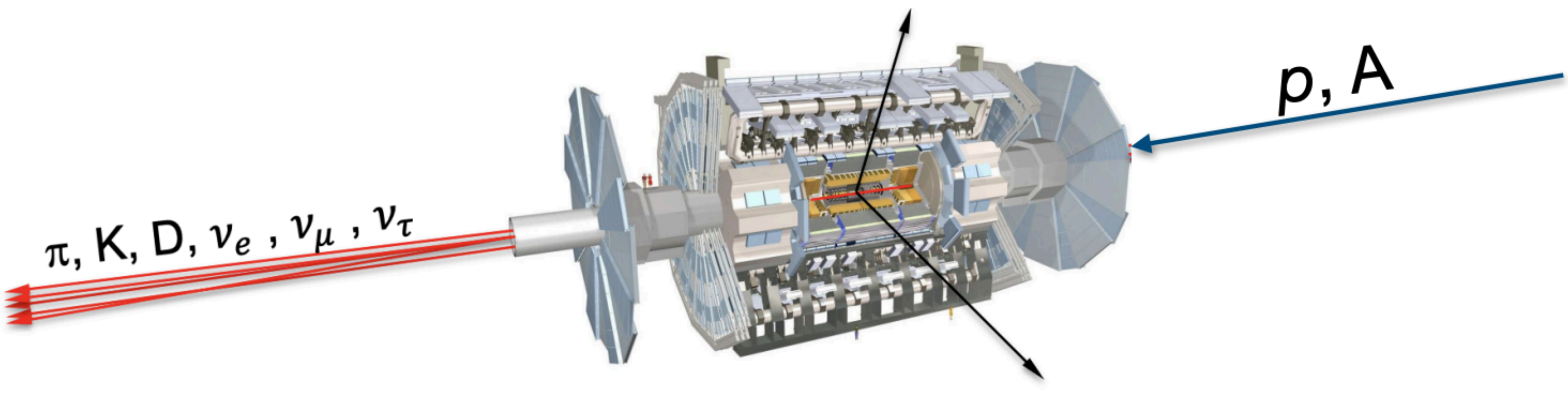
TeV Neutrino Physics & Light BSM Searches at the LHC Far-Forward Detectors

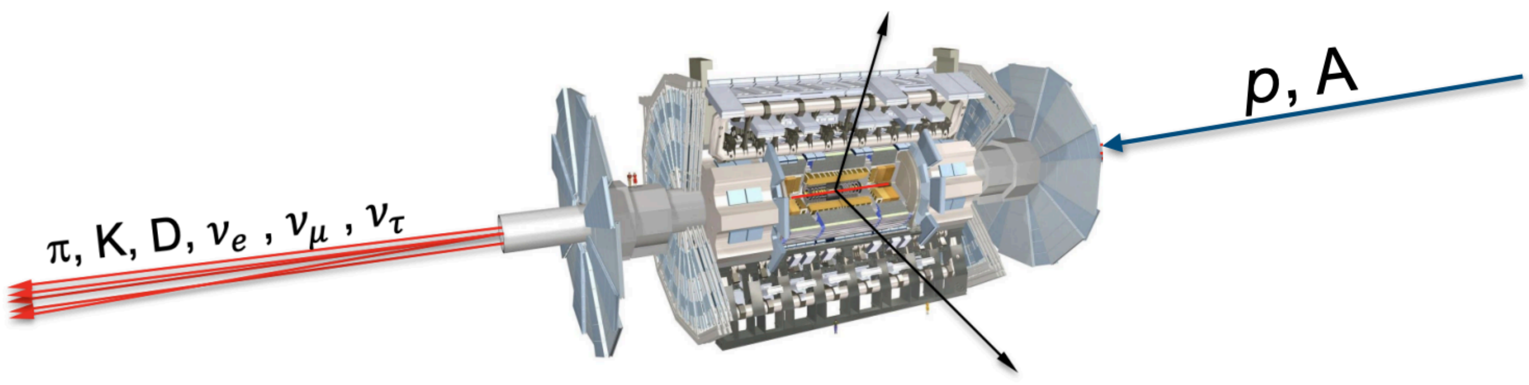
Lydia Brenner & Juan Rojo



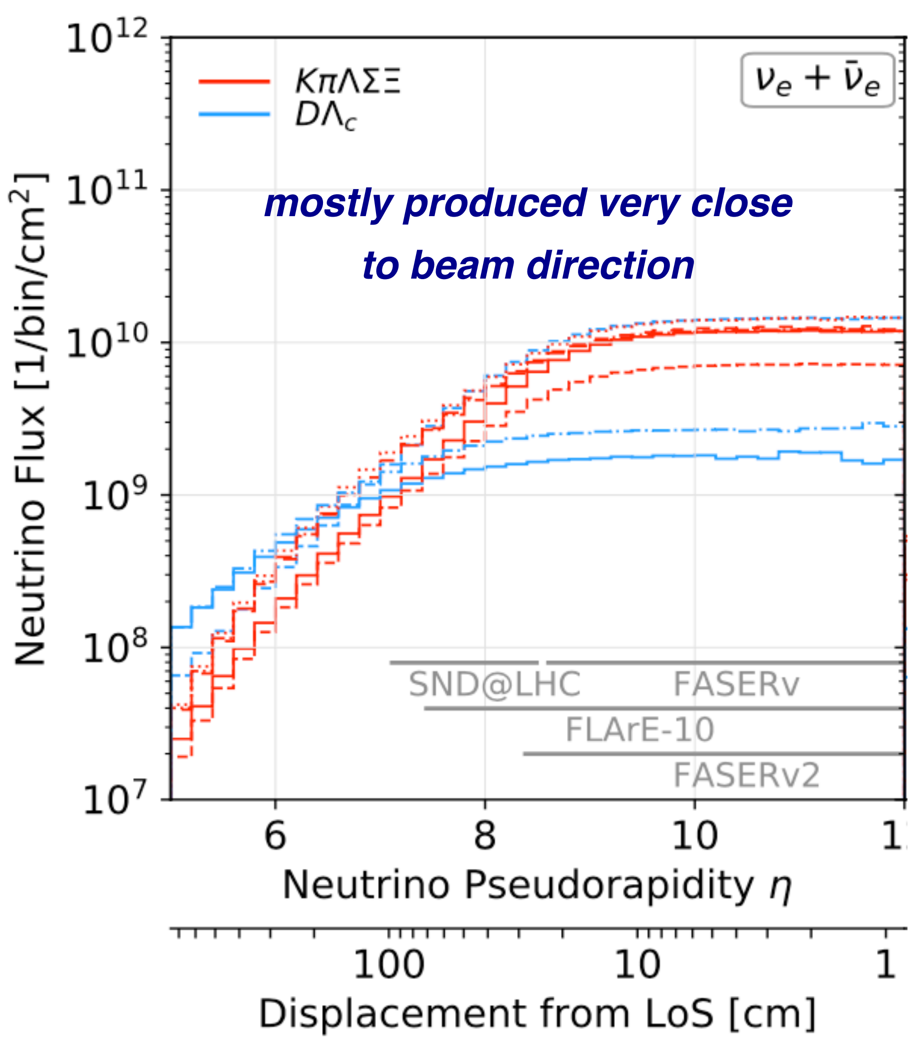
ESPPU-NL Diversity Meeting

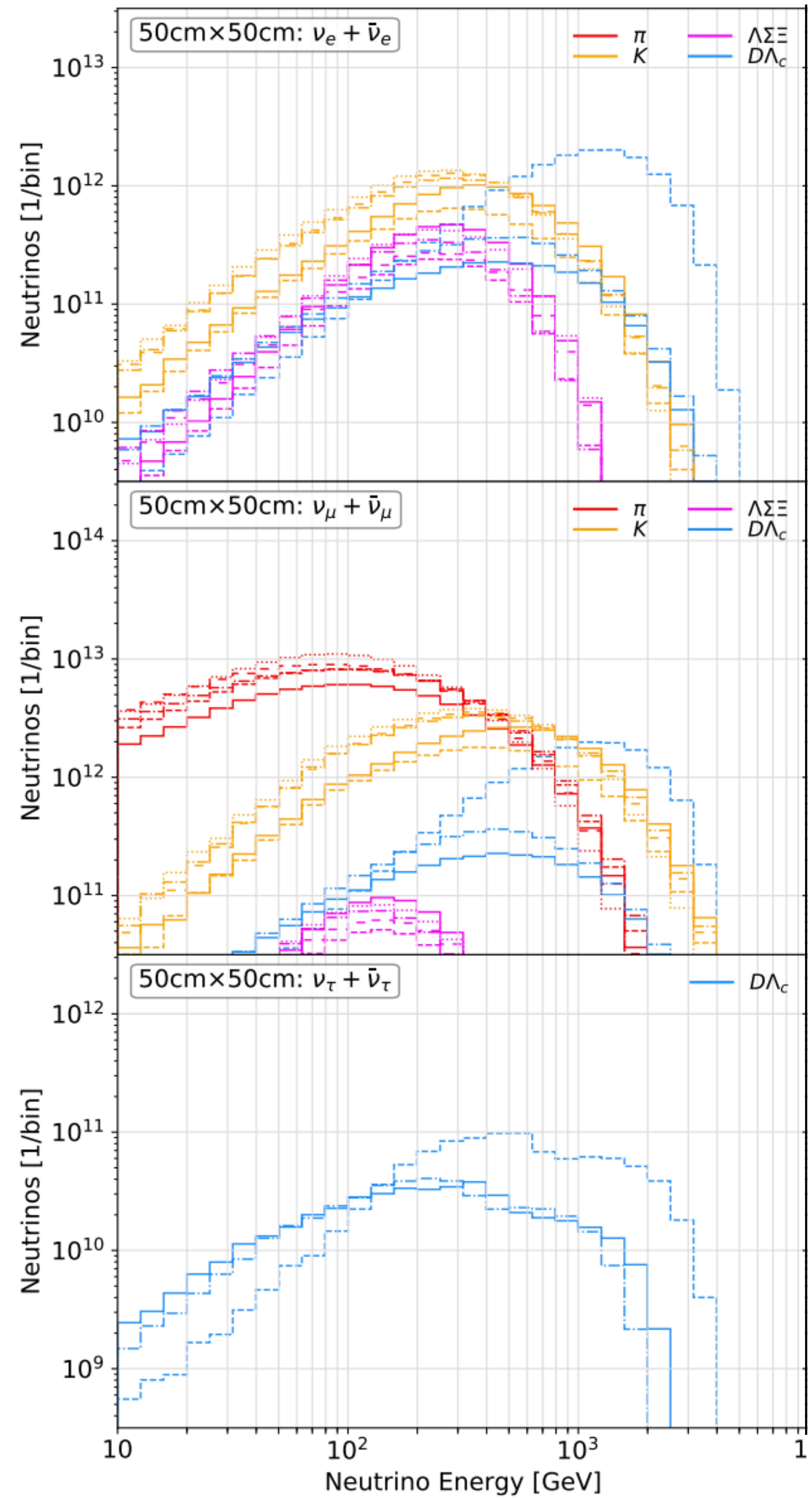
Nikhef, January 13th 2025

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 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

