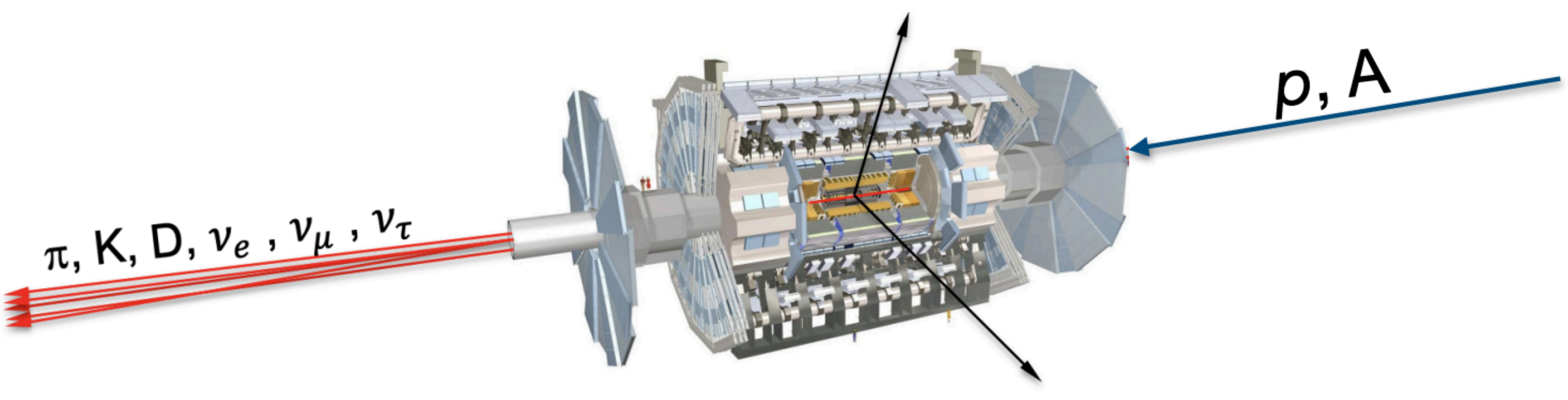
Deep-Inelastic Scattering with Collider Neutrinos

Juan Rojo, VU Amsterdam & Nikhef

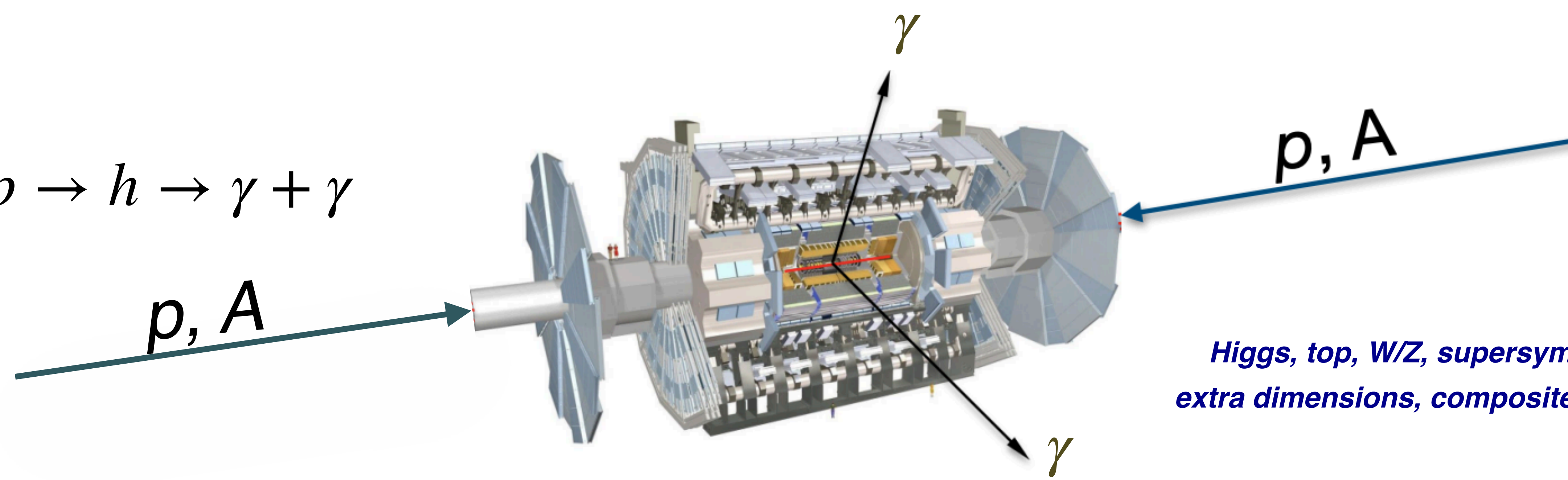


DIS2024, Grenoble, 9th April 2024

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

$$p + p \to h \to \gamma + \gamma$$



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**

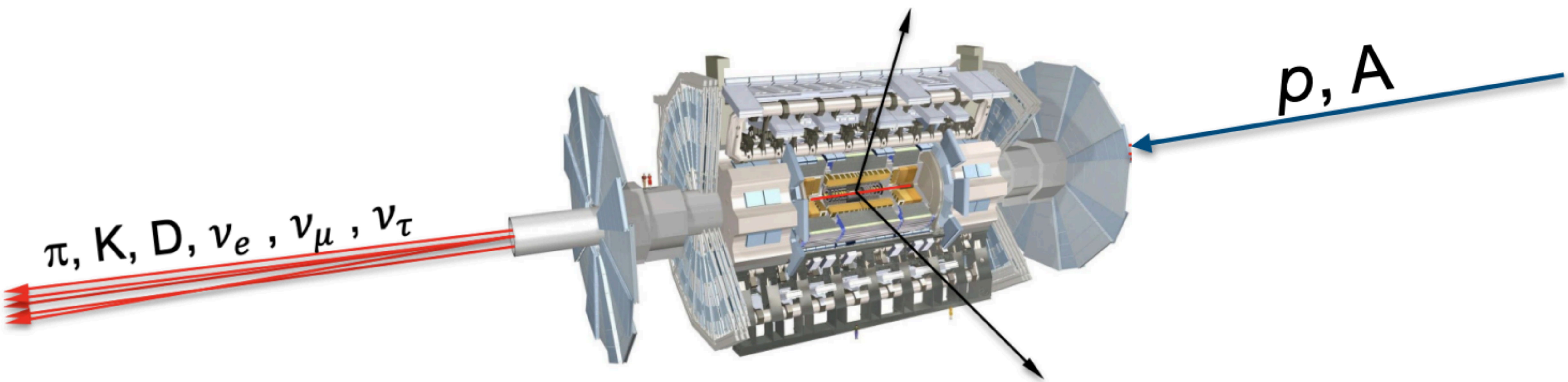
for LHCb

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

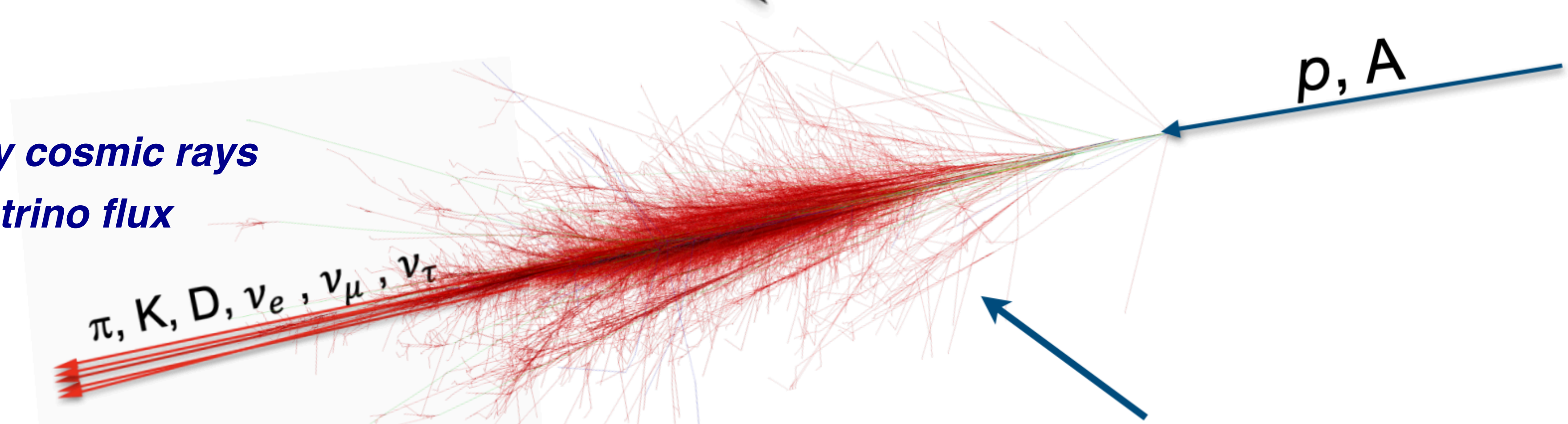
Neutrinos at the LHC

- 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**

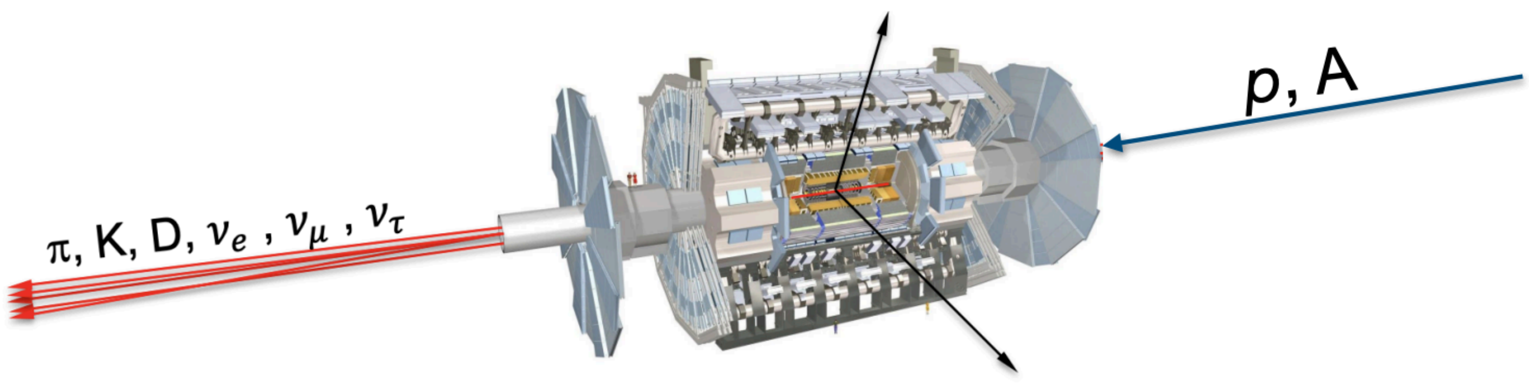
- In addition, there are **guaranteed physics targets** to be reached should we instrument the forward region of the LHC, based on exploiting **the most energetic, high-intensity neutrino beam ever produced in a laboratory**



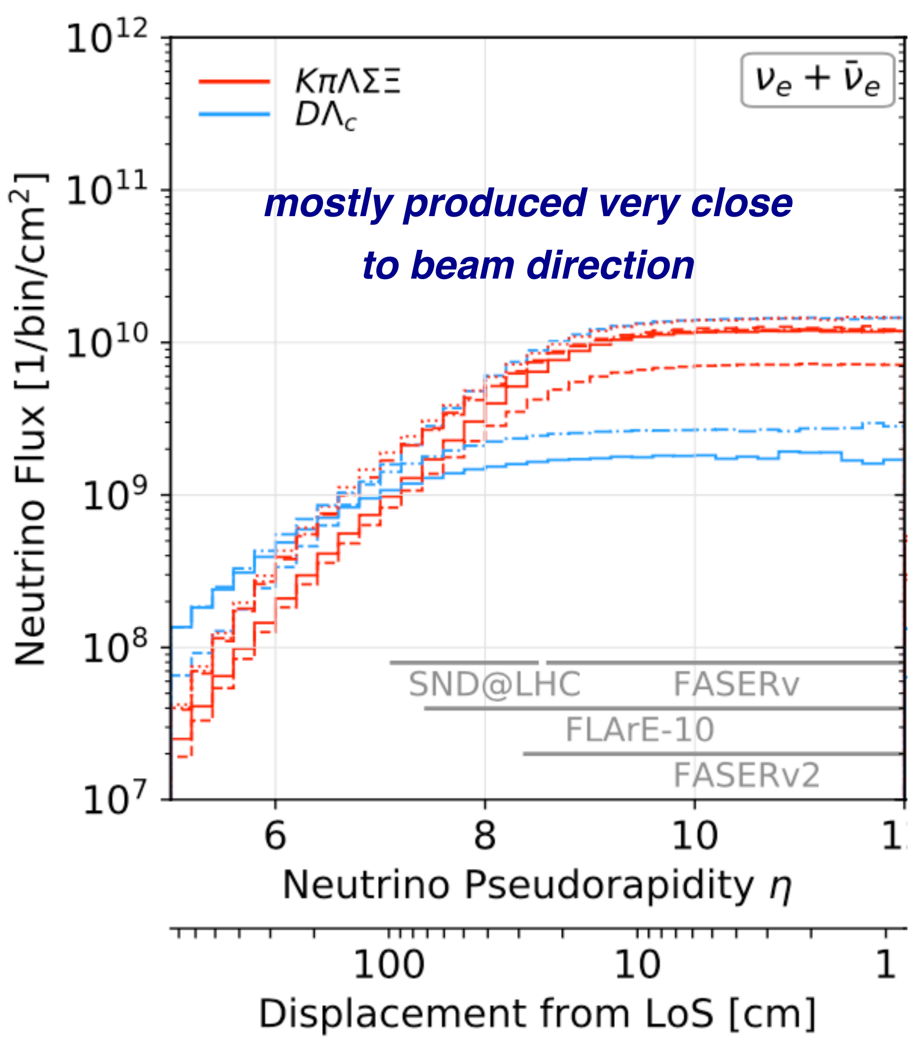
Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux

