九州大学
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Neutrino experiments at the LHC

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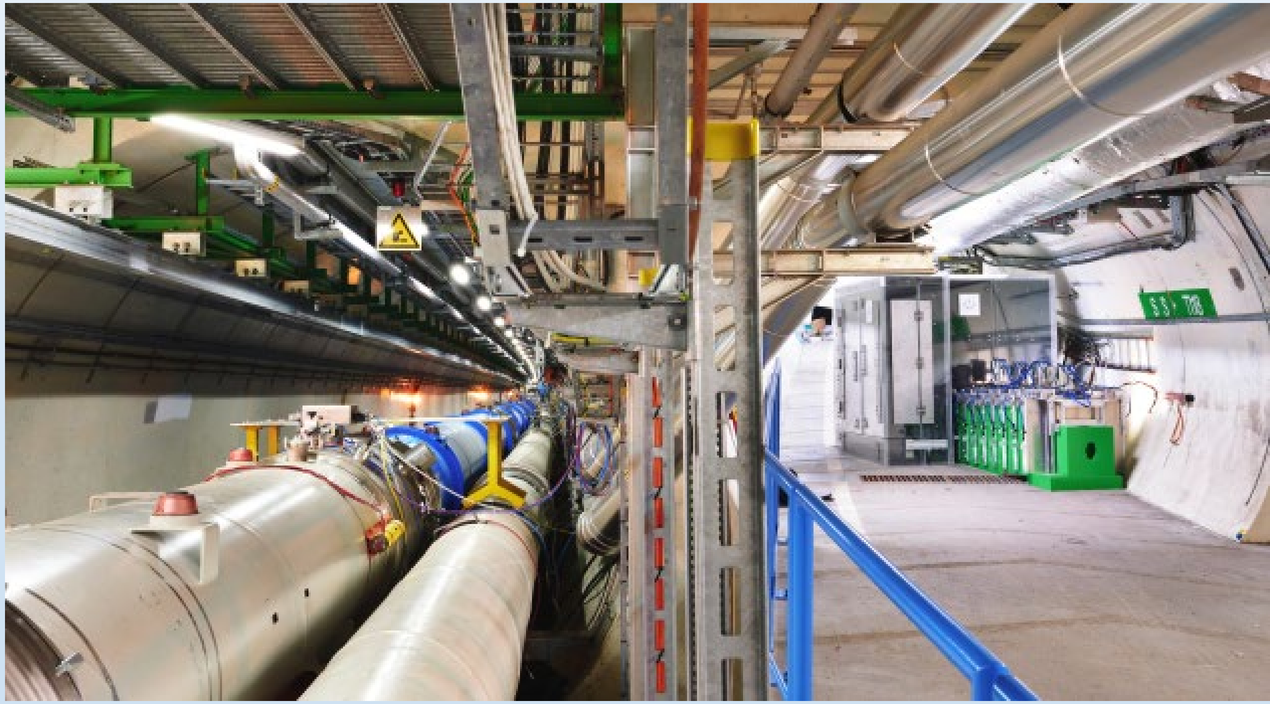
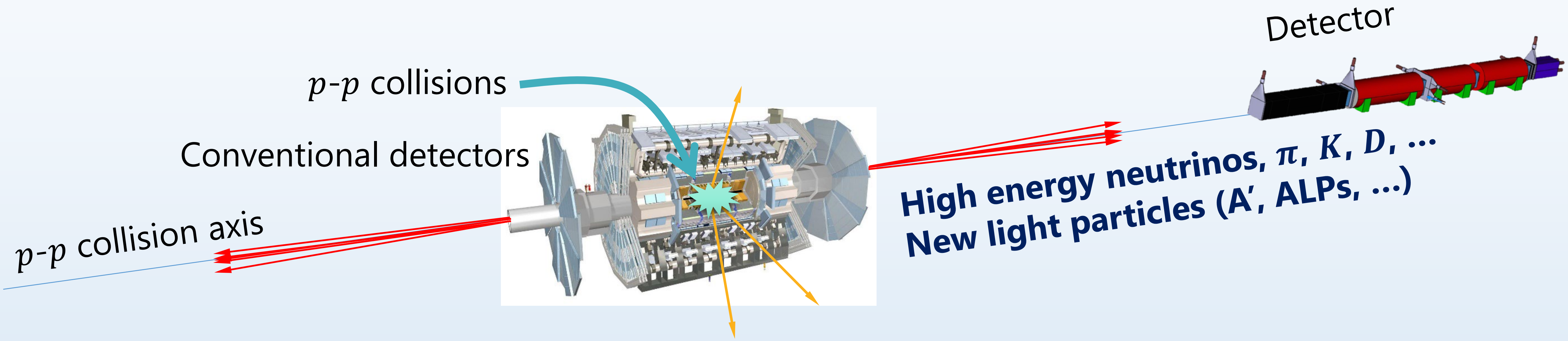


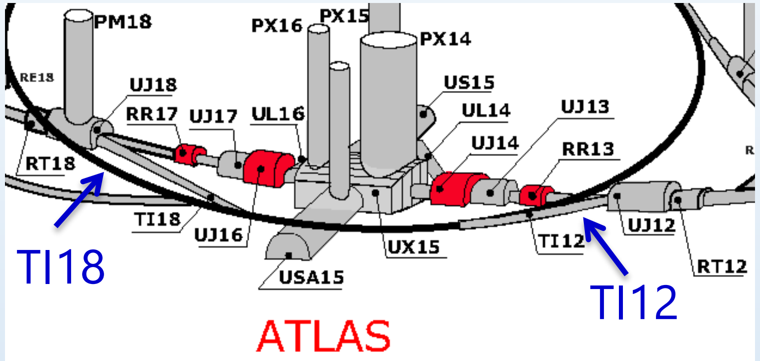
Neutrinos at the LHC

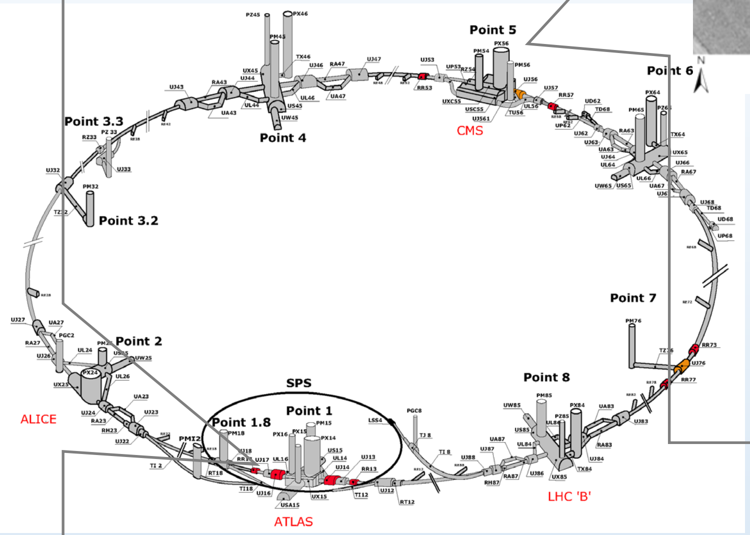


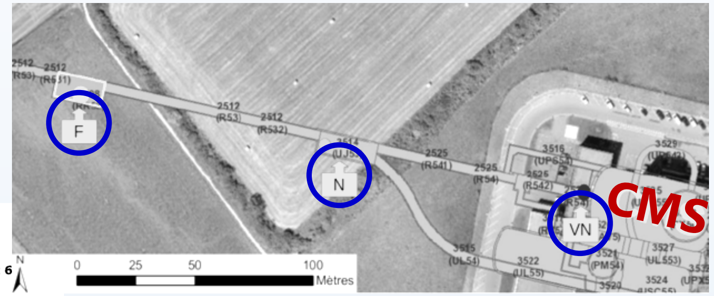
- LHC produces the most energetic neutrinos created by humankind (~TeV region)
- Interest in detecting LHC neutrinos had been expressed earlier, e.g.,
  - A. De Rujula and R. Ruckl, "Neutrino and muon physics in the collider mode of future accelerators", 1984
- However, neutrinos had never been directly observed at a collider before the 2020s.

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

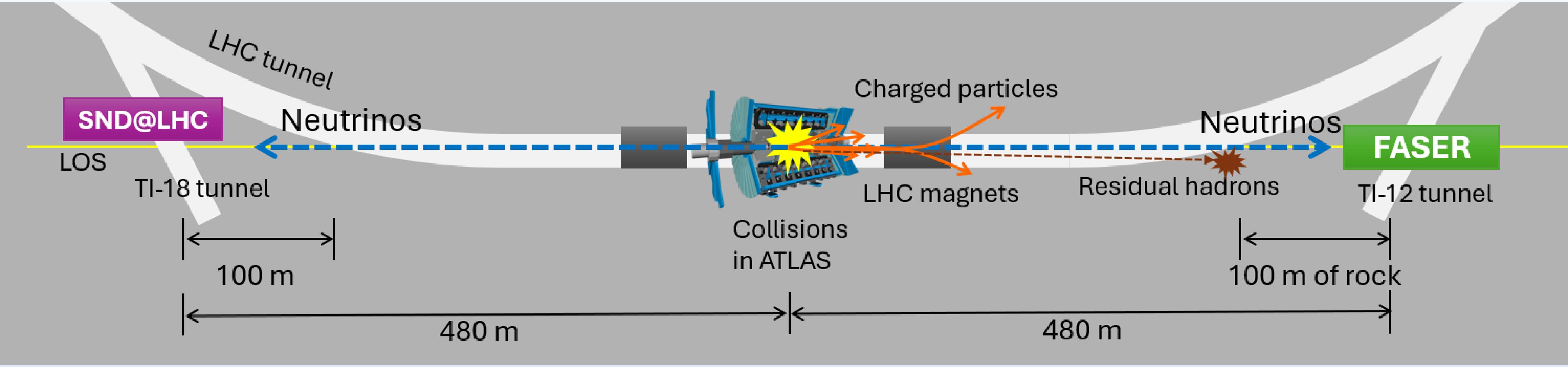
- VN: Q1 at 25 m
- N: UJ53, UJ57 at 90, 120 m
- F: RR53 at 240 m

- **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 **FASERν** 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**.

Neutrino experiments at the LHC

Parallel talks on Oct 1
- Yuxiao Wang, “Neutrino studies with FASER”
- Fabio Alicante, “The Scattering and Neutrino Detector 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)
  - Operations continue until end of Run 3 (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: $7.2 < \eta < 8.4$

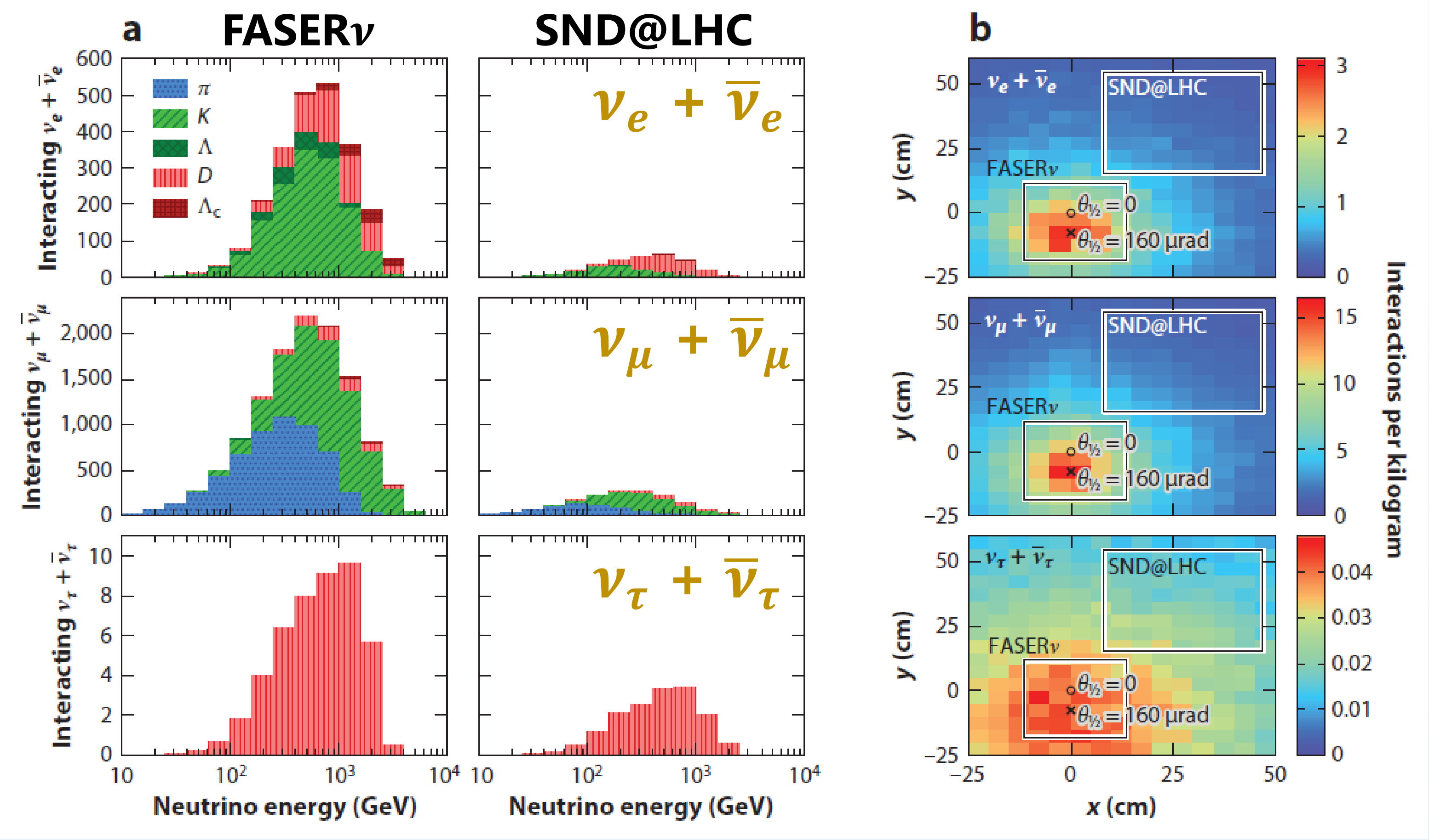
Neutrino energy and spatial distributions

