Overview of the FASER experiment with a focus on neutrino studies

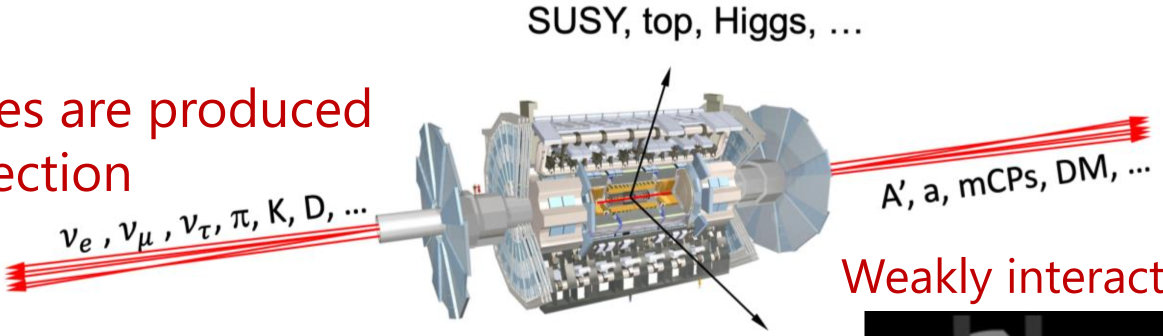
Haruhi Fujimori (Chiba University) on behalf of the FASER Collaboration

8th May 2025, 13th Edition of the Large Hadron Collider Physics Conference, Taipei, Taiwan

Introduction

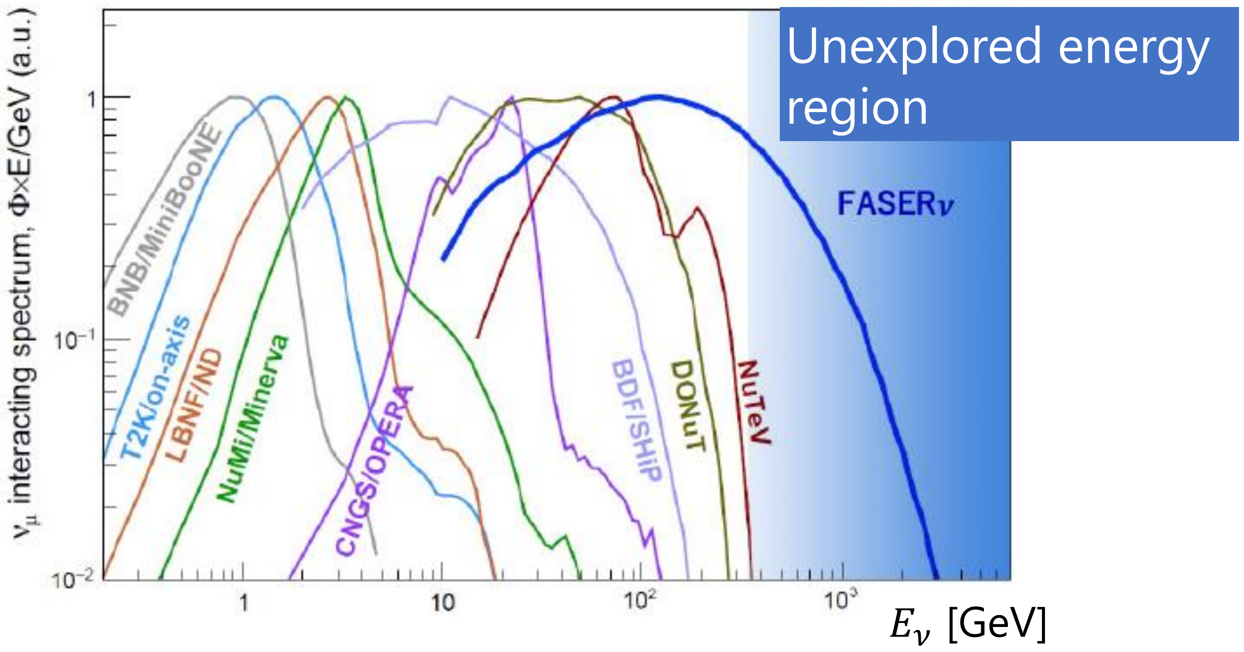
The existing collider detector (e.g. ATLAS) were designed to find strongly interacting particles

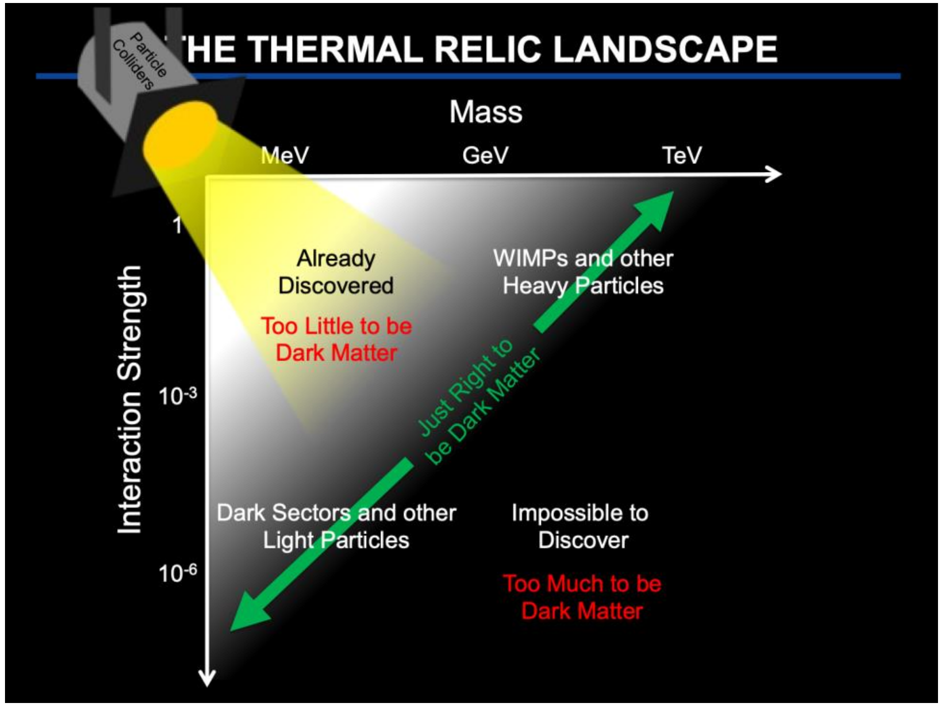
Energetic light particles are produced in the far-forward direction



Weakly interacting light particle (BSM) search

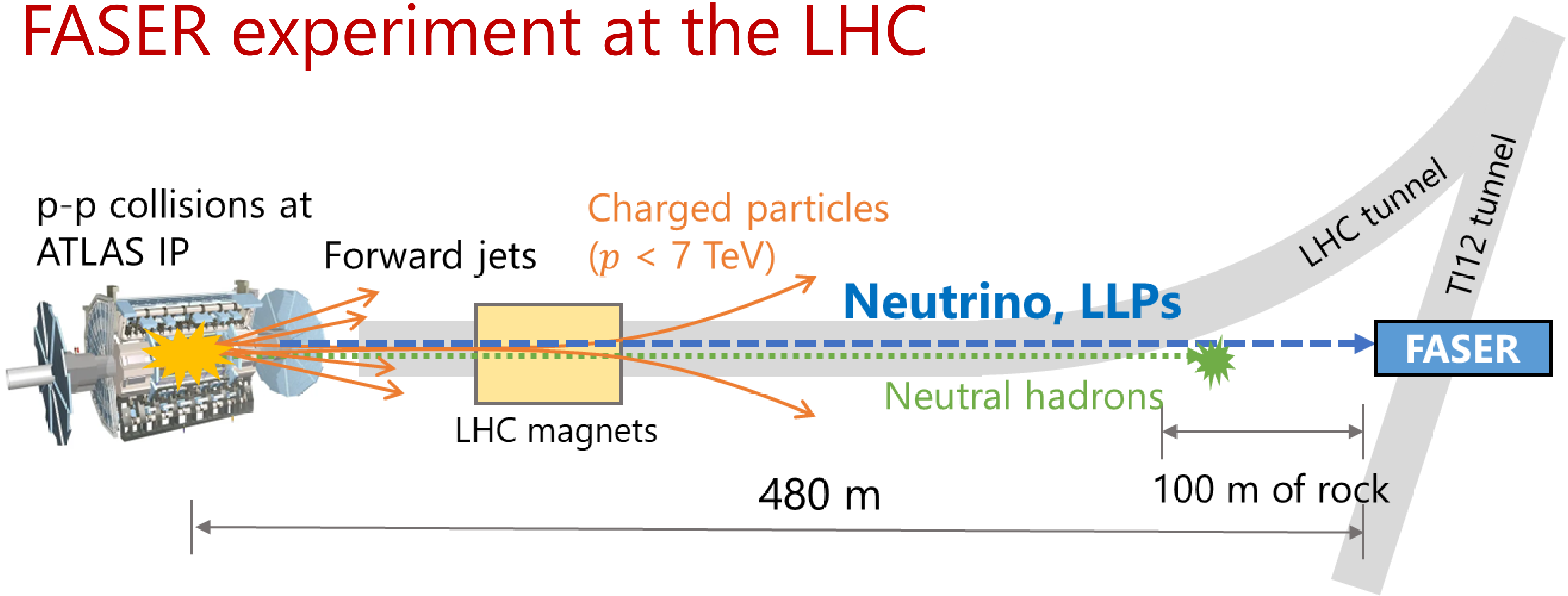
TeV neutrino measurement





There is a rich and unexplored physics program in the far forward direction!

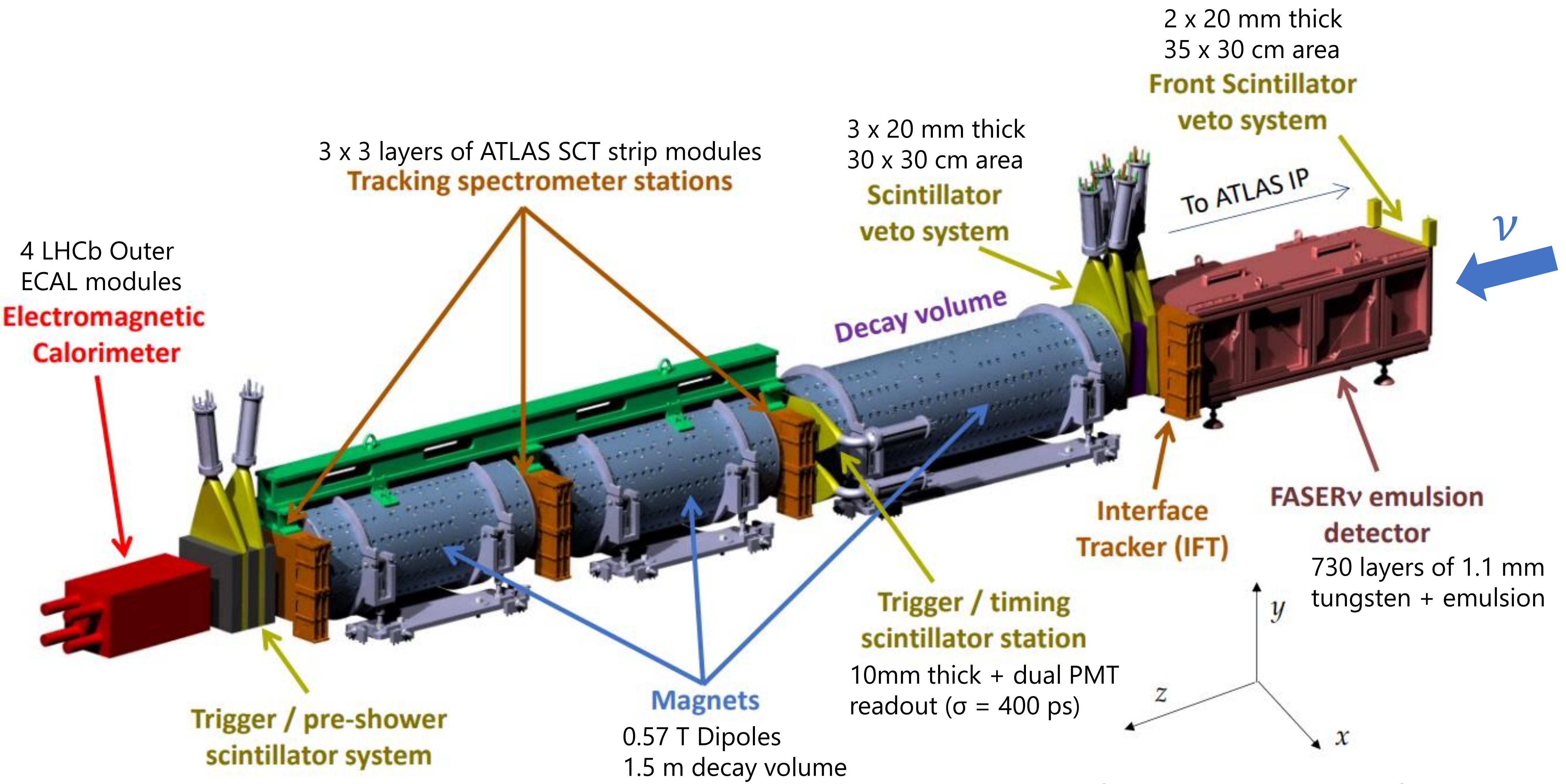
The FASER experiment at the LHC



- **Neutrino measurement in the unexplored TeV region and search for long-lived BSM particles** (LLPs)
- Located on 480 m downstream of ATLAS interaction point
- Low background environment
  - Charged particles are bent by LHC magnets
  - Neutral hadrons are absorbed by 100 m of rocks

FASER at TI12 tunnel

FASER detector



Length ~7 m

Performance highlights from FASER

- Talked by Oscar on 6th May

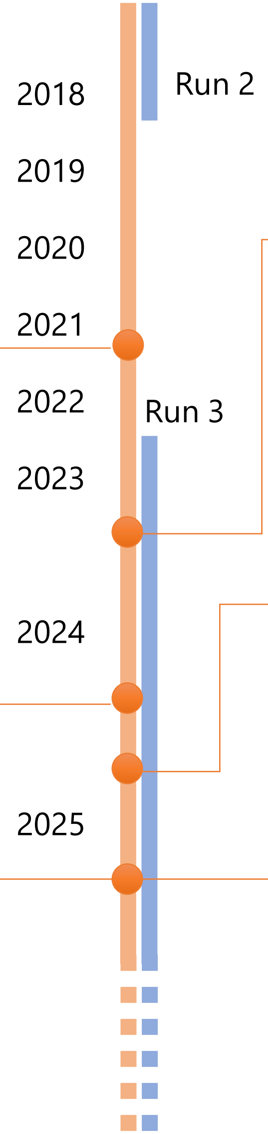
Neutrino results from the FASER experiment

Emulsion detector

- Neutrino candidates with Run2 data
  - PhysRevD.104.L091101
- First ν_e, ν_μ cross section measurements
  - PhysRevLett.133.021802
  - PRL editor’s suggestion
  - Selected PRL Collection of the Year in 2024
  - Nature Research Highlights
- Update with increased statistics
  - CERN-FASER-CONF-2025-002

New

105 fb^{-1} data collected so far



Electronic detector

- Neutrino detection with 2022 data
  - PhysRevLett.131.031801
  - PRL editor’s suggestion

New

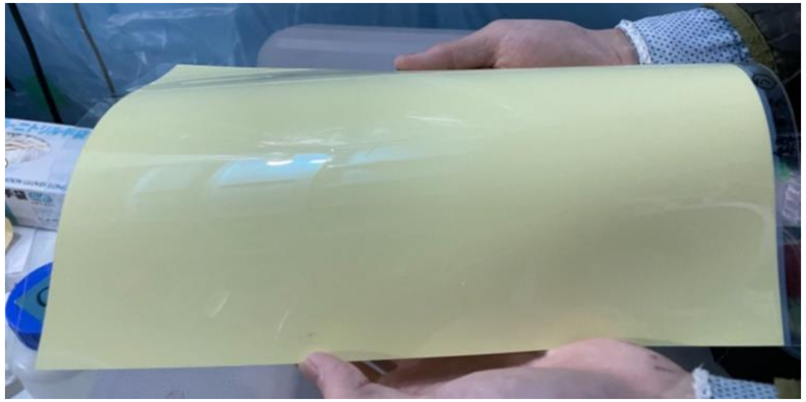
- Differential ν_μ cross section and flux measurements with 2022-23 data
  - arXiv:2412.03186 to appear in PRL
- Neutrino rapidity measurements with 2022-23 data
  - CERN-FASER-CONF-2025-001

New

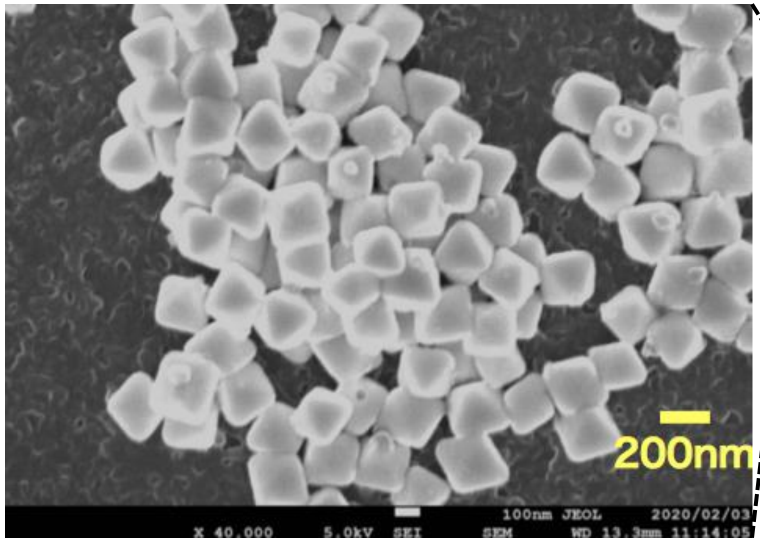
190 fb^{-1} data collected so far

Emulsion detector

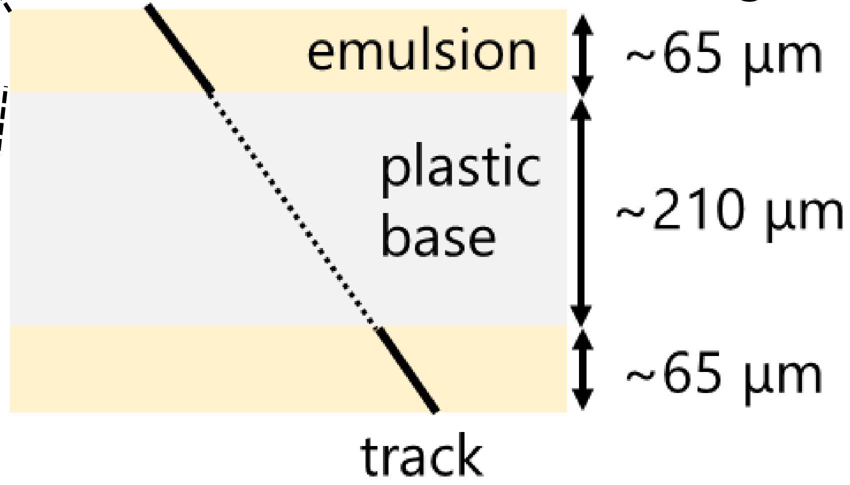
Emulsion films produced in Japan
(30 x 25 cm^2 in FASER)



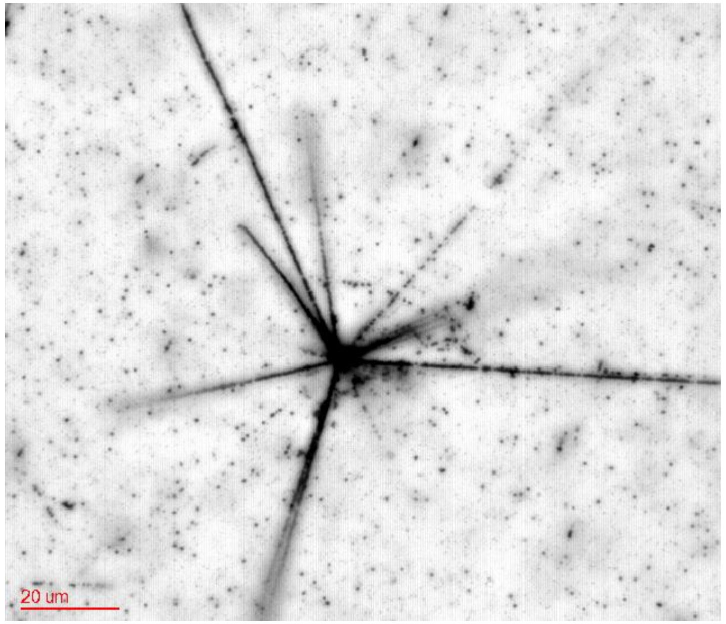
Silver bromide crystals



Double-sided emulsion coating



e.g. Anti-proton annihilation



- 200 nm diameter silver bromide crystals dispersed in gelatin
- O(100) nm position resolution can be achieved

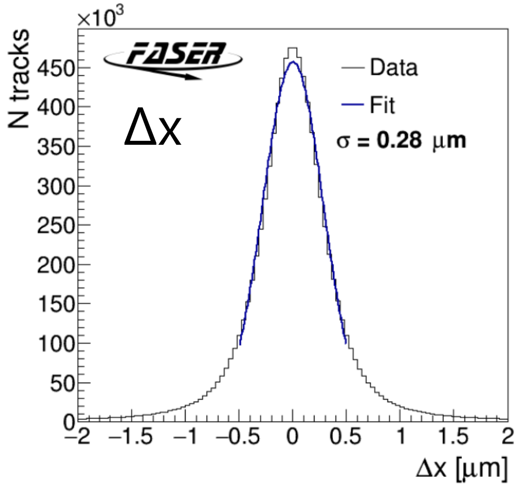
FASERν emulsion detector

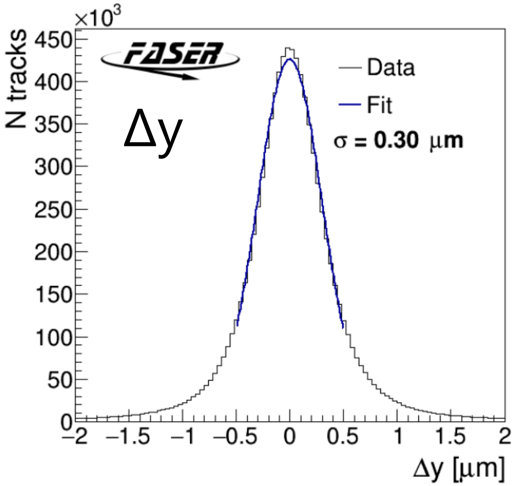
- Layered structure of 730 emulsion films and tungsten plates (1.1 mm thick)
- 25 x 30 cm², 1.1 m, 1.1 tons (8 λ_{int}, 220 X_0)
- Exchange emulsions ~3 times a year

