Precision Physics with TeV Neutrinos at the LHC

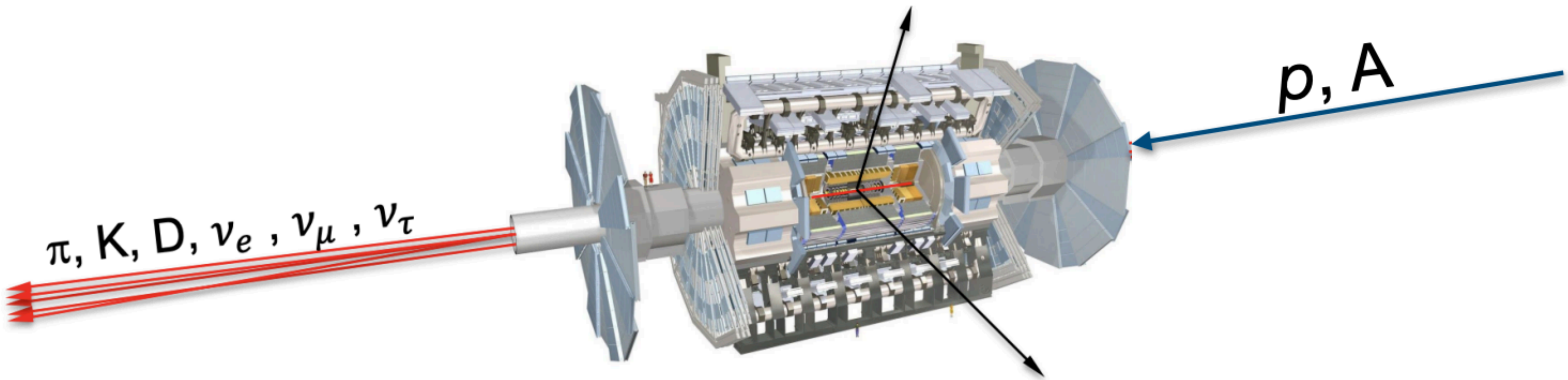
Juan Rojo, VU Amsterdam & Nikhef

The LHC Precision Program

Centro de Ciencias de Benasque, 6th September 2023

Neutrinos at the LHC

- LHC collisions result into a **large flux of energetic neutrinos** which escape the detectors unobserved: **major blind spot of the LHC**



- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

Neutrino Physics

Precision study of **tau-neutrino interactions**

Neutrino **coupling universality** at TeV energies

BSM/DM in neutrino sector e.g. **sterile neutrino**

QCD & Hadron Structure

Proton and nuclear **antimatter & charm**

Gluon PDF at ultra-small-x; saturation/QGP

Cross-sections for **UHE astroparticle physics**

Neutrinos at the LHC

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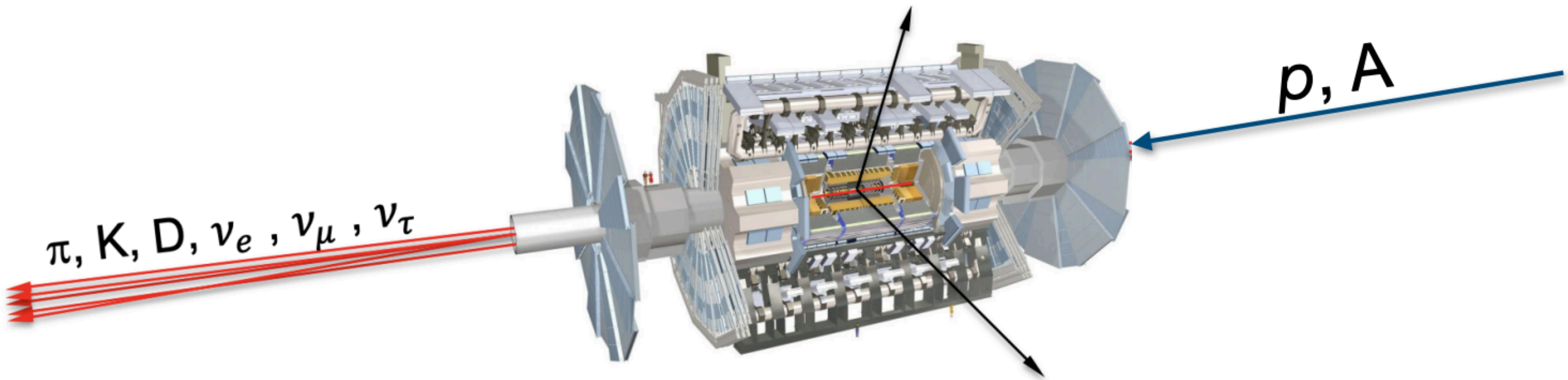
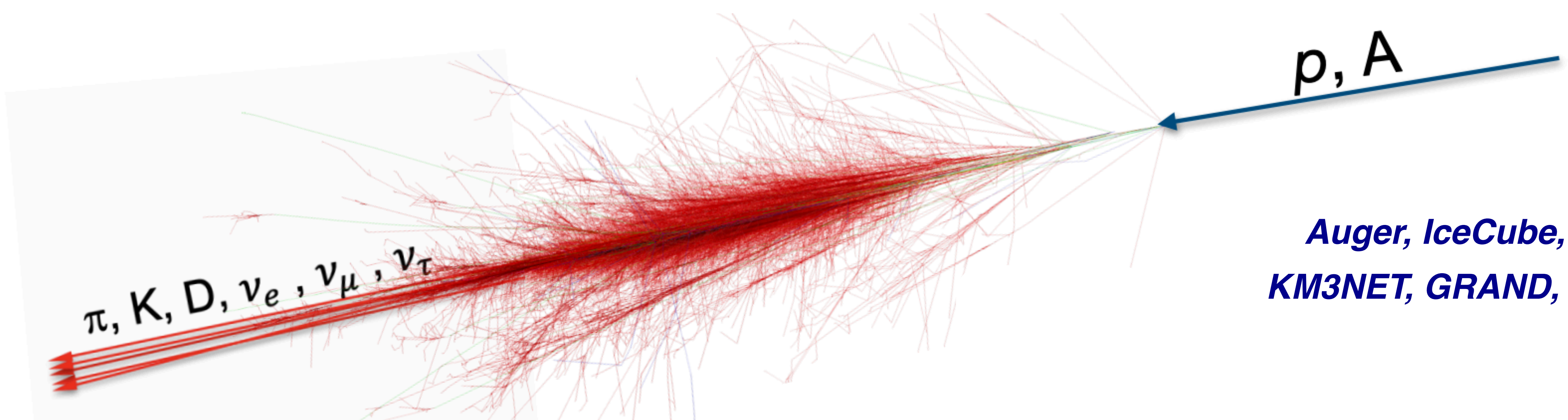


- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux



Auger, IceCube, KM3NET, GRAND, …

The dawn of the LHC neutrino era

- 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)

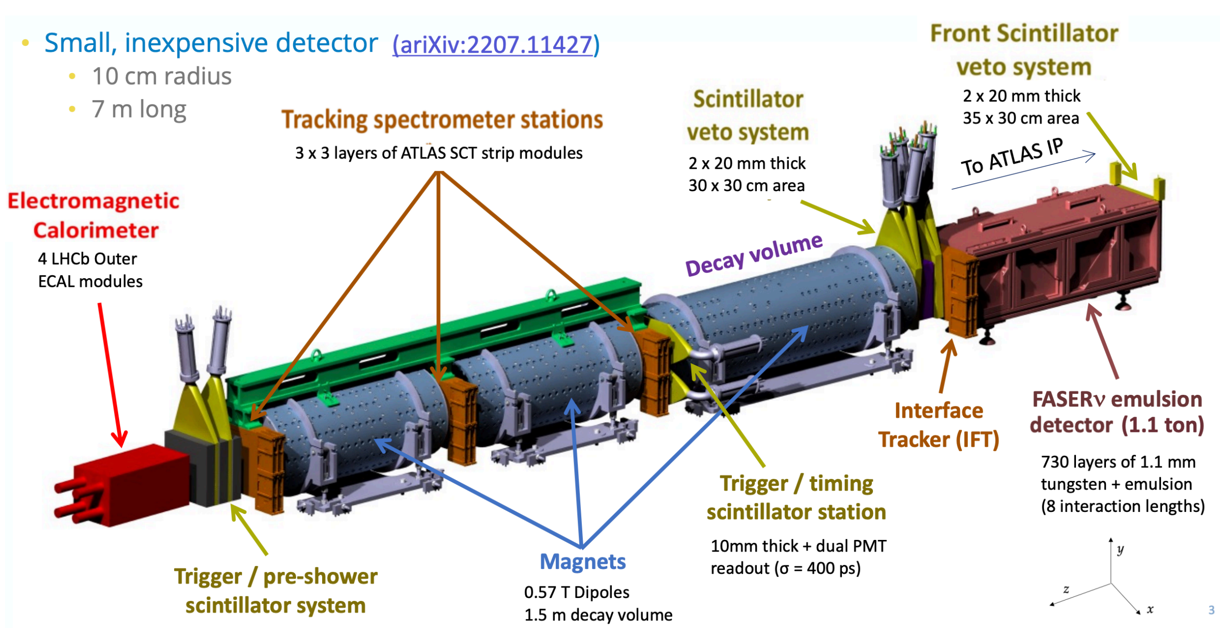
Editors' Suggestion | Featured in Physics

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

153 neutrinos detected, 151± 41 expected



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

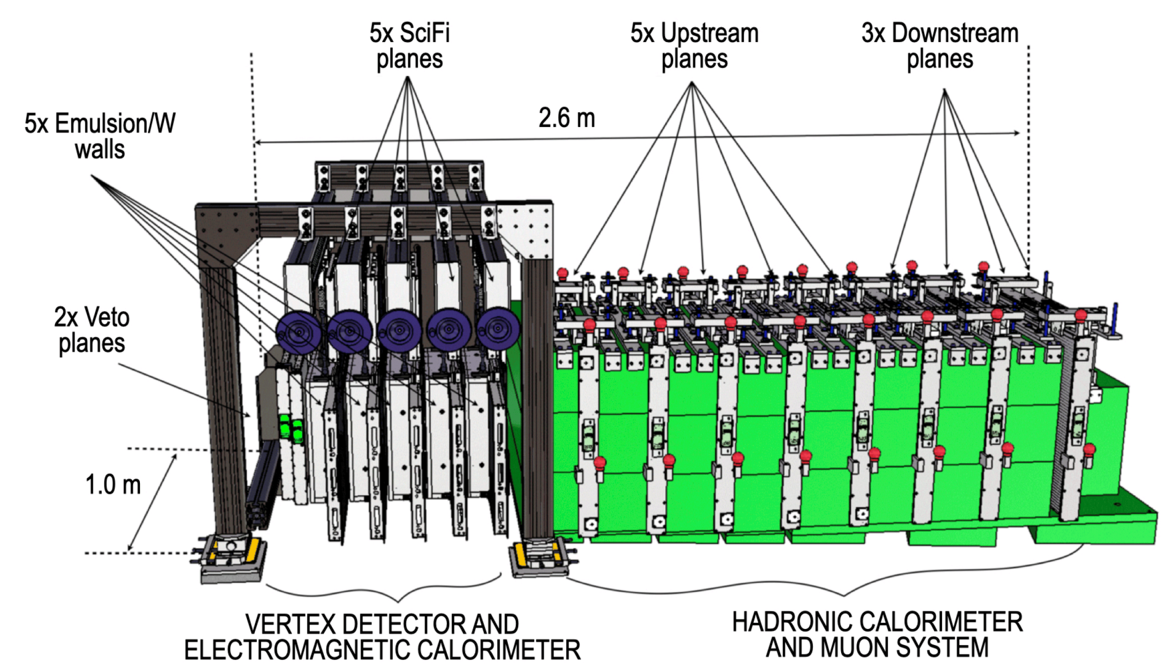
Editors' Suggestion

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

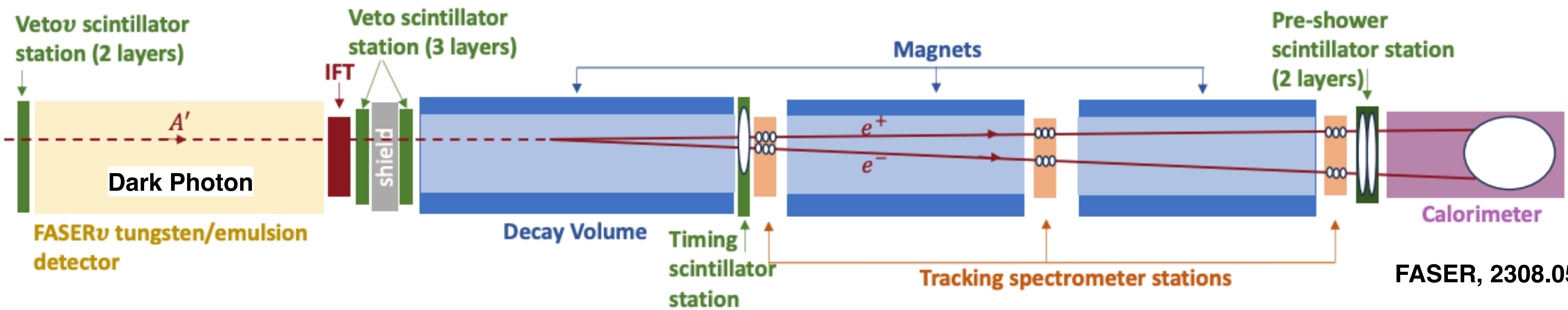
8 neutrinos detected, 4 expected



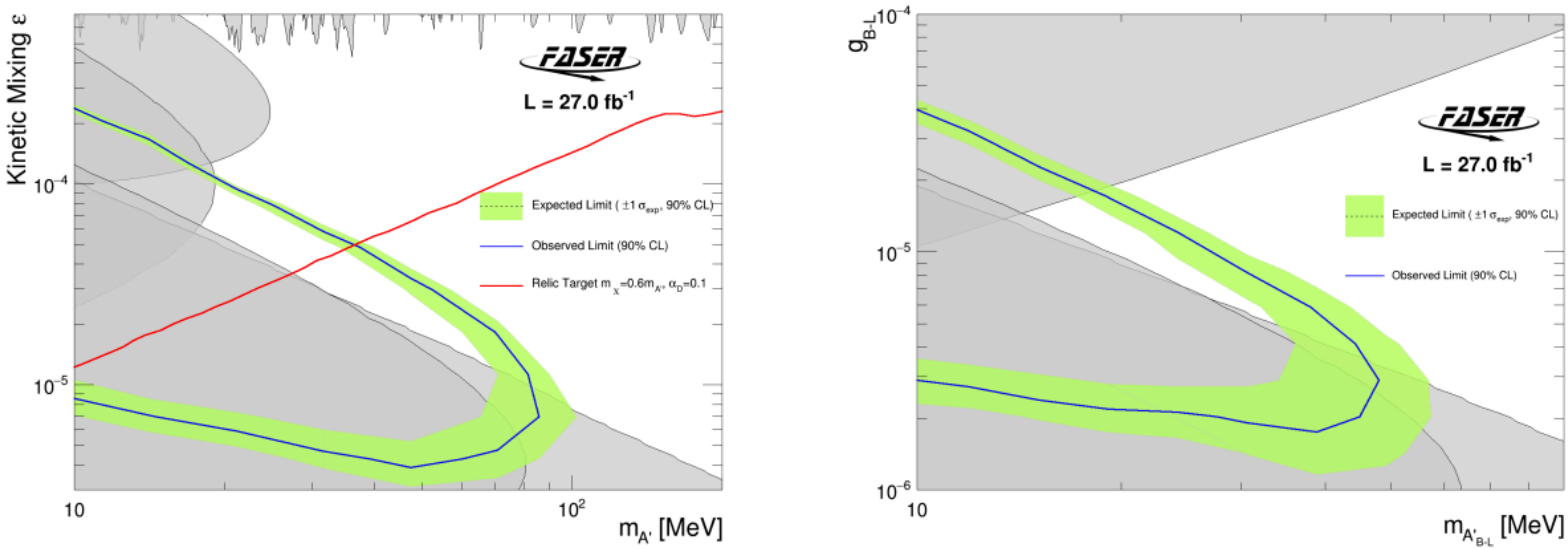
Now is the time to start exploiting their physics potential!

