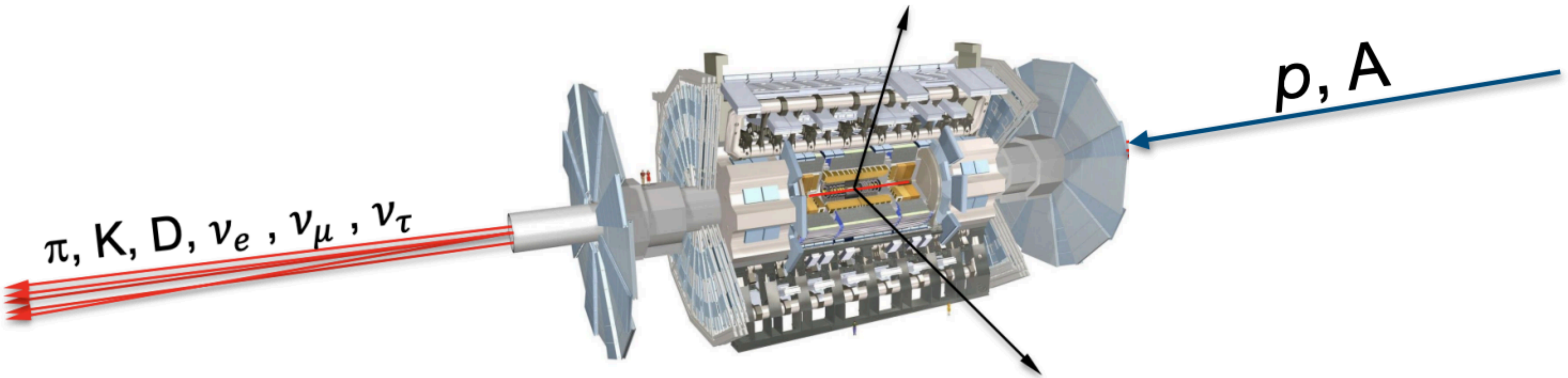
Neutrino Facilities at CERN

Juan Rojo, VU Amsterdam & Nikhef



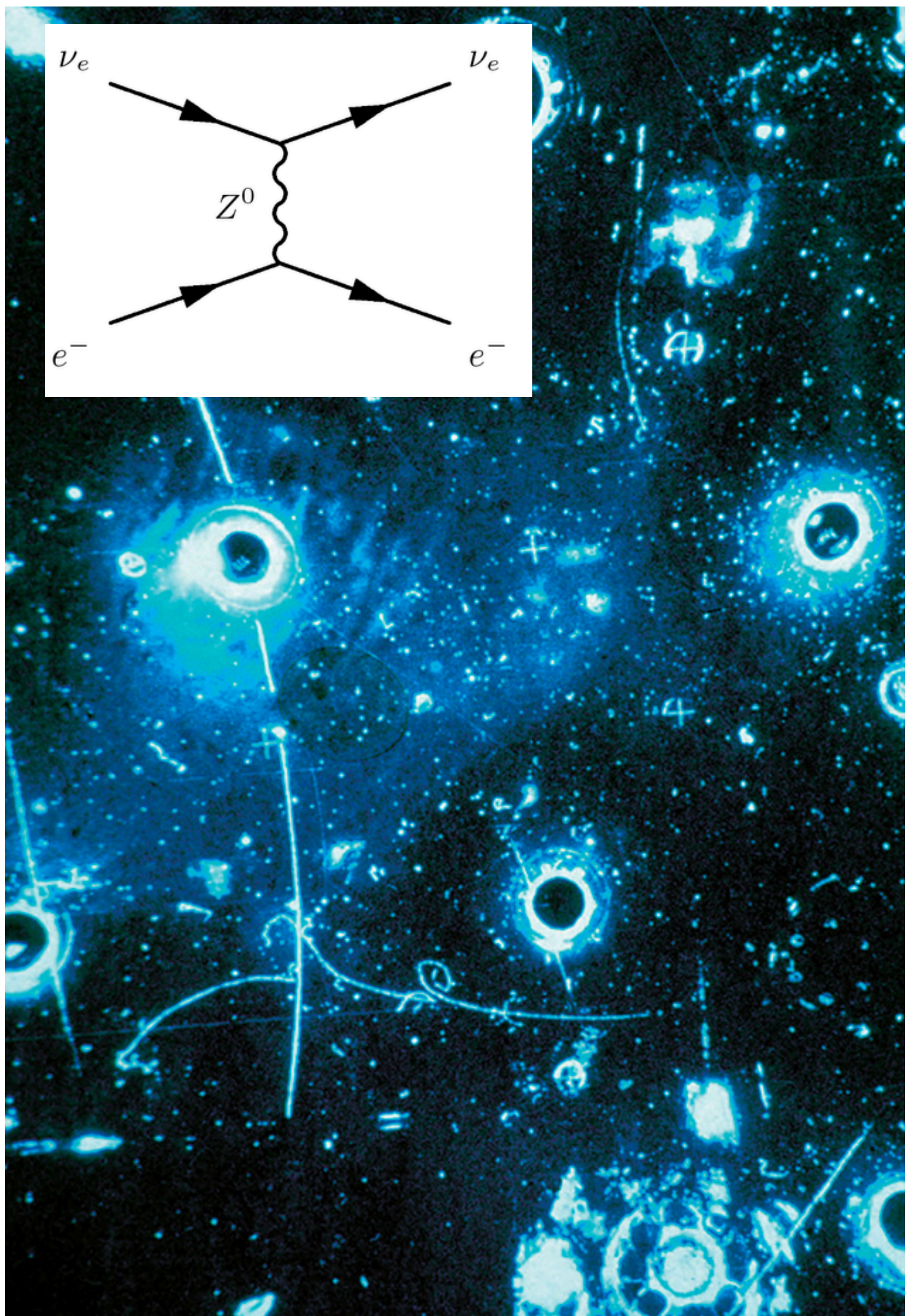
NuPhys2023: Prospects in Neutrino Physics

UCL, 20th December 2023

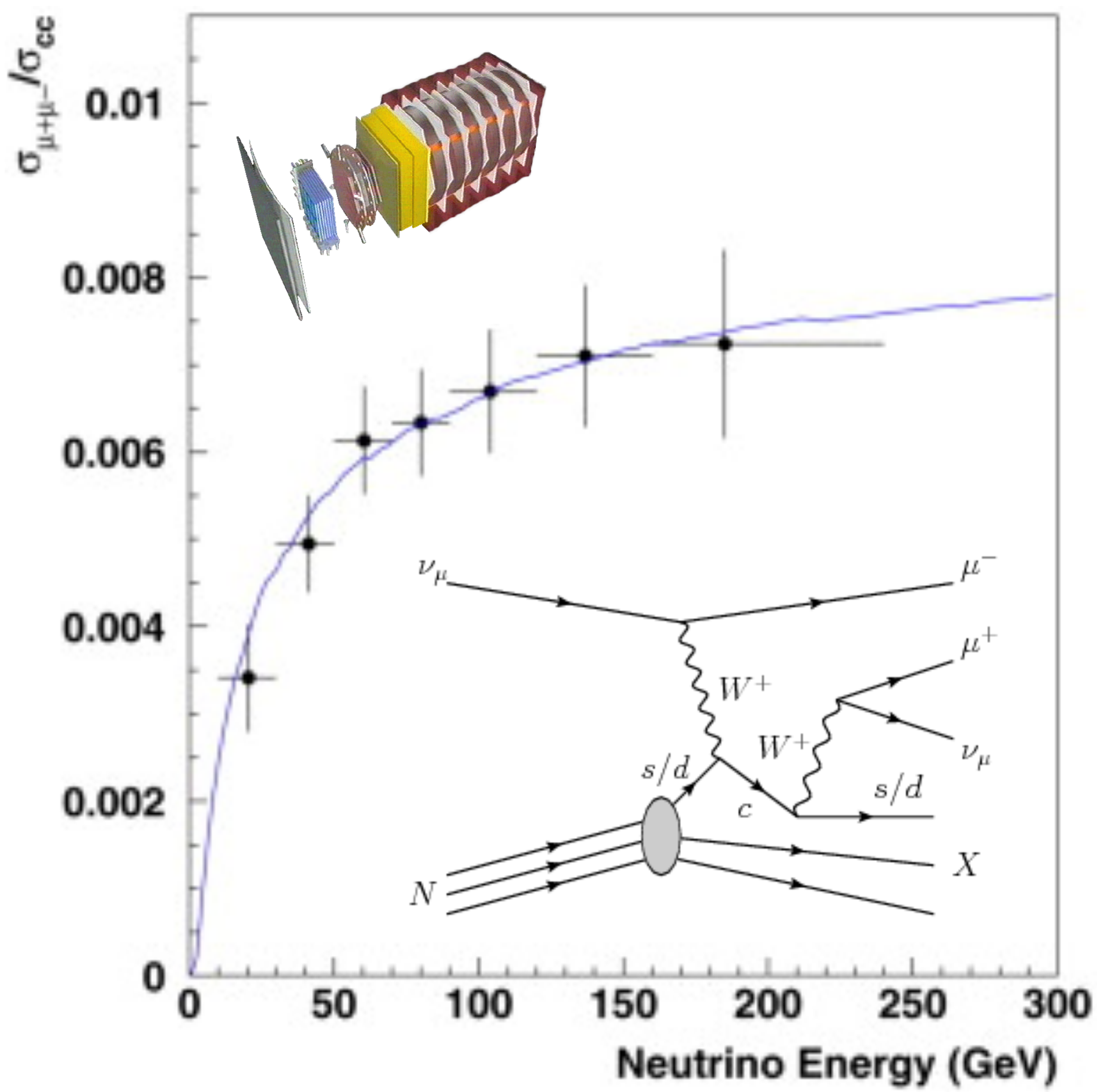
CERN & Neutrinos

- Neutrino experiments at CERN have provided significant contributions to our modern understanding of **hadronic, nuclear, and particle physics**

discovery of weak neutral currents @ Gargamelle (1972)



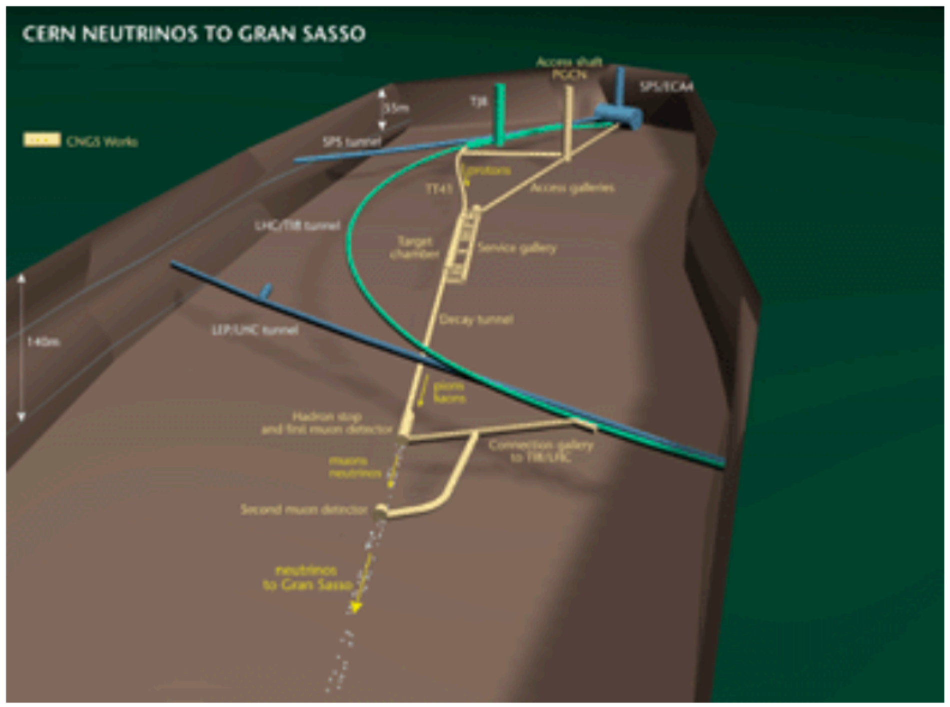
measurement of proton's strange content @ CHORUS (2008)



