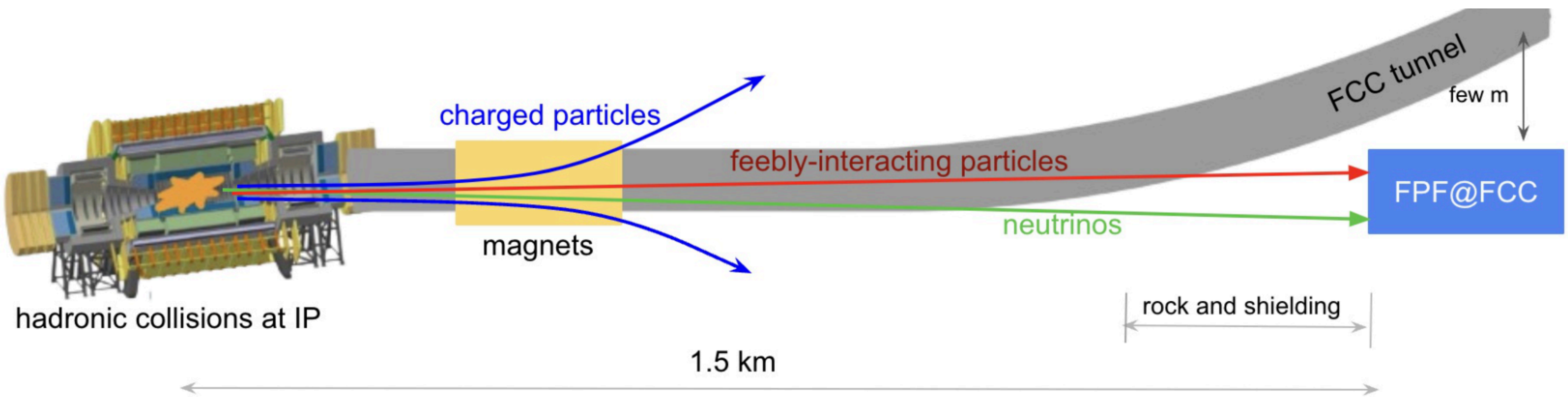
FPF@FCC: a Forward Physics Facility integrated with the FCC-hh

Juan Rojo, VU Amsterdam & Nikhef



based on Roshan Mammen Abraham, Jyotismita Adhikary, Jonathan Feng, Max Fieg, Felix Kling, Jinmian Li, Junle Pei, Tanjona Rabemananjara, **JR**, and Sebastian Trojanowski**, arXiv:2409:02163**

FCC Physics Week

CERN, 11th January 2025

The dawn of the LHC neutrino era

- Two 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)

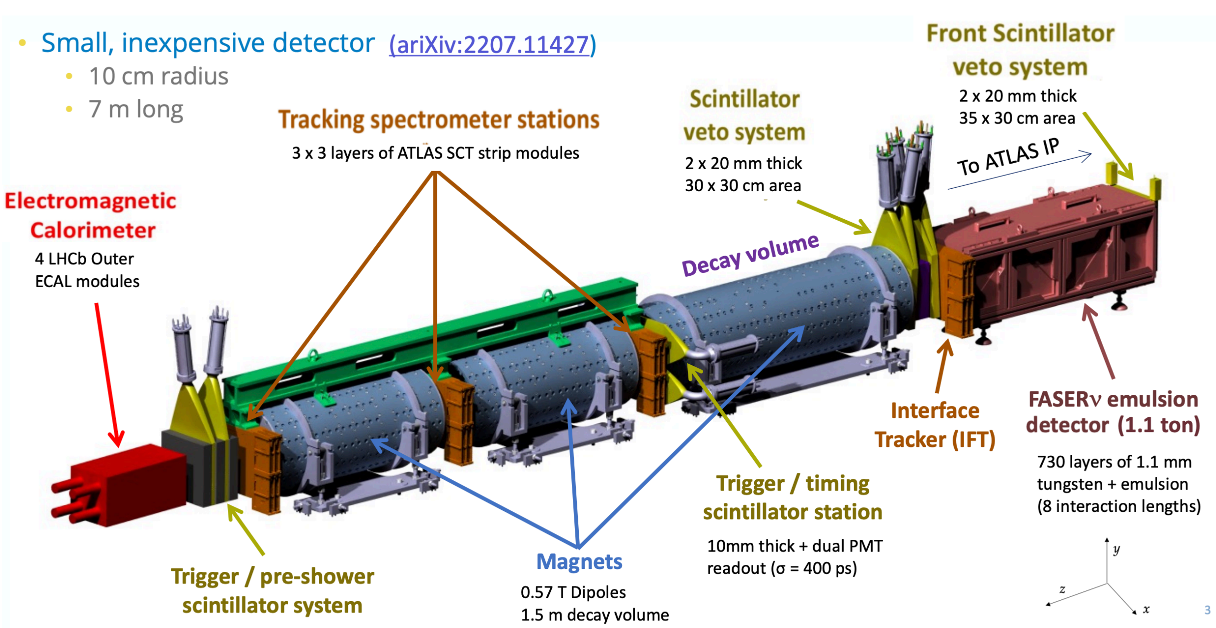
Editors' Suggestion | Featured in Physics

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)

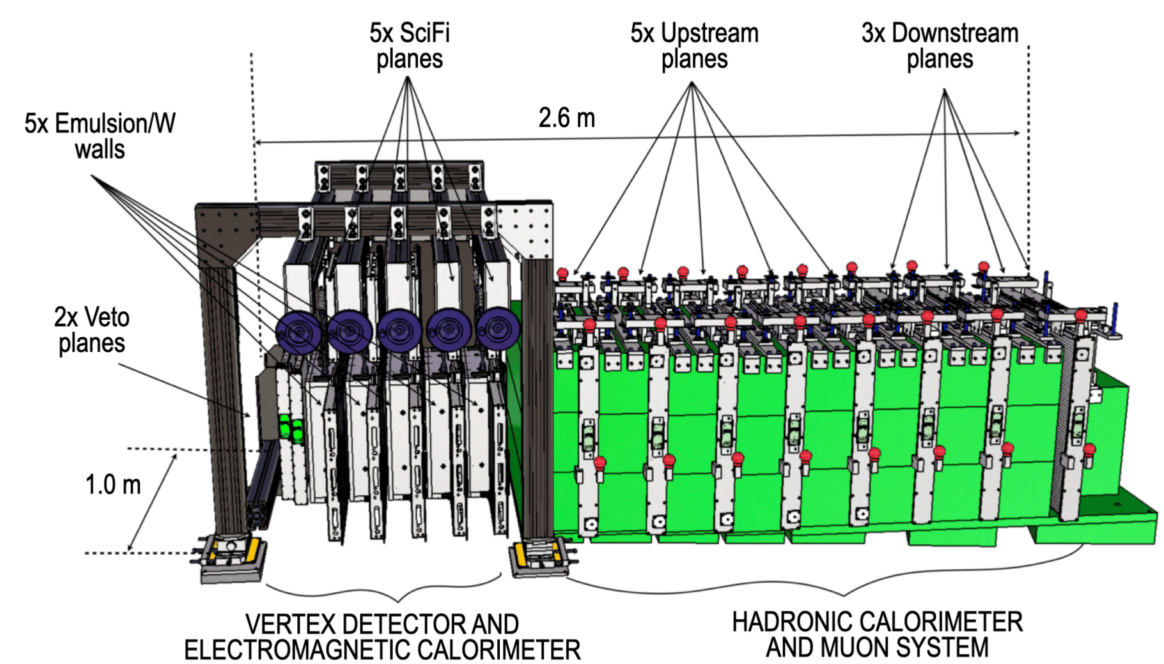
Editors' Suggestion

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.

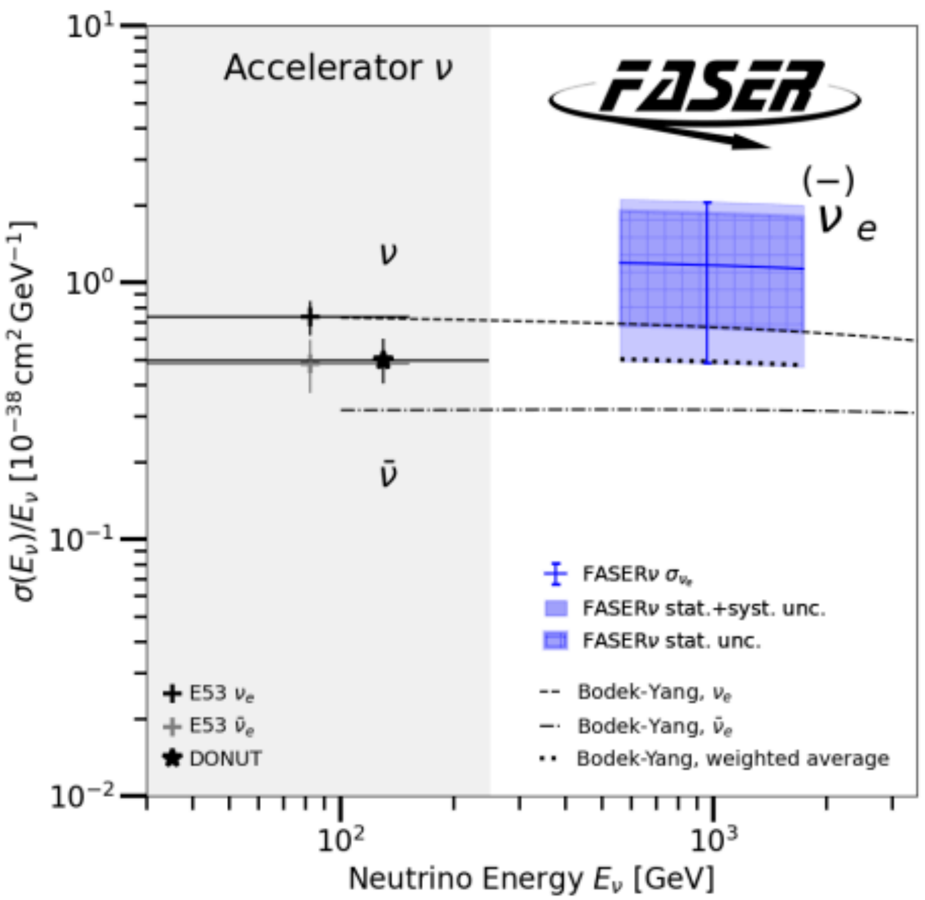
DOI: 10.1103/PhysRevLett.131.031802

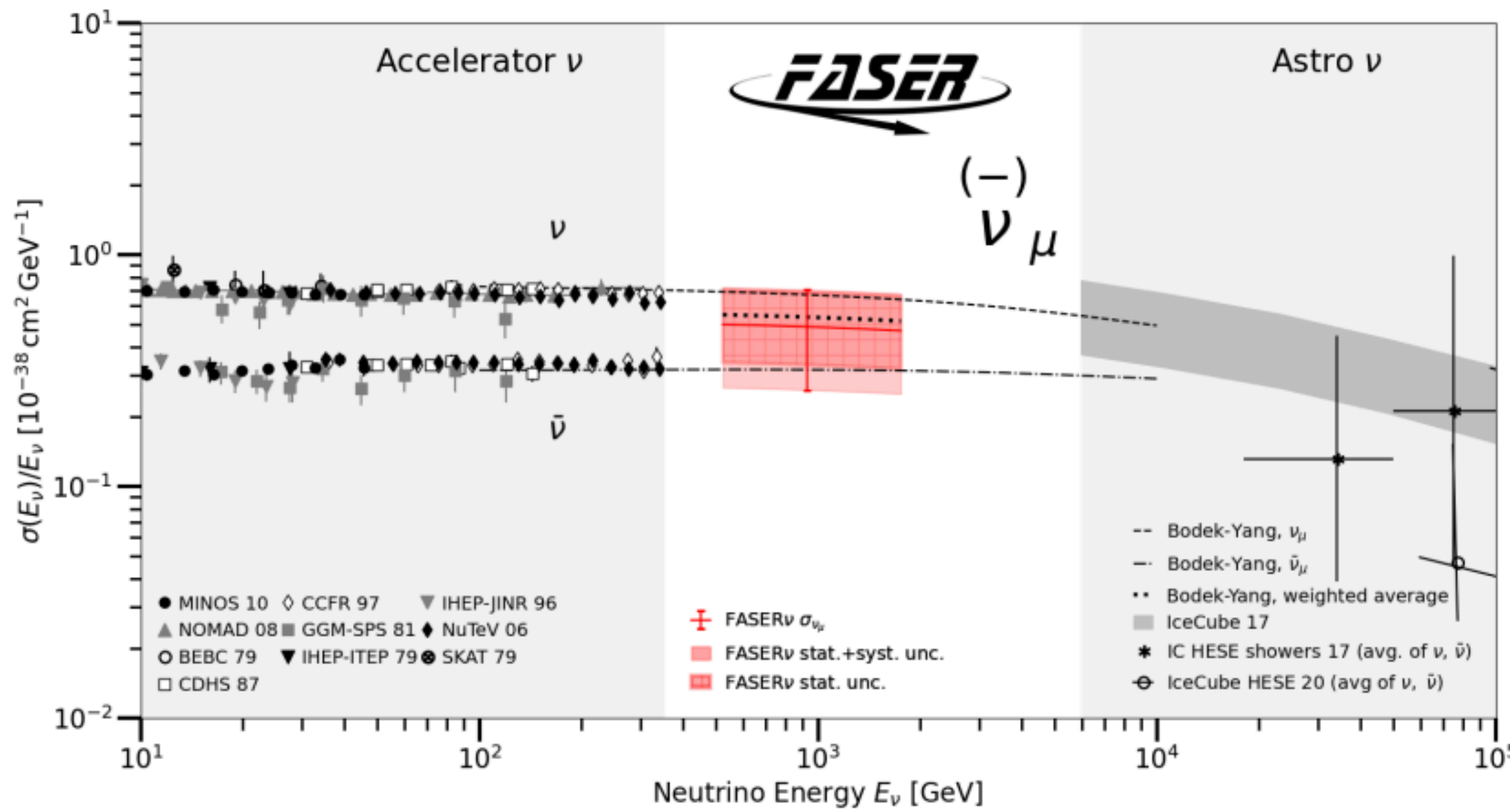
8 neutrinos detected, 4 expected

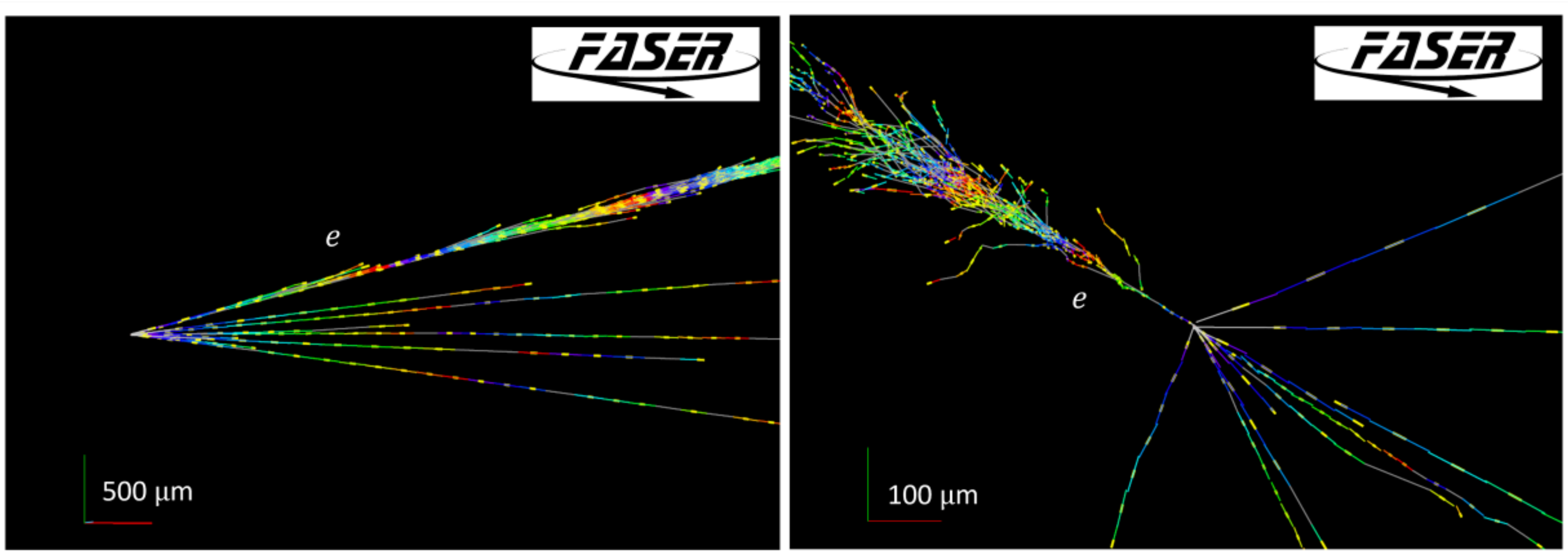


The dawn of the LHC neutrino era

- **… the first direct measurement of neutrino cross-section at TeV energies** from FASERnu ….