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

Editors' Suggestion

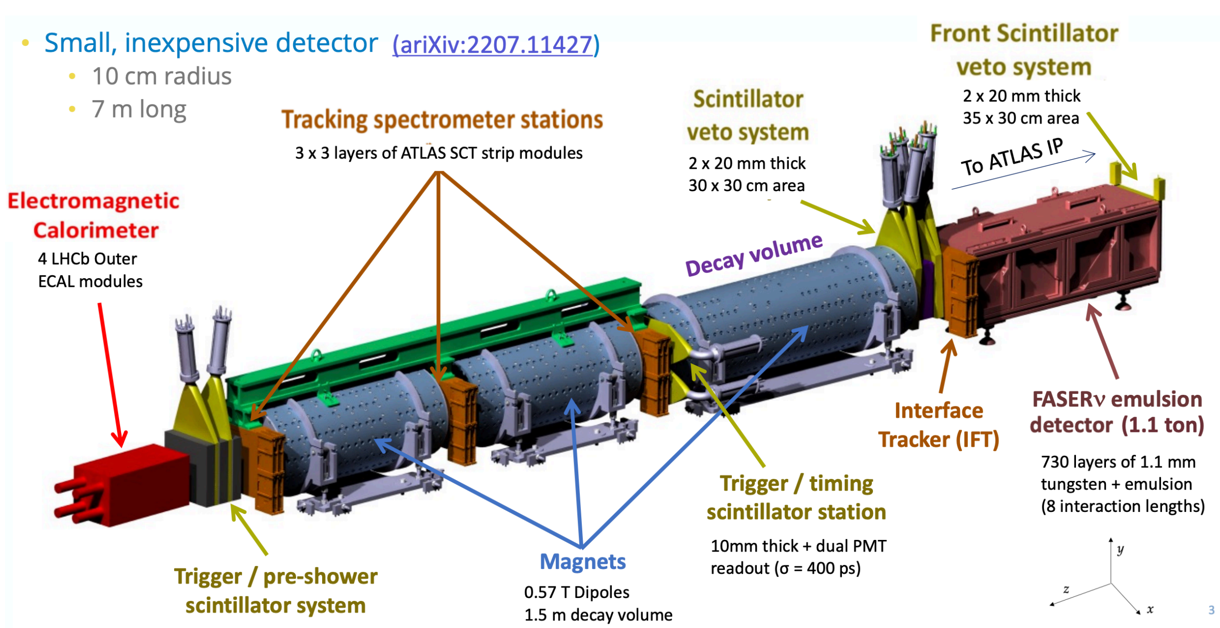
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

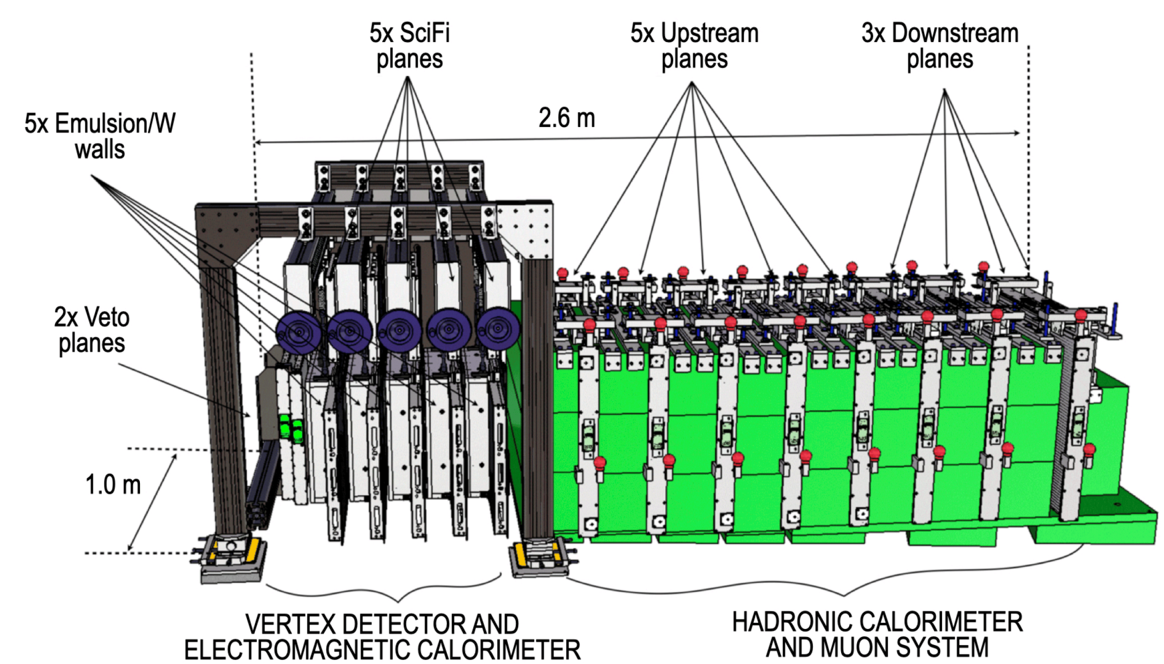
We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on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

