QCD and Neutrino Physics for Small LHC experiments

Juan Rojo, VU Amsterdam & Nikhef

Small LHC experiments

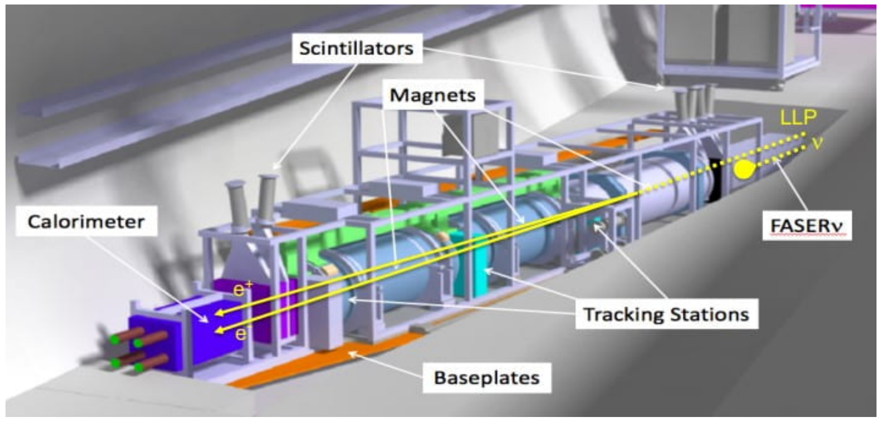
Small LHC experiments

Ongoing

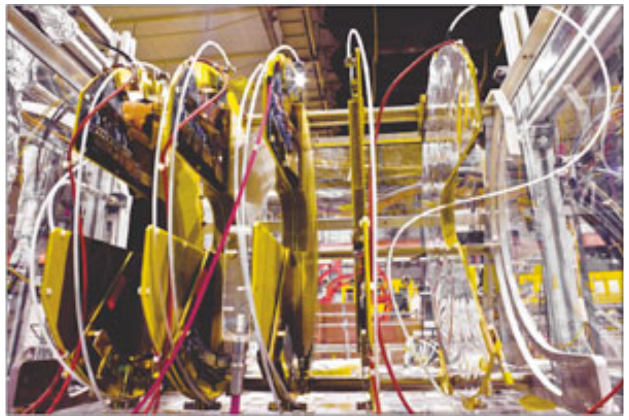
Far-Forward

Forward

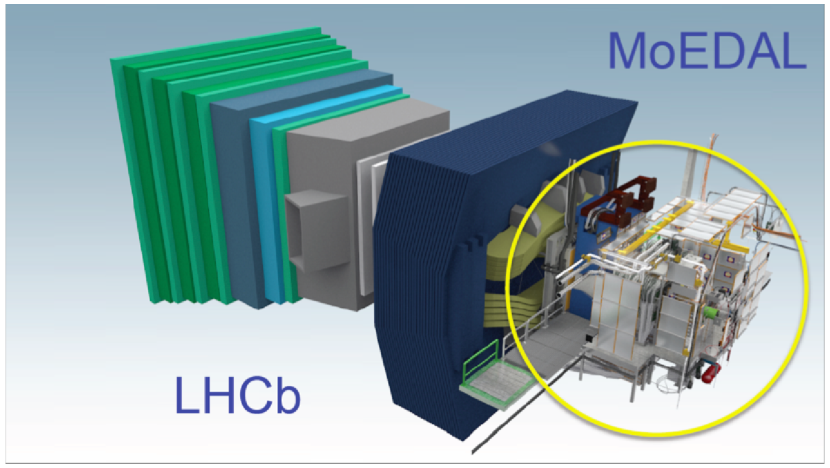
FASER(ν)



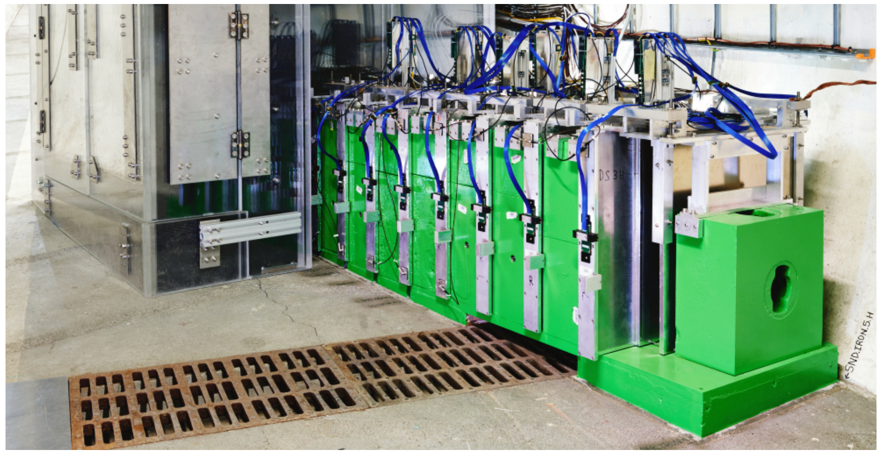
TOTEM



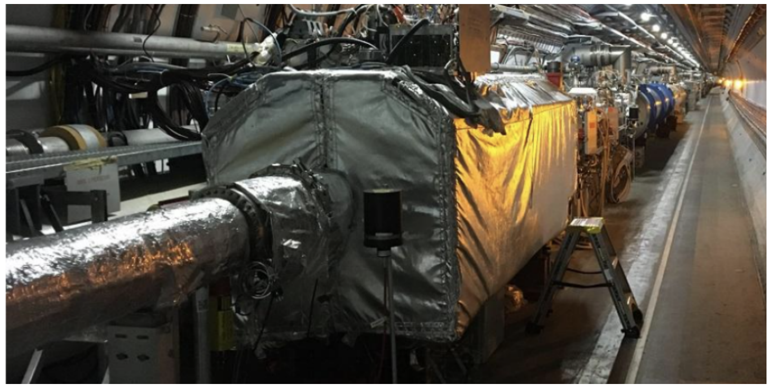
MoEDAL



SND@LHC



LHCf



- Search for **magnetic monopoles**
- Search for highly ionising particles

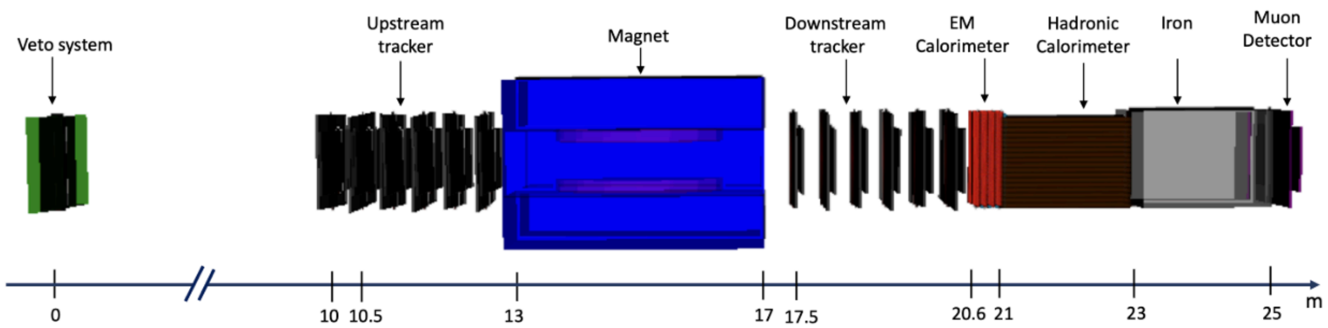
- Forward particle production
- **Total, elastic, and diffractive scattering**

- **Forward neutrino detection**
- Search for FIPs & LLPs

Small LHC experiments

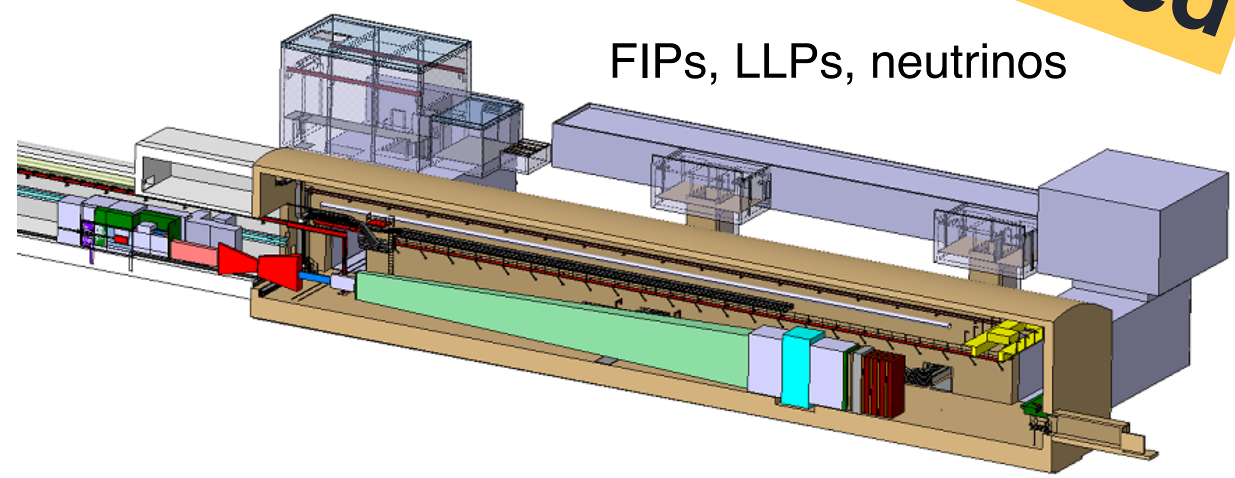
Future & Proposed

FASER2(v)

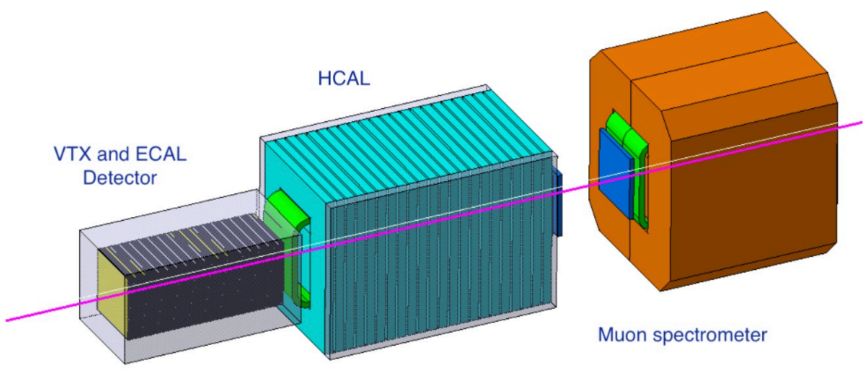


SHiP/BDF (incl SND)

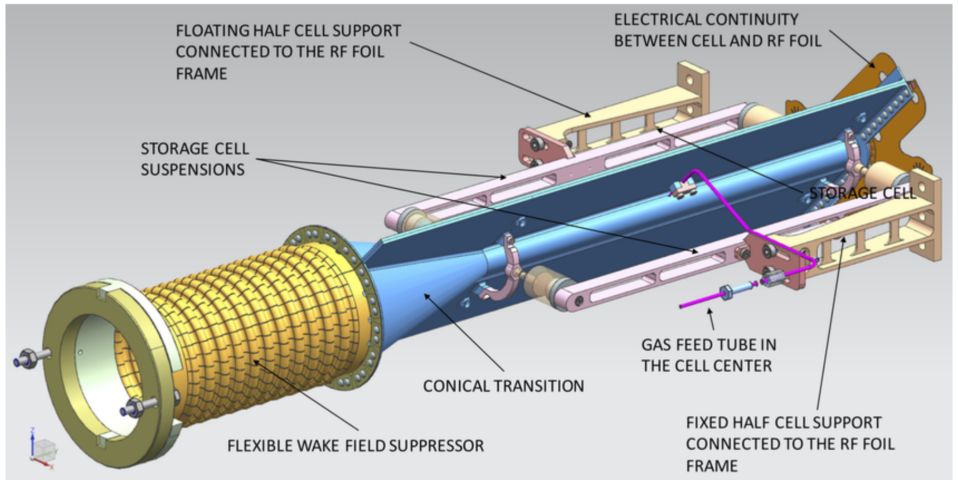
FIPs, LLPs, neutrinos



AdvSND@LHC



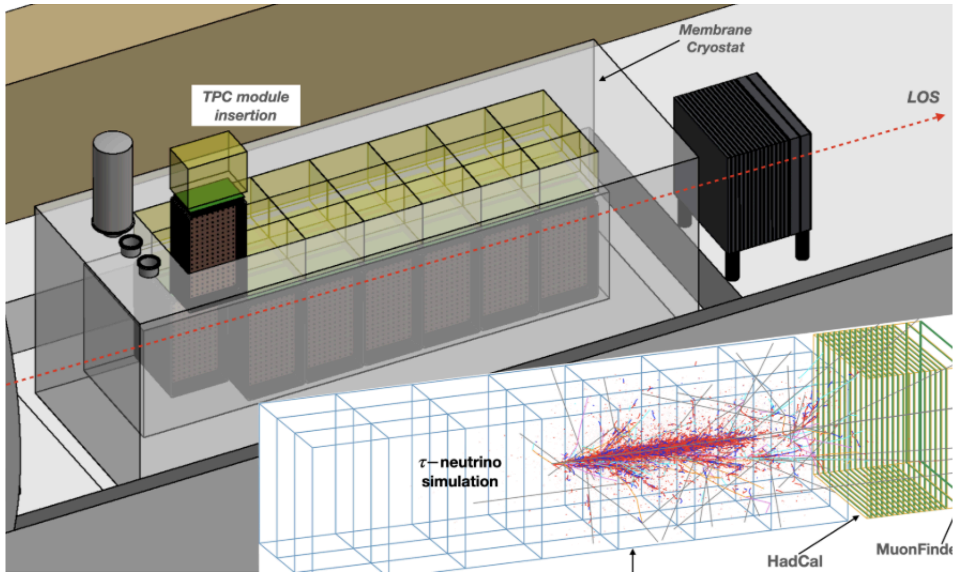
SMOG@LHCb & LHCSpin



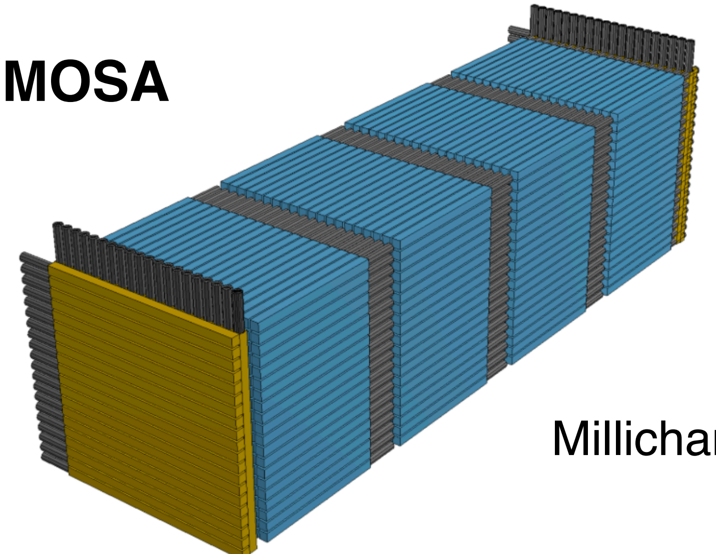
QCD, hadron structure, CRs

FLArE

Neutrino & light DM



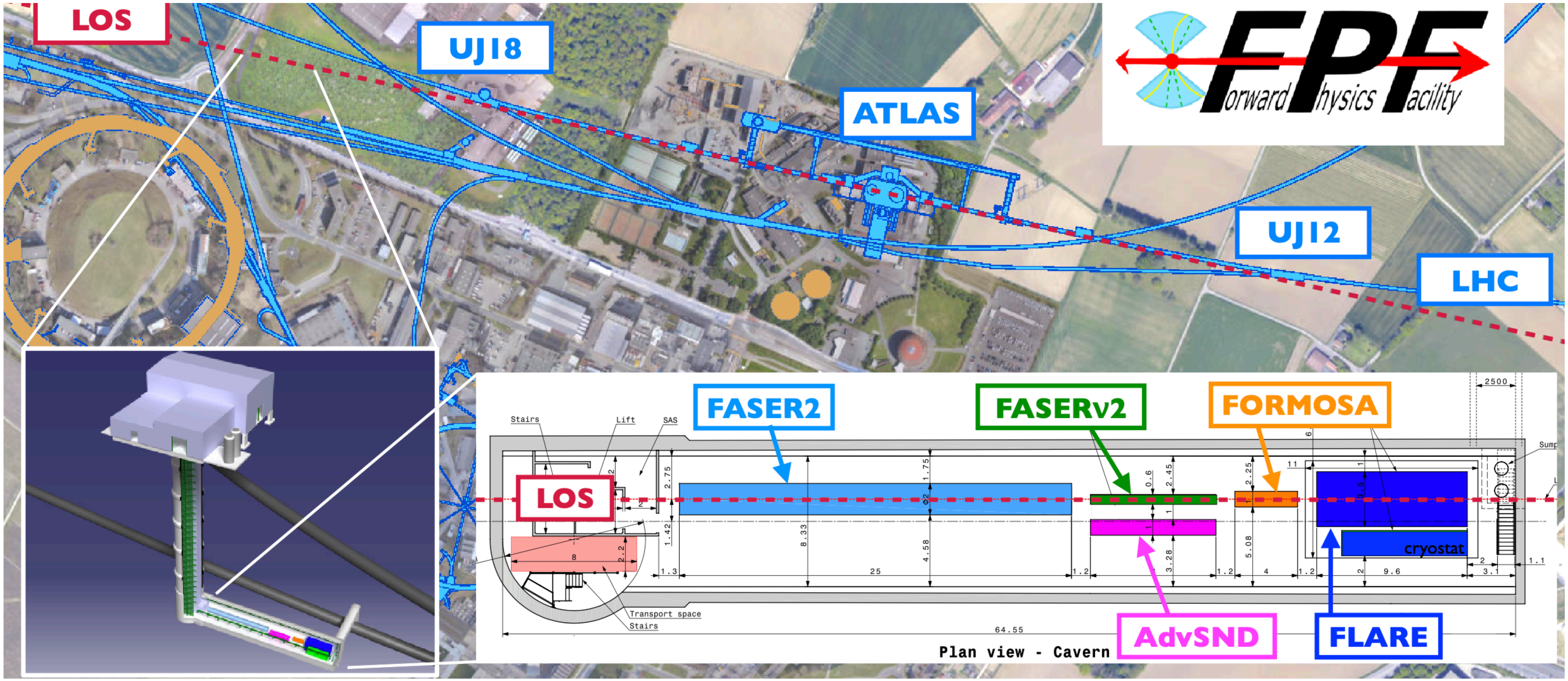
FORMOSA



Millicharged particles

The Forward Physics Facility

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

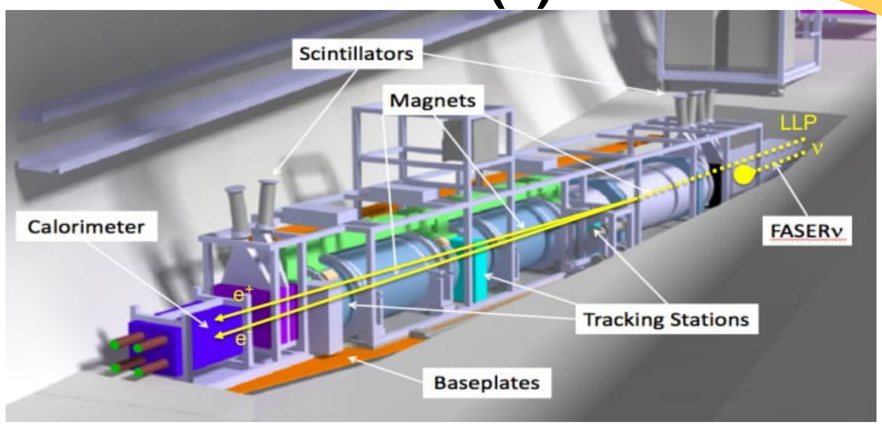


- Complementary suite of **far-forward experiments,** operating **concurrently with the HL-LHC**
- Start **civil engineering during LS3** or shortly thereafter, to maximise overlap with HL-LHC
- Positive outcome of **ongoing site investigation** studies (geological drill down to the cavern depth)

