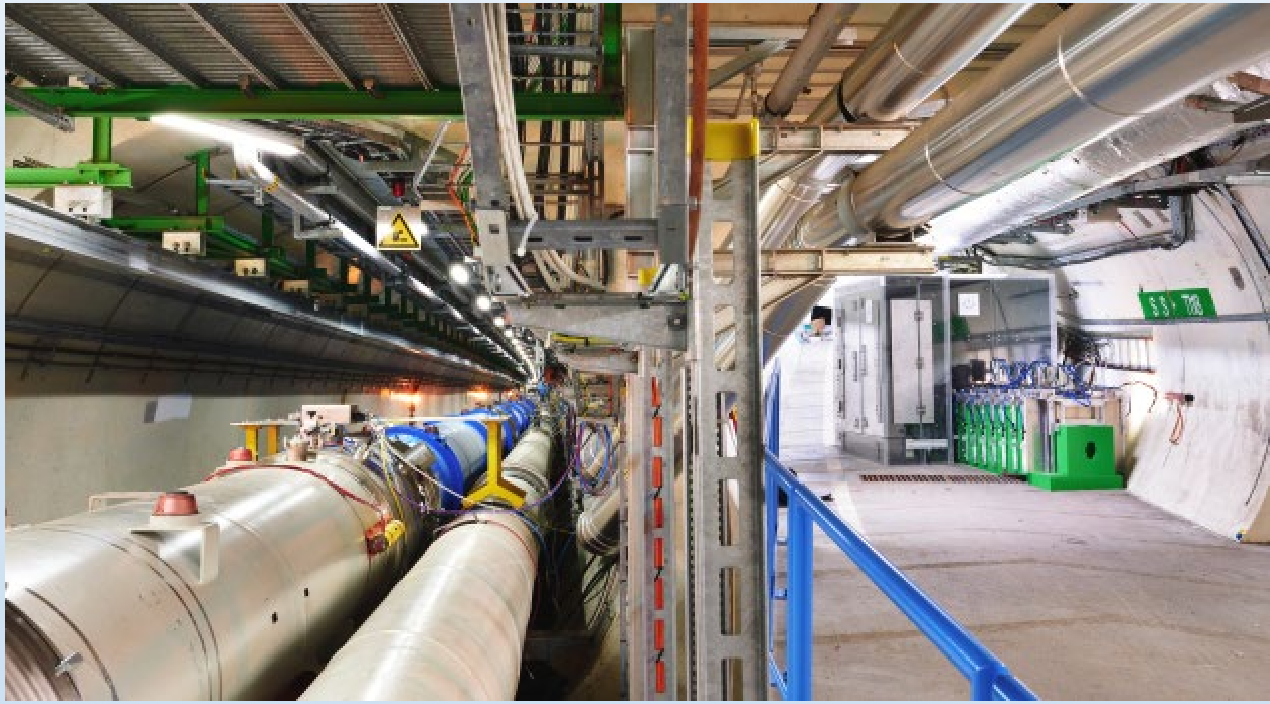
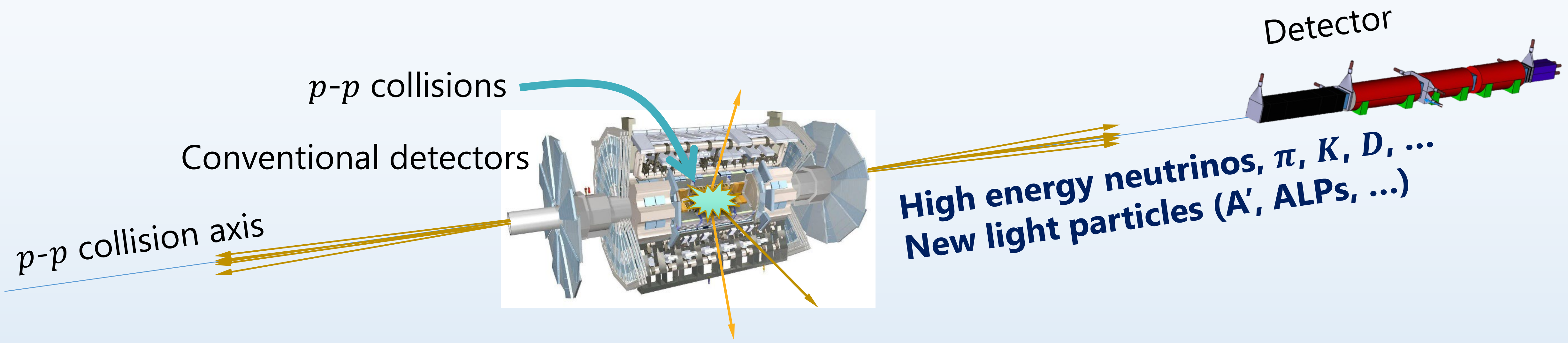
Neutrinos at the LHC

Tomoko Ariga (Kyushu University)
ariga@artsci.kyushu-u.ac.jp

Neutrino 2026, Irvine, 22-26 June 2026

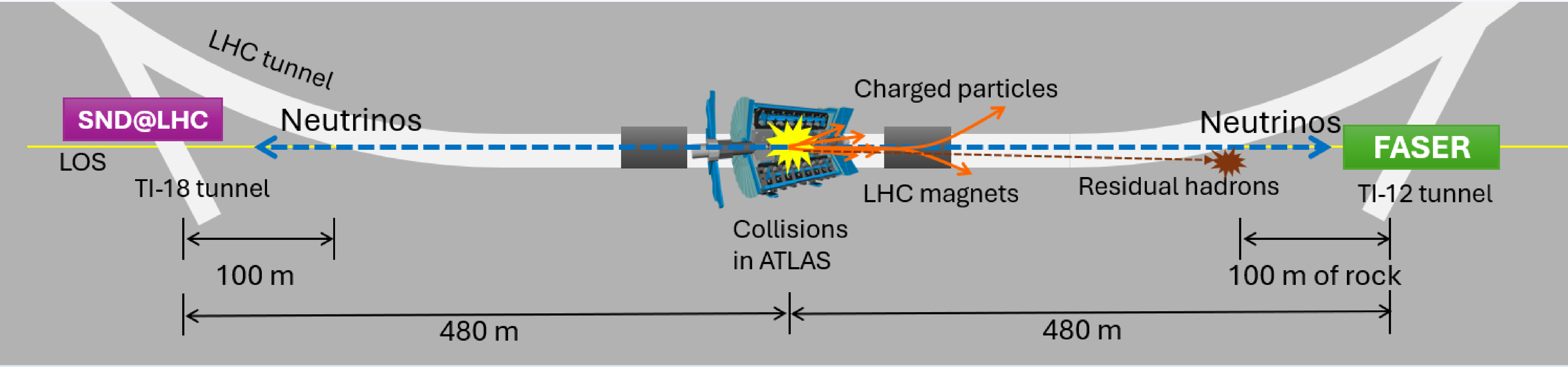


Neutrinos at the LHC



- LHC produces the highest-energy accelerator neutrinos (up to the TeV scale).
- Interest in detecting collider neutrinos had already been expressed in the 1980s.
- In 2018, site studies by FASER identified a low-background location ~480 m downstream of ATLAS. A small emulsion prototype placed on the collision axis observed neutrino candidates, leading to the proposal of FASERν.
- Independent studies at other tunnel locations later led to SND@LHC.

Neutrino experiments at the LHC



- Installation and data taking
  - FASER and SND@LHC installed during LS2 (2019–2022)
  - Taking data since start of LHC Run 3 (2022) and completed in 2026
- Future prospects
  - Upgrades and extended running in Run 4 (from 2030)
  - Expansion with larger detectors at the HL-LHC: Forward Physics Facility (FPF)

FASERν: $\eta > 8.8$

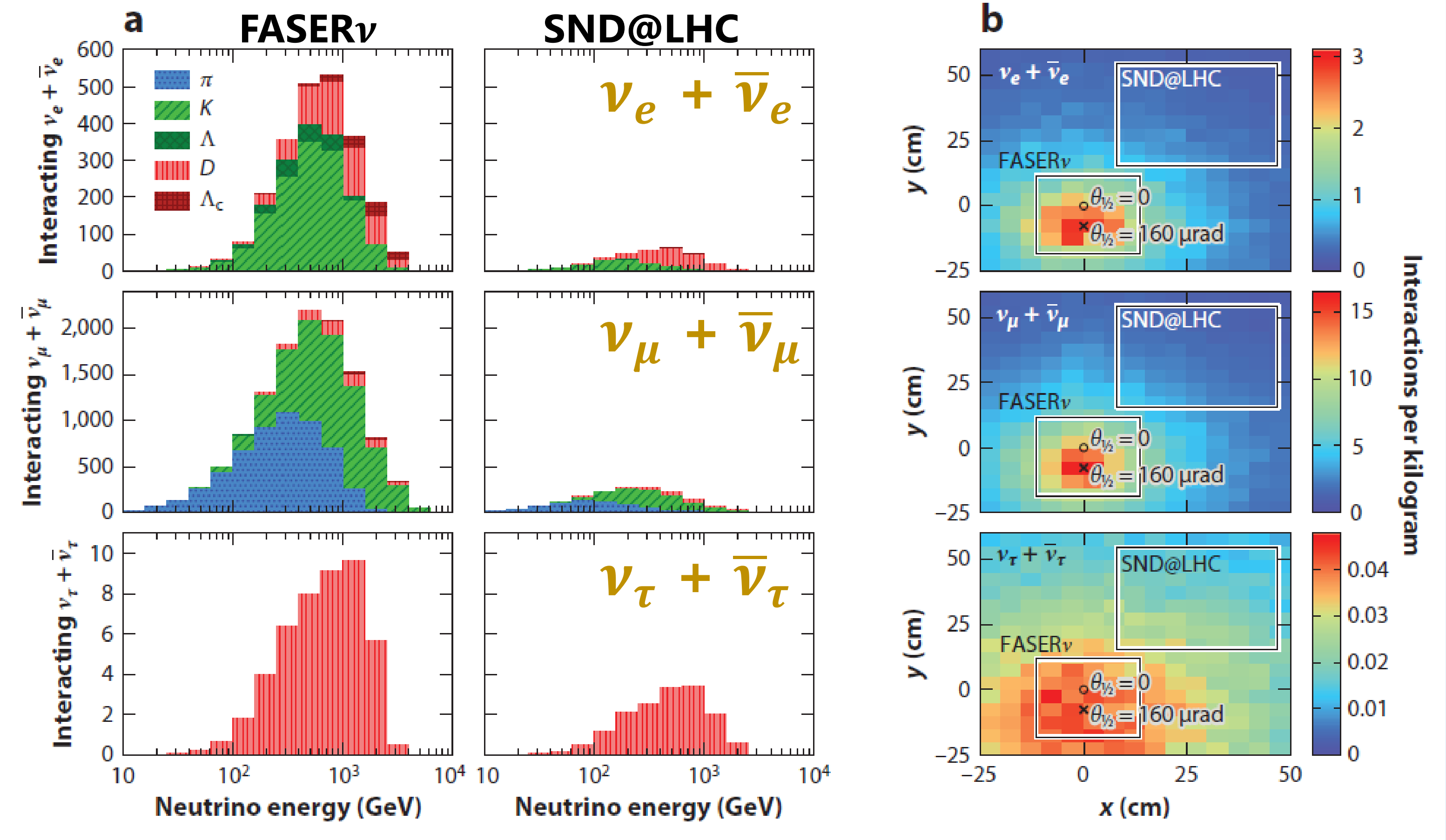
SND@LHC: $7.2 < \eta < 8.4$

Neutrino energy and spatial distributions

- This prediction uses **EPOS-LHC** to simulate the **production of forward light hadrons** and the envelope formed by EPOS-LHC, Sibyll 2.3d, and Qgsjet 2.04 as well as the forward physics tune of Pythia to define an uncertainty band.
- **Charm hadron production** is modeled using **Powheg** matched with Pythia 8.3 for parton shower and hadronization, with the uncertainties described by scale variations.
- The expected event rates were estimated using the neutrino interaction cross section implemented in Genie, based on the Bodek–Yang model.

Energy and spatial distributions of interacting neutrinos for 350 fb^{-1}

On-axis **Off-axis** Annu. Rev. Nucl. Part. Sci. 2025. 75:57–81



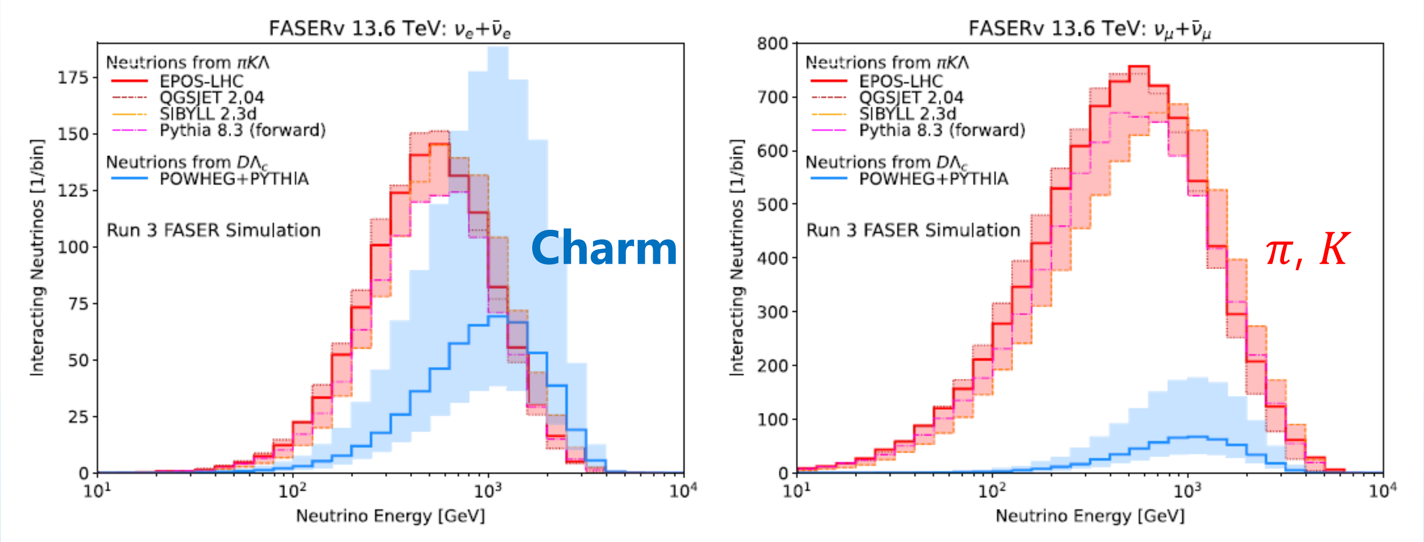
Experiments	η coverage	Tungsten target mass [kg]		ν_e	ν_μ	ν_τ
FASER	$\eta > 8.8$	1100	**N int** **E average**	2331^{+1227}_{-544} 785 GeV	12014^{+1145}_{-1636} 716 GeV	46^{+77}_{-21} 849 GeV
SND@LHC	$7.2 < \eta < 8.4$	830	**N int** **E average**	307^{+307}_{-116} 442 GeV	1694^{+297}_{-549} 357 GeV	15^{+26}_{-7} 596 GeV

Uncertainties in the flux predictions

The dominant uncertainty in the flux prediction comes from hadron production in the forward region.

Phys. Rev. D 110, 012009 (2024)
"Neutrino rate predictions for FASER"

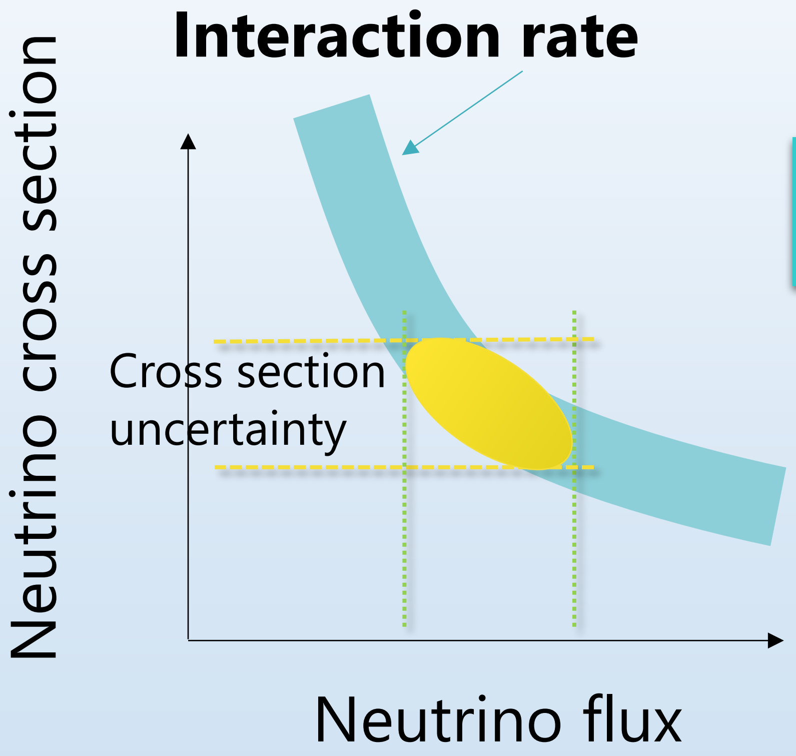
$\nu_e + \bar{\nu}_e$ $\nu_\mu + \bar{\nu}_\mu$



LHC Run 3 with 250 fb^{-1} **LHC Run 4 with 680 fb^{-1}**

Generators		FASERν at Run 3			FASERν at Run 4		
Light hadrons	Charm hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
EPOS-LHC	...	1149	7996	...	3382	23054	...
SIBYLL 2.3d	...	1126	7261	...	3404	21532	...
QGSJET 2.04	...	1181	8126	...	3379	22501	...
PYTHIAforward	...	1008	7418	...	2925	20508	...
...	POWHEG Max	1405	1373	76	4264	4068	255
...	POWHEG	527	511	28	1537	1499	91
...	POWHEG Min	294	284	16	853	826	51
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}	4919^{+2748}_{-1141}	24553^{+2568}_{-3219}	91^{+163}_{-41}