Experiments	η coverage	Tungsten target mass [kg]		ν_e	ν_μ	ν_τ
FASER	η >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< η <8.4	800	**N int** **E average**	307^{+307}_{-116} 442 GeV	1694^{+297}_{-549} 357 GeV	15^{+26}_{-7} 596 GeV

Annu. Rev. Nucl. Part. Sci. 2025. 75:57–81
"Neutrino Experiments at the Large Hadron Collider"

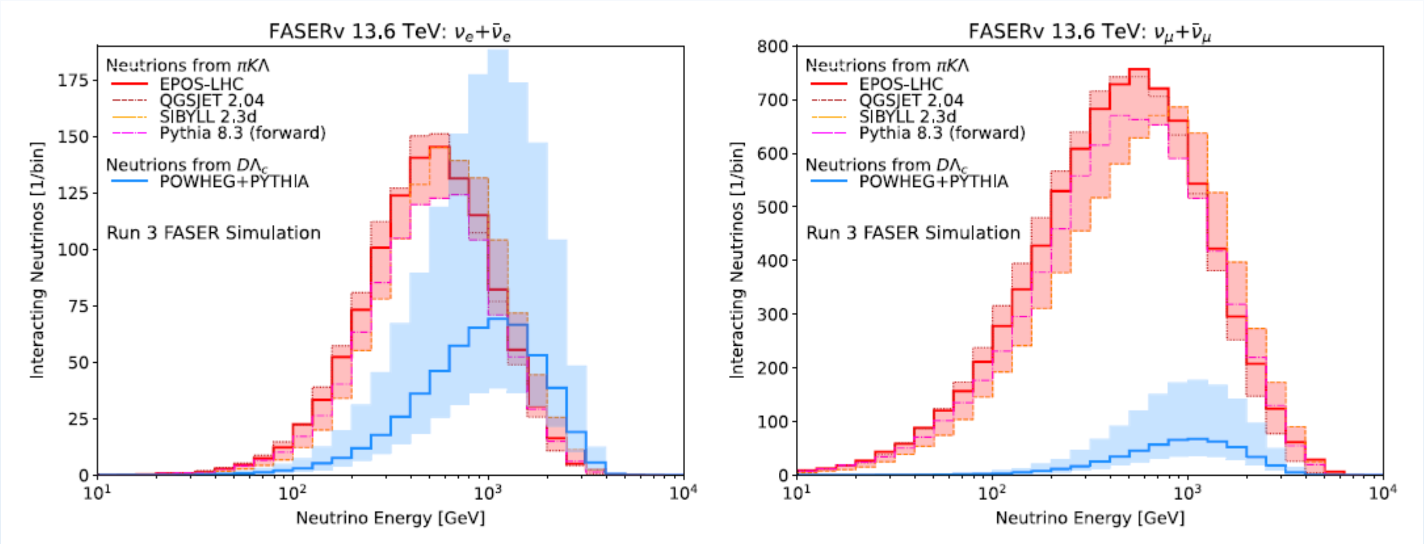
- This prediction uses **Epos-lhc** to simulate the **production of forward light hadrons** and the envelope formed by Epos-lhc, Sibyll 2.3d, and Qgsjet 2.04 as well as the forward physics tune of Pythia to define an uncertainty band.
- **Charm hadron production** is modeled using **Powheg** matched 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}



Uncertainties in the flux predictions

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

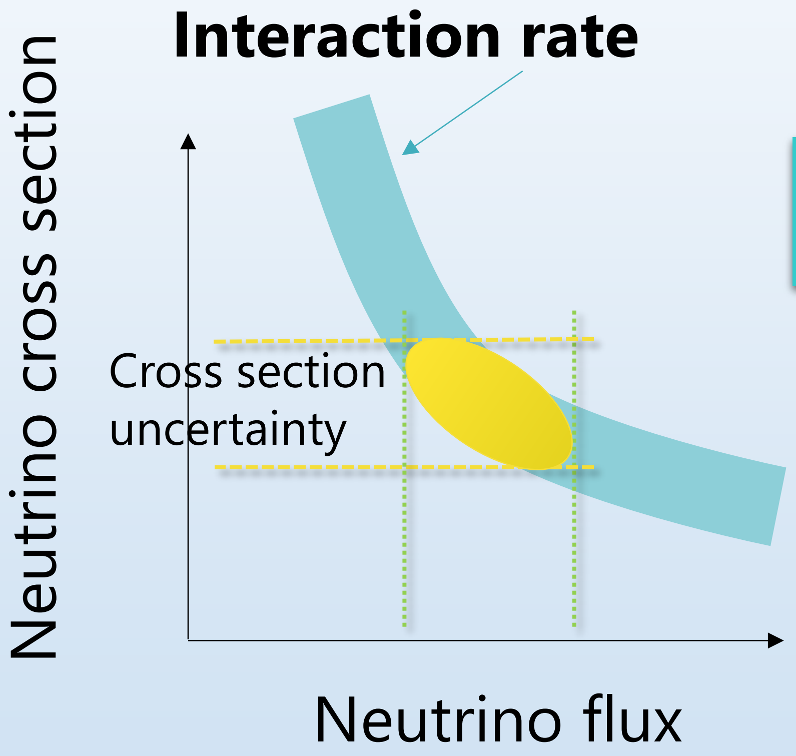


Phys. Rev. D 110, 012009 (2024)
"Neutrino rate predictions for FASER"

LHC Run 3 with 250 fb^{-1} $\qquad$ **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

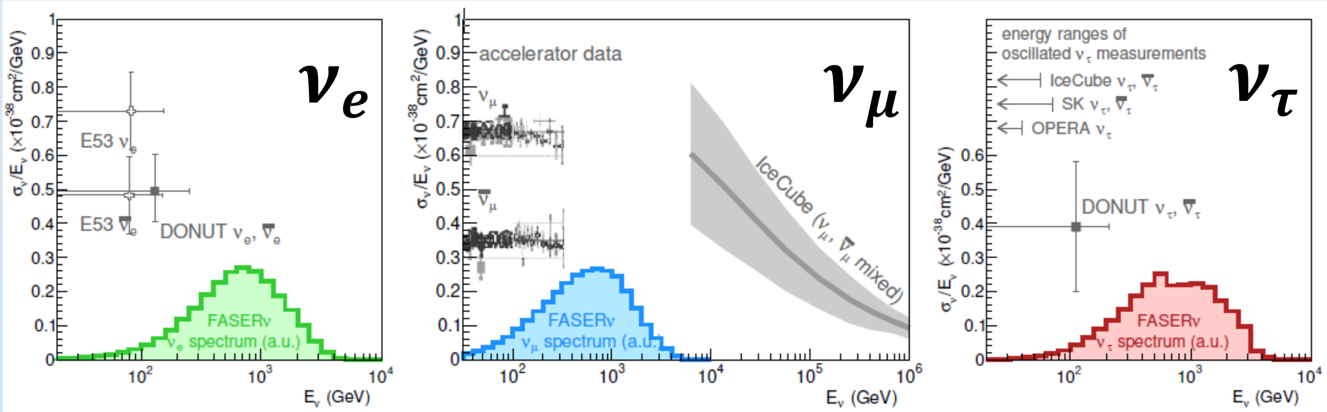
- Assuming LFU is valid

Neutrino flux measurements

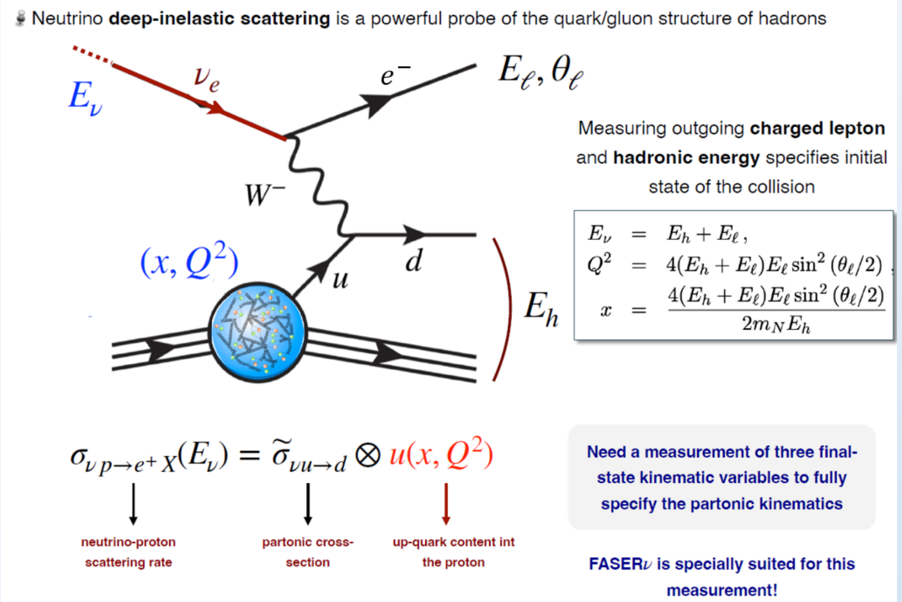
- Study hadron/neutrino production at very high-energy
- Prompt neutrinos
- QCD at small x

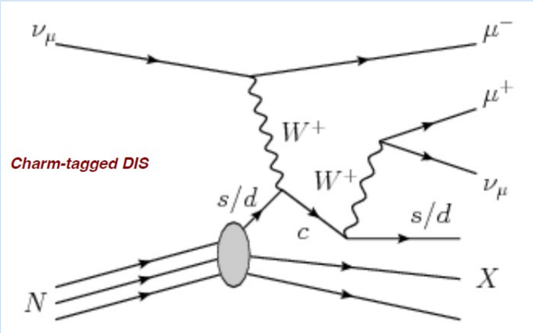
Physics motivation of neutrino interaction measurements

- Direct observation of TeV-energy neutrino interactions: 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 in neutrino interactions
- Neutral-current interaction measurements and searches for non-standard interactions



- Proton and nuclear parton distribution studies to reduce PDF uncertainties

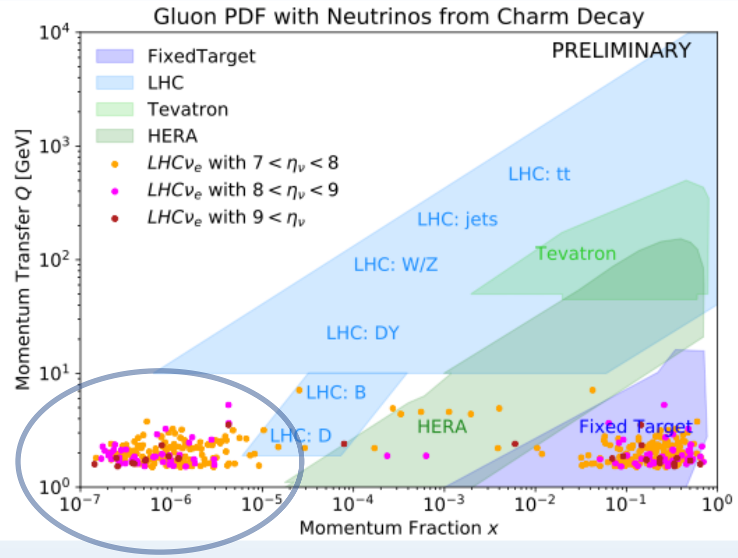


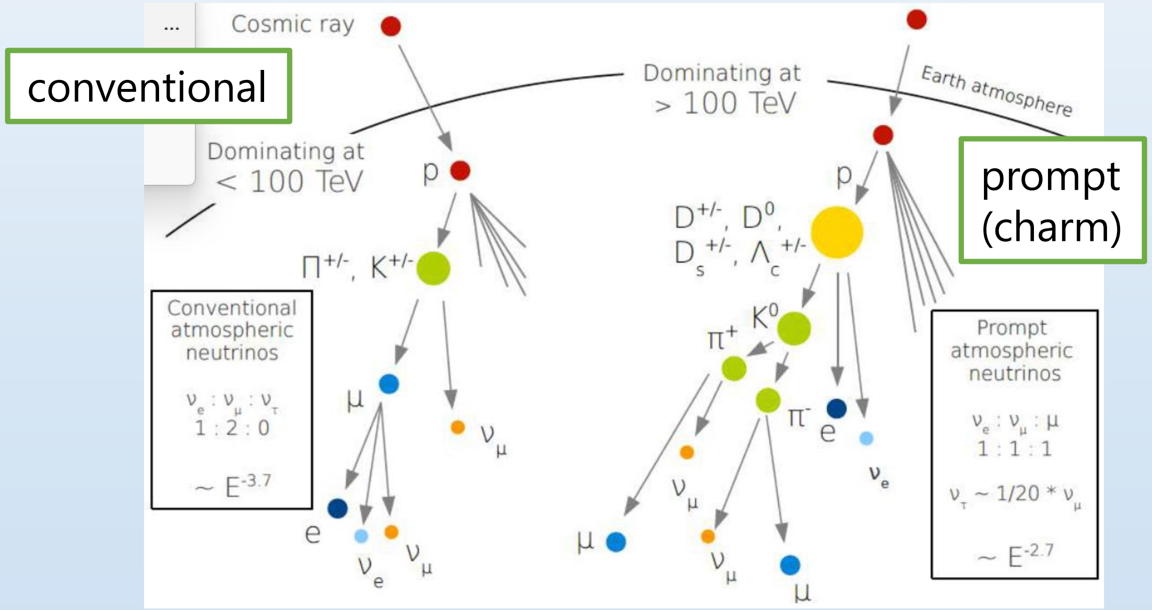


Eur. Phys. J. C 84 (2024) 369
"The LHC as a Neutrino-Ion Collider"

