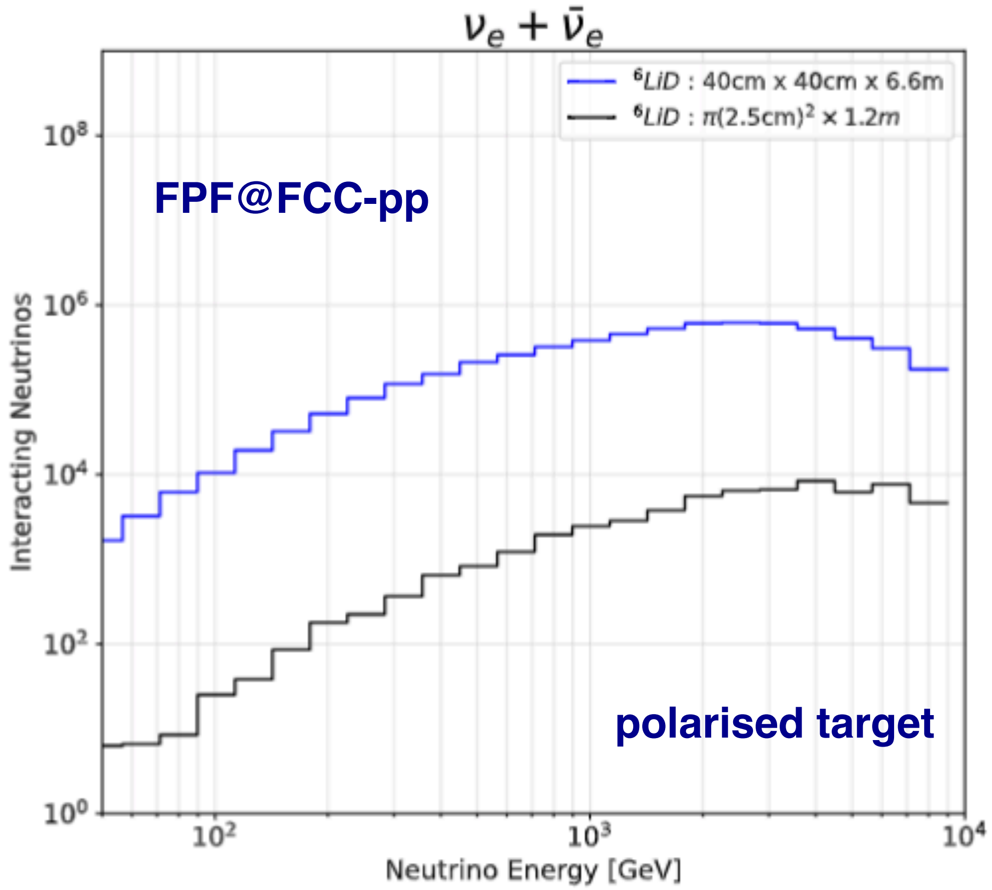


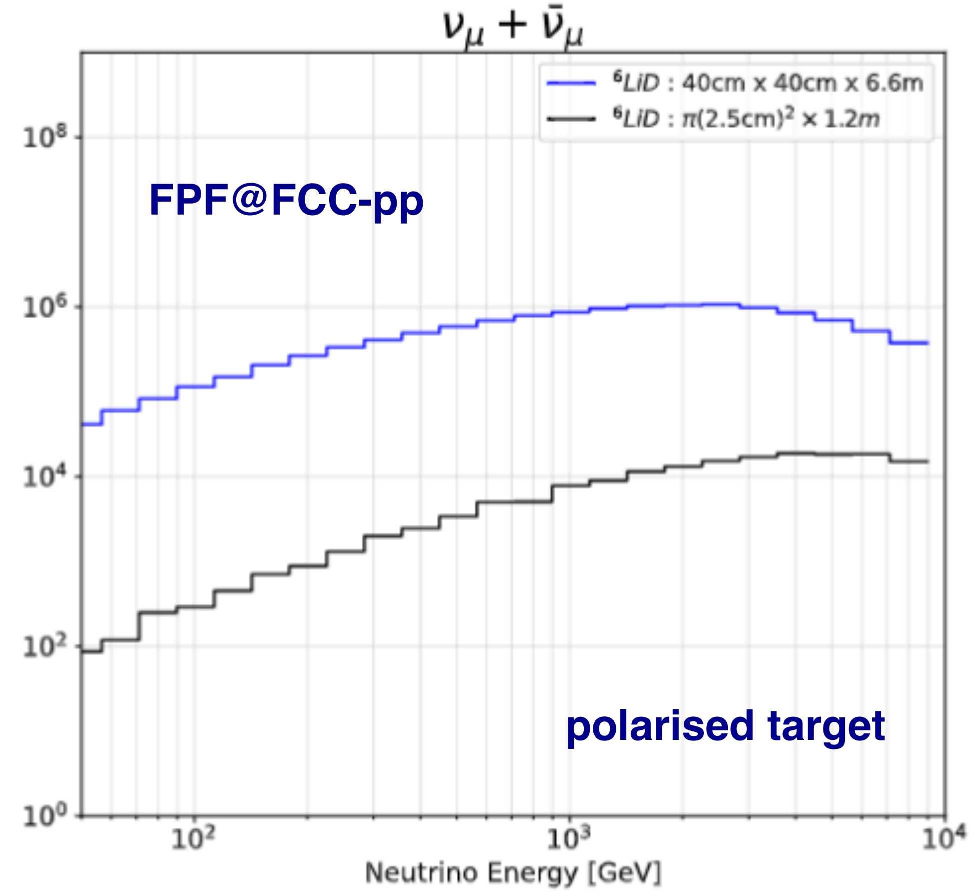
- Realise first neutrino DIS experiment on polarised target: **CC analog of polarized EIC collisions**
- Assuming a COMPASS-like **^{6}LiD polarised target**, FPF@HL-LHC would record O(10 events)