What can be done from neutrino interaction rate measurements



Knowledge of flux

- Hadron production models
- External validation data

Interaction rate measurements

Neutrino cross section measurements

- Test lepton flavor universality
- Search for new interactions

SM predictions for neutrino cross sections

- Assuming LFU is valid

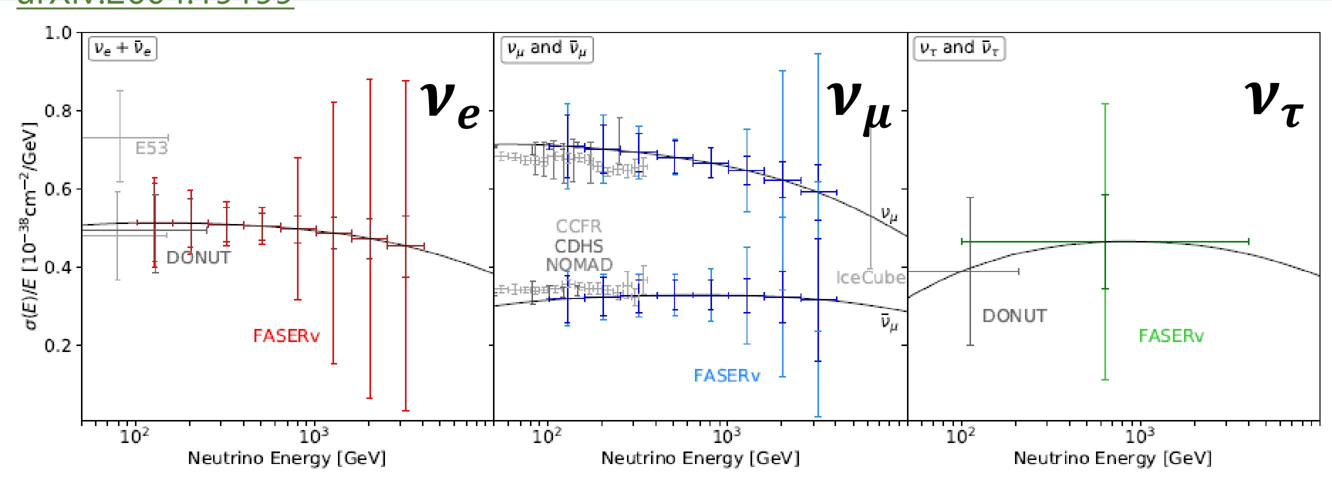
Neutrino flux measurements

- Study hadron/neutrino production at very high-energy
- Prompt neutrinos
- QCD at small x

Physics motivation of neutrino interaction measurements

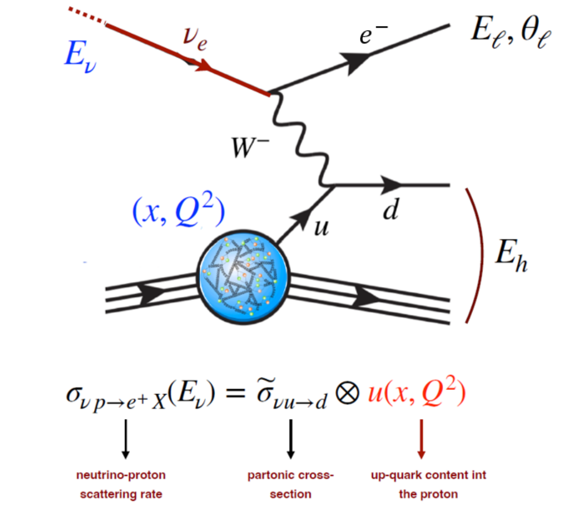
- Direct observation of TeV-energy neutrino interactions for ν_e, ν_μ, and ν_τ
- Measurement of charged-current cross sections at TeV energies for three flavors of neutrinos, and tests of lepton universality
- Neutral-current interaction measurements and searches for non-standard interactions

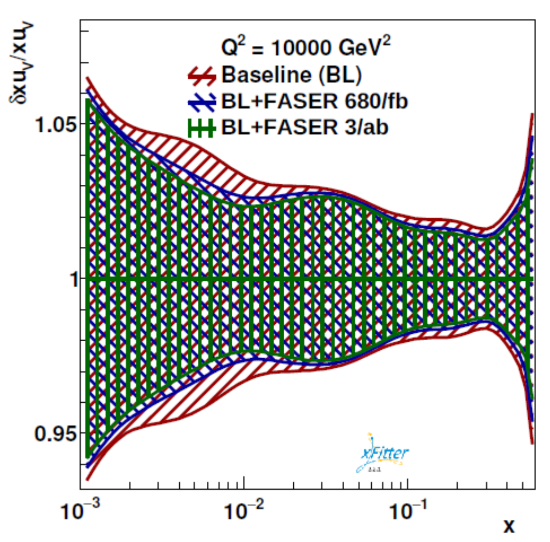
arXiv:2604.19199

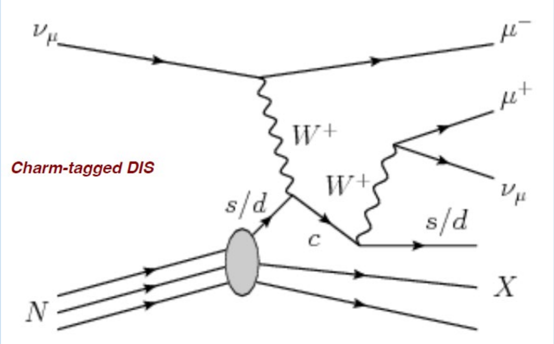


- Proton and nuclear parton distribution studies to reduce PDF uncertainties

Eur. Phys. J. C 84 (2024) 369, "The LHC as a Neutrino-Ion Collider"



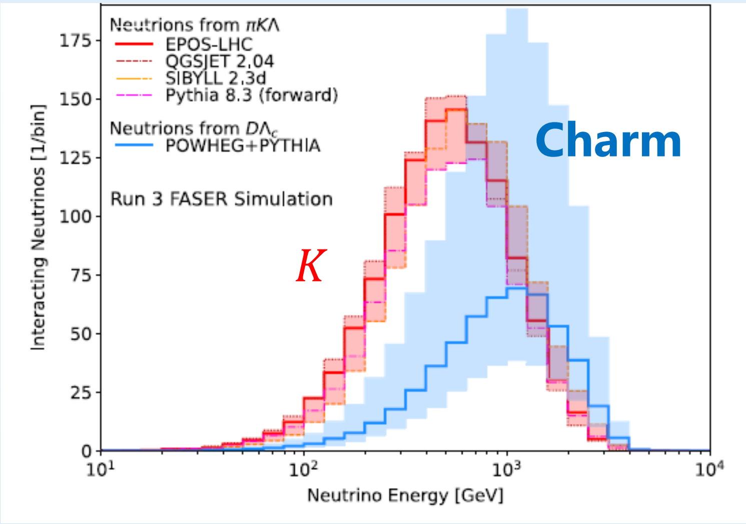


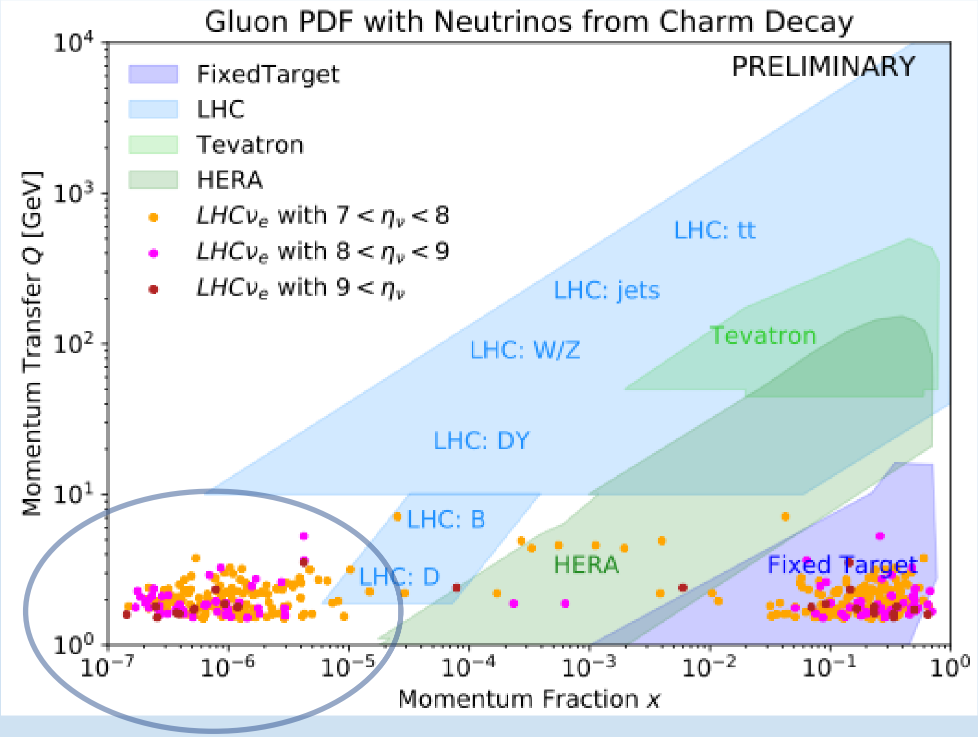


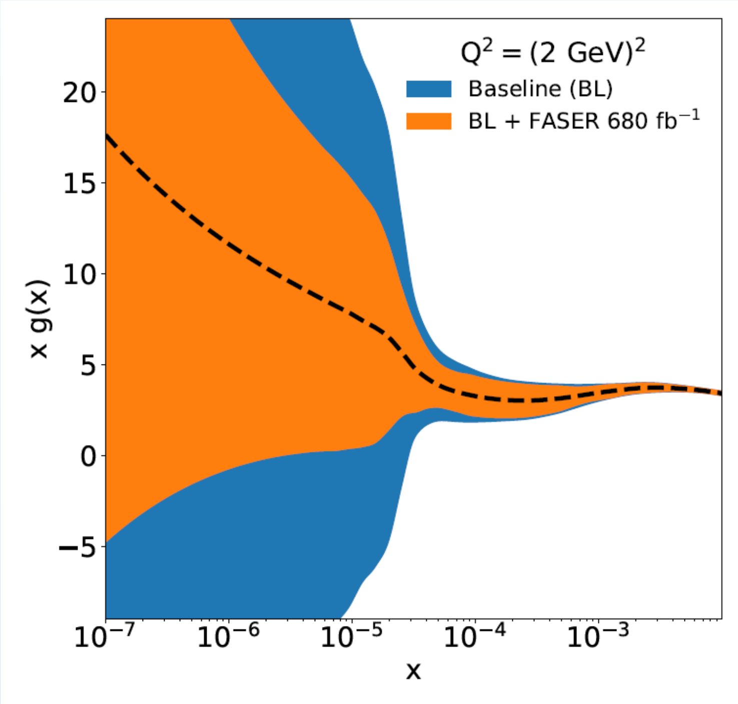
Physics motivation of neutrino flux measurements

- Neutrino measurements as a probe of very forward hadron production
- Measurements of LHC neutrinos provide novel input to QCD studies (low-x PDFs, intrinsic charm, saturation) and to astroparticle physics (prompt atmospheric neutrinos, cosmic-ray muon puzzle)

$\nu_e + \bar{\nu}_e$ at FASERν





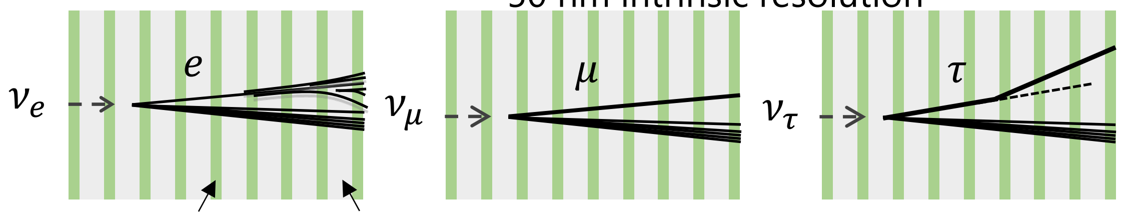


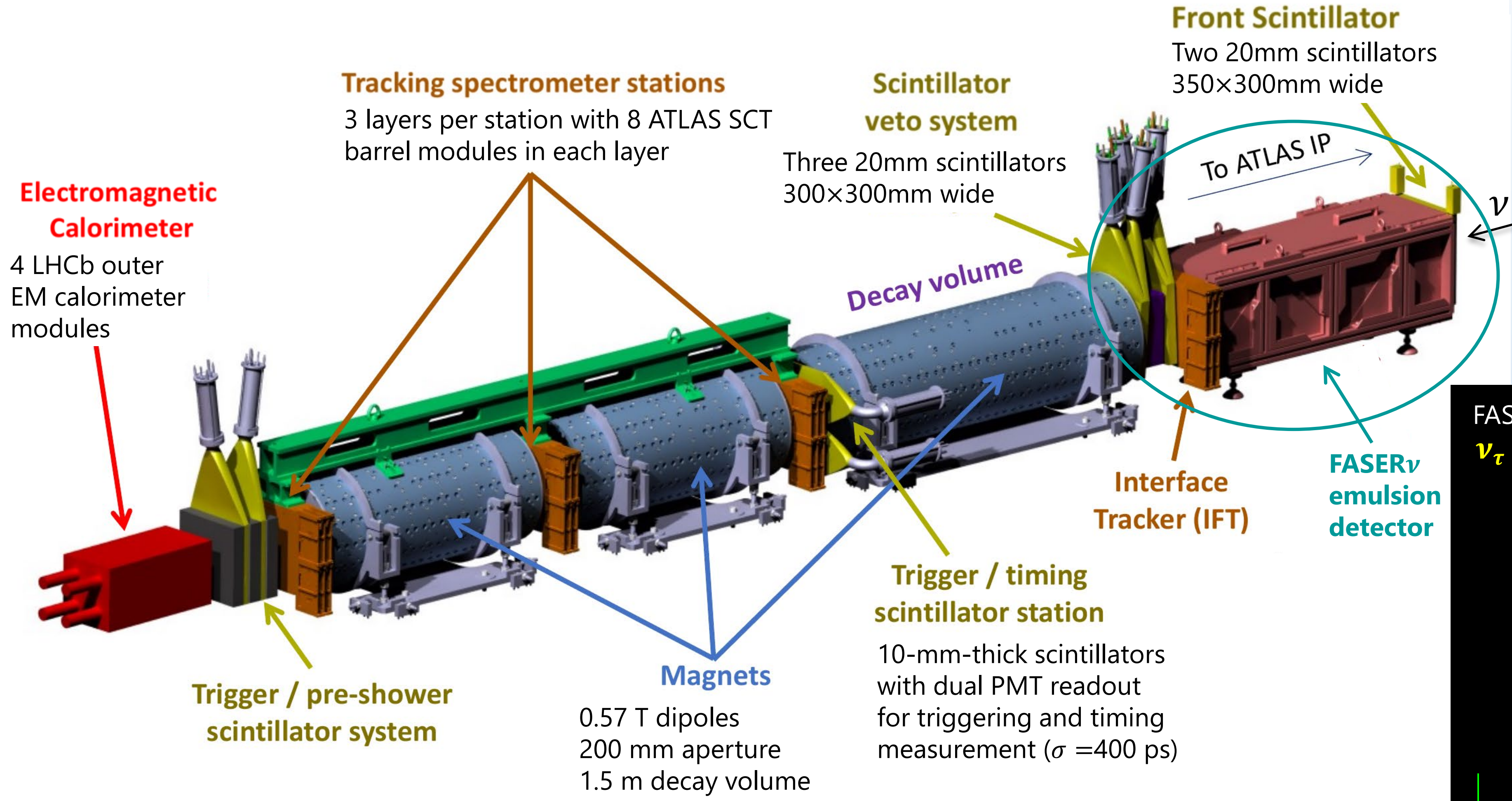
FASER detector

JINST 19 P05066 (2024), The FASER detector

FASERν detector

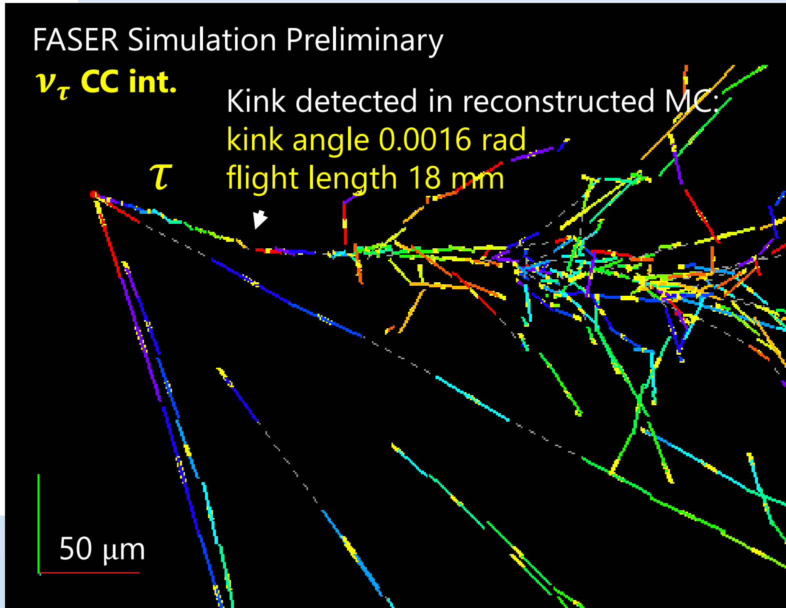
Emulsion: 3D tracking device with 50 nm intrinsic resolution





- 1.1-ton detector
- 730 layers of 1.1-mm-thick tungsten + emulsion
- neutrino target + tracking detector ($8\lambda_{int}$)

Capability of identifying three-flavor neutrinos (ν_e, ν_μ, ν_τ) with detection of short-lived particles



SND@LHC detector

Veto system

- 2 (2022 - 2023) / 3 (2024 -) scintillator planes
- Tag incoming charged particles

Target, vertex detector and ECal

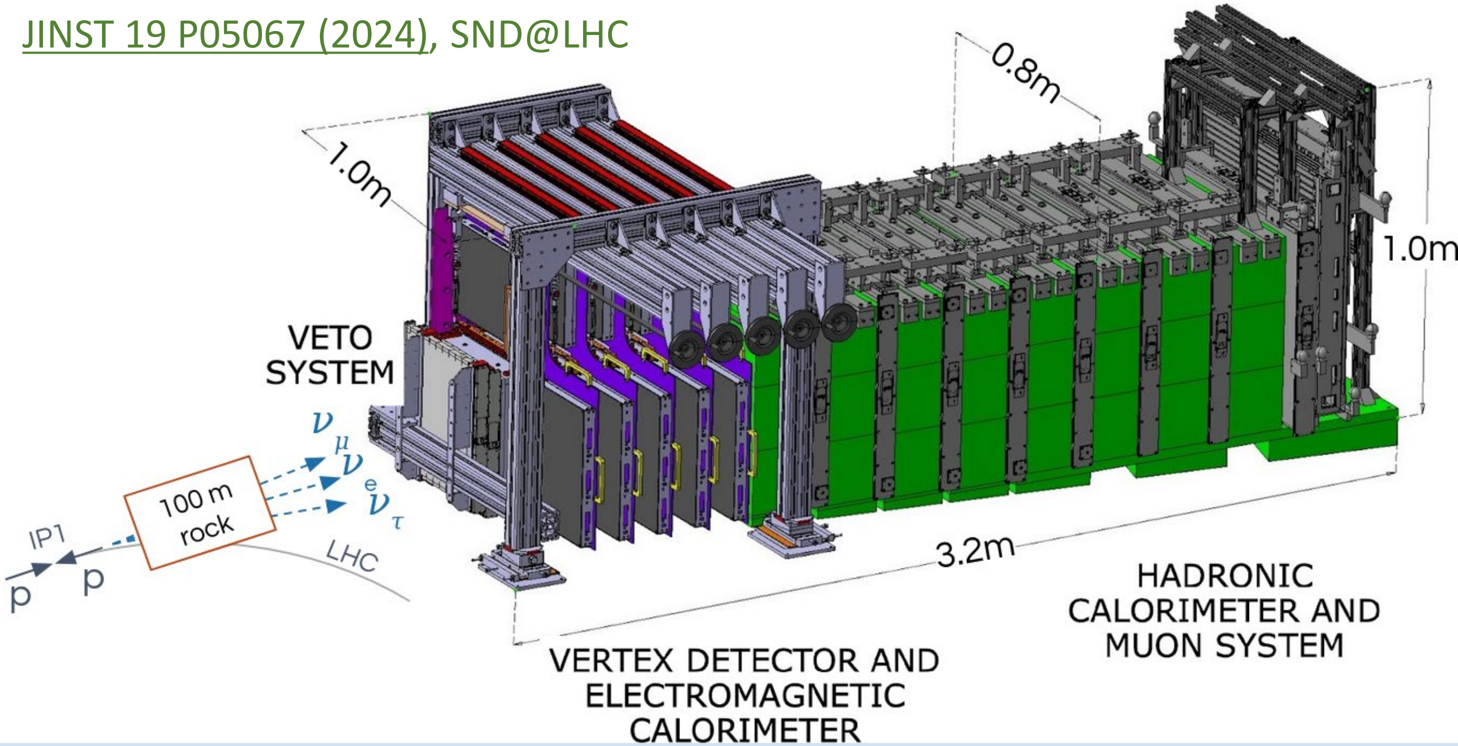
- 830 kg tungsten target
- Five walls × 59 emulsion layers + five scintillating fibre stations (SciFi)
- $84X_0$, $3\lambda_{int}$

HCal and muon system

- Eight 20 cm Fe blocks + scintillator planes
- Last 3 planes have finer granularity to track muons
- Drift-tubes installed in 2026
- $9.5\lambda_{int}$

Courtesy of the SND@LHC coll.