PhysRevD.110.012009

~10000 neutrino interactions

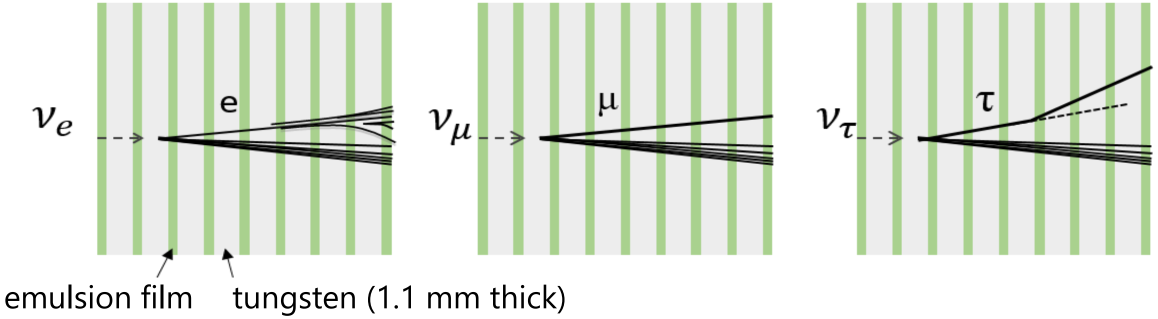
Run3, 250 fb^{-1}	ν_e	ν_μ	ν_τ
Expected CC interactions in FASERν	1675	8507	28



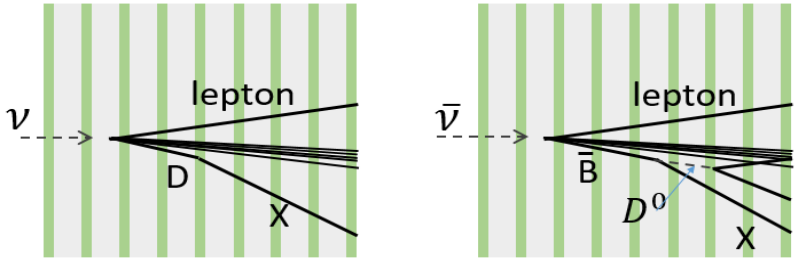


0.3 μm position resolution

ν flavor tagging with topological/kinematical information

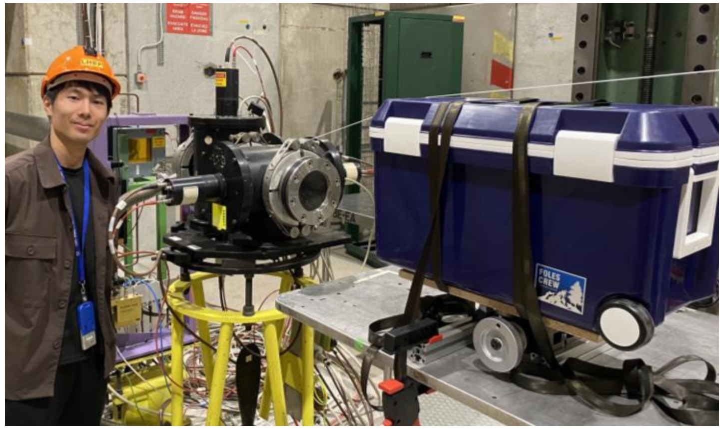


Short-lived particle search: c, b quarks

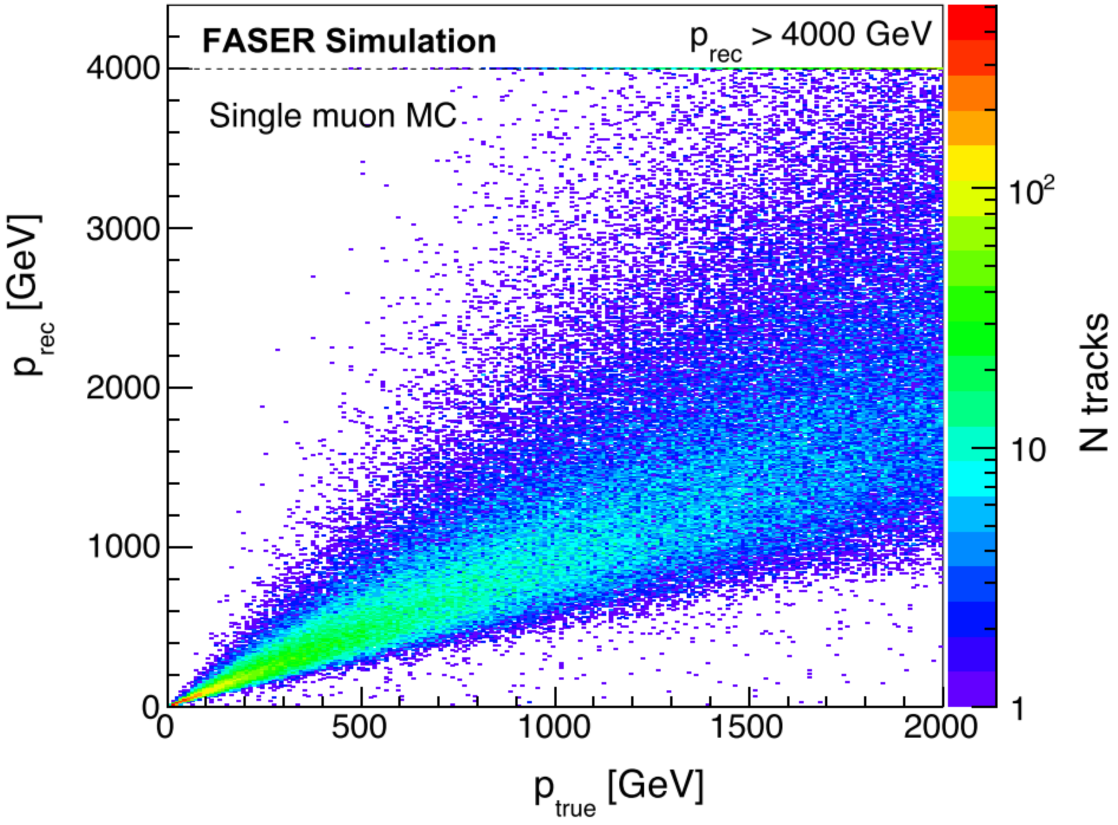


Kinematical tools: Muon momentum measurement

- p_μ > 200 GeV is required for ν_μ event selection
- Based on multiple Coulomb scattering of charged particle
  - Taking advantage of 0.3 μm position resolution

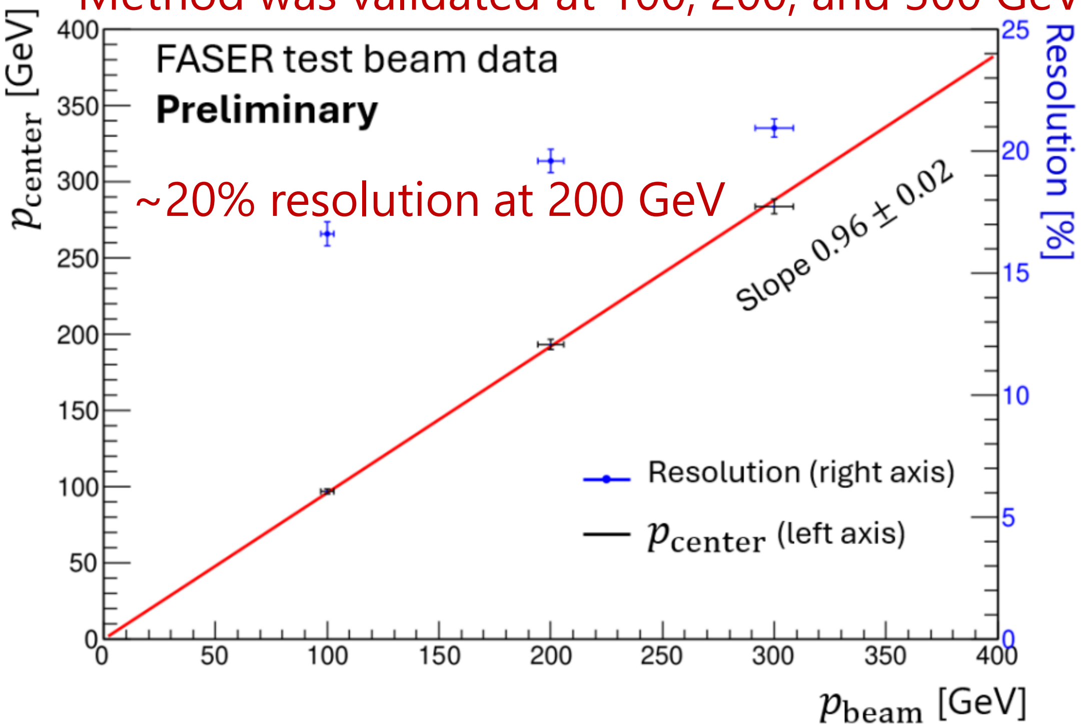


Good linearity even above 1 TeV



Test beam at SPS(H8 beamline) in 2024

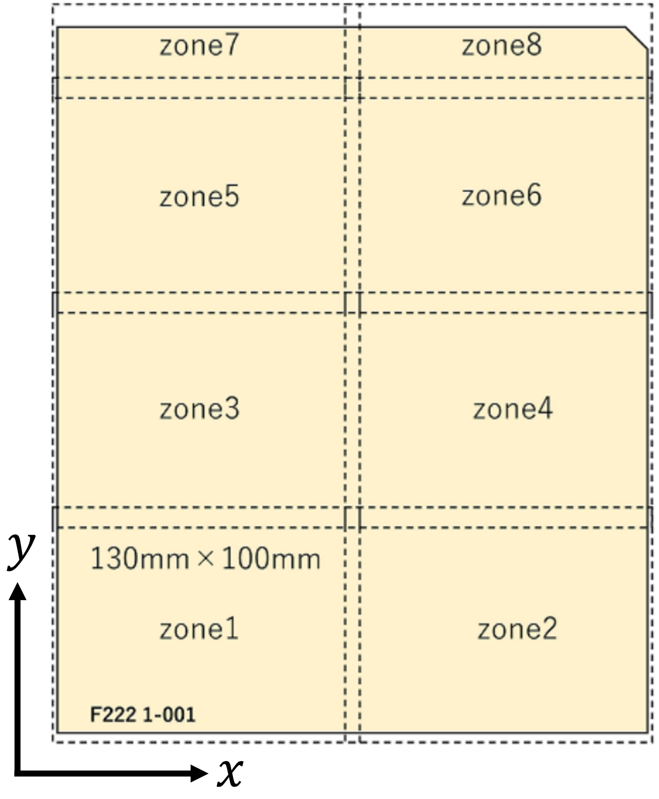
Method was validated at 100, 200, and 300 GeV



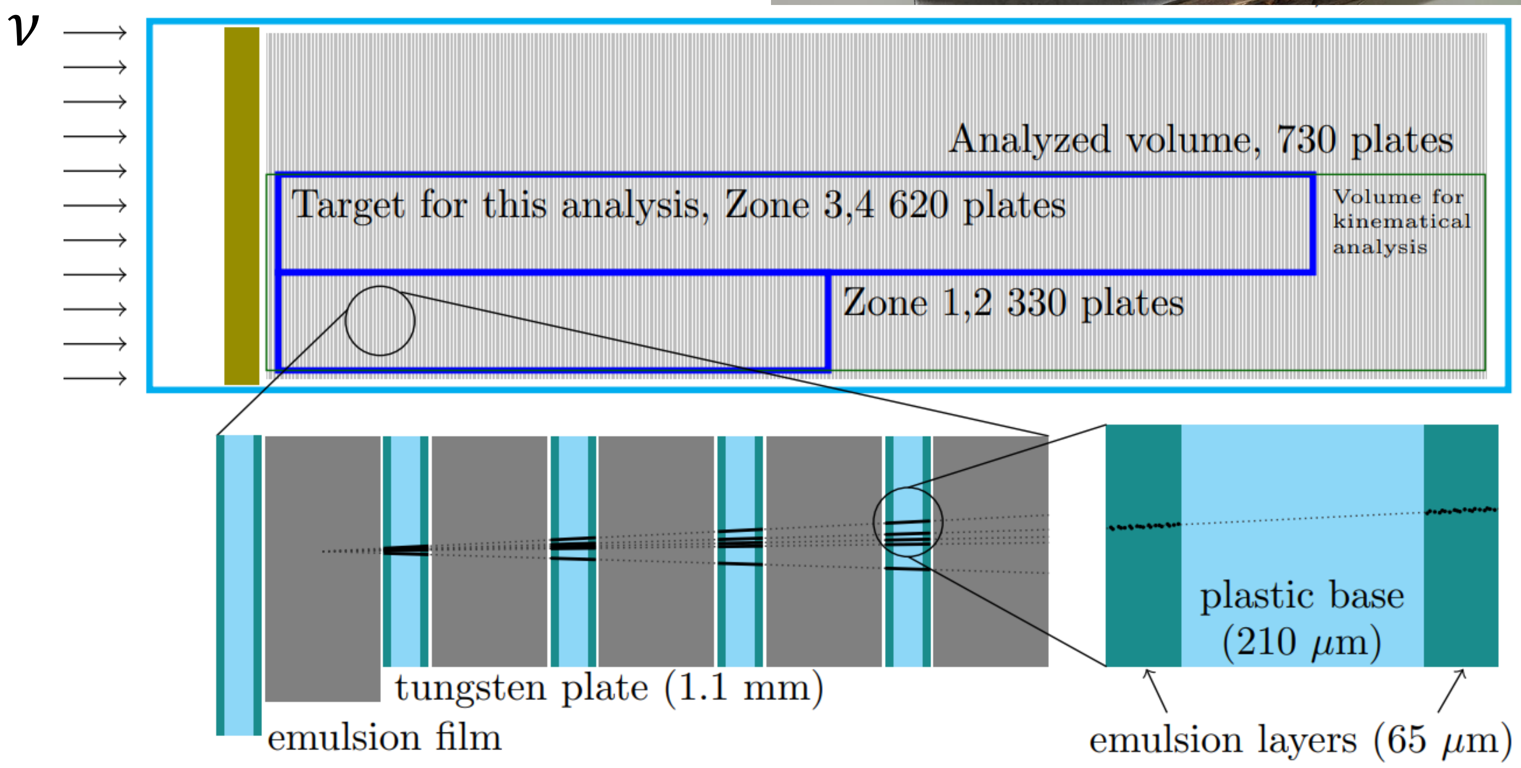
Dataset for the latest analysis

- 9.5 fb^{-1} in 2022 run
- Analyzed target mass is 314.7 kg

Emulsion film



FASERν emulsion detector

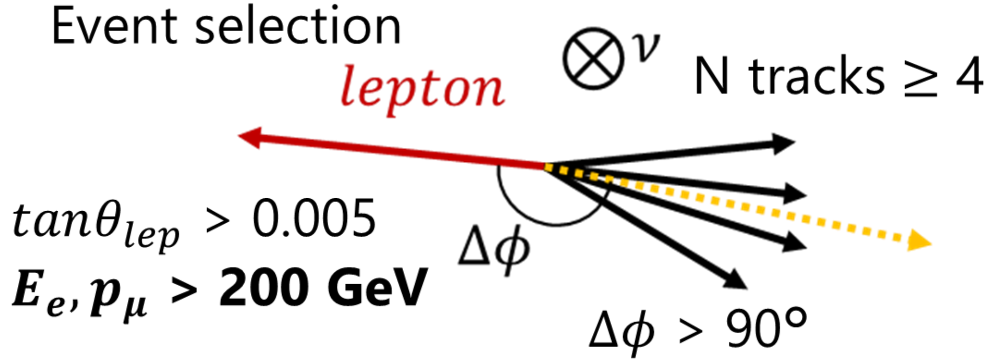


Neutrino event selections and results

- Strategy
  - Search for neutral vertex
- Signal: Neutrino interaction
- Background: Neutral hadron interaction

→ Suppressed by topological and kinematical selections

Event selection



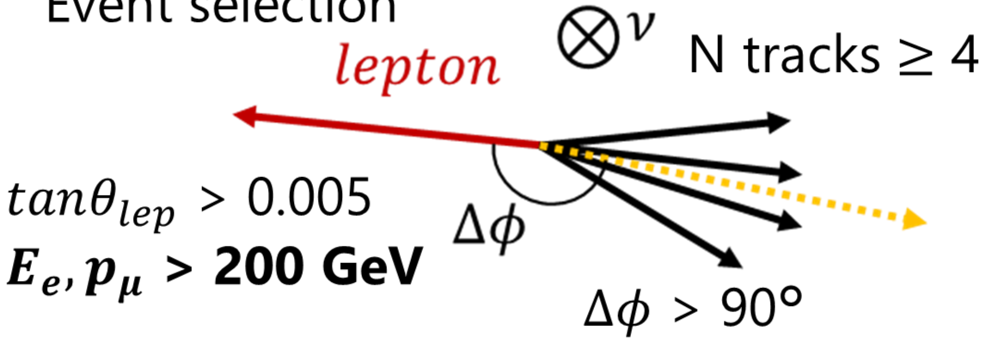
Note: E_e ~25% resolution at 200 GeV from the simulation

Neutrino event selections and results

- Strategy
    - Search for neutral vertex
- Signal: Neutrino interaction
- Background: Neutral hadron interaction

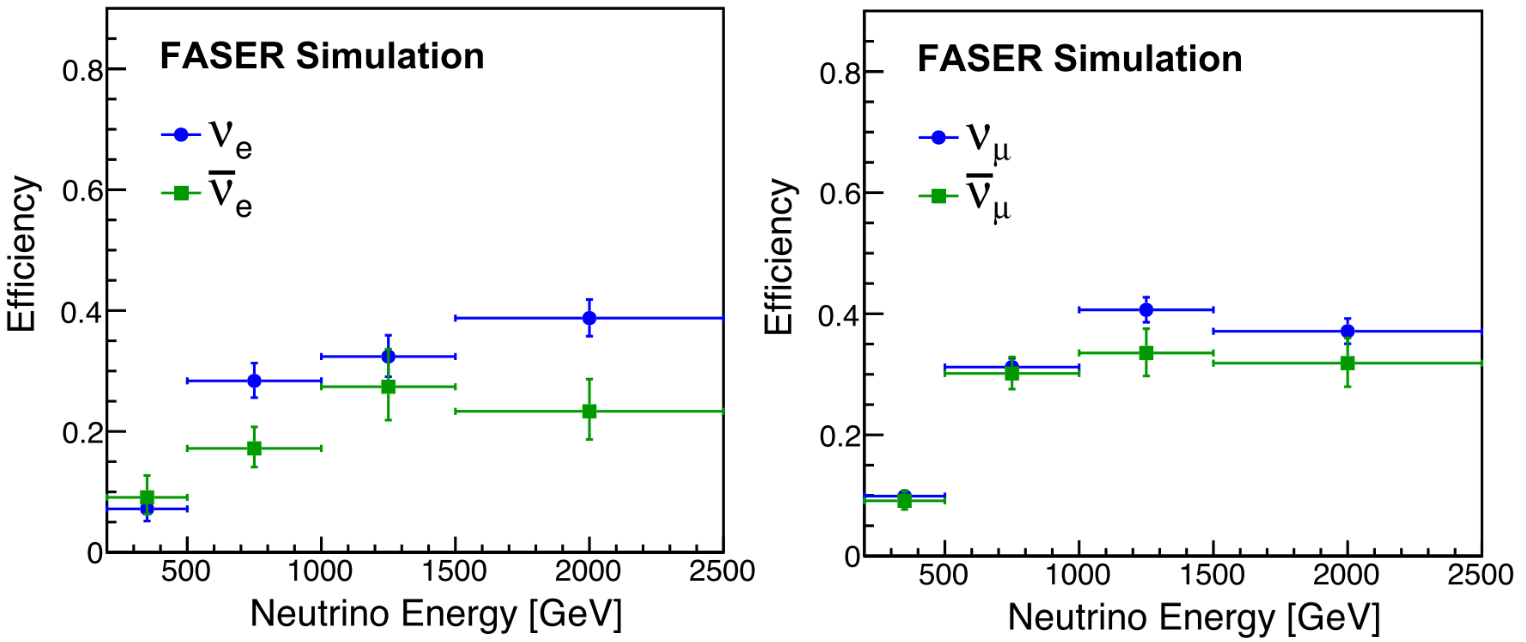
→ Suppressed by topological and kinematical selections