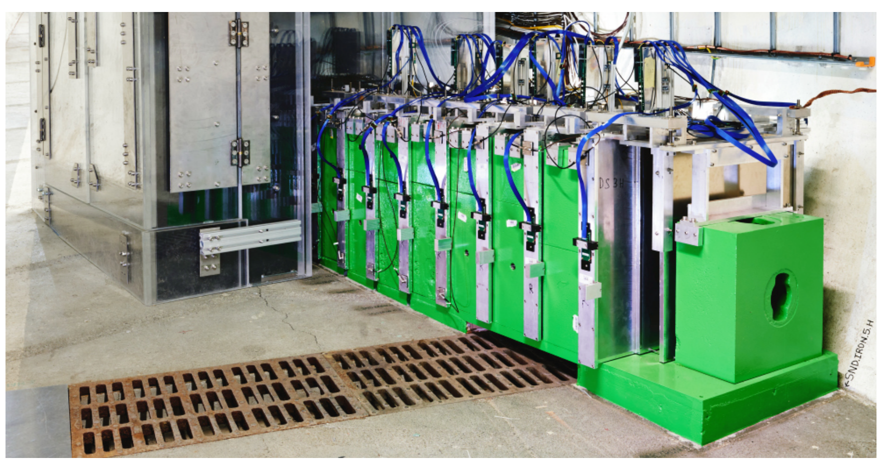
LHC far-forward experiments

Ongoing

FASER(ν)

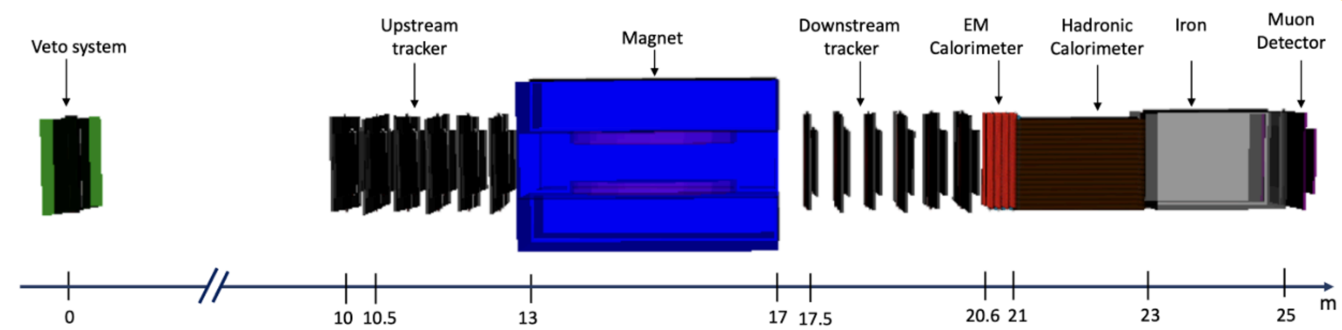


SND@LHC

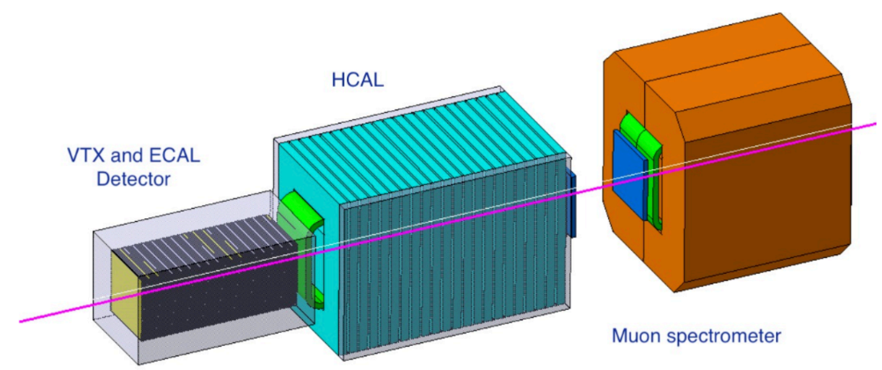


Proposed

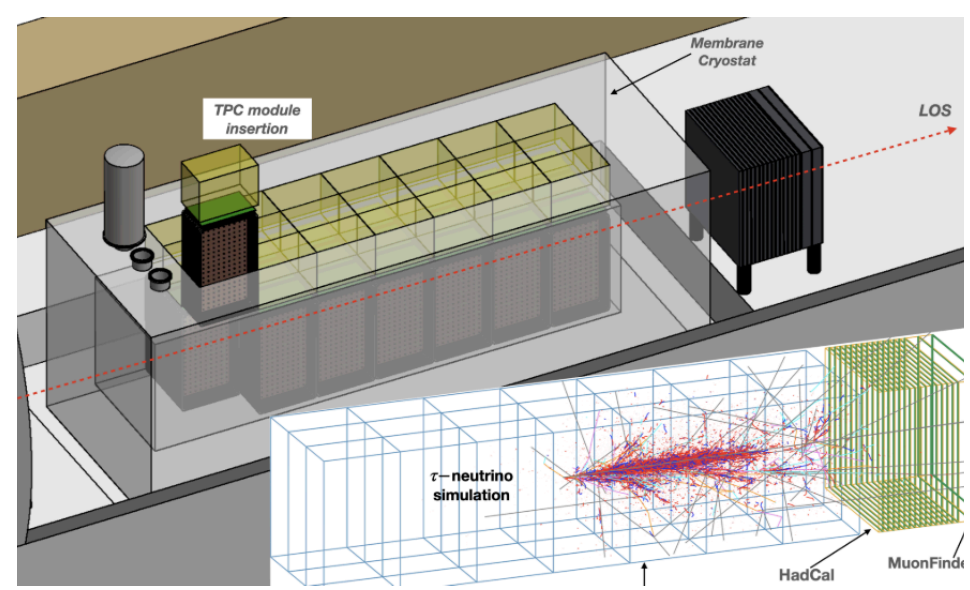
FASER2(ν)



AdvSND@LHC



FLArE

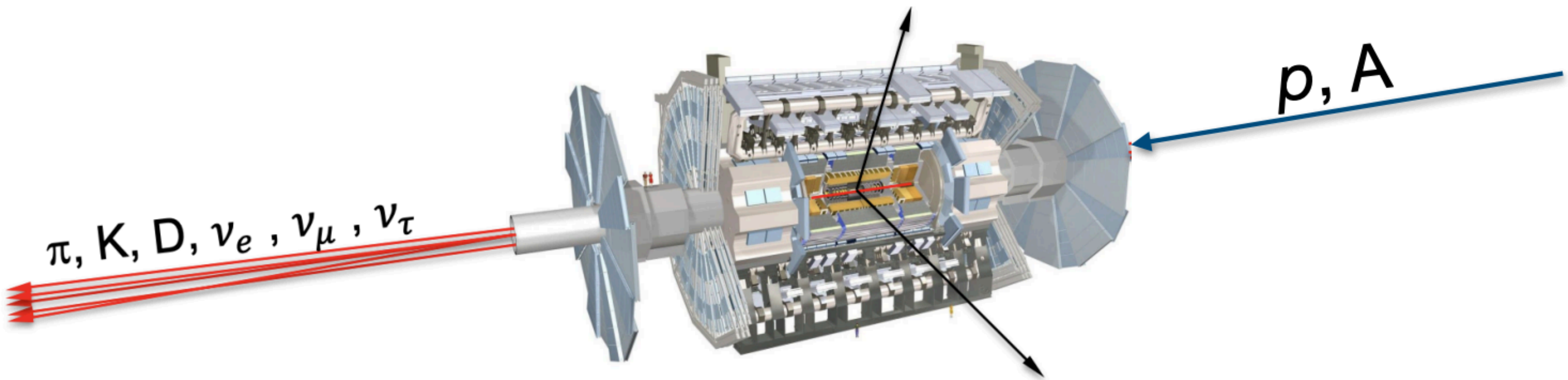


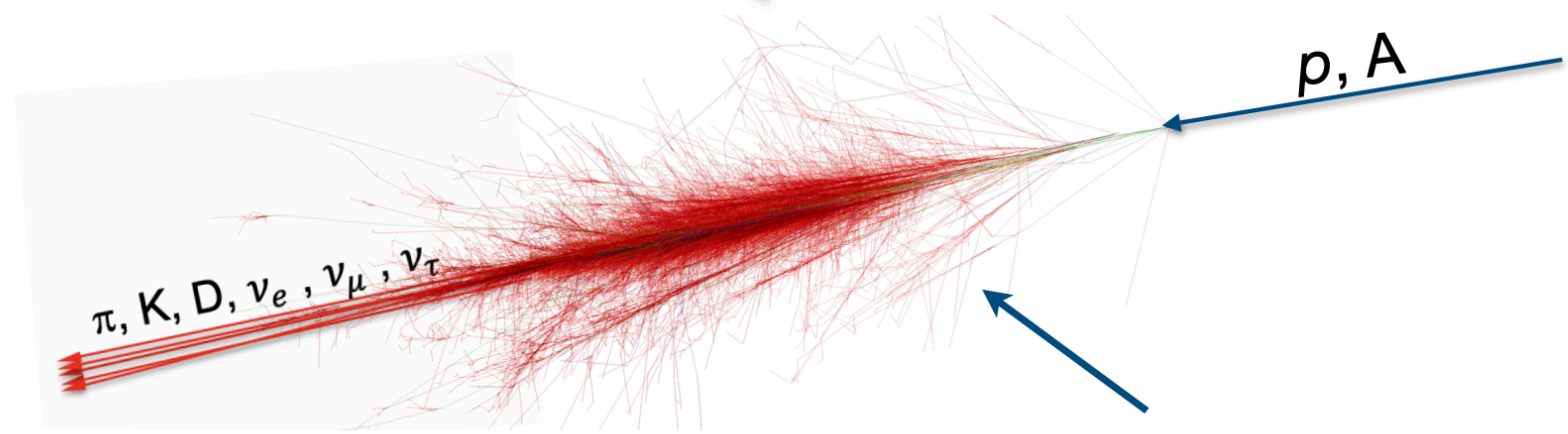
- FASER2(ν) and FLArE would be installed within this new **Forward Physics Facility**
- FASER will also operate during **Run-4** (without the neutrino detector)
- Focus on **QCD & neutrino physics**

Neutrinos from LHC Collisions

Neutrinos at the LHC

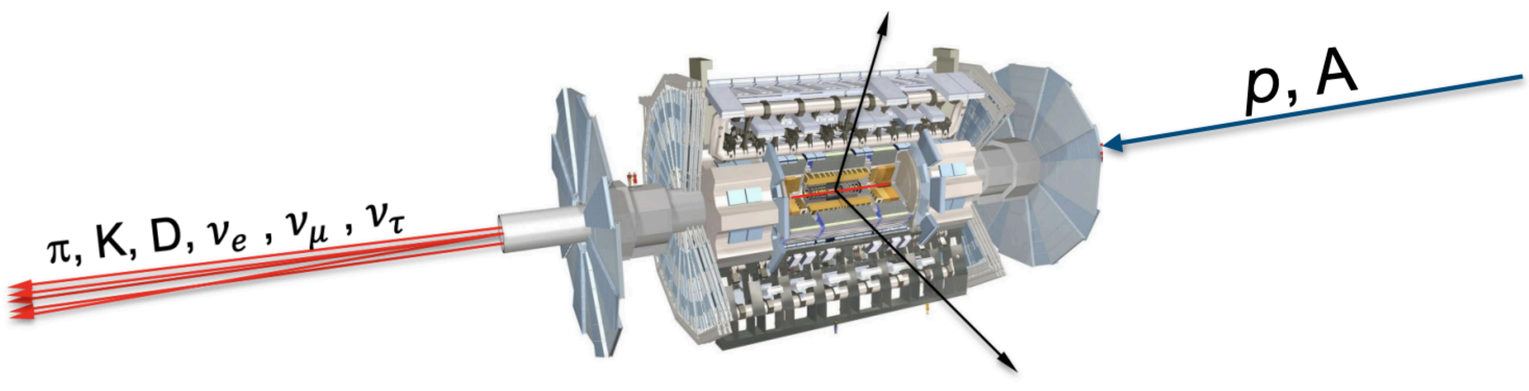
There are **guaranteed physics targets** to be reached should we instrument the forward region of the LHC, based on exploiting **the most energetic, high-intensity neutrino beam ever produced in a laboratory**



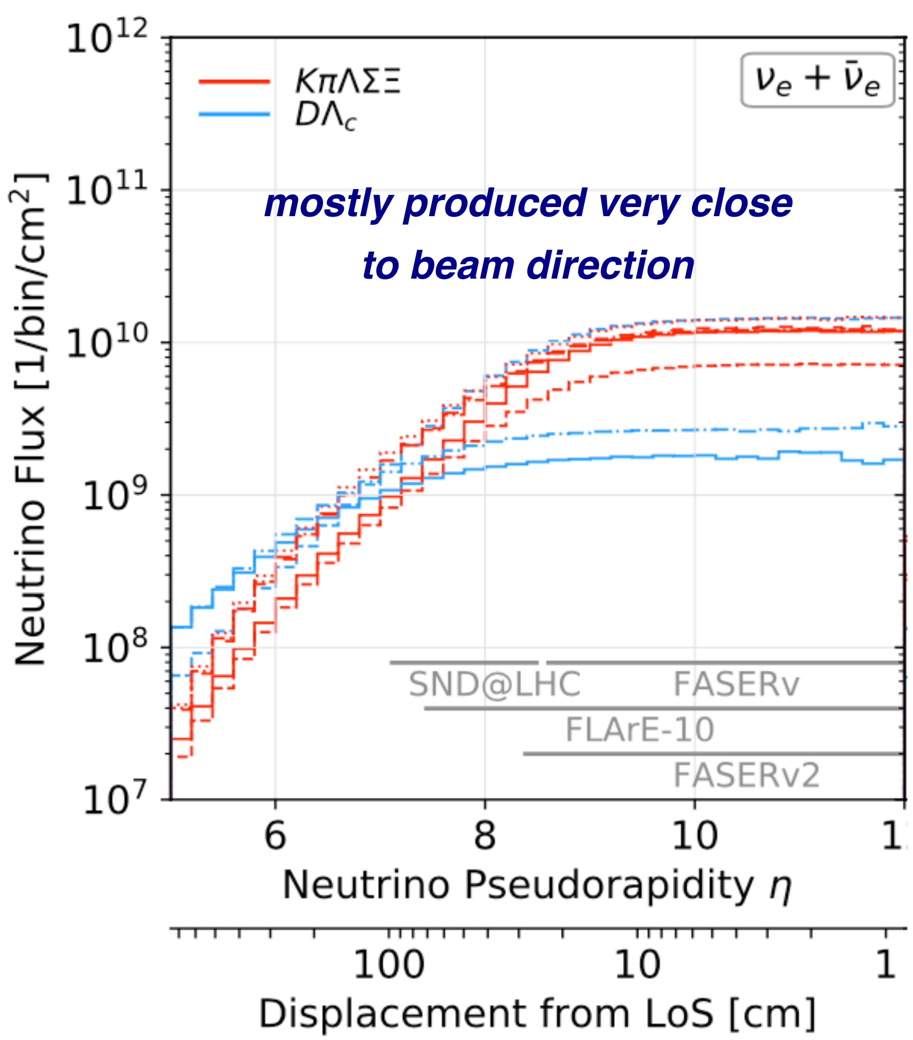


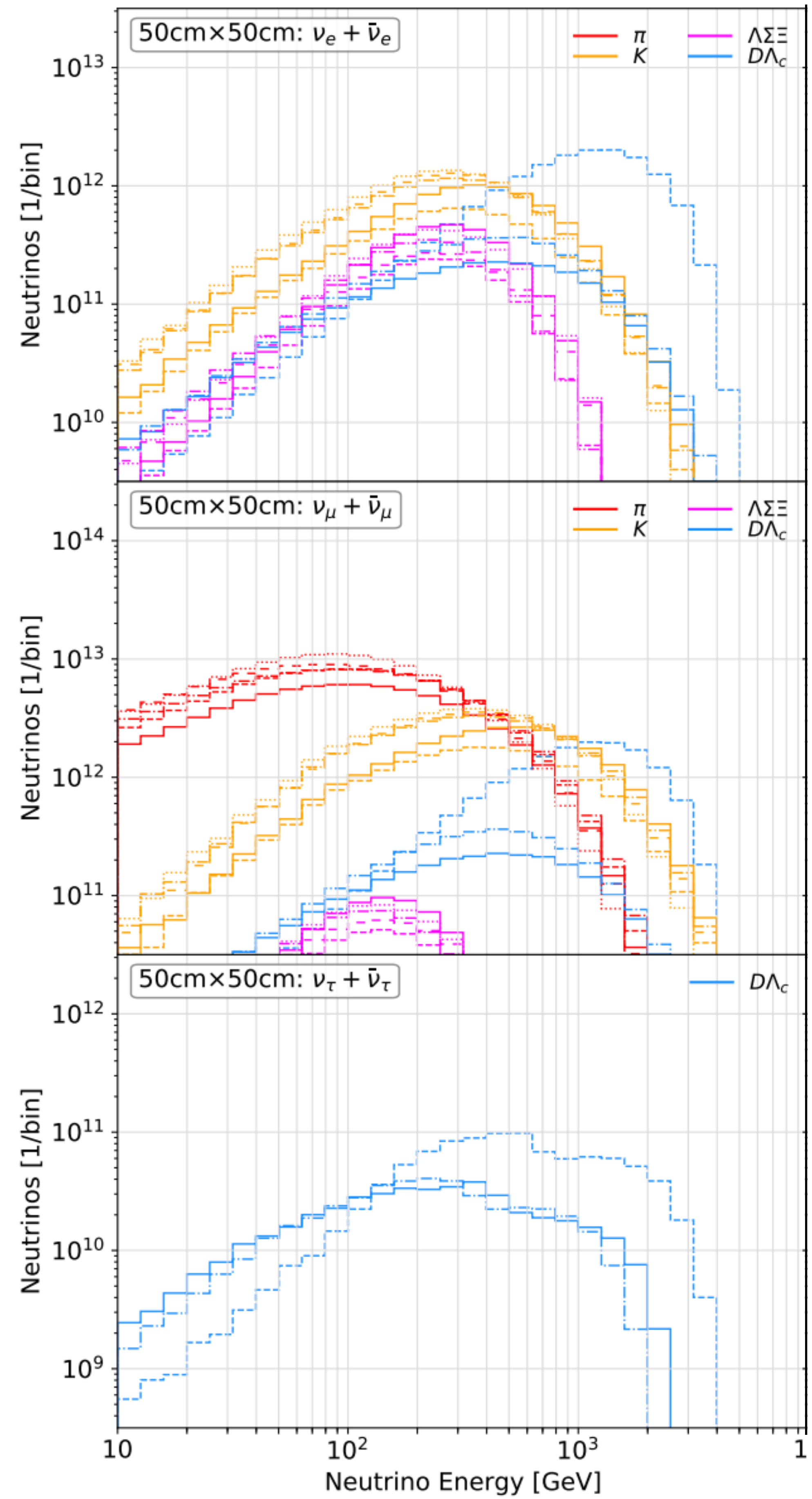
Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux