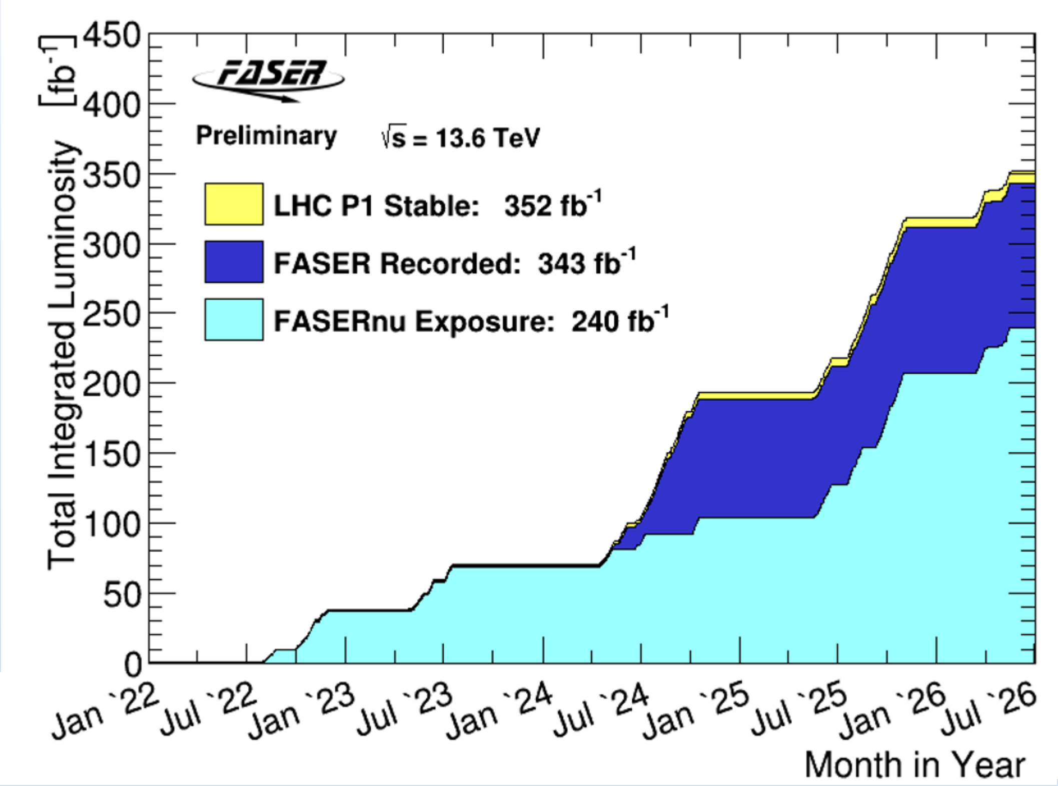
JINST 19 P05067 (2024), SND@LHC



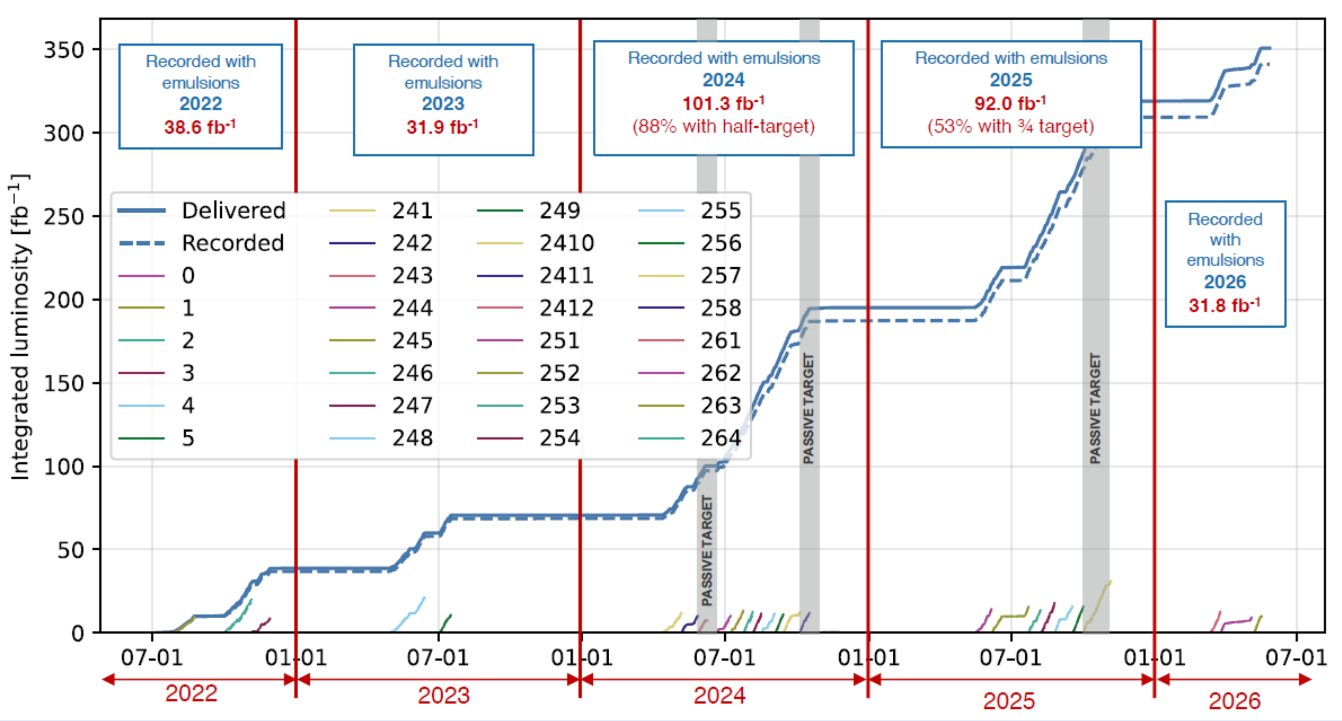
LHC Run 3 data taking completed

- FASER detector
  - >97% data taking efficiency
  - 343 fb^{-1} recorded
- FASERν detector
  - 240 fb^{-1} in emulsion (full target)
  - ~657 m^2 of emulsion in 12 modules exposed
  - Up to ~30 fb^{-1} per module before replacement

- SND@LHC detector
  - 97% detector uptime
  - 341 fb^{-1} recorded
- SND@LHC emulsion detector
  - 296 fb^{-1} in emulsion (not always full target)
  - Up to ~15 fb^{-1} per module before replacement



Courtesy of the SND@LHC coll.



Muon flux studies in the LHC forward region

- Muons are the dominant background in the forward region.
- Muon flux depends on LHC optics and beam conditions.

FASER

	μ flux [$\times 10^4$/cm^2/fb^{-1}]
Data (2022, emulsion)	$1.39\ ^{+0.05}_{-0.07}$
MC (2022, BDSIM, preliminary)	1.53 ± 0.07

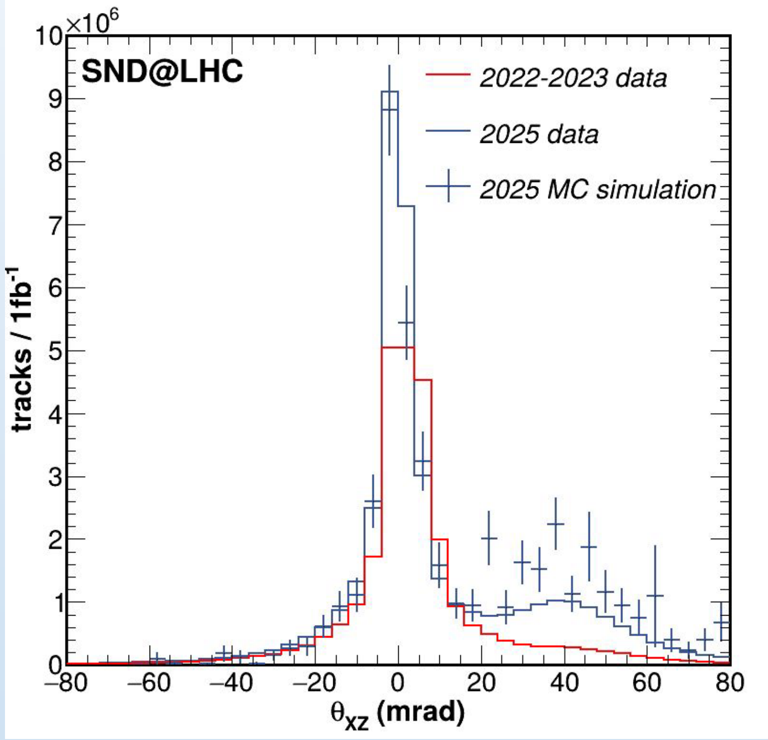
Fiducial region: $|x|$, $|y|$<5 cm from the FASER magnet center; tanθ<0.01

SND@LHC

Eur. Phys. J. C (2024) 84 and arXiv:2602.23412

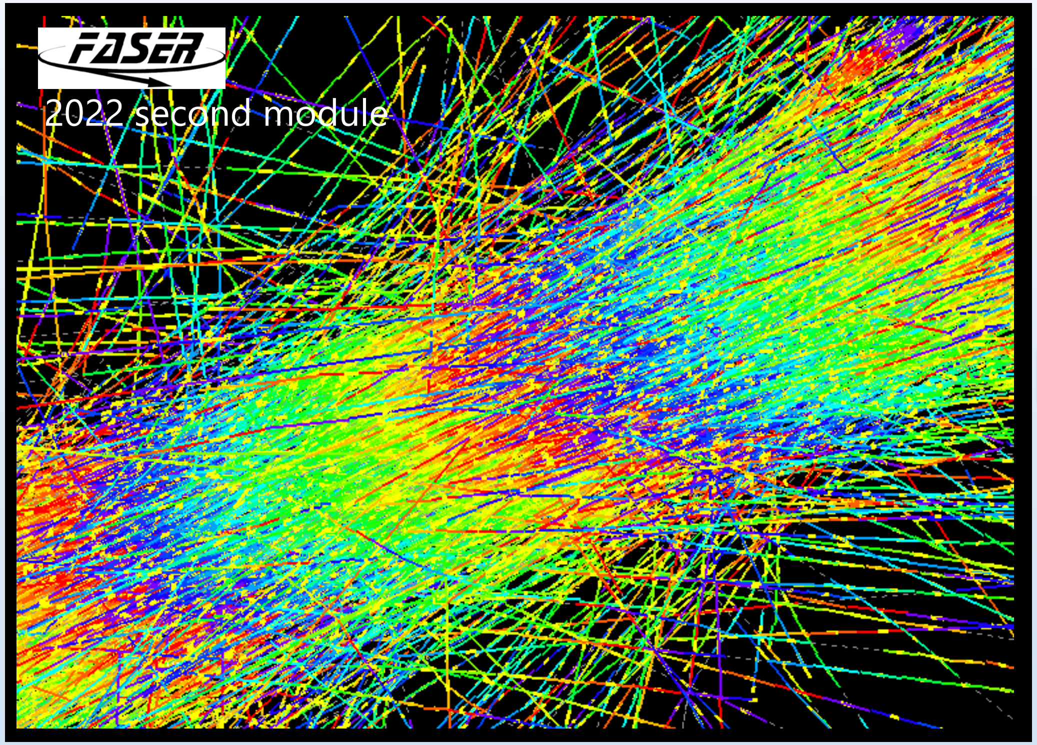
	μ flux [$\times 10^4$/cm^2/fb^{-1}]
Data (2022)	2.06 ± 0.12
MC (2022)	1.60 ± 0.19
Data (2023)	1.90 ± 0.04
MC (2023)	1.67 ± 0.05
Data (2024)	3.74 ± 0.06
MC (2024)	3.34 ± 0.12
Data (2025)	2.48 ± 0.04
MC (2025)	3.13 ± 0.14

Muon angular distributions depend on LHC configuration

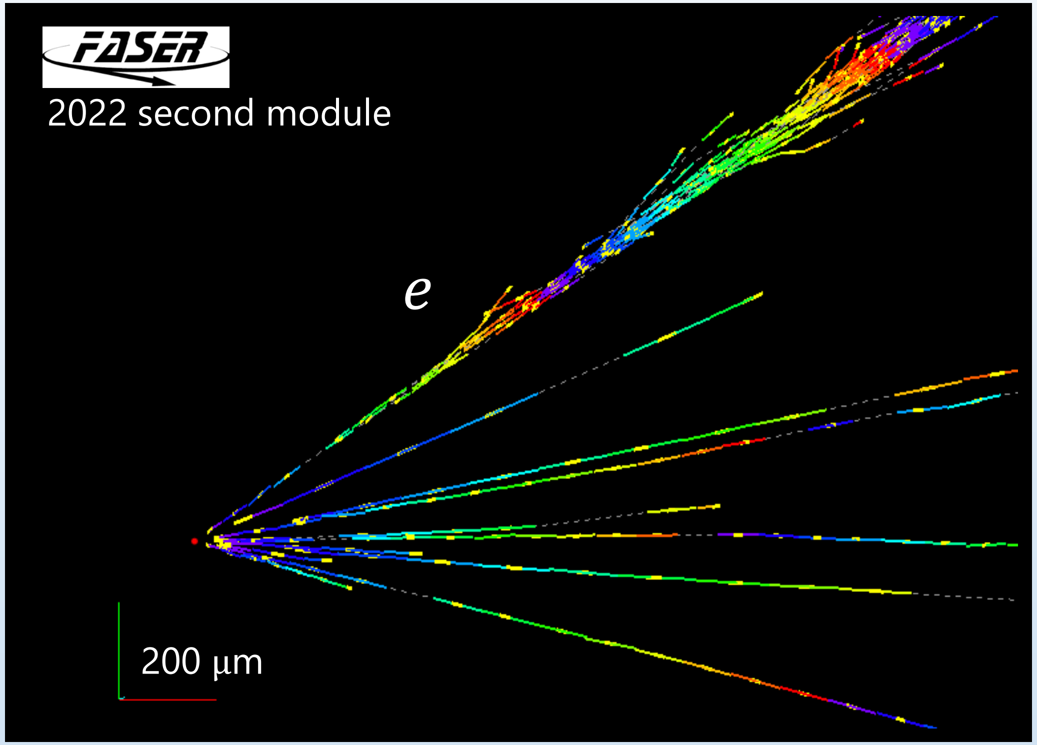


Neutrino interactions detected among the muon background

ν_e CC candidate event
with muon background tracks



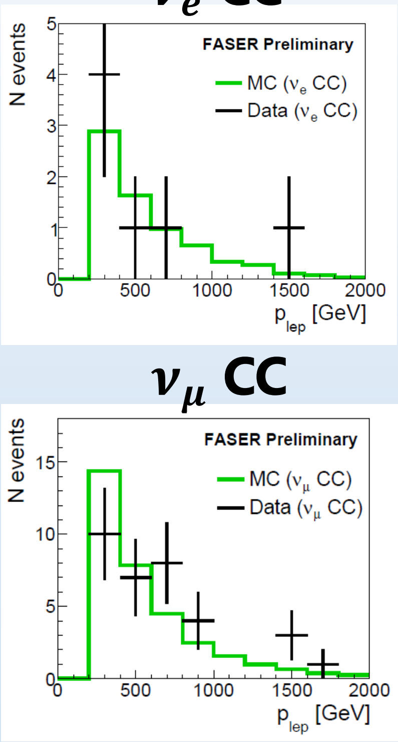
Neutrino interactions can be identified
despite background muon tracks



Data–MC agreement for
selected ν candidates

ν_e CC

ν_μ CC



Event reconstruction details: JINST 20 P12018 (2025)
Momentum measurement of charged particles: arXiv:2602.17575
EM shower reconstruction: arXiv:2606.18517

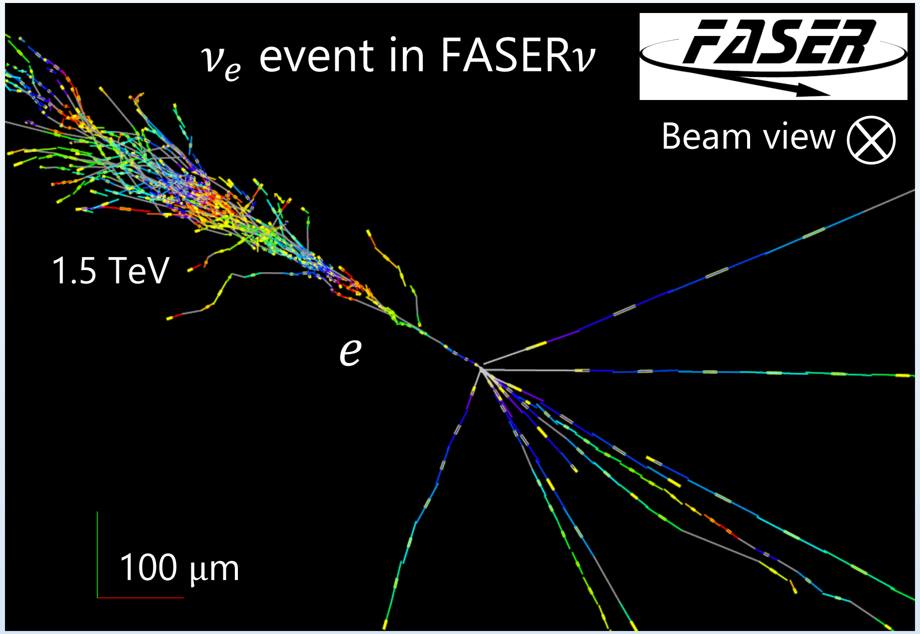
Results with LHC neutrinos

This talk will emphasize results published after Neutrino 2024

- **First neutrino candidate events** with Run 2 data
  - FASER Collaboration, Phys. Rev. D 104, L091101 (Nov. 2021)
- **First ν_μ detection** with 2022 data
  - FASER Collaboration, Phys. Rev. Lett. 131, 031801 (July 2023)
  - SND@LHC Collaboration, Phys. Rev. Lett. 131, 031802 (July 2023)
- **First ν_e detection & First ν_e, ν_μ cross sections at TeV energies**
  - FASER Collaboration, Phys. Rev. Lett. 133, 021802 (July 2024)
- Muon Neutrino Interaction Cross Section and Flux as a Function of Energy
  - FASER Collaboration, Phys. Rev. Lett. 134, 211801 (May 2025)
- Observation of neutrino interactions without final-state muons (0μ)
  - SND@LHC Collaboration, Phys. Rev. Lett. 134, 231802 (June 2025)

