LHC Neutrino Physics at the FASER Experiment

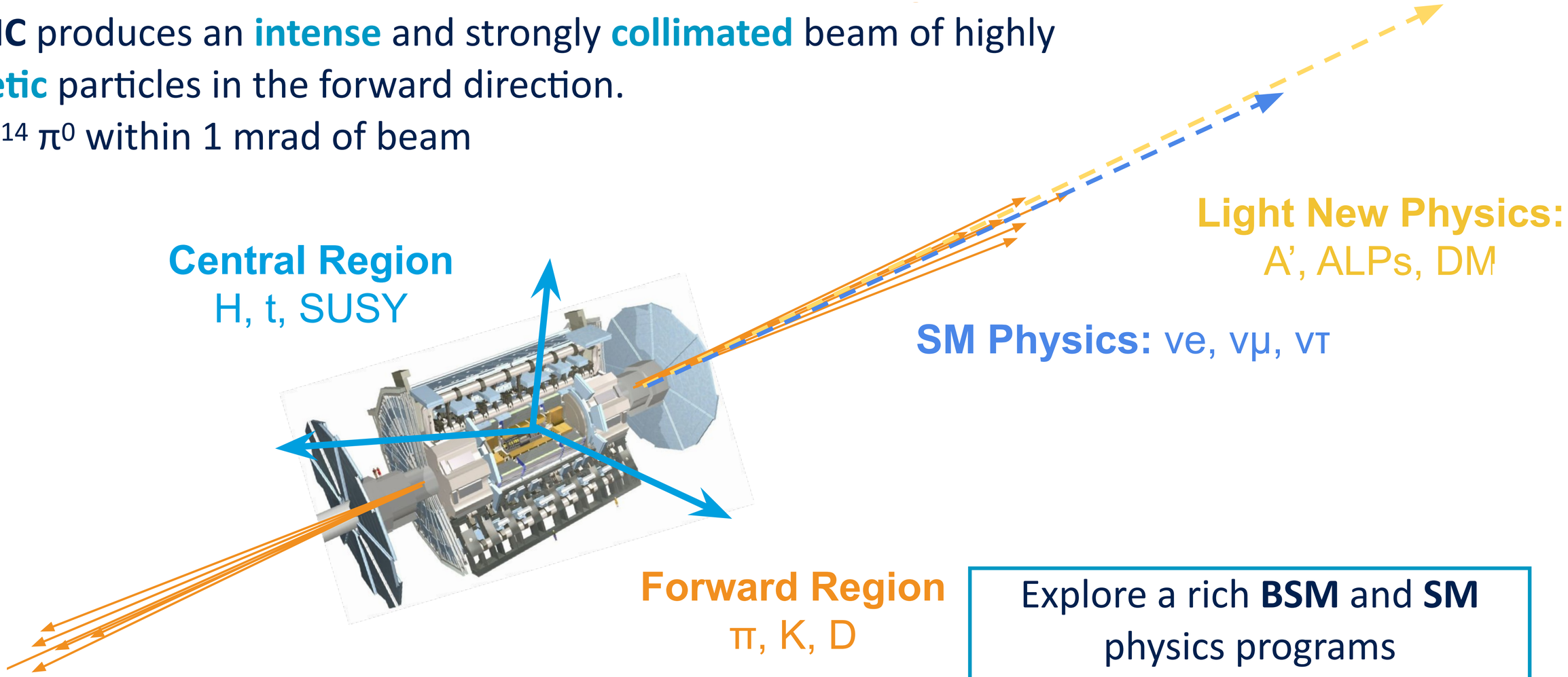
Tomohiro Inada (tomohiro.inada@cern.ch)
Kyushu University
on behalf of the FASER collaboration

FASER - New experiment at the LHC Run3

FASER has started operation since July 2022

Idea and Motivation

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.
e.g. 10^{14} π^0 within 1 mrad of beam

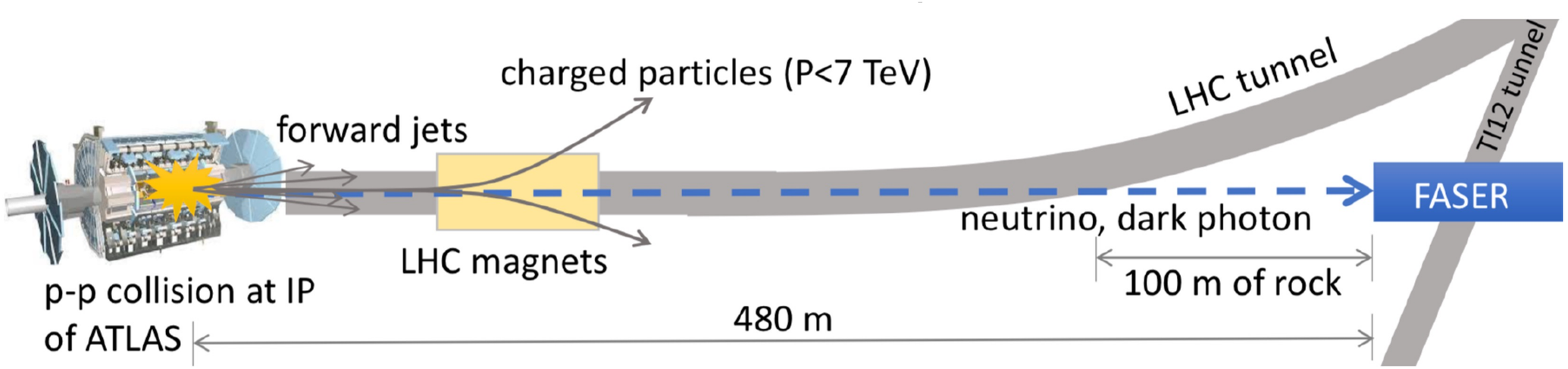


Explore a rich **BSM** and **SM** physics programs **in the far farward region**

FASER

- **ForwArd Search ExpeRiment (FASER) at the LHC**
  - Placed **480 m downstream of the ATLAS IP** on the beam axis
  - Started the **operation** from July 2022 (LHC run3)
- **Physics motivation**
  - **New long-lived particle searches** in **MeV-GeV masses**
  - **All flavors of neutrinos** at the **TeV-energy frontier**

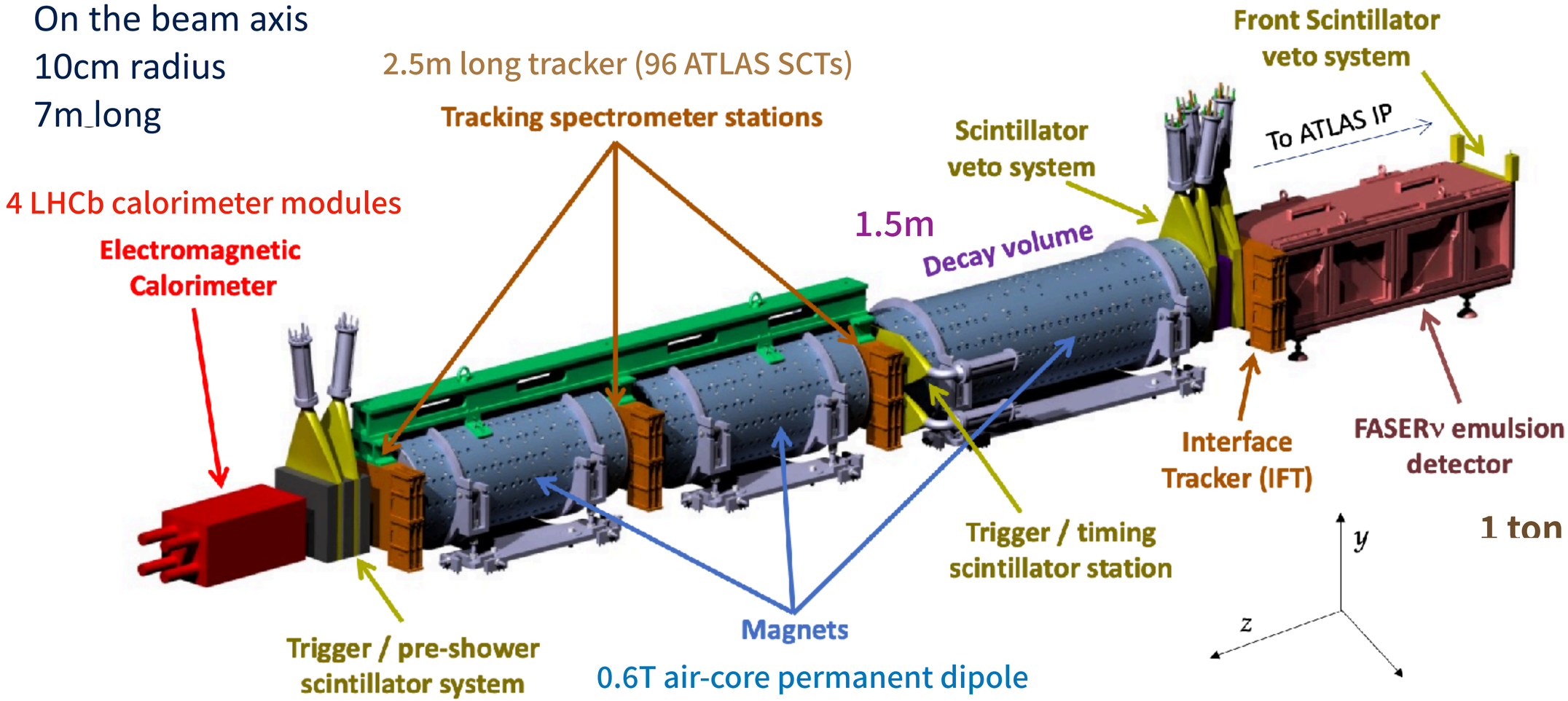
- **Favorable location**
  - **Very low background from collision**
    - **Only high-energy muon** at about $1/cm^2/sec$
  - **Low radiation level from the LHC**
    - 4×10^6 1-MeV neutron/cm^2/year



FASER detector

JINST 19 (2024), P05066

On the beam axis
10cm radius
7m long

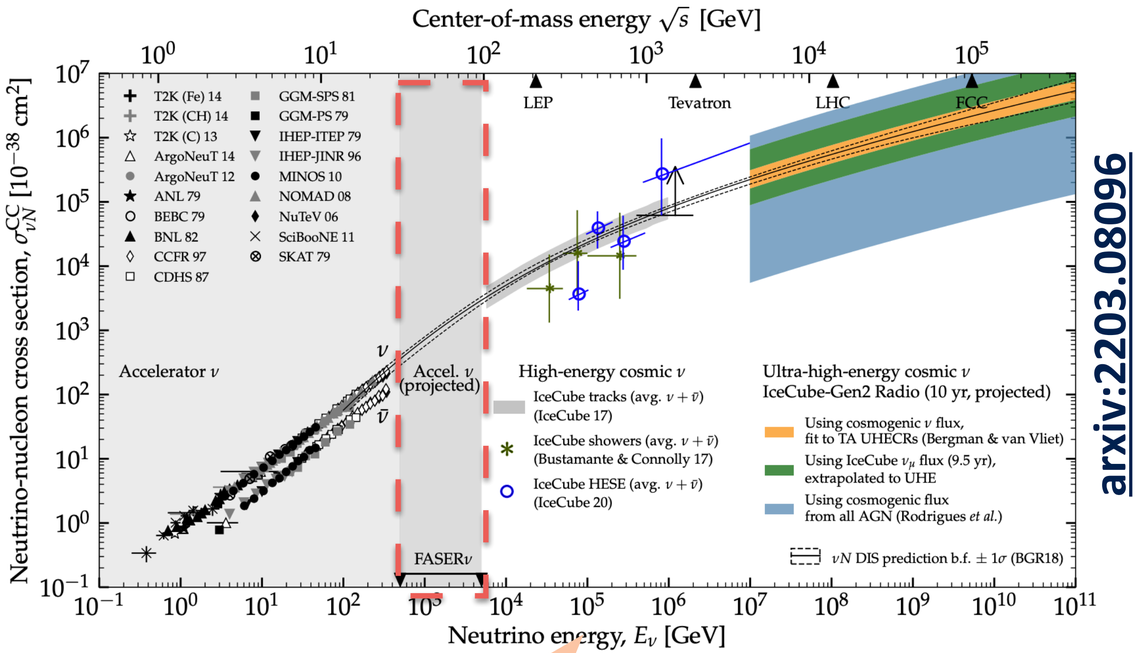


Scintillators for veto, trigger, and preshower (particle ID)

