First neutrino physics at colliders with FASER

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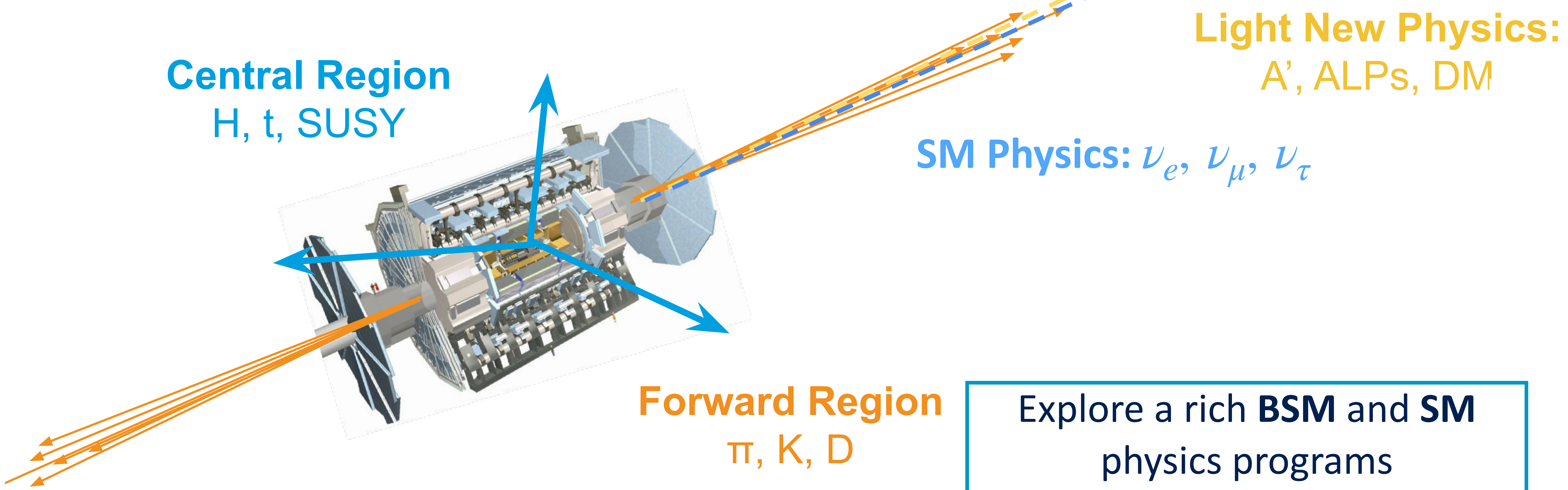
Idea and Motivation

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

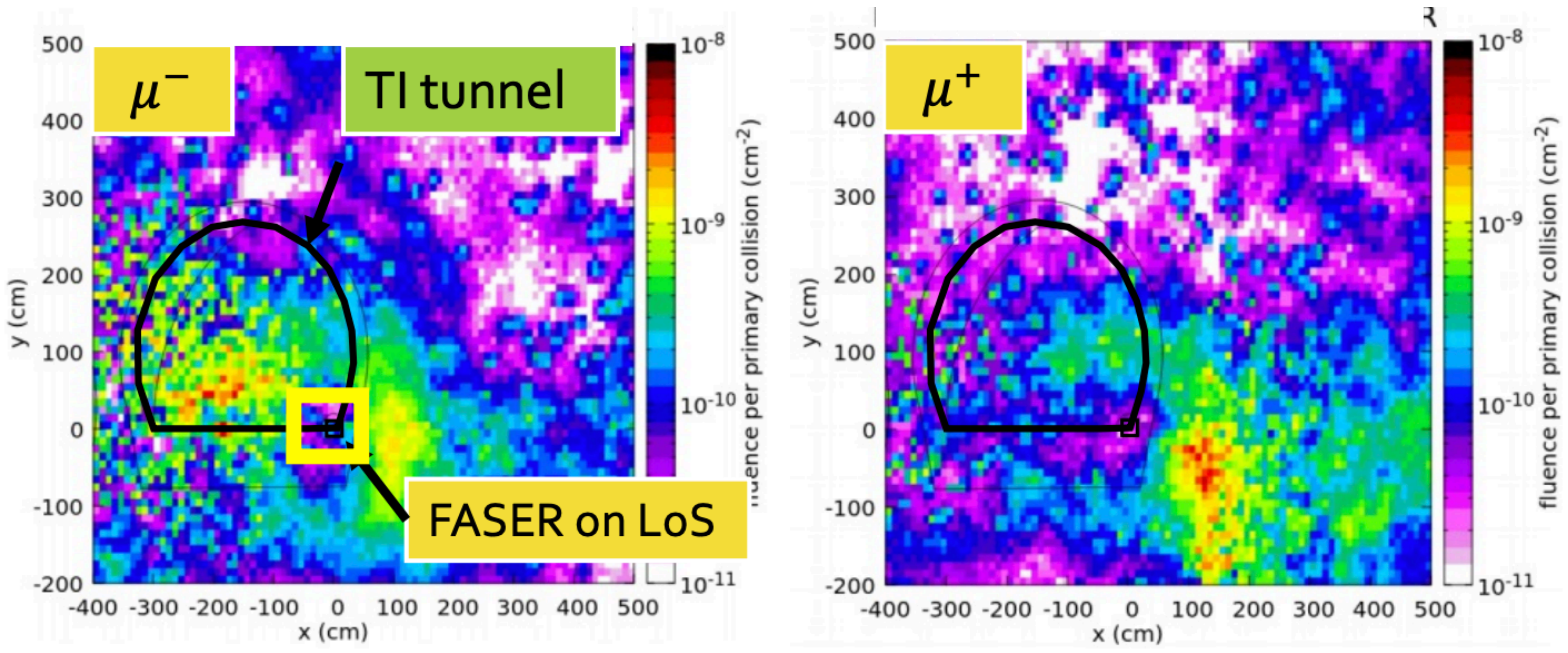
- e.g. 10^{14} π^0 within 1 mrad of beam



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

FASER

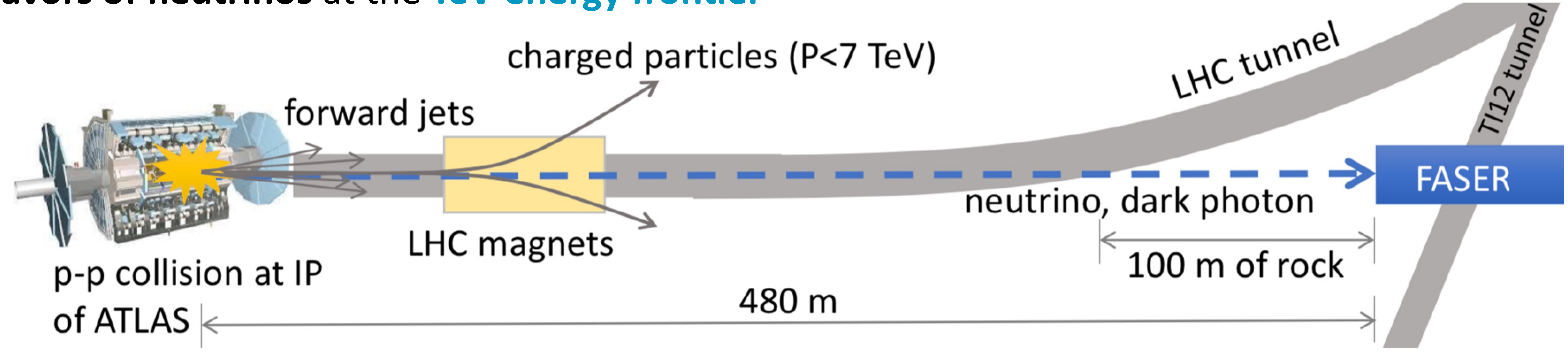
FLUKA simulation



- **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)