Searching for the invisible

- These far-forward LHC detectors also operate as background-free to search for dark sector particles, feebly-interacting particles (FIPs), long-lived particles (LLP), ….

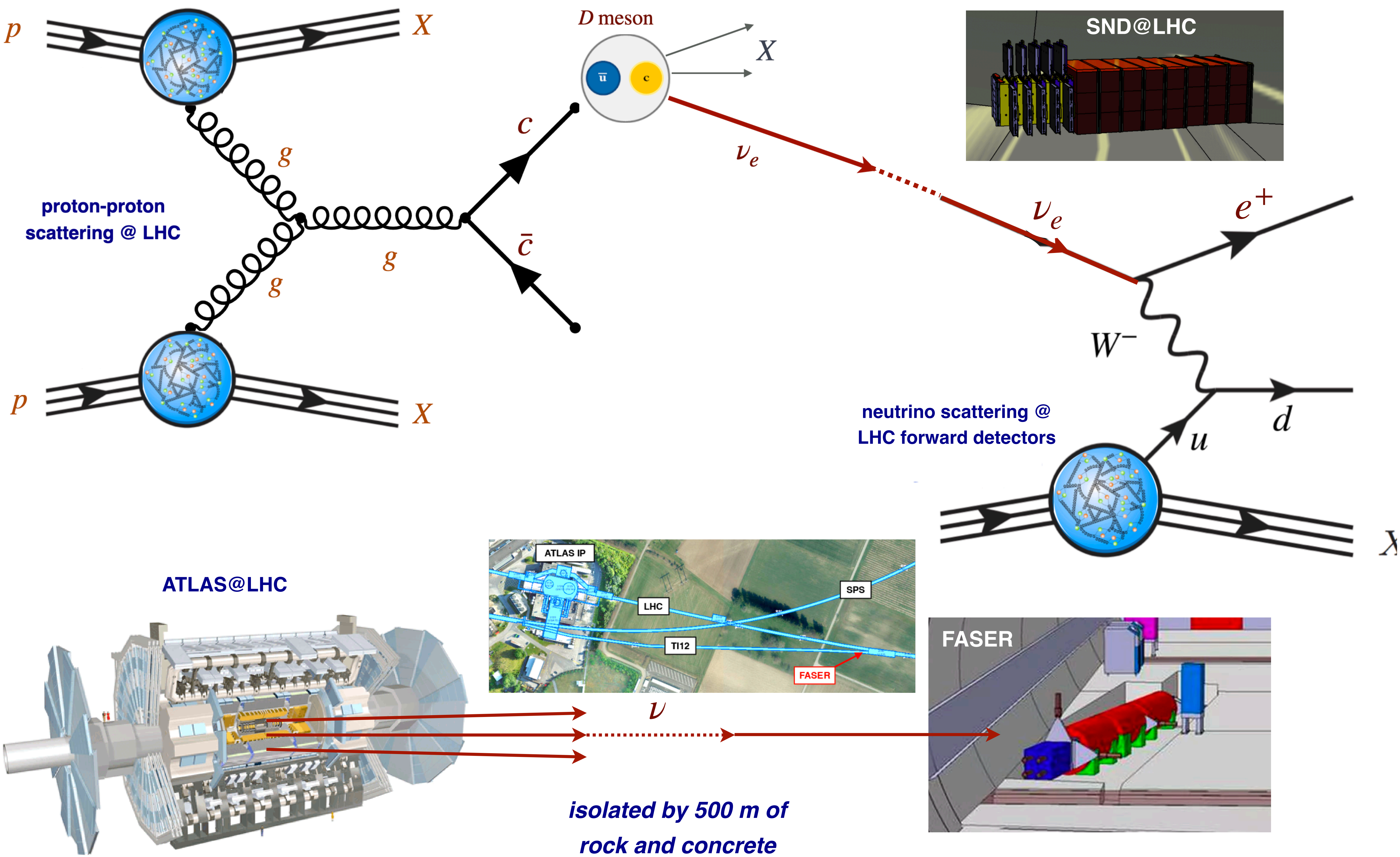


FASER, 2308.05587

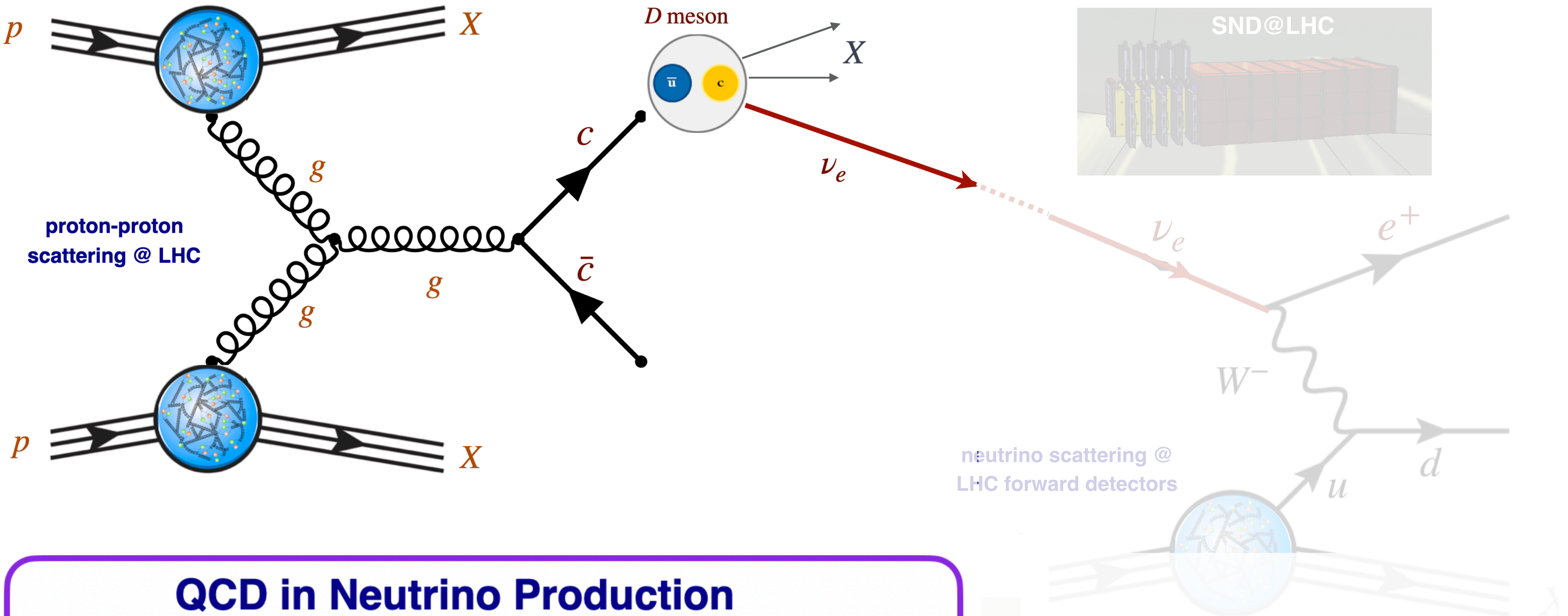


Unique blend of guaranteed deliverables and exploration potential

QCD Studies with LHC neutrinos



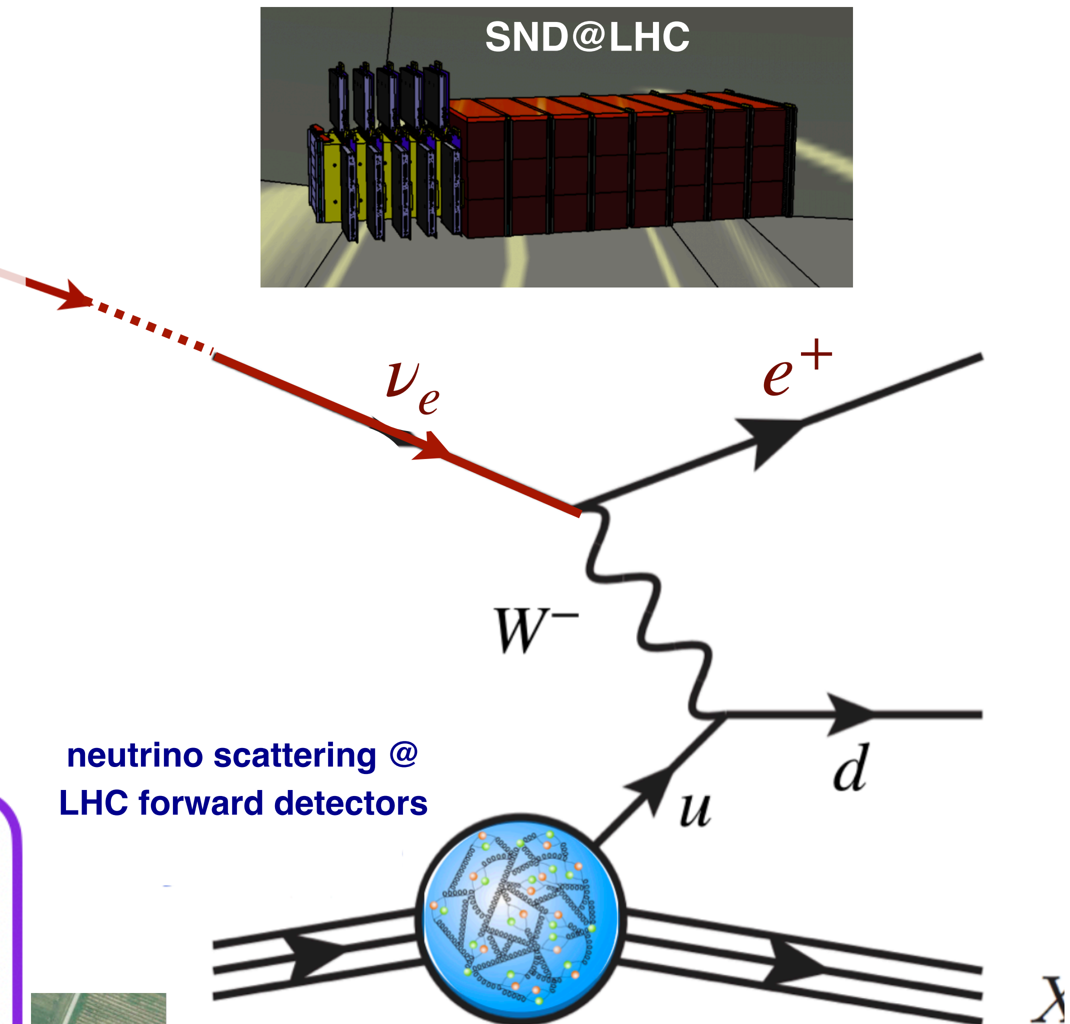
Physics with LHC neutrinos



QCD in Neutrino Production

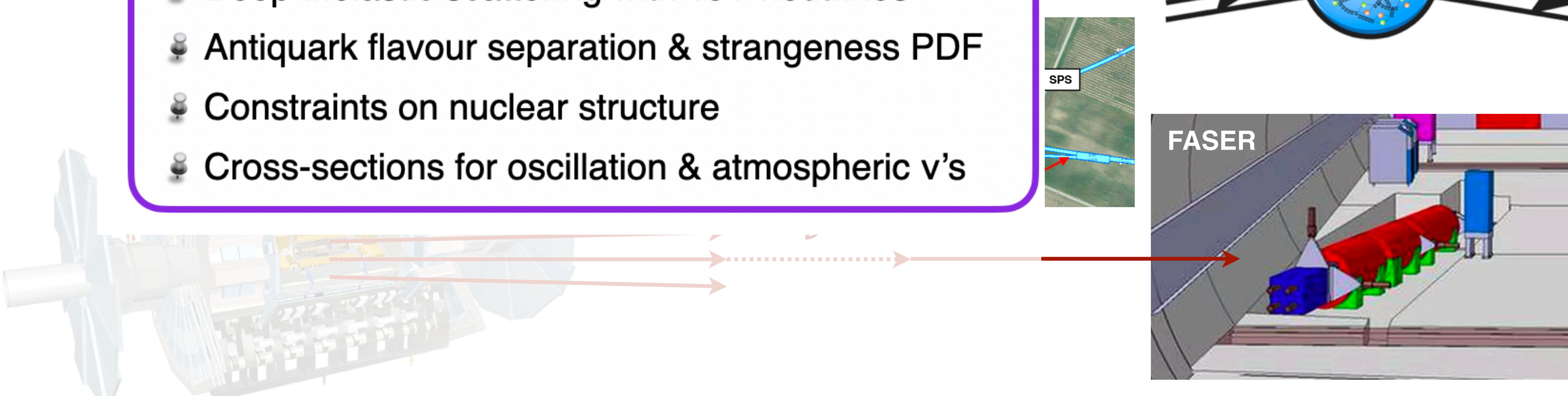
- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
- Forward light hadron production & cosmic ray modelling