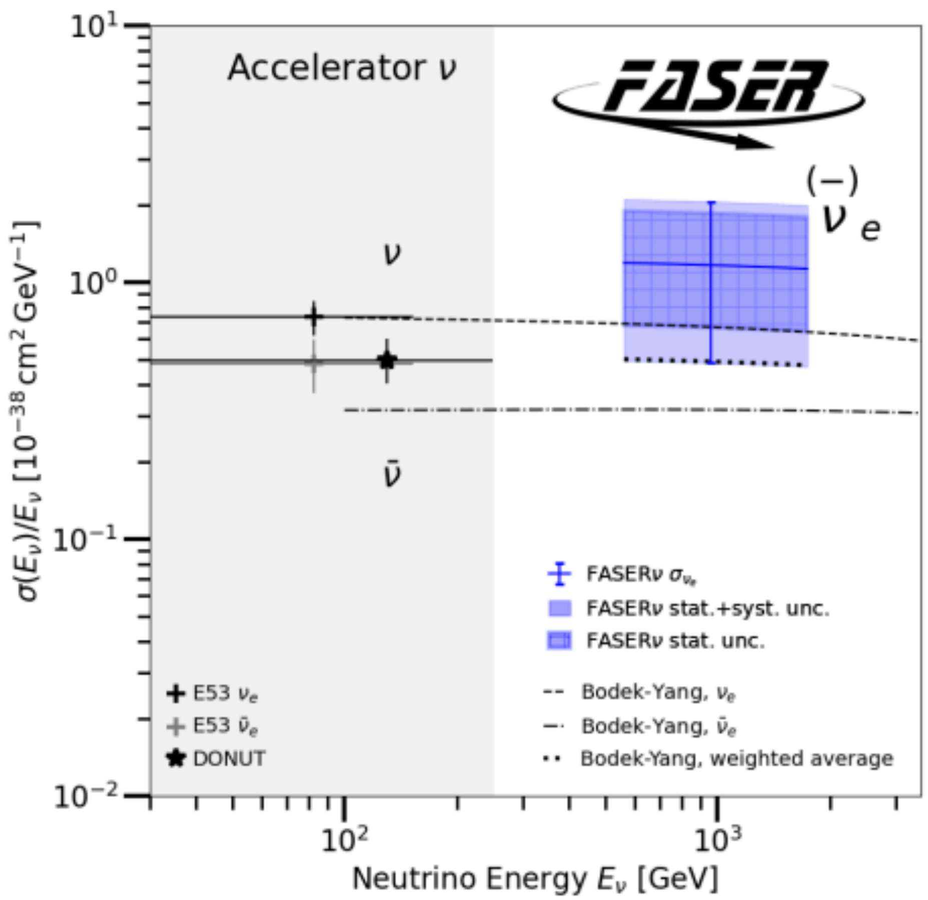
8 neutrinos detected, 4 expected

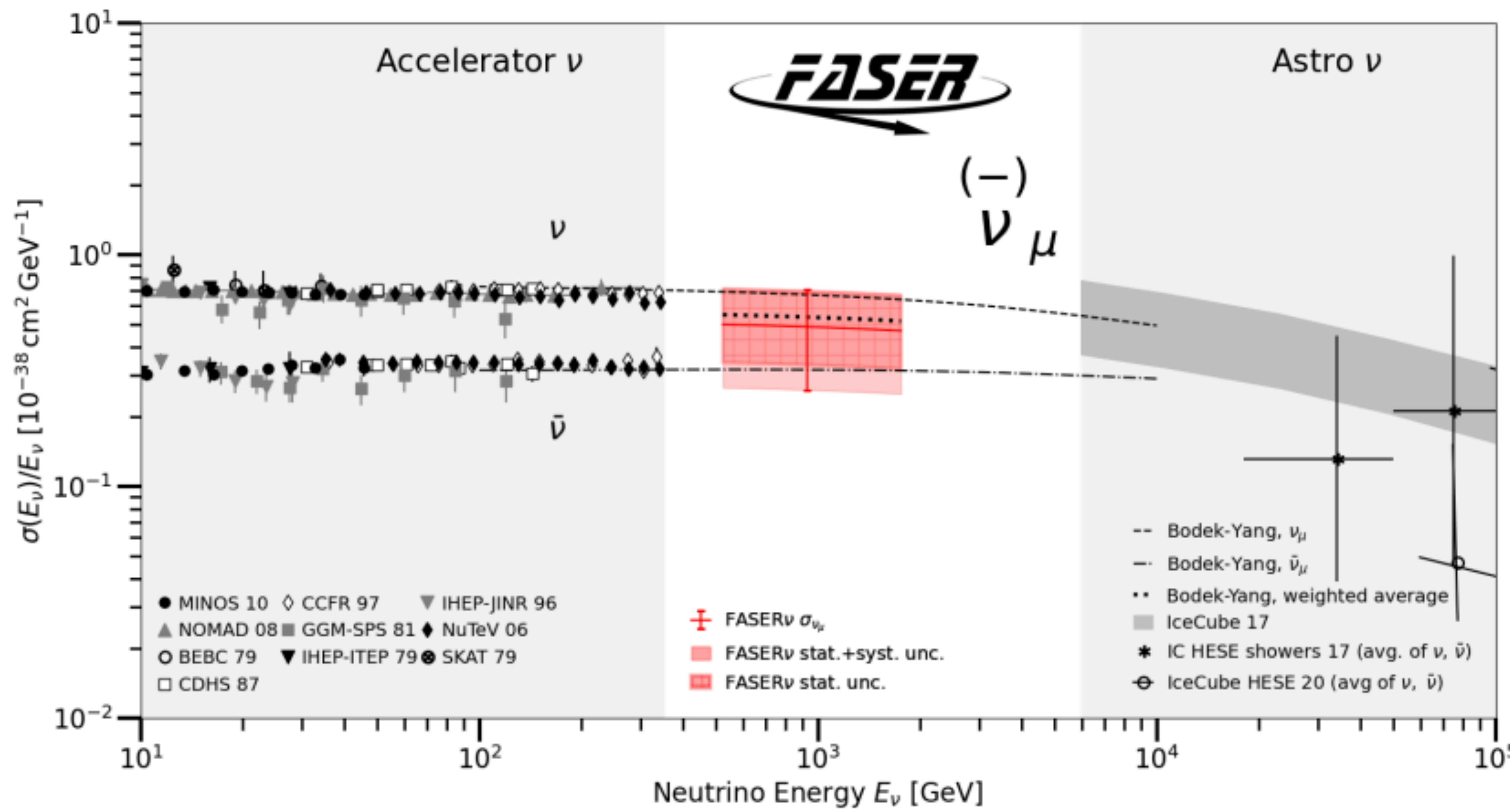


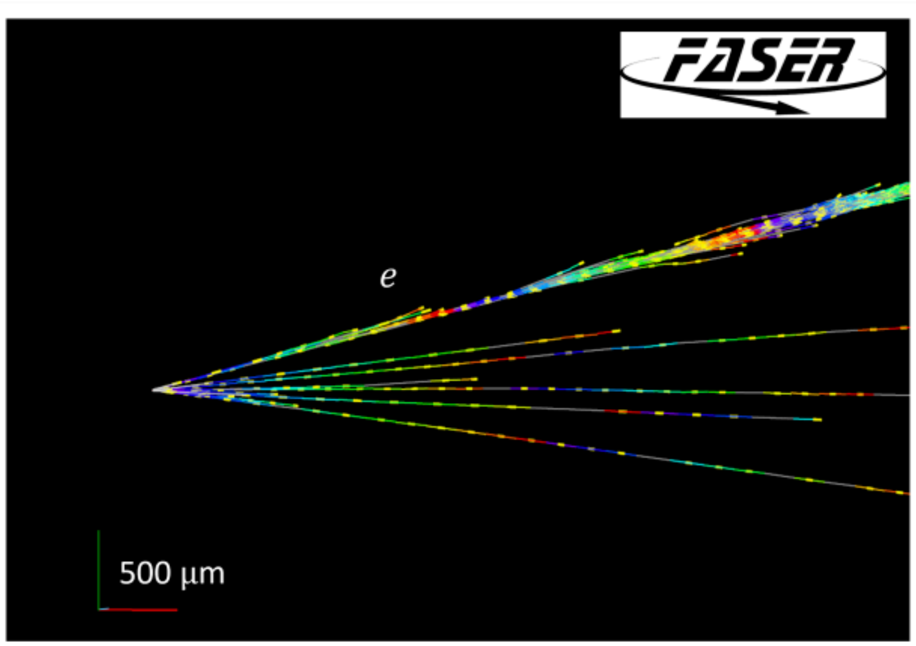


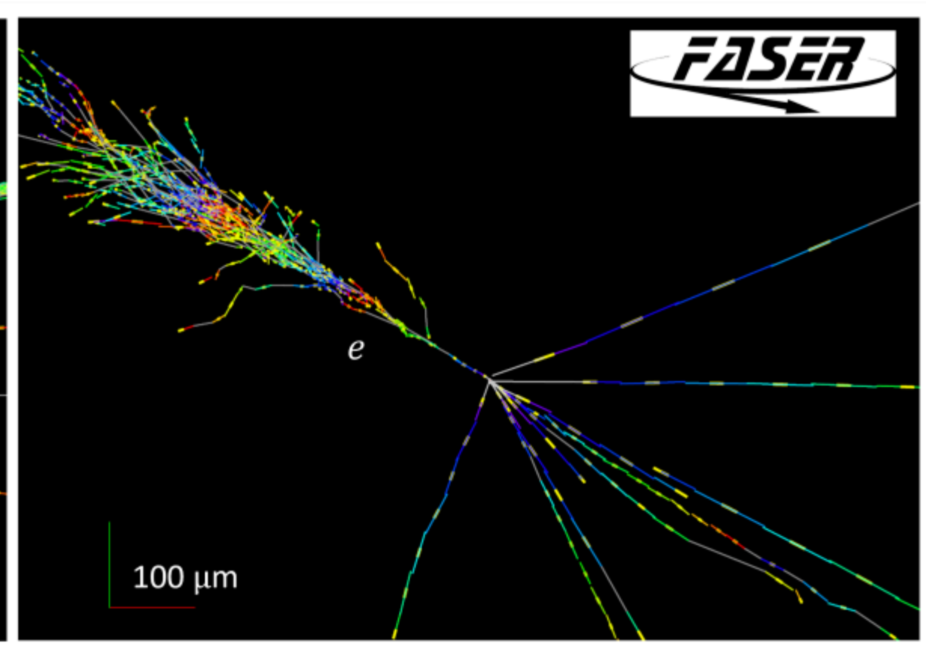
The dawn of the LHC neutrino era

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





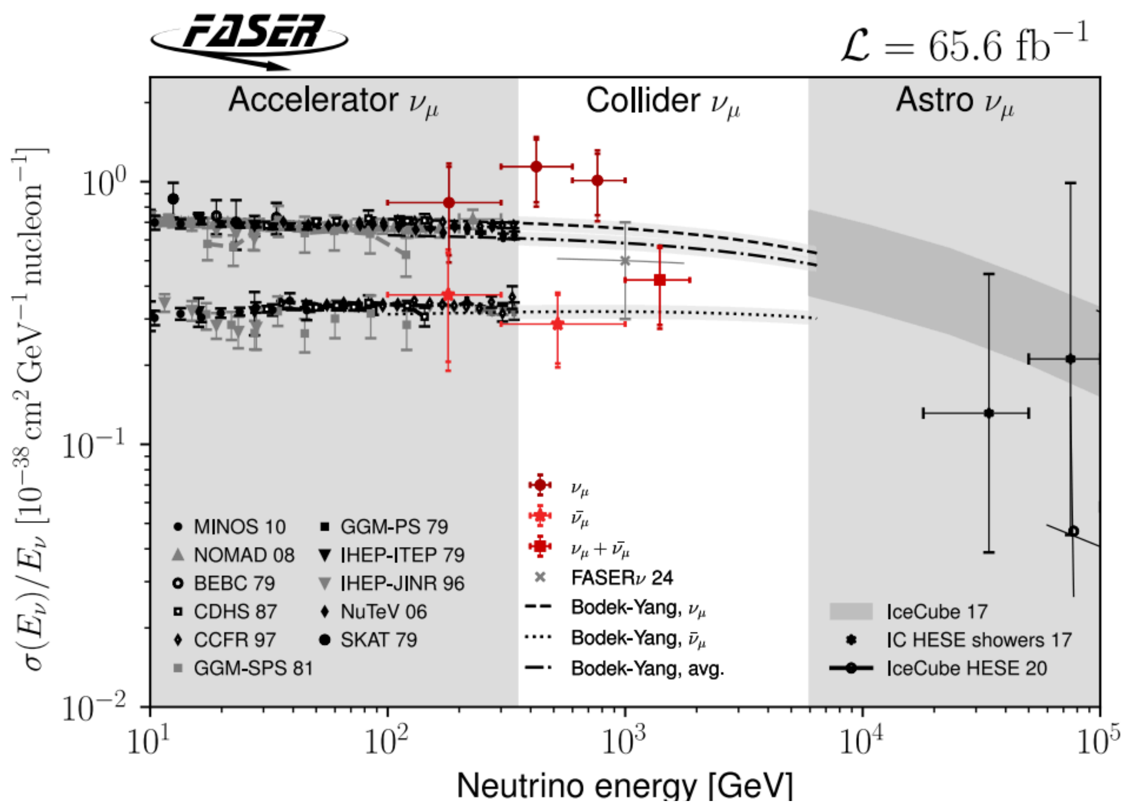


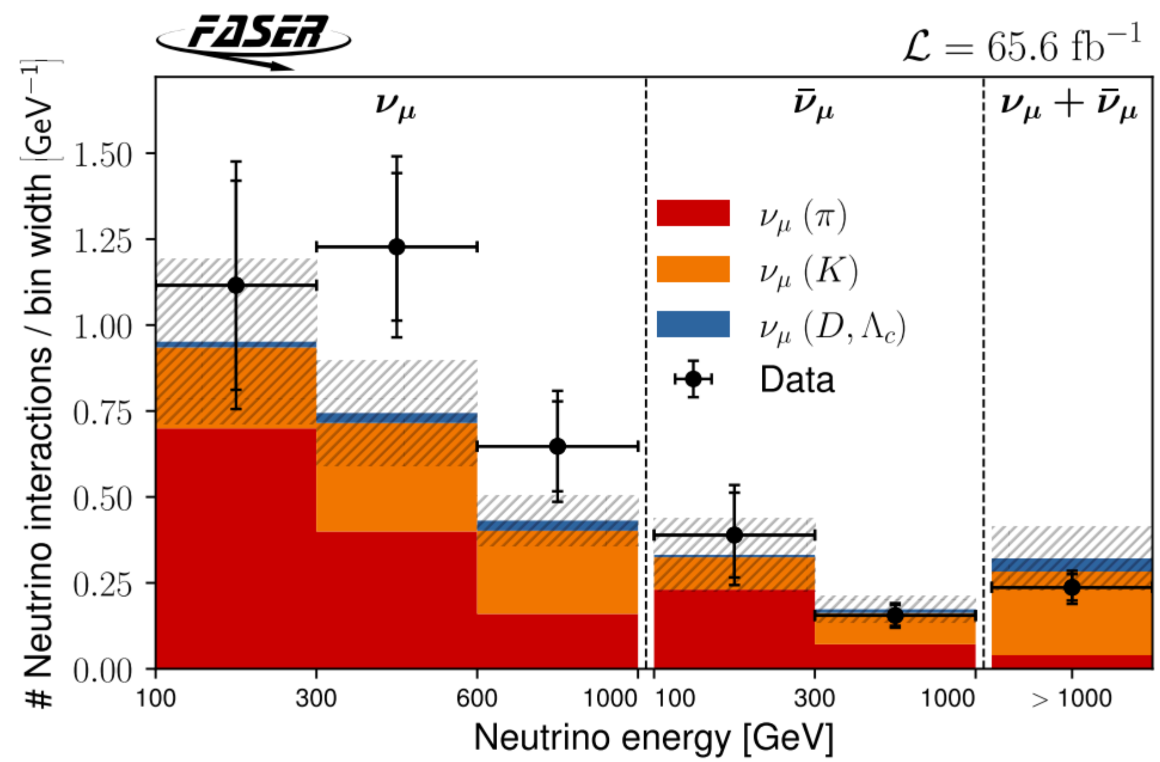


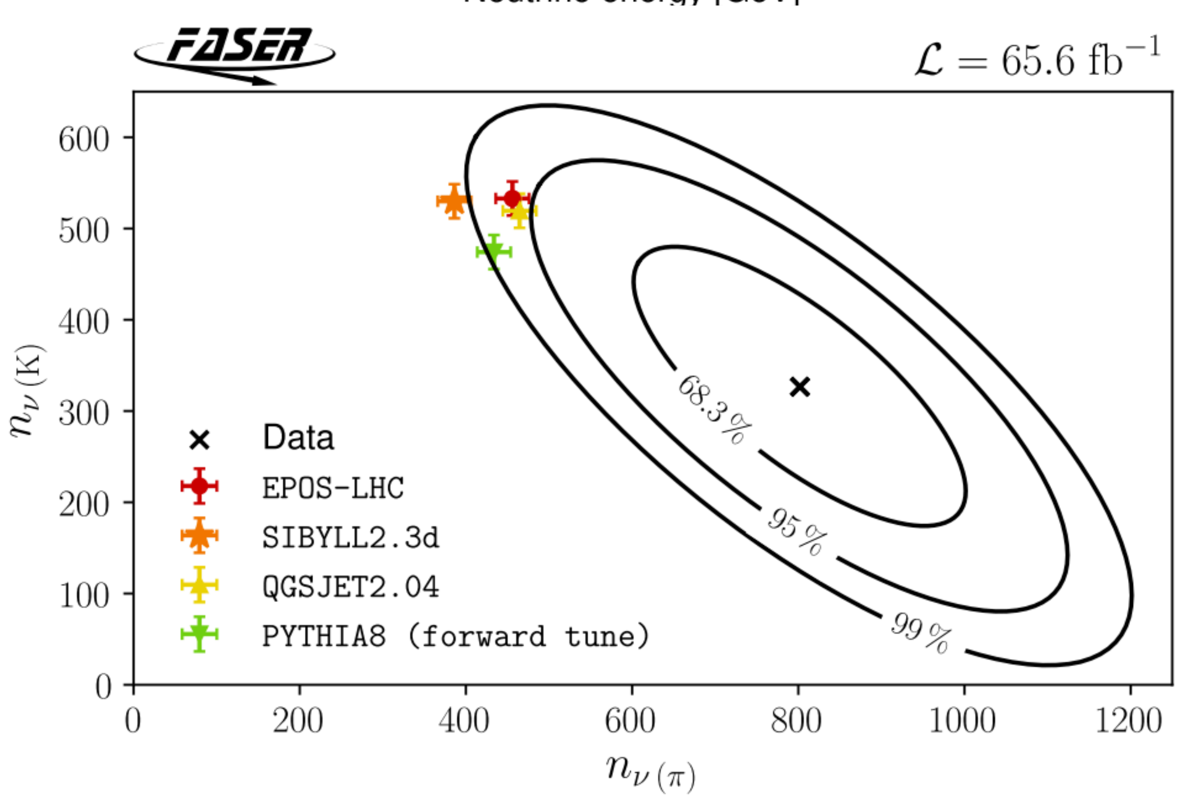
FASER's emulsion detector (FASERν) has excellent particle ID and spatial resolution

