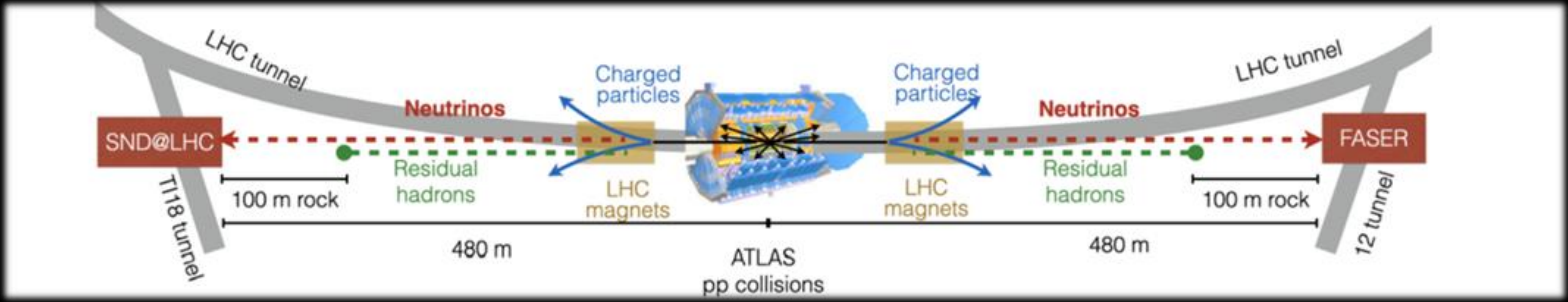
LHC neutrinos at FASER/FASERν

Umut KOSE
On behalf of the FASER Collaboration

Lake Louise Winter Institute
LLWI2005, 2-8 March 2025

Introduction

- Neutrinos detected from many sources, but not from colliders until now!
- ForwArd Search ExpeRiment (**FASER**) approved on 2019 to study for high energetic neutrinos as well as to search light and extremely weakly interacting long-lived particles produced in forward region at the Large Hadron Collider (LHC) at CERN
- First neutrino interaction candidates at collider/LHC observed by the FASERν pilot run in 2018* (using 29 kg emulsion-W module, collecting 12.2 fb^{-1}) FASER Collaboration: arXiv:2105:06197
- A new era in collider neutrino physics allowing to explore unexplored energy region

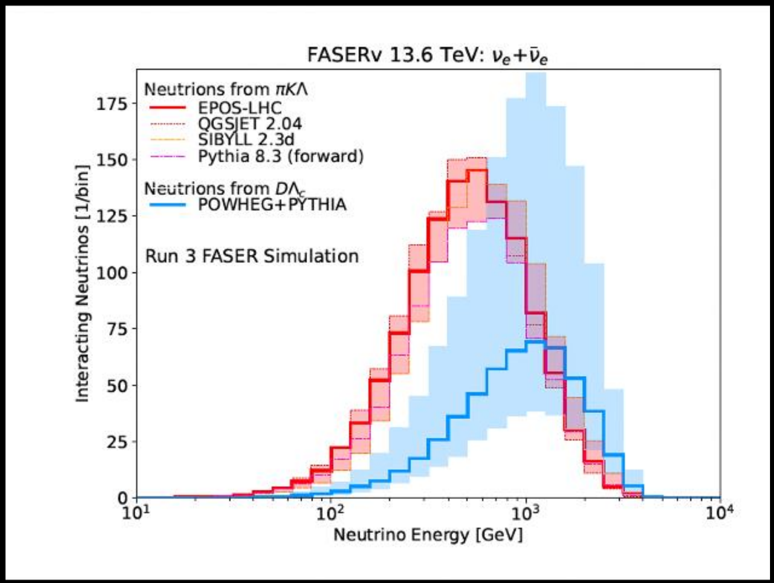


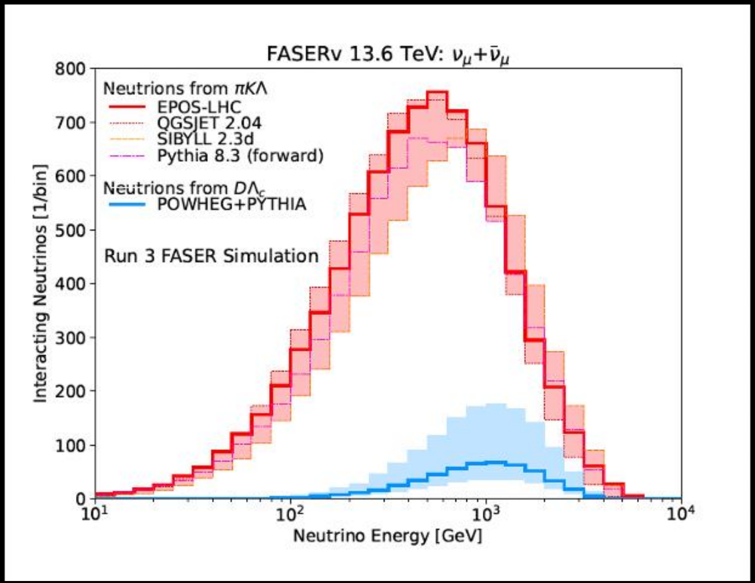
LHC as Neutrino Beam Line

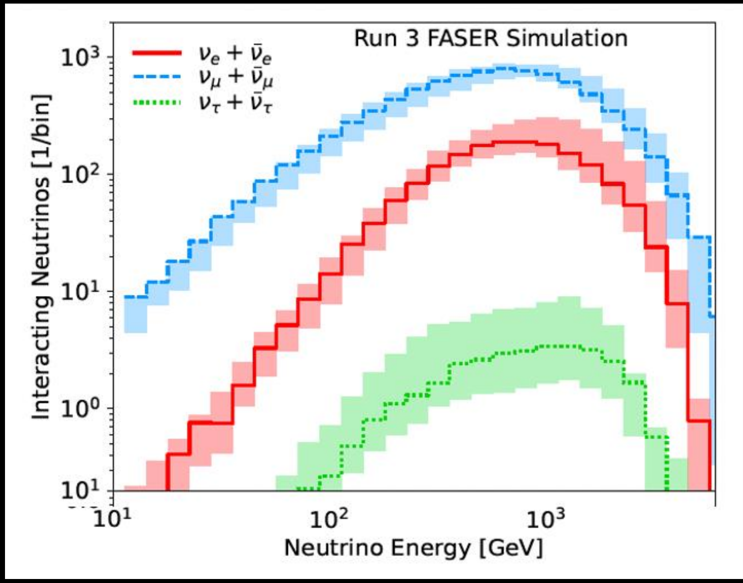
* Two FASERν pilot run in 2018 to study the charged particle flux and for neutrino detections as a proof of principle.

Neutrinos at LHC

- Huge flux of neutrinos at LHC produced at collision points in the far forward direction, from a variety of sources: pion, kaon, hyperon and charm decays.
  - Intense and highly collimated: ~10^{12} neutrino in LHC Run3 w/ beam size $\approx O(10cm)$
  - ~TeV neutrinos/antineutrinos in all flavours
  - Expecting ~1700 ν_e , ~8500 ν_μ and ~30 ν_τ charged current neutrino interactions in FASERν in LHC Run-3 (250/fb)
- FASER/FASERν is dedicated to study unexplored energy regime (TeV neutrinos)
- Study production, propagation and interactions of high energy neutrinos
- Probing neutrino related models to new physics







[FASER Coll. arXiv:2402.13318](https://arxiv.org/abs/2402.13318)

Physics potential: high energy neutrino interactions

- Cross section measurements of different flavor at TeV energies.

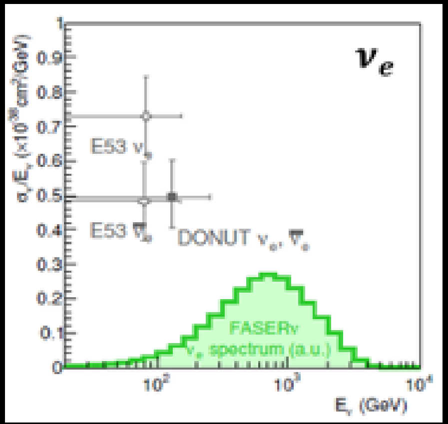
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

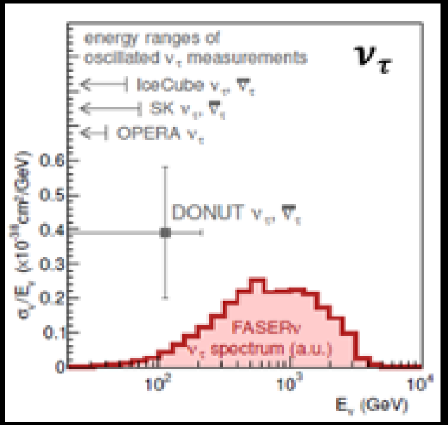
J.M. Cruz-Martinez, Eur. Phys. J. C 84 (2024) 369, arXiv:2309.09581

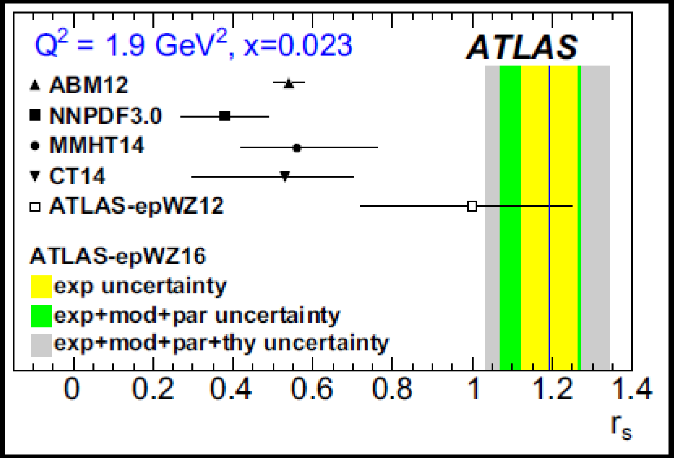
- Test lepton flavour universality in neutrino interactions by comparing cross-sections
- Neutrino CC interaction with charm production ($\nu s \to lc$):
  - Study the strange quark content: $r_s = \frac{s+\bar{s}}{2\bar{d}}$
  - Probe inconsistency between the predictions and the LHC data

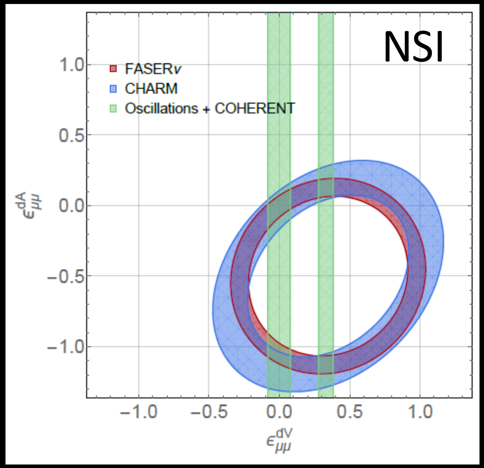
    Eur. Phys. J. C77 (2017) 367
  - to date no charmed hadron observed in $\nu_e CC$ interactions
- Search for anomalous b-quark production in neutrino interactions
- Neutrino NC measurements could constrain neutrino non-standard interactions.

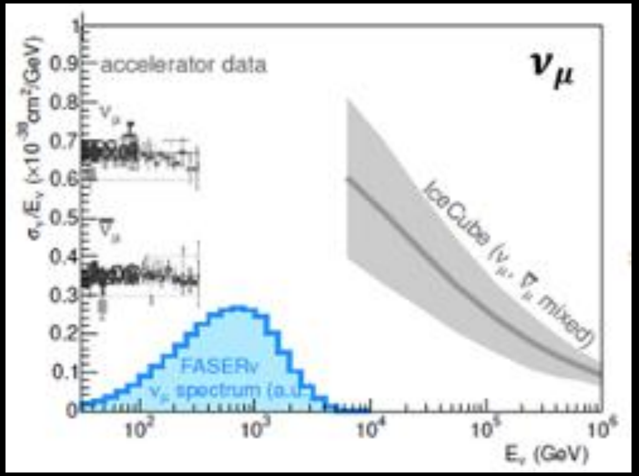
A. Ismail, R.M. Abraham, F. Kling ,Phys. Rev. D 103, 056014 (2021), arXiv:2012.10500