Physics with LHC neutrinos



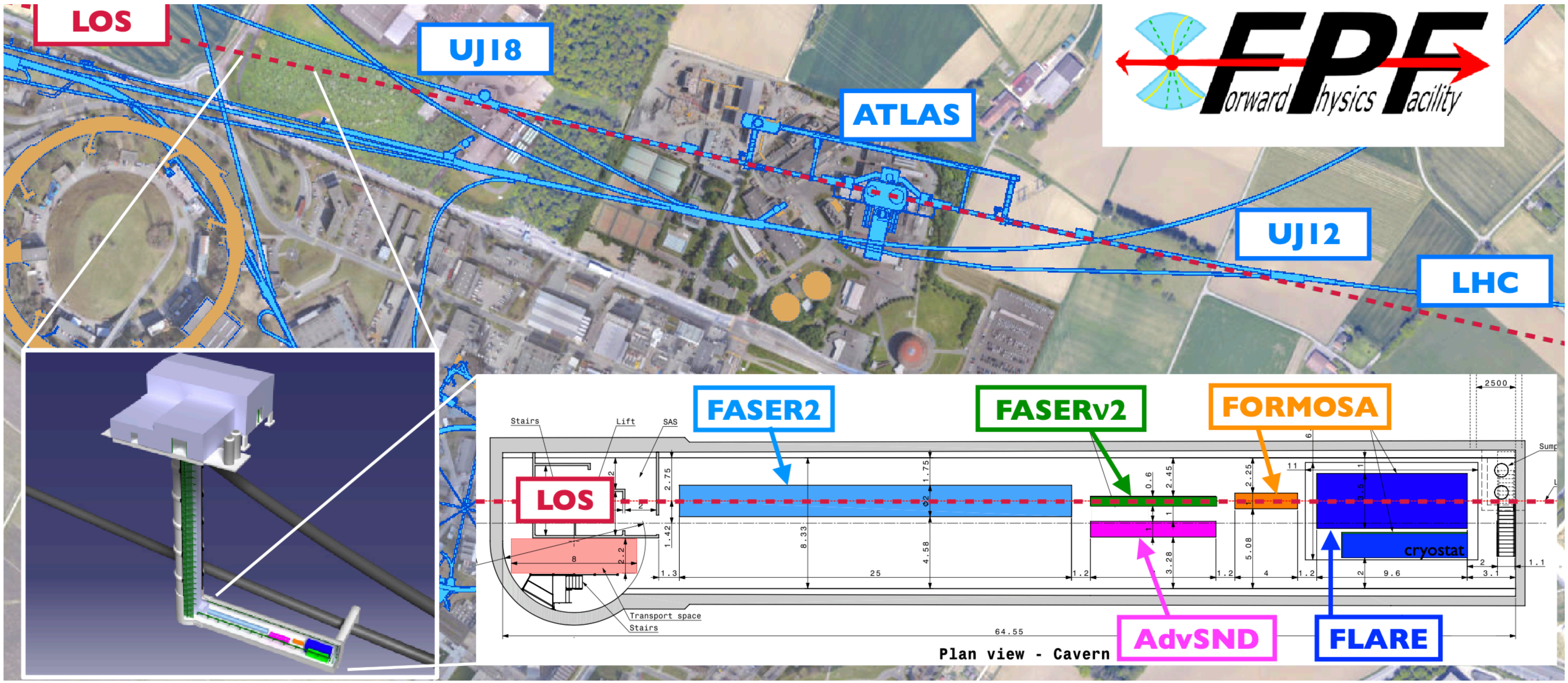
QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's



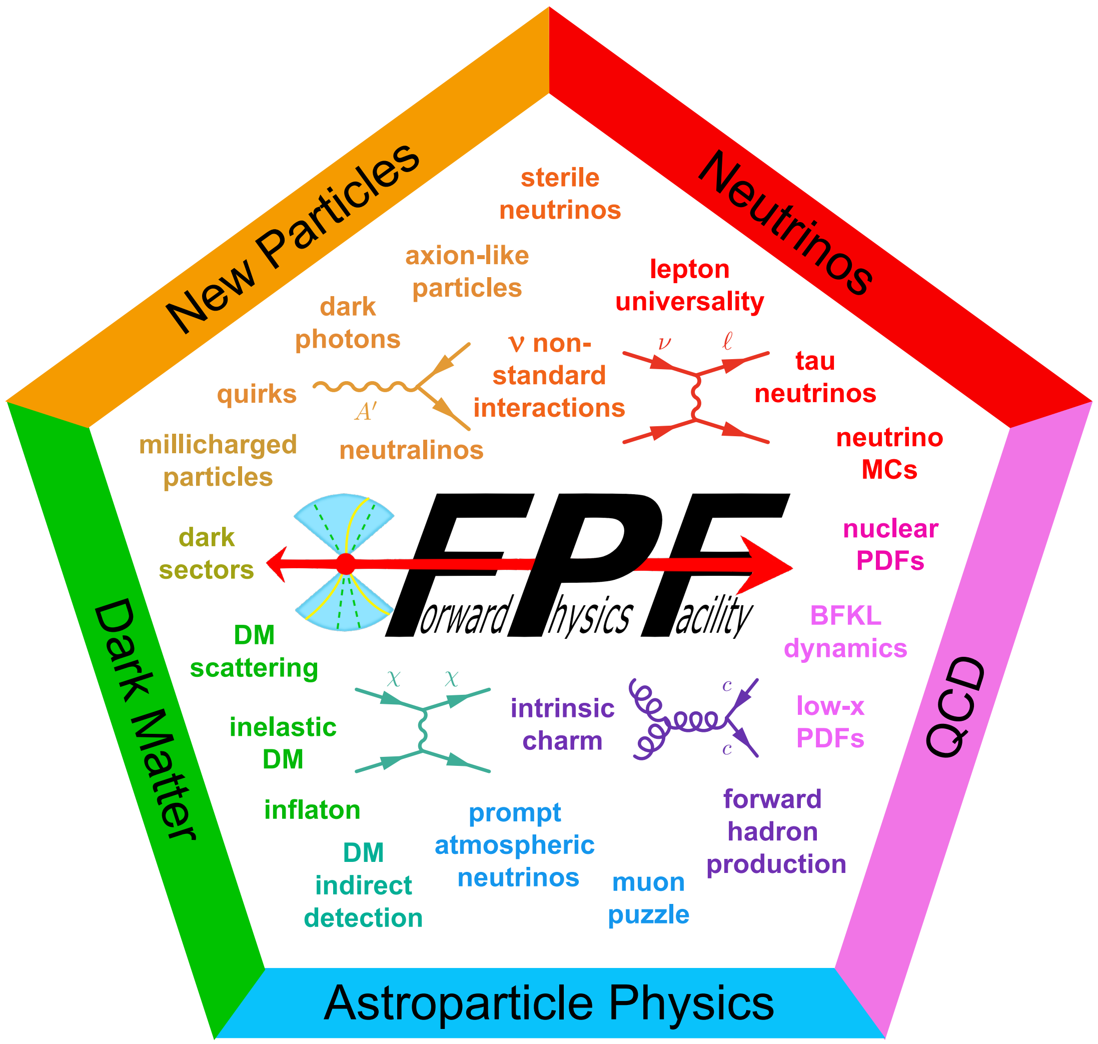
The Forward Physics Facility

The FPF: a 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)

The Forward Physics Facility



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

arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

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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Topical Conveners

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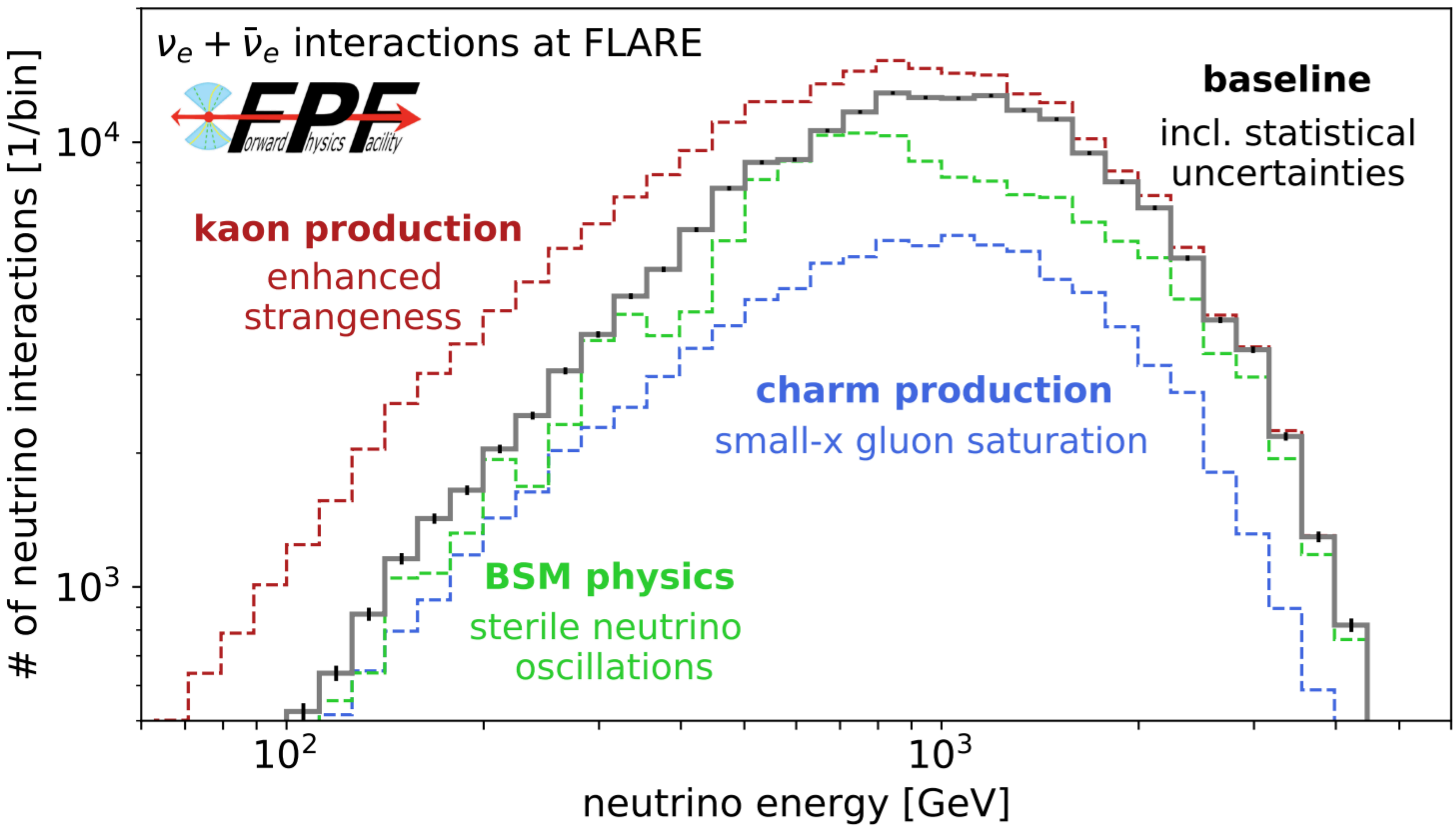
Physics with LHC Neutrinos



Broad, far-reaching program on **QCD** (small-x gluon, saturation), **cosmic rays** (muon puzzle), **neutrino BSM** (sterile neutrinos), hadronic structure, **UHE neutrinos**, **FCC-pp cross-sections** …

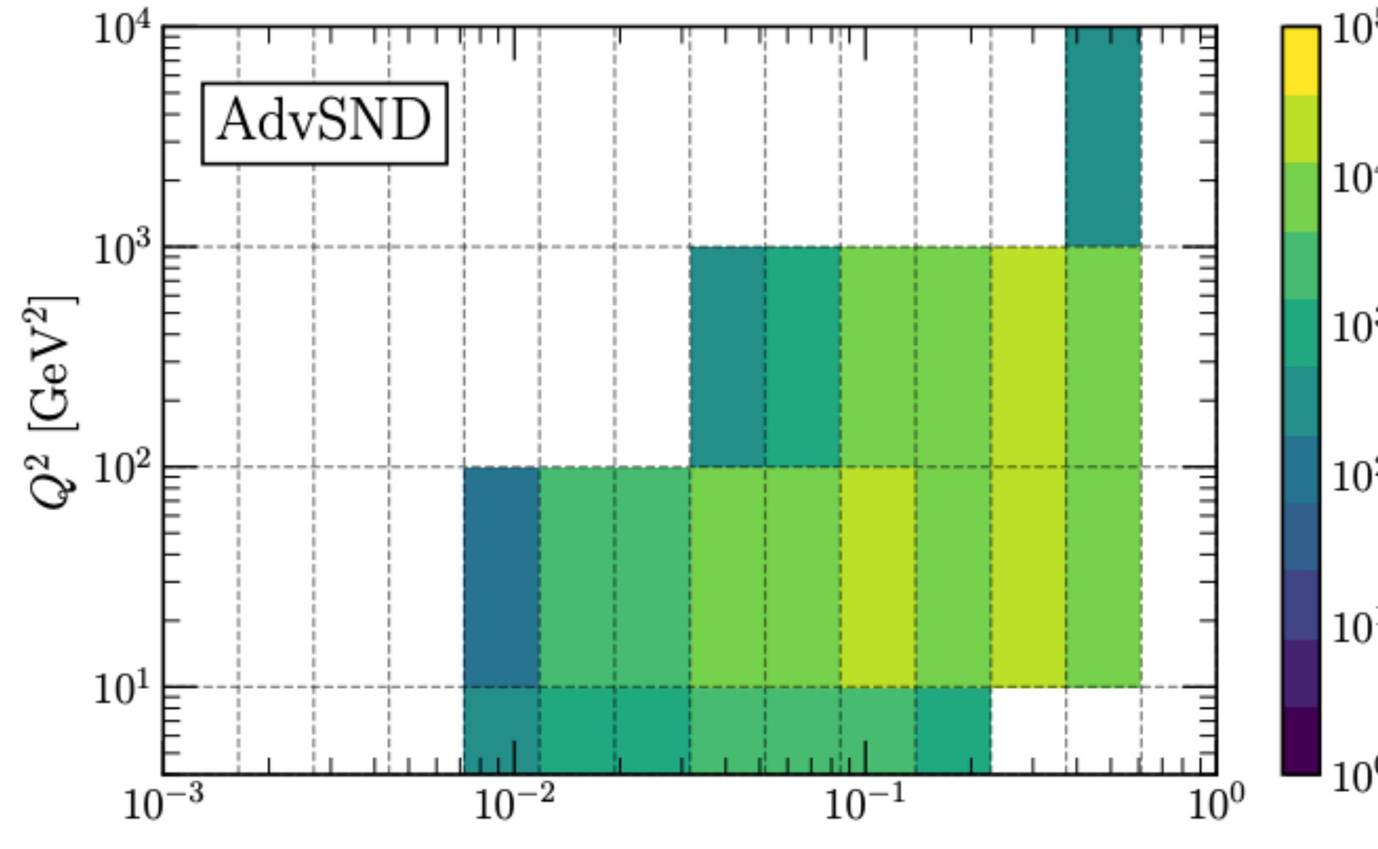
The LHC as a Neutrino-Ion Collider

Juan M. Cruz-Martinez, Max Fieg, Tommaso Giani, Peter Krack, Toni Makela ,Tanjona Rabemananjara, and Juan Rojo, arXiv:2309.09581