First ν_e and ν_μ cross section measurements at TeV energies

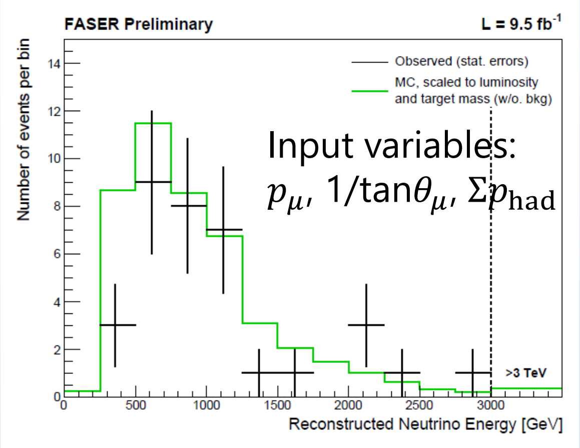
- Preliminary results reported in Neutrino 2024 and published after that: Phys. Rev. Lett. 133, 021802 (2024), (Selected for PRL Collection of the Year 2024)



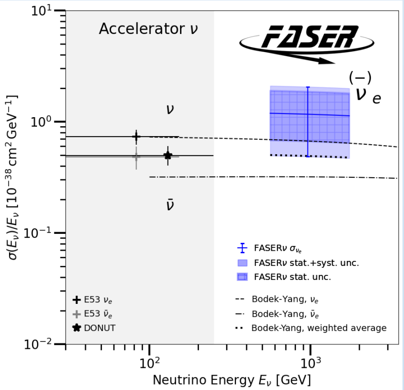
- Updated emulsion analysis (2022 module 9.5 fb^{-1}): target mass 129 kg → 681 kg
- Neutrino energy reconstruction introduced.

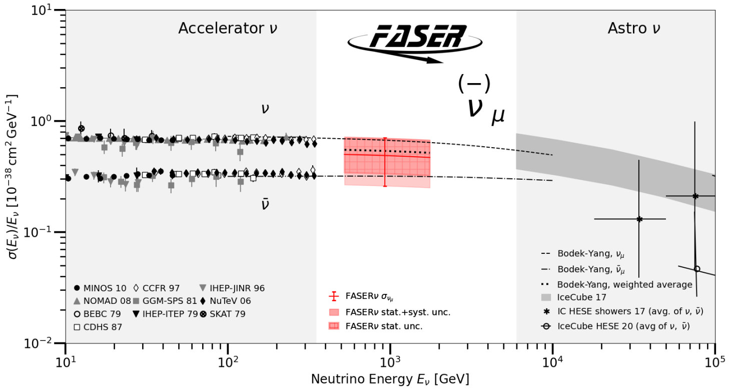
CERN-FASER-CONF-2026-002

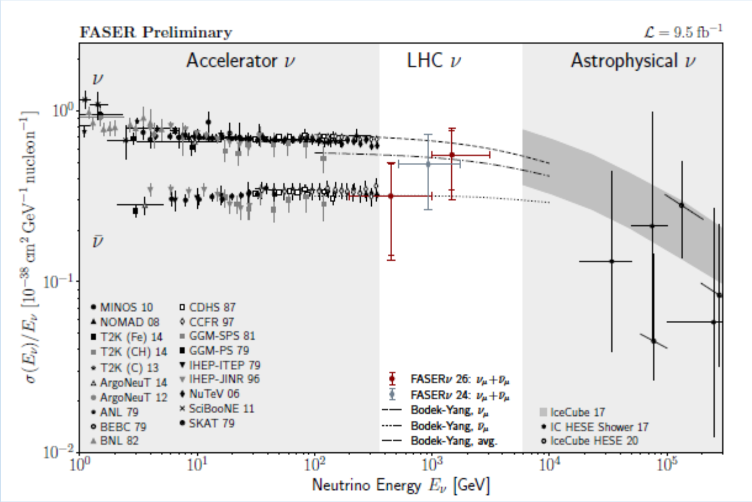
	ν_e CC	ν_μ CC
Expected signal	$7.7^{+6.3}_{-2.5}$	$40.0^{+14.5}_{-9.7}$
Expected background	$0.13^{+0.08}_{-0.05}$	$1.17^{+0.62}_{-0.40}$
Observed events	7	33

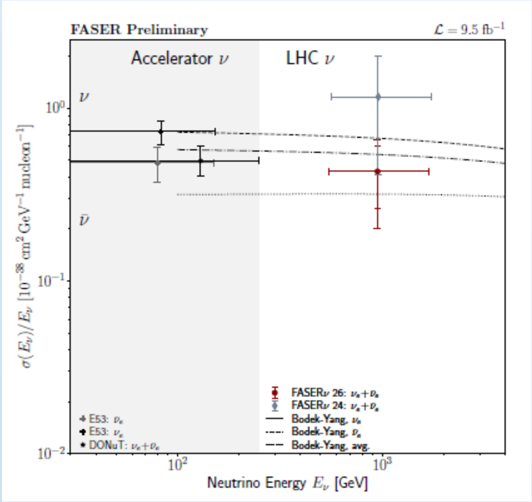


About 4% of the Run 3 data published so far. More than 20× larger statistics expected with the full dataset and efficiency improvements.



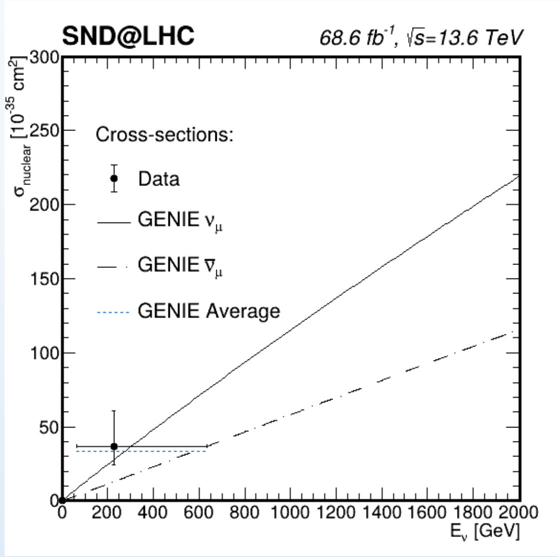






Measurement of ν_μ flux and cross sections

with electronic detectors

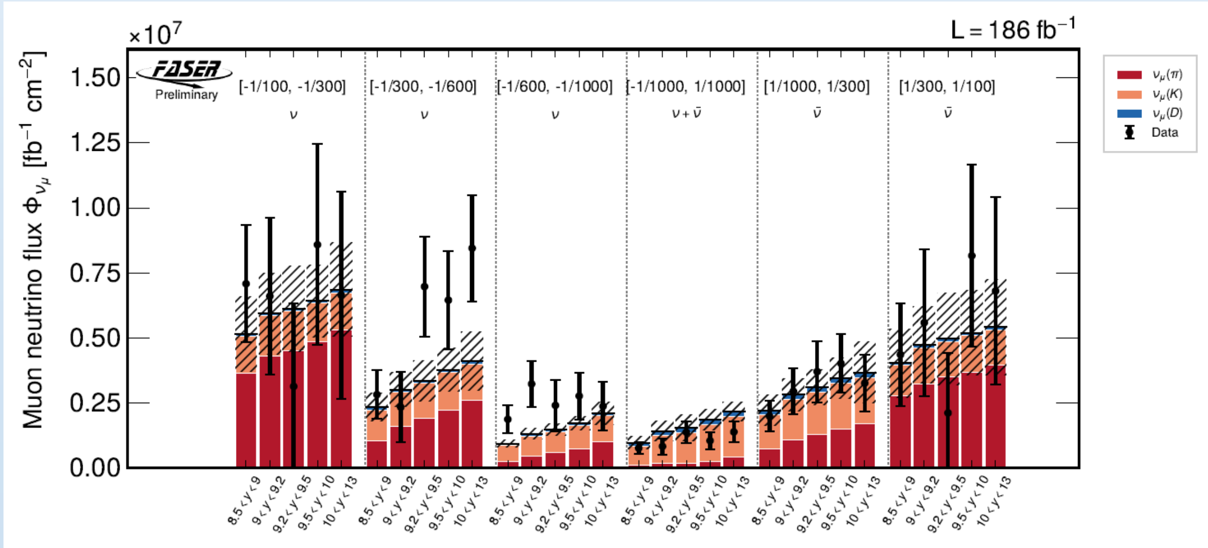


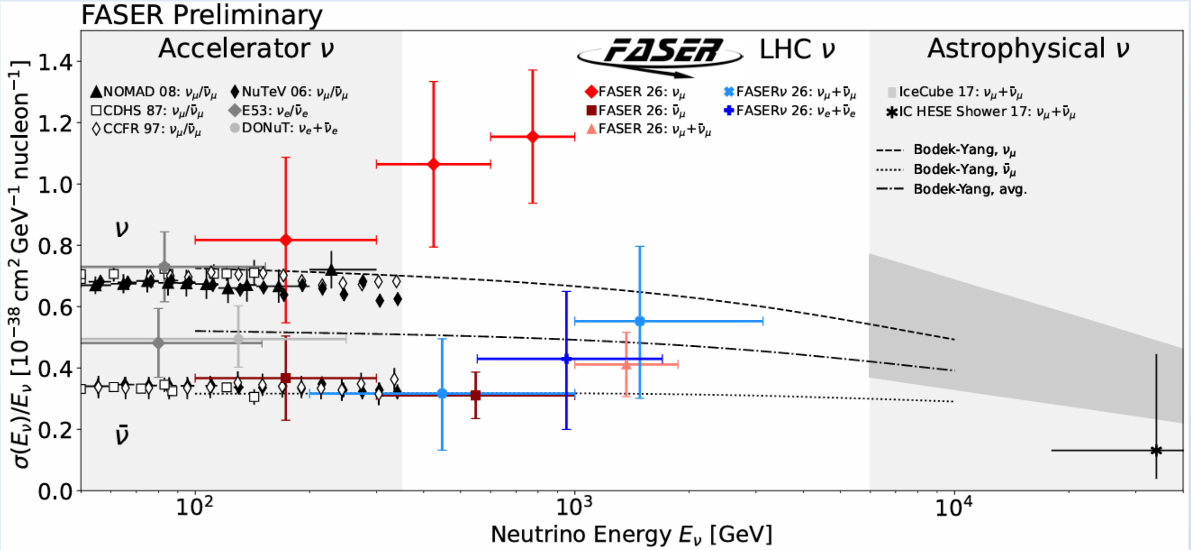
FASER (Phys. Rev. Lett. 134, 211801 (2025) and CERN-FASER-CONF-2026-005):

- Integrated luminosity of (186±4) fb^{-1}
- 766.8±29.6 ν_μ CC events are identified, with backgrounds subtracted
- First measurement separating ν_μ and $\bar{\nu}_\mu$ as functions of energy and rapidity

SND@LHC (arXiv:2606.14669):

- Integrated luminosity of 68.6 fb^{-1}
- 31 ν_μ CC candidates against an expected background of 5.0±1.1 events
- $\sigma(\nu_\mu + \bar{\nu}_\mu)$ on tungsten = $(37^{+24}_{-12})\times10^{-35}$ cm^2 (median E_ν=228 GeV)





Observation of ν_e interactions in the calorimeter at FASER

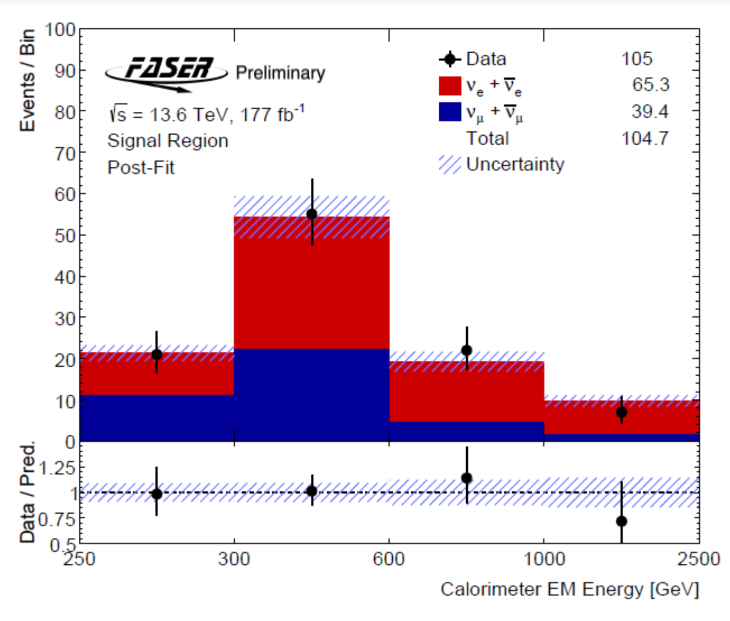
CERN-FASER-CONF-2026-004

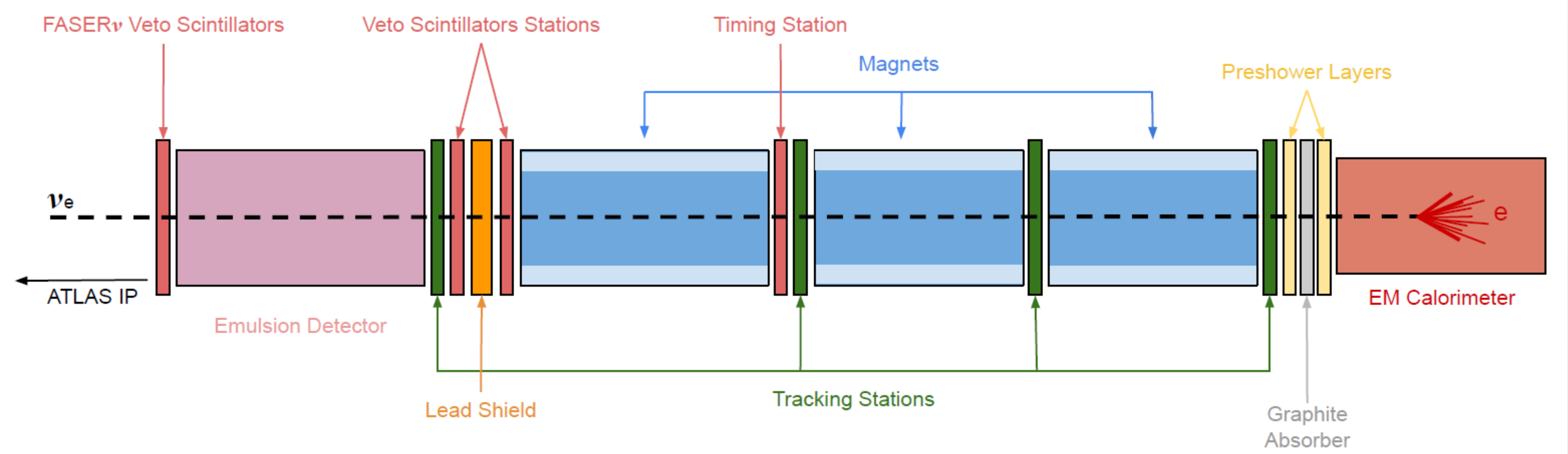
ν_e interactions selected using electromagnetic energy deposits in the calorimeter

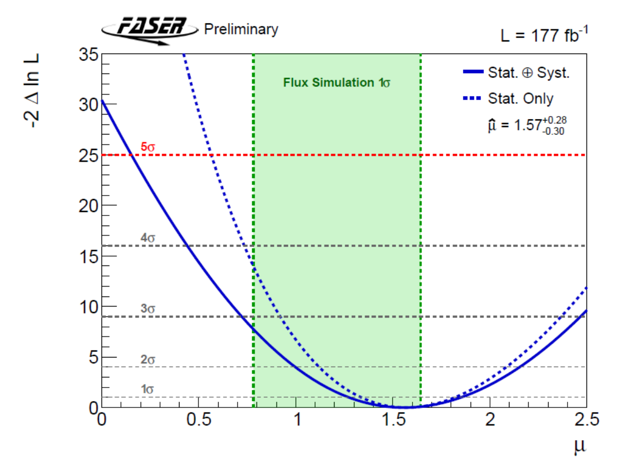
- Selection targets ν_e and $\bar{\nu}_e$ CC and NC interactions
- Event selection: no upstream activity + large downstream EM energy deposit
- Dominant ν_μ background constrained using upstream measurements

Results (177 fb^{-1} analyzed, 2022-2024):

- 105 candidates observed
- Best-fit ν_e signal: 65±12 events
- Highest energy candidate: 2.1 TeV calorimeter energy deposit
- Background-only hypothesis rejected at 5.5σ (4.6σ expected)