Neutrinos at the LHC

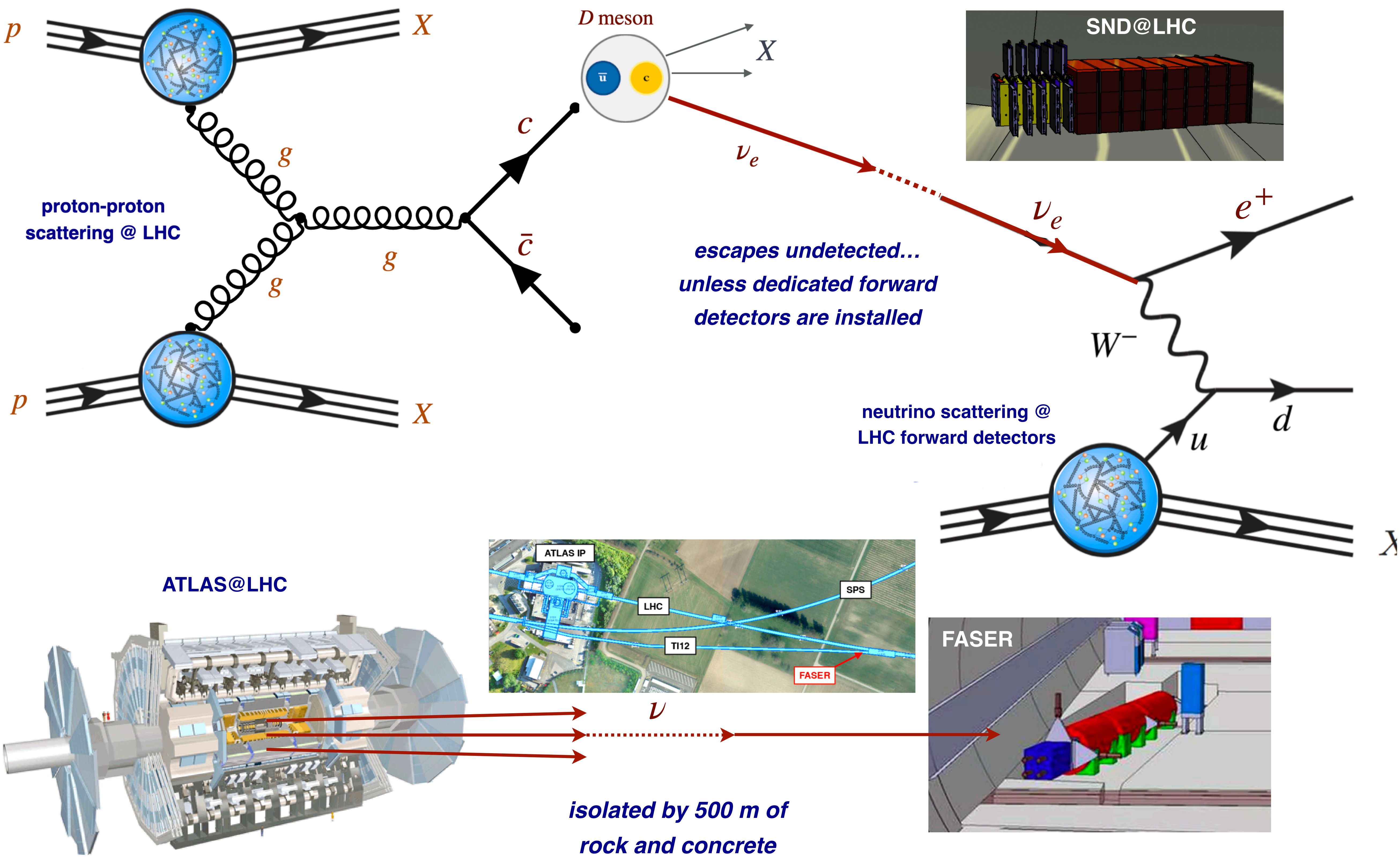


- **electron neutrinos** mostly from *D*-meson decays above 500 GeV, below it mostly from kaon decays
- **muon neutrino** flux dominated by pion & kaon decays
- **tau neutrinos** entirely from D-meson decays



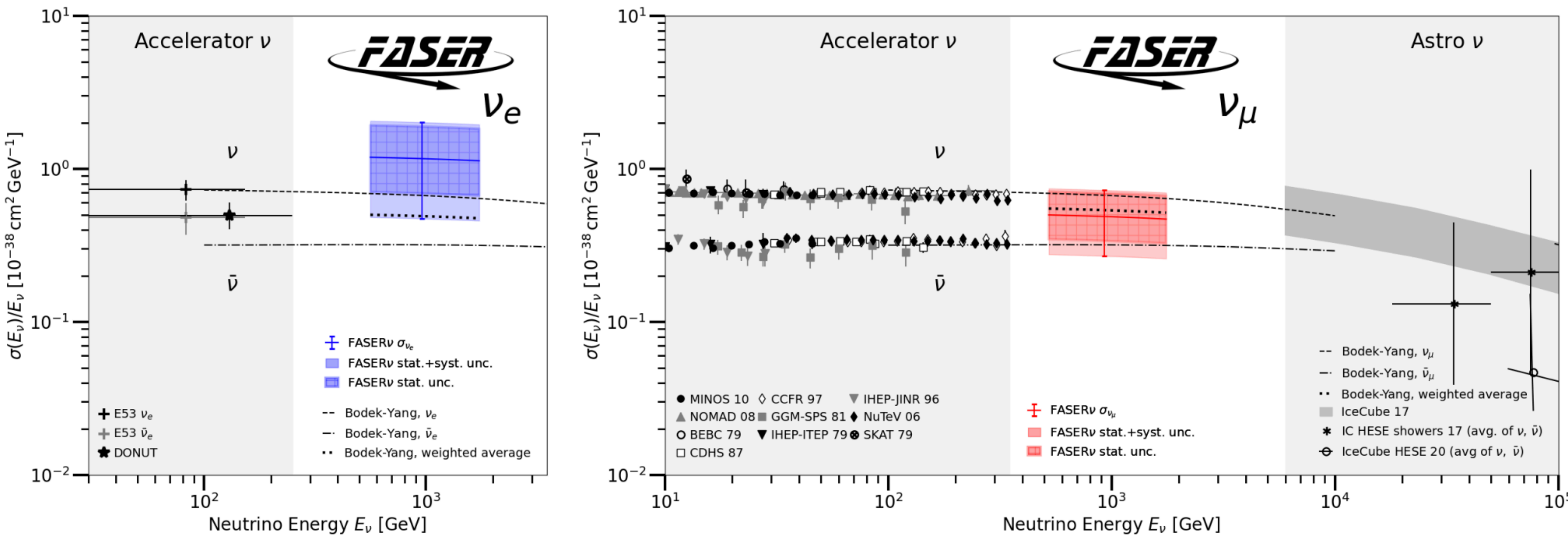


Neutrinos at the LHC



The dawn of the LHC neutrino era

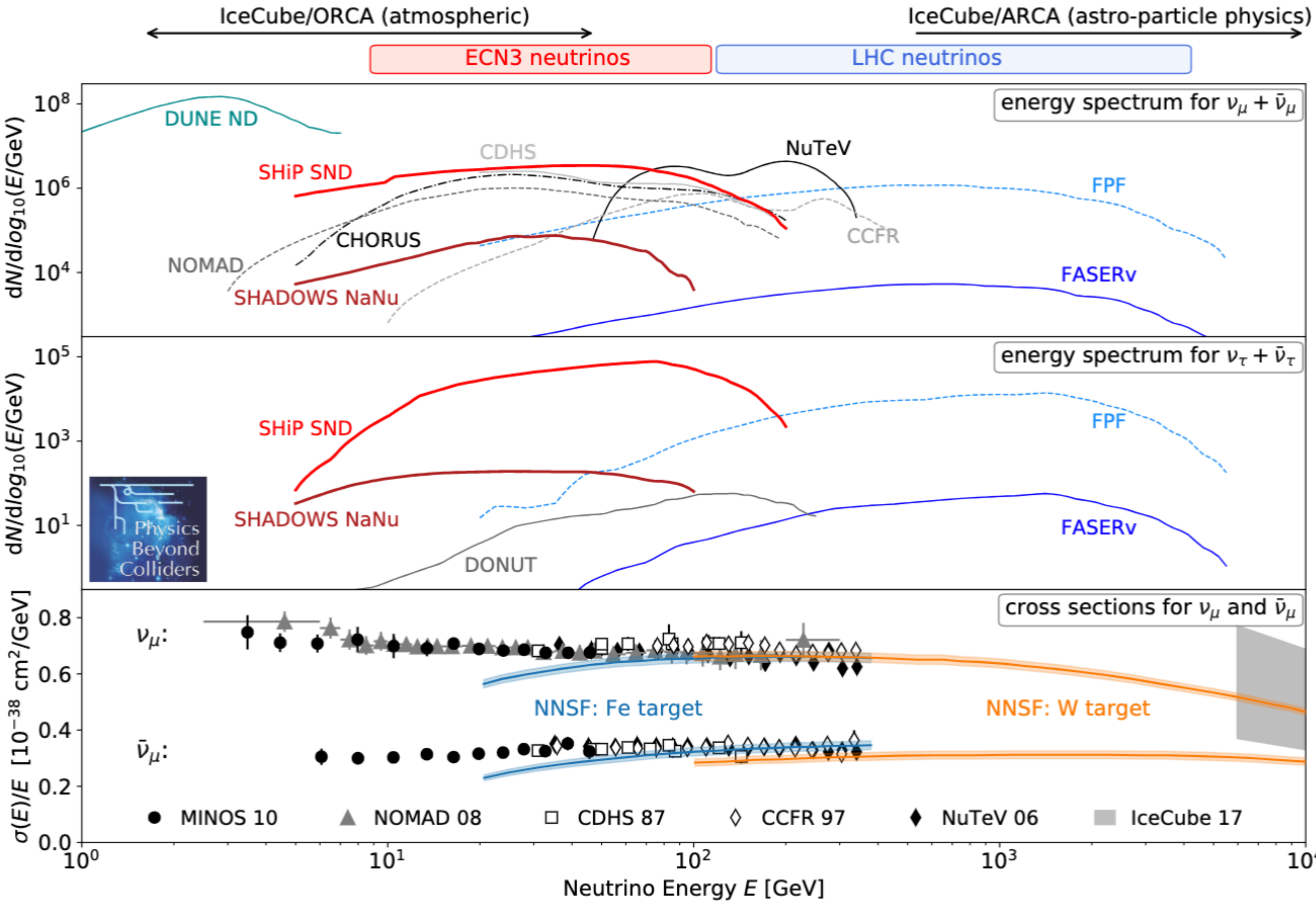
- **FASER** recently presented the first measurement of **cross-sections of** collider (TeV) neutrinos



- 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

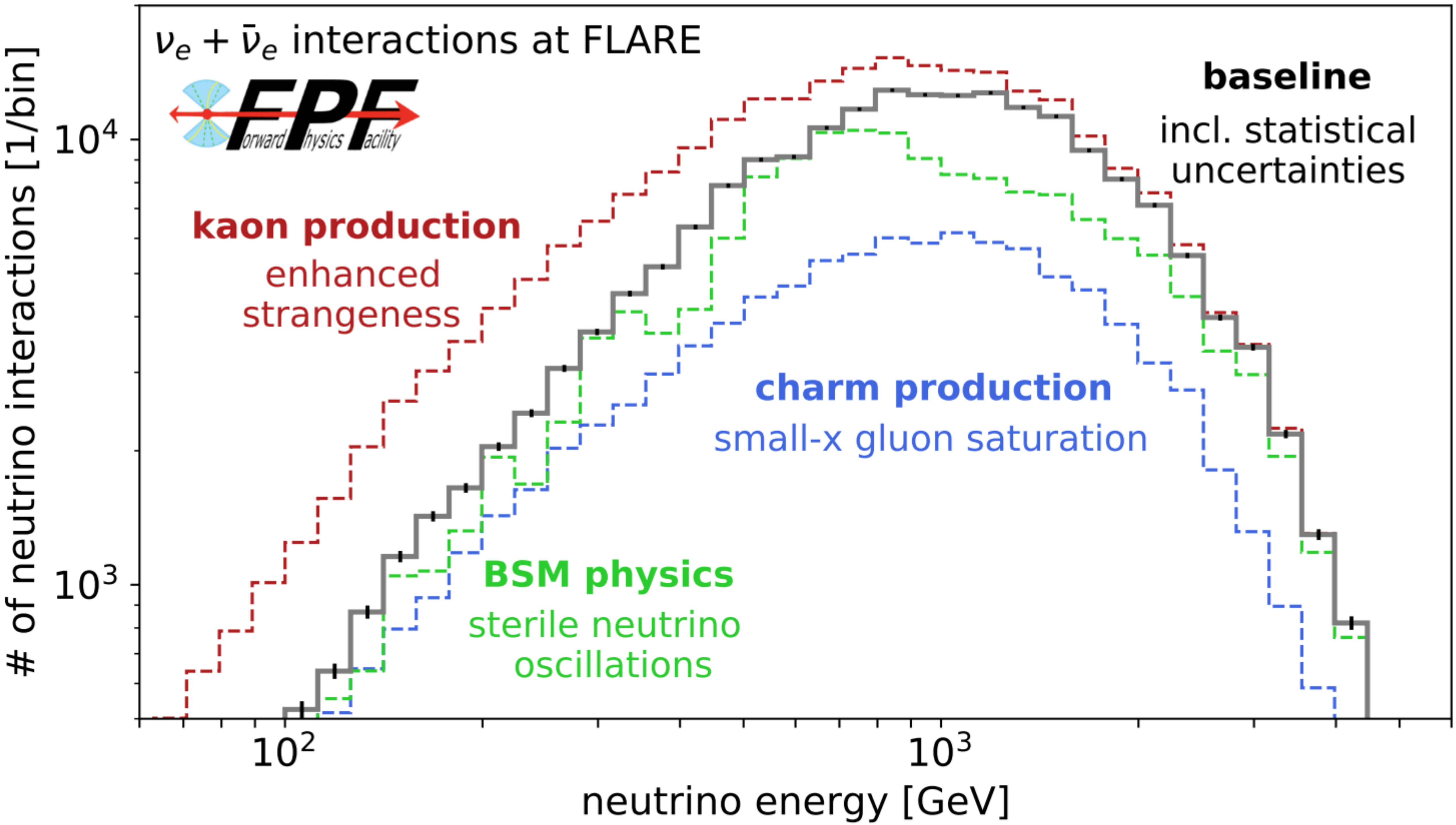
Physics with LHC neutrinos



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

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

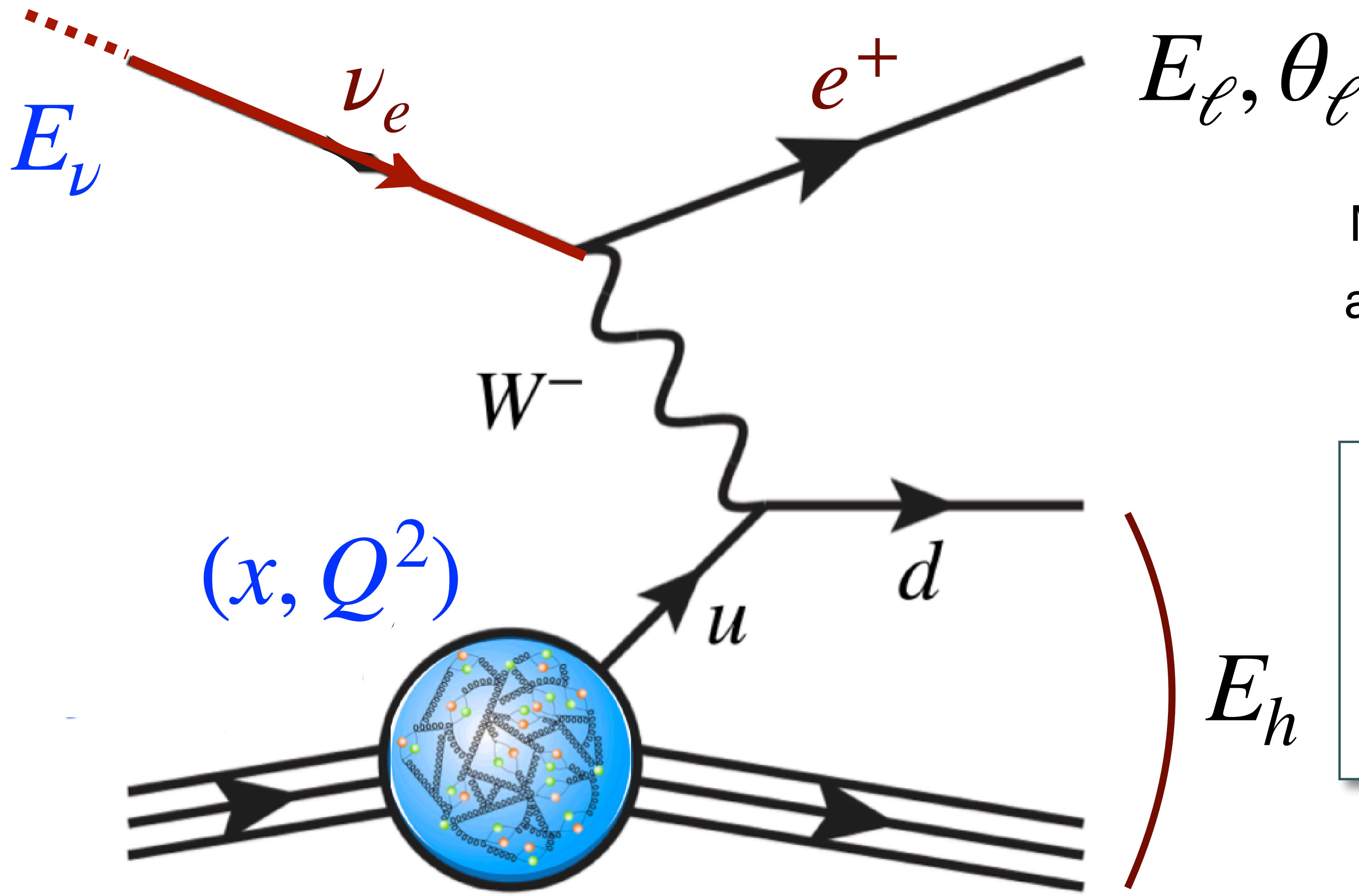
Physics with LHC neutrinos



- 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

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**

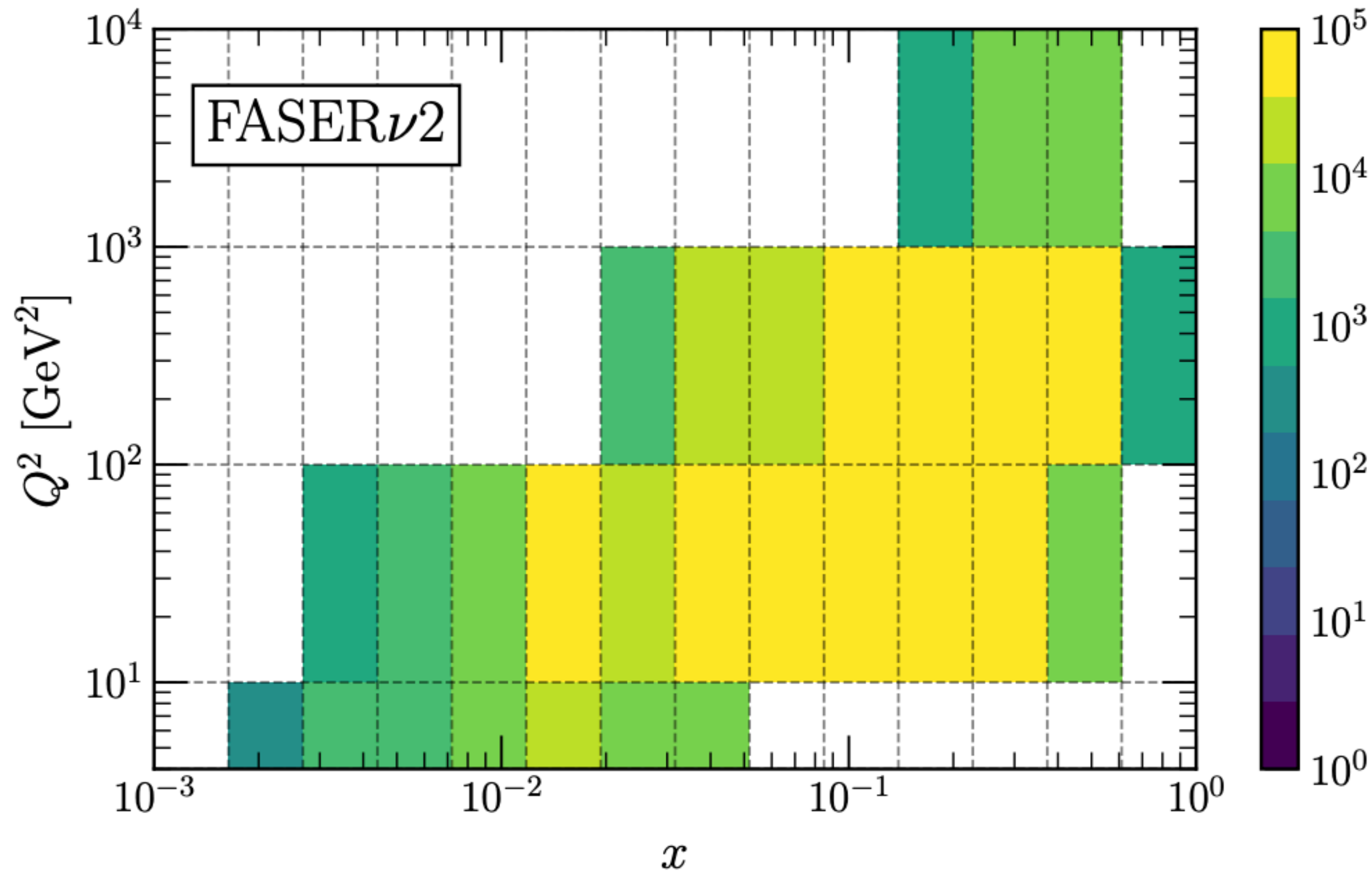
Unique information on **quark & antiquark flavour separation**