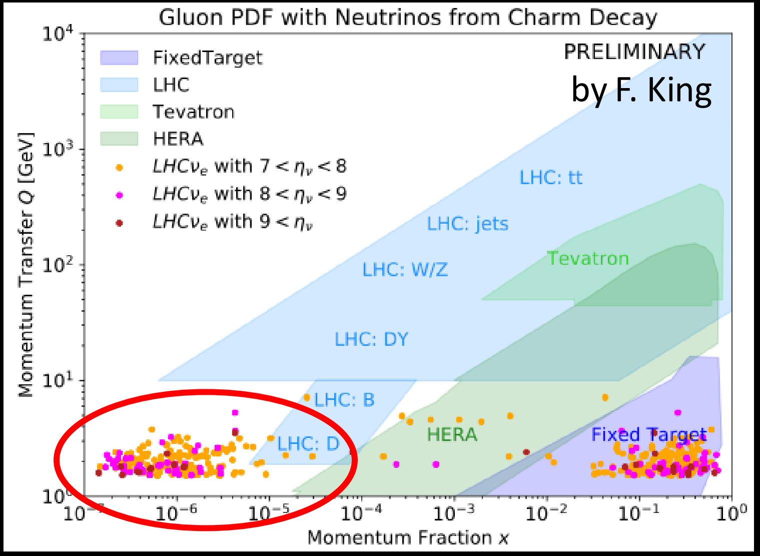


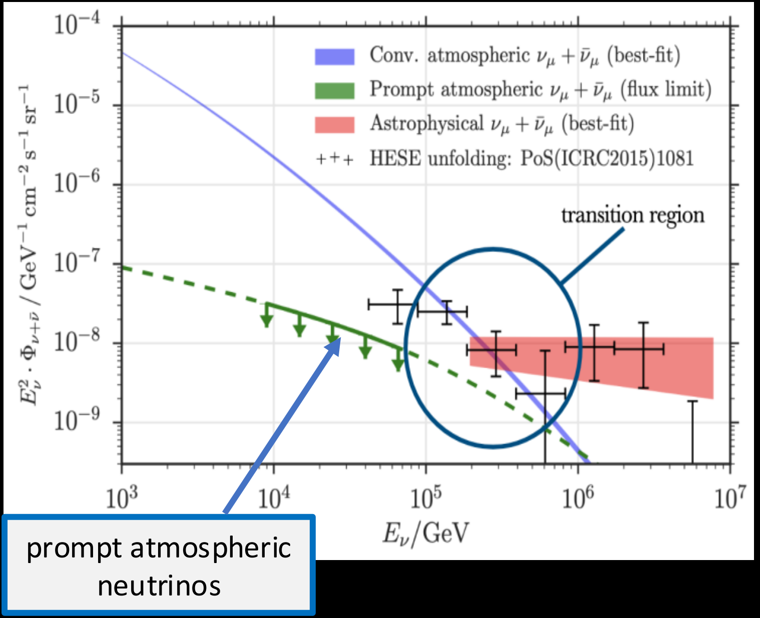




Physics potential: Forward particle production

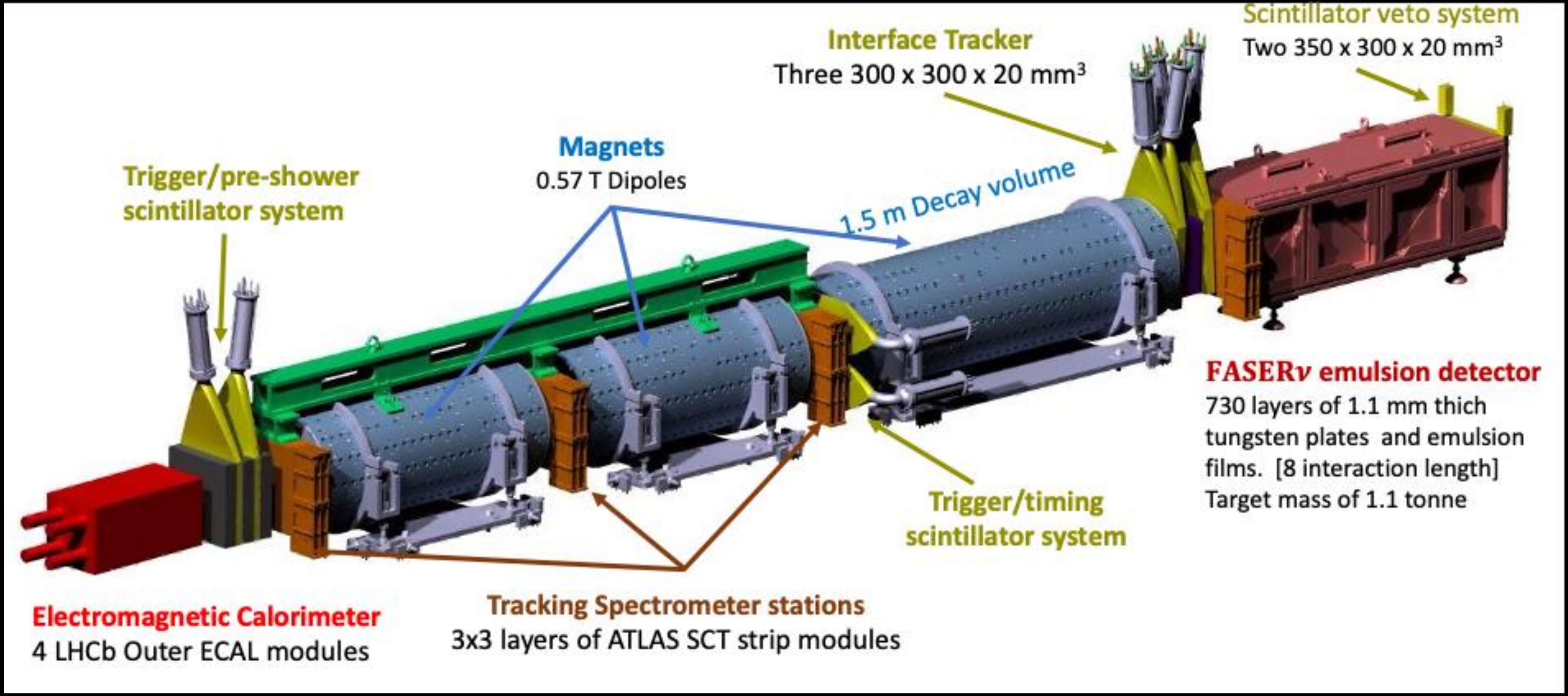
- Neutrinos produced in the forward direction at the LHC originate from the decay of hadrons, mainly pions, kaons, and charm particles.
- Forward particle production is poorly constrained by other LHC experiments. Neutrino flux measurement will provide complimentary constraints that can be used to validate/improve MC generators.
- Neutrinos from charm decay could allow to test transition to small-x factorization, constrain low-x gluon PDF and probe intrinsic charm contributing to QCD → **relevant for FCC**
- Having precise measurements of the cosmic neutrino flux in high energy neutrino telescopes, accelerator measurements of high energy and large rapidity charm production are needed. As 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode, a direct measurement of the prompt neutrino production would provide important basic data for current and future prompt atmospheric high-energy neutrino telescopes, such as ICECUBE.





FASER Detector at LHC

- Small detector: 10 cm radius of active volume, 7 m long
- Angular acceptance: $\eta > 8.8$, on-axis
- Successfully constructed, installed and commissioned in 2020-2021 and started data taking in 2022

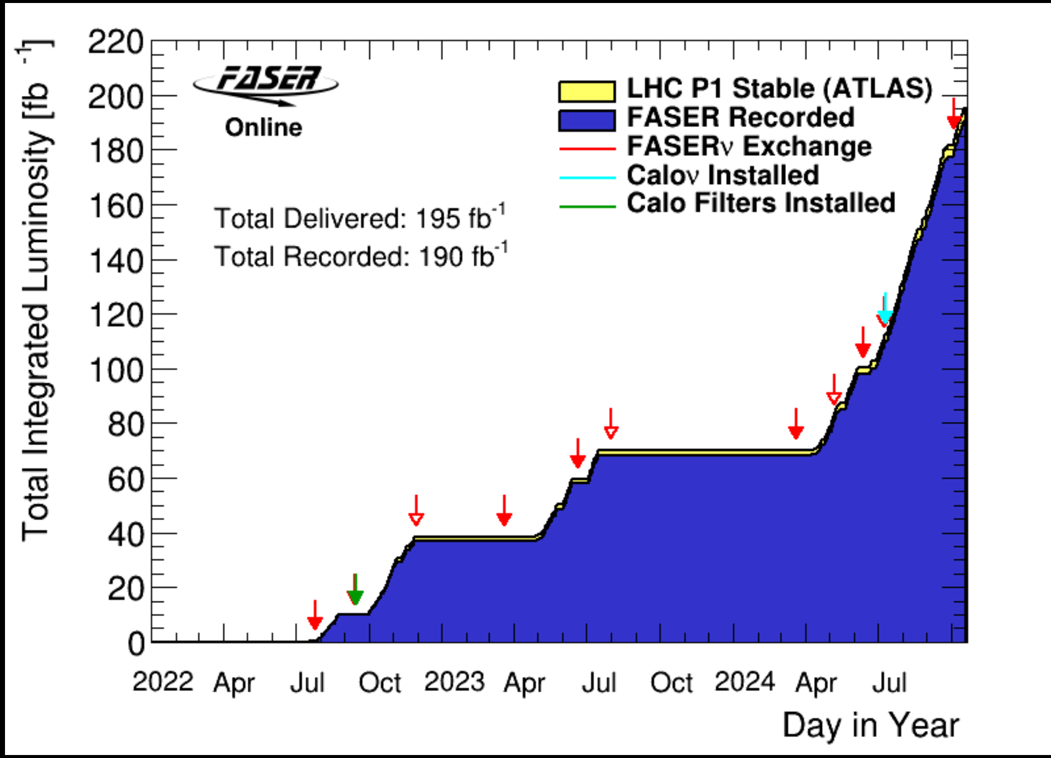


arXiv:2207.11427

FASER operations in LHC Run3

Successfully in operation since 2022

- Continuous data taking;
- Largely automated;
- Physics Trigger rates on average 1kHz and DAQ dead-time of < 2%
- Recorded >97% of delivered luminosity since startup:
  - 35 fb^{-1} in 2022
  - 33 fb^{-1} in 2023
  - 122 fb^{-1} in 2024



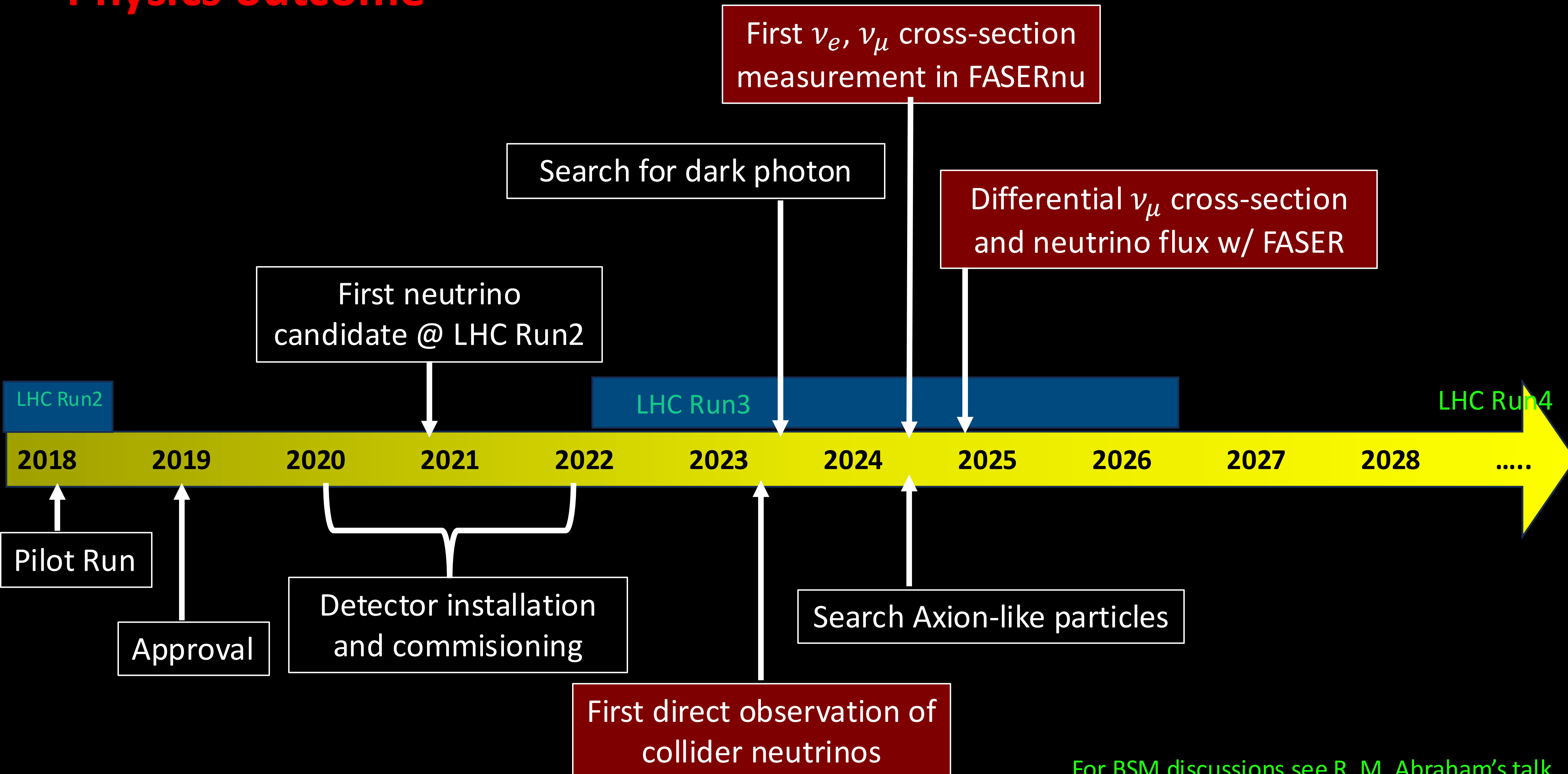
- Until now 7 FASERν emulsion detector exposed

  Limited data taking needed to keep detector occupancy an acceptable level for analysis ($\mathcal{O}(10^6)$ tracks/cm)

  About 105 fb^{-1} of data collected by FASERν

190 fb^{-1} of integrated luminosity recorded with data taking efficiency of >97%

Physics outcome



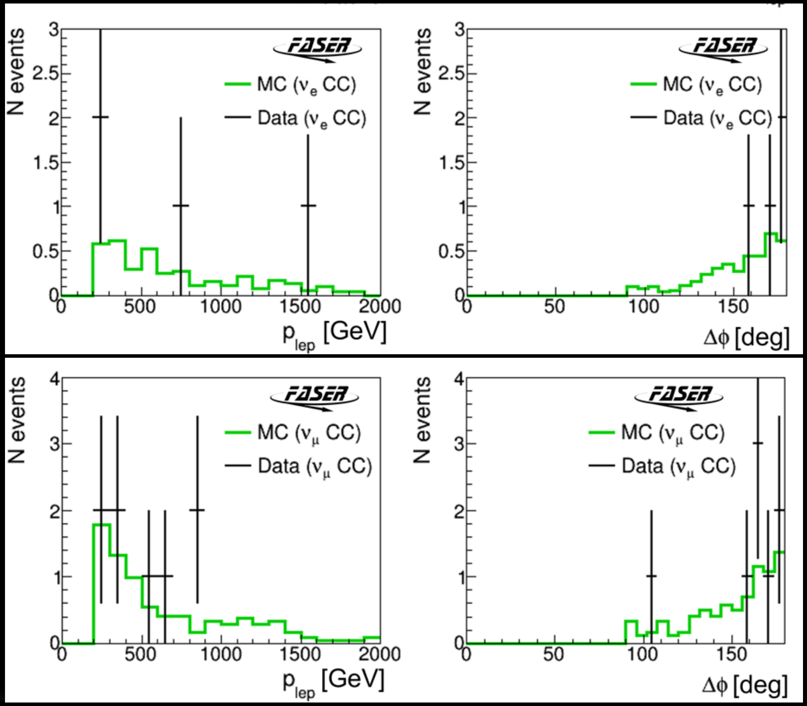
For BSM discussions see R. M. Abraham's talk

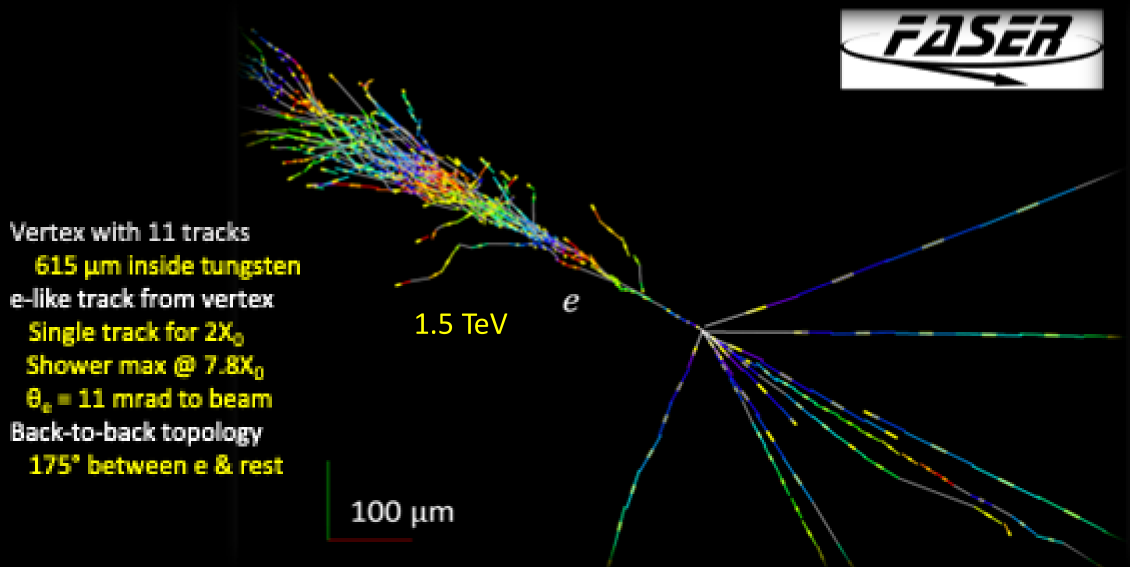
First direct observation of ν_e interactions at the LHC