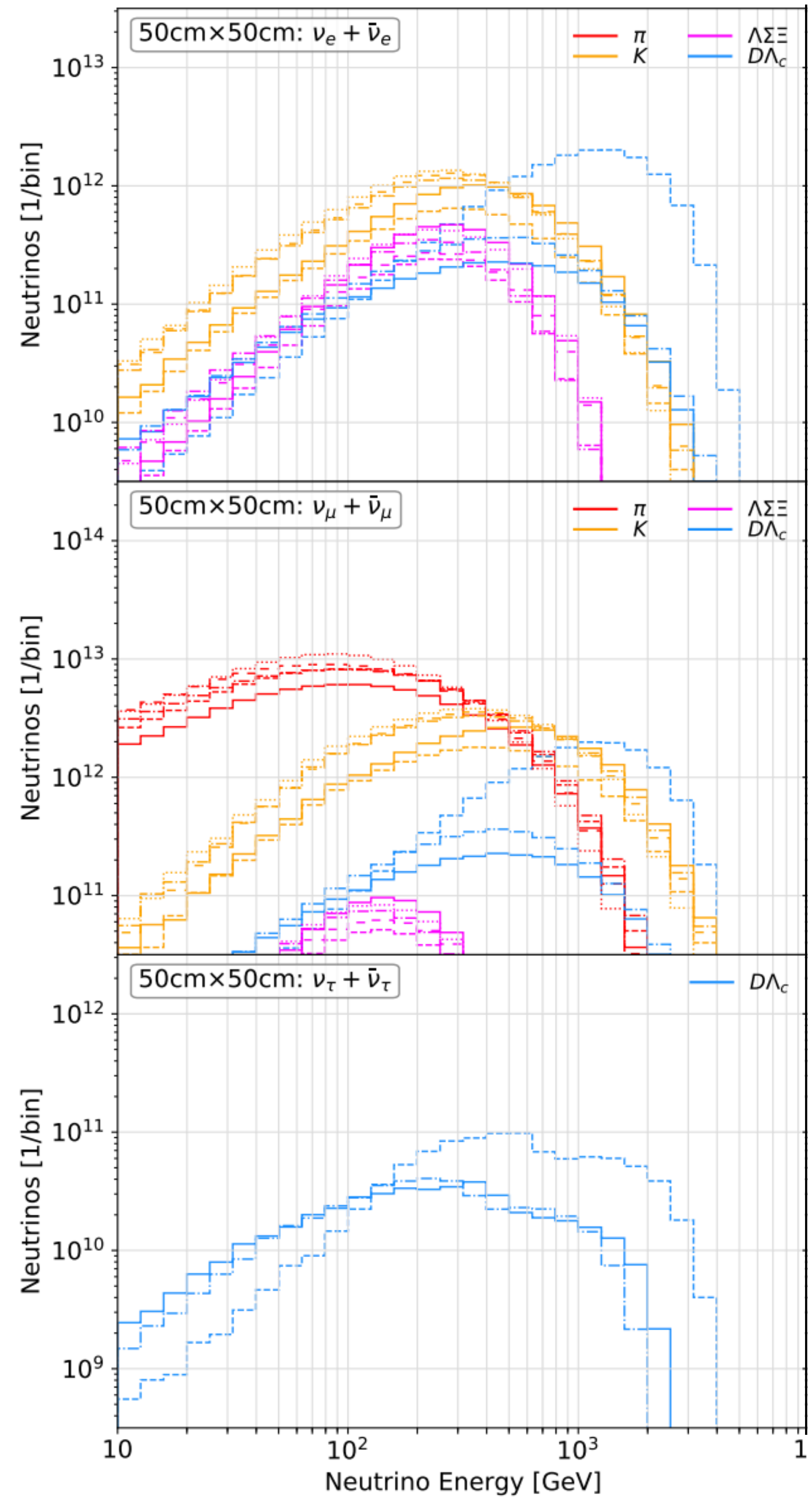


Neutrinos at the LHC

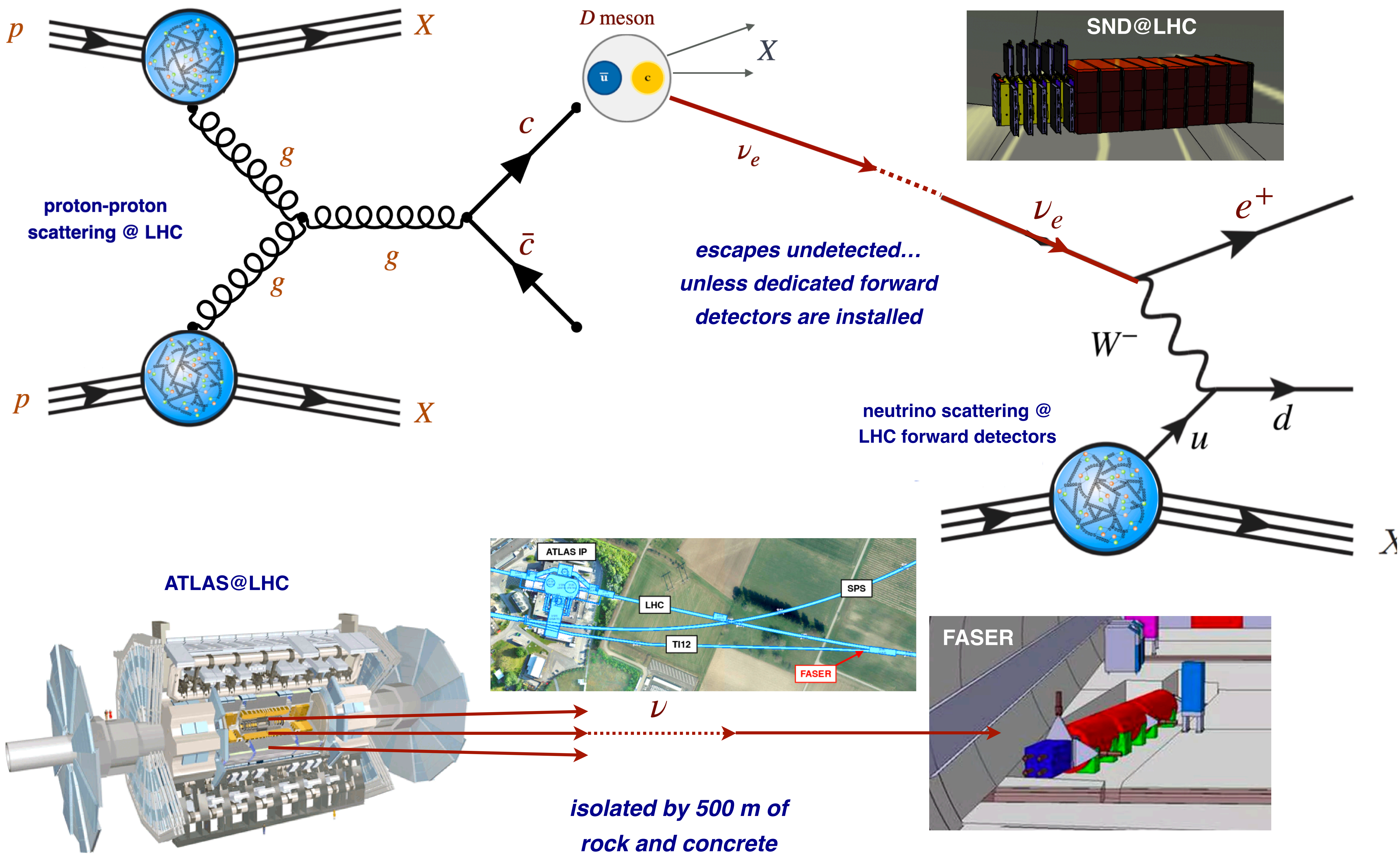


- **electron neutrinos** mostly from *D*-meson decays above 500 GeV, below it mostly from kaon decays
- **muon neutrino** flux dominated by pion & kaon decays
- **tau neutrinos** entirely from D-meson decays





Neutrinos at the LHC



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

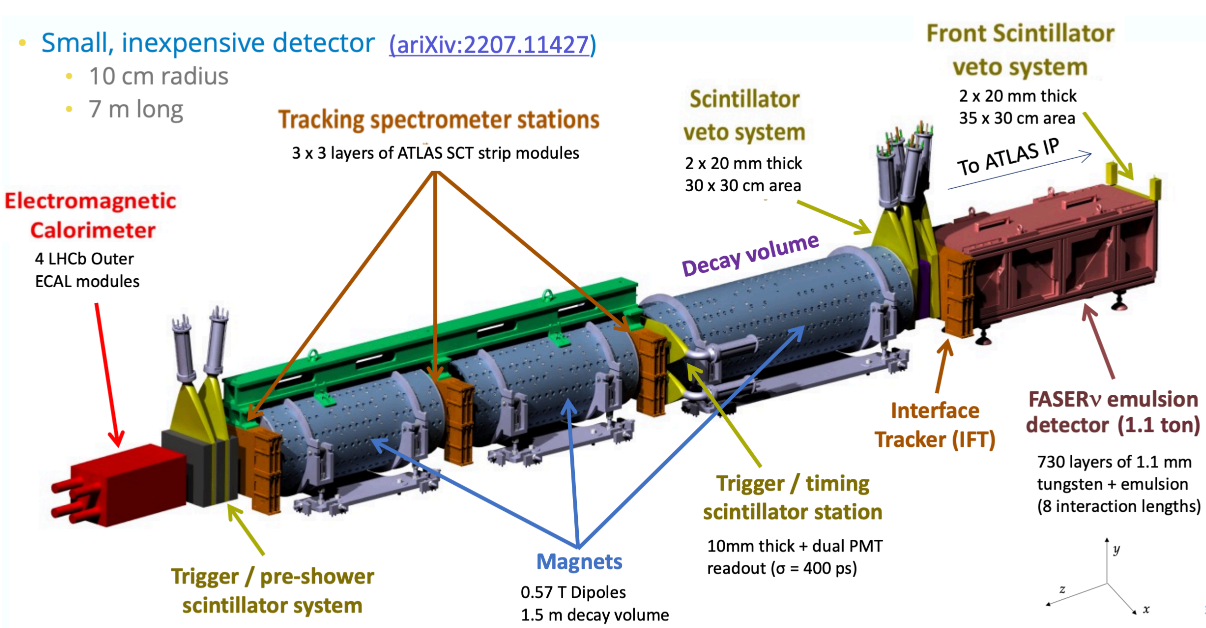
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

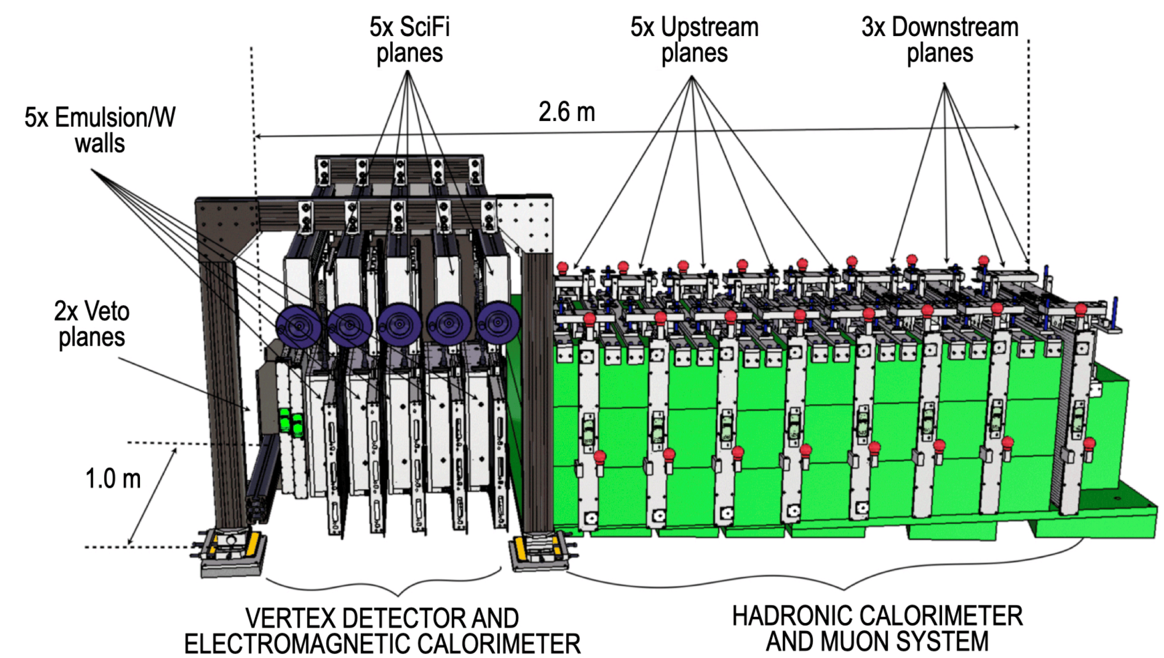
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on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

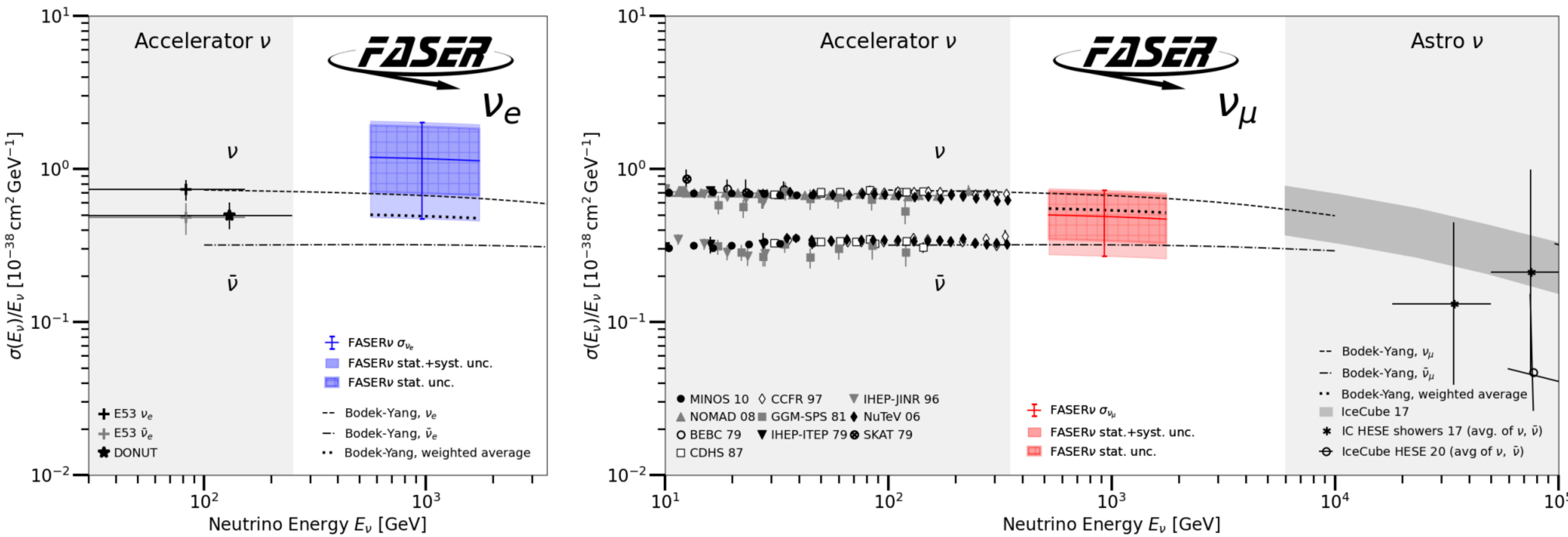




Now is the time to start exploiting their physics potential

The dawn of the LHC neutrino era

- **FASER** recently presented the first measurement of **cross-sections of** collider (TeV) neutrinos