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

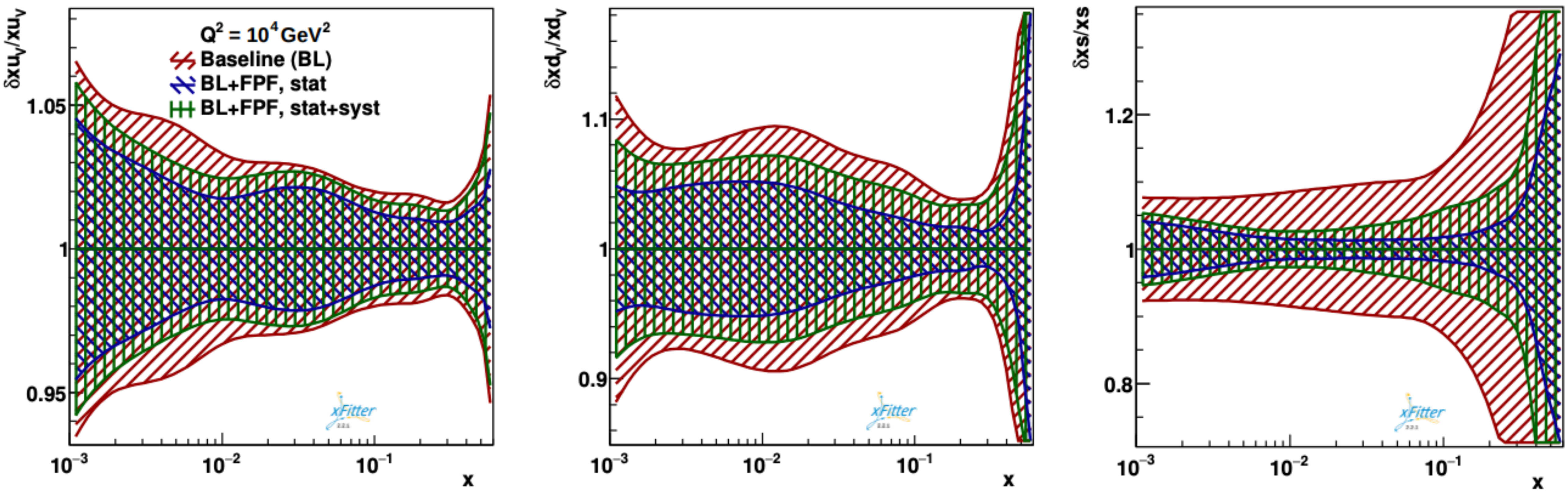
$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

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

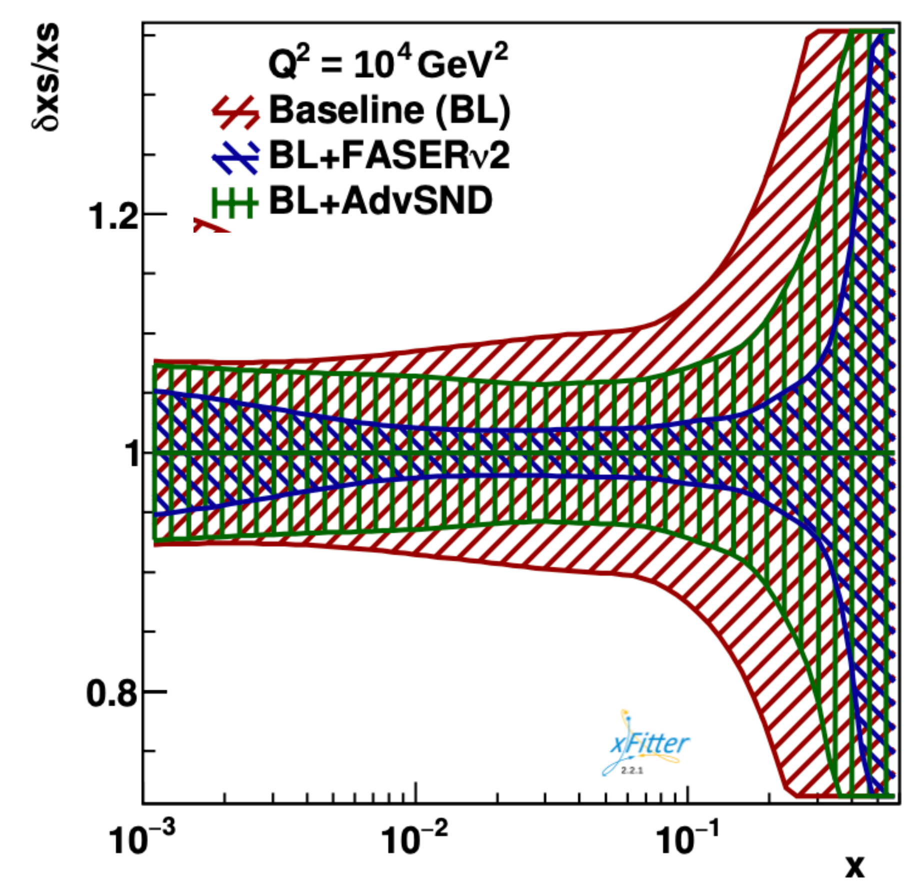
Extend CERN infrastructure with an (effective) Neutrino-Ion Collider by ``recycling" an otherwise discarded beam

Charged-current counterpart of the **Electron-Ion Collider** covering same region of phase space

PDF constraints from LHC neutrinos

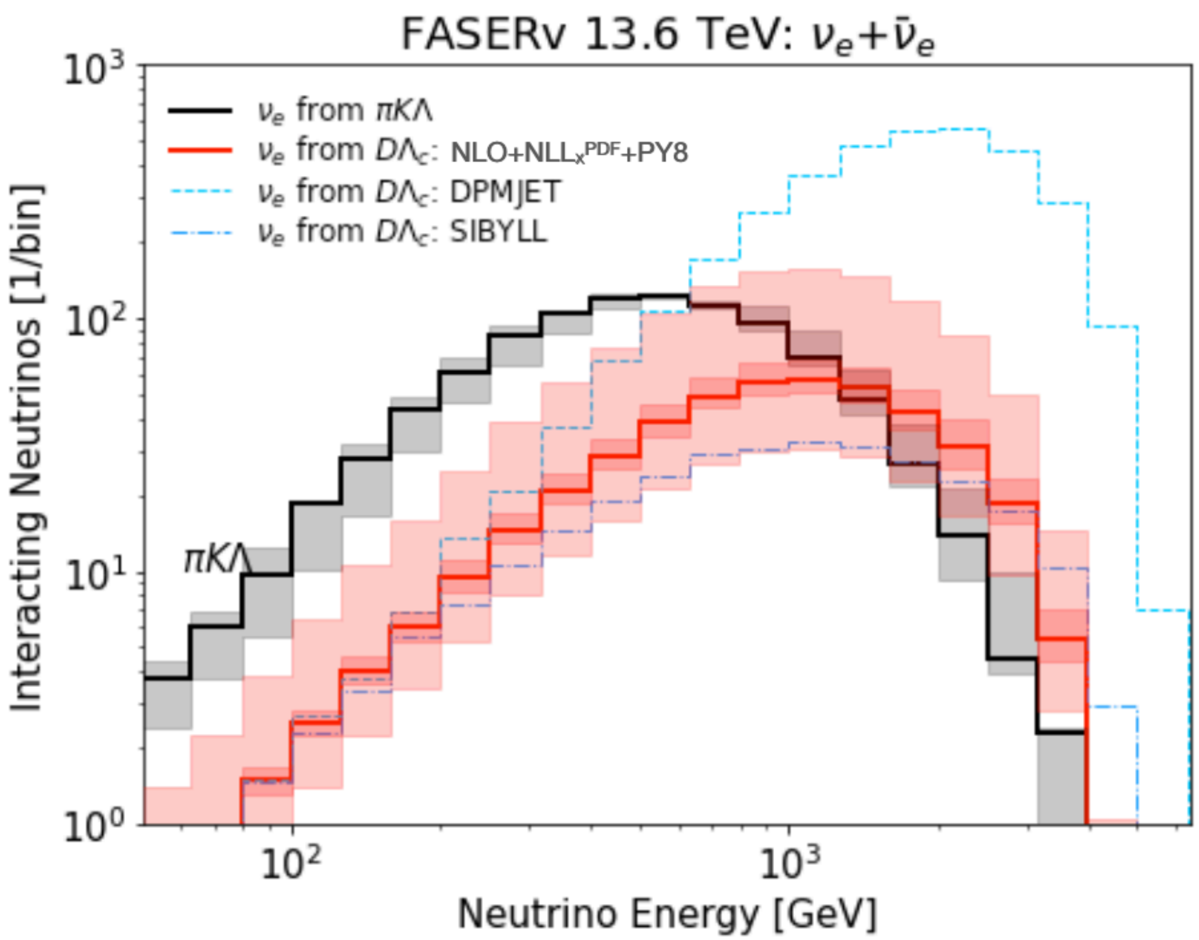


- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics
- Uncertainties in **incoming neutrino fluxes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

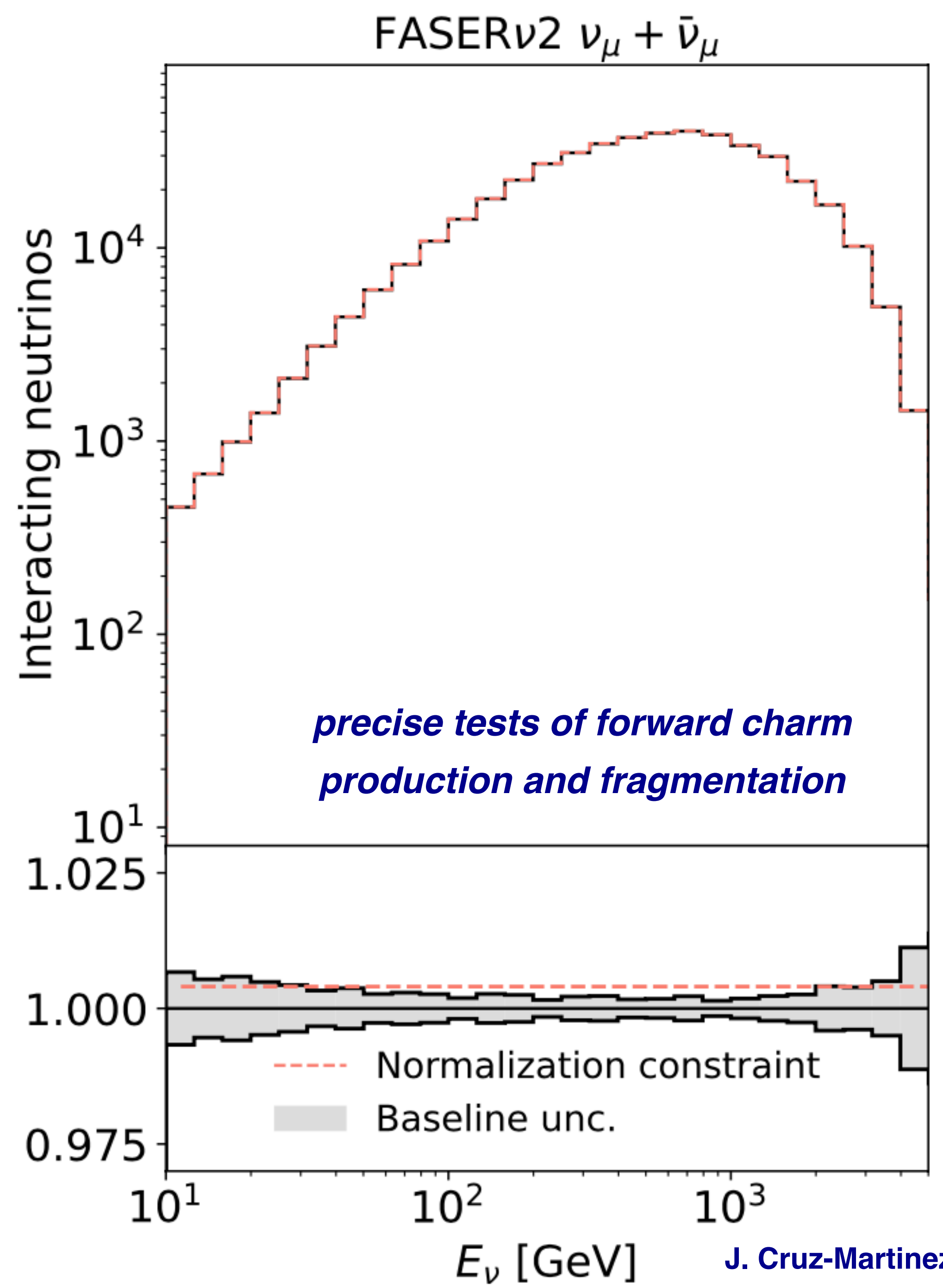


J. Cruz-Martinez et al (2023)

Constraints on forward hadron production



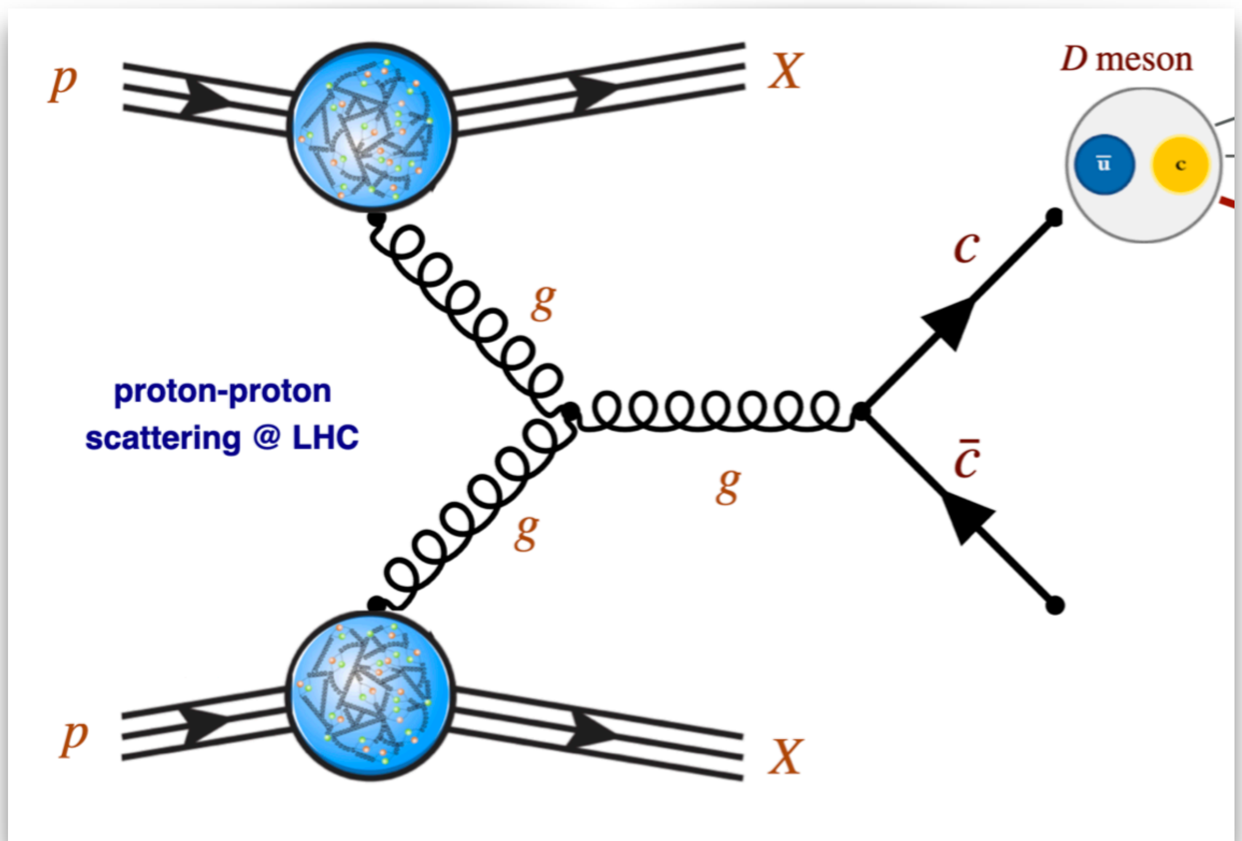
F. Kling et al (2023)