Physics motivation of neutrino flux measurements

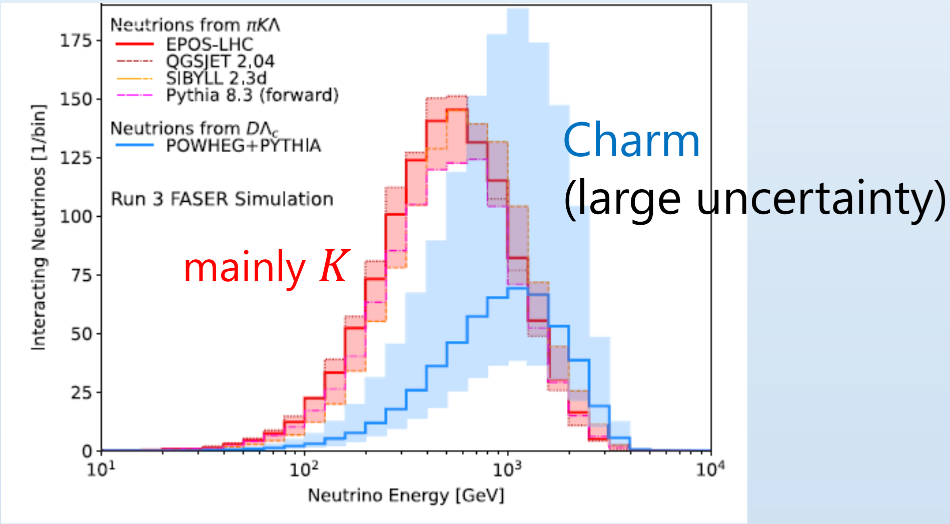
- Neutrino measurements as a probe of very forward hadron production
- Measurements of LHC neutrinos provide novel input to astroparticle physics (prompt atmospheric neutrinos, cosmic-ray muon puzzle), and to QCD studies (low-x PDFs, intrinsic charm, saturation)





https://indico.cern.ch/event/1296658/contributions/5541999/

$\nu_e + \bar{\nu}_e$ at FASERν

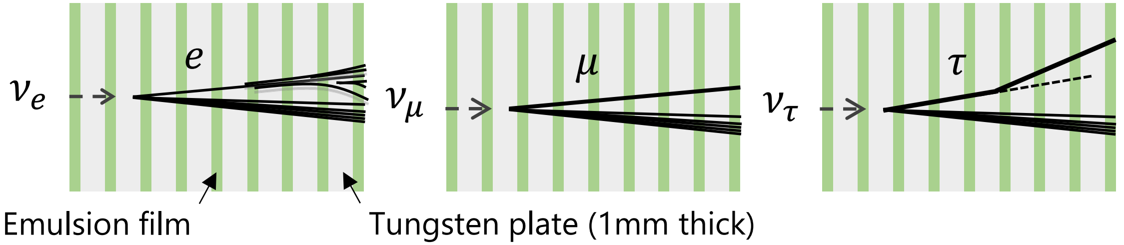


FASER detector

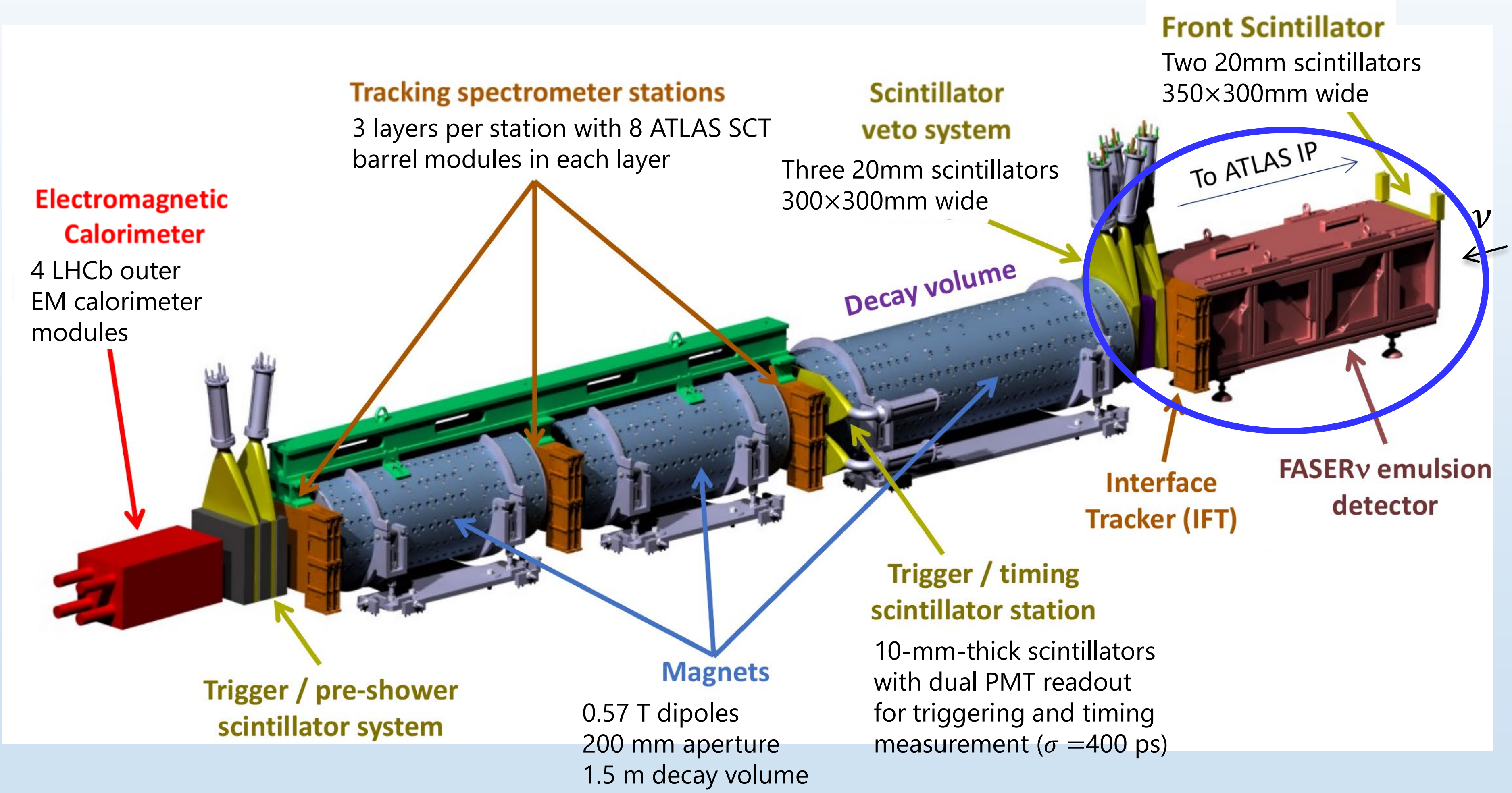
[JINST 19 P05066 (2024)](#)
"The FASER detector"

FASERν detector

Emulsion: 3D tracking device with an intrinsic resolution of 50 nm



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



Data taking is in progress

FASER detector
- >97% data taking efficiency
- 35 fb^{-1} in 2022
- 33 fb^{-1} in 2023
- 122 fb^{-1} in 2024
- ~90 fb^{-1} in 2025 (ongoing)

FASERν detector
- 548 m^2 of emulsion in 10 modules exposed in 2022-2025
- ~175 fb^{-1} integrated
- 1100 kg × 60 fb^{-1} scanned.

SND@LHC detector

Slide adapted from Fabio Alicante

JINST 19 P05067 (2024)
"SND@LHC: the scattering and neutrino detector at the LHC"

Veto system

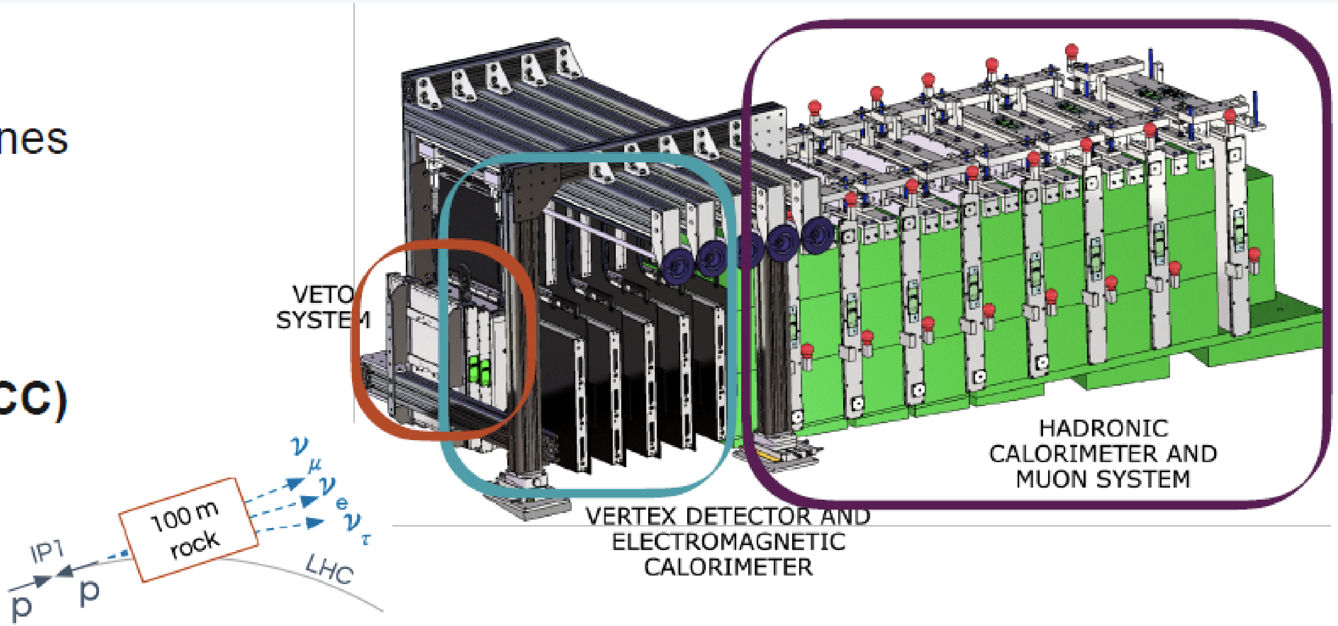
- 2 (2022 - 2023) / 3 (2024 -) scintillator planes
- Tag incoming charged particles

Target, vertex detector and ECal

- ~800 kg tungsten target
- Five walls of Emulsion Cloud Chamber **(ECC)** + five scintillating fibre stations **(SciFi)**
- 84 X0, $3\lambda_{int}$

HCal and muon system

- Eight Fe blocks + scintillator planes
- Last 3 planes have finer granularity to track muons
- (2025) Drift-tube plane
- $9.5\ \lambda_{int}$

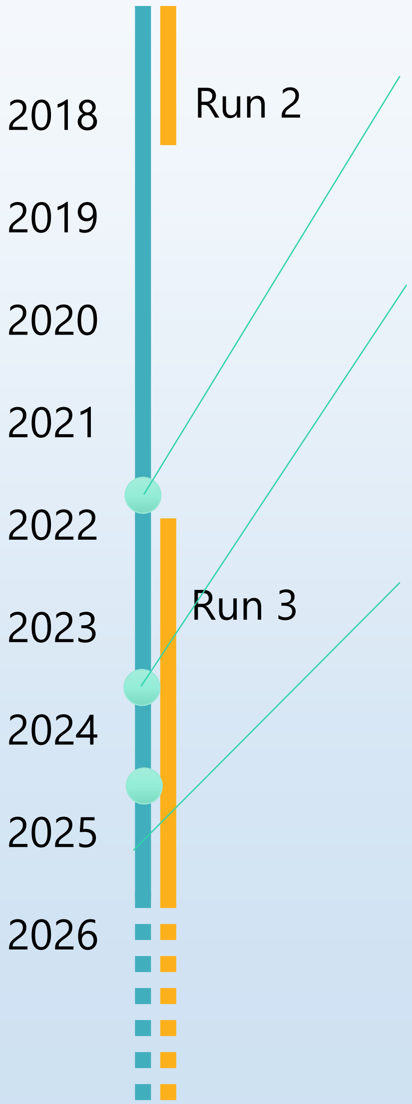


Detector operation

Electronic detectors
- 97% detector uptime
- 187 fb^{-1} in 2022 - 2024
- 88 fb^{-1} in 2025 (ongoing)

Emulsion detector
- 215 m^2 of emulsion in 20 modules exposed in 2022-2025
- 240 fb^{-1} integrated
- 800 kg × 42 fb^{-1} scanned