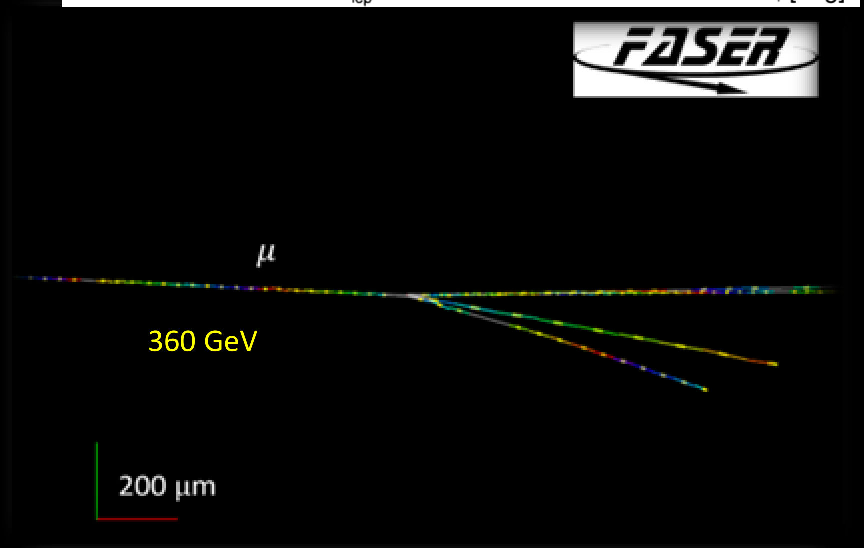
- Analysed dataset was collected by exposing to 9.5 fb^{-1} pp collision data from July to November 2022 at $\sqrt{s} = 13.6\ TeV$.
- A subset of the FASERν module corresponding to 128.6 kg analyzed
- Selecting vertices with associated lepton candidate, e or μ, with E_{lep} > 200 GeV

Phys. Rev. Lett. 133 (2024) 021802, arxiV:2403.12520

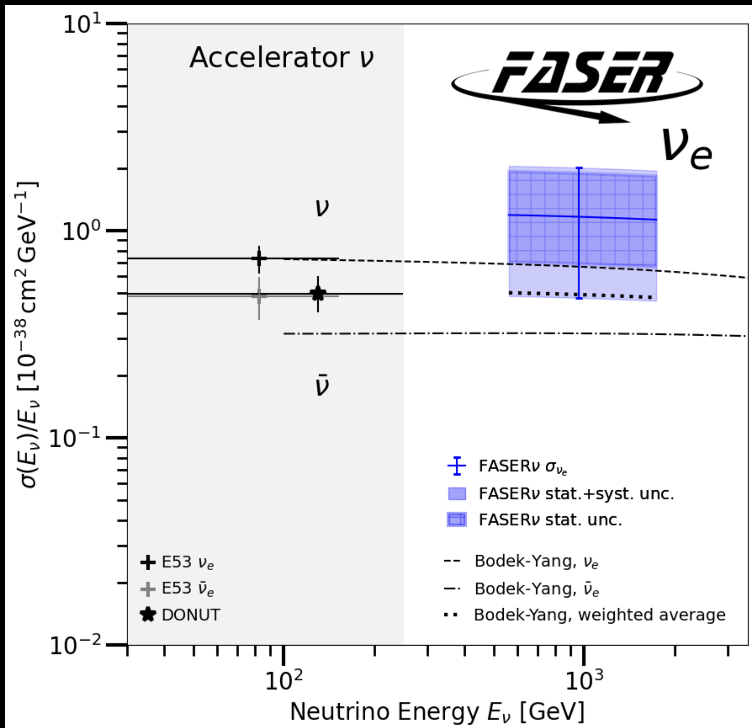
	Background	Expected	Observed	Significance
$\nu_e CC$	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3	4	5.2σ
$\nu_\mu CC$	$0.22^{+0.09}_{-0.07}$	6.5 – 12.4	8	5.7σ

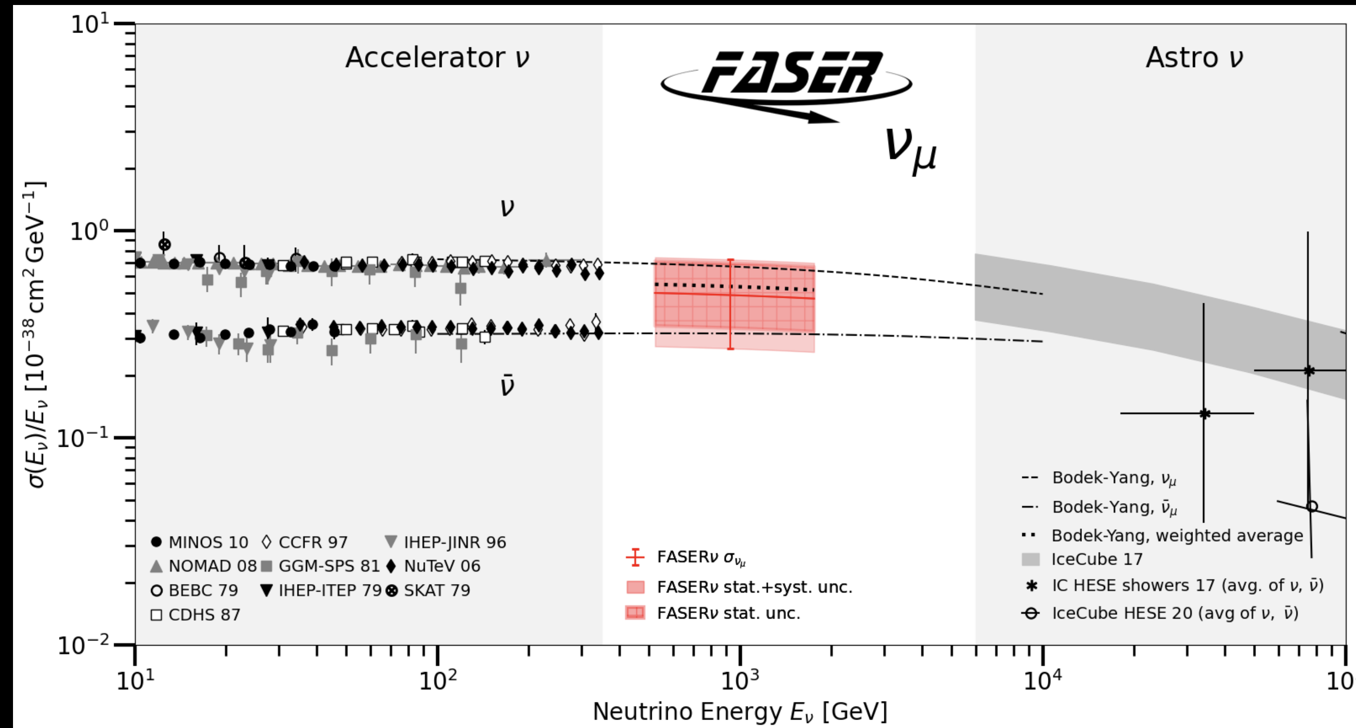






First measurement of the ν_e and ν_μ interaction cross-sections





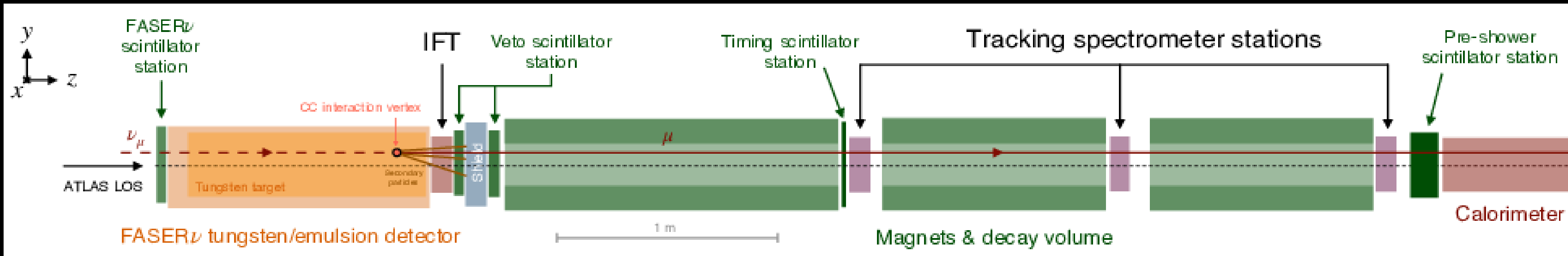
- The interaction cross-section per nucleon measured over an unexplored energy range
- Relative measurement with respect to theoretical curve
- 2% of the data used
- More measurements to come with higher statistics

	Energy range [GeV]	$\sigma_{obs}/E_\nu\ [cm^2 GeV^{-1}]$
$\nu_e - N$	560 – 1740	$(1.2^{+0.8}_{-0.7})\times10^{-38}$
$\nu_\mu - N$	520 - 1760	$(0.5^{+0.2}_{-0.2})\times10^{-38}$

Phys. Rev. Lett. 133 (2024) 021802,

Selected for PRL collection of the year 2024

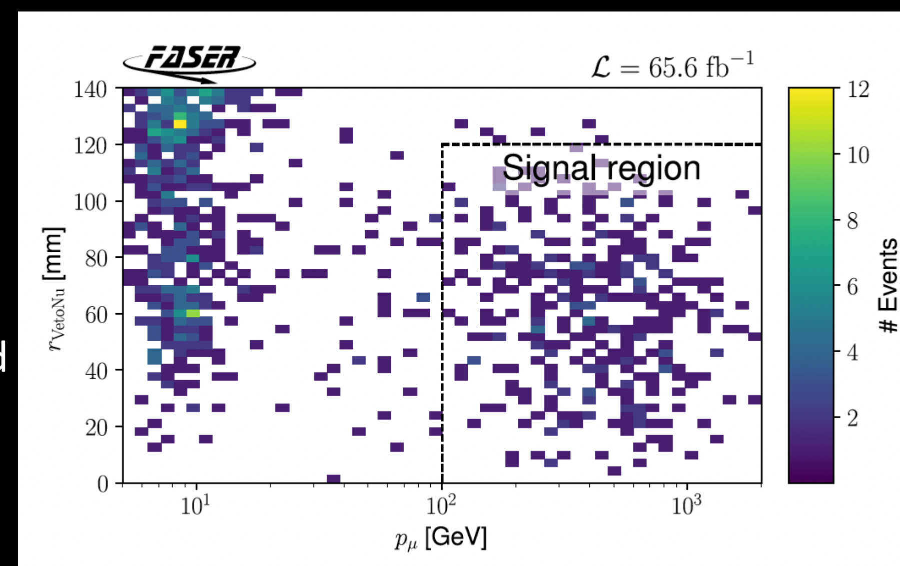
LHC Neutrinos with FASER detector



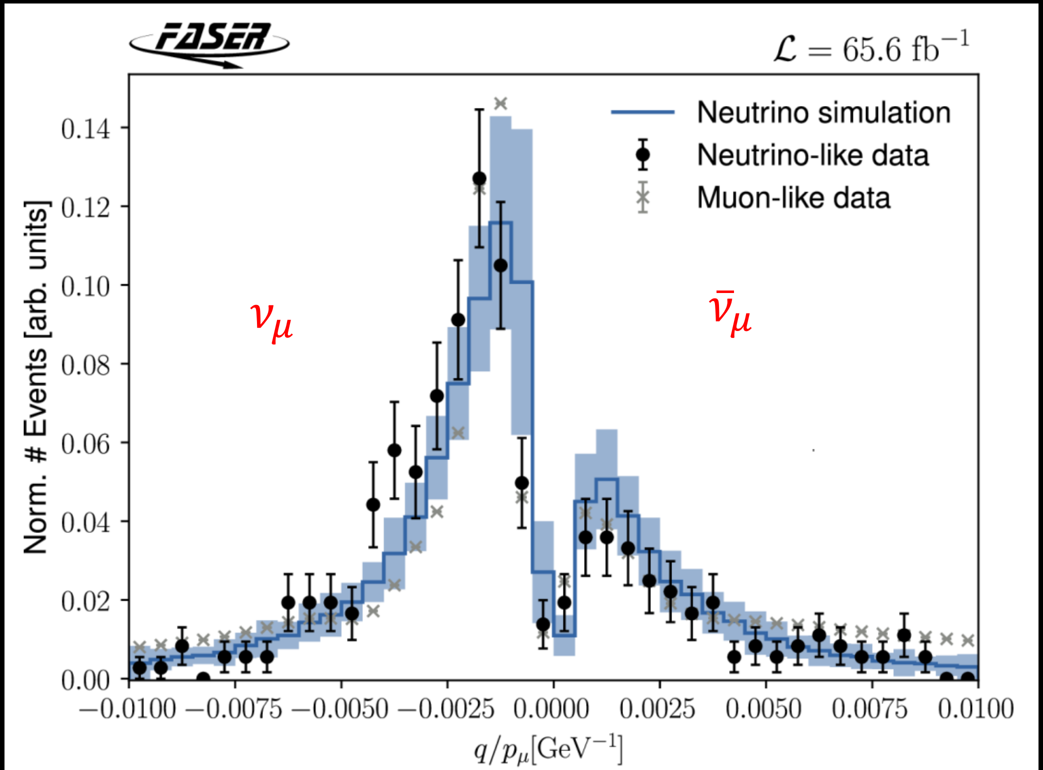
- First direct observation of neutrino interactions using FASER electronic detector reported using integrated lumiosity of 35.4 fb^{-1} : 151 ± 41 neutrino events expected from GENIE simulation and 153 event observed with signal significance of 16σ.
  [Phys. Rev. Lett. 131, 031801 (2023)]

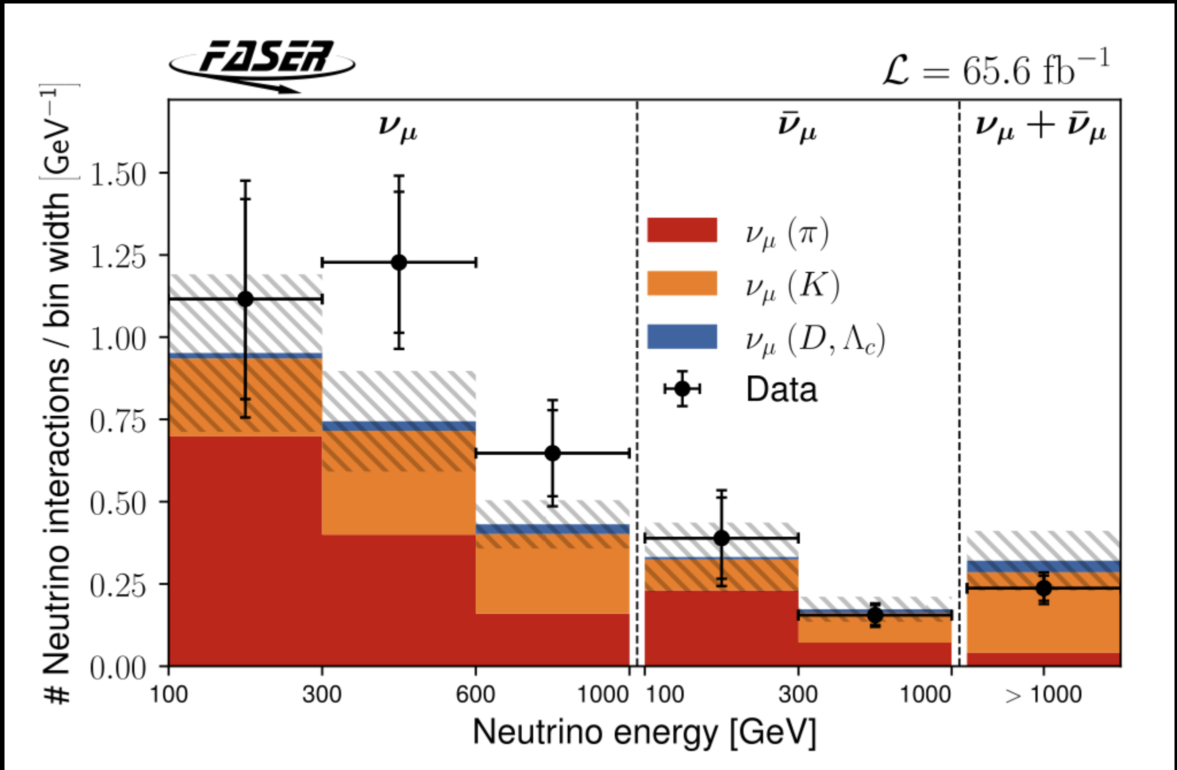
- Combining data collected in 2022-2023 corresponding to integrated lumiosity of 65.6 fb^{-1} used to measure the energy dependent neutrino nucleon cross-section in W target and the differential flux of muon neutrinos and antineutrinos
  - 362 $\nu_\mu/\bar{\nu}_\mu$CC interactions observed, agrees well with expected number of 322.3±50.5.