Event selection



Note: E_e ~25% resolution at 200 GeV from the simulation

Neutrino detection efficiency as a function of neutrino energy

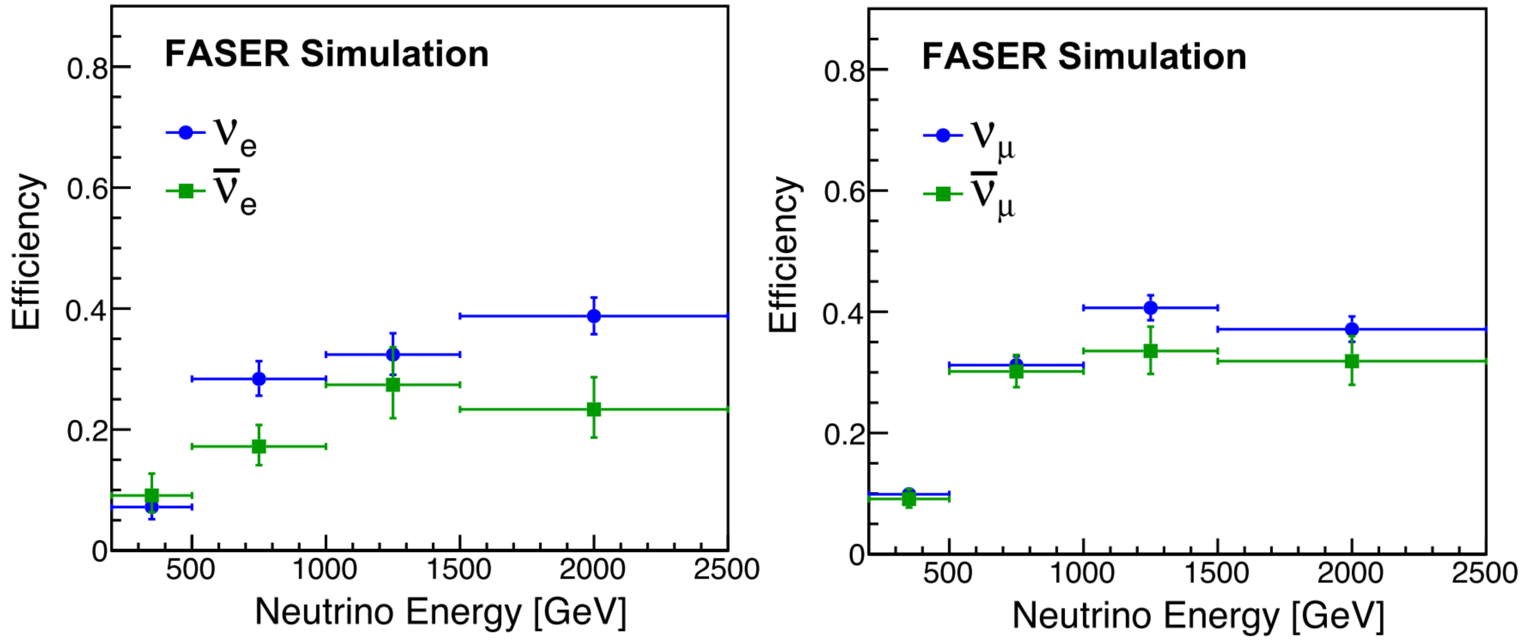


Neutrino event selections and results

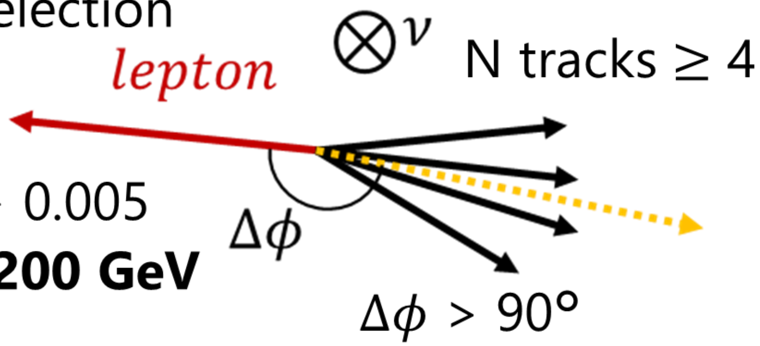
- Strategy
  - Search for neutral vertex
- Signal: Neutrino interaction
- Background: Neutral hadron interaction

→ Suppressed by topological and kinematical selections

Neutrino detection efficiency as a function of neutrino energy



Event selection



$tan\theta_{lep}$ > 0.005

$\boldsymbol{E_e, p_\mu}$ **> 200 GeV**

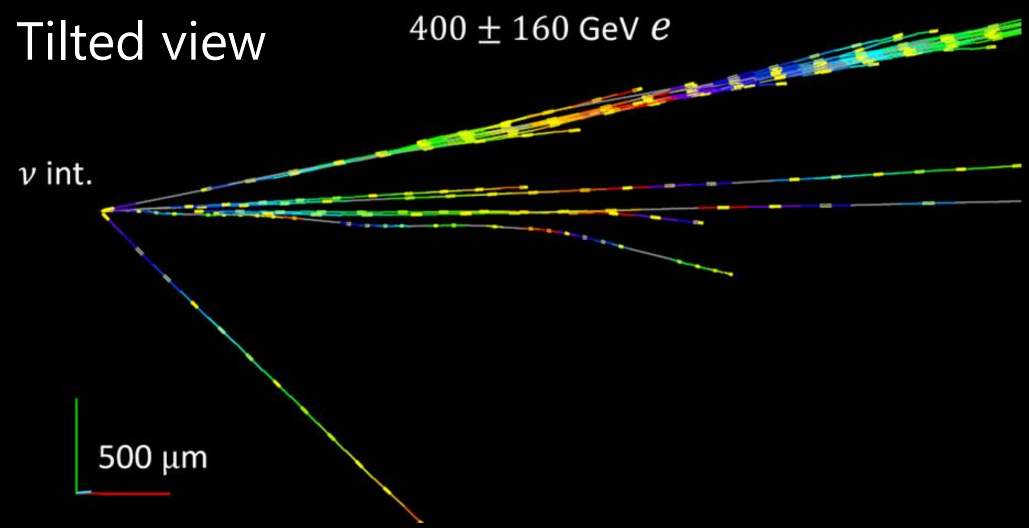
Note: E_e ~25% resolution at 200 GeV from the simulation

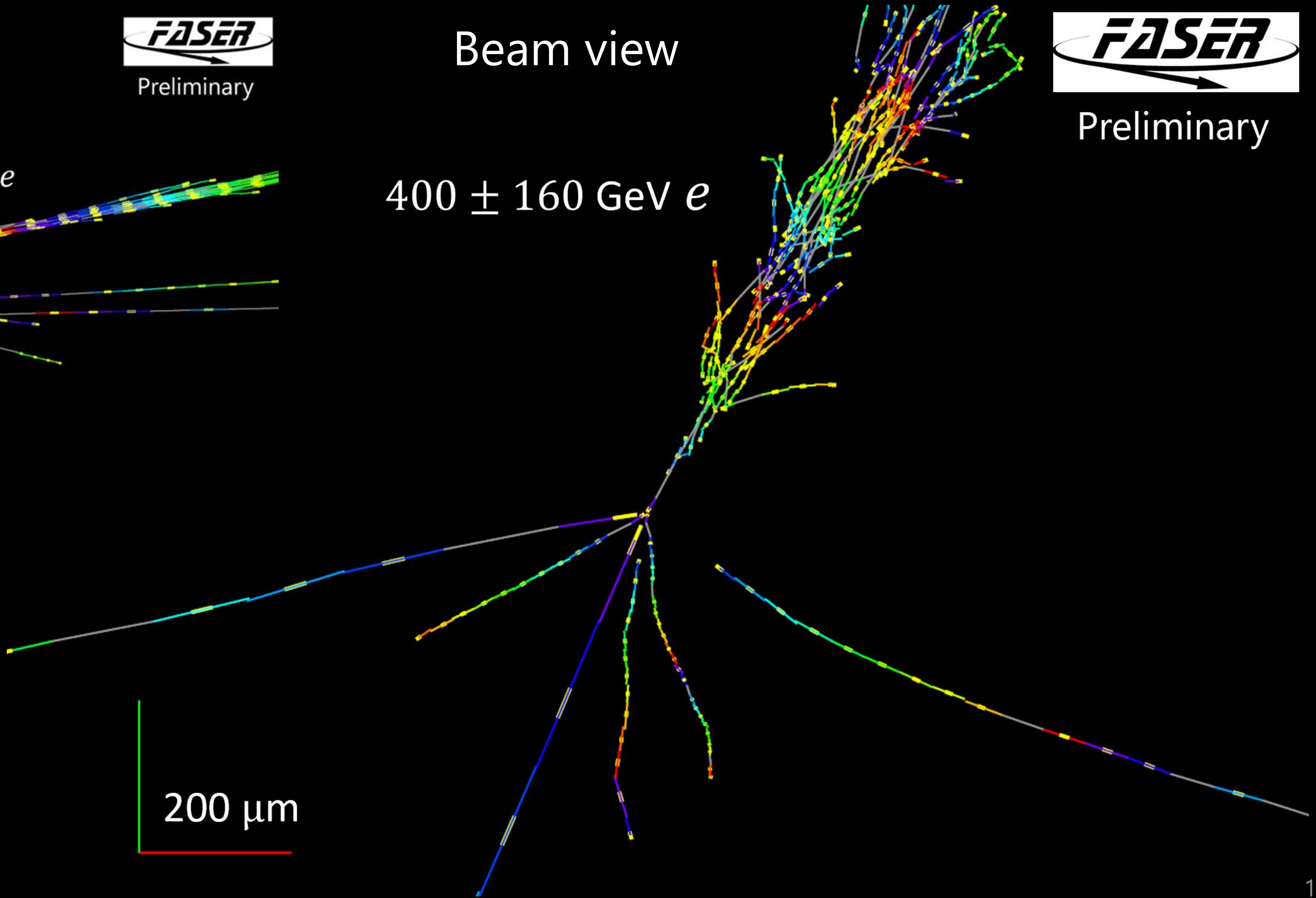
Preliminary results with ~300 kg x 9.5 fb^{-1} data

	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

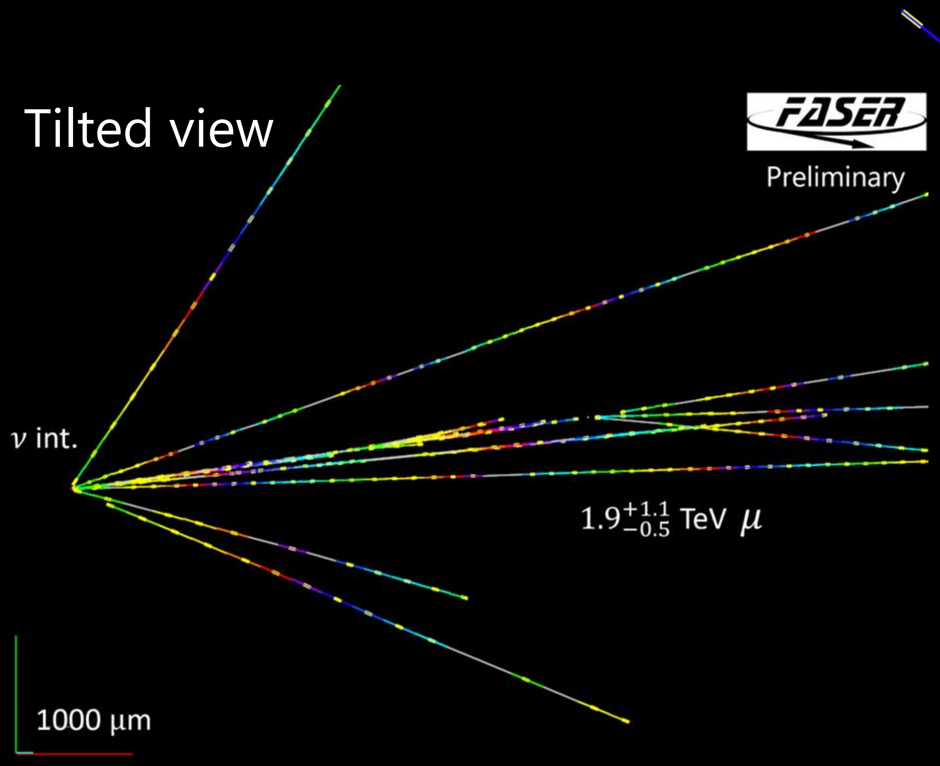
CERN-FASER-CONF-2025-002

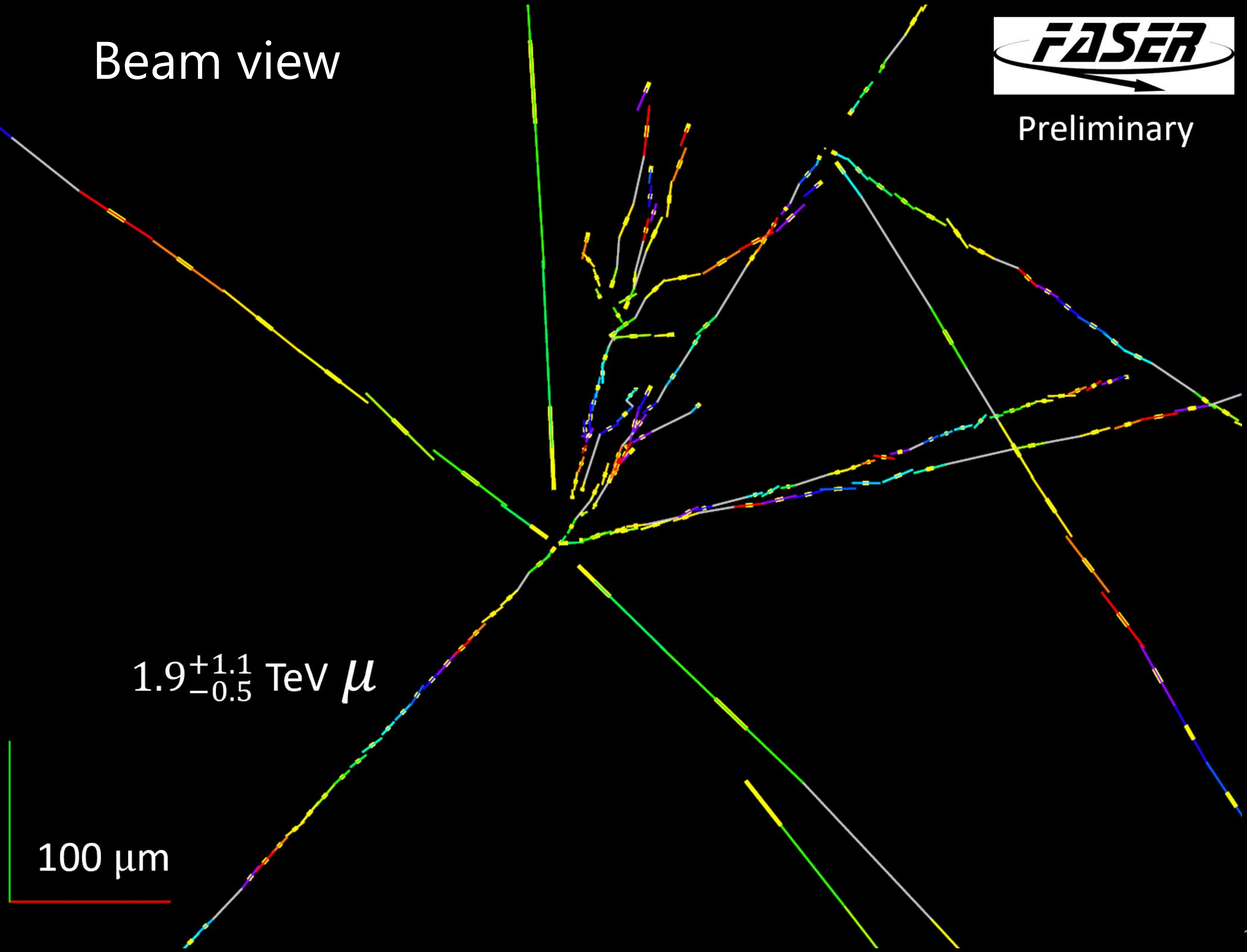
Event display of new ν_e event candidate



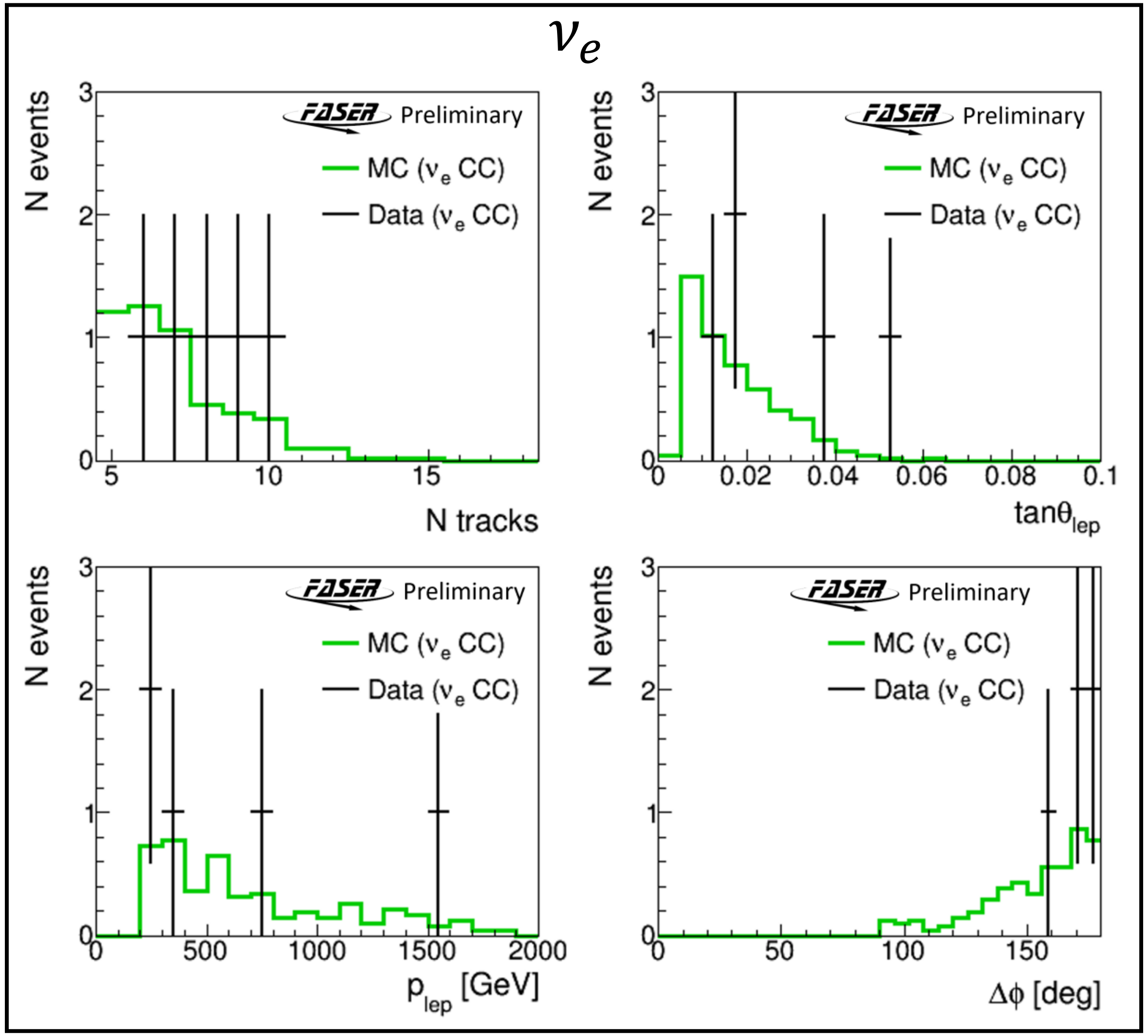


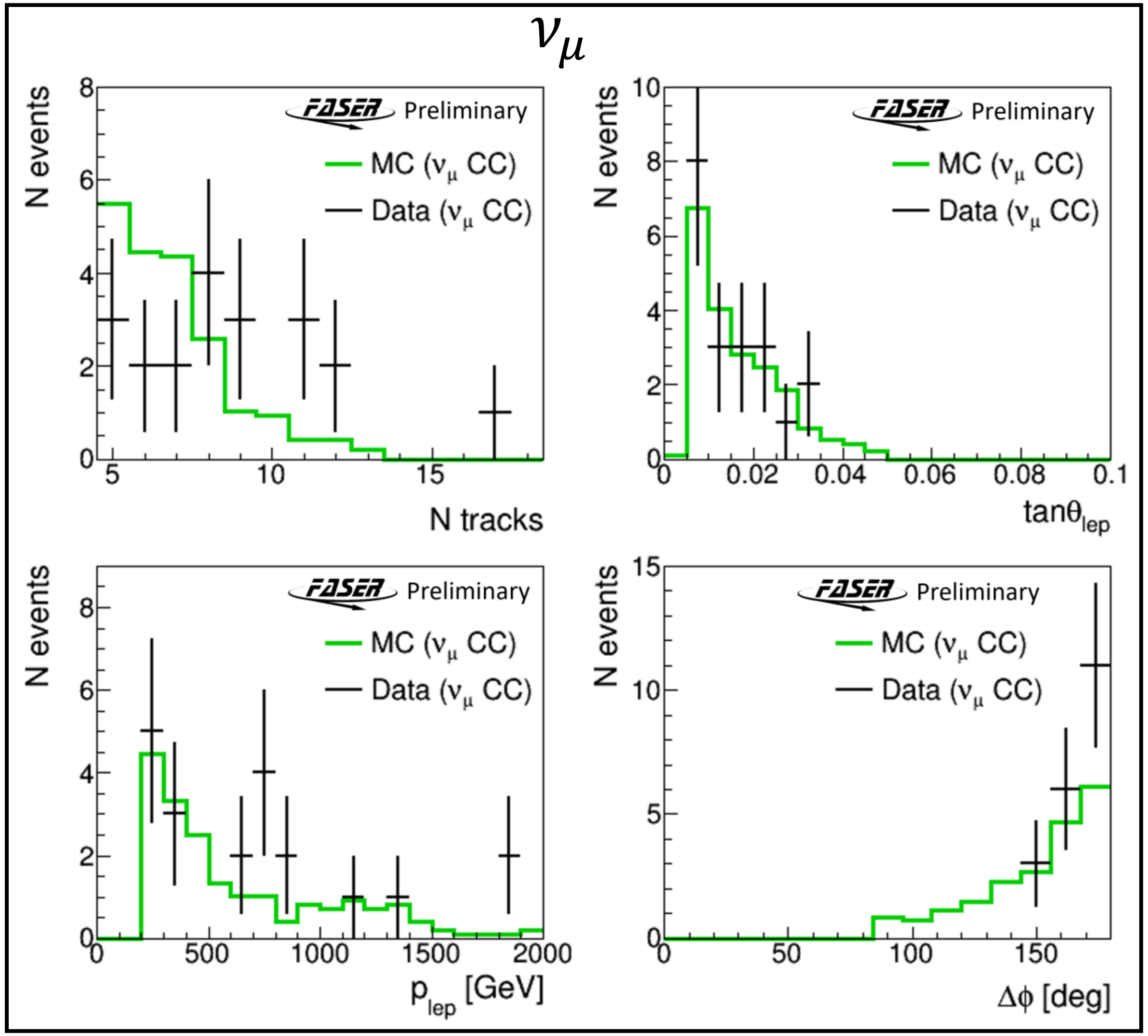
Event display of new ν_μ event candidate