New SM Opportunities

Polarised DIS with neutrinos: **spin mapping**

Novel probe to scrutinize **proton spin and 3D structure!**





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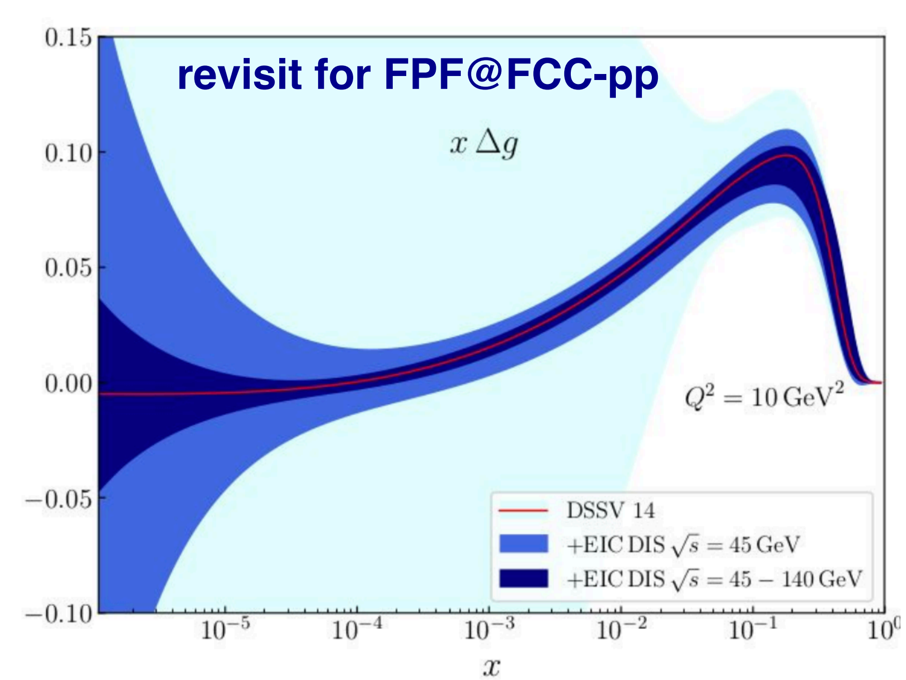