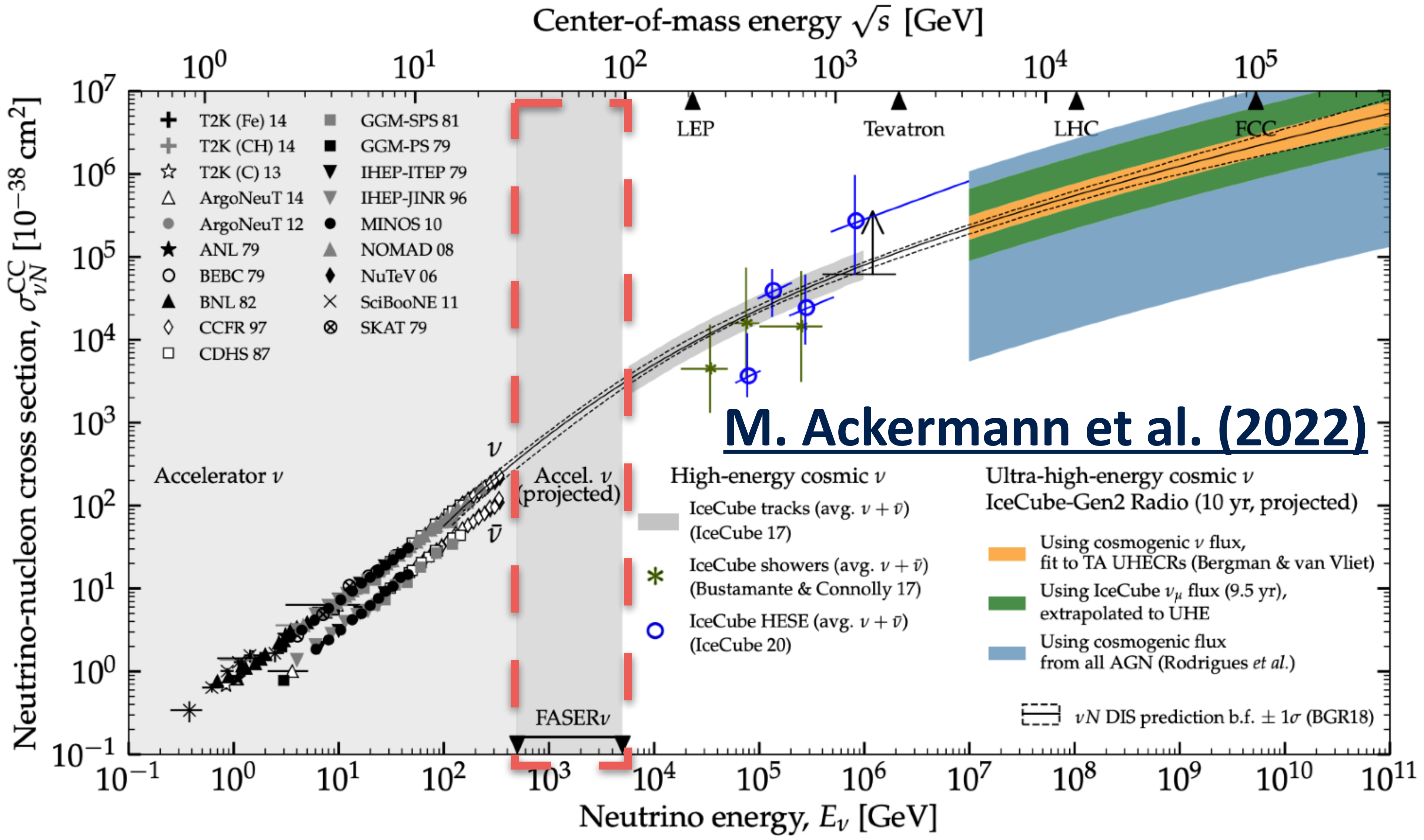
- **Physics motivation**
  - **New long-lived particle searches** in **MeV-GeV masses**
    - **See J.Anders' talk**
  - **All flavors of neutrinos** at the **TeV-energy frontier**

- **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

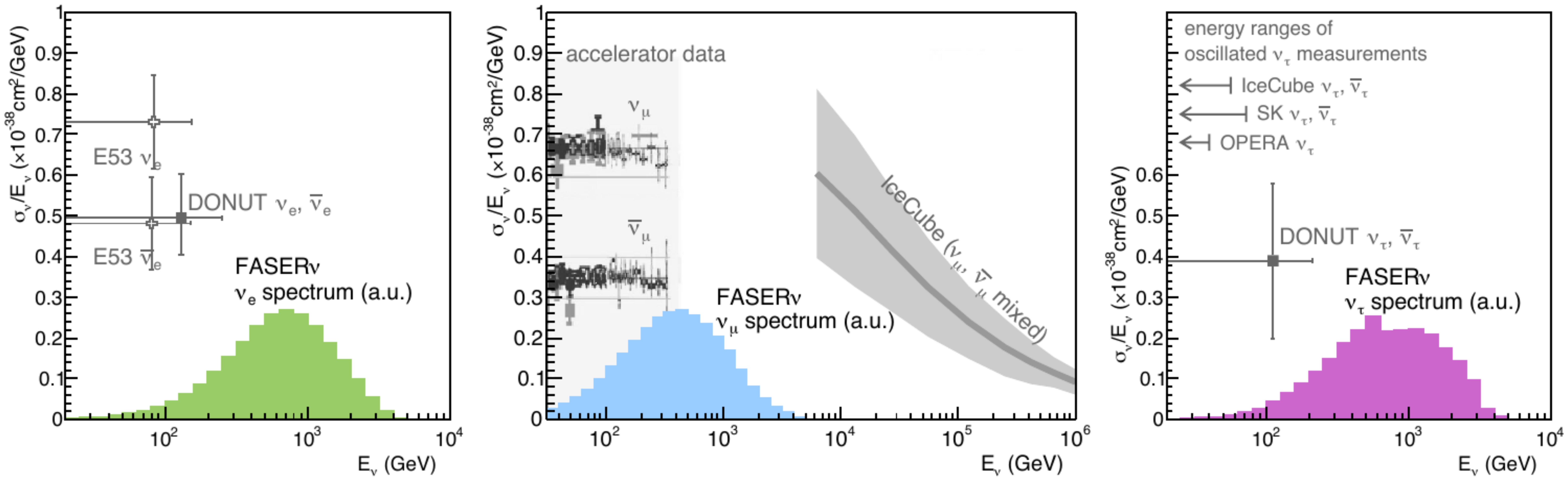


Collider neutrino

- **Neutrinos** produced copiously **in decays of forward hadrons**
  - Highly energetic (TeV scale)->high interaction cross-section



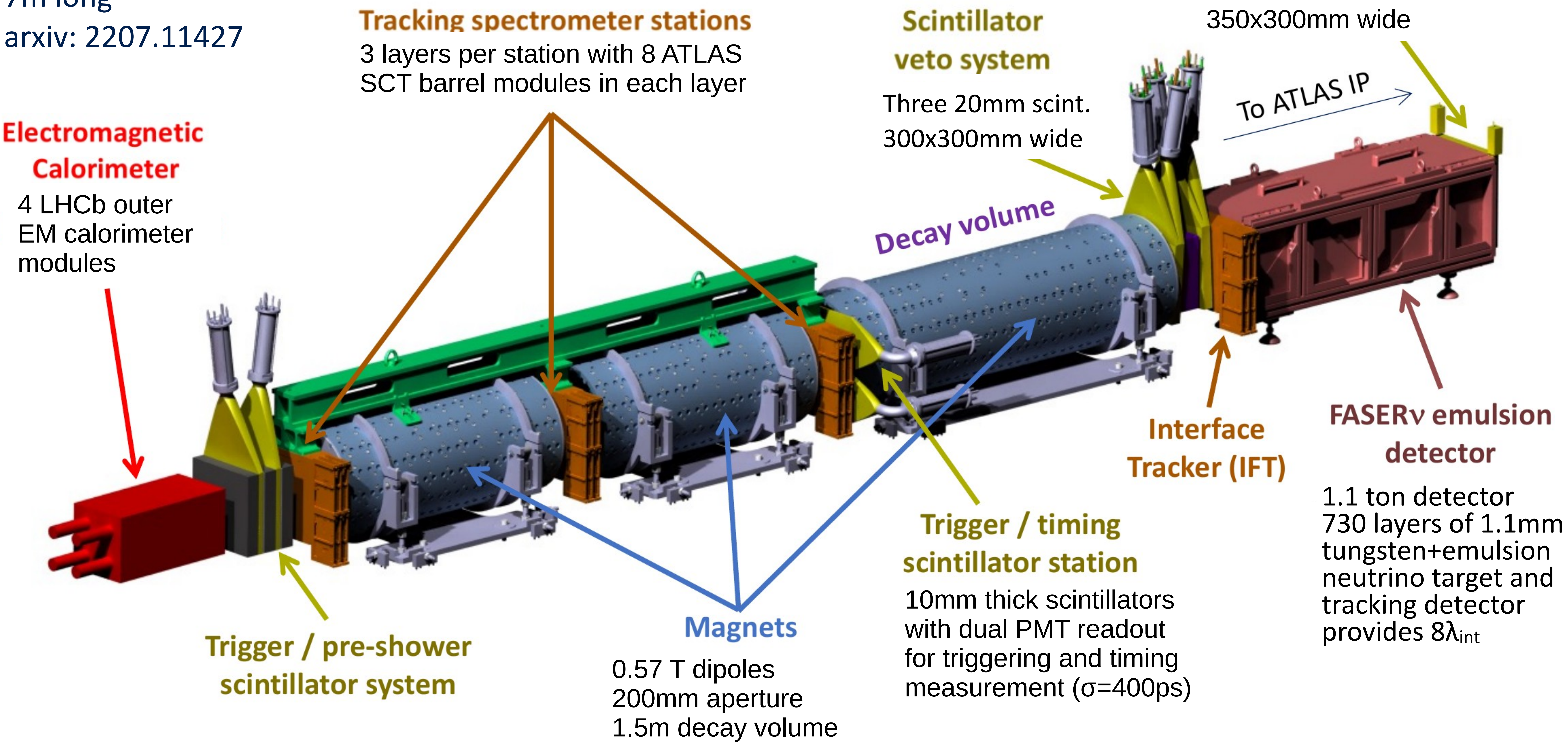
- Extends FASER physics program into **SM measurements**
  - Targets measurement of highest energy man-made neutrinos
  - Energy range complementary to existing neutrino experiments
  - **the FASERν detector** enables to be sensitive to **all-flavors**, in particular, **tau neutrino** is interesting



