Neutrino Physics at the ForwArd Search ExpeRiment

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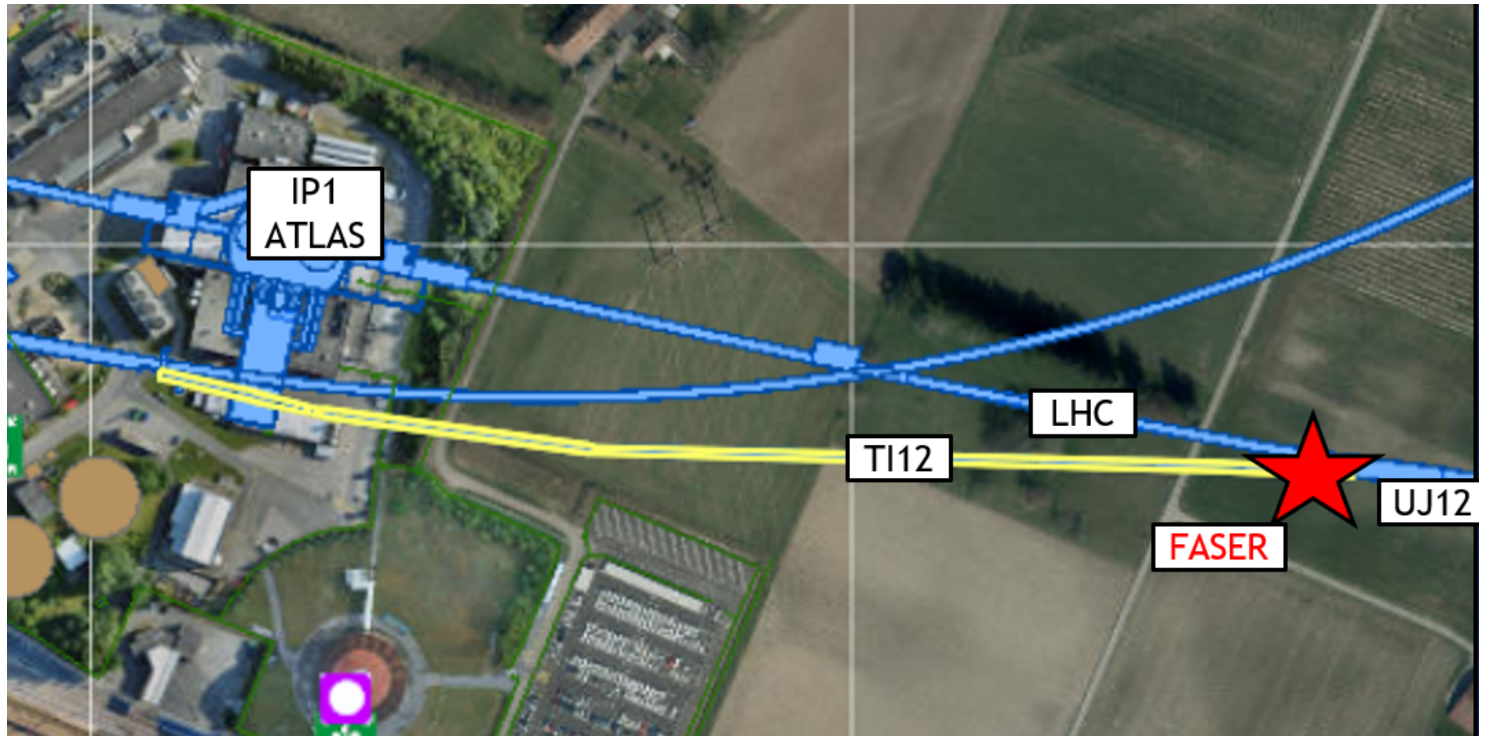
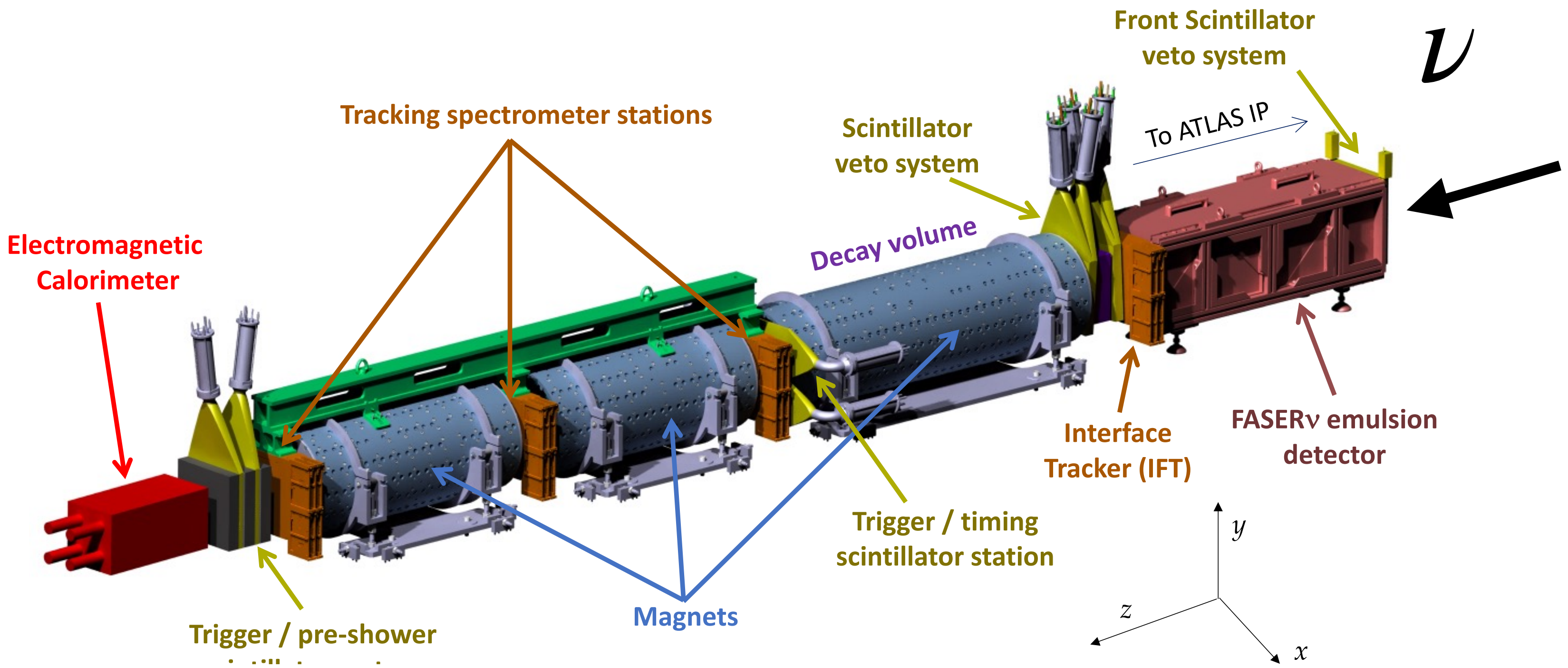
on behalf of the FASER collaboration

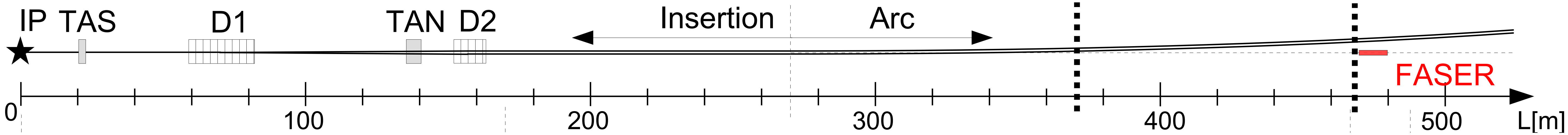
Lake Louise Winter Institute 2024
2024 Feb. 18-23

The FowArd Search ExpeRiment (FASER)

An experiment at LHC for Neutrino measurements & Long-lived particle search







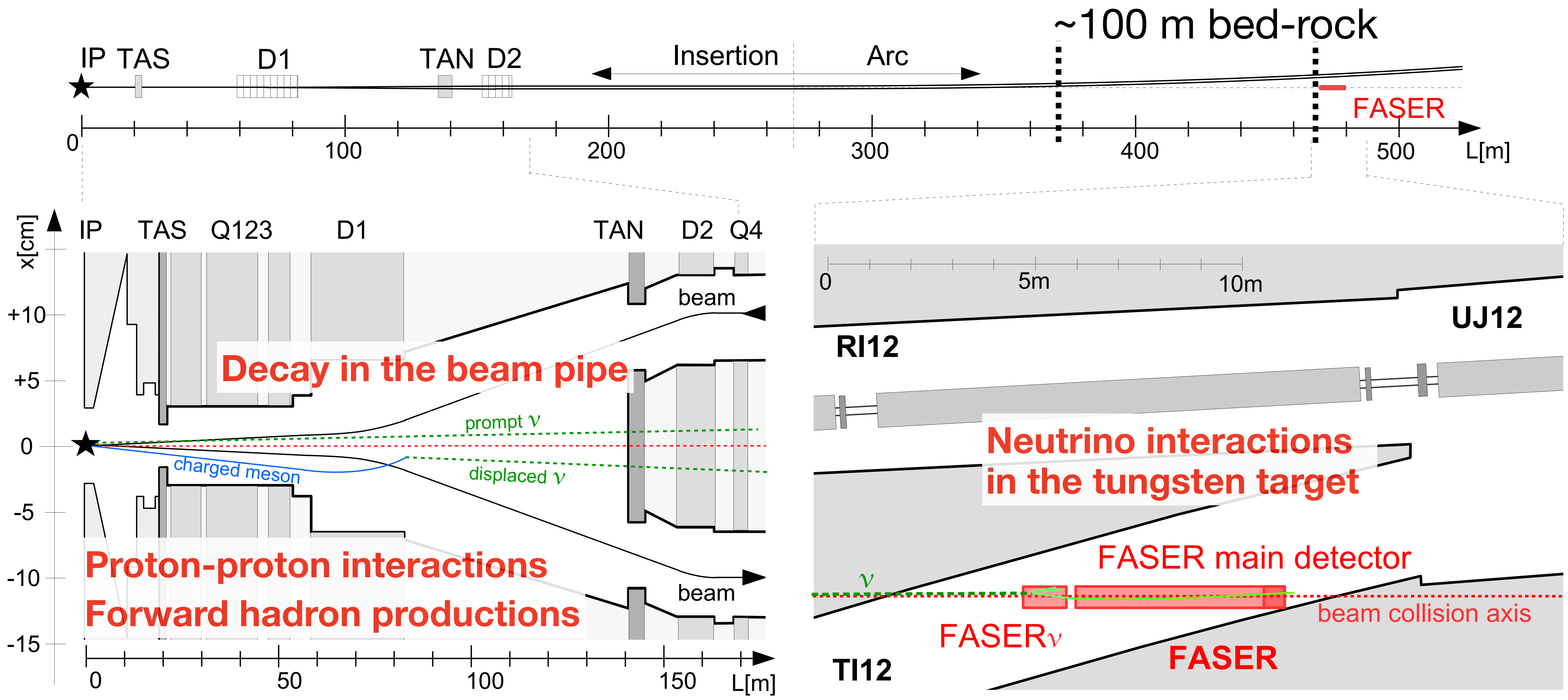
~100 m bed-rock

In this talk, I focus on the Neutrino program

For Long-lived particle search, see Eli's talk on Friday

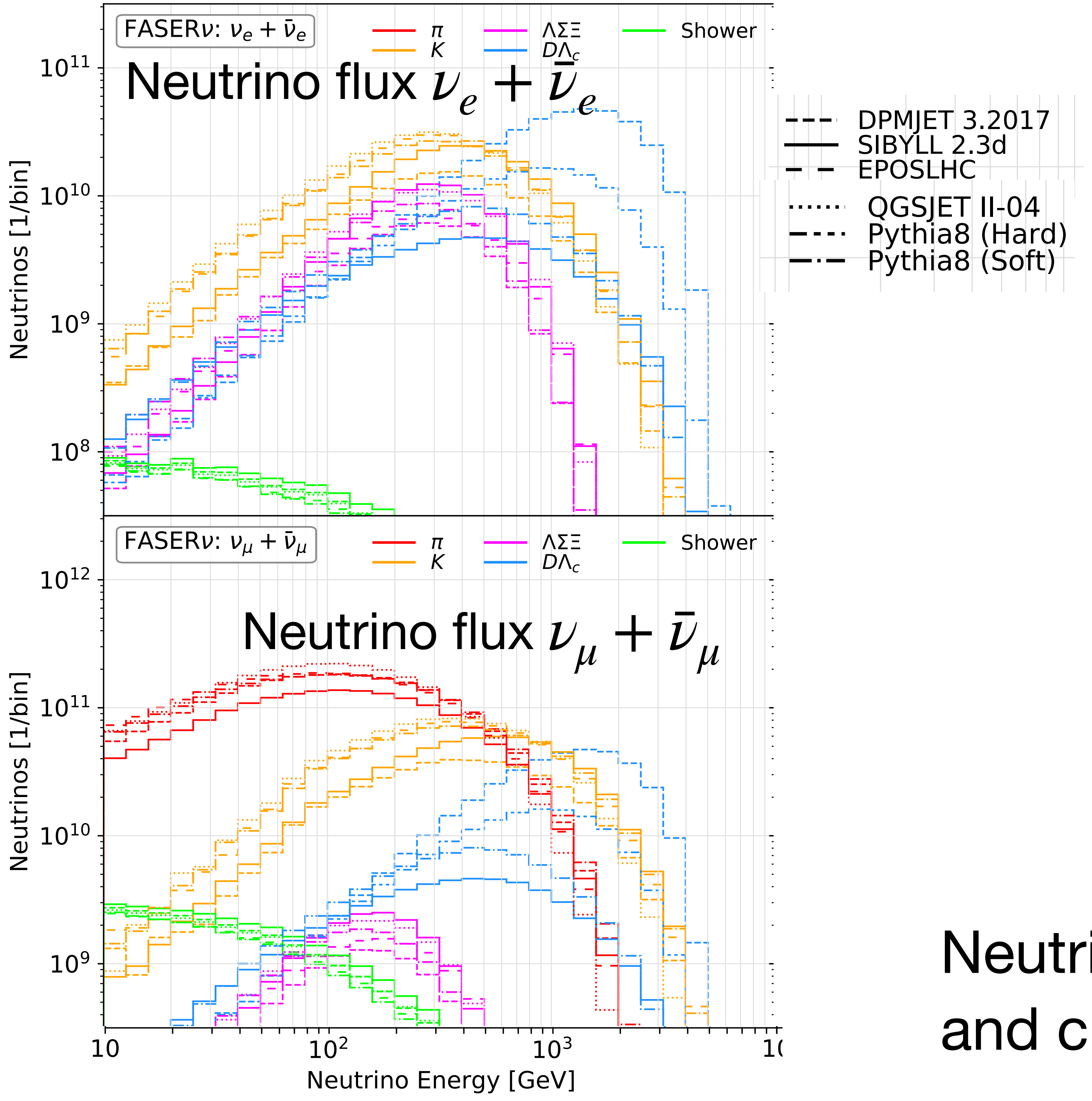
Figures from arxiv 2207.11427 & 1908.02310

Neutrinos at the FASER detector



Figures from arxiv 2207.11427 & 1908.02310

Neutrino flux expectations



Expected charged-current neutrino interaction (250 fb^{-1})

Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1501	7971	24.5
DPMJET	DPMJET	5761	11813	161
EPOSLHC	Pythia8 (Hard)	2521	9841	57
QGSJET	Pythia8 (Soft)	1616	8918	26.8
Combination (all)		2850^{+2910}_{-1348}	9636^{+2176}_{-1663}	67.5^{+94}_{-43}
Combination (w/o DPMJET)		1880^{+641}_{-378}	8910^{+930}_{-938}	$36^{+20.8}_{-11.5}$

Felix Kling, Laurence J. Nevay, arxiv 2105.08270

Neutrinos from light hadron decays, e.g. π, K, and charmed hadron decays, e.g. D, Λ_c.