    [arXiv:2412.03186]



LHC Neutrino Interactions Observed in FASER Detector





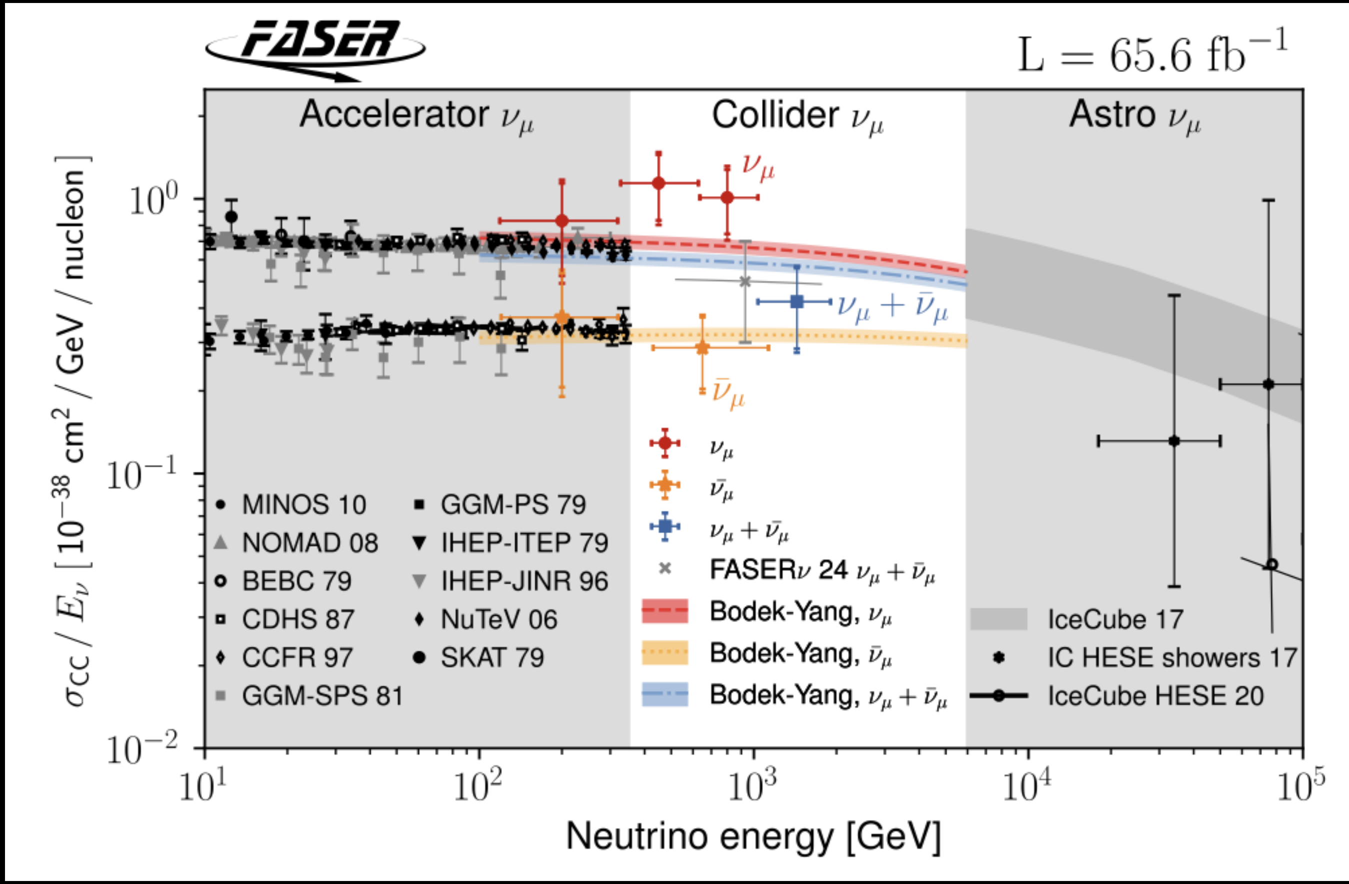
Observed ν_μ and $\bar{\nu}_\mu$ interactions

Unfolded number of neutrino interactions compared to the expectation from the simulation

arXiv:2412.03186

Result 1: measurement of neutrino-nucleon cross sections:

using expected neutrino flux and uncertainty from the simulation



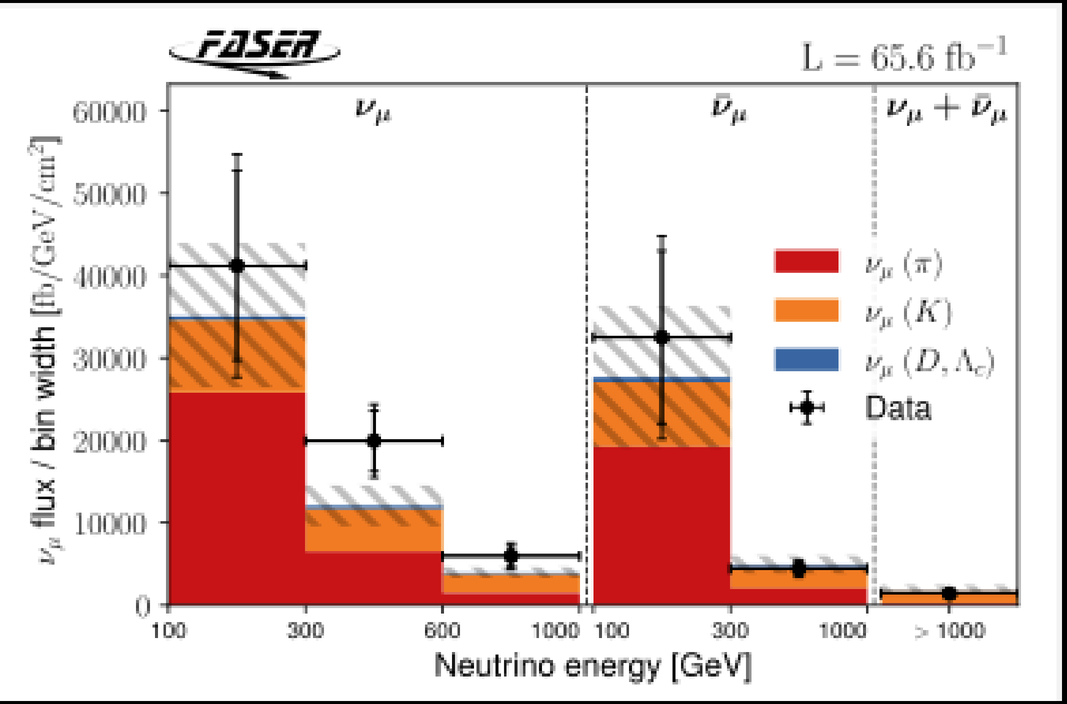
arXiv:2412.03186

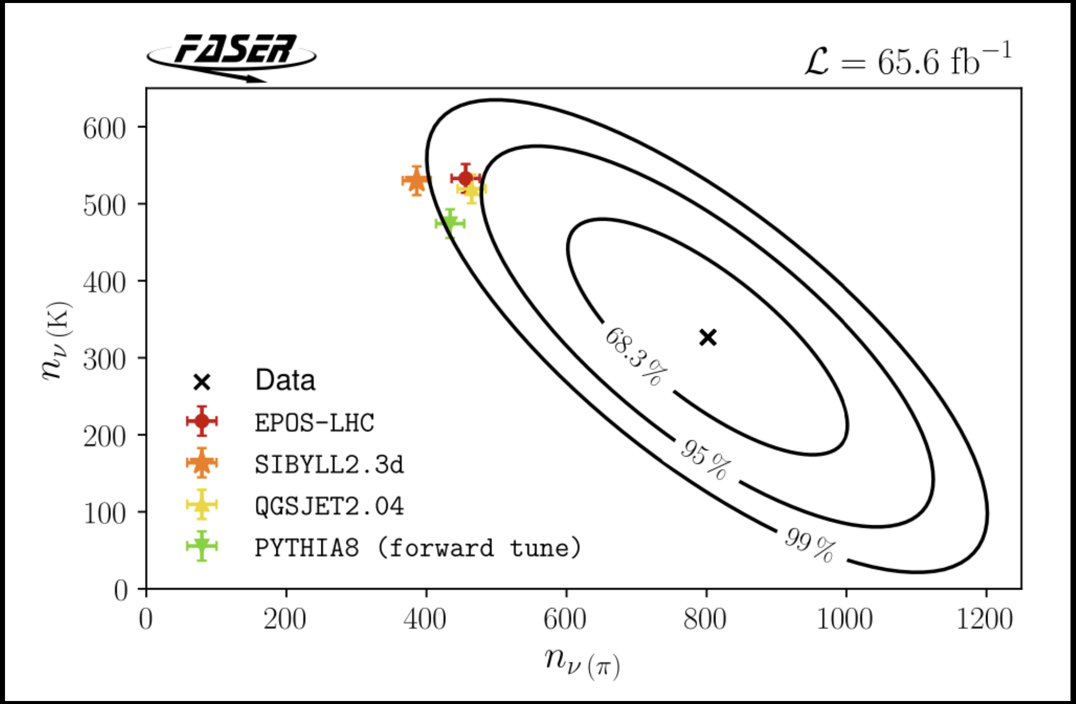
- Measured neutrino-nucleon cross sections, normalized to the neutrino energy, compared to previous measurements from fixed-target and astrophysical sources

Results 2: First neutrino flux measurements:

The theoretical cross-section is assumed to derive the neutrino flux from the data

arXiv:2412.03186





- The measured neutrino flux is compared to the expectation from the simulation
- The number of neutrino interactions from pion and kaon decays are compared with different MC generators.

FASER Approved for LHC Run4

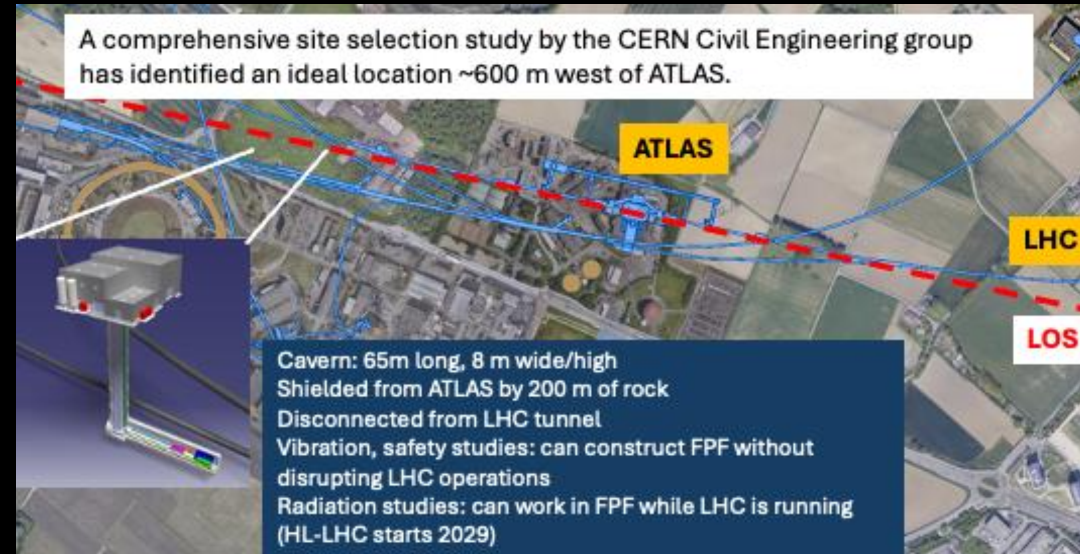
FASER expressed interest in taking data exploring further TeV neutrinos in LHC Run4, with expected total integrated luminosity of 680 fb^{-1}

- Expecting to collect 5000 ν_e, 25000 ν_μ and 100 ν_τ interactions at **FASERν**
- With the HL-LHC operating at luminosity five times larger than the current run
  → Discussion ongoing on possible upgrade of neutrino detector at LHC Run4
  → Possibility to cover both on-axis and off-axis providing wide rapidity coverage and complementarity physics program

Future programs at the LHC: Forward Physics Facility (FPF)

- FPF studied in context of PBC for last 3 years
- FPF is proposed new facility to fully exploit the LHC's physics potential in the forward direction during the HL-LHC era
  - BSM physics searches, neutrino physics, QCD and astro-particle physics
- High statistics highest energy $\nu/\bar{\nu}$:
  - $\mathcal{O}$(10tonne) detectors with HL-LHC
  - $\mathcal{O}(10^5)$ ν_e, $\mathcal{O}(10^6)$ ν_μ and $\mathcal{O}(10^4)$ ν_τ interactions

  with energies from $\mathcal{O}$(100) GeV to a few TeV



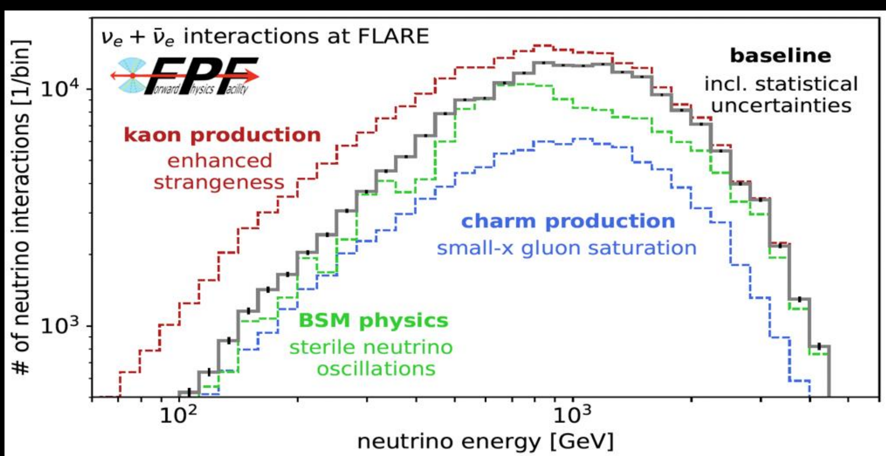
J. Phys. G 50 (2023) 030501, 1-410 https://cds.cern.ch/record/2851822/