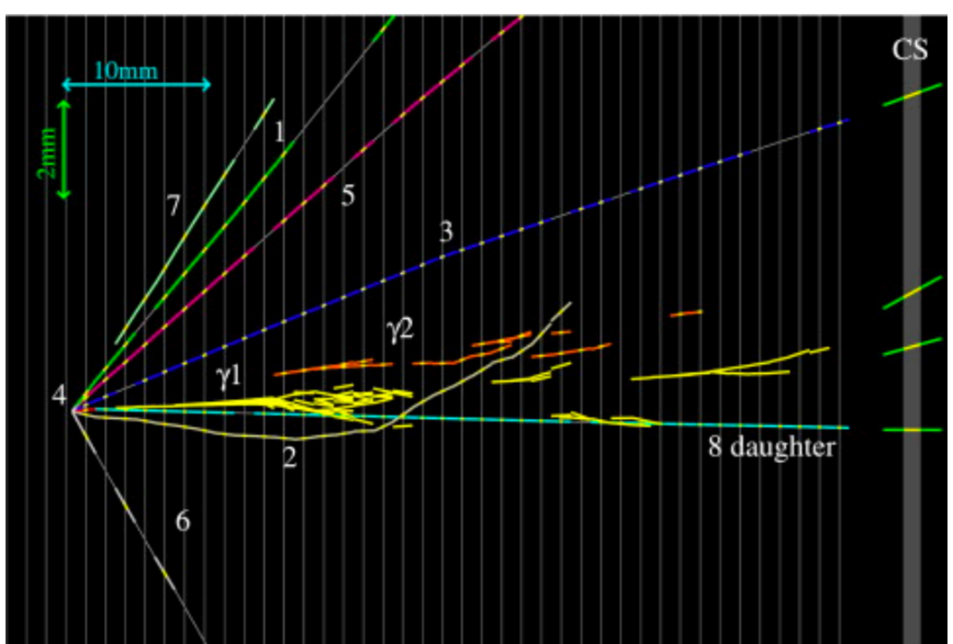
CERN & Neutrinos

- Neutrino experiments at CERN have provided significant contributions to our modern understanding of **hadronic, nuclear, and particle physics**

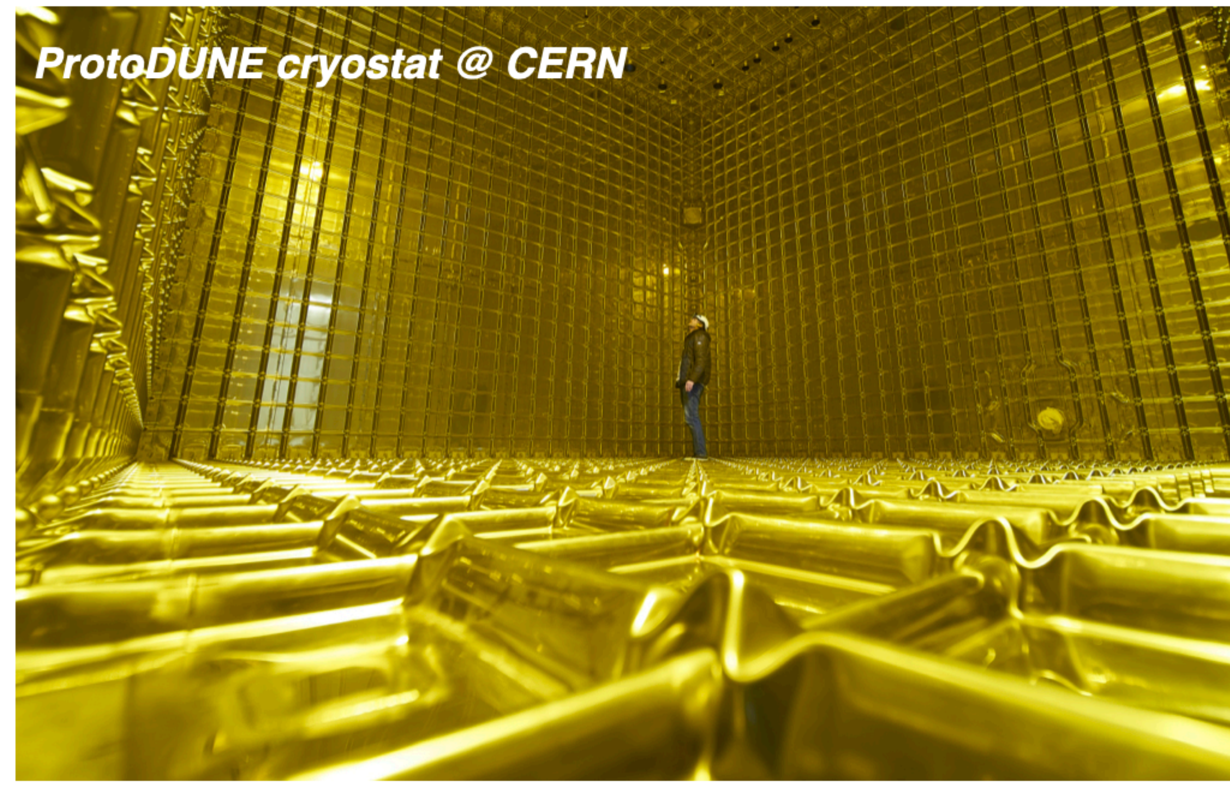
CERN to Gran Sasso neutrino beams (2006-2012)



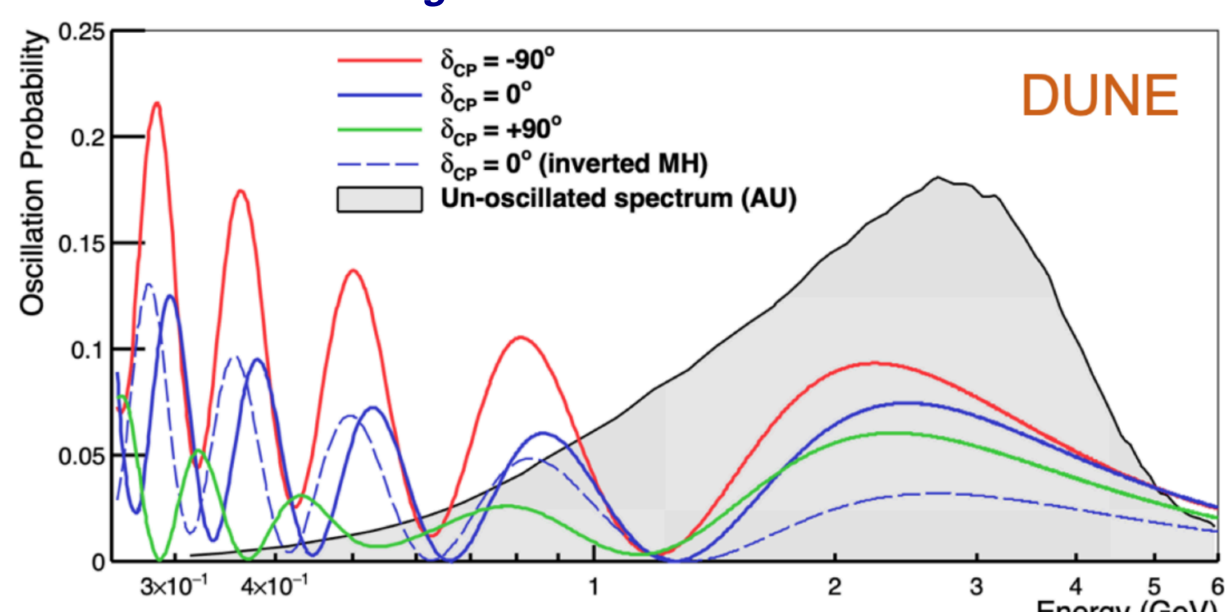
Observation of tau neutrino candidates @ OPERA



CERN Neutrino Platform: paving the way for DUNE



Establishing CP violation in the neutrino sector

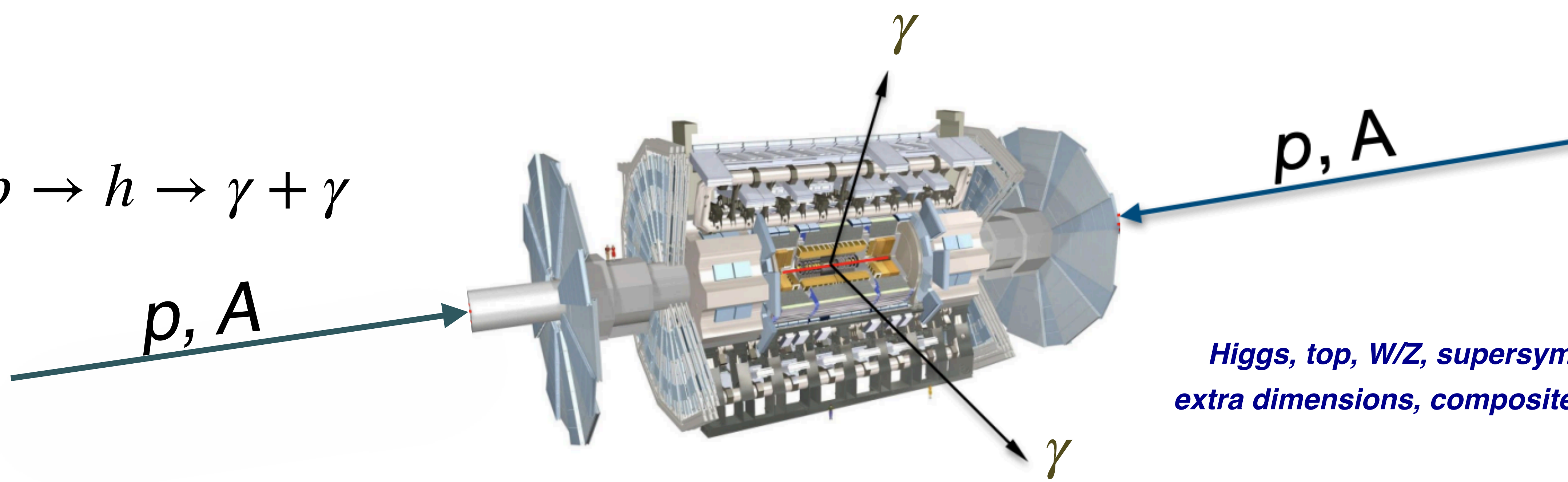


The Dawn of the Collider Neutrino Era

Neutrinos at the LHC

- The ATLAS and CMS detectors were designed with a focus on identifying particles **with masses at the electroweak and TeV scale**
- Due to kinematics**,** their decay products lie in the **central rapidity** acceptance region

$$p + p \rightarrow h \rightarrow \gamma + \gamma$$



Higgs, top, W/Z, supersymmetry, extra dimensions, composite Higgs…

neglecting mass effects

$$y \simeq \eta = \log \tan(\theta/2)$$

scattering angle

$$\cosh(\eta_{\rm max}) = \frac{\sqrt{s}}{m_h}$$

for ATLAS & CMS

$$|\eta_{\rm max}| \leq 2.5 \ (3.5)$$

central region covered

- Light particles (pions, kaons, protons, heavy flavour mesons) produced predominantly in the **forward rapidity region**, justifying e.g. the design of **LHCb**