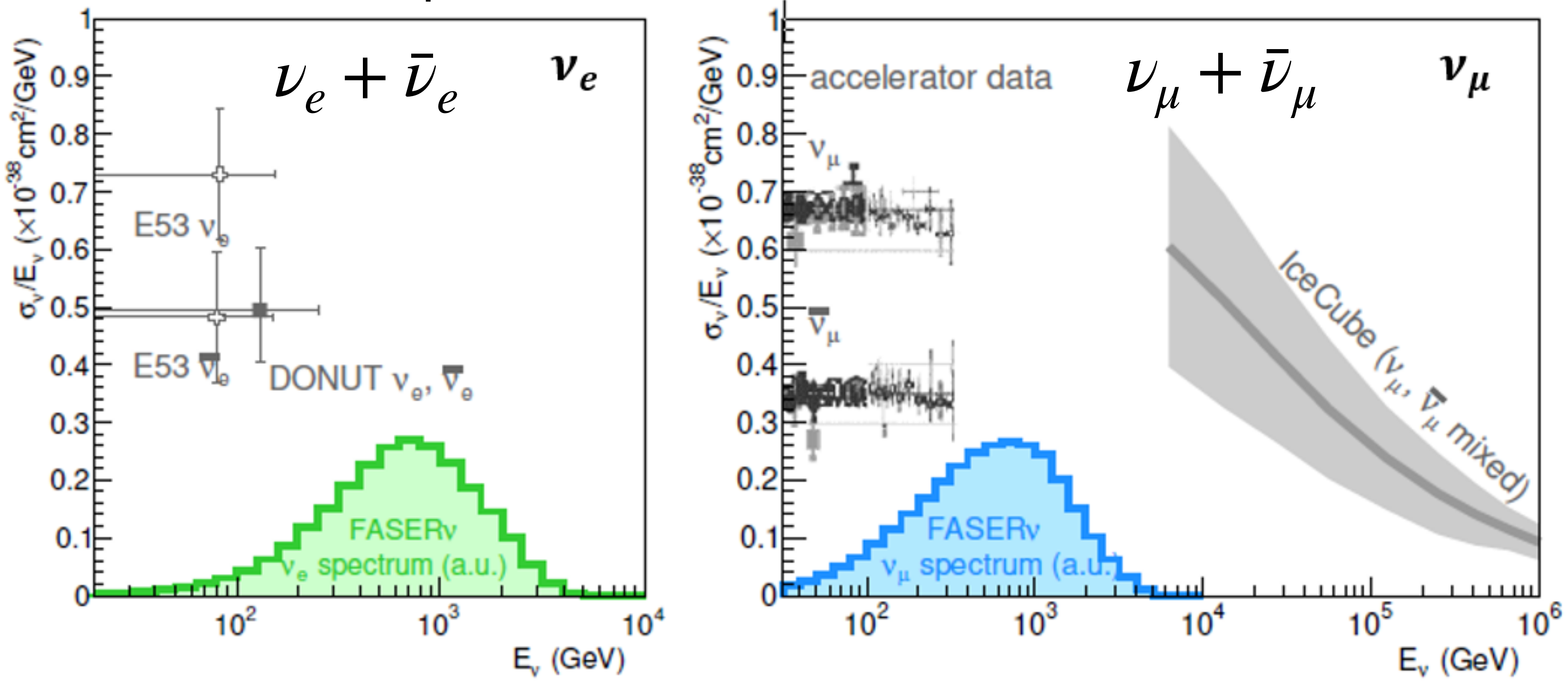
Physics motivation for neutrino measurements

Neutrino-nucleus interactions

Interactions of TeV neutrinos and tungsten targets

Cross-section measurements for different flavors

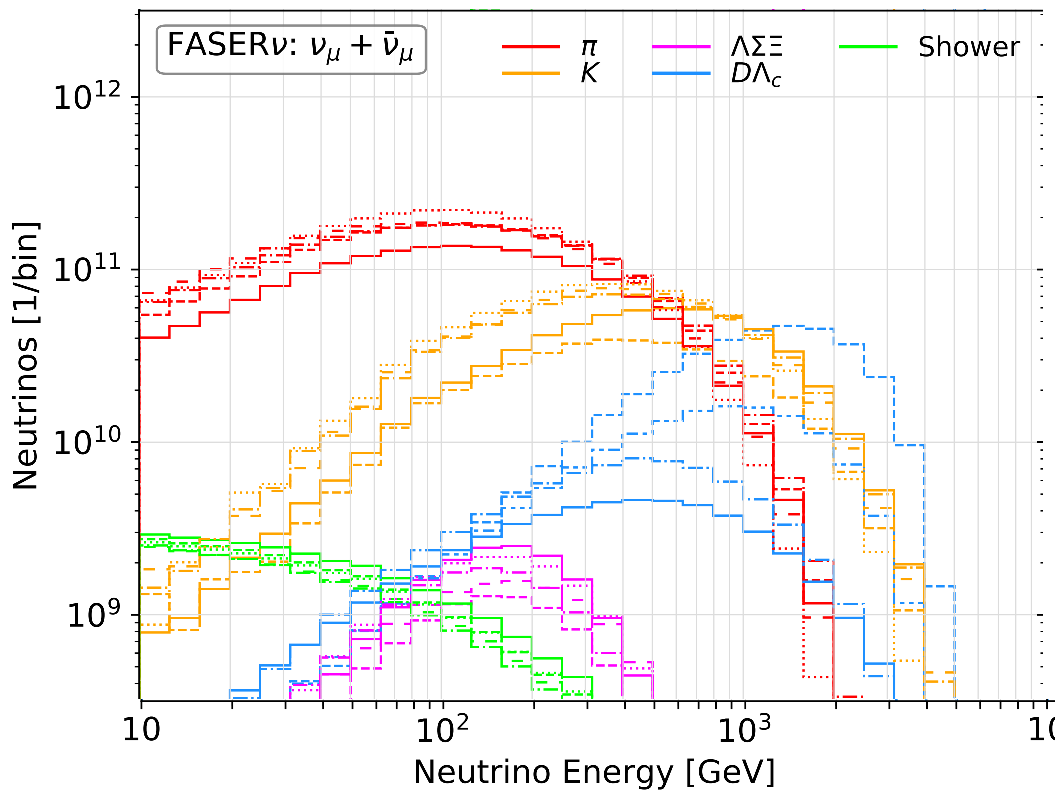
Expected neutrinos



Forward hadron productions using neutrinos

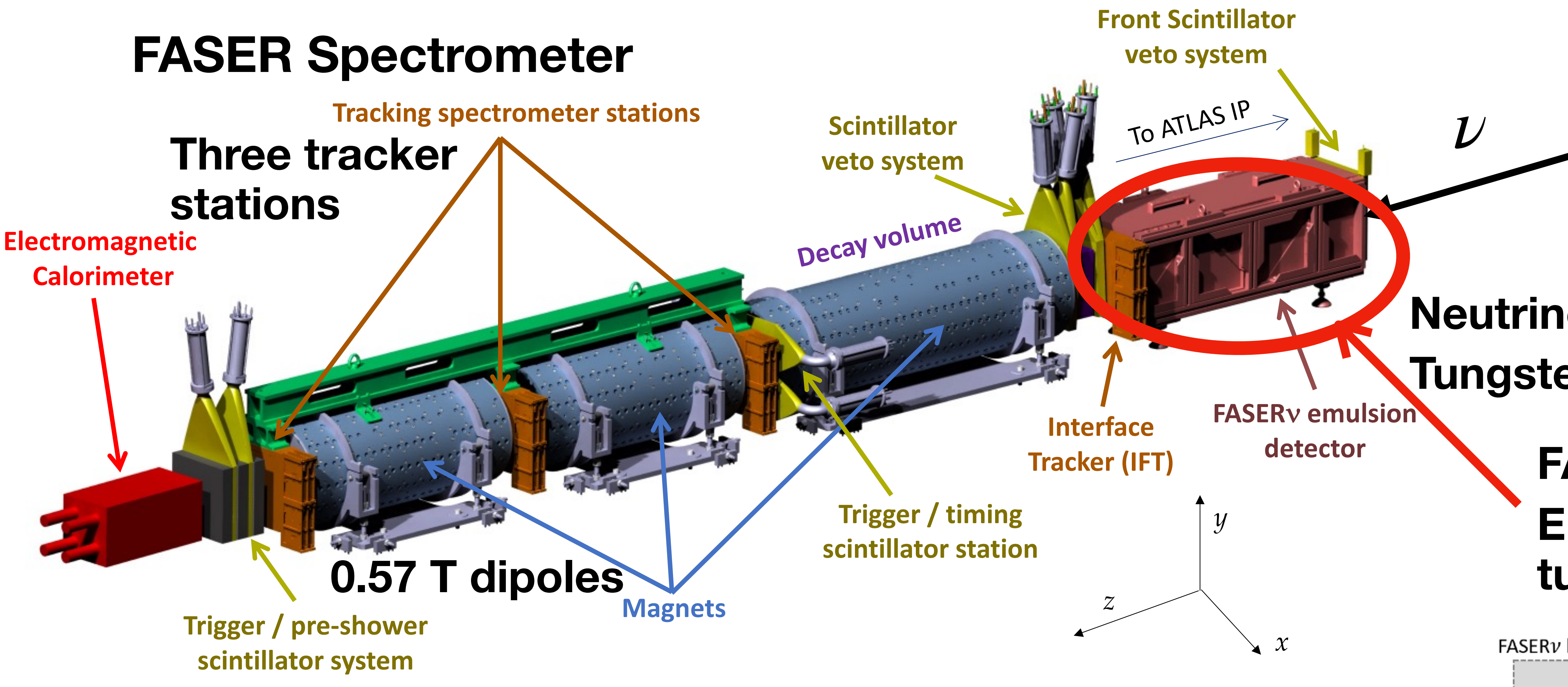
Probing forward light hadron and charmed hadron productions

-> Good inputs for cosmic-ray physics



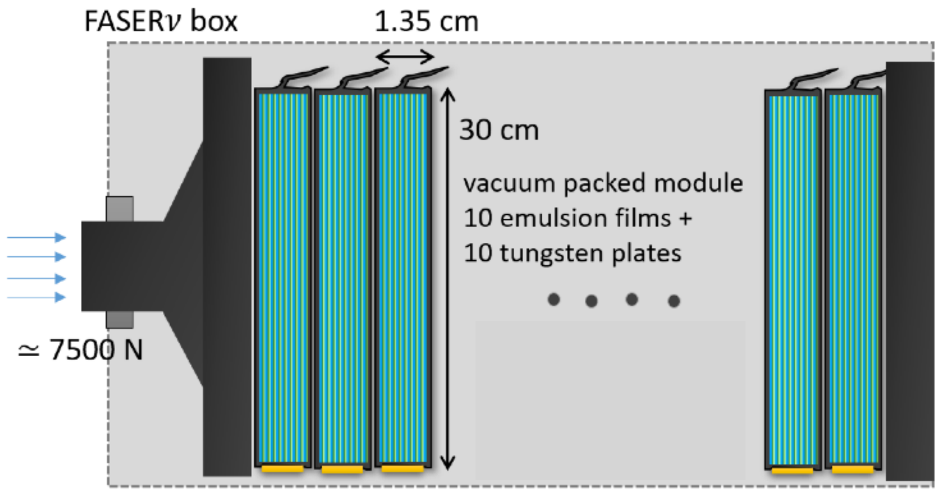
Figures from arxiv 2105.08270 & 1908.02310