Study at colliders originally proposed by Rújula and Rückl in 1984

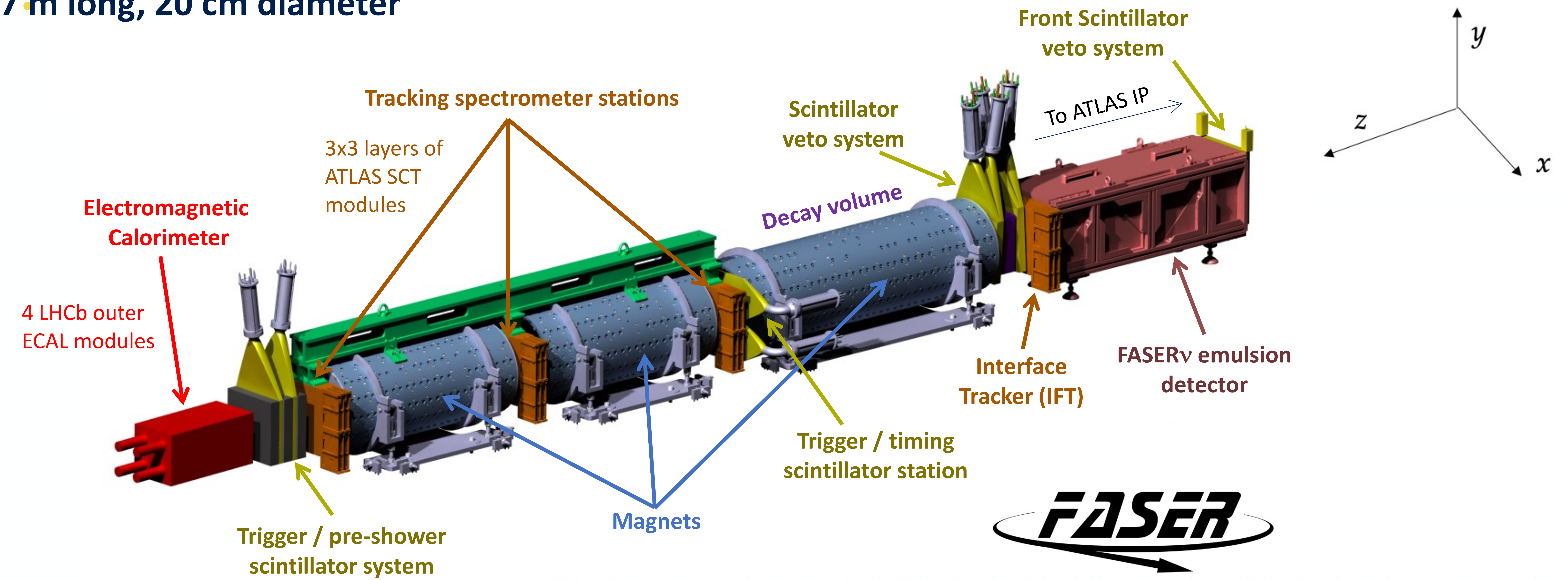
FASER detector

10cm radius
7m long
arxiv: 2207.11427

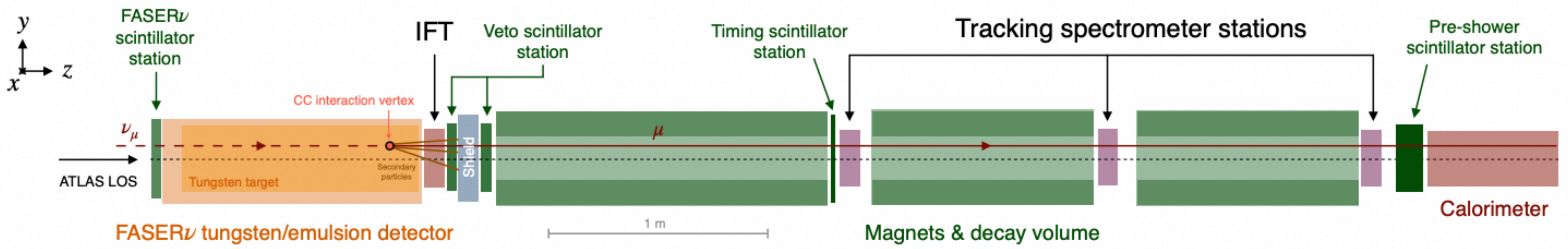


FASER detector - Neutrino Signature in Electronic Detectors

7 m long, 20 cm diameter

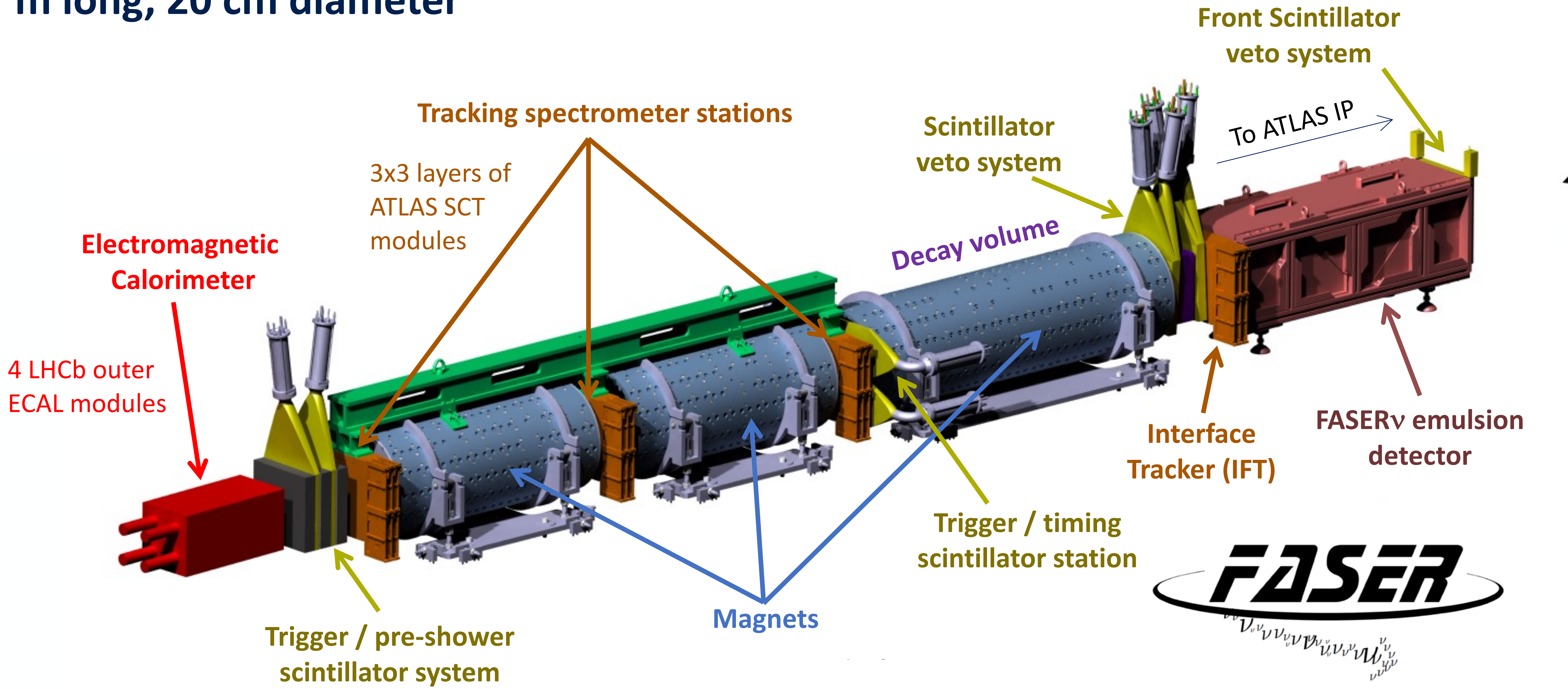


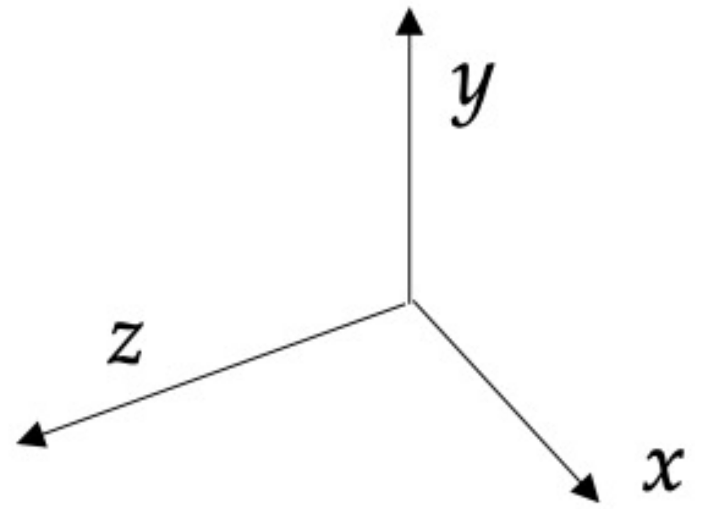
Neutrino signal with electric detectors

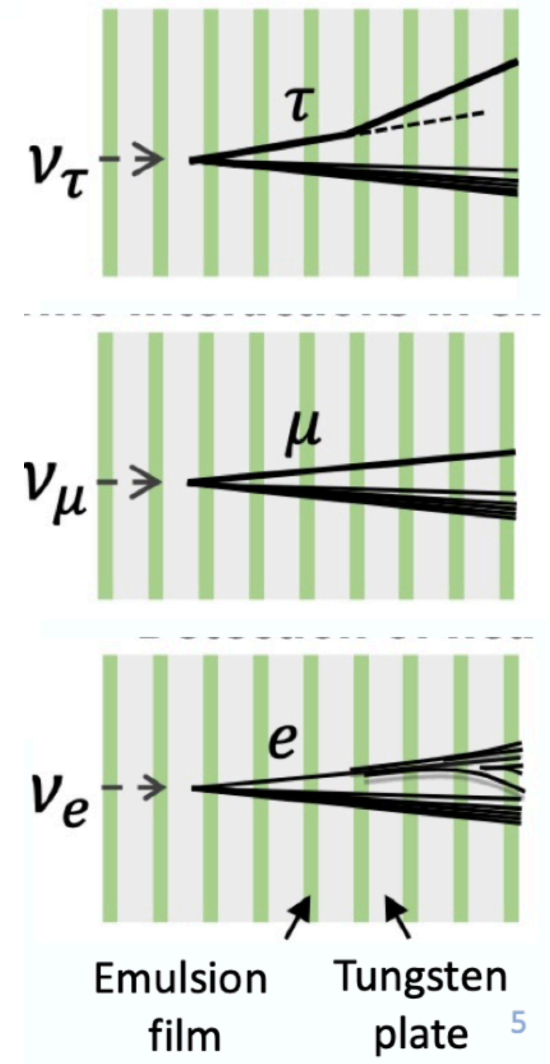


FASER detector - Emulsion Detectors

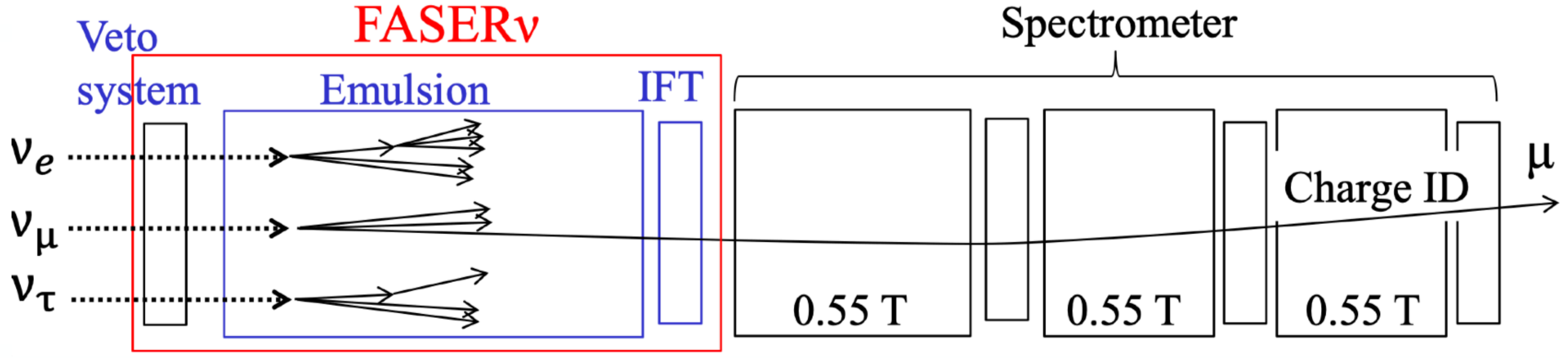
7 m long, 20 cm diameter



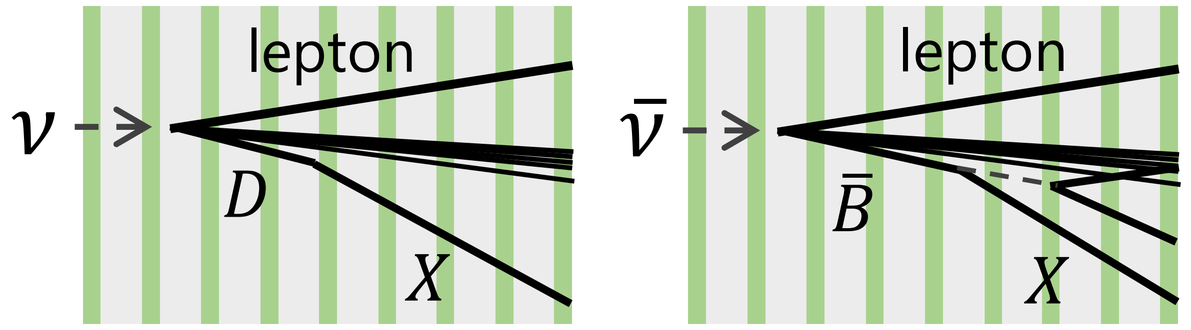




FASERν signatures for neutrino



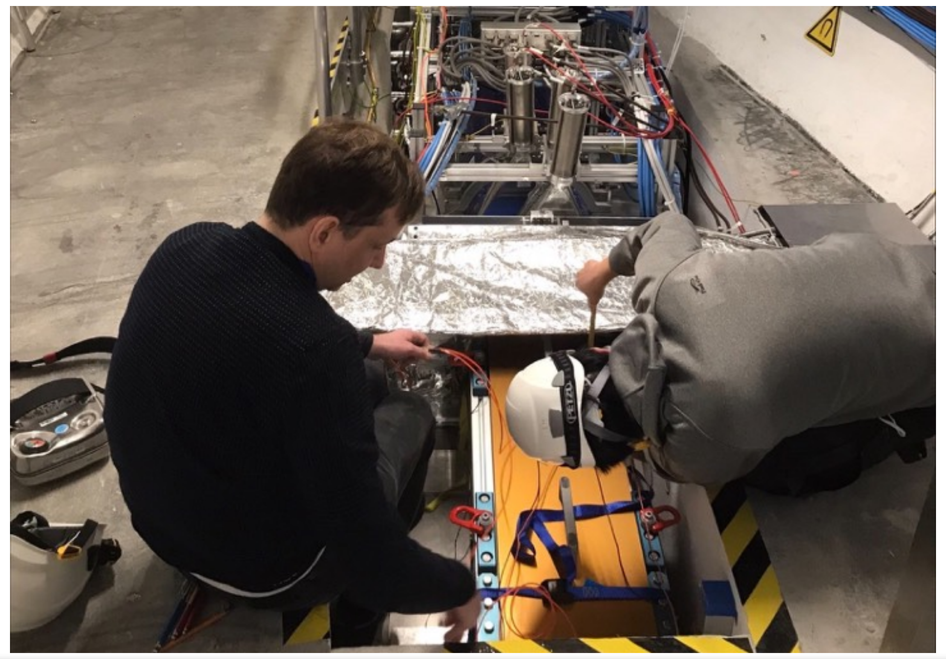
CC heavy quark production

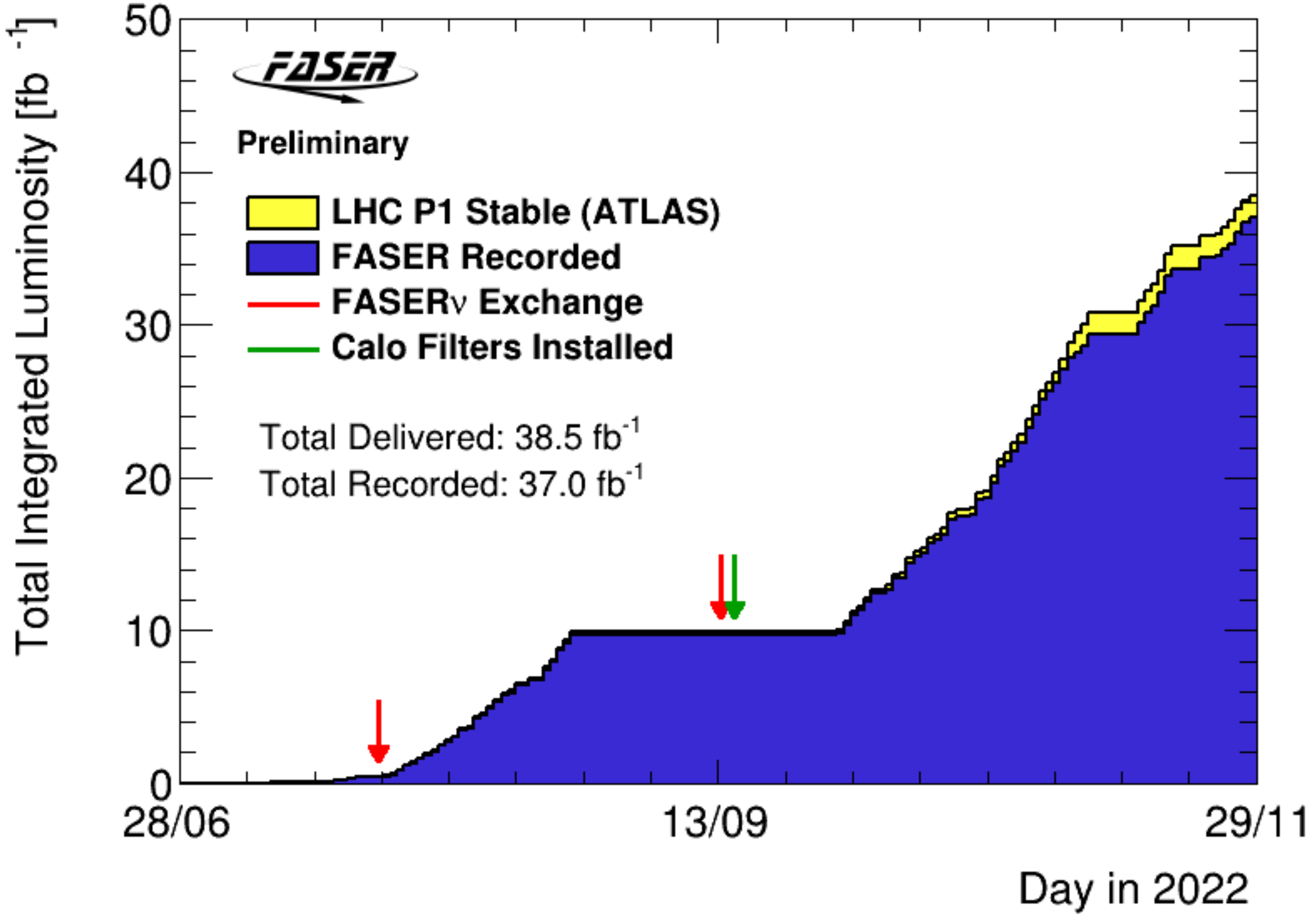


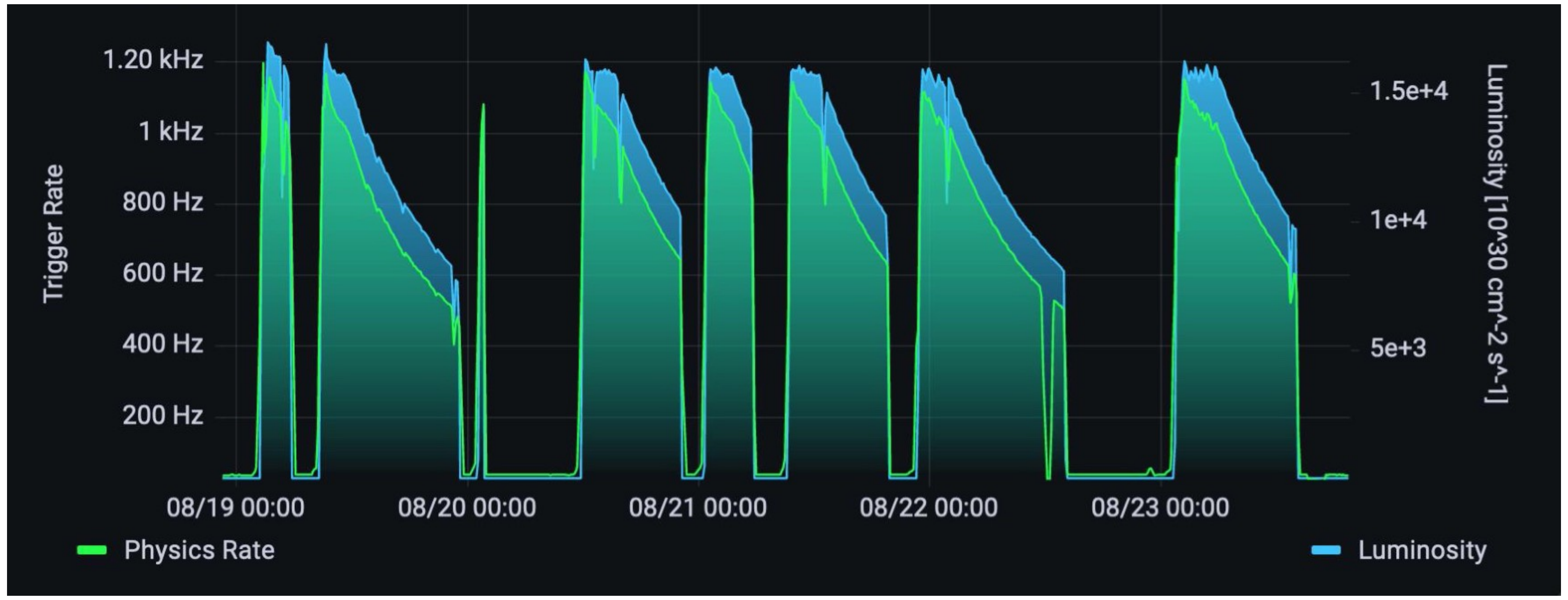
Final detector component (FASERν) successfully installed in T12 in March 2022

FASER Operation

- **Successfully operated during 2022**
  - Continuous and largely automatic data-taking at up to 1.3 kHz
  - Emulsion detector exchanged twice to manage reasonable track density