for LHCb

$$2.0 \leq \eta \leq 4.5$$

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

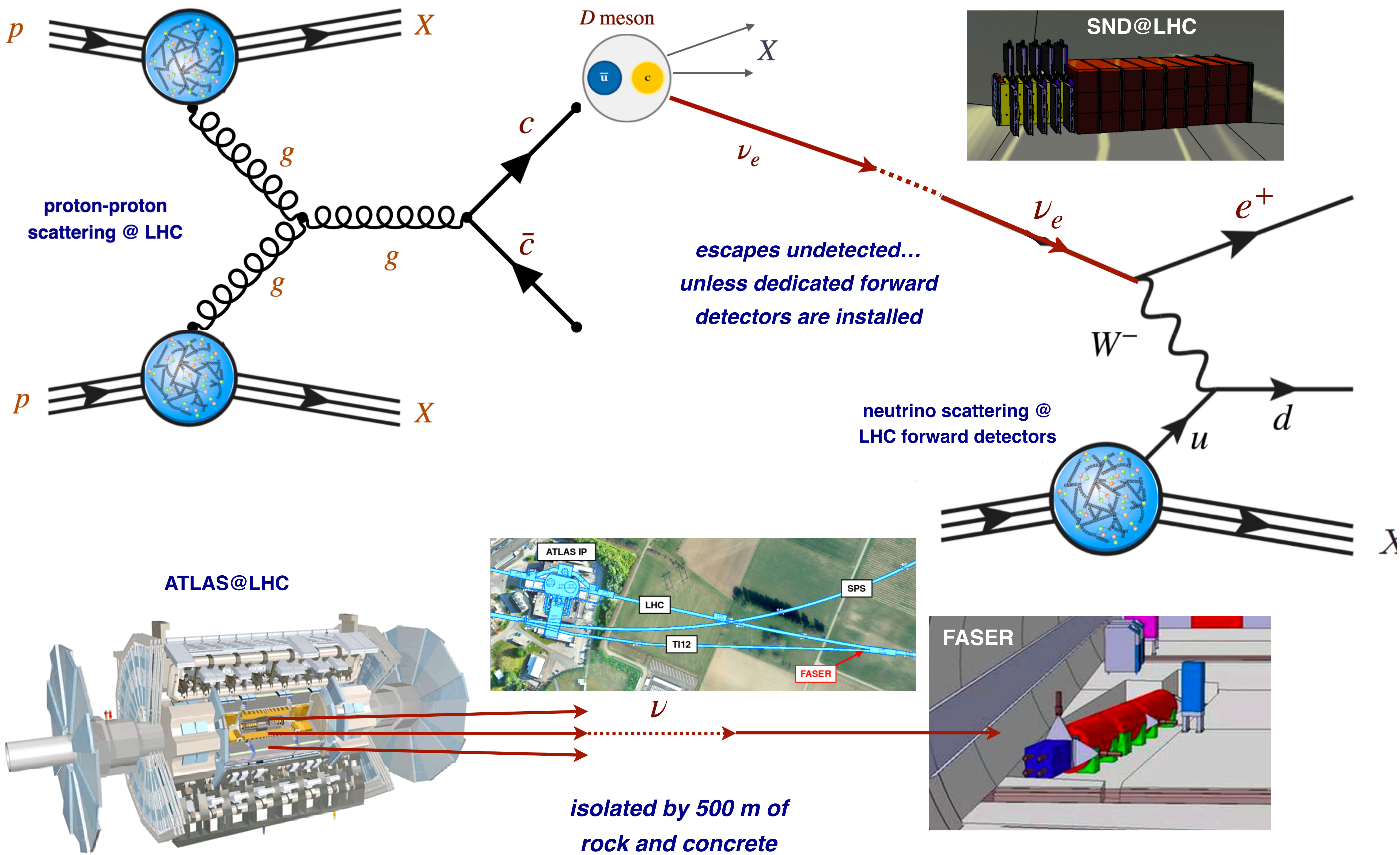
A. De Rujula (CERN), R. Ruckl (CERN)
May, 1984

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

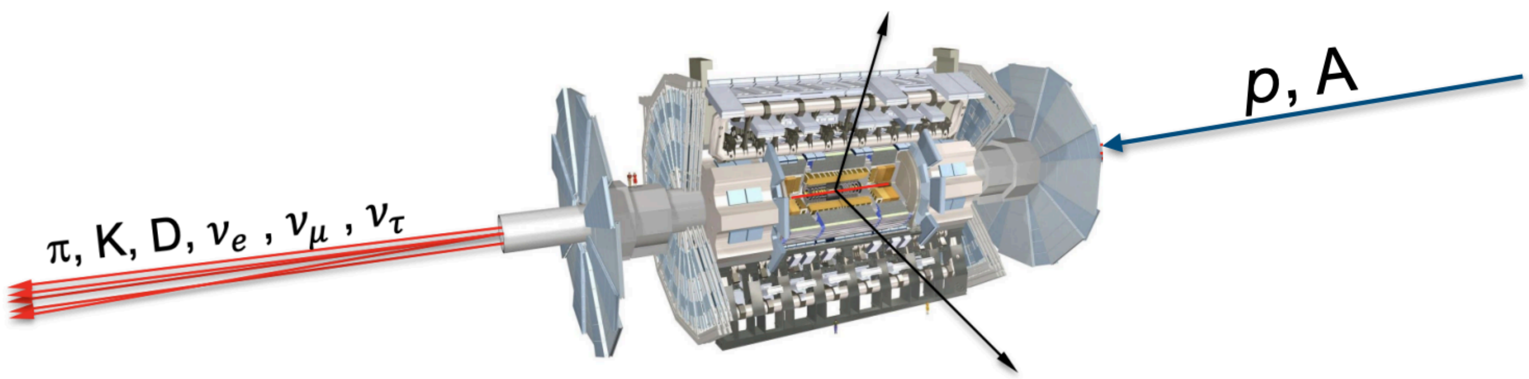
pdf cite claim reference search 14 citations