New SM Opportunities

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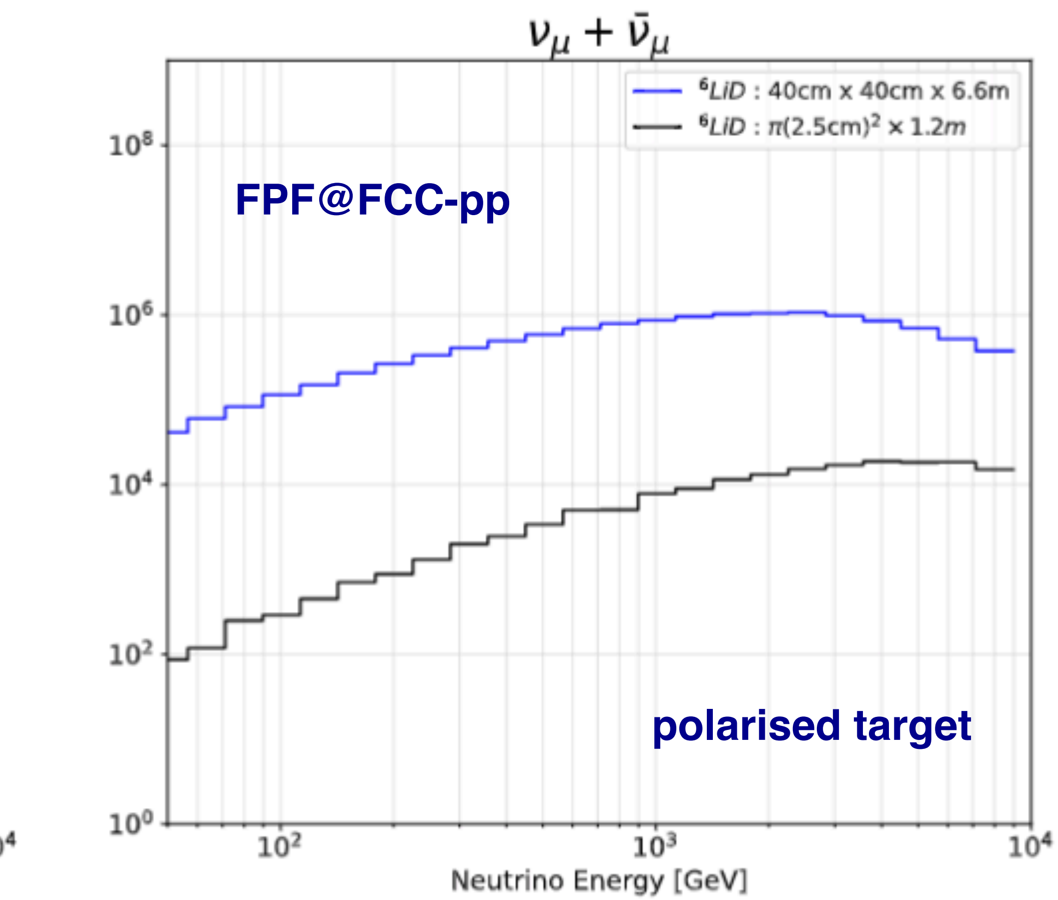

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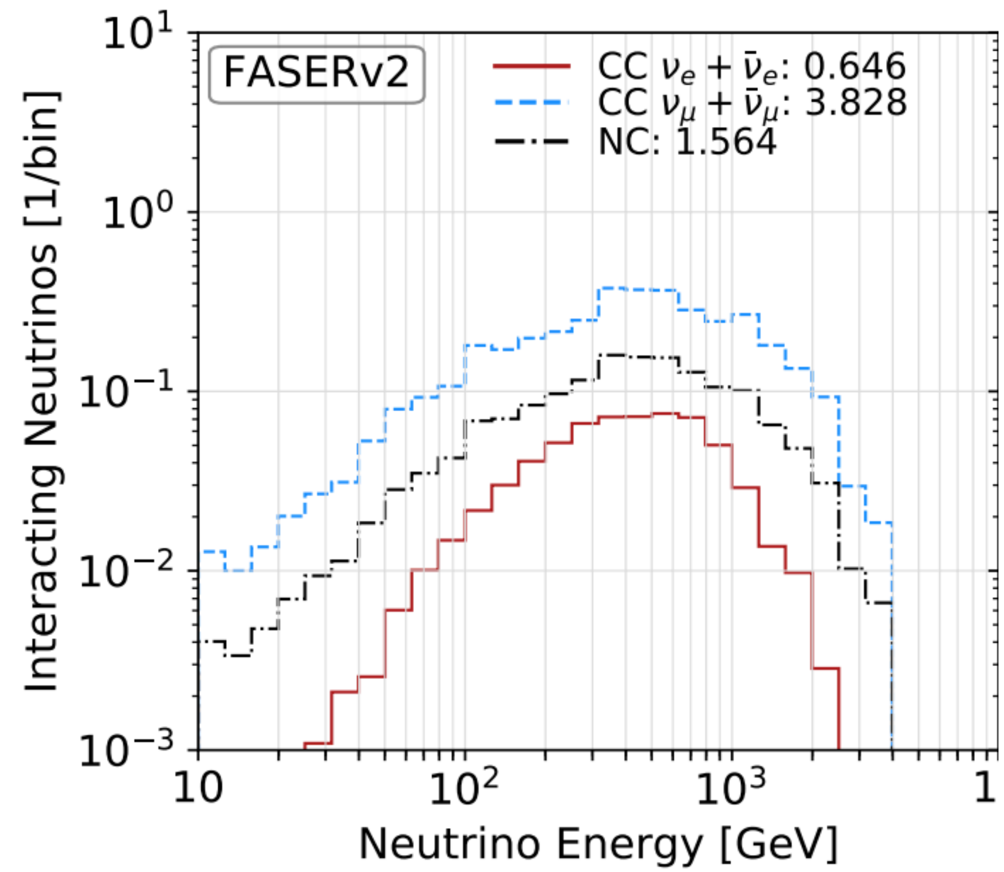
Neutrinos from **proton-ion collisions**

