New neutrino results from the FASER experiment at the LHC

Motoya Nonaka (Chiba University) on behalf of the FASER collaboration

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

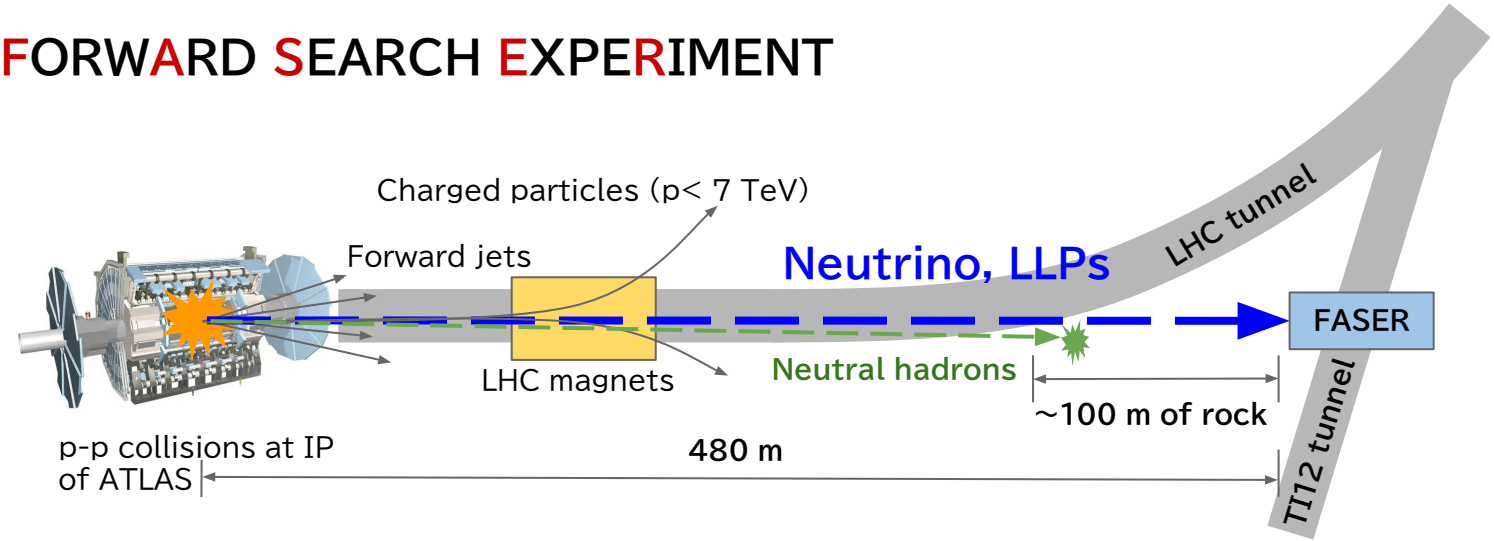
CHIBA UNIVERSITY

Swiss National Science Foundation

科研費 KAKENHI

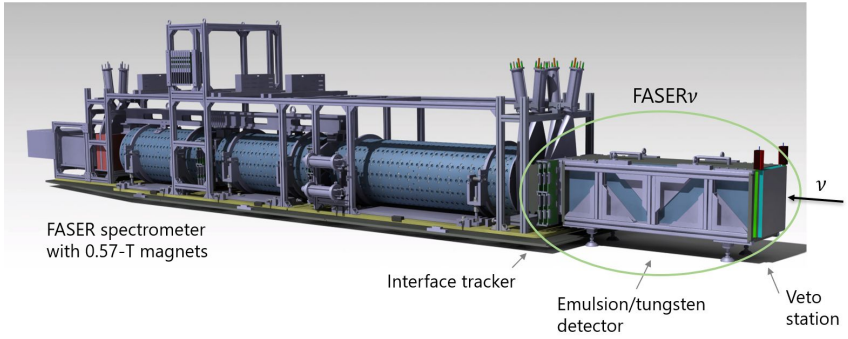
Neutrino studies in FASER

FORWARD SEARCH EXPERIMENT



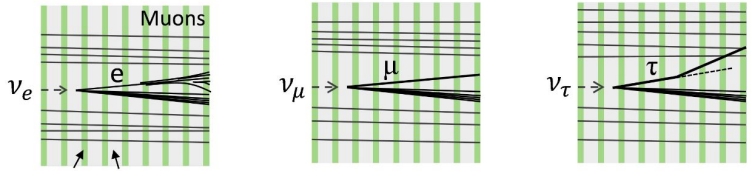
- Neutrinos at unexplored TeV energy regions
- Located 480 m downstream of ATLAS interaction point on-axis
- Background for LLP searches

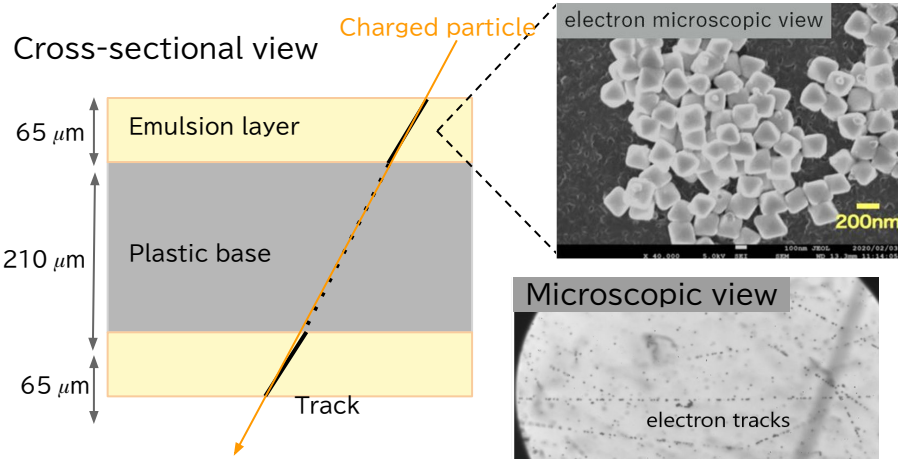
FASERν emulsion detector



- **Emulsion-based detector**
  - 730 × [emulsion film + **tungsten** (1.1 mm thickness)]
  - 250 mm × 300 mm, 1 m long, **1.1 tons ($8\lambda_{int}$, $220X_0$)**

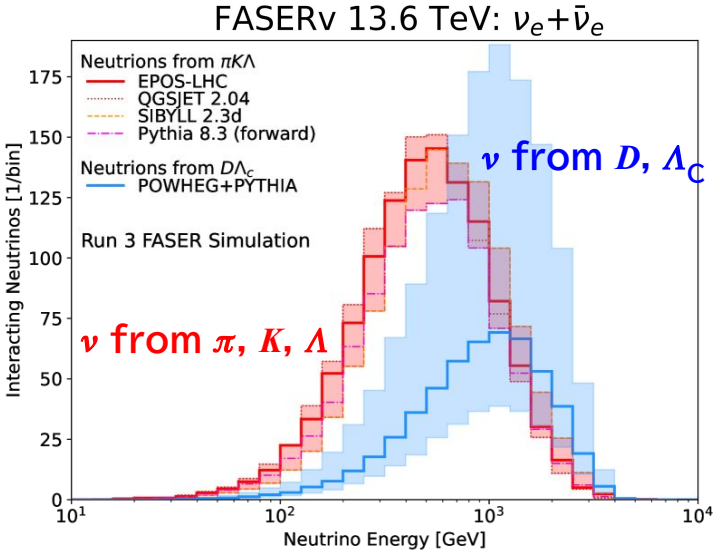
ν flavors are tagged with topological/kinematical informations