Results with LHC neutrinos

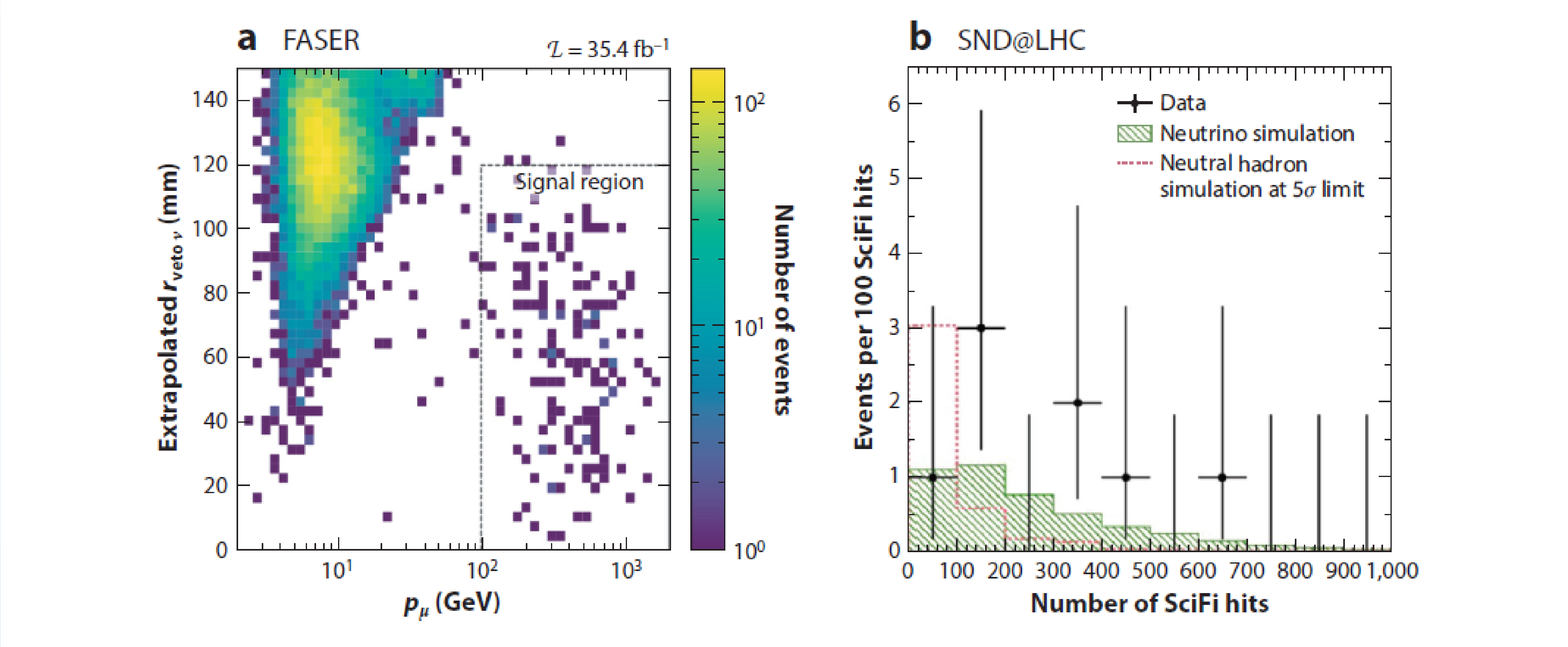


- **First neutrino candidate events** with Run 2 data
  - FASER Collaboration, Phys. Rev. D 104, L091101 (Nov. 2021)
- **First ν_μ detection** with 2022 data
  - FASER Collaboration, Phys. Rev. Lett. 131, 031801 (July 2023)
  - SND@LHC Collaboration, Phys. Rev. Lett. 131, 031802 (July 2023)
- **First ν_e detection & First ν_e, ν_μ cross sections**
  - 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 events without final-state muons (0μ)
  - SND@LHC Collaboration, Phys. Rev. Lett. 134, 231802 (June 2025)

First direct observation of ν_μ interactions at the LHC

FASER result:
153 ν_μ candidate events in the signal region
(significance of 16σ)
Phys. Rev. Lett. 131, 031801 (2023)

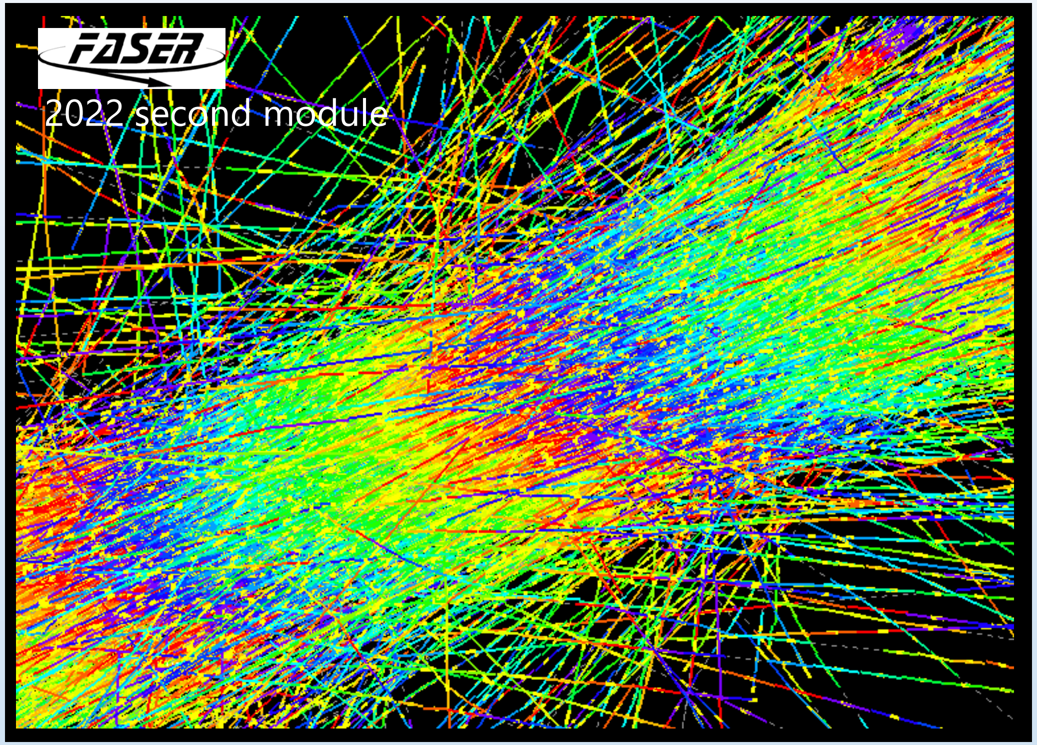
SND@LHC result:
8 ν_μ candidate events in the signal region
(significance of 7σ)
Phys. Rev. Lett. 131, 031802 (2023)

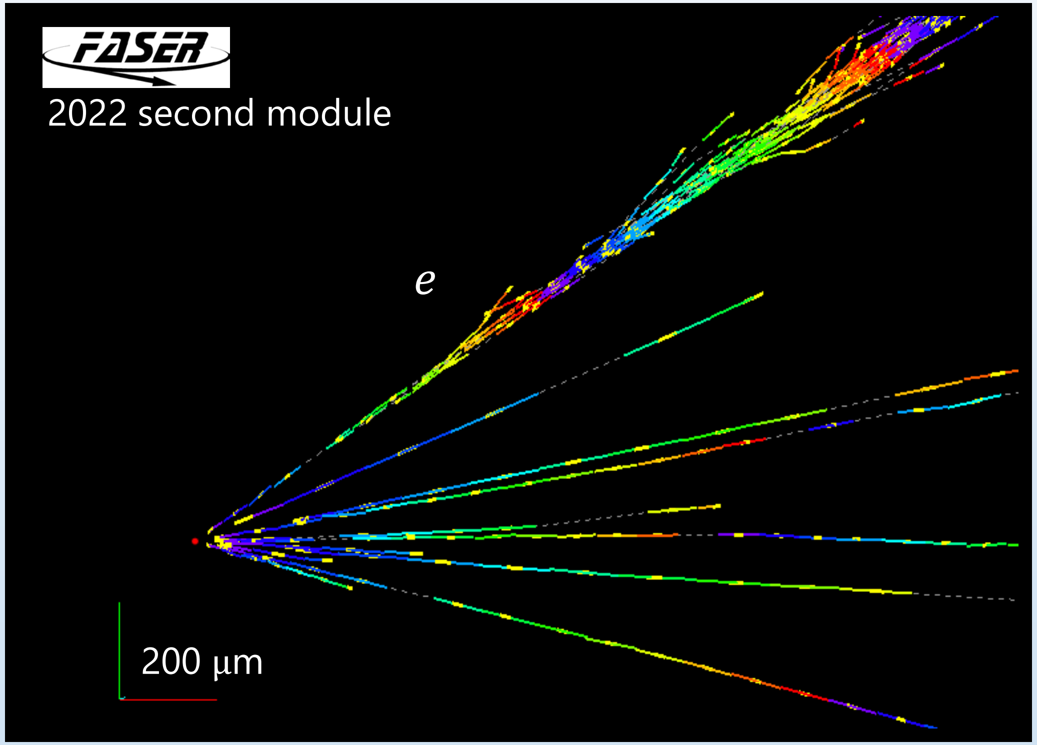


Neutrino interactions in emulsion

ν_e CC signal event
with muon background tracks

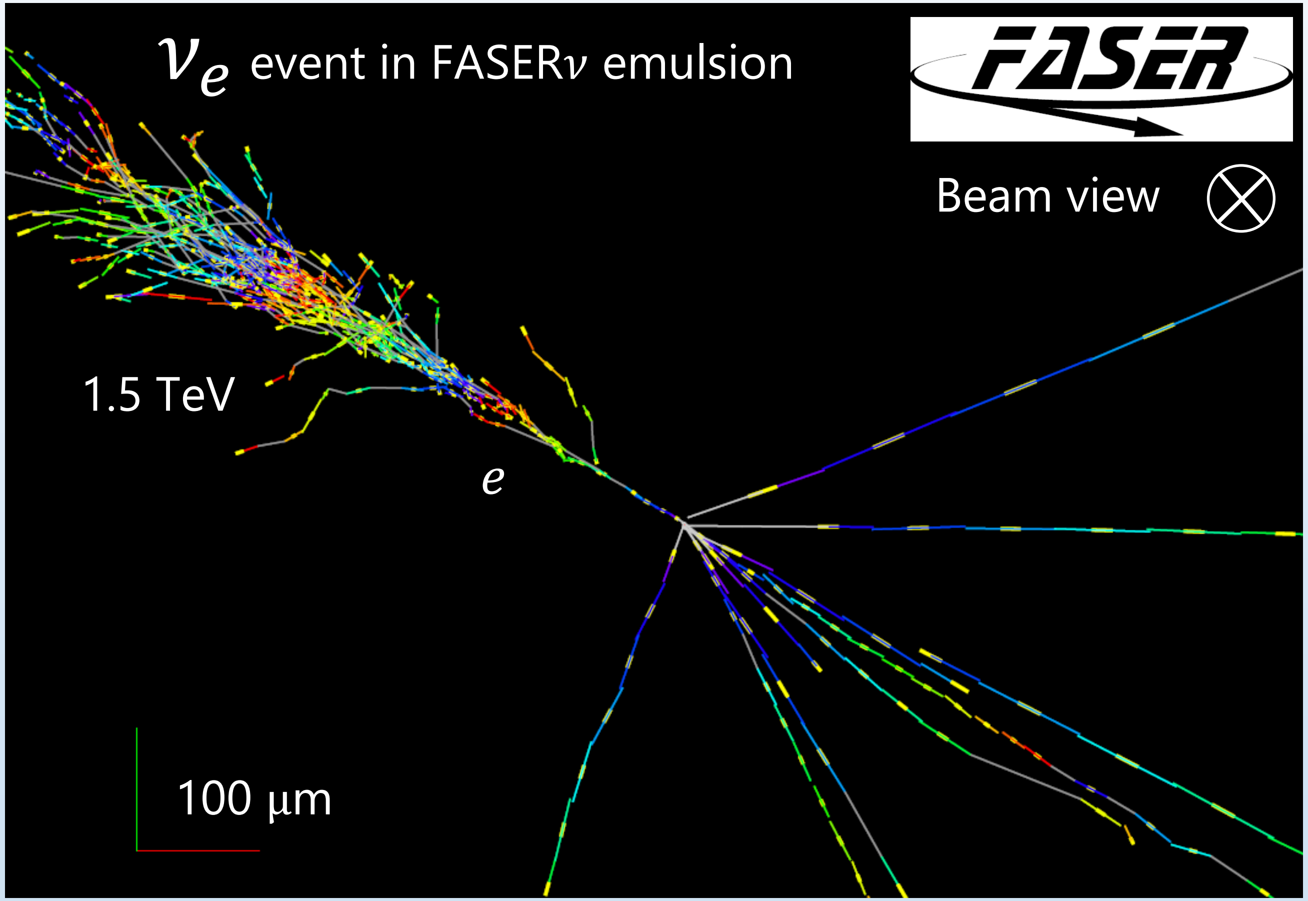
[arXiv:2504.13008](https://arxiv.org/abs/2504.13008)
"Reconstruction and Performance Evaluation of FASER's Emulsion Detector at the LHC"



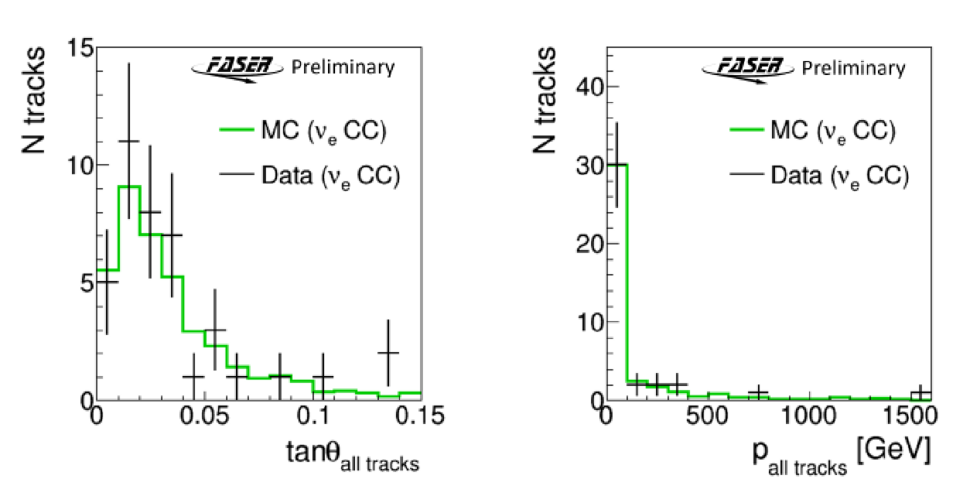


First direct observation of ν_e interactions at the LHC

- Following the first measurement of ν_e and ν_μ cross sections (Phys. Rev. Lett. 133, 021802), more data was analyzed and released CERN-FASER-CONF-2025-002.



