Neutrino measurements with the FASER detector at the LHC

24th International Workshop on Next Generation Nucleon Decay & Neutrino Detectors
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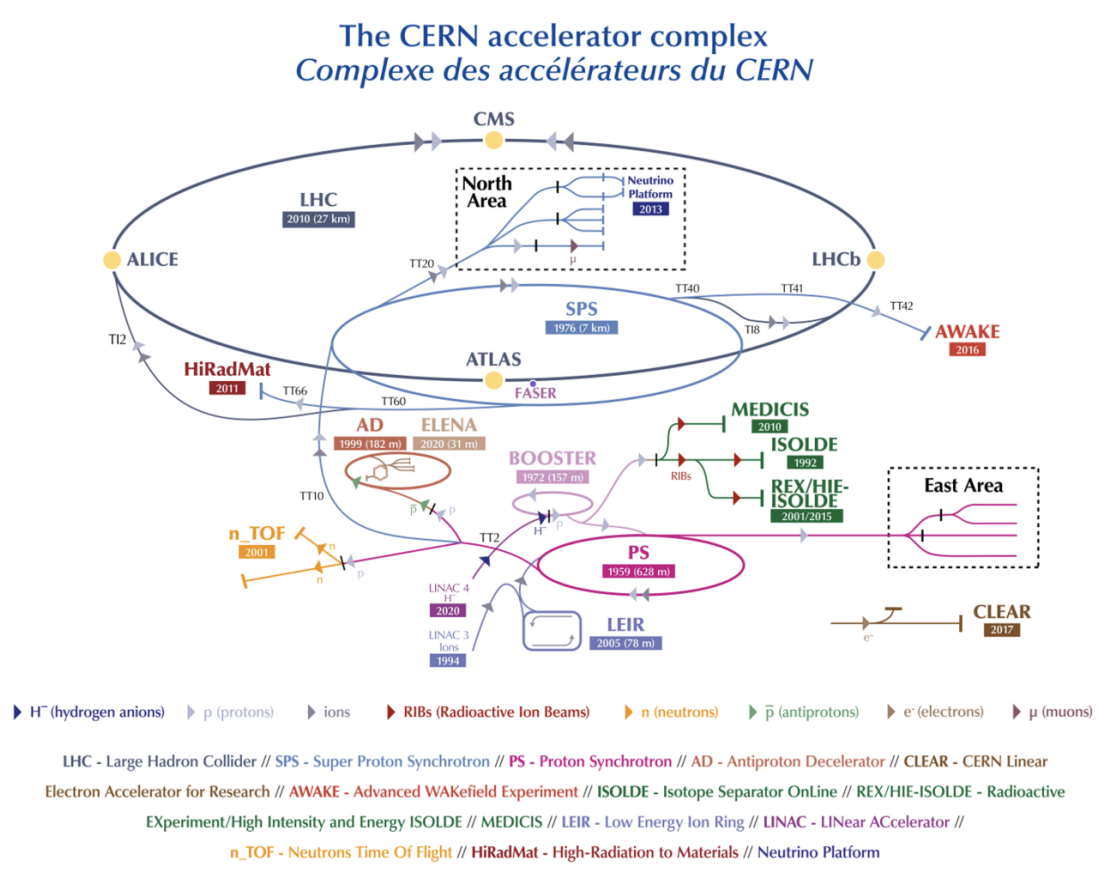
Outline

- The components of the FASER detector
- LHC neutrinos at FASER
- FASERν results
- Muon neutrino observation with the FASER electronic detector
- Muon neutrino cross section and flux measurement
- Future Prospects
- Summary and Outlook

The FASER Collaboration

107 members, 27 institutes, 11 countries

Introduction



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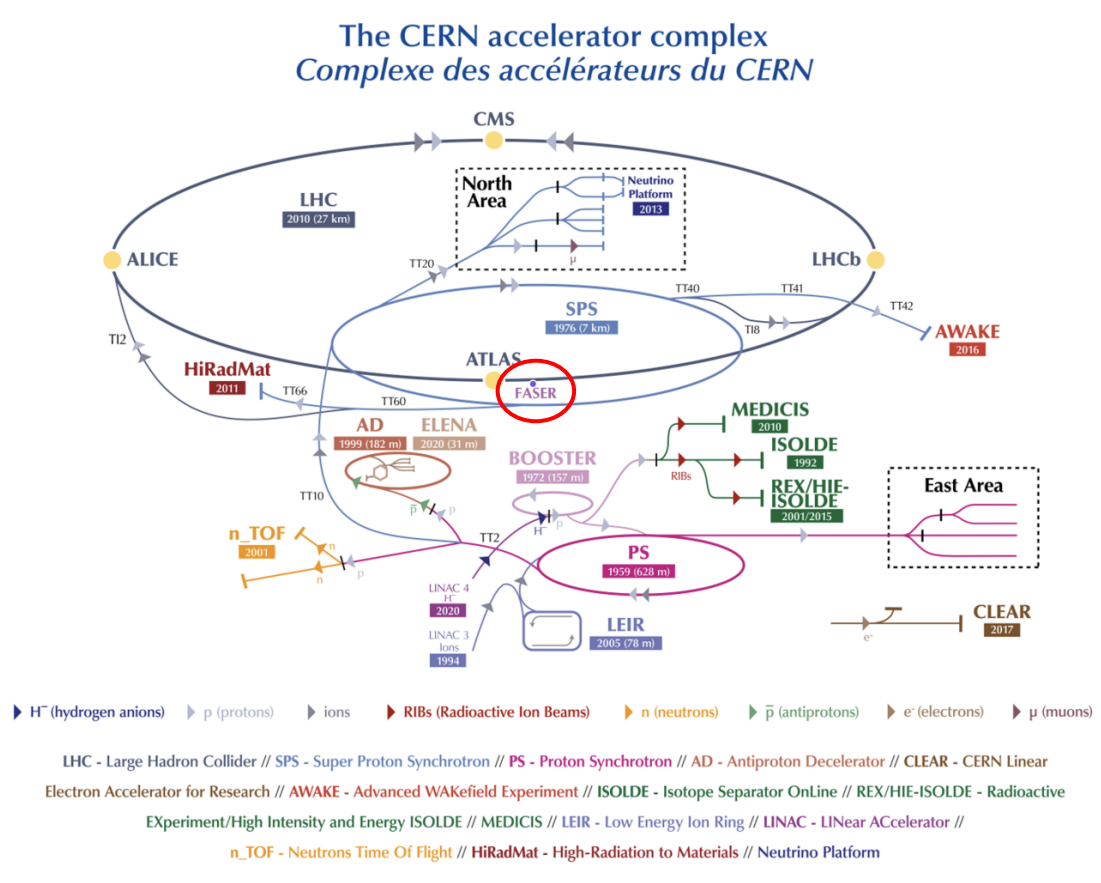

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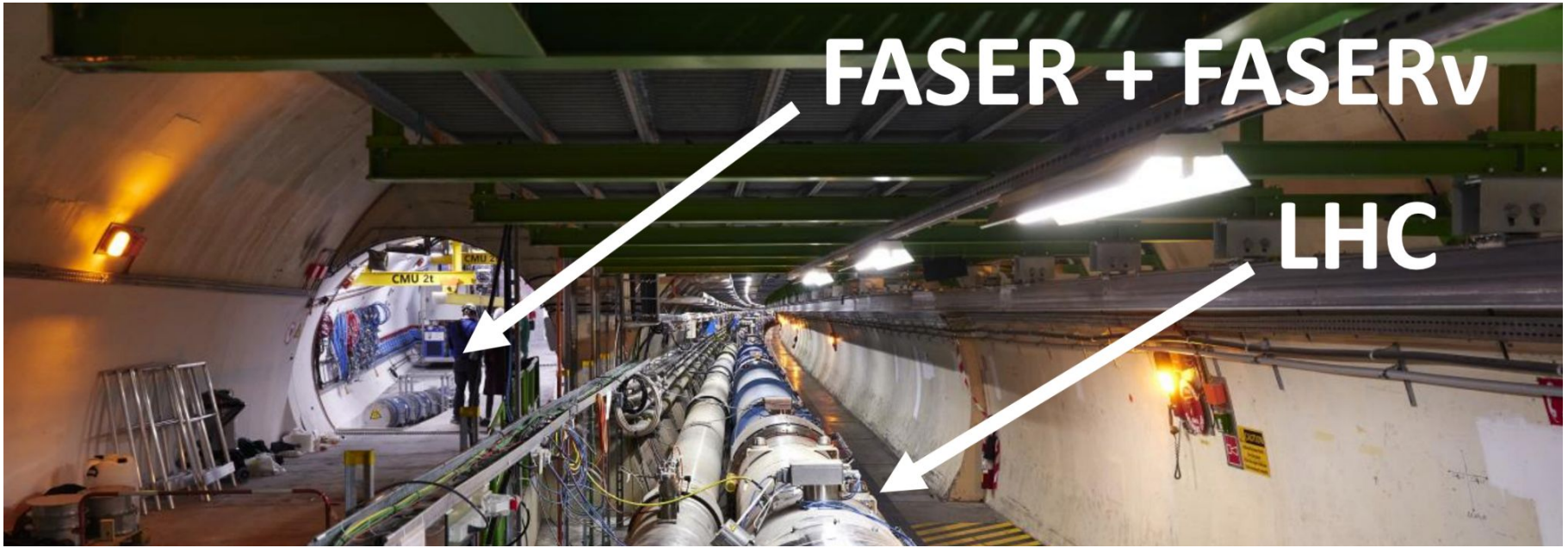
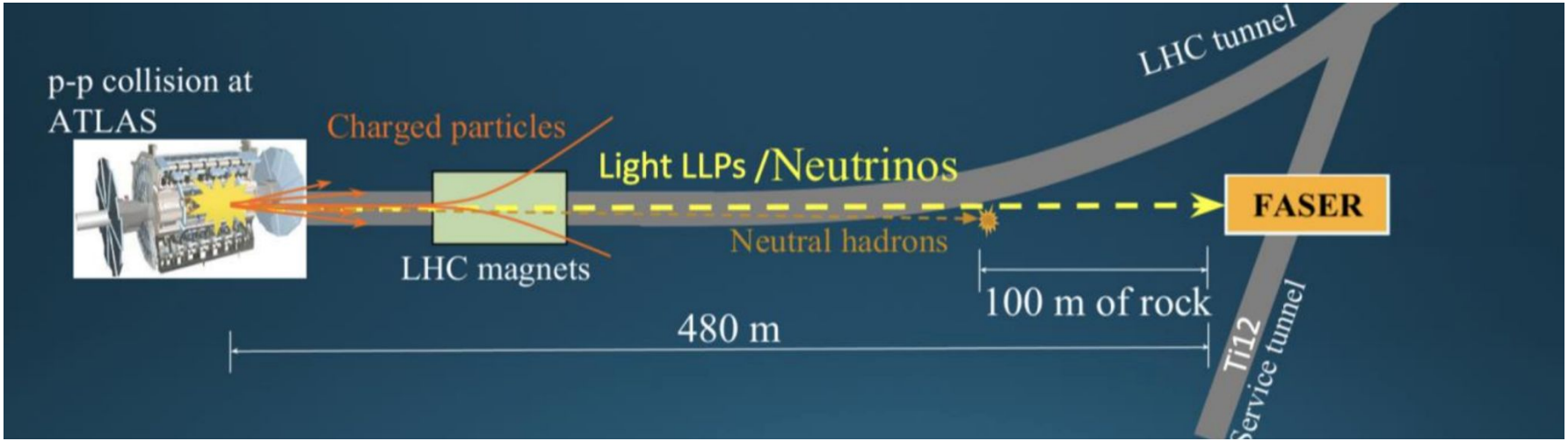