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



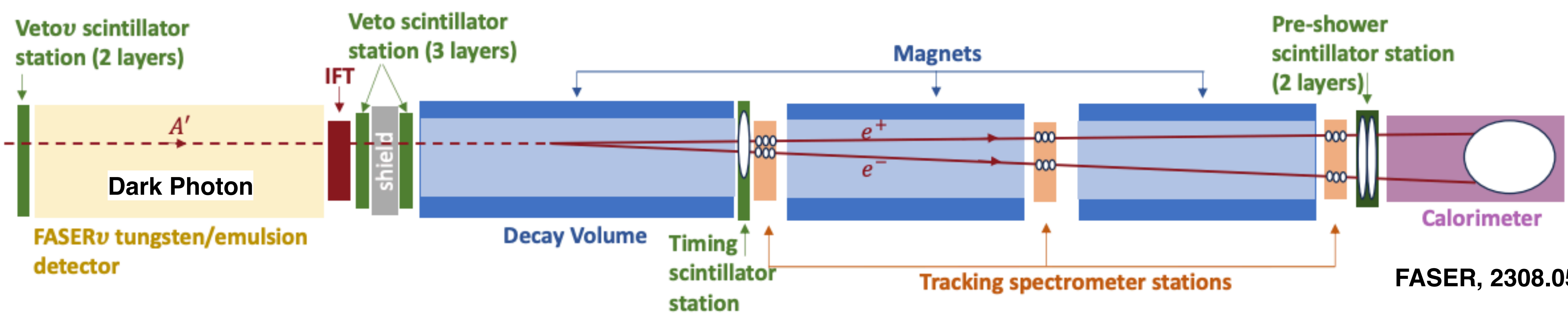




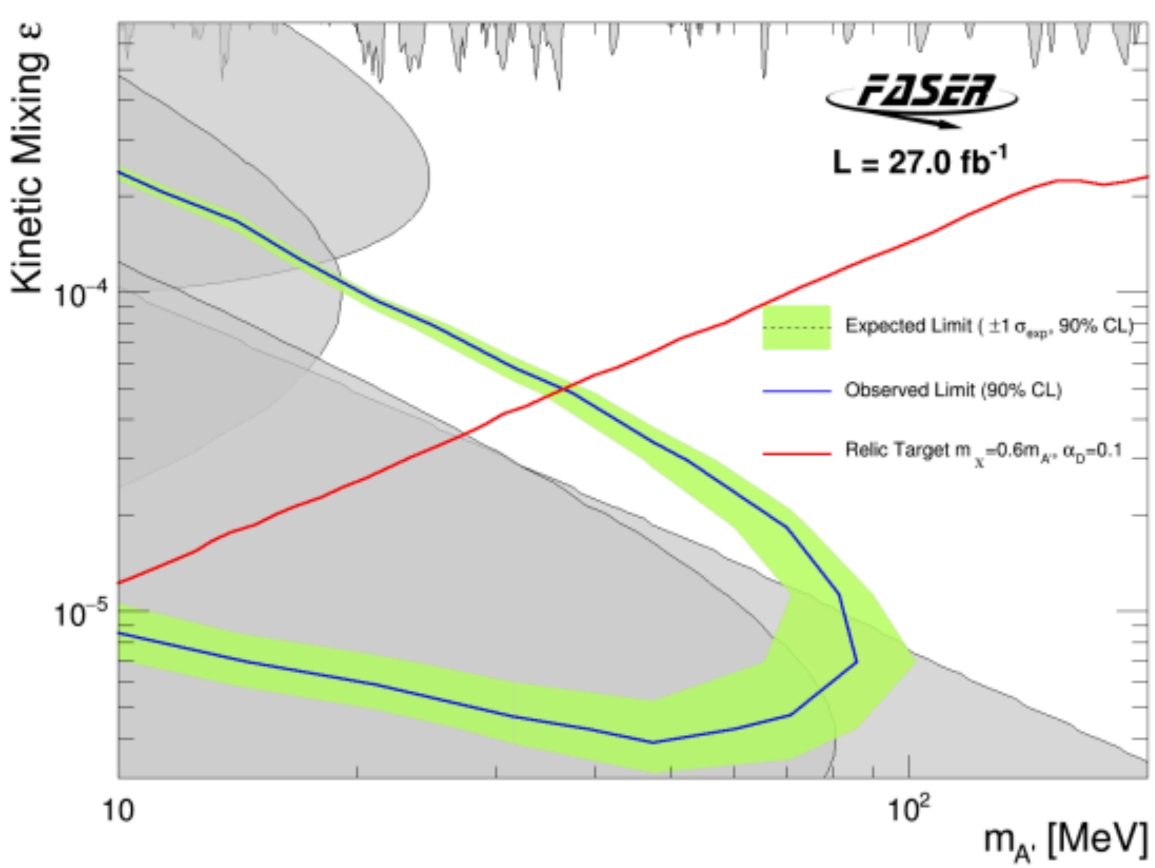
- Constrain **neutrino interactions in the TeV region** and their flavour dependence
- Validate models of forward pion and kaon production relevant for **cosmic ray physics** (muon puzzle)
- Enable dedicated tunes of **forward physics** in hadronic collisions

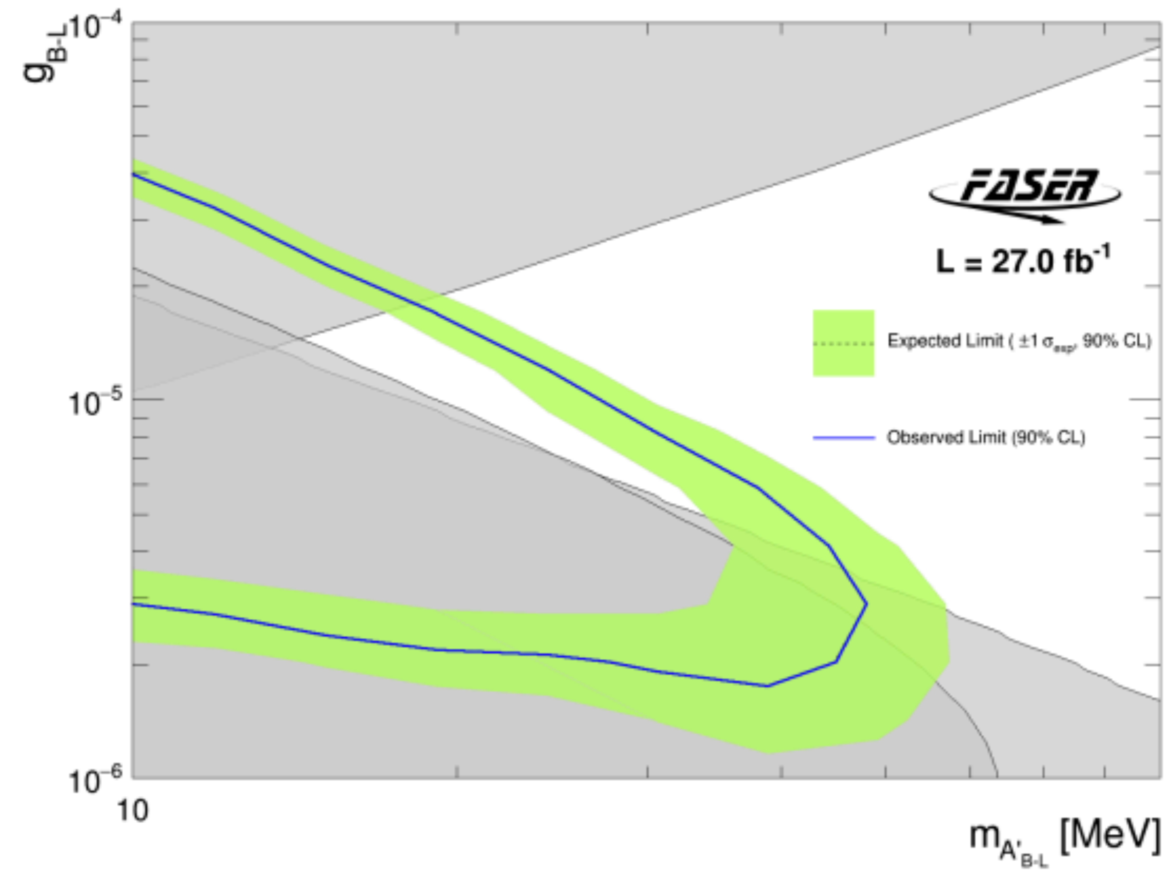
Light BSM Searches at FASER

- 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

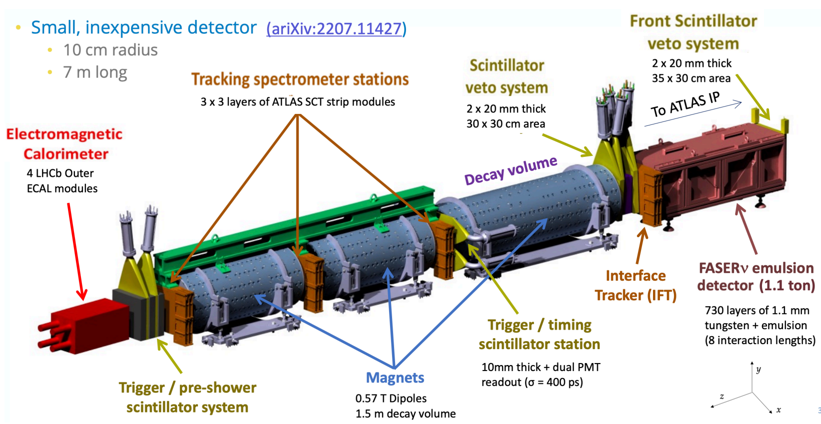




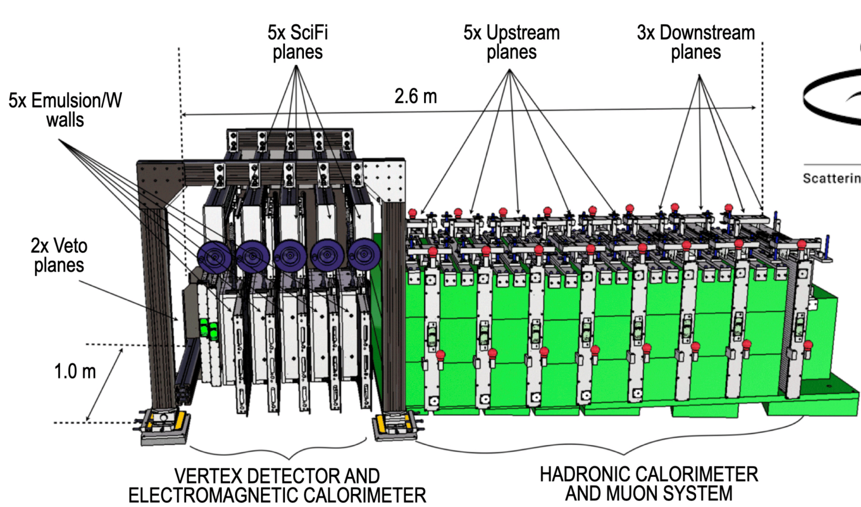
Unique blend of guaranteed deliverables and exploration potential

Neutrinos at the LHC

FASER



2022-2026 (Run-3)