All detector components are successfully installed in T12 in March 2022

Particles from ATLAS

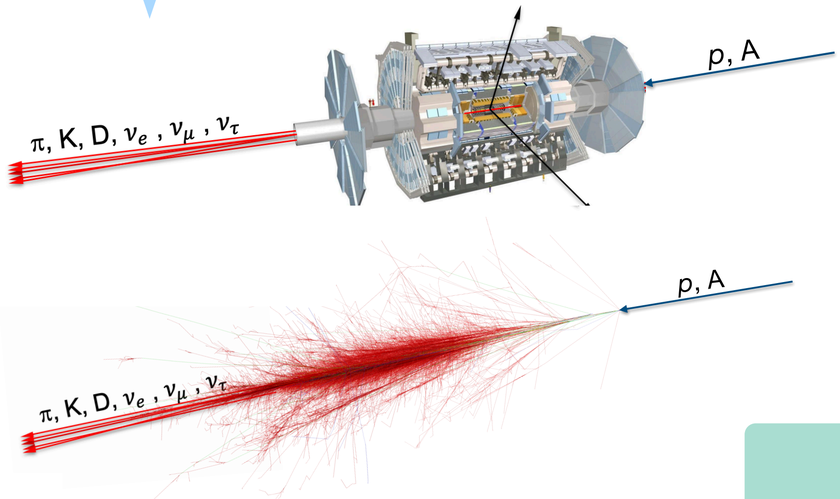
Collider neutrinos w/ FASER



arxiv:2203.08096

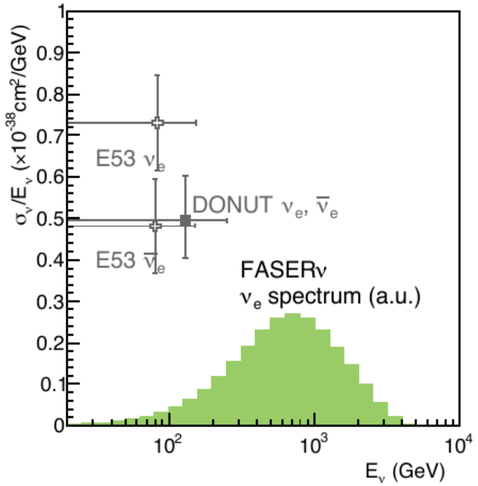
$\sqrt{s}$ = **13.6 TeV ⇄ lab. frame 100 PeV p-p interaction**

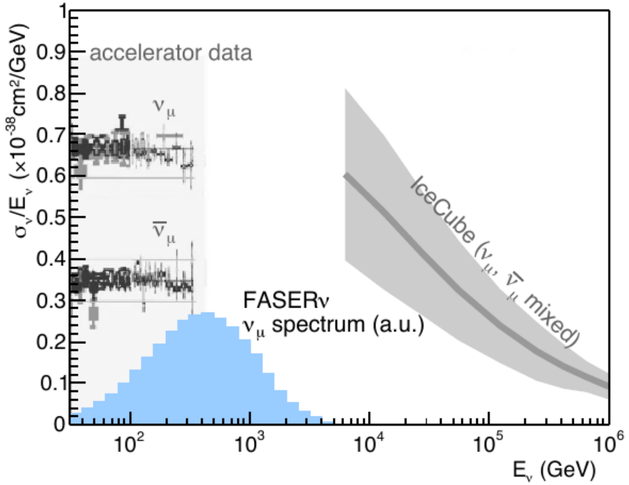
Possible to study hadron interaction models of neutrino flux
e.g. application into air-showers study like prompt neutrino

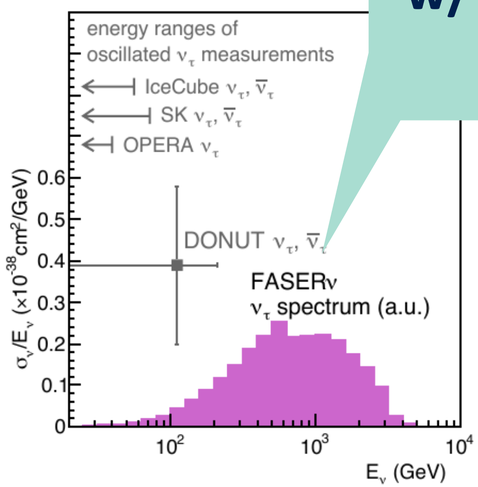


GeV-TeV ν beam

Fill **gaps** between fixed target experiments and cosmic-ray experiments **w/ highest energy human-made TeV neutrinos**







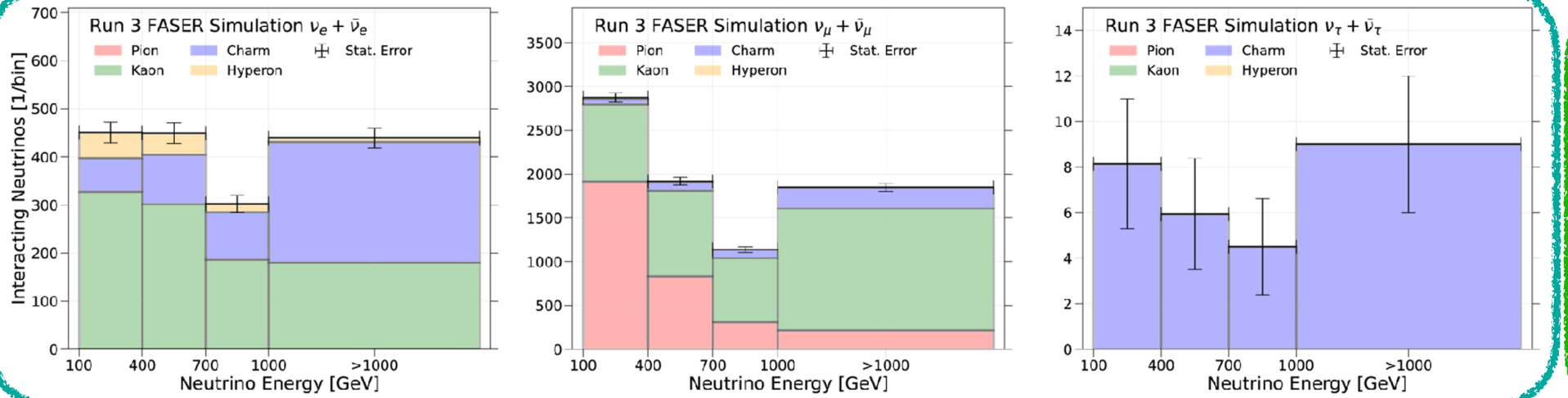
w/ all flavors

Neutrino flux

Phys. Rev. D 110, 012009

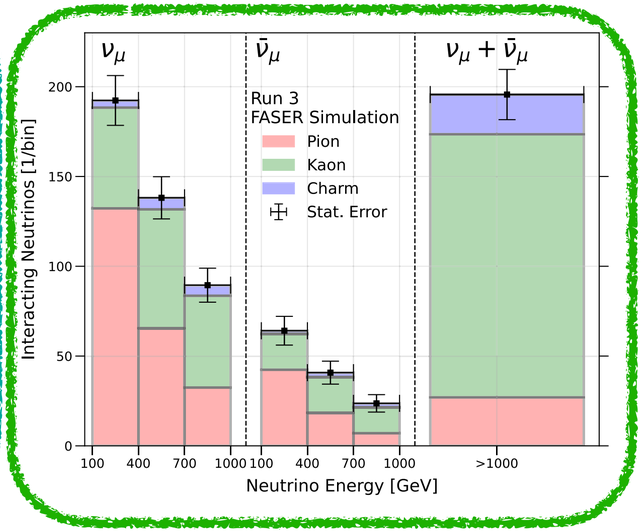
FASERν (Emulsion-based detector)

Sensitive to all 3 flavors



"Electric" detector technique

Charge separation $\nu_\mu/\nu_{\bar{\mu}}$



- **Two strategies for measurements**
  - Emulsion-based detector → all flavor sensitive
  - "Electonic" detector technique → $\nu_\mu/\bar{\nu_\mu}$ separation
- ~10,000 neutrinos should be collected

Expected CC interaction events (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^{+18}_{-12}

Neutrino flux

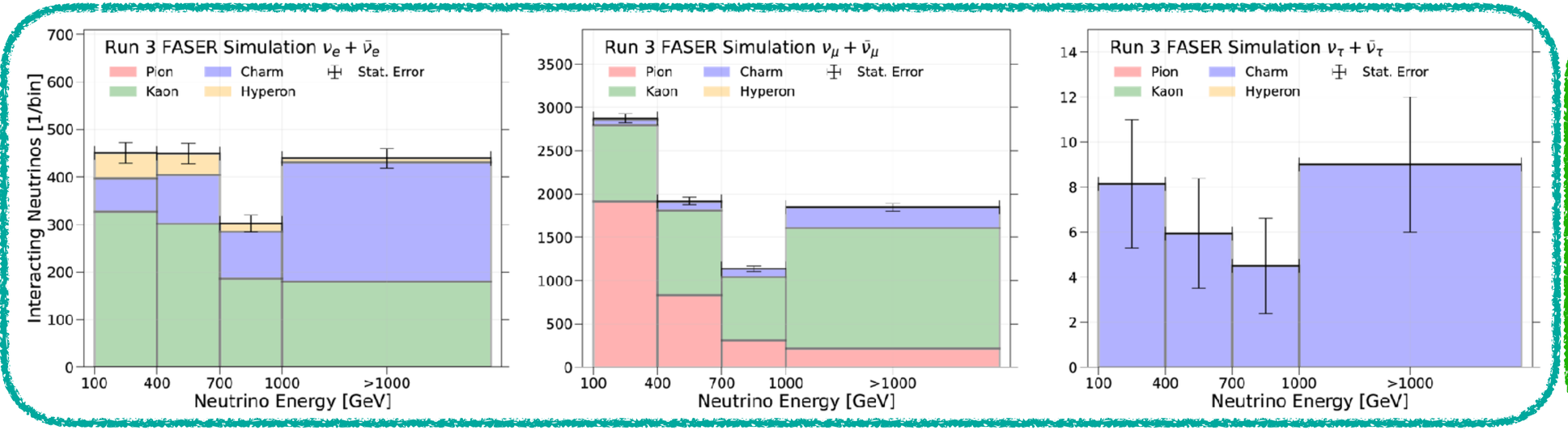
Phys. Rev. D 110, 012009

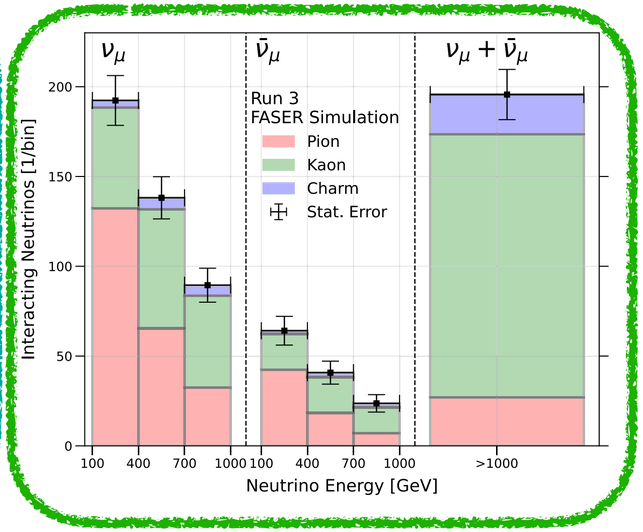
FASERν (Emulsion-based detector)

Sensitive to all 3 flavors

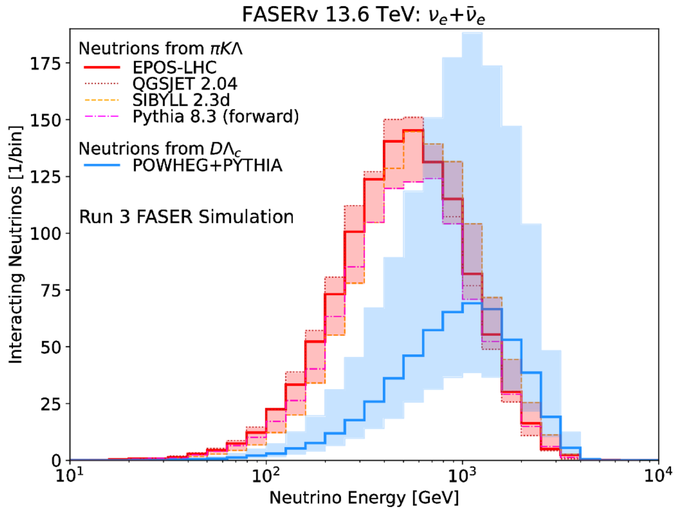
"Electric" detector technique

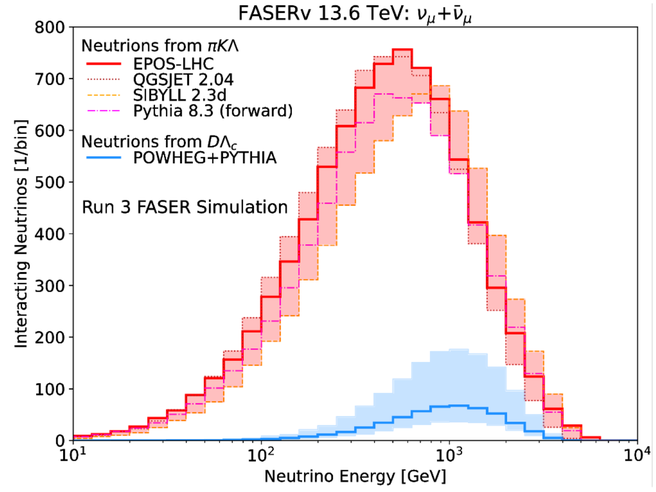
Charge separation $\nu_\mu/\nu_{\bar{\mu}}$





- **Flux uncertainties**
  - about 10-15% from light hadrons
  - 50-100% from **charm**