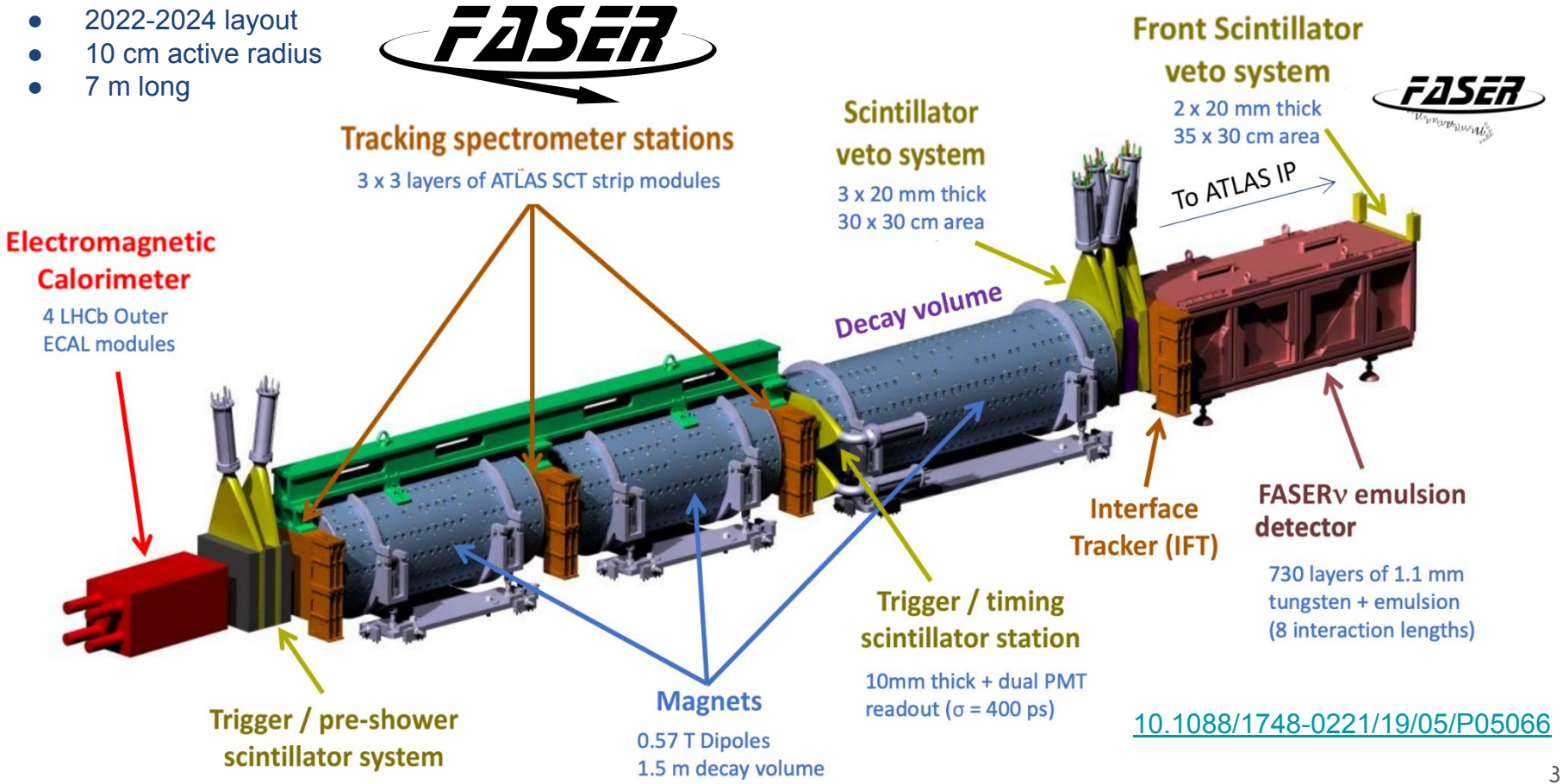
Introduction

- FASER is a small experiment designed to search for new long-lived particles (LLPs), and to study high energy neutrinos, produced at the ATLAS Interaction Point
- Located 480m downstream of ATLAS, shielded with 100m of rock and concrete
- Detector aligned with beam collision axis line of sight



The FASER Detector

- 2022-2024 layout
- 10 cm active radius
- 7 m long

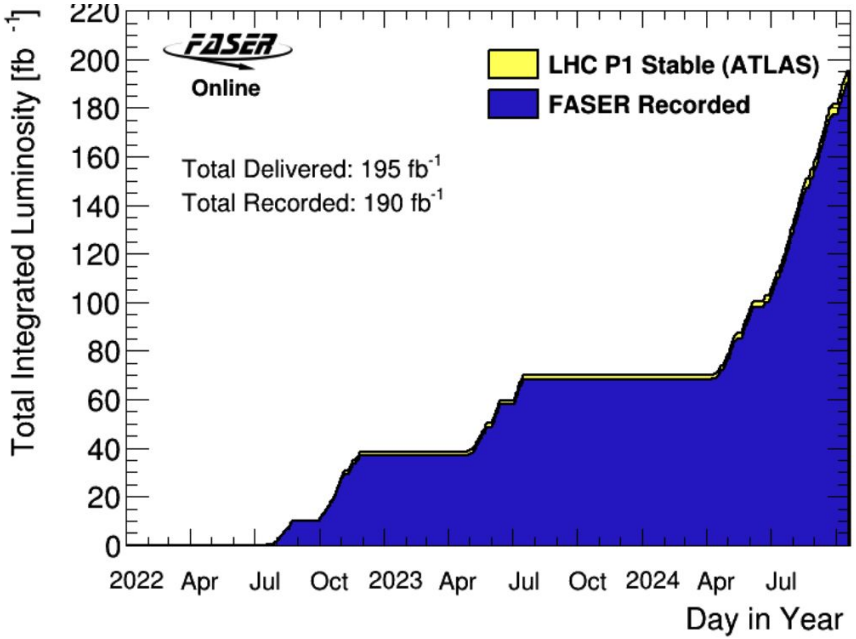


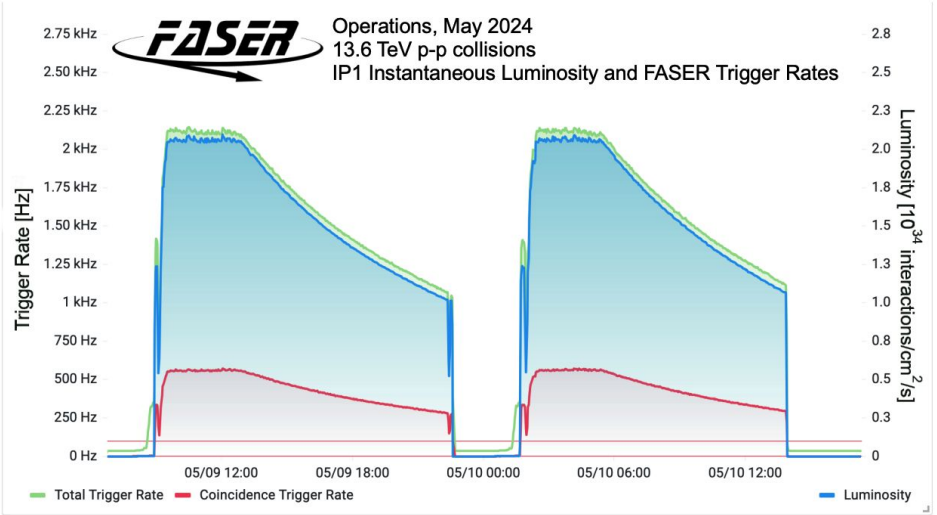
10.1088/1748-0221/19/05/P05066

The FASER Detector

Data Taking

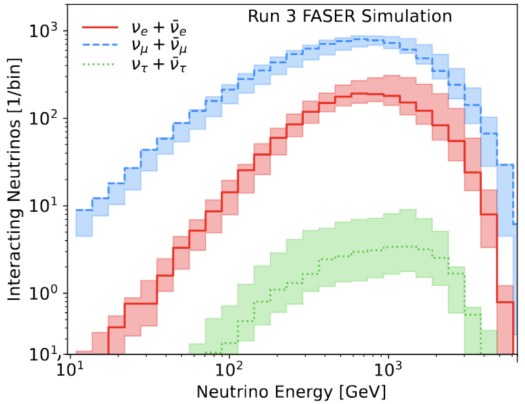
- Installed and commissioned in time for Run 3 data taking
  - Run 3 date recorded with 97% efficiency
  - ~275 fb^{-1} collected so far in Run 3