First proposal in 1984

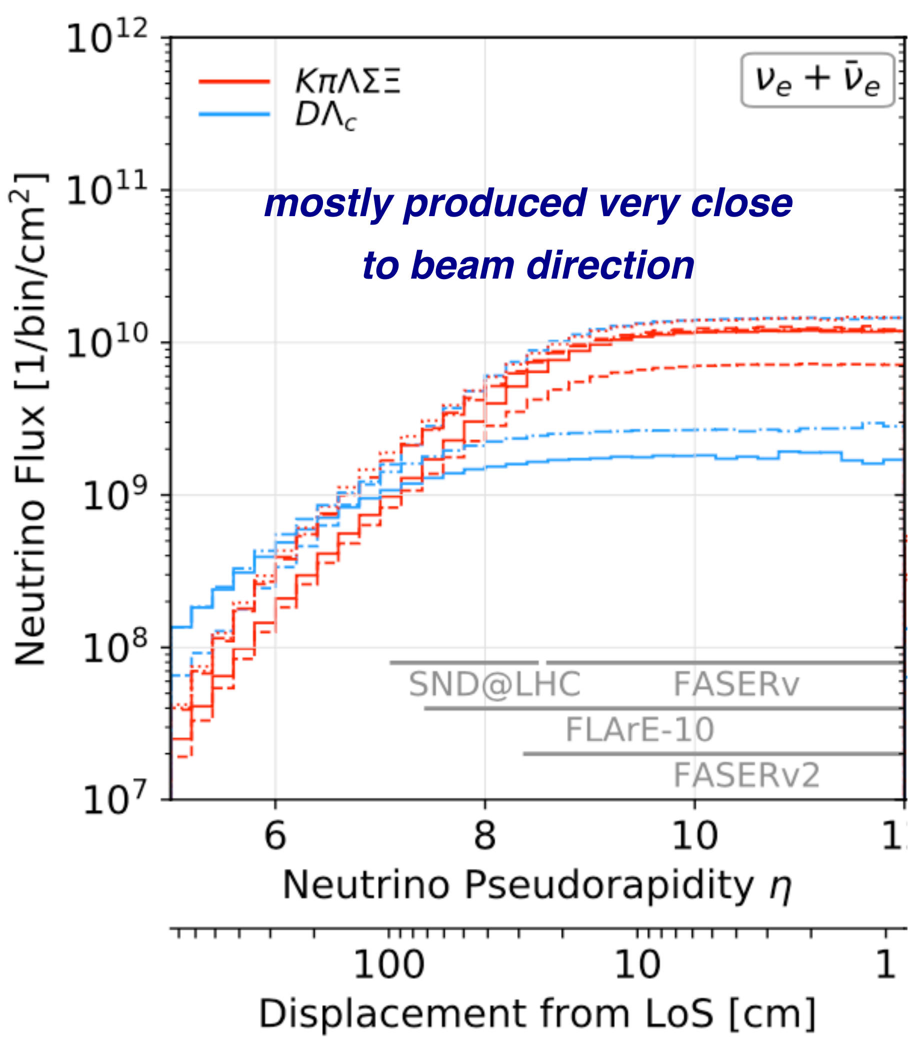
Neutrino production and scattering

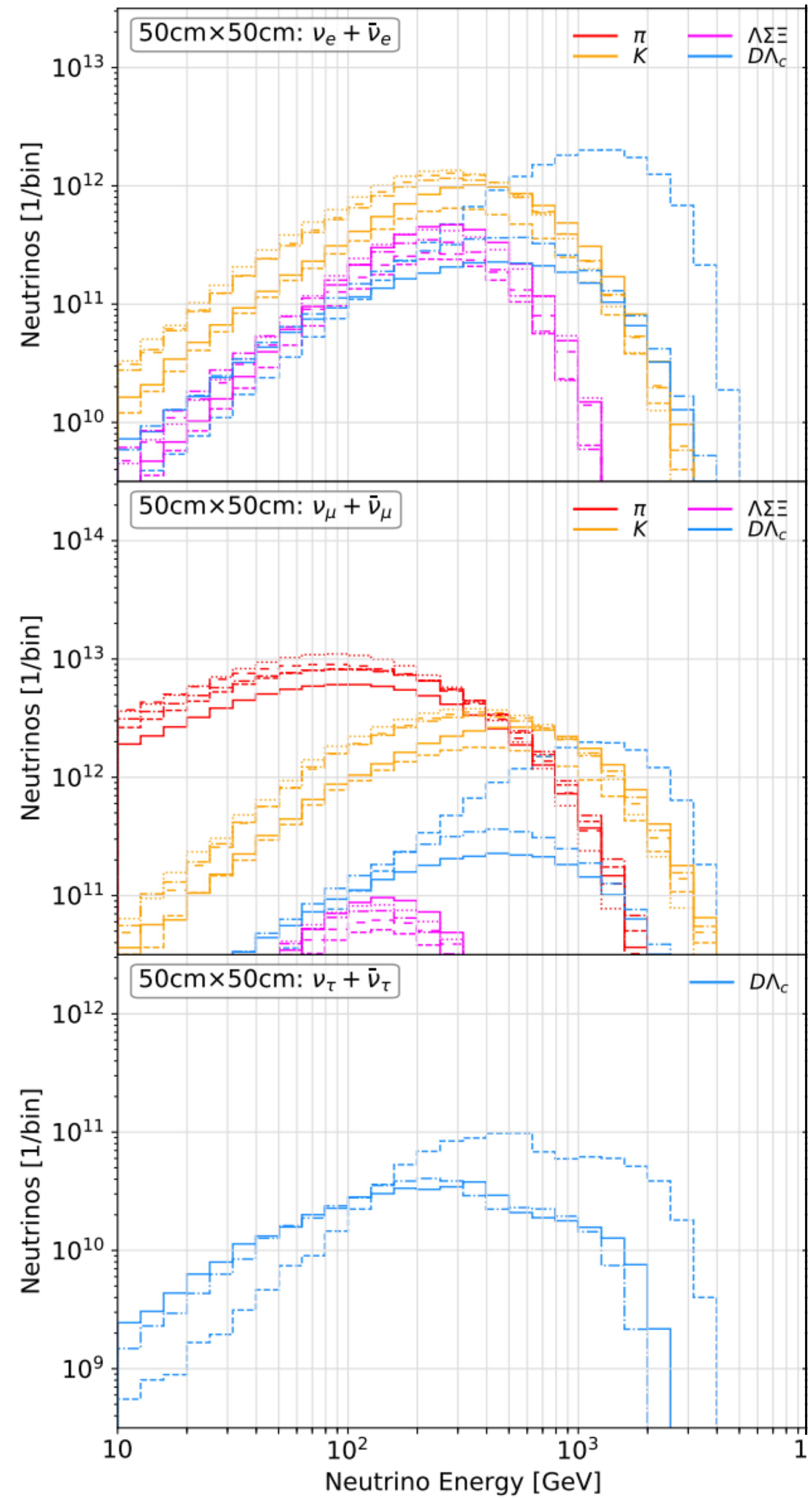


Neutrinos at the LHC



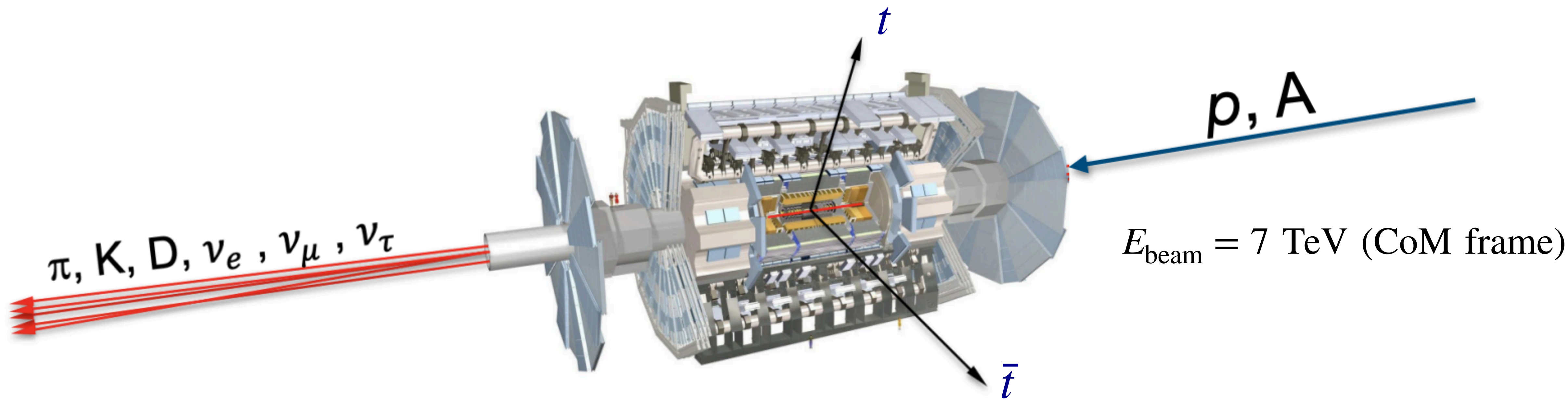
- **electron neutrinos** mostly from *D*-meson decays above 500 GeV, below it mostly from kaon decays
- **muon neutrino** flux dominated by pion & kaon decays
- **tau neutrinos** entirely from D-meson decays



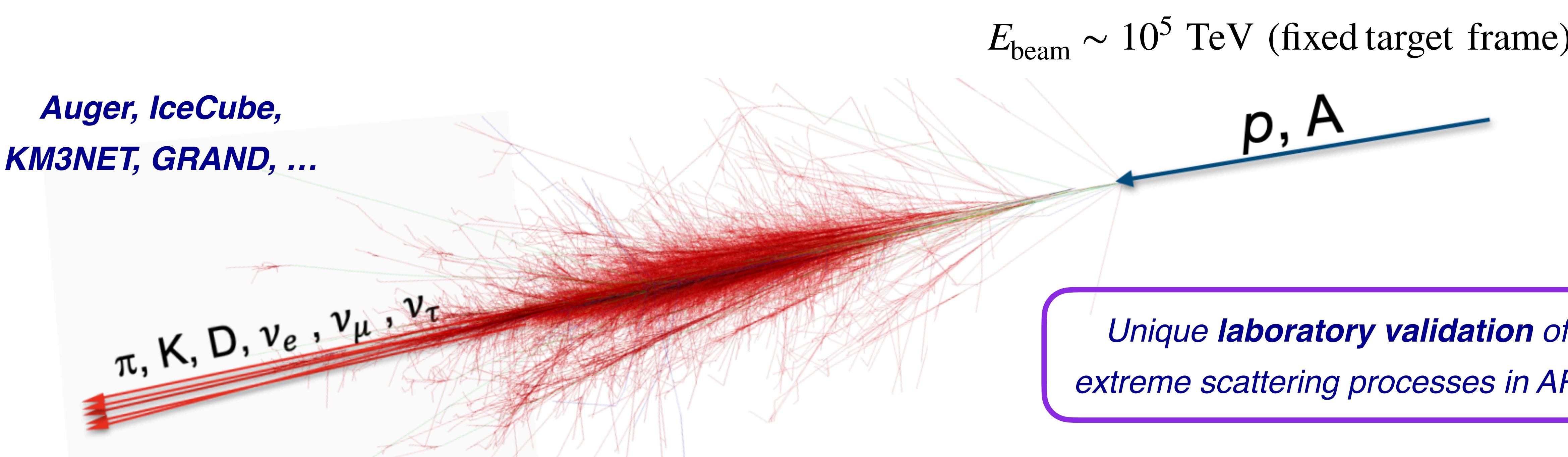


The Cosmic Connection

- 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



*Unique **laboratory validation** of extreme scattering processes in APP*

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

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

Editors' Suggestion

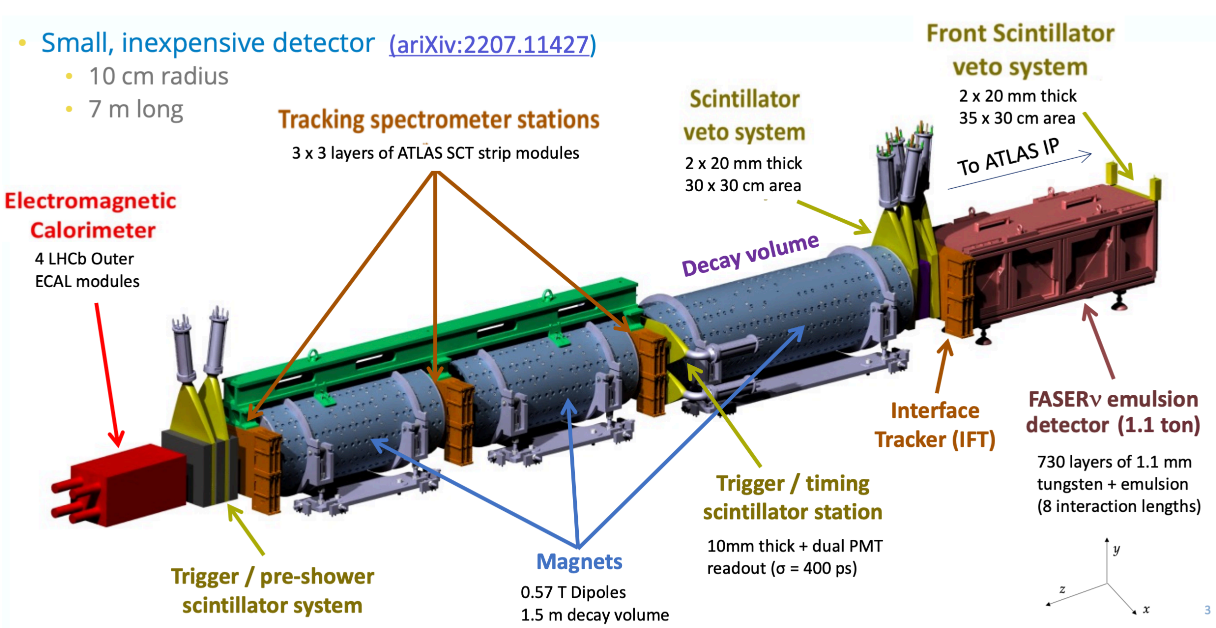
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

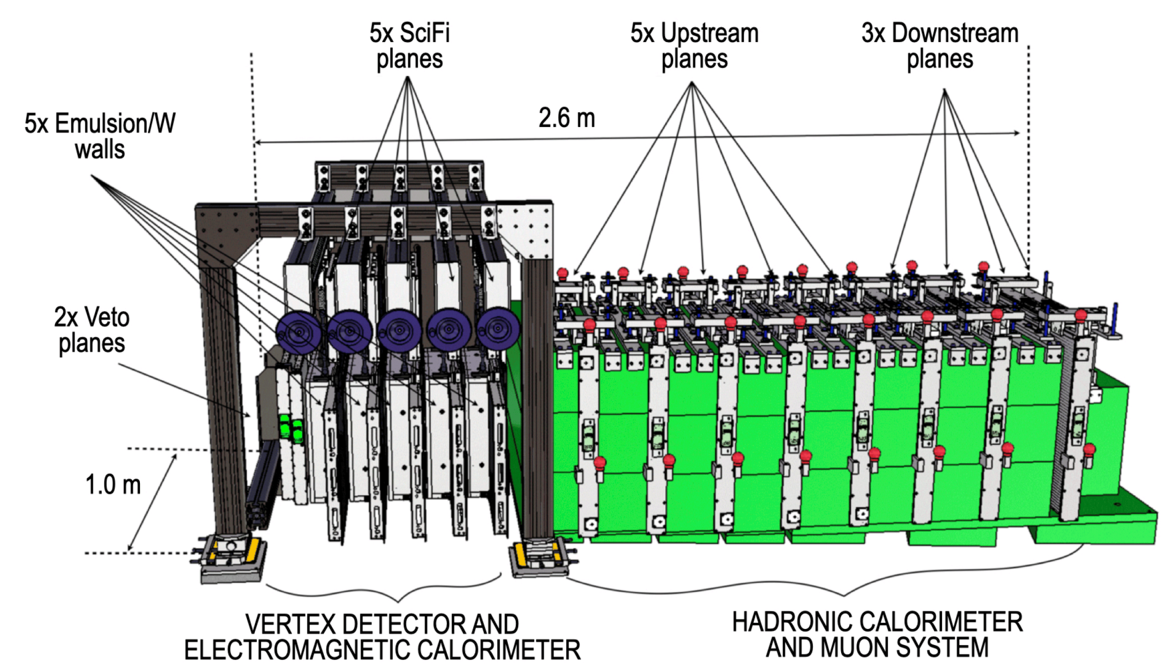
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on 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