The FASER detector



FASERν detector

Emulsion films between tungsten plates



Successful data-taking during 2022 and 2023

Total ~68.4 fb^{-1}

FASERν detector was installed 5 times in total

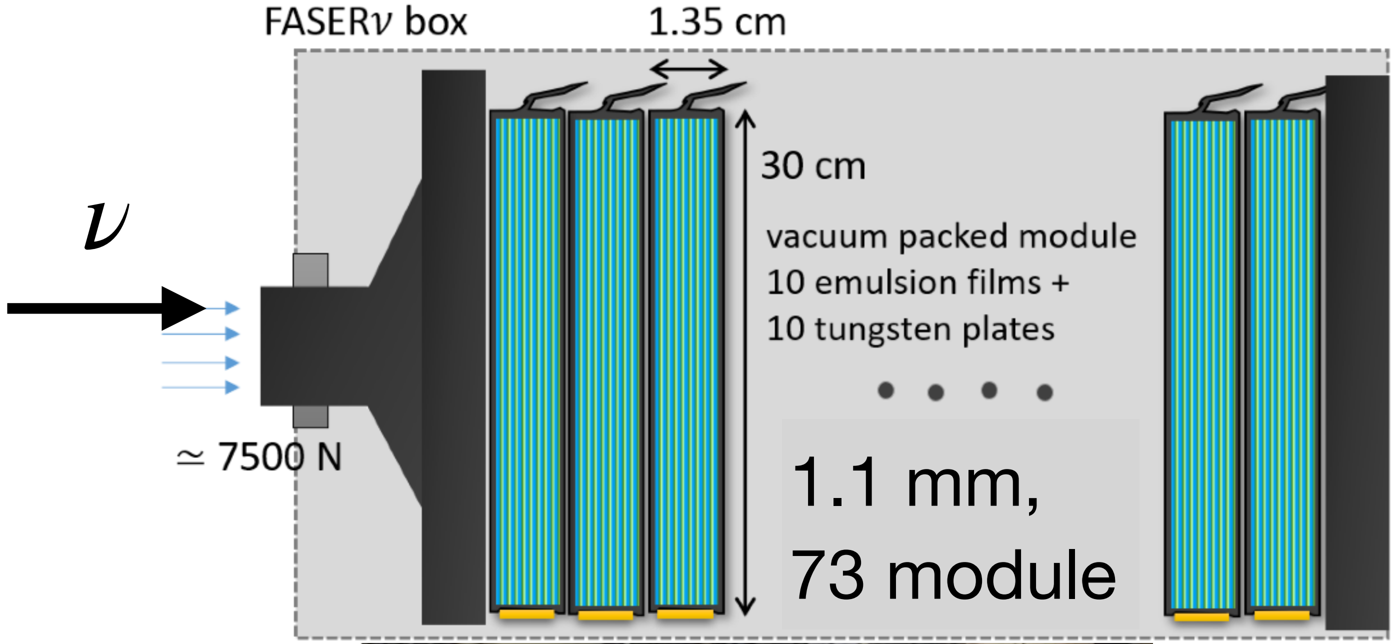
The FASERν detector

FASERν detector

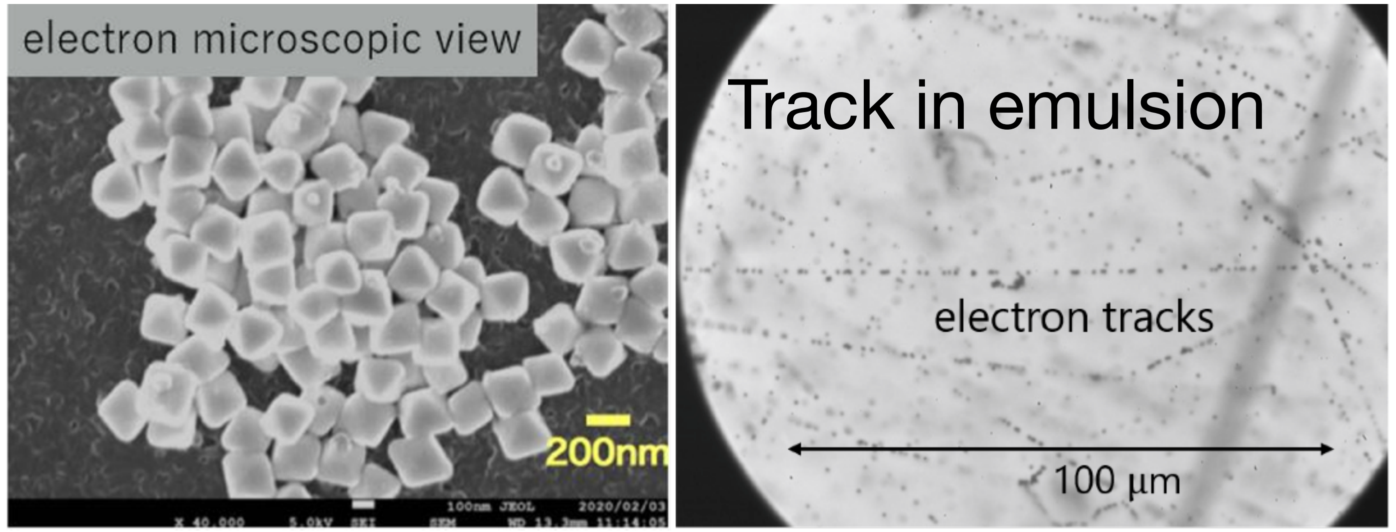
Emulsion films between tungsten plates

1.1 mm tungsten plates x 730: target

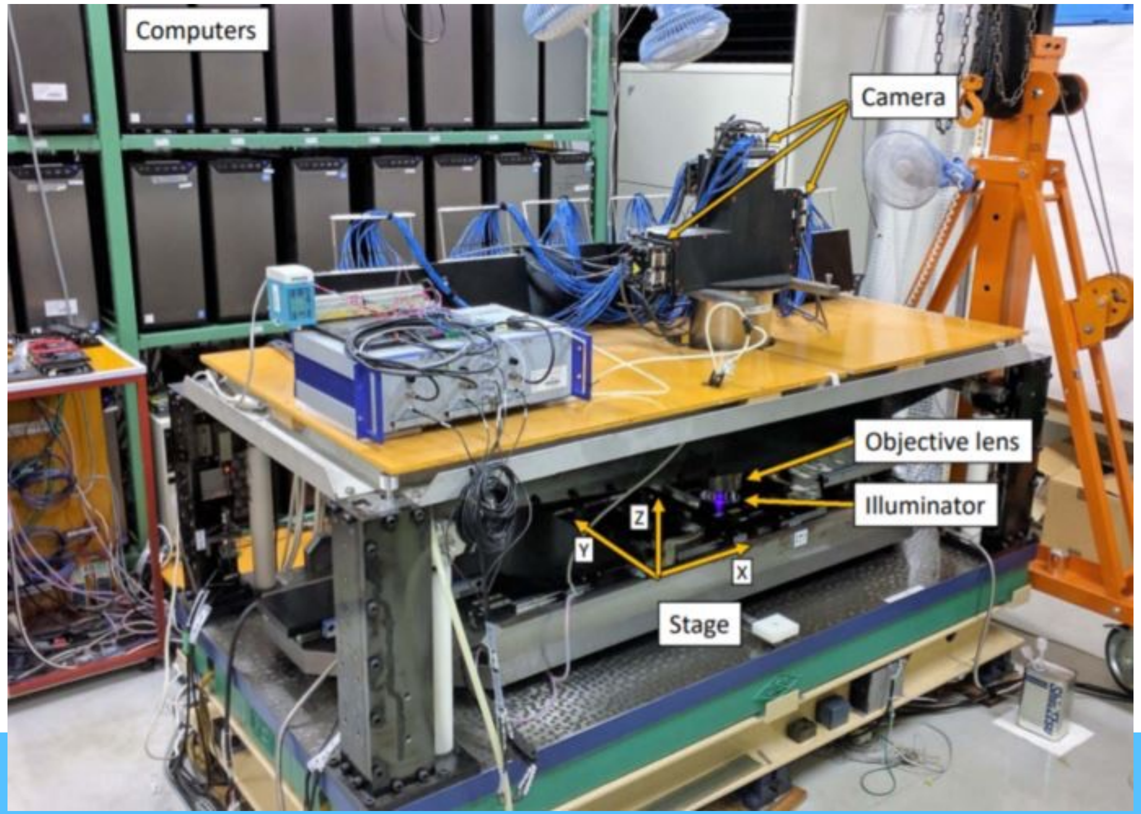
Emulsion film x 730: to measure tracks



Emulsion films (25cm x 30cm)



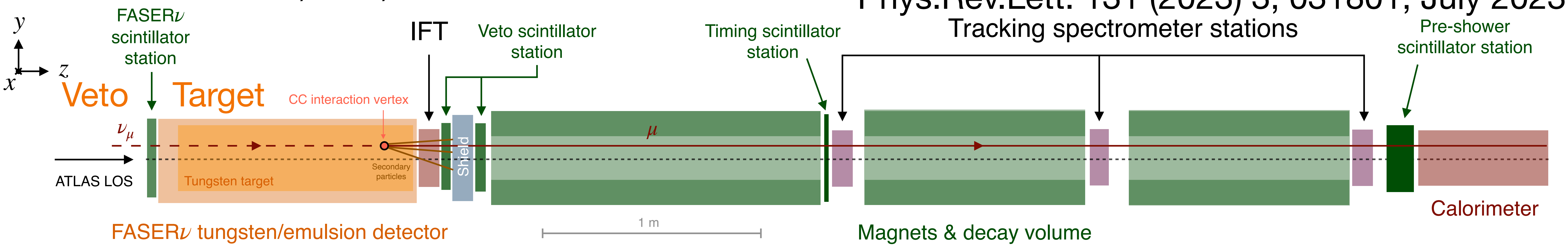
Microscope in Nagoya Univ.



Analysis using the FASER spectrometer

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

FASER Collaboration,
Phys.Rev.Lett. 131 (2023) 3, 031801, July 2023



Event selections

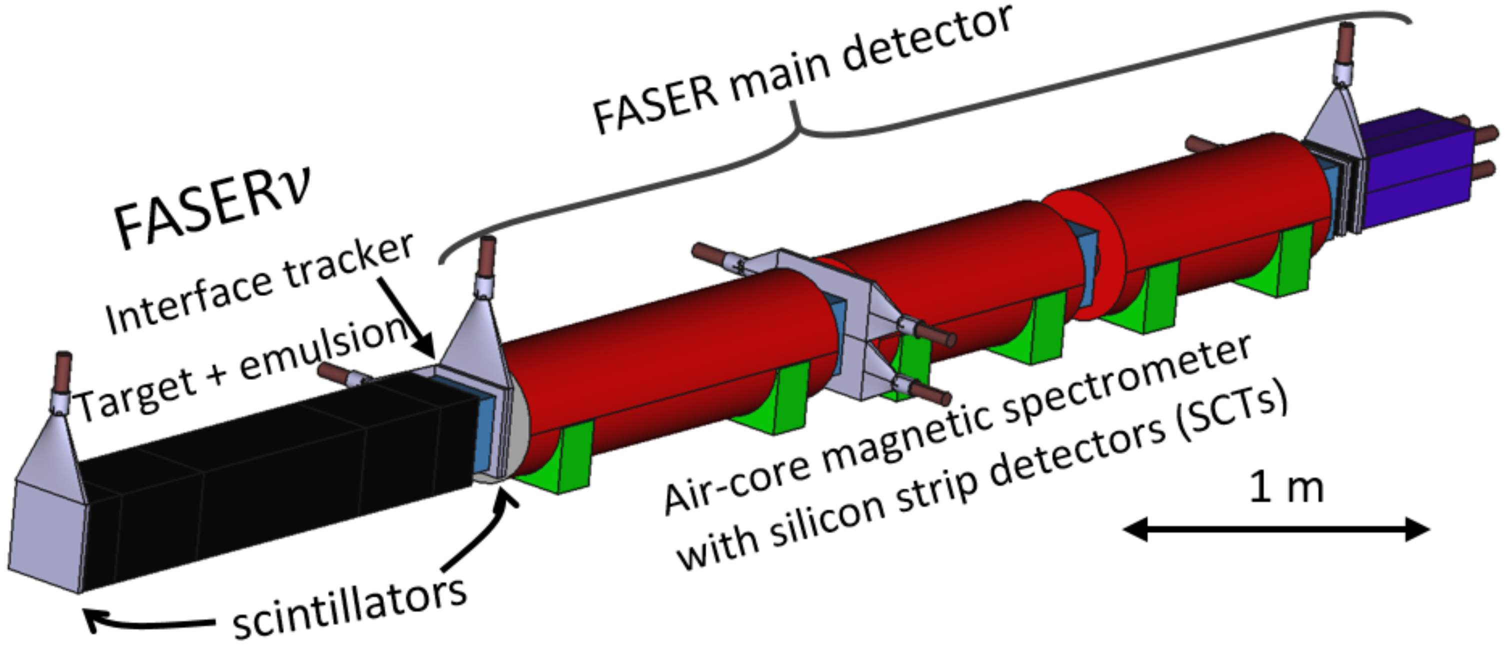
Signals

One track with > 100 GeV

- Collision event with good data quality (35.4 fb-1)
- No signal in two front veto scintillators(<40 pC~0.5 MIP)
- Signal in last two veto layers
- Signal in calorimeter consistent with ≥1 MIPs
- Exactly one good quality spectrometer track with >100 GeV
- Track in fiducial tracking volume, <95 mm
- Track extrapolate to <120 mm in front veto scintillator