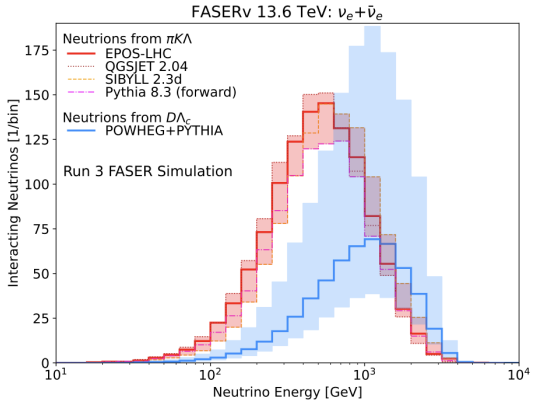
Neutrinos at FASER

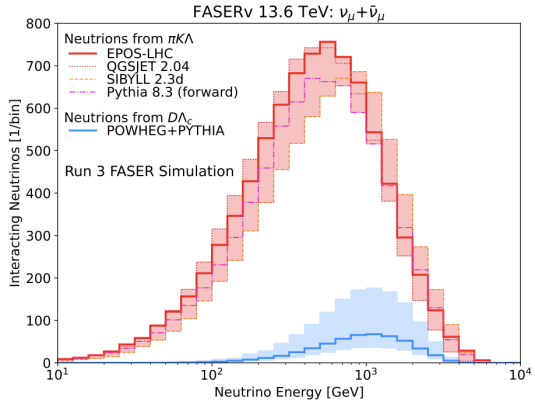
- FASER is able to probe neutrino at unexplored TeV energies
  - Highest energy of man-made neutrinos
  - First measurement of neutrino interaction cross section at TeV energies
  - Probes the gap between fixed-target and astroparticle measurements
  - Large uncertainties on charm production, probes forward hadron production



Expected neutrino interactions in FASERν:
(1 tonne detector, on beam axis line of sight)

	Luminosity	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
Run 3	250 fb^{-1}	1700	8500	30
Run 4	680 fb^{-1}	4900	25000	90





10.1103/PhysRevD.110.012009

Timeline of Neutrino Results at FASER

- **2021 - First Neutrino Interaction Candidates at the LHC**
- **2023 - First Direct Observation of Collider Neutrinos with FASER at the LHC**
- **2024 - First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector**
- **2024 - First Measurement of the Muon Neutrino Interaction Cross Section and Flux as a Function of Energy at the LHC with FASER**

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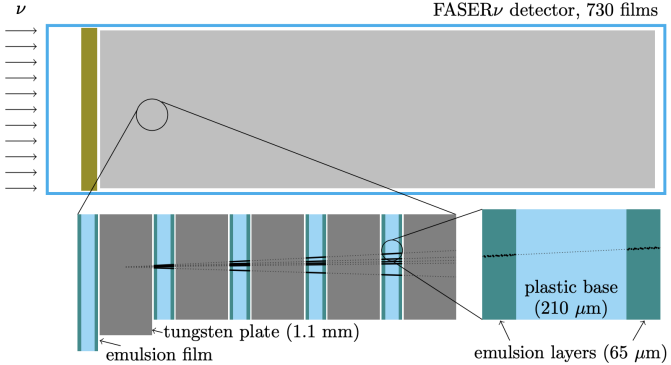
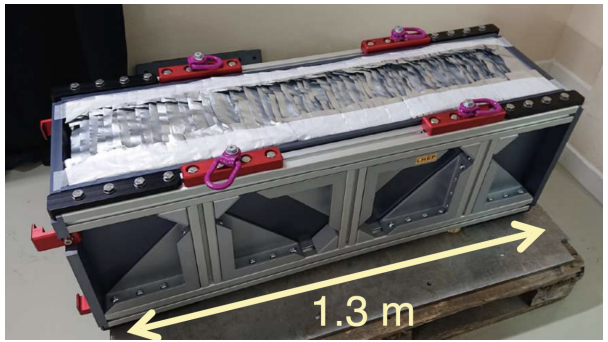
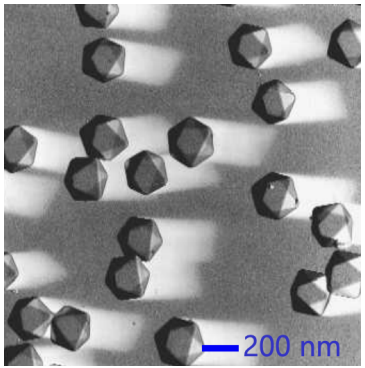
FASERν Emulsion Detector

- The FASERν detector is made up of 730 alternating layers of tungsten sheets and emulsion films
- Emulsion technology allows for precision measurement
  - < 0.3 μm position resolution and < 0.05 mrad angular resolution





- Silver Bromide crystal



- Emulsion film

Steps:

Emulsion Production

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Assembly

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Data Taking

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Emulsion Development

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Emulsion Film Scanning

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Reconstruction

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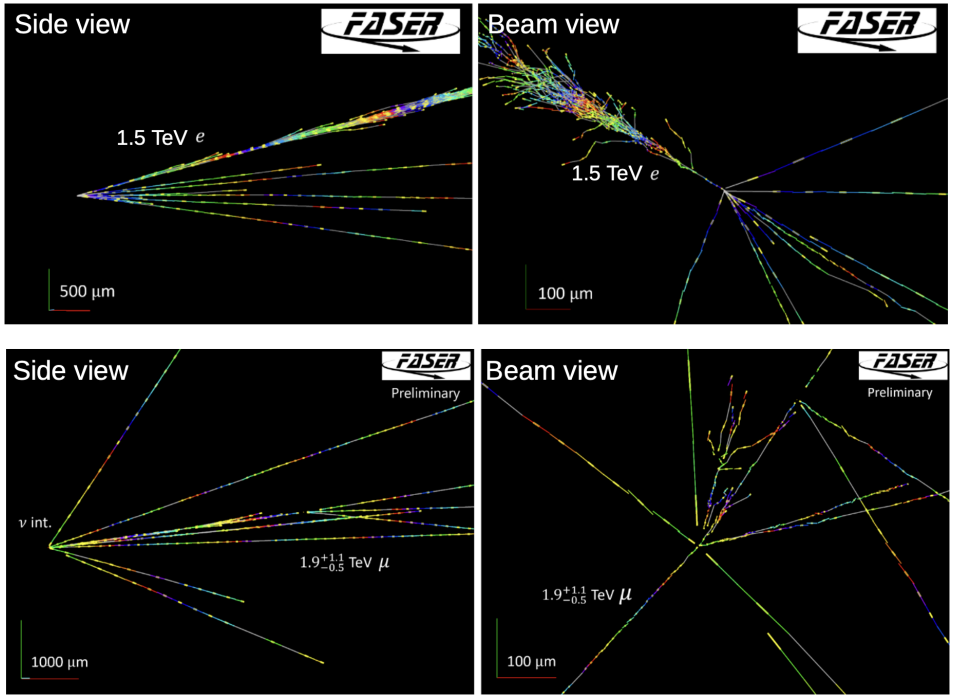
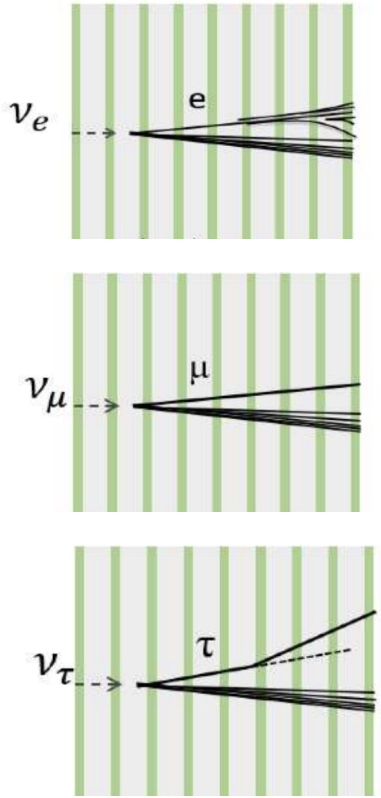
Physics Analysis

FASERν Neutrino Interactions

- Emulsion films replaced every 25-30 fb^{-1}
- Results using 9.5 fb^{-1}



- Neutrino interactions within emulsion:

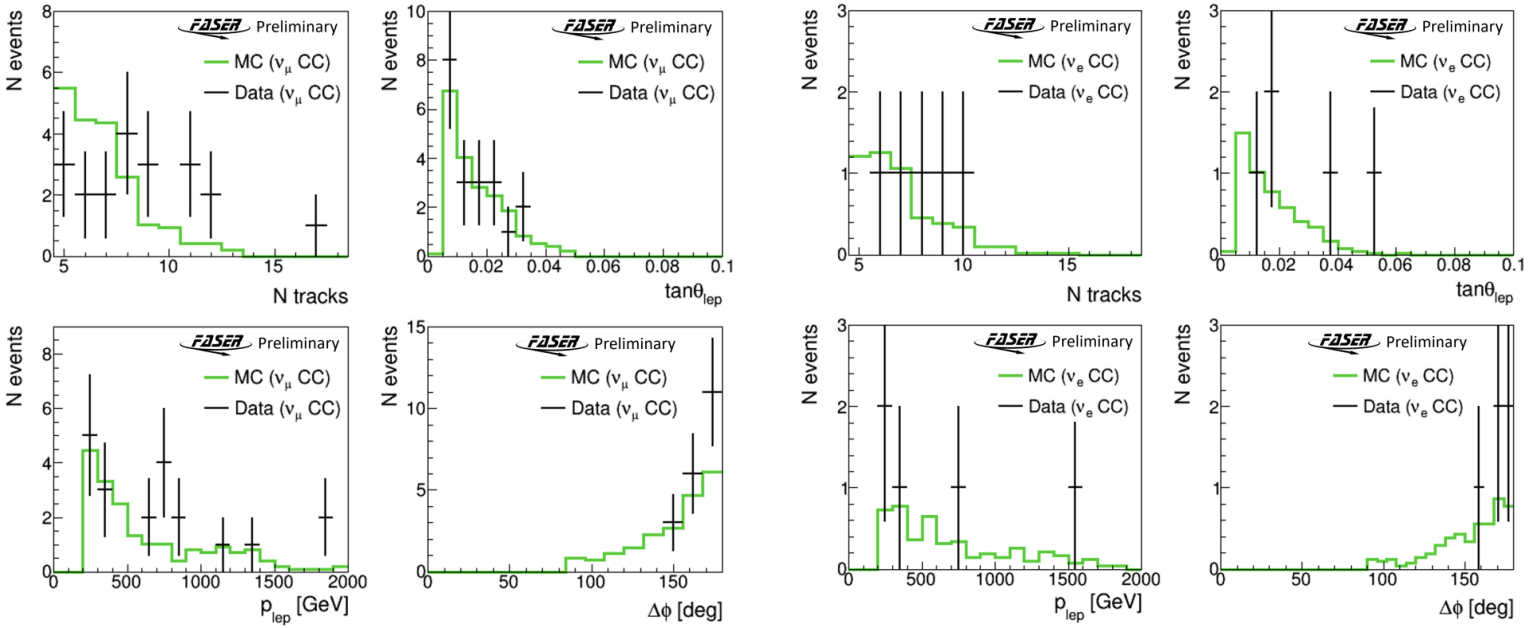


FASERν Physics Analysis: ν_μ and ν_e CC events

- Updated results using 9.5 fb^{-1} and 314.7 kg target mass
  - Building on original 2024 results with 2.5 x larger dataset