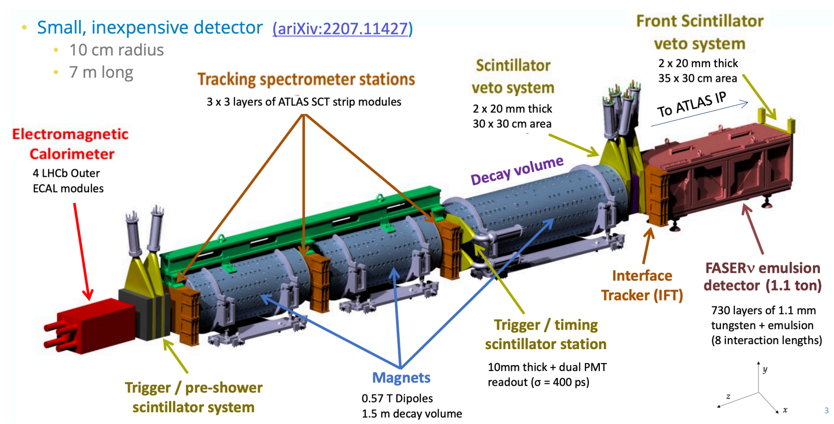
LHC

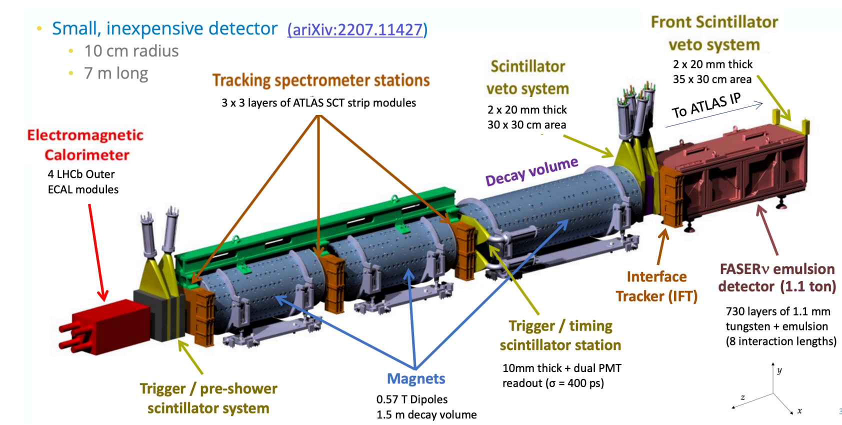
Scattering and Neutrino Detector at the LHC

Neutrinos at the LHC

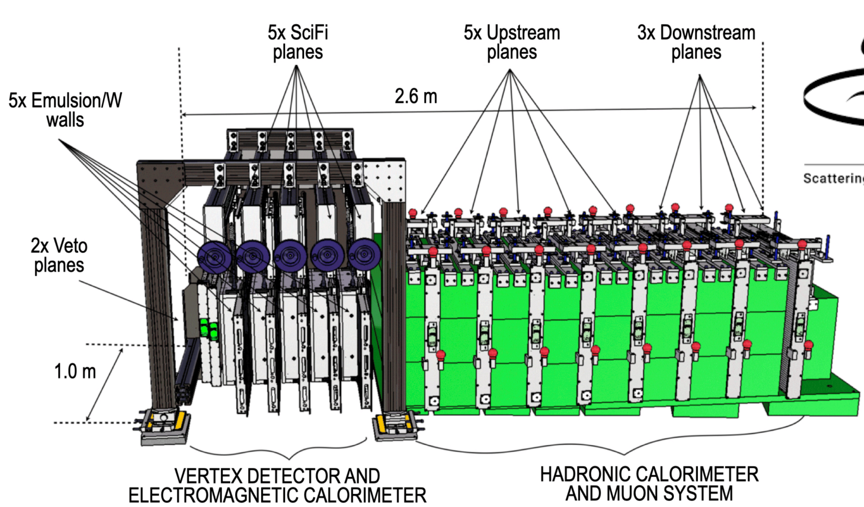
FASER @ HL-LHC

(approved, new ν detectors under discussion)





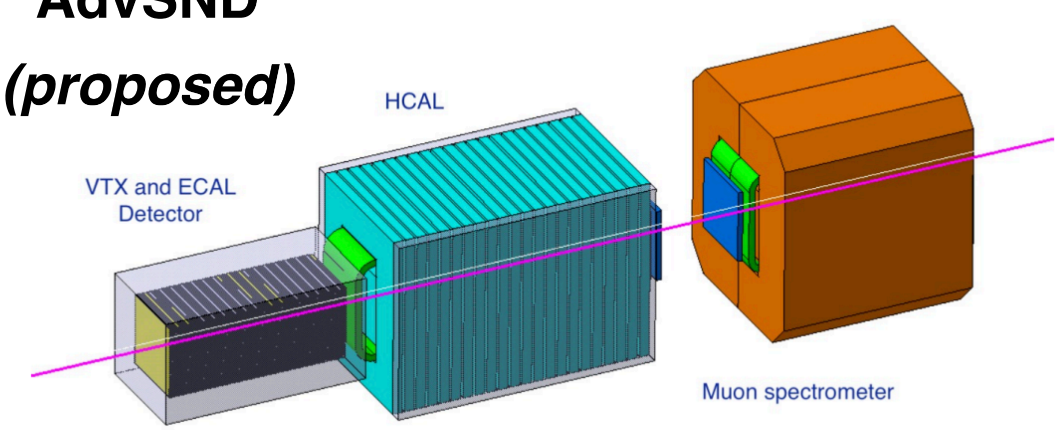
2022-2026 (Run-3) **2027-2029 (LS3)** **> 2030 (overlap with HL-LHC)**



LHC
Scattering and Neutrino Detector at the LHC

AdvSND

(proposed)

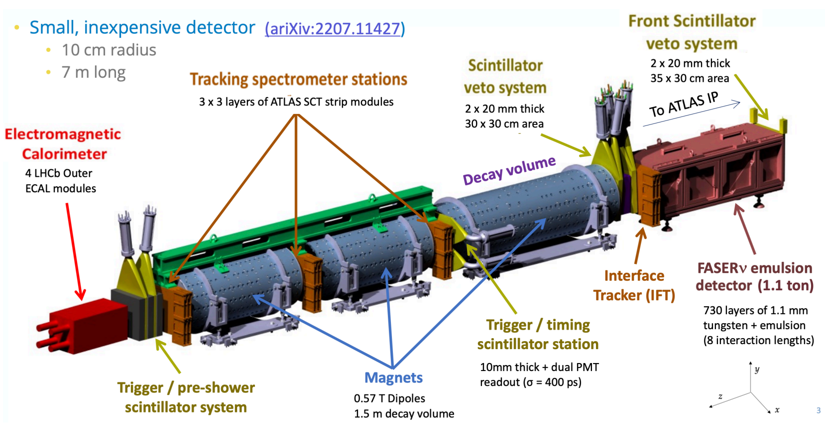


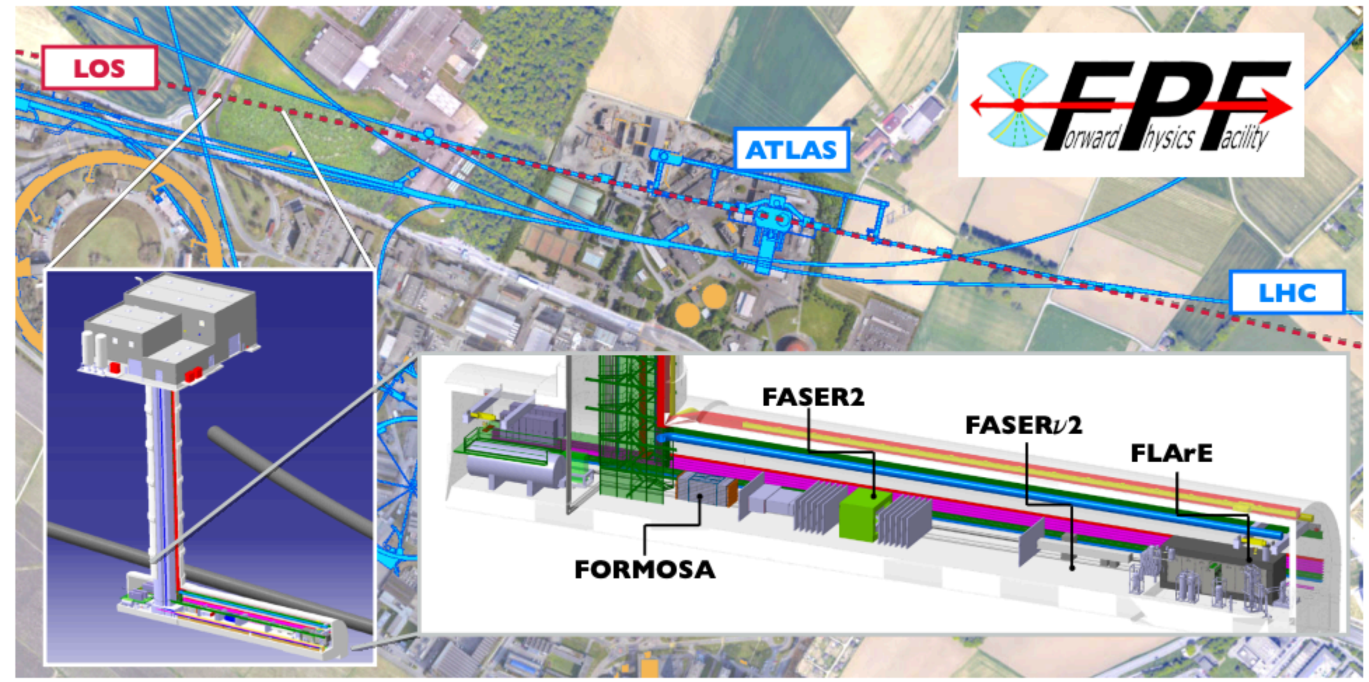
Neutrinos at the LHC

Forward Physics Facility (FPF)

(Proposed)

FASER





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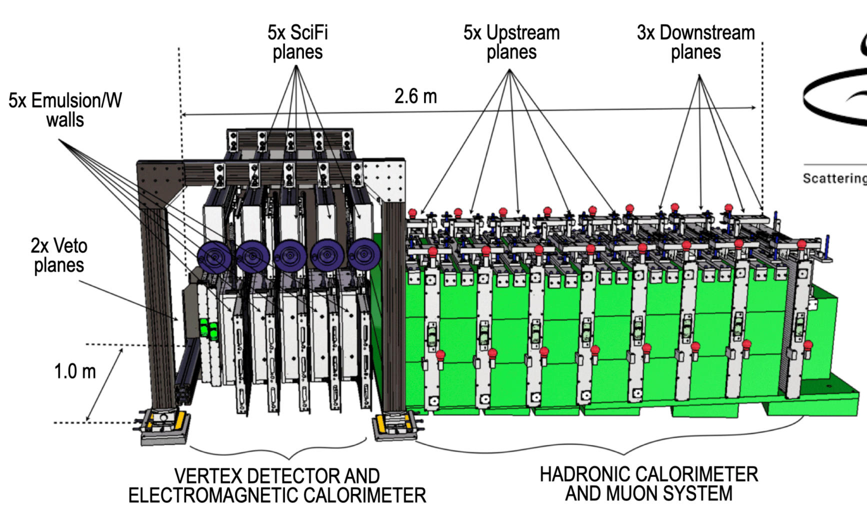

SND LHC
Scattering and Neutrino Detector at the LHC

- 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**

FPF & FASER-Run4: the Physics Case

While here we focus on FPF projections, most physics targets also accessible at FASER@Run-4 (albeit with lower statistics)

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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

SCIENCE AND PROJECT PLANNING FOR THE FORWARD PHYSICS FACILITY IN PREPARATION FOR THE 2024–2026 EUROPEAN PARTICLE PHYSICS STRATEGY UPDATE

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on behalf of the FPF Working Groups