Neutrino event characteristics



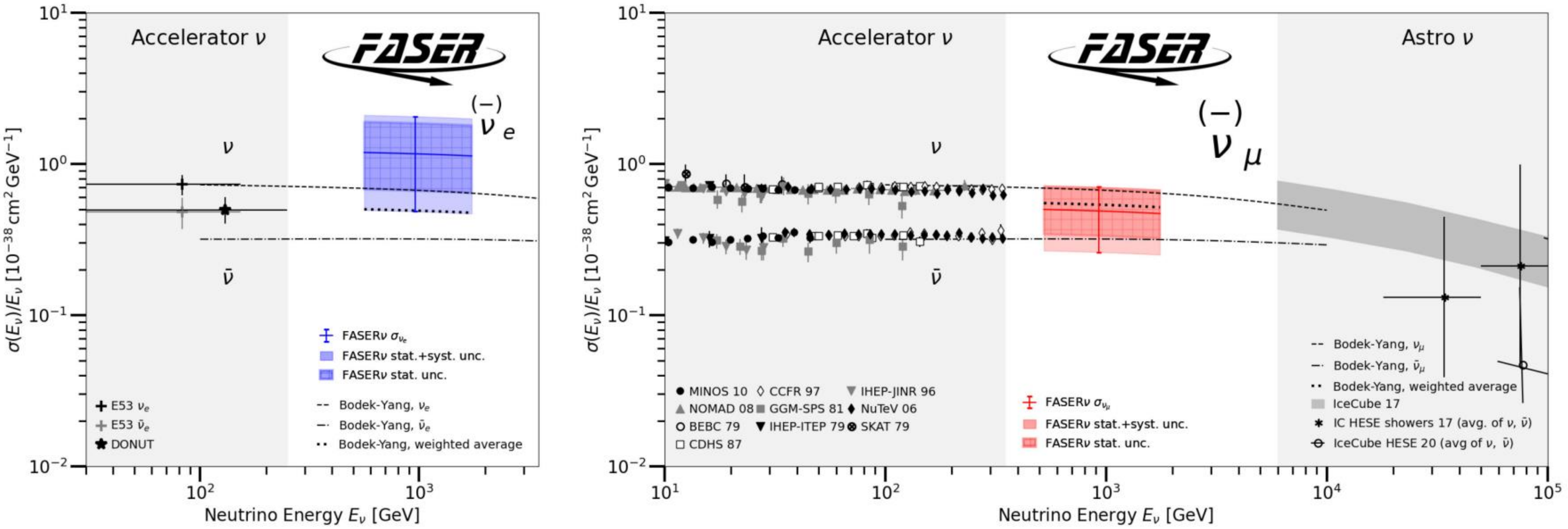


- Characteristics of the observed ν interactions are in good agreement with MC

PhysRevLett.133.021802

Neutrino cross section measurements

- First measurement of ν_e and ν_μ cross sections in TeV energy region (128.6 kg x 9.5 fb^{-1})

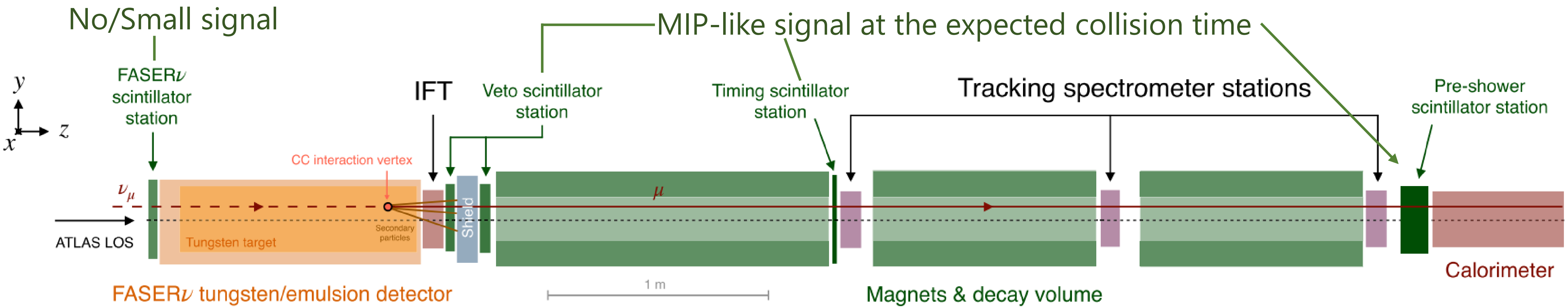


- Working on a differential cross section measurement with the full 1.1 tons detector volume for 9.5 fb^{-1} data

arXiv:2412.03186

ν_μ measurement with the FASER electronic detector

- Strategy
  - Use the FASERν detector only as target for neutrino interaction
  - Reconstruct muon tracks with spectrometer
- Data set: 65.6 fb^{-1} collected in 2022-23



- At least 1 good fiducial (r < 95 mm) track
  - p_μ > 100 GeV and θ_μ < 25 mrad
  - Extrapolating to r < 120 mm in front veto

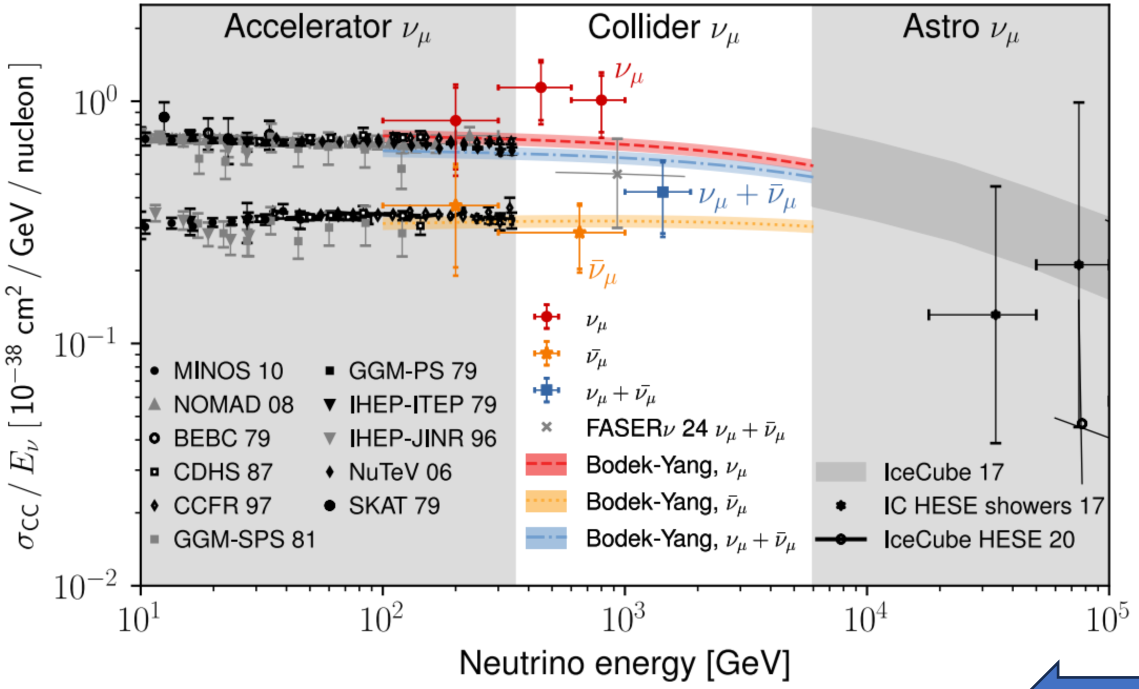
→ Negligible background from non-neutrino interactions

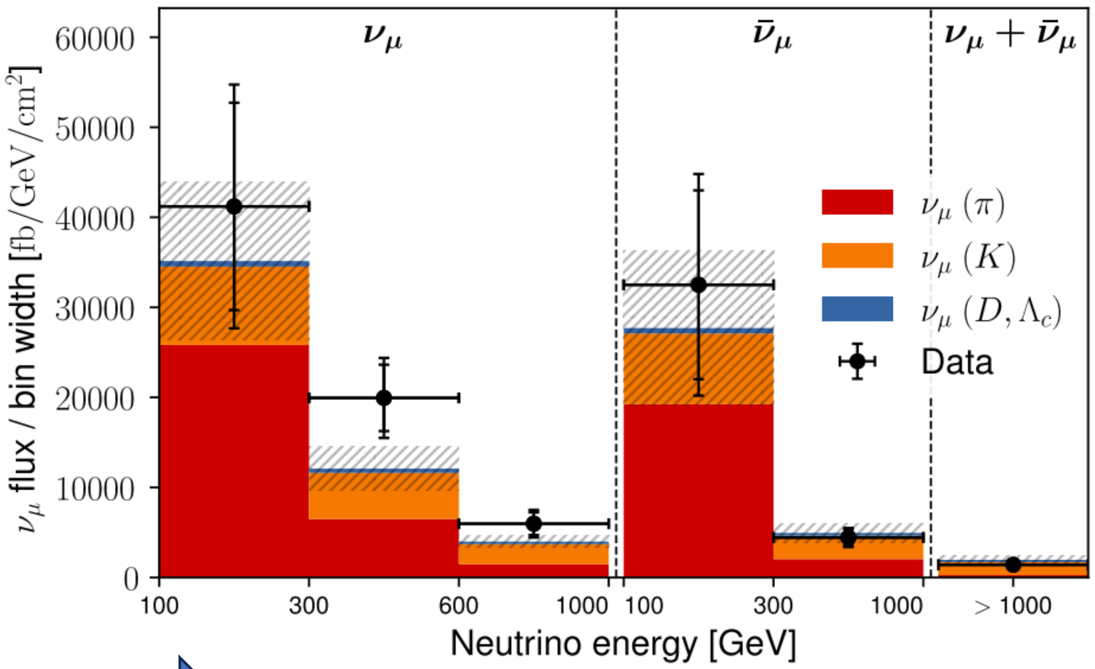
First differential ν_μ cross section and flux measurements

- $n_\nu^{obs} = 338.1 \pm 21.0$ events after the expected BG subtraction

(cf. $n_\nu^{exp} = 298.4 \pm 42.6$ events from GENIE simulation + neutrino flux estimate from PhysRevD.110.012009)

- Muon momentum is unfolded into neutrino energy
  - 3 energy bins for ν_μ, 2 energy bins for $\bar{\nu}_\mu$, 1 high energy bin for $\nu_\mu/\bar{\nu}_\mu$ (deterioration of charge ID)

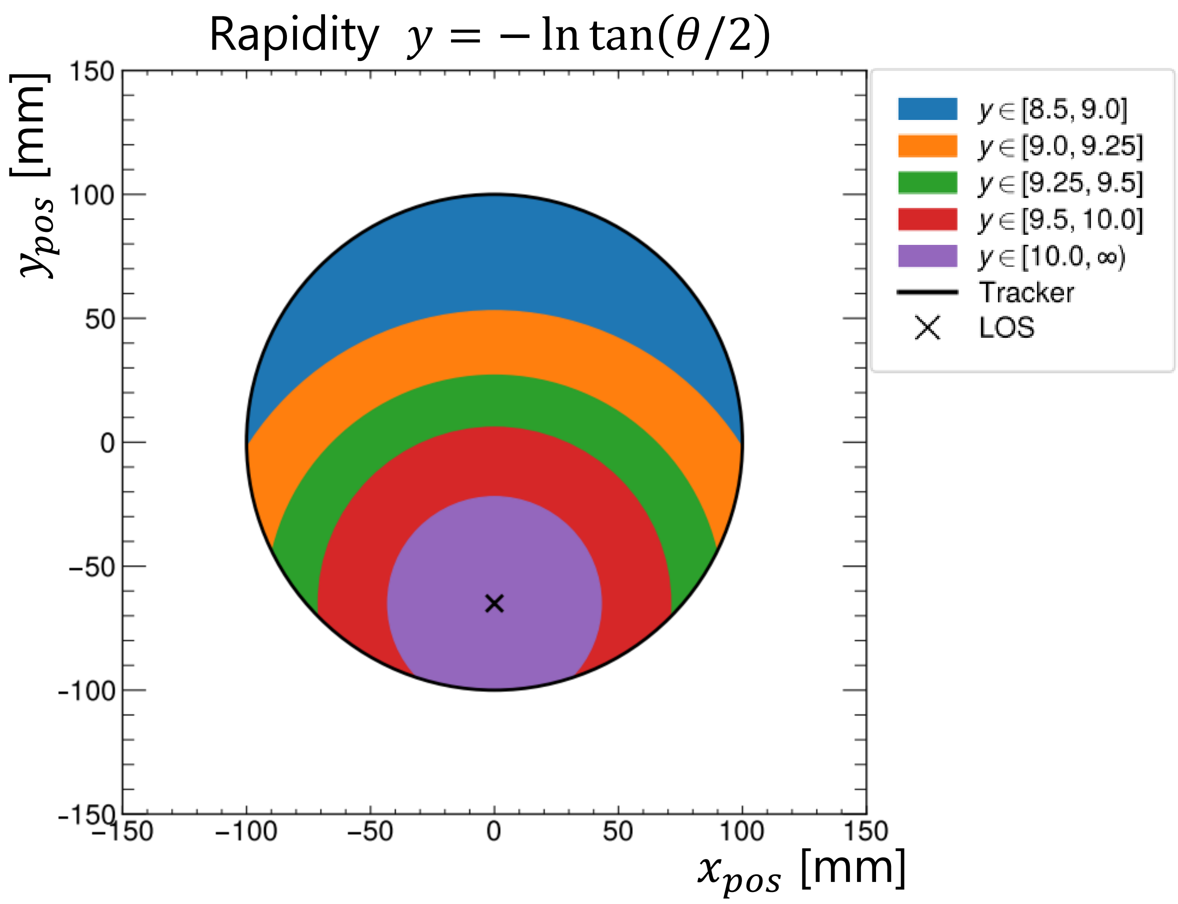


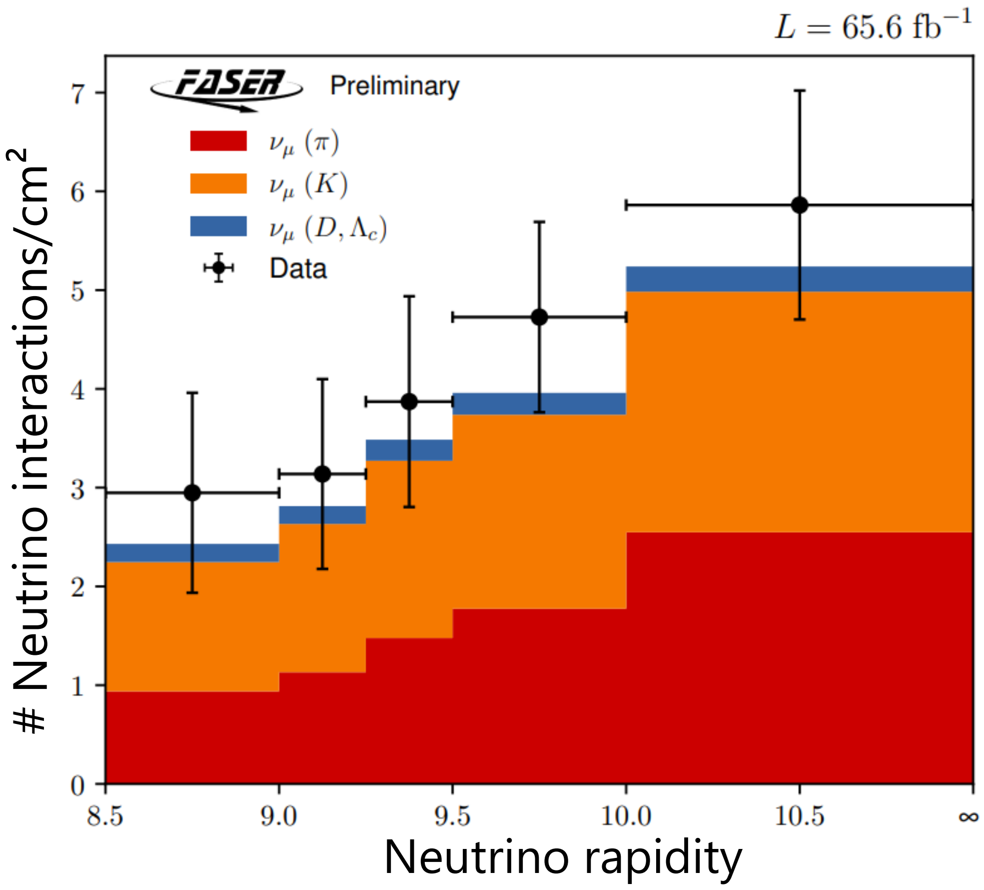


Fixing one using the MC prediction with uncertainty

Neutrino rapidity measurement

- To study the characterization of forward hadron production at the LHC
  - Define five rapidity bins (annular regions) around line of sight (black cross)
  - Rapidity from transverse position of reconstructed μ, then unfolded to ν rapidity





Summary

- FASER studies three generation neutrinos in unexplored TeV energy range and search for new long-lived particles
- FASER is taking data during Run 3 (2022–2026), with about 10,000 neutrino interactions expected
- FASERν emulsion detector
  - First ν_e and ν_μ cross section measurements with ~130 kg x 9.5 fb^{-1} data
  - 5 ν_e and 20 ν_μ events have been observed analyzing ~300 kg x 9.5 fb^{-1} data
  - Working on a differential cross section measurement with the full 1.1 tons detector volume for 9.5 fb^{-1}
- FASER electronic detector
  - First measurement of differential ν_μ cross section and flux with 65.6 fb^{-1} data
  - The results is also studied in terms of neutrino rapidity

Future prospects

- Discussing extended physics programs in FASER2 and FASERν2 at FPF and in FASER at Run4

Other talks

Performance highlights from FASER
- Talked by Oscar on 6th May
- Performance and Upgrade Tools session

FASER status and prospects
- Talked by Shih-Chieh on 9th May
- Future Projects session

BACK UP

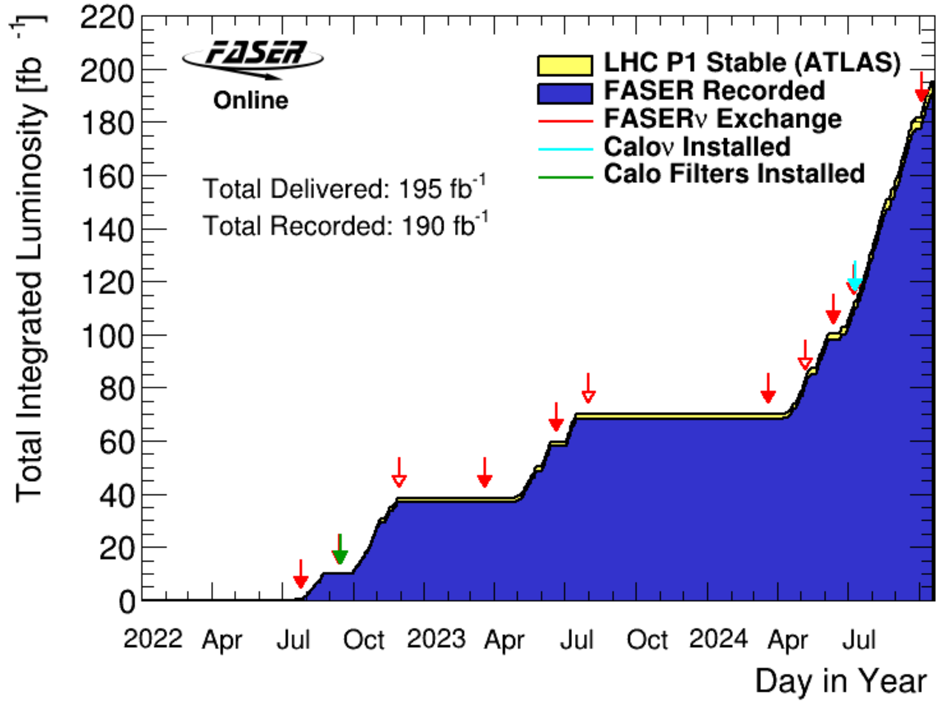
FASER COLLABORATION

107 collaborators, 27 institutions, 11 countries

International laboratory covered by a cooperation agreement with CERN

Data taking in LHC-Run3

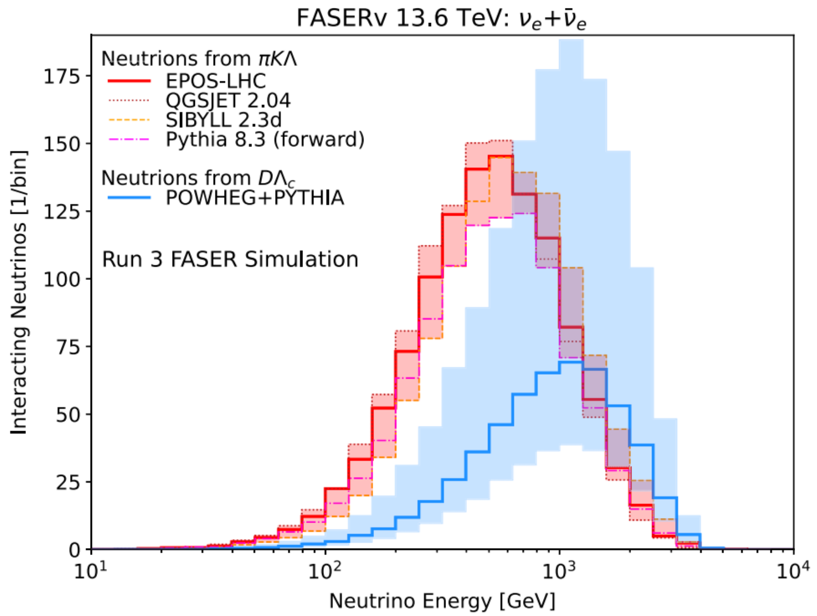
- The experiment has been successfully operating since data taking began in 2022
  - Excellent detector performance: >97% data-taking efficiency
    - Average physics trigger rates of 2 kHz in 2024
  - Total recorded 190 fb^{-1} so far
    - 35 fb^{-1} in 2022
    - 33 fb^{-1} in 2023
    - 122 fb^{-1} in 2024
  - 8 FASERν emulsion detector has been exposed
    - Receiving ~105 fb^{-1} of data
    - Limited data taking due to high muon flux in 2024