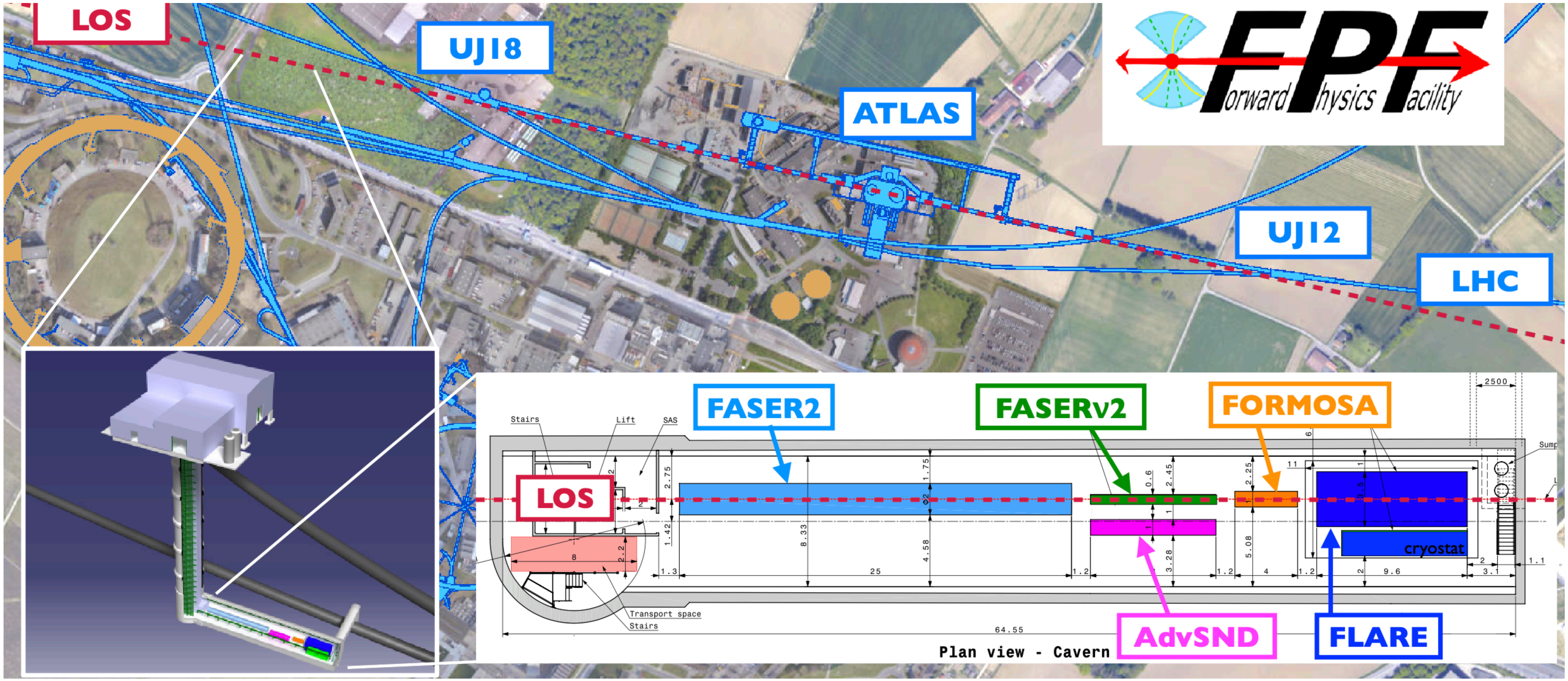




Now is the time to start exploiting their physics potential

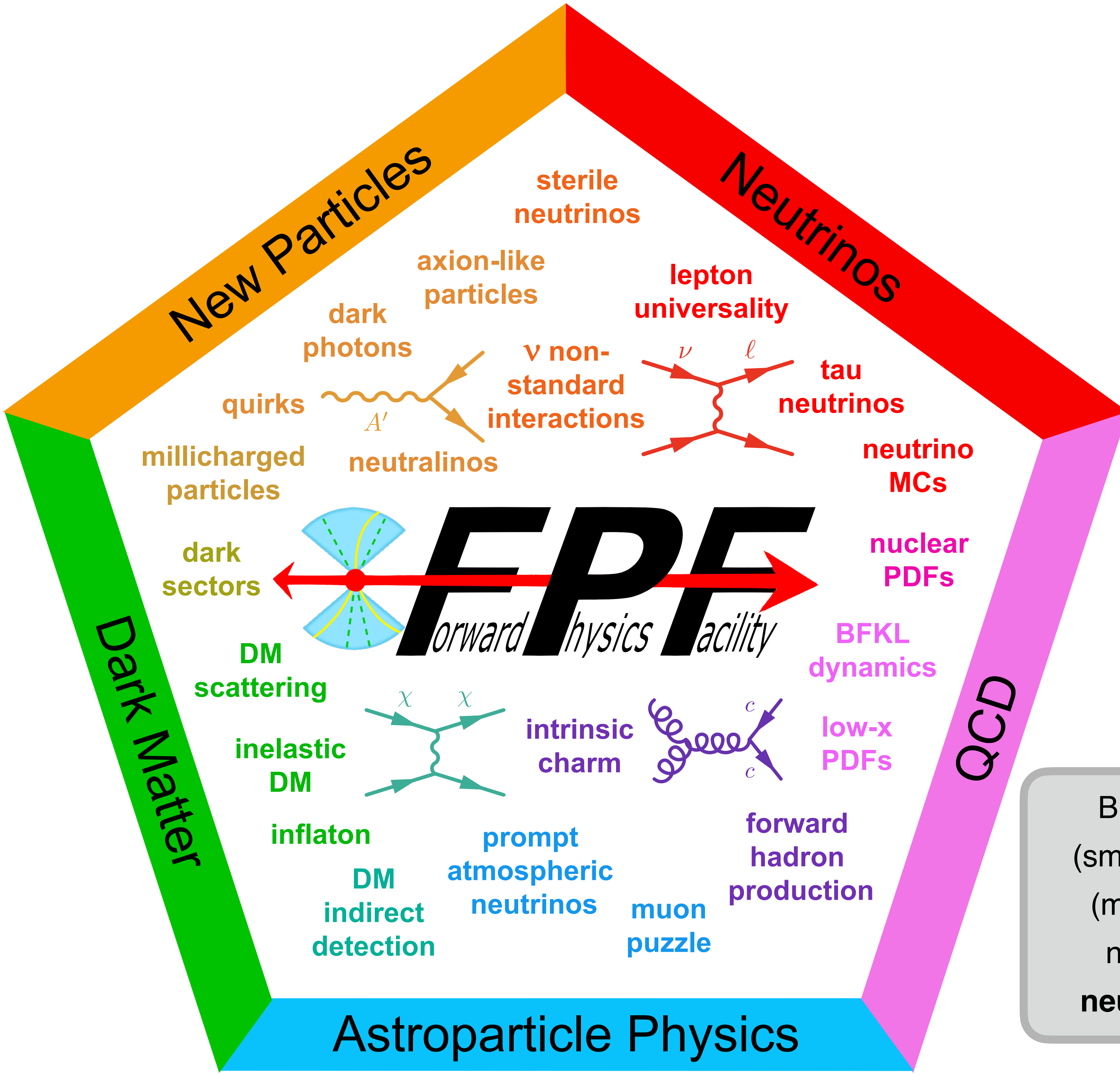
The Forward Physics Facility

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



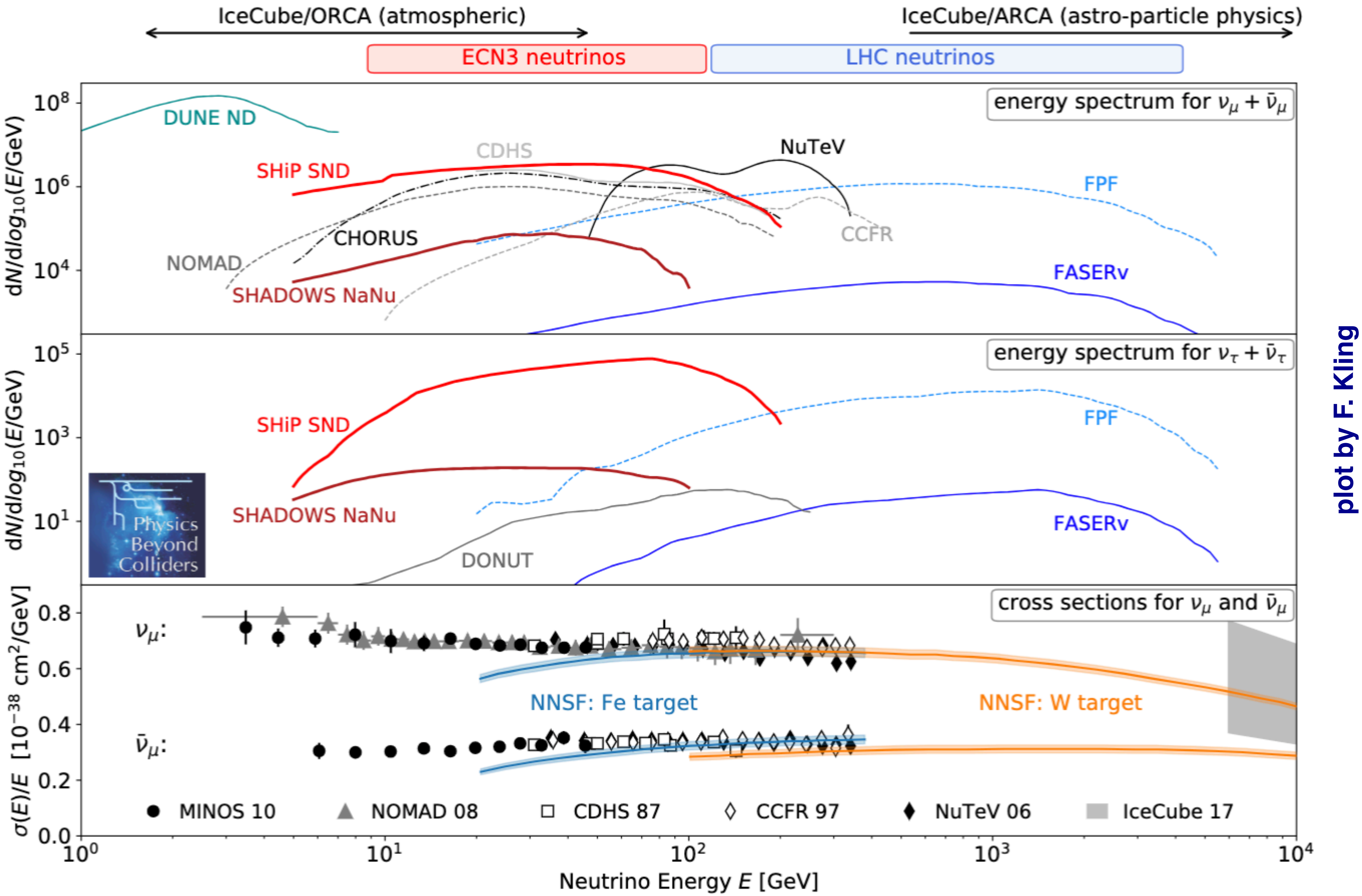
- Complementary suite of **far-forward experiments,** operating **concurrently with the HL-LHC**
- Start **civil engineering during LS3** or shortly thereafter, to maximise overlap with HL-LHC
- Positive outcome of **ongoing site investigation** studies (geological drill down to the cavern depth)