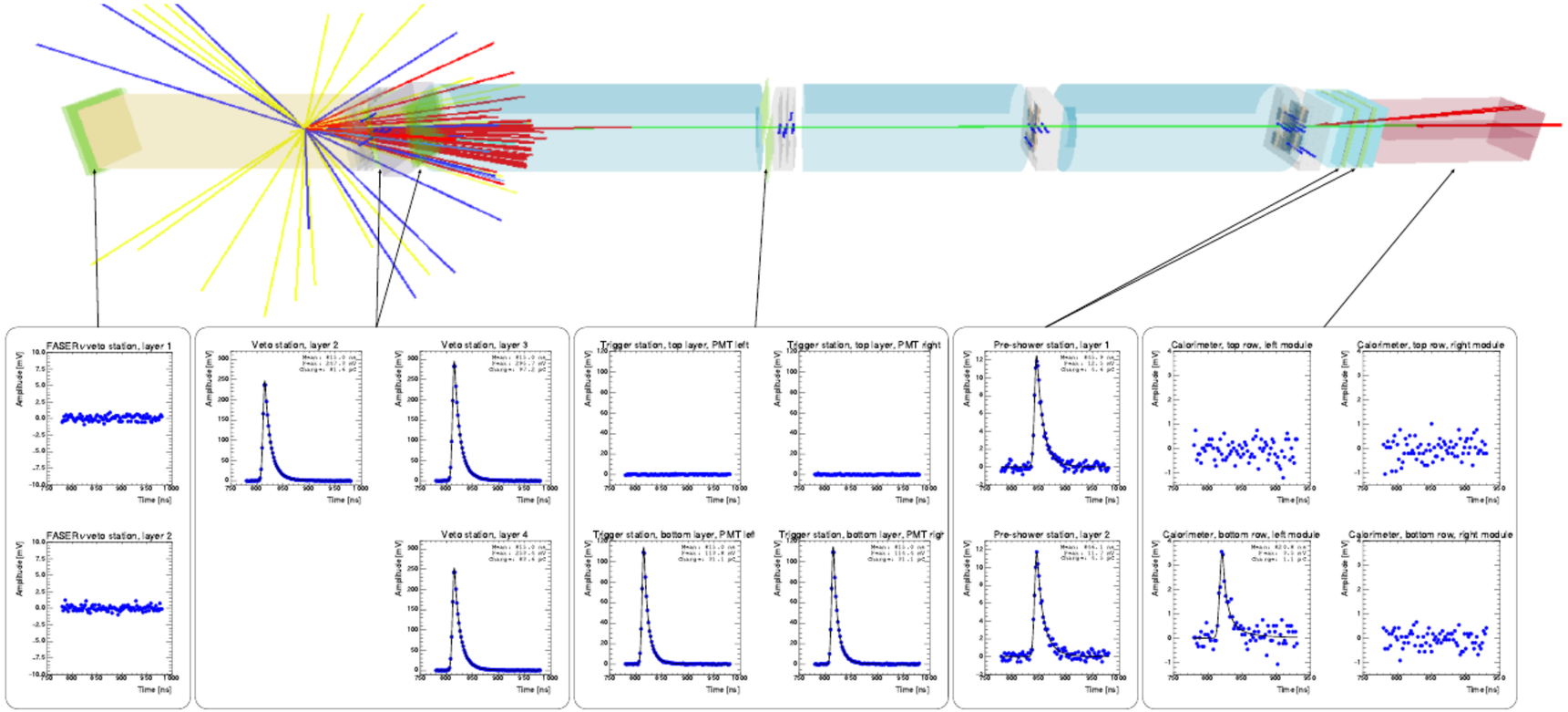


Observing Neutrino in FASER spectrometer

- Try to make a first observation of neutrinos using trackers and veto system
- Signal: **no signal in two front veto** and **one high momentum track** in the rest of detector

1. Good collision events
2. No signal (<40 pc) in 2 front vetos
3. Signal (>40 pC) in other 3 vetos

4. Timing and preshower consistent with ≥1 MIP
5. Exactly **1 good fiducial** (r < 95 mm) track
   - p_T>100 GeV and θ<25 mrad
   - Extrapolating to r<120 mm in front veto



Expect **151 ± 41 signals** from **GENIE simulation**

- Uncertainty from DPMJET vs SIBYLL
- No experimental errors

Background

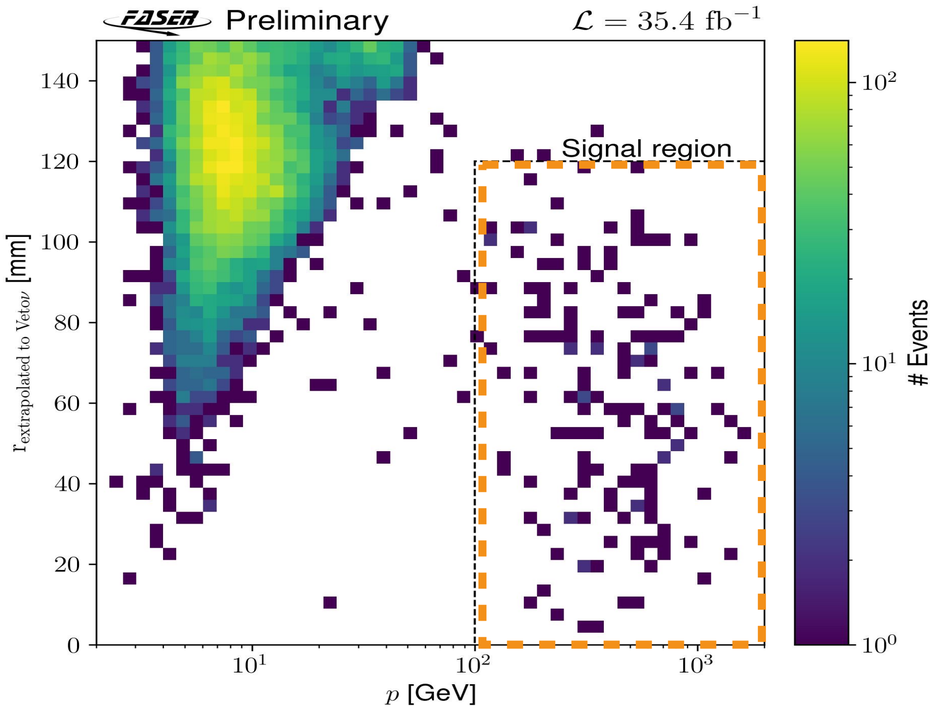
- Veto inefficiency: negligible
- Neutral hadrons: **0.11±0.06** events (MC)
- Scattered large-angle muons: **0.08±1.83** events (sideband)

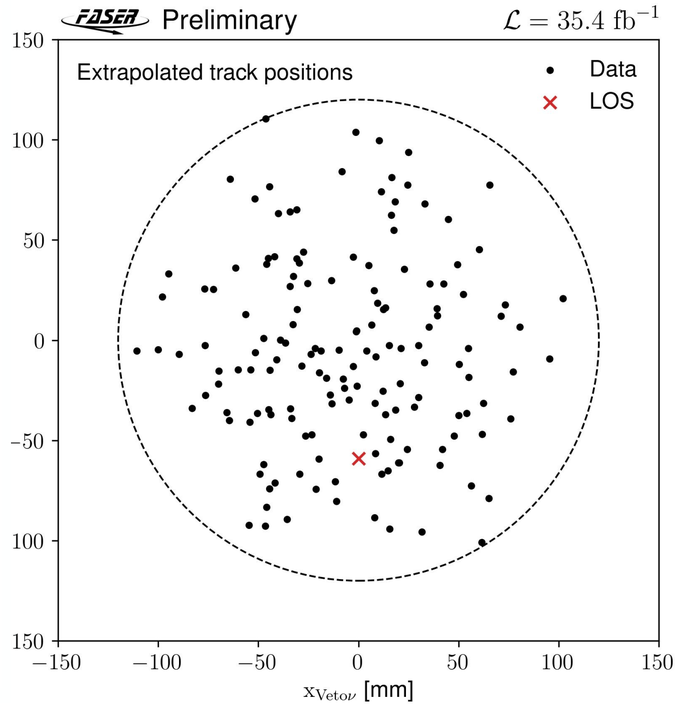
First detection of collider neutrino

- Upon unblinding find **153 events** with no veto signal
  - Just 10 events with one veto signal
- **First direct detection of collider neutrinos!**
  - **With signal significance of 16σ**
- Candidate neutrino events match expectation from signal
  - Observed both neutrinos and anti-neutrinos as we expected

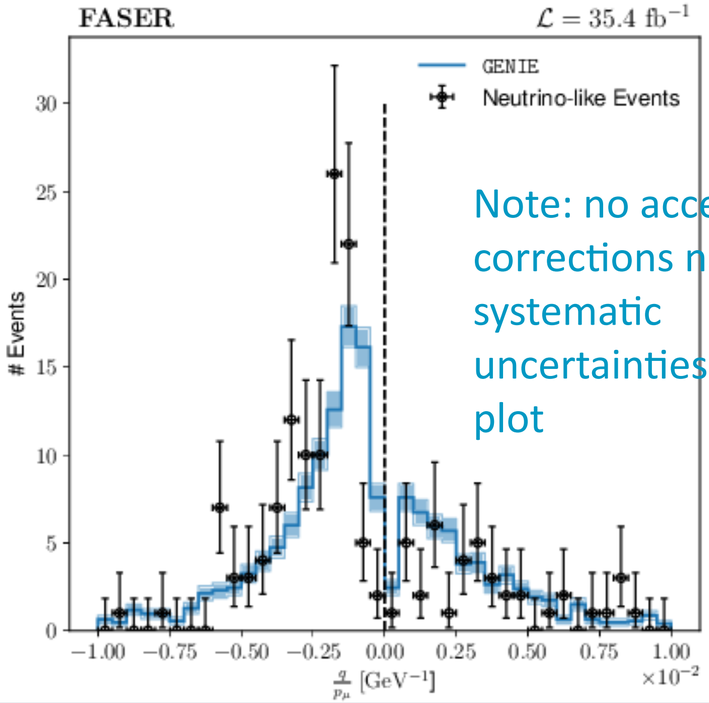
Phys. Rev. Lett. 131, 031801 (2024)

Candidate	Events
ν enriched Events (Passed all event selection)	153, (151±41, MC)
Events (1 veto signal at the first layer)	4
Events (1 veto signal at the second layer)	6
Events (Veto signals for both layers)	64014695