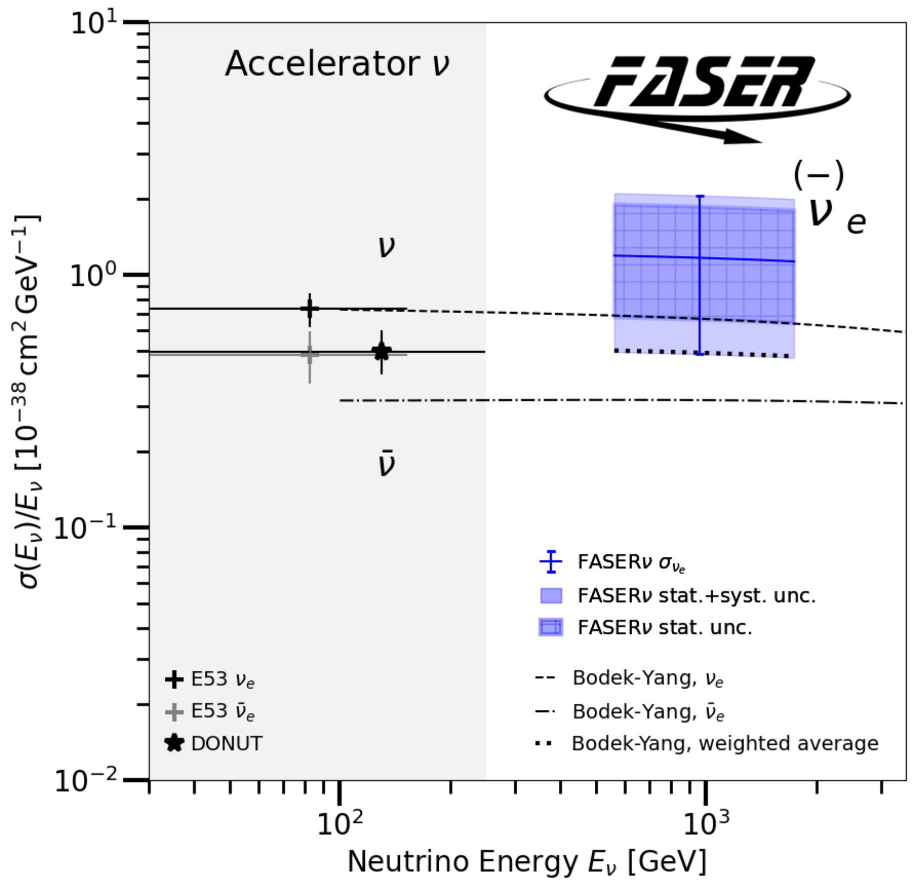
	ν_e CC	ν_μ CC
Expected signal	2.8–7.2	16.2–28.7
Expected background	$0.06^{+0.04}_{-0.02}$	$0.54^{+0.22}_{-0.17}$
Observed events	5	20

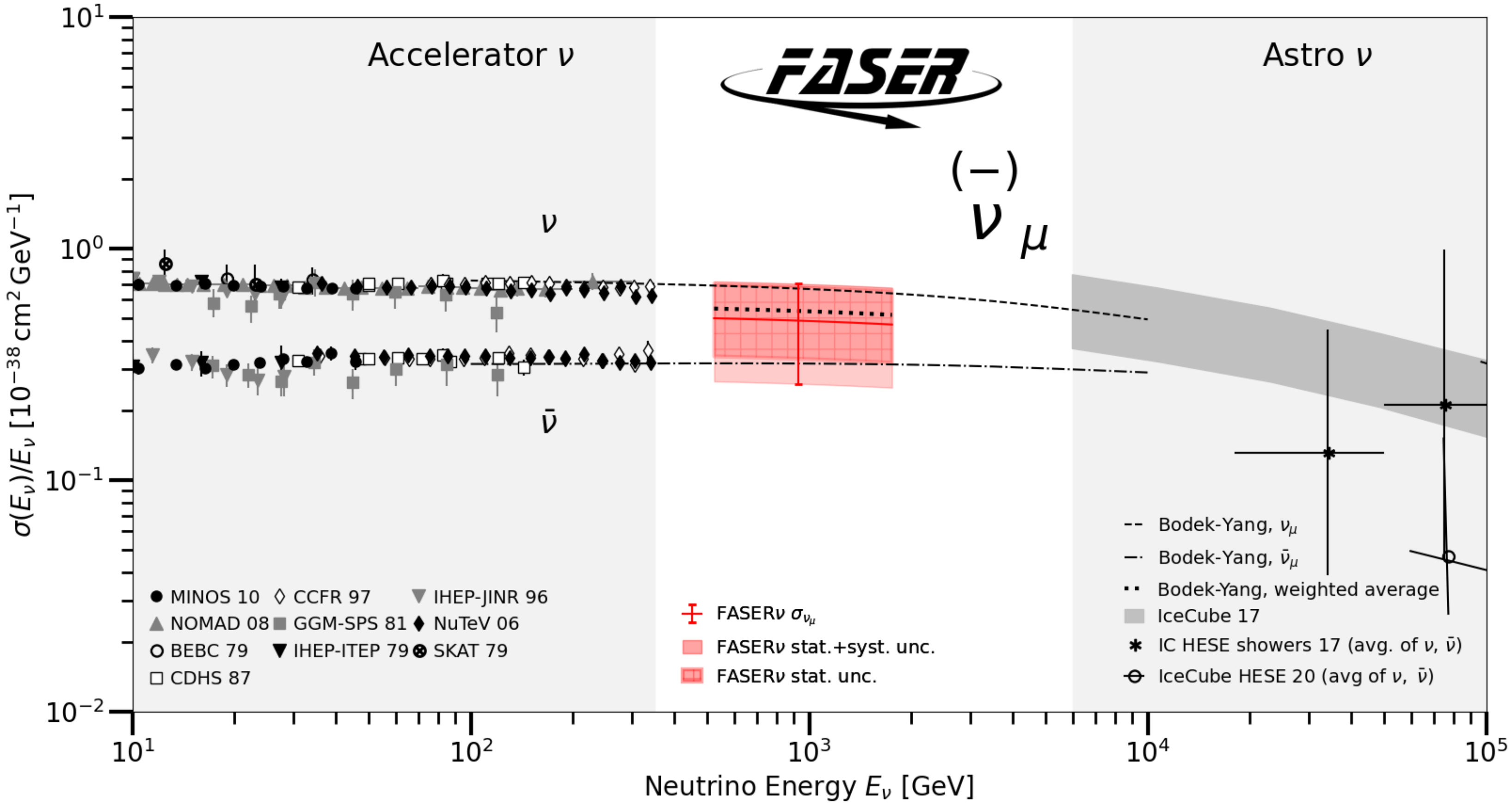


First cross section measurements at TeV energies

[Phys. Rev. Lett. 133 (2024) 021802](#)
"First Measurement of ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector"

Physical Review Letters collection of the year 2024
(selected among the top 2% of papers published in Physical Review Letters)

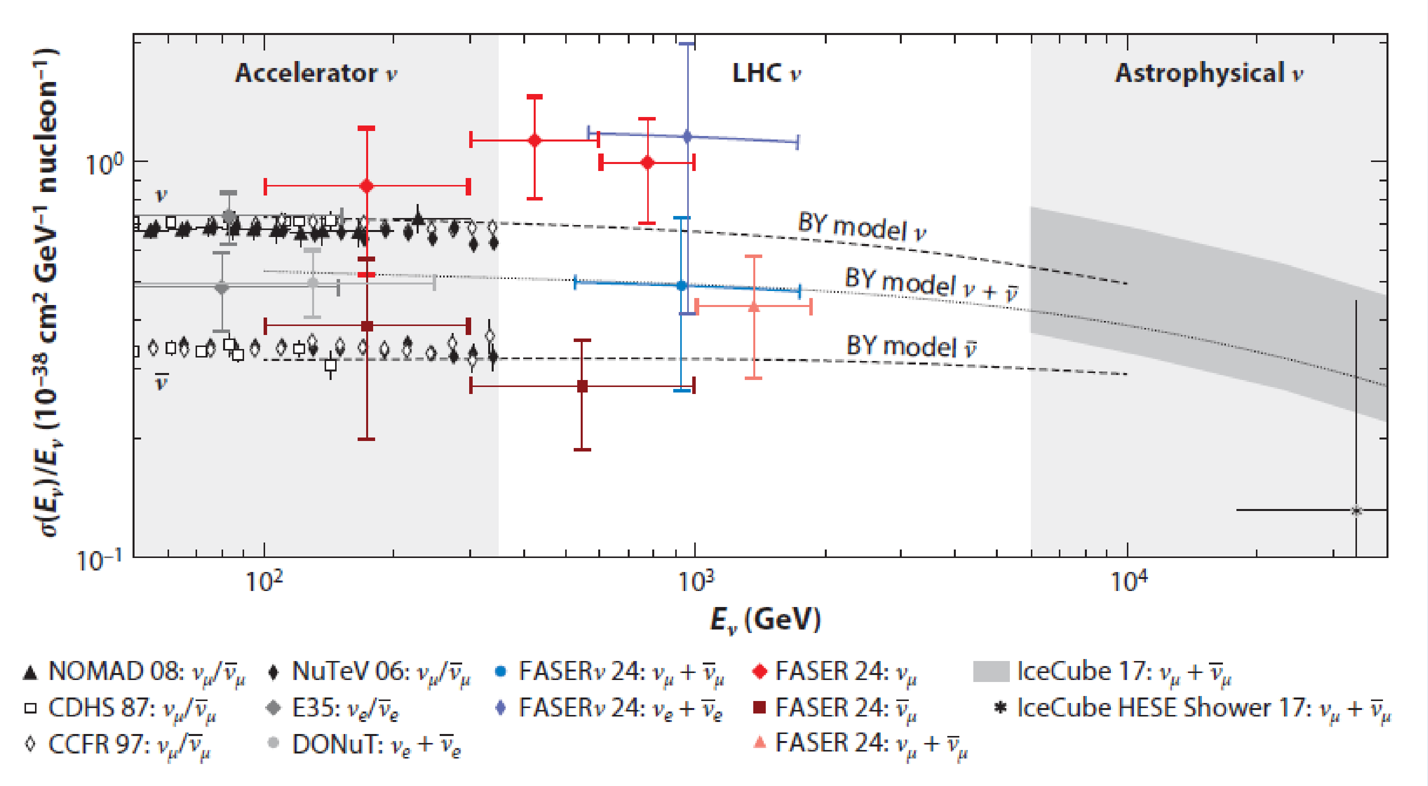


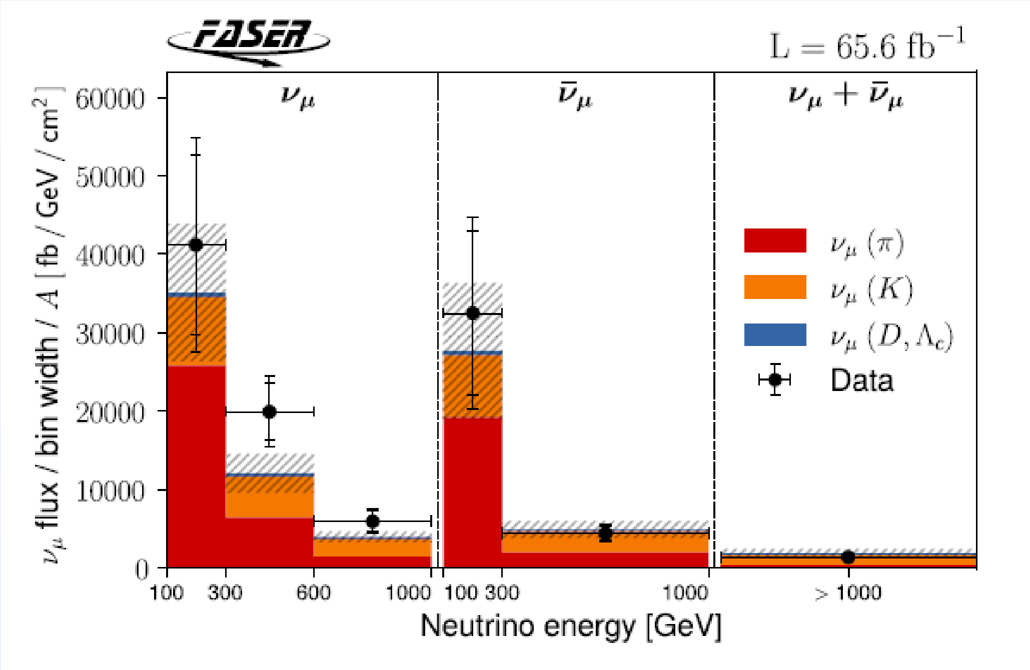


Measurement of energy-dependent cross section and neutrino flux

[Phys. Rev. Lett. 134, 211801 (2025)](#)
"First Measurement of the Muon Neutrino Interaction Cross Section and Flux as a Function of Energy at the LHC with FASER"

Integrated luminosity of (65.6±1.4) fb^{-1}
338.1±21.0 ν_μ CC events are identified, with backgrounds from other processes subtracted