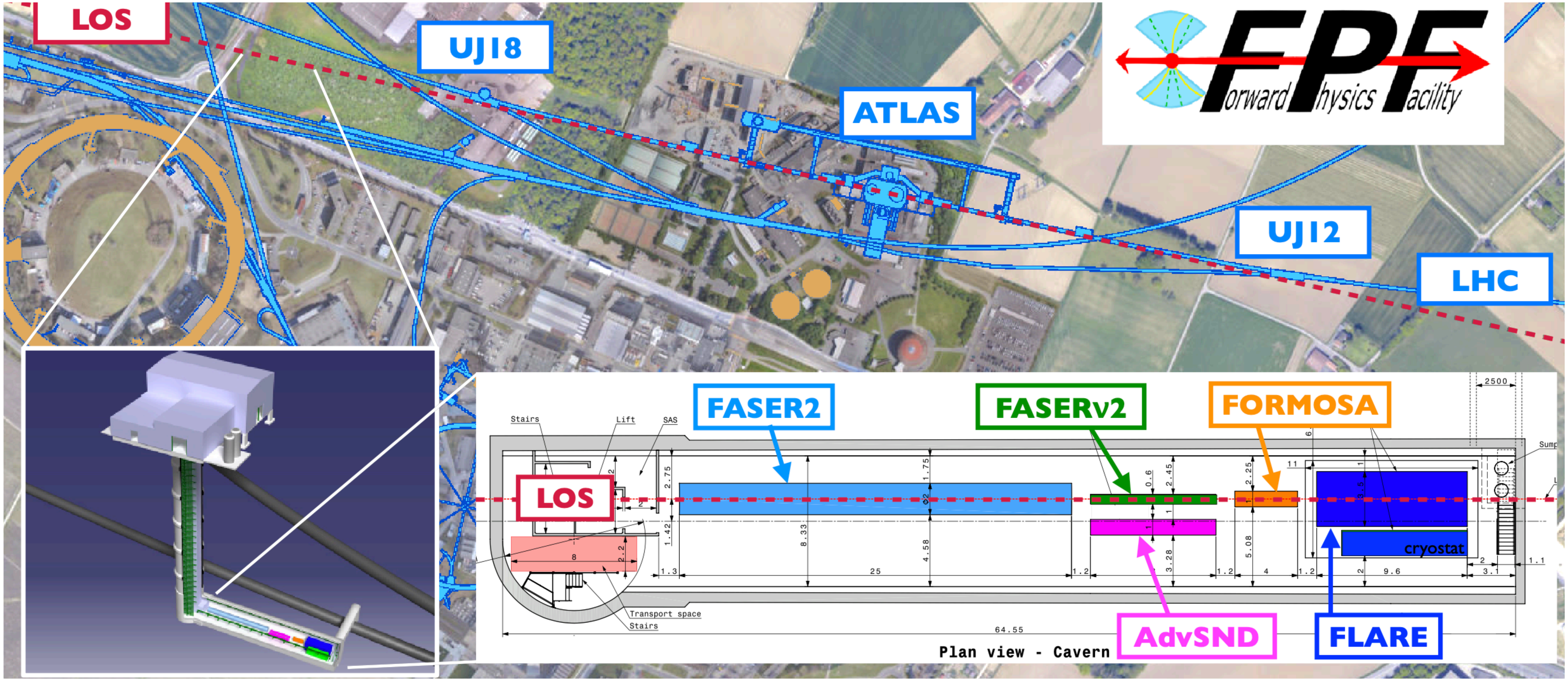


- Demonstrates the excellent performance of the experiment for neutrino interaction measurements
- Paves the way to more refined measurements, including **multi-differential** (structure functions)
- Ultimately FASER and SND@LHC neutrino measurements **will be limited by statistics …**

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

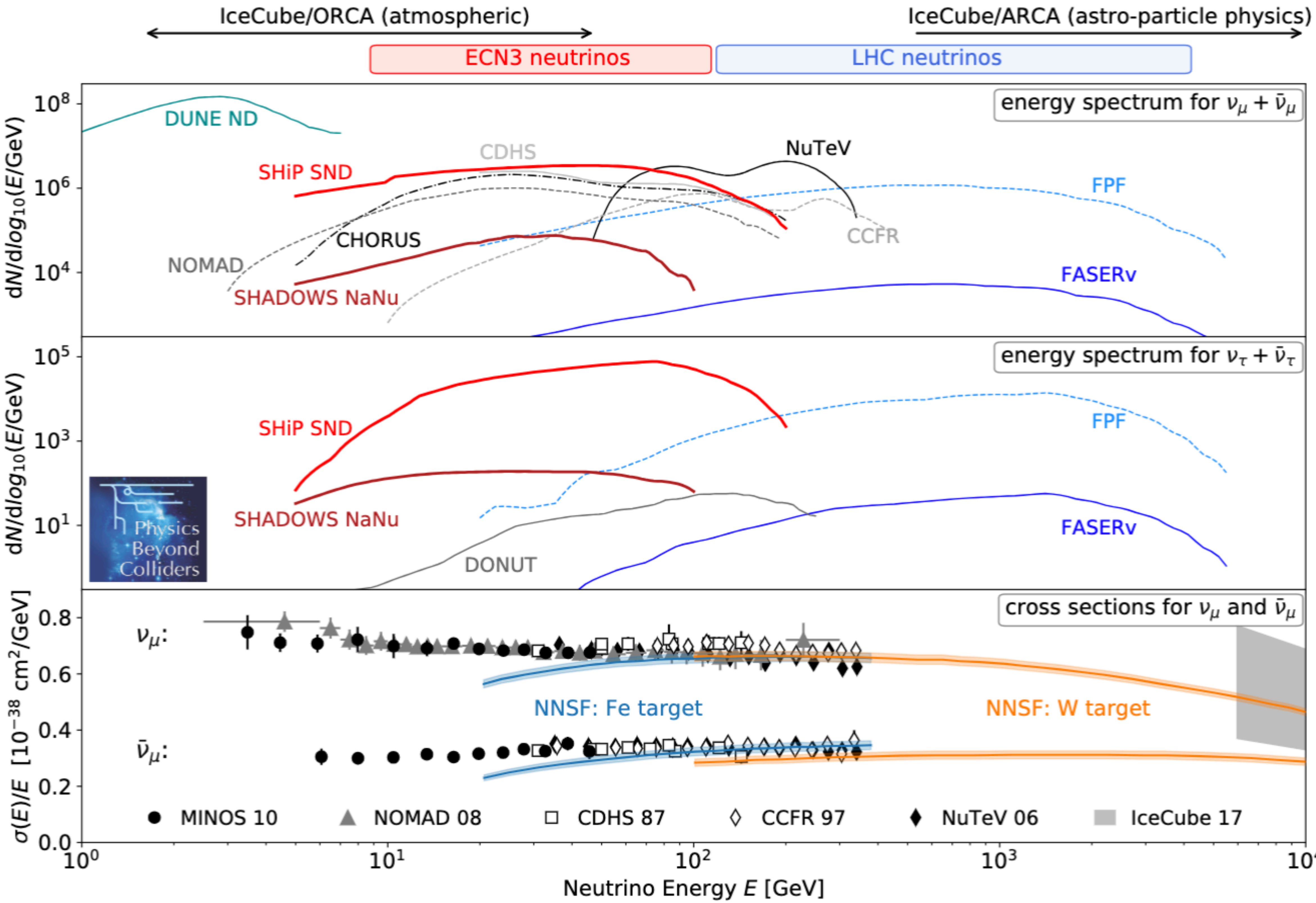
The Forward Physics Facility

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)

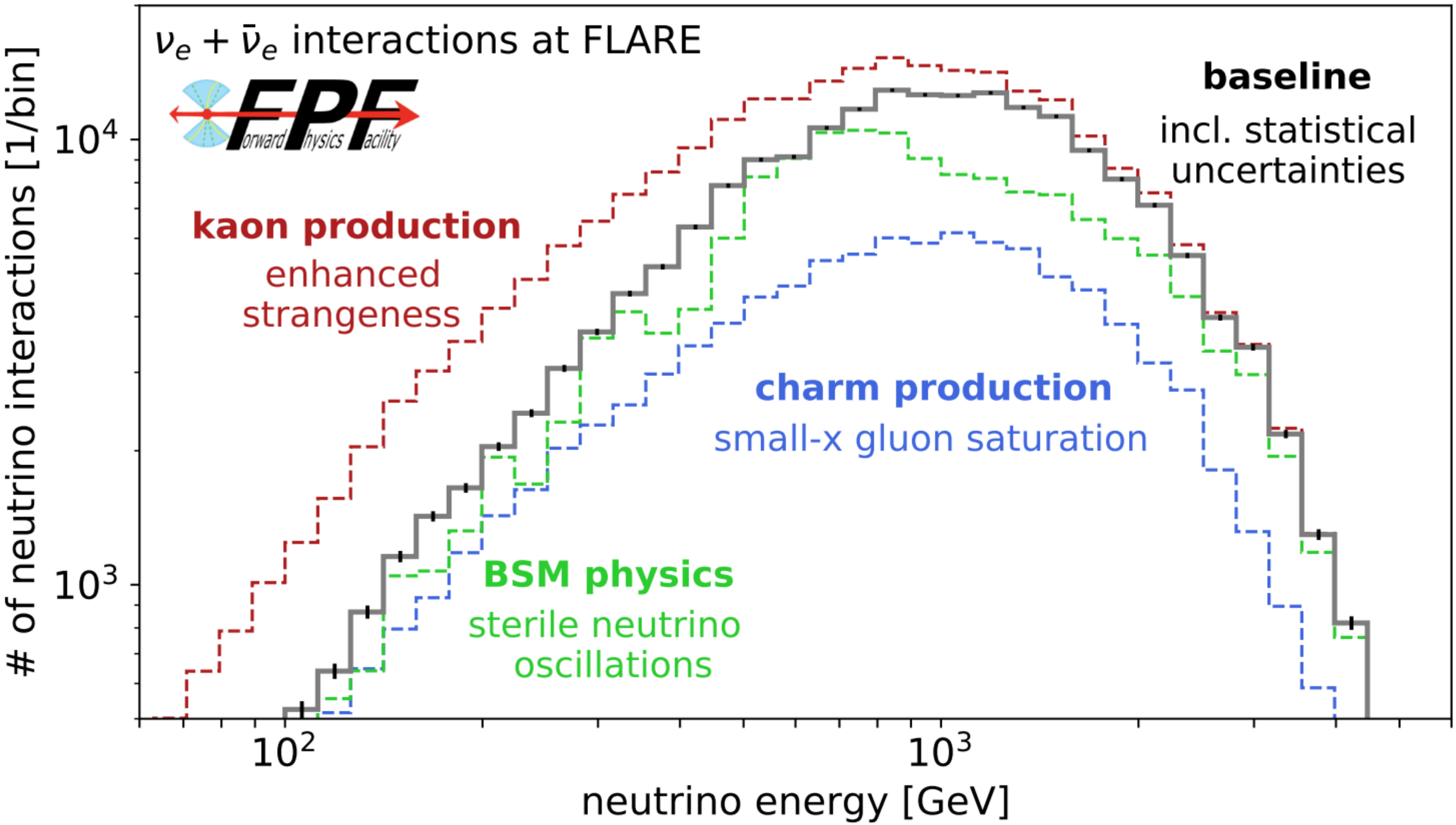
Physics with LHC neutrinos



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



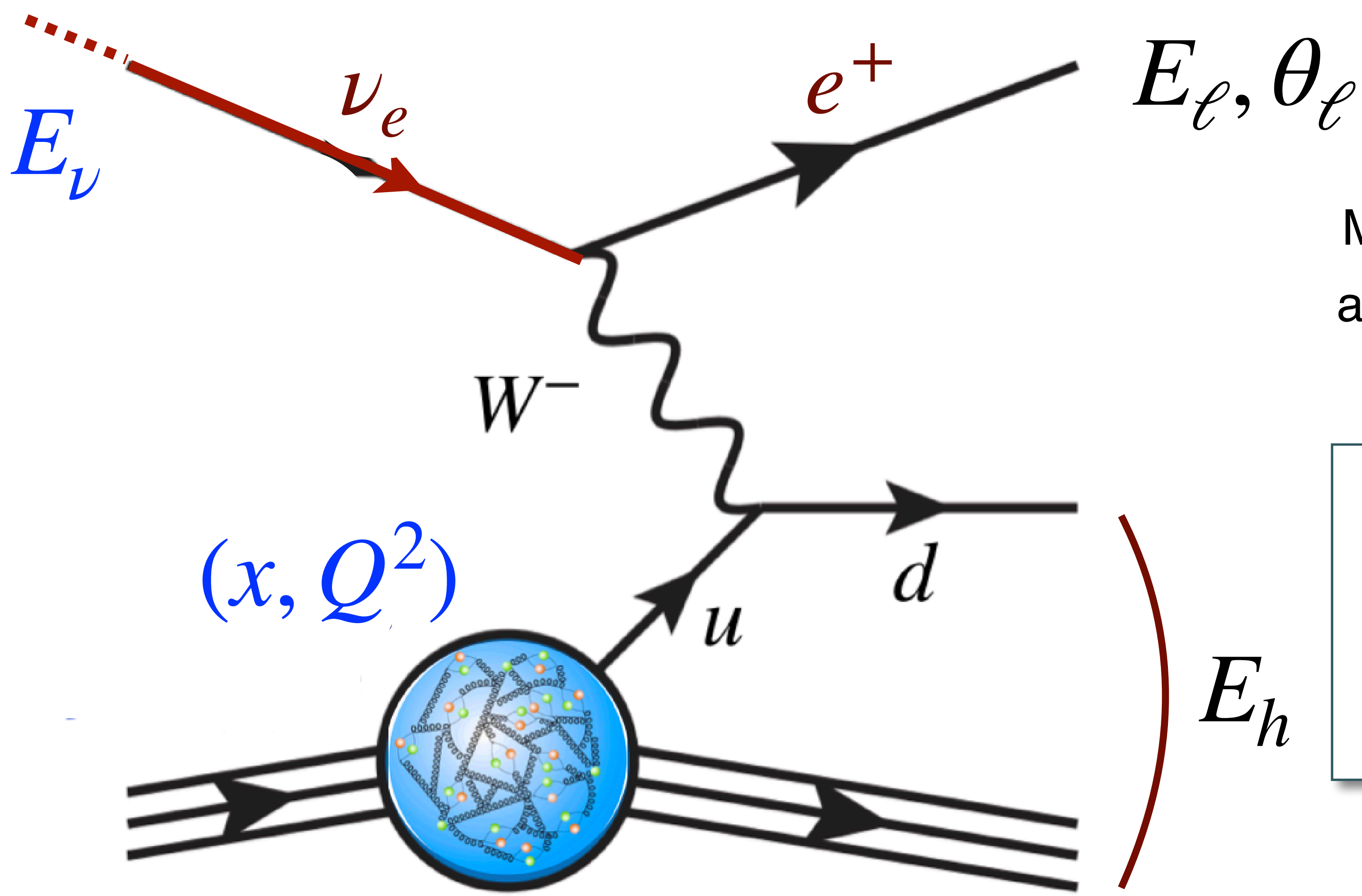
- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Provide a laboratory validation of **muon puzzle** predating **cosmic ray physics**
- New channels for **BSM searches** e.g. via sterile neutrino oscillations

Impact on Proton Structure

J. M. Cruz-Martinez, M. Fieg, T. Giani, P. Krack, T. Makela, T. Rabemananjara, 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