Track momentum distribution

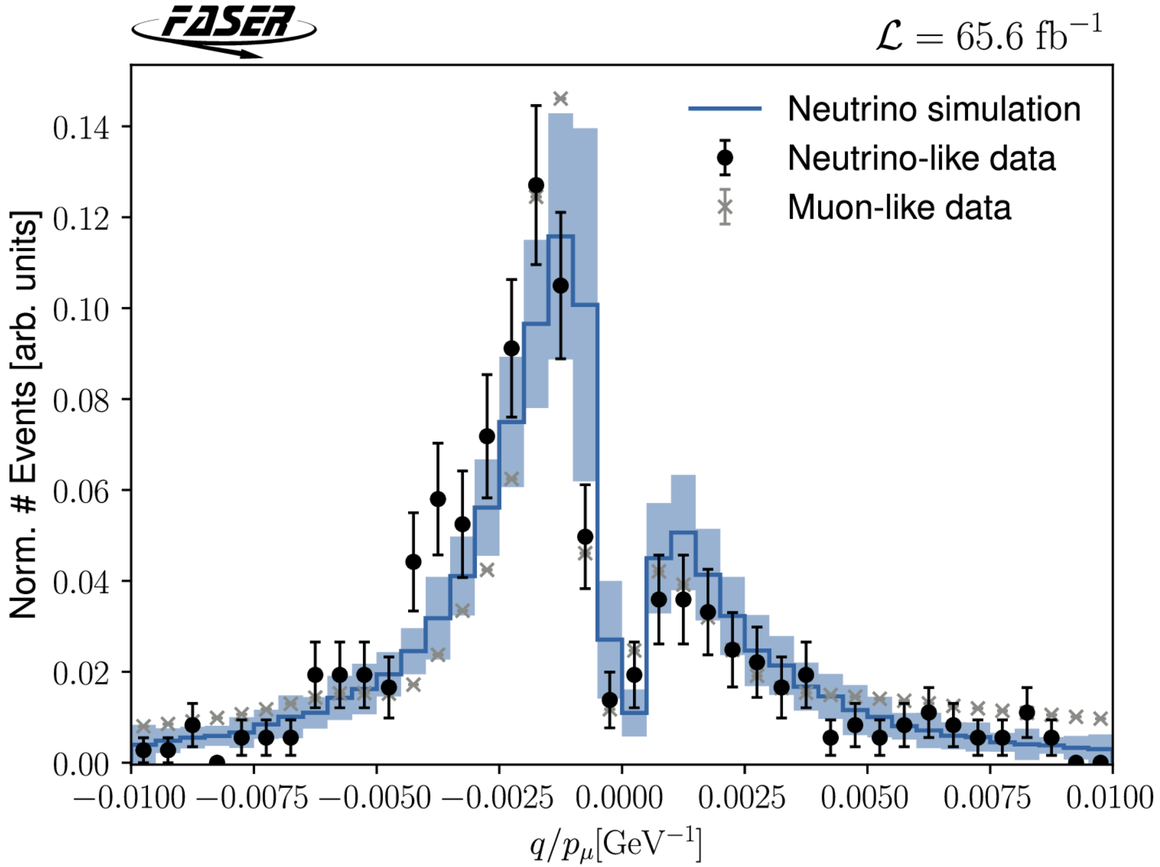


Note: no acceptance corrections nor systematic uncertainties in the plot

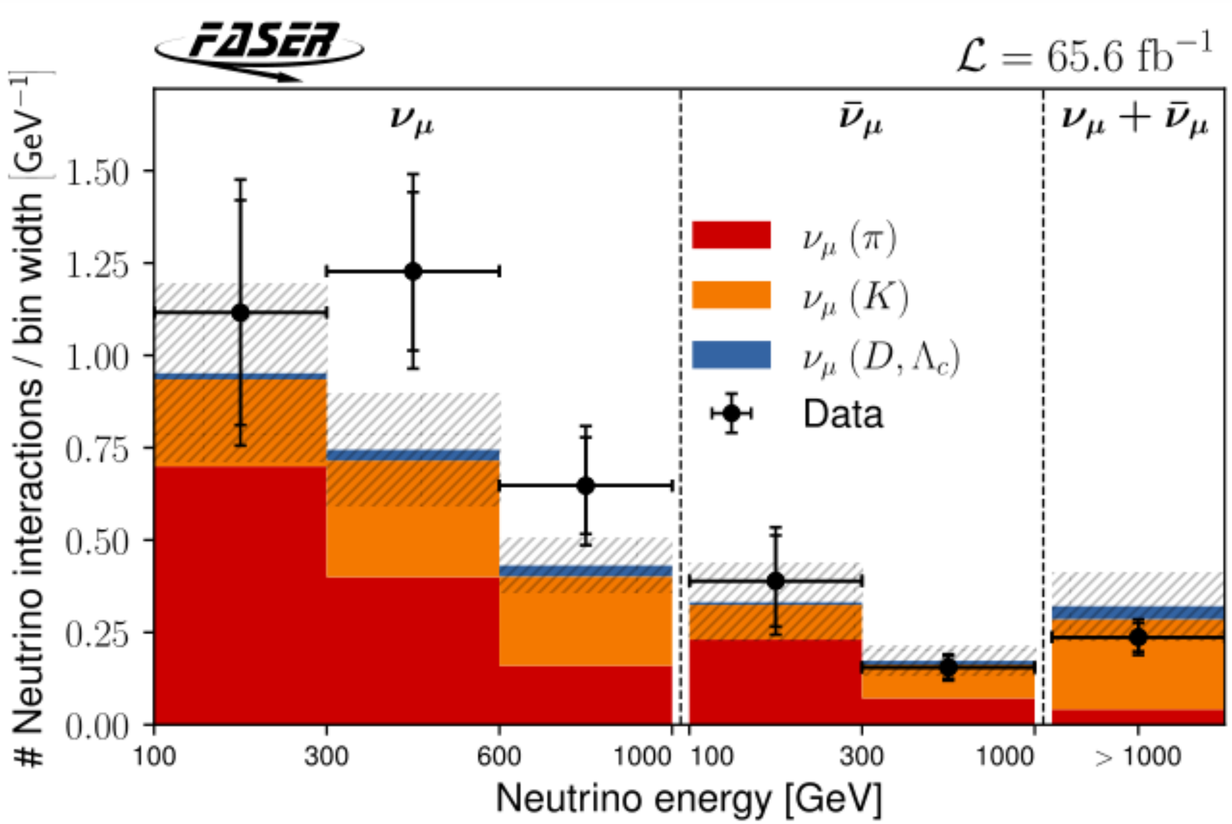
Updates in 2025: Observed events and kinematics

362 observed

322 ± 51 ν_μ CC expected + 24 non-ν_μ CC BG



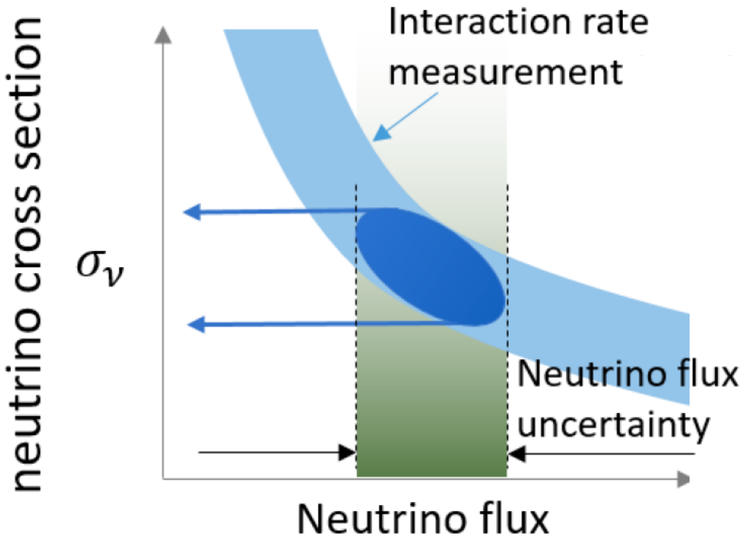
Muon momentum is unfolded into neutrino energy with $\nu_\mu/\bar{\nu}_\mu$ separation



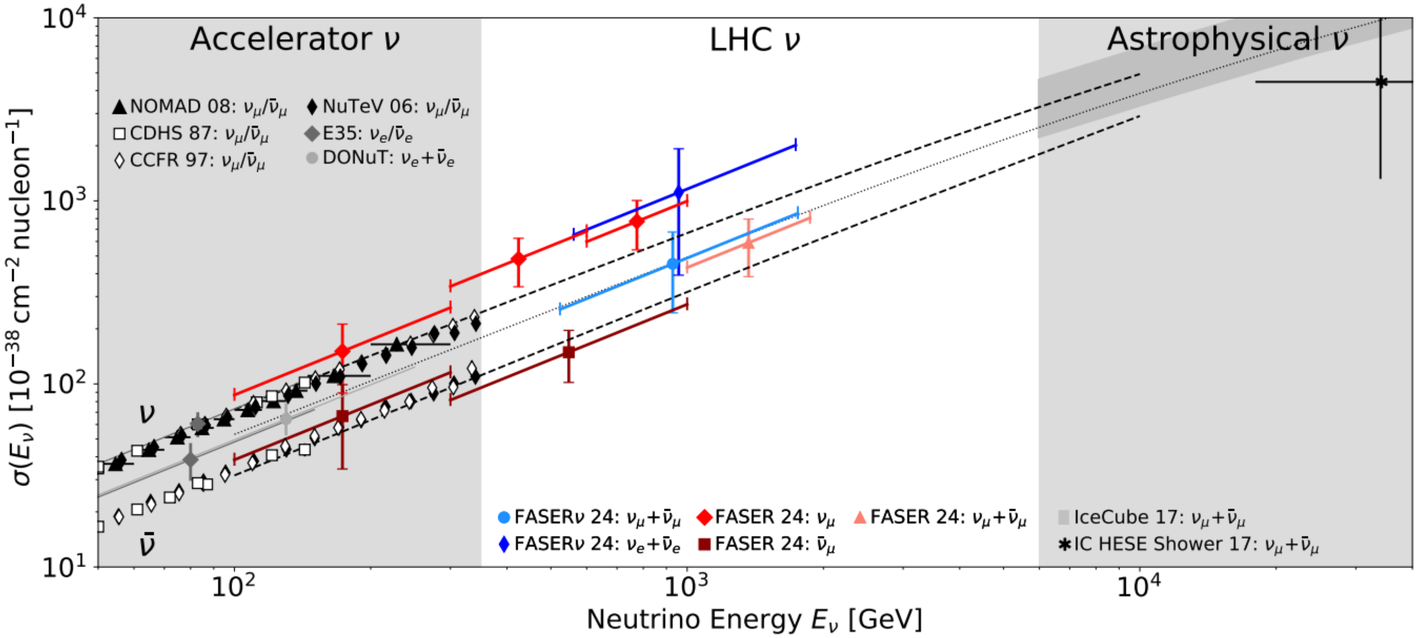
Interpretations of ν_μ interaction rate

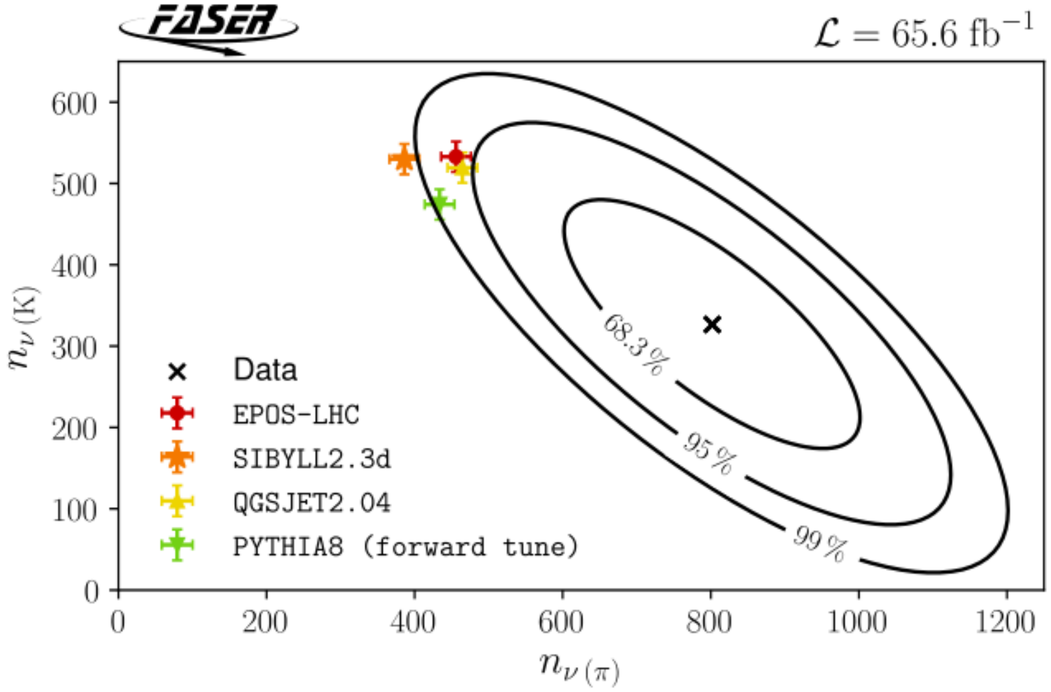
- FASER's result can be interpreted in two ways
  - Neutrino Cross-sections
  - Flux measurements・hadron production measurements

Achieved first $\bar{\nu_\mu}$ cross-section measurements!!