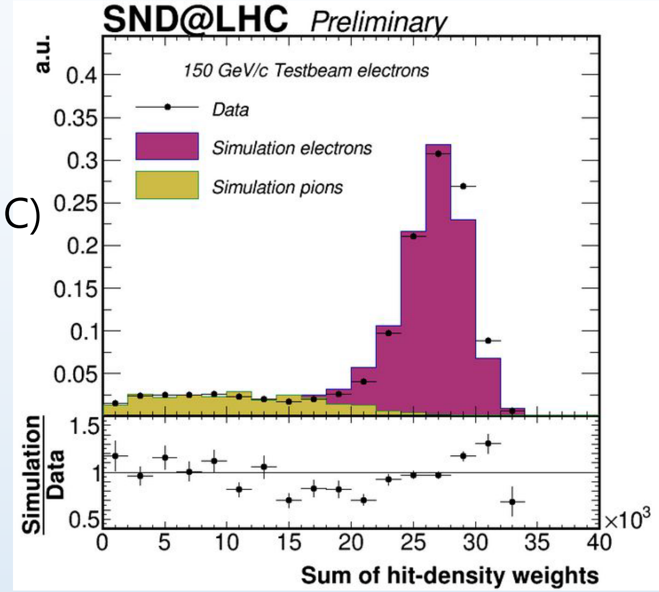


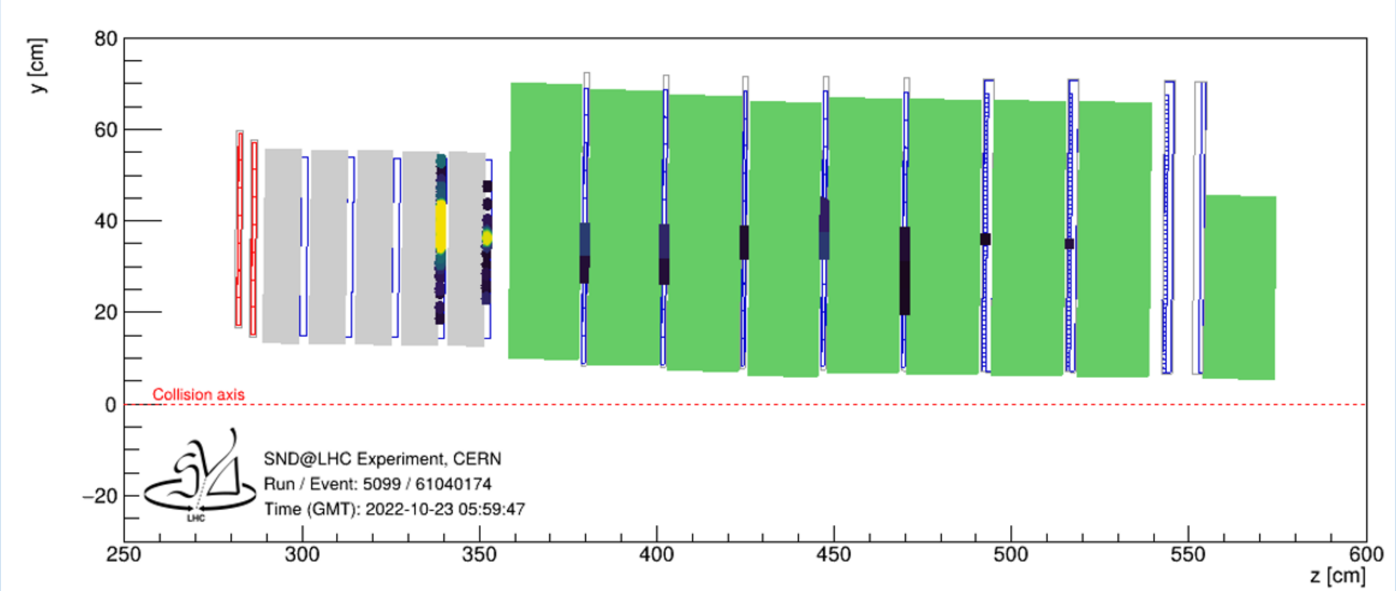
Neutrino interactions without final-state muons

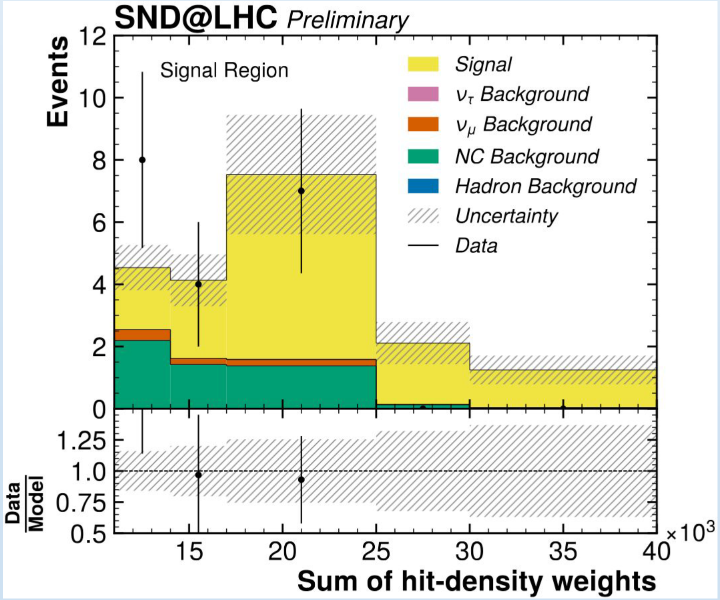
in electronic detectors at SND

Courtesy of the SND@LHC coll.

- Observation of events without final-state muons (0μ) with 2022-2023 data
  - Presented at Neutrino 2024 and published after that: [Phys. Rev. Lett. 134 (2025) 231802]
  - 9 events observed over 0.32±0.06 expected background (signal dominated by ν_e CC and NC)
- ν_e candidate results (Preliminary)
  - Binned likelihood analysis on the summed hit density in the target
  - 19 events observed (13±5 signal, 6±1 background expected)
  - Significance: 2.7σ (binned), 3.6σ (unbinned)
  - Evidence for ν_e interactions in electronic detector data







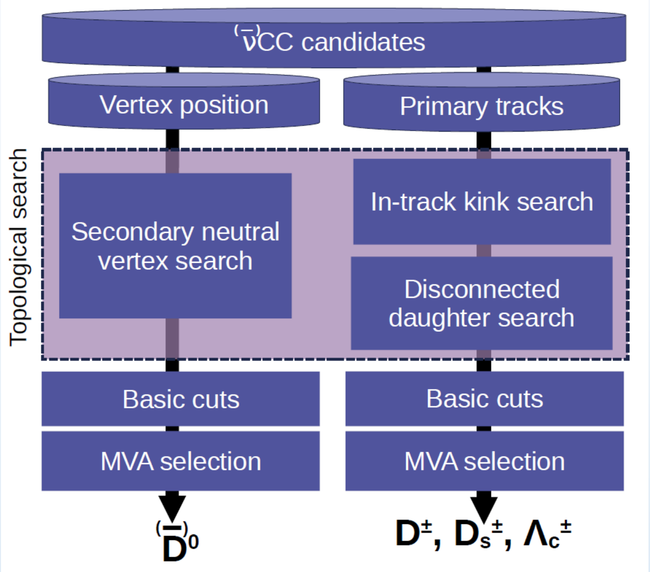
First search for neutrino-induced charm production with FASERν

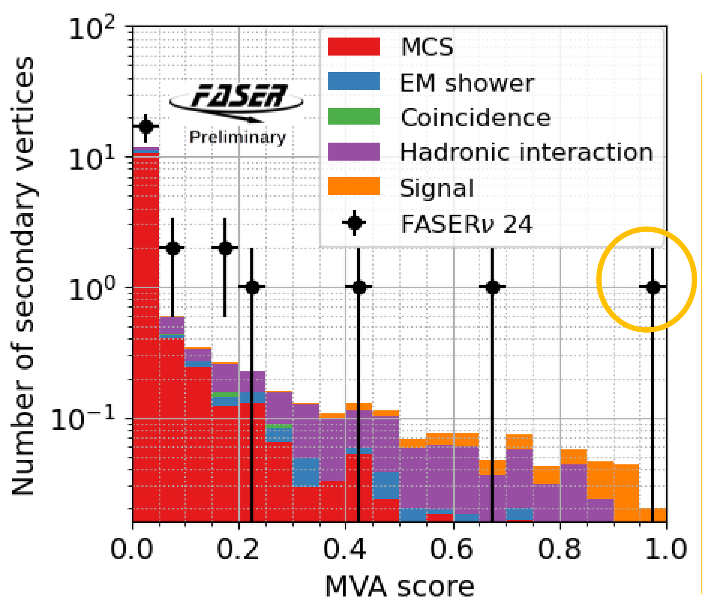
- First search using the first FASERν Run-3 dataset (9.5 fb^{-1}, 2022 first module):
  [CERN-FASER-CONF-2026-003]

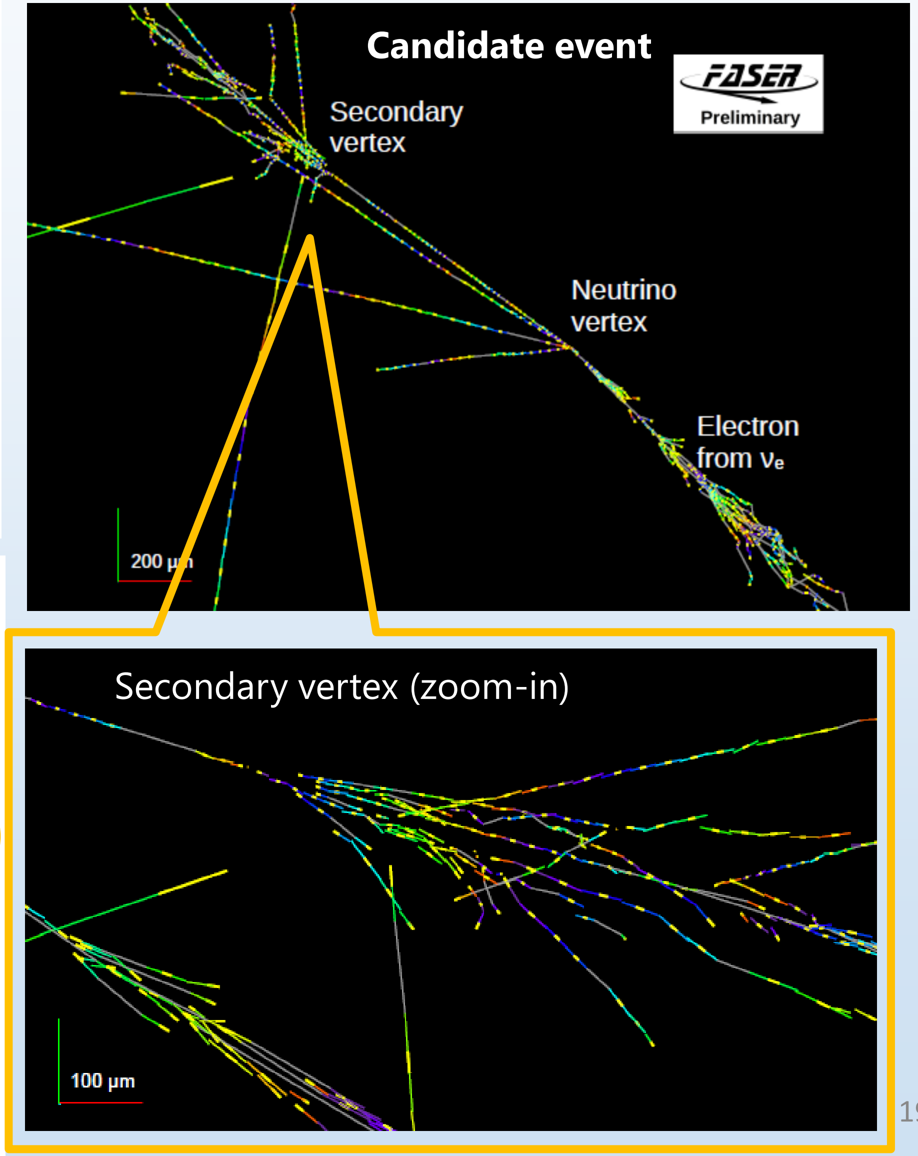
Motivations
- First search for charm hadrons in TeV-scale neutrino interactions
- Access to strange PDFs and charm production
- Path toward first ν_e-induced charm measurements and lepton universality tests
- Important milestone toward ν_τ searches

Analysis strategy
- Search for charged charm decays using secondary vertices in emulsion
- Kinematic selection followed by an interpretable ML classifier

Status
- 40 neutrino candidates analyzed
- Data and simulation broadly agree; selected charm candidates under investigation





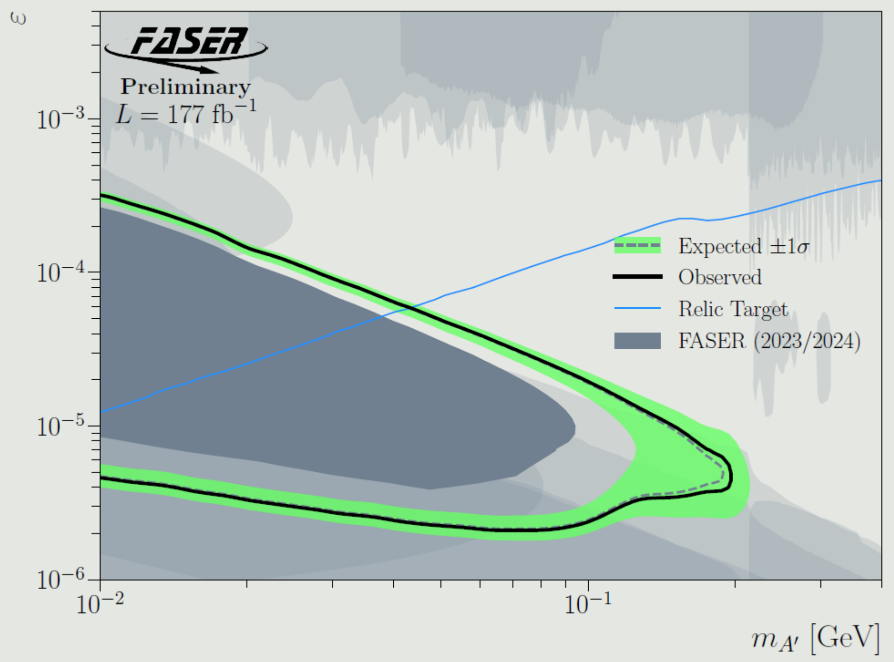


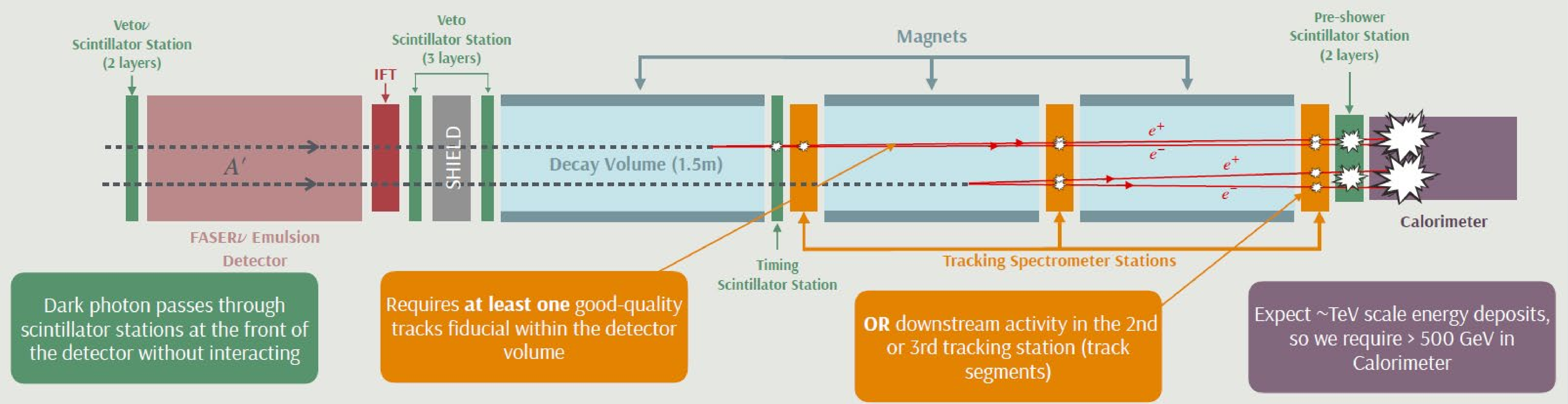
Other BSM searches: Dark photons

Search for dark photons decaying into e^+e^- using 2022-2024 data

Previous result: Phys. Lett. B 848, 138378 (2024)
- 27 fb^{-1} of data collected in 2022

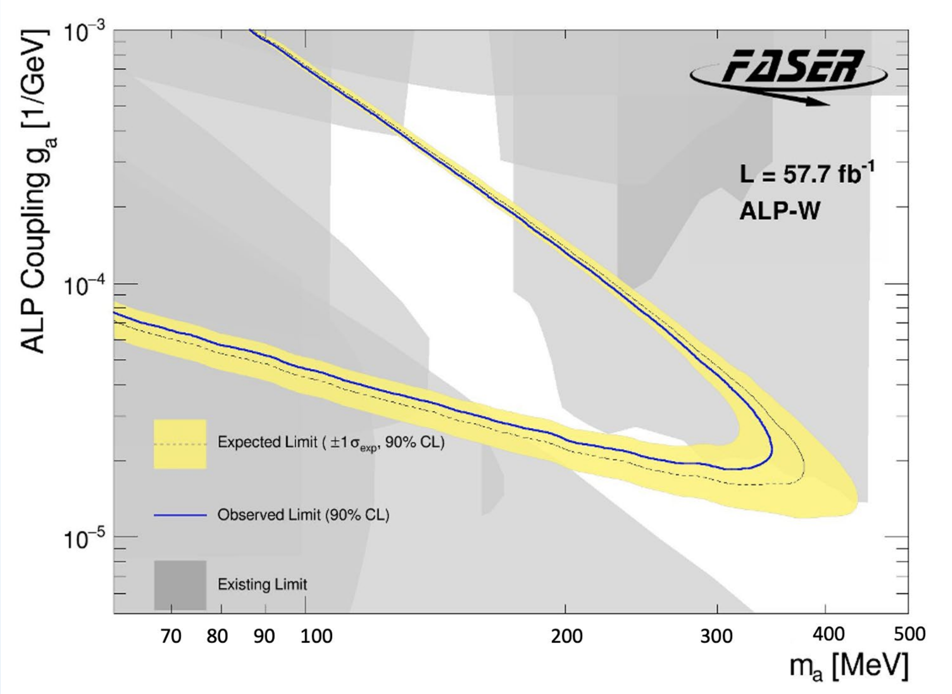
Updated result: CERN-FASER-CONF-2026-001
- Improved signal selection strategy (2.5x better acceptance)
- 2022, 2023, 2024 data (>6x more data)

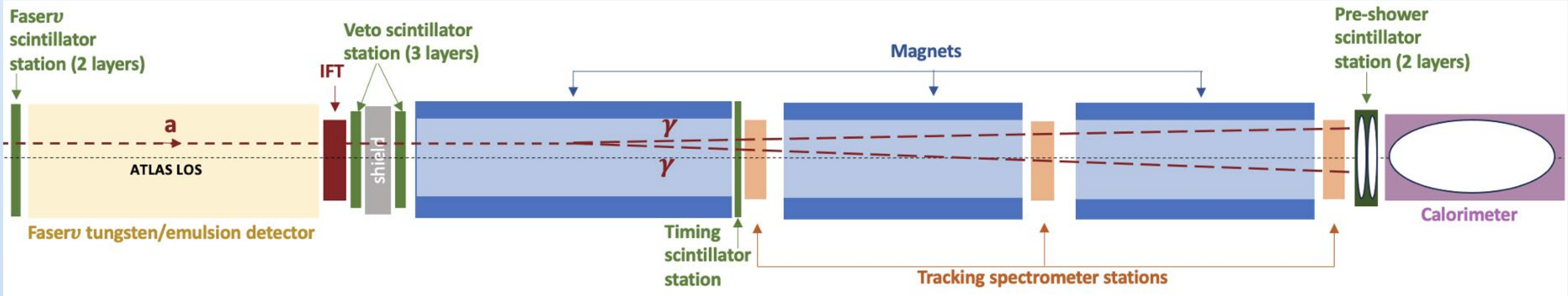




Other BSM searches: Axion-like-particles

- First FASER search for a light, long-lived particle decaying into a pair of photons (2022-2023, 57.7 fb^{-1}): JHEP01, 199 (2025)
- Signature: high-energy EM deposits + no veto activity
- 1 observed (0.44±0.39 expected background from neutrino interactions)
- World-leading constraints in previously unexplored parameter space





Prospects for HL-LHC

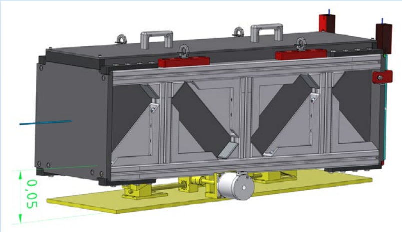
- LHC Run 3 has been completed with successful operation and first physics results from both FASER and SND@LHC.
- Both collaborations are preparing upgrades and extended neutrino programs for LHC Run 4.