FASER-CONF-NOTE

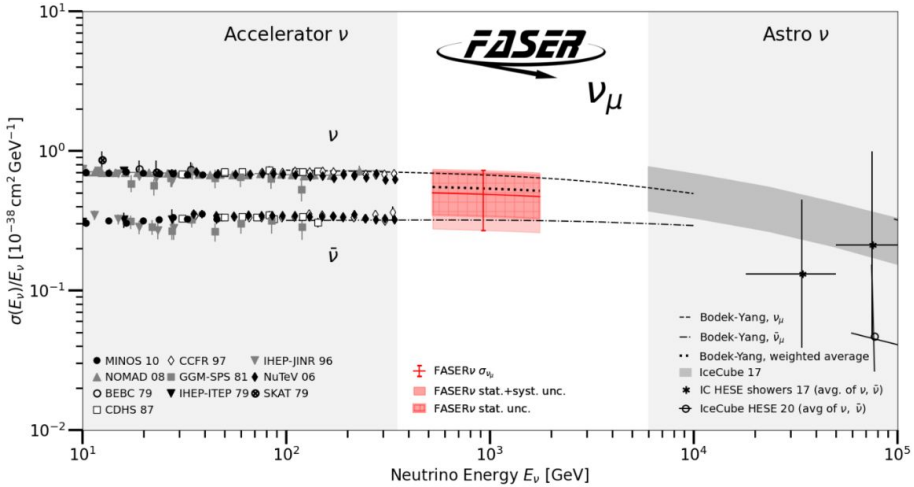
	ν_e CC	ν_μ CC
Expected signal	2.8–7.2	16.2–28.7
Expected background	$0.06^{+0.04}_{-0.02}$	$0.54^{+0.22}_{-0.17}$
Observed events	5	20

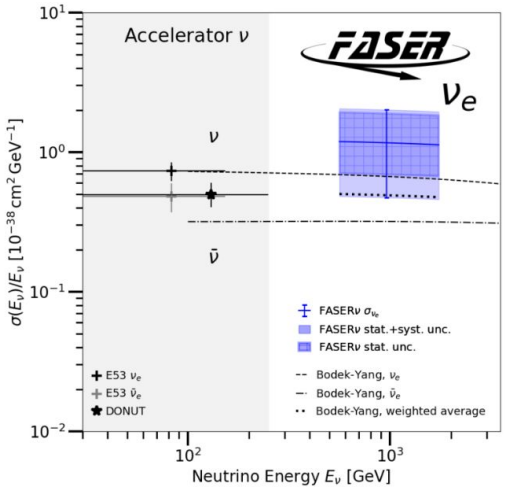


FASERν: Cross section measurement

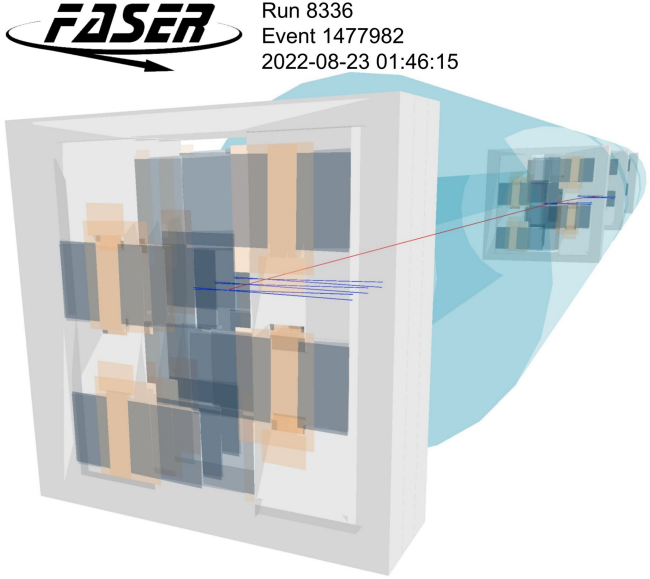
10.1103/PhysRevLett.133.021802

- The interaction cross section per nucleon is measured over an unexplored energy range
- of 560 - 1740 GeV for ν_e and 520 -1760 GeV for ν_μ
  - Using 128.6 kg target mass exposed to 9.5 fb^{-1} of LHC pp collisions
- In these energy ranges, the neutrino-antineutrino combined cross sections for ν_e and ν_μ are both consistent with the cross section predictions of the standard model





Neutrino studies with the electronic detector

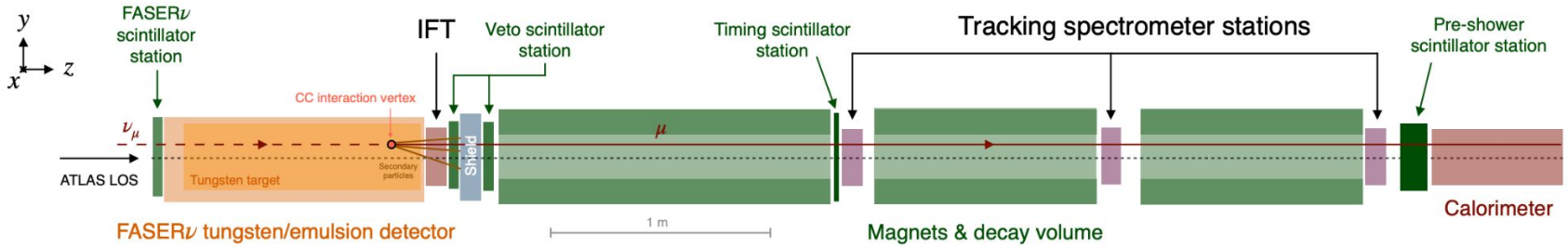


- Targeting ν_μ CC interactions in the tungsten target
- Fiducial muon track in downstream electron components of FASER

- Muon track throughout the entire detector with p > 100 GeV
- Within a fiducial radius of r < 120 mm
- ν_μ and anti-ν_μ CC events
- Requiring no signal in the front veto scintillator stations

Backgrounds:

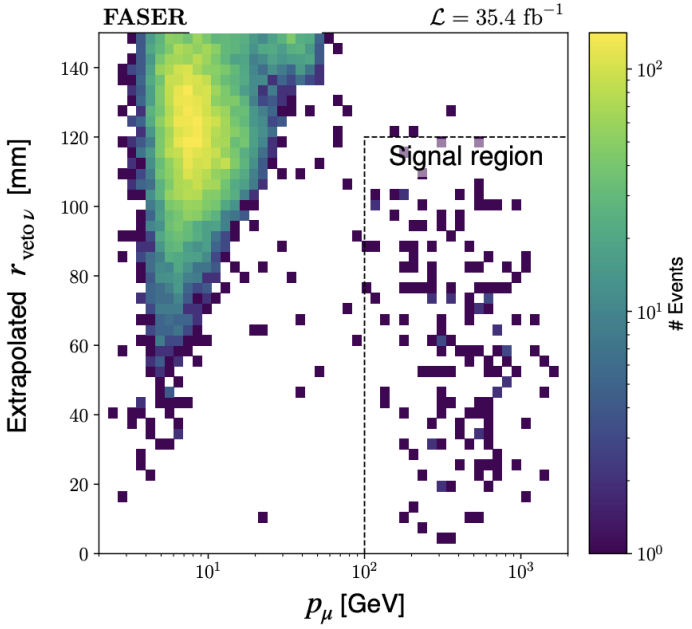
- Neutral hadrons produced in the rock
- Large-angle muons

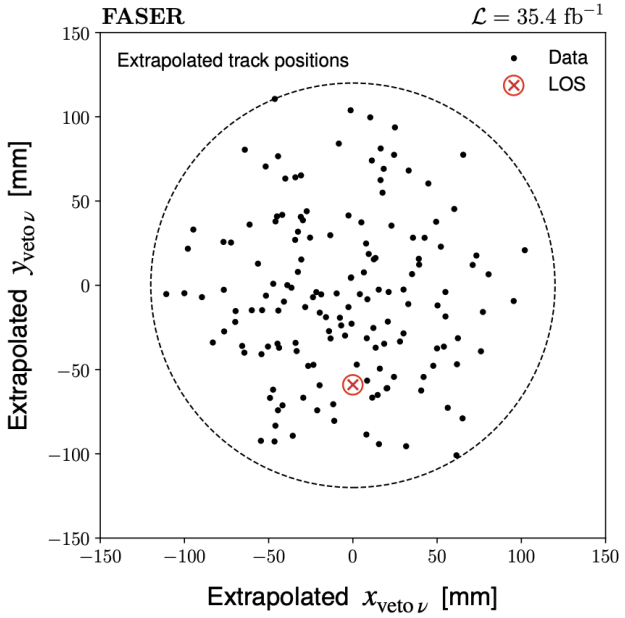


FASER Results: Muon neutrino observation

- 2023: FASER identified **153 muon neutrino candidate events** in a 35.4 fb^{-1} dataset
  - Region with low momentum + and large radius dominated by background events
    - Charged particles that miss FASERv scintillators station

10.1103/PhysRevLett.131.031801

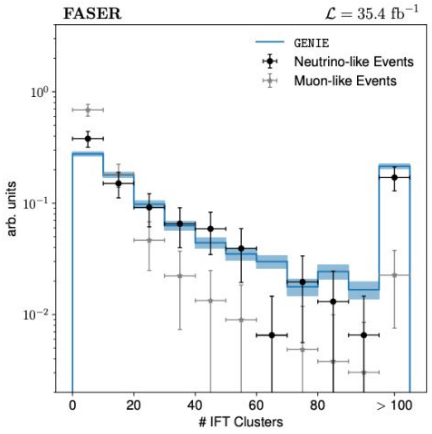


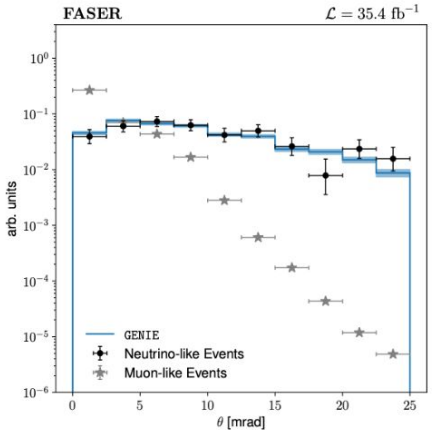


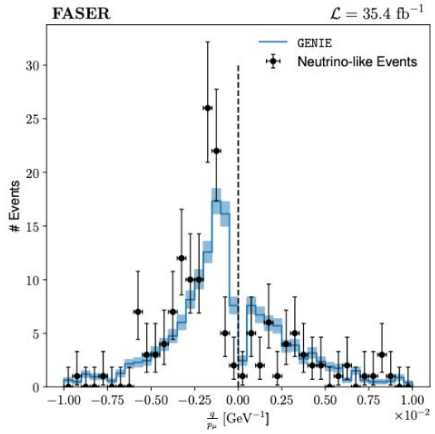
FASER Results: Muon neutrino observation