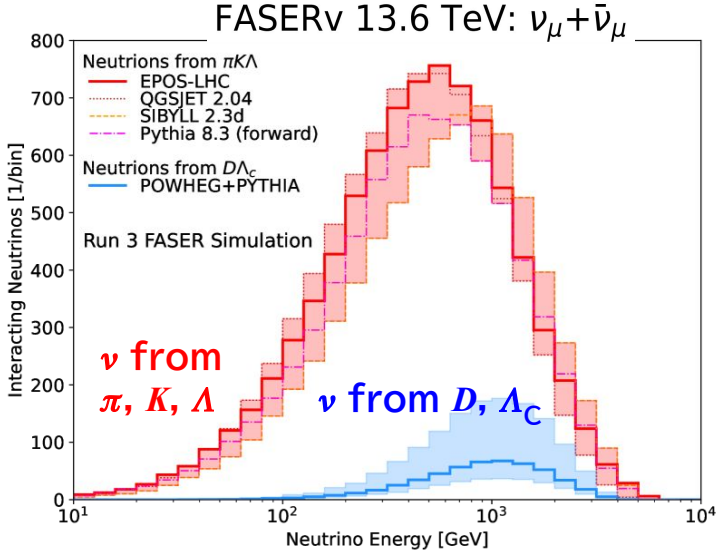




- All ν flavors can be tagged thanks to the good resolution of the emulsion
  - 200 nm silver bromide crystals dispersed in gelatin
  - **O(100) nm position resolution** can be achieved
- Install (exchange) emulsions 3 times a year

FASERν expected number of CC interactions





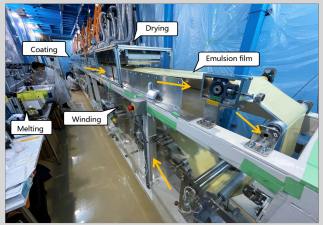
2402.13318

Run3, 250 fb^{-1}	ν_e	ν_μ	ν_τ
The expected CC interaction in FASERν	1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}

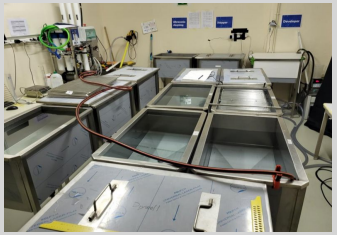
- Large uncertainty for forward charm production
- **~10,000ν interactions at unexplored energy regions** expected in LHC Run 3 (250 fb^{-1})

FASERν operations/analyses

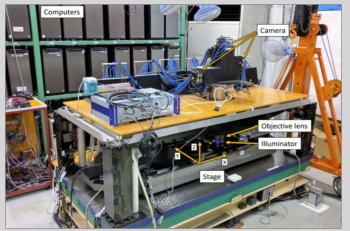
Japan



CERN



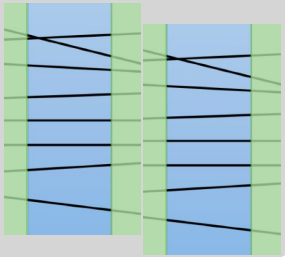
Japan

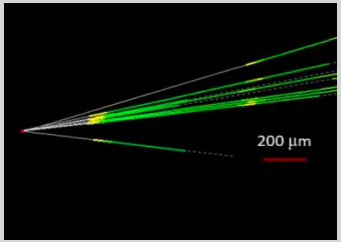


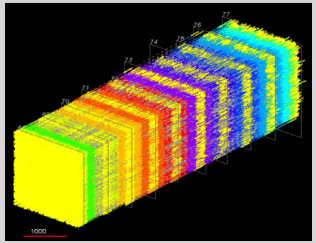
Film production → Assembly → Exposure → Disassembling → Development → Readout

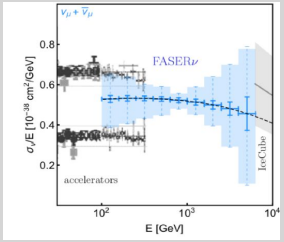
Offline analysis

Alignment → Track reconstruction → Vertex reconstruction → e, μ ID
τ decay search
charge ID
$E\nu$ reco
charm/beauty
etc. → Physics analysis



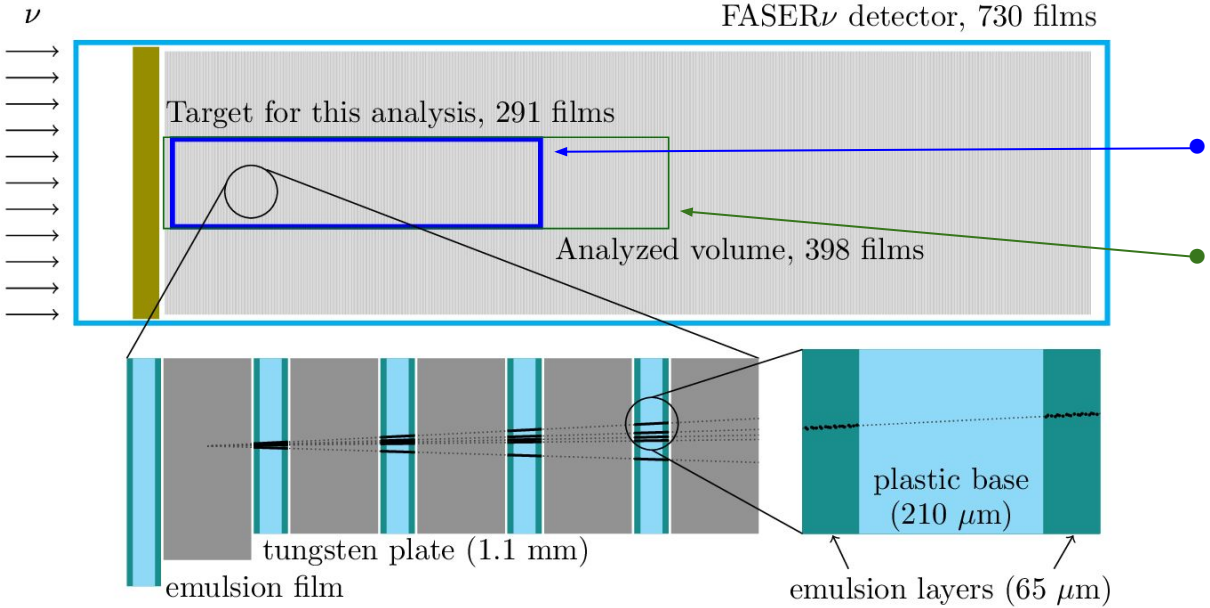






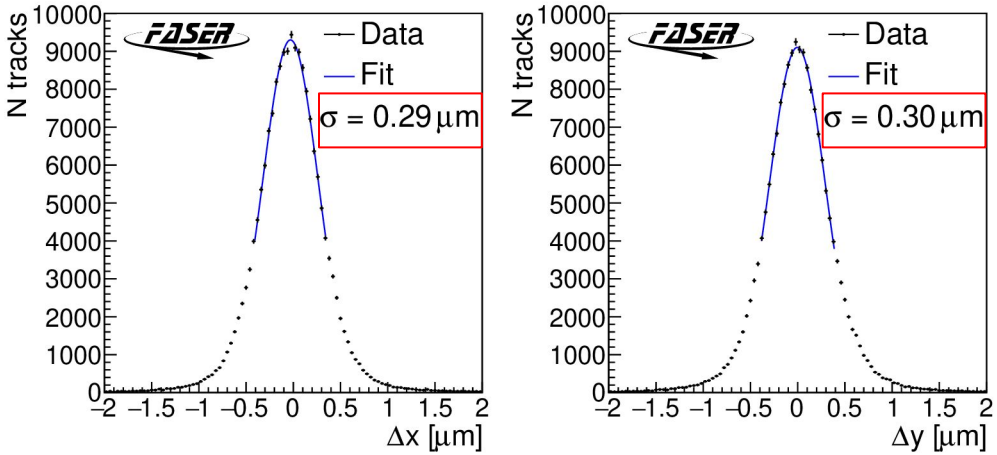
Datasets for current analysis

- 9.5 fb^{-1} in 2022 run
- Analyzed target mass of 128.6 kg
- ~1.7% of the data collected so far