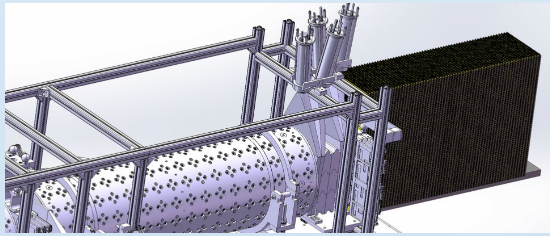
- The available space at FASER and SND@LHC is limited; The Forward Physics Facility (FPF) has been proposed to expand the forward physics reach at the HL-LHC, including neutrino and LLP programs.
- Additional concepts based on surface- and lake-based detectors have also been discussed.

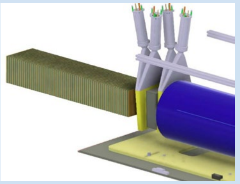
Upgrade for LHC Run 4: FASER and SND@LHC

FASER

- Continue the neutrino program with complementary detector concepts
- Main direction: on-axis neutrino detector
  - combine the proven FASERν emulsion approach with an on-axis electronic detector
  - overlap with the FASER spectrometer for muon momentum and charge measurements
- Additional off-axis option under study
- Technical proposal to LHCC planned for Sep 2026

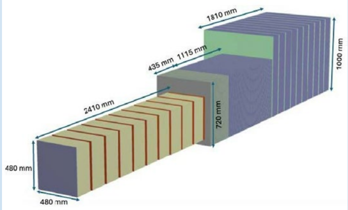


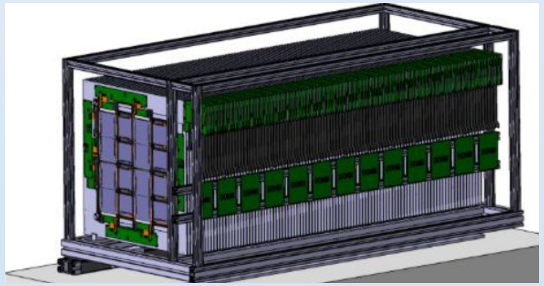




SND@LHC

- Continue the off-axis neutrino program
- Detector upgrade for higher HL-LHC rates
  - target replaced with silicon strip tracking
- Magnetized calorimeter foreseen
  - muon momentum and charge measurements
  - separation of neutrinos and anti-neutrinos



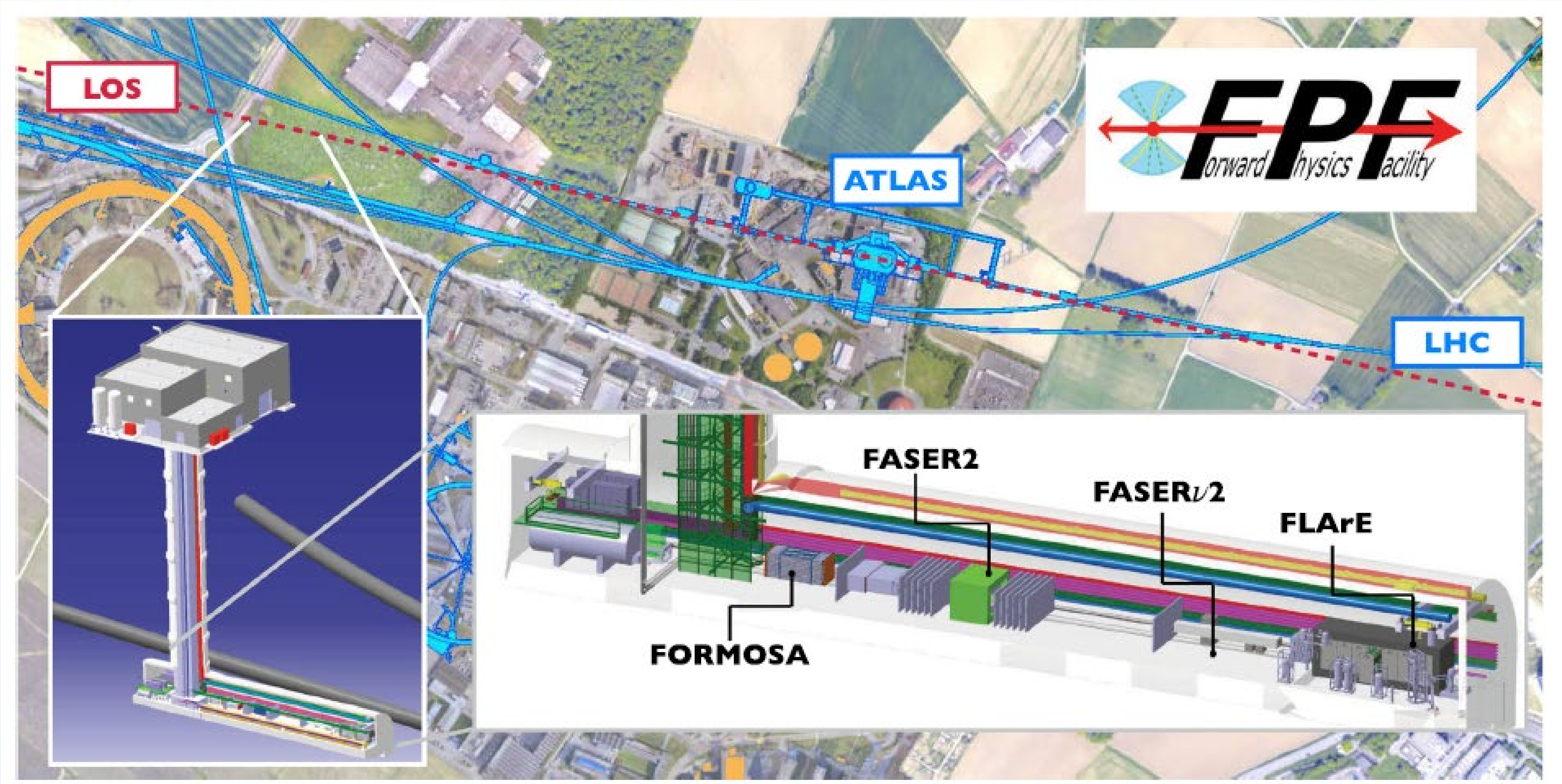


Extended neutrino measurements at the TeV scale with increased statistics

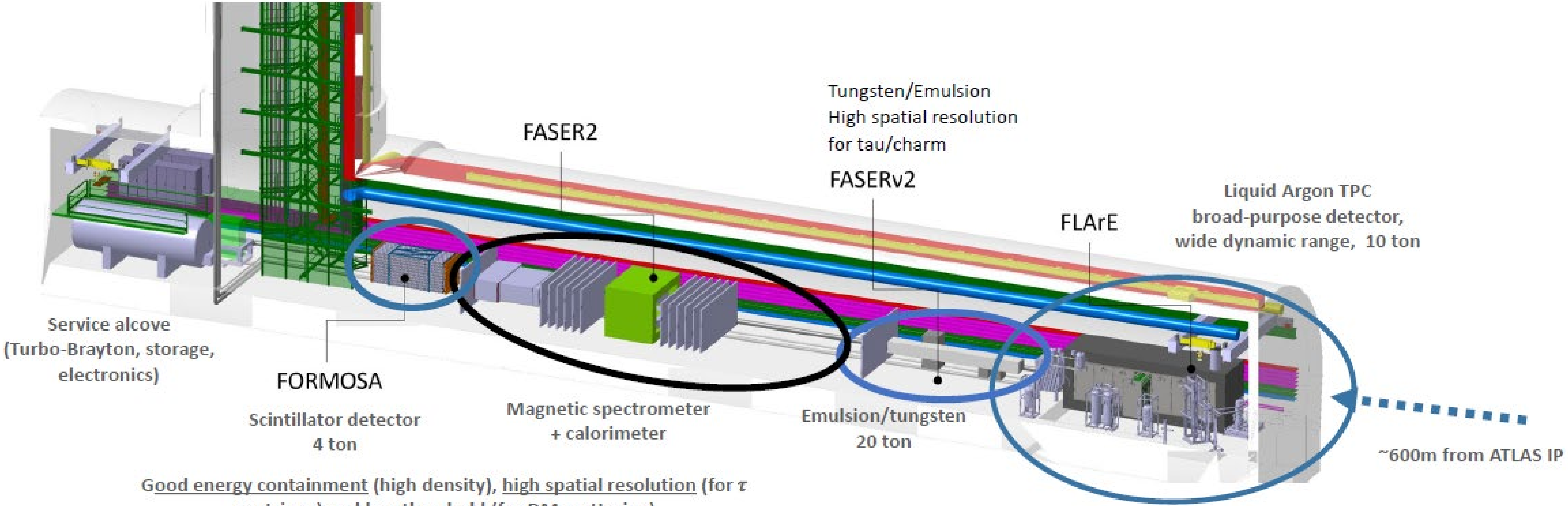
Forward Physics Facility (FPF)

- Proposed facility for an expanded forward neutrino and LLP program at the HL-LHC
- 627-702 m from the ATLAS IP
- 75 m long and 12 m wide

- Eur. Phys. J. C 85:430 (2025), "Scientific program for the Forward Physics Facility"
- Nucl. Phys. B 1026, 117398 (2026), "The forward physics facility: Physics opportunities and conceptual design"

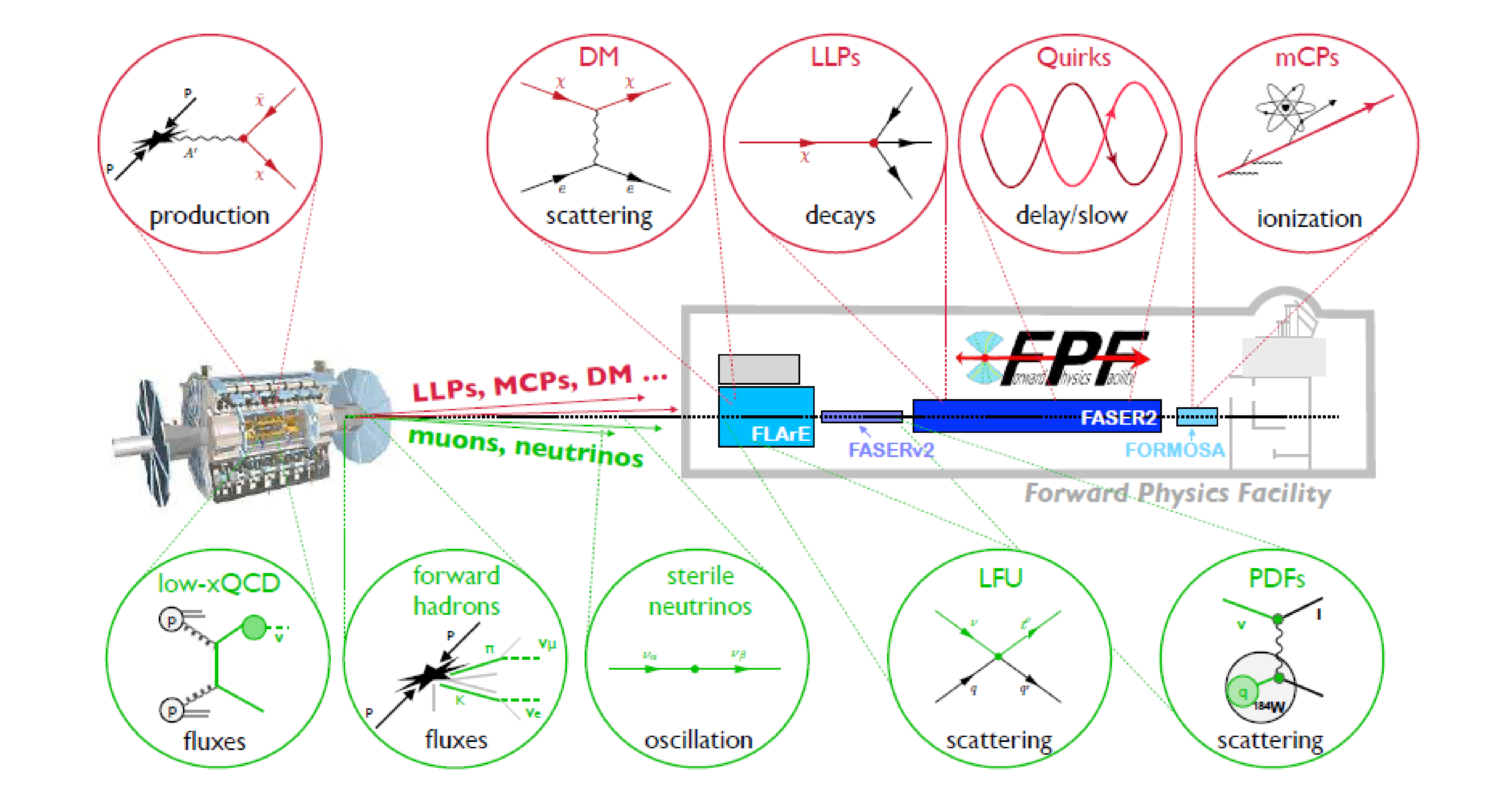


FPF experiments



Good energy containment (high density), high spatial resolution (for τ neutrinos) and low threshold (for DM scattering)

New particle searches and neutrino measurements at the FPF

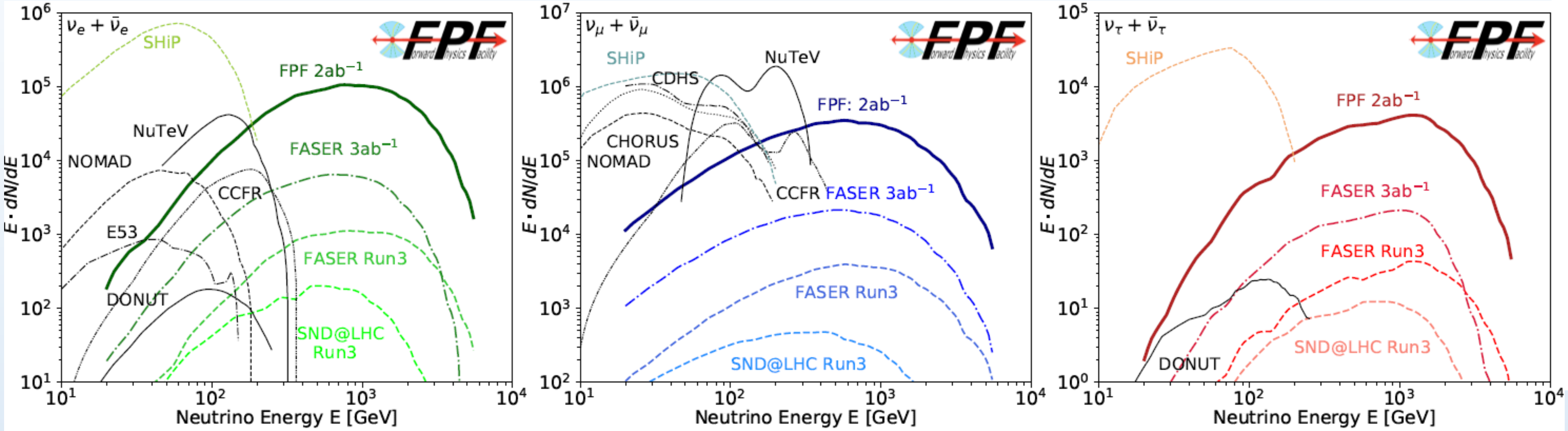


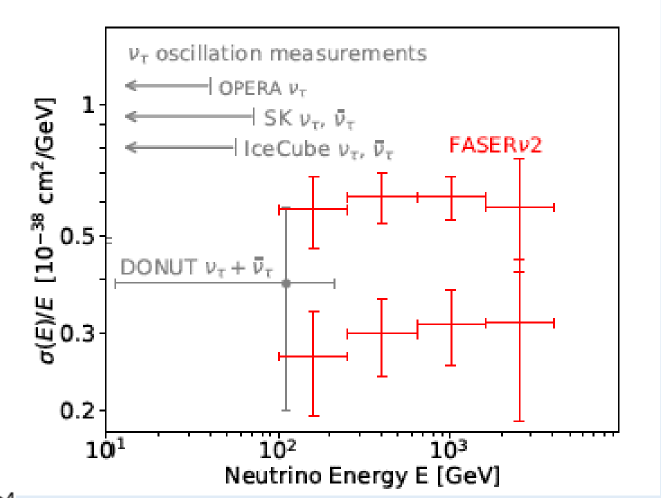
Neutrino physics case

at the FPF (1)

Expected data set

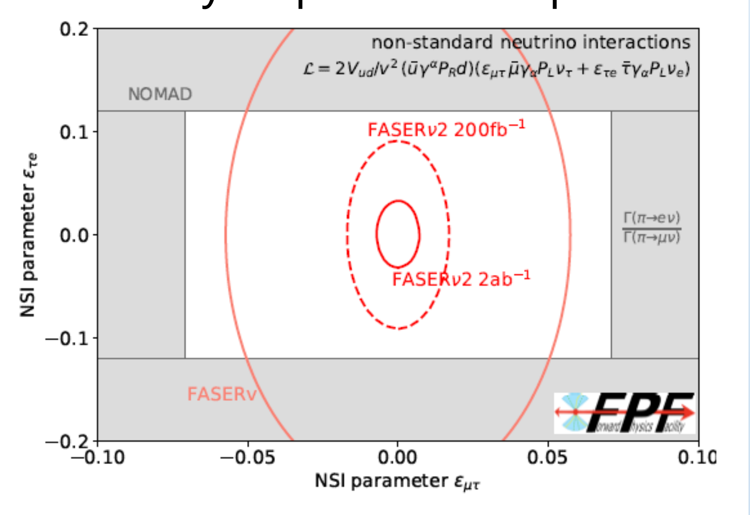
~10^6 ν_μ, ~10^5 ν_e, ~10^4 ν_τ interactions from HL-LHC