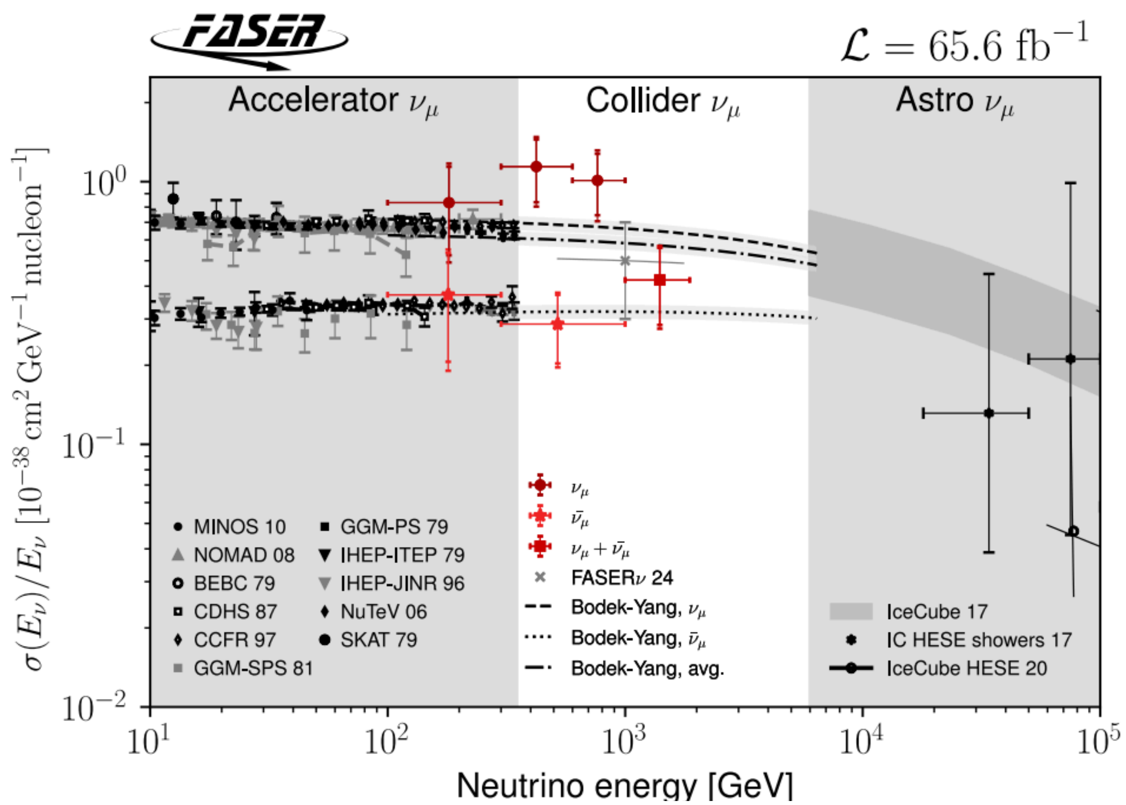


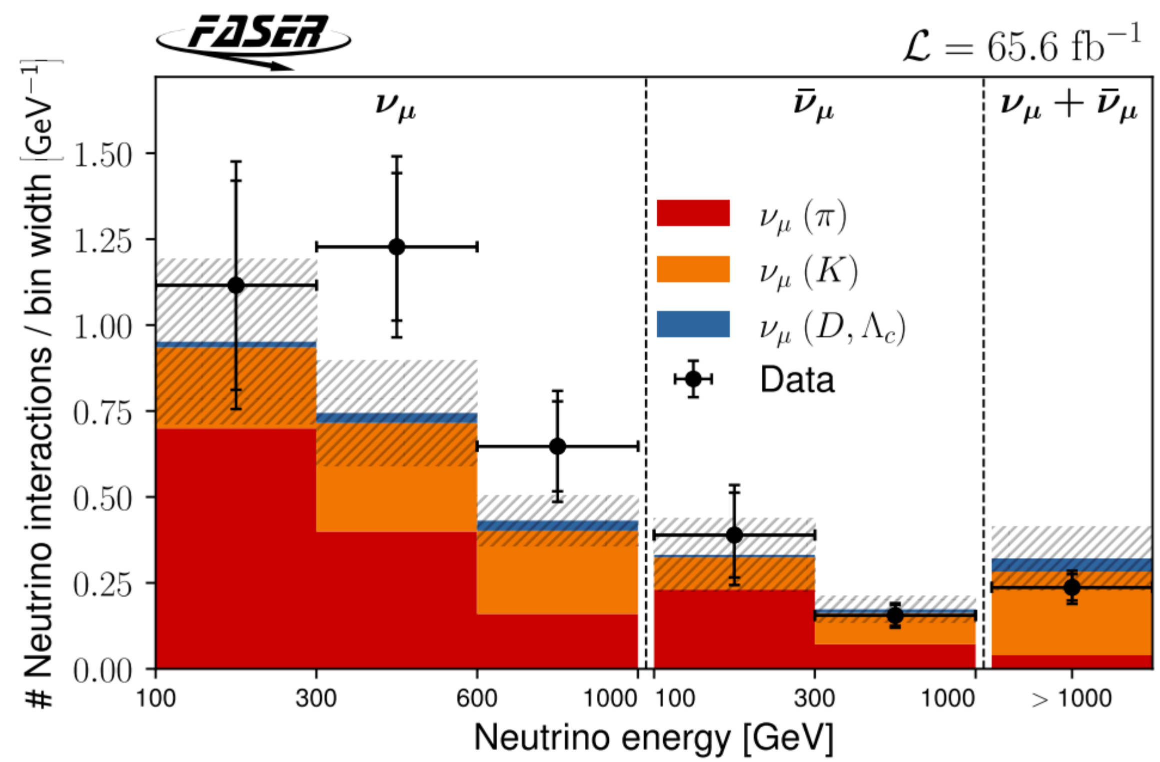


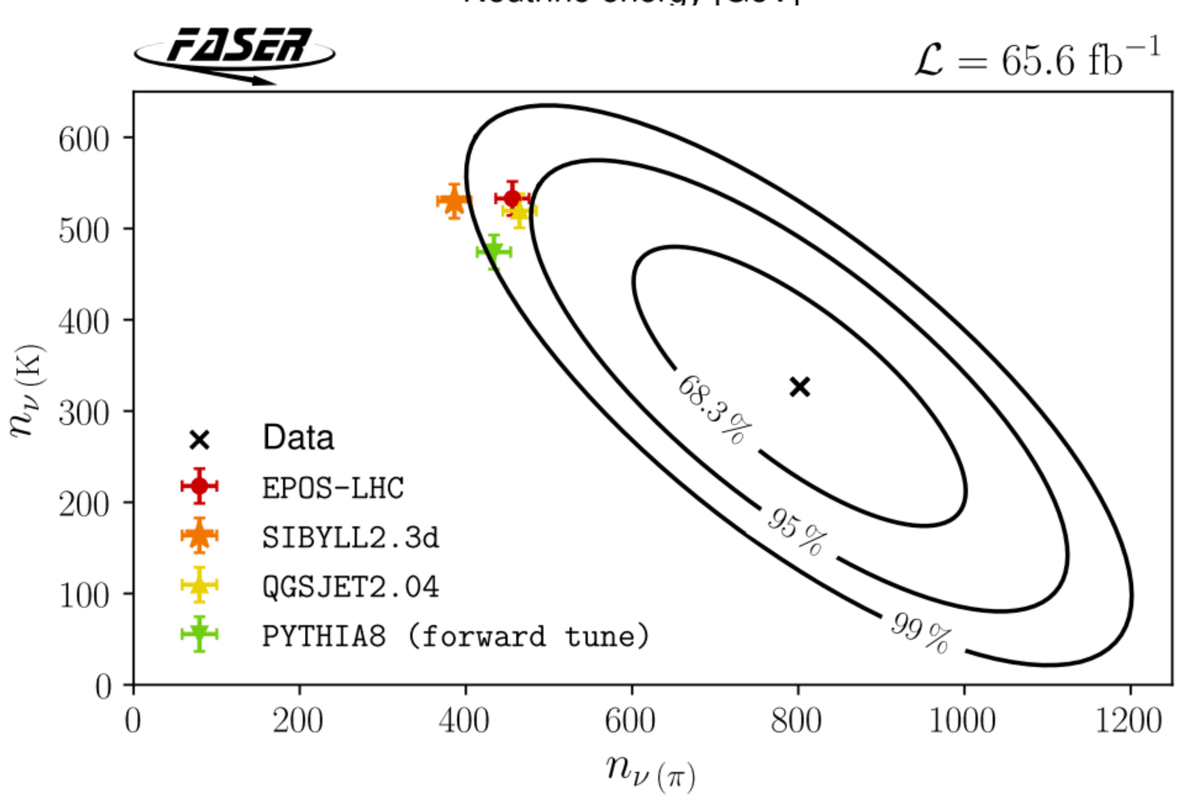
FASER's emulsion detector (FASERν) has excellent particle ID and spatial resolution

The dawn of the LHC neutrino era

- … and **energy-differential measurements** with the electronic FASER detector which provide first direct constraints on **models of forward light particle production** in proton-proton collisions







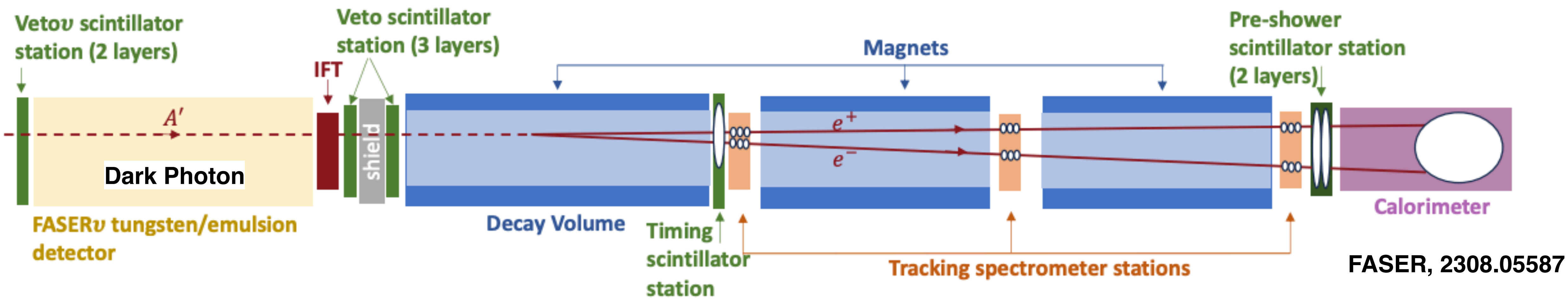
- Constrain **neutrino interactions in the TeV region** and their flavour dependence

- Validate models of forward pion and kaon production relevant for **cosmic ray physics** (muon puzzle)

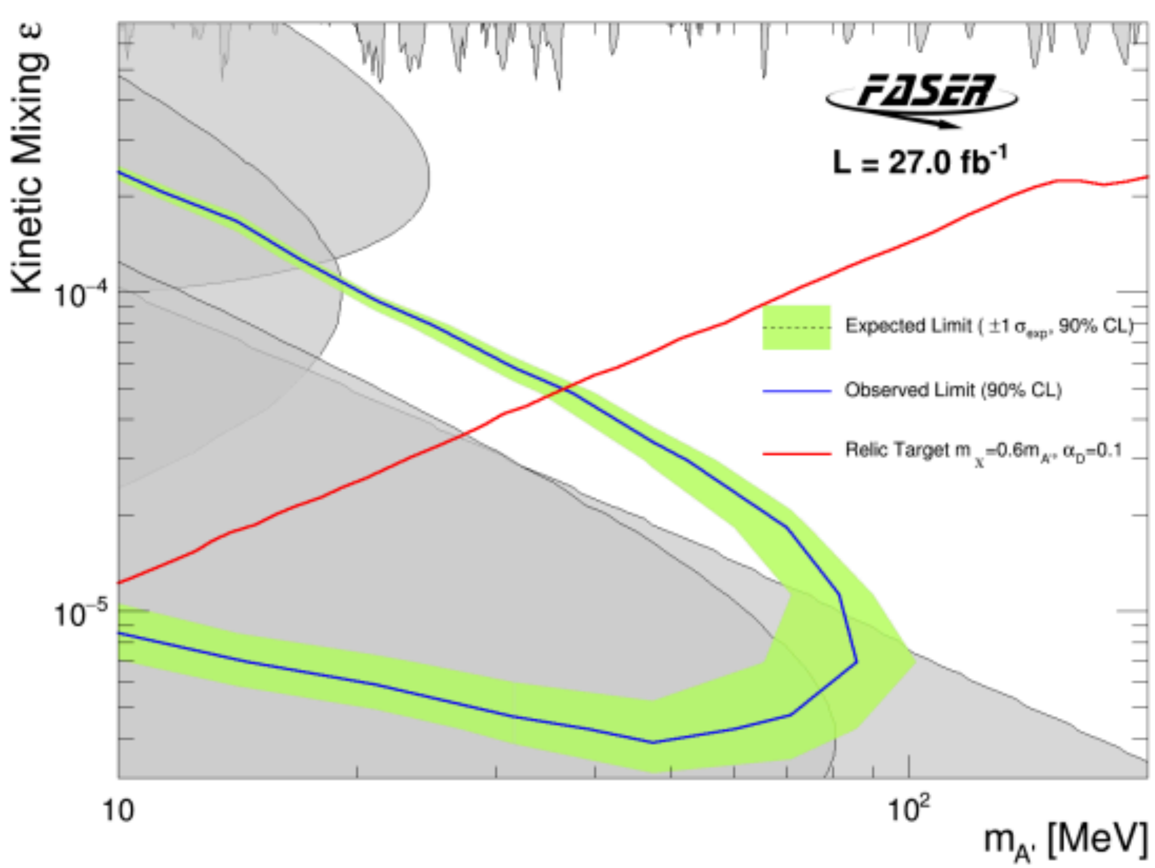
- Enable dedicated tunes of **forward physics** in hadronic collisions