designed to observe neutrinos for the first time at a collider

Backgrounds



Neutral hadron background

0.11 ± 0.06

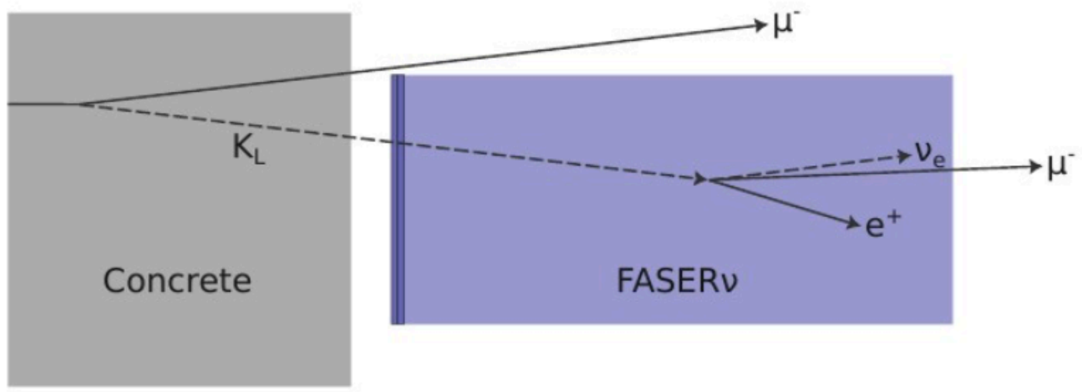
Scattered muons

0.08 ± 1.83

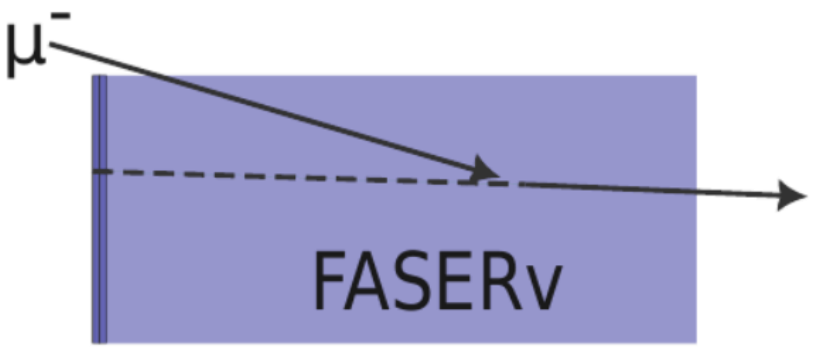
Veto inefficiency

Negligible

Neutral hadrons



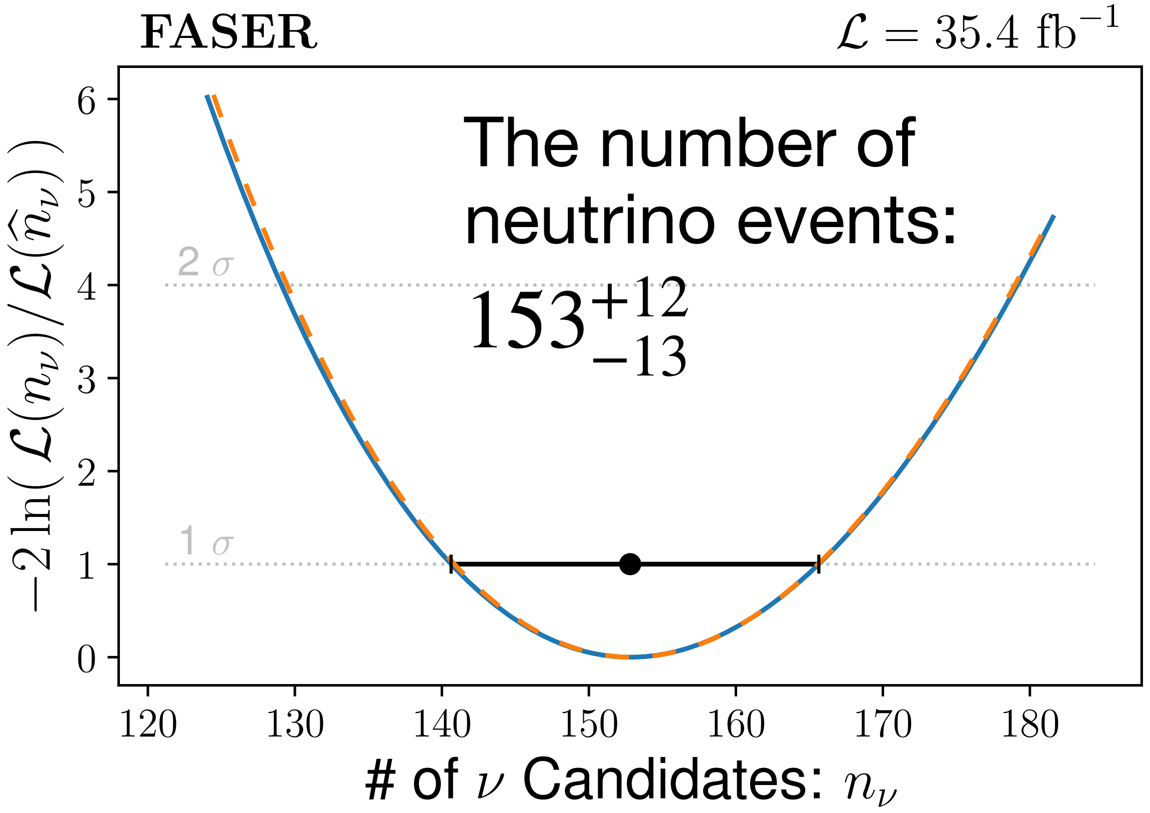
Scattered muons



Veto inefficiency

Neutrino detections by the FASER spectrometer

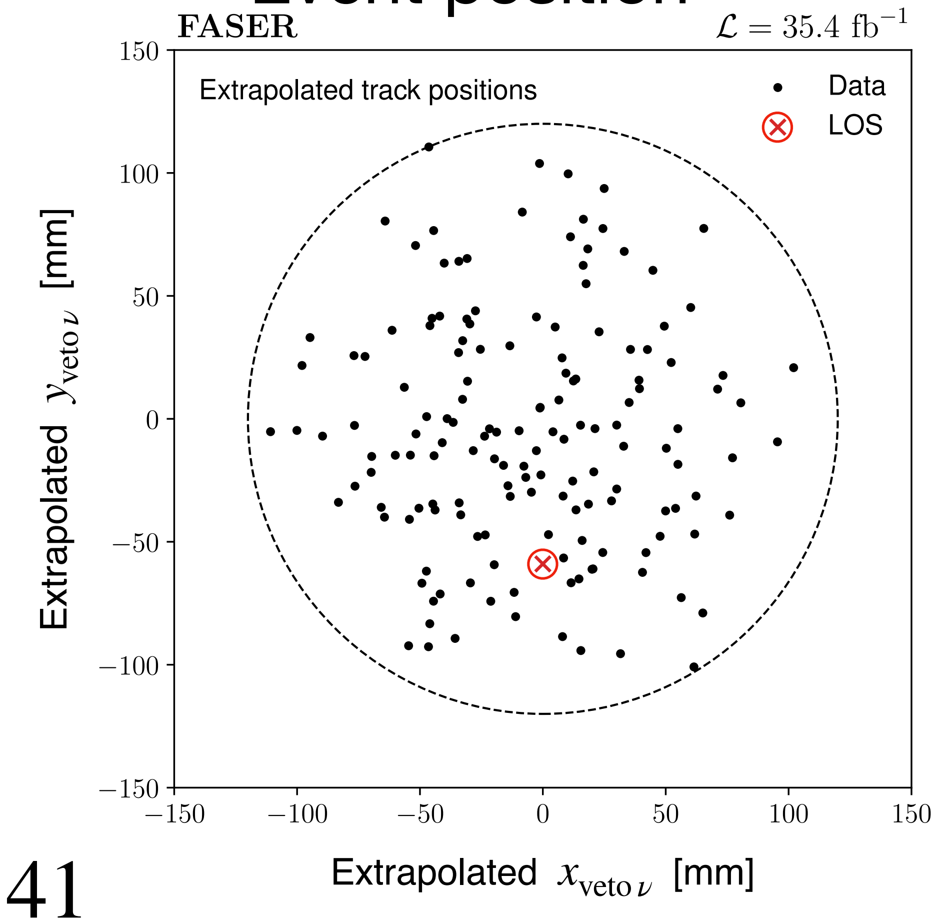
153 events passed, 16 σ

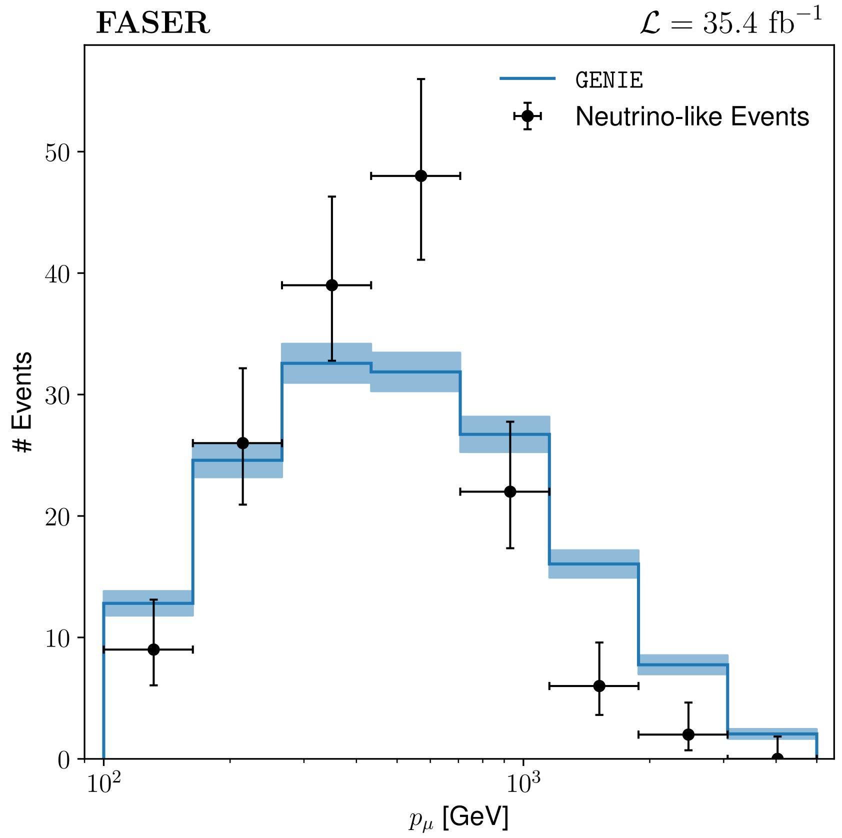


Expected by simulations 151 ± 41

(Average & differences btw two generators)