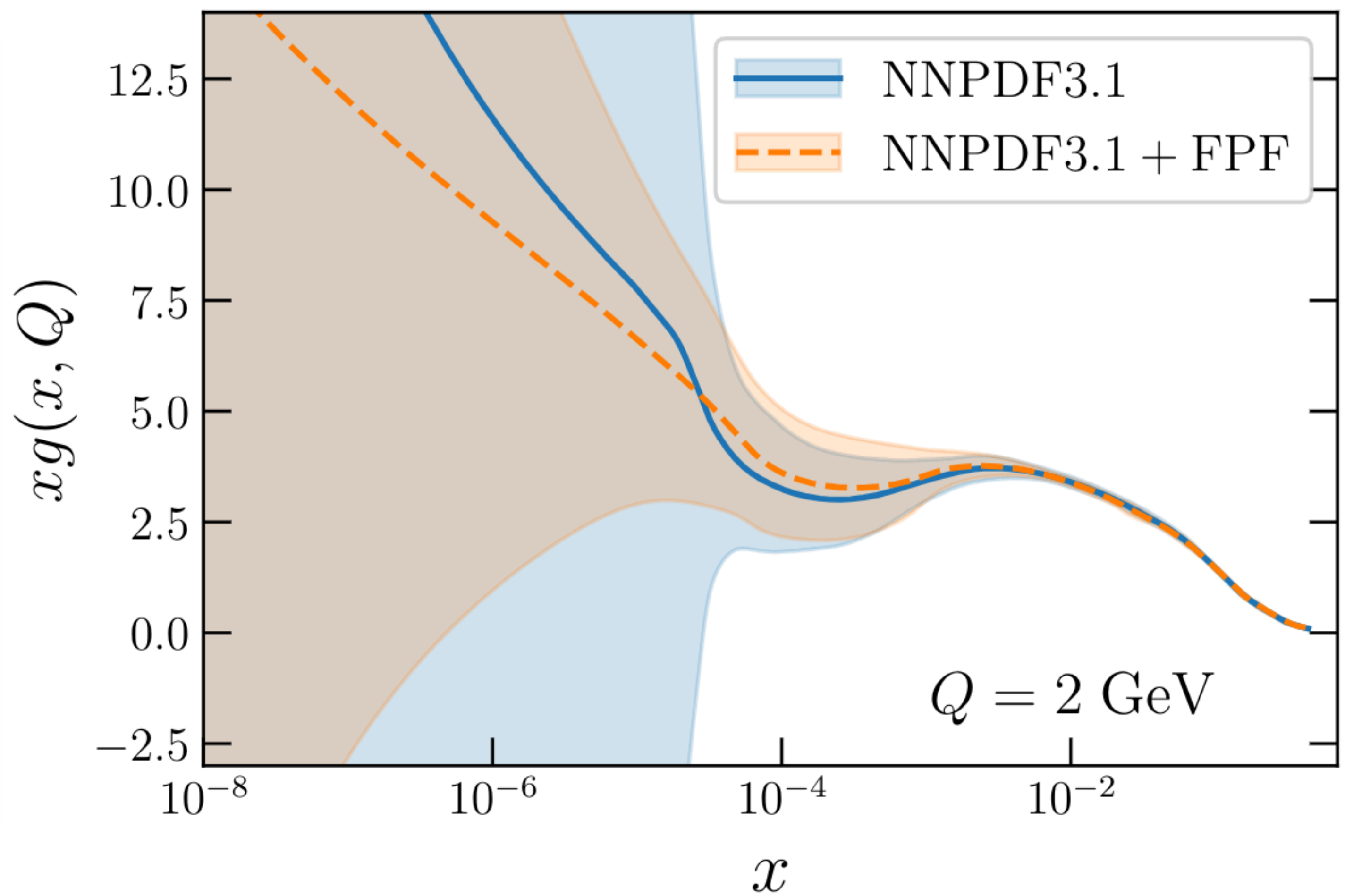


J. Cruz-Martinez et al (2023)

- Forward particle production at the LHC is affected by **large model uncertainties**
- Specially problematic for **neutrinos from charm**
- Can be **constrained *in-situ*** by the LHC far forward experiments
- 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**

Constraints on small-x PDFs

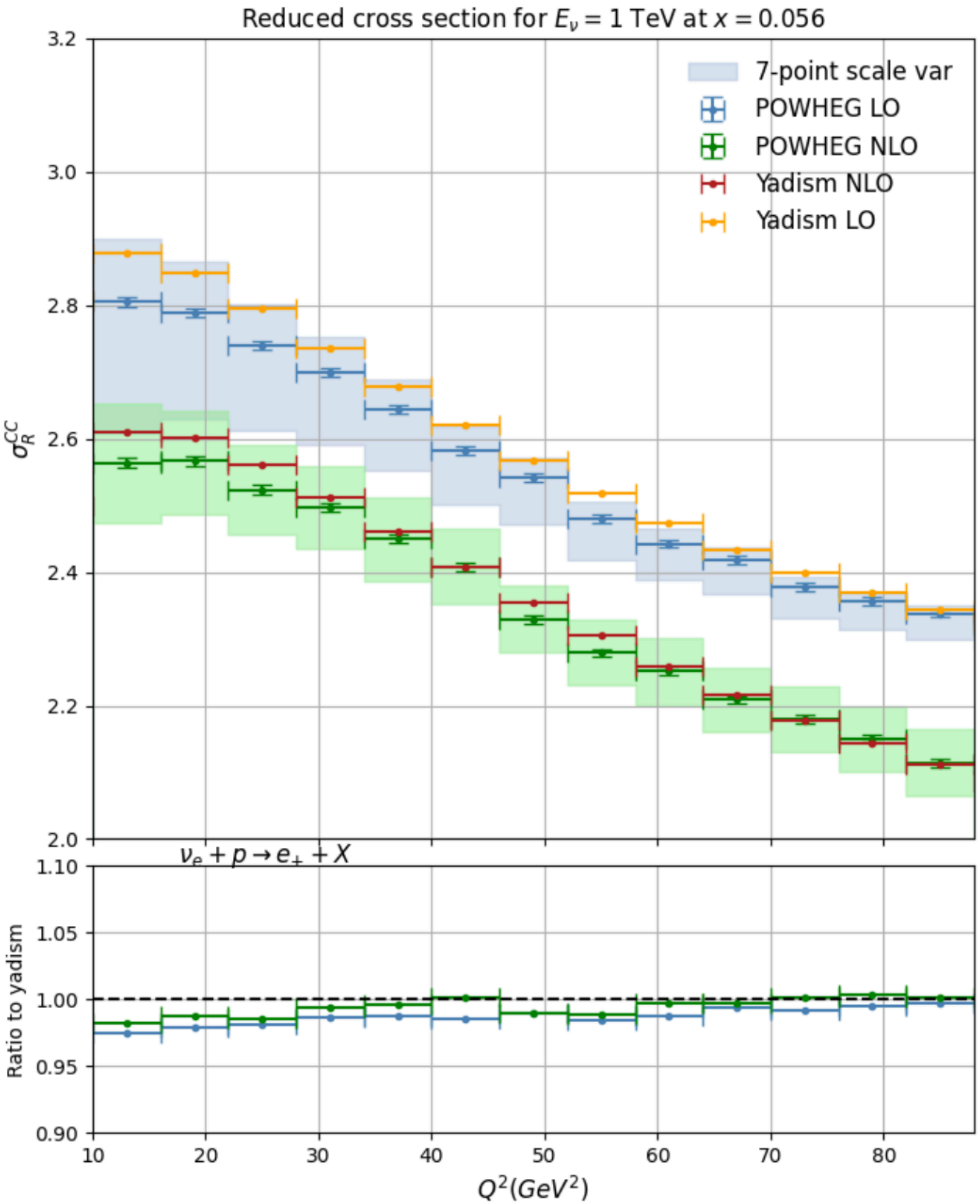




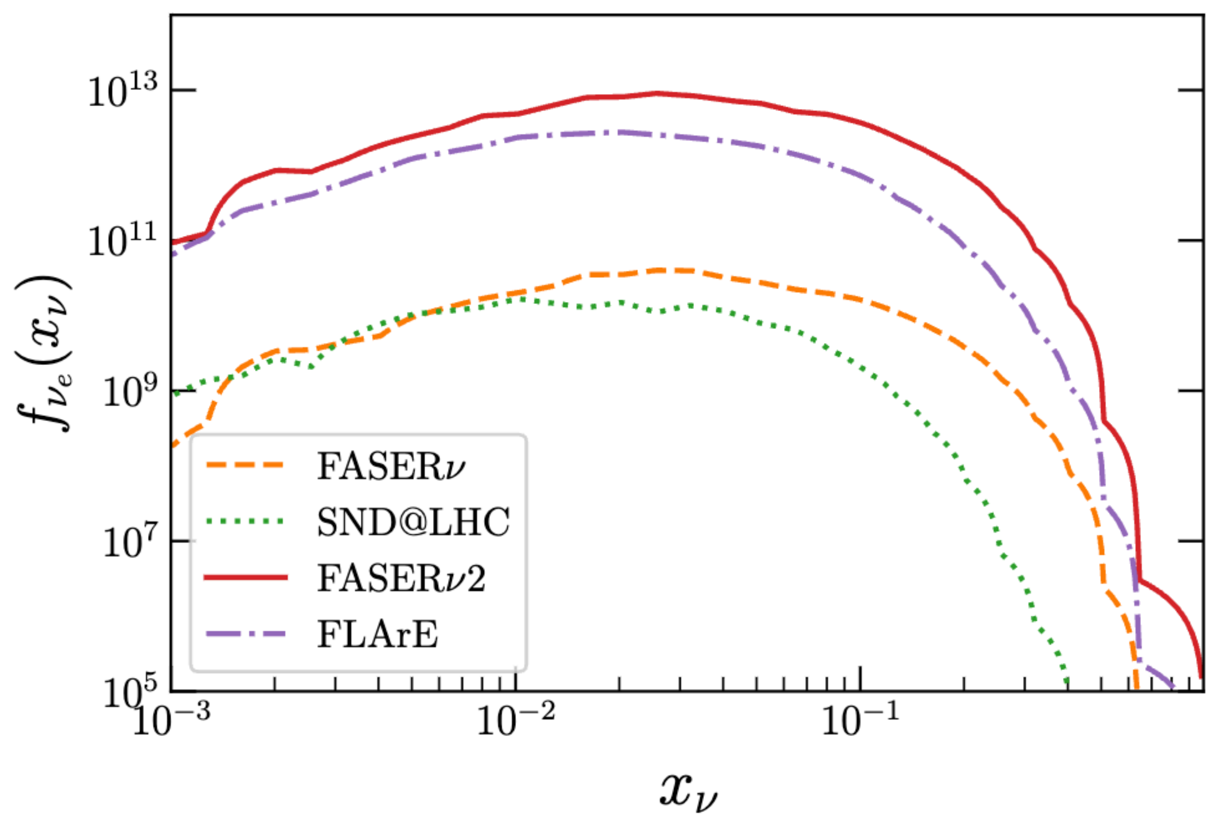
$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- Generate pseudo-data for electron neutrino cross-sections at **different rapidities**
- Constraints small-x PDFs **down to 10^{-7}** , beyond the reach of any other (laboratory) experiment
- **Direct measurement of the prompt neutrino flux** limiting astrophysical measurements at IceCube

Tuning Monte Carlo simulations



M. van Beekveld et al (in preparation)

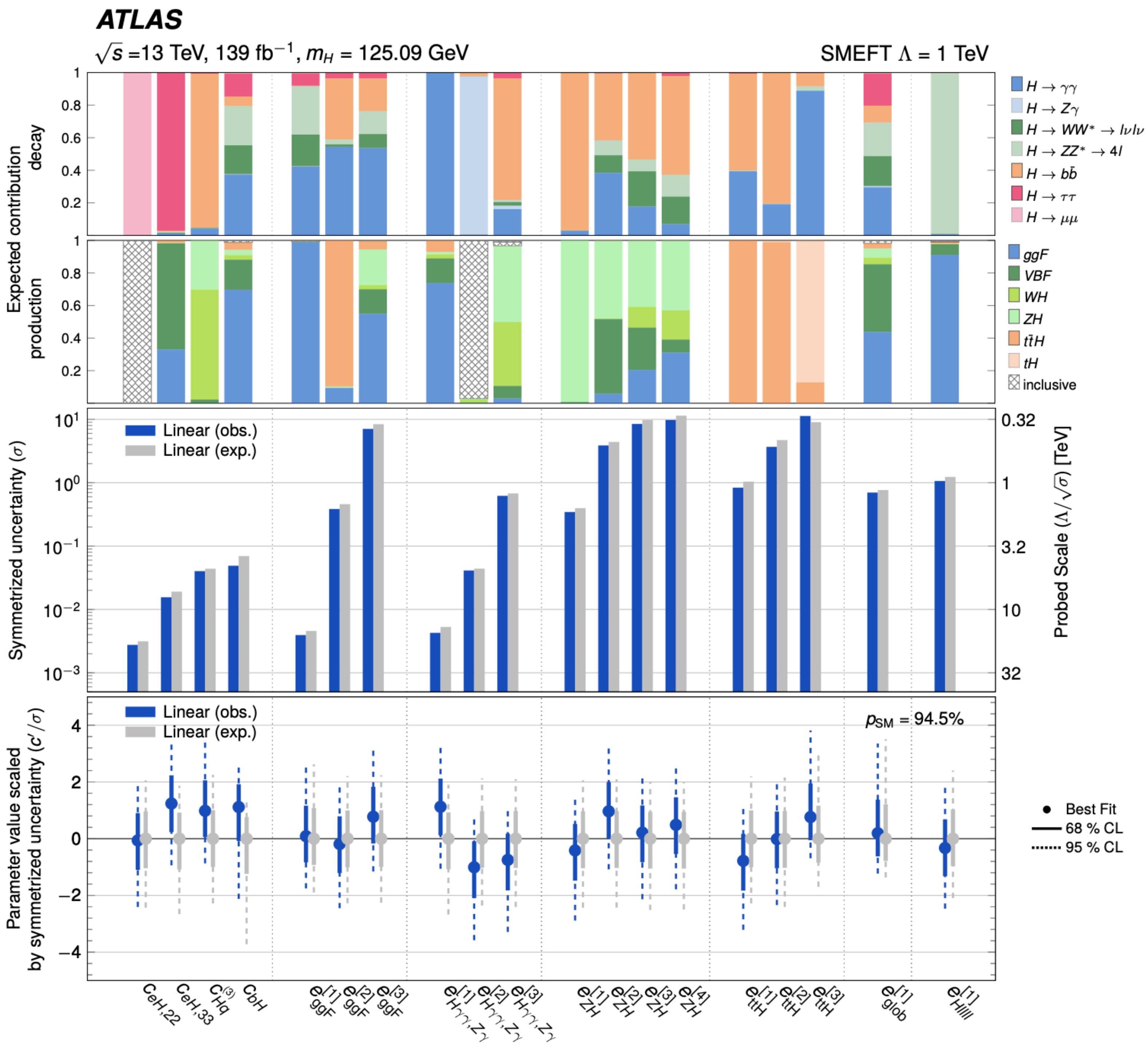


- Interpretation of LHC neutrino experiments demands p**recise Monte Carlo event generators**
- Neutrino MC simulations tuned to LHC data would be valuable for **atmospheric and astrophysical neutrino experiments**
- **NLO QCD simulations based on POWHEG with neutrino PDFs** enable accurate simulations of the final state in high-energy neutrino scattering

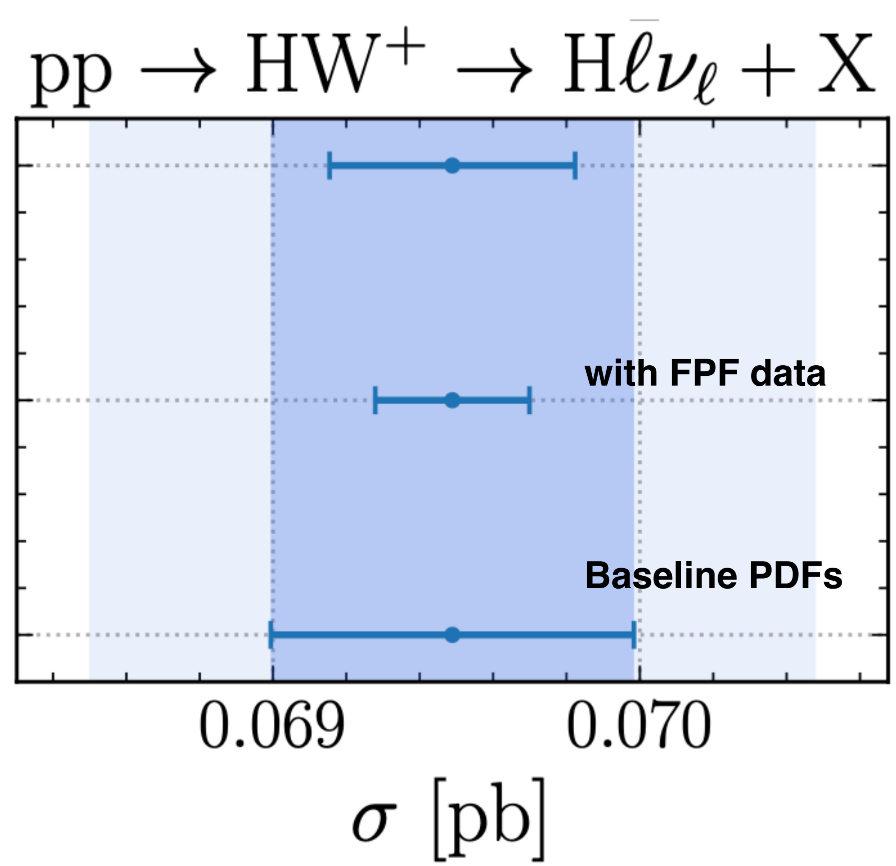
Impact on BSM Searches at the HL-LHC

Higgs couplings

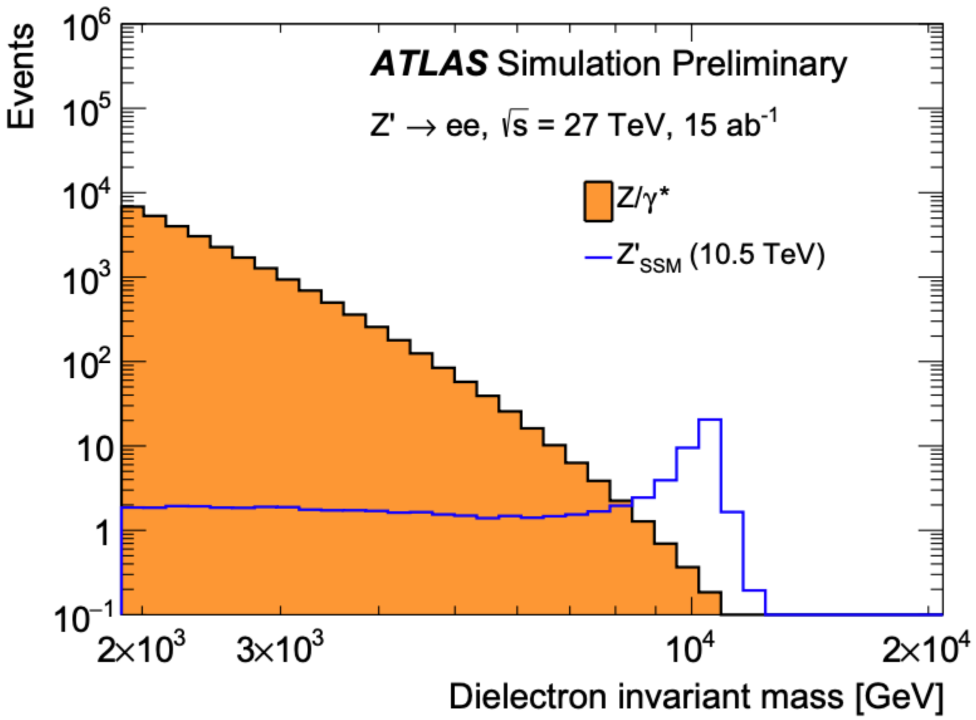
- Common misconception: the BSM program of the FPF is limited to **FIPs/LLPs** and related light BSM scenarios
- Rich **direct high-p_t BSM program** via TeV neutrino cross-sections and interactions (e.g. via EFTs)
- Rich **indirect high-p_t BSM program** via PDF constraints essential for BSM searches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