Neutrino DIS at the LHC

- Generate **DIS pseudo-data** at current and proposed LHC neutrino experiments
- Fully differential calculation based on **state-of-the-art QCD calculations**
- Model **systematic errors** based on the expected performance of the experiments
- Consider both inclusive and **charm-production DIS**

number of DIS events per bin



Events per bin

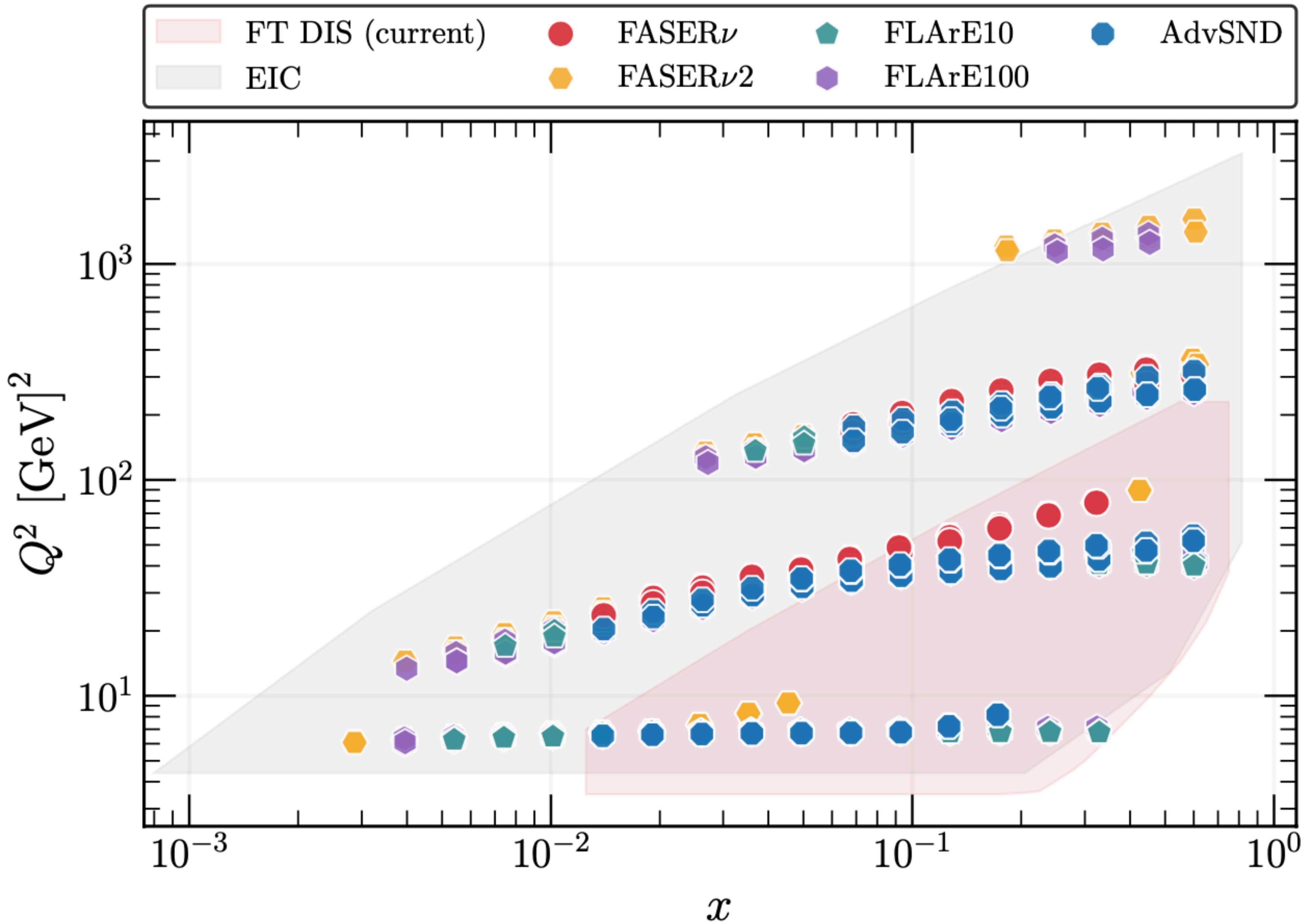
$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

Geometry | *Binning* | *neutrino fluxes (include rapidity acceptance)* | *DIS differential cross-section* | *Acceptance*

Based on **current designs**, may be different in final experiments

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

Neutrino DIS at the LHC

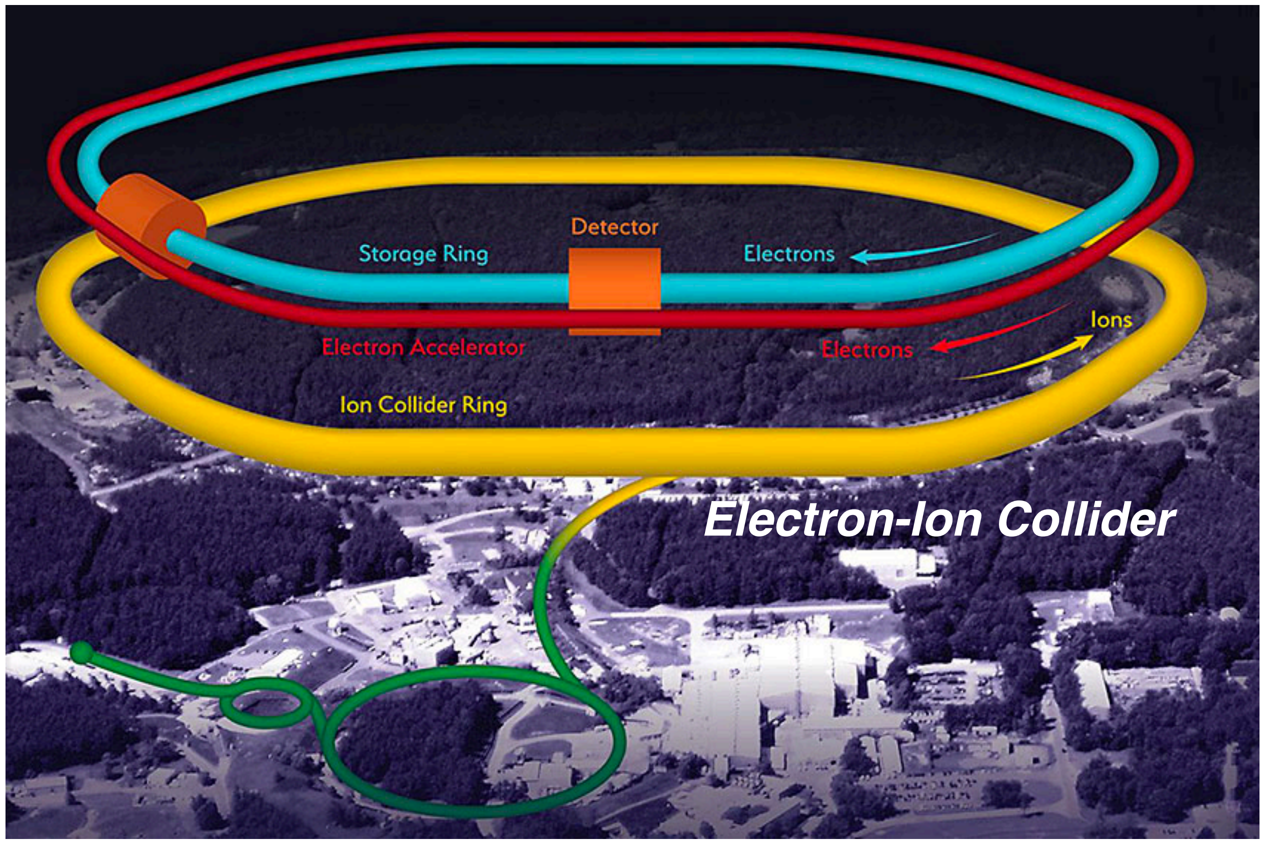


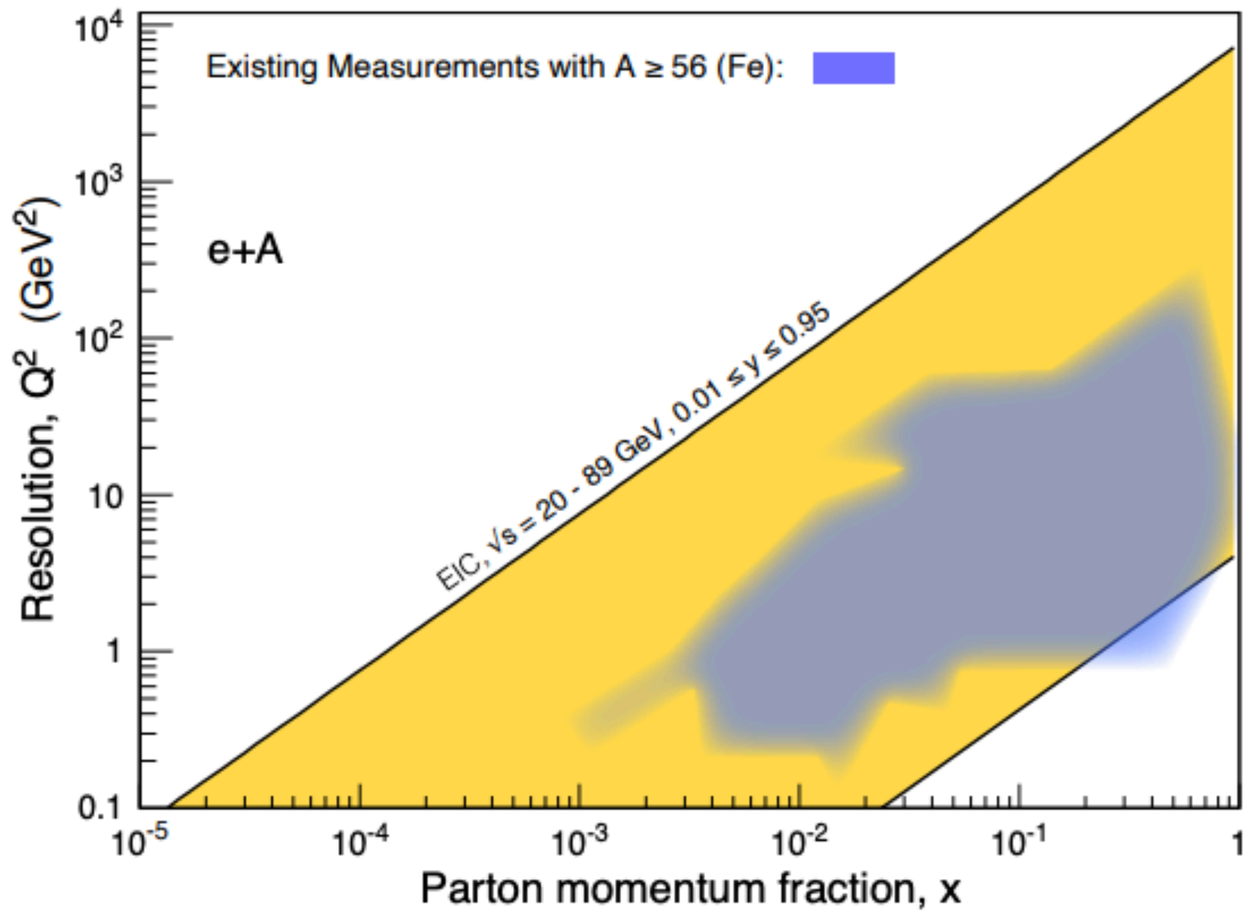
x: momentum fraction of quarks/gluons in the proton

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 Q^2

Neutrino DIS at the LHC



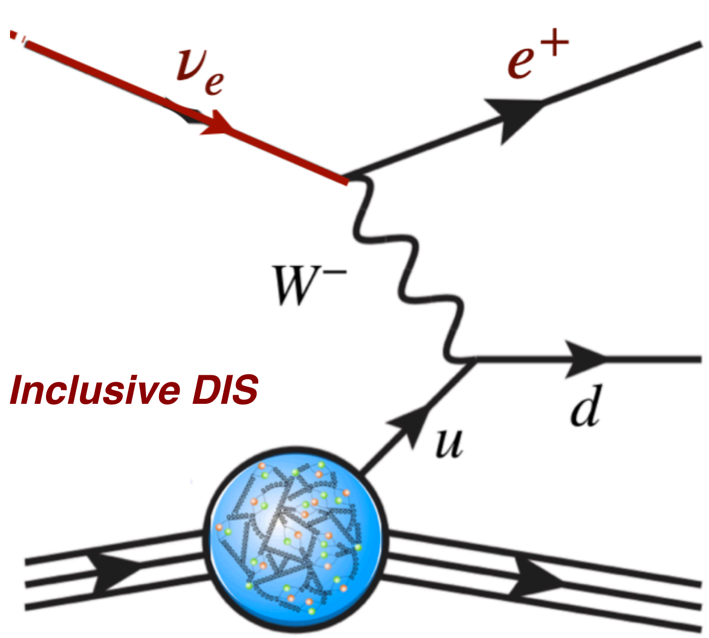


- Continue highly succesful program of neutrino **DIS experiments @ CERN,**
- **Expand kinematic coverage** of available experiments by an order of magnitude in x and Q^2
- Charged-current counterpart of the **Electron-Ion Collider** in a comparable region of phase space

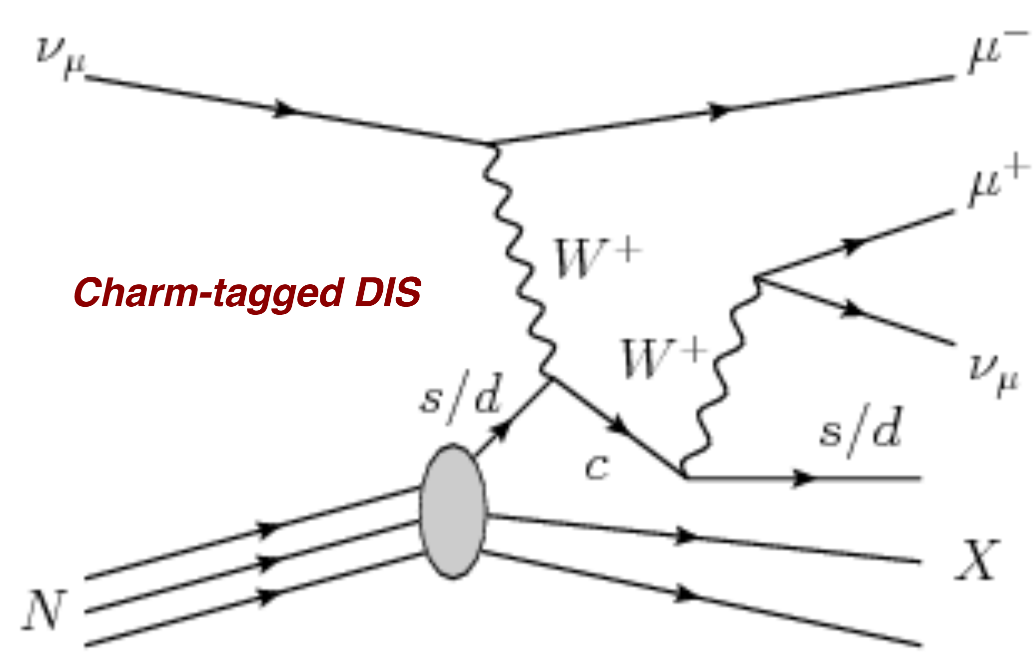
Neutrino DIS at the LHC

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

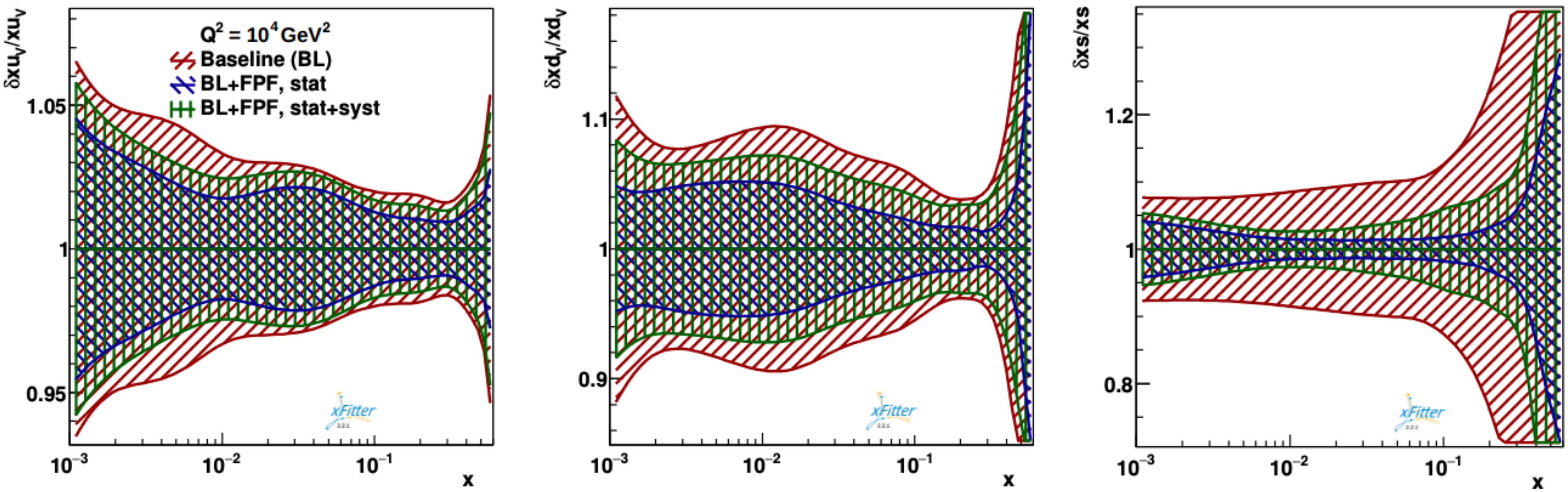
Detector	N_{ν_e}	$N_{\bar{\nu}_e}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	N_{ν_μ}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
FASERν	400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	180 (22)	76 (11)	260 (32)	510 (59)	190 (25)	700 (83)
FASERν2	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)	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)