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

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

neutrino-proton scattering rate

partonic cross-section

up-quark content int the proton

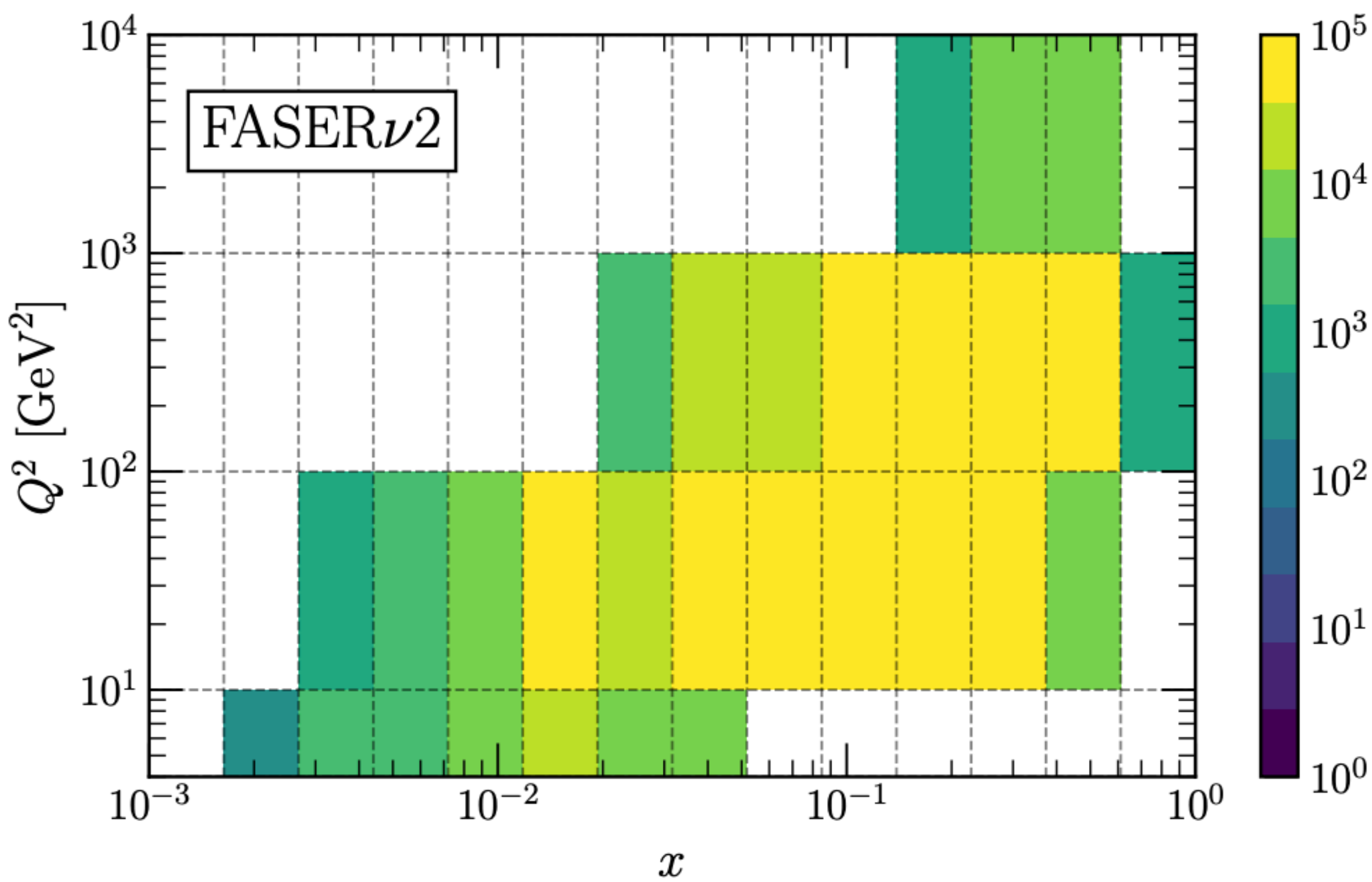
Unique information on **quark & antiquark flavour separation**

key for core LHC theory predictions

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



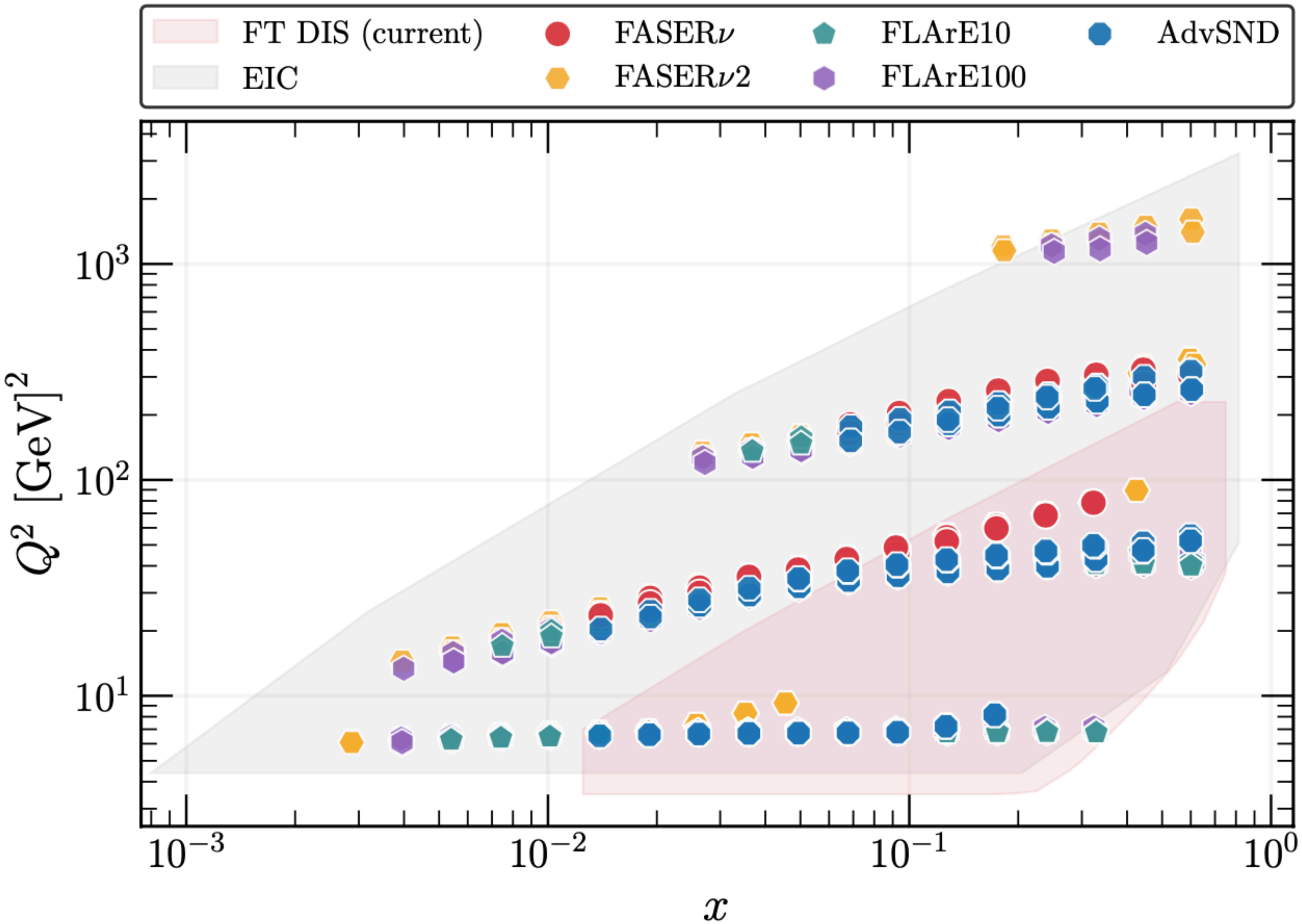
Events per bin

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

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

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

Neutrino DIS at the LHC



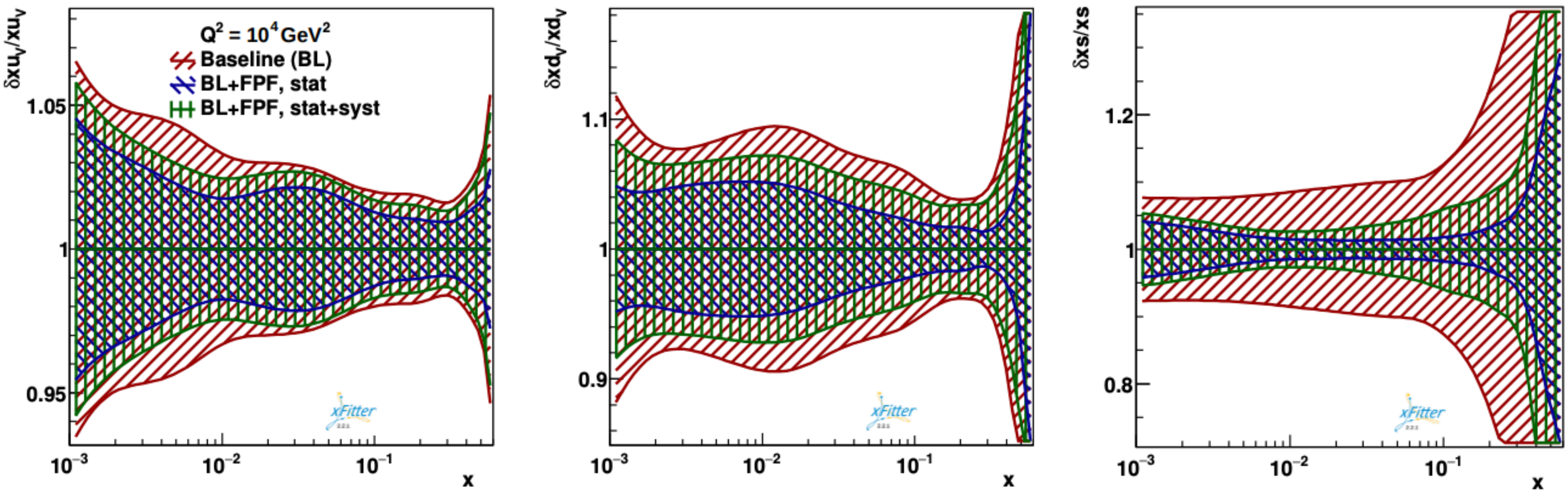
x: momentum fraction of quarks/gluons in the proton

Q^2: momentum transfer from incoming lepton

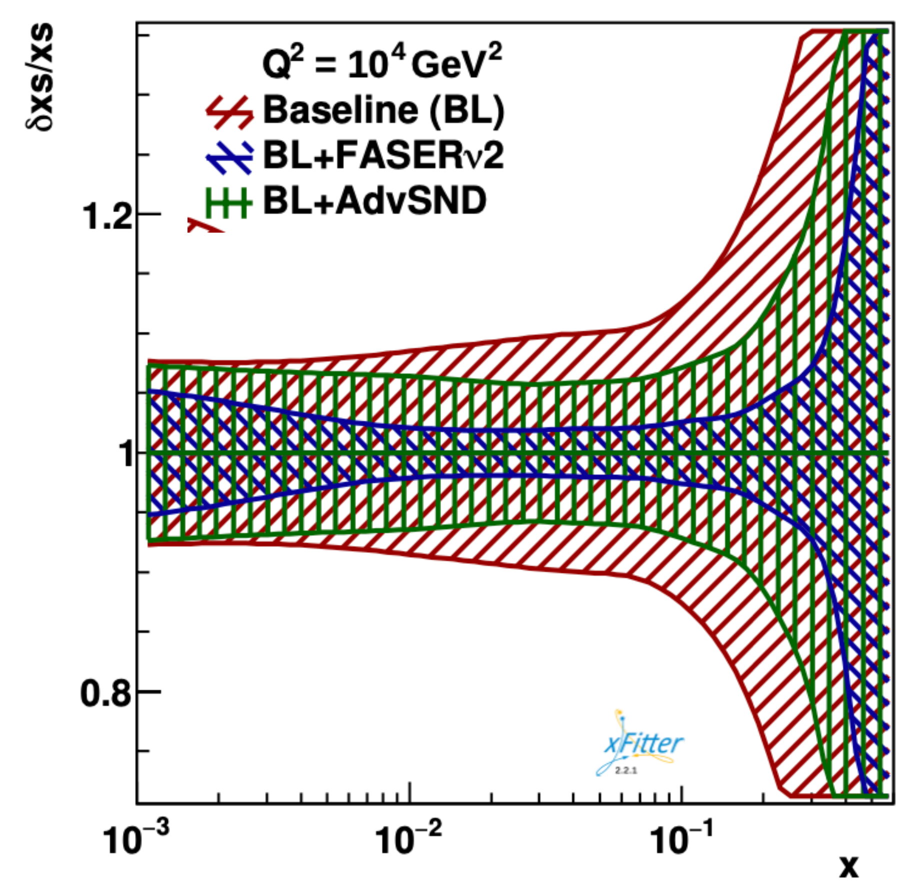
- Continue highly succesful program of neutrino **DIS experiments @ CERN**
- **Expand kinematic coverage** of available experiments by an order of magnitude in x and Q^2
- Charged-current counterpart of the **Electron-Ion Collider** covering same region of phase space