    - Only for 1st box, partially filled and the rests are fully filled







arXiv > hep-ex > arXiv:2303.14185

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High Energy Physics – Experiment

[Submitted on 24 Mar 2023]

First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration: Henso Abreu, John Anders, Claire Antel, Akitaka Ariga, Tomoko Ariga, Jeremy Atkinson, Florian U. Bernlochner, Tobias Blesgen, Tobias Boeckh, Jamie Boyd, Lydia Brenner, Franck Cadoux, David W. Casper, Charlotte Cavanagh, Xin Chen, Andrea Coccaro, Ansh Desai, Sergey Dmitrievsky, Monica D'Onofrio, Yannick Favre, Deion Fellers, Jonathan L. Feng, Carlo Alberto Fenoglio, Didier Ferrere, Stephen Gibson, Sergio Gonzalez-Sevilla, Yuri Gornushkin, Carl Gwilliam, Daiki Hayakawa, Shih-Chieh Hsu, Zhen Hu, Giuseppe Iacobucci, Tomohiro Inada, Sune Jakobsen, Hans Joos, Enrique Kajomovitz, Hiroaki Kawahara, Alex Keyken, Felix Kling, Daniela Köck, Umut Kose, Rafaella Kotitsa, Susanne Kuehn, Helena Lefebvre, Lorne Levinson, Ke Li, Jinfeng Liu, Jack MacDonald, Chiara Magliocca, Fulvio Martinelli, Josh McFayden, Matteo Milanesio, Dimitar Mladenov, Théo Moretti, Magdalena Munker, Mitsuhiro Nakamura, Toshiyuki Nakano, Marzio Nessi, Friedemann Neuhaus, Laurie Nevay, Hidetoshi Otono, Hao Pang, Lorenzo Paolozzi, Brian Petersen, Francesco Pietropaolo, Markus Prim, Michaela Queitsch-Maitland, Filippo Resnati, Hiroki Rokujo, Elisa Ruiz-Choliz, Jorge Sabater-Iglesias, Osamu Sato, Paola Scampoli, Kristof Schmieden, Matthias Schott, Anna Sfyrla, Savannah Shively, Yosuke Takubo, Noshin Tarannum, Ondrej Theiner, Eric Torrence, Serhan Tufanli, Svetlana Vasina, Benedikt Vormwald, Di Wang, Eli Welch, Stefano Zambito

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision data set of 35.4 fb^{-1} using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

Comments: Submitted to PRL on March 24 2023
Subjects: **High Energy Physics – Experiment (hep-ex)**; High Energy Physics – Phenomenology (hep-ph)
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Accepted Paper

First direct observation of collider neutrinos with FASER at the LHC

Phys. Rev. Lett.