Physics with LHC neutrinos



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** …

Physics with LHC neutrinos

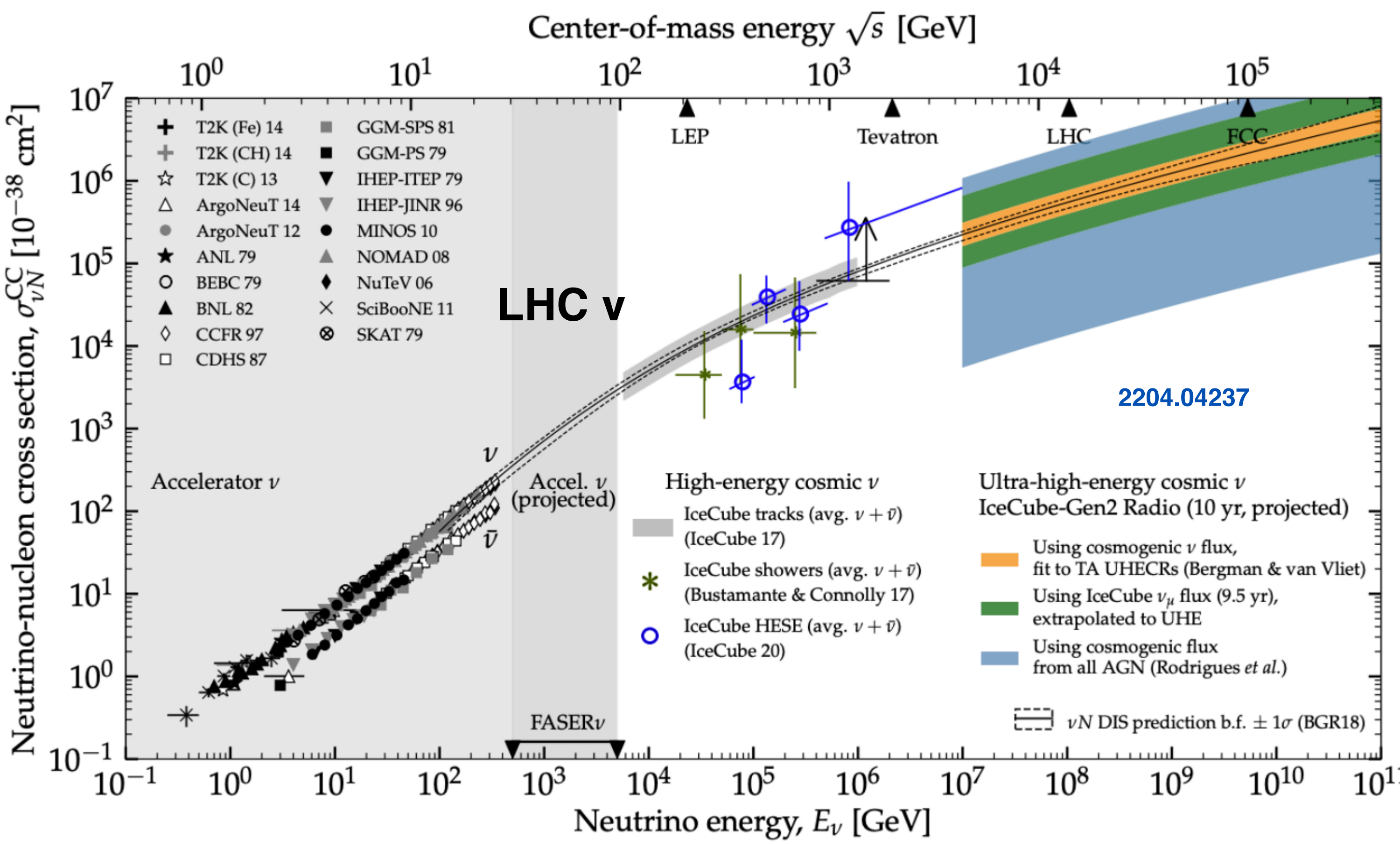


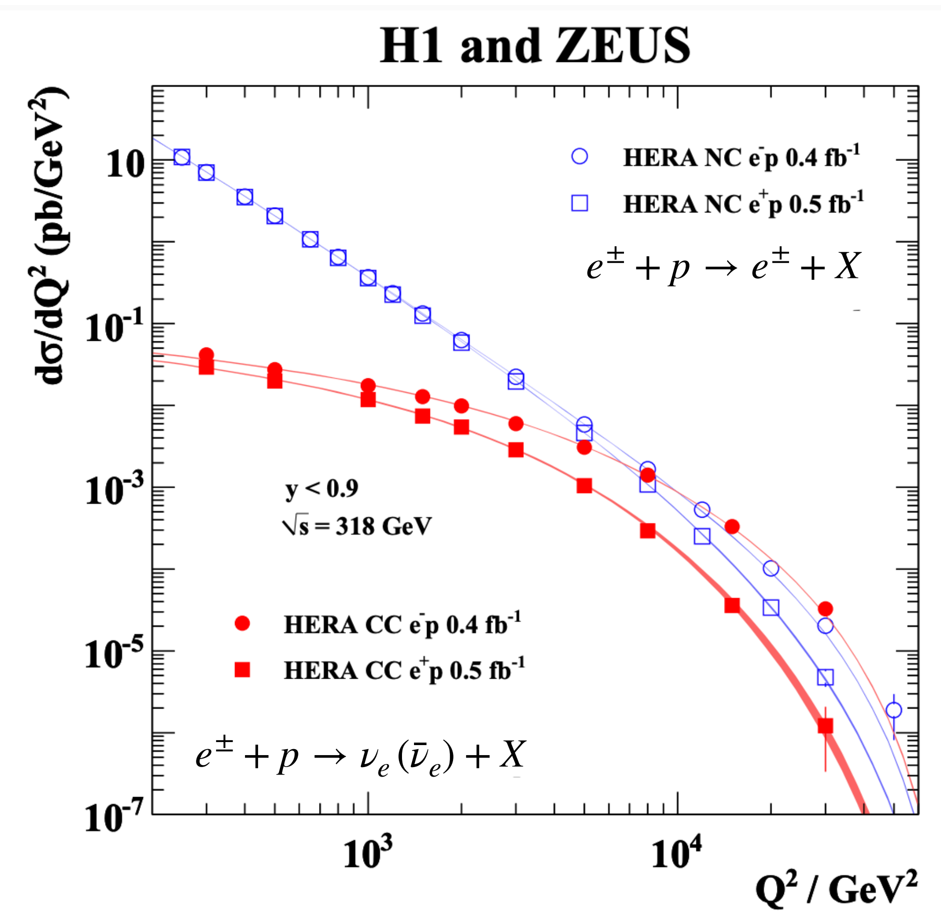
unique coverage of **TeV energy region**, high-statistics for **all three neutrino flavours**

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

Neutrino Interactions at the TeV

- 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

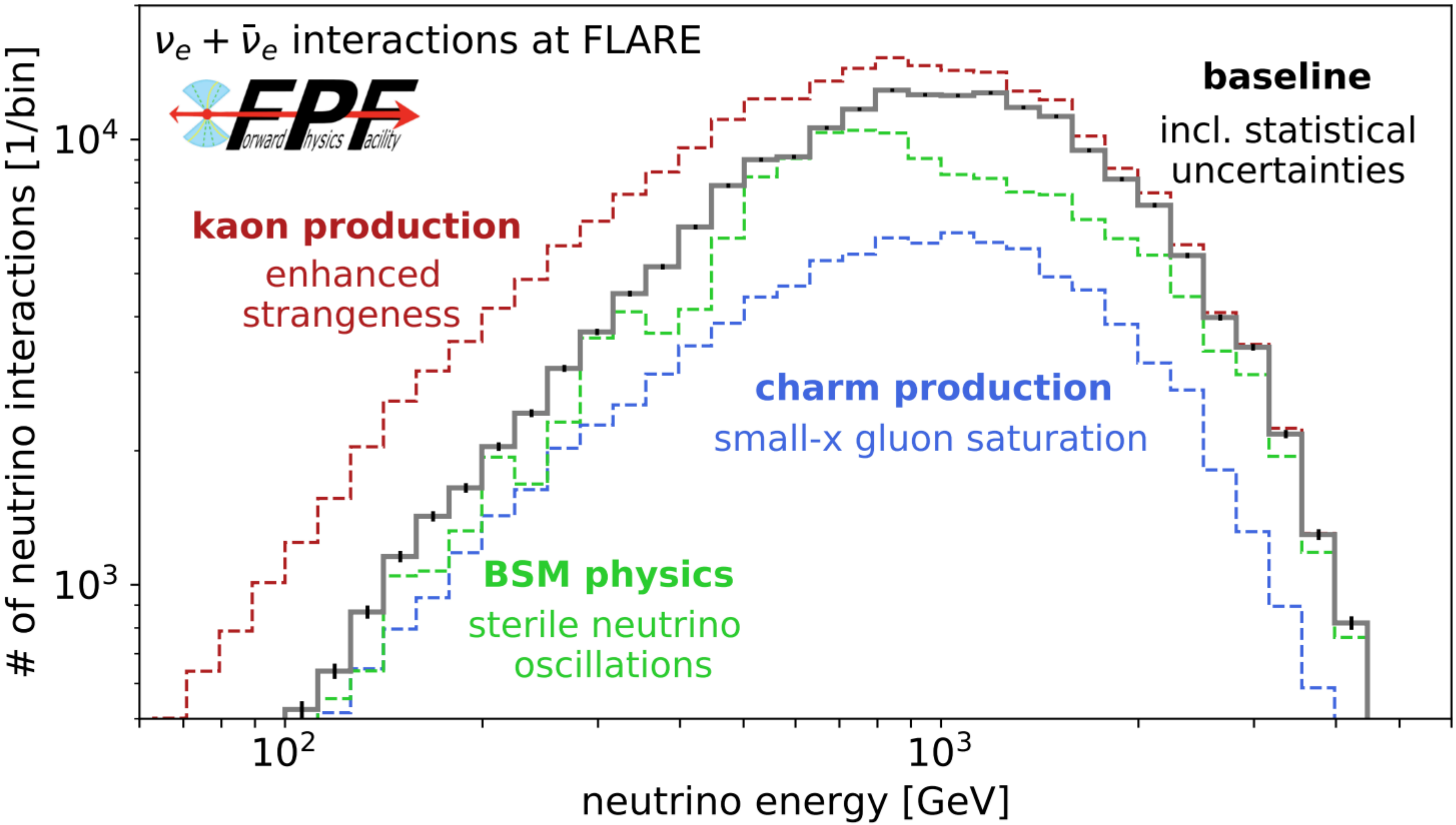
Indirect HERA constraints restricted to electron neutrinos, cross-sect measured at the 15% level at TeV energies

- **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



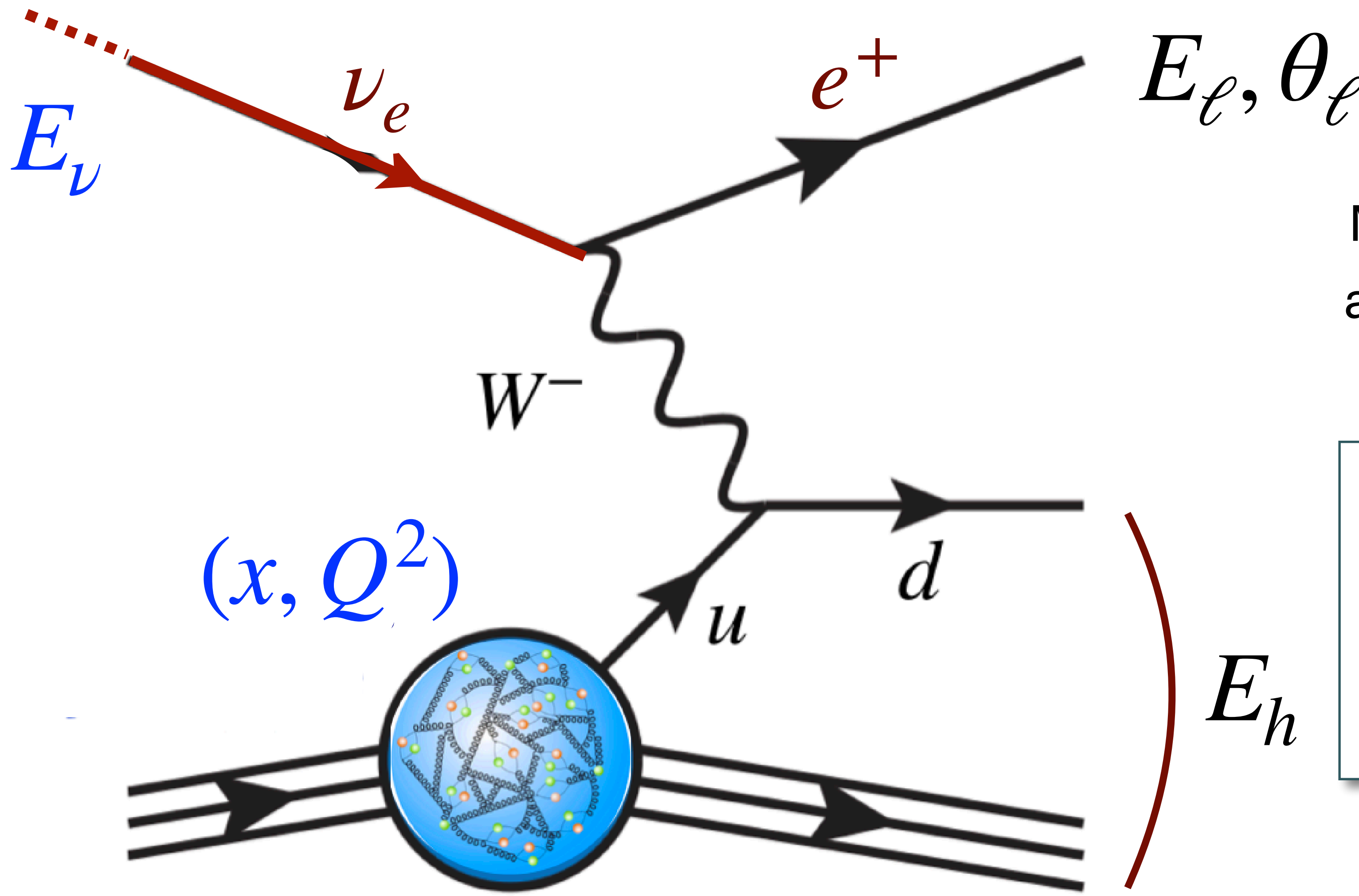
- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Provide a laboratory validation of **muon puzzle** predating **cosmic ray physics**
- New channels for **BSM searches** e.g. via sterile neutrino oscillations

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

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

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

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

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

key for core LHC theory predictions

Parton Distributions

$$u(x, Q^2)$$

Probability of **finding an up quark inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

$$u(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

constrain from global fit to high-p_T data

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to aN^{3}LO

$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

Neutrino DIS at the LHC

- Neutrino **deep-inelastic scattering** is a powerful probe of the quark/gluon structure of hadrons
- **Double-differential** measurements provide direct access to different flavour combinations