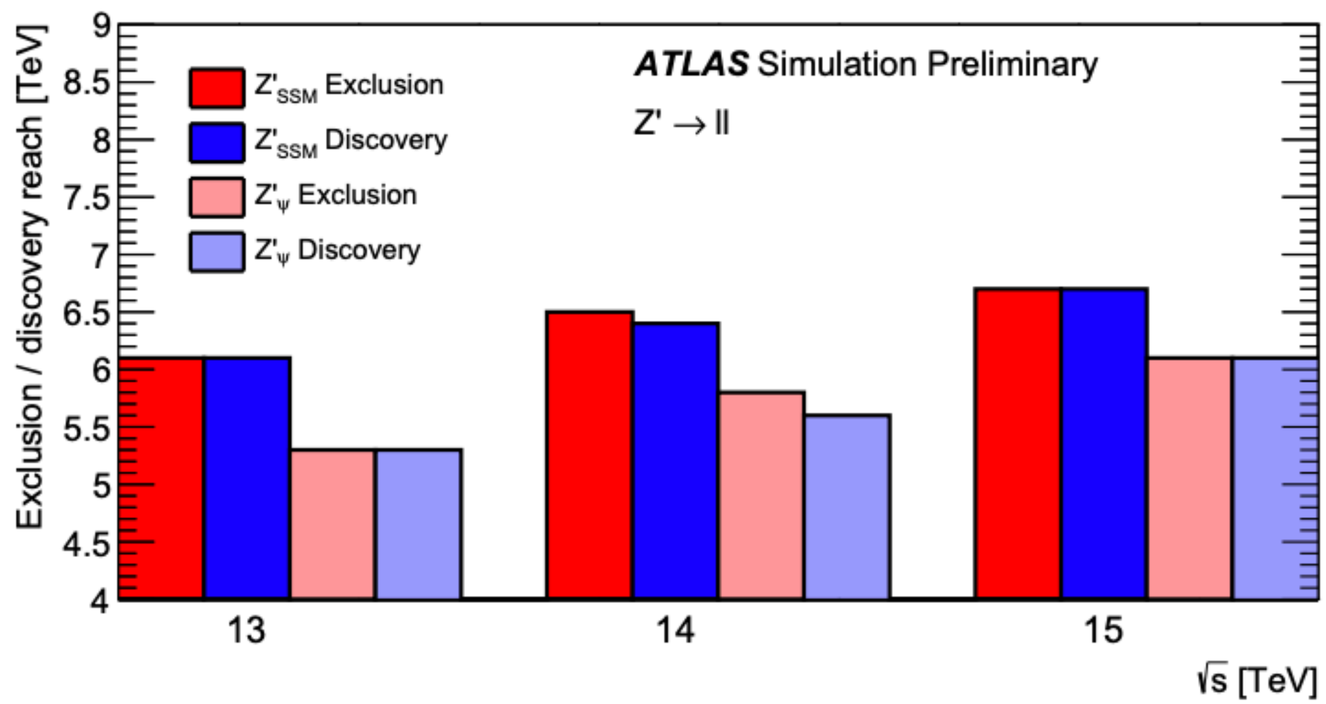


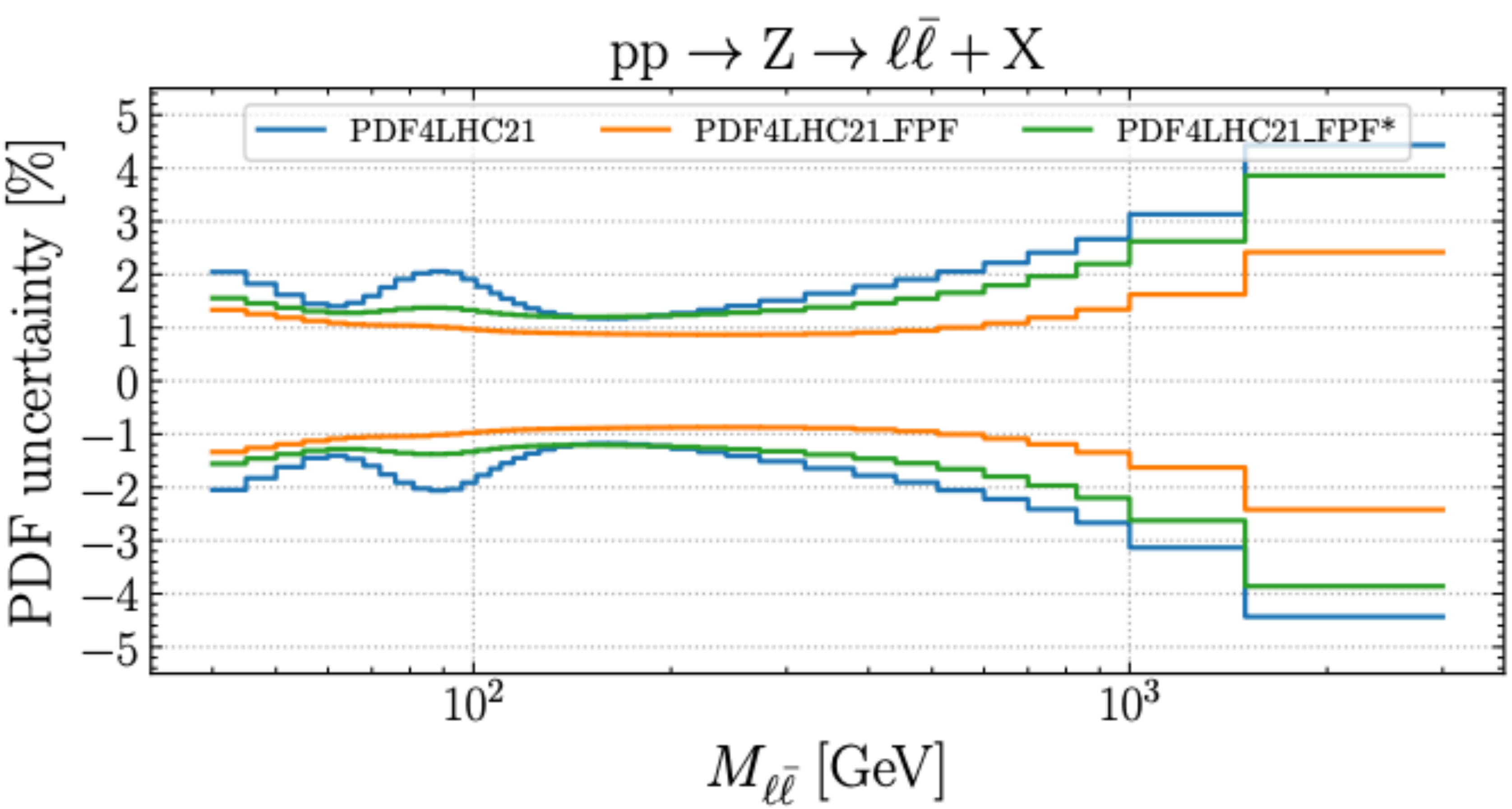
- Cornerstone of HL-LHC: search for BSM via **precision Higgs measurements** and their EFT global interpretation
- Full potential requires marked **reduction of current PDF uncertainties**



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:**

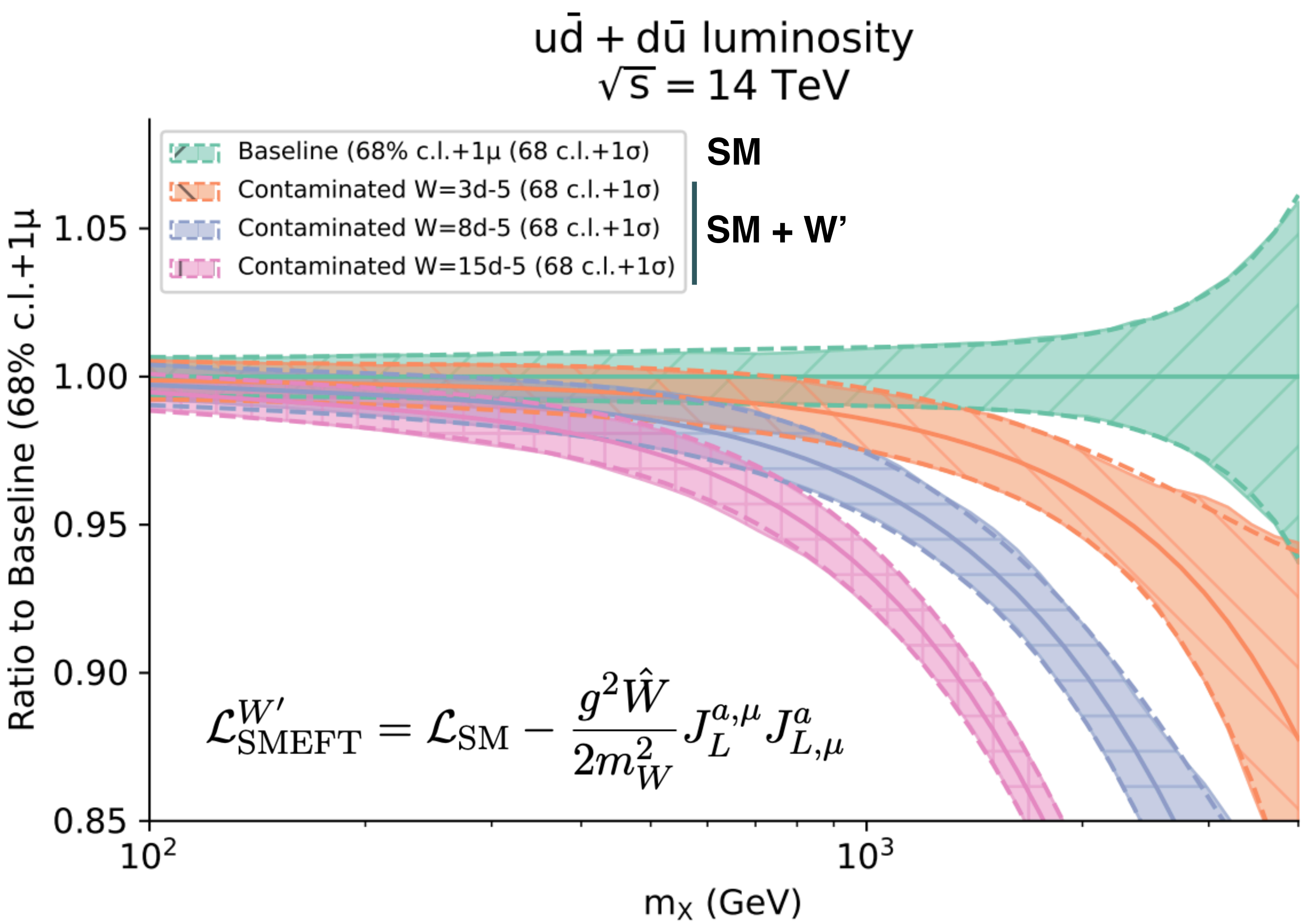
$$\widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s, \boldsymbol{c}/\Lambda^2) = \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s)\left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m^{ij}}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}^{ij}}{\Lambda^4}\right)$$

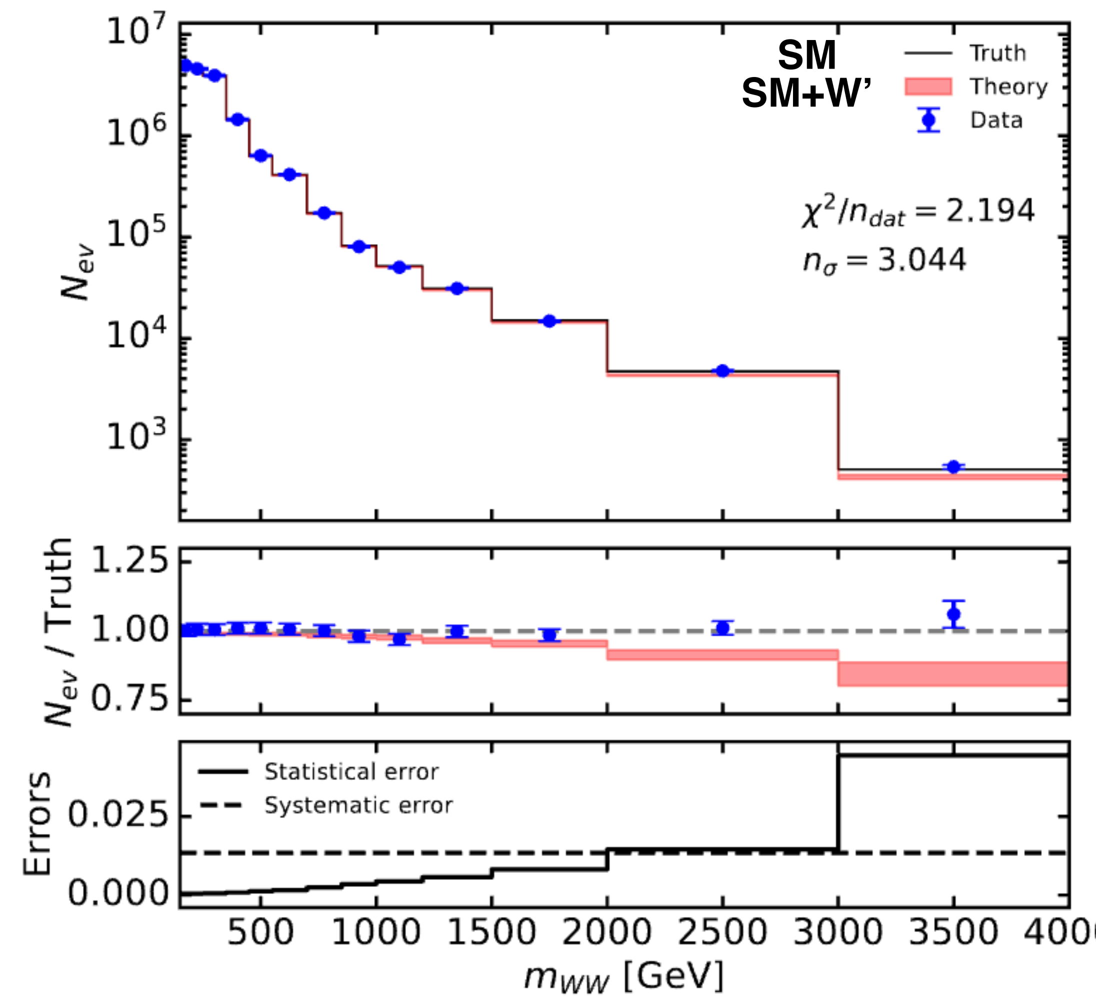
SMEFT PDFs *defined as PDFs extracted from the data when SMEFT used to model* ***partonic hard-scattering***

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

SMEFT analyses 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)