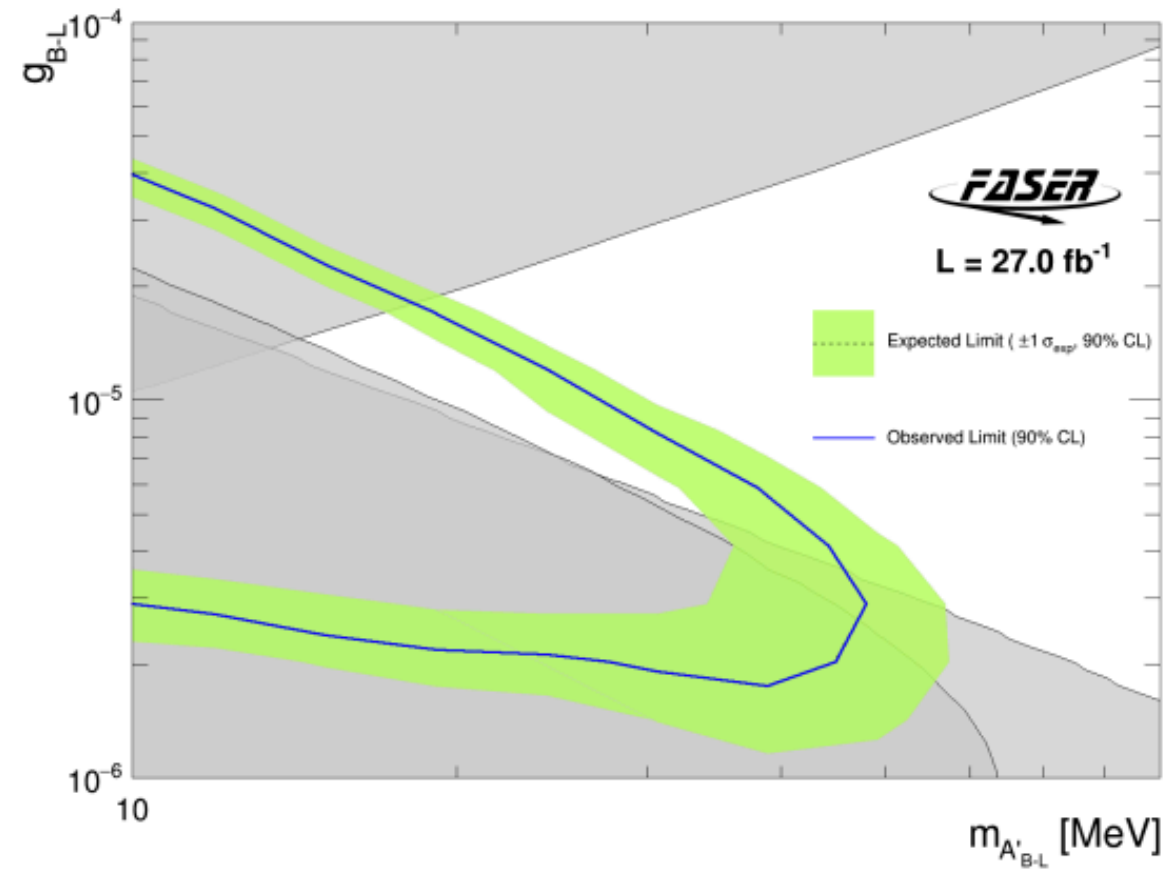
Light BSM Searches at FASER

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



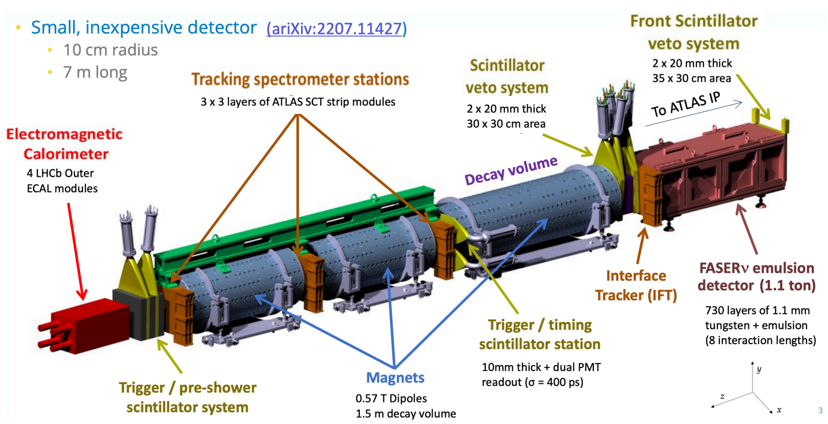
FASER, 2308.05587



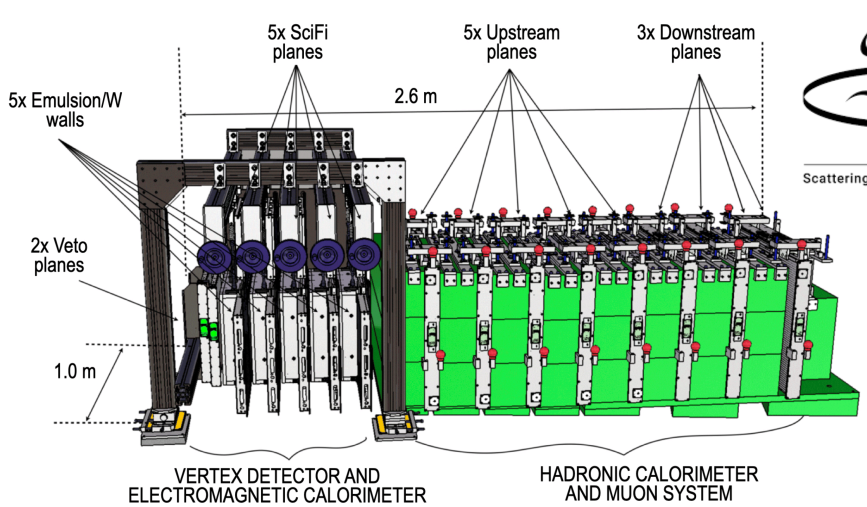


Unique blend of guaranteed deliverables and exploration potential

Neutrinos at the LHC



2022-2026 (Run-3)

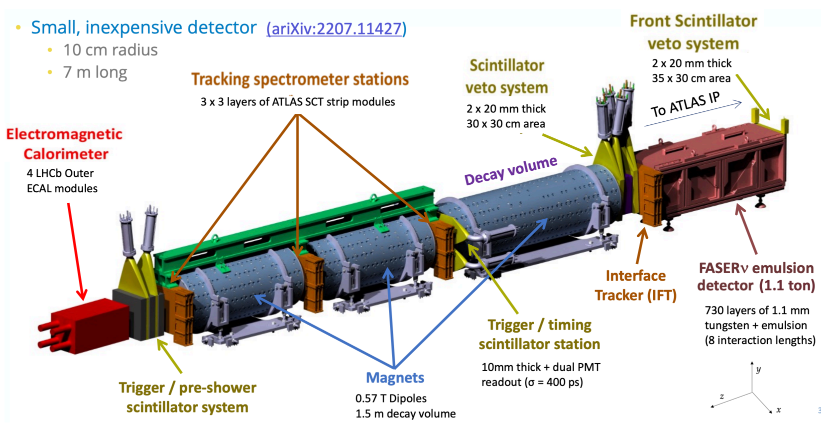


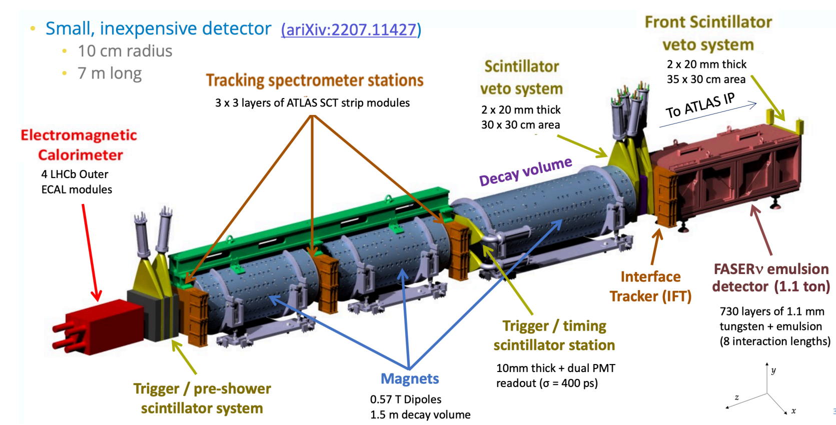
LHC
Scattering and Neutrino Detector at the LHC

Neutrinos at the LHC

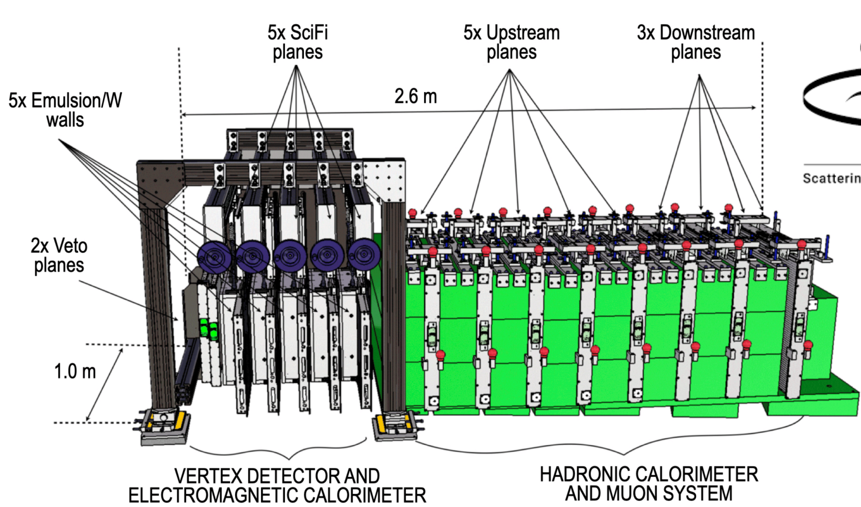
FASER @ HL-LHC

(approved, new ν detectors under discussion)





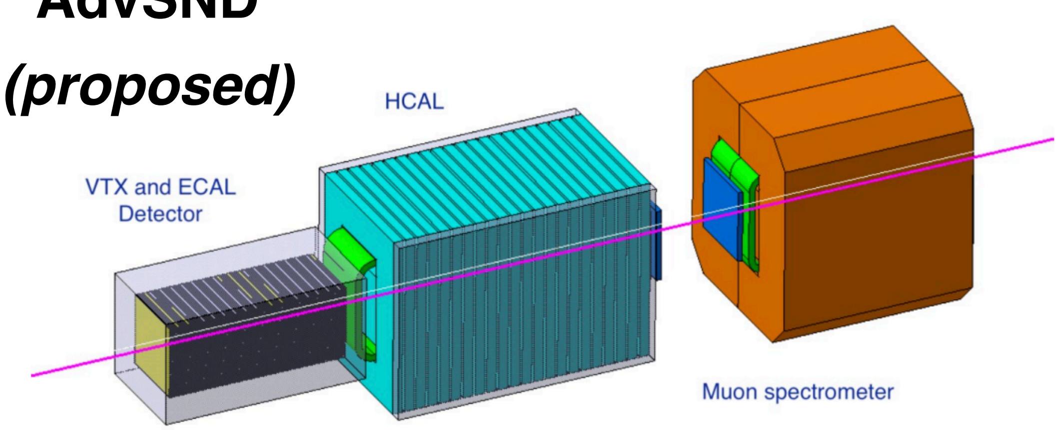
2022-2026 (Run-3) **2027-2029 (LS3)** **> 2030 (overlap with HL-LHC)**



LHC
Scattering and Neutrino Detector at the LHC

AdvSND

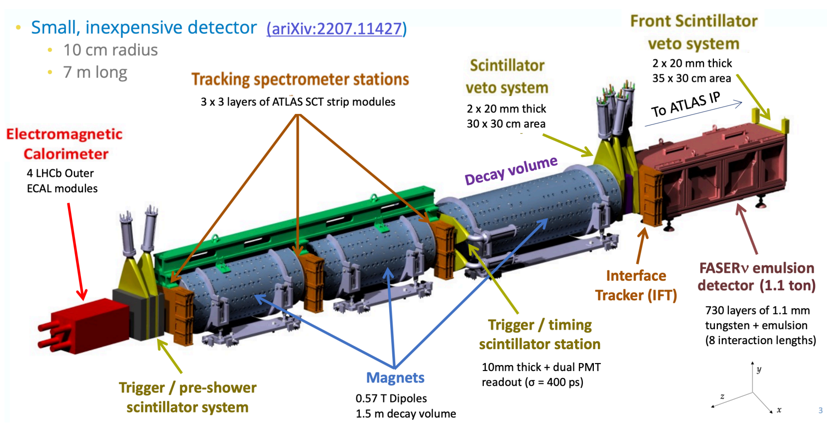
(proposed)

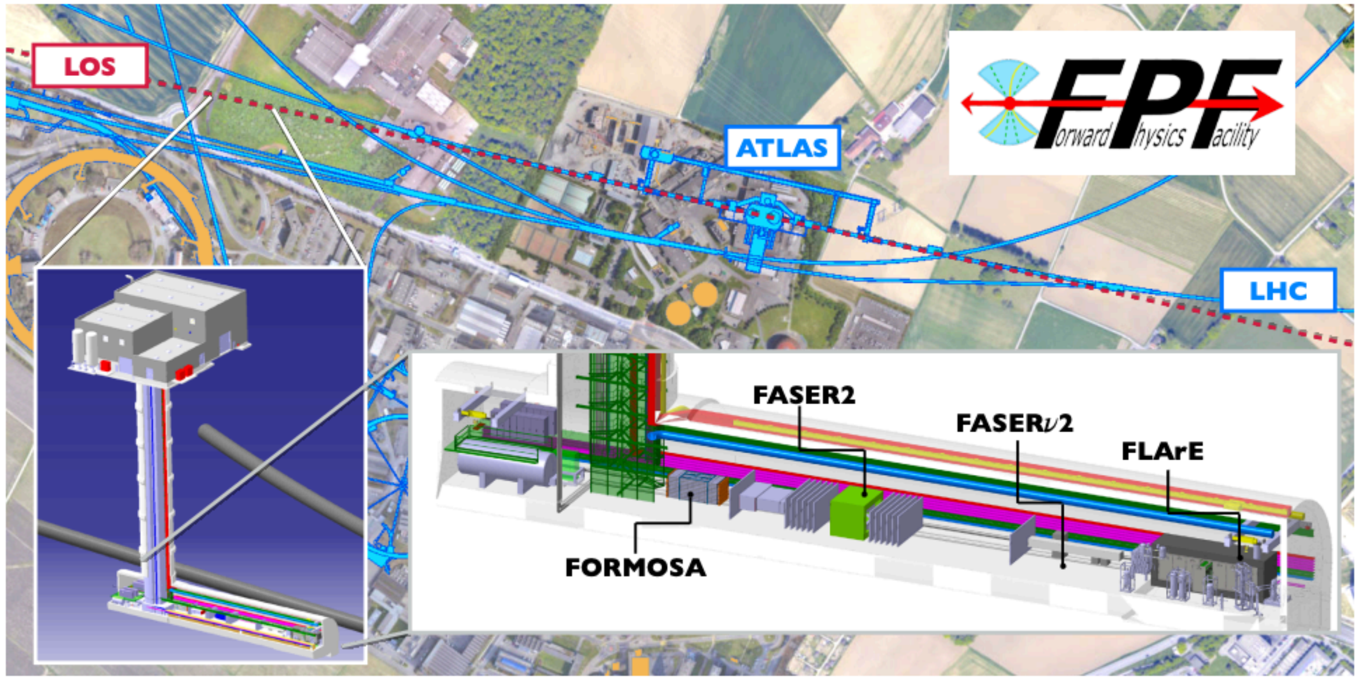


Neutrinos at the LHC

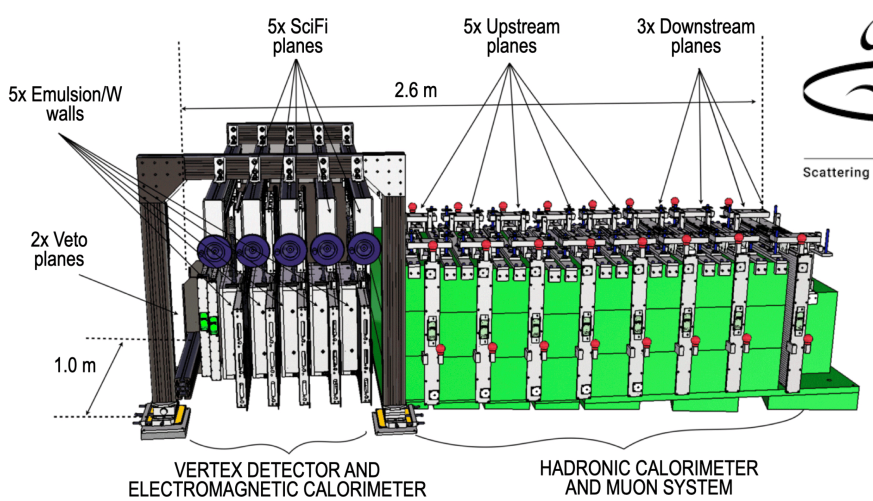
Forward Physics Facility (FPF)