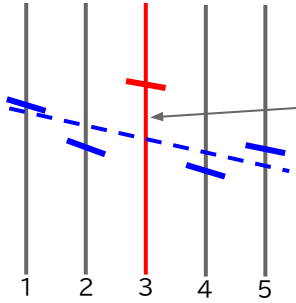


- Search for neutrino interactions
- Follow down tracks and measure the momeutm

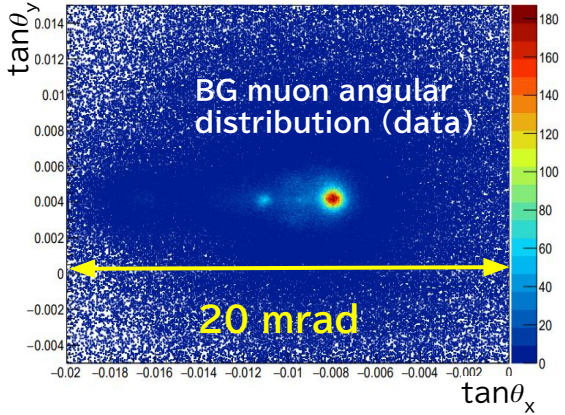
Detector performances



~300 nm position resolution



Position deviation
$\Delta x = x_3 - x_3^{fit}$

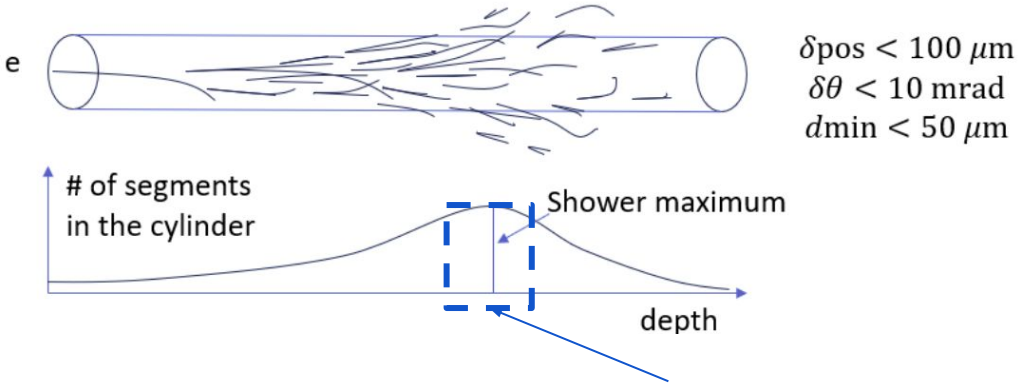


Angular spread of muon peaks
~0.4 mrad

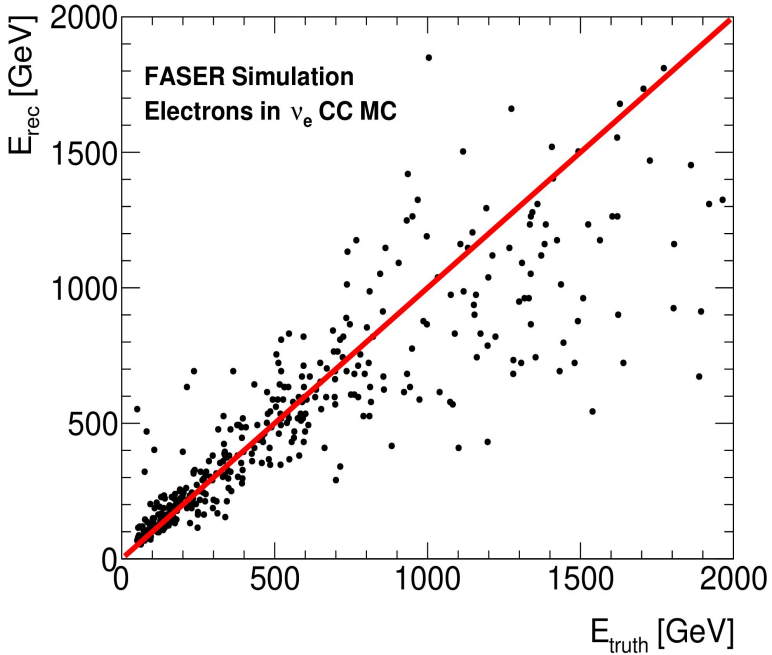
FASER Preliminary

Electron energy measurement

- Search for track segments in a cylinder of radius 100 μm around the shower axis



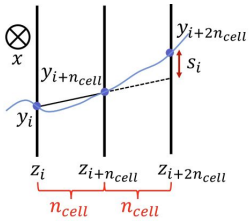
- Estimate the energy with the number of segments in ±3 films around the shower maximum using the MC simulation



~25% resolution @ 200 GeV
from the simulation studies

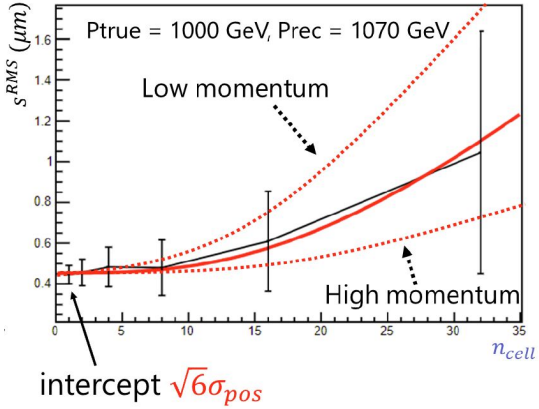
Muon momentum measurement

- Based on multiple Coulomb scattering
- **~30% resolution @ 200 GeV** from the reproductivity studies in both MC and data



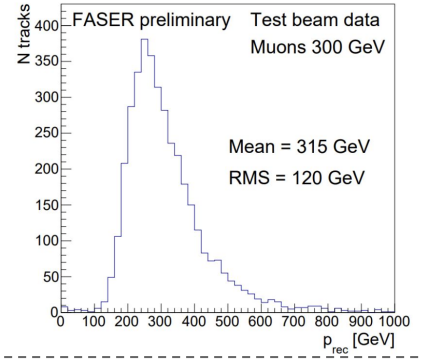
$$s_{plane}^{RMS} = \sqrt{\left(\sqrt{\frac{2}{3}} \cdot \frac{13.6MeV}{P} n_{cell} \cdot z_{cell} \sqrt{\frac{n_{cell} \cdot z_{cell}}{X_C}}\right)^2 + \left(\sqrt{6}\sigma_{pos}\right)^2} \quad ...(1)$$

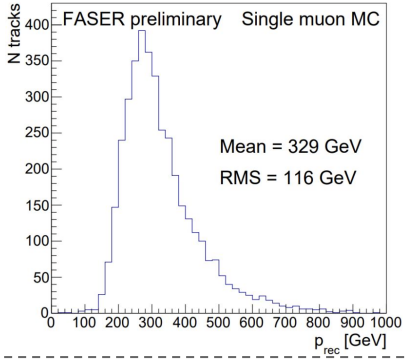
z_{cell} : The thickness of one emulsion film and tungsten plate
X_C : Compound radiation length (4.57 mm, cf: X_W=3.5 mm)
σ_{pos} : Position resolution



- Performed test beam experiment to validate the momentum measurement method in 2023

Result from the 2023 test beam (Preliminary)