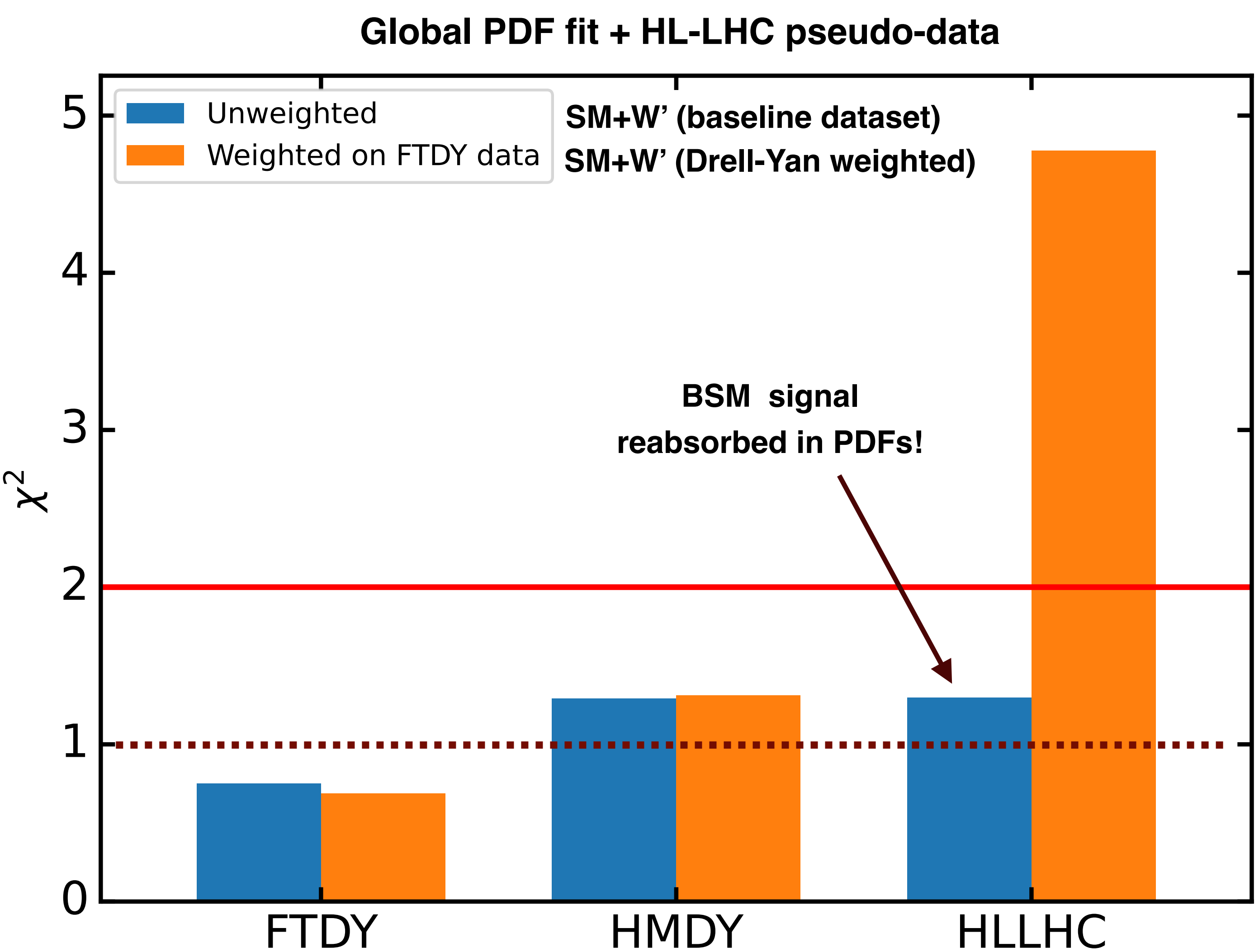


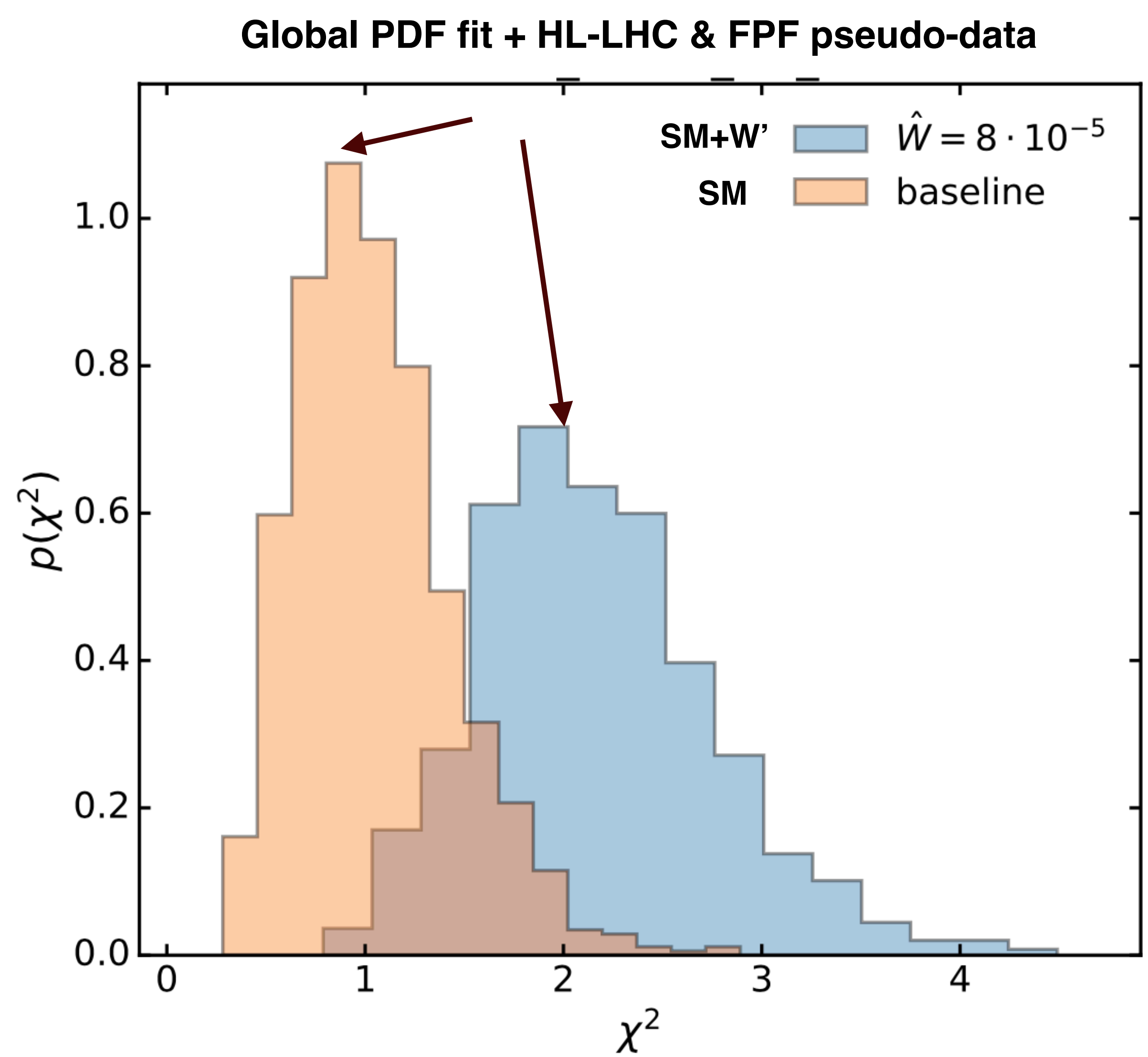


Hammou, Madigan, Mangano, Mantani, Morales, Ubiali, 2307.10370

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**





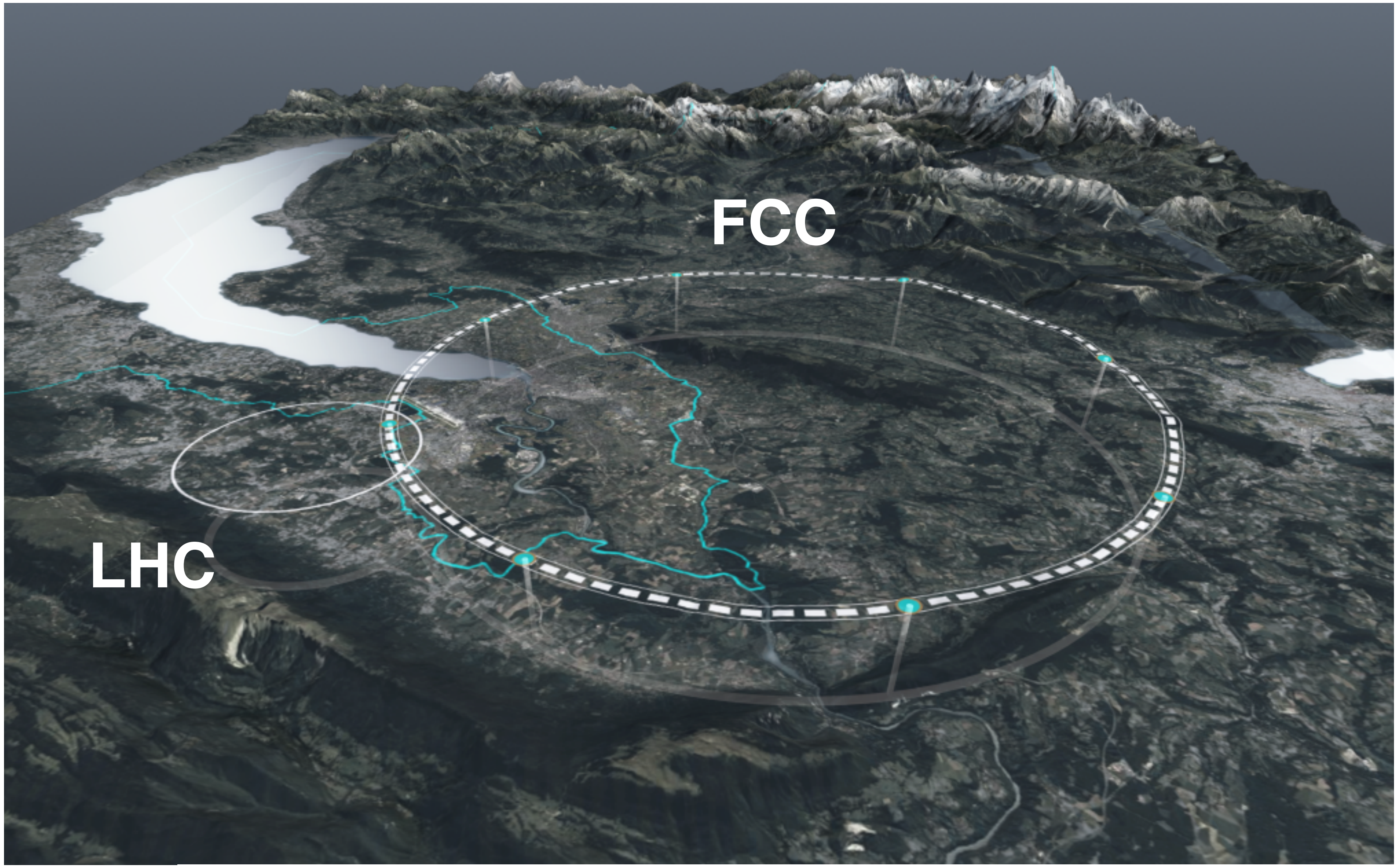
Hammou, Madigan, Ubiali, **WIP**

QCD and Neutrino Physics for Small ~~LHC~~ experiments

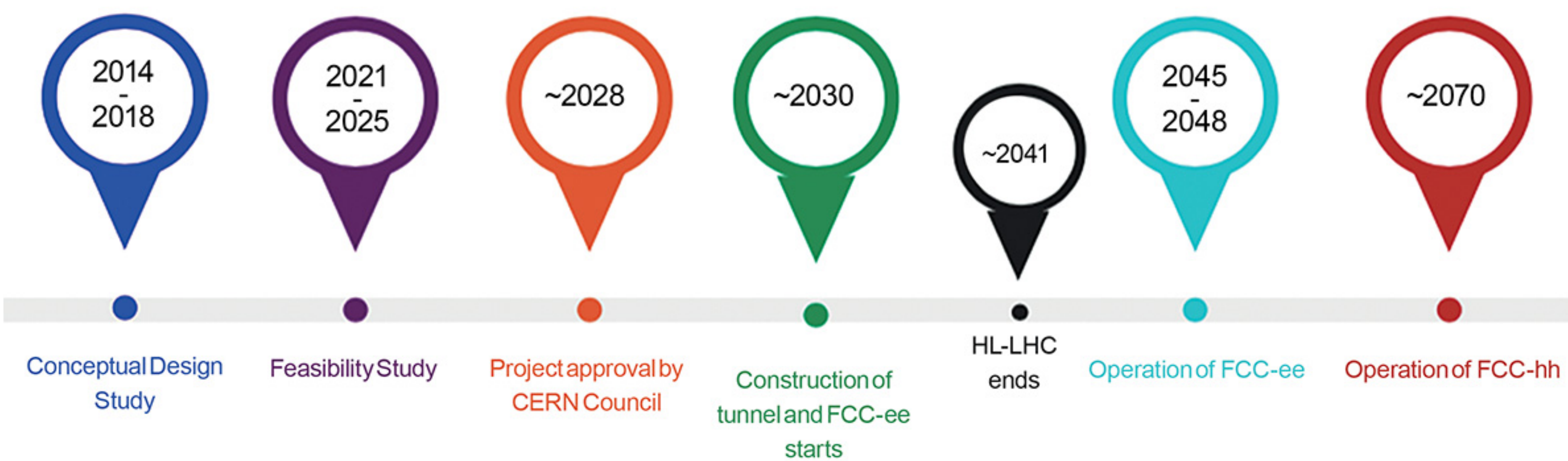
FCC

J. Adhikary et al (in preparation)

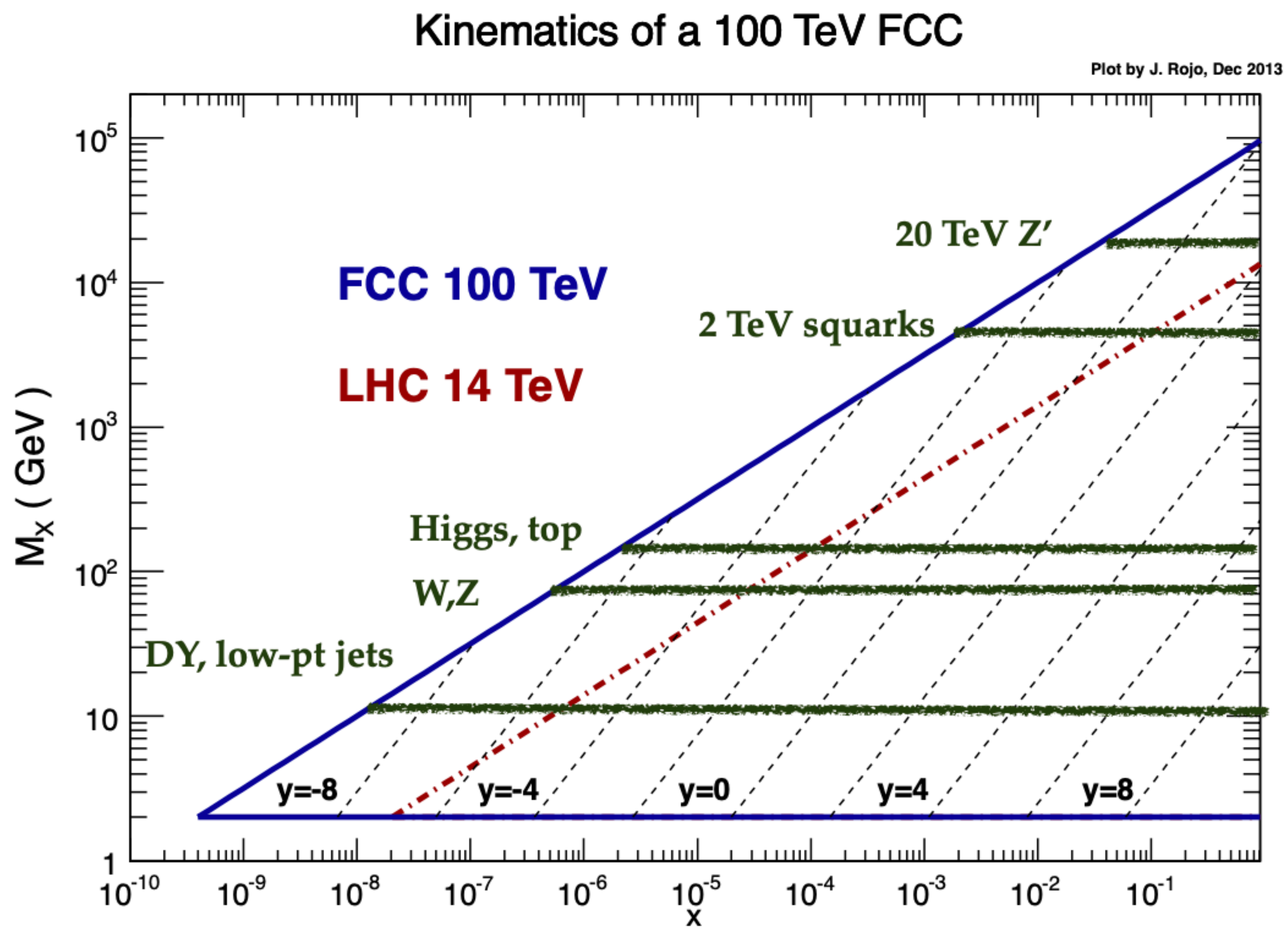
The Future Circular Collider



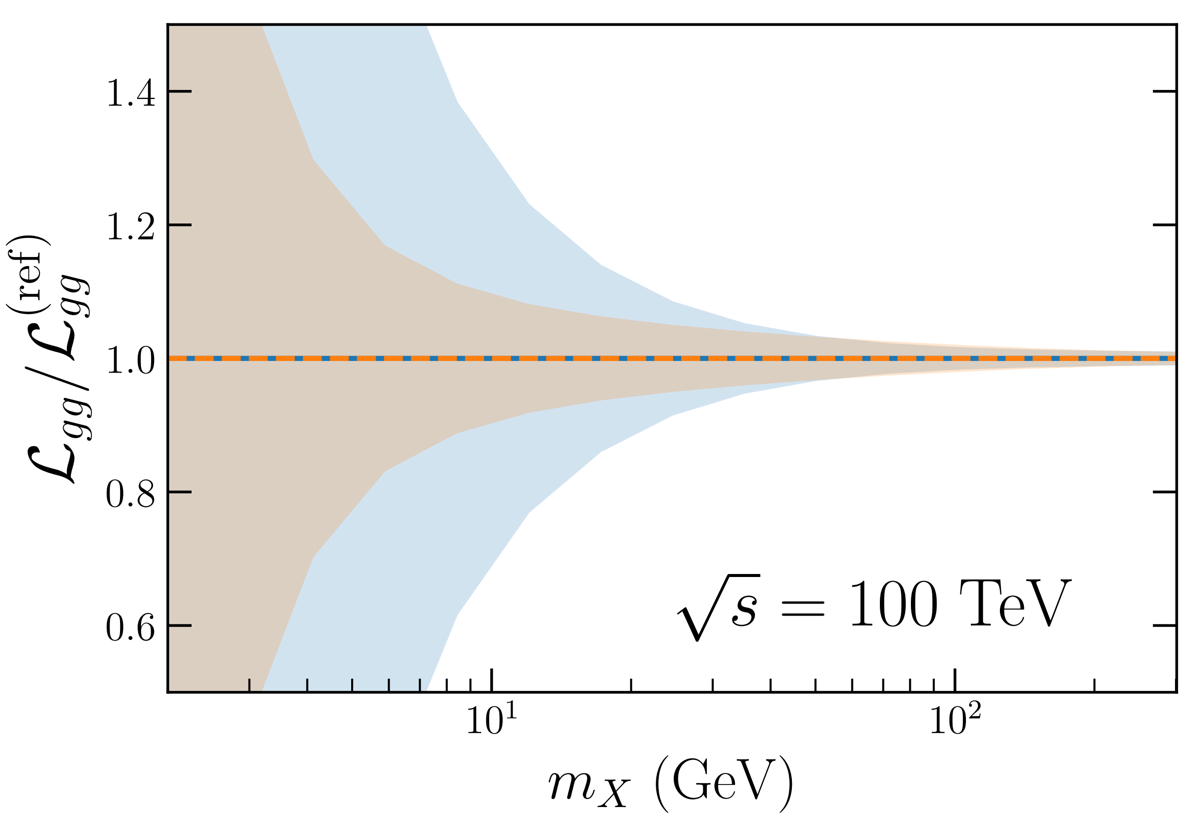
- A proposed new **91-km tunnel** in the CERN site
- First phase: **electron-positron collider** from the Z-pole to ttbar threshold
- Second phase: **proton-proton collider at 100 TeV** or beyond, with pA and AA options

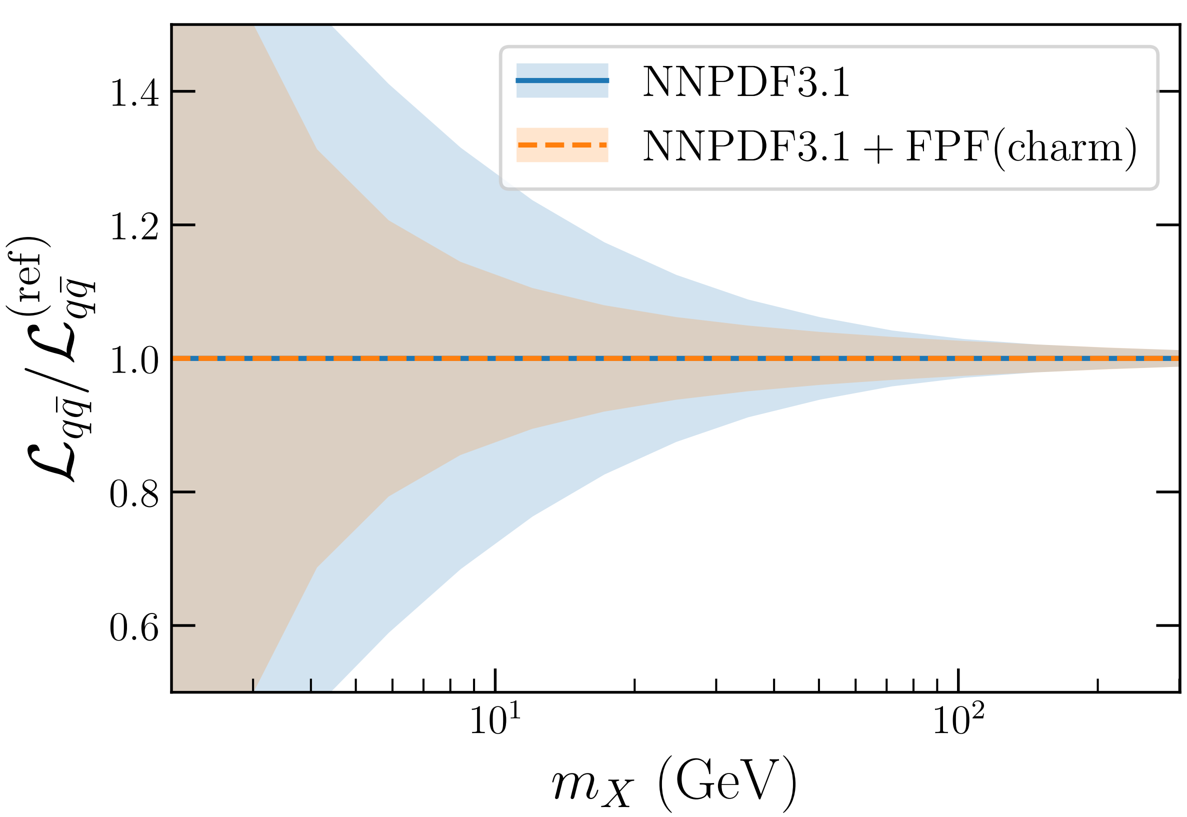


LHC neutrinos and FCC-pp



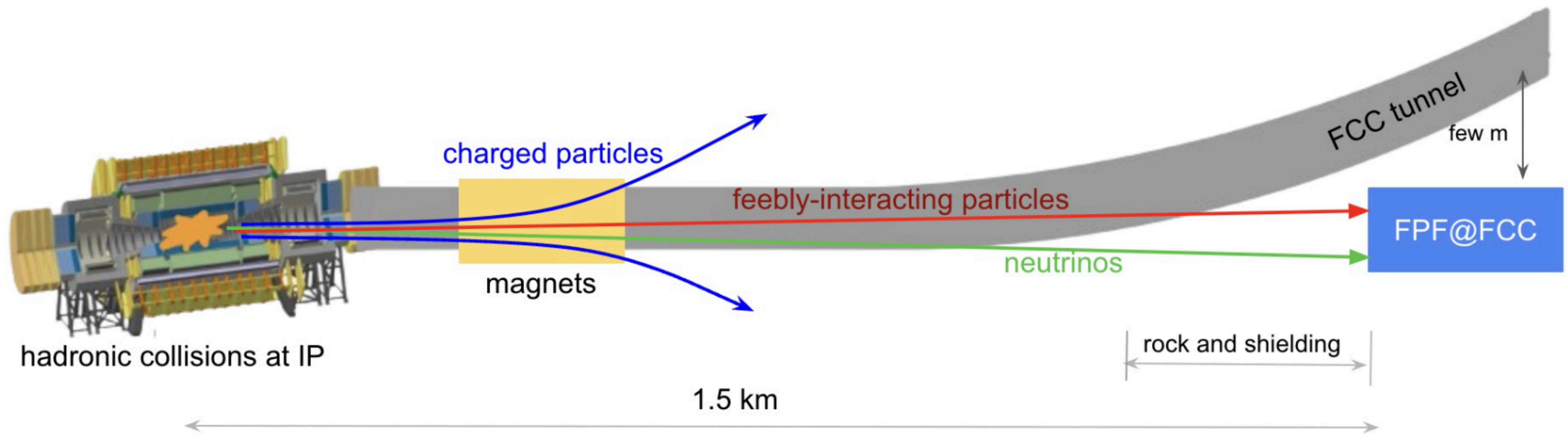
- FCC-pp would be a **small-*x* machine,** even Higgs and EWK sensitive to small-*x* QCD
- LHC neutrinos: laboratory to test **small-x QCD** for **dedicated FCC-pp physics** and simulations
- Current projections show a marked PDF error reduction on **FCC-pp cross-sections** thanks to constraints from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