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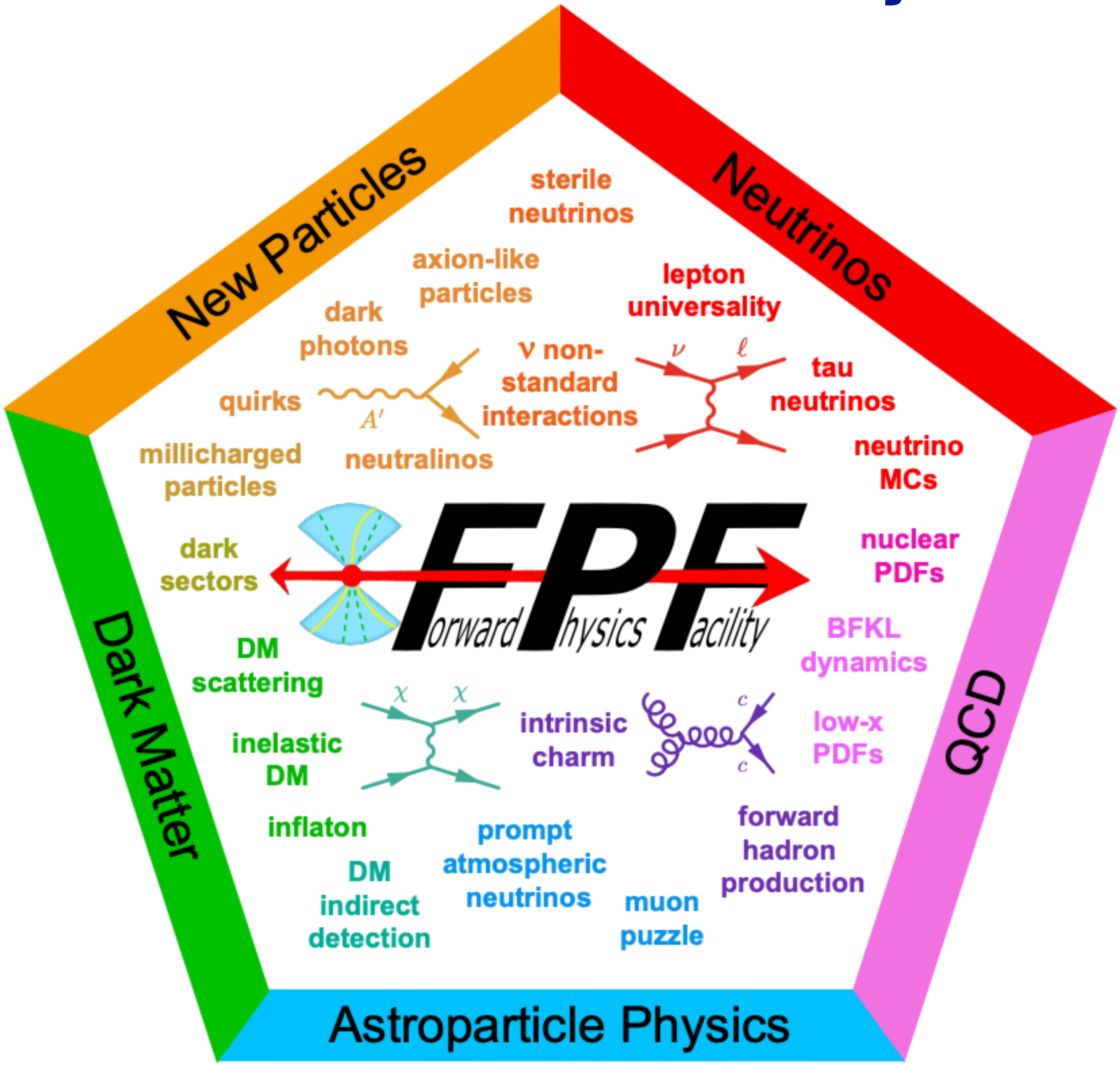
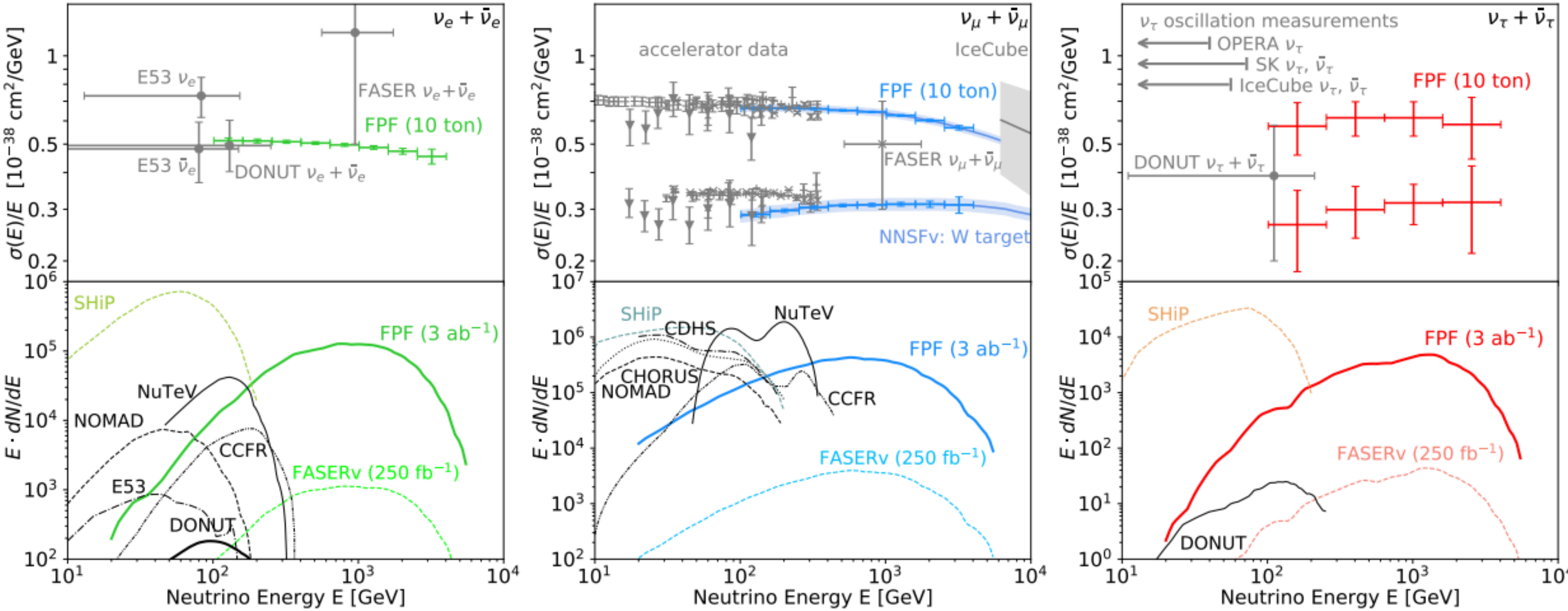
The recent direct detection of neutrinos at the LHC has opened a new window on high-energy particle physics and highlighted the potential of forward physics for groundbreaking discoveries. In the last year, the physics case for forward physics has continued to grow, and there has been extensive work on defining the Forward Physics Facility and its experiments to realize this physics potential in a timely and cost-effective manner. Following a 2-page Executive Summary, we present the status of the FPF, beginning with the FPF's unique potential to shed light on dark matter, new particles, neutrino physics, QCD, and astroparticle physics. We summarize the current designs for the Facility and its experiments, FASER2, FASERν2, FORMOSA, and FLArE, and conclude by discussing international partnerships and organization, and the FPF's schedule, budget, and technical coordination.

FPF & FASER-Run4: the Physics Case

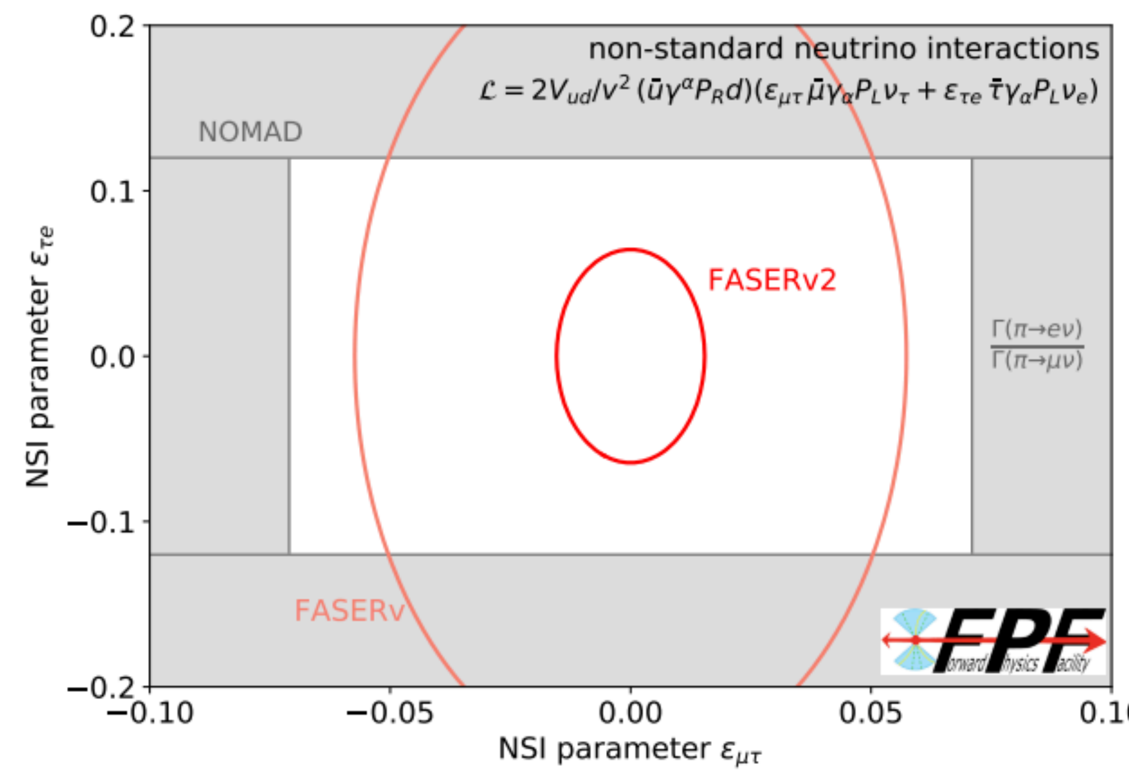


Impact on Neutrino Physics

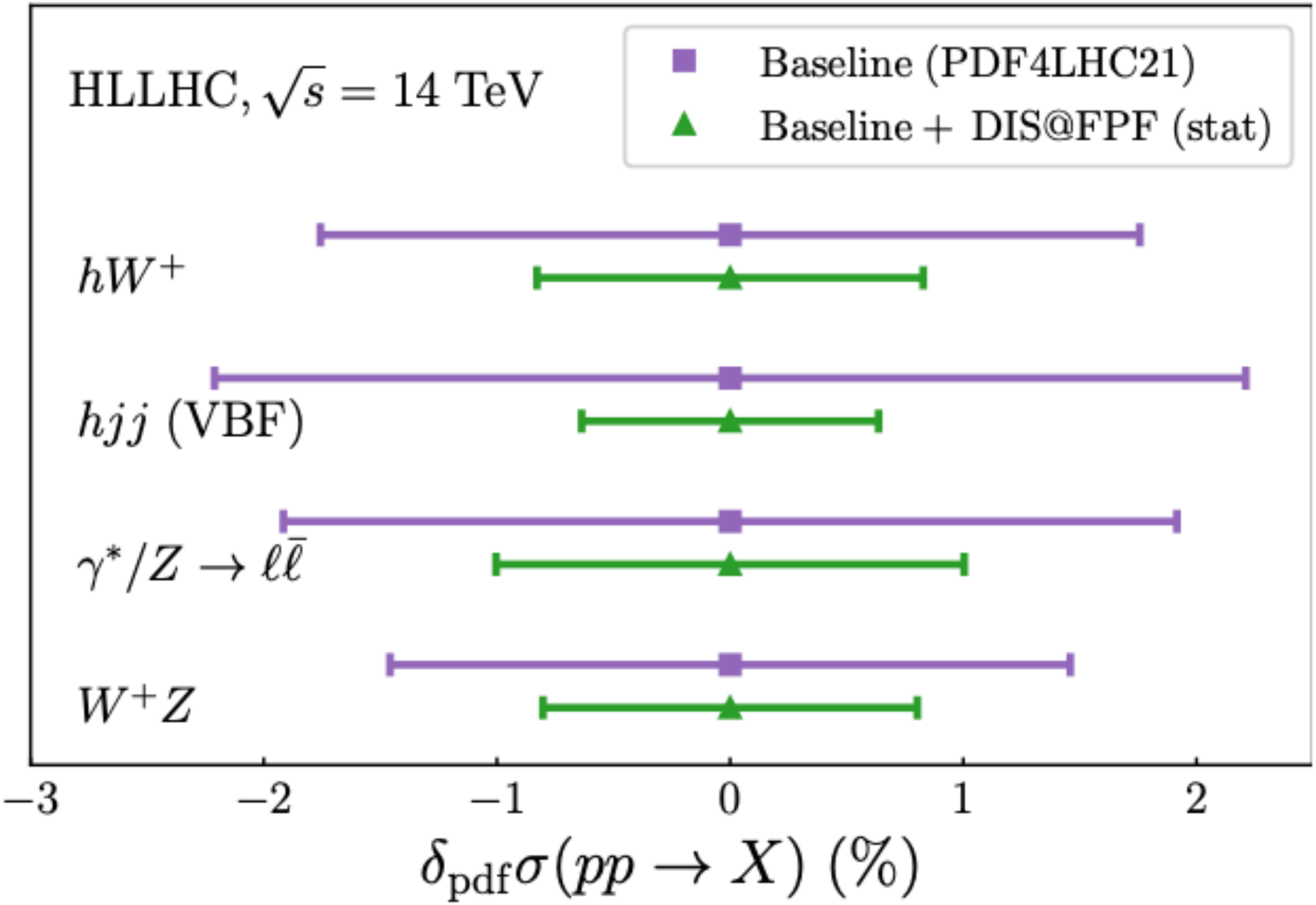


unique coverage of **TeV energy region**, high-statistics for **all three neutrino flavours**