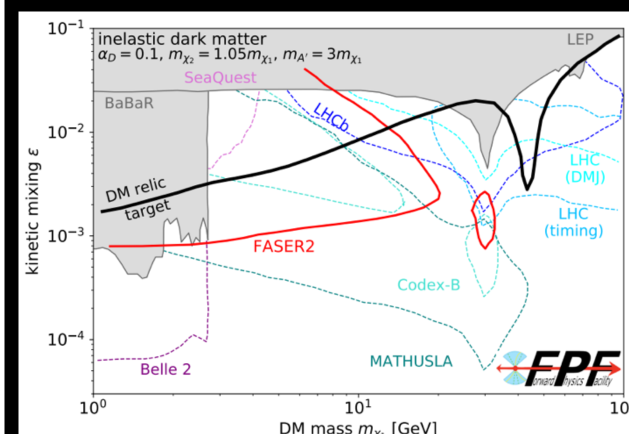
EPPS Update 2024-2026 arXiv:2411.04175

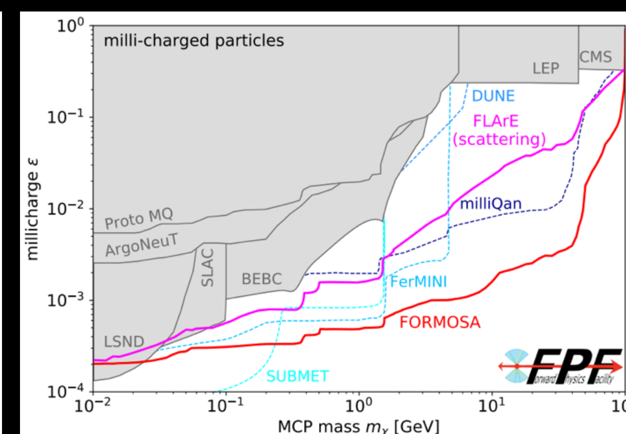
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

arXiv:2203.05090 EPSS 2024-2026: arXiv:2411.04175

Detectors at FPF: AdvSND, FASER2, FASERν2, FLArE and FORMOSA







Conclusions

- A new era in collider neutrino physics: FASER opening a new window to explore previously unexplored energy regions

- FASER at on-axis ($\eta > 8.8$): Successfully taking data since 2022 at LHC Run3:
  - 195 fb^{-1} of integrated luminosity delivered, with 190 fb^{-1} recorded at an efficiency of >97% since the beginning. Annual breakdown: 35 fb^{-1} in 2022, 33 fb^{-1} in 2023 and 122 fb^{-1} in 2024
  - Expected by the end of LHC Run3 reaching 350 fb^{-1}

- Neutrino search at the LHC

  First direct observation of collider neutrinos by FASER and FASERν:

  Observing for the first time the highest energy, 1.5 TeV, $\nu_e CC$ interaction

  First measurement of neutrino charged current (CC) interaction cross-sections:

  $\nu_e N$ and $\nu_\mu N$ CC interaction cross-sections by FASERν

  $(\nu_\mu - \bar{\nu}_\mu)N$ CC interaction cross-sections by FASER

  First measurement of neutrino flux as a function of energy by FASER

- More results are coming!

- Great potential and Physics opportunities in future:
  - FASER in LHC Run4 approved to continue its exploration
  - Forward Physics Facility (FPF) under discussions

Thank you

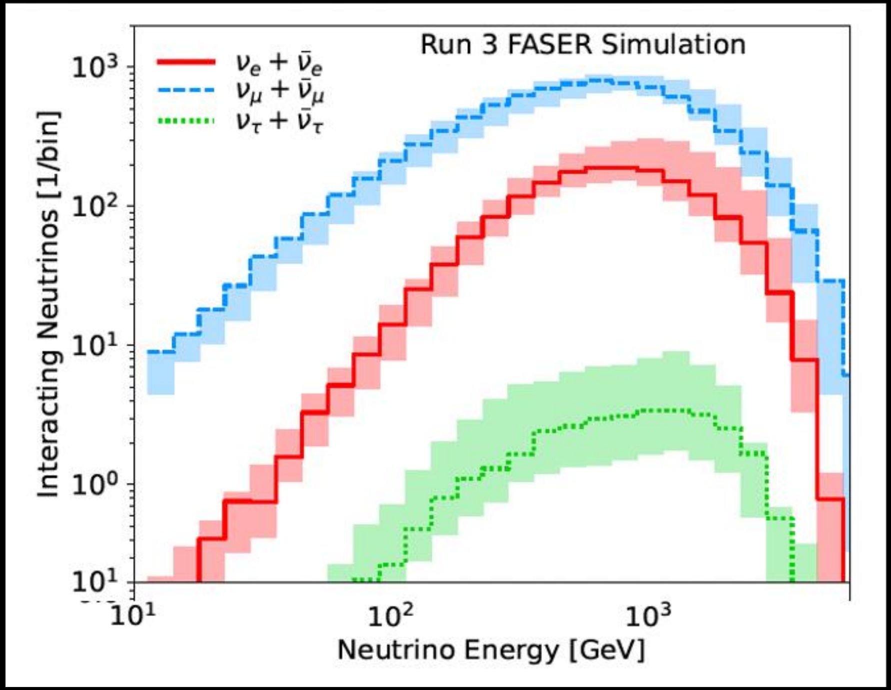
FASER supported by

Back-Up

Expected neutrino event rate in LHC Run3

- Neutrino production:
  - For light hadrons (pions, kaons and hyperons) EPOS-LHC, QGSJET II-04, SIBYLL2.3d, PYTHIA8, DPMJET
  - For charm hadrons POWHEG+PYTHIA8, DPMJET
- Propagation to detectors BDSIM/FLUKA model of the LHC
- Neutrino interactions with tungsten/emulsion GENIE
- Propagation in the detector GEANT4
- LHC Run3 with an integrated luminosity of 250 fb^{-1}

Generators		FASERν at Run 3		
light hadrons	charm hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–
SIBYLL 2.3d	–	1126	7261	–
QGSJET 2.04	–	1181	8126	–
PYTHIAforward	–	1008	7418	–
–	POWHEG Max	1405	1373	76
–	POWHEG	527	511	28
–	POWHEG Min	294	284	16
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}

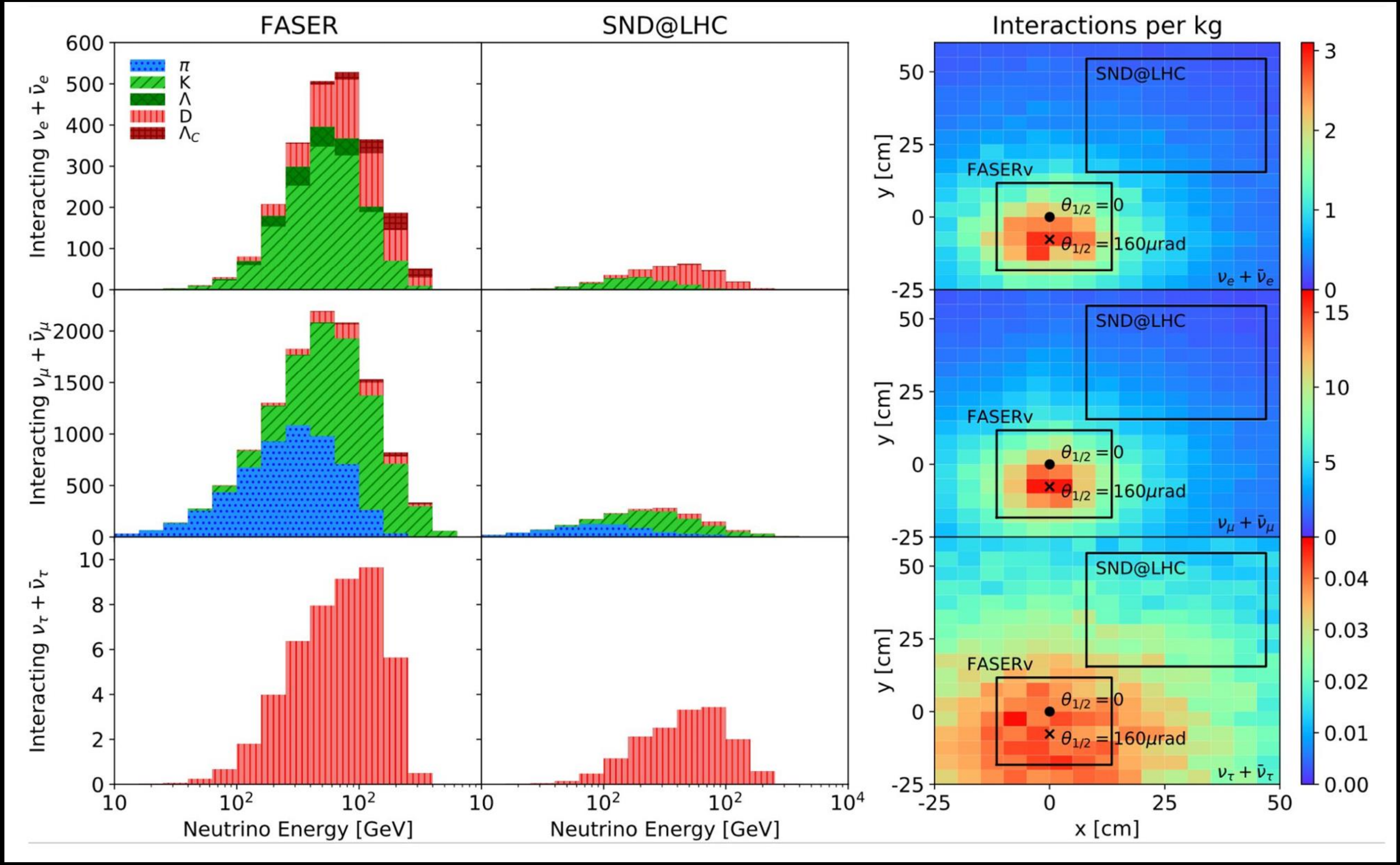


[FASER Coll. arXiv:2402.13318](https://arxiv.org/abs/2402.13318)

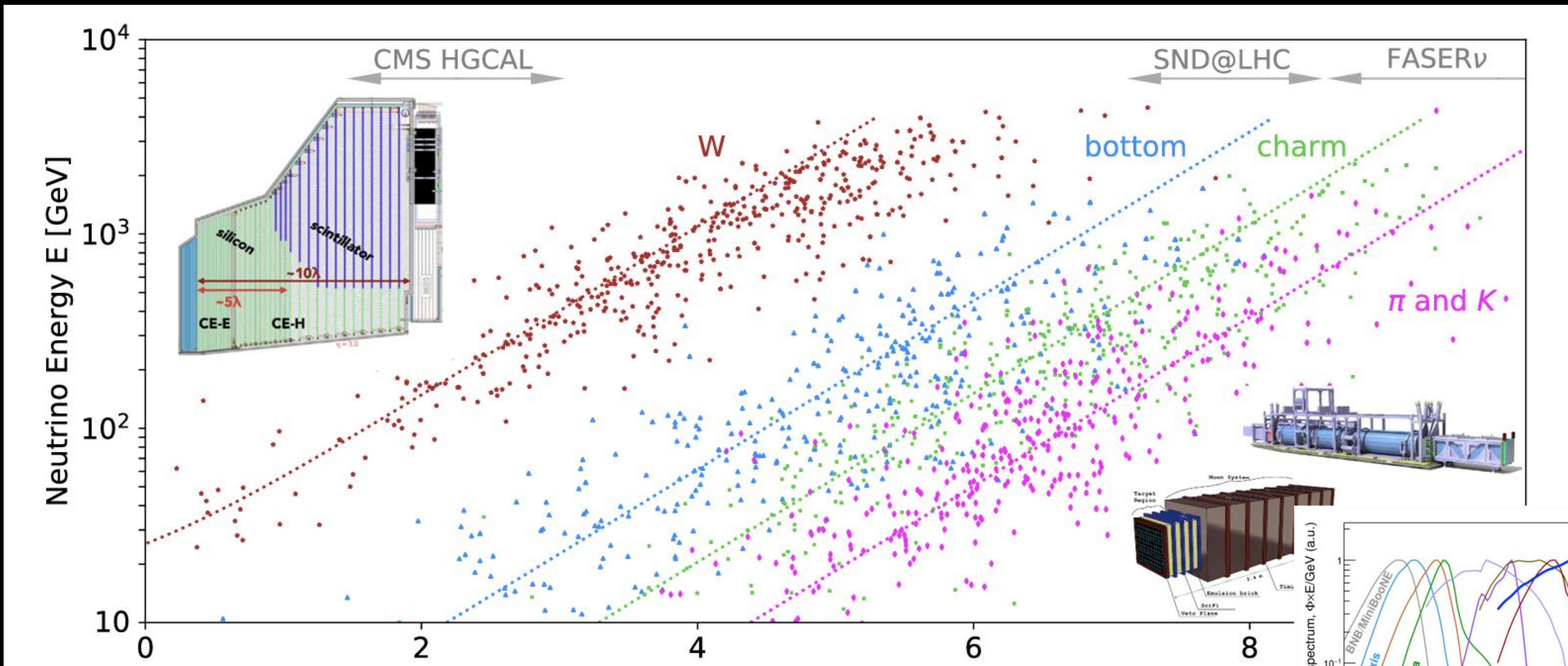
Directly observed $\nu_\tau CC$ interactions: 9 at DONUT and 10 at OPERA experiments