(Proposed)





2022-2026 (Run-3) → **2027-2029 (LS3)** → **> 2030 (overlap with HL-LHC)**

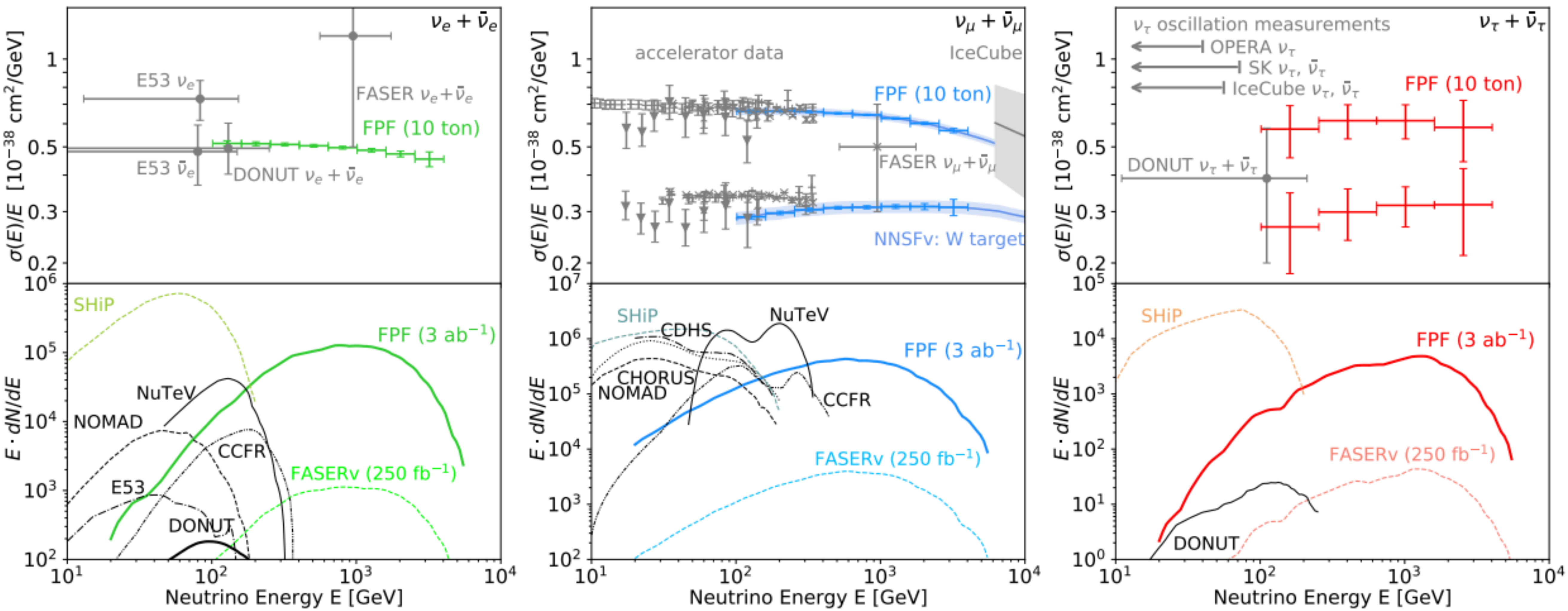


LHC

Scattering and Neutrino Detector at the LHC

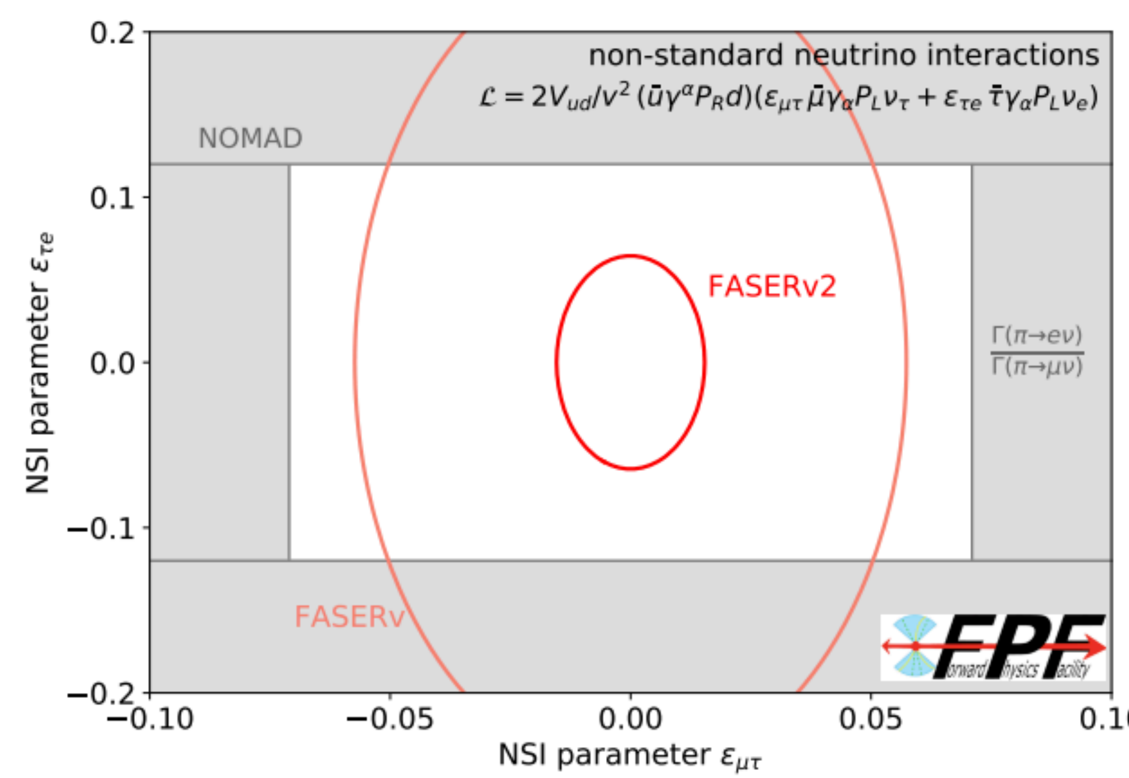
- Complementary suite of **far-forward experiments** operating **concurrently with the HL-LHC**
- Start **civil engineering during LS3** or shortly thereafter the cavern depth)
- Decision to be taken **following ESPPU**

Impact on Neutrino Physics

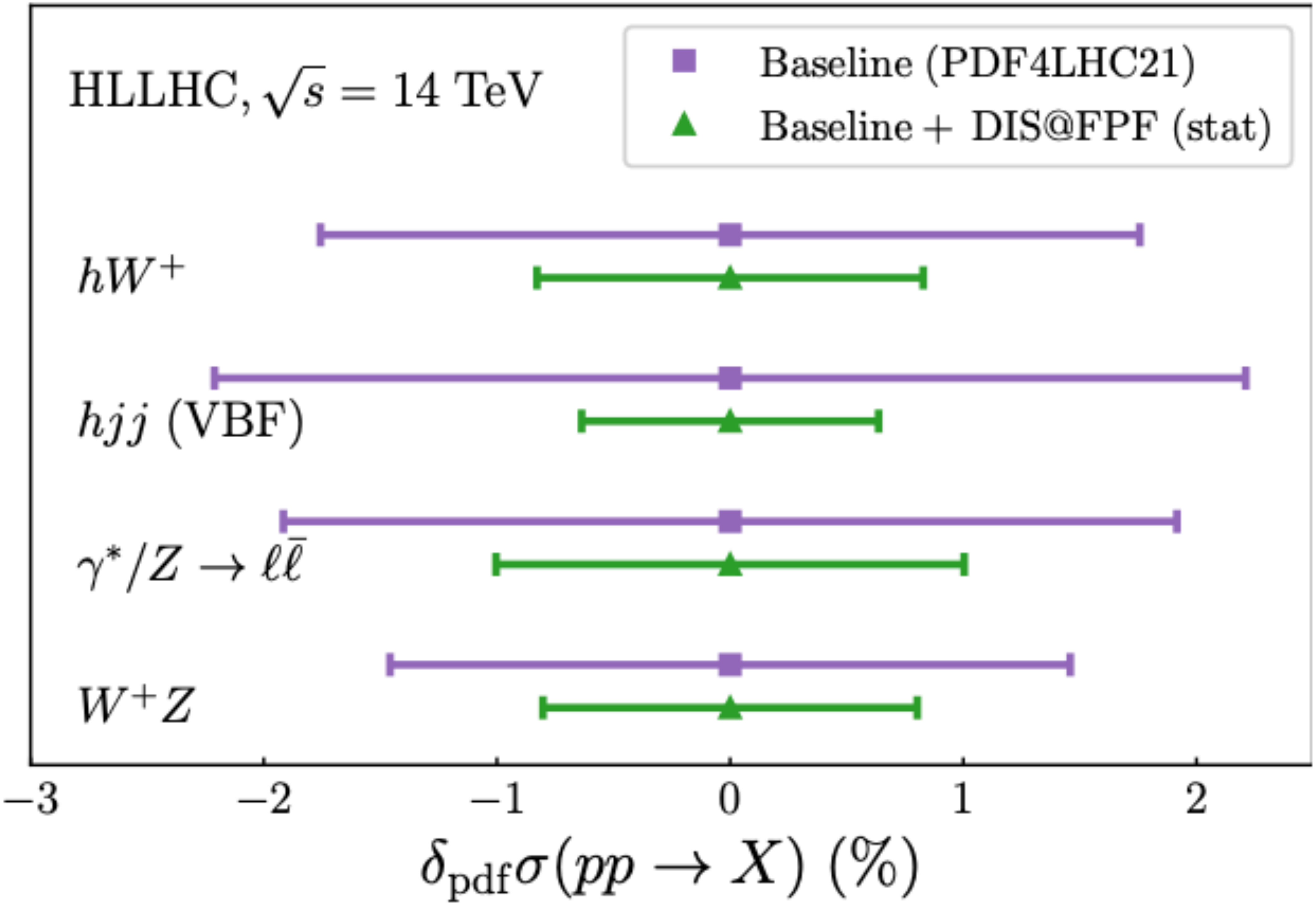


unique coverage of **TeV energy region**, high-statistics for **all three neutrino flavours**