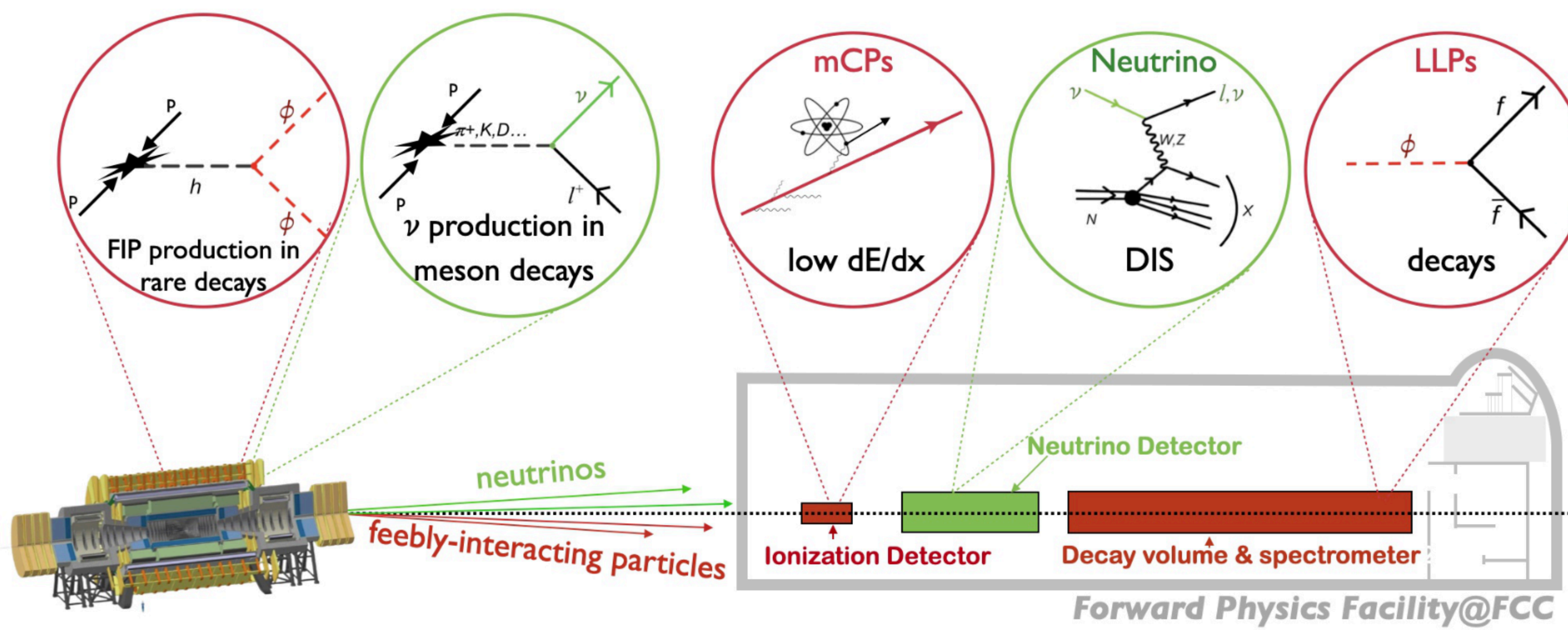




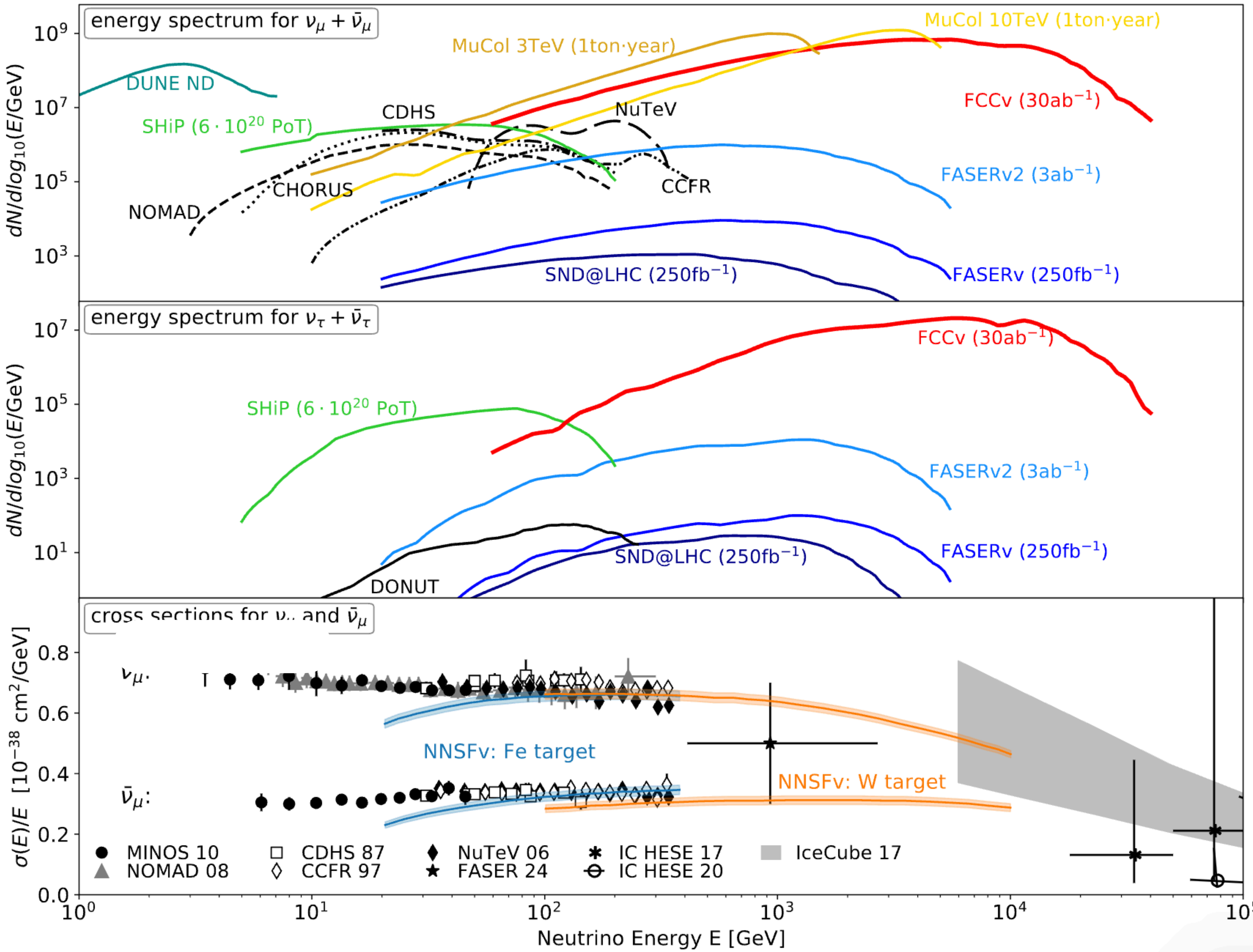
FPF@FCC

- 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**



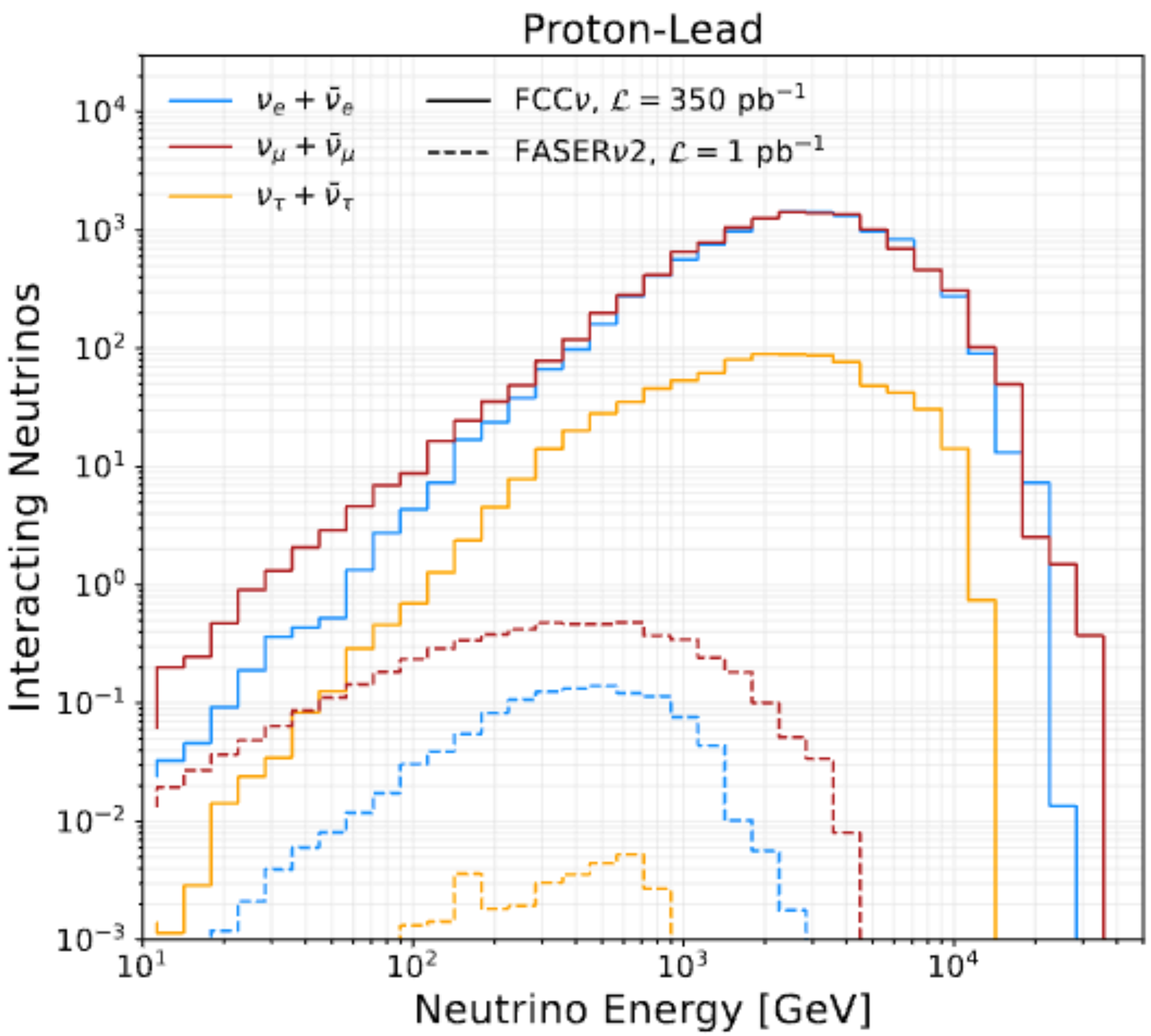


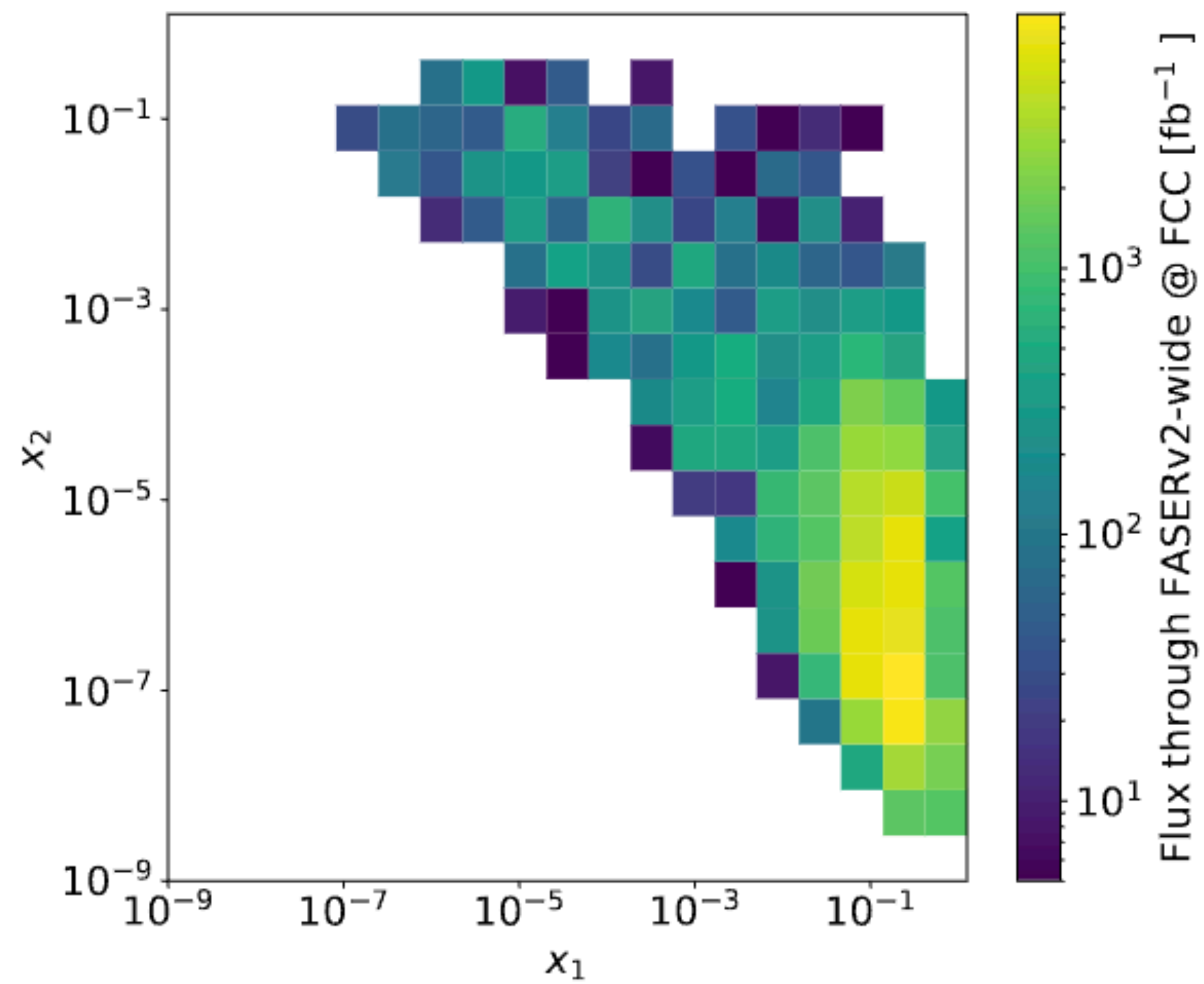
Event rates



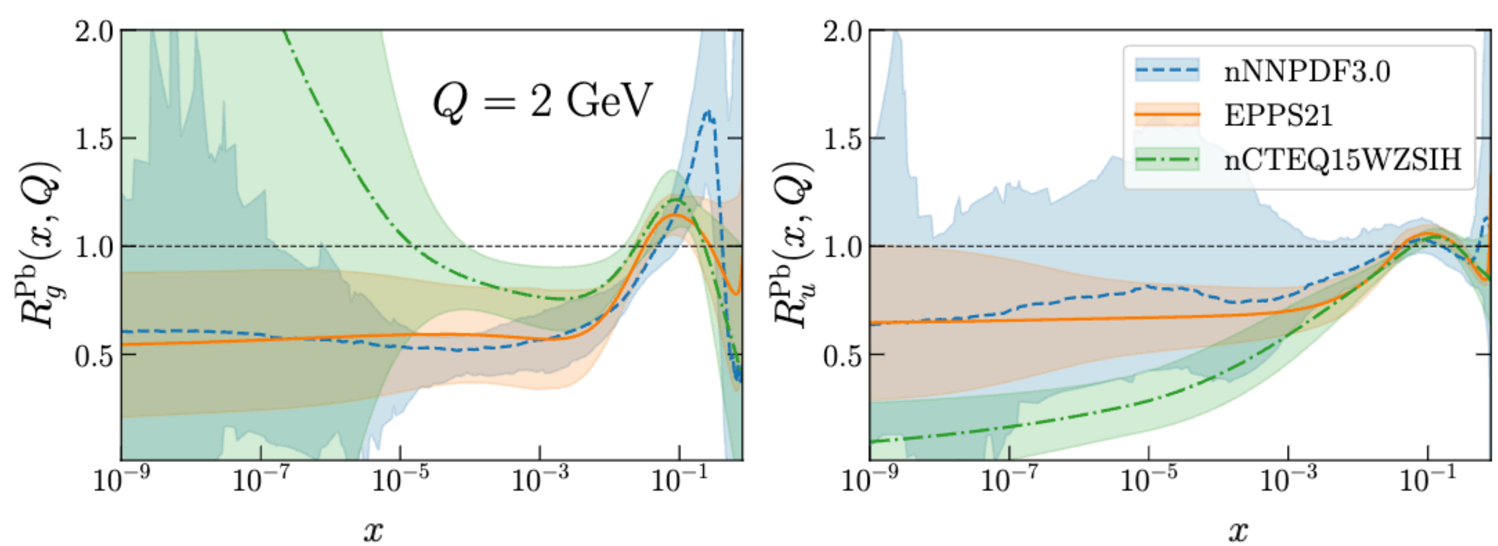
- Up to **1B muon neutrinos & 30M tau neutrinos**
- Sizable flux up to neutrinos with **40 TeV**
- Access neutrino cross-sections at multi-TeV energies
- test **Lepton Flavour Universality** for the three neutrino generations
- Search for **anomalous interactions** with permille precision

Small-x QCD and nuclear physics





- Up to **200K neutrinos** from proton-lead collisions
- Reaching ultra-small-*x*: sensitivity to **extreme QCD phenomena** (*e.g.* non-linear dynamics) as well as nuclear structure in unconstrained regions
- Direct input for astroparticle physics experiments



+ first polarised DIS experiment with 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**

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

- LHC neutrinos enable **tuning neutrino MC event generators** in the controlled laboratory setup

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

- An FPF@FCC would accumulate **unprecedented high-energy neutrino scattering samples**, including the first neutrinos from proton-lead collisions and from scattering on polarised targets