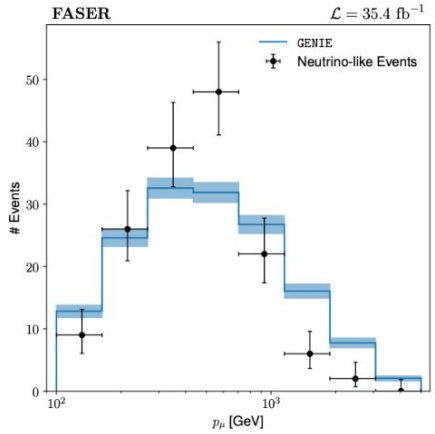
- There is a clear charge separation in q/p_{μ} for the reconstructed tracks
- In total 40 events with a positively-charged track showing the presence of anti-ν_{μ} CC neutrinos
- ν_{μ} CC neutrino interactions produce larger number of particles than MIP interactions

10.1103/PhysRevLett.131.031801



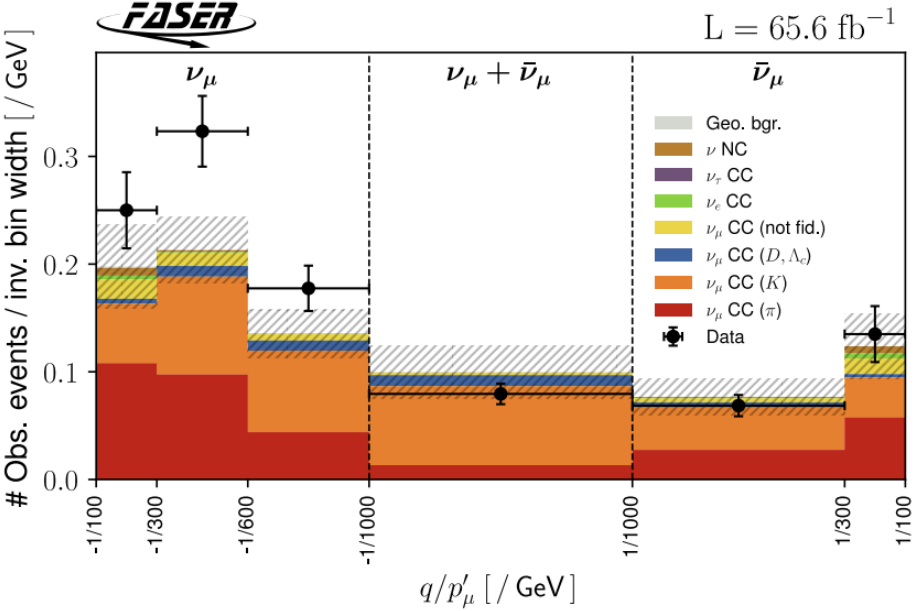


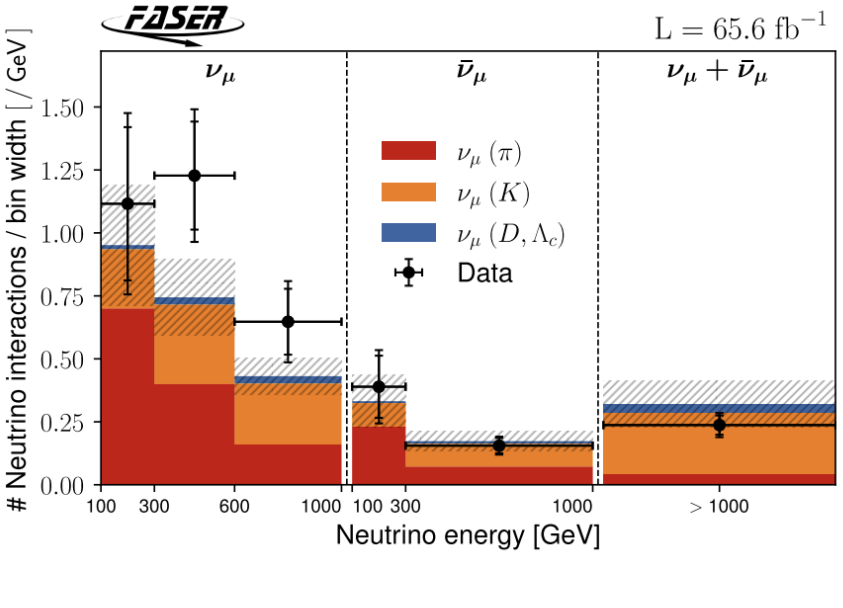




FASER Results: Cross section and flux measurement

- The addition of 30.5 fb^{-1} from the 2023 data strengthened these results, enabling the observation of 362 muon neutrino events [10.1103/PhysRevLett.134.211801](https://doi.org/10.1103/PhysRevLett.134.211801)
  - A total of 65.6 fb^{-1} from 2022 and 2023 FASER data
  - Increased statistics allows for the unfolding into bins of (anti-)neutrino energy





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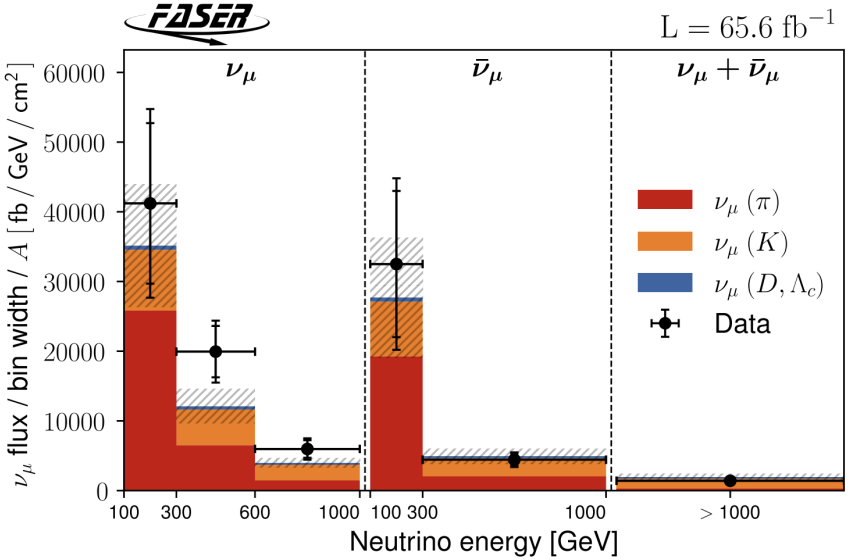
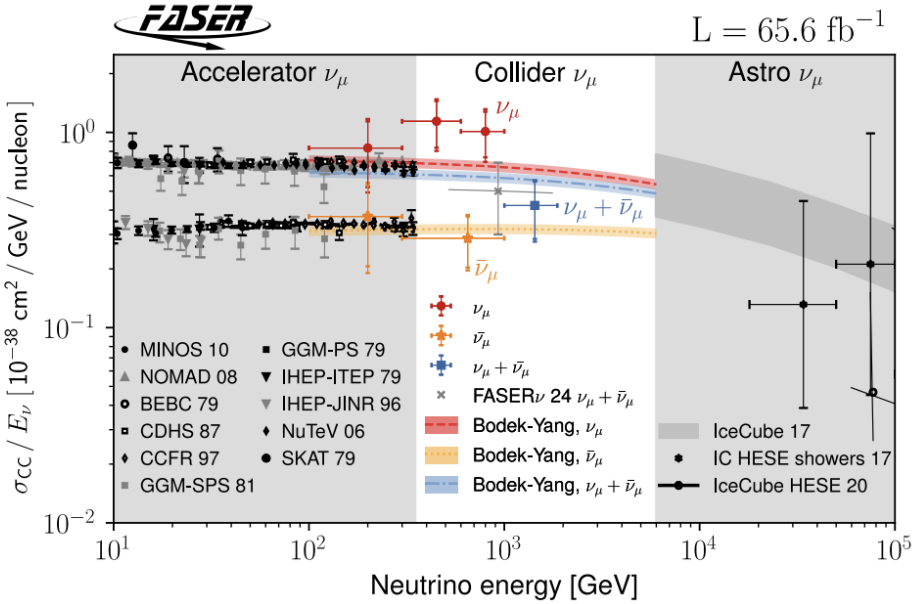
  - The neutrino cross section extracted assuming the neutrino flux
  - The flux extracted from fitting neutrino cross sections to theoretical predictions