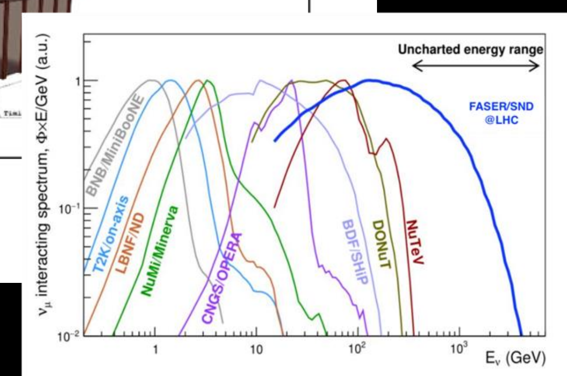
Neutrino rates in LHC Run3

arXiv:2501.10078



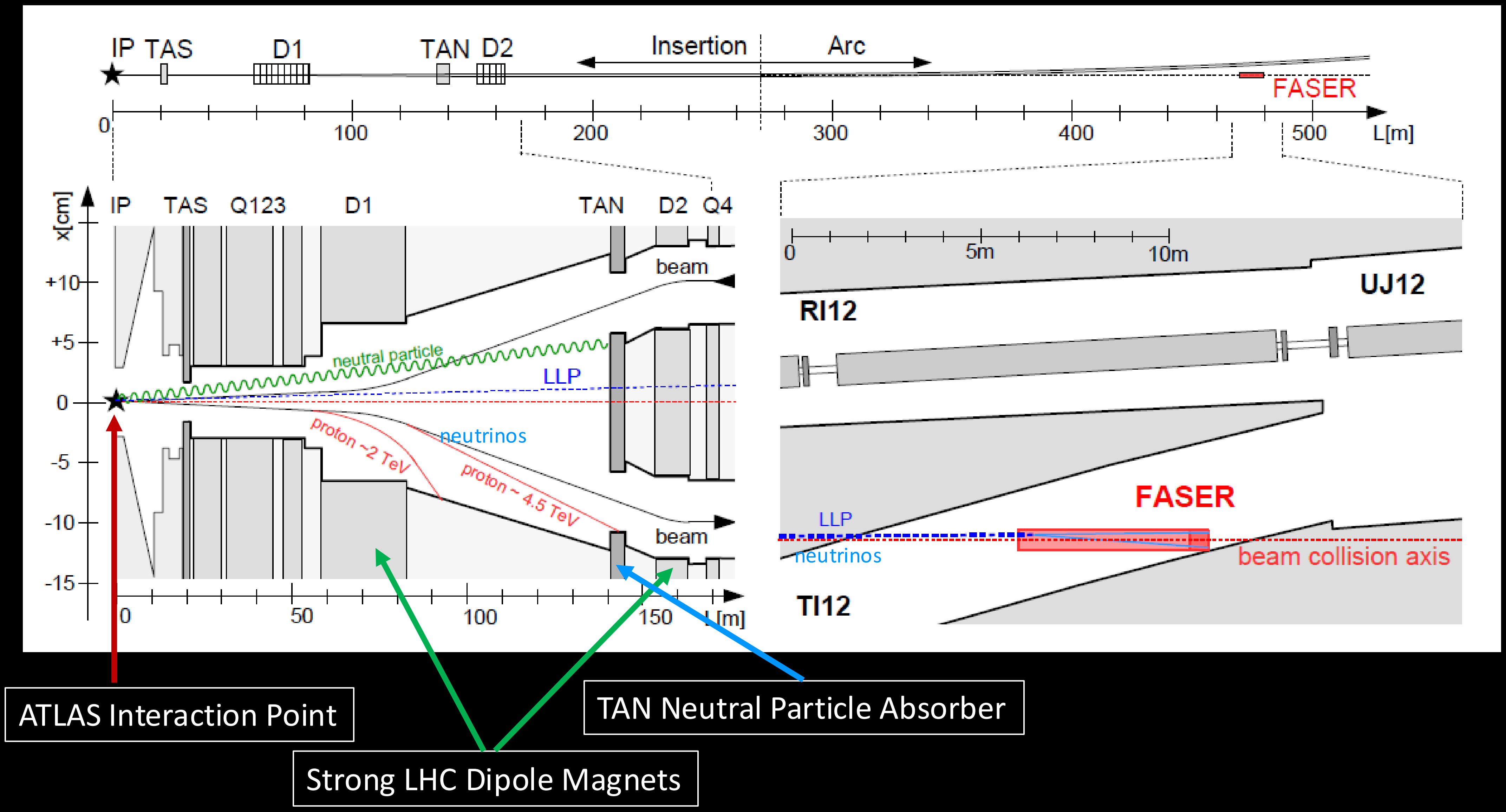
High energy neutrino distribution at the LHC



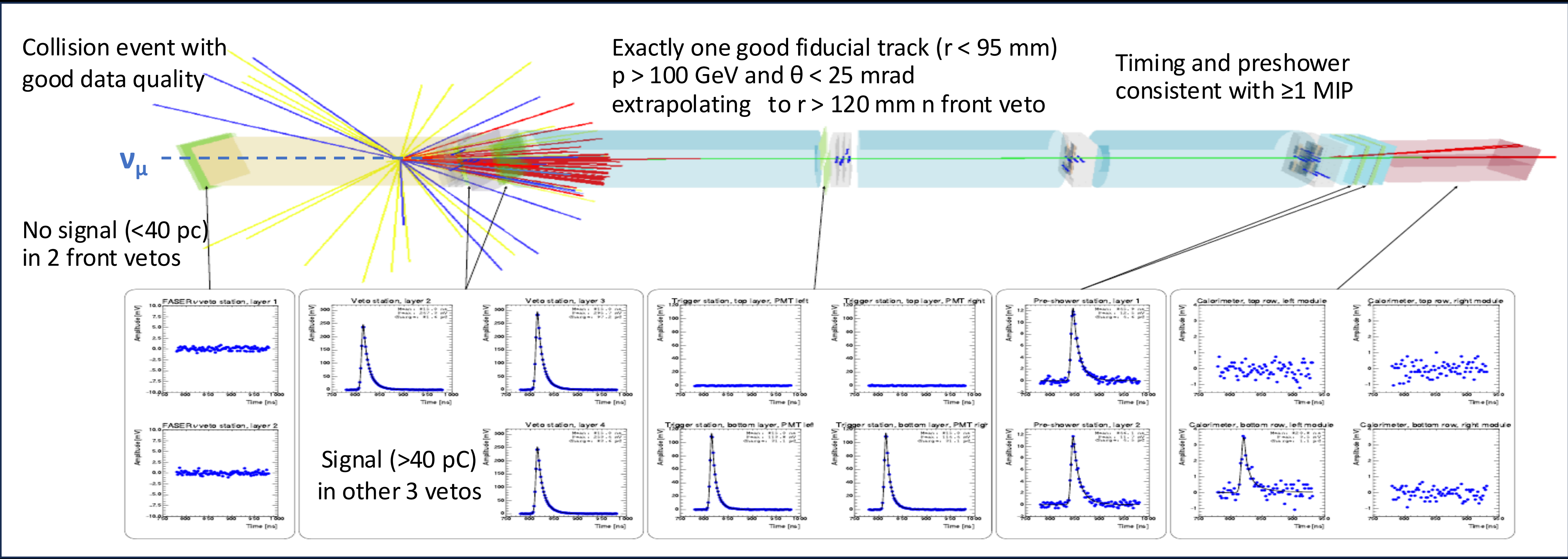


[arXiv:2108.05370v2](https://arxiv.org/abs/2108.05370v2)

Surrounding LHC infrastructure and FASER



Event Selection



[Phys. Rev. Lett. 131, 031801 (2023)]

Good tracks must leave no signal in the FASERν scintillator, have timing consistent with colliding bunches and p >100 GeV.

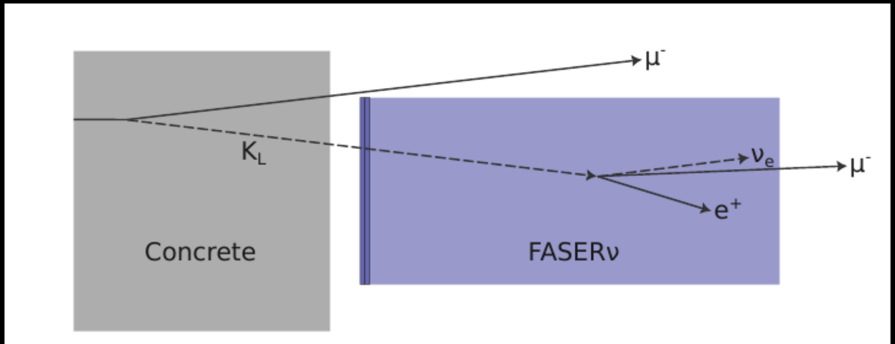
Neutrino Backgrounds for neutrino interaction search in FASER

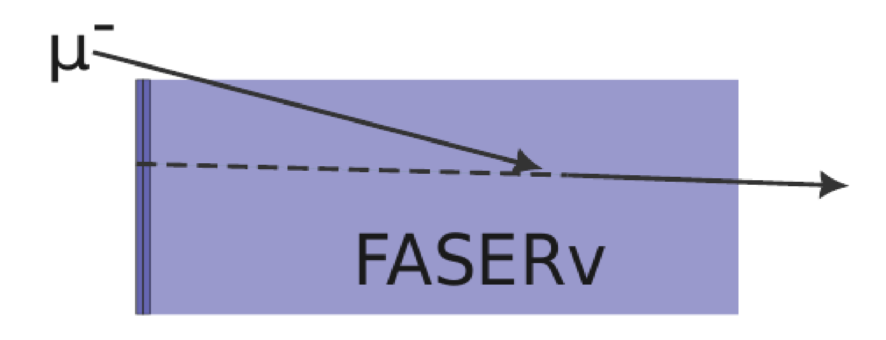
- Neutral hadrons
  - Neutral hadrons interact after. Passing the veto
  - less than 10^{-3} events after event selection

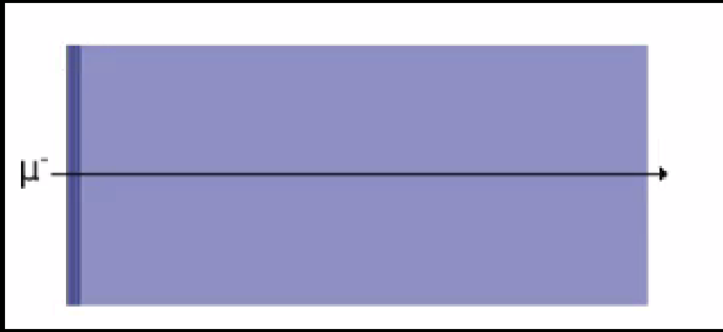
- Geometric muons
  - Large incidence angle muons miss the veto
  - Compatible with zero using the sideband method

- Veto inefficiency
  - less than 10^{-6} events after event selection

- Non-collision background
  - Cosmic events and beam-1 background
  - Expected negligible from non-collision data taking



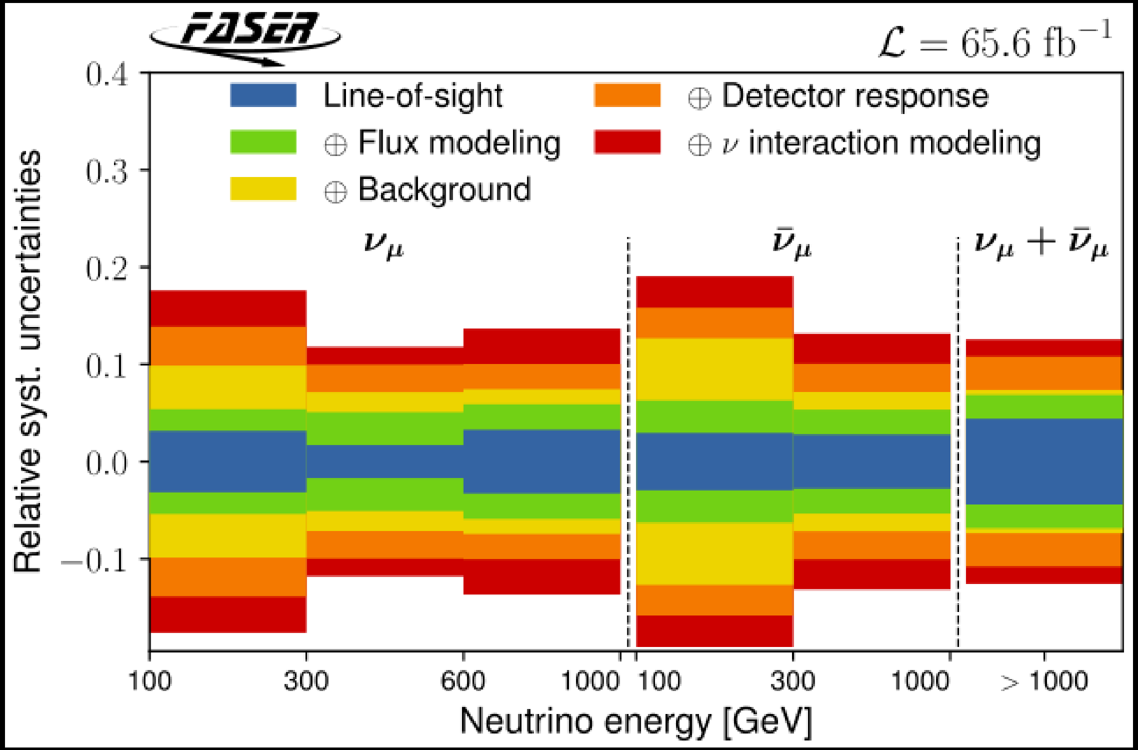




Systematic uncertainties

The primary sources of systematic uncertainties include:

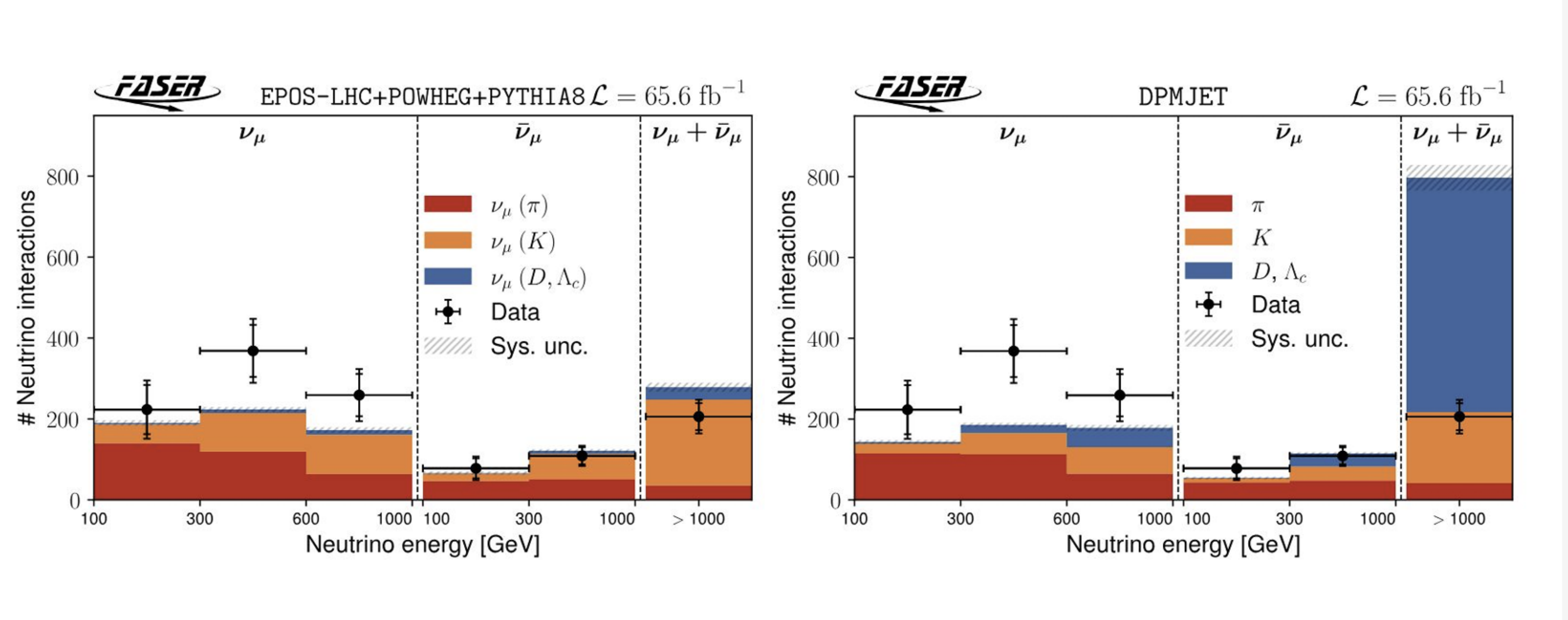
- Neutrino Interaction and Particle Transport Modeling
- Detector Response and Alignment
- Background Estimation: Geometric Muon, non-signal neutrino interactions
- Neutrino Flux Predictions: Hadron production models, beam crossing angle variations
  - EPOS-LHC, Sibyll 2.3d, QGSJET 2.04, and the forward physics tune of PYTHIA



arXiv:2412.03186

Comparison with hadronic interactions

arXiv:2412.03186



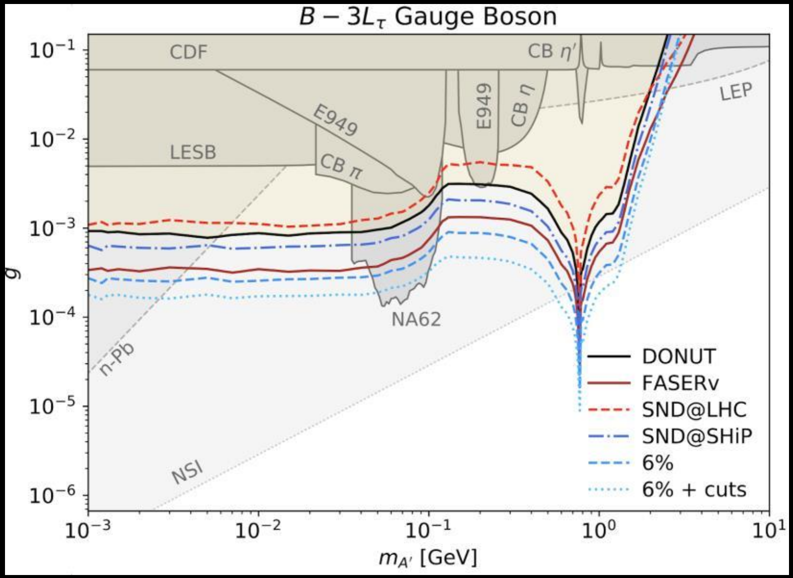
The unfolded number of neutrino interactions with the expectation from EPOS-LHC, POWHEG+PYTHIA8 tune and DPMJET 3.2019.1