Comparison with predictions from recent hadronic interaction model

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

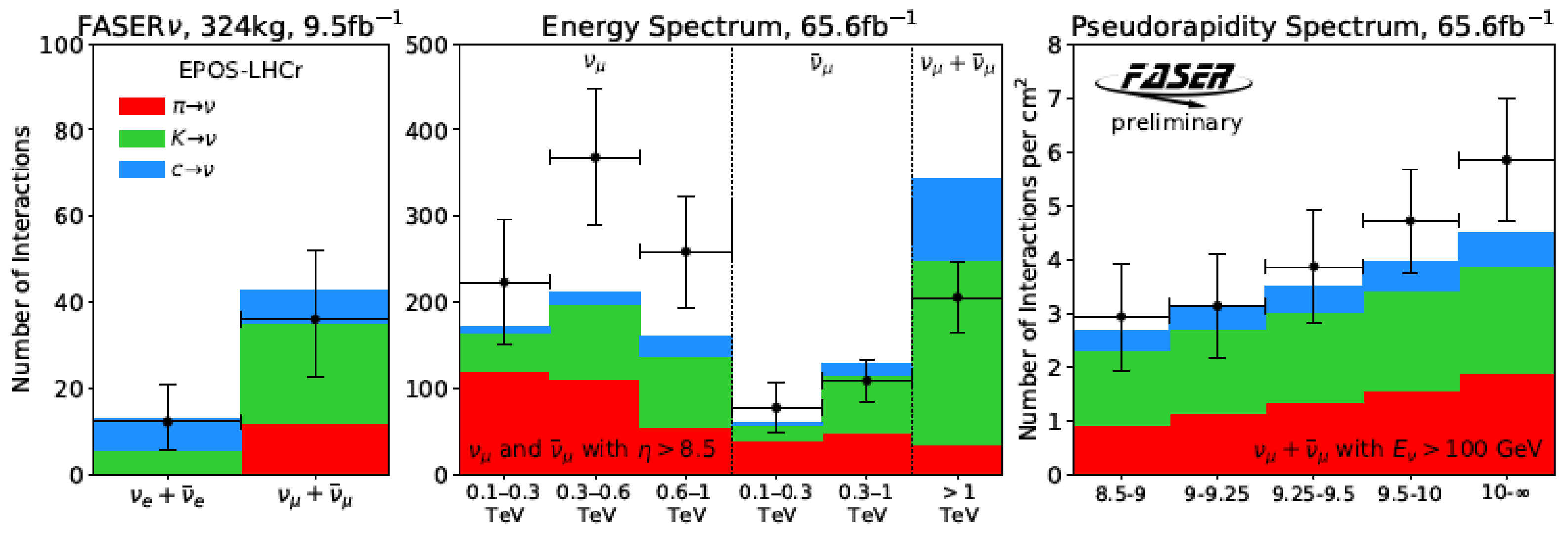


Figure 2: Comparison of EPOS-LHCr, split by production modes, to FASER data.

- 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.

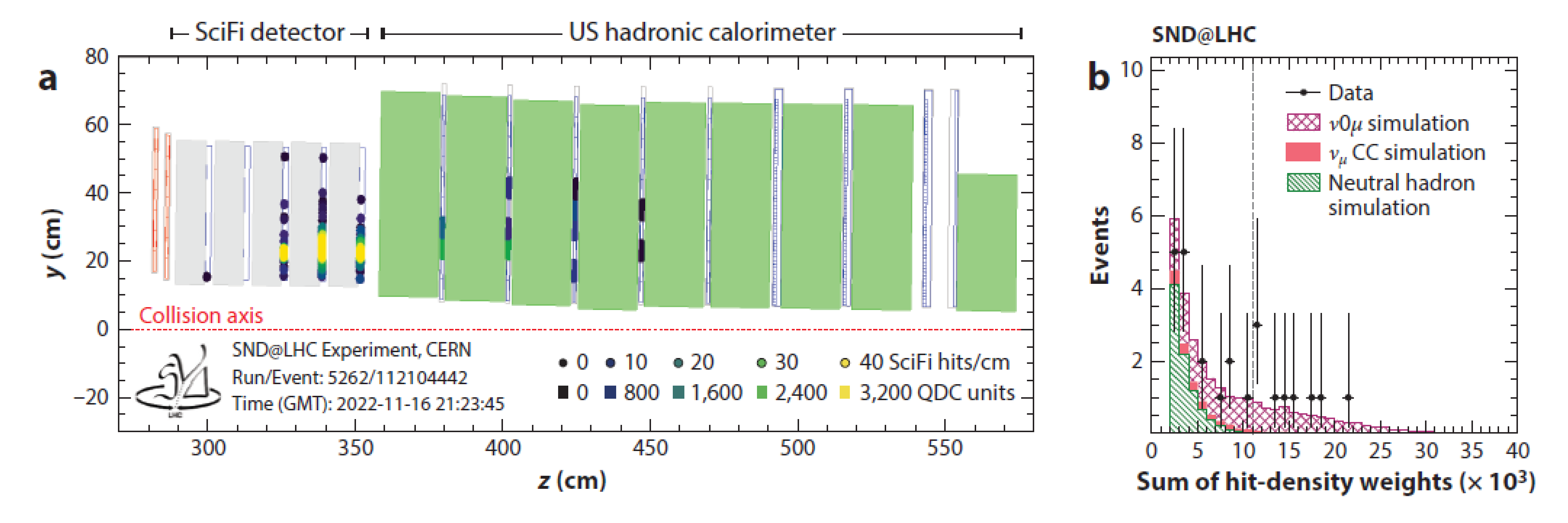
Slide adapted from
Fabio Alicante

Observation of events without final-state muons (0μ)

Phys. Rev. Lett. 134, 231802 (2025)
"Observation of Collider Neutrinos without Final State Muons with the SND@LHC Experiment"

- Expected background: 0.32±0.06 events
- Expected signal: 7.2 events (4.9 ν_e CC, 2.2 NC, 0.1 ν_τ CC)
- Expected significance: 5.5 σ

- Number of observed events: 9
- Observation significance: 6.4 σ
- ν_e CC observation significance 3.7 σ



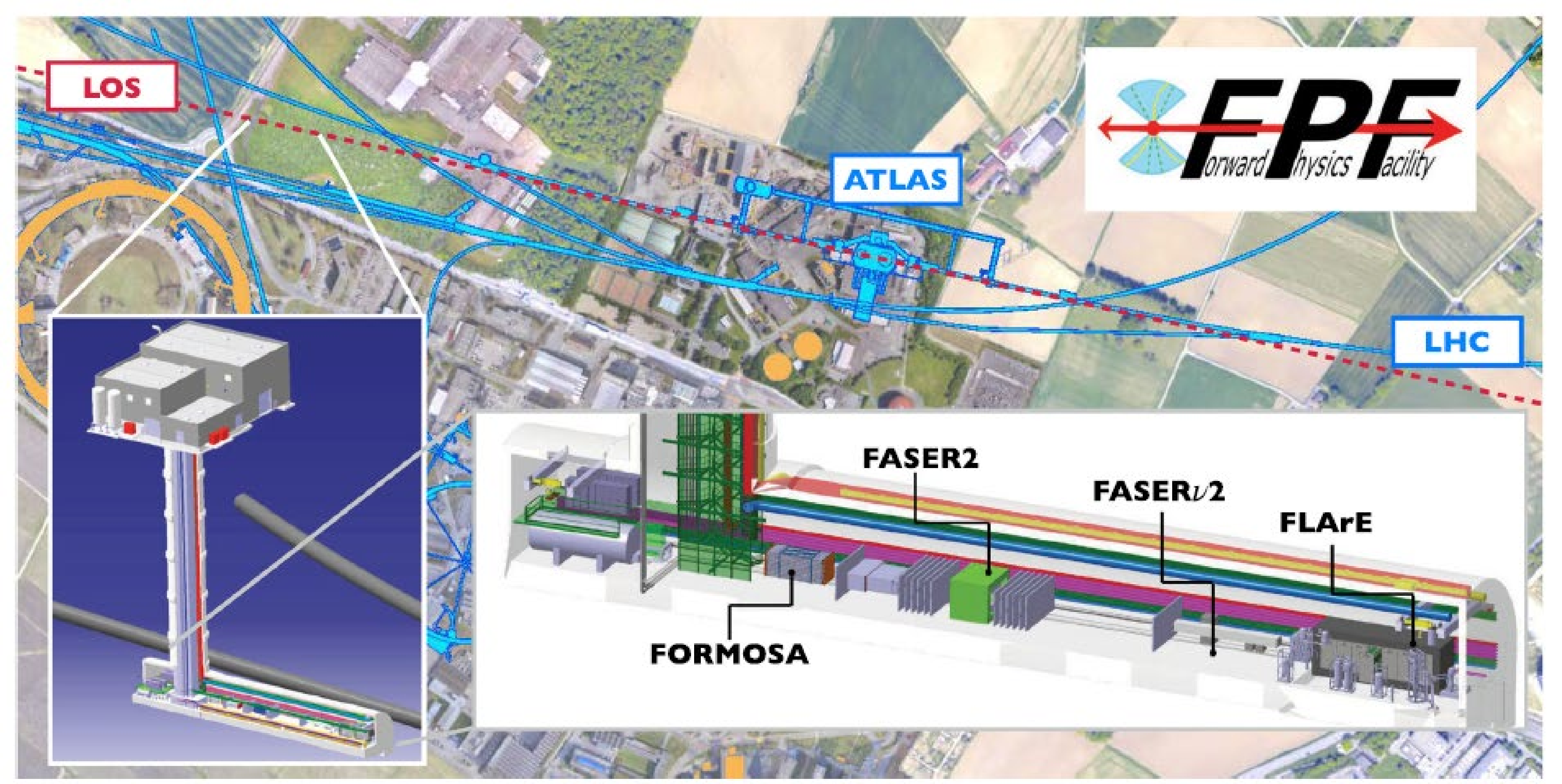
Future prospects

- Both FASER and SND@LHC will continue to take data for the remaining period of LHC Run 3.
- Upgrades and extended running in LHC Run 4 are planned.
- The space at FASER and SND@LHC is limited, Forward Physics Facility (FPF) has been proposed to expand the measurements with larger detectors at the HL-LHC.

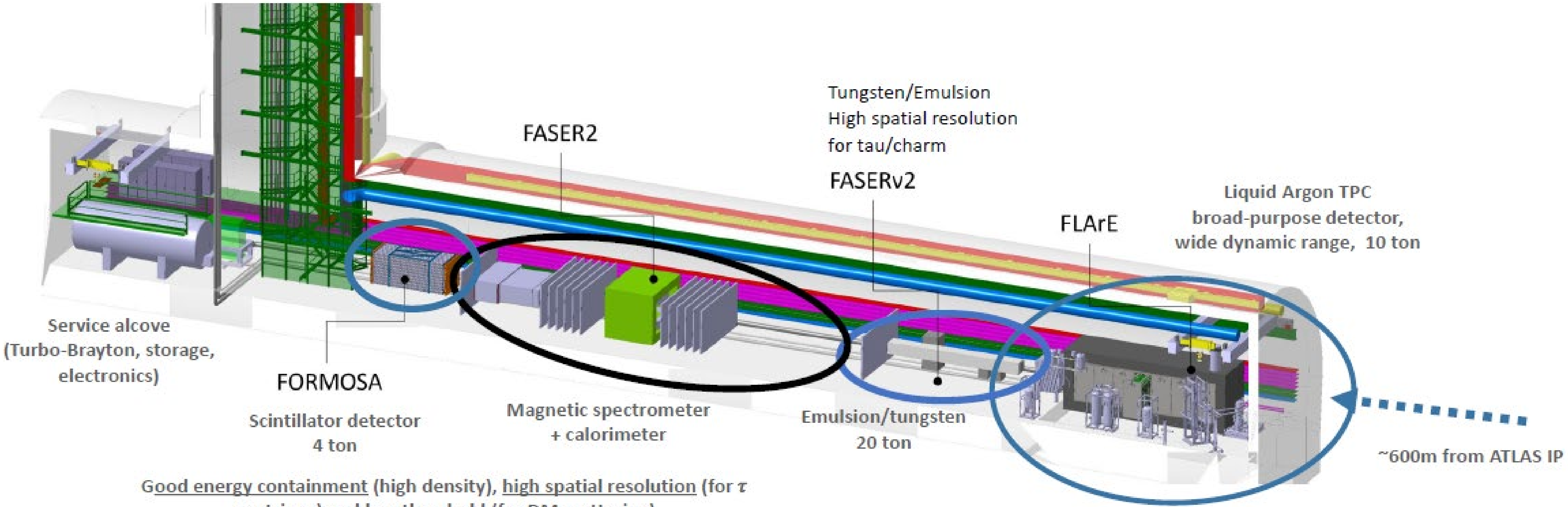
Forward Physics Facility (FPF)

[Eur. Phys. J. C 85:430 (2025)](https://doi.org/)
"Scientific program for the Forward Physics Facility"