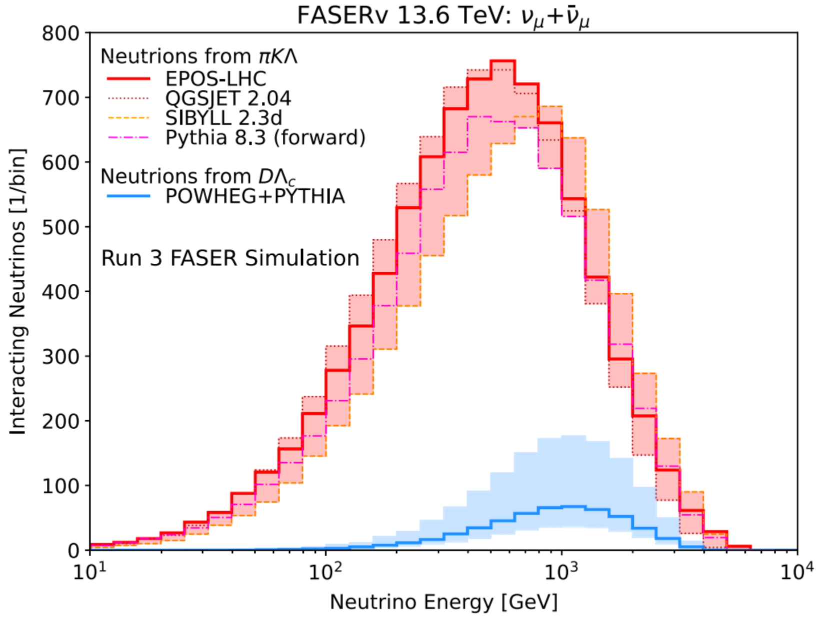


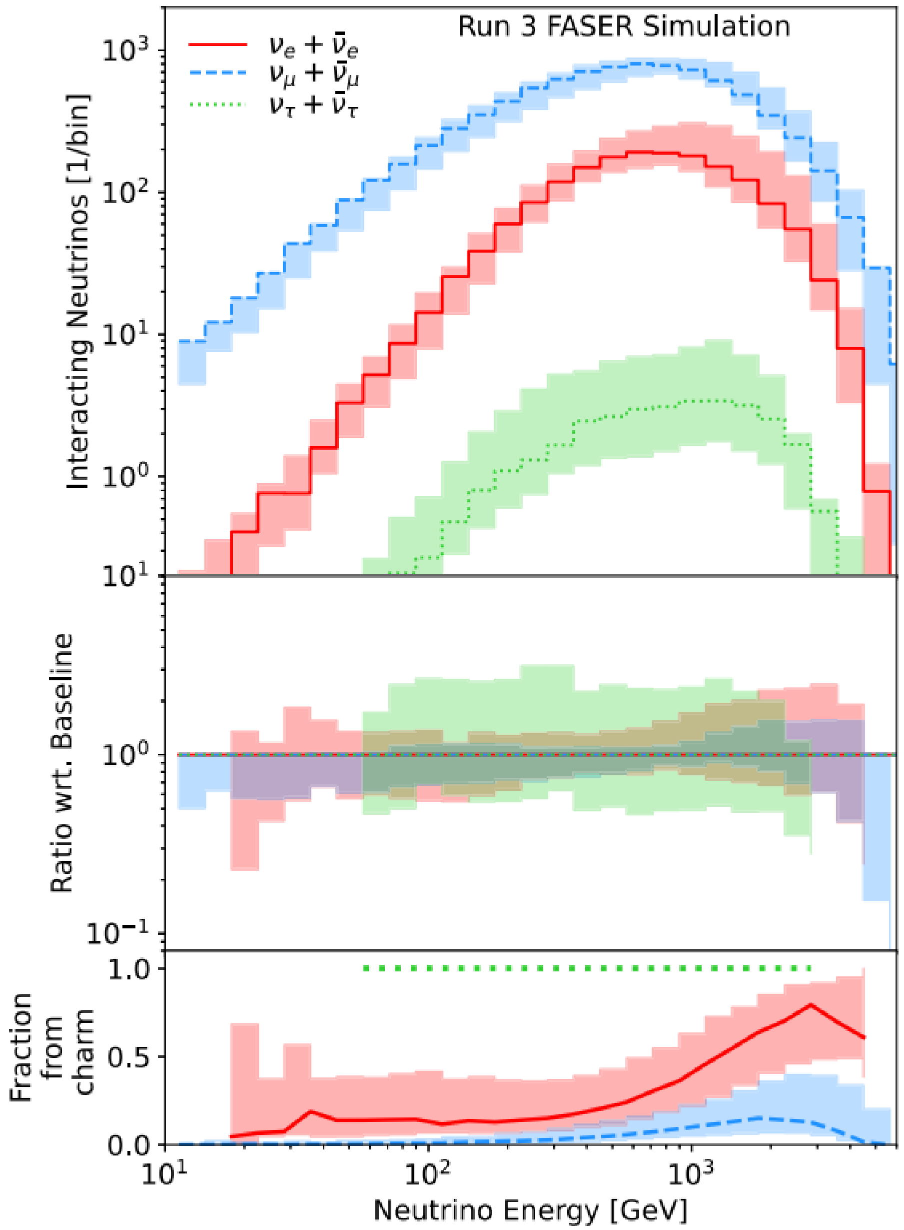

CMU 2t
CMU 2t
2t
FASERν
IFT
Veto
Decay volume
Tracking spectrometer
Pre-shower
Calorimeter
FASERν installation
3 times / year

PhysRevD.110.012009

Neutrino rate predictions in FASER





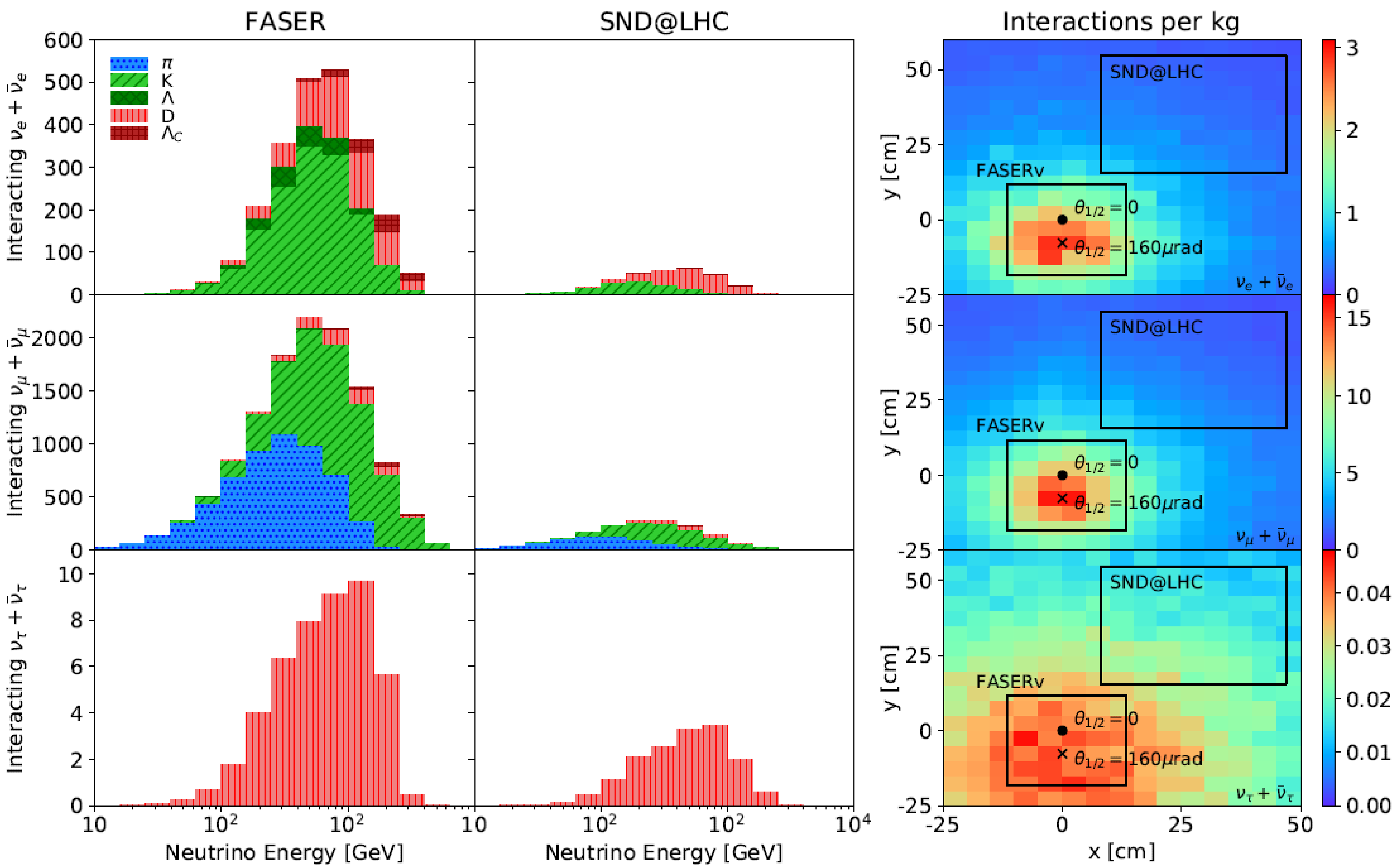


Neutrino rate comparison between FASER and SND@LHC

$\nu_e + \bar{\nu}_e$

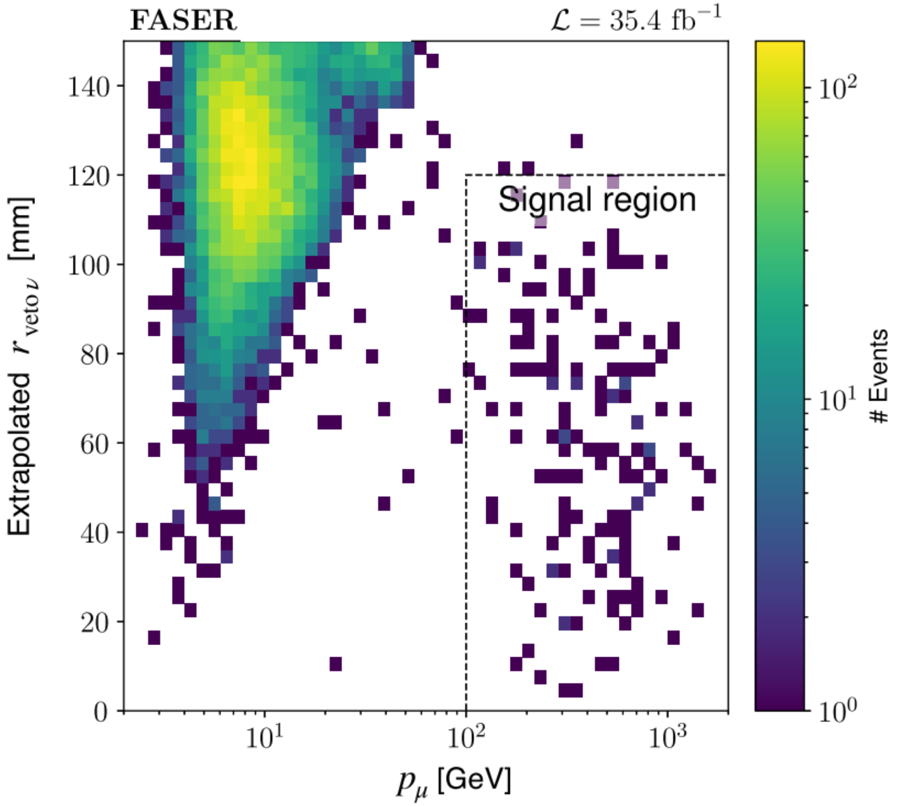
$\nu_\mu + \bar{\nu}_\mu$

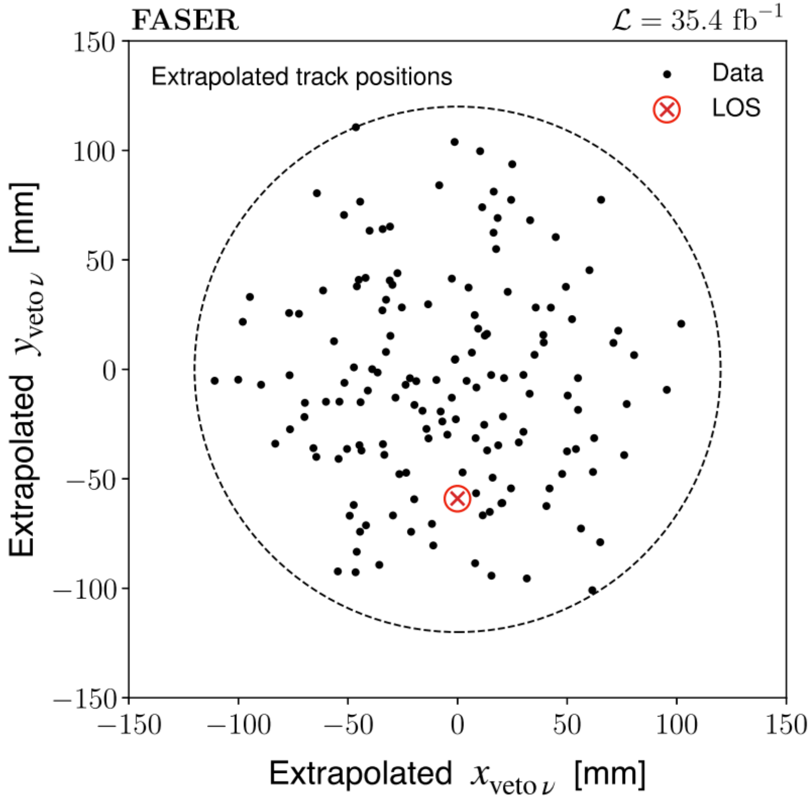
$\nu_\tau + \bar{\nu}_\tau$



PhysRevLett.131.031801

First direct observation of collider neutrinos





Category	Events
Signal	153
n_{10}	4
n_{01}	6
n_2	64014653

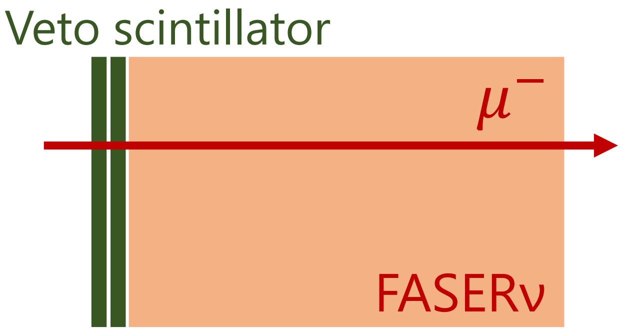
$$\mathcal{L} = \prod_i \mathcal{P}(N_i | n_i) \cdot \prod_j \mathcal{G}_j$$

Likelihood fit with four event categories and three gaussian priors

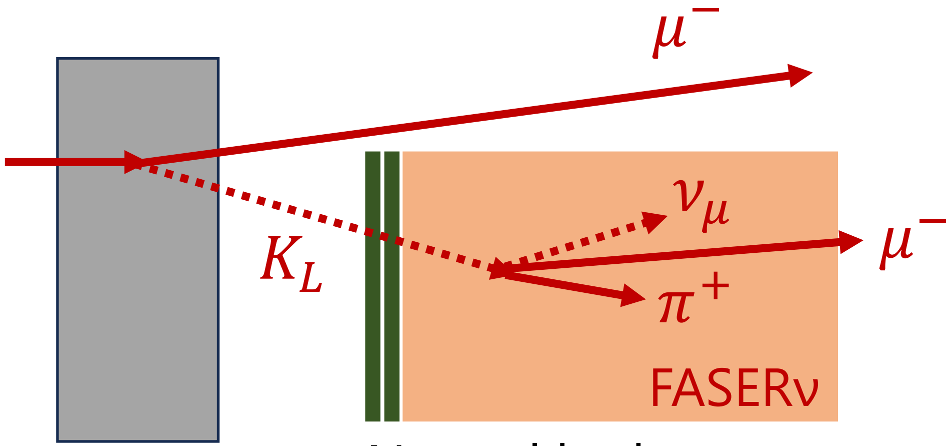
- Observed 153^{+12}_{-13} events (151±41 events expected)
- Signal significance of 16σ

[arXiv:2412.03186](https://arxiv.org/abs/2412.03186)

Background estimation

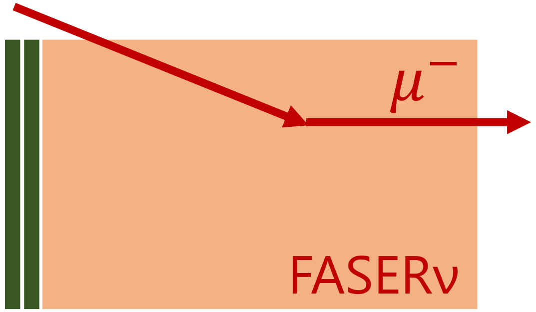


Veto inefficiency



concrete

Neutral hadrons



Scattered muons

- Estimate based on data comparing hit differences in first and second veto layers

Negligible: <10^{-6} undetected muons (65.6 fb^{-1})

- Estimate based on MC simulation
- Most hadrons absorbed in FASERν tungsten plates
- Parent muon often hitting veto

Estimate: **<0.001 events** (65.6 fb^{-1})

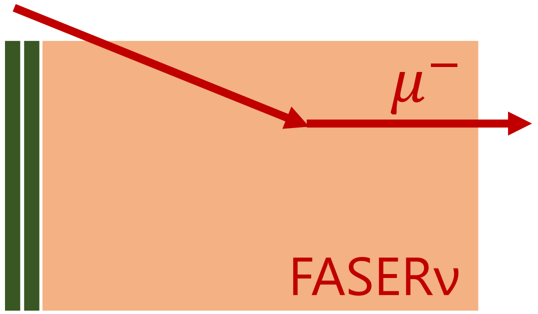
- Data-driven estimate from low-p_μ sideband (p_μ < 100 GeV)
- Contribution from neutrino events was subtracted using MC and extrapolated to signal region

Estimate: **0.2 ± 0.6 events** (65.6 fb^{-1})

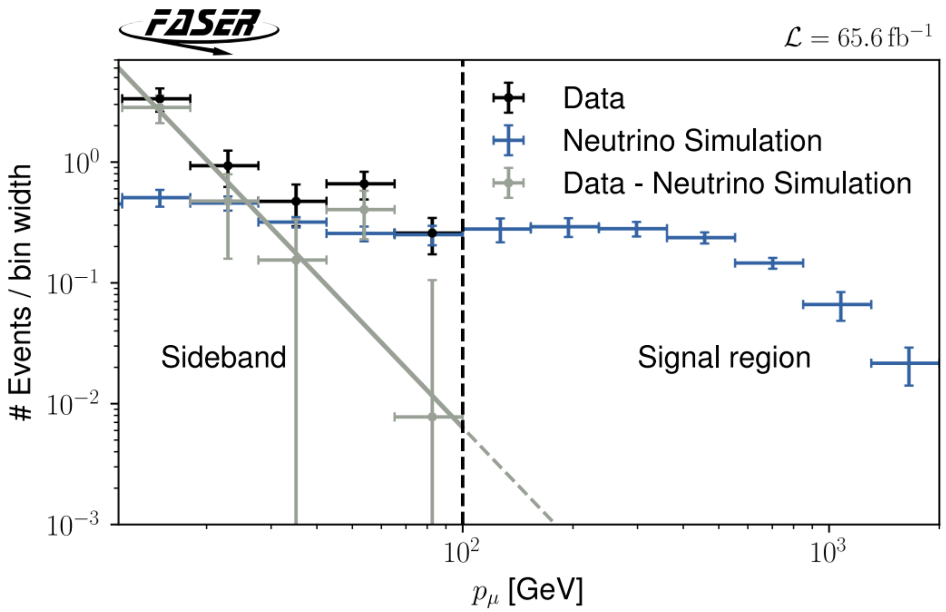
Main background is from non-fiducial ν_μ CC interactions, or non ν_μ CC neutrino interactions

arXiv:2412.03186

Scattered muons (Geometric background)

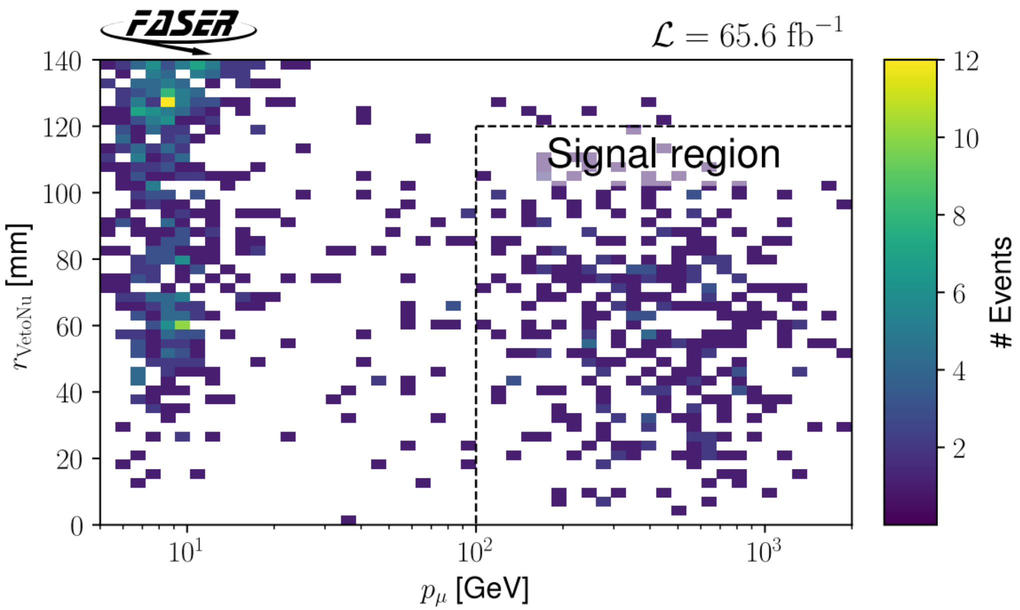


Scattered muons

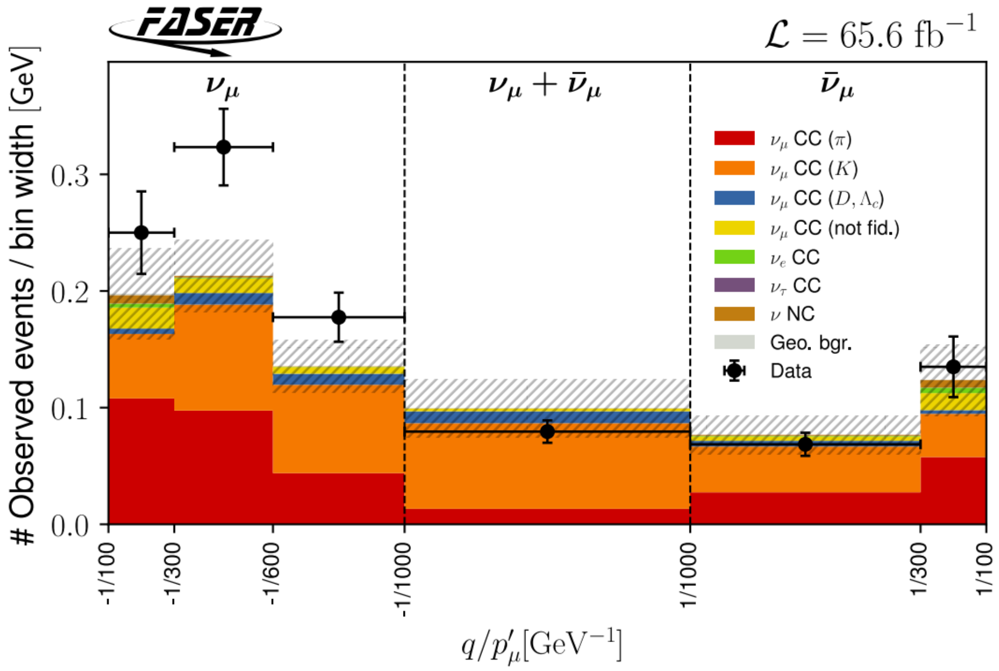


- Data-driven estimate from low-p_μ sideband (p_μ < 100 GeV)
- Contribution from neutrino events was subtracted using MC and extrapolated to signal region