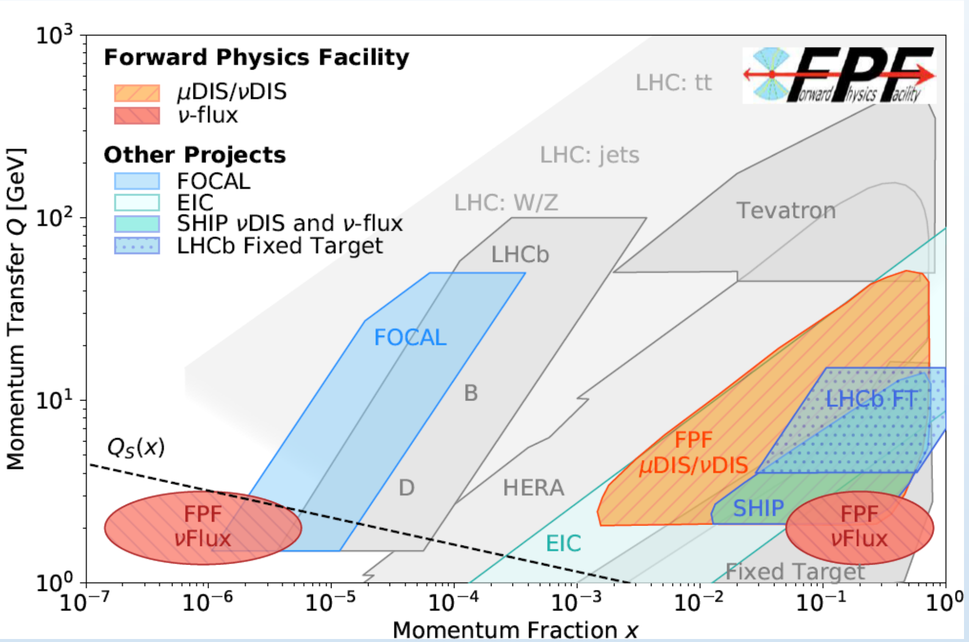


Detector				CC Interactions		
Name	Mass	Luminosity	Rapidity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν at Run 3	1.1 t	350 fb^{-1}	$\eta > 8.8$	2.3k	12k	40
SND@LHC at Run 3	0.8 t	350 fb^{-1}	$7.2 < \eta < 8.4$	300	1.5k	12
FASERν / FASER at HL-LHC	1.1 t	3 ab^{-1}	$\eta > 8.8$	19k	102k	360
SND@HL-LHC	1.3 t	3 ab^{-1}	$6.9 < \eta < 7.6$	2.9k	15k	143
FASERν2 at FPF	20 t	2 ab^{-1}	$\eta > 8.5$	127k	647k	2.3k
FLArE at FPF	10 t	2 ab^{-1}	$\eta > 7.5$	34.7k	167k	1.0k
FLArE HCAL at FPF	41 t	2 ab^{-1}	$\eta > 6.5$	34.0k	180k	1.5k
FASER2 veto at FPF	0.9 t	2 ab^{-1}	$\eta > 6.7$	1.6k	6.8k	54

Sensitivity to probe NSI operators

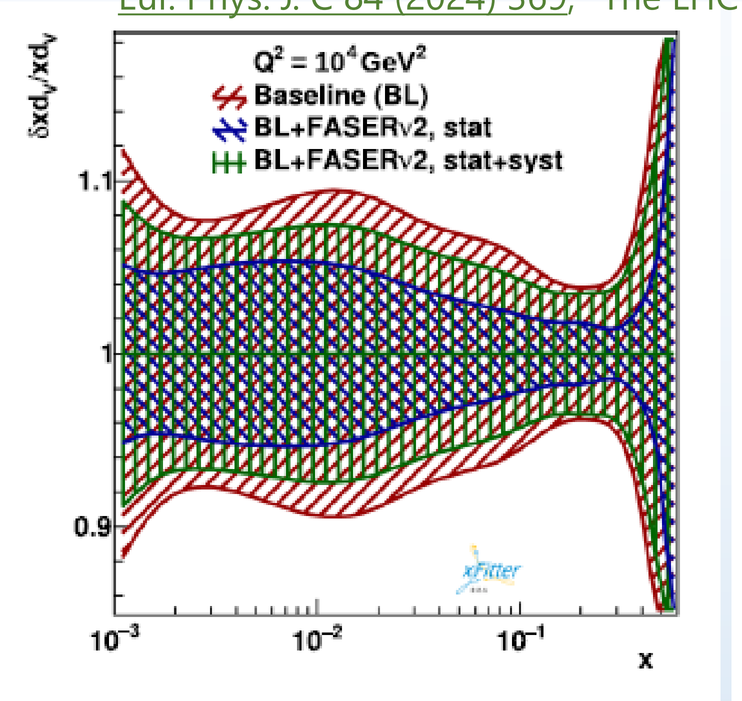


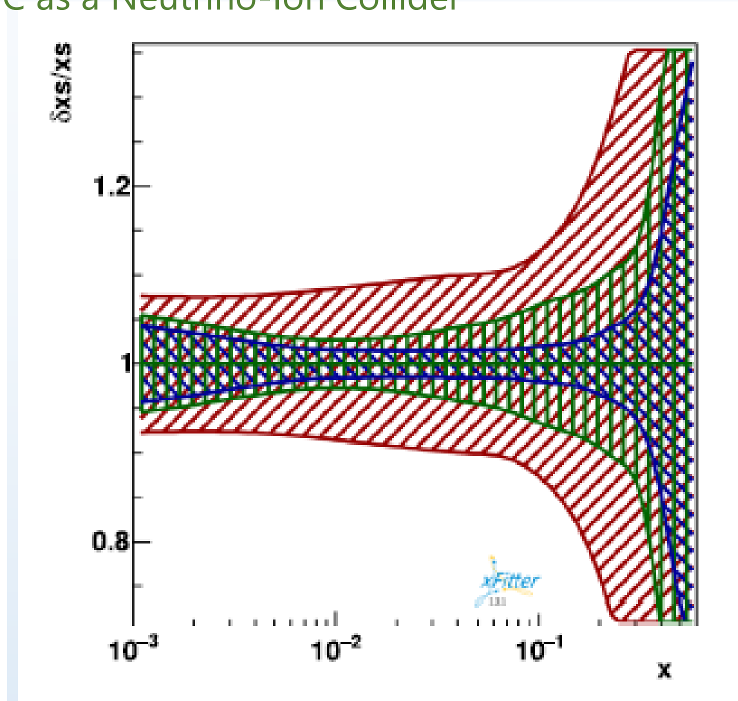
Neutrino physics case
at the FPF (2)



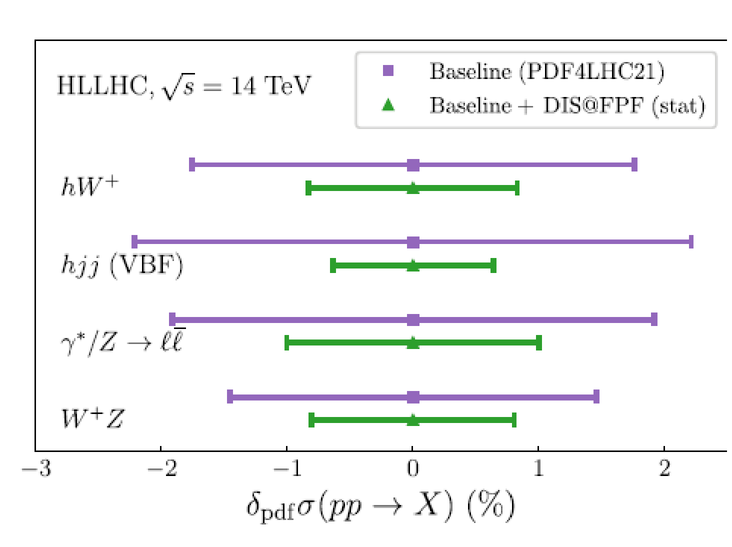
PDF uncertainties for the down valence quark and strangeness PDFs

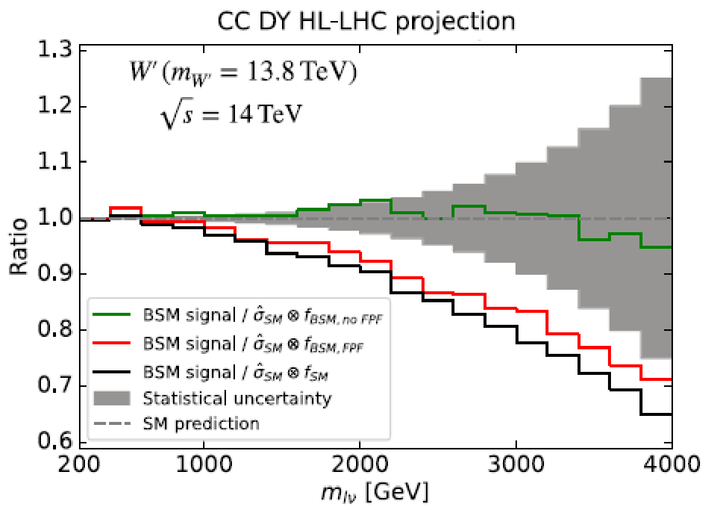
Eur. Phys. J. C 84 (2024) 369, "The LHC as a Neutrino-Ion Collider"





Eur. Phys. J. C 85:430 (2025), "Scientific program for the Forward Physics Facility"





Additional Surface- and Lake-Based Concepts

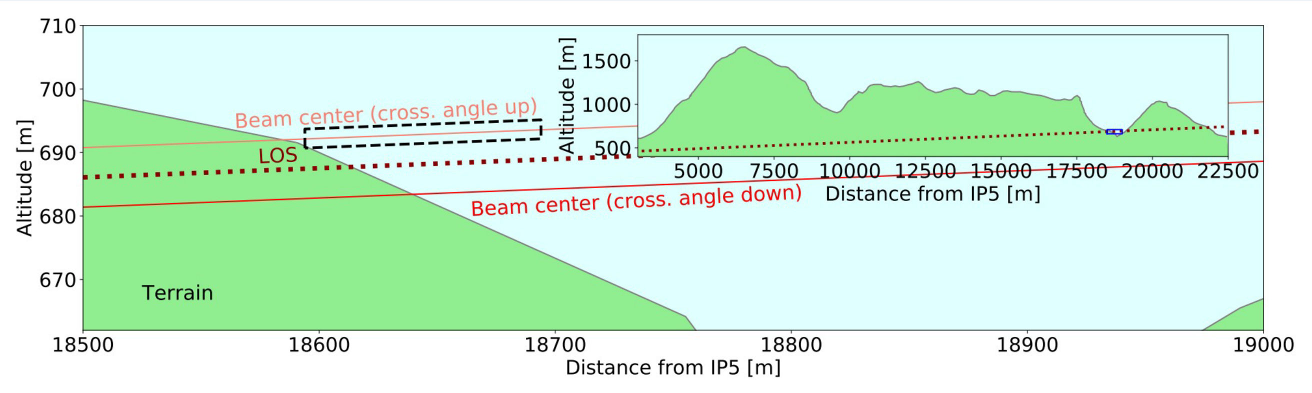
Courtesy of Toni Mäkelä

Surface-level LHC neutrino opportunities: JHEP07, 270 (2025)

- Explored surface-level detector opportunities using the natural topography around CERN
- Detailed site studies to identify possible detector locations
- Considered multiple detector concepts

Conclusion:

- At present, the physics potential of surface-level detectors remains limited compared to detectors closer to the interaction point, including the proposed FPF.



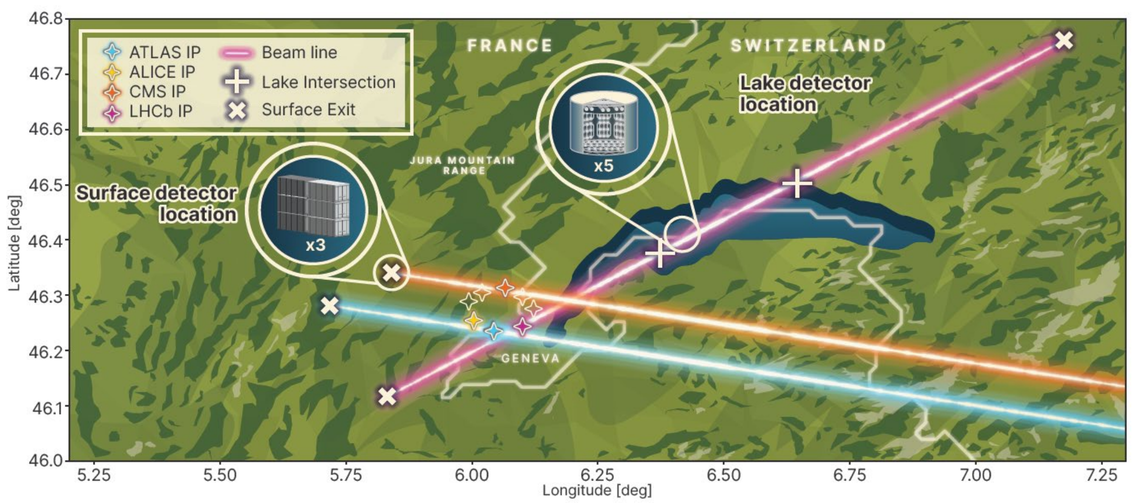
Courtesy of Carlos A. Argüelles and Nicholas W. Kamp

Lake- and Surface-Based Detectors for Forward Neutrino Physics: Phys. Rev. D 113, 052002 (2026)

- Proposed concrete detector concepts:
  - SINE (surface scintillator)
  - UNDINE (lake water Cherenkov)
- Medium-baseline, kton-scale experiments
- Physics targets: ν cross sections, forward charm, HNL

Conclusion:

- Proposed as a cost-effective medium-baseline complement to the short-baseline FPF

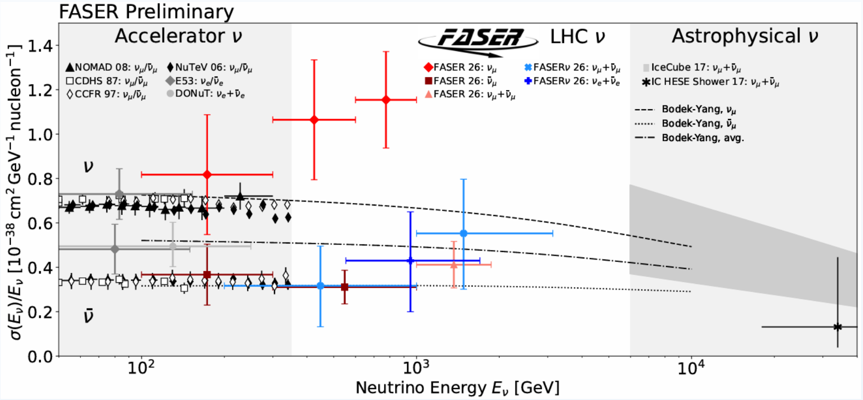


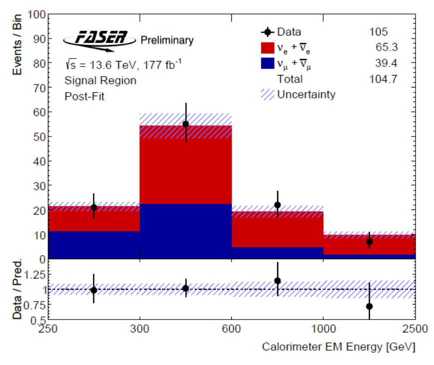
Two recent studies explored different concepts and detector strategies, leading to somewhat different conclusions.

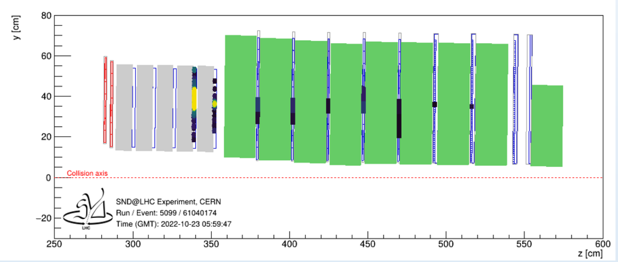
Summary and outlook

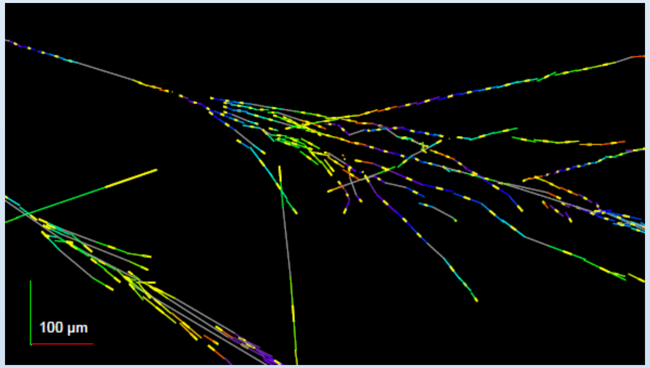
The LHC provides the highest-energy accelerator neutrinos (up to the TeV scale)

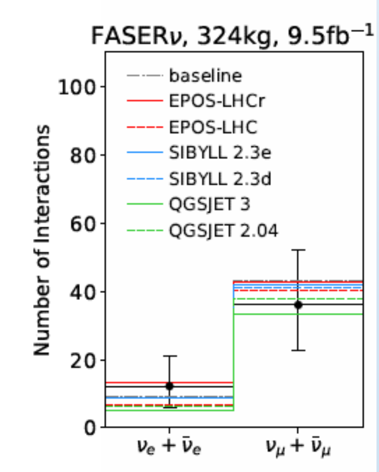
- Experiments at the LHC
  - FASERν (η > 8.8) and SND@LHC (7.2 < η < 8.4) installed during LS2
  - Data taking completed in Run 3 (2022-2026)
- Key results
  - First direct detection of collider neutrinos (ν_μ, ν_e)
  - First measurements of ν_e and ν_μ CC cross sections at TeV energies
  - Energy-dependent ν_μ cross section and flux
  - First charm search in TeV neutrino interactions
- Physics impact
  - Tests of lepton universality at TeV scale
  - Inputs to hadron production and PDF studies
  - Relevance to astroparticle physics
- Future prospects
  - Detector upgrades for LHC Run 4
  - Forward Physics Facility (FPF) proposed for a larger-scale HL-LHC neutrino program











Related posters at Neutrino 2026

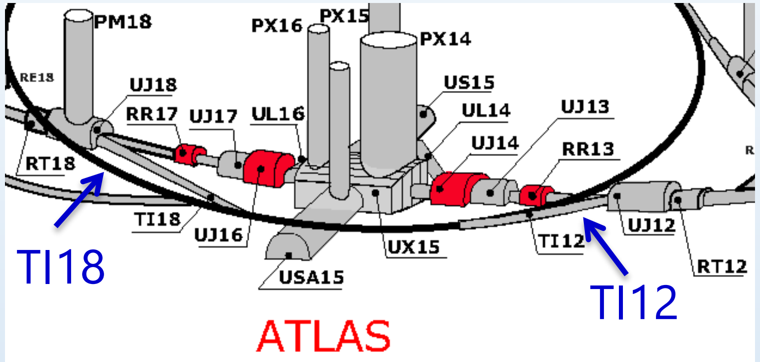
- **Poster 170**: Neutrino cross section measurements and momentum reconstruction with the FASERν detector (Haruhi Fujimori)
- **Poster 121**: First search for charm production in LHC neutrino interactions in the FASERν detector (Simon Thor)
- **Poster 122**: Studying Electron Neutrino at the LHC with FASER's Electronic Detectors (Lawson Michael Mccoy)
- **Poster 40**: Toward foundation models for neutrino interactions with multimodal masked autoencoder pretraining (Fabio Cufino)
- **Poster 221**: FLArE: Forward Liquid Argon Experiment at the Forward Physics Facility (Matteo Vicenzi)
- **Poster 103**: Anti-Electron Neutrinos at High-Energy Neutrino Experiments: Identification Strategies and Physics Potential (Toni Makela)
- **Poster 317**: Lake- and Surface-Based Detectors for Forward Neutrino Physics (Nicholas Kamp)

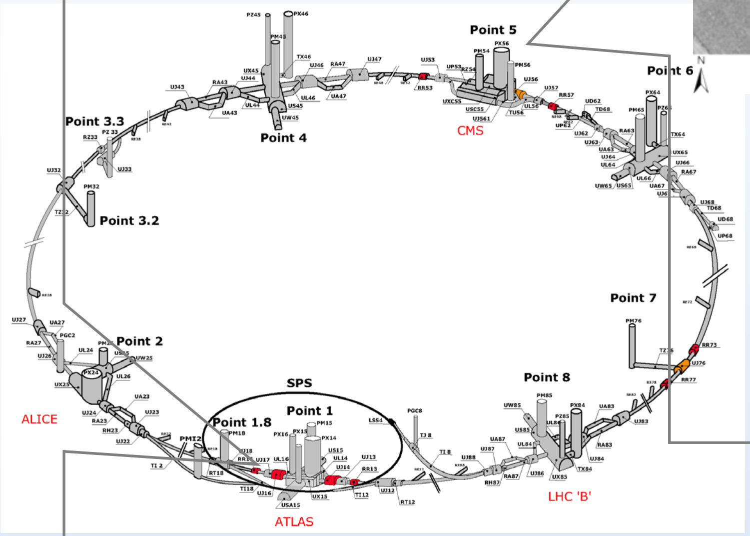
More details can be found in these dedicated poster contributions.