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

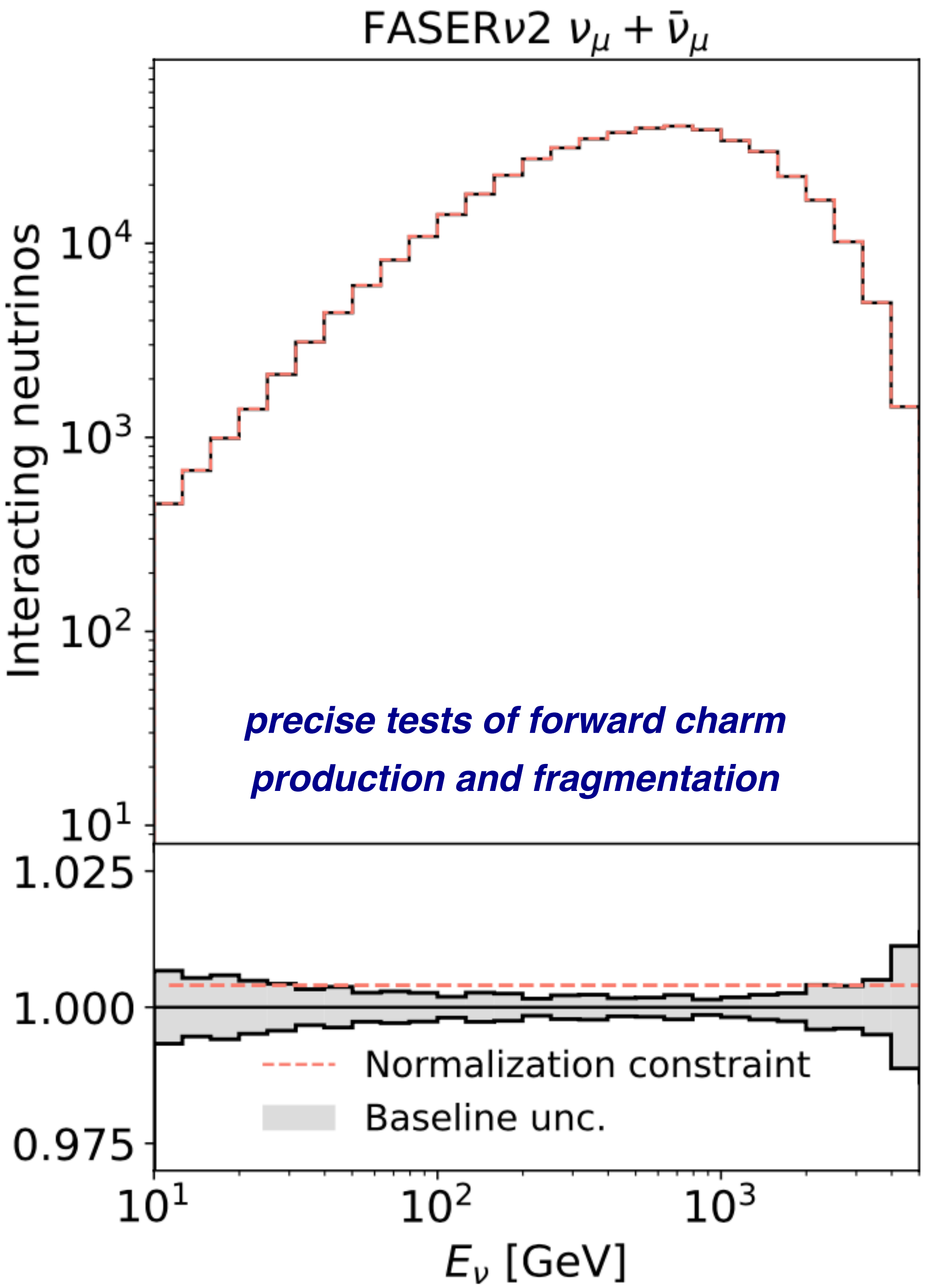
PDF constraints from LHC neutrinos

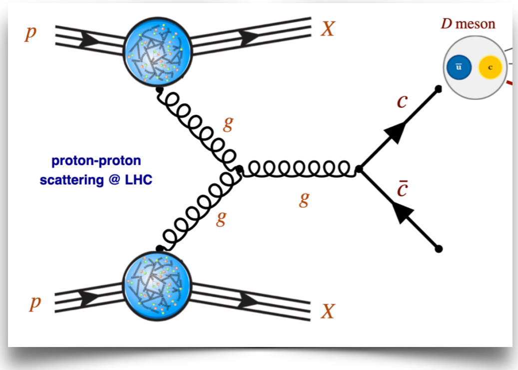


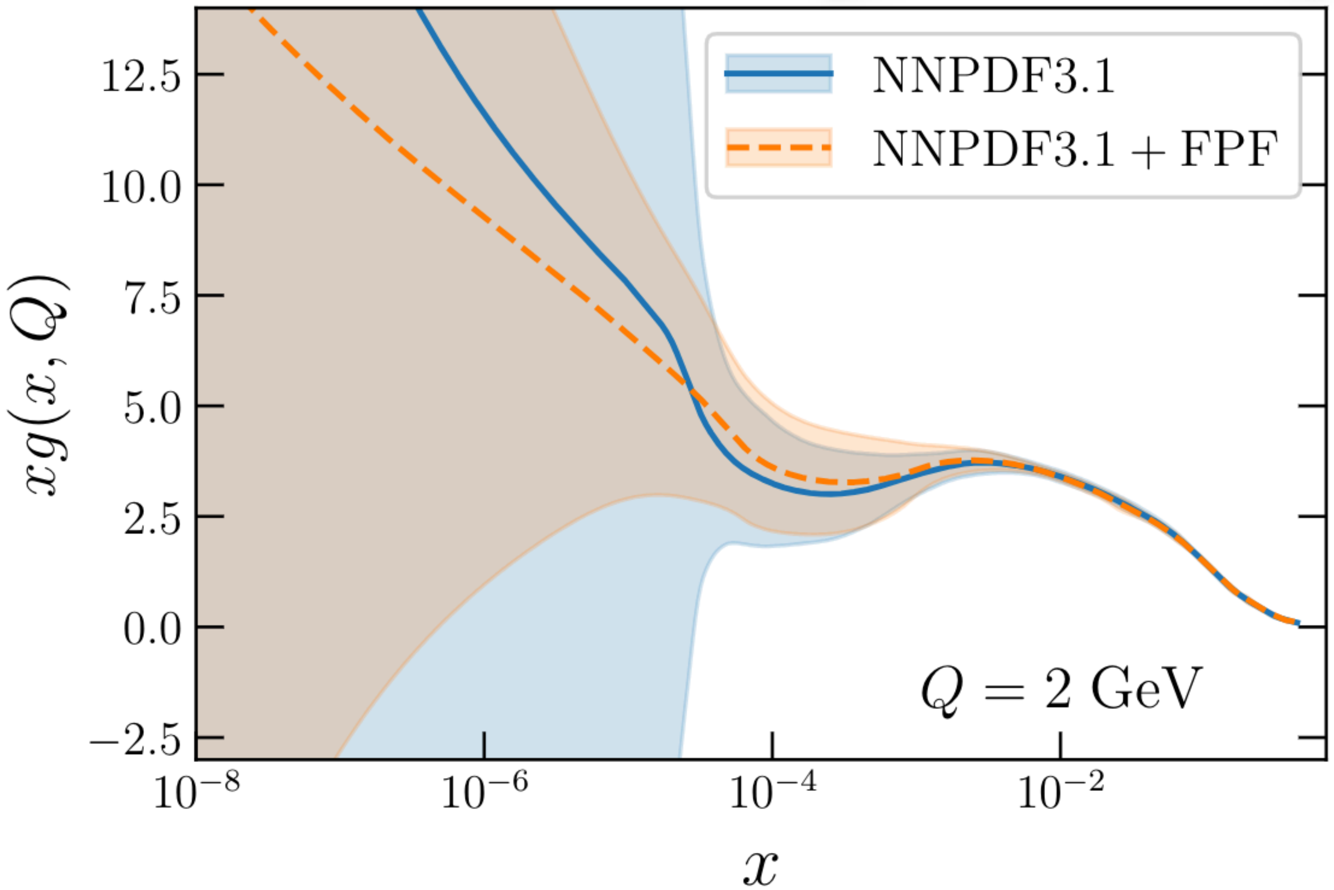
- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics
- Uncertainties in **incoming neutrino fluxes subdominant,** once constrained *in-situ* at FASER & FPF



FPF and small-x QCD



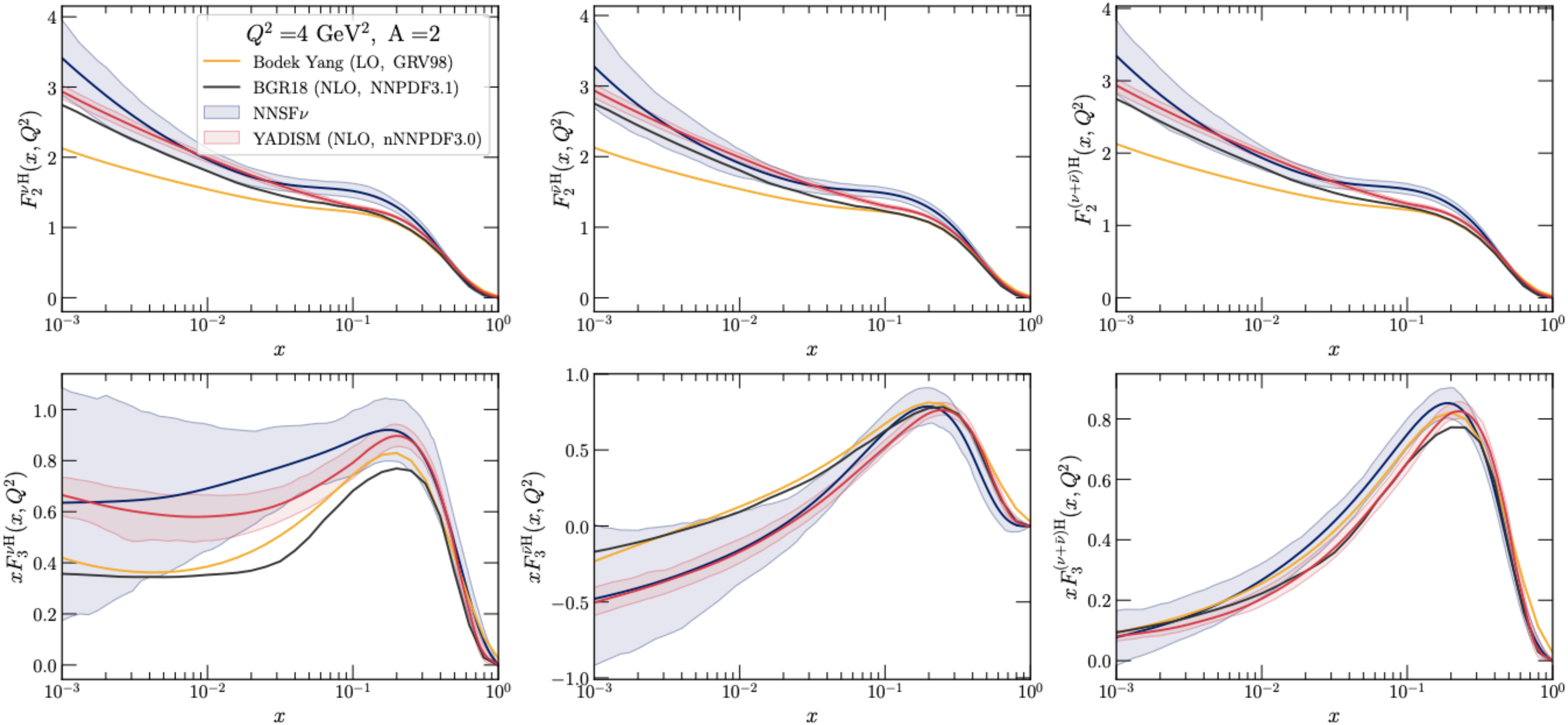




$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- Combined determination of the proton PDFs and the **normalisation** of muon neutrino flux
- FASER (Run-3) fixes flux normalisation to 6%, FASER2 pins it down at the **few-permille level**
- Pseudo-data for electron neutrino cross-sections at **different rapidities**
- Constraints small-x PDFs **down to 10^{-7}** , beyond the reach of any other (lab) experiment

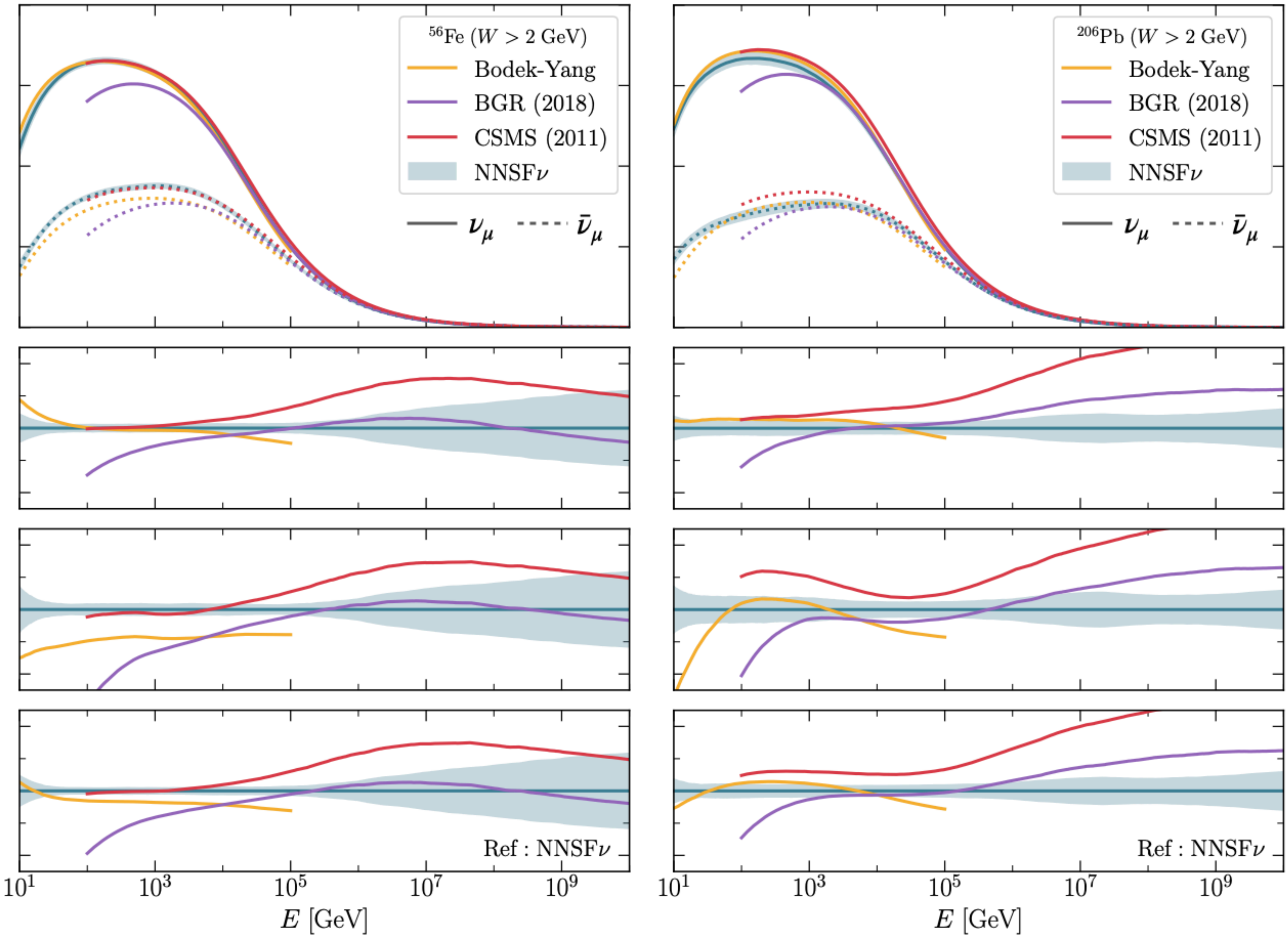
The NNSFν approach



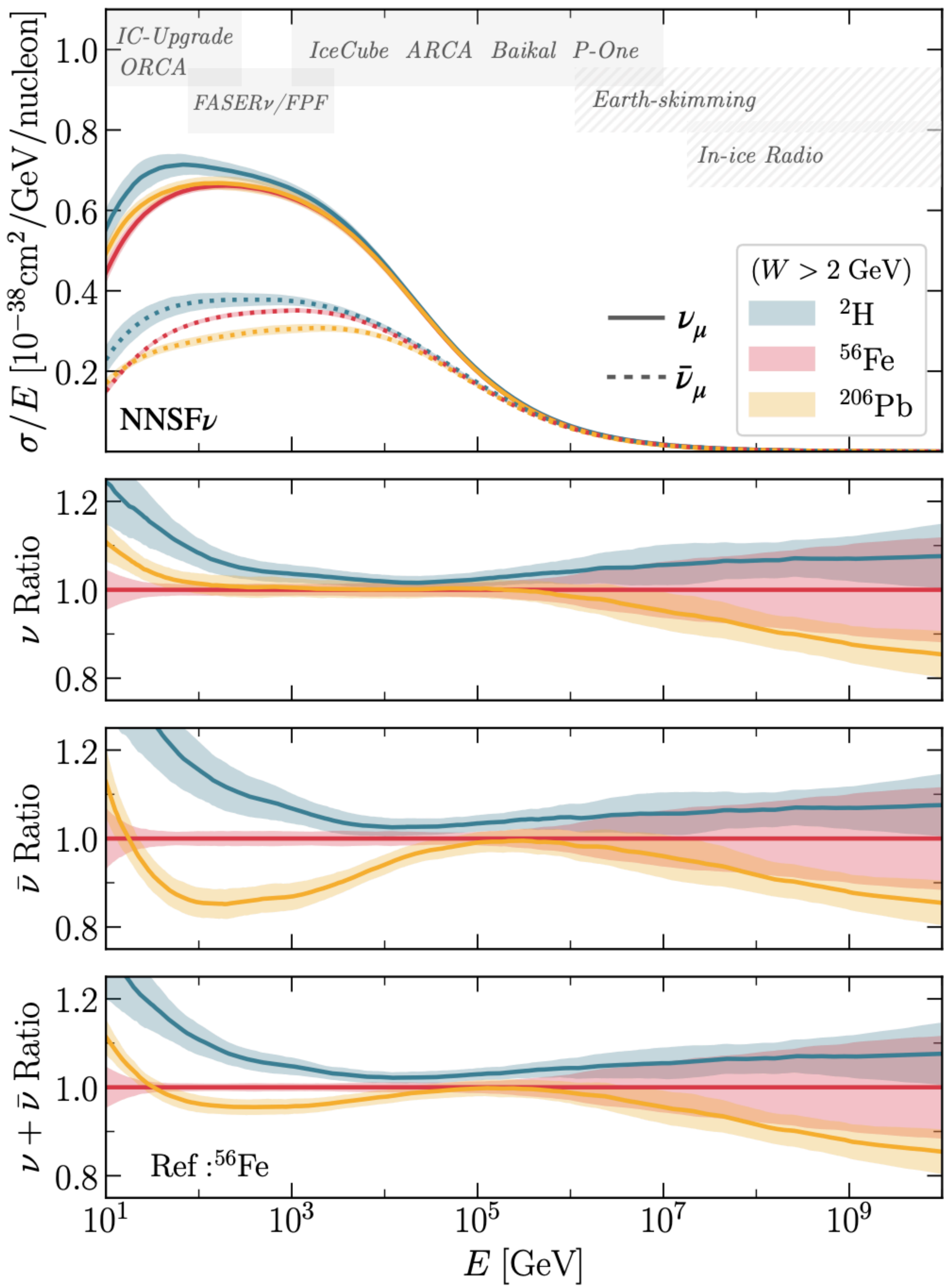
- The interpretation of LHC neutrino measurements demands robust models of **neutrino structure functions**
- **NNSFnu: smooth matching** between a data-driven (ML) parametrisation a la NNPDF (for $Q < 5$ GeV) and the NLO pQCD calculation (for $Q > 5$ GeV)
- Suitable for neutrinos with energies **from a few GeV** (e.g. DUNE) up to the **multi-EeV region** (e.g. IceCube)