Estimate: **0.2 ± 0.6 events** (65.6 fb^{-1})

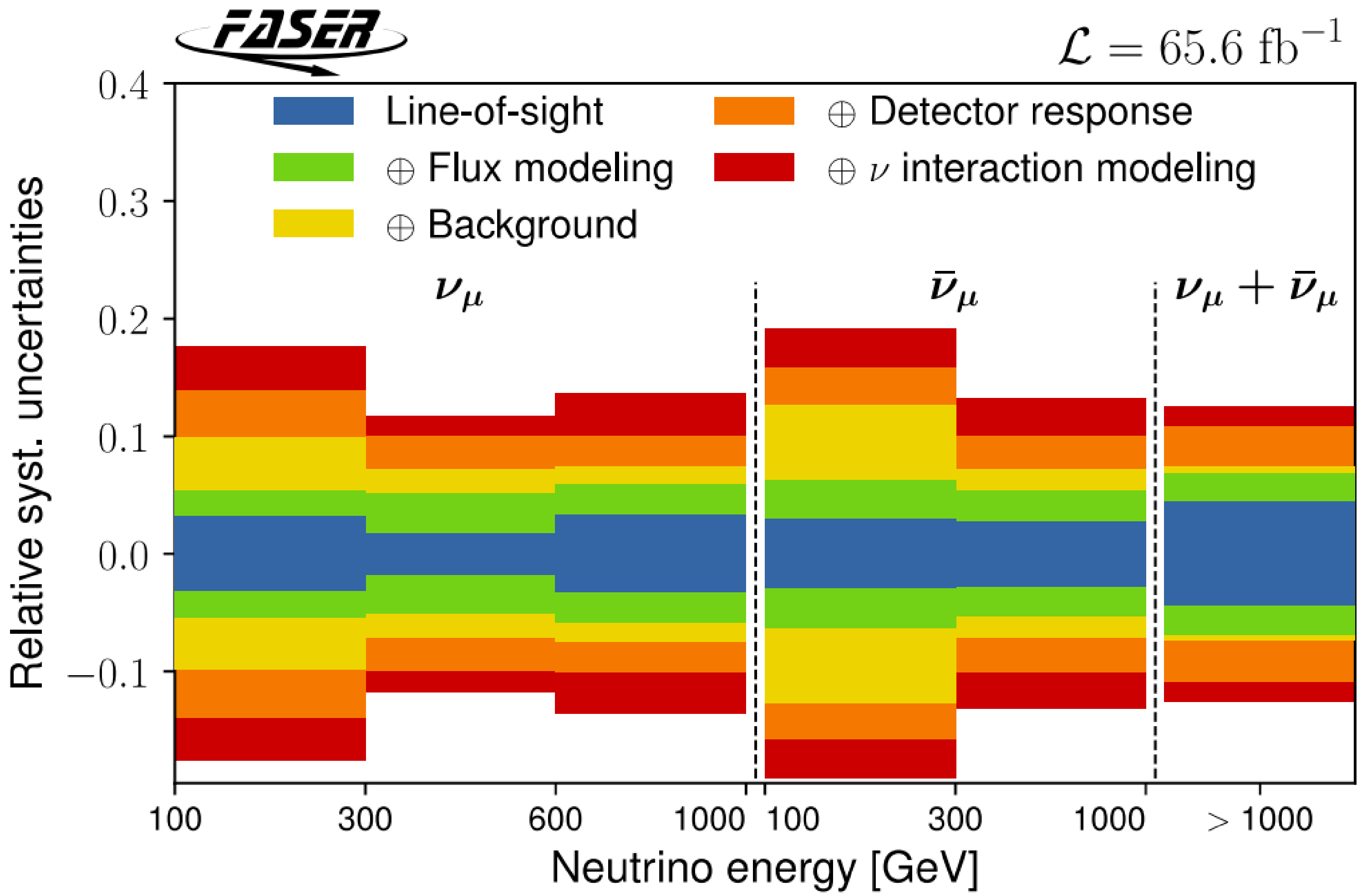


The number of observed neutrino candidate events



	$q/p'_\mu [\mathrm{GeV}^{-1}]$	$[\frac{-1}{100}, \frac{-1}{300}]$	$[\frac{-1}{300}, \frac{-1}{600}]$	$[\frac{-1}{600}, \frac{-1}{1000}]$	$[\frac{-1}{1000}, \frac{1}{1000}]$	$[\frac{1}{1000}, \frac{1}{300}]$	$[\frac{1}{300}, \frac{1}{100}]$	Total
				Simulation				
Signal	ν_μ CC (fid.)	33.6± 7.6	59.5± 9.1	51.6± 8.8	84.1±21.4	50.1±11.4	19.6± 5.9	298.4±42.6
Bgr.	ν_μ CC (non-fid.)	3.6± 1.4	3.7± 1.7	2.3± 1.3	2.0± 1.2	2.6± 1.3	2.9± 1.3	17.1± 6.6
	ν_e CC	0.7± 0.5	0.2± 0.2	0.1± 0.1	0.1± 0.2	0.4± 0.5	0.9± 0.7	2.3± 1.9
	ν_τ CC	0.0± 0.1	0.0± 0.1	0.0± 0.1	0.0± 0.0	0.1± 0.1	0.0± 0.1	0.2± 0.4
	ν NC	1.4± 0.5	0.4± 0.4	0.1± 0.2	0.1± 0.2	0.6± 0.4	1.3± 0.8	4.0± 1.4
	Geo. bgr.	0.2± 0.6	0.0± 0.1	0.0± 0.0	0.0± 0.0	0.0± 0.0	0.0± 0.0	0.3± 0.6
	Total	39.5± 9.2	63.9±10.2	54.1± 9.6	86.3±22.3	53.7±12.1	24.7± 7.5	322.3±50.5
				Data				
	Total	50	97	71	69	48	27	362

Systematic uncertainties



Unfolding number of true ν interactions n_ν

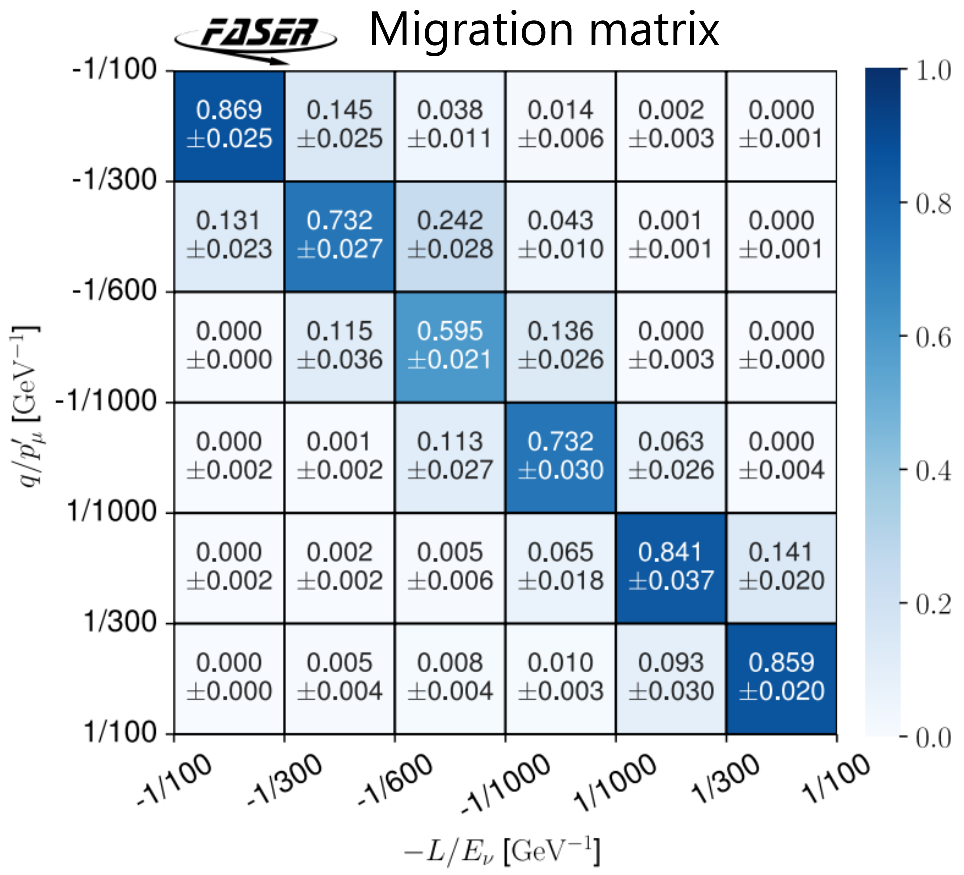
Binned likelihood fit incorporating background estimates and systematics

$$n_\mu^i = \sum_j M_{ij}\,\epsilon_j\,n_\nu^j + n_{\rm bkg}^i$$

- n_μ^i: Expected number of reco. events
- M_{ij}: Migration matrix
- ϵ_j: Total efficiency in each bin
- n_ν^j: True ν int. in fiducial volume
- n_{bkg}^i: Background event counts

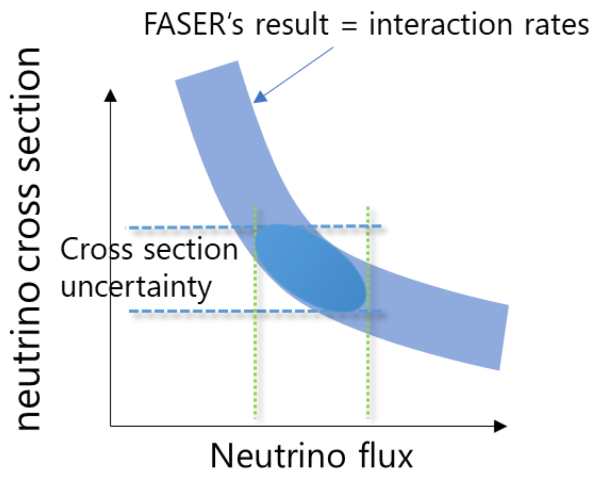
$$\mathcal{L} = \prod_i^{\rm bins} \mathcal{P}(N_\mu^i | n_\mu^i) \times \prod_l \mathcal{G}_l$$

- N_μ^i: Observed event counts
- n_μ^i: Expected number of reco. events
- $\mathcal{G}_l$: Gaussian priors for nuisance parameters



$-L/E_\nu$ $\left[\mathrm{GeV}^{-1}\right]$	$\left[\frac{-1}{100}, \frac{-1}{300}\right]$	$\left[\frac{-1}{300}, \frac{-1}{600}\right]$	$\left[\frac{-1}{600}, \frac{-1}{1000}\right]$	$\left[\frac{-1}{1000}, \frac{1}{1000}\right]$	$\left[\frac{1}{1000}, \frac{1}{300}\right]$	$\left[\frac{1}{300}, \frac{1}{100}\right]$
Acceptance α [%]	16.7± 0.6	30.0± 1.2	38.8± 2.6	46.6± 3.0	47.5± 1.9	27.8± 2.5
Reco. efficiency $\epsilon_{\rm reco.}$ [%]	80.8± 7.2	79.0± 4.9	79.3± 5.0	78.8± 5.5	84.4± 4.7	84.5± 6.9
Efficiency $\epsilon = \alpha \cdot \epsilon_{\rm reco}$ [%]	13.5± 1.2	23.7± 1.7	30.8± 2.6	36.8± 3.0	40.1± 3.1	23.5± 2.4

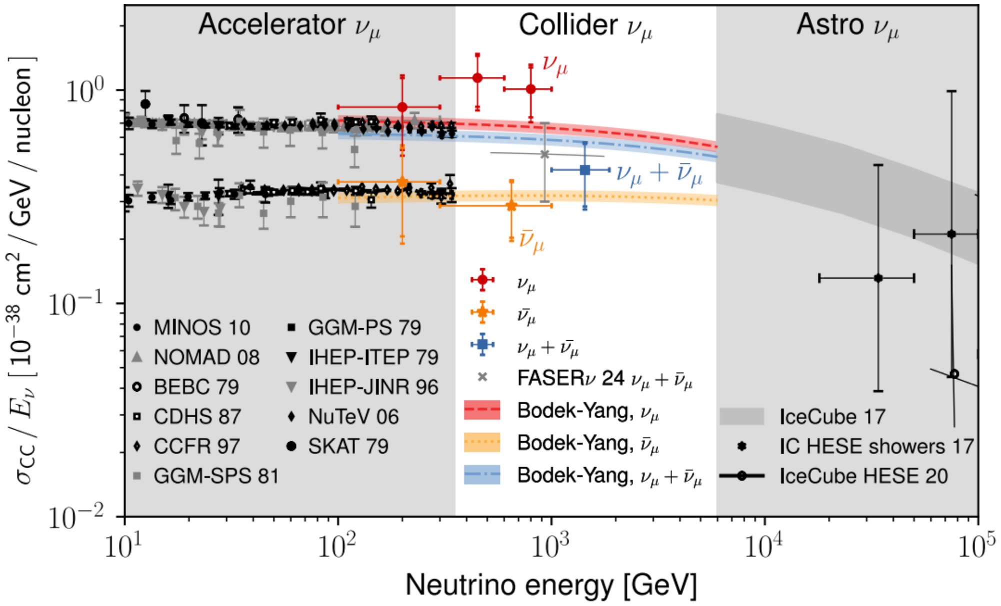
Differential cross section and flux measurement



Cross section measurement

$$\sigma_\nu^j = \frac{n_\nu^j}{\rho_T \cdot \mathcal{L} \cdot \iint \phi_{\text{sim}}^j \, \mathrm{d}E\mathrm{d}A}$$

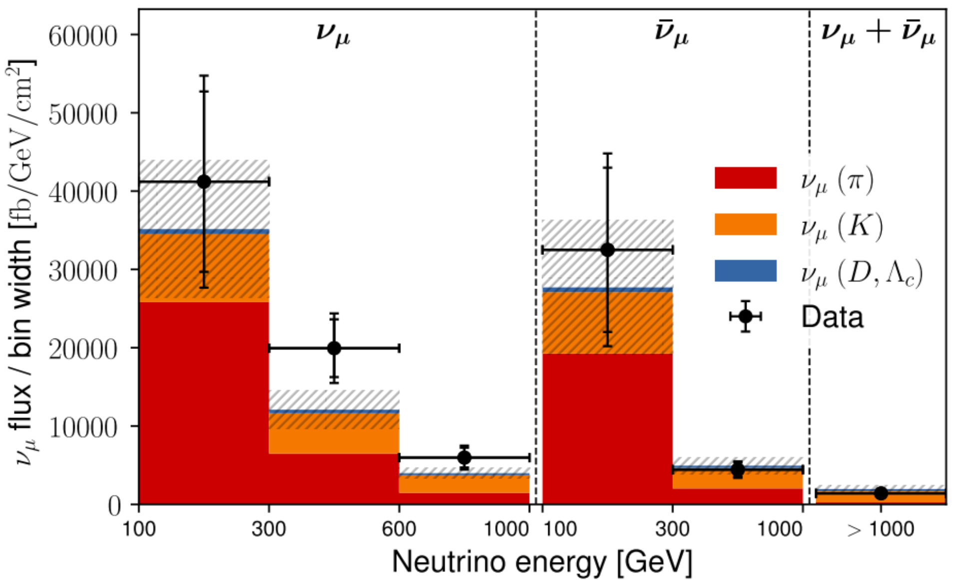
ϕ_{sim}: simulated neutrino flux



Flux measurement

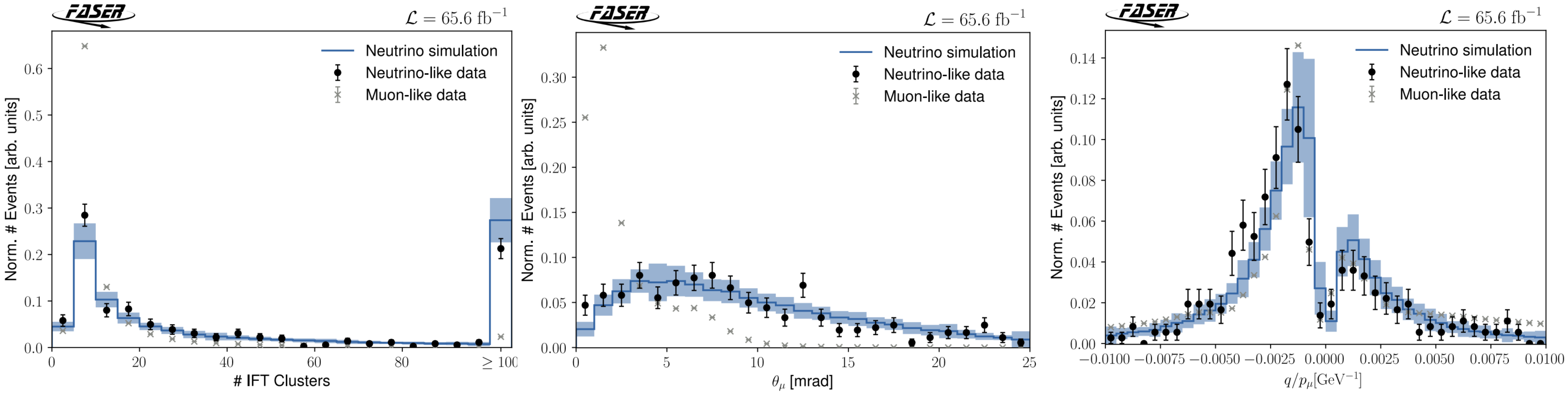
$$\phi^j = \frac{n_\nu^j}{\sigma_{\text{sim}}^j \cdot A \cdot \rho_T \cdot \mathcal{L}}$$

σ_{sim}: effective cross section



$-L/E_\nu$ $\left[\mathrm{GeV}^{-1}\right]$	$\left[\frac{-1}{100}, \frac{-1}{300}\right]$	$\left[\frac{-1}{300}, \frac{-1}{600}\right]$	$\left[\frac{-1}{600}, \frac{-1}{1000}\right]$	$\left[\frac{-1}{1000}, \frac{1}{1000}\right]$	$\left[\frac{1}{1000}, \frac{1}{300}\right]$	$\left[\frac{1}{300}, \frac{1}{100}\right]$
$\phi_{\text{Sim.}}$ $[10^6 \text{fb cm}^{-2}]$	7.0 ± 1.8	3.6 ± 0.7	1.6 ± 0.3	1.7 ± 0.5	3.5 ± 0.8	5.5 ± 1.7
$\sigma_{\text{sim.}}$ $[10^{-38}$ cm^2 / nucleon$]$	128.5 ± 7.9	292.2 ± 17.6	514.6 ± 31.3	799.3 ± 68.1	166.3 ± 10.5	56.8 ± 3.4