Event position

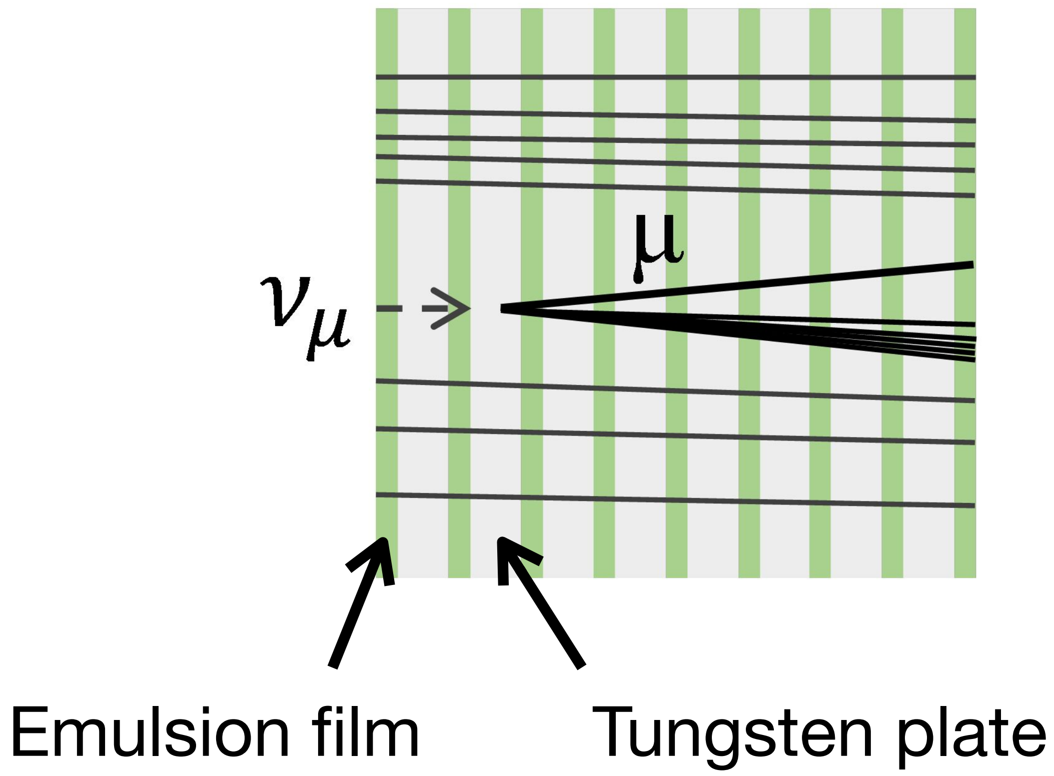


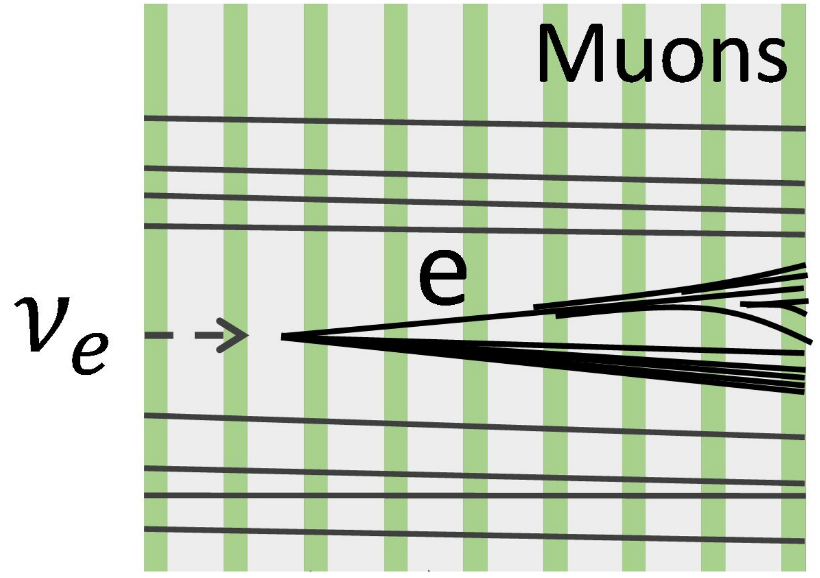


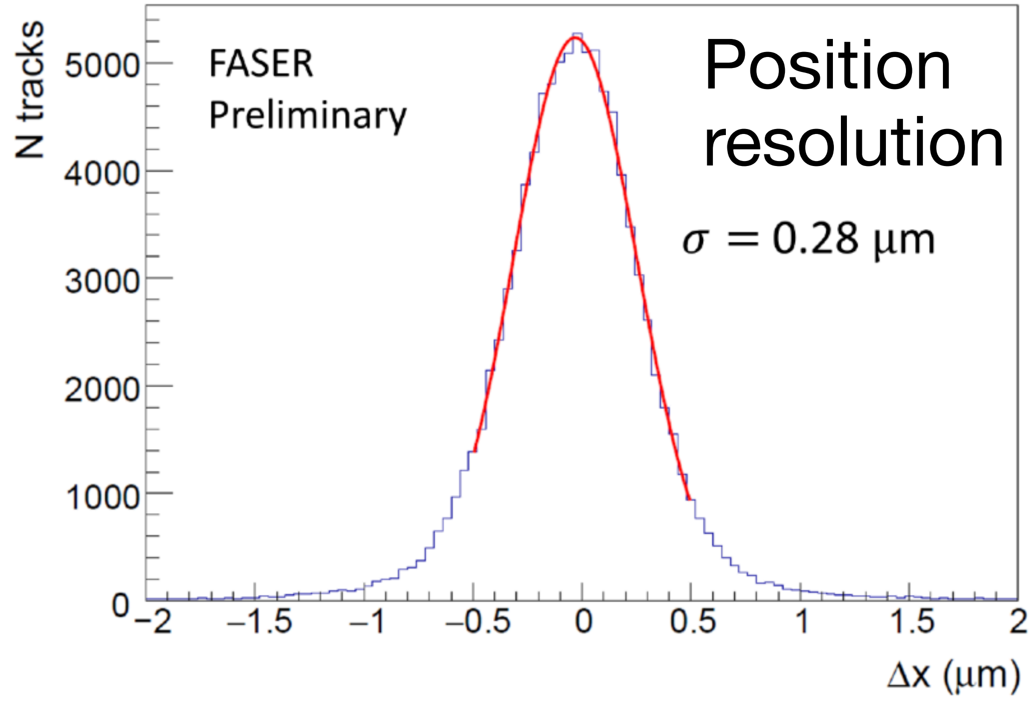
Reconstructed muon momentum

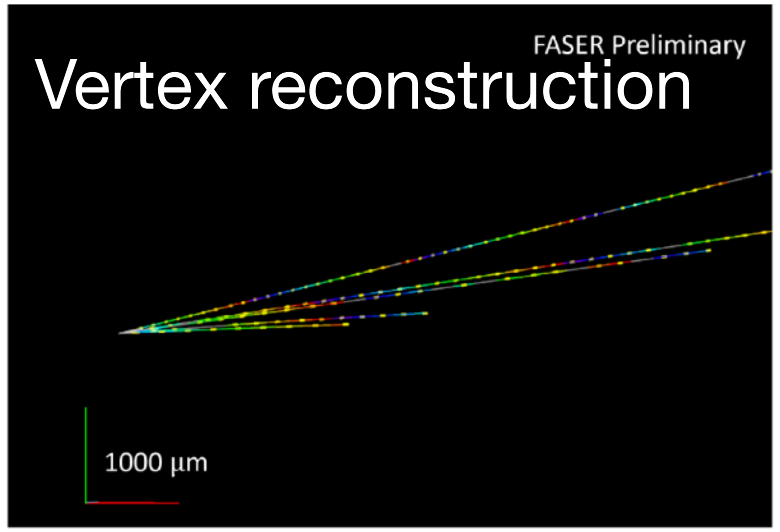
First direct detection of neutrinos produced at a collider experiment

Analysis using the FASERν detector





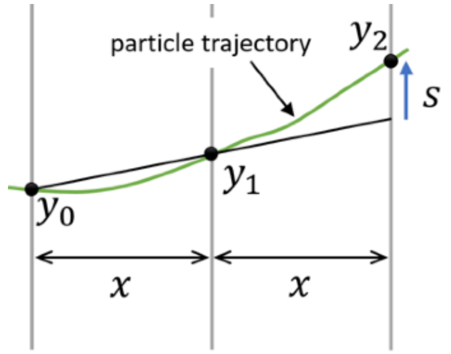




Muon momentum estimation

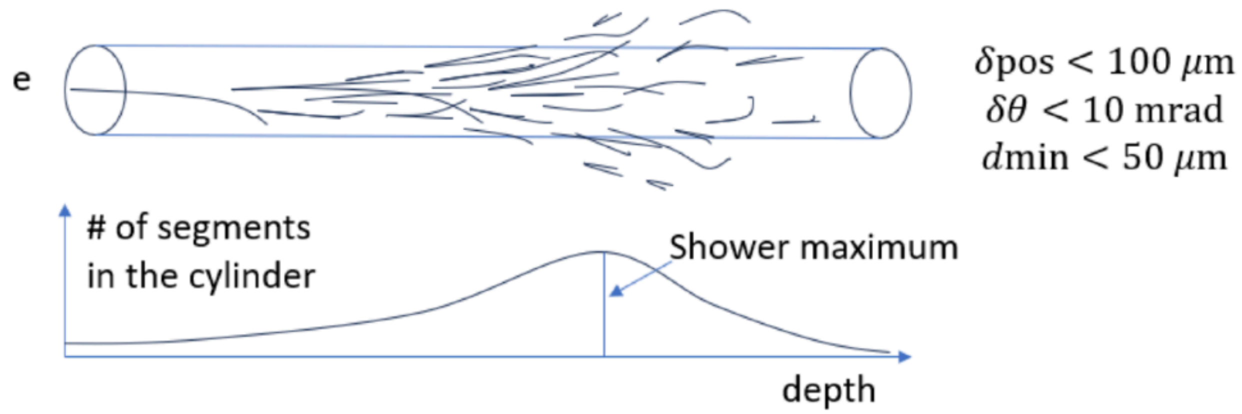
Multiple coulomb scattering

Momentum dependency in the scattering angle



Resolution: ~20% at 200 GeV

EM shower energy estimation



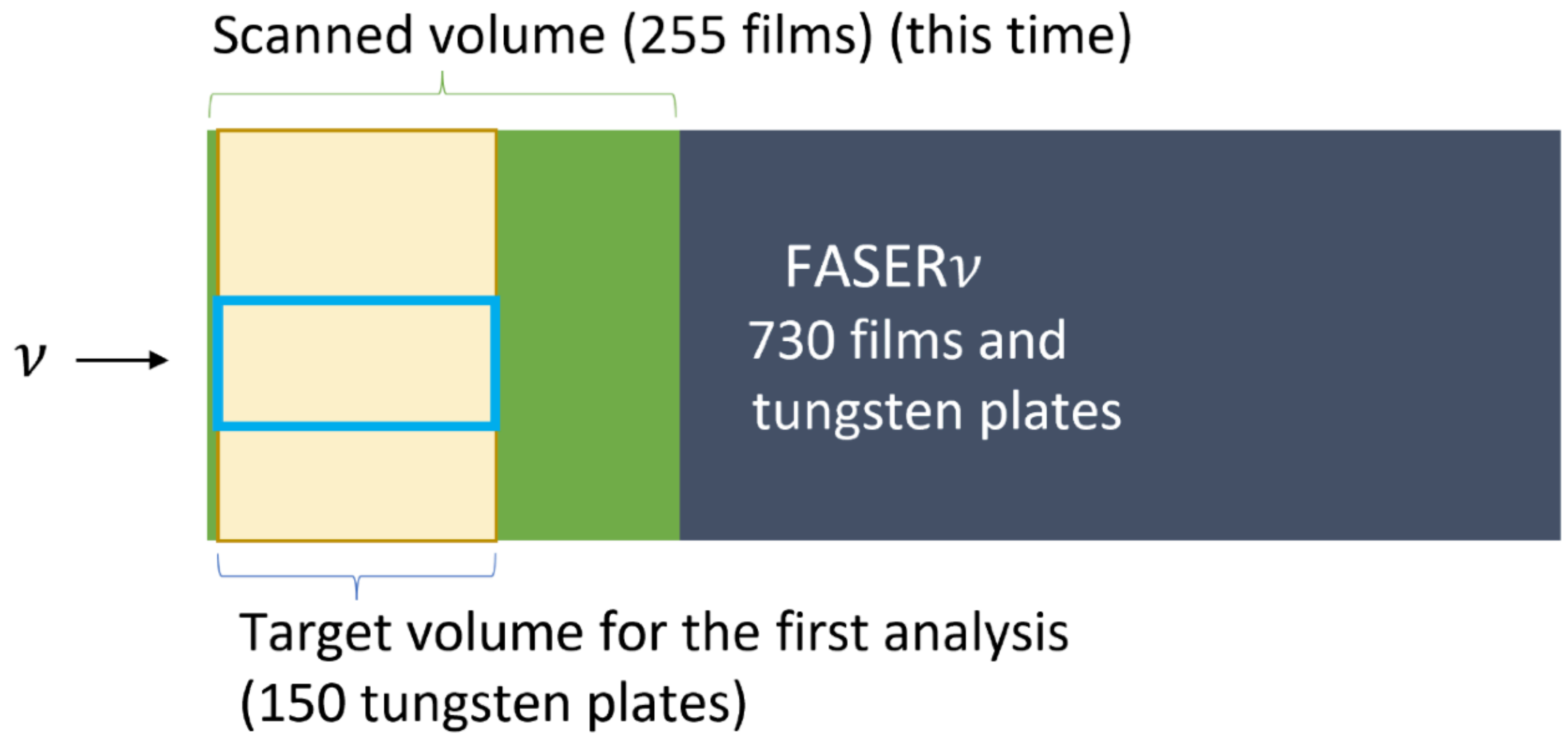
Resolution: ~25% at 200 GeV

Event selection

FASER Collaboration
CERN-FASER-CONF-2023-002 (Aug. 2023)

2nd module of 2022,

Installed from July 26th to September 1, 9.5 fb^{-1}

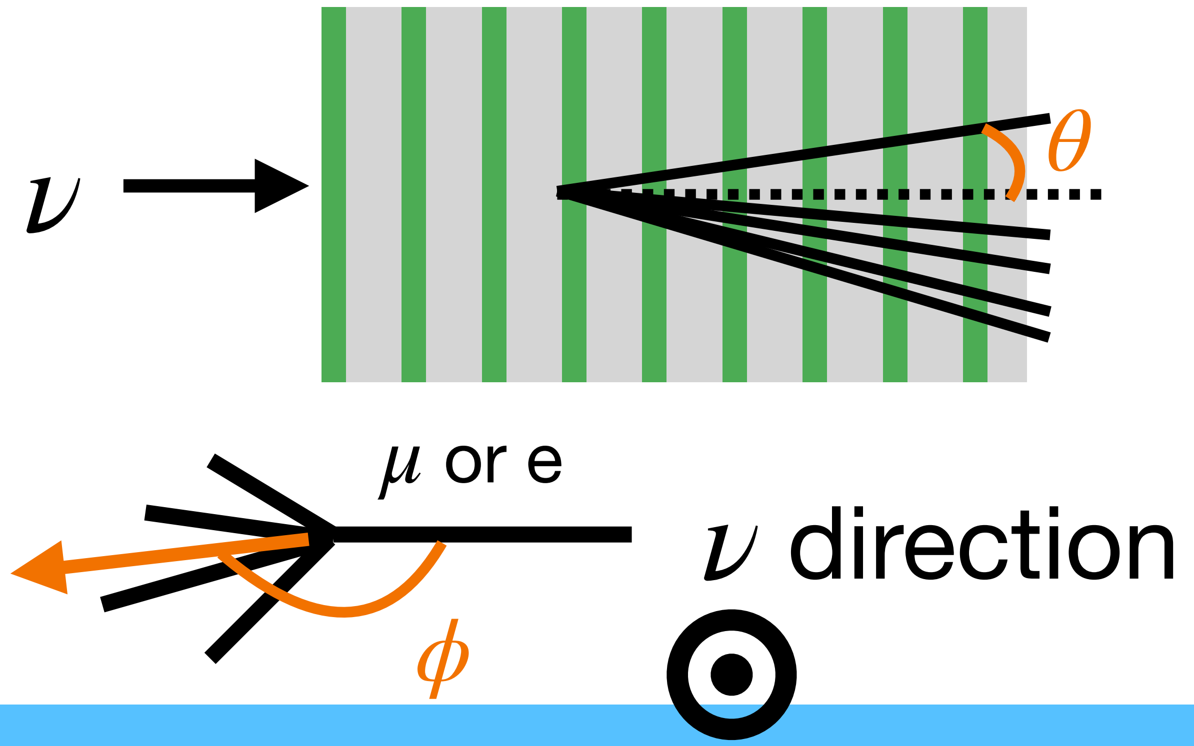


Main background: neutral hadrons

- lower energy
- Well removed by applying a track or a EM shower more than 200GeV

Event selections

- 5 or more tracks attached to a vertex
- No charged parent track
- 4 or more tracks with $\tan_\theta < 0.1$
- $\tan\theta > 0.005$ for muon or EM shower
- An EM shower or a track of more than 200 GeV
- $\phi > 90^\circ$