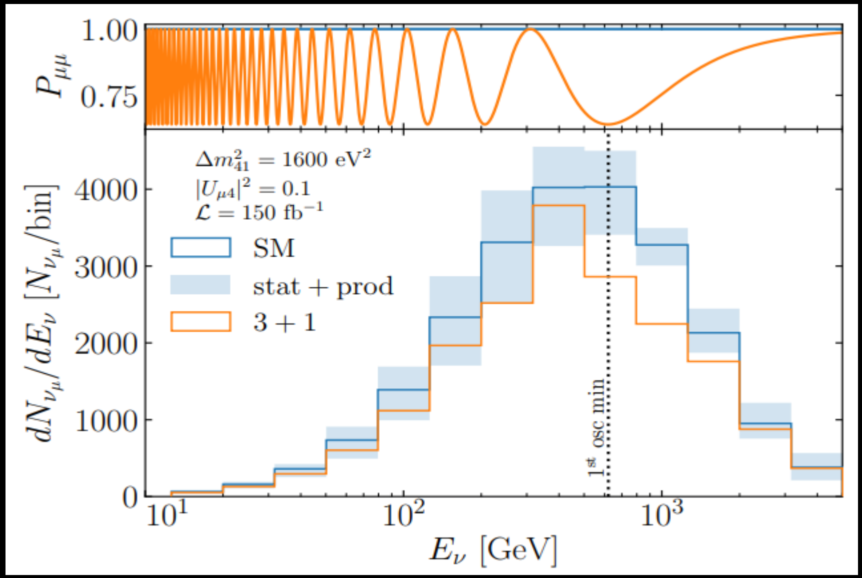
FASER data already ruled out some models

Physics potential: Beyond standard model physics

The tau neutrino flux is small in Standard Model. A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux.
F. Kling, Phys. Rev. D 102, 015007 (2020), arXiv:2005.03594

In SM, no neutrino oscillations are expected. However, sterile neutrinos with mass ~40 eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment. FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310





FASERν pilot run in 2018

- The pilot runs were taken place for charged particles flux measurement and neutrino detection at tunnels TI12 and TI18, 480 m from ATLAS in 2018. Both tunnels are symmetric to ATLAS.

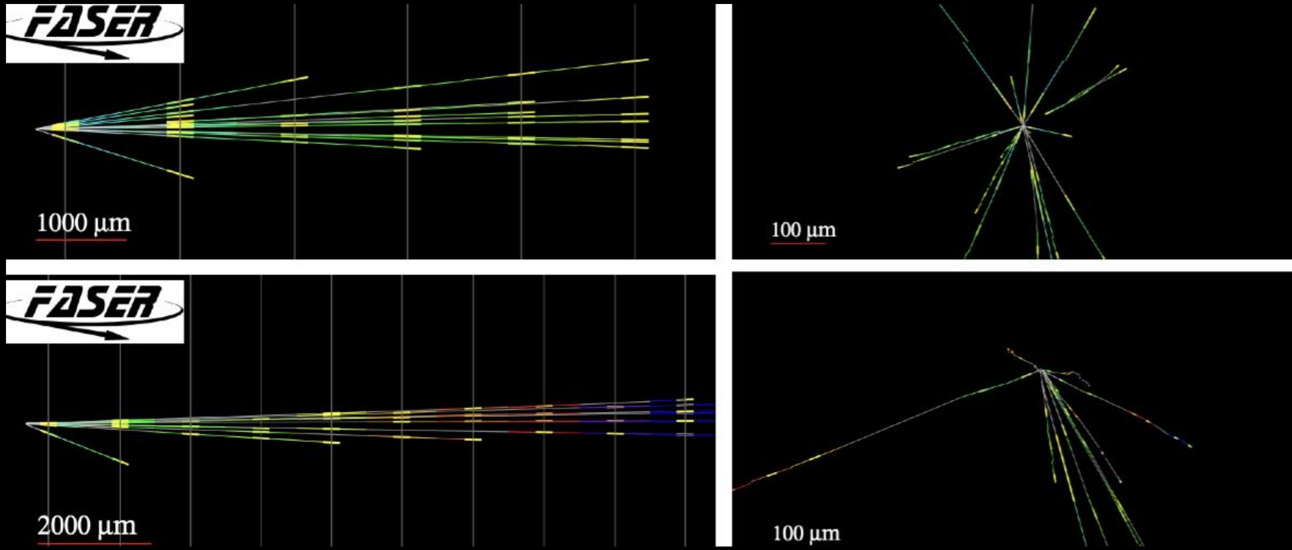
- For neutrino detection: ~30 kg mass emulsion:
  - Lead (1-mm-thick, 100 layers) and Tungsten (0.5-mm-thick, 120 layers)
  - Installed in TI18
  - 12.2 fb^{-1} of data collected in Sep - Oct. 2018 (~1. 5months)

- 18 neutral vertices passed the vertex selection criteria

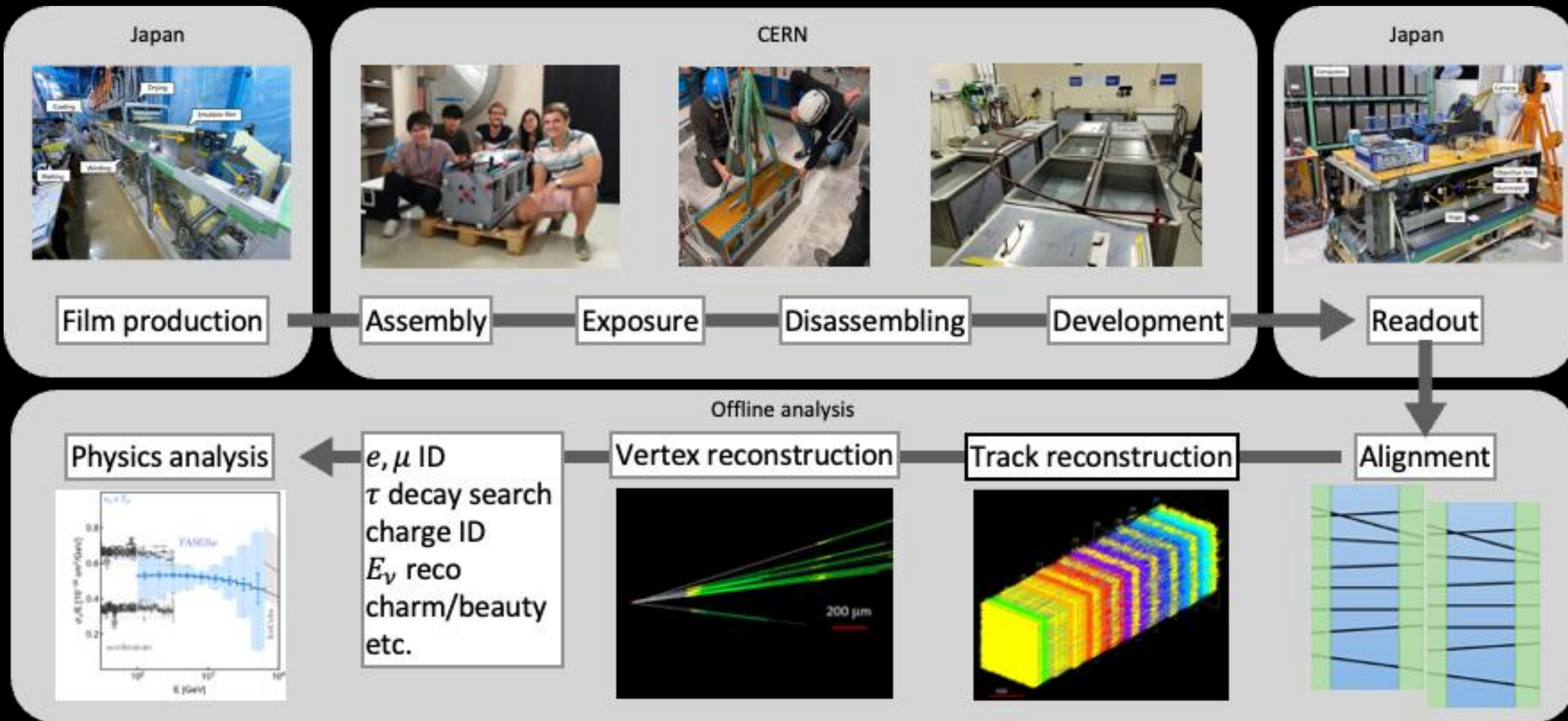
- Expected # of neutrino signal = $3.3^{+1.7}_{-0.95}$

- Expected # of background = 11.0 events.

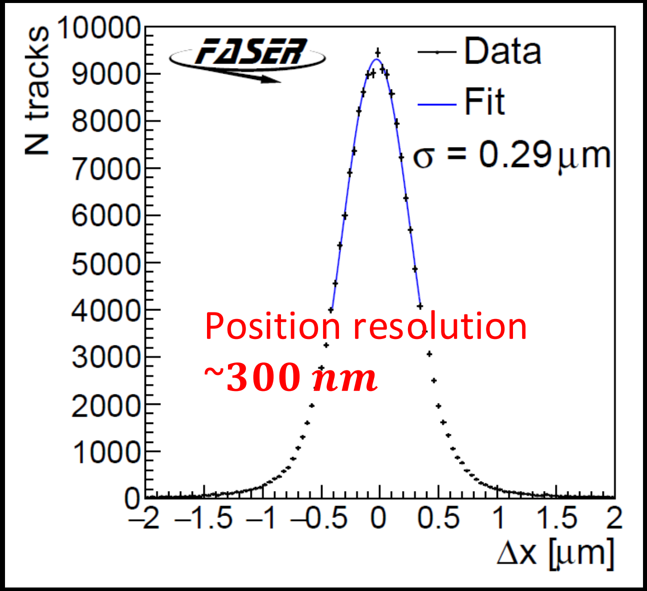
- The background-only hypothesis is disfavored with a statistical significance of 2.7σ



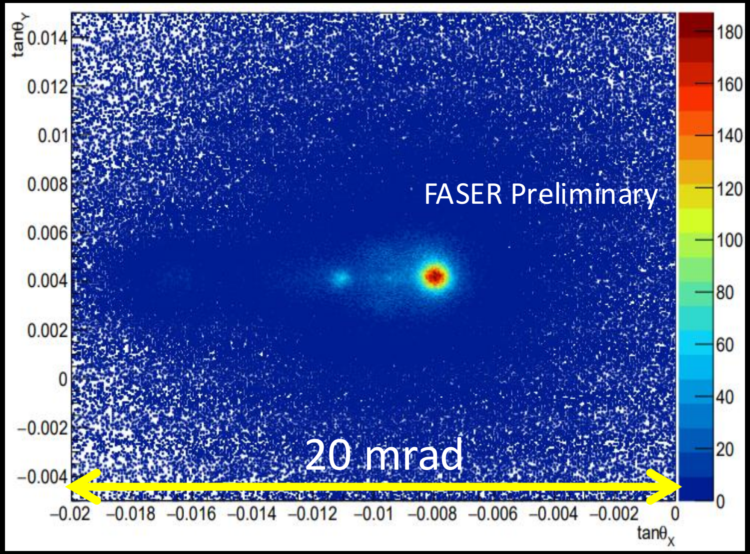
Emulsion film production to physics analysis in FASERν



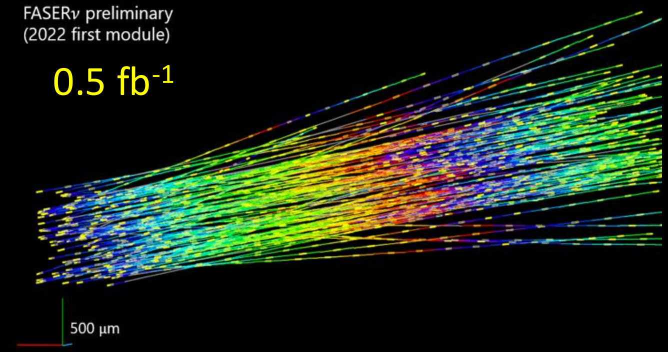
FASERν Detector Performance

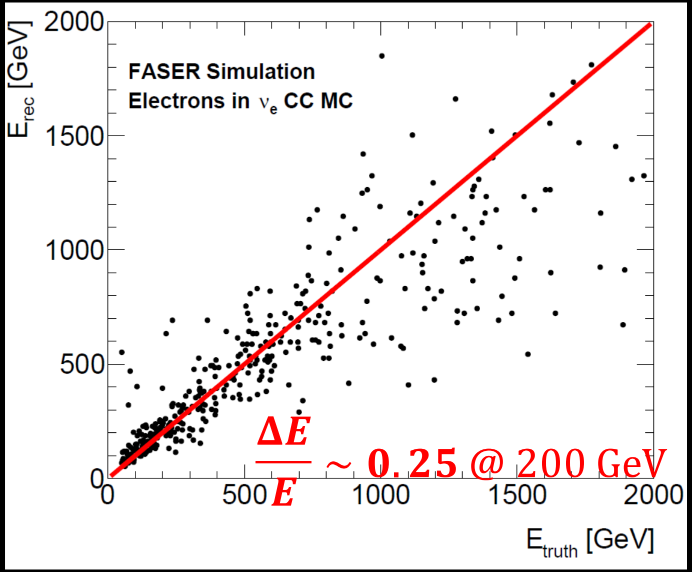


BG muon angular distribution (Data)