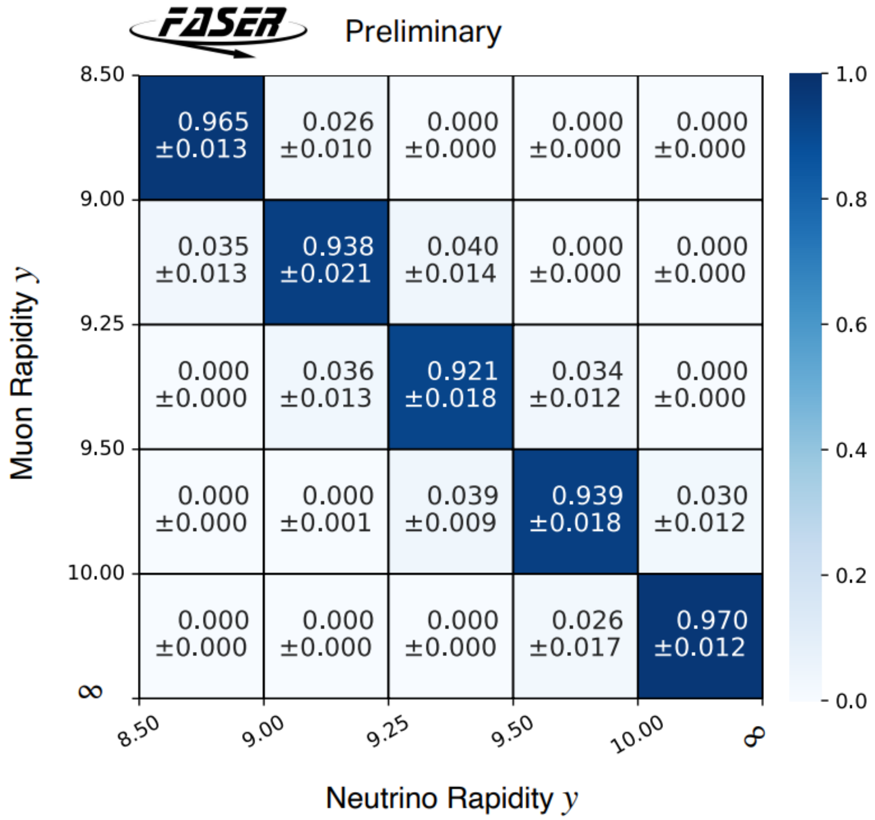
Neutrino event characteristics

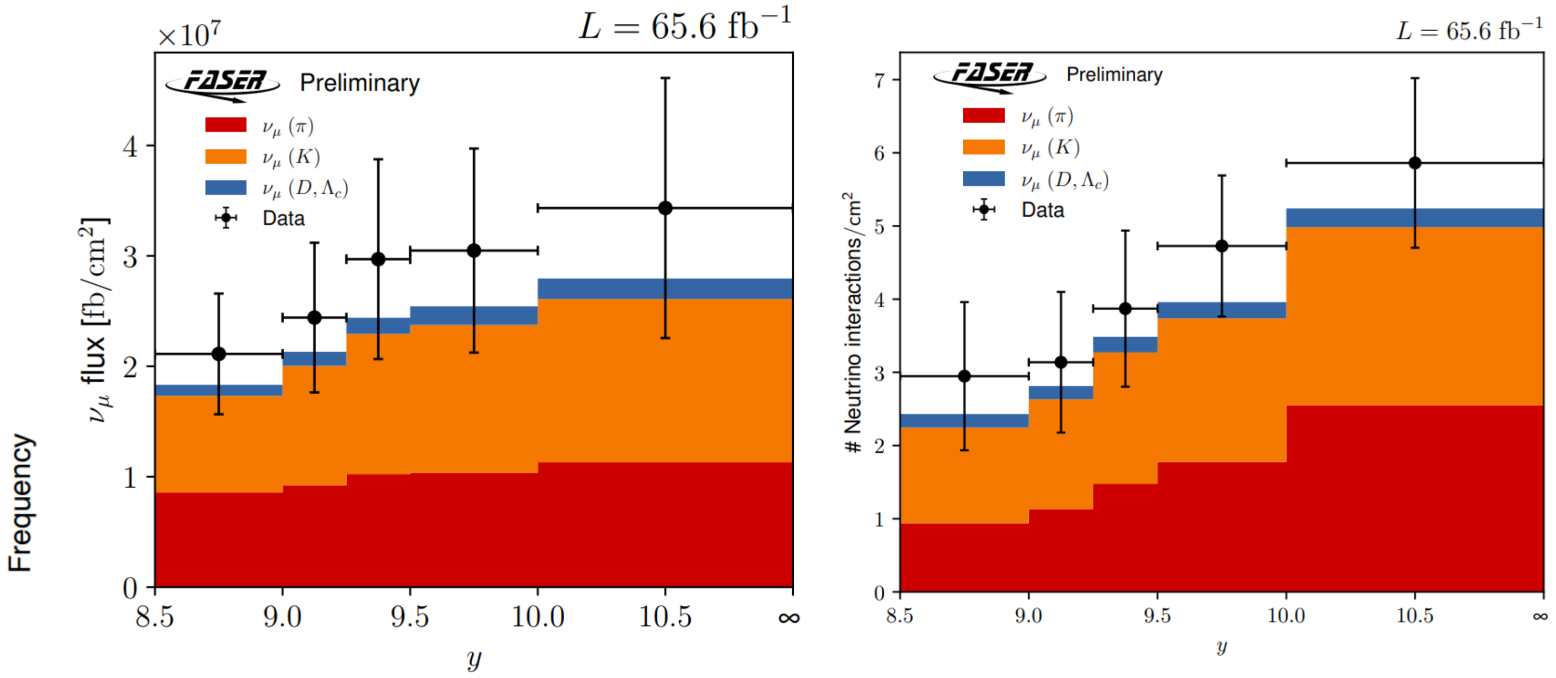


- Compared to MC and muon-like data, show good agreement with simulation
  - # IFT Clusters: neutrino interactions produce significant hadron activity ($\neq \mu$ background)
  - θ_μ: μ from neutrino interactions have a broader angular distribution
  - q/p_μ: Both ν_μ and $\bar{\nu}_\mu$ are present

Neutrino rapidity measurement

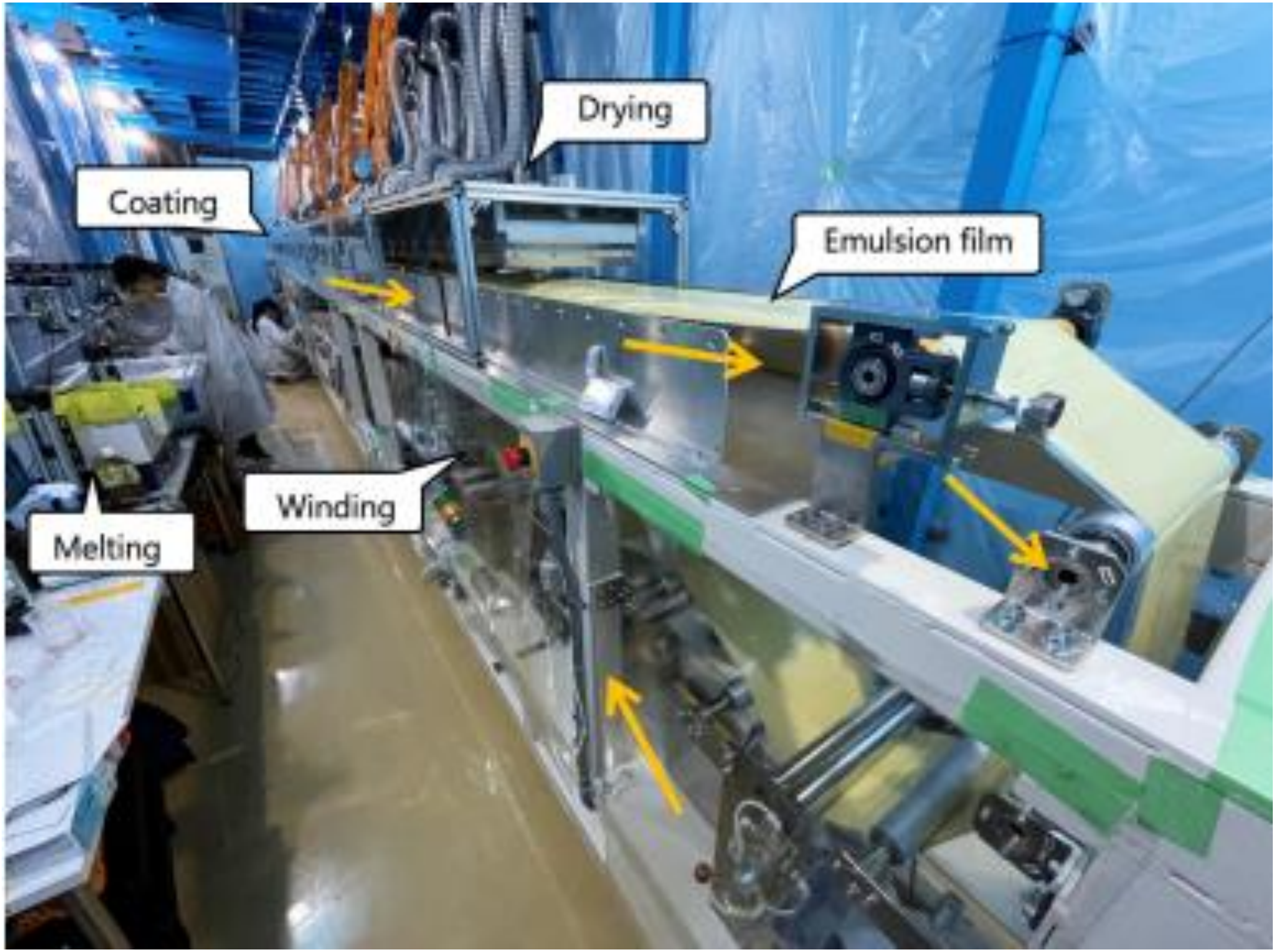
Migration matrix





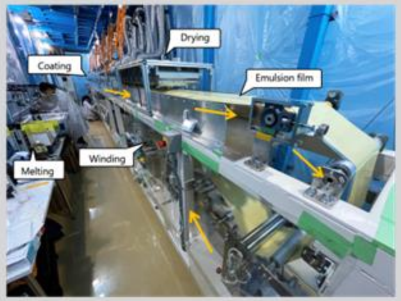
Rapidity bin	[8.5, 9.0]	[9.0, 9.25]	[9.25, 9.5]	[9.5, 10]	[10, ∞)
Uncertainty Sources [%]					
MC Stat. unc.	2.3	3.0	3.7	3.4	3.7
Geant4, GENIE unc.	0.9	1.5	2.3	1.2	1.7
Neutrino Flux Modeling unc.	0.9	0.9	1.1	3.0	1.4
LOS unc.	0.1	0.1	0.9	0.4	0.6
Alignment unc.	0.1	0.1	0.0	0.0	0.1
Event selection unc.	1.7	1.4	1.5	1.5	1.3
Total	3.2	3.8	4.8	5.0	4.5

Dedicated pouring machine



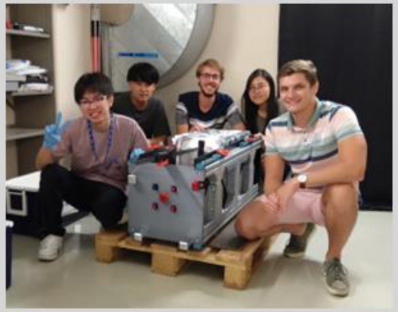
FASERν operations/analysis

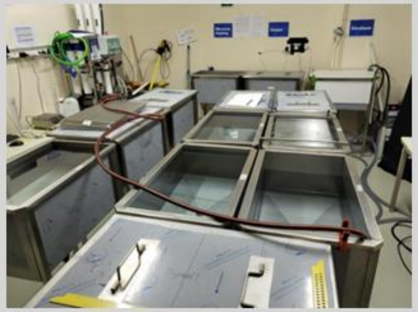
Japan



Film production

CERN





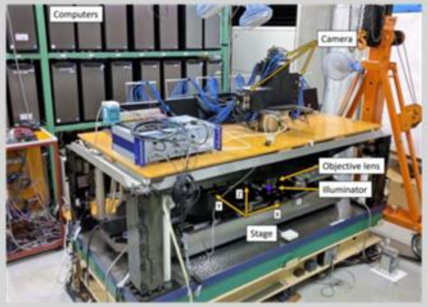
Assembly

Exposure

Disassembling

Development

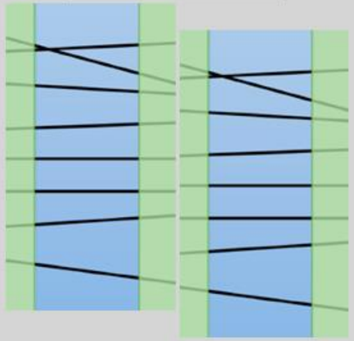
Japan



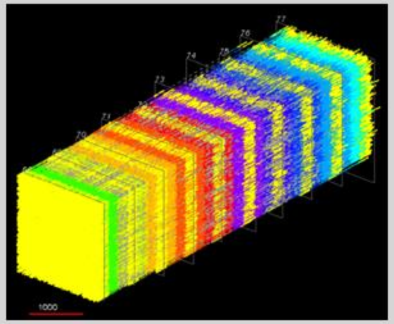
Readout

Offline analysis

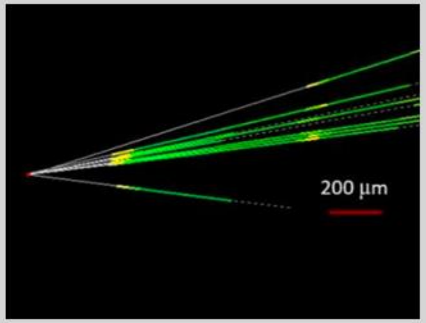
Alignment



Track reconstruction

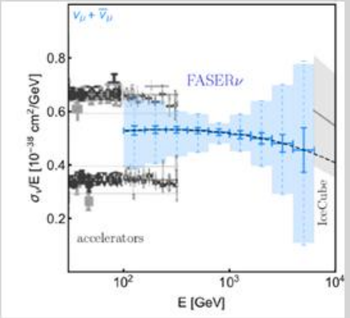


Vertex reconstruction



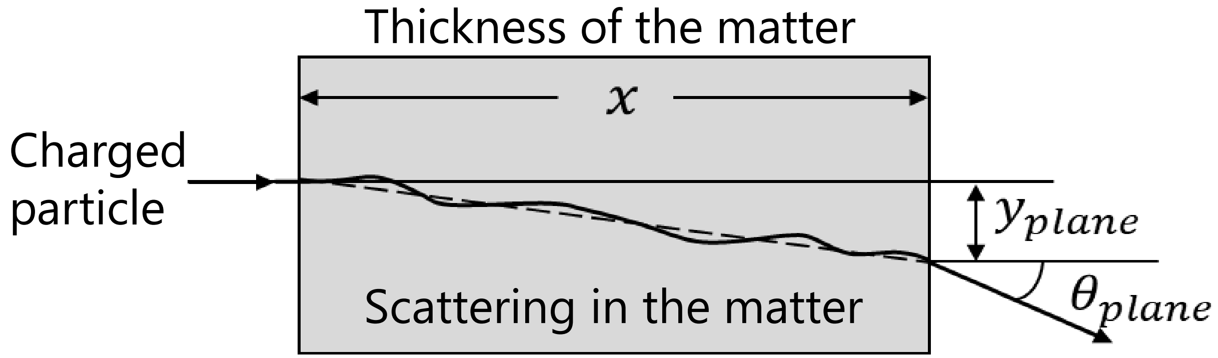
e, μ ID
τ decay search
charge ID
$E\nu$ reco
charm/beauty
etc.

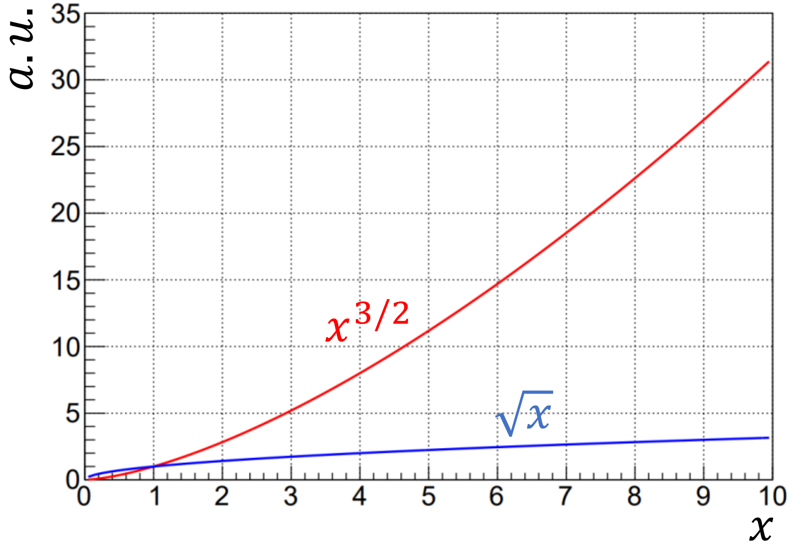
Physics analysis



Momentum measurement method with emulsion detector

- Challenge: The method has only been established **up to 100 GeV**
- Momentum measurement is based on multiple Coulomb scattering (MCS)
- 1 TeV muon: only 1 µm scattered with 2.5 cm tungsten (~25 plates)



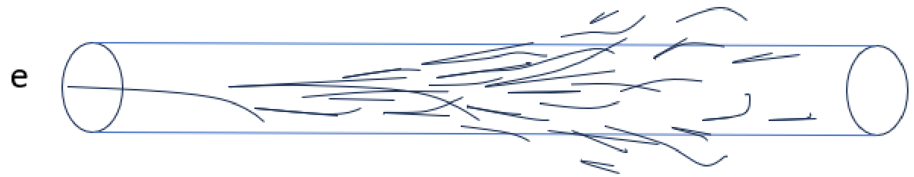


$$\theta_{plnae}^{RMS} = \sqrt{\textstyle\sum_{i=1}^{i=n} \theta_{i,plane}^2 / n}$$

Angular method	$\theta_{plane}^{RMS} = \frac{13.6MeV}{\beta P}\sqrt{\frac{x}{X_0}} \propto \frac{1}{P}\cdot\sqrt{x}$	• Limited to 10 GeV in OPERA
Coordinate method	$y_{plane}^{RMS} \propto \frac{1}{P}\cdot x^{3/2}$	• Applied up to 100 GeV in DONUT • Measurable up to a few TeV

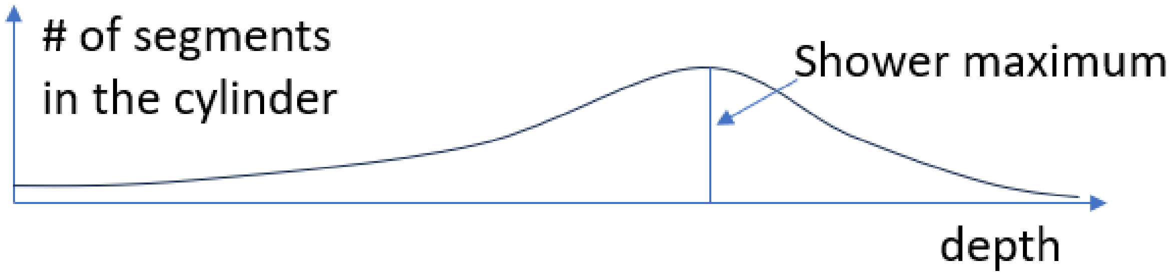
Kinematical tools: Electron energy measurement

The EM shower quickly developed in the FASERν detector

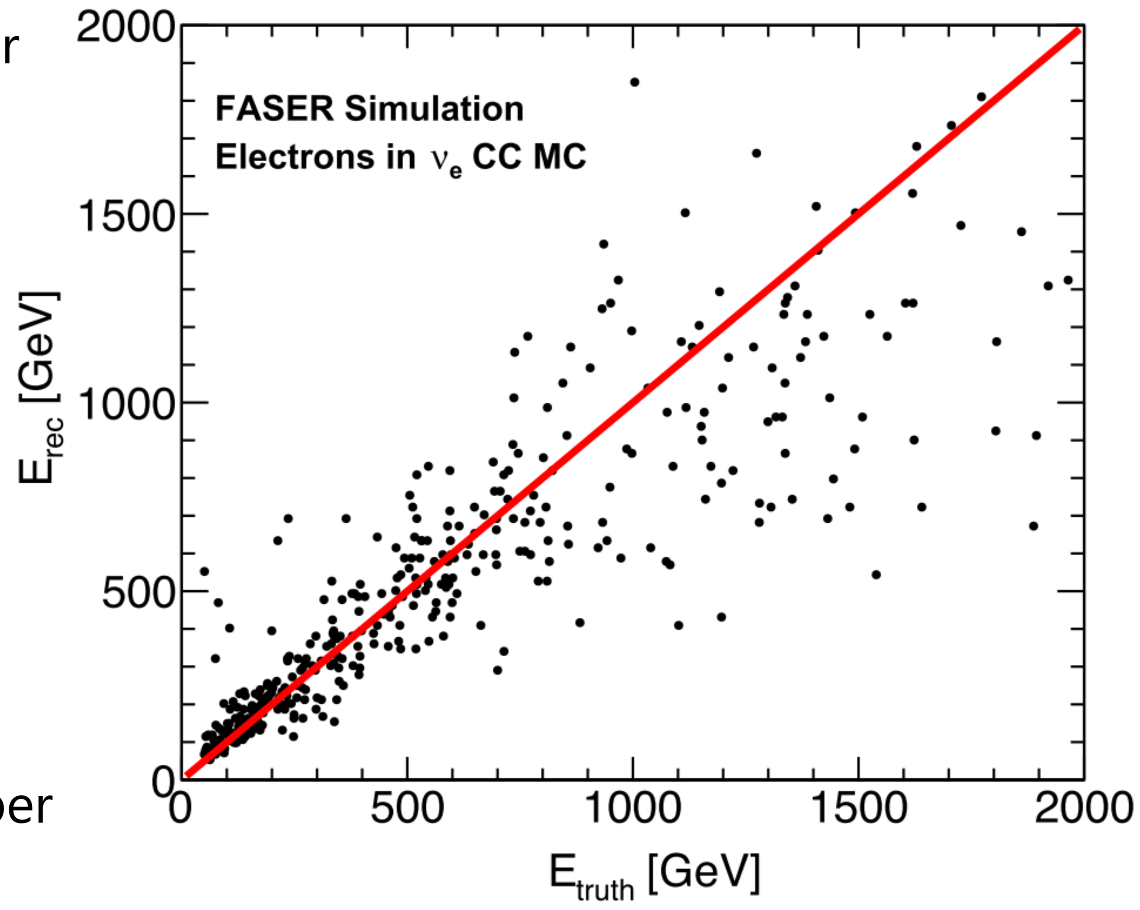


δpos $< 100\ \mu$m
$\delta\theta < 10$ mrad
$d$min $< 50\ \mu$m

Open a 100 μm radius cylinder around shower axis

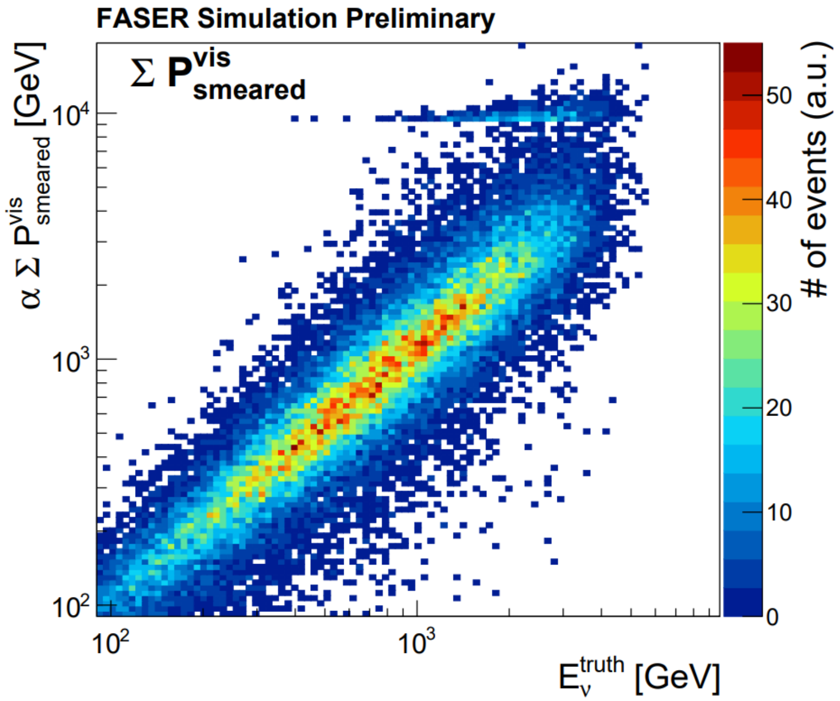


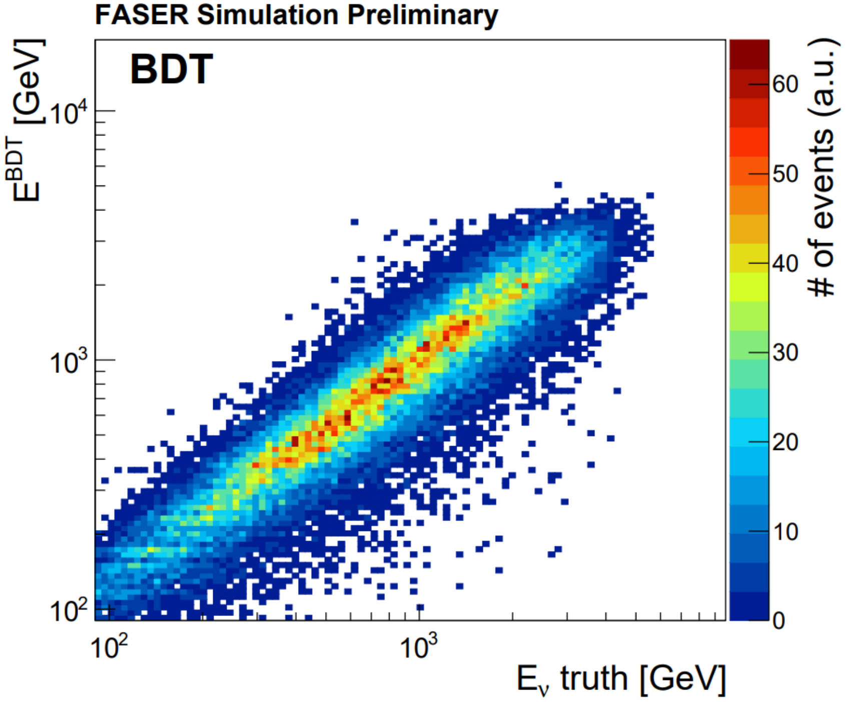
Using MC, the energy is estimated from the total number of hits in the three plates around the shower maximum