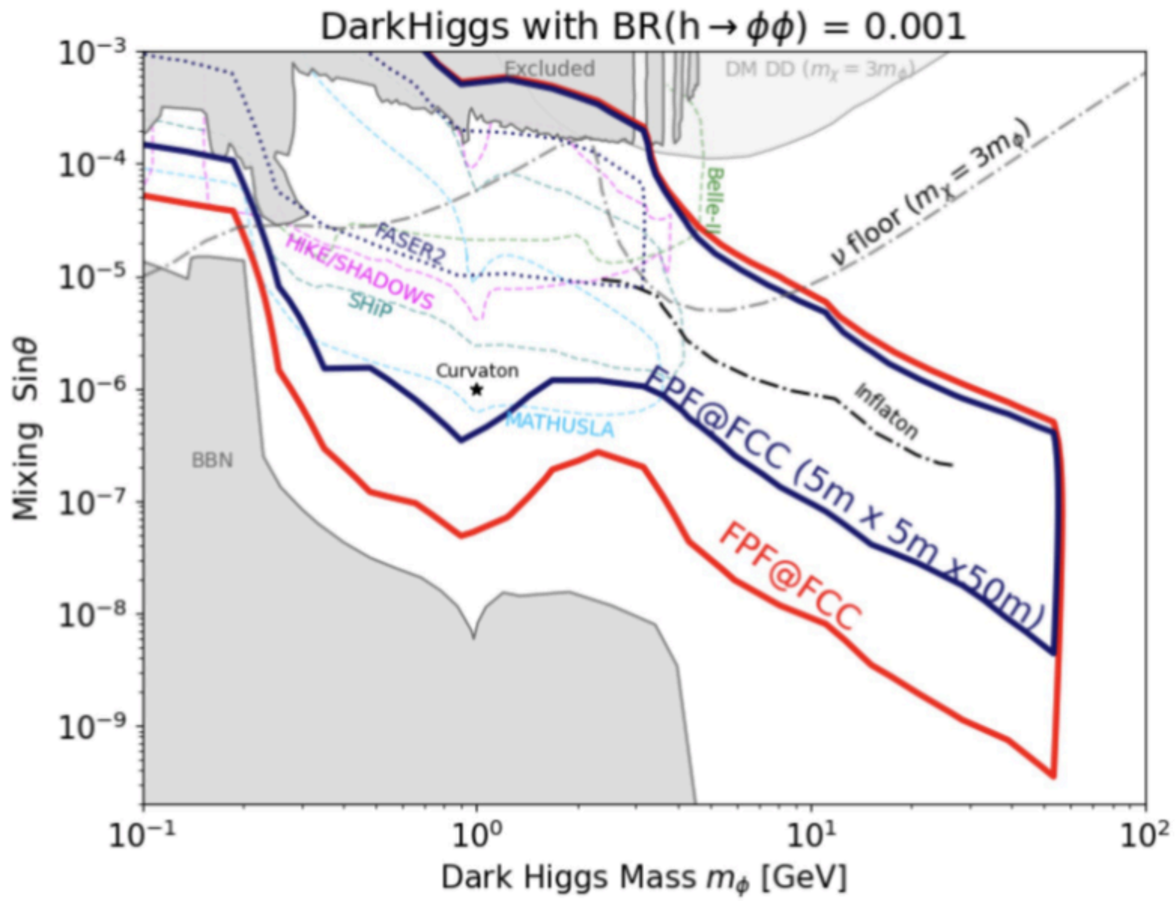
FPF@HL-LHC: $\sqrt{s_{NN}}$ = **8.16 TeV**, L_{pPb} = **1 pb^{-1}**