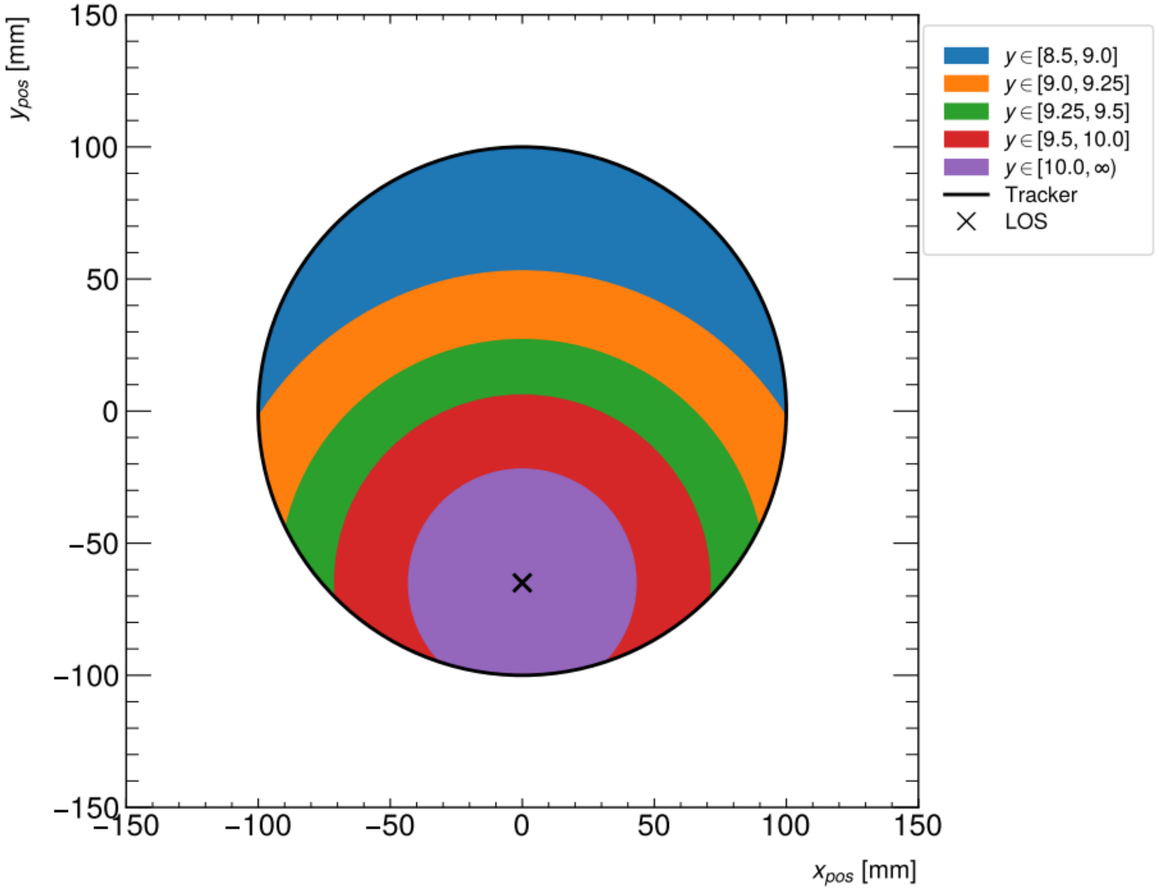
Phys. Rev. Lett. 134, 211801

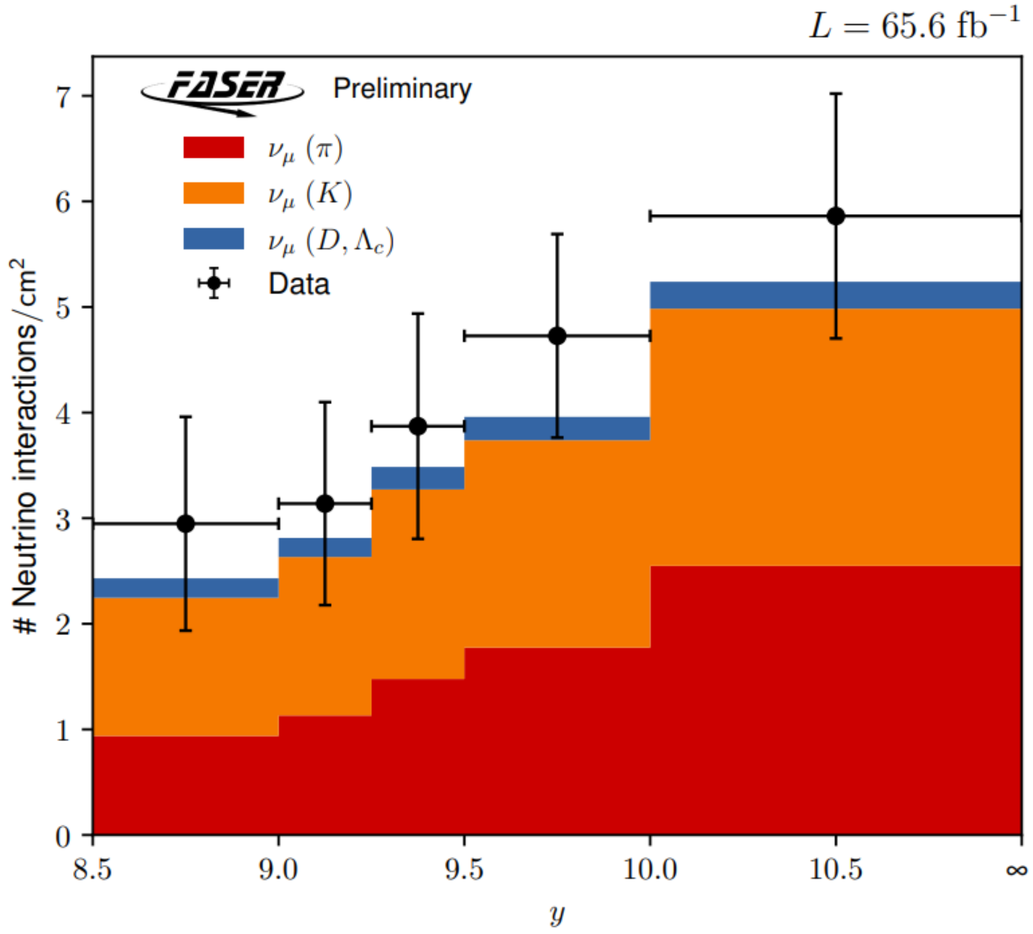




Neutrino measurement with rapidity distribution

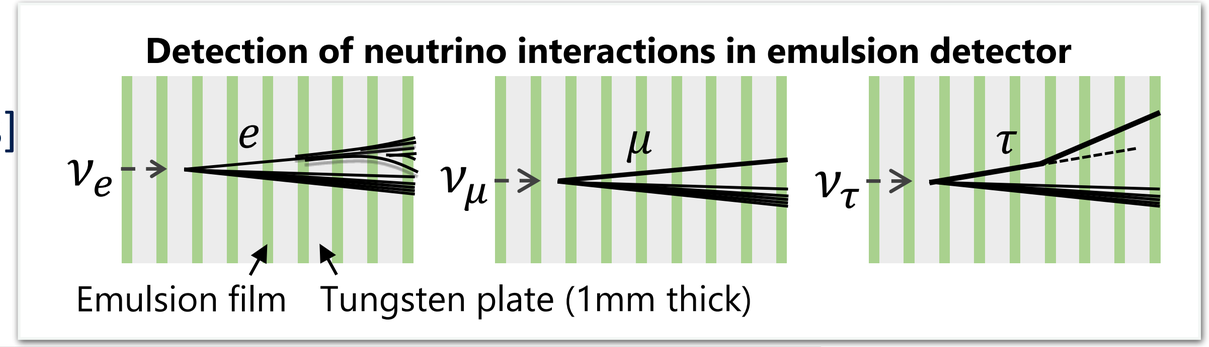
- To study the characterization of forward hadron production at the LHC **CERN-FASER-CONF-2025-001**
  - Define five rapidity bins (annular regions) around line of sight (black cross)
  - Rapidity from transverse position of reconstructed muon, then unfolded to neutrino rapidity
    - Rapidity y = -ln tan(θ/2)





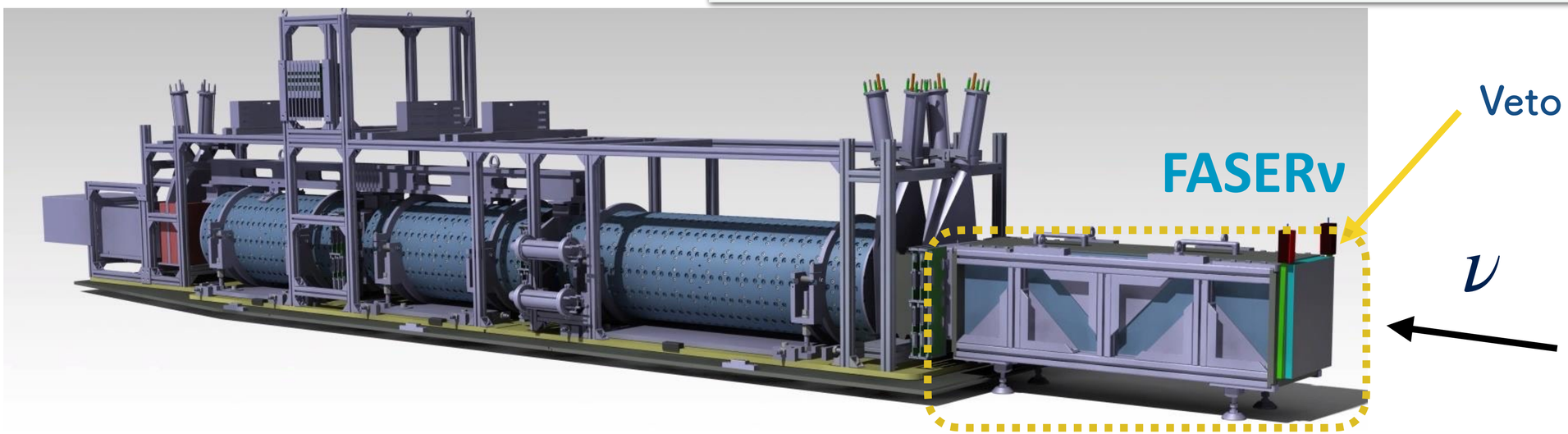
FASERv Emulsion detector

flavor tagging with topological/kinematical informations



Emulsion/tungsten detector

- 730 x [tungsten plates(1.1 mm thickness) + emulsion films]
  25×30 cm², 1 m long, 1.1t (220 X_0)
- **Emulsion films are replaced every 20-30 fb^{-1}**
  - (3 times per year)

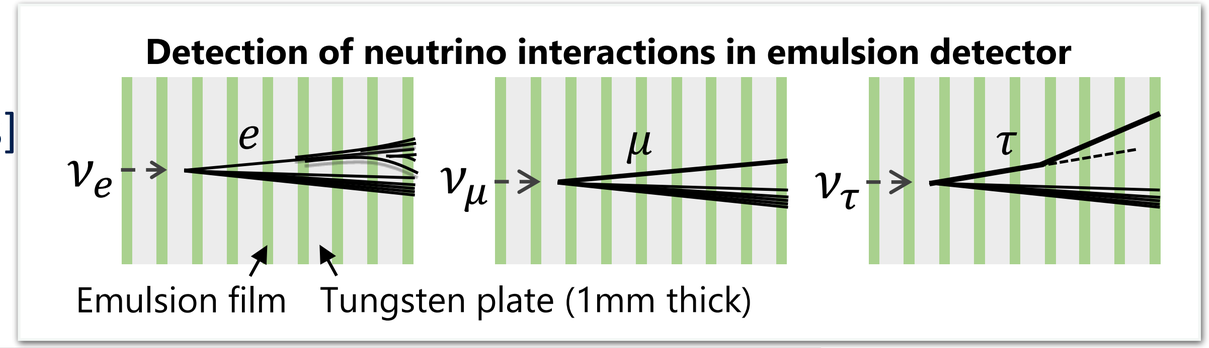


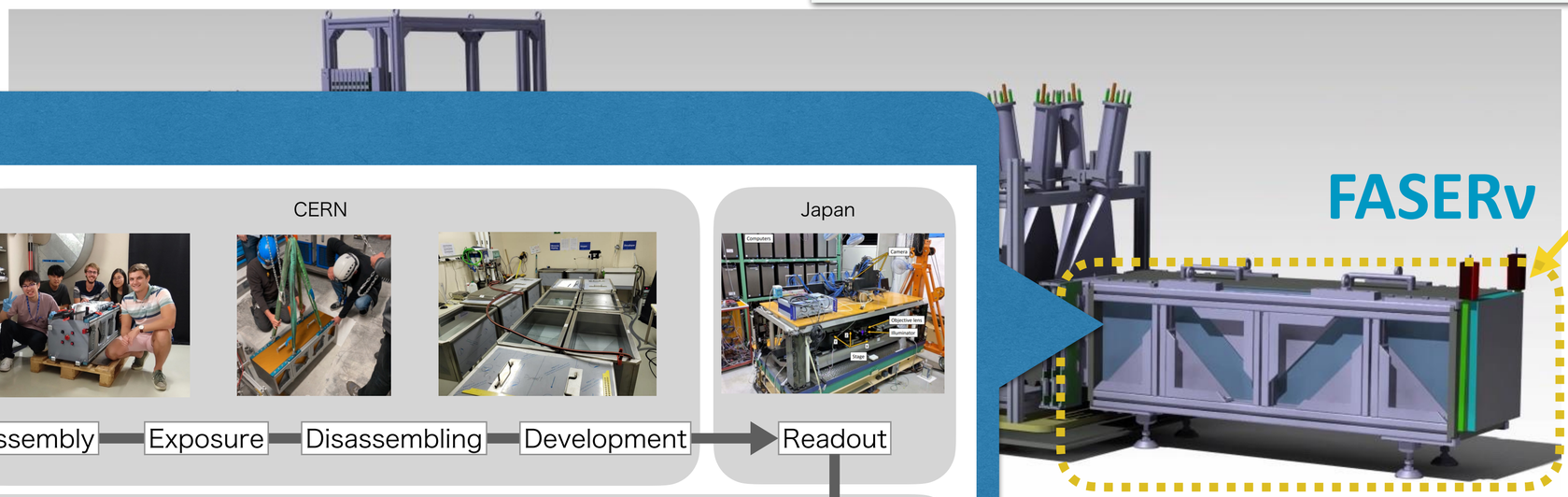
FASERv Emulsion detector

flavor tagging with topological/kinematical informations

Emulsion/tungsten detector

- 730 x [tungsten plates(1.1 mm thickness) + emulsion films]
  25×30 cm², 1 m long, 1.1t (220 X_0)
- **Emulsion films are replaced every 20-30 fb^{-1}**
  - (3 times per year)