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



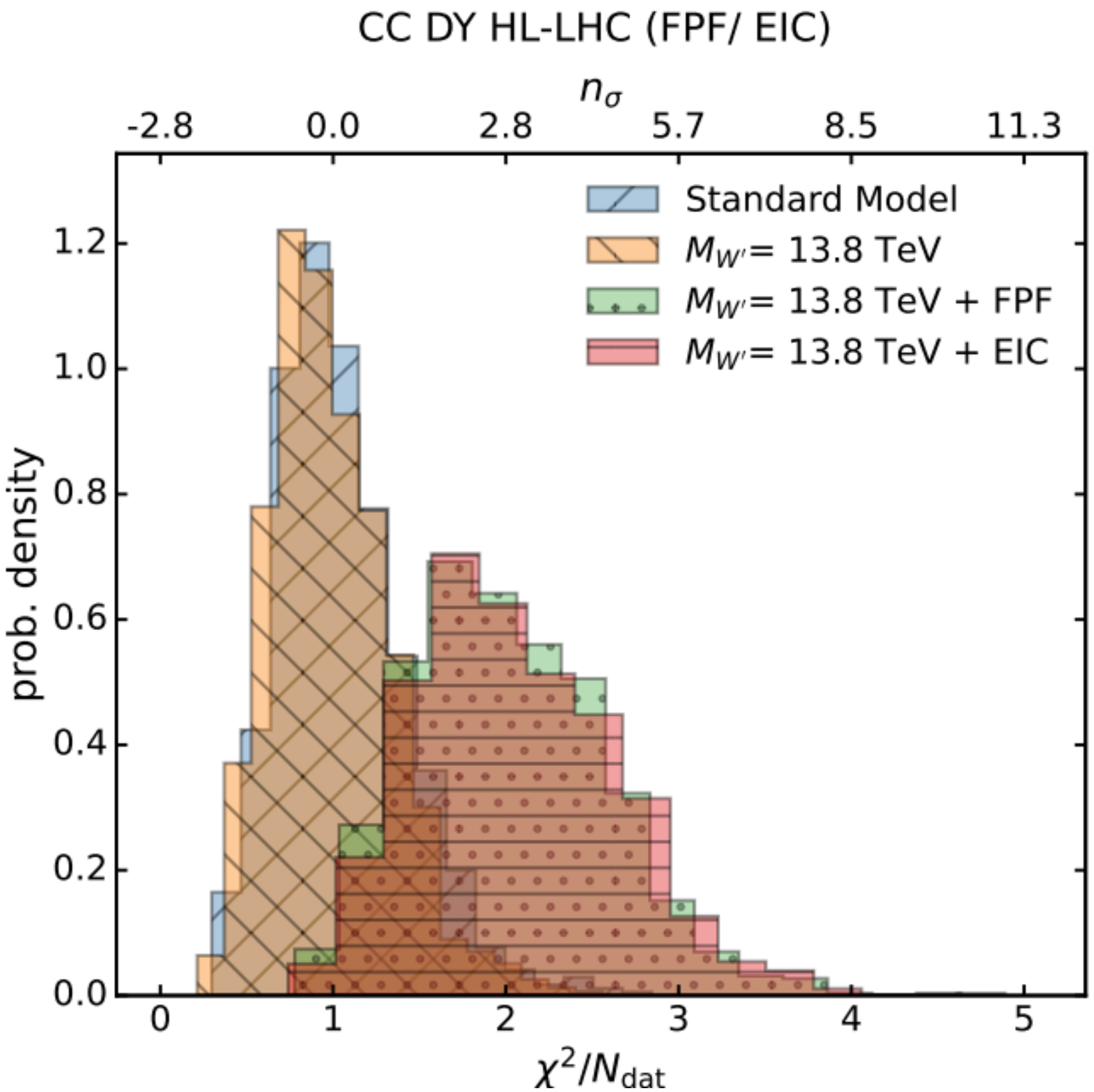
Impact at the HL-LHC: Higgs Physics

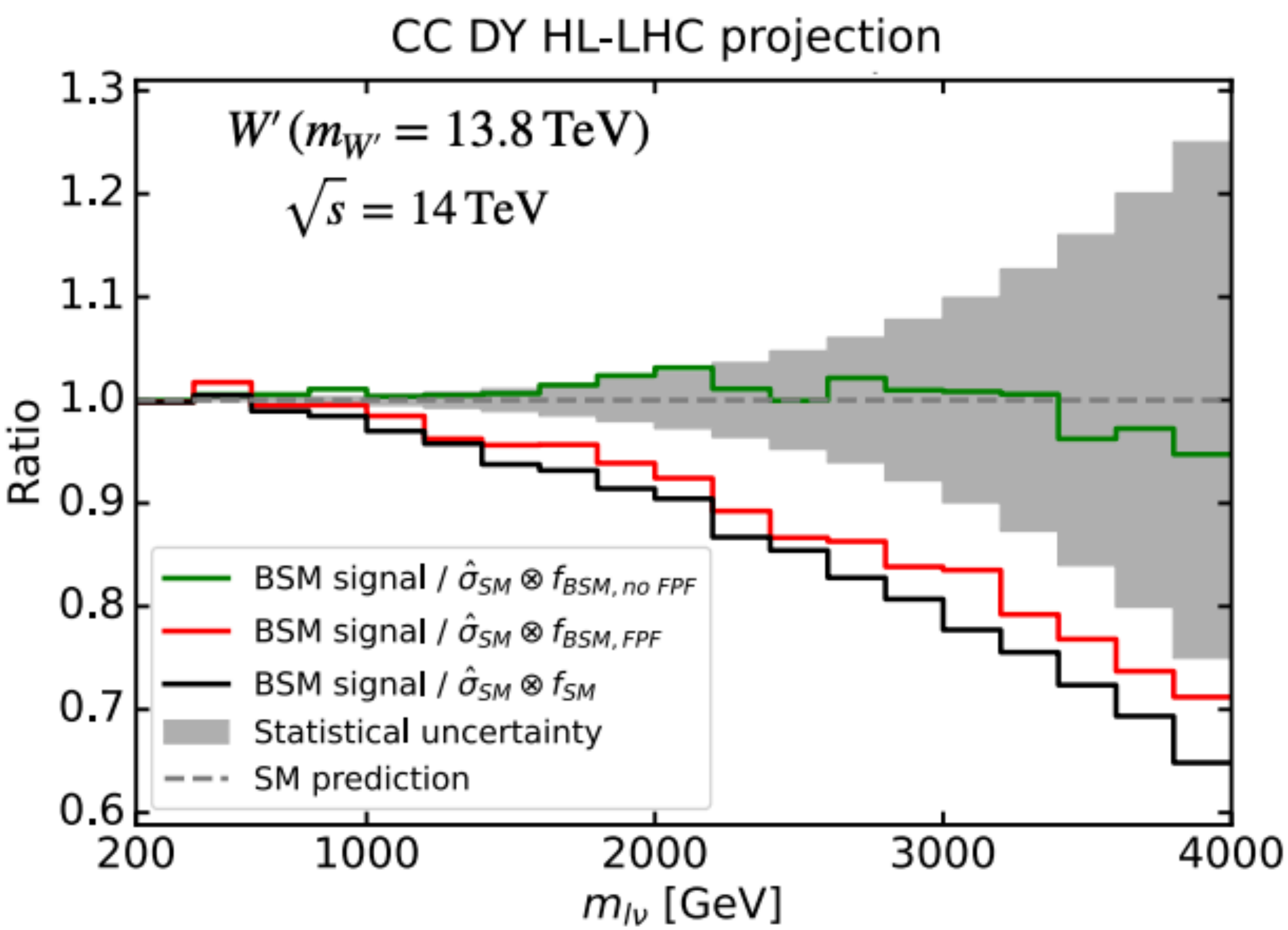


Realising the full potential of **TeV-energy neutrino DIS** at the LHC

Impact at the HL-LHC: BSM searches

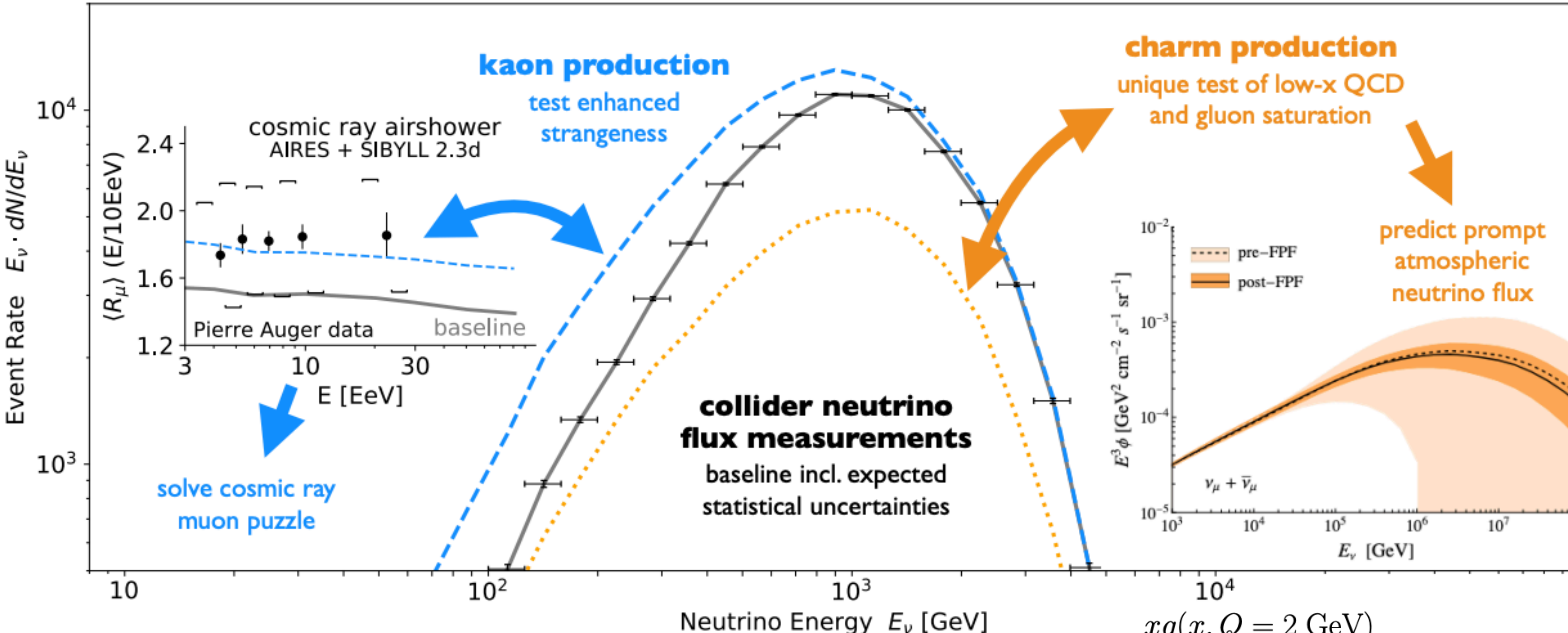
- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- Without FPF, this BSM signal is completely reabsorbed by the PDF fit (softer large-x antiquarks)
- LHC neutrino DIS **disentangles BSM signals from QCD effects in LHC high-p_T tails**



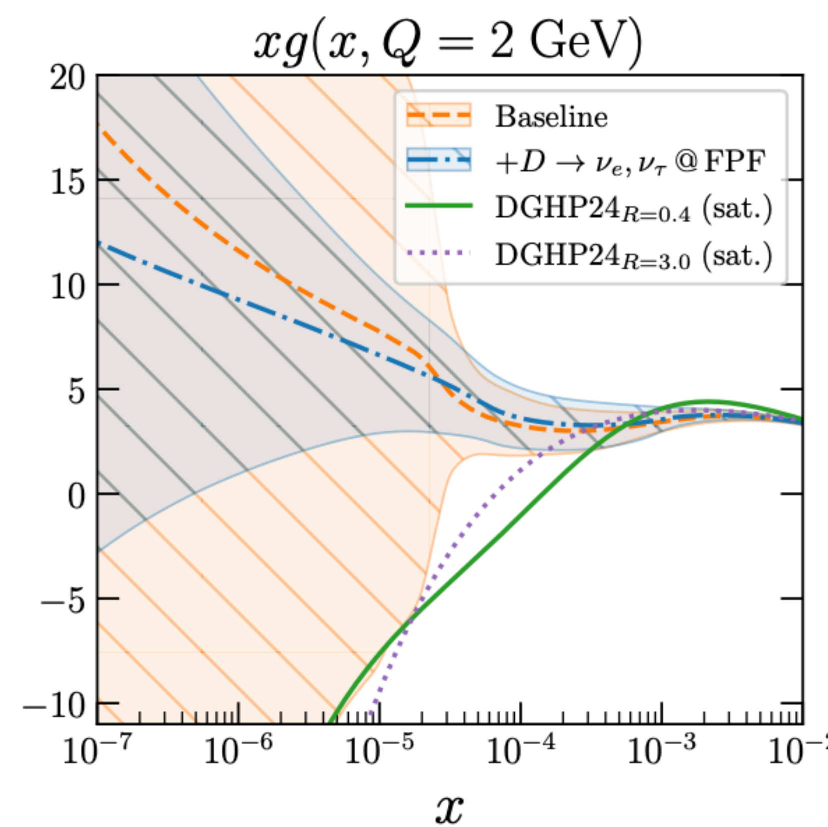


Hammou & Ubiali, 2024

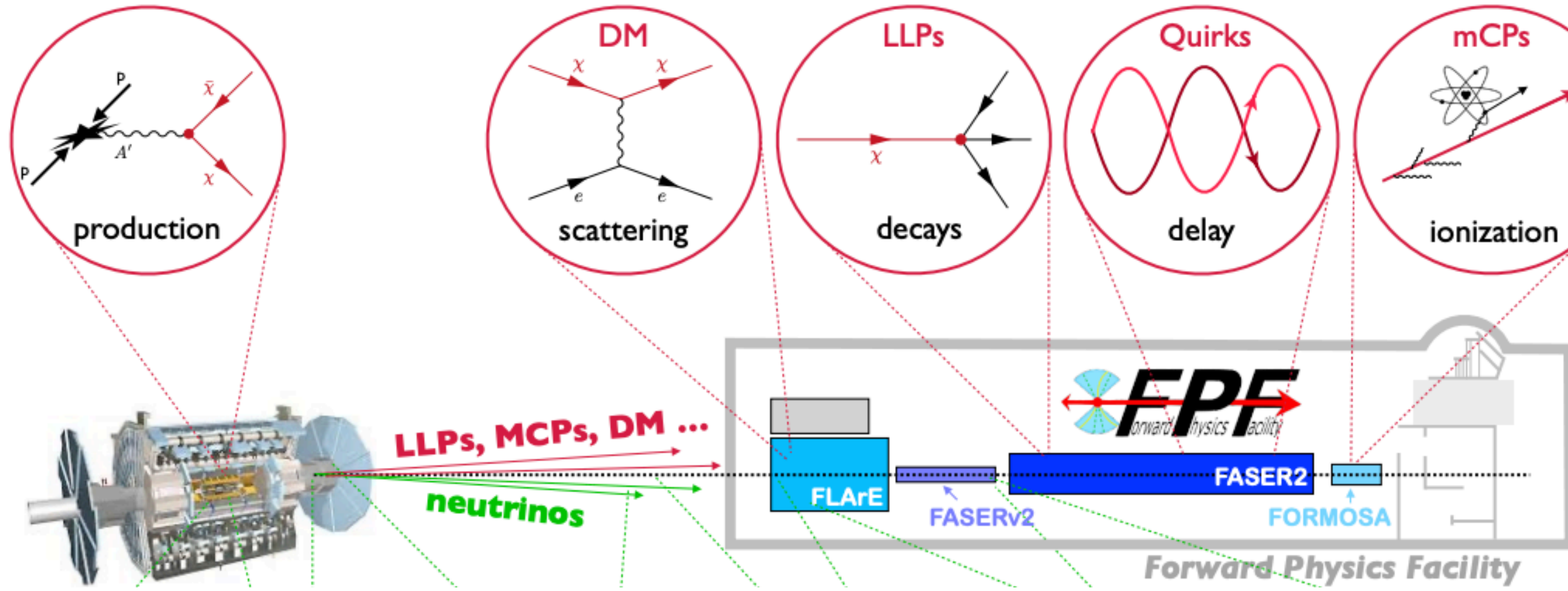
Impact on Astroparticle Physics



- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Data-driven prediction of the prompt neutrino flux
- Laboratory validation of **muon puzzle** predating **cosmic ray physics**

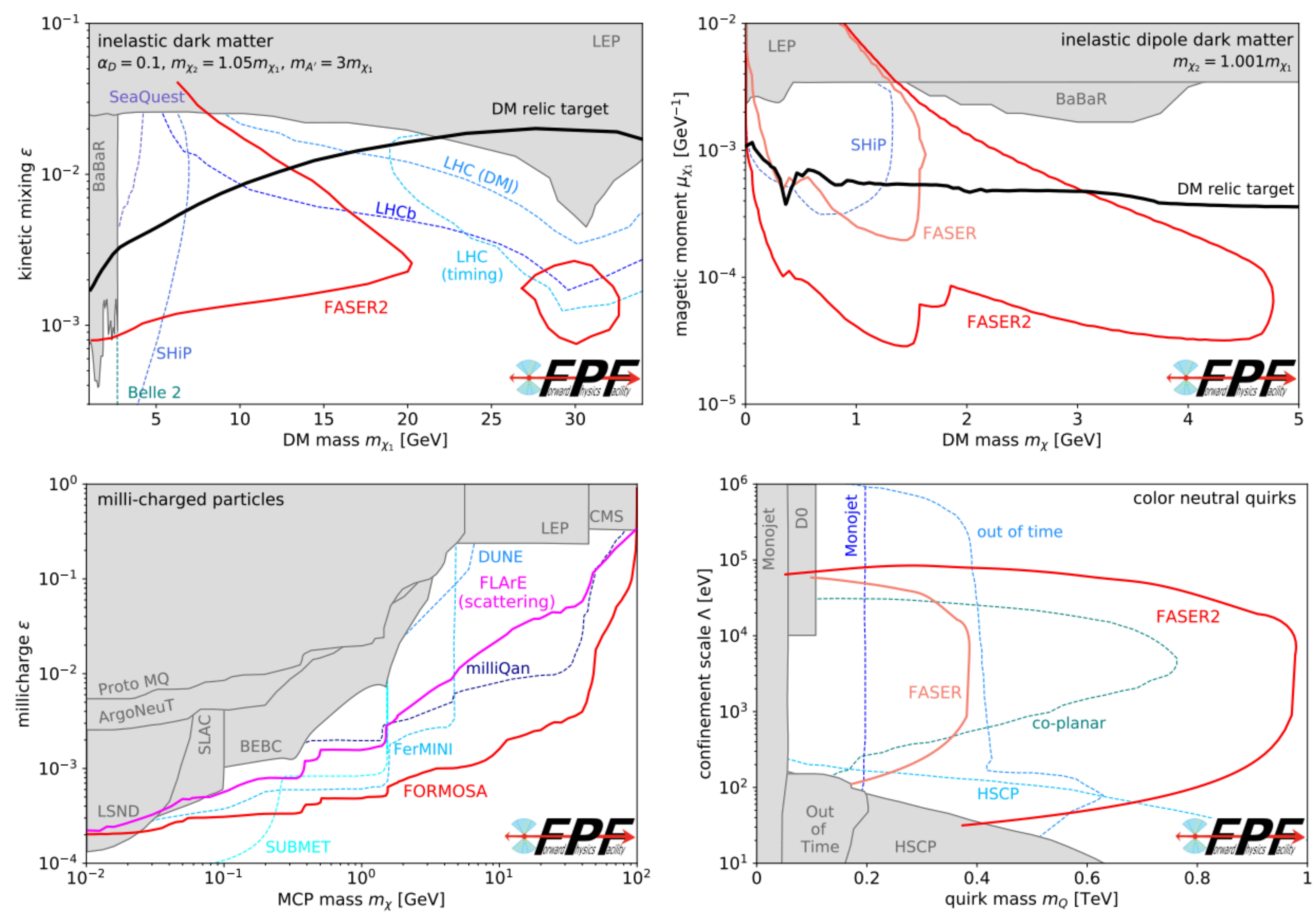


Light BSM Discovery Potential



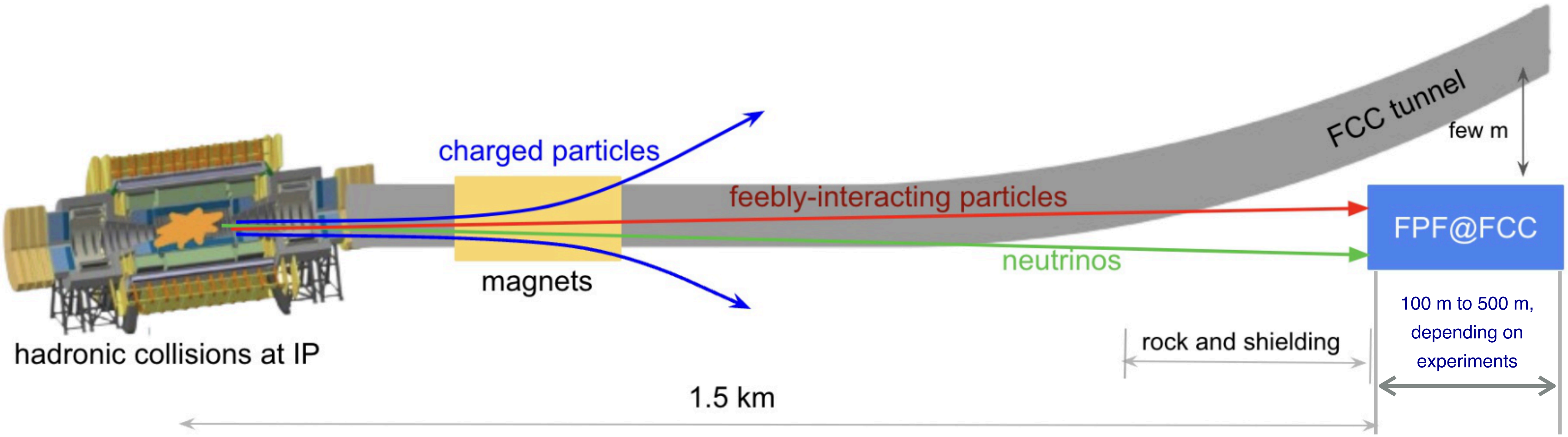
Rich and diverse light BSM search program:

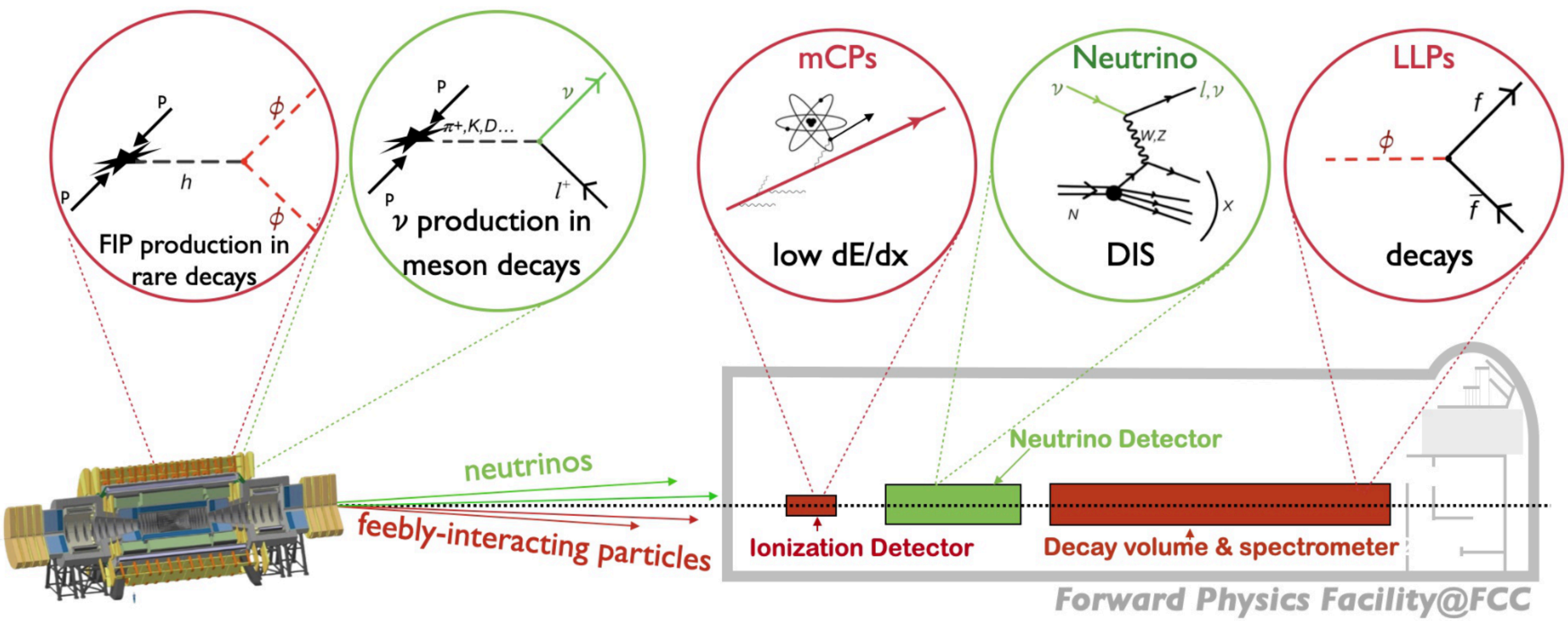
- Inelastic dark matter
- Millicharged particles
- Color neutral quarks
- & many more: Dark Higgs, dark photons, ALPs, …



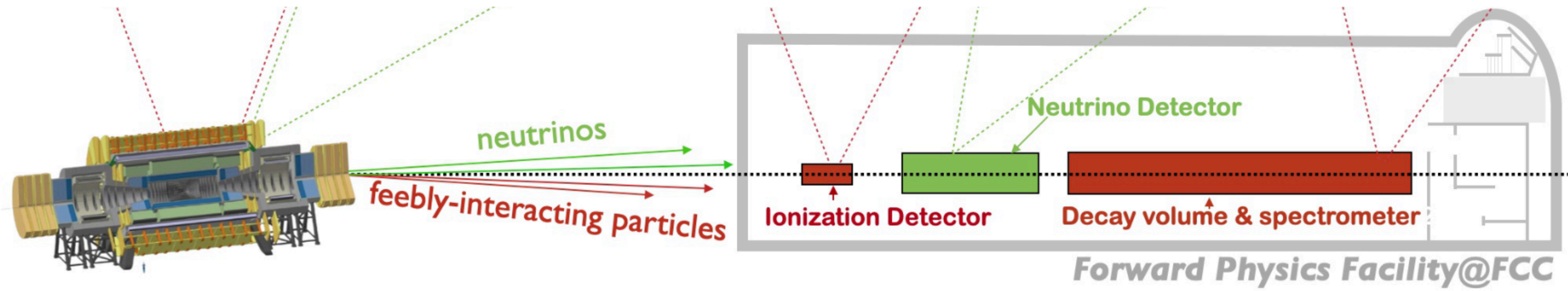
FPF@FCC

Facility to **detect neutrinos and BSM particles** produced at the FCC-hh in the **forward direction**





Detectors



Neutrino detectors

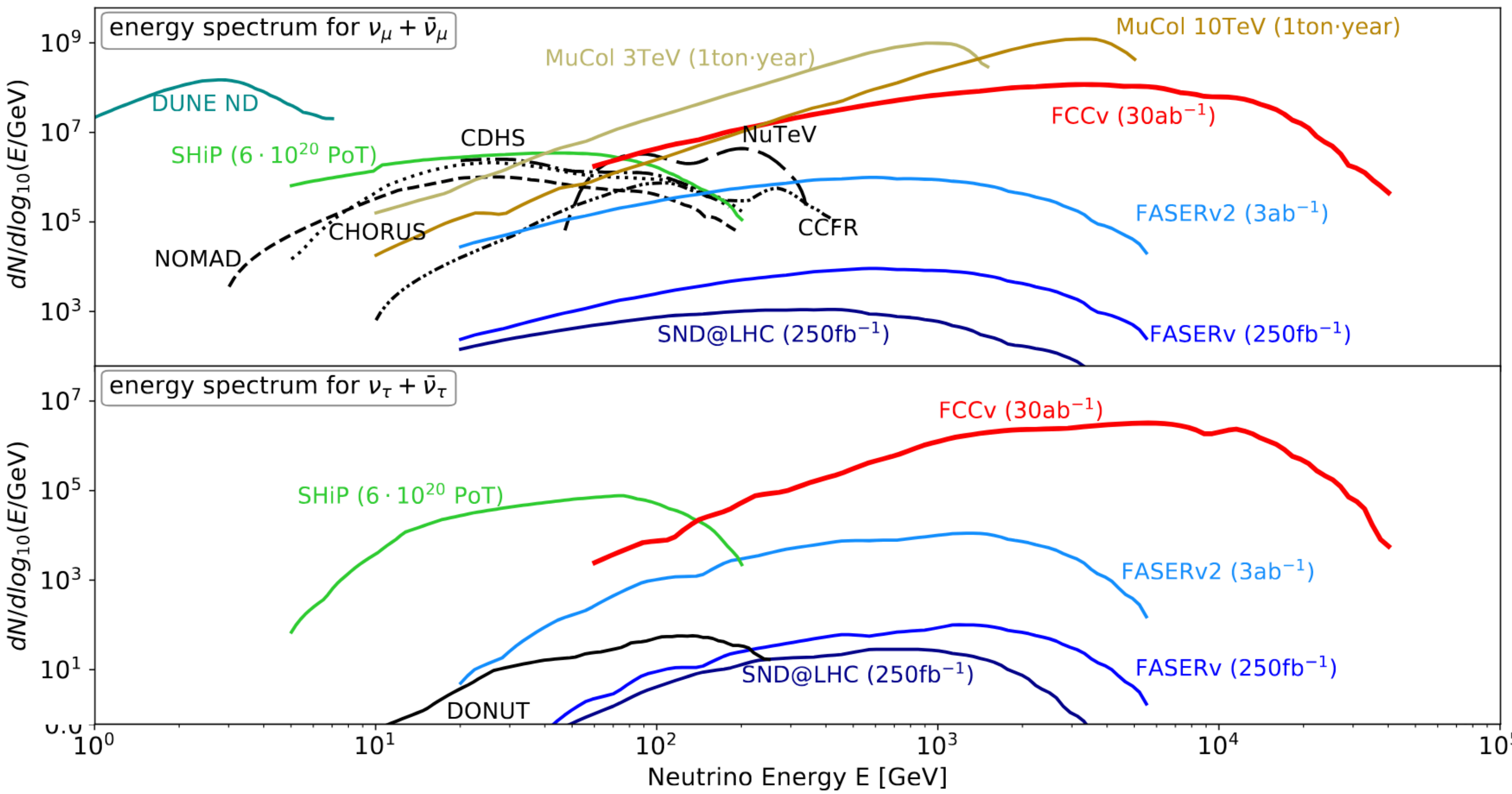
Detector	Geometry	Rapidity	$\mathcal{L}_{pp}$	$\sqrt{s}$	Acceptance
FASERν	20 cm × 25 cm × 80 cm	$\eta_\nu \geq 8.5$	250 fb^{-1}	13.6 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.025$
FASERν2	40 cm × 40 cm × 6.6 m	$\eta_\nu \geq 8.4$	3 ab^{-1}	14 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν	40 cm × 40 cm × 6.6 m	$\eta_\nu \geq 9.2$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν(d)	40 cm × 40 cm × 66 m	$\eta_\nu \geq 9.2$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν(w)	1.25 m × 1.25 m × 6.6 m	$\eta_\nu \geq 8.1$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$

Decay volume & spectrometer (targeting BSM)

Detector	Geometry	$\mathcal{L}_{pp}$	$\sqrt{s}$	Acceptance
FASER	$\pi(10\text{ cm})^2 \times 1.5$ m	150 fb^{-1}	14 TeV	$E_{vis} \gtrsim 100$ GeV
FASER2	$\pi(1\text{ m})^2 \times 5$ m	3 ab^{-1}	14 TeV	$E_{vis} \gtrsim 100$ GeV
FCC-LLP1	5 m × 5 m × 50 m	30 ab^{-1}	100 TeV	$E_{vis} \gtrsim 100$ GeV
FCC-LLP2	20 m × 20 m × 400 m	30 ab^{-1}	100 TeV	$E_{vis} \gtrsim 100$ GeV

- Ambitious detector concepts, **technology-agnostic**
- For neutrino physics take **FASER ν2 as baseline**
- Consider also a **polarised detector** for neutrino DIS
- Costing of FPF@LHC is **O(CHF50M) for facility +** **O(CHF30M) for experiments**

Neutrino Fluxes

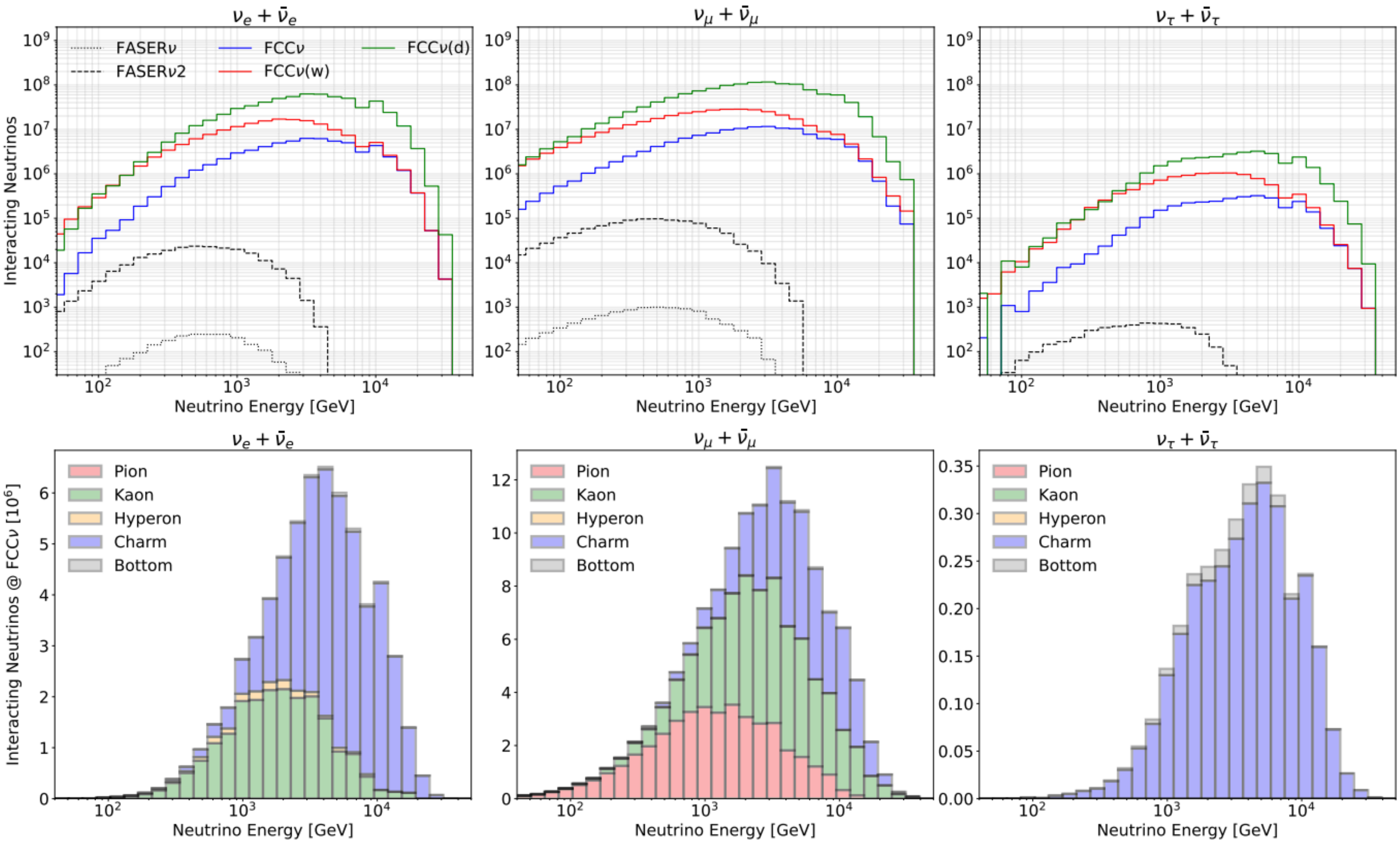


Detector	$N_{\nu_e} + N_{\bar{\nu}_e}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$	$N_{\nu_\tau} + N_{\bar{\nu}_\tau}$
FASERν	2.1k	11k	36
FASERν2	220k	1.1M	4.3k
FCCν	62M	130M	3.2M
FCCν(d)	620M	1.3B	32M
FCCν(w)	170M	370M	11M