- 627-702 m from the ATLAS IP
- 75 m long and 12 m wide



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

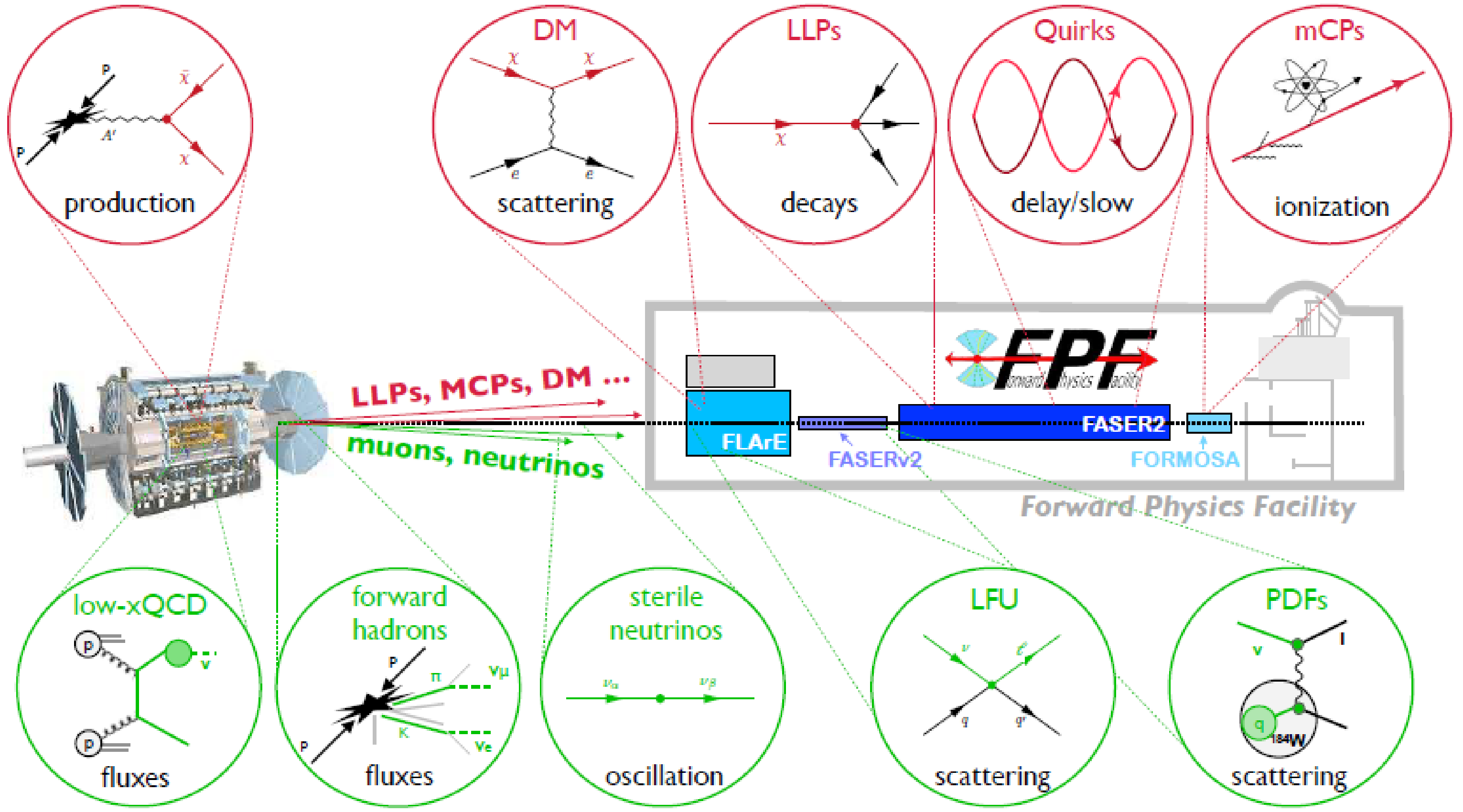
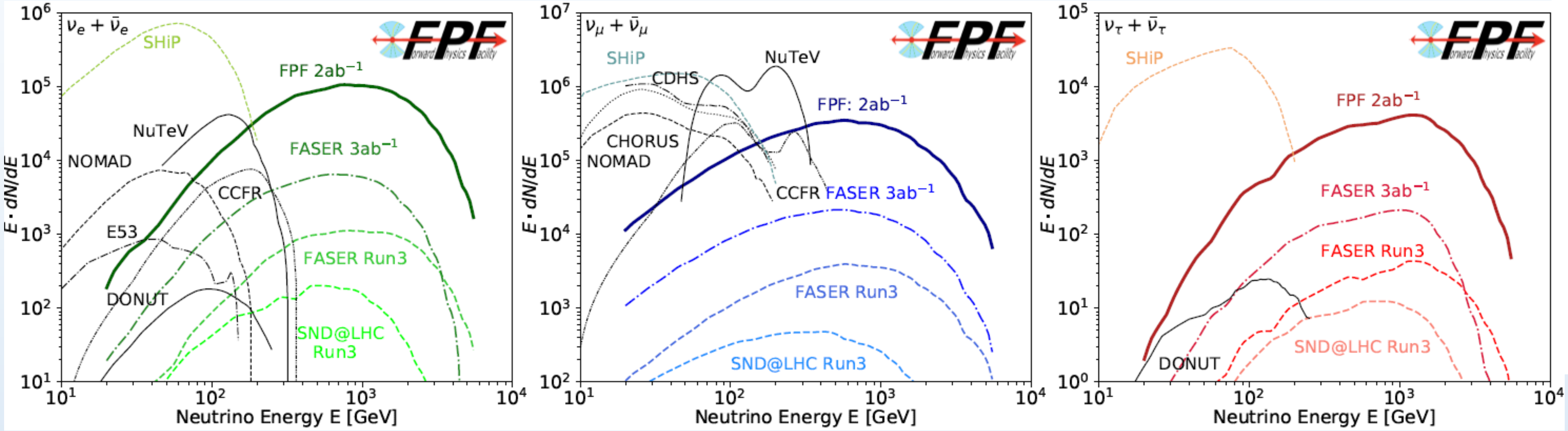


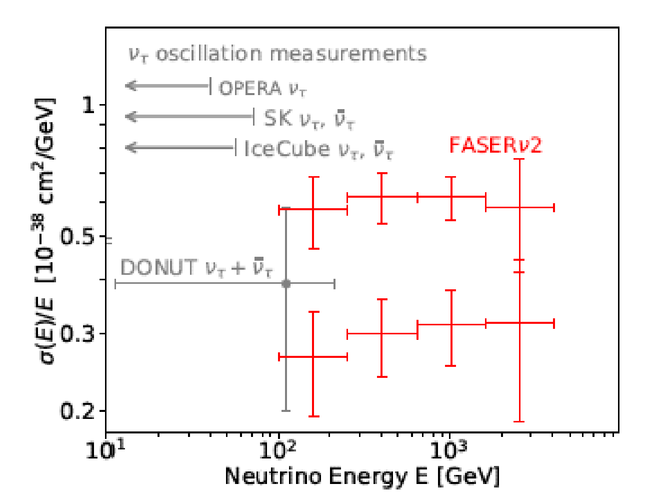
FIG. 2. **New Particle Searches and Neutrino Measurements at the FPF.** Representative examples of DM and other new particles that can be discovered and studied at the FPF (top) and of some of the many topics that can be illuminated by TeV-energy neutrino measurements at the FPF (bottom).

Physics case

Expected data set

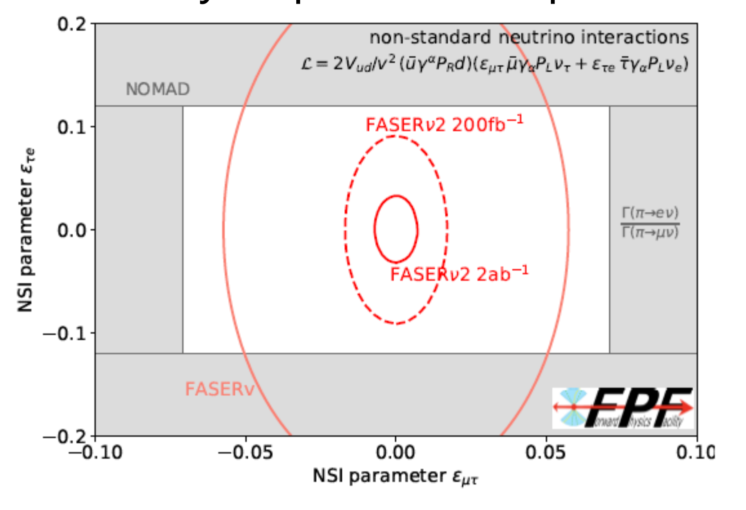
$\sim 10^6\ \nu_\mu$, $\sim 10^5\ \nu_e$, $\sim 10^4\ \nu_\tau$ interactions from HL-LHC





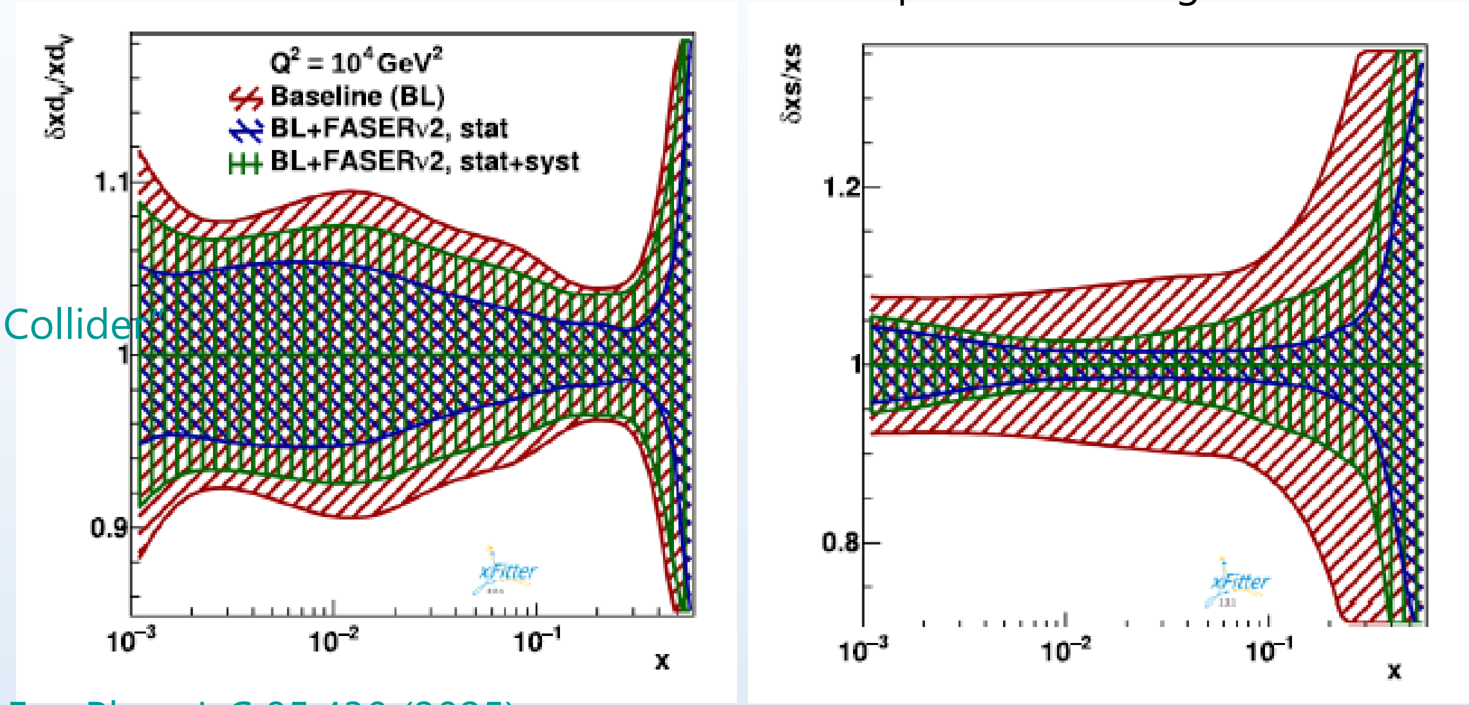
Detector				CC Interactions		
Name	Mass	Luminosity	Rapidity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν at Run 3	1.1 t	350 fb^{-1}	$\eta > 8.8$	2.3k	12k	40
SND@LHC at Run 3	0.8 t	350 fb^{-1}	$7.2 < \eta < 8.4$	300	1.5k	12
FASER at HL-LHC	1.1 t	3 ab^{-1}	$\eta > 8.8$	19k	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

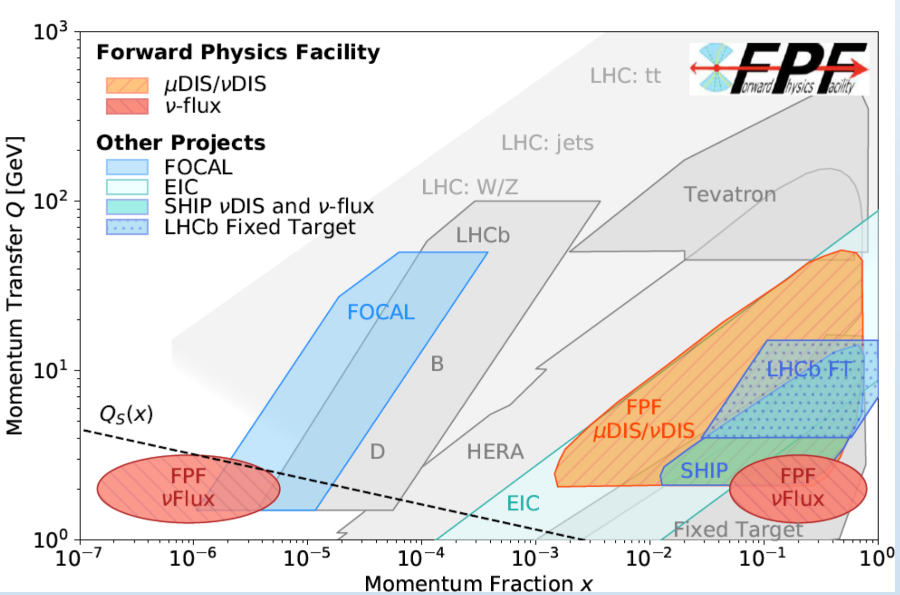


Physics case

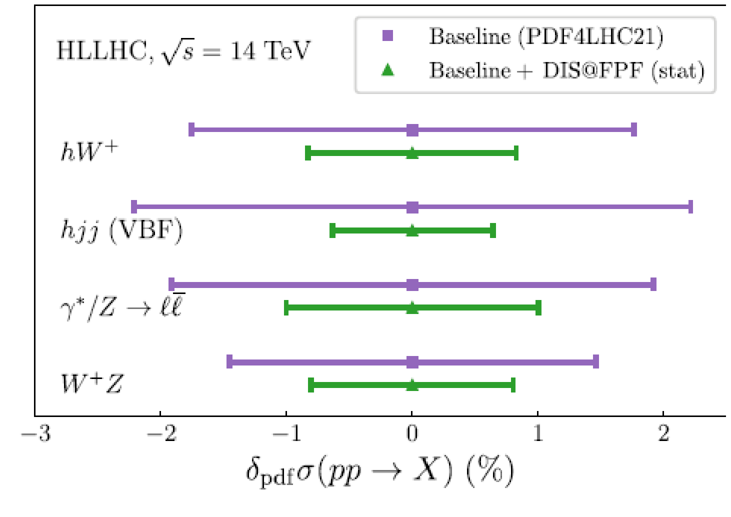
PDF uncertainties for the down valence quark and strangeness PDFs