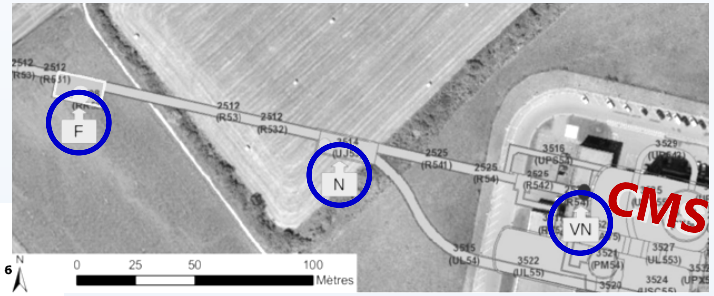
Backup

Site investigation in 2018

FASER measured backgrounds in the tunnels **TI18 and TI12**, located 480 m from the ATLAS IP.







Another group (later leading to XSEN and SND@LHC) investigated the background around CMS

- VN: Q1 at 25 m
- N: UJ53, UJ57 at 90, 120 m
- F: RR53 at 240 m

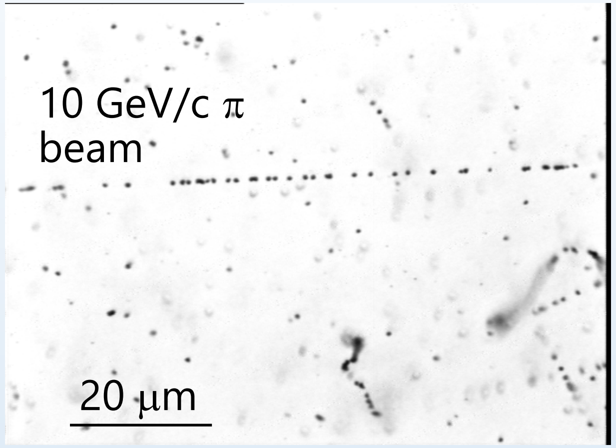
- **FASER** was proposed in 2018.
- **Small emulsion prototype was installed** on the LHC collision axis, measured backgrounds and provided first neutrino candidates. Dedicated neutrino detector **FASER**ν was added to FASER.

- Another group investigated possible neutrino detector sites in the LHC tunnel, which led to the XSEN proposal.
- Later merged with SHiP's SND proponents to form **SND@LHC**.

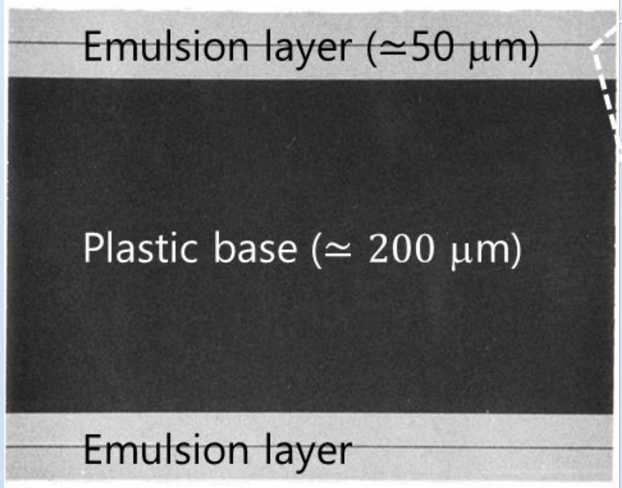
Emulsion Detector: Principle and Applications

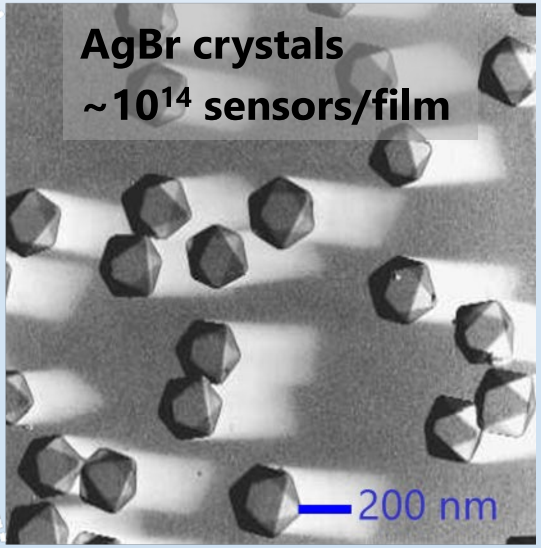
3D tracking device with ~50 nm position resolution:
Charged particles leave tracks as a sequence of silver grains

Emulsion film

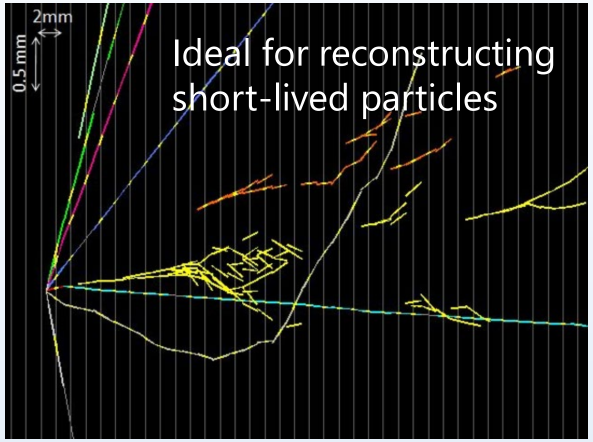


Cross-sectional view



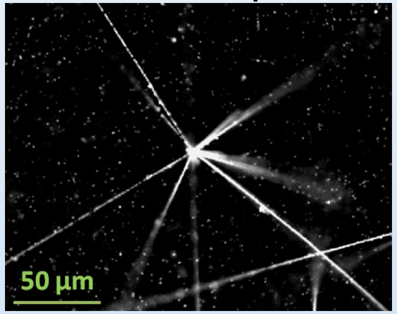


Neutrino experiments

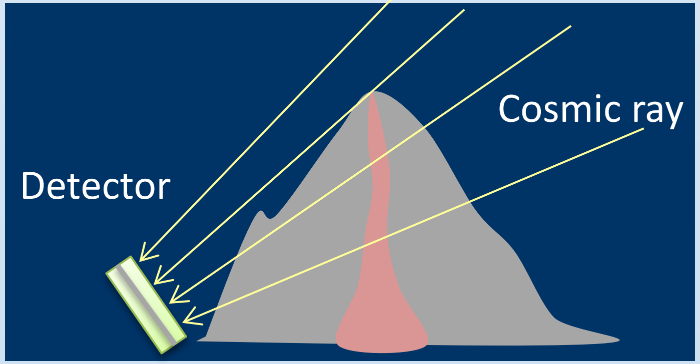


Gamma-ray telescope

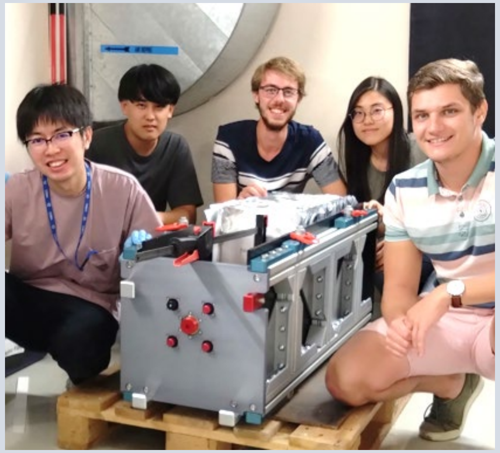
Antimatter experiments

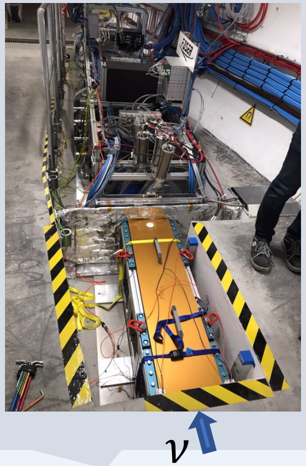


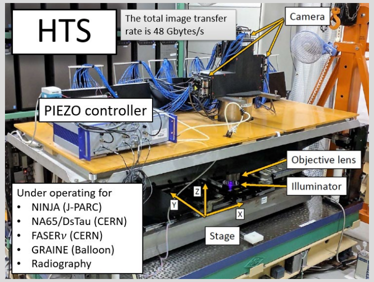
Muon radiography

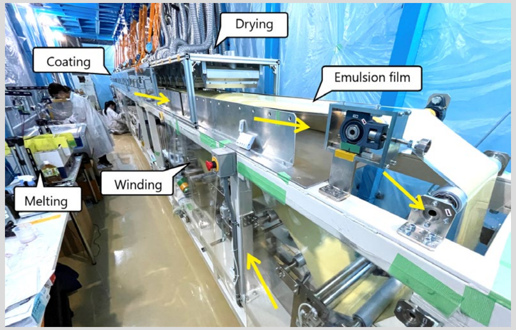


FASERν workflow









Japan

Emulsion film production →

CERN

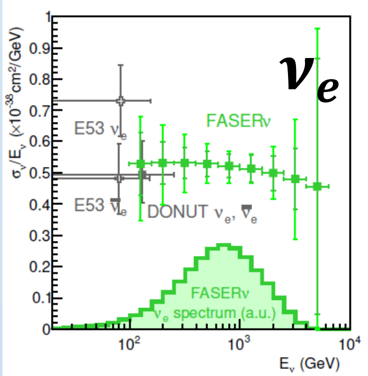
Detector assembly → **Exposure** → **Disassembly and development** →

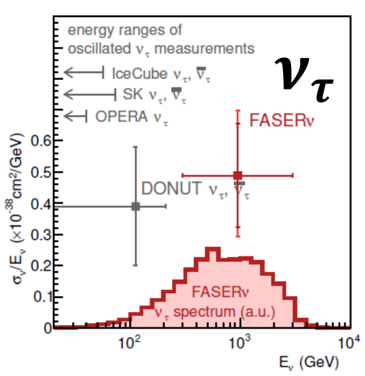
Japan

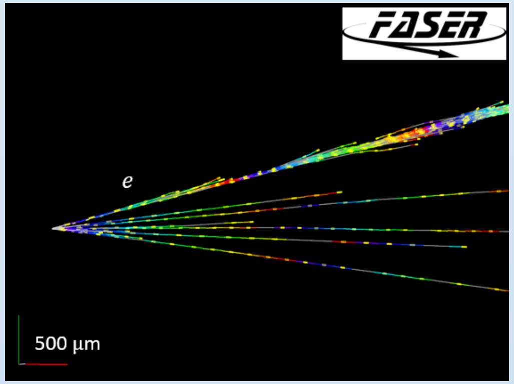
Readout

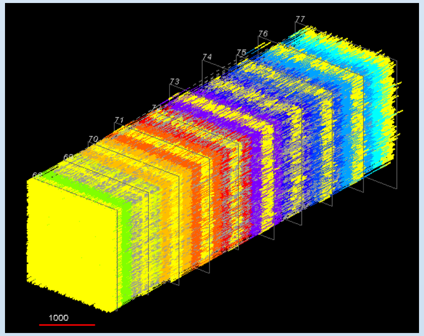
↓

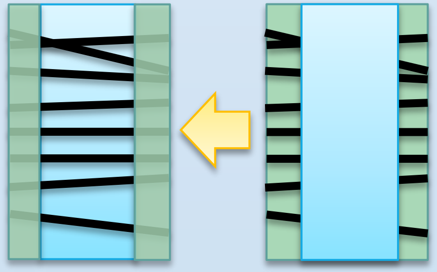
Alignment ← Track reconstruction ← Vertex reconstruction ← μ / e ID ← τ / charm decay search ← Further analysis











Comparison with predictions from recent hadronic interaction model

arXiv:2507.23552
CERN-FASER-CONF-2025-004

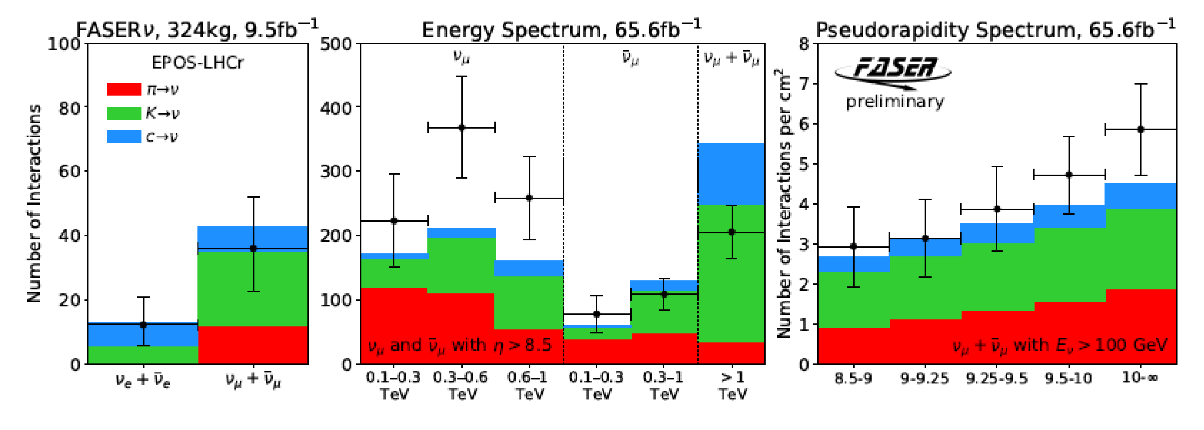
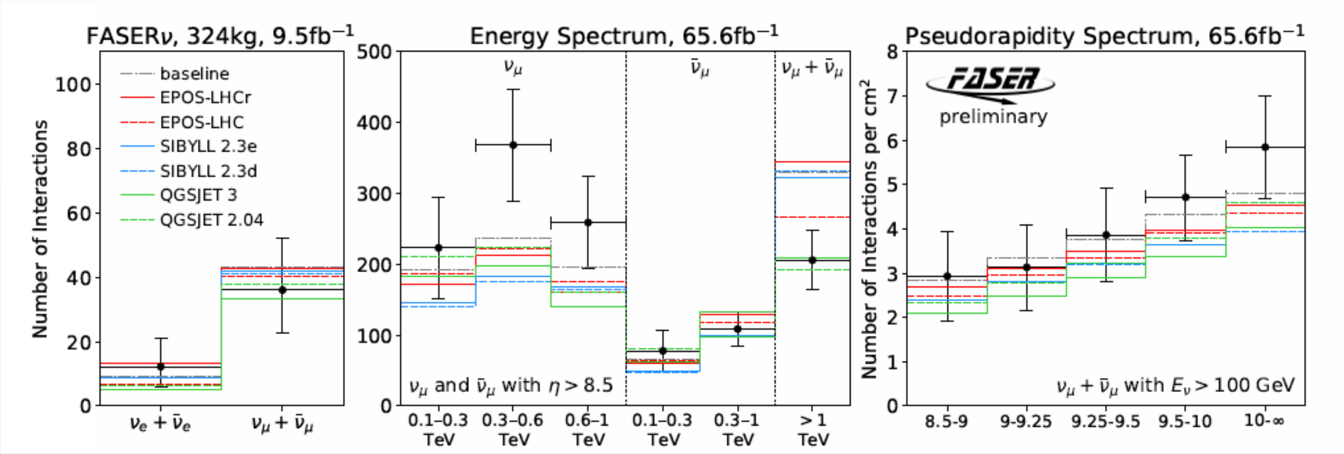


Figure 2: Comparison of EPOS-LHCr, split by production modes, to FASER data.



- The predictions are generally consistent with the measured fluxes from FASER, although some discrepancies appear in certain energy bins.
- More precise flux measurements with additional data will follow soon, enabling validation of pion, kaon, and charm meson production with finer energy binning, reduced uncertainties, and multi-differential analyses.

Additional Surface- and Lake-Based Concepts
(Location and Flux)

Surface-level LHC neutrino opportunities:
JHEP07, 270 (2025)

IP/Side	luminosity	distance	relative flux	comment
IP1W	$3000\,\text{fb}^{-1}$	26.9 km	0.1	in Jura mountains
IP1E	$3000\,\text{fb}^{-1}$	183 km	0.0025	very far
IP5W	$3000\,\text{fb}^{-1}$	18.7 km	0.25	in Jura mountains
IP5L	$3000\,\text{fb}^{-1}$	9 km	1	in Lake Geneva
IP5E	$3000\,\text{fb}^{-1}$	166 km	0.0029	very far
IP8L	$300\text{–}600\,\text{fb}^{-1}$	26 km	0.0125–0.025	in Lake Geneva
IP8S	$300\text{–}600\,\text{fb}^{-1}$	24.6 km	0.0133–0.0266	in Jura mountains
FASER/SND	$3000\,\text{fb}^{-1}$	480 m	351	TI12/TI18
FPF	$3000\,\text{fb}^{-1}$	620 m	210	purpose-built cavern

Lake- and Surface-Based Detectors for Forward Neutrino Physics: Phys. Rev. D 113, 052002 (2026)