Henso Abreu et al.

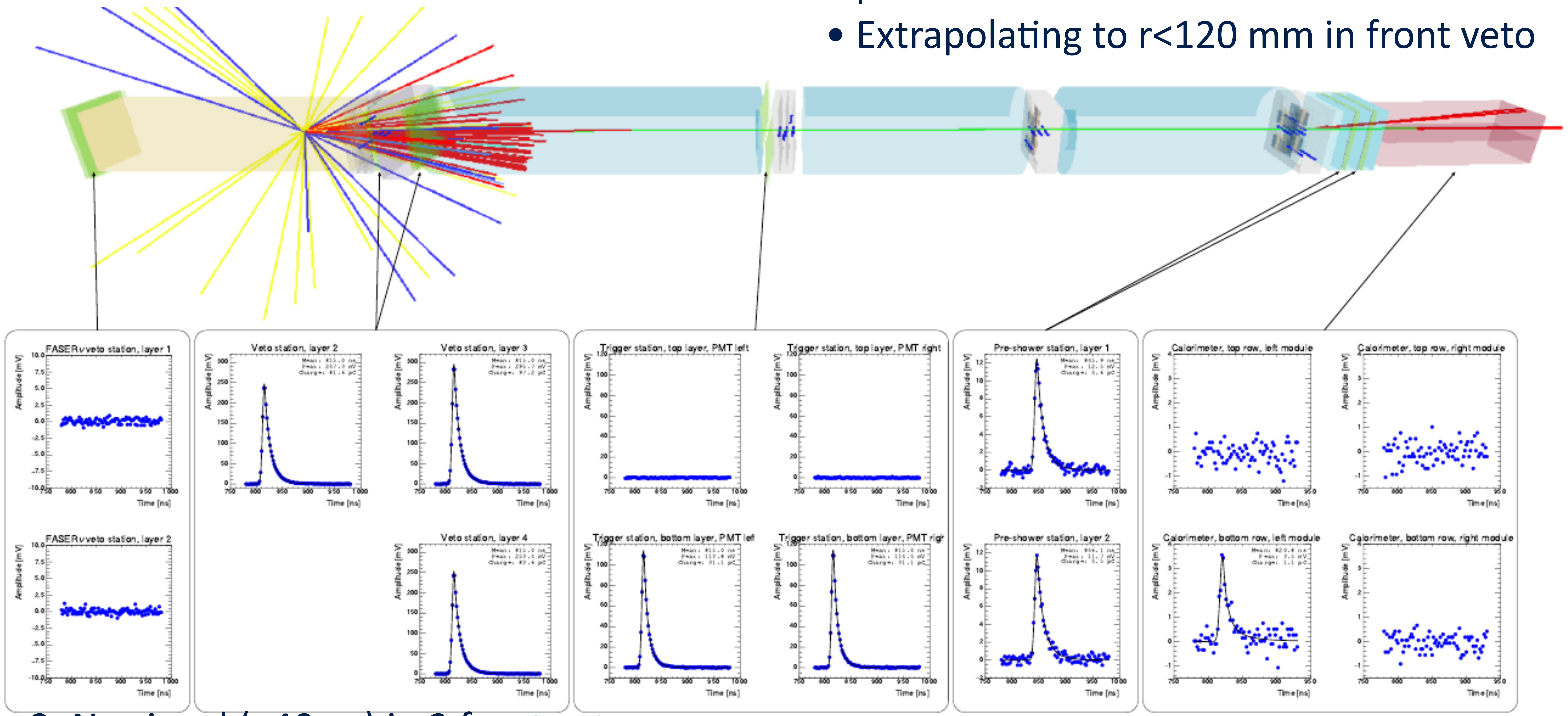
Accepted 8 May 2023

Observing Neutrino Candidates 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

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



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

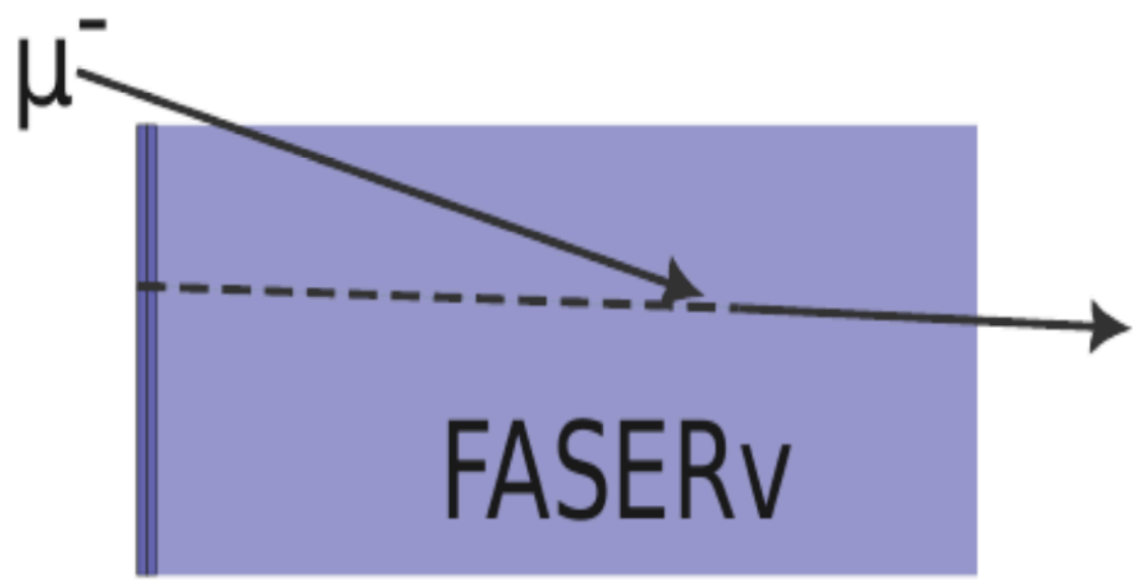
4. Timing and preshower consistent with ≥1 MIP

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

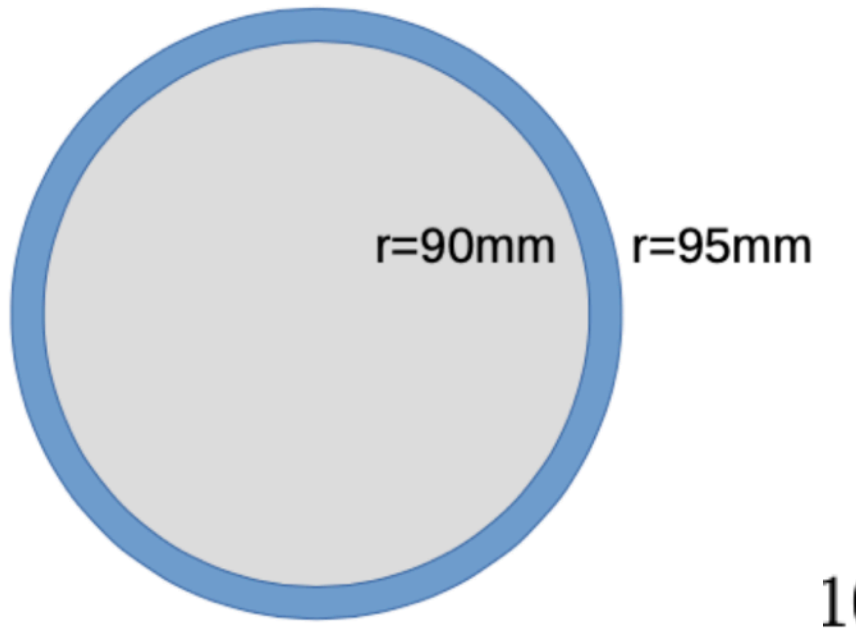
- Uncertainty from DPMJET vs SIBYLL
  - No experimental errors
  - Currently not trying to measure cross section