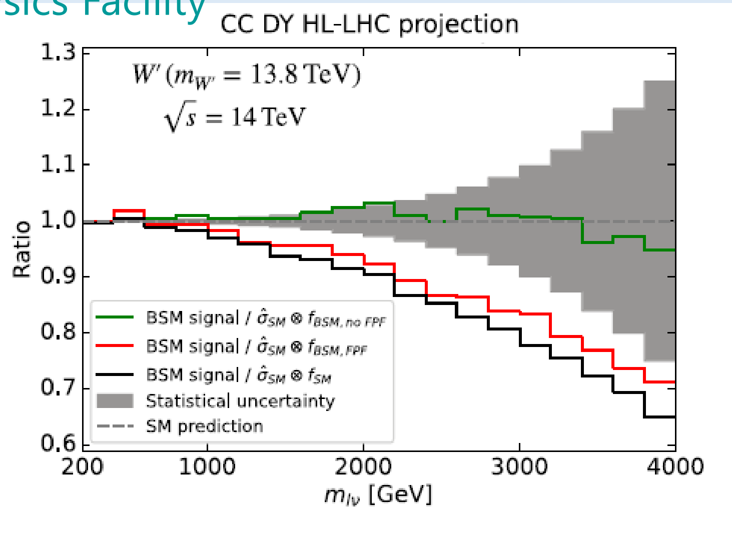


[Eur. Phys. J. C 84 (2024) 369]
"The LHC as a Neutrino-Ion Collider"



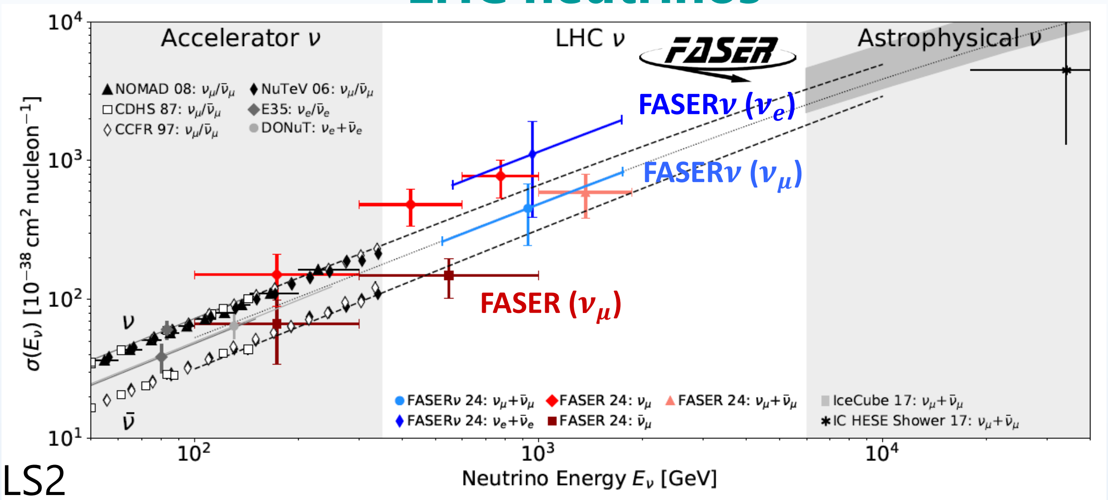
[Eur. Phys. J. C 85:430 (2025)]
"Scientific program for the Forward Physics Facility"



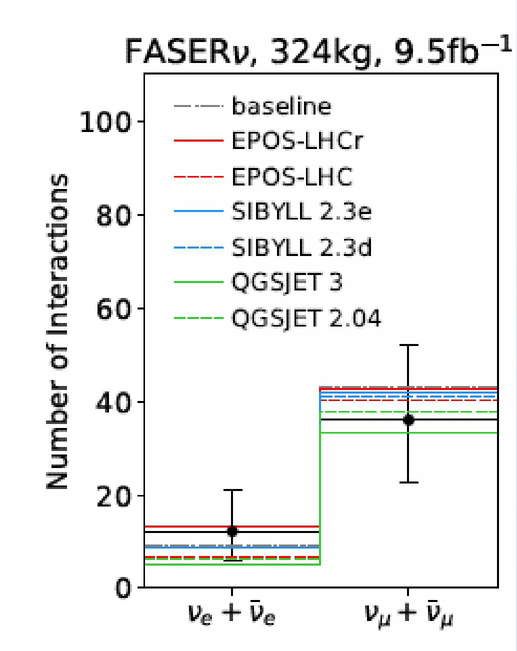


Summary

LHC neutrinos



- Motivations
  - LHC provides highest-energy (TeV) man-made neutrinos
  - Opportunity to study neutrino interactions and flux in unexplored energy regime
- Experiments at the LHC
  - FASERν (η > 8.8) and SND@LHC (7.2 < η < 8.4) installed during LS2
  - Data taking since Run 3 (2022)
- Key results
  - First direct detection of collider neutrinos (ν_μ, ν_e)
  - First measurements of ν_e and ν_μ charged-current cross sections at TeV energies
  - Energy-dependent ν_μ cross section and flux determined
- Physics impact
  - Tests of lepton universality at TeV scale
  - Inputs to hadron production and PDF studies
  - Relevance to astroparticle physics (prompt atmospheric neutrinos, cosmic-ray puzzles)
- Future prospects
  - Continued operation through Run 3 (until 2026) and upgrades for Run 4 (from 2030)
  - Forward Physics Facility (FPF) proposed at HL-LHC for larger-scale neutrino program



Backup

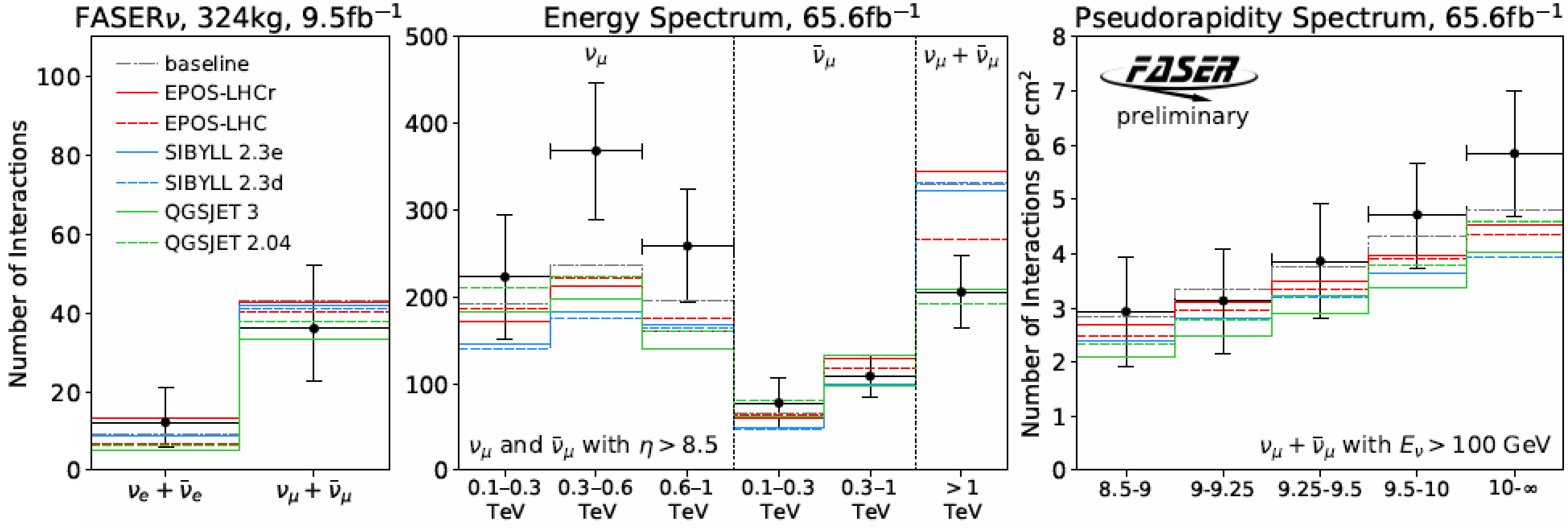
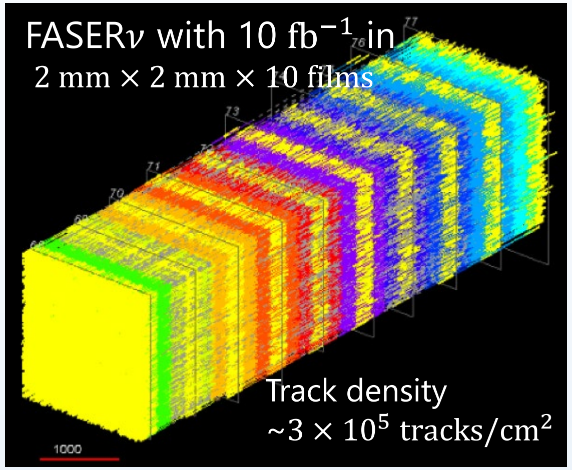


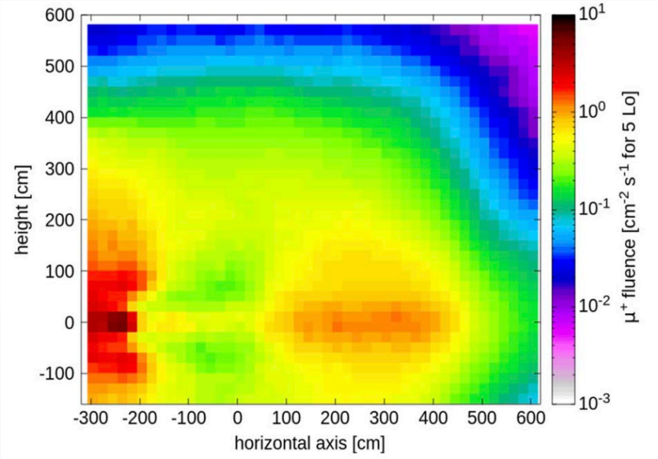
Figure 1: Comparison of Cosmic Ray Monte Carlos to FASER data. The number of neutrino interactions in the respective target volumes as measured by FASERν (left), as measured by FASER as a function of the neutrino energy (center), and by FASER as a function of rapidity (right) are shown. The measured values are compared to prediction by `EPOS-LHC` [4], `EPOS-LHCr` [7], `SIBYLL 2.3d` [5], `SIBYLL 2.3e`, `QGSJET 2.04` [6], `QGSJET 3` [9], and the FASER baseline model (see texts). The analyzed area on FASERν corresponds to the pseudo-rapidity region of $\eta \geq 8.76$. The majority of the systematic uncertainties of FASERν data points are correlated. Data points in the center and right panels are correlated because they use the same dataset.

Background muons

- Background muon limits sensitivities in FASERν2 and others
  - Estimated to be O(1) Hz/cm^2
- Reducing background muons is essential both for cost and physics reach

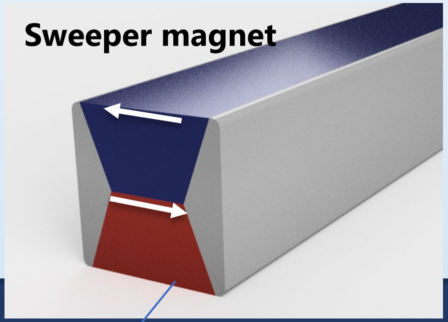
→ Implementation of a "Sweeper magnet"

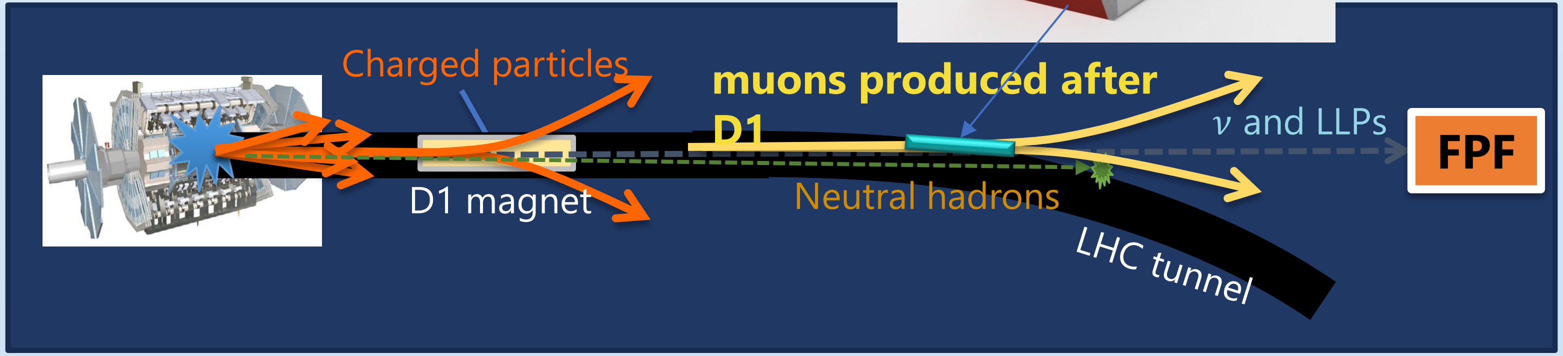




μ^+ fluence expected in FPF
~O(1) Hz/cm^2

Place a permanent magnet along the wall of the LHC tunnel
1 T x 40 m long





Simulated muon rates with/without sweeper magnet