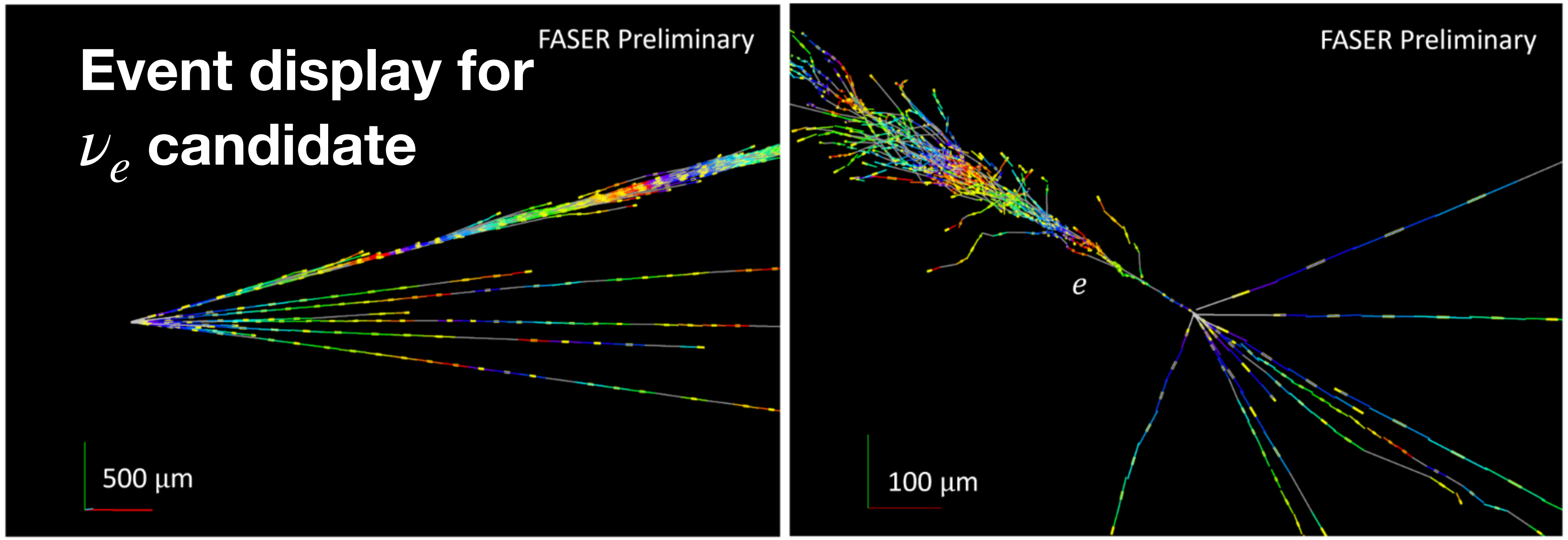
Background expectations and candidates

Background estimation by simulation

Background	ν_μ CC	ν_e CC
Neutral-hadron interactions	0.32 ± 0.15 (stat.) $\pm$ 0.16 (syst.)	0.002 ± 0.002 (stat.) $\pm$ 0.002 (syst.)
NC neutrino interactions	0.19 ± 0.15	-
Total	0.51 ± 0.27	0.002 ± 0.003

3 ν_e candidate and
4 ν_μ candidate

-> over 5σ for ν_e



Summary

- The FASER experiment at LHC is measuring high-energy neutrinos using the FASER spectrometer and the FASERν emulsion detector.
- In 2023, we reported the first direct observation of muon neutrinos using the FASER spectrometer.
    - We found 153 events, corresponding to 16 σ over the background-only hypothesis.
- Also, we reported the preliminary result of the electron neutrino analysis using the FASERν detector.
    - We found 3 ν_e candidates corresponding to >5 σ
- We have lots more data already taken to increase the precision of the neutrino studies
- We proposed upgrades as part of the Forward Physics Facility could provide millions of neutrino interactions

Backup slides

The number of expected signals

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

ν_μ analysis using FASER Spectrometer

Expected signals

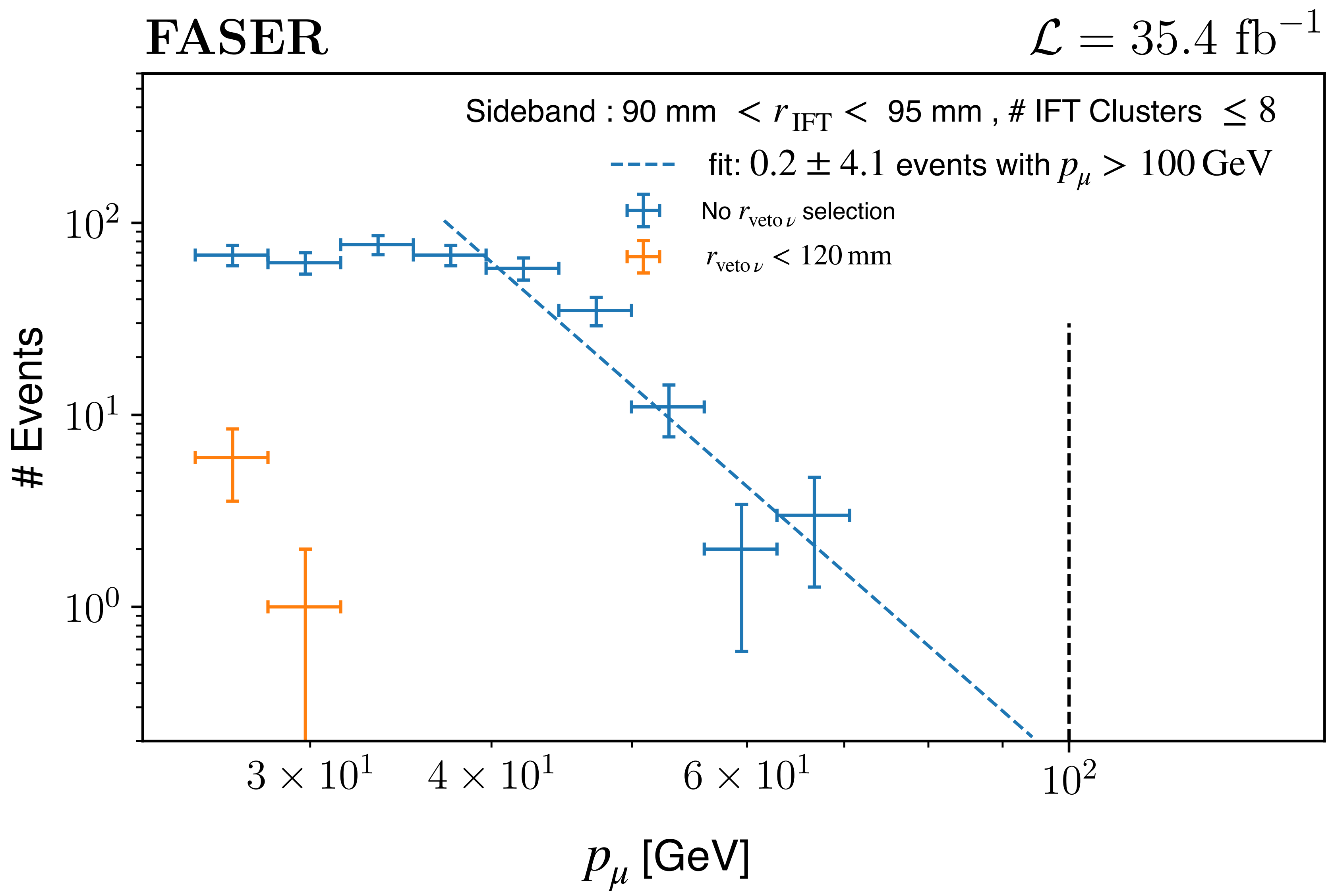
The predicted numbers of neutrino and anti-neutrino interactions from SIBYLL and DPMJET are listed in Table II. Results are shown requiring the interactions to be (1) in the FASERν detector volume or (2) in the target region and within a radius of 95 mm from the center of the FASER detector. Note that no additional acceptance and efficiency corrections are applied and the second requirement approximates the fiducial volume used in the analysis.

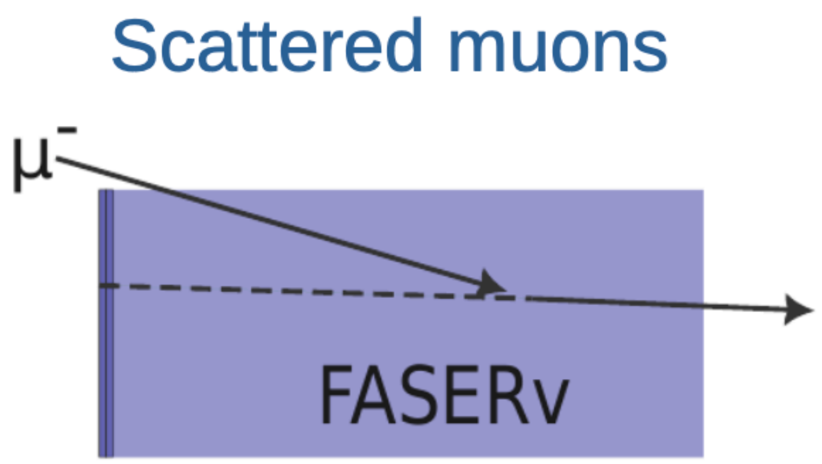
Volume	Type	$0 < E_\nu < 500$ GeV	$500 < E_\nu < 1000$ GeV	$E_\nu > 1000$ GeV	$\sum$	$\overline{E}_\nu$ [GeV]
FASERν	ν_μ	359 / 379	239 / 273	291 / 790	890 / 1442	880 / 1376
FASERν	$\overline{\nu}_\mu$	116 / 130	62 / 85	49 / 151	227 / 367	657 / 1028
$r < 95$ mm	ν_μ	147 / 154	105 / 118	141 / 375	394 / 647	943 / 1477
$r < 95$ mm	$\overline{\nu}_\mu$	48 / 53	28 / 37	23 / 67	99 / 157	687 / 1057

TABLE II. The expected numbers of neutrino and anti-neutrino events from SIBYLL (first number) and DPMJET (second number) for an integrated luminosity of $35.4\,\text{fb}^{-1}$ i and different energy intervals, along with the sum over all energy intervals, and the average neutrino energy $\overline{E}_\nu$. Results are shown requiring the interactions to be (1) in the FASERν detector volume or (2) in the target region and within a radius of 95 mm from the center of the FASER detector.

Geometrical backgrounds for the FASER spectrometer

Sideband method





Event selections

- Collision event with good data quality (35.4 fb-1)
- No signal in two front veto scintillators(<40 pC~0.5 MIP)
- Signal in last two veto layers
- Signal in calorimeter consistent with ≥1 MIPs
- Exactly one good quality spectrometer track
- Track in fiducial tracking volume, 90-95 mm
- at most 8 IFT clusters

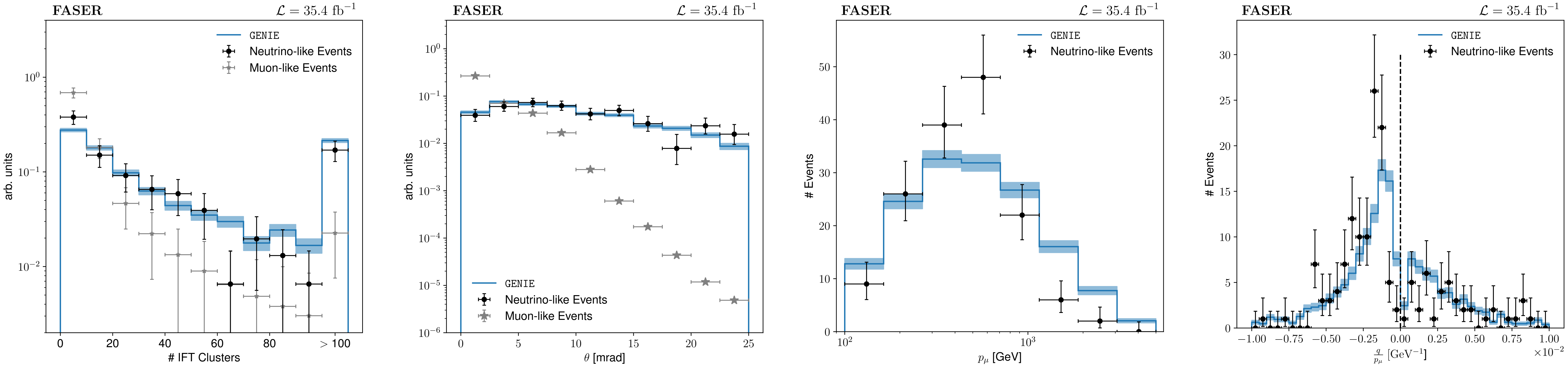
(0.2 ± 4.1)x (upper limit of N with $r_{\mathrm{veto}\ \nu}$))/(N without $r_{\mathrm{veto}\ \nu}$)=0.01 ± 0.23

Scaling factor from background region to signal region: $f_{\mathrm{geo}} = 7.8 \pm 2.3$