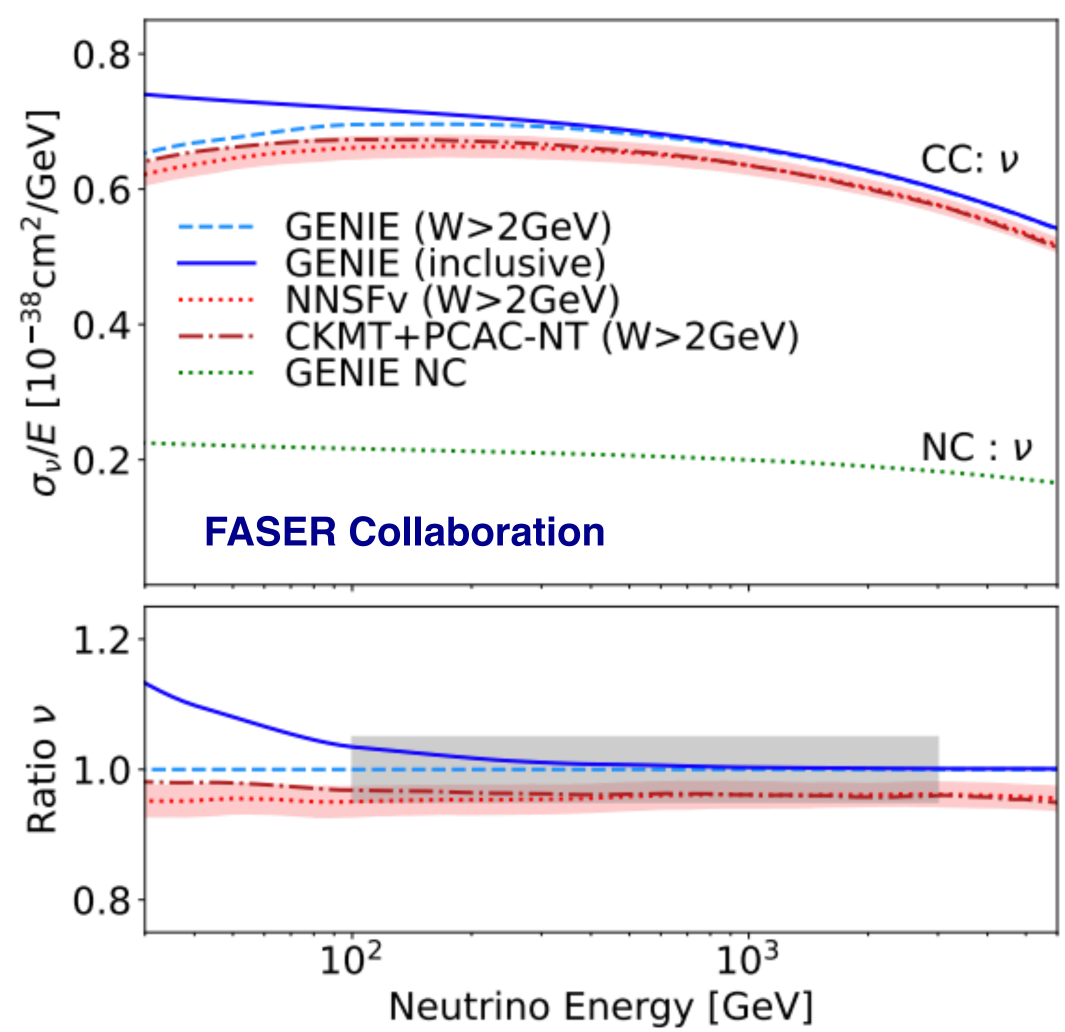
A. Candido, A. Garcia, G. Magni, T. Rabemananjara, J. Rojo, R. Stegeman, arXiv:2302.08527

The NNSFν approach



The NNSFν approach



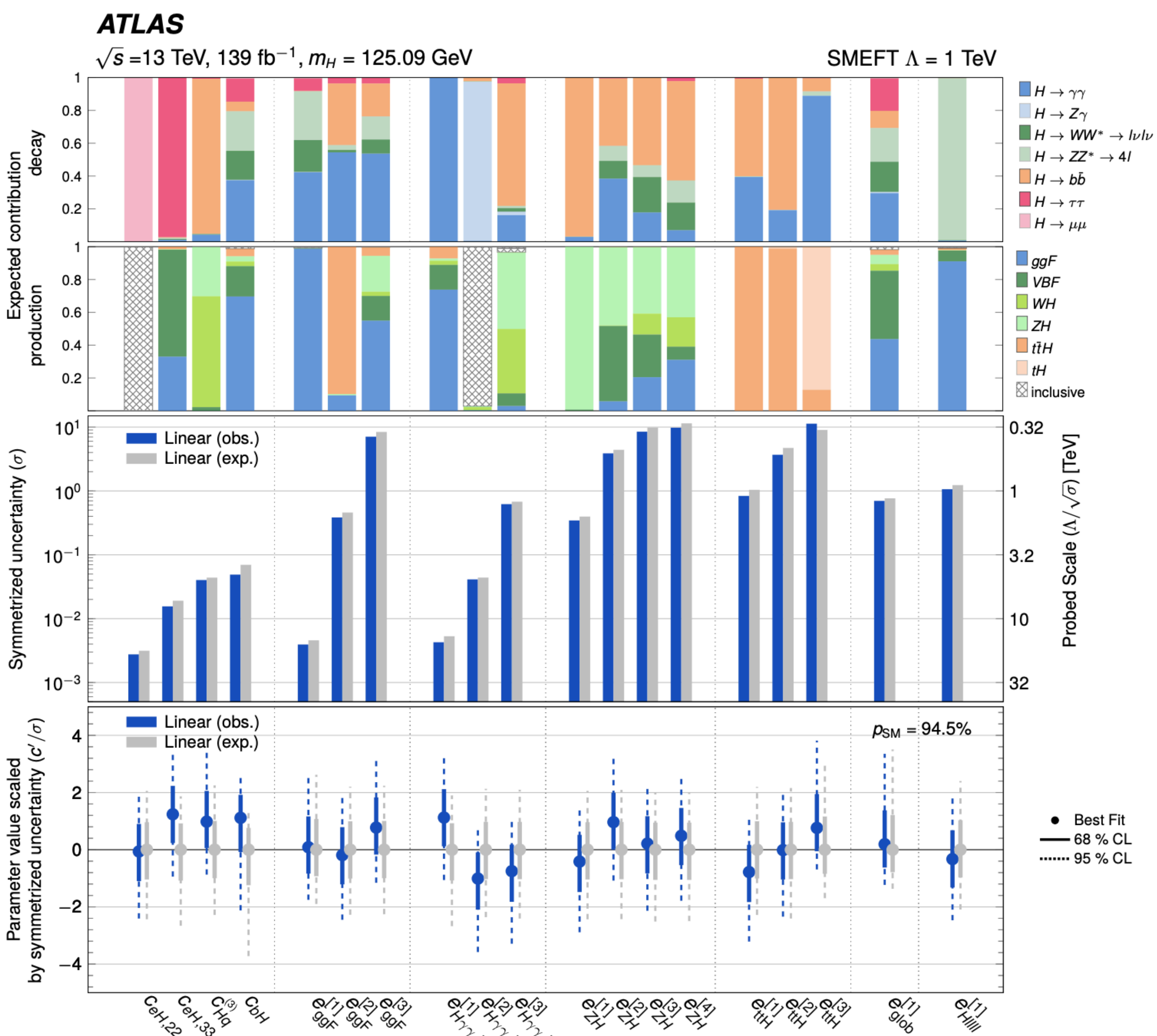


- Excellent agreement with available neutrino structure function and **cross-section data**
- Data-driven estimate of **nuclear effects**
- **Implemented in GENIE**, already used in FASER analyses of LHC neutrinos

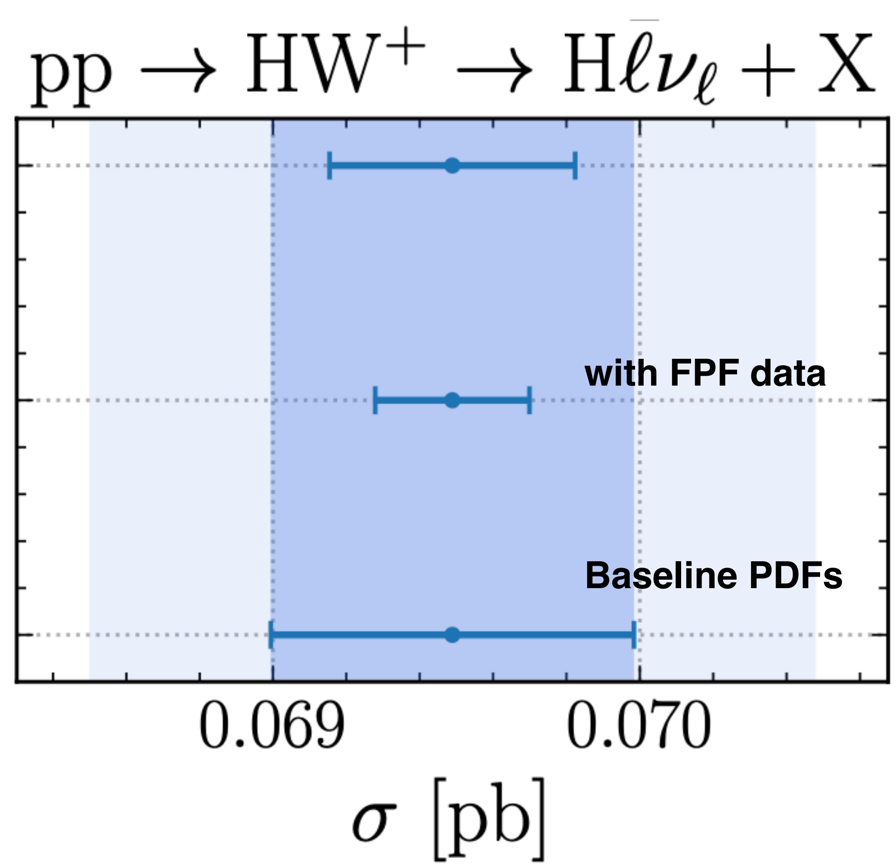
Impact on BSM Searches at the HL-LHC

Higgs couplings

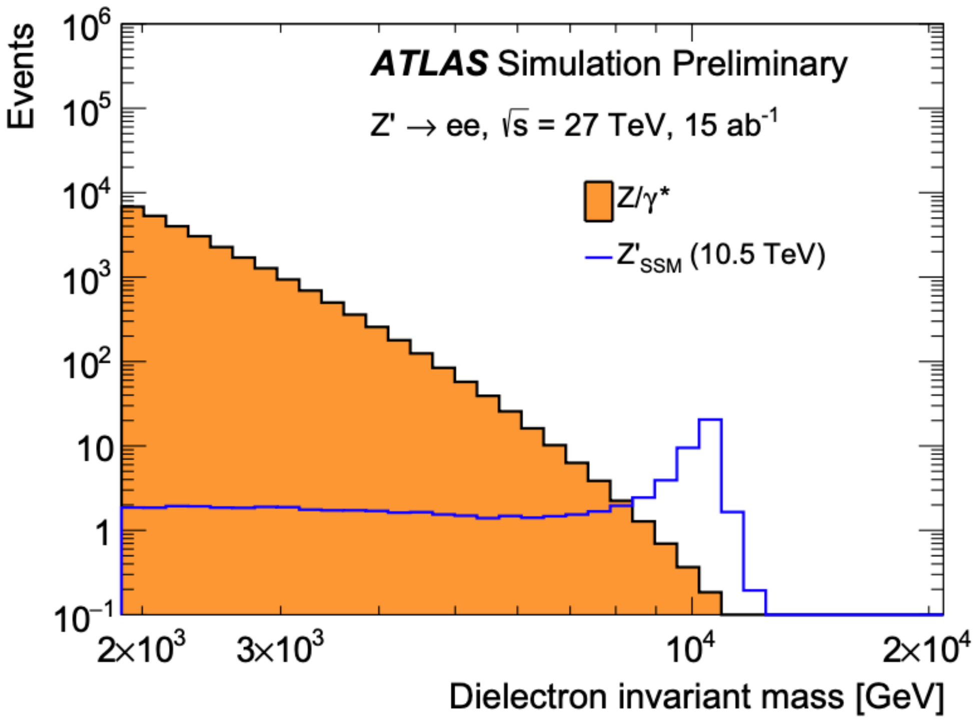
- Common misconception: the BSM program of the FPF is limited to **FIPs/LLPs** and related light BSM scenarios
- Rich **direct high-p_t BSM program** via TeV neutrino cross-sections and interactions (e.g. via EFTs)
- Rich **indirect high-p_t BSM program** via PDF constraints essential for BSM searches at the HL-LHC