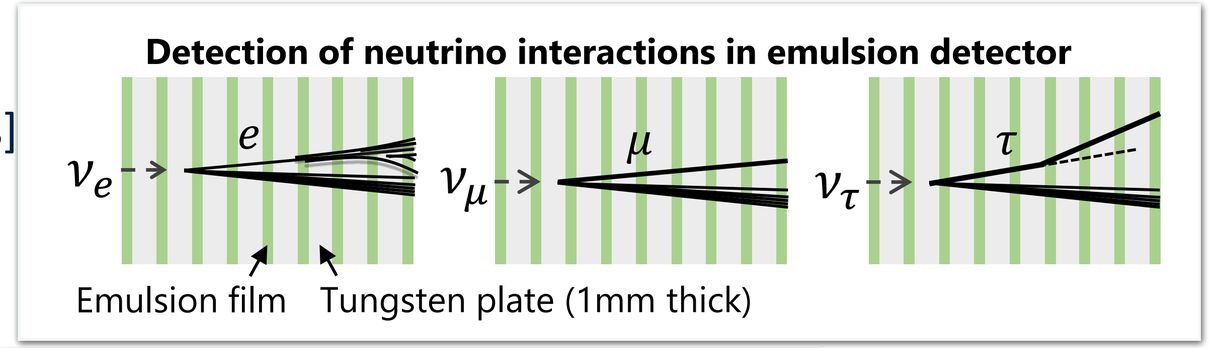
Overview for emulsion analysis

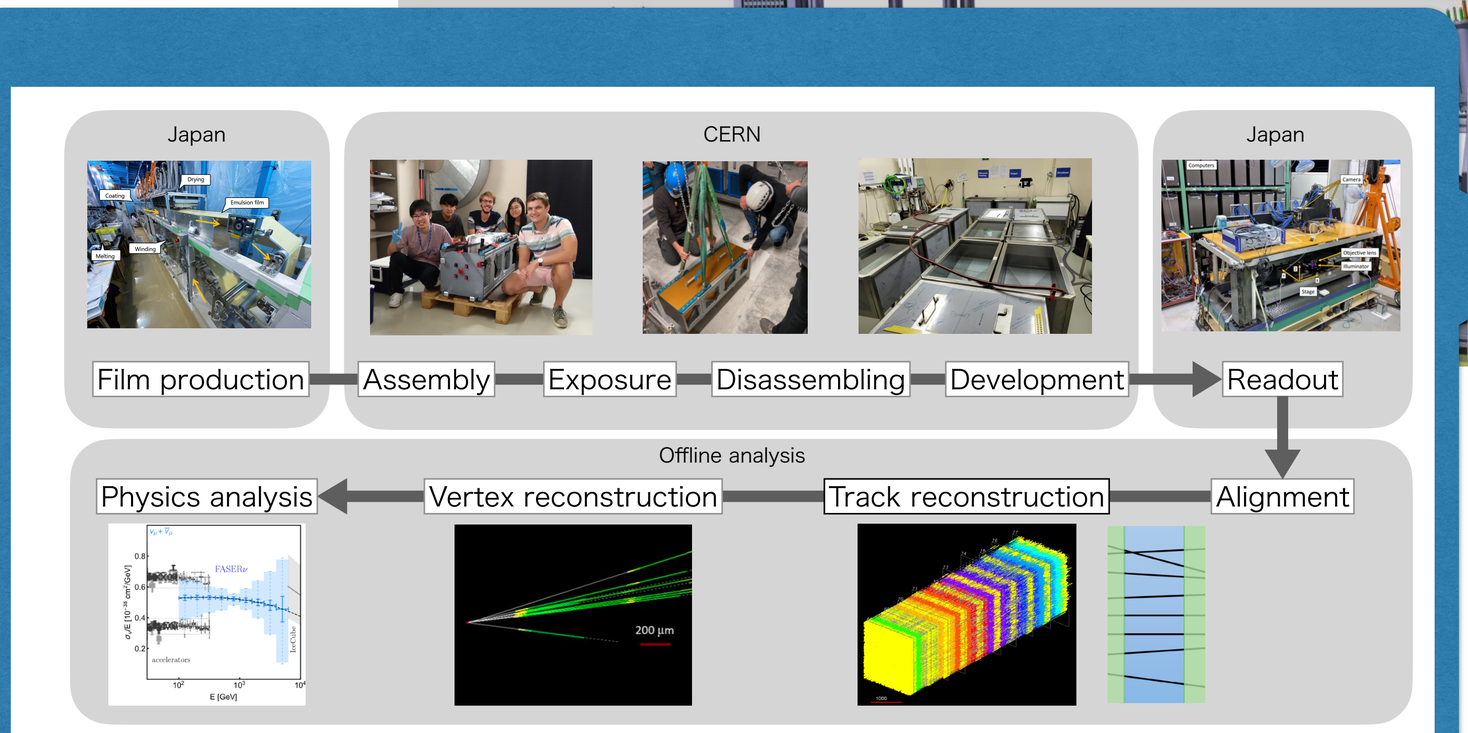
FASERv Emulsion detector

flavor tagging with topological/kinematical informations

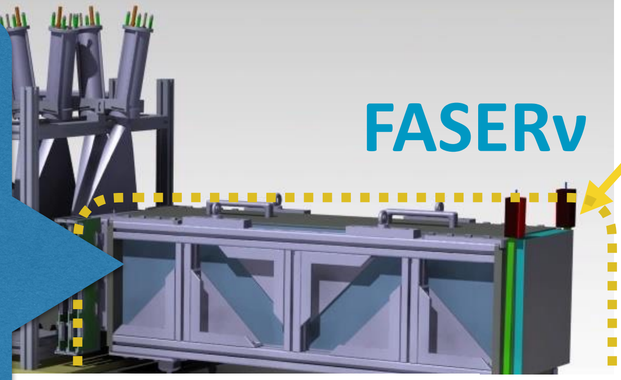
Emulsion/tungsten detector

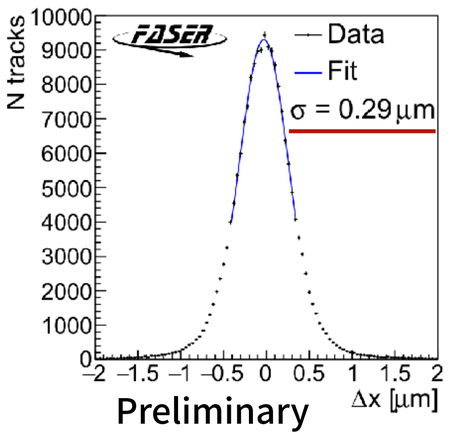
- 730 x [tungsten plates(1.1 mm thickness) + emulsion films]
  25×30 cm², 1 m long, 1.1t (220 X_0)
- **Emulsion films are replaced every 20-30 fb^{-1}**
  - (3 times per year)

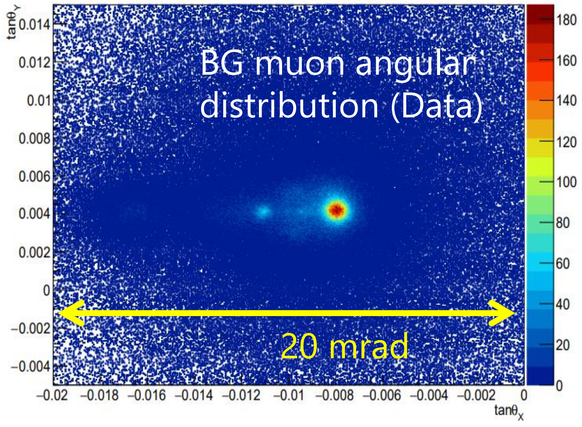




Overview for emulsion analysis



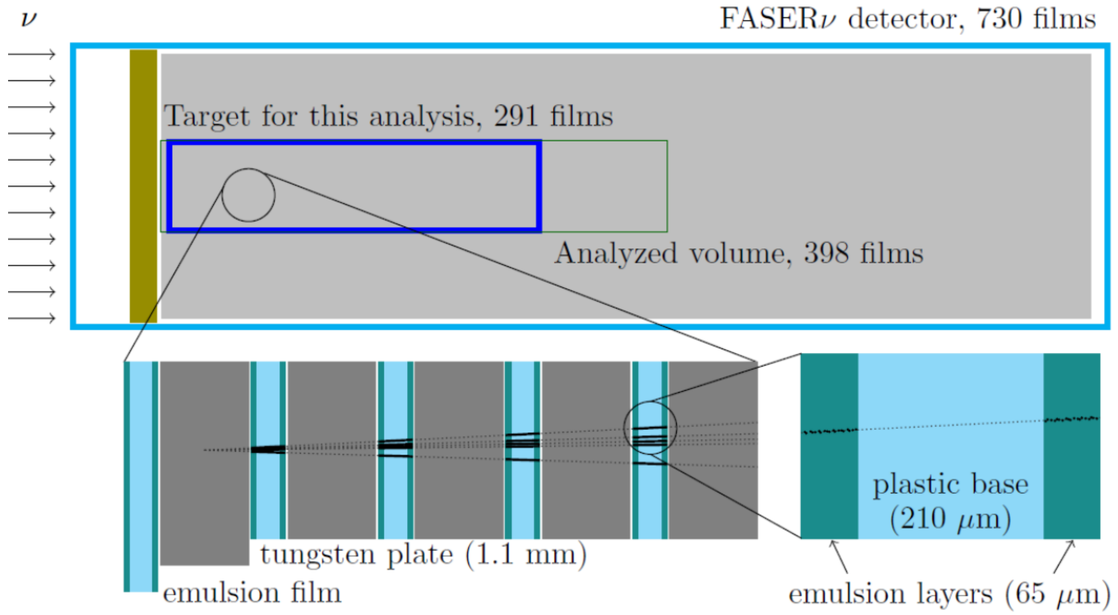




FASERv Analysis toward ν_e and ν_μ detections

Data set:

- 2022 second module→9.5 fb^{-1};
  - Target mass: 128.6 kg;
  - ~ 1.7% of data collected to date.



Selection criteria:

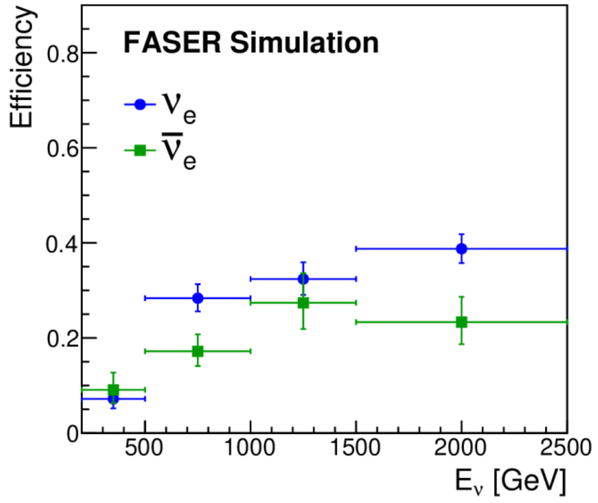
Vertex reconstruction:

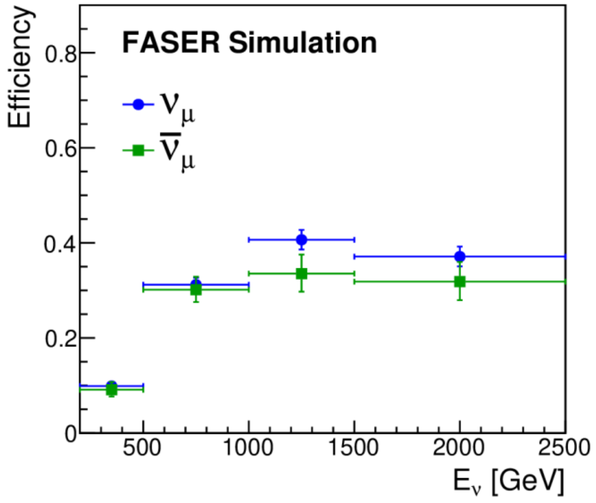
- $N_{track} \geq 5$
- $N_{track}(\tan\theta \leq 0.1) \geq 4$

Lepton requirements:

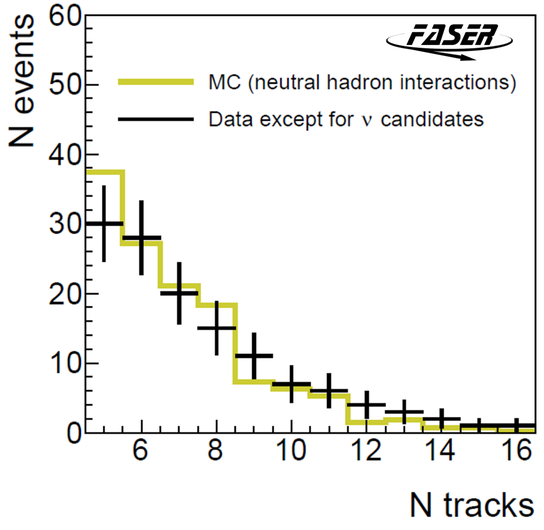
- E_e or p_μ >200GeV
- $\tan\theta_e$ or $\tan\theta_\mu$ > 0.005

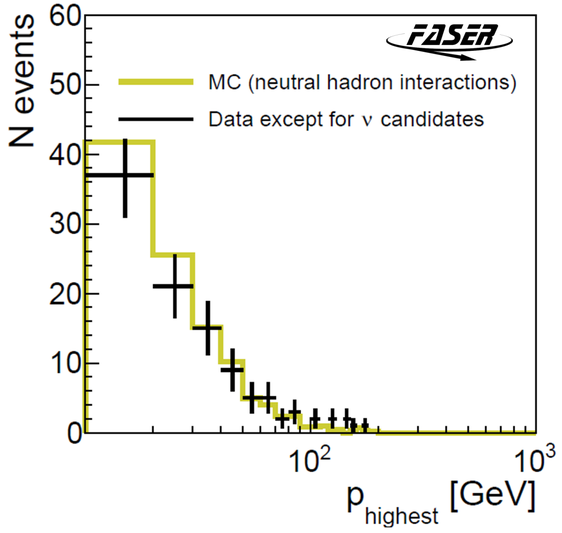
Back-to-back topology: $\Delta\phi > 90°$