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



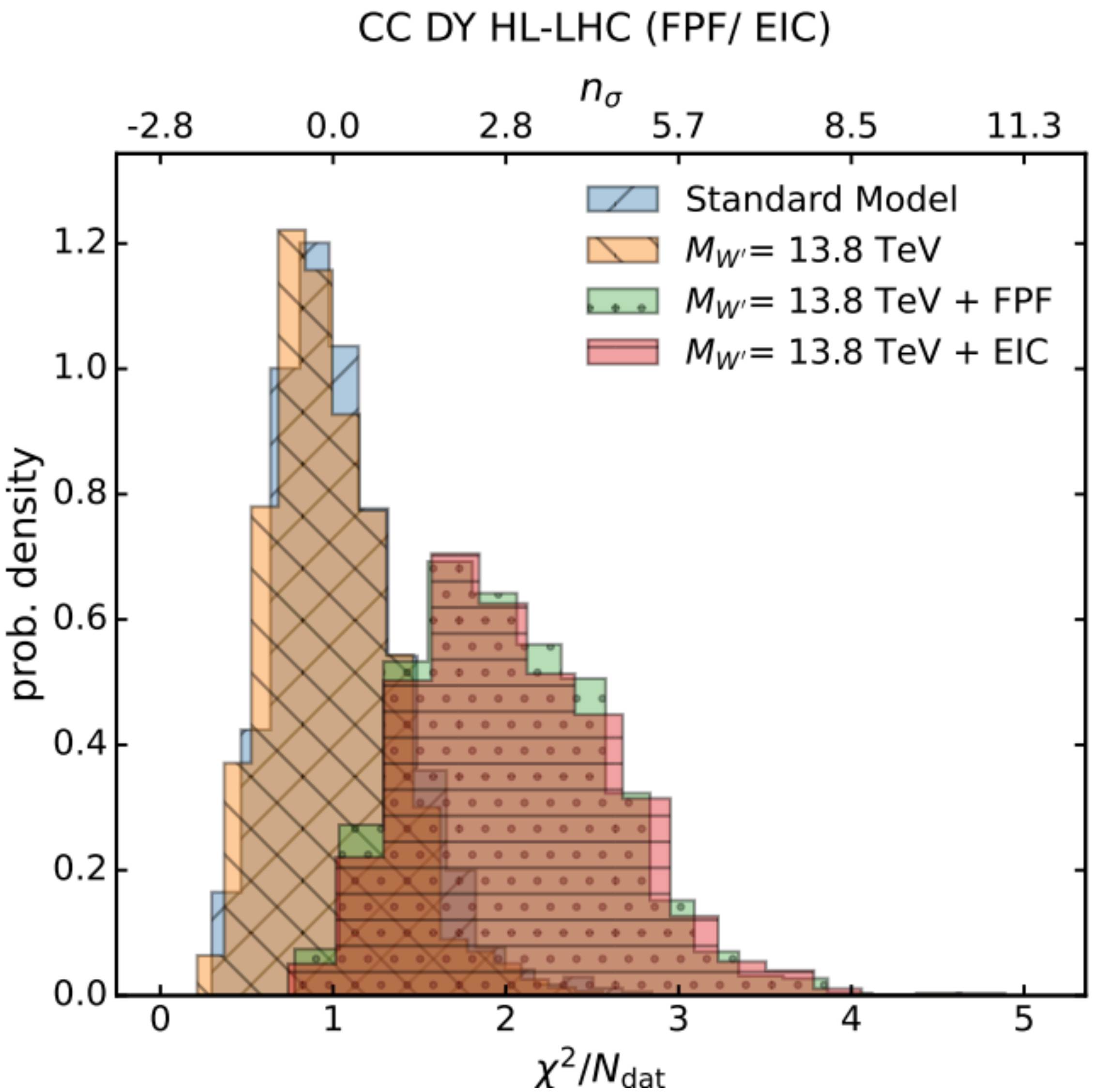
Impact at the HL-LHC: Higgs Physics

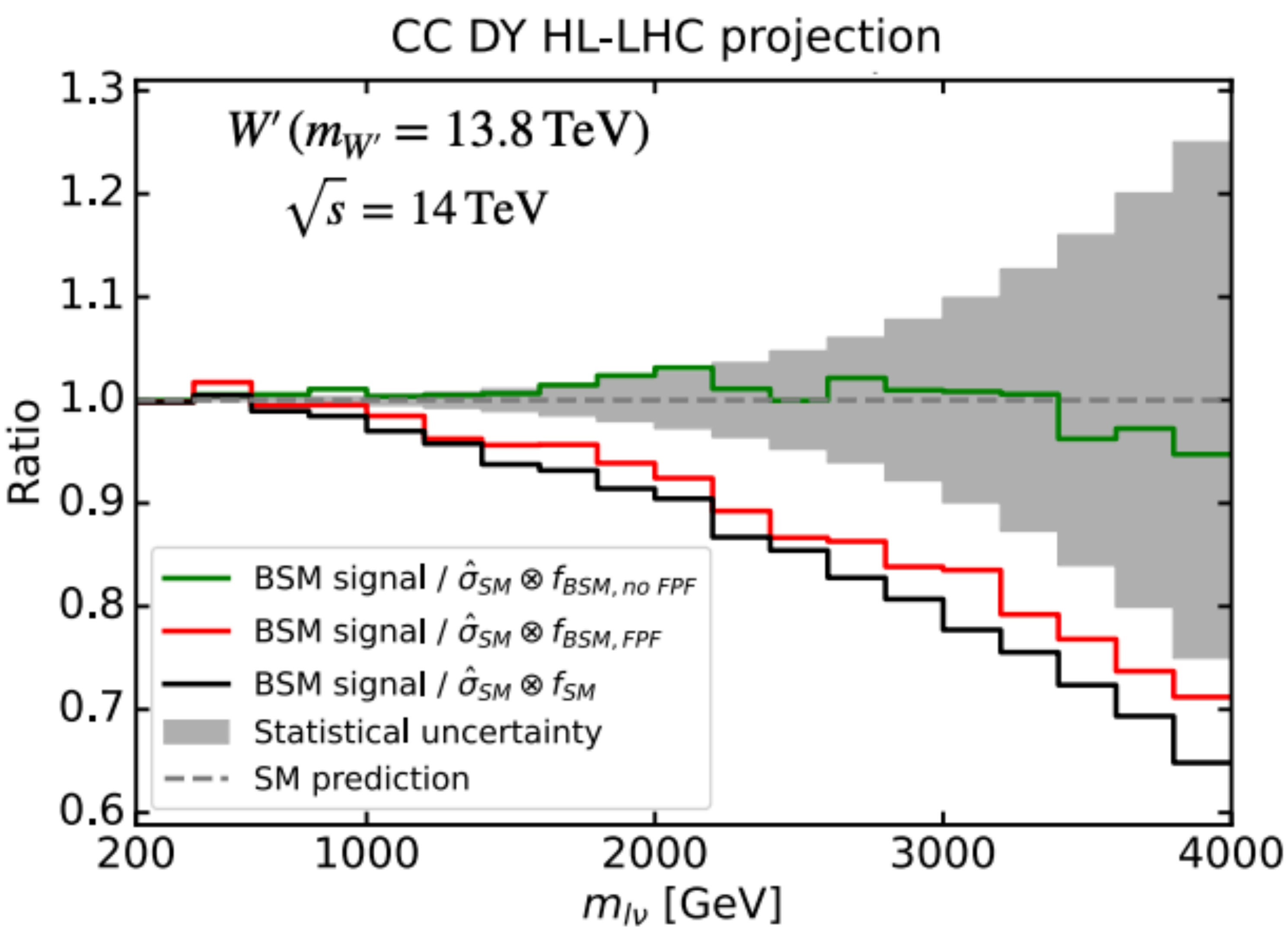


Realising the full potential of **TeV-energy neutrino DIS** at the LHC

Impact at the HL-LHC: BSM searches

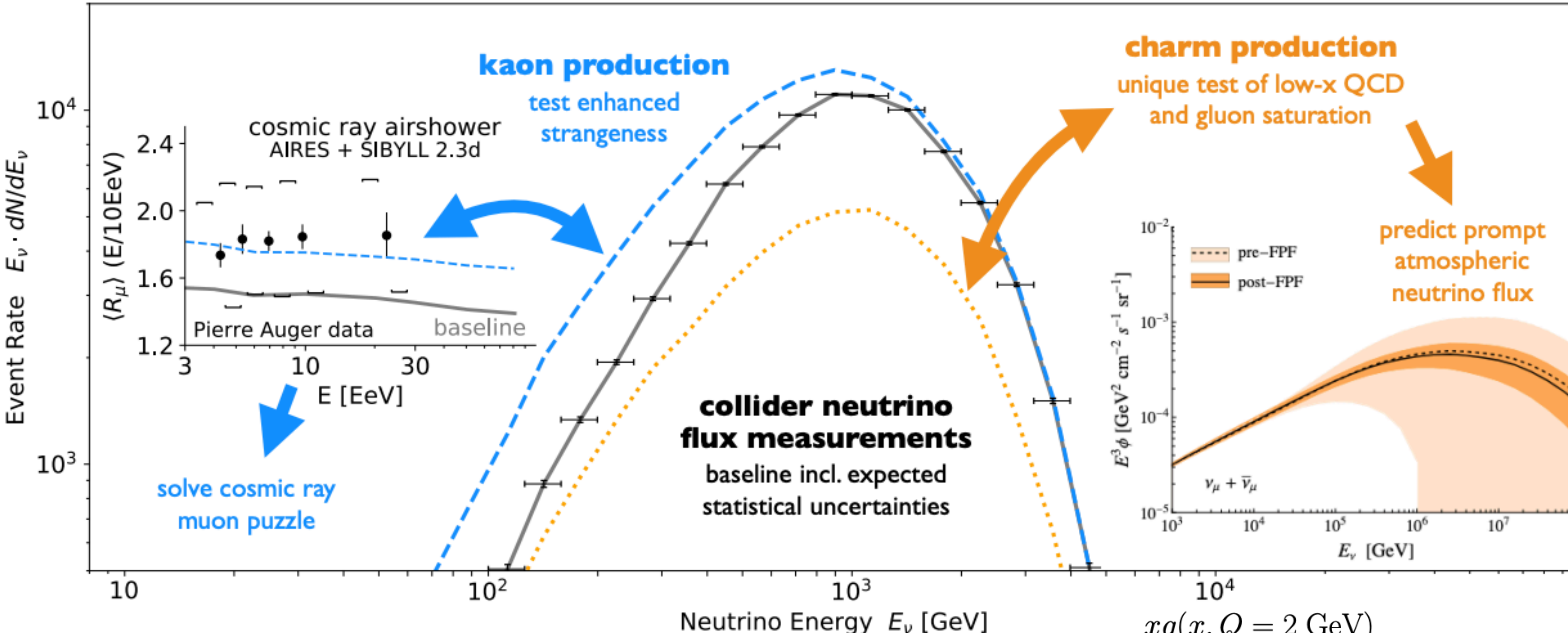
- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- Without FPF, this BSM signal is completely reabsorbed by the PDF fit (softer large-*x* antiquarks)
- LHC neutrino DIS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