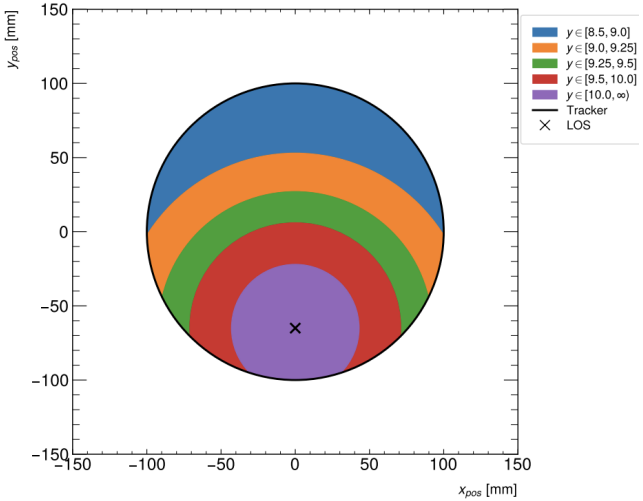


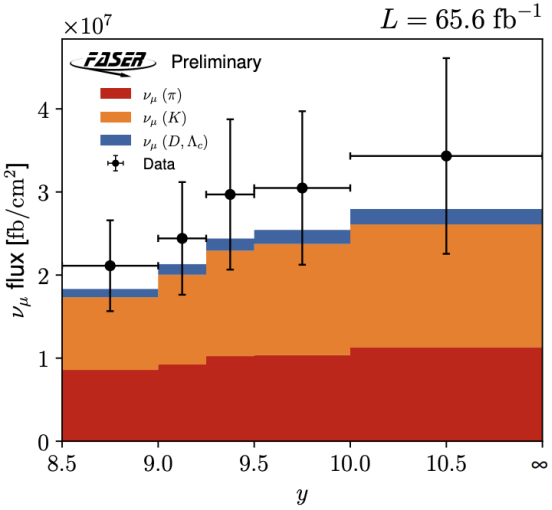


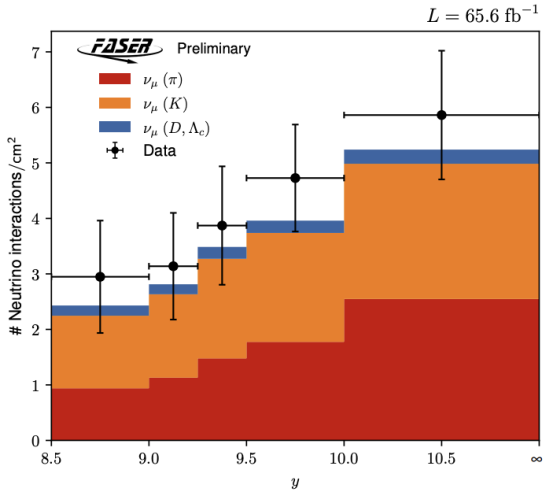
FASER Results: Rapidity measurement

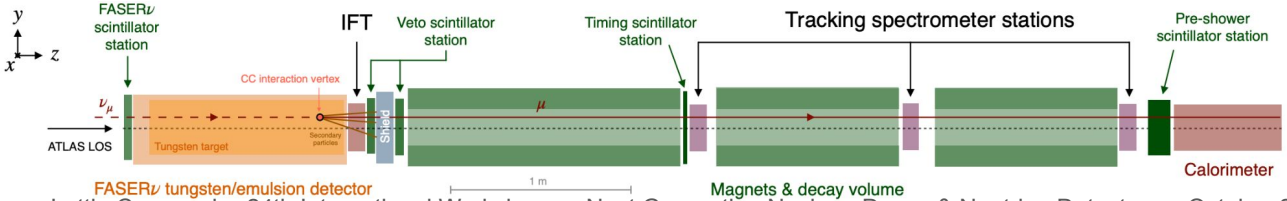
- Rapidity of the neutrino can be reconstructed using inferred polar angle θ
- θ is estimated from the observed muon track position
- Unfold the number of reconstructed neutrino interactions in rapidity bins
- First differential muon neutrino flux as a function of rapidity

FASER-CONF





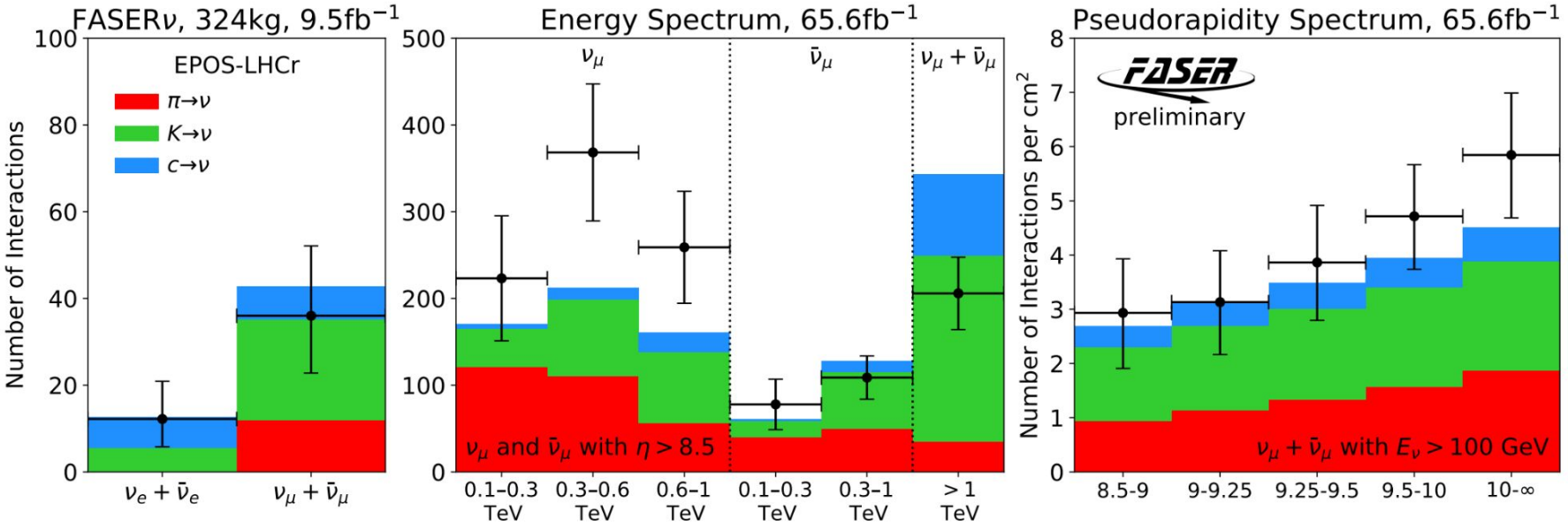




Forward Hadron Production

10.48550/arXiv.2507.23552

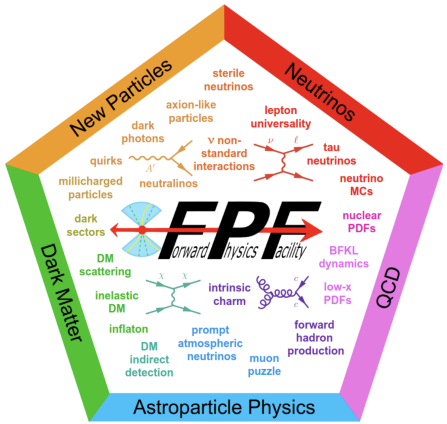
- Experimental test of forward pion, kaon, and charm production at the LHC
- Discrepancies in a few energy bins of muon neutrinos are found
  - Motivates upcoming measurements to understanding these discrepancies

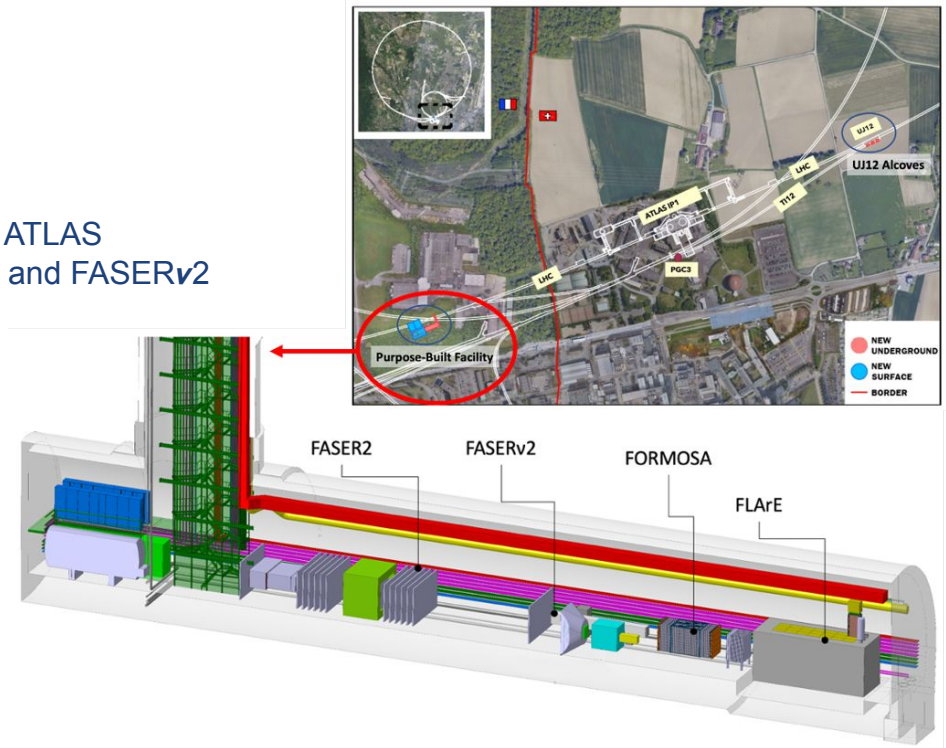


Future Prospects: Run 4 and beyond

10.1088/1361-6471/ac865e

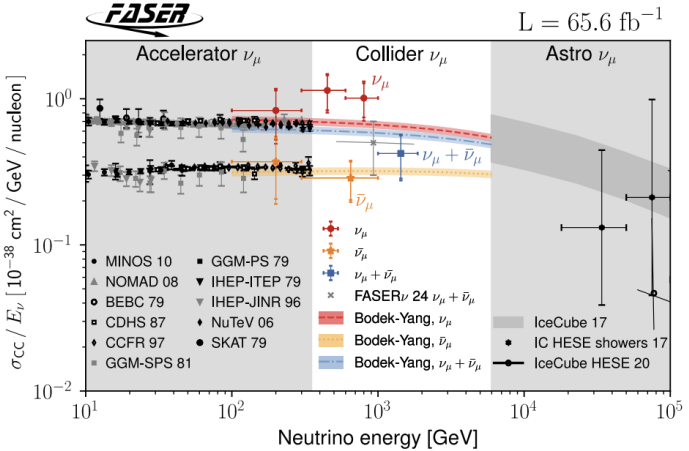
- Planned upgrades for Run 4
  - Additional electronic detectors and prototypes proposed
  - Prospects and Opportunities with an upgraded FASER Neutrino Detector during the HL-LHC era: Input to the EPPSU
- FASER approved for Run 4 at HL-LHC
- Forward physics facility
  - Proposed dedicated facility at HL-LHC
    - New ~65 m long cavern, 620 m from ATLAS
  - 4 dedicated experiments including FASER2 and FASER*ν*2





Summary and Outlook

- Successful data-taking in Run 3
- First ever observation of collider neutrinos
- Latest results from TeV neutrino measurements
- Studies of forward hadron production
- Results from FASERν emulsion detector
  - ν_e CC observation and cross section measurement
  - ν_μ CC observation and cross section measurement
- Results from FASER electronic detector
  - ν_μ and anti-ν_μ CC observation and cross section measurement
  - ν_μ and anti-ν_μ CC flux measurement
  - First differential muon neutrino flux as a function of rapidity
- Thank you!