Final value of backgrounds

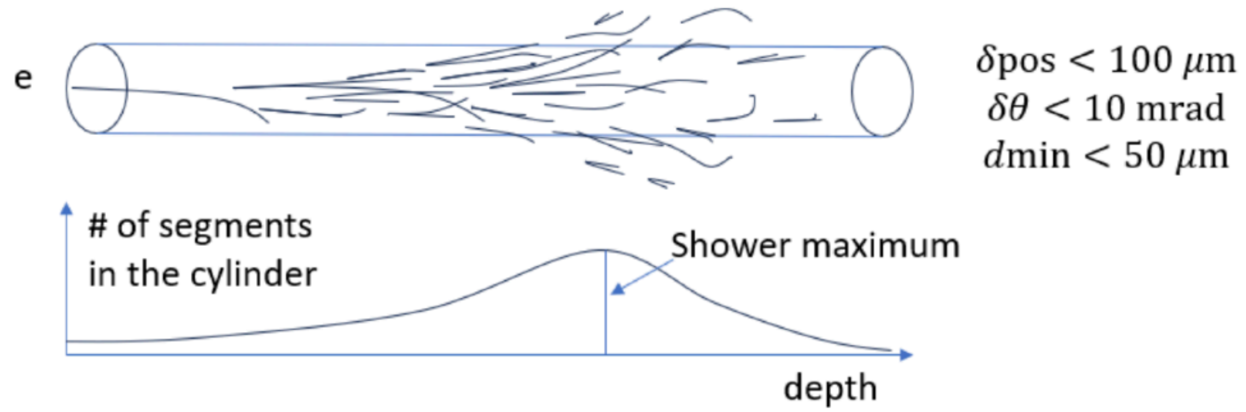
0.08 ± 1.83

Additional plots for selected events



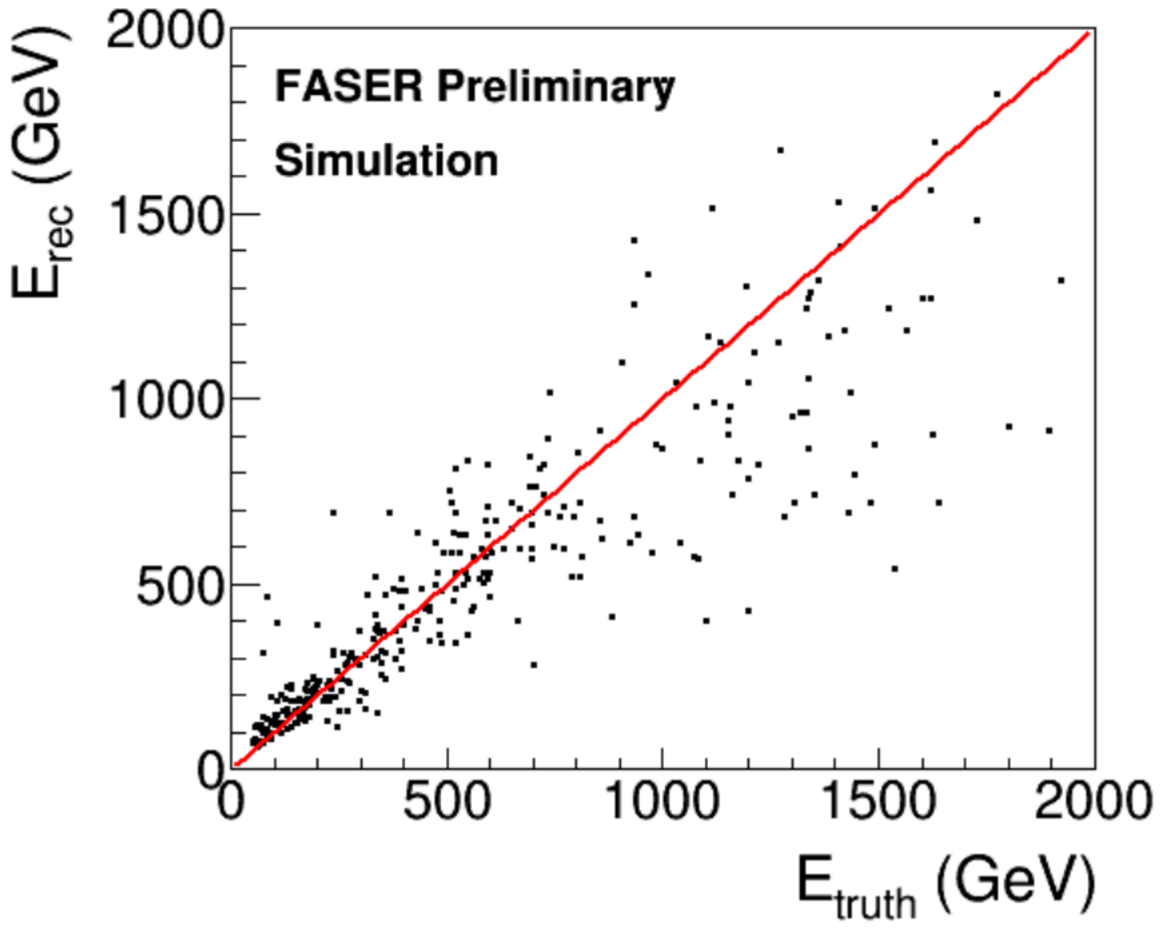
The blue bands correspond to the statistical error of the simulated samples and are luminosity scaled for q/pμ and pμ. The other figures are normalized to unity.

FASERν EM shower energy estimation



Count the number of segments in ±3 films around the shower maxim (total 7 films)

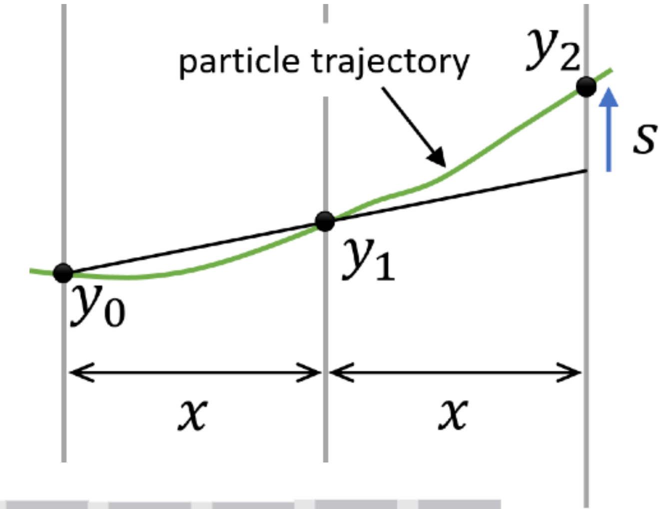
The number of backgrounds was estimated and subtracted by counting the number of segments at the cylinder randomly opened.

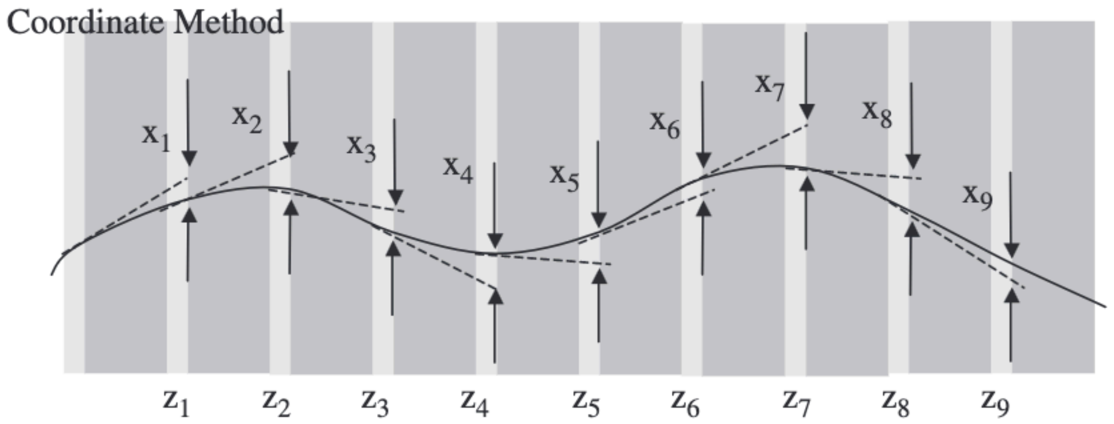


Resolution: ~25% at 200 GeV

FASERν track momentum estimation

Momentum dependency in the scattering angle

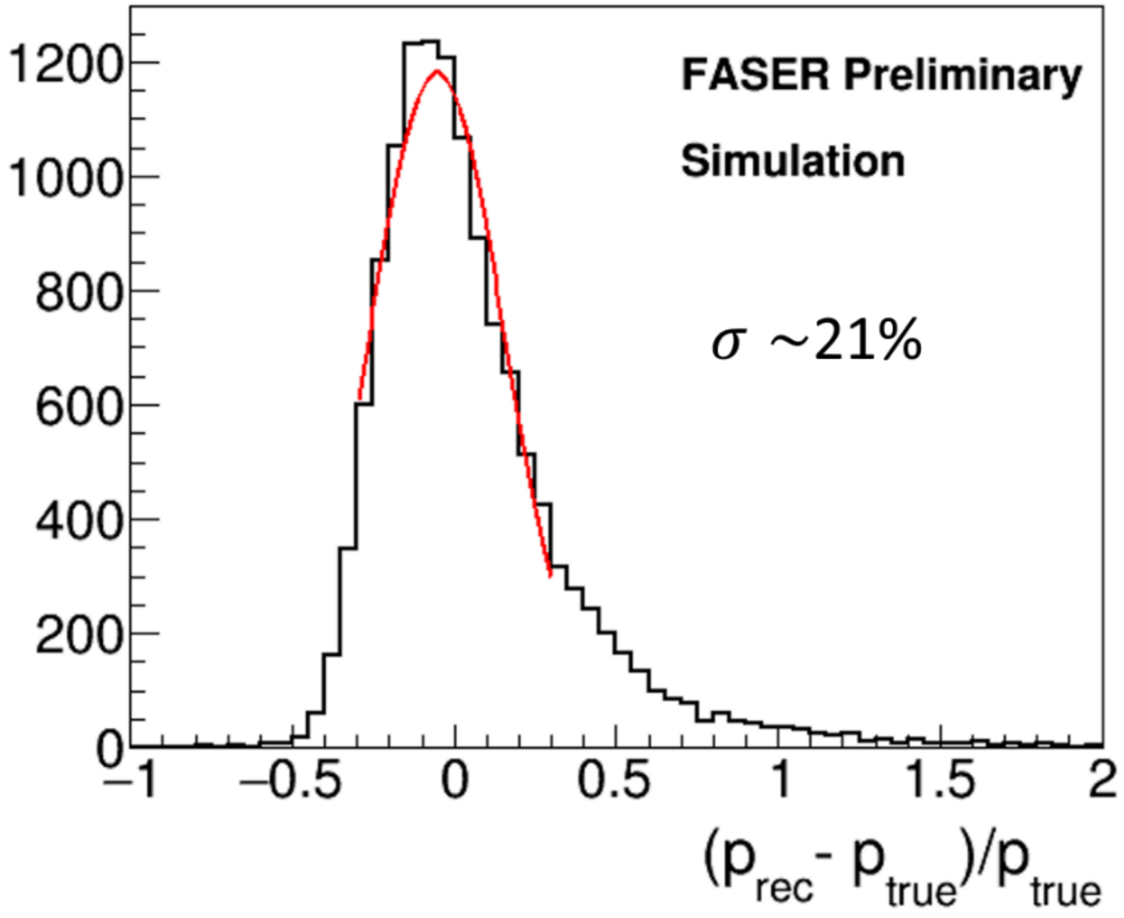




$$\theta^{RMS}_{plane} = \frac{0.0136}{\beta pc}\sqrt{\frac{z}{X_0}}\left\{1 + 0.038\ ln\left(\frac{z}{X_0\beta^2}\right)\right\},$$

z: thickness
p: momentum

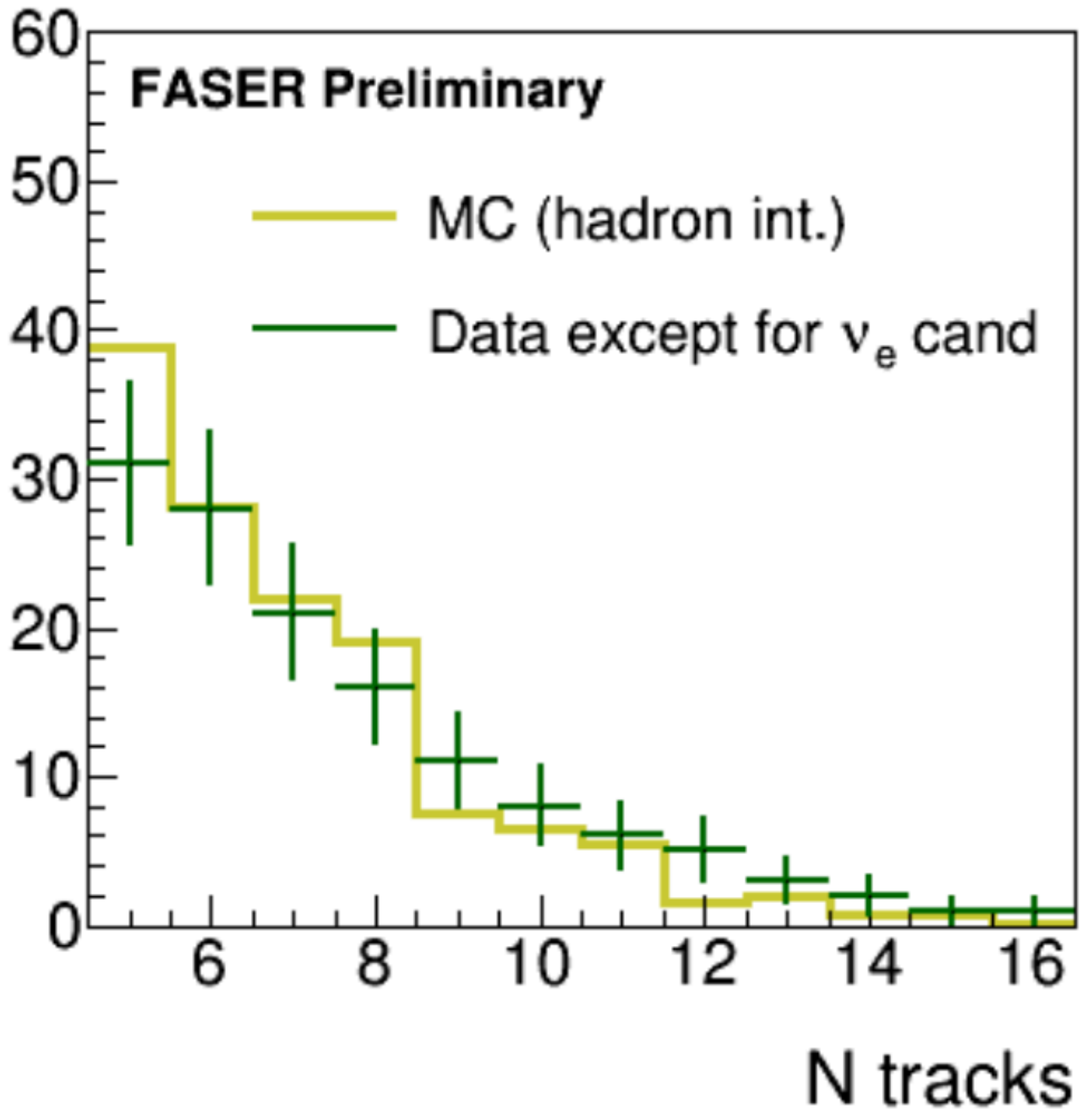
Momentum is estimated by measuring displacements for every 1 plate, every 2 plates, every 4 plates, every 8 plates, and every 16 plates and calculating RMS for each case.