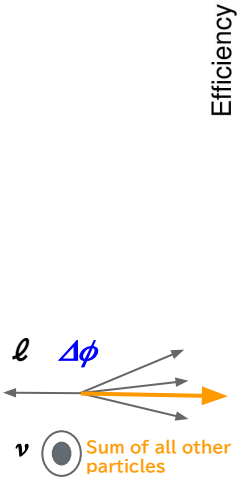
	Center value	Resolution
Test beam	286 GeV	31%
MC expectation	300 GeV	30%

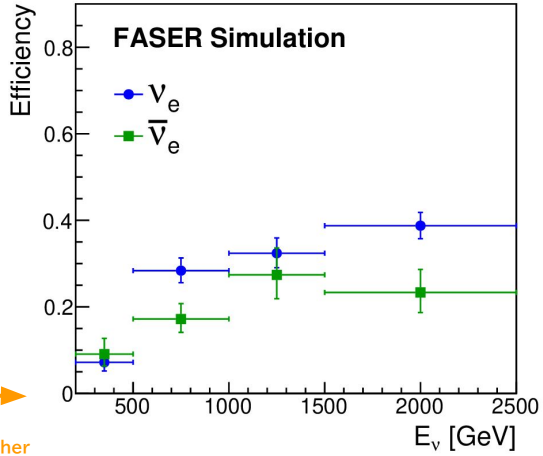
Center value = 1/mean
Resolution = sigma/mean

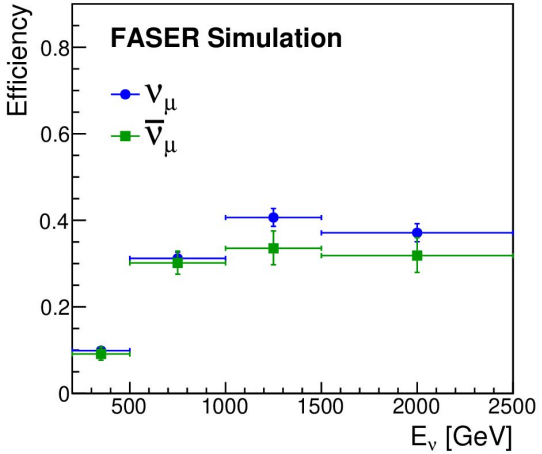
30% error agrees well with simulation

First detection of ν_e and ν_μ with FASERν detector

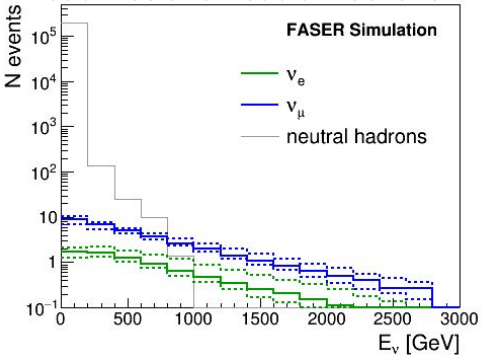
Event selection
Vertex reconstruction ($N_{track} \geq 5$, $N_{track}(\tan\theta \leq 0.1) \geq 4$
E_e or p_μ>200 GeV
$\tan\theta_e$ or $\tan\theta_\mu$>0.005
$\Delta\phi$>90°







Expected energy spectrum of neutrinos and neutral hadrons

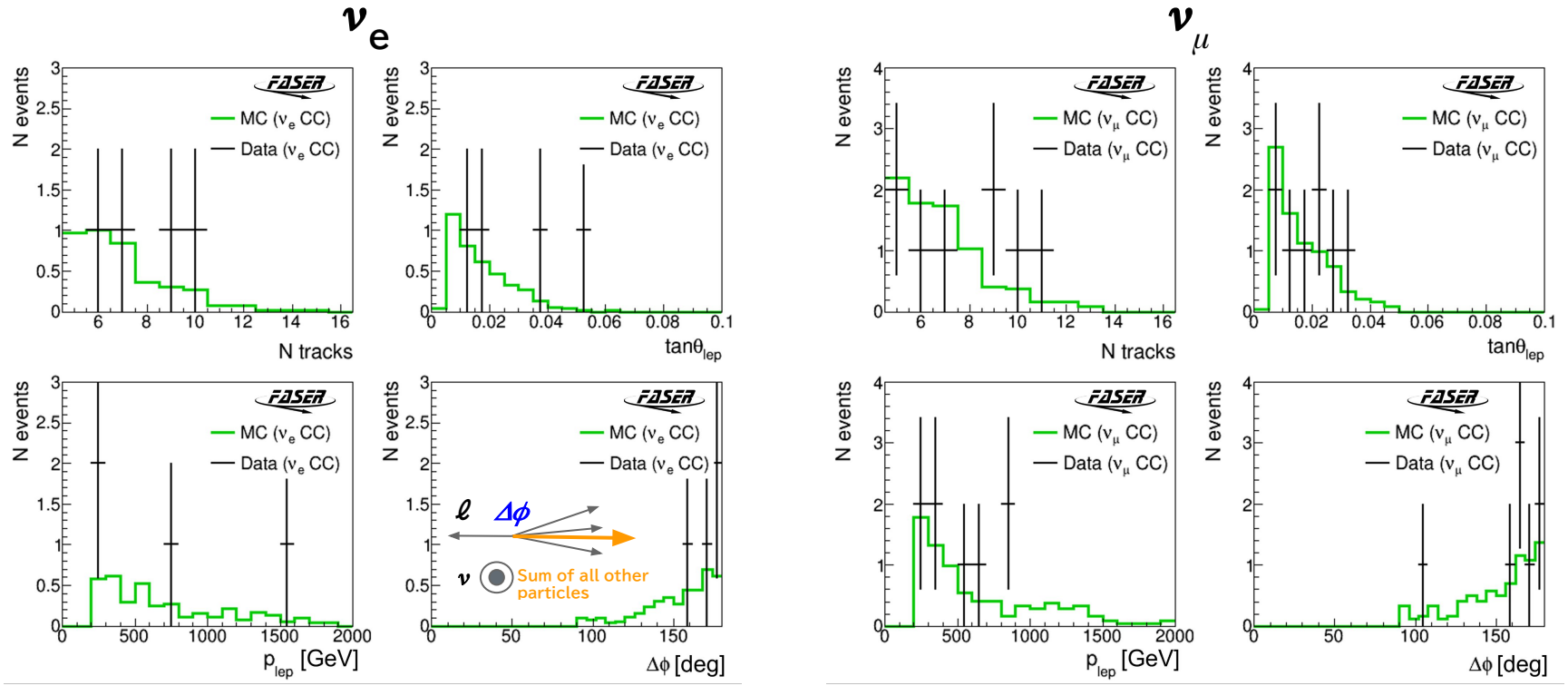


9.5 fb^{-1}, target mass of 128.6 kg (~1.7% of data)