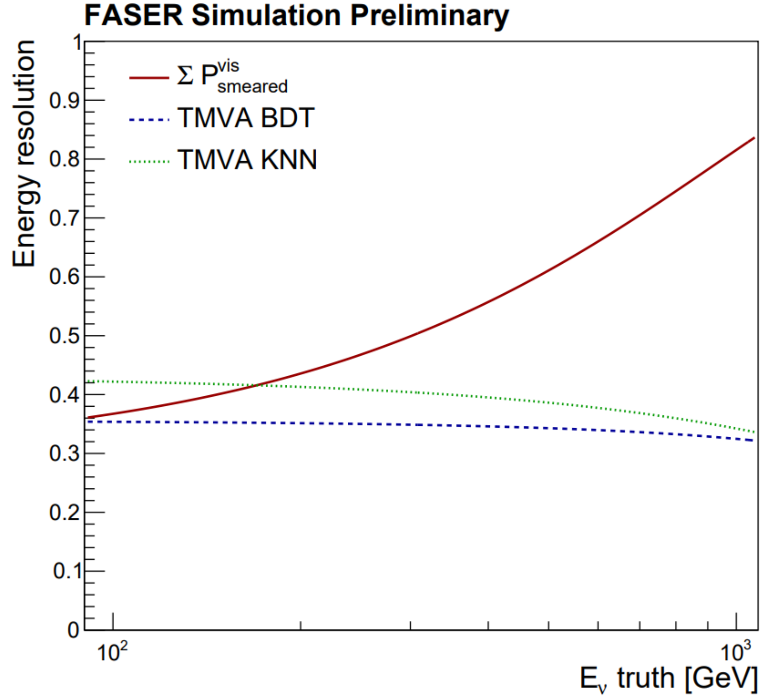


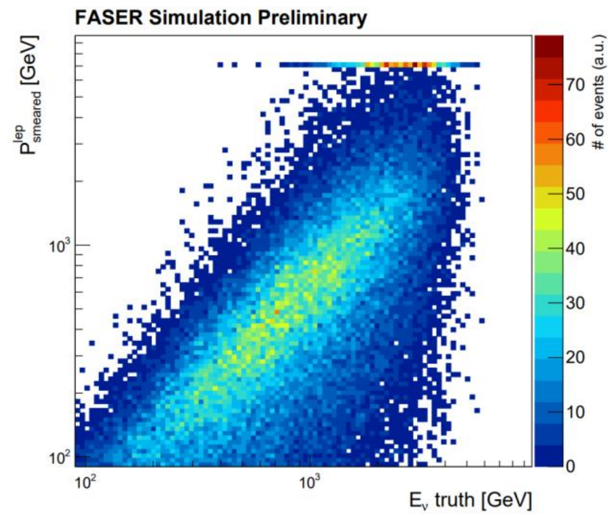
~25% resolution at 200 GeV from the simulation
→ Will be validated with testbeam data

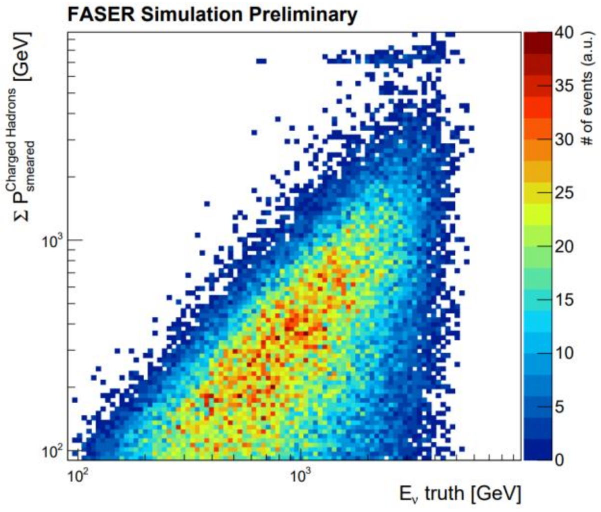
Kinematical tools: Neutrino energy reconstruction

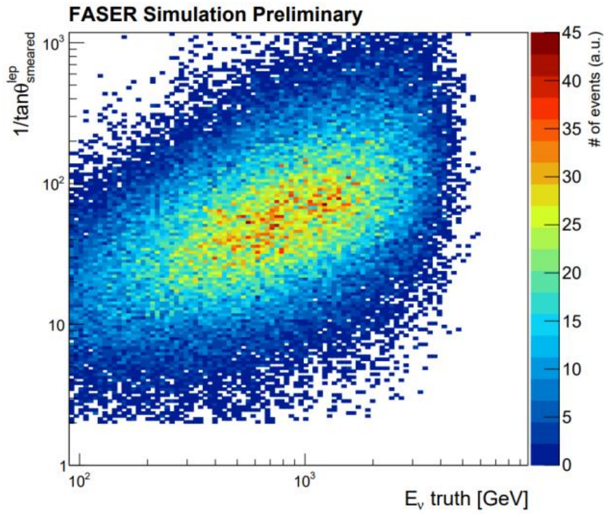






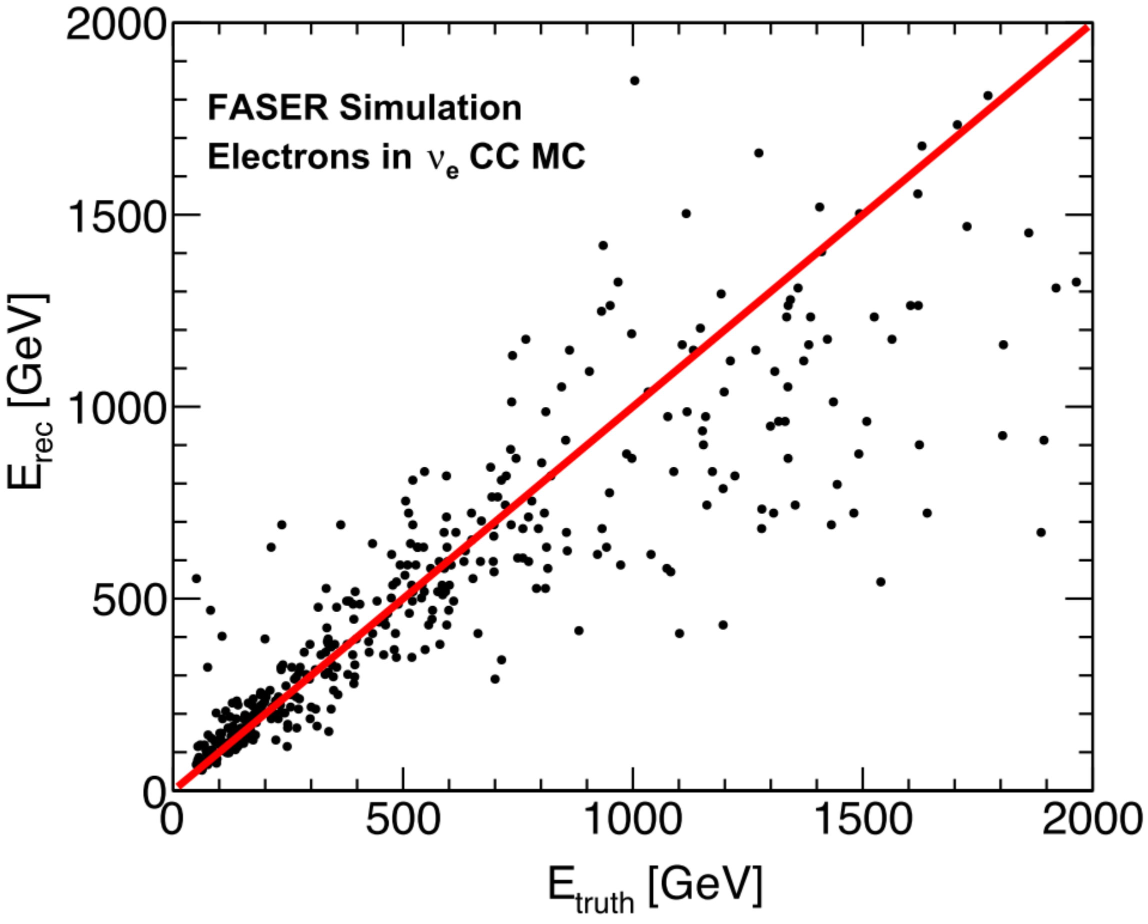






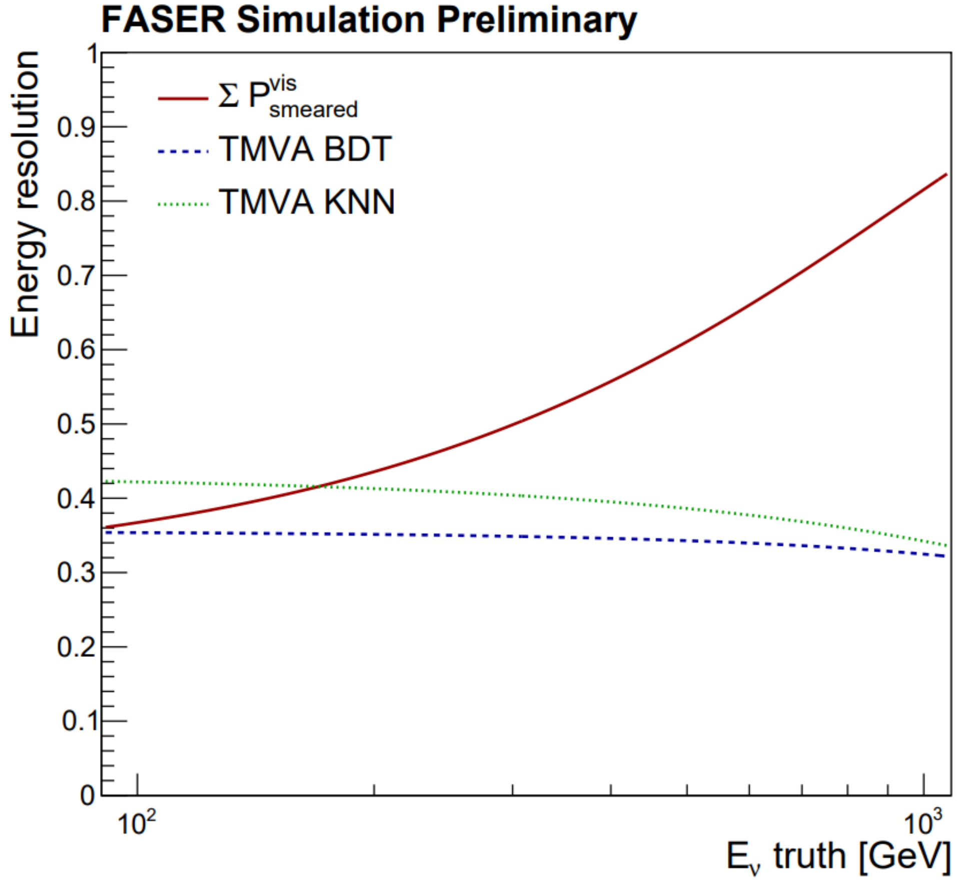
Kinematical tools

- Electron energy measurement



~25% resolution at 200 GeV from the simulation
→ Will be validated with test beam data

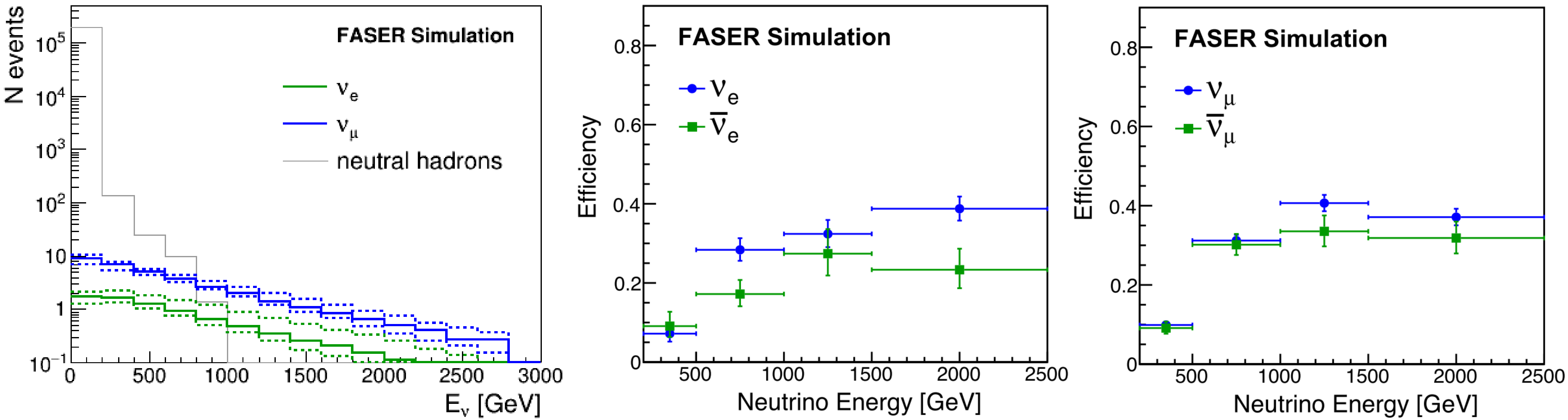
- Neutrino energy reconstruction



Resolution is improved by machine learning
Inputs are P_{lep}, $\sum P_{charged\ had}$ and $1/tan\theta_{lep}$

~40% resolution from 100 GeV to 1 TeV in the simulation

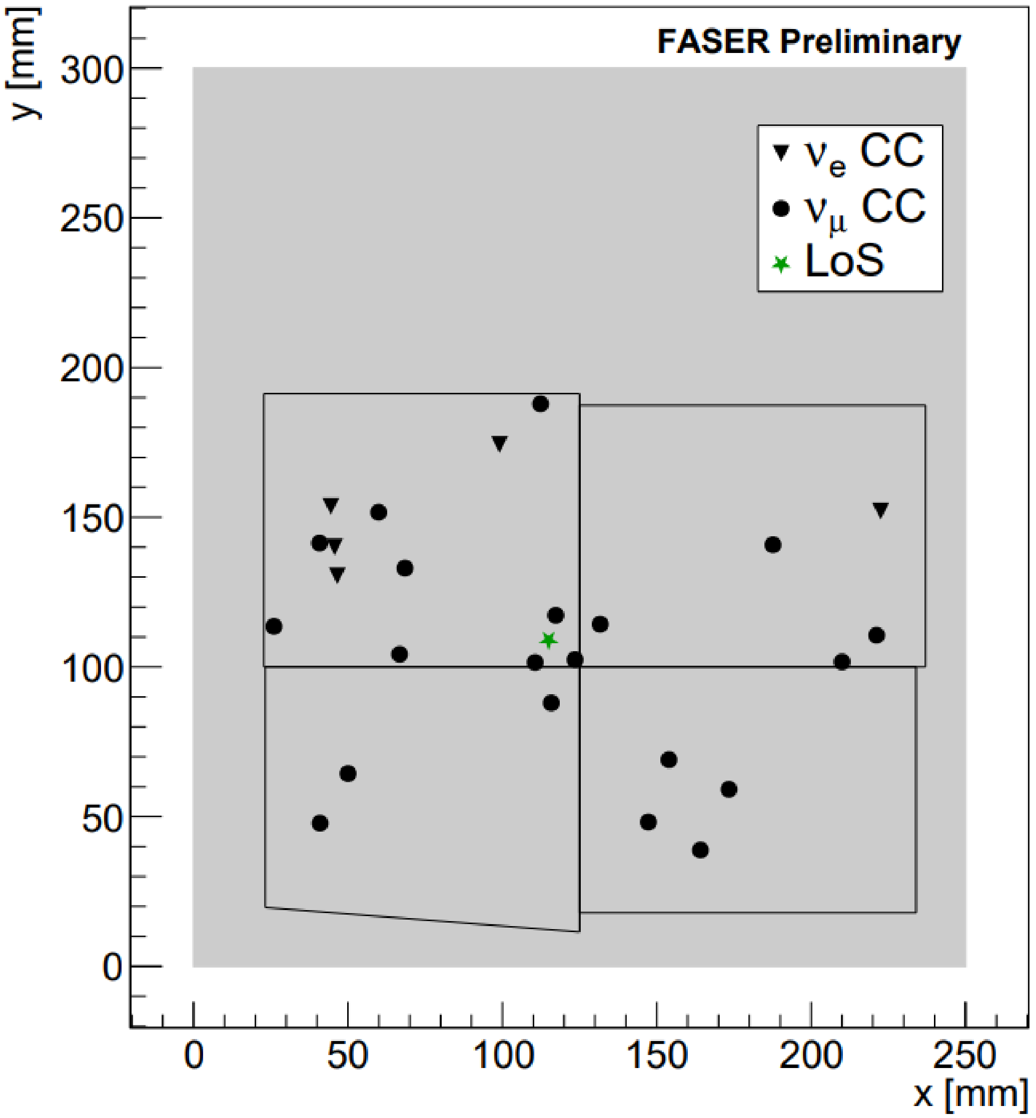
Neutral hadron BG and neutrino detection efficiency

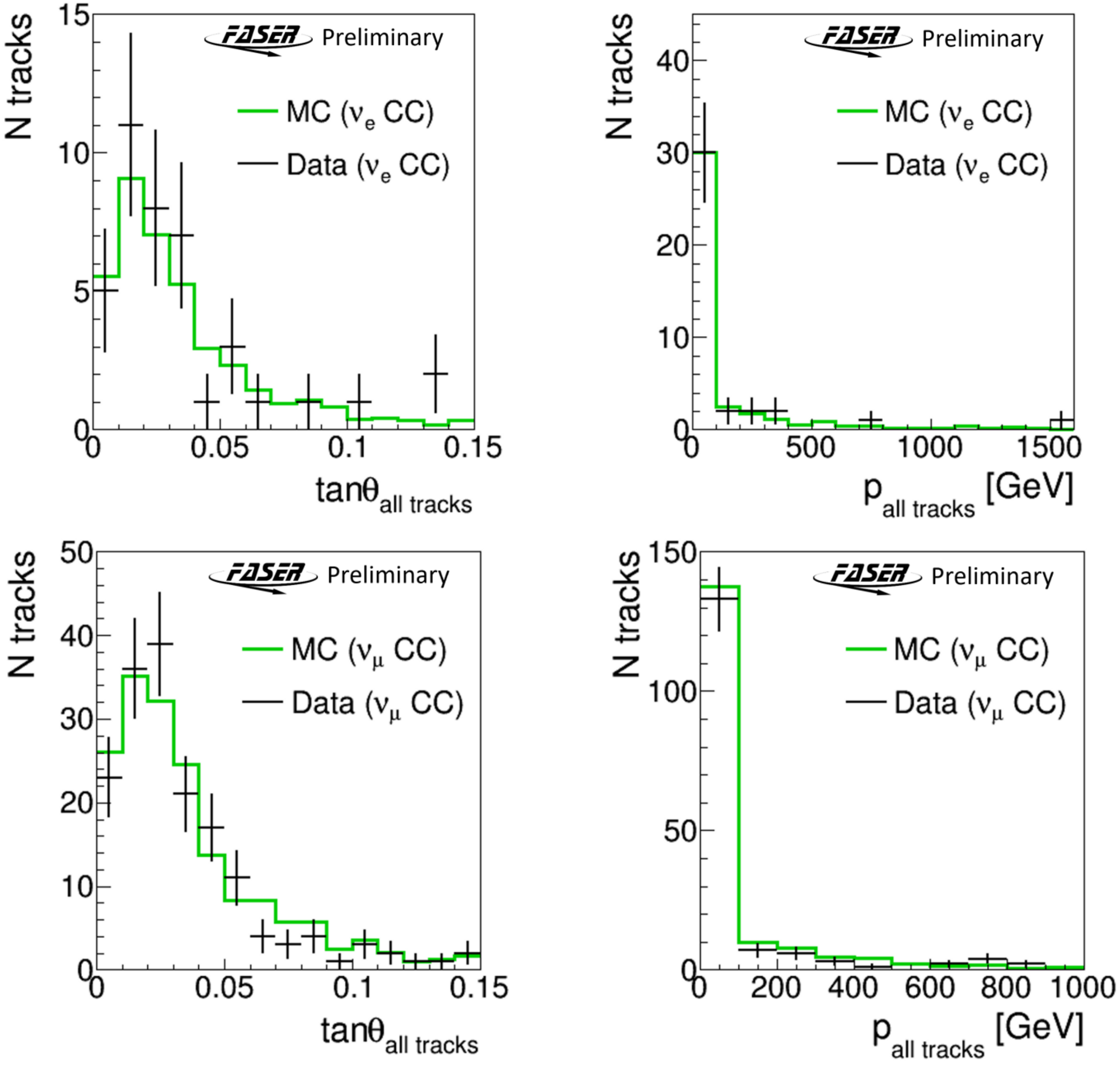


Systematic uncertainty

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)

Neutrino event characteristics






CMU 2t
CMU 2t
CAUTION
WE ARE GOING TO DISCOVER NEW PHYSICS