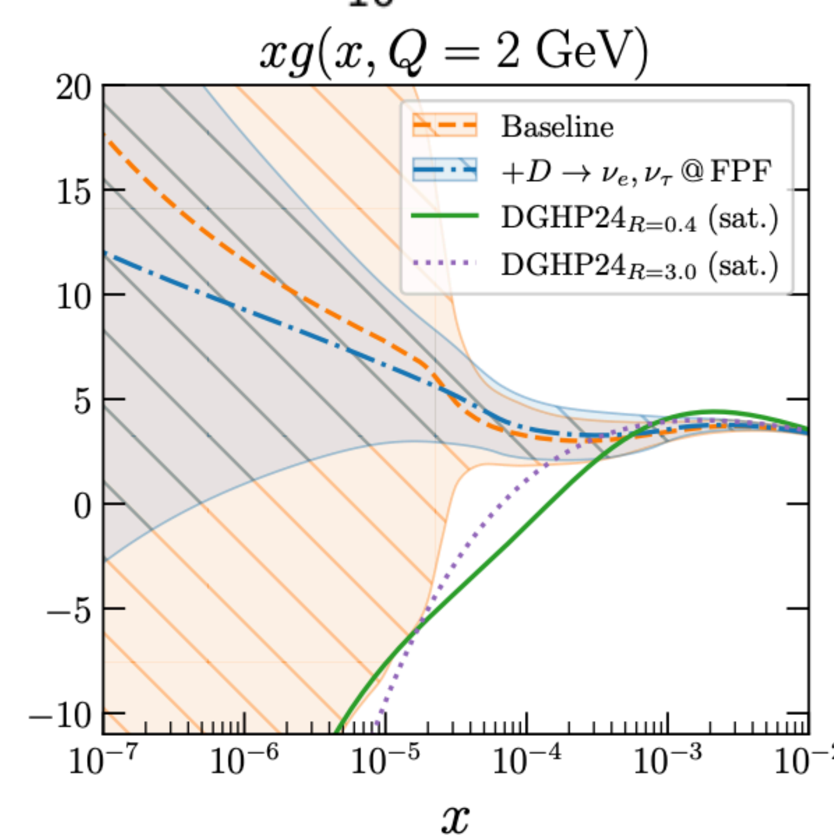




Hammou & Ubiali, 2024

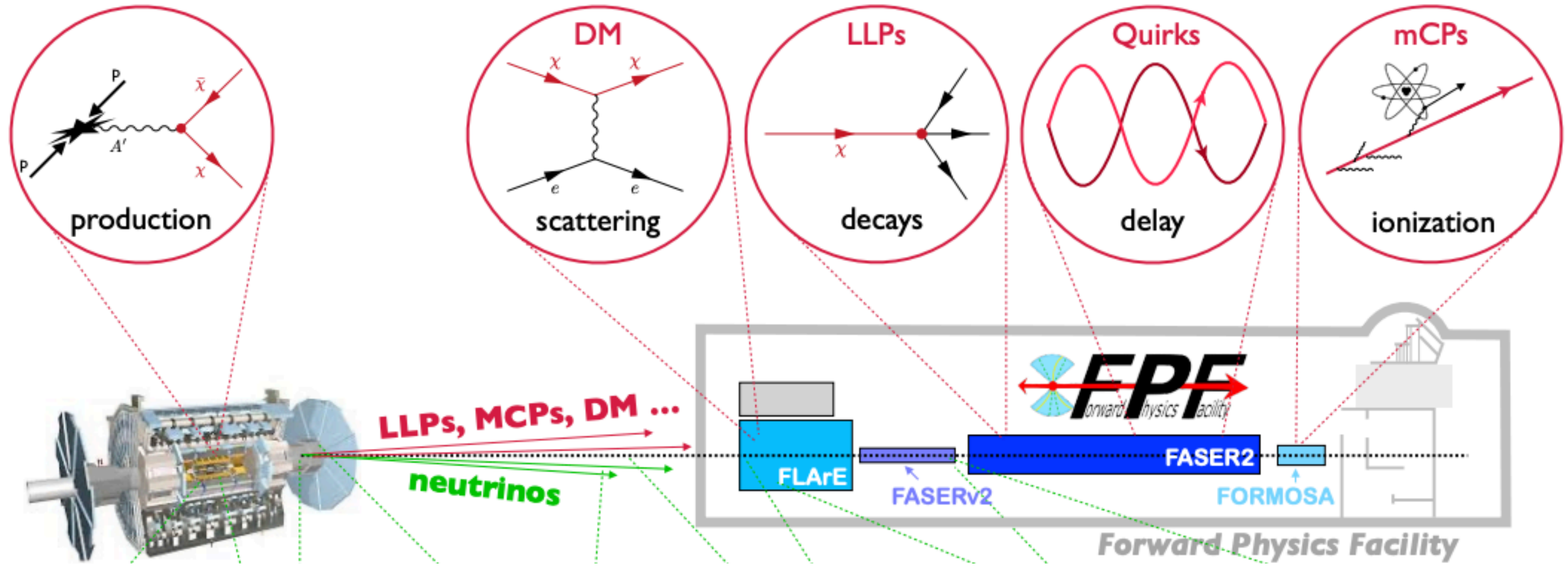
Impact on Astroparticle Physics





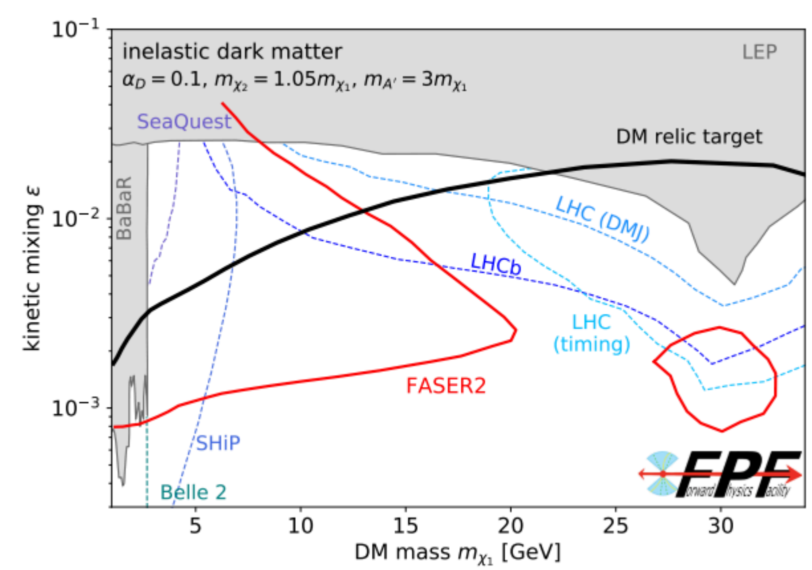
- Probe **small-*x* QCD** (e.g. non-linear dynamics) in uncharged regions
- Data-driven prediction of the prompt neutrino flux
- Laboratory validation of **muon puzzle** predating **cosmic ray physics**

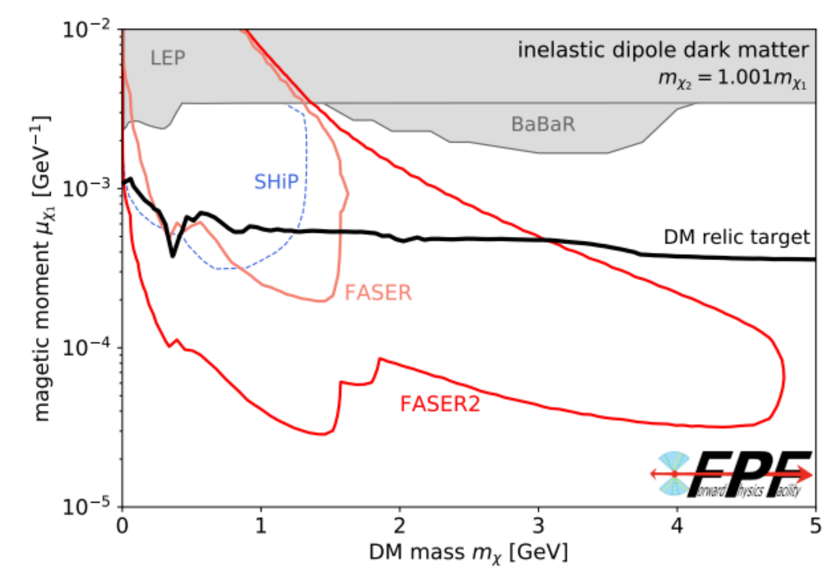
Light BSM Discovery Potential

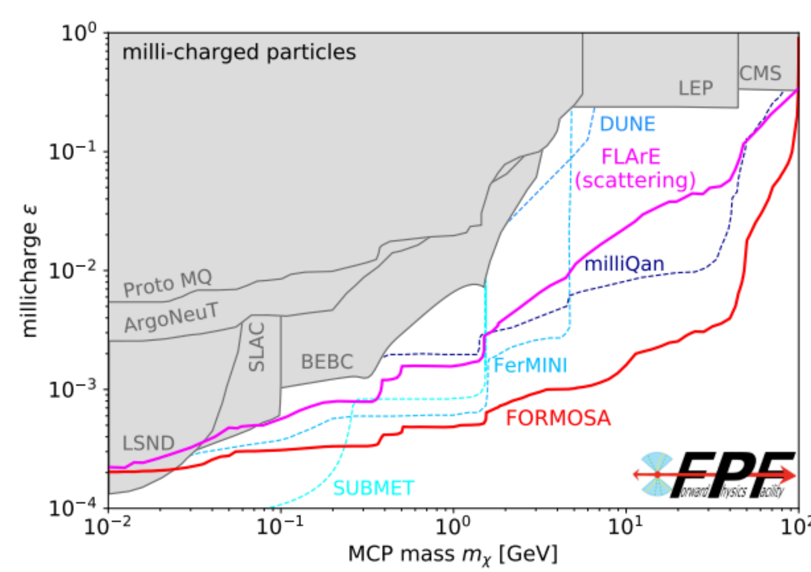


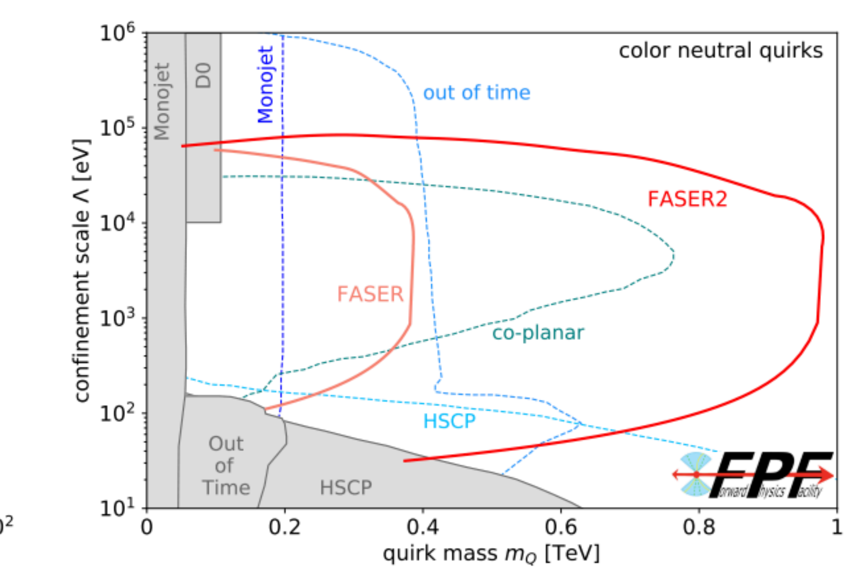
Rich and diverse light BSM search program:

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









ESPPU-NL Proposed Statement

LHC far-forward experiments such as **FASER** and the **Forward Physics Facility** enable a significant extension of the **HL-LHC physics portfolio** and ensure a thriving **high-energy neutrino and light BSM search program at CERN** for the 2030s, with far-reaching implications for **hadronic physics** and **astroparticle experiments**