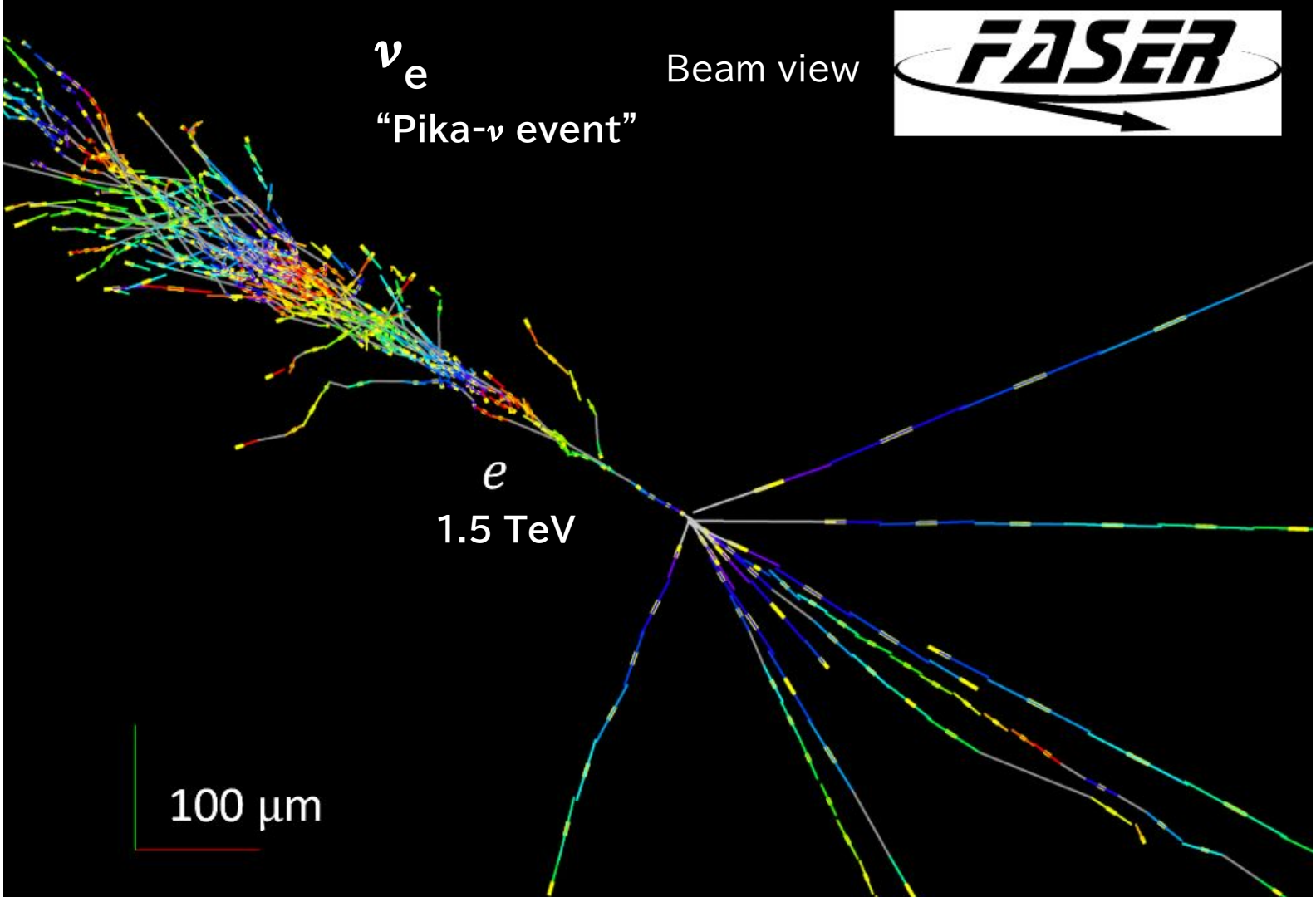
	Expected background	Expected signal	Observed	Significance
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1-3.3	**4**	**5.2σ**
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5-12.4	**8**	**5.7σ**

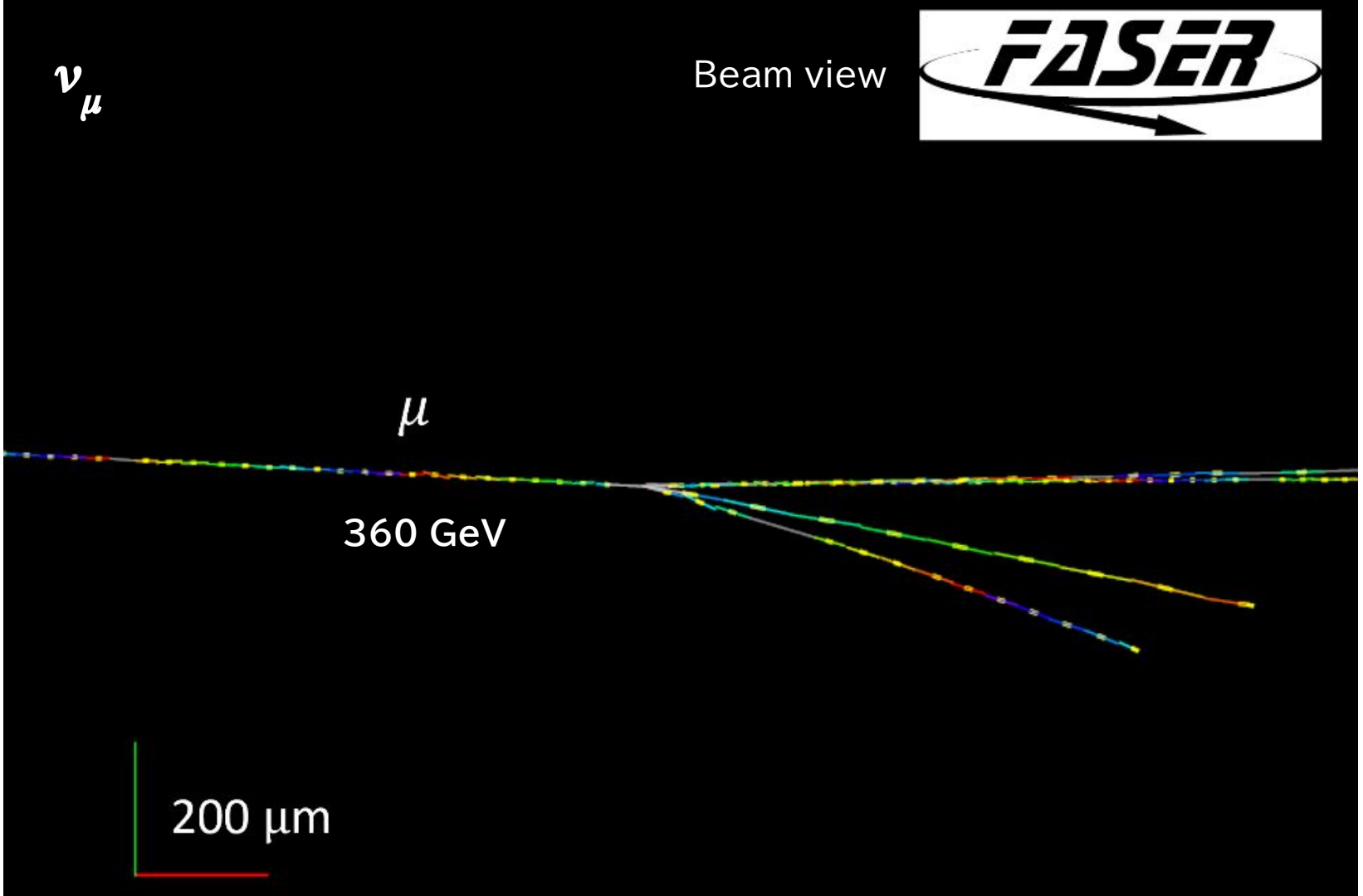
The modeling of the neutral-hadron backgrounds are validated using data