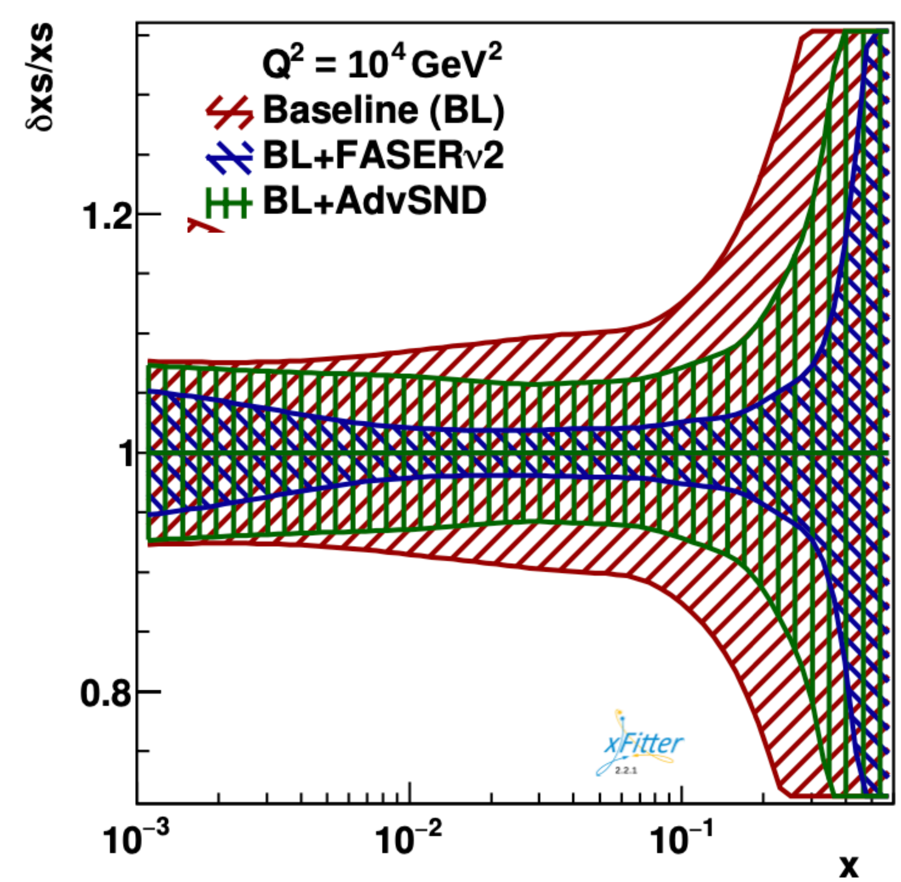
- Muon-neutrinos: **larger event rates, smaller production uncertainties**
- Current experiments limited by statistics, FPF **by systematics**
- Ultimate reach achieved by **combining all experiments**



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
- PDFs improved with LHC neutrino data **enhance precision HL-LHC measurements like *W* mass**



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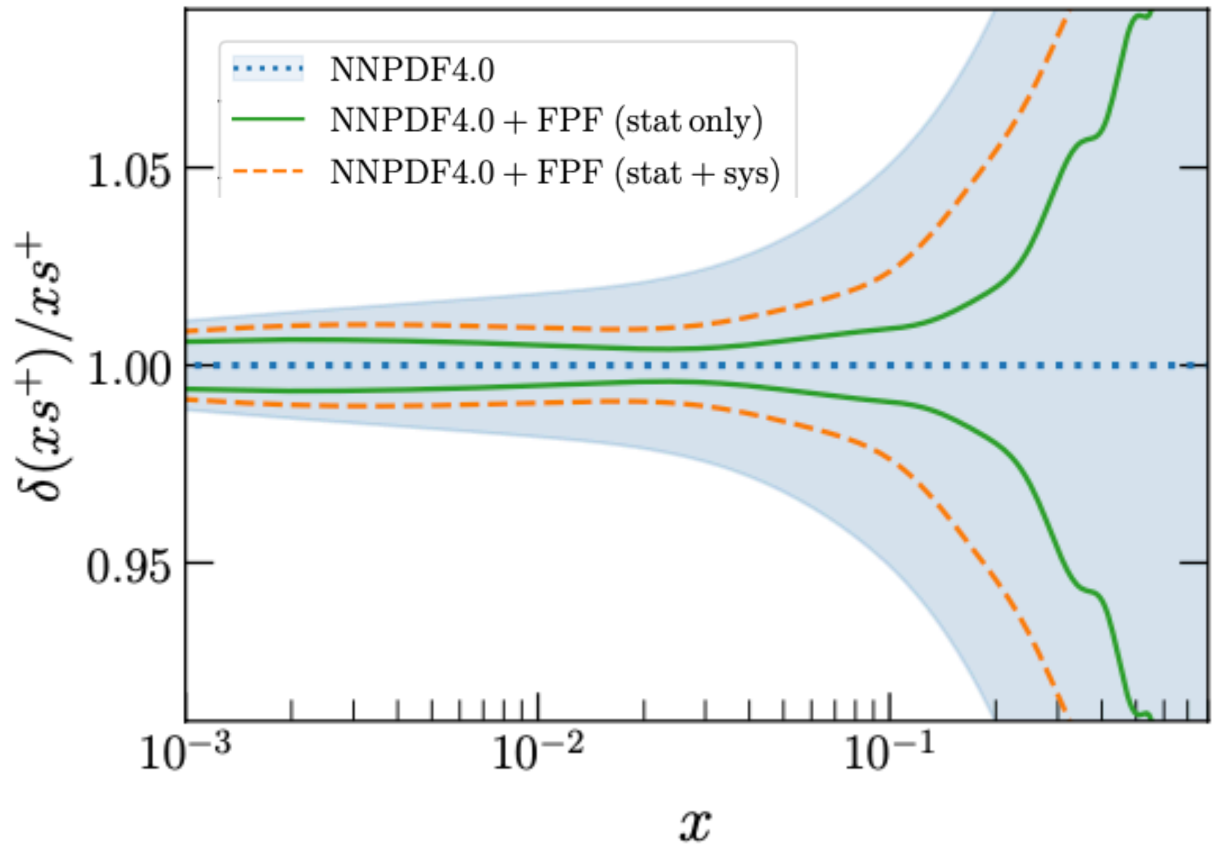
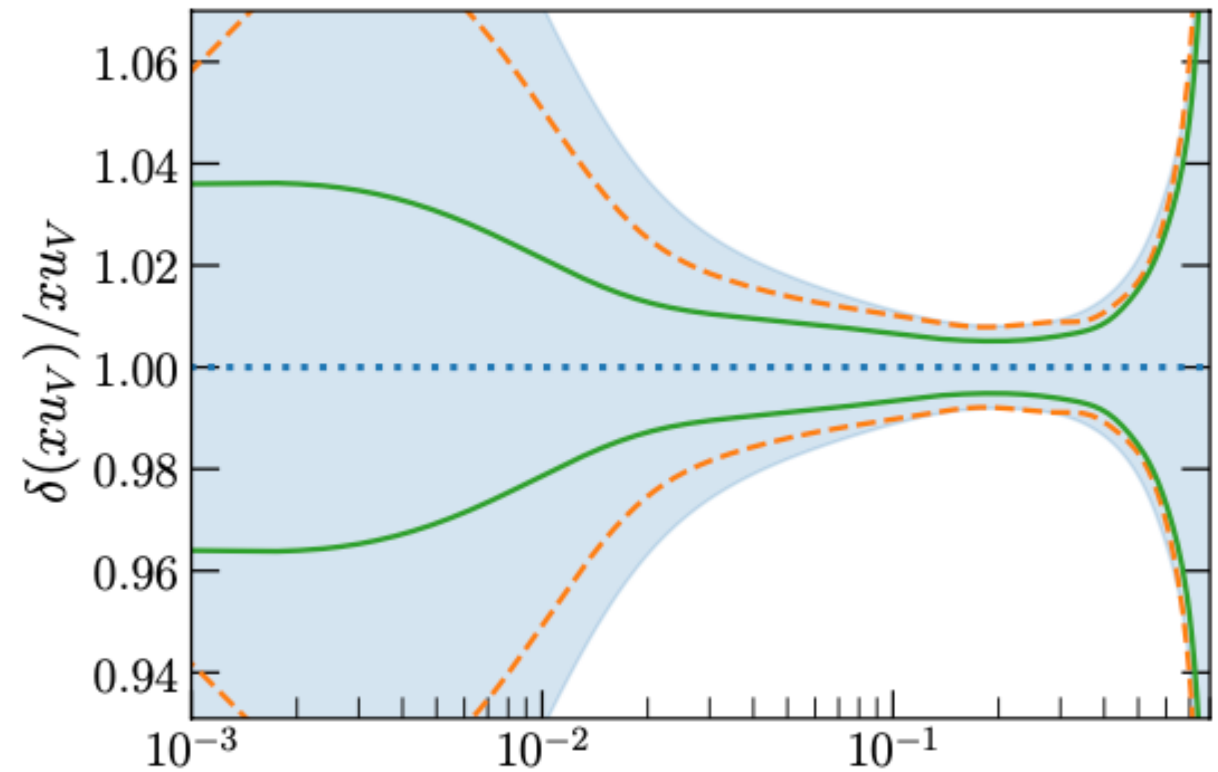
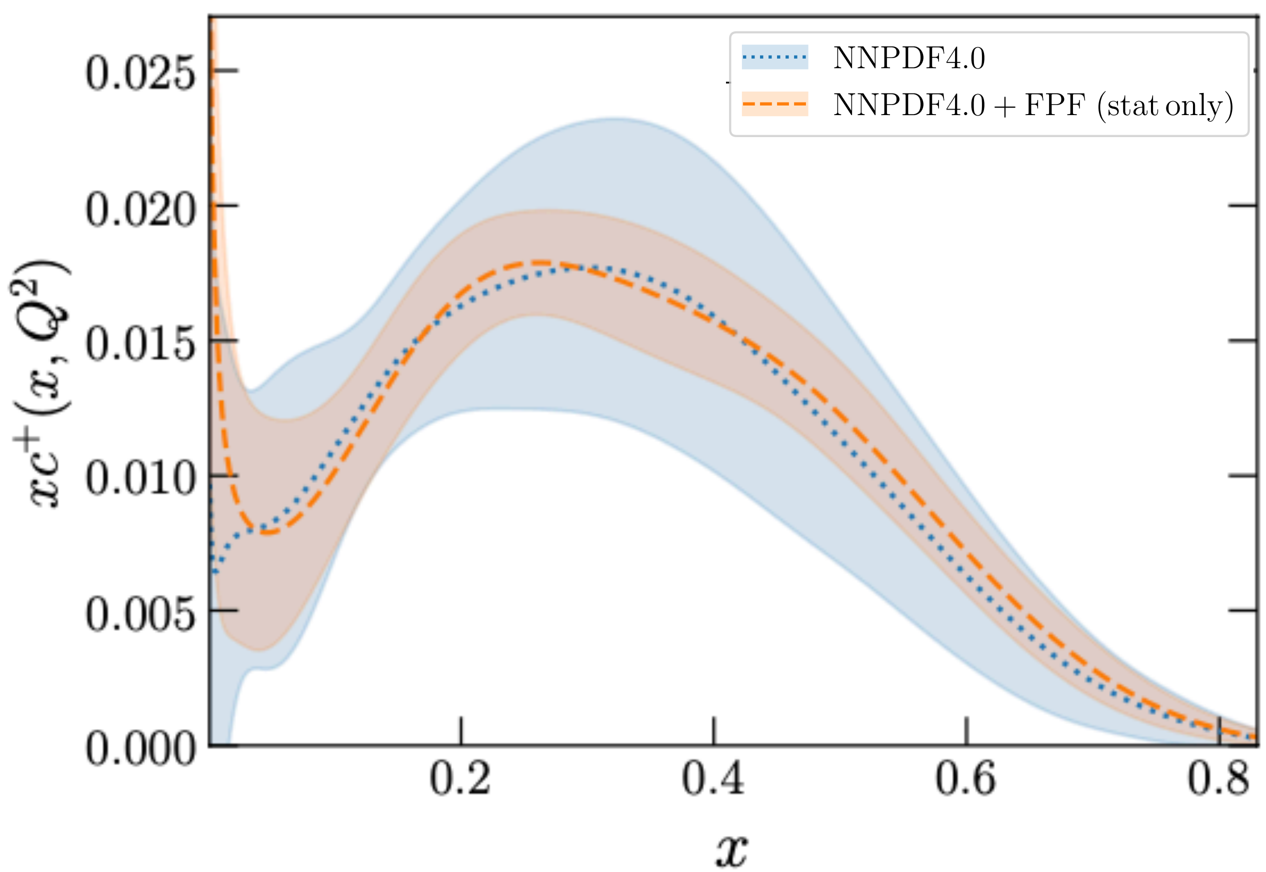
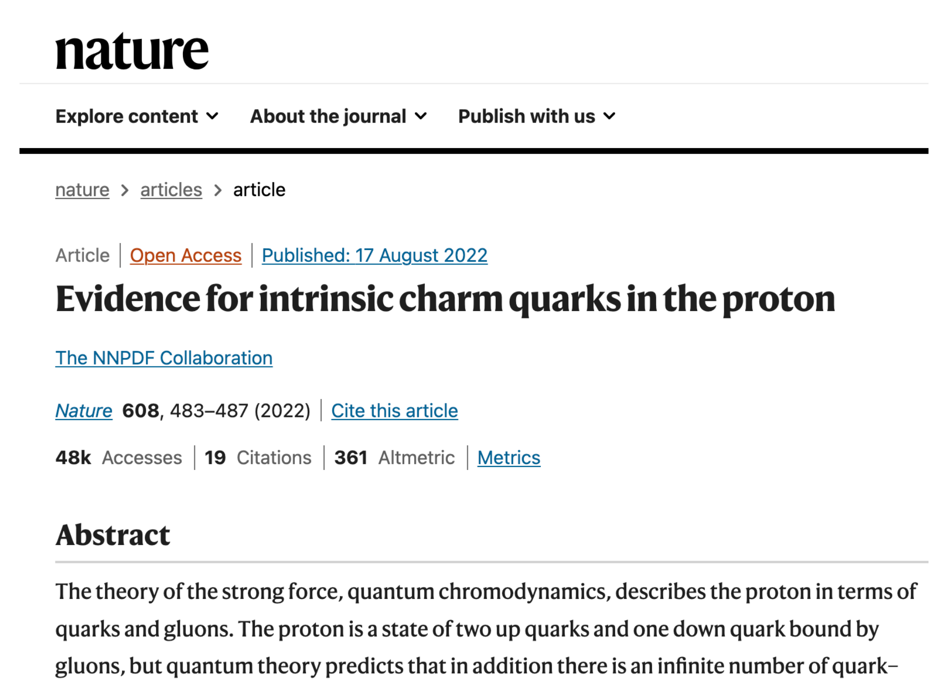