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2)\right]$$

$$y = Q^2/(2xm_n E_\nu)$$

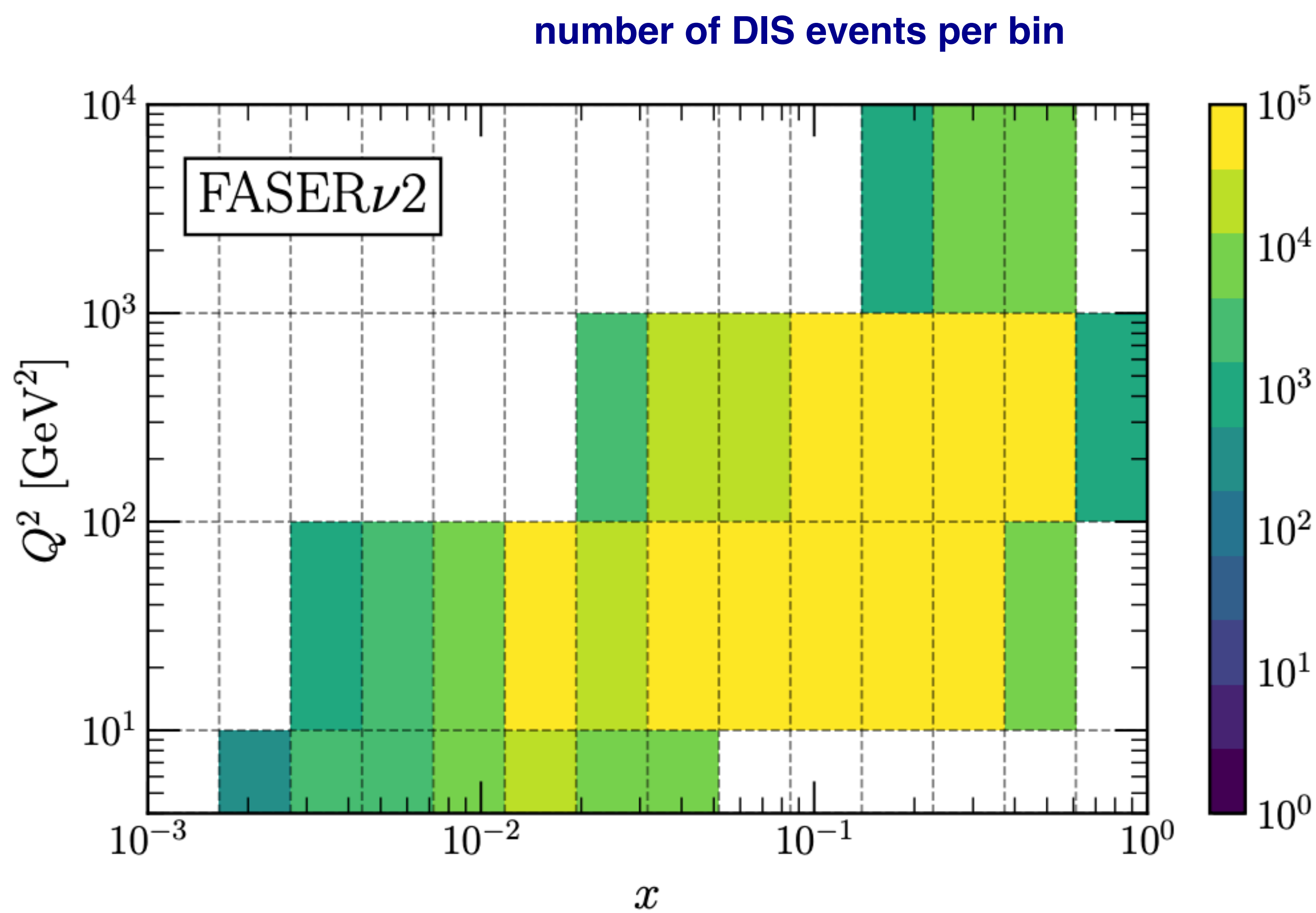
Cross-section expressed in terms of LO structure functions:

$$\begin{aligned}
F_2^{\nu p}(x,Q^2) &= 2x\left(f_{\bar u} + f_d + f_s + f_{\bar c}\right)(x,Q^2)\,,\\
F_2^{\bar\nu p}(x,Q^2) &= 2x\left(f_u + f_{\bar d} + f_{\bar s} + f_c\right)(x,Q^2)\,,\\
xF_3^{\nu p}(x,Q^2) &= 2x\left(-f_{\bar u} + f_d + f_s - f_{\bar c}\right)(x,Q^2)\,,\\
xF_3^{\bar\nu p}(x,Q^2) &= 2x\left(f_u - f_{\bar d} - f_{\bar s} + f_c\right)(x,Q^2)\,.
\end{aligned}$$

Goal: quantify the impact of **ongoing and future LHC neutrino experiments** on the proton PDFs, and assess their implications for the (**HL)-LHC precision physics program**

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**



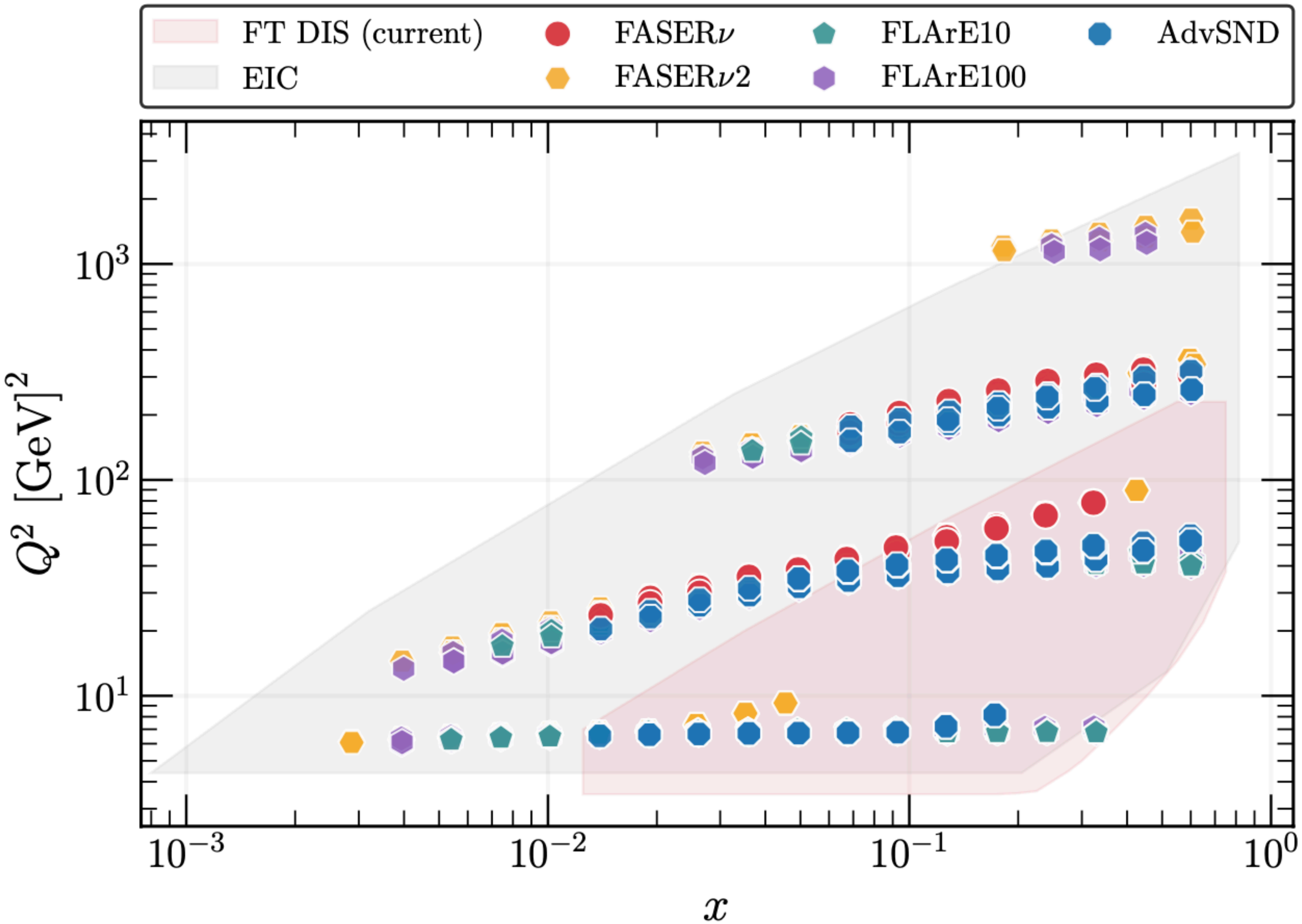
Events per bin

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

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

Model **detector performance** based on most updated design

Neutrino DIS at the LHC



x: momentum fraction of quarks/gluons in the proton

Q²: momentum transfer from incoming lepton

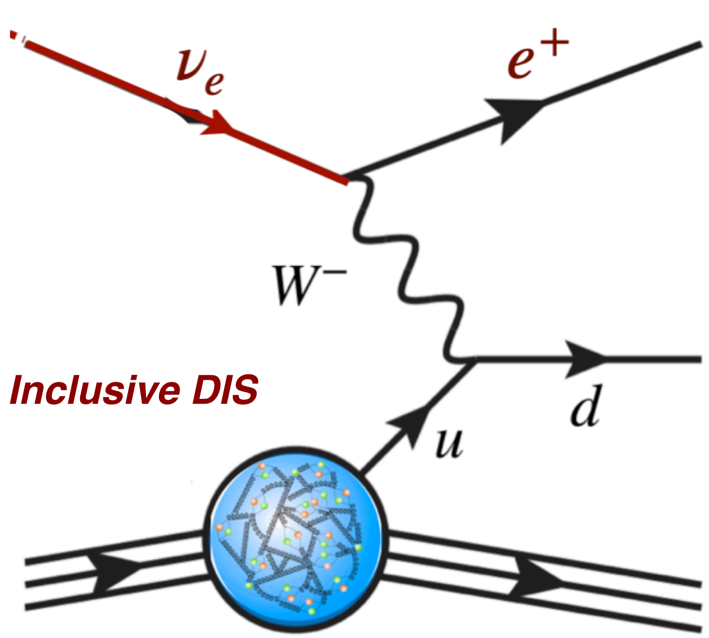
- Continue highly succesful program of neutrino **DIS experiments @ CERN**
- **Expand kinematic coverage** of available experiments by an order of magnitude in *x* and *Q²*
- Charged-current counterpart of the **Electron-Ion Collider** covering same region of phase space