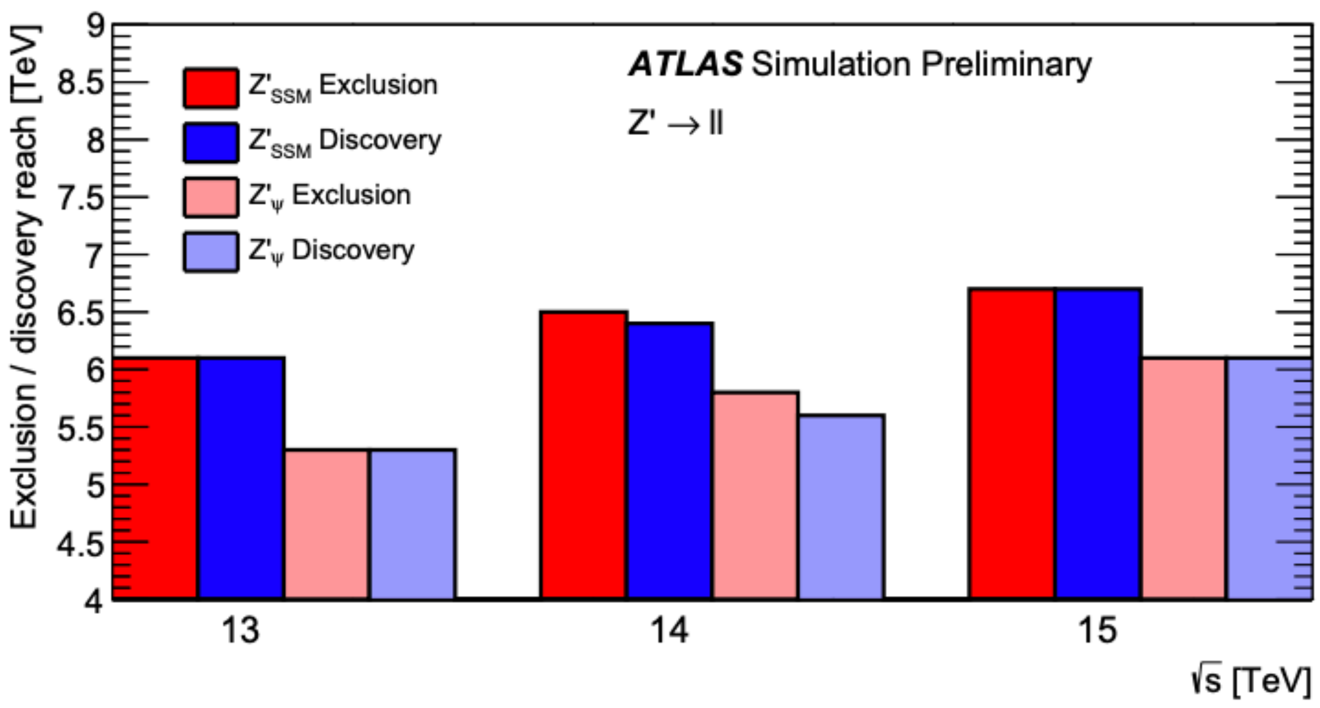


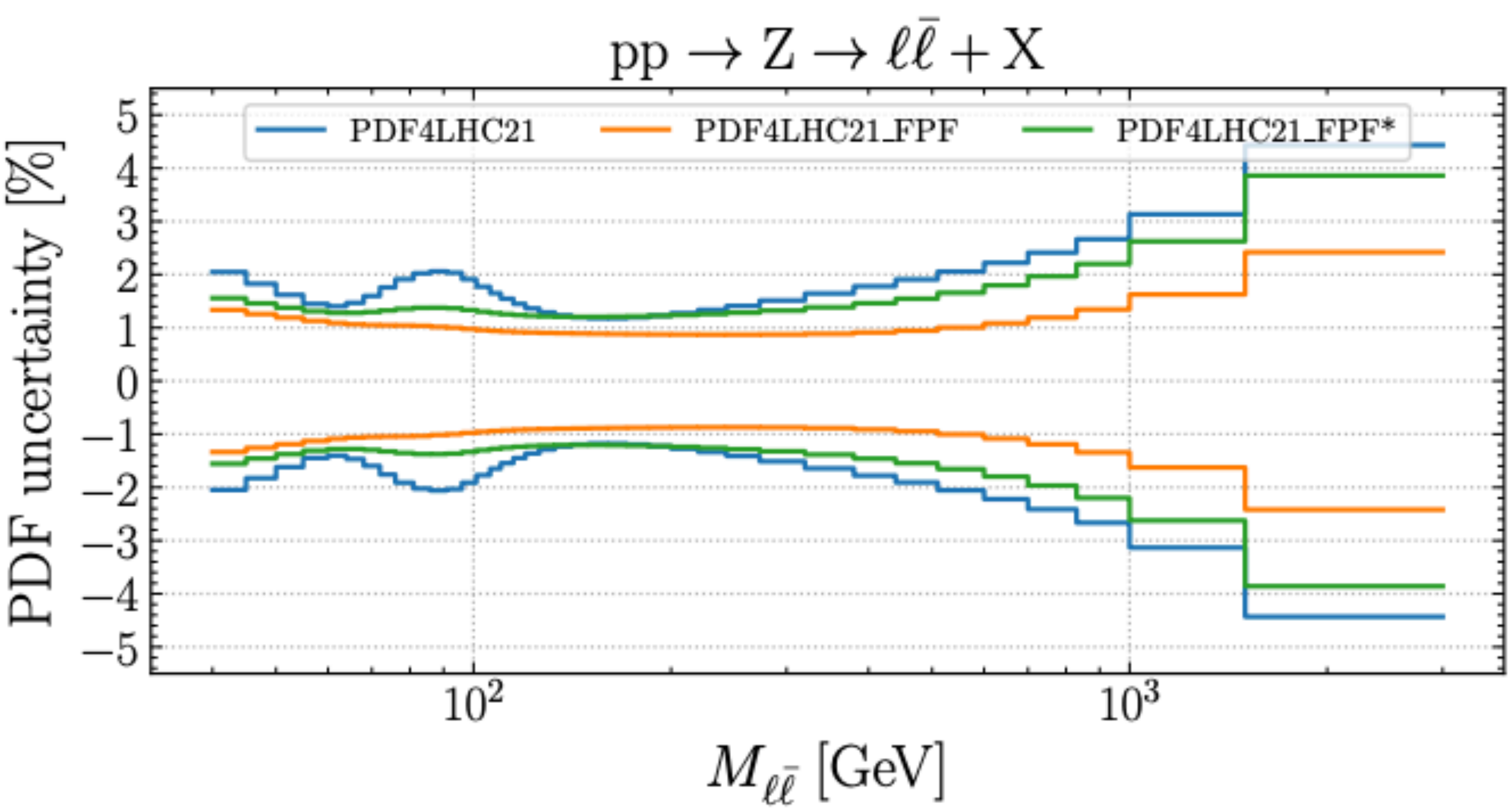
- Cornerstone of HL-LHC: search for BSM via **precision Higgs measurements** and their EFT global interpretation
- Full potential requires marked **reduction of current PDF uncertainties**



Direct Searches







- The HL-LHC will also extend the mass reach in **direct searches for new heavy particles** e.g. a Z'
- Large-*x* PDFs represent the dominant **theory uncertainty** limiting these analysis
- Again, PDF constraints at the FPF enable improved **background modelling for BSM searches** at HL-LHC

SMEFT analyses

Global PDF determinations are based on **Standard Model theoretical** calculations:

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\; \mathscr{L}_{ij}^{(\rm sm)}(M, \sqrt{s}, \boldsymbol{\theta})\, \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s(M)) \qquad \hat{s} = M^2/s$$

hadronic cross-section — Theory prediction to compare with experiment

SM PDF Luminosity — Constrain from data

PDF parameters

SM partonic cross-section — NNLO QCD & NLO EW

$$\mathscr{L}_{ij}^{(\rm sm)}(M, \sqrt{s}, \boldsymbol{\theta}) = \frac{1}{s}\int_{-\ln\sqrt{s}/M}^{\ln\sqrt{s}/M} {\rm d}y\, f_i^{(\rm sm)}\left(\frac{Me^{y}}{\sqrt{s}}, \boldsymbol{\theta}\right) f_j^{(\rm sm)}\left(\frac{Me^{-y}}{\sqrt{s}}, \boldsymbol{\theta}\right)$$

PDF parameters from likelihood maximisation: BSM effects potentially **``fitted away" into PDFs**

$$\chi^2\left(\boldsymbol{\theta}\right) = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{\rm i,th}(\boldsymbol{\theta}) - \sigma_{\rm i,exp}\right) \left({\rm cov}^{-1}\right)_{ij} \left(\sigma_{\rm j,th}(\boldsymbol{\theta}) - \sigma_{\rm j,exp}\right)$$

SMEFT analyses

What is the underlying short-distance theory is **not the SM** but instead the **SMEFT**?

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\; \mathscr{L}_{ij}^{(\rm smeft)}(M, \sqrt{s}, \boldsymbol{\theta}, \boldsymbol{c}/\Lambda^2)\; \widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s(M), \boldsymbol{c}/\Lambda^2)$$

hadronic cross-section — *SMEFT PDF luminosity* — PDF parameters — *SMEFT partonic cross-section* — EFT coefficients

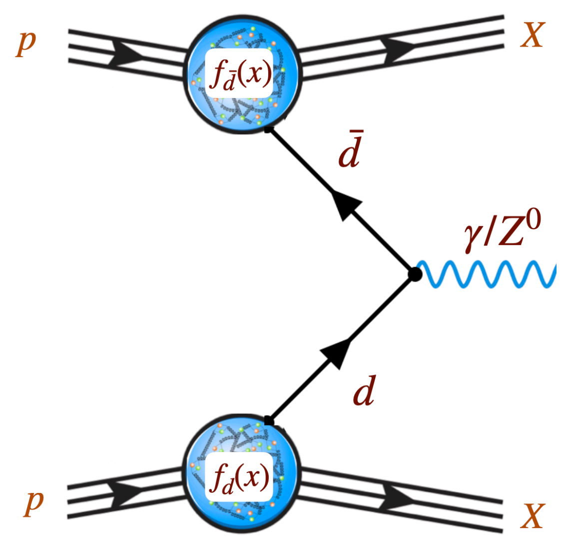
In the case of new physics described within the **dimension-6 SMEFT framework:**

$$\widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s, \boldsymbol{c}/\Lambda^2) = \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s)\left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m^{ij}}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}^{ij}}{\Lambda^4}\right)$$

SMEFT PDFs** defined as PDFs extracted from the data when SMEFT used to model **partonic hard-scattering

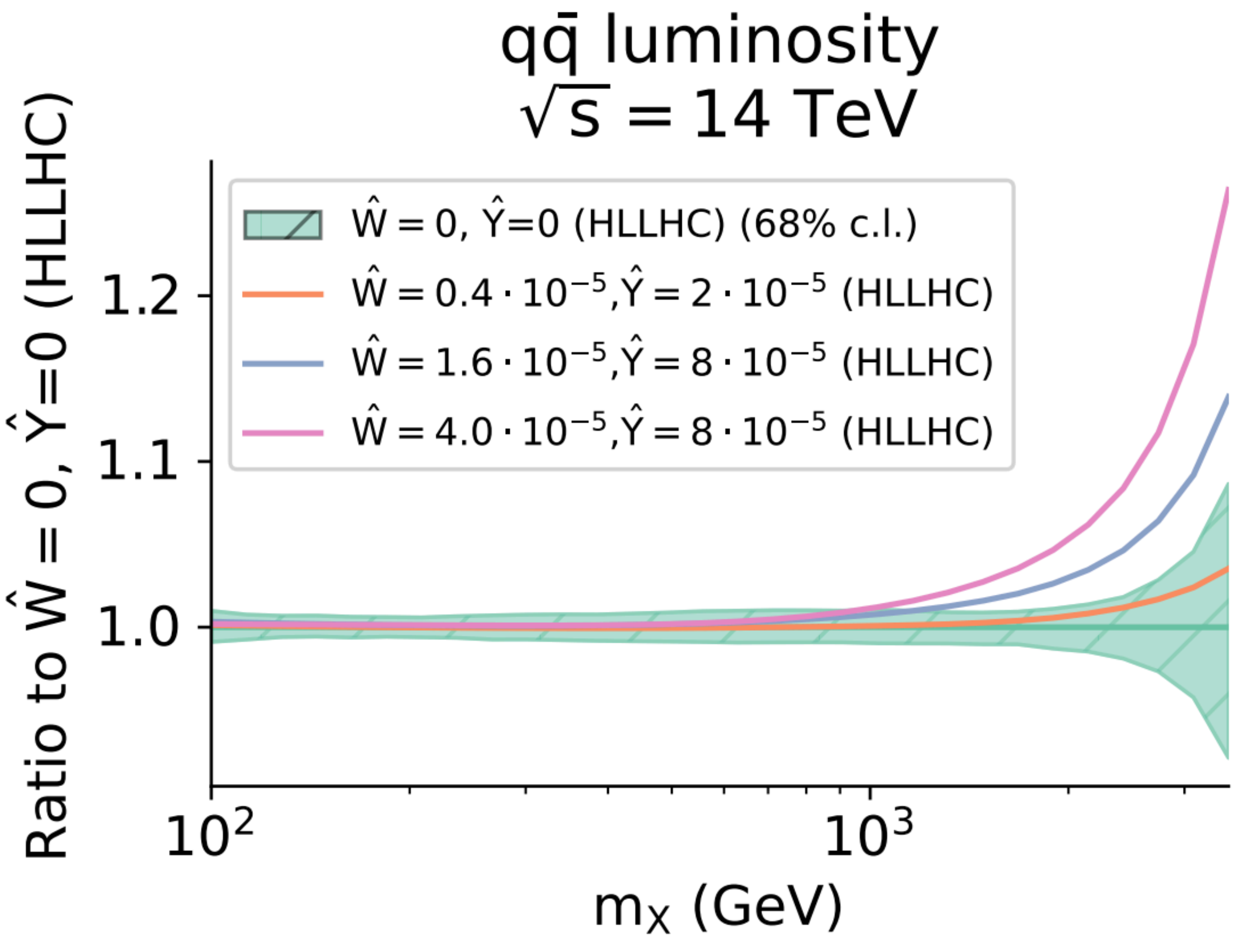
Given experimental constraints, how **different are SM and SMEFT PDFs**? Is there a risk to **fit away EFT effects into the PDFs?**