Neutrino event characteristics

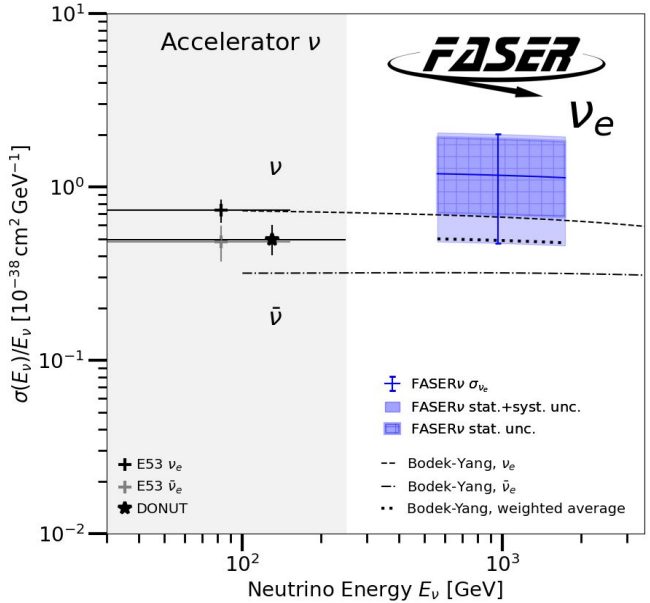


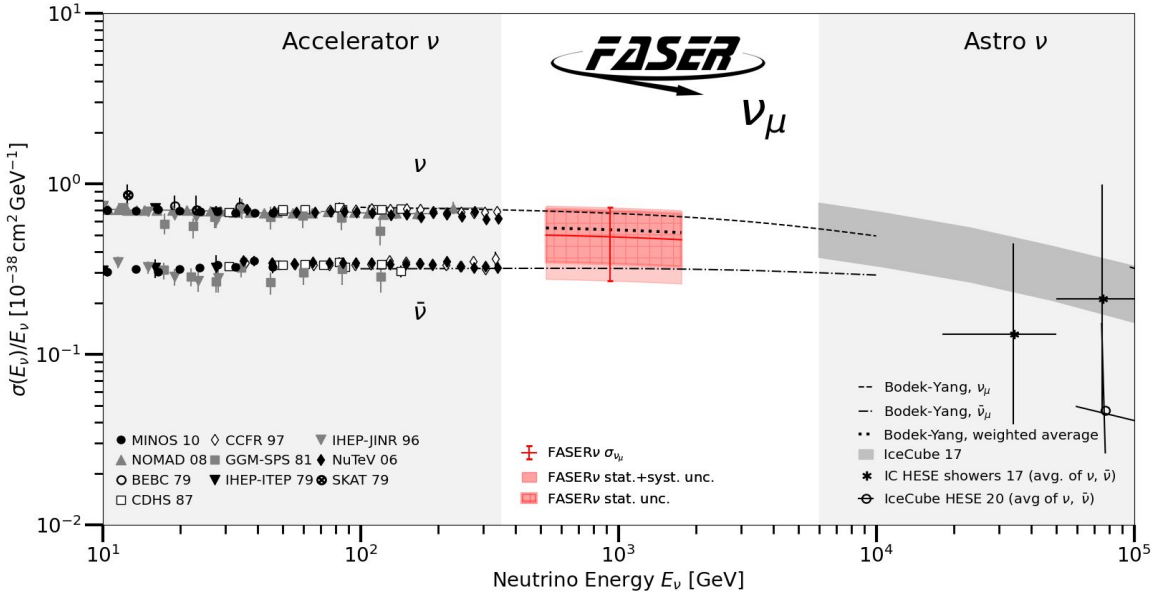
- Characteristics of the observed ν interactions are in good agreement with MC


ν_e
Beam view
FASER
"Pika-ν event"
e
1.5 TeV
100 μm


ν_μ
Beam view
FASER
μ
360 GeV
200 μm

First cross section measurement at TeV energies





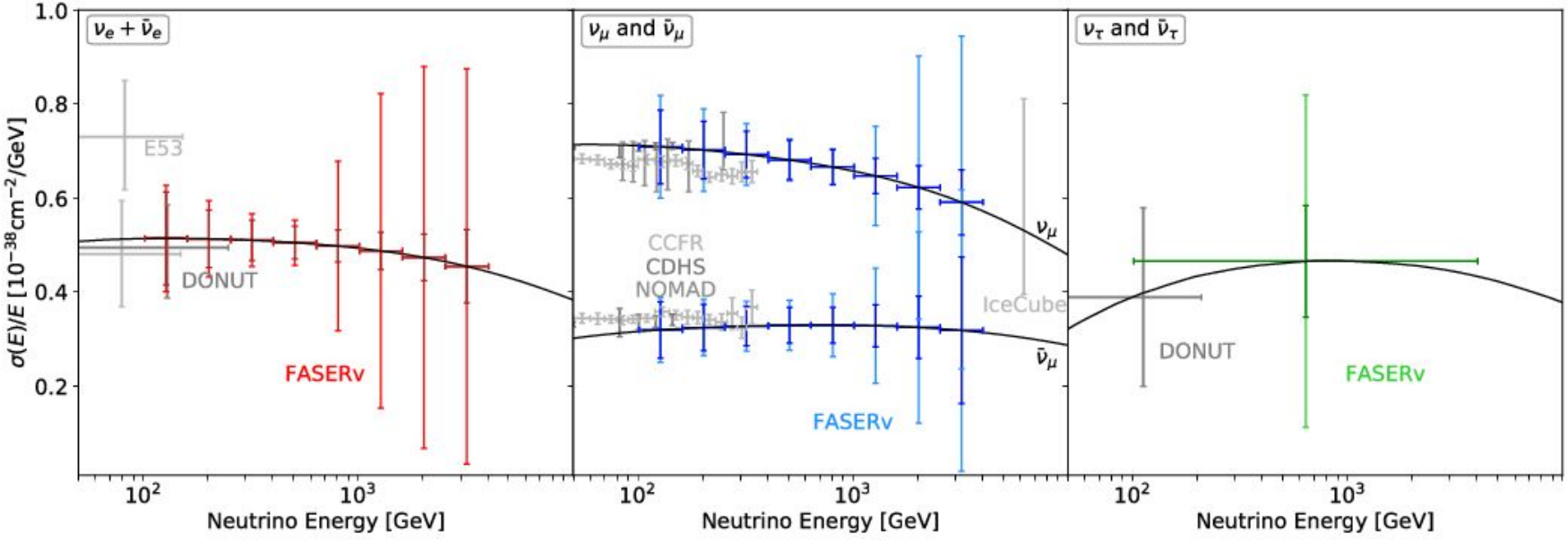
- **First measurement of the ν_e and ν_μ interaction cross section at the LHC with emulsion detector at TeV energy regions**
- L=9.5 fb^{-1}, m=128.6 kg
- To appear in PRL
- arXiv:2403.12520

Summary

- FASERν studies three flavor neutrinos at the **unexplored TeV energy regions**
- FASER is taking data in the far-forward direction of the LHC from 2022 to 2025
  - ~10,000ν interactions expected
- Excellent performances of the FASERν detector
  - **~300 nm position resolution, ~25% electron energy resolution**
  - **~30% muon momentum resolution** @300 GeV from the test beam result
- **First observation of ν_e at the LHC**
  - **4 ν_eCC and 8 ν_μ CC interactions are observed (signal significance of 5.2σ, 5.7σ respectively)**
- **First measurement of the ν_e and ν_μ cross sections at TeV energies** (with 1.7% of the data)
- Plan to analyze 10× more data for the next analysis
- Discussing extended physics programs in Forward Physics Facility in HL-LHC era