Neutrinos: Geometric background

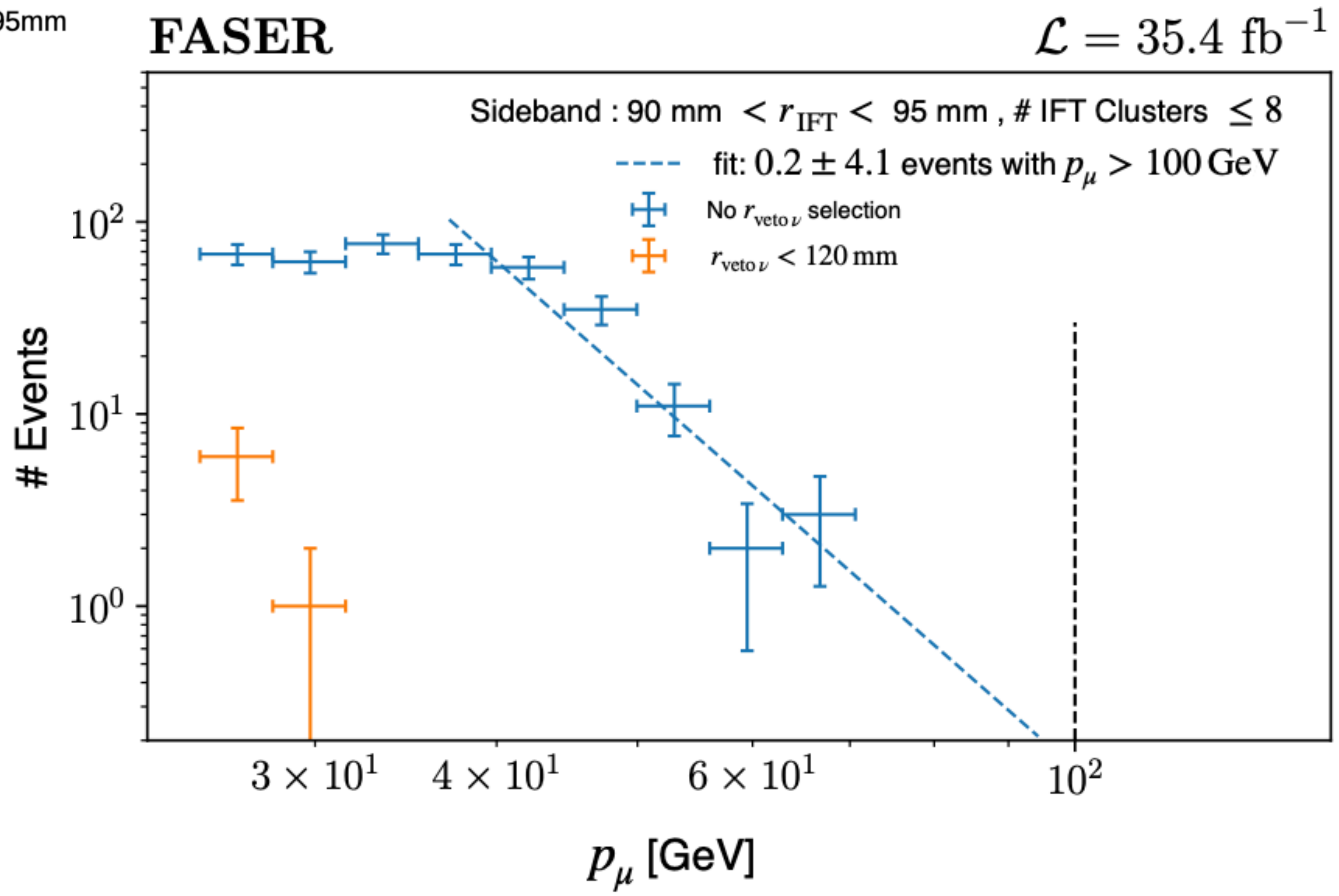
- **Measure geometric background by counting # events in SB and scale to SR**



- **SB defined to enhance muons missing FASERν veto that still give a track in the spectrometer**
  - Single IFT segment in 90 < r < 95 mm anulus
  - Loosened momentum requirement
  - No FASERν veto radius requirement (blue)



- **Fit mom. to extrapolate to p > 100 GeV**
- **Scale to rate of events with r_{VetoNu} < 120 mm (orange)**
  - 0 events > 30 GeV so use 5.9 events as 3σ upper limit
- **Scale from anulus to full acceptance**
  - Using large angle muon simulation
- **Expect 0.08 ± 1.83 events**

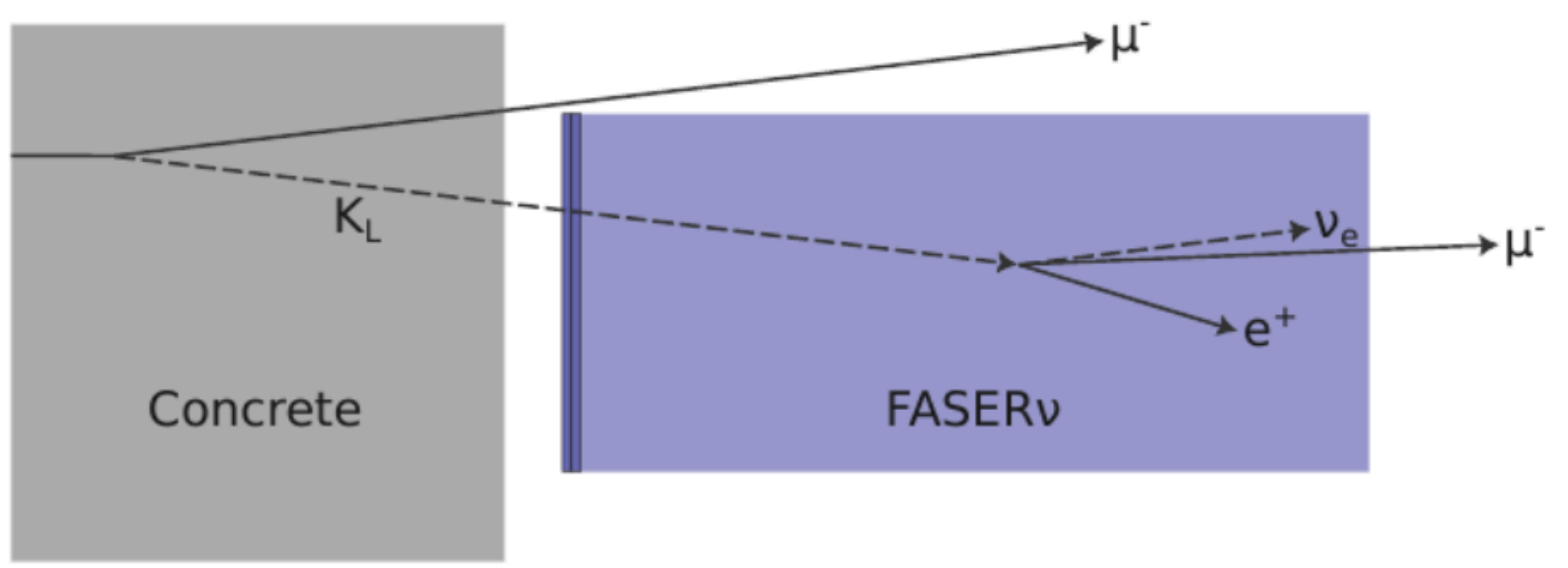


Neutrinos: Neutral Hadron Background

Estimated neutral hadron background produced by muons

(1) Simulate muon interactions in rock and count neutral hadrons

(2) Simulate neutral hadrons starting in the FASERν box and calculate the fraction of events which pass our event selection



(1) Simulated 10^9 μ^+ and μ^- events

- Start from FLUKA Spectra
- G4 propagation through last 8 m of rock
- p > 100 GeV reaching FASER
  - Number of produced hadrons ≈ 300 (conservative estimate)
  - Most of these are vetoed by the parent muon