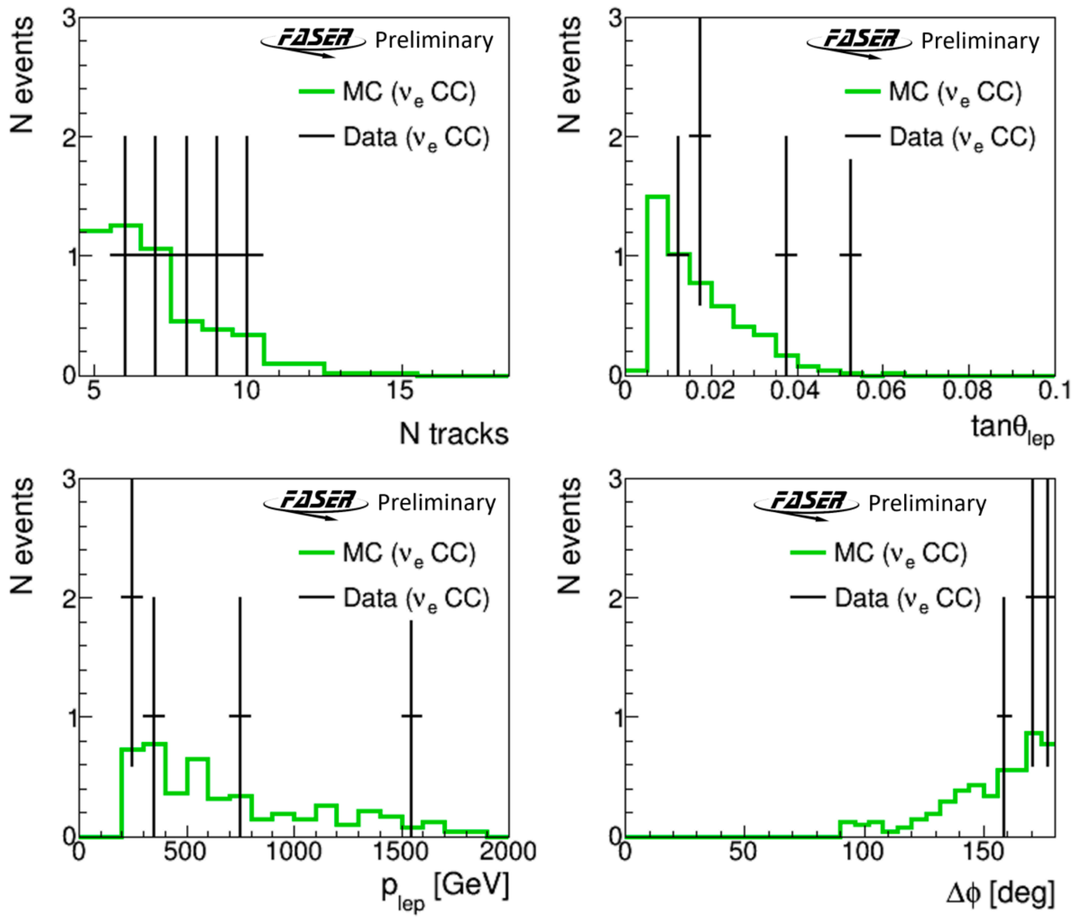
Background model

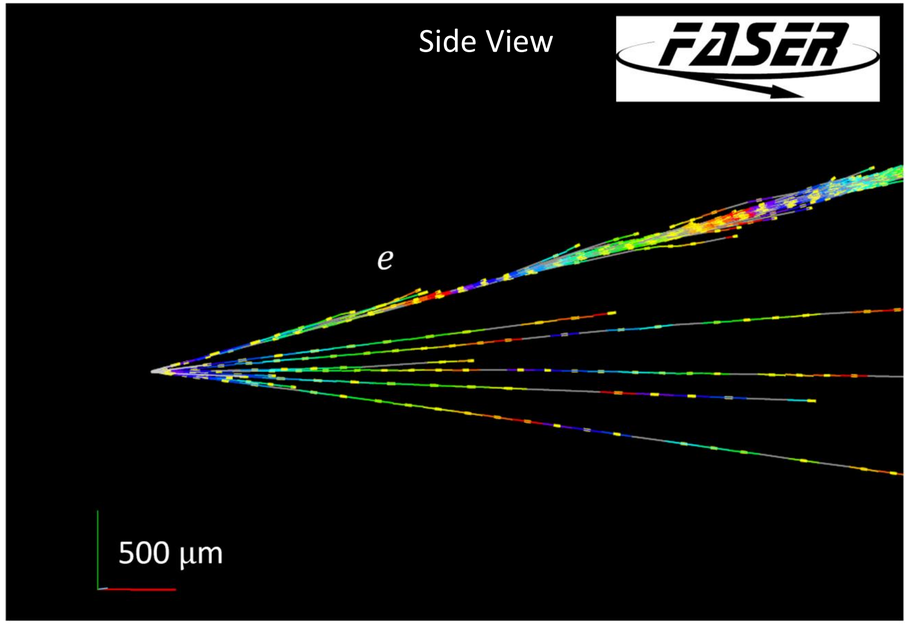


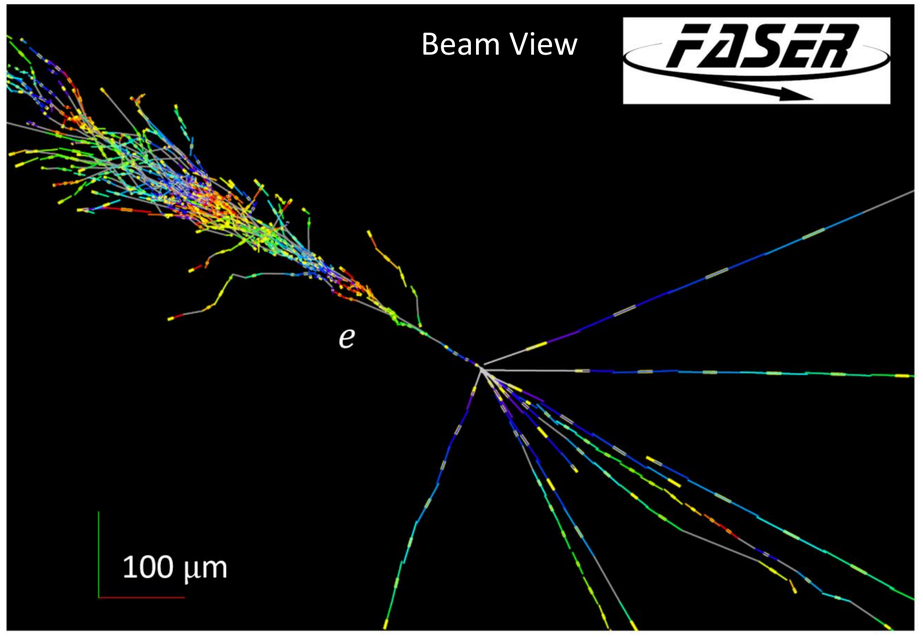


ν_e events

- E_e = 1.5 TeV, highest ν_e measured
- MC normalized to number of observed events.

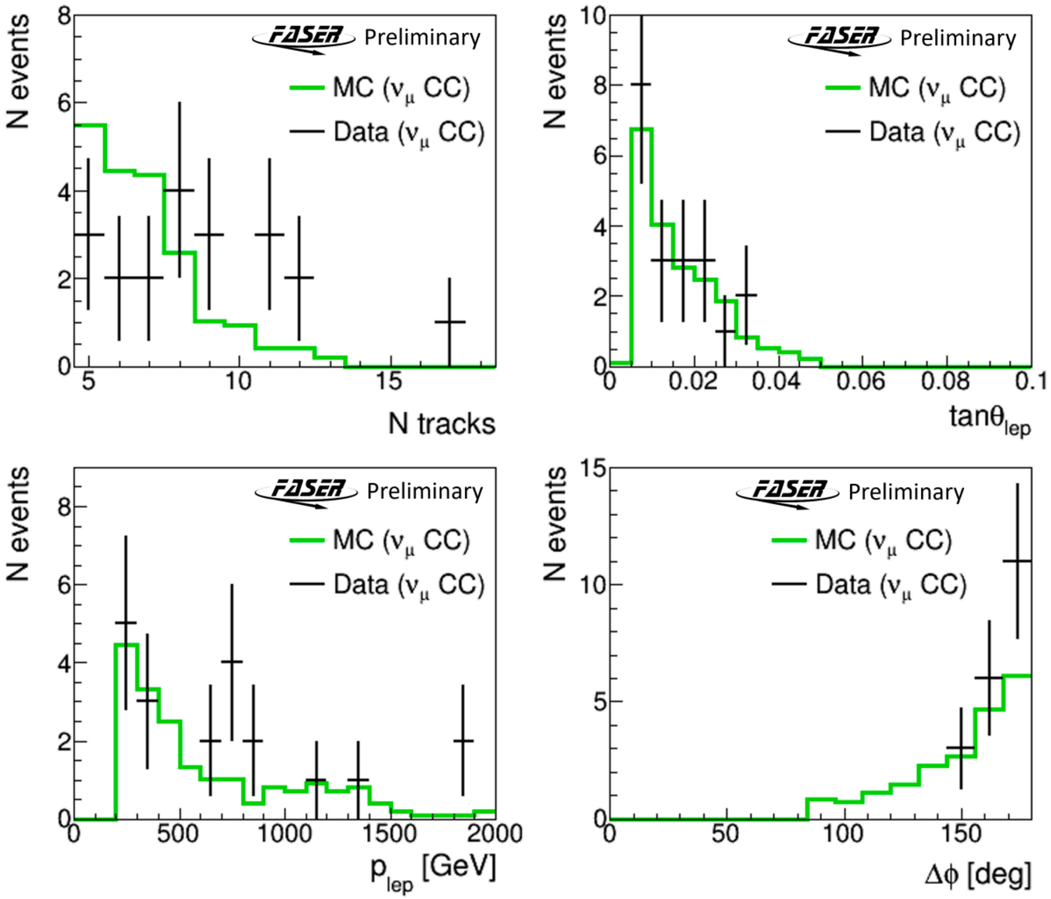


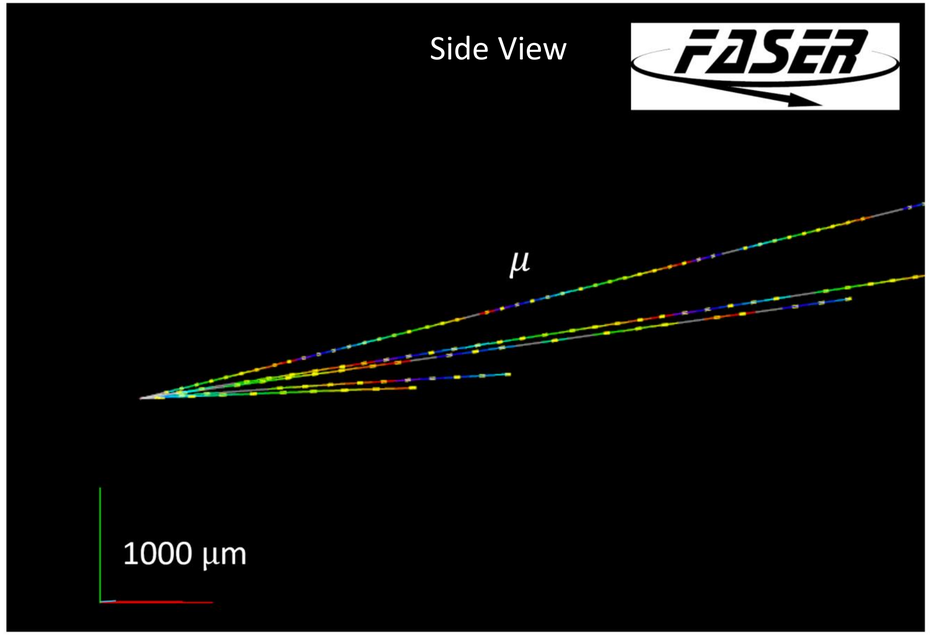


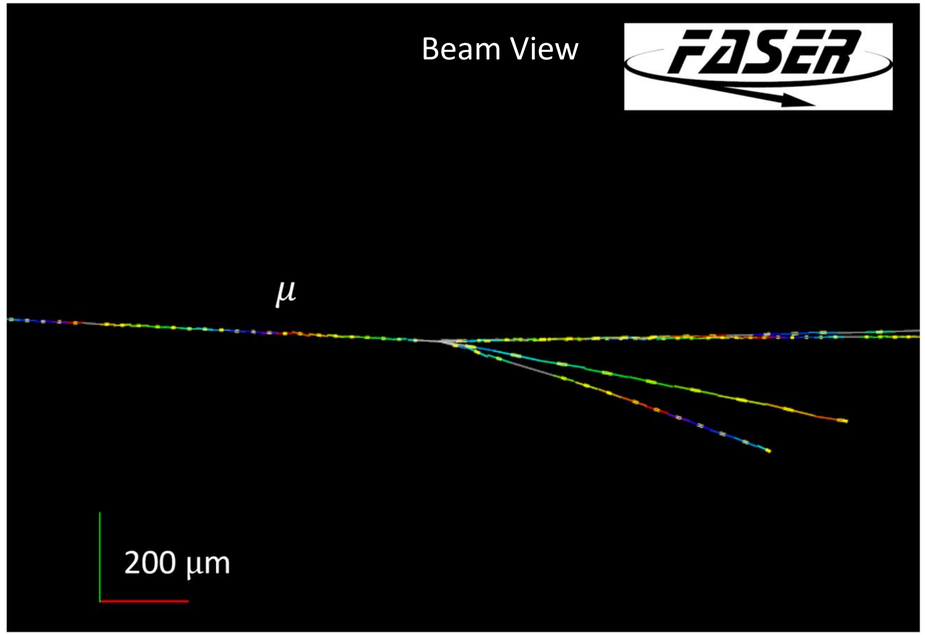


ν_μ events

- p_μ = 360 GeV.
- MC normalized to number of observed events.