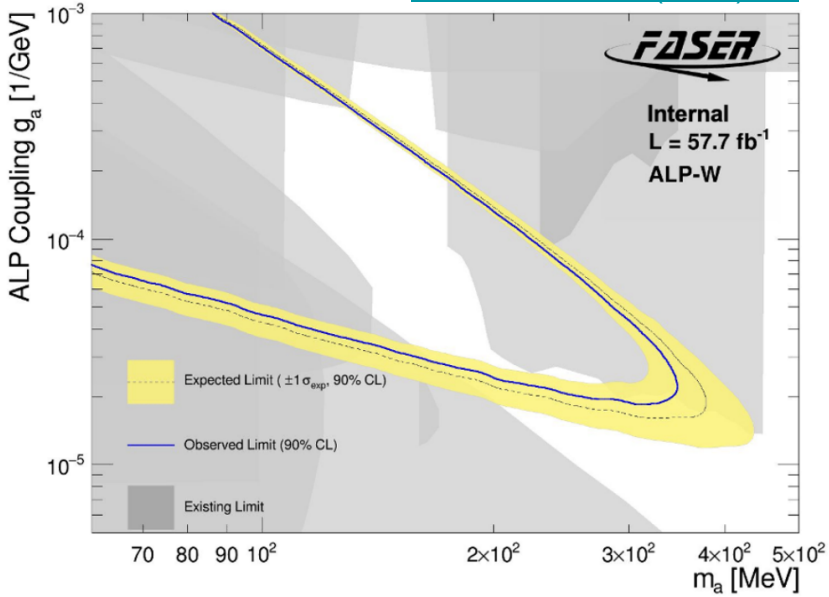


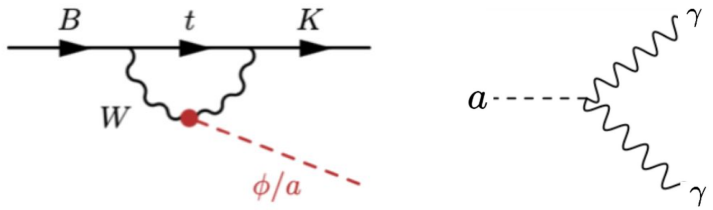
Backup Slides

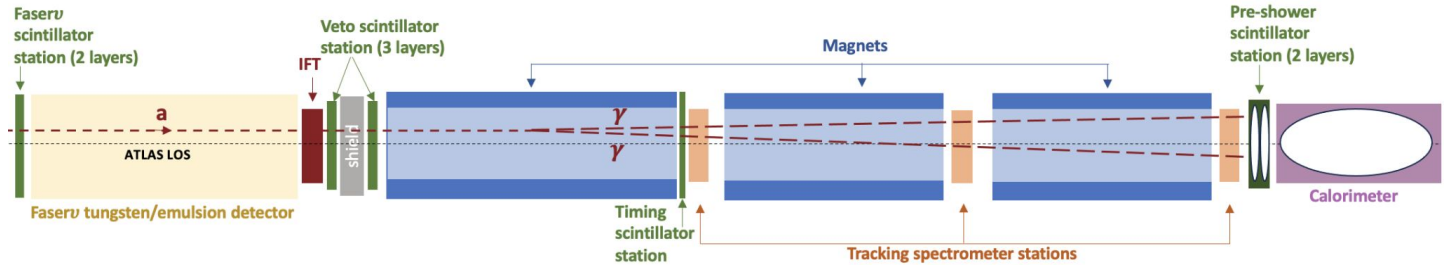
FASER Studies: Axion-like particle BSM search

- FASER is sensitive to axion-like particles (ALPs)
  - Coupling to SU(2)L gauge bosons
- Primarily produced in B meson decays in our sensitivity range
- Can decay anywhere between veto scintillators and preshower
- Decays to 2 high energy photons
  - Cannot be distinguished in our calorimeter
- 57.7 fb-1 of 2022 and 2023 FASER data

10.1007/JHEP01(2025)199

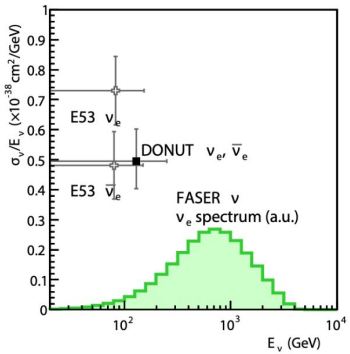


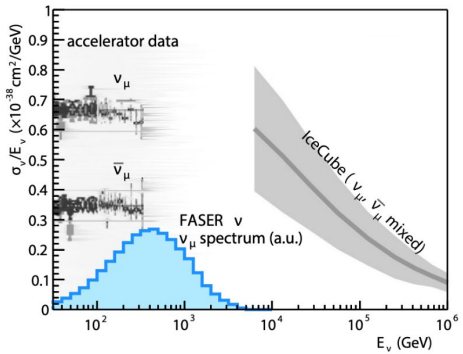


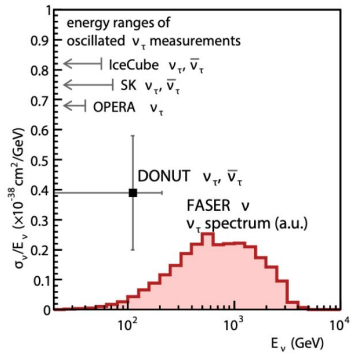


Detecting and studying high-energy collider neutrinos with FASER at the LHC

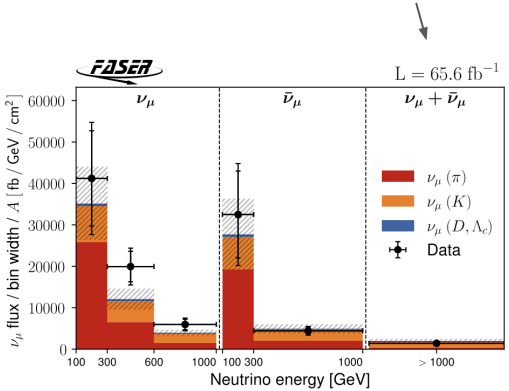
- [10.1140/epjc/s10052-020-7631-5](https://doi.org/10.1140/epjc/s10052-020-7631-5)

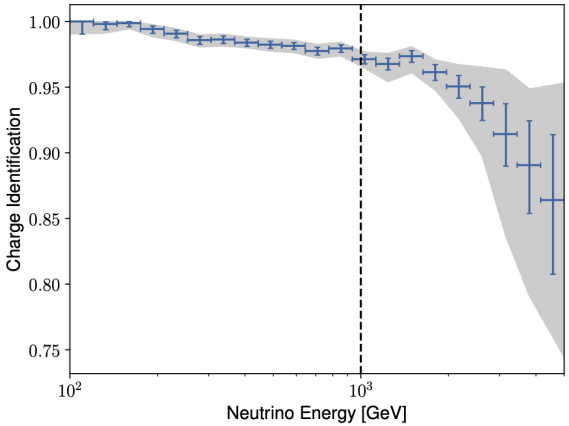




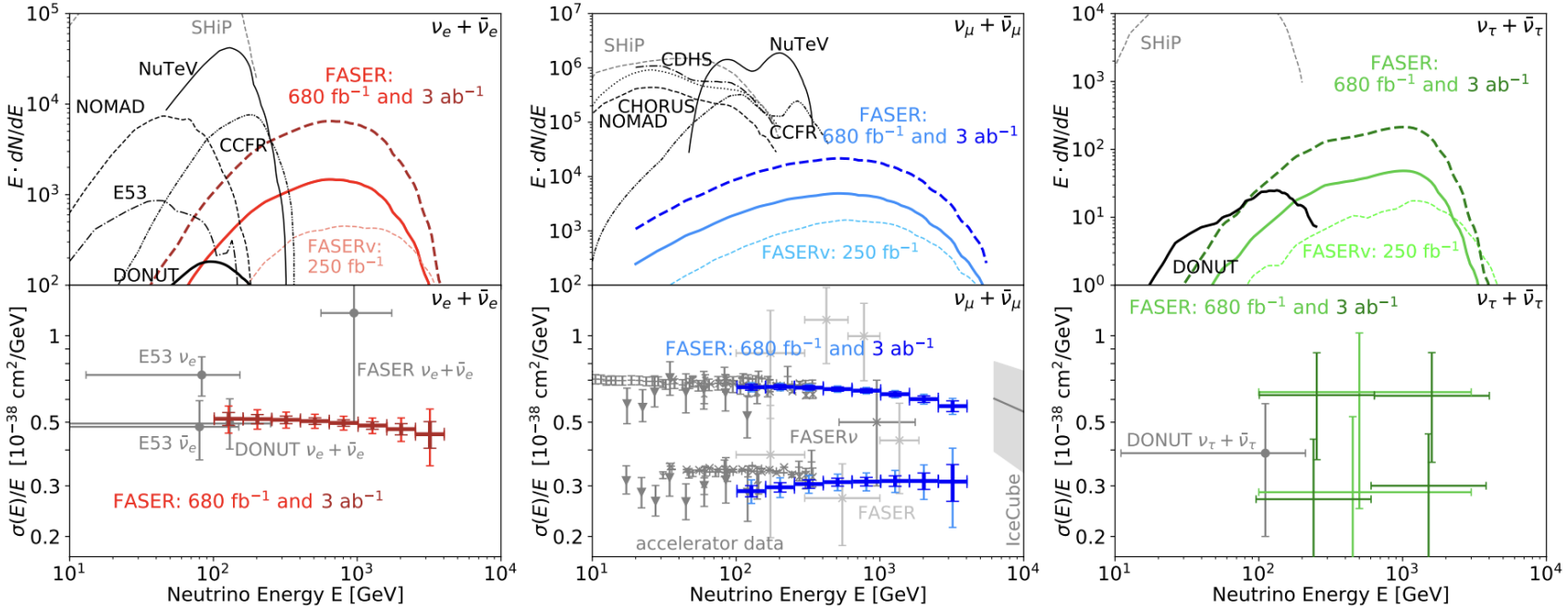


- Why a combined bin at 1 TeV?