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

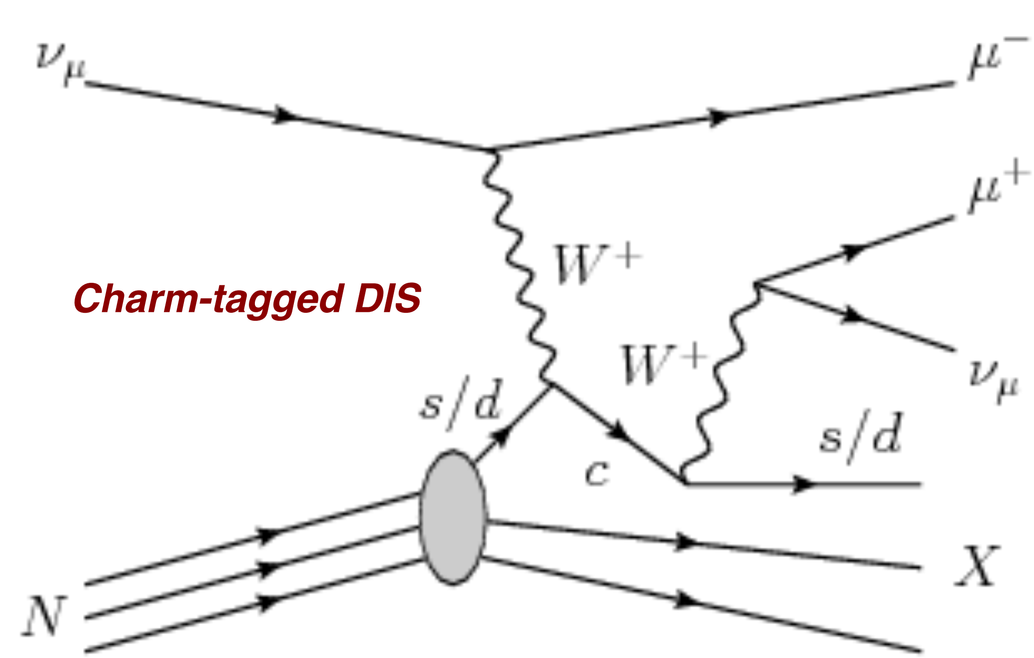
Neutrino DIS at the LHC

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

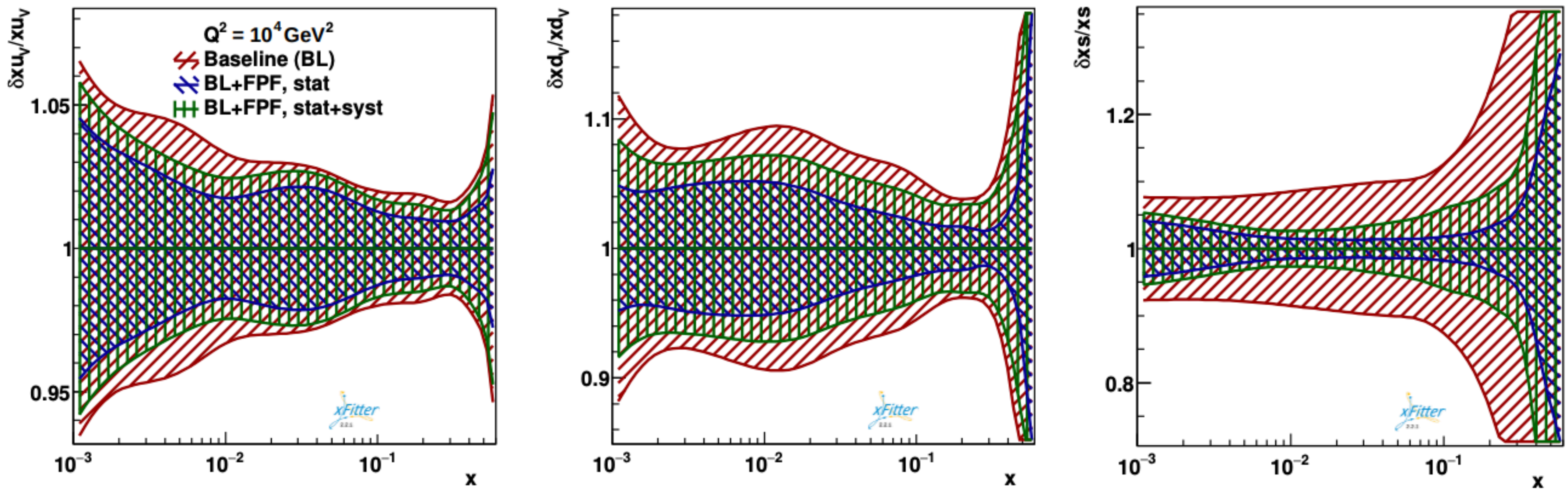
Detector	N_{ν_e}	$N_{\bar{\nu}_e}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	N_{ν_μ}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
FASERν	400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	180 (22)	76 (11)	260 (32)	510 (59)	190 (25)	700 (83)
FASERν2	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)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



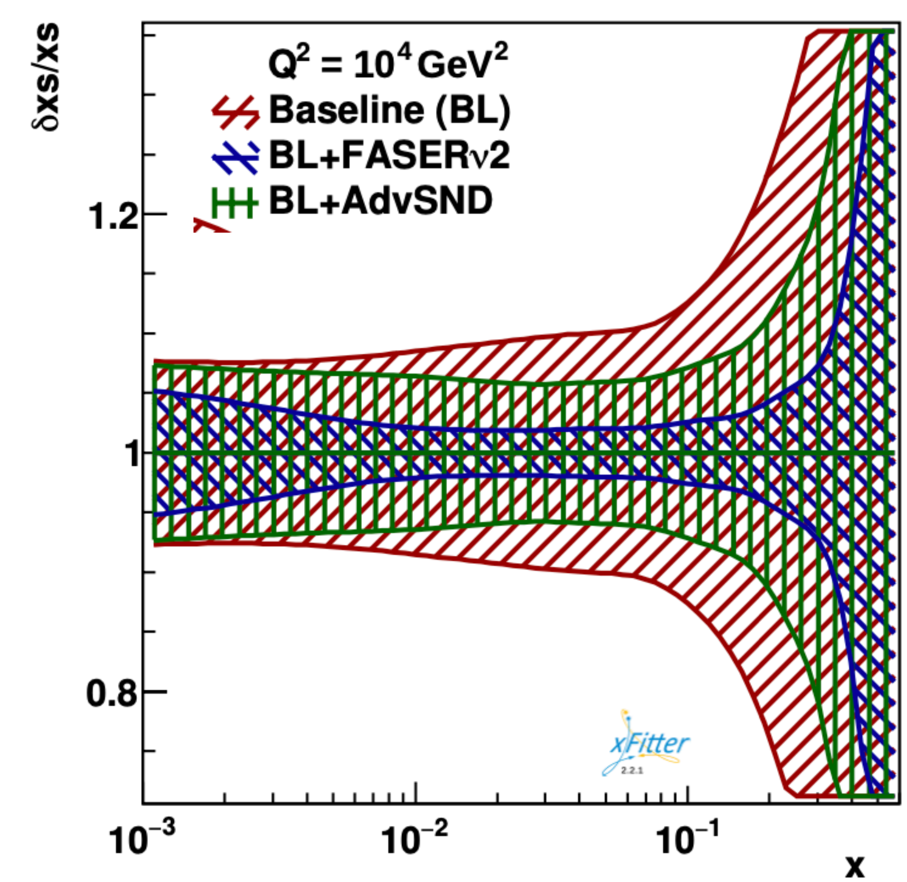
- Muon-neutrinos: **larger event rates, smaller production uncertainties**
- Current experiments limited by statistics, FPF **by systematics**
- Ultimate reach achieved by **combining all experiments**



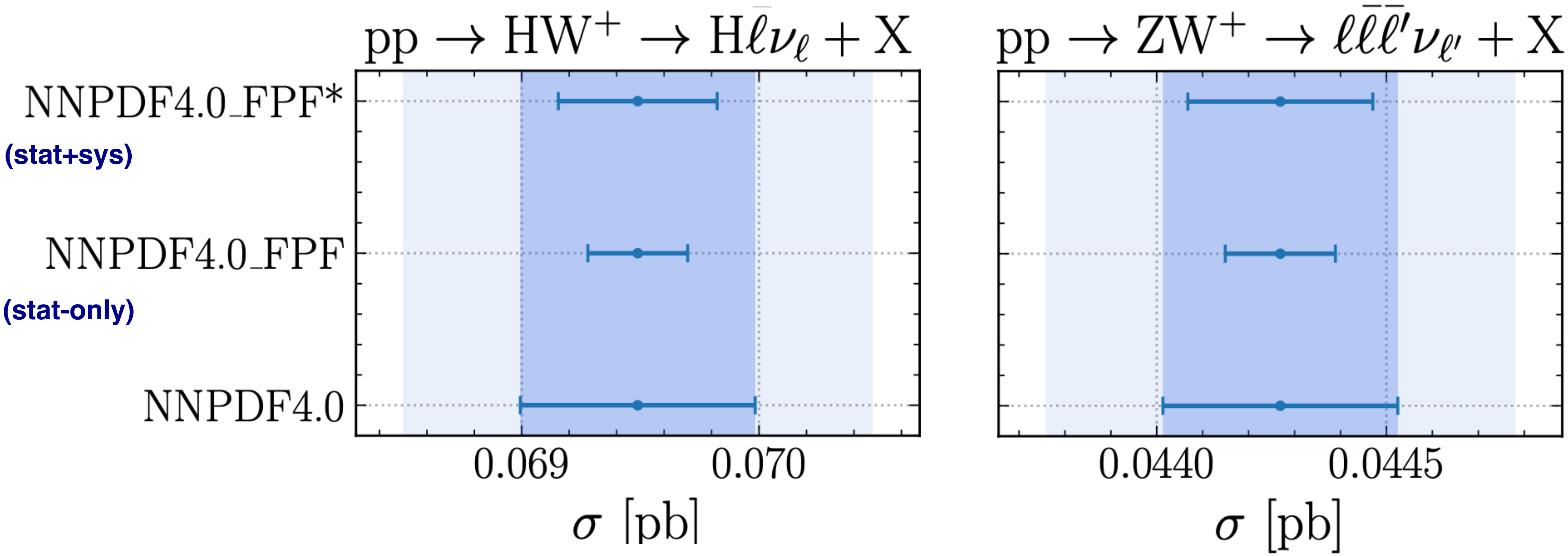
PDF constraints from LHC neutrinos

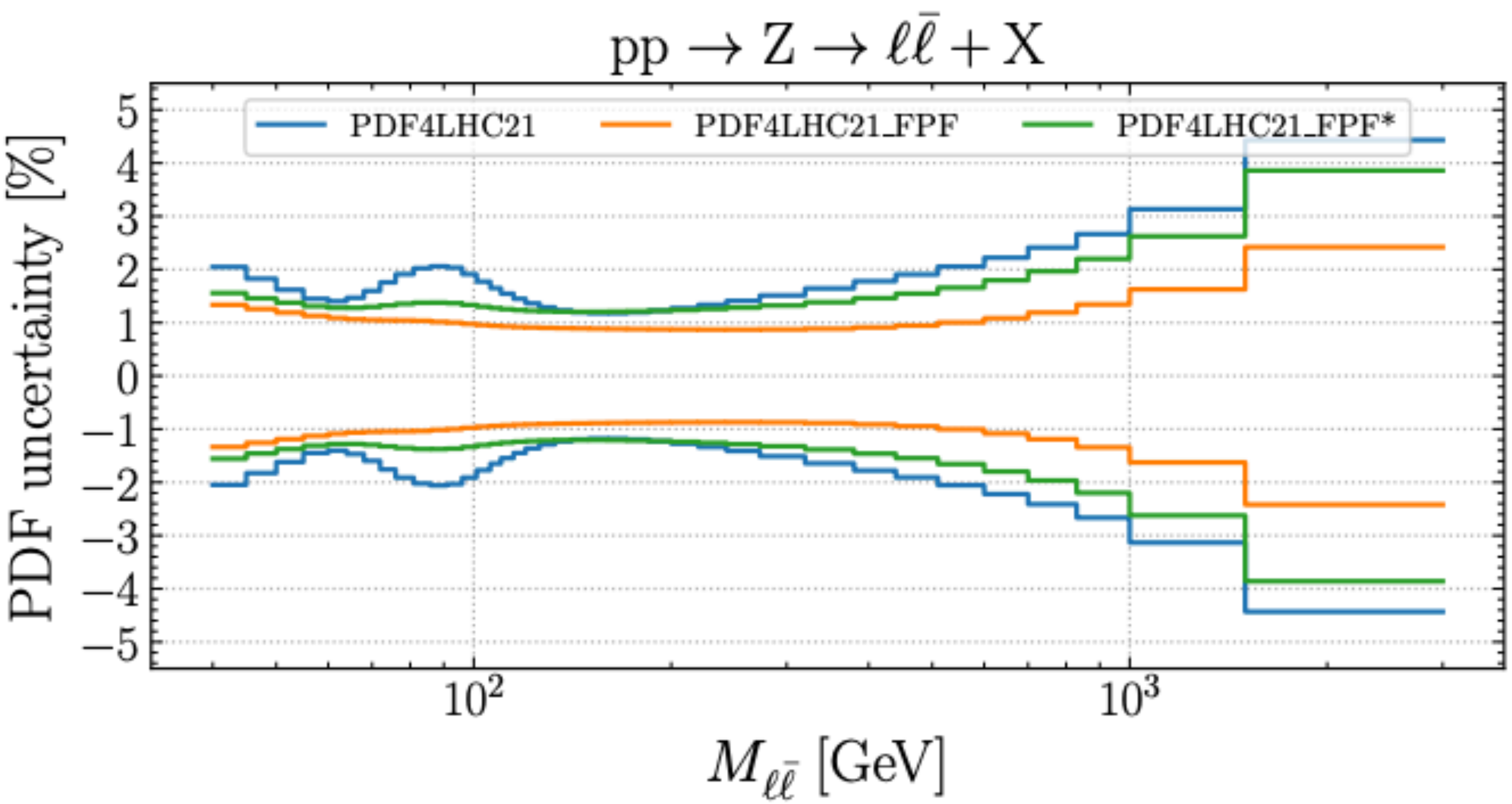


- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics
- Quantitative analysis **guiding detector design**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

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**

- They provide a unique perspective on **quark flavour separation,** enhance theory predictions for HL-LHC observables, and scrutinise the **charm content of the proton**

- 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