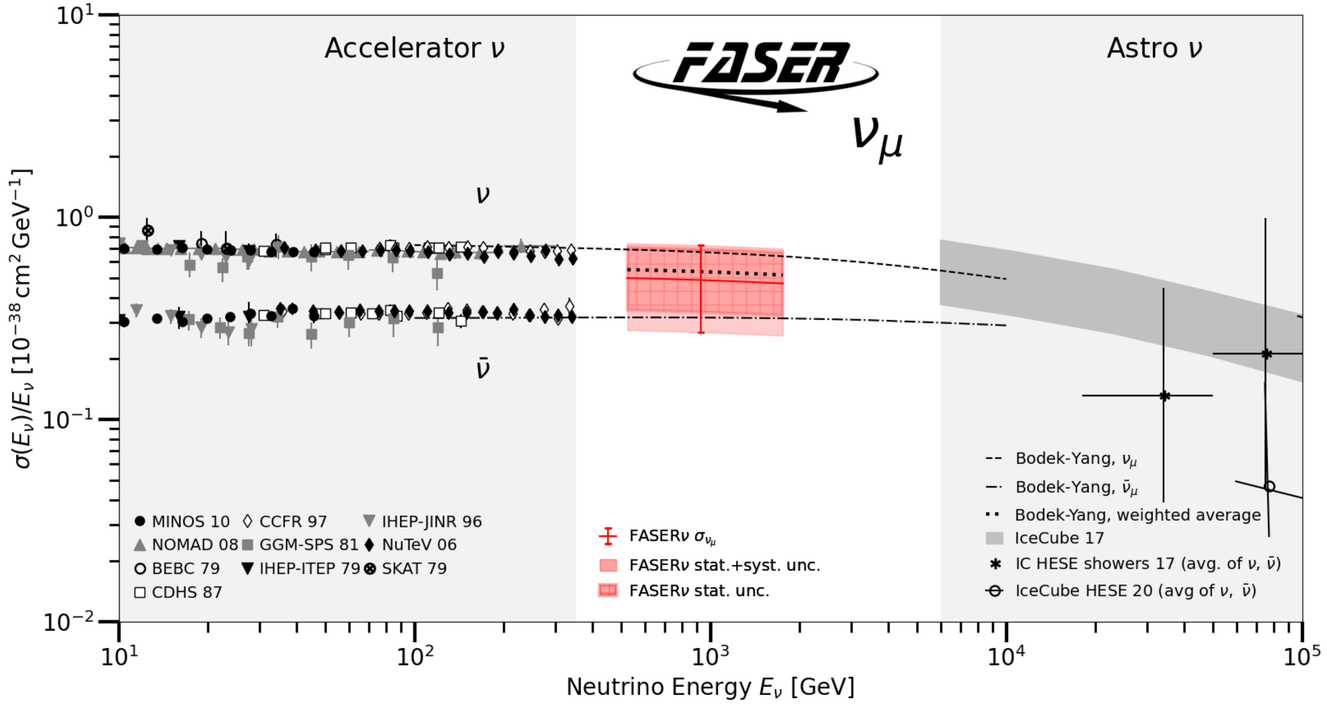


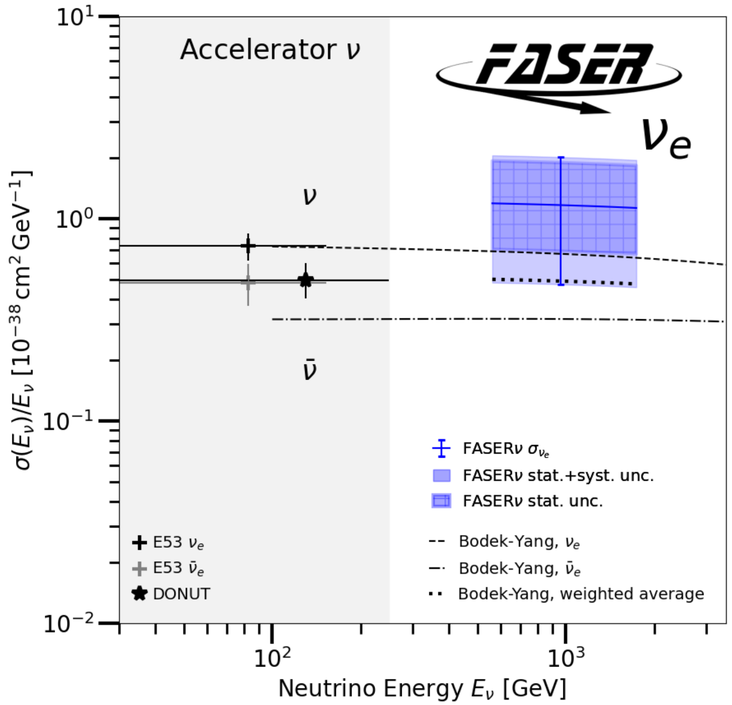
Phys. Rev. Lett. 133, 021802 (2024)

Results from FASERν: ν_μ and ν_e events!

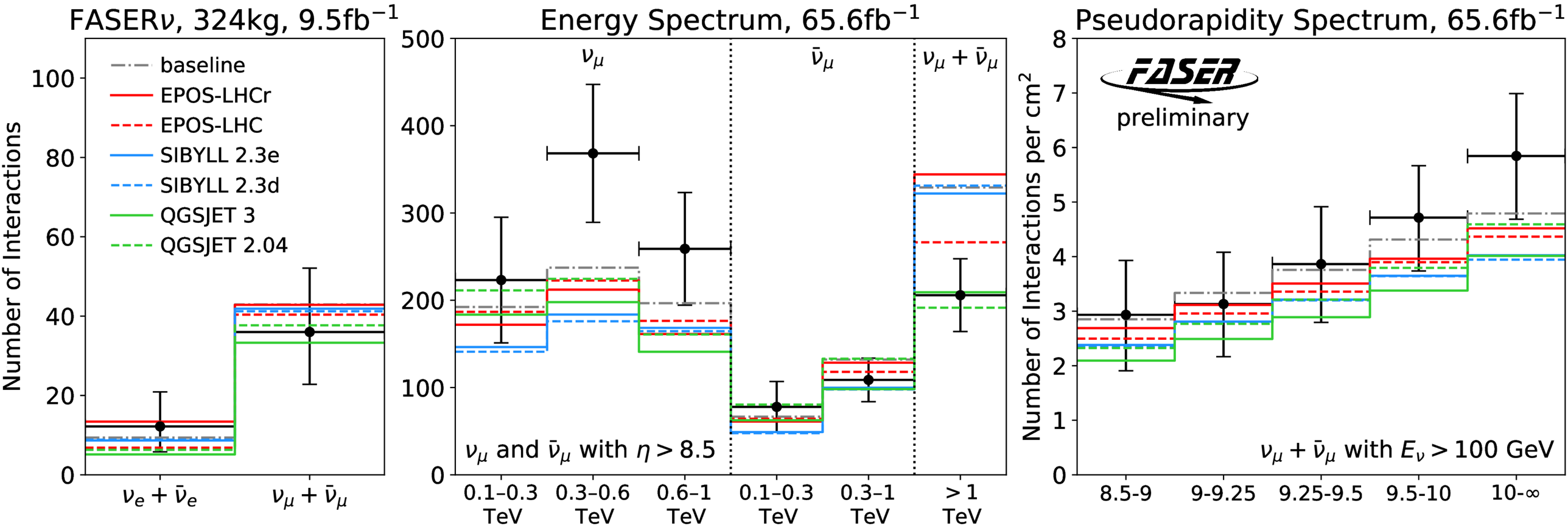
Interaction	Expected background	Expected signal	Observed	Significance
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3	4	5.2σ
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5 – 12.4	8	5.7σ

- First observation of ν_e at the LHC!
- First neutrino cross-section measurement in the TeV range!
- Large uncertainty from neutrino flux





Forward hadron producution Study



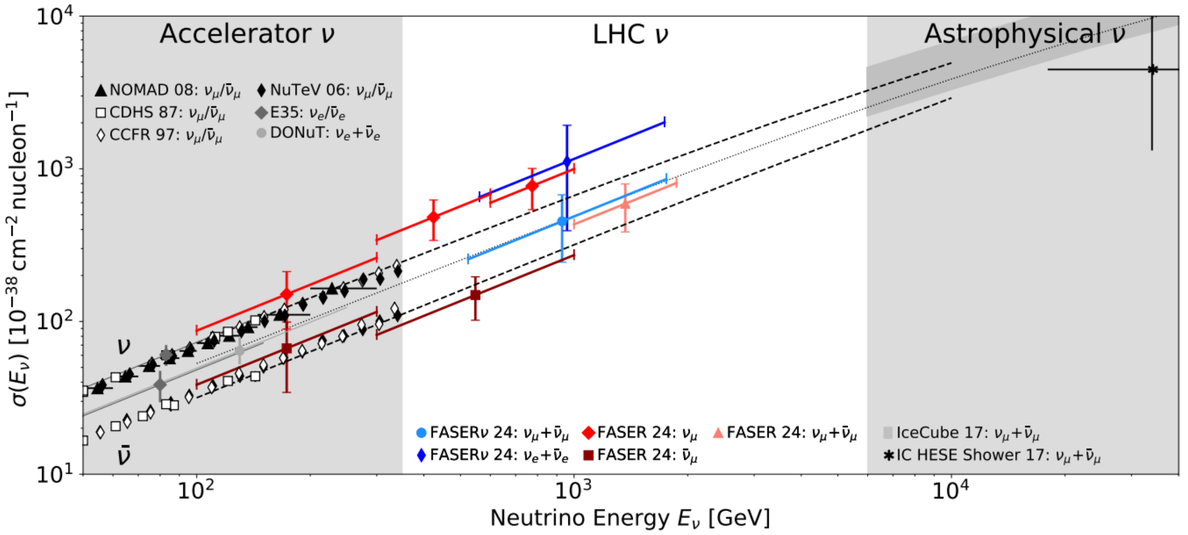
- Experimental test of forward pion, Kaon, and Charm production at the LHC CERN-FASER-CONF-2025-004

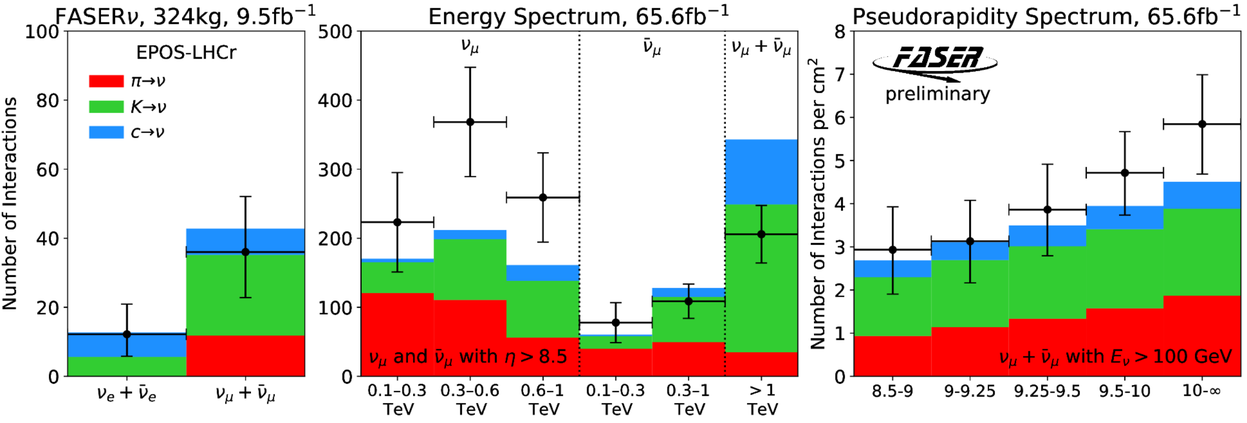
Summary

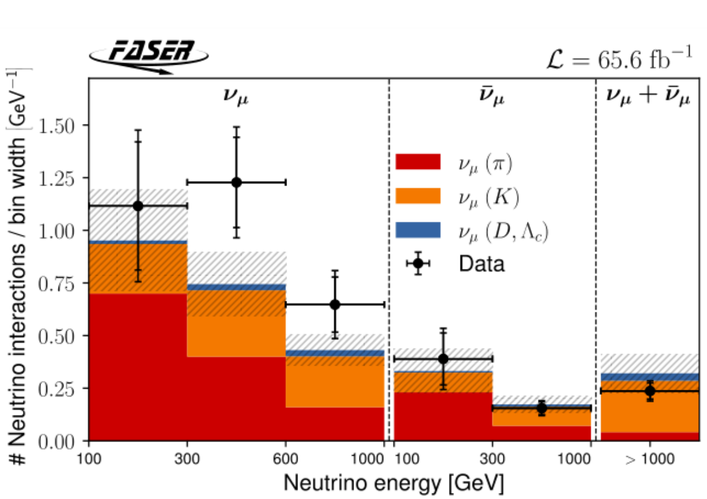
- LHC-FASER is taking data in Run3 of LHC operation, we had collected ~190 fb^{-1} collected and since then another 55 fb^{-1}
- Providing timely physics results
  - First ν_e, ν_μ x sections (with 2 % of data)
  - First $\bar{\nu_\mu}$ x-section and, differential x-section
  - Neutrino rapidity distribution

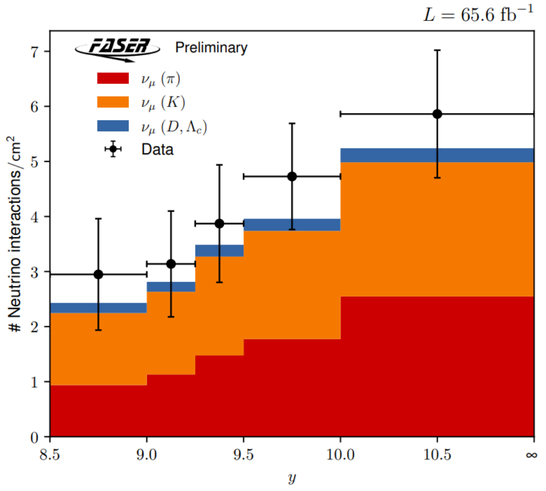
Prospects

- Additional 180 fb^{-1} to be collected in 2024. 2025
- FASER in Run4 approved
- Discussing extended physics programs
  - Forward Physics Facility (2031-) in HL-LHC era
  - Details are In this paper









Acknowledgement