- Consistent results with two different methodologies
- Realising a **Neutrino-Ion Collider** at CERN
- A new window to **intrinsic charm!**

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Article | Open Access | Published: 17 August 2022

Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

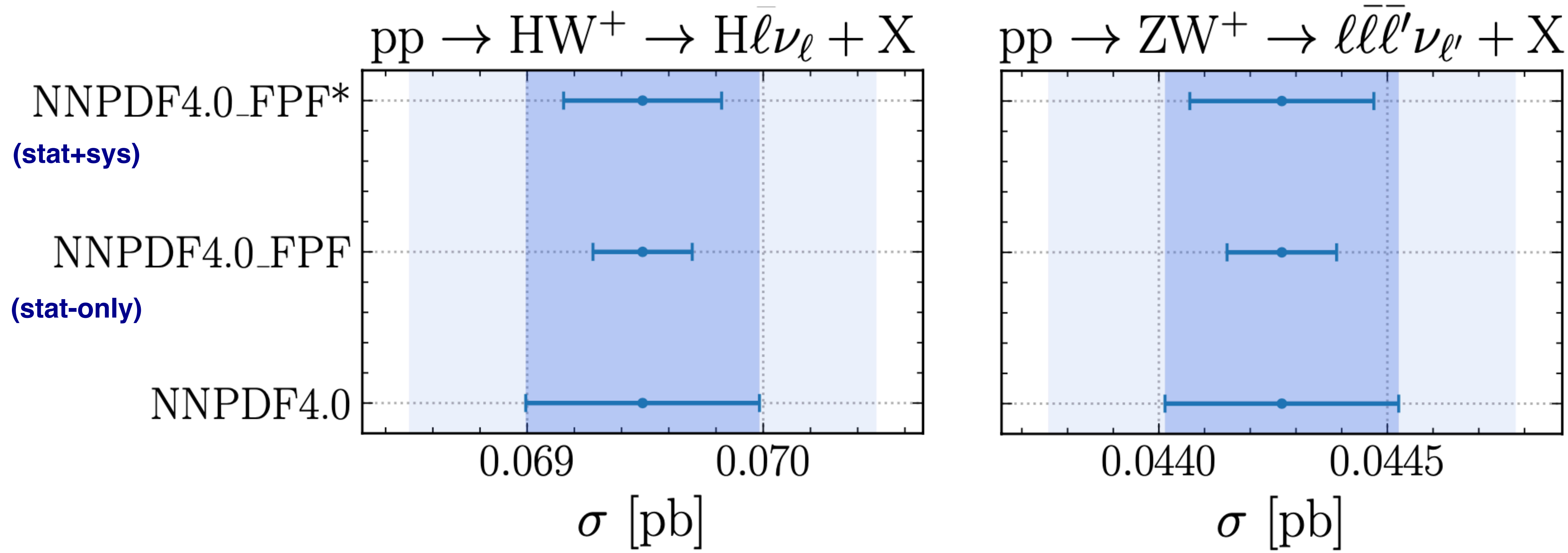
Nature **608**, 483–487 (2022) | Cite this article

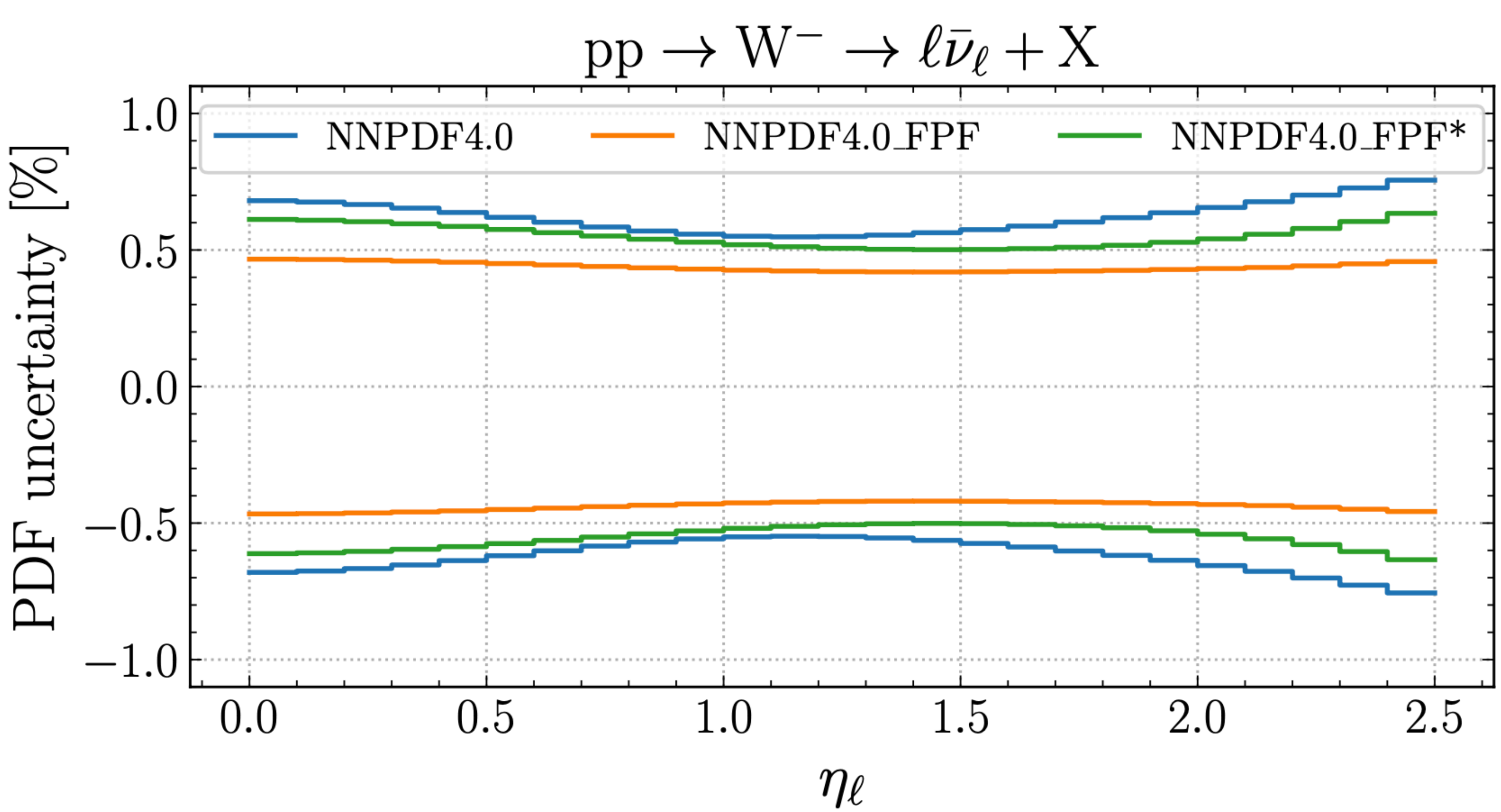
48k Accesses | **19** Citations | **361** Altmetric | Metrics

Abstract

The theory of the strong force, quantum chromodynamics, describes the proton in terms of quarks and gluons. The proton is a state of two up quarks and one down quark bound by gluons, but quantum theory predicts that in addition there is an infinite number of quark–

PDF constraints from LHC neutrinos

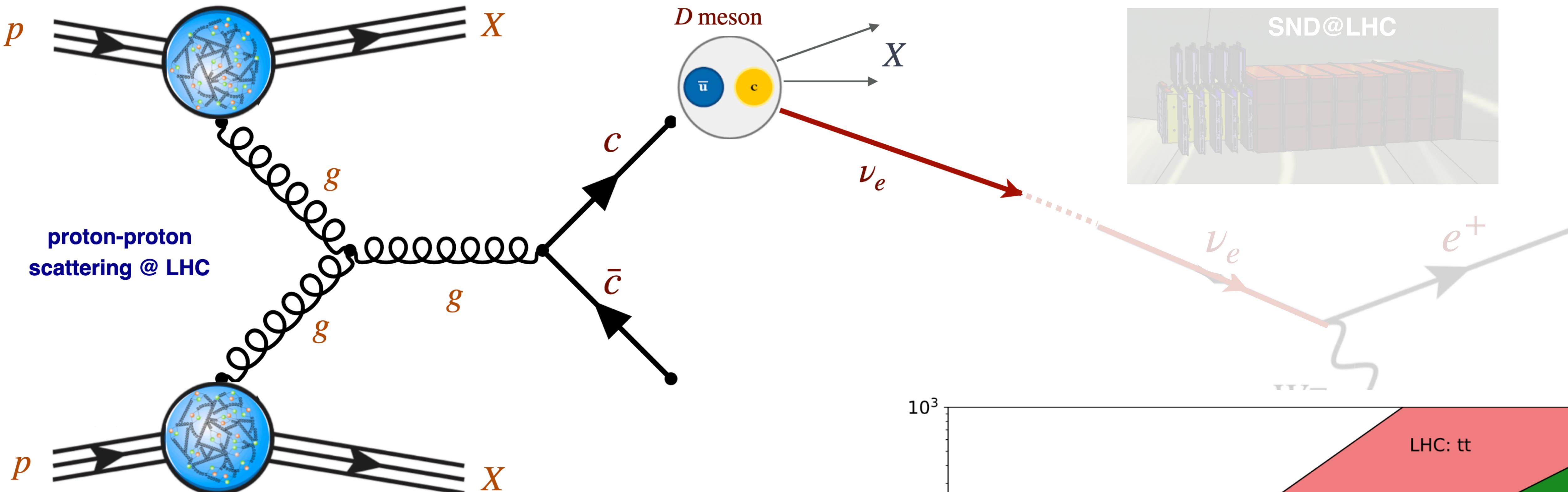




- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

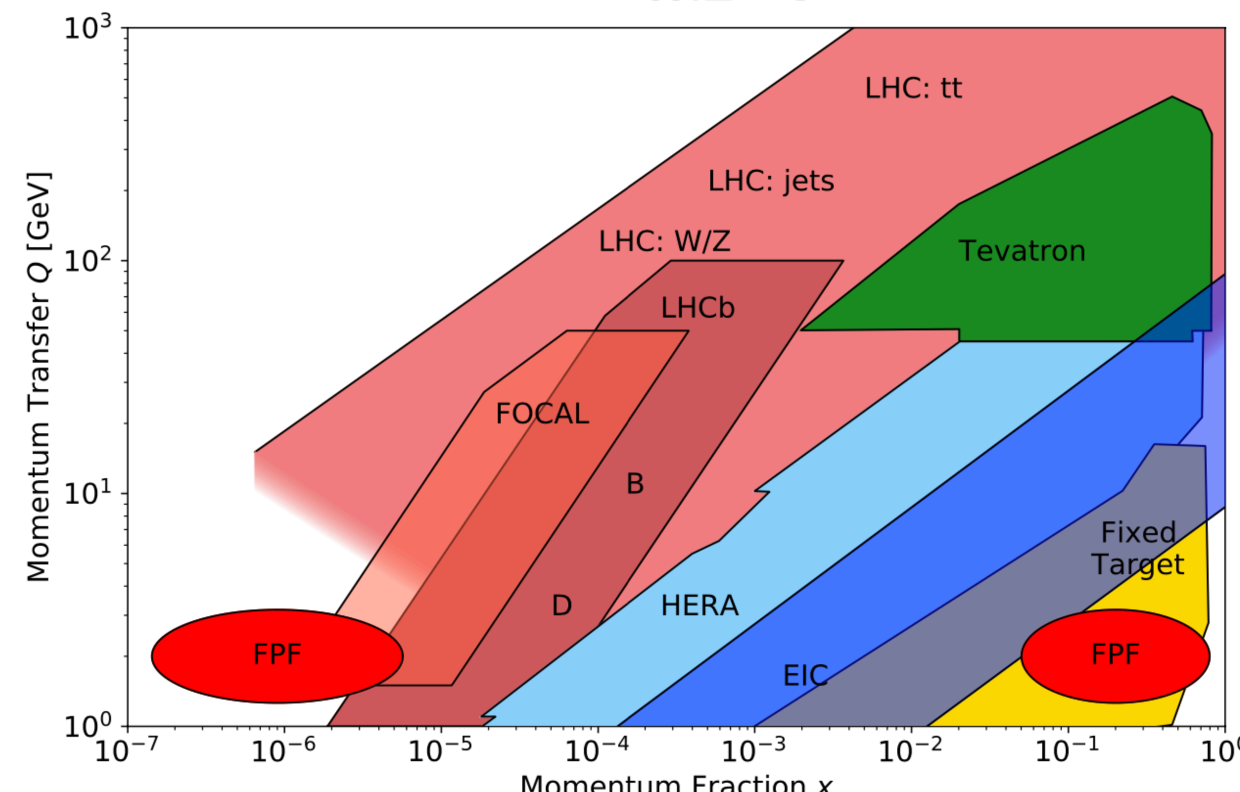
Proton structure at small-x from forward LHC neutrinos