Backup

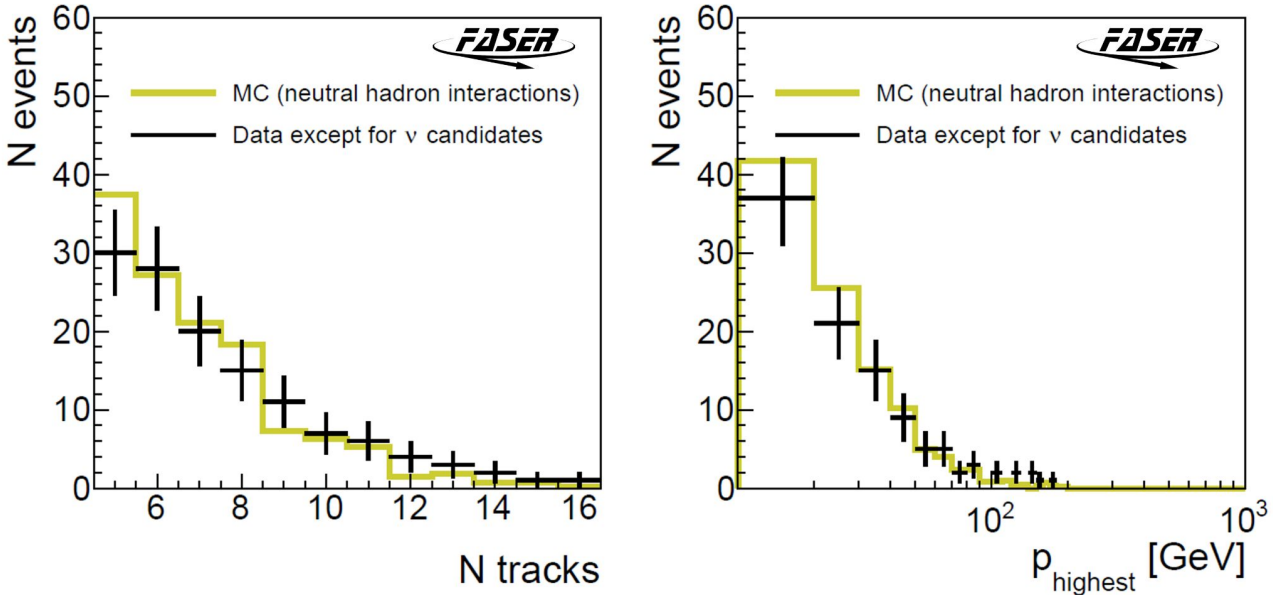
FASERν cross section sensitivity



(inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate)

- **Three flavors neutrino cross section at unexplored TeV energy regions**
- Neutrino energy reconstruction with resolution of 30% expected from simulation studies

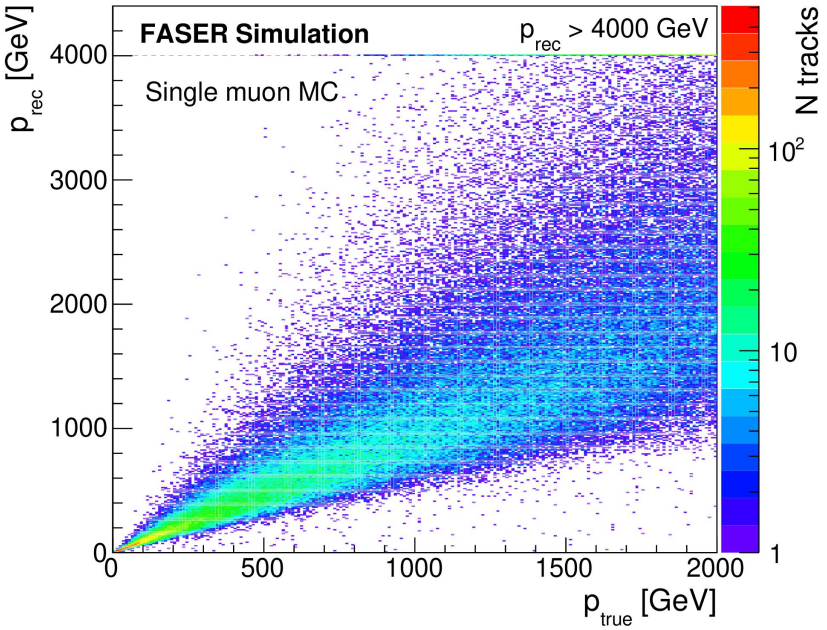
Validation of background simulation

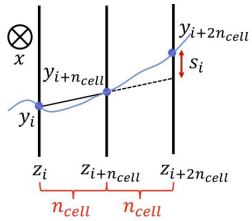


The MC distributions are normalized to the number of events observed in the data

- The modeling of the neutral-hadron backgrounds are validated using data
  - The number of interaction is compatible at better than 50%
  - The shape of the distributions are well modelled

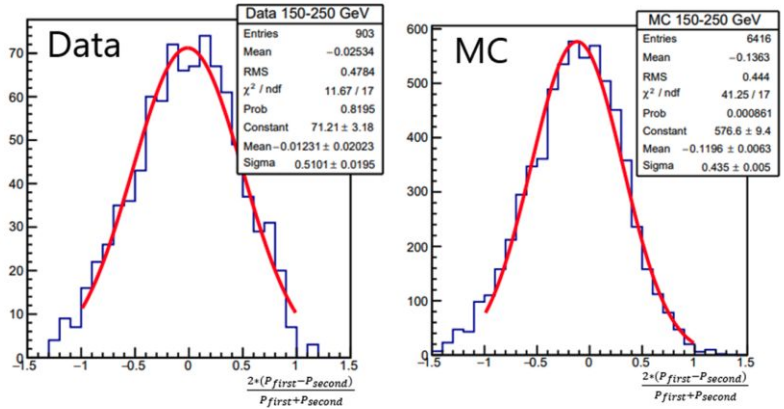
Muon momentum measurement



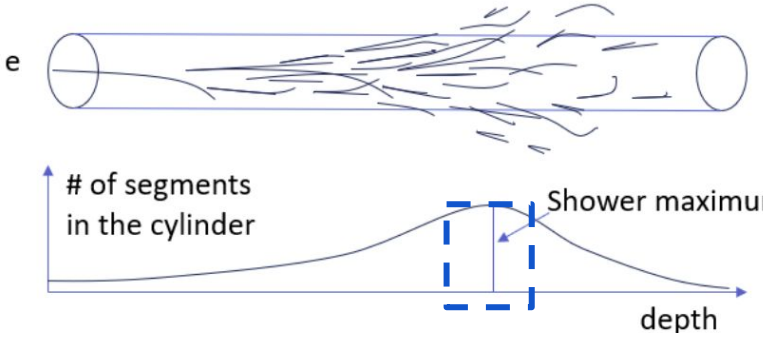


$$s_{plane}^{RMS} = \sqrt{\left(\sqrt{\frac{2}{3}} \cdot \frac{13.6MeV}{P} n_{cell} \cdot z_{cell} \sqrt{\frac{n_{cell} \cdot z_{cell}}{X_C}}\right)^2 + \left(\sqrt{6}\sigma_{pos}\right)^2} \quad \ldots(1)$$

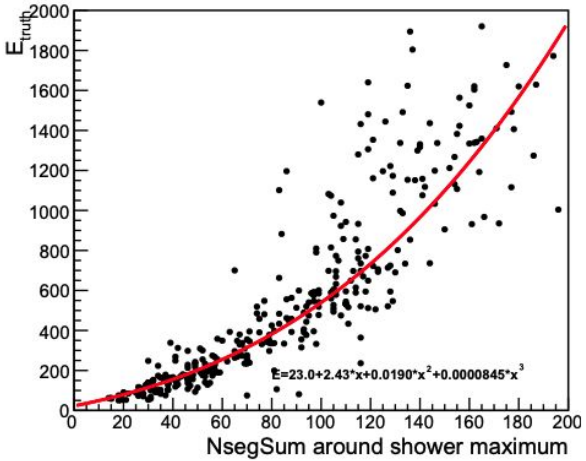
z_{cell} : The thickness of one emulsion film and tungsten plate
X_C : Compound radiation length (4.57 mm, cf: X_W=3.5 mm)
σ_{pos} : Position resolution