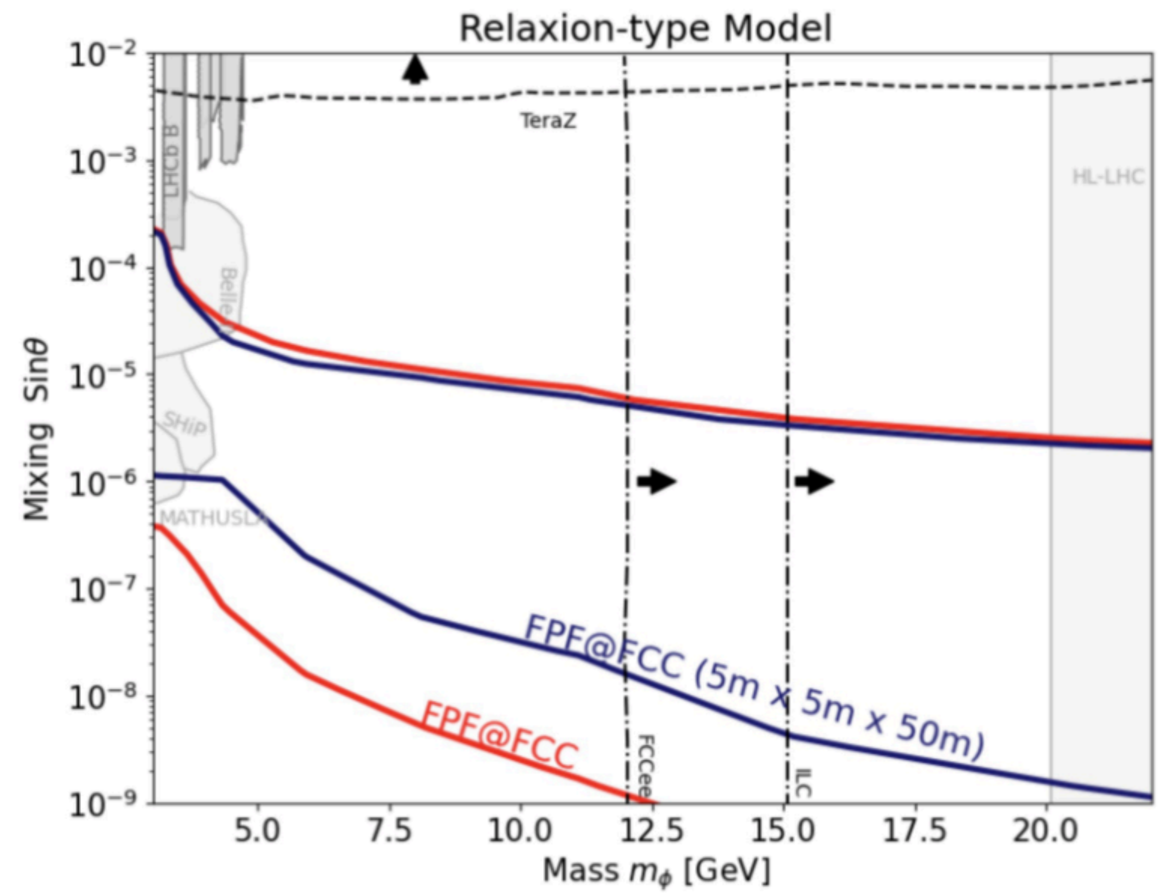


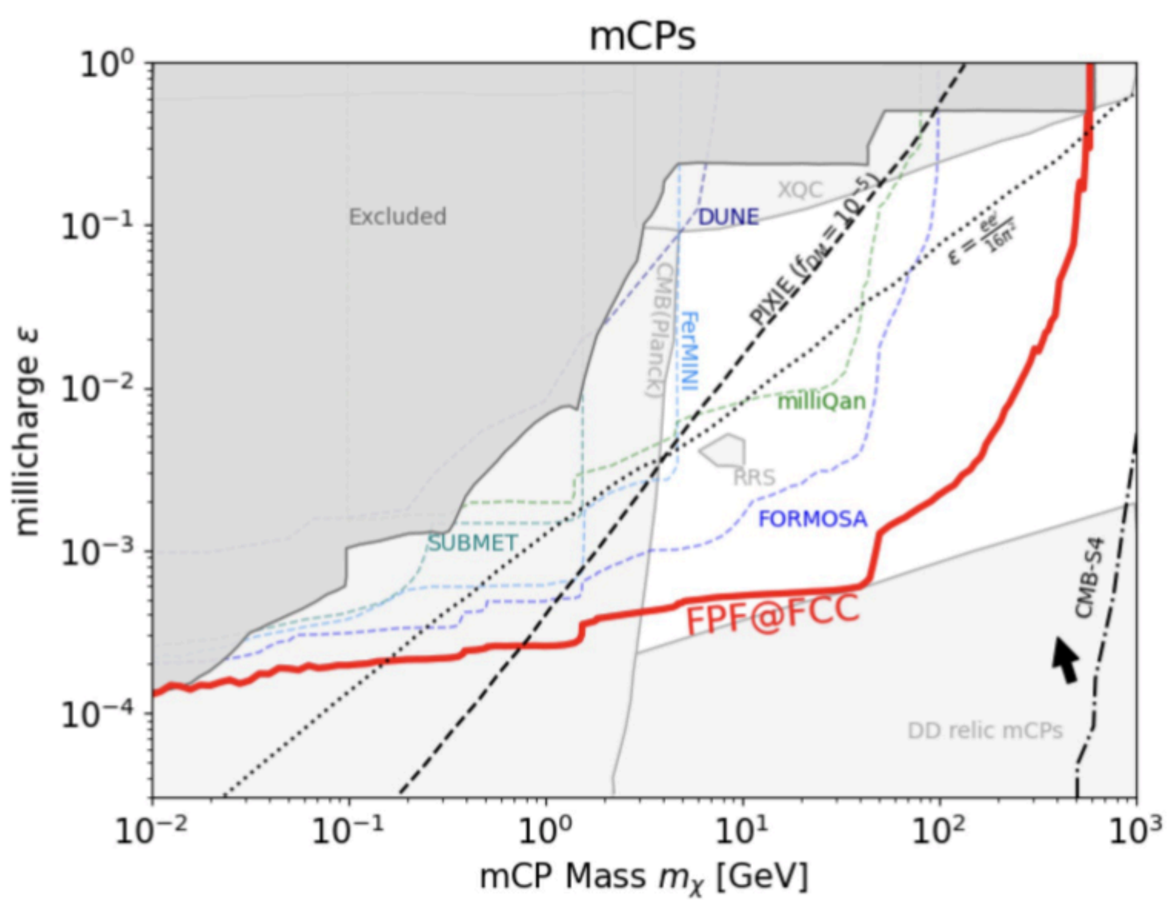
FPF@FCC $\sqrt{s_{NN}}$ = **63 TeV**, L_{pPb} = **29 pb^{-1}**/month

- x100 from **higher $\sqrt{s_{NN}}$** , x150 **higher L_{pPb} (6m)**
- **O(30K) muon neutrinos** from p-Pb scattering
- Unique probe of **ultra-dense gluonic matter**
- Different ions: map **nuclear dependence**

BSM Opportunities







Huge increase in light forward particle production fluxes leads to many new avenues for BSM searches: e.g. dark Higgs, relaxion-type, milli-charged particle scenarios

see **Sebastian's talk** at the parallel session on Wednesday

Summary and outlook

- LHC neutrinos realise an exciting program in a broad range of topics from BSM and long-lived particles to **neutrinos, QCD and hadron structure**, and astroparticle physics

- Measurements of **neutrino DIS structure functions** at the LHC open a new probe to proton and nuclear structure with a **charged-current counterpart of the EIC**

- Measurements of neutrino event rates at the LHC constrain the **small-*x* gluon and large-*x* charm** in unexplored regions: **key input for FCC-pp program**

- An FPF-like suite of experiments could be **integrated in FCC design from day one:** unique physics opportunities within the SM and beyond it, for a **moderate increase of the overall price tag**)