Small-*x* QCD with Forward LHC Neutrinos



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



small-x gluon

large-x

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

Small-x QCD with Forward LHC Neutrinos

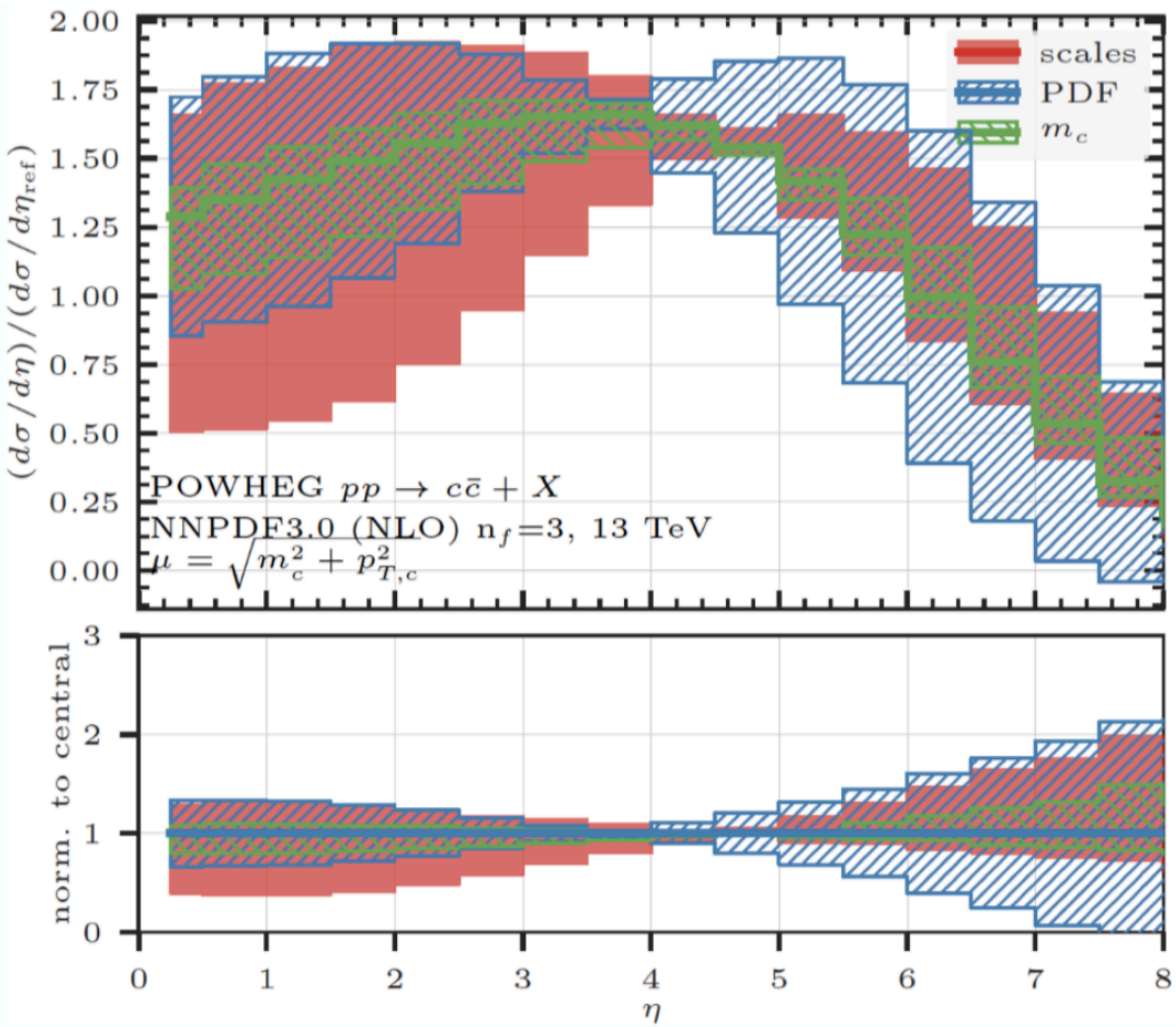
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\hat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

Extract from measured neutrino fluxes

Constrain from LHC neutrino data

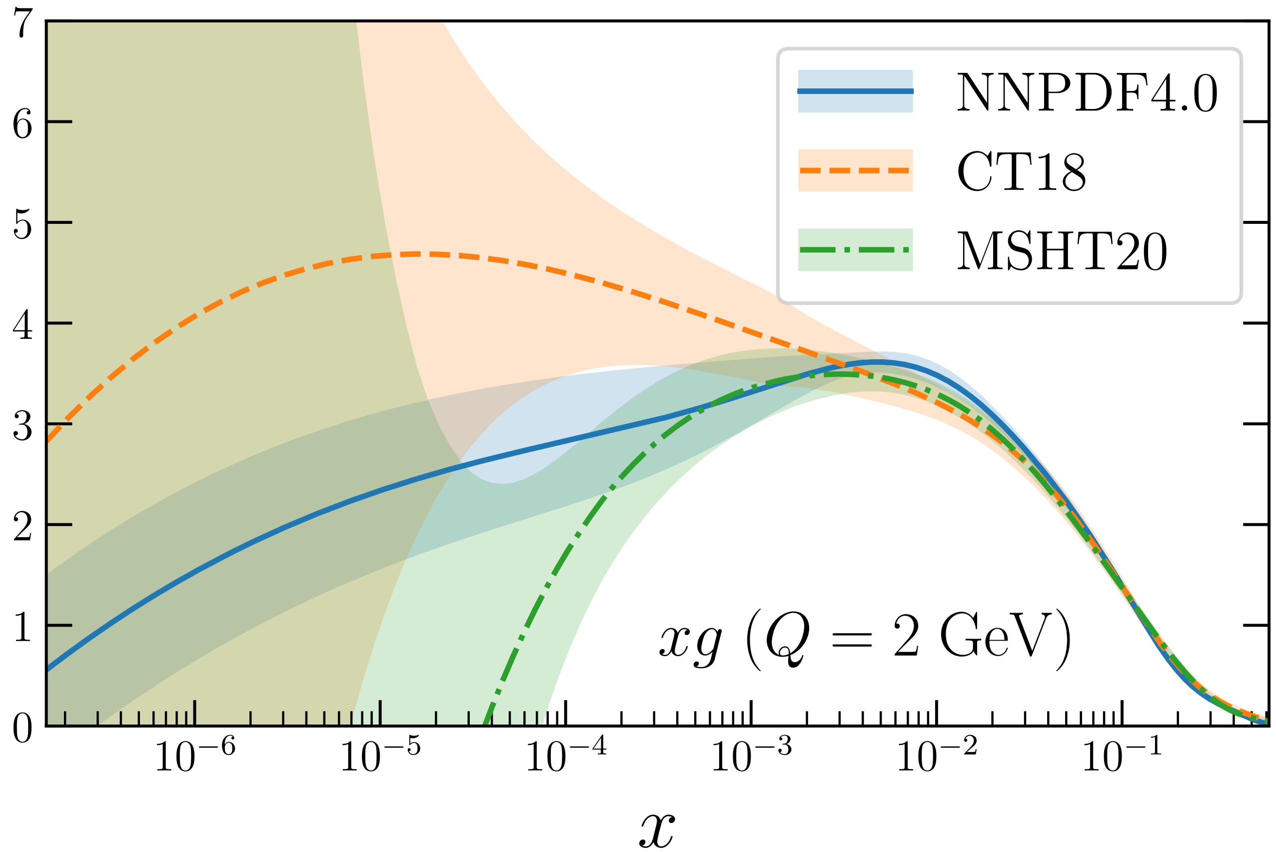
QCD prediction: NLO + PS large theory uncertainties

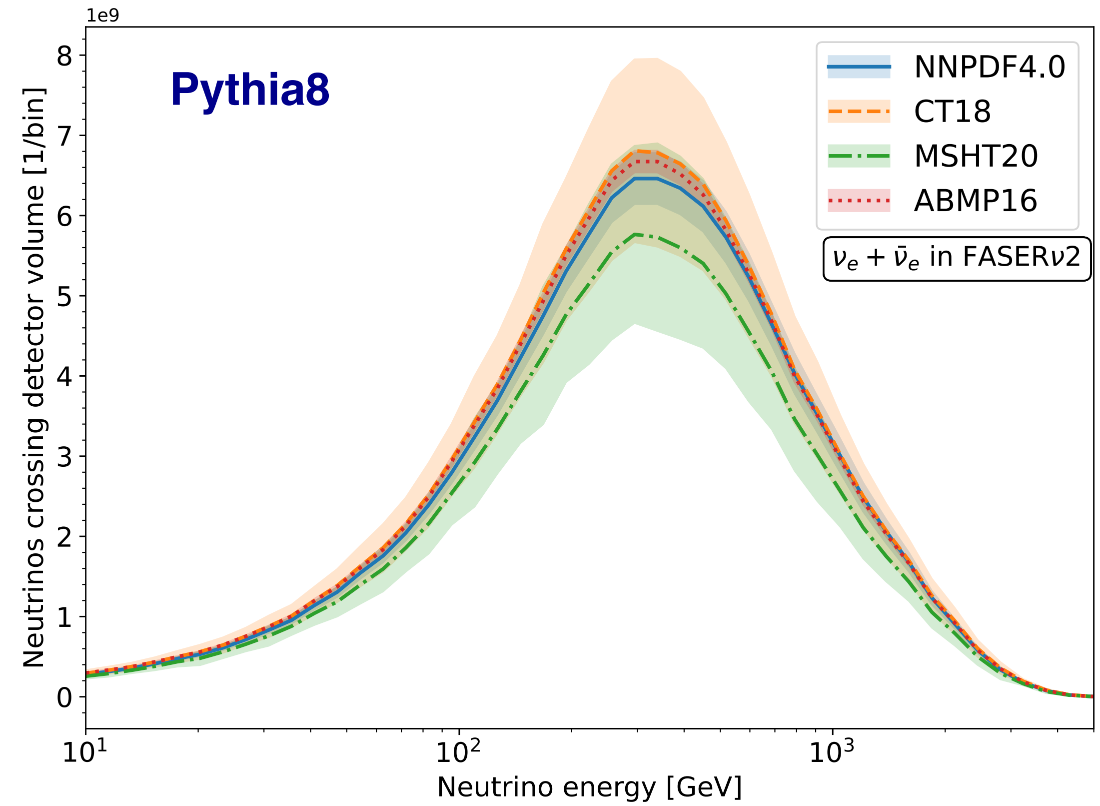
QCD prediction/models + non-perturbative physics



- **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

Small-x QCD with Forward LHC Neutrinos





- 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

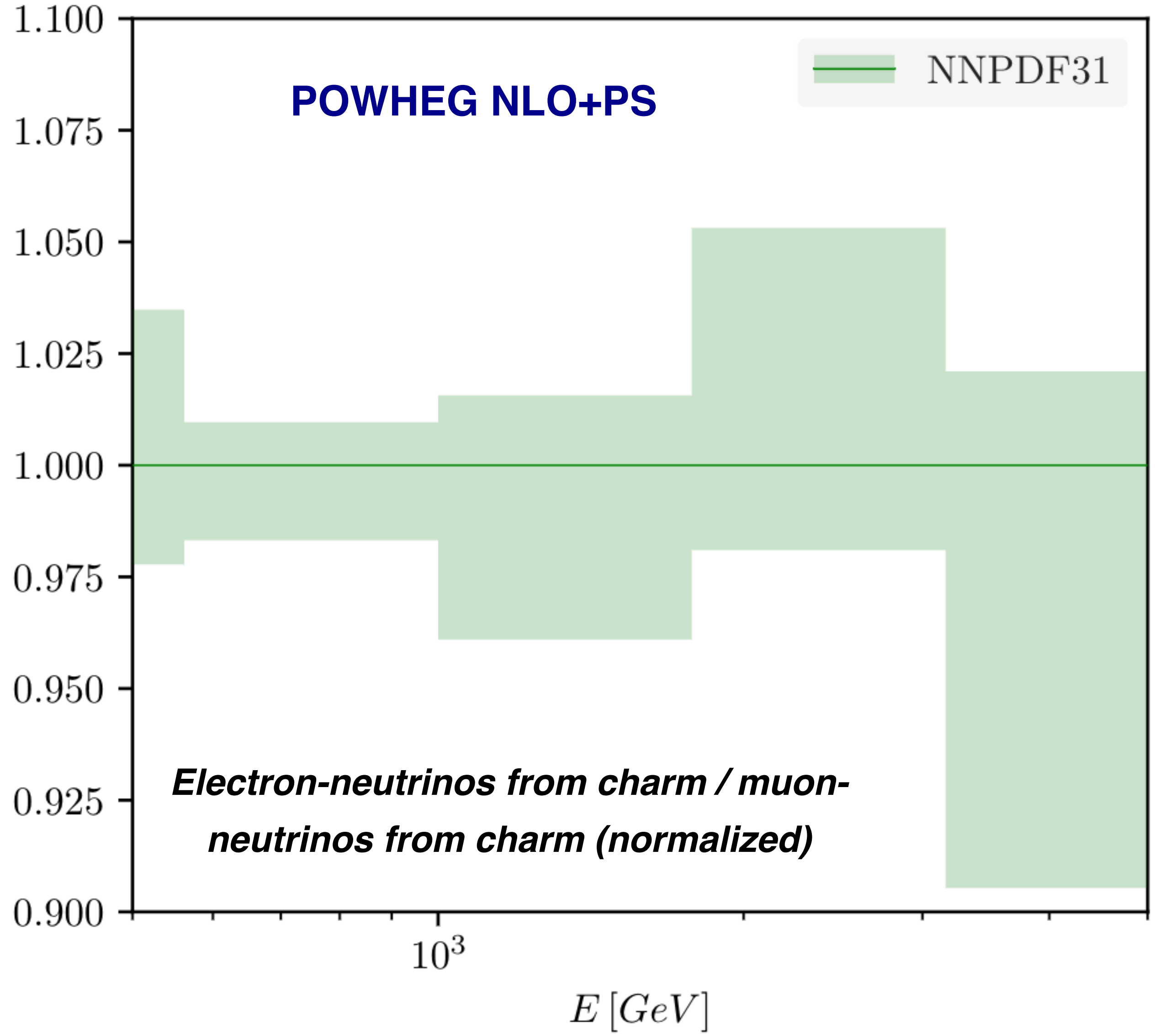
$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)},$$