- Enormous neutrino fluxes with energies **reaching 40 TeV**
- Up to **10^9 electron & muon neutrinos**, **10^4 tau neutrinos**
- Sizeable event samples also for **neutrinos from p+Pb collisions**
- Extend FCC-hh physics program with a rich portfolio of **neutrino science**
- Most energetic neutrinos that would be ever produced in lab experiments, **overlap with cosmic neutrinos**

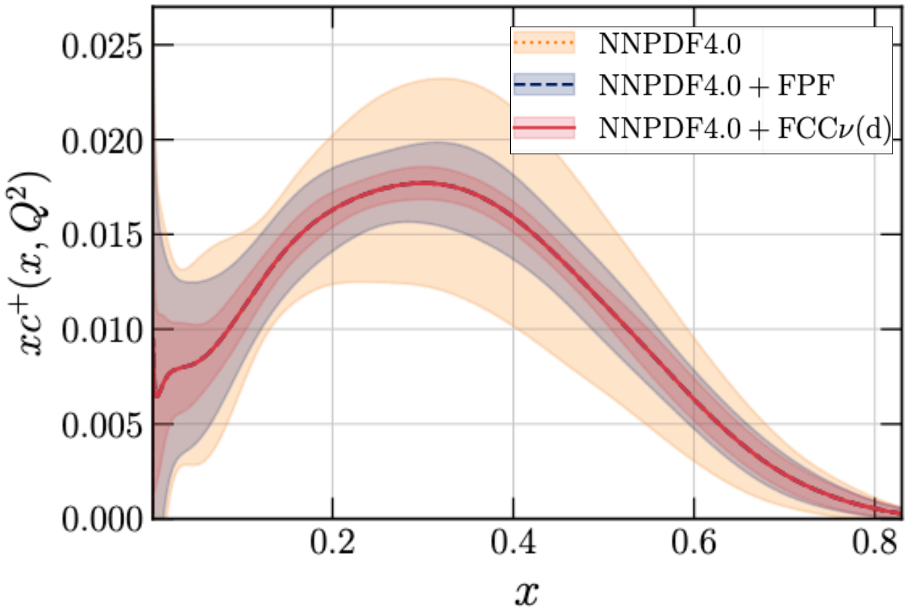
Which physics can we do with **1B electron and muon multi-TeV neutrinos?**

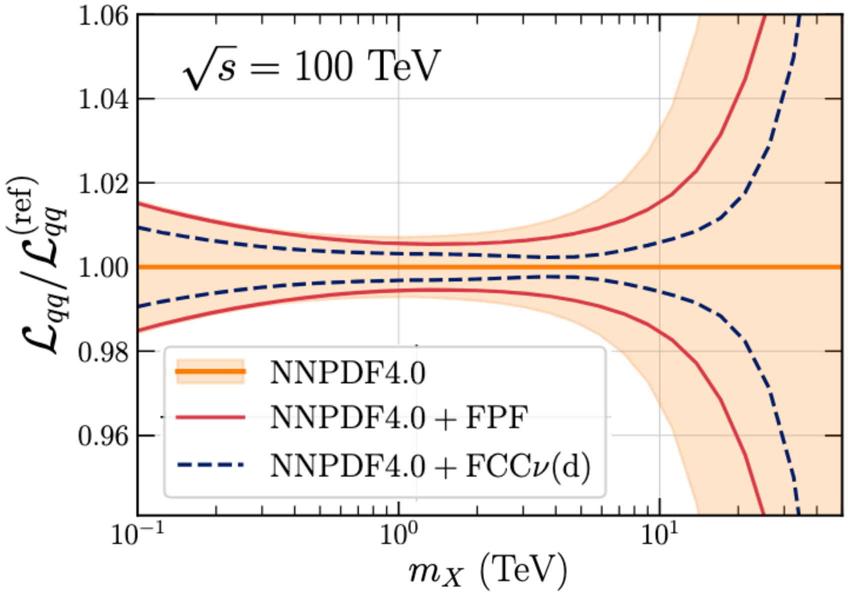
Neutrino Fluxes



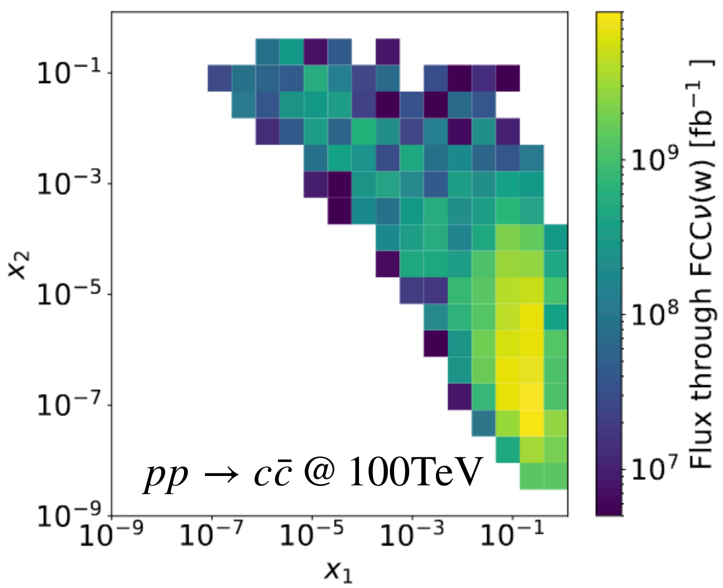
Which physics can we do with **1B electron and muon multi-TeV neutrinos?**

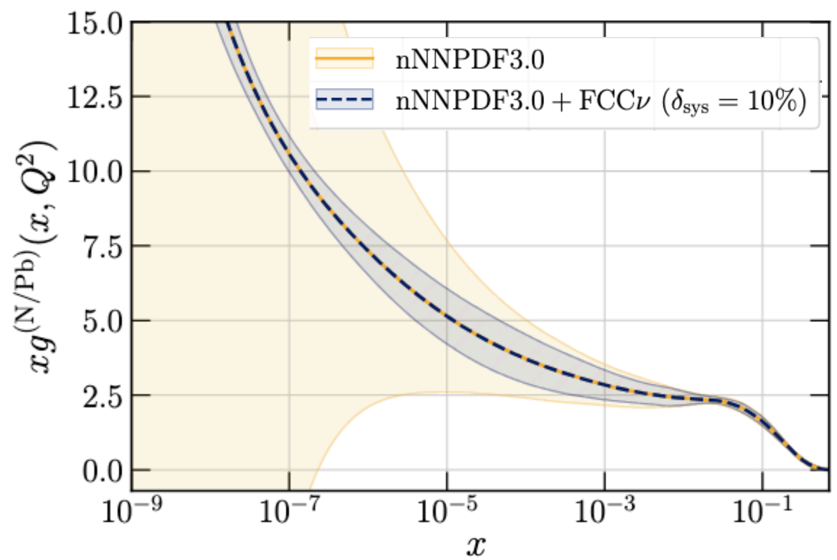
QCD studies



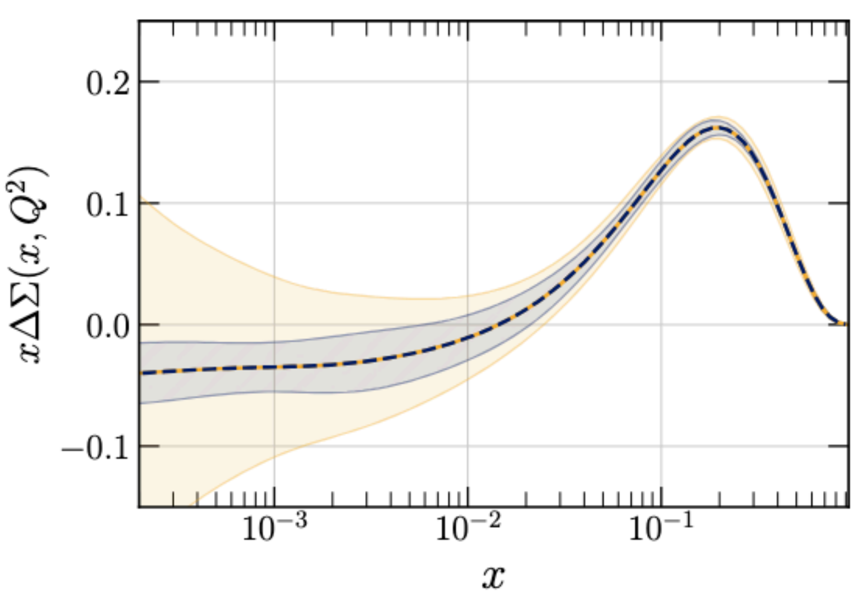


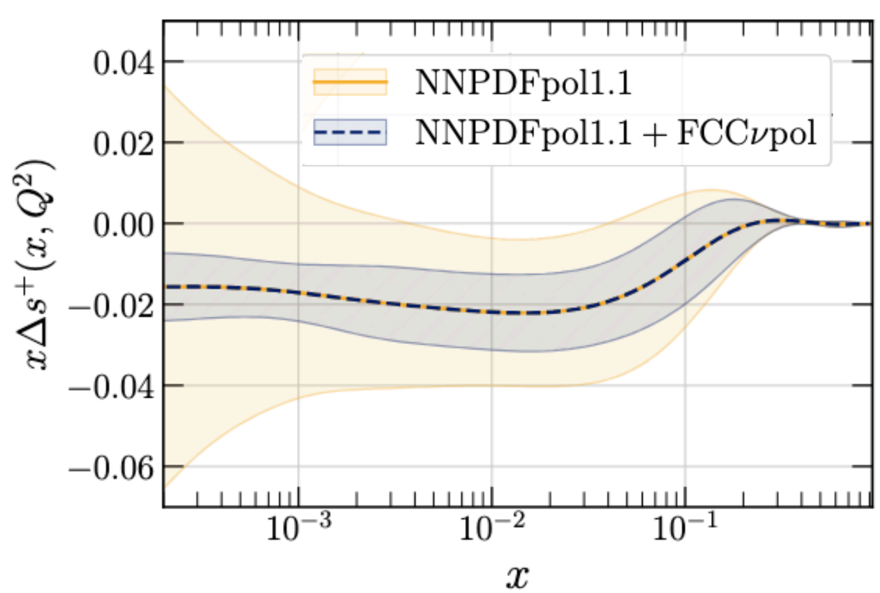
- Neutrino DIS with **< 0.1% statistical uncertainties**
- Stringent constraints in large-x PDFs, relevant for **searches in the $m_X > 10$ TeV region**





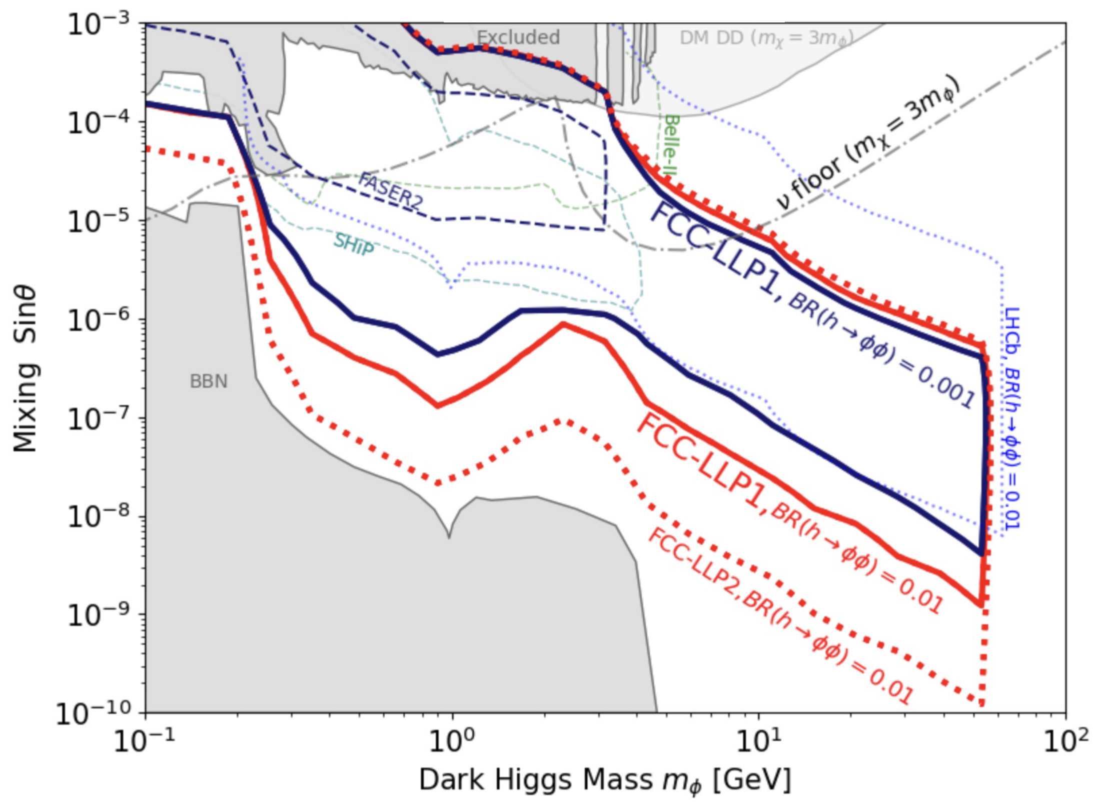
- Constrain **nuclear PDFs down to** $x \sim 10^{-9}$ via $\mathrm{p} + \mathrm{Pb} \to c + \bar{c} + X$
- Up to **10^5 events for charm production** (in hard scattering) in p+Pb at $\sqrt{s_{\mathrm{NN}}} = 63$ TeV