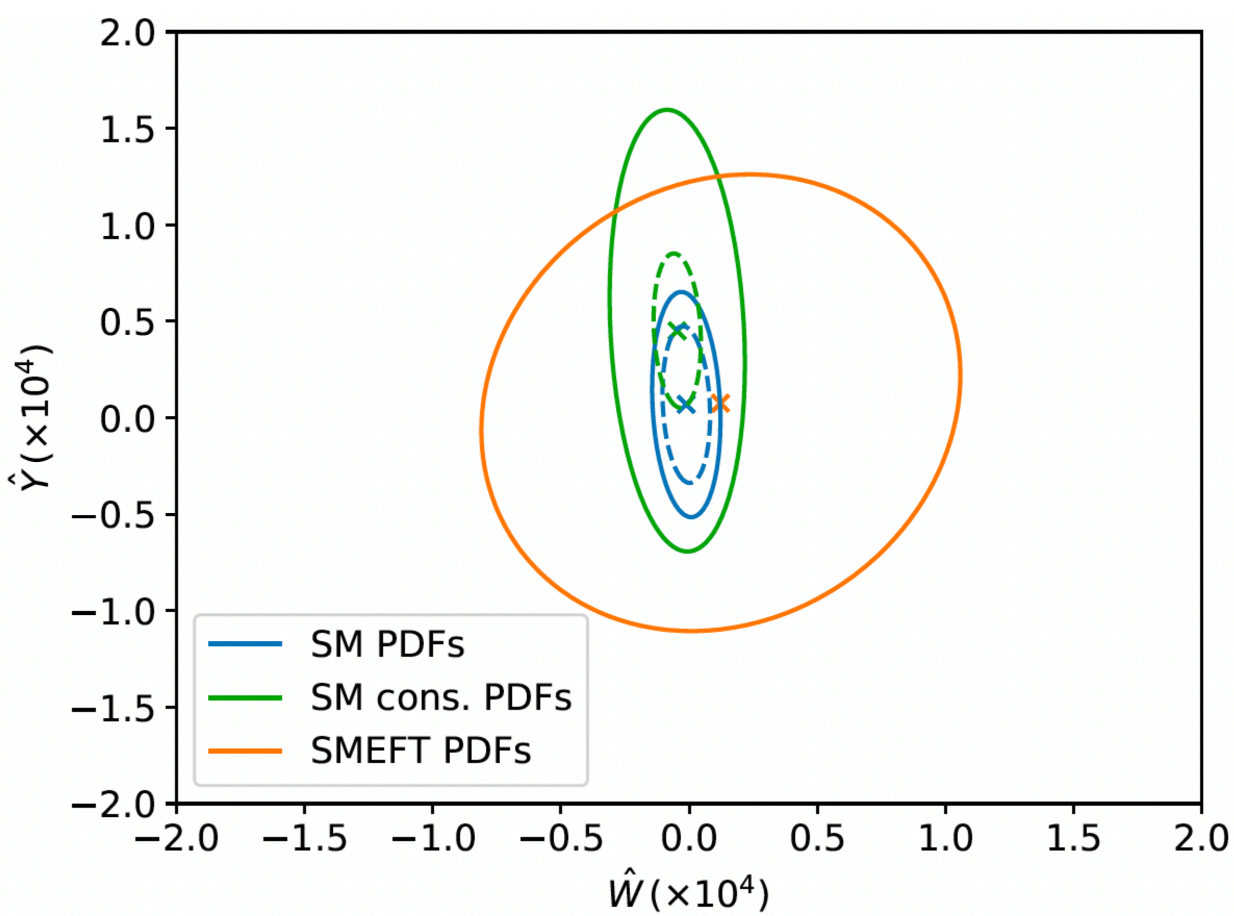
SMEFT analyses



High-mass Drell-Yan: *A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021*

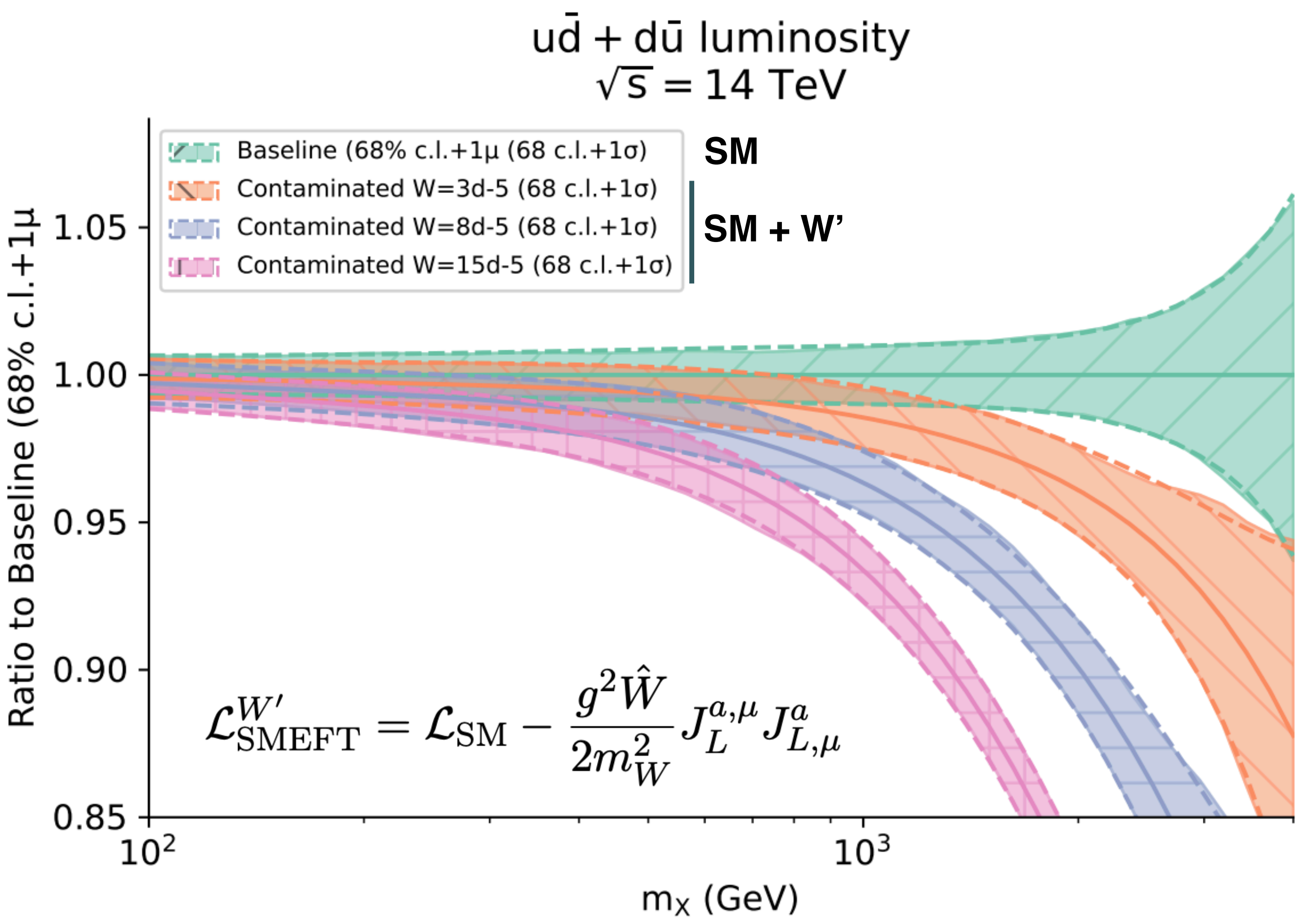
- HL-LHC projections: strong constraints on large-*x* antiquark PDFs, may be **reabsorbed into SMEFT PDFs**
- Bounds based on SM-PDFs **overly optimistic** as compared to those obtained from SMEFT-PDFs
- Emphasises importance of **SMEFT-PDF interplay** at the HL-LHC

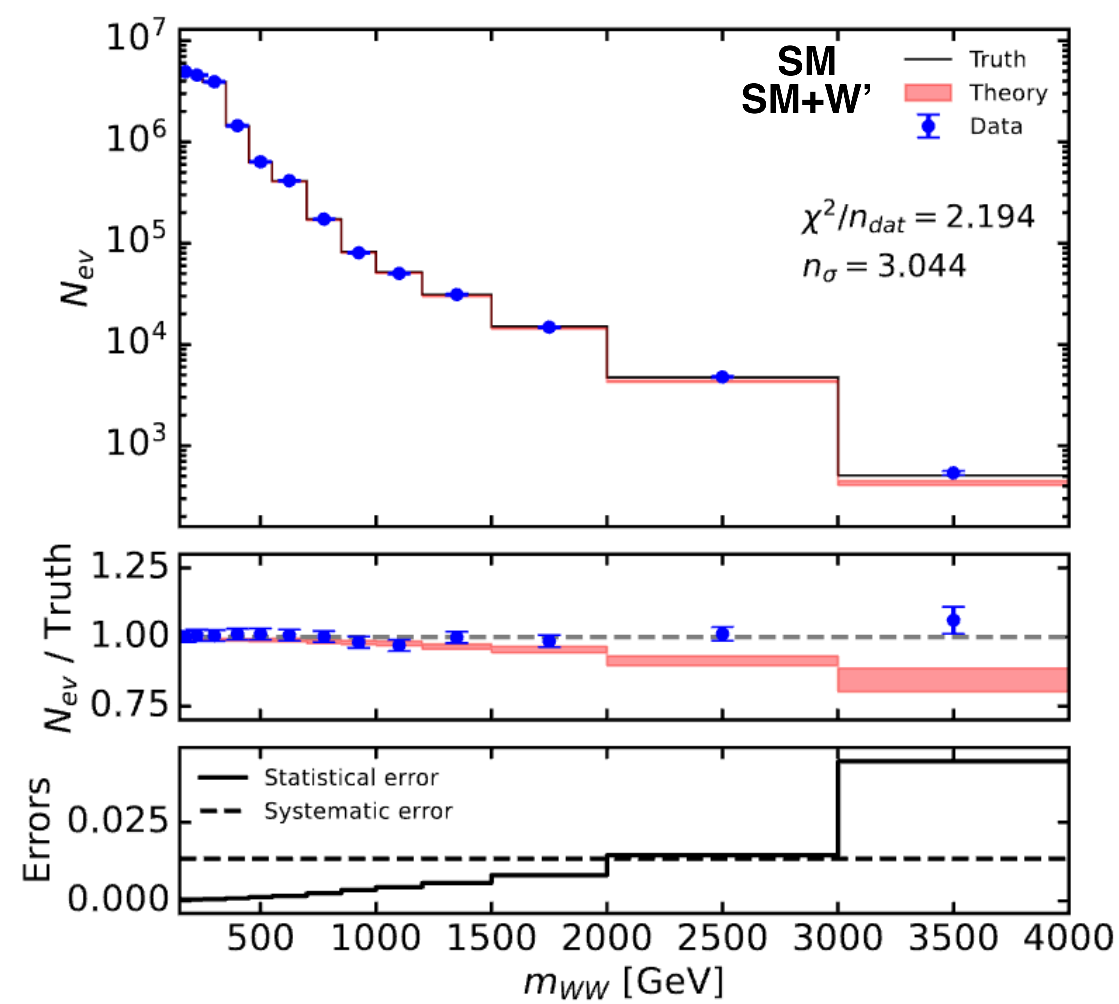




SMEFT analyses with FPF data

- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- **Data-theory agreement unchanged,** but the qqbar luminosity **shift far beyond PDF uncertainties**.
- Why? Because anti-quark PDFs at large-*x* poorly constrained, **"fitting away" BSM signals!**
- Result: miss BSM signals in SMEFT analysis & spurious effects in ``SM" processes (e.g. diboson)

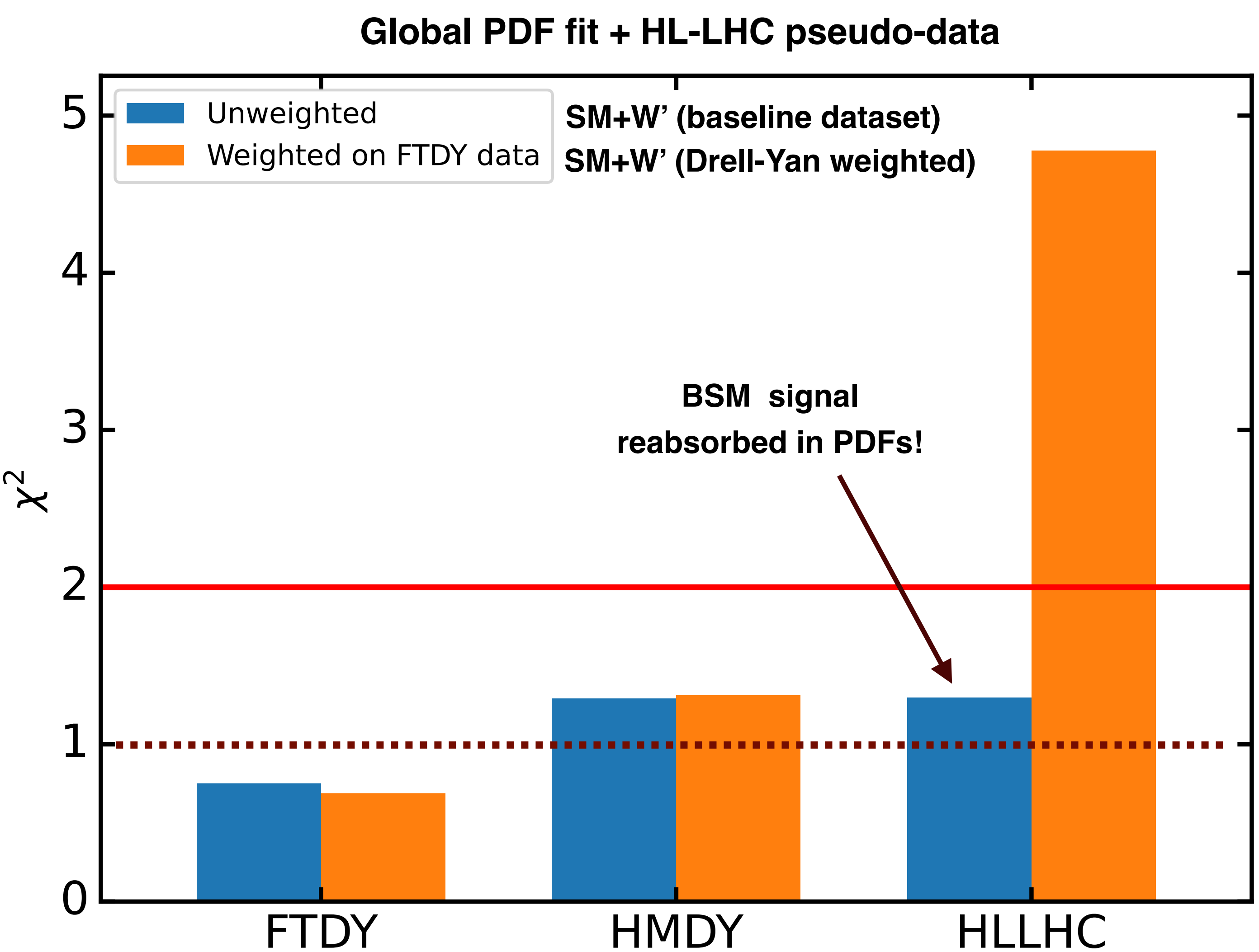


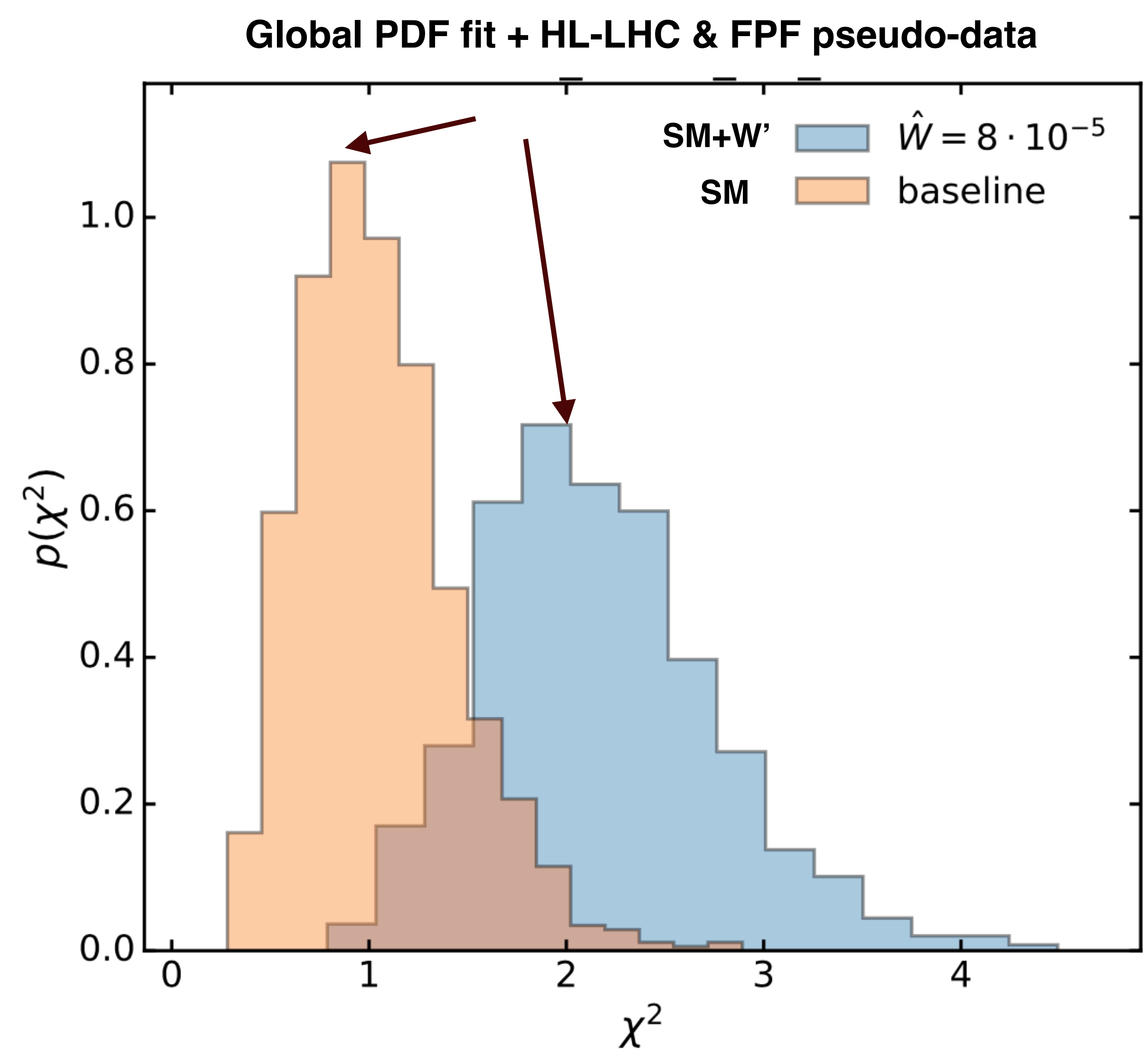


Hammou, Madigan, Mangano, Mantani, Morales, Ubiali, 2307.10370

SMEFT analyses with FPF data

- **Low-energy measurements** constraining **large-*x* PDFs** to disentangle QCD from BSM effects
- Including **FPF neutrino DIS measurements** would break this PDF/BSM degeneracy!
- Essential input to realise the **full BSM search potential of the HL-LHC**





Hammou, Madigan, Ubiali, **WIP**

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**

- Precision tests of **neutrino interactions** and their flavour universality in the TeV region

- Measuring LHC neutrino fluxes enables **unprecedented probe of small-x QCD and forward hadron production**, instrumental for astroparticle physics but also **future colliders**

- In addition to FIP searches, the FPF provides unique constraints for **high-p_T searches at LHC**