Detecting and studying high-energy collider neutrinos with FASER at the LHC



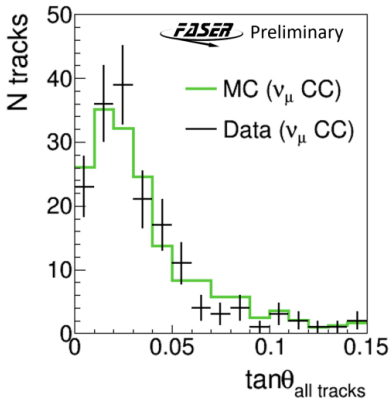
FASERν Physics Analysis: ν_μ and ν_e CC events

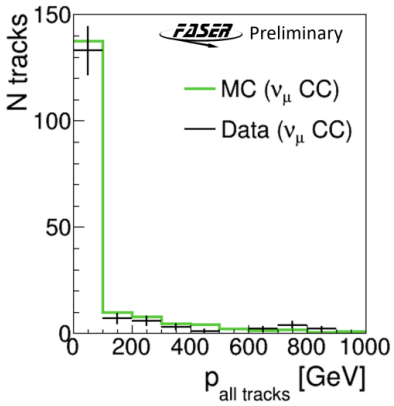
- Updated results using 9.5 fb^{-1} and 314.7 kg target mass
  - Building on original 2024 results with 2.5 x larger dataset

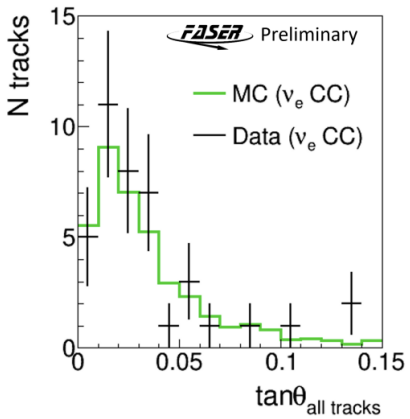
  FASER-CONF-NOTE

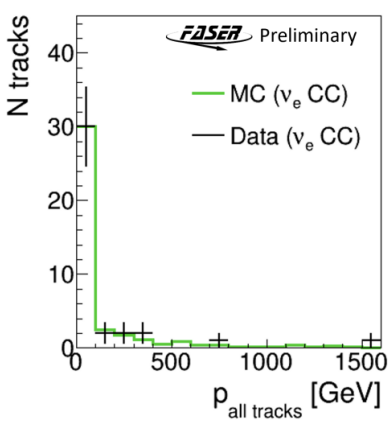
- Results plots from individual tracks (instead of selected vertices)

	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





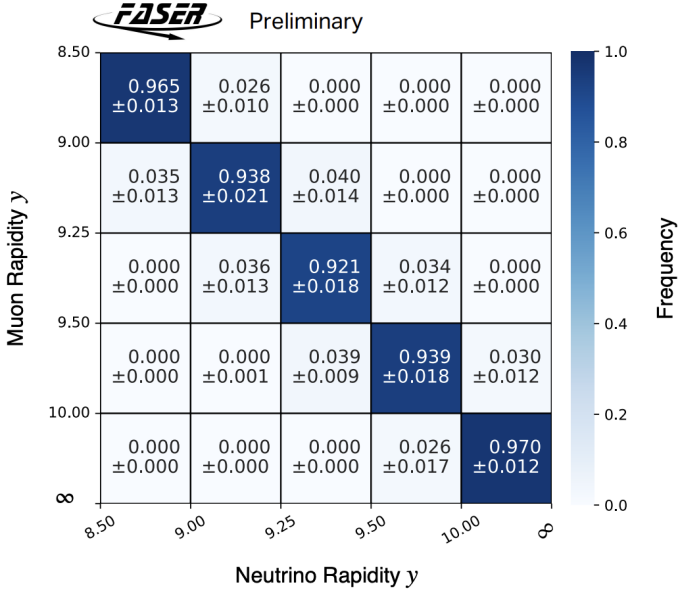




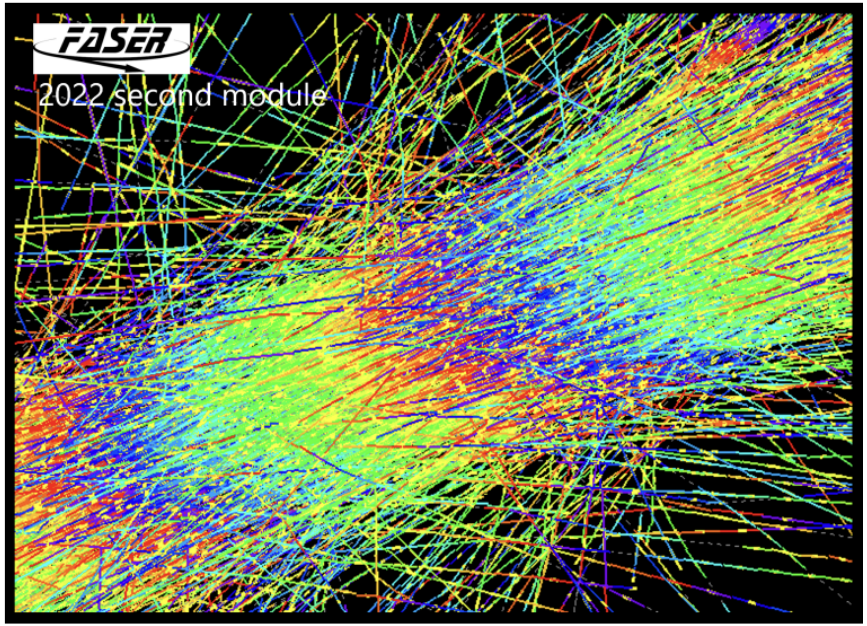
FASER Results: Rapidity measurement migration matrix

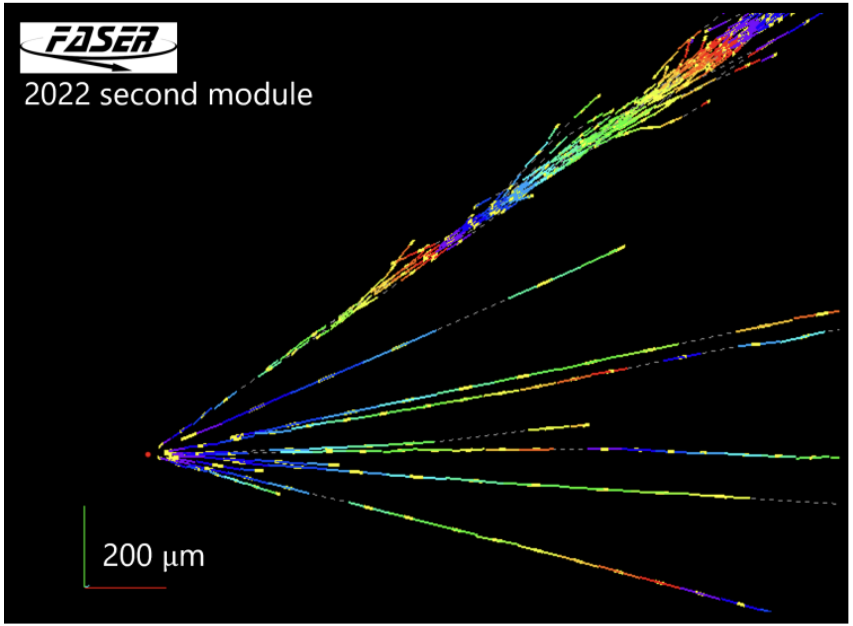
- Rapidity of the neutrino can be reconstructed using inferred polar angle θ
- θ is estimated from the observed muon track position
- Unfold the number of reconstructed neutrino interactions in rapidity bins

FASER-CONF



FASERν Neutrino Interactions





FASERν Neutrino Interactions

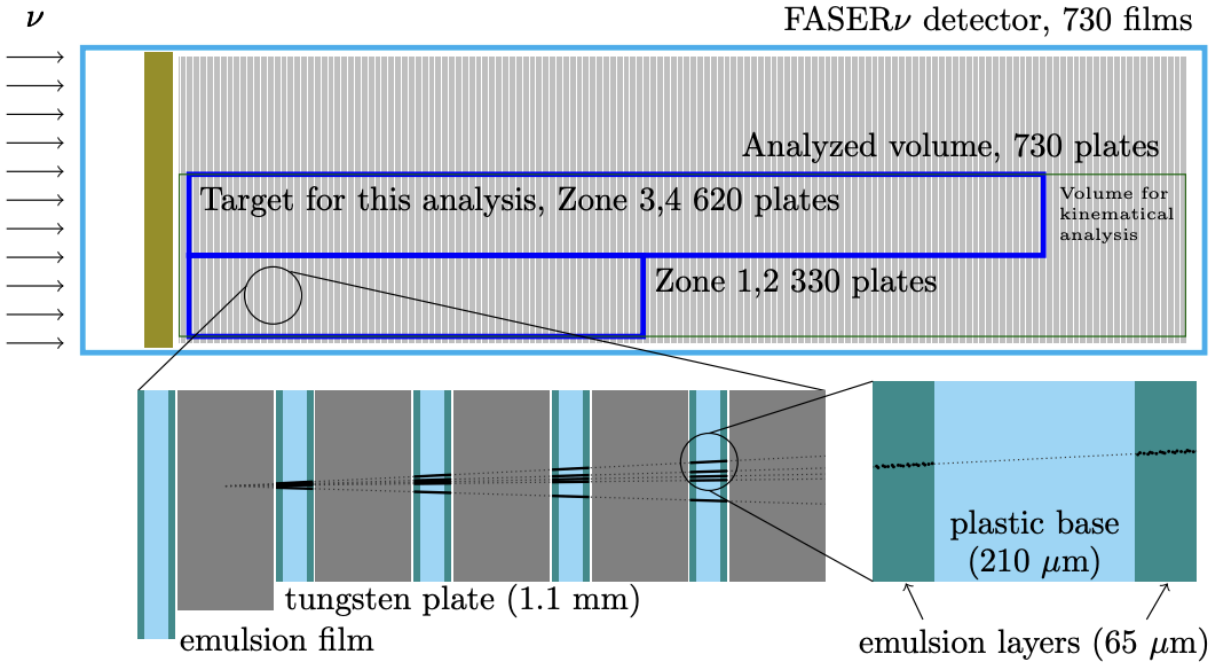


FIG. 2. Data volume schematics for the current analysis.

- The previous analysis focused on interactions occurring in zones 3 and 4 across 291 films.
- The current analysis extends the coverage to include films 8-627 in zones 3–4, and films 8-337 in zones 1-2.
- Films 1–7 are used as a veto for charged parent particles, while 100 films after the target volume are used to identify muons and measure particle momenta via multiple Coulomb scattering (MCS).

CaloNu installation