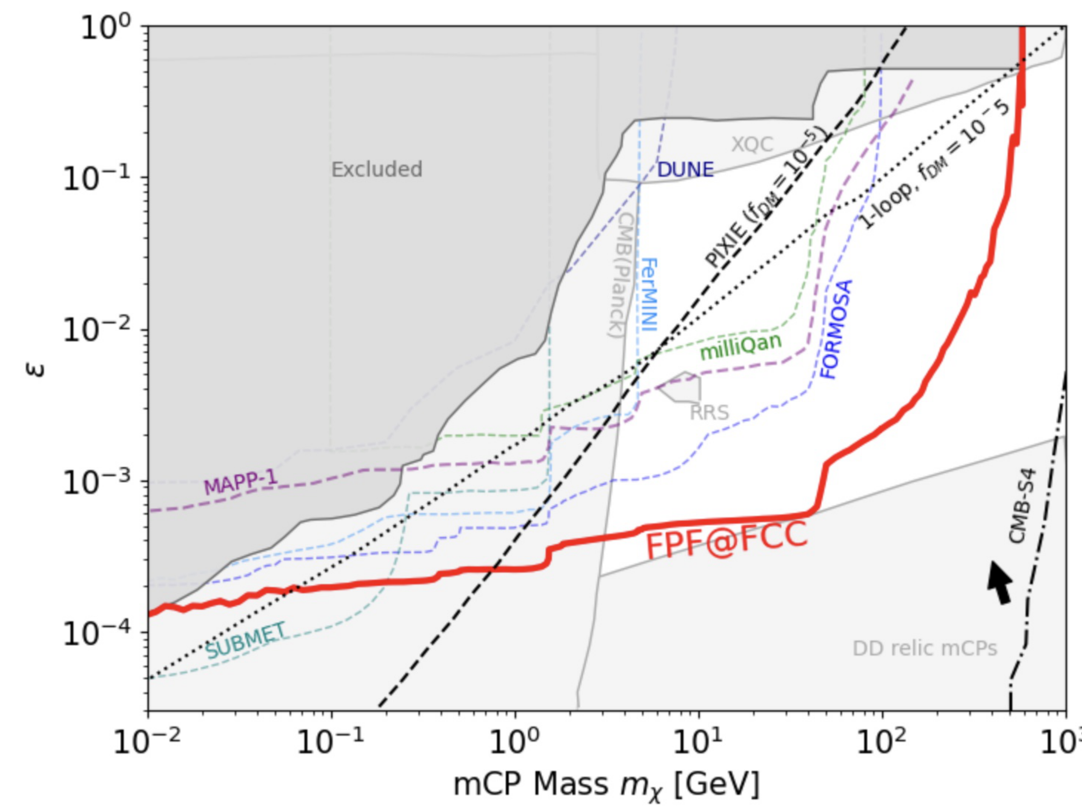


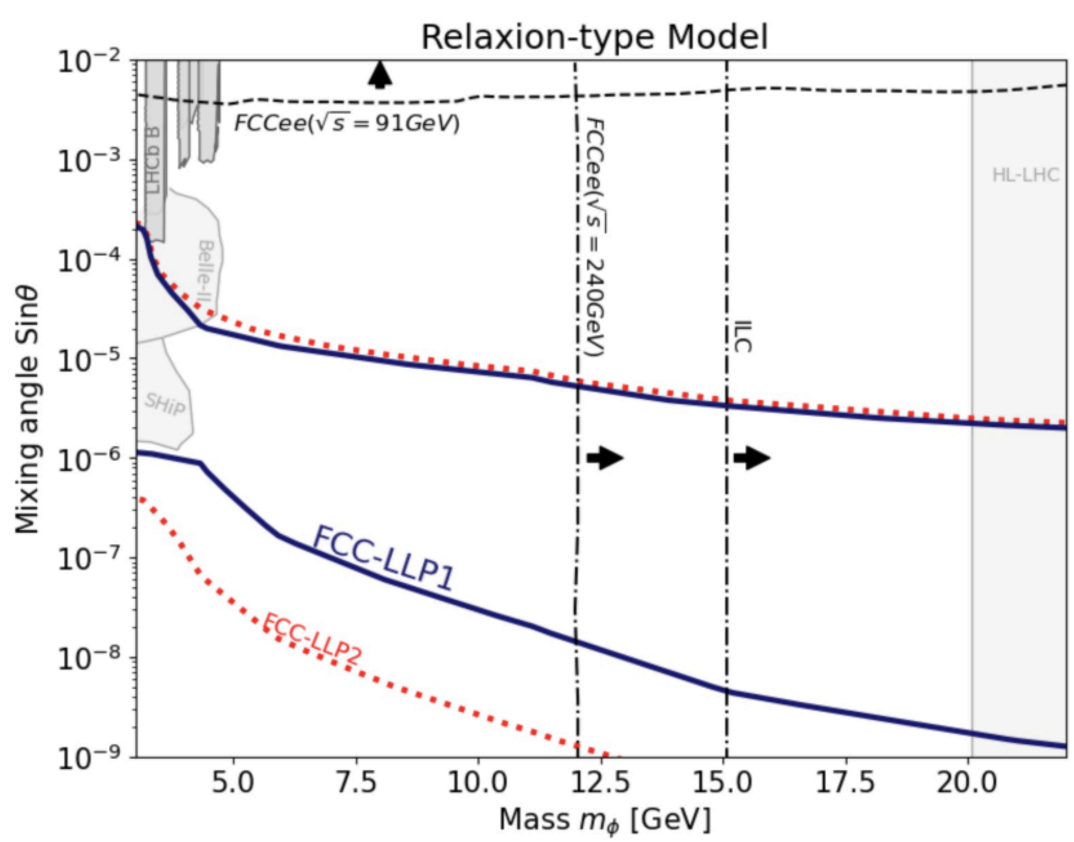


- First-ever neutrino DIS on polarised targets: pin down **proton spin decomposition**
- Up to **10^6 events** for COMPASS-like detector with FASERν2 geometry

BSM physics sensitivity

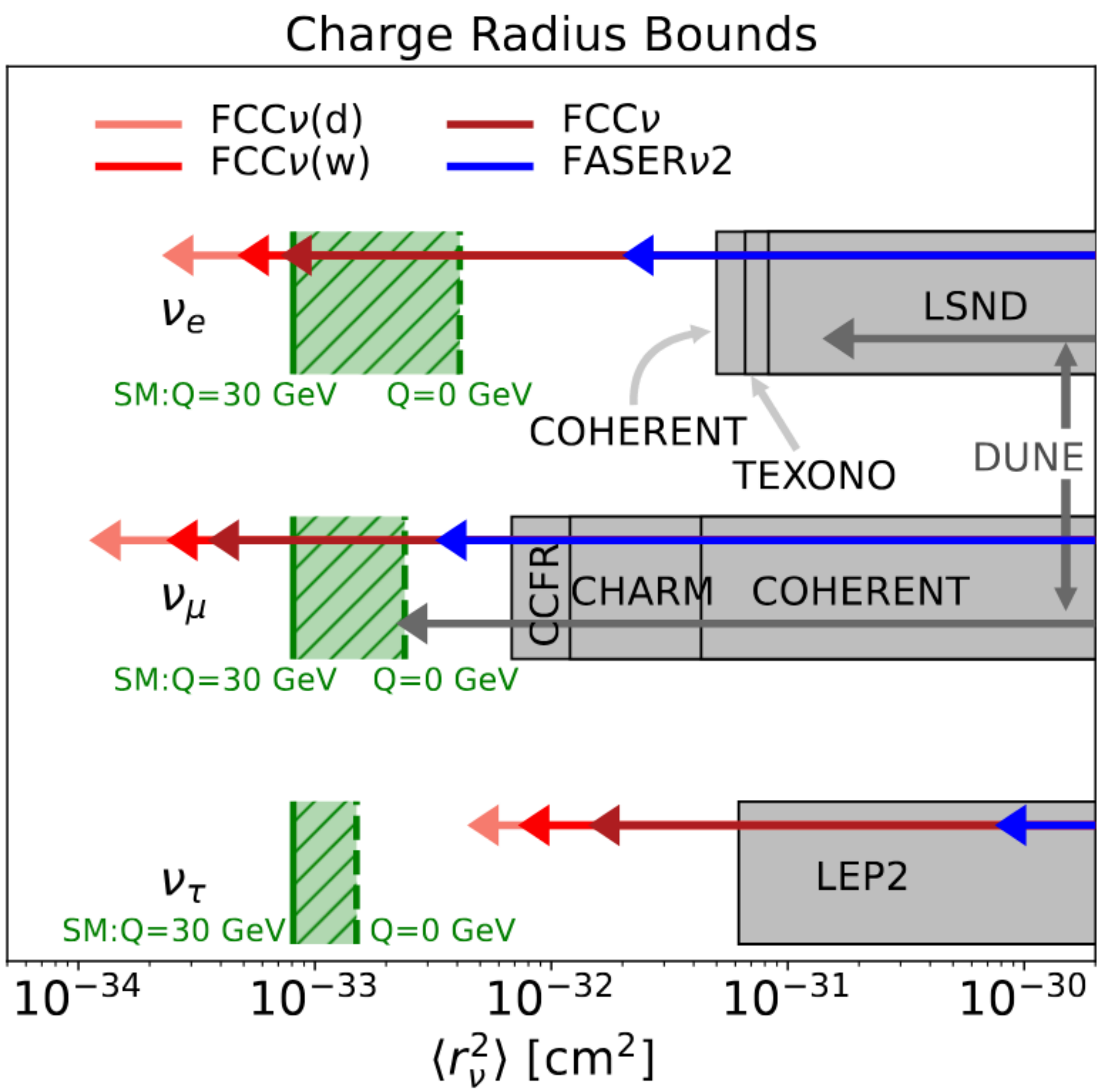


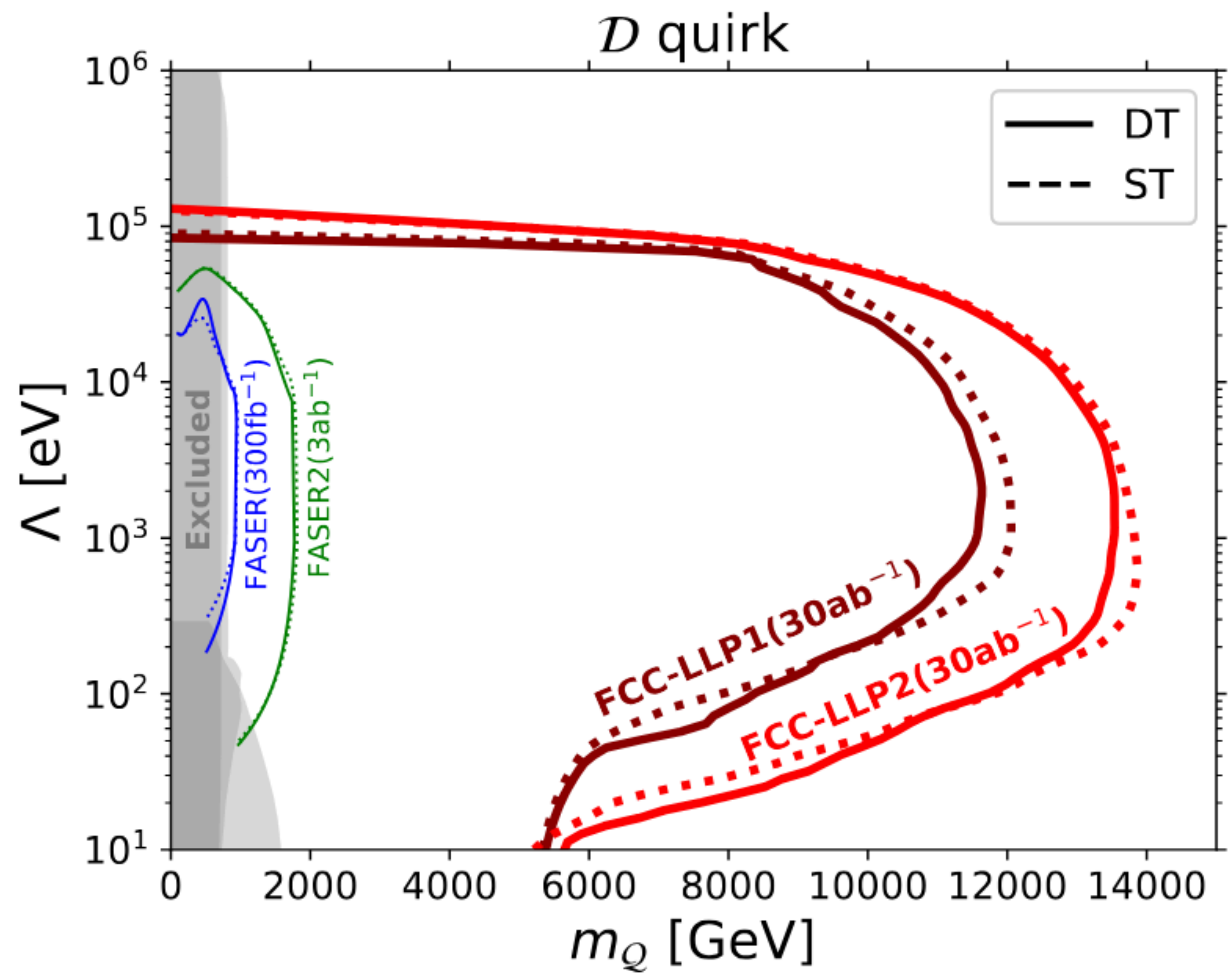




- **Dark Higgs bosons** produced from h→ϕϕ, thanks to enormous forward rate at 100 TeV
- Test **scalar portal to dark matter** far below the neutrino floor
- **Relaxion-type LLPs** sensitivity in low-mass region beyond reach of FCC-ee
- Close the gap **between accelerator and direct detection searches** for millicharged dark matter

BSM physics sensitivity





Measure for the first time **neutrino charge radius** and its flavour dependence

sterile neutrino oscillations, neutrino-philic new particles, neutrino **non-standard interactions**, …

Quirks: dark-sector particles charged under dark QCD, motivated by **neutral naturalness**

Discover Quirks **up to ~14 TeV** for a wide range of (dark) confinement scales Λ

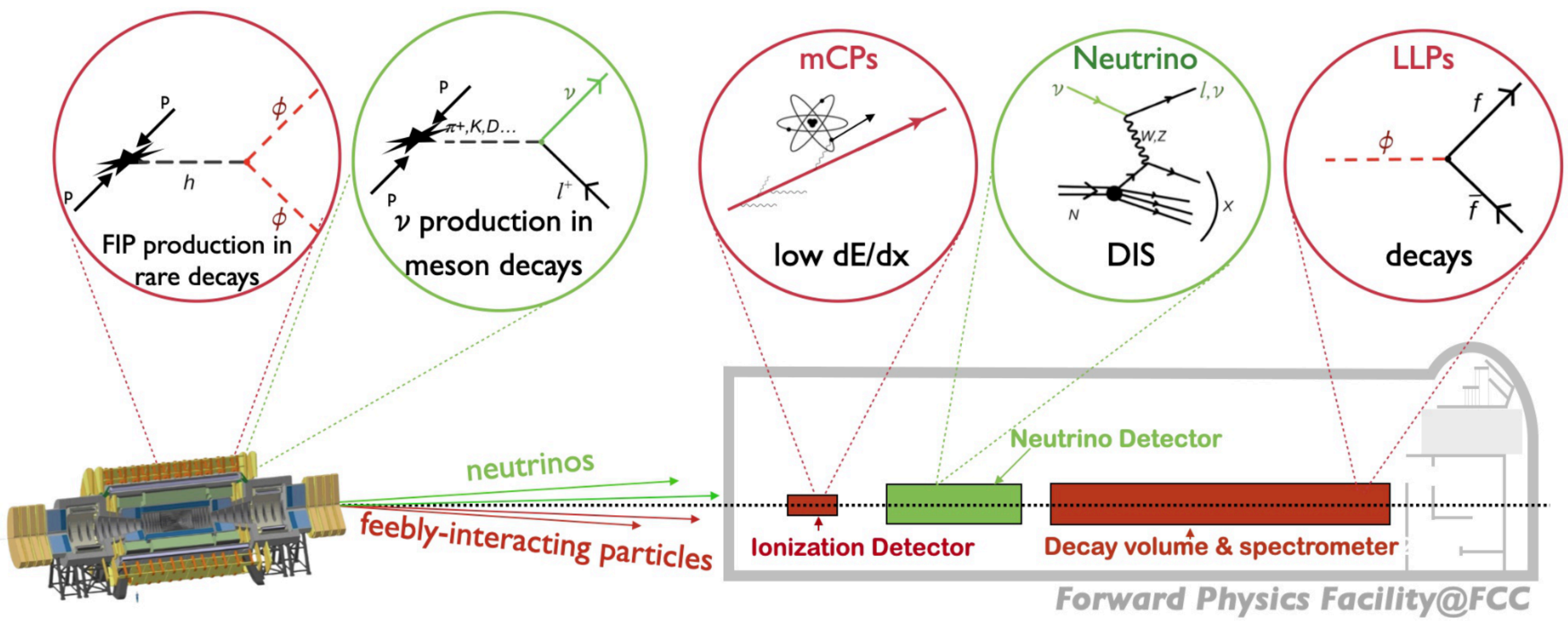
Summary and outlook

- FPF@FCC would have a rich program in **QCD physics, neutrino properties, and BSM sensitivity** (e.g. discovering LLPs up to $m \sim 50$ GeV GeV, quirks up to $m \sim 10$ TeV

- Would be built with **minimal interference** with the FCC-hh construction and operation

- Technology-agnostic study, but several successful detector realisations available

An FPF-like suite of experiments **integrated in the FCC-hh** offers unique, cost-effective physics opportunities that markedly extend its science portfolio



Additional motivation to **realise the FPF at the HL-LHC** as an **essential precedent** to optimise forward physics experiments enabling the FCC to fully achieve its physics potential