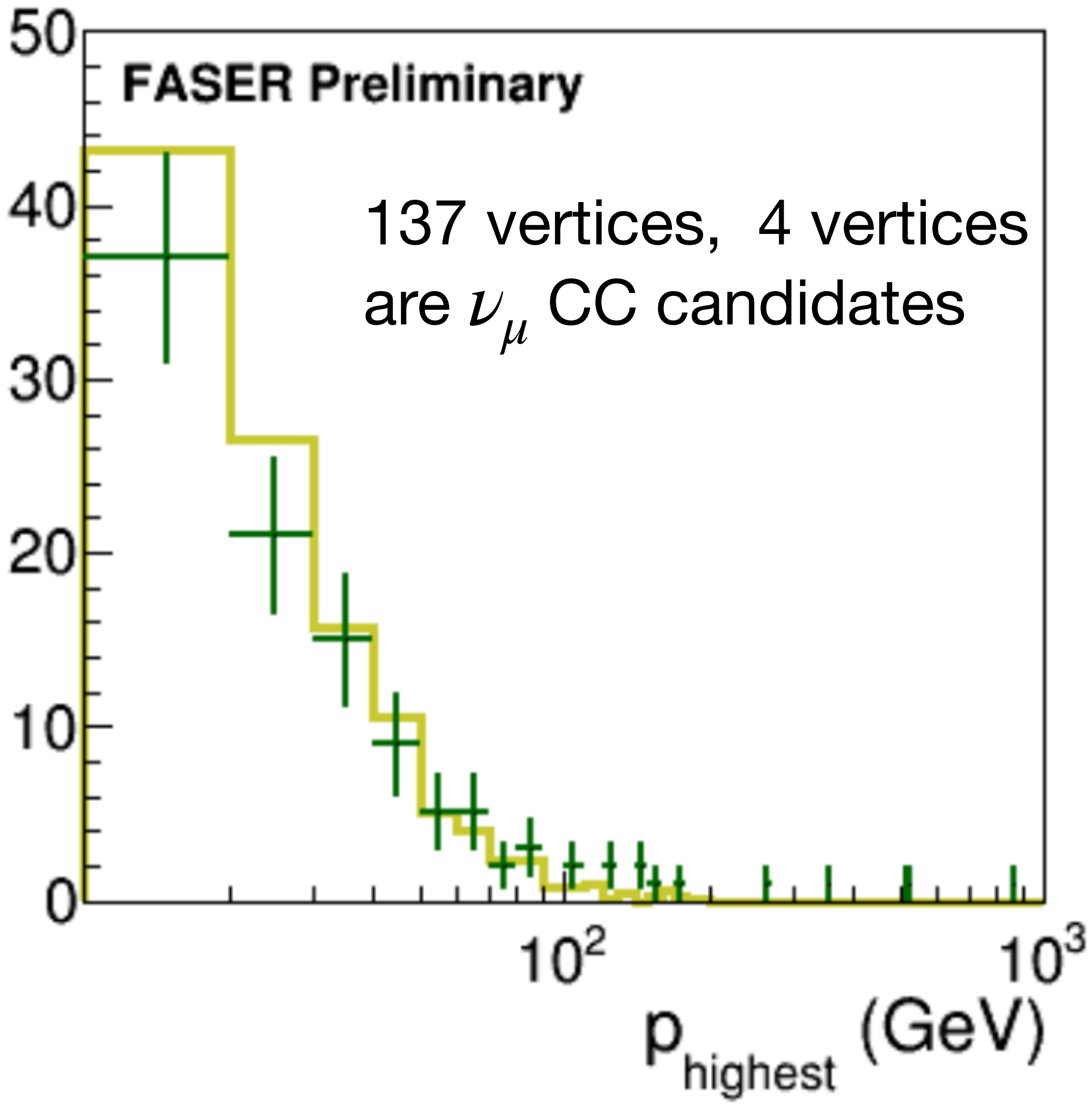


Resolution: ~20% at 200 GeV

FASERν: MC and neutral hadron-like events

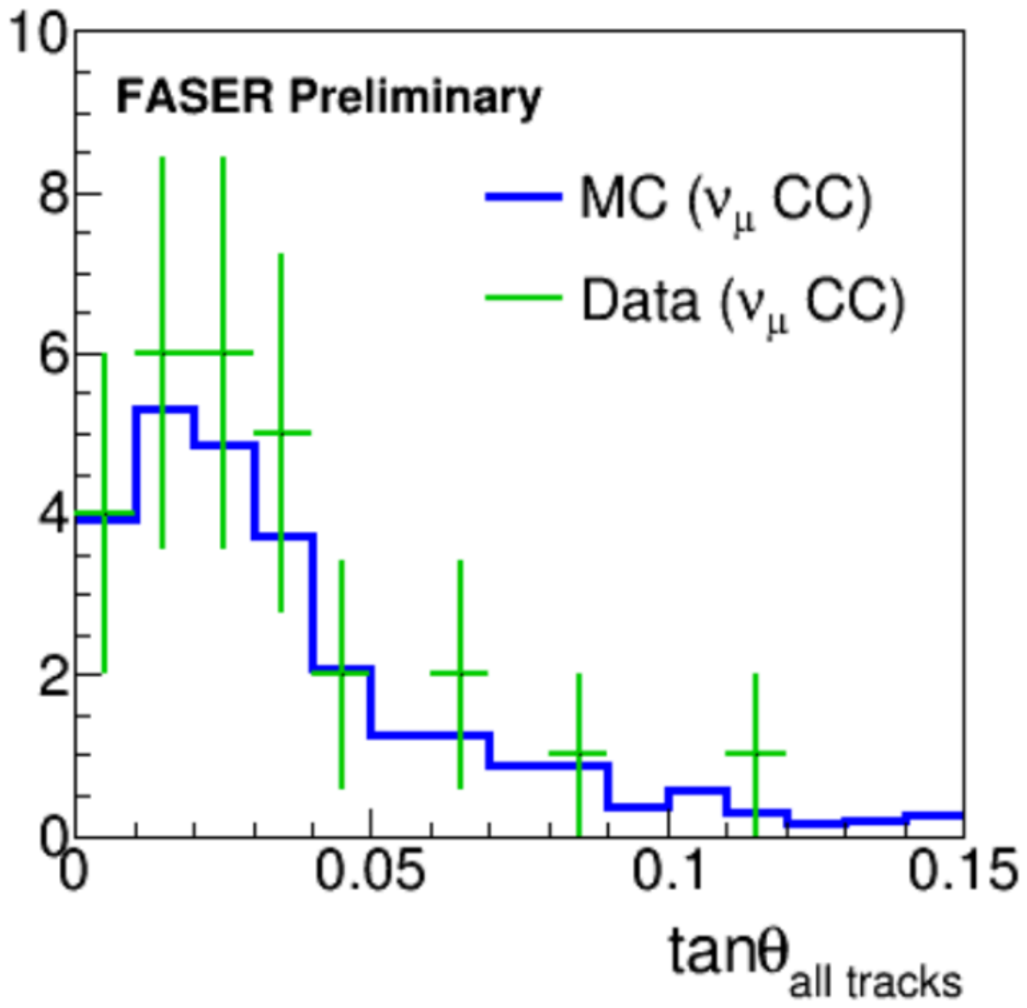
The MC simulation distributions are normalized to the number of observed track

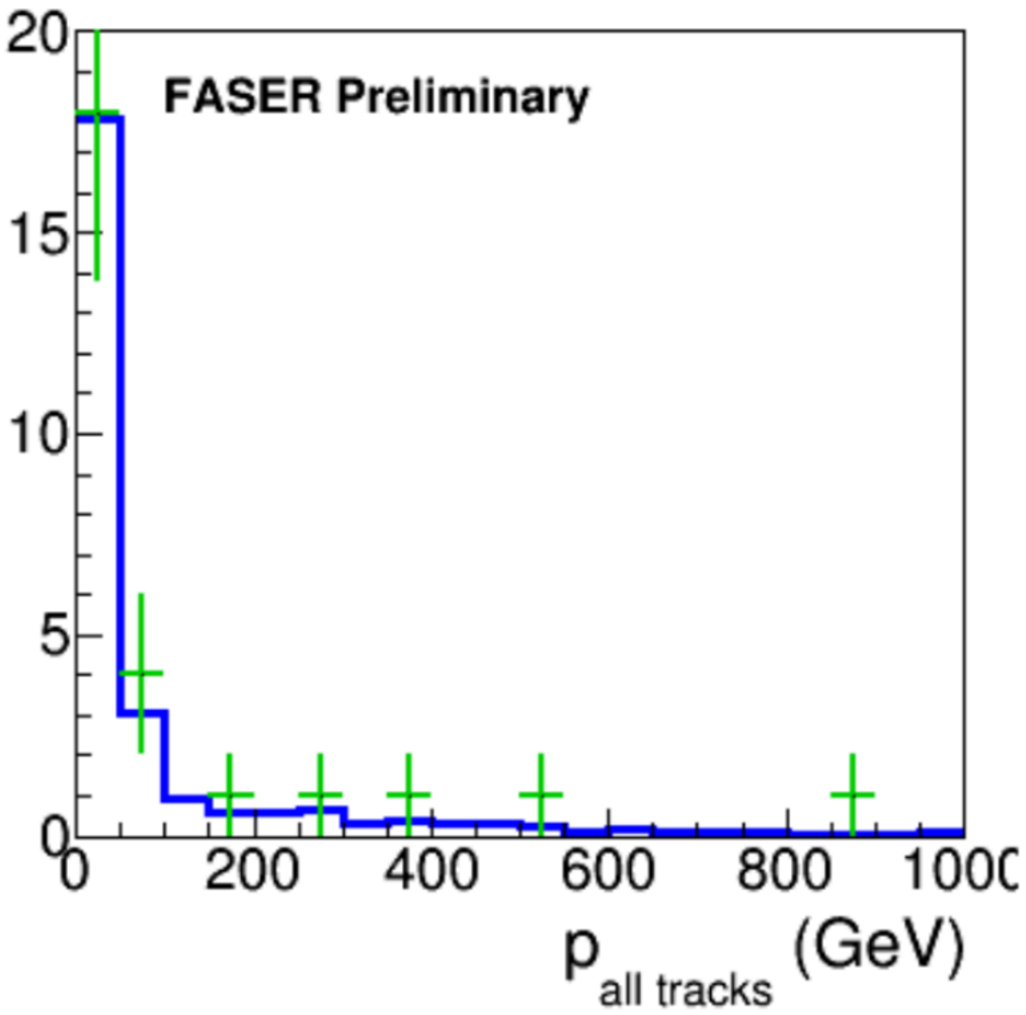




FASERν: ν_μ candidates and Signal MCs

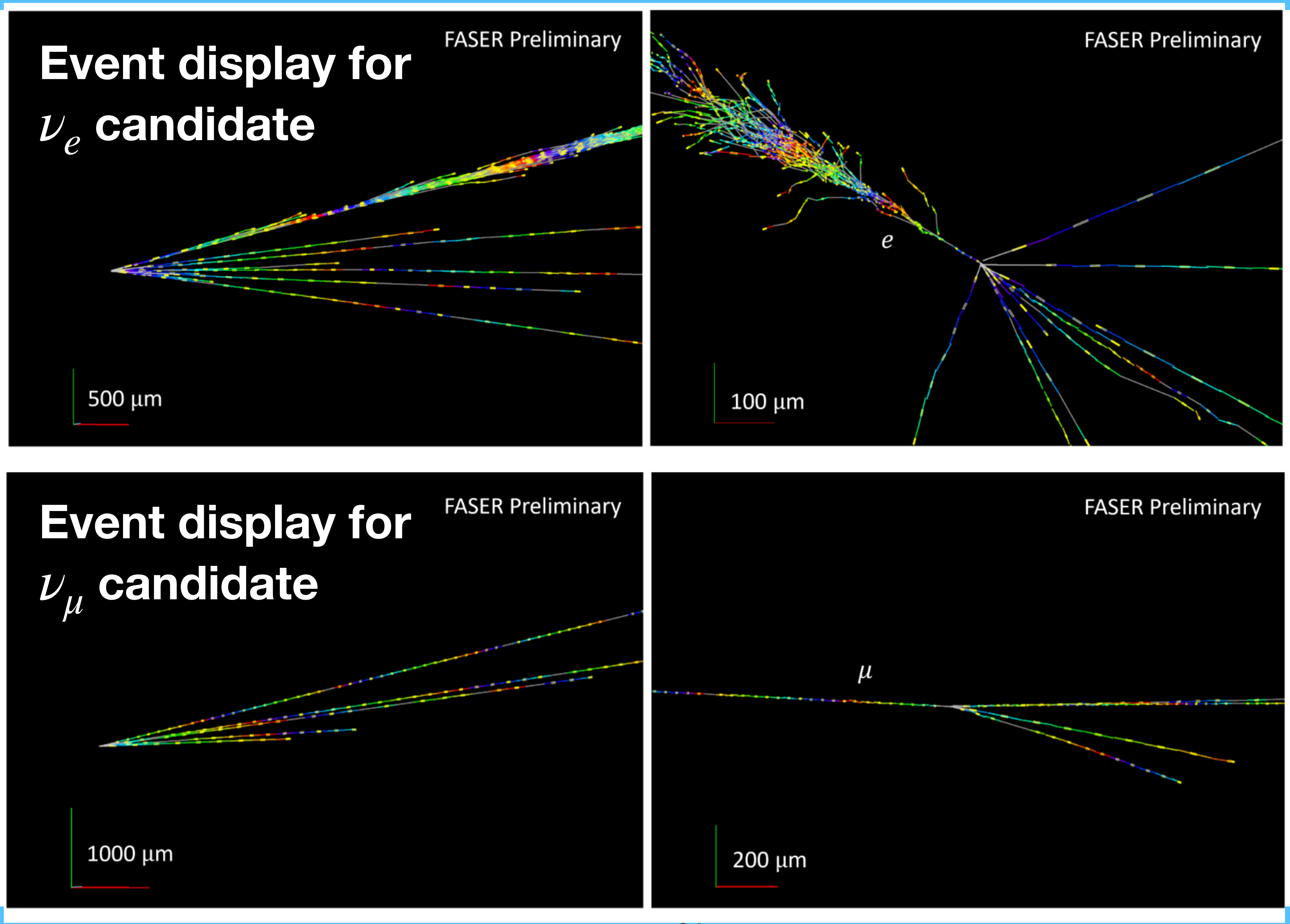
Angles and momentum of tracks for
4 ν_μ candidates and signal simulation





The MC simulation distributions are
normalized to the number of observed track

FASERν: candidates



FASERν: vertices positions