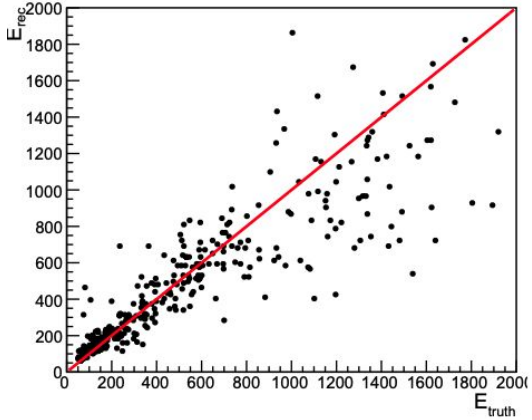


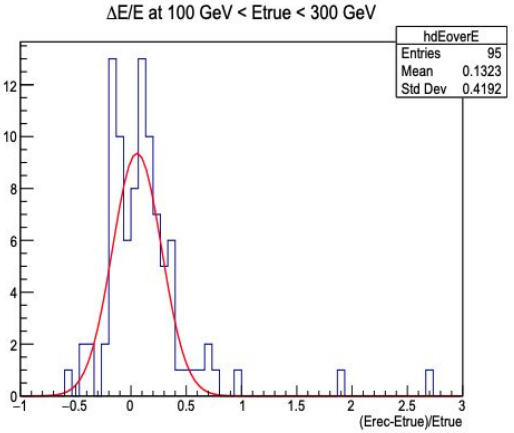
Electron energy measurement



$\delta \mathrm{pos} < 100\ \mu\mathrm{m}$
$\delta\theta < 10\ \mathrm{mrad}$
$d\mathrm{min} < 50\ \mu\mathrm{m}$







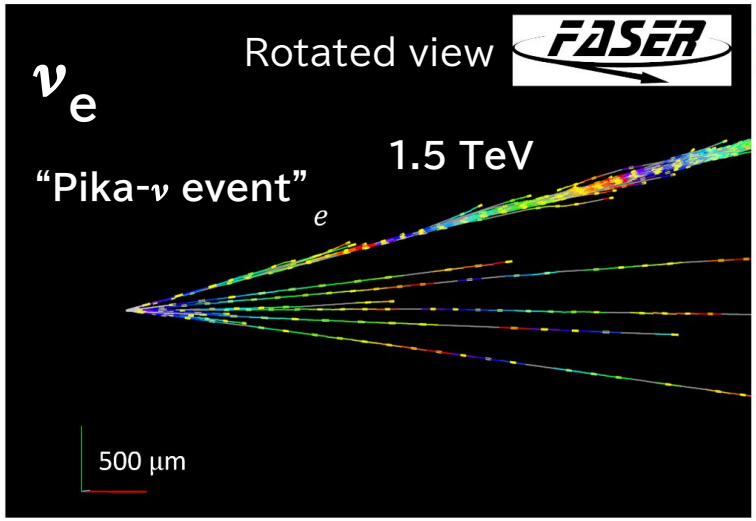
Efficiencies of the selection

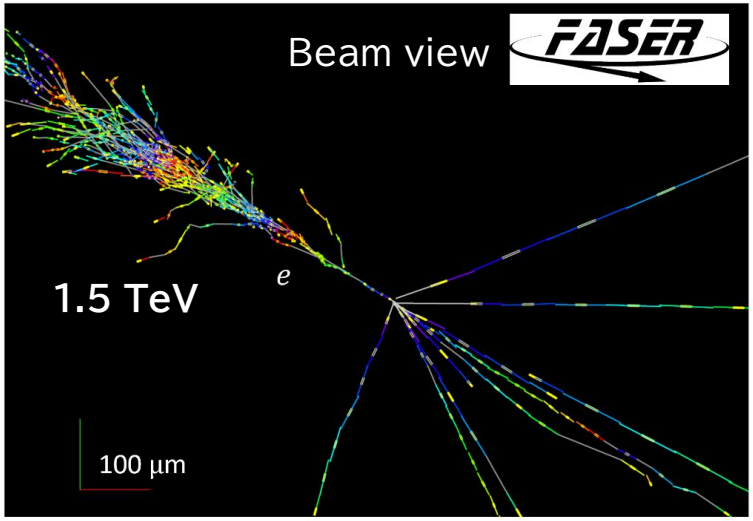
Selection	ν_e CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction and $N_{\text{track}} \geq 5$	0.516	0.336	0.813	0.803	0.753
E_e >200 GeV	0.340	0.001	0.000	0.000	0.000
E_e >200 GeV, tanθ >0.005	0.270	0.001	0.000	0.000	0.000
E_e >200 GeV, tanθ >0.005. $\Delta\phi$>90deg	0.244	0.000	0.000	0.000	0.000

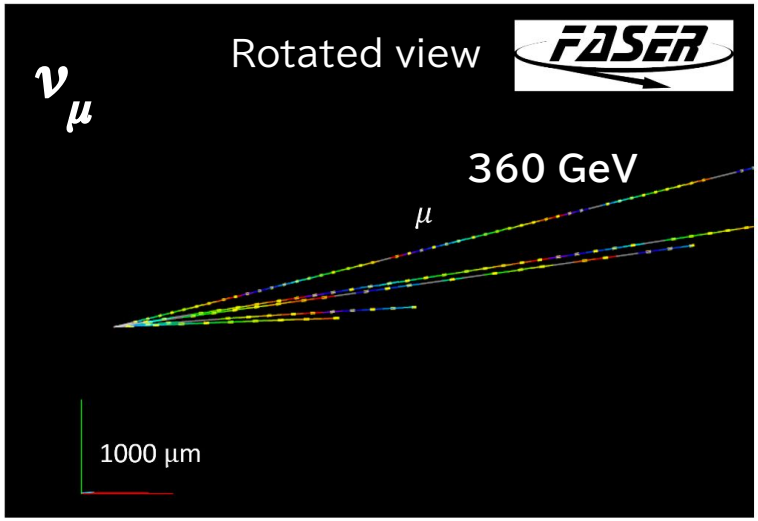
Selection	ν_μ CC	ν NC	K_L	n	Λ
	1.000	1.000	1.000	1.000	1.000
Vertex reconstruction and $N_{\text{track}} \geq 5$	0.446	0.336	0.813	0.803	0.753
p >200 GeV	0.284	0.071	0.028	0.026	0.018
p >200 GeV, tanθ >0.005	0.236	0.051	0.007	0.013	0.007
p >200 GeV, tanθ >0.005. ϕ>90deg	0.221	0.004	0.002	0.006	0.004

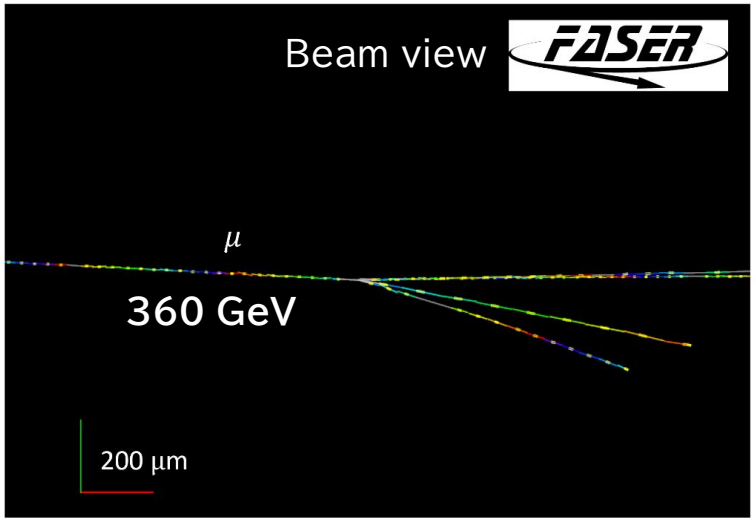
Systematic uncertainty

Source	Relative uncertainty	
	ν_e	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) $^{+30}_{-21}$% (other)	$^{+16}_{-9}$% (flux) $^{+31}_{-21}$% (other)


Rotated view
FASER
ν_e
"Pika-ν event"
1.5 TeV
e
500 μm


Beam view
FASER
1.5 TeV
e
100 μm


Rotated view
FASER
ν_μ
360 GeV
μ
1000 μm


Beam view
FASER
μ
360 GeV
200 μm