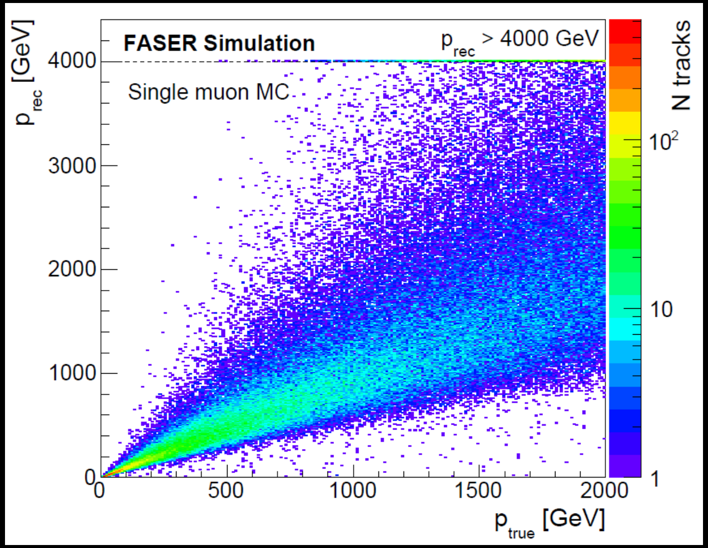
Angular spread of muon peaks
$\sim \mathbf{0.4}$ **mrad**





$$\frac{\Delta E}{E} \sim \mathbf{0.25} \text{ @ 200 GeV}$$

Electron energy reconstruction



Muon momentum measurement by MCS

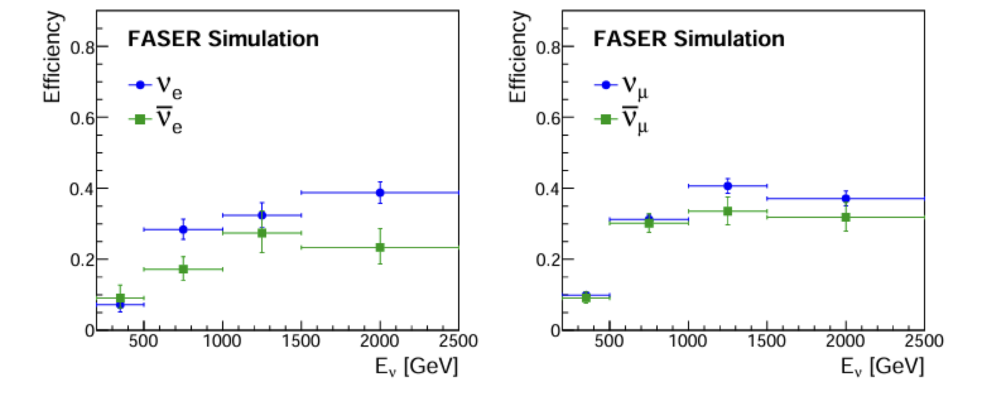
$$\frac{\Delta P^{RMS}}{P} \sim \mathbf{0.3} \text{ @ 200 GeV}$$

FASERν Analysis

Selection criteria:

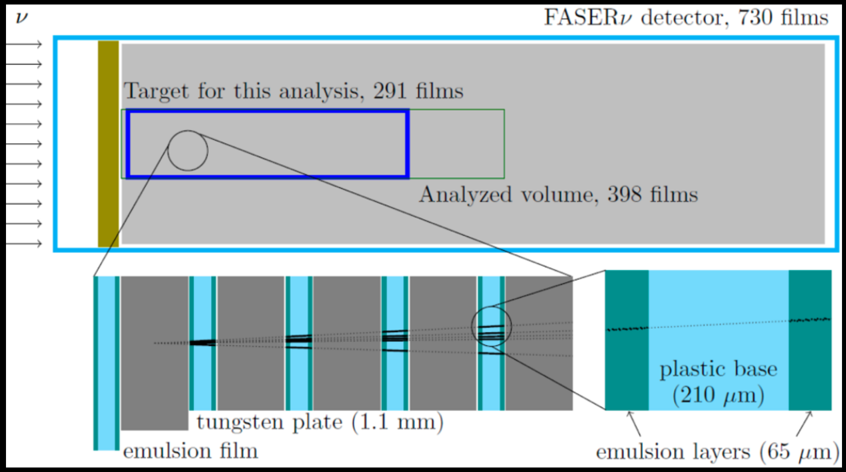
- Vertex reconstruction with $N_{track} \geq 5$ and $N_{track}(\tan\theta \leq 0.1) \geq 4$
- Lepton requirements with E_e or $p_\mu > 200\ GeV$ and $tan\theta_e$ or $tan\theta_\mu > 0.005$
- Back-to-back topology: $\Delta\phi > 90°$

Selection efficiencies



$$N_{obs} = \frac{L\rho l}{m_{nucleon}} \int \sigma(E)\phi(E)\varepsilon(E)dAdE$$

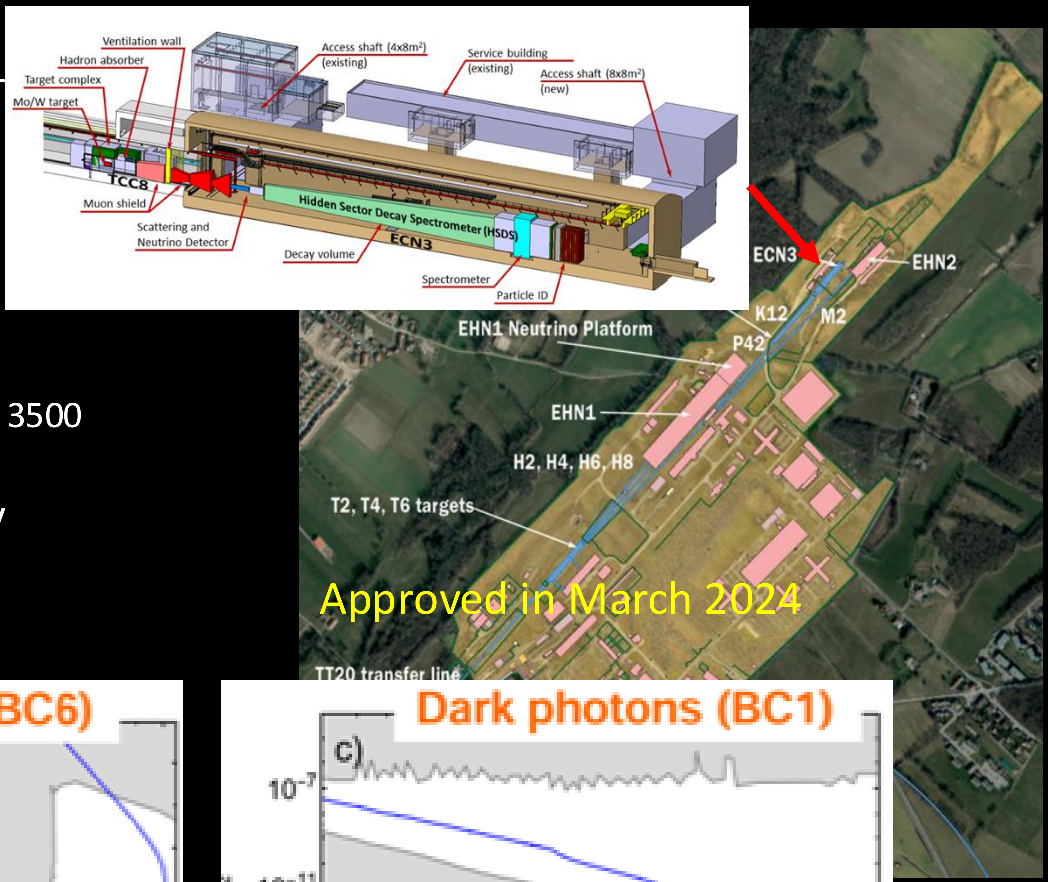
- ν_e and ν_μCC sections measured in a single energy bin
- $\sigma_{obs} = \alpha\sigma_{theory}$
- The α is measured to be $2.4^{+1.8}_{-1.3}$ for ν_e and $0.9^{+0.5}_{-0.3}$ for ν_μ

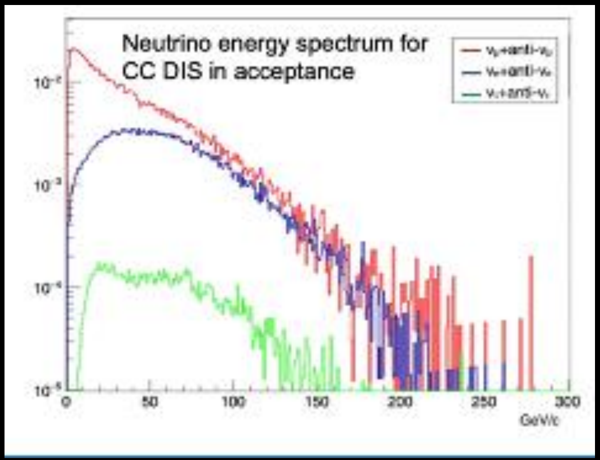


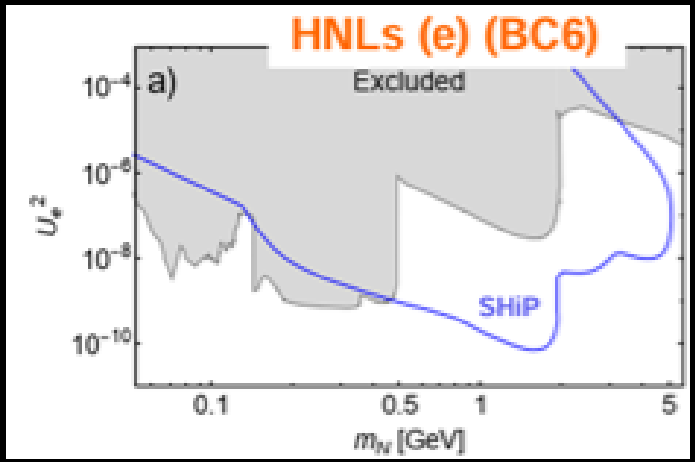
Source	Relative uncertainty ν_e	Relative uncertainty ν_μ
Luminosity	2.2%	2.2%
Tungsten thickness	1%	1%
Interactions with emulsions	$^{+3.6}_{-0}$%	$^{+3.6}_{-0}$%
Flux uncertainty	$^{+70}_{-22}$%	$^{+16}_{-9}$%
Line of sight position	$^{+2.1}_{-2.4}$%	$^{+1.9}_{-2.5}$%
Efficiency from hadronization	$^{+22}_{-5}$%	$^{+23}_{-5}$%
Efficiency from reconstruction	20%	20%
Efficiency from MC statistics	4.9%	2.8%
Total	$^{+70}_{-22}$% (flux)	$^{+16}_{-9}$% (flux)
	$^{+30}_{-21}$% (other)	$^{+31}_{-21}$% (other)

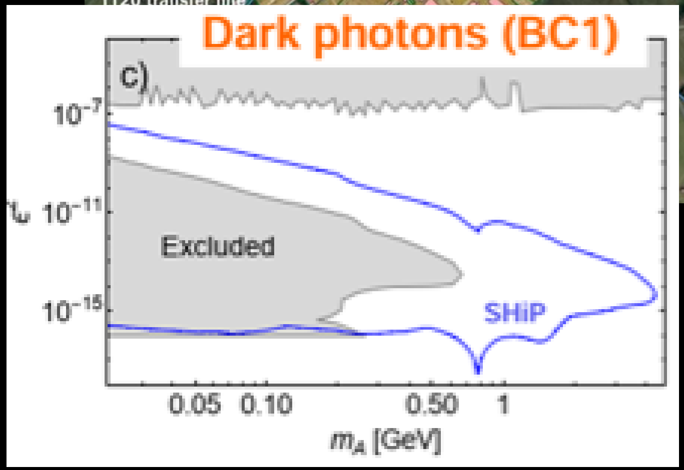
Future programs at CERN: Beam Dump Facility/Search for Hidden Particles (BDF/SHIP)

- 400 GeV protons on W/Mo target: 4×10^{19} pot/year for 15 years
- Expected luminosity > $4 \times 10^{45}\ cm^2/year$
- BDF/SHIP (annually yield)
  - $\sim 2 \times 10^{17}$ charmed hadrons,
  - $\sim 2 \times 10^{12}$ beauty hadrons,
  - $\sim 2 \times 10^{15}$ tau leptons
  - $O(10^{20})$ photons above 100 MeV
  - Large number of seutrinos detected with 3tons emulsion-W target: 3500 $\nu_\tau + \bar{\nu}_\tau$, $2 \times 10^5\ \nu_e + \bar{\nu}_e$ and $7 \times 10^5\ \nu_\mu + \bar{\nu}_\mu$
- Search for light dark matter and associated mediators, feebly interacting particles (Dark photons, HNL, ALP, etc), neutrino physics (x-section, LFU, etc)





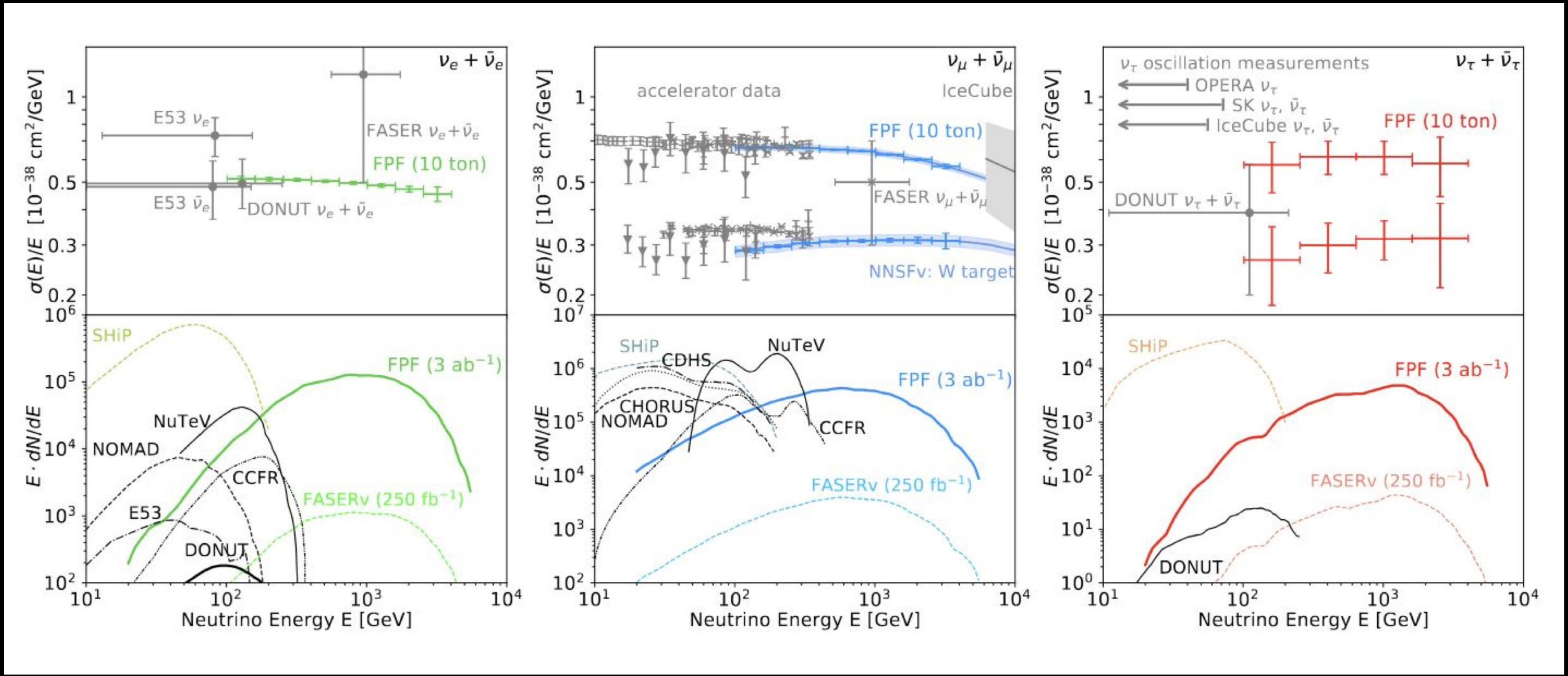




Richardson: BDF/SHIP ECN3, Plenary ECFA meeting, 2023

CERN-SPSC-2022-032 / SPSC-I-258

Neutrino interactions at FPF



Neutrino interaction identification in FASERν