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

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

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

Small-x QCD with Forward LHC Neutrinos



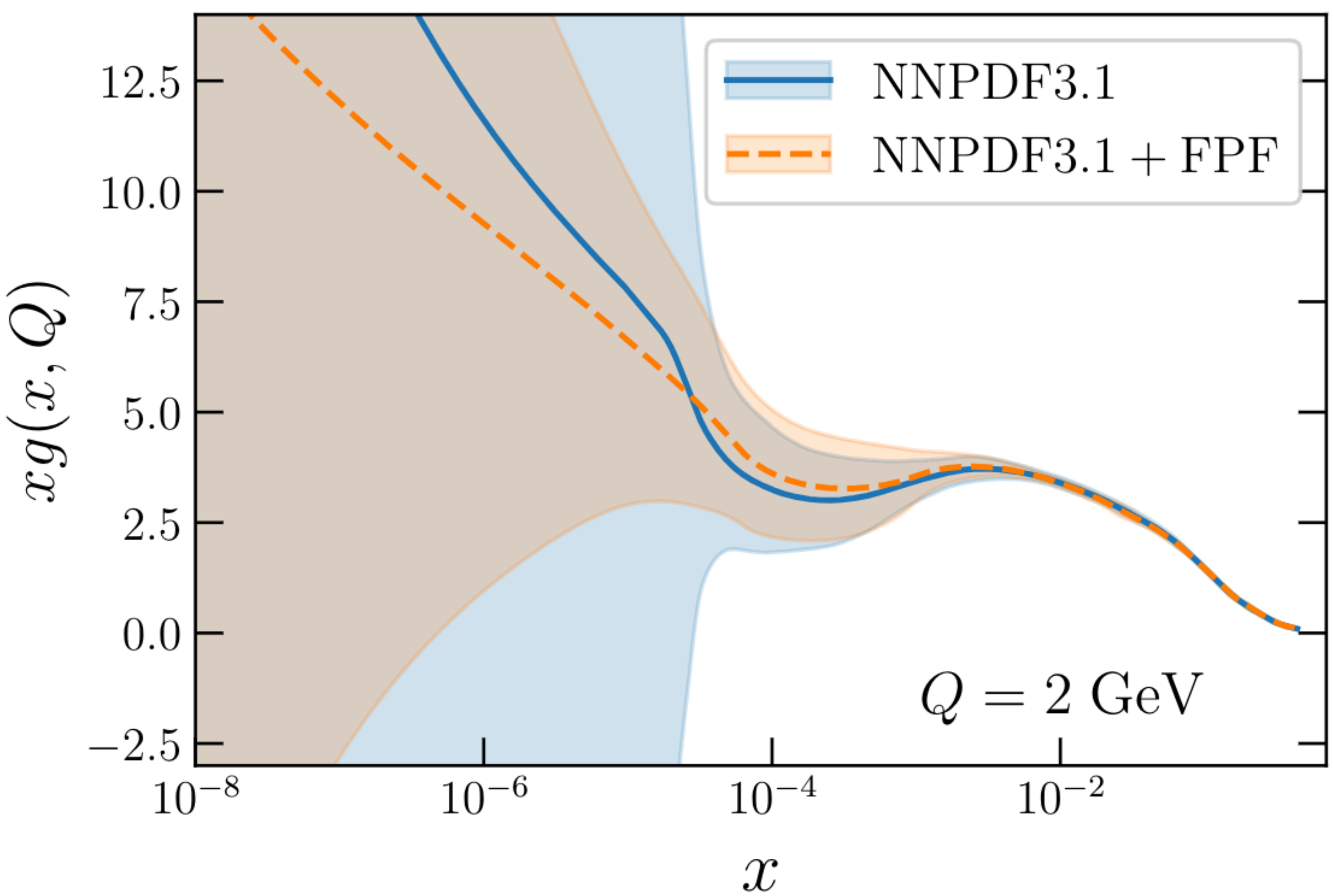
- When taking **ratios of event rates** (e.g. charm electron neutrinos vs charm muon neutrinos), QCD uncertainties reduced to O(few %)
- Strategy: assume a measurement of **inclusive event rates** as a function of neutrino energy with a given precision, quantify impact on PDFs via **Bayesian reweighting**
- Generate pseudo-data for a **measurement of the rapidity ratio** for forward neutrinos

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

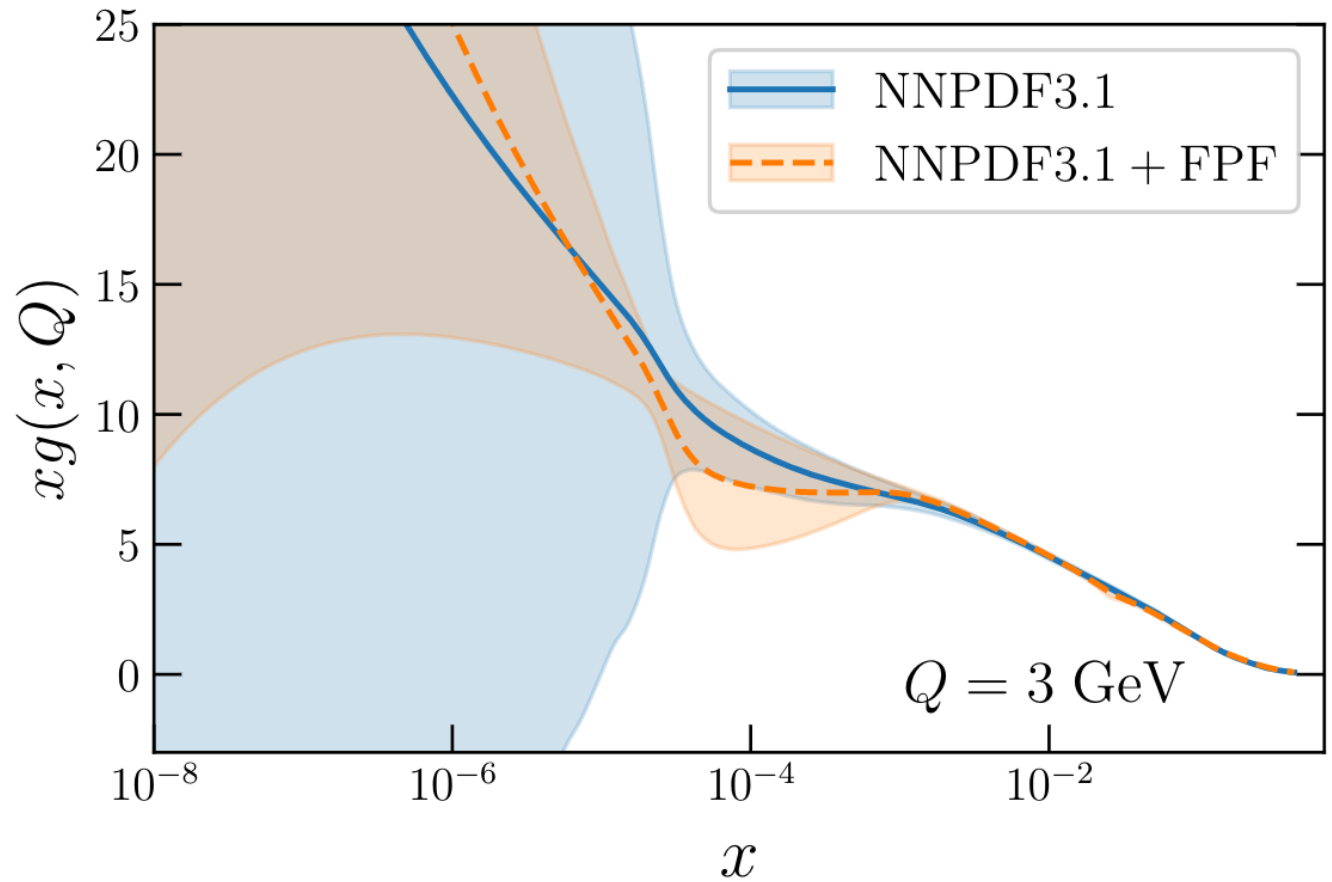
Proxy for "SND@LHC over FASER" ratio

Small-*x* PDFs with Forward LHC Neutrinos

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates

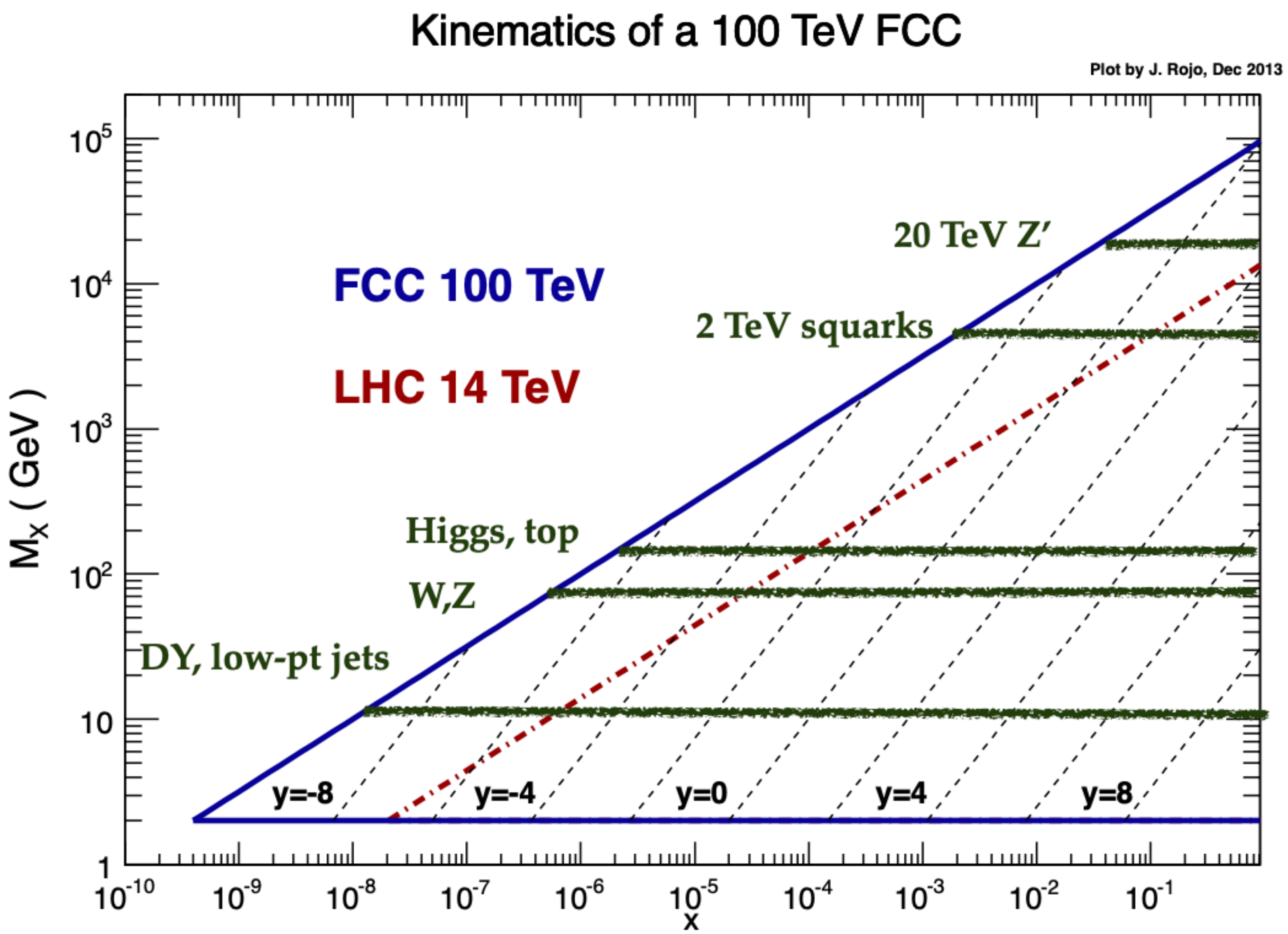


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

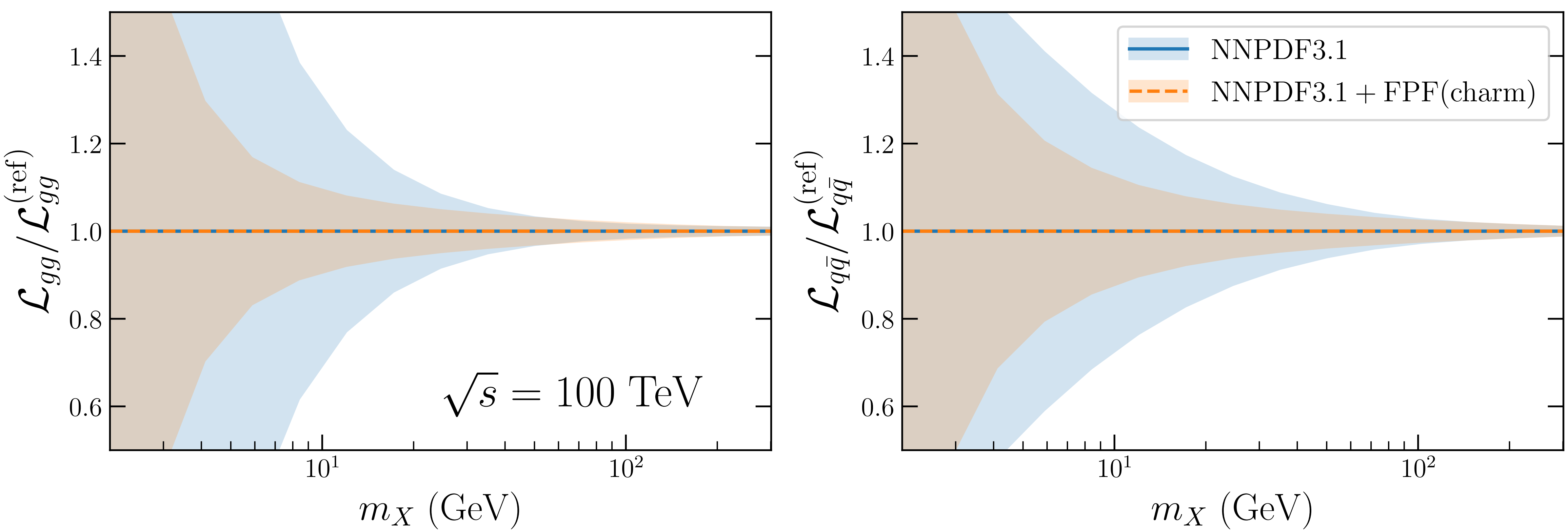
$$R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- 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

Impact at 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



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 Electron Ion Collider

- Measurements of **electron and tau neutrino event rates** at the LHC constrain the **small-*x* gluon and large-*x* charm** in unexplored regions by using dedicated observables

- Improved **neutrino MC generators** demand state-of-the-art QCD calculations suitable for a wide kinematic range: a key ongoing development for LHC neutrino experiments

Neutrino DIS at the LHC

Detector	Rapidity	Target	Charge ID	Acceptance	Performance
FASERν	$\eta_\nu \geq 8.5$	Tungsten (1.1 ton)	muons	$E_\ell \gtrsim 100$ GeV $\tan\theta_\ell \lesssim 0.025$ reco E_h & charm ID	$\delta E_\ell \sim 30\%$ $\delta\theta_\ell \sim 0.06$ mrad $\delta E_h \sim 30\%$
SND@LHC	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (0.83 ton)	n/a	$E_\mu \gtrsim 20$ GeV $\theta_\mu \lesssim 0.15, \theta_e \lesssim 0.5$	n/a
FASERν2	$\eta_\nu \geq 8.5$	Tungsten (20 ton)	muons	$E_\ell \gtrsim 100$ GeV $\tan\theta_\ell \lesssim 0.05$ reco E_h & charm ID	$\delta E_\ell \sim 30\%$ $\delta\theta_\ell \sim 0.06$ mrad $\delta E_h \sim 30\%$
AdvSND-far	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (5 ton)	muons	$E_\mu \gtrsim 20$ GeV $\theta_\mu \lesssim 0.15, \theta_e \lesssim 0.5$ reco E_h	n/a
FLArE (*)	$\eta_\nu \geq 7.5$	LAr (10 ton) **(also 30 ton option)**	muons	$E_\mu \gtrsim 2$ GeV, $E_e \lesssim 2$ TeV $\theta_\mu \lesssim 0.025,\ \theta_e \lesssim 0.5$ reco E_h	$\delta E_e \sim 5\%,\ \delta E_\mu \sim 30\%$ $\delta\theta_e \sim 15,\ \delta\theta_\mu \sim 0.06$ mrad $\delta E_h \sim 30\%$

Realistic **acceptance** and **efficiencies** included in our event rate calculations