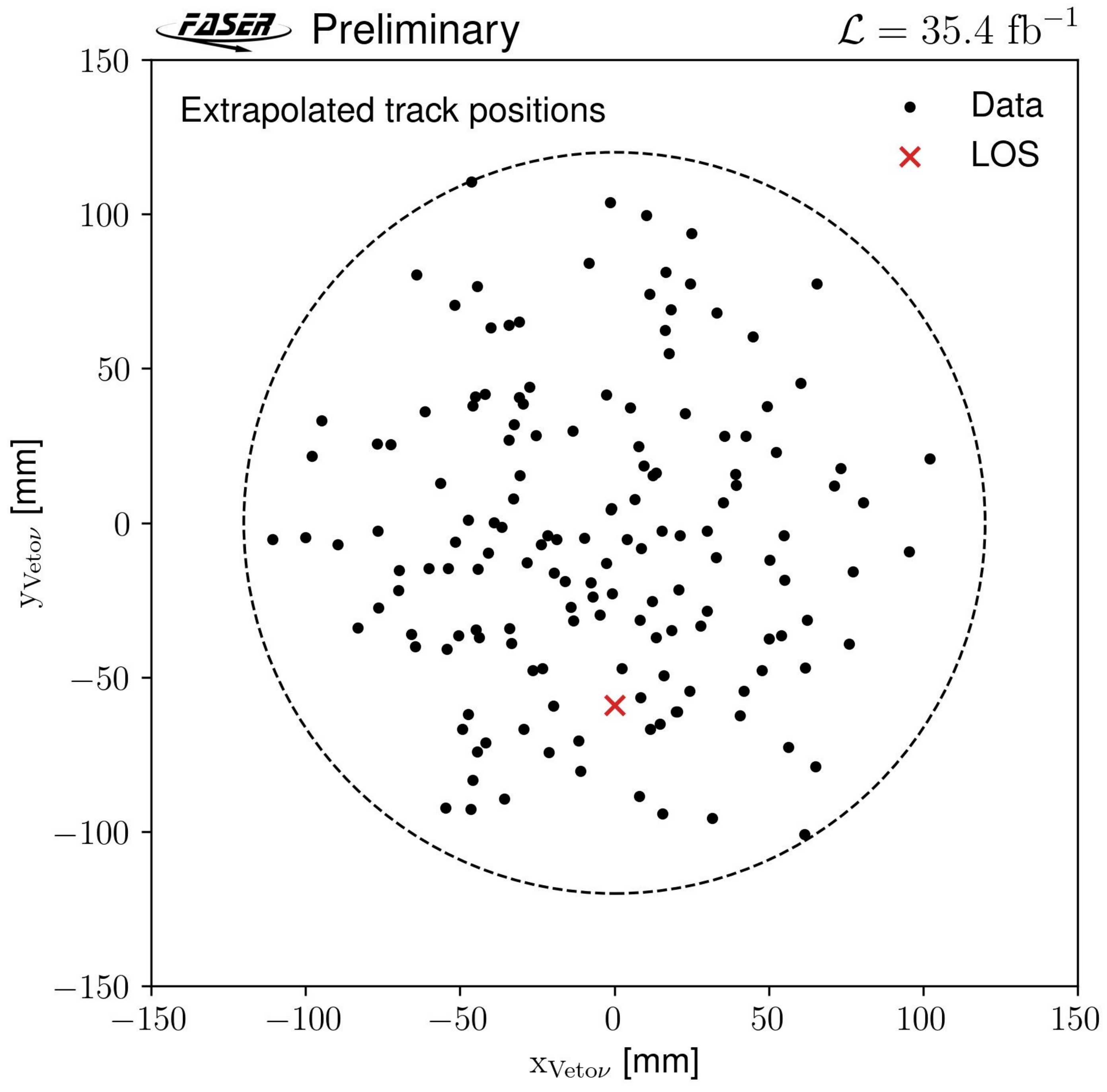
(2) Estimate fraction of these passing event selection

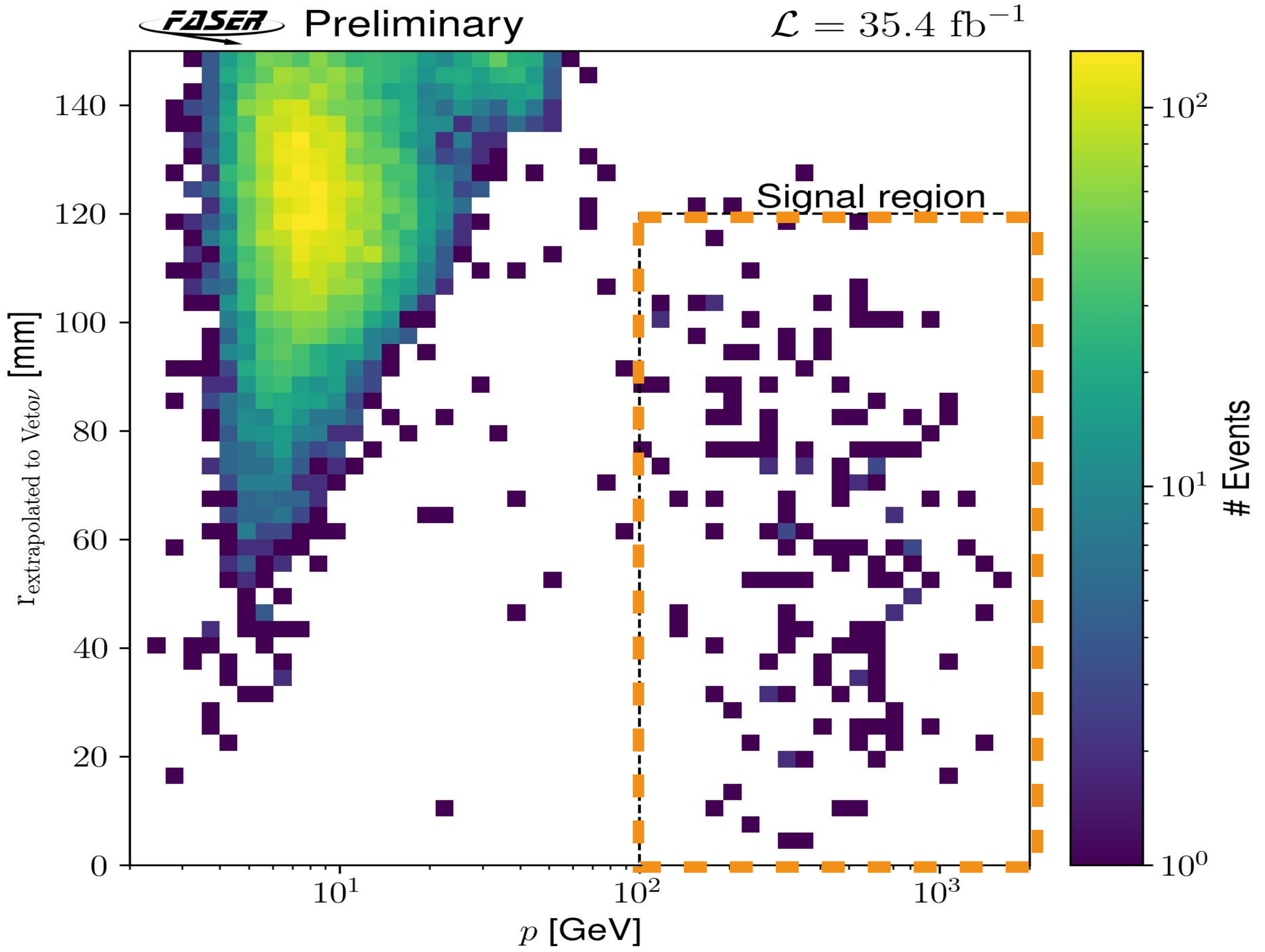
- Simulate kaons and neutrons with p > 100 GeV following expected spectra
- Most are absorbed in tungsten with no high momentum track and only small fraction pass

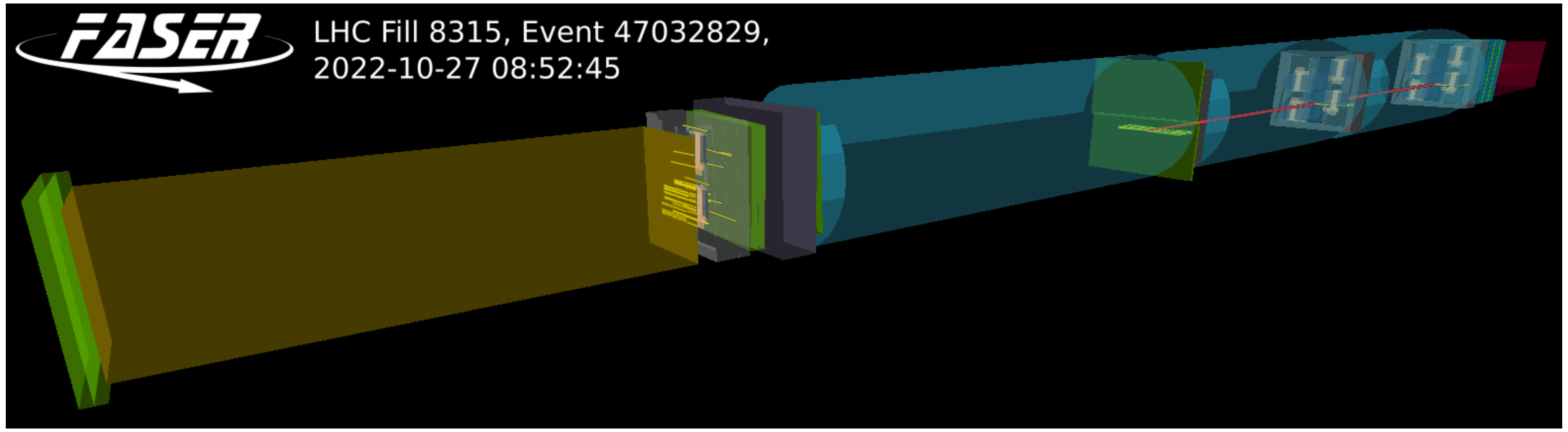
- **Scale neutral hadrons produced by muons reaching FASER by fraction passing selection**
  - Predicts N = 0.11 ± 0.06 events

Neutrino results

- Simulation expected 151 ± 41 neutrino events!
  - Uncertainty from difference in generators (DPMJET and SIBYLL)
- Upon unblinding find **153 events** with no veto signal
  - Expected background 0.2 ± 1.8
- **First direct detection of collider neutrinos!**
  - **With signal significance of 16σ, accepted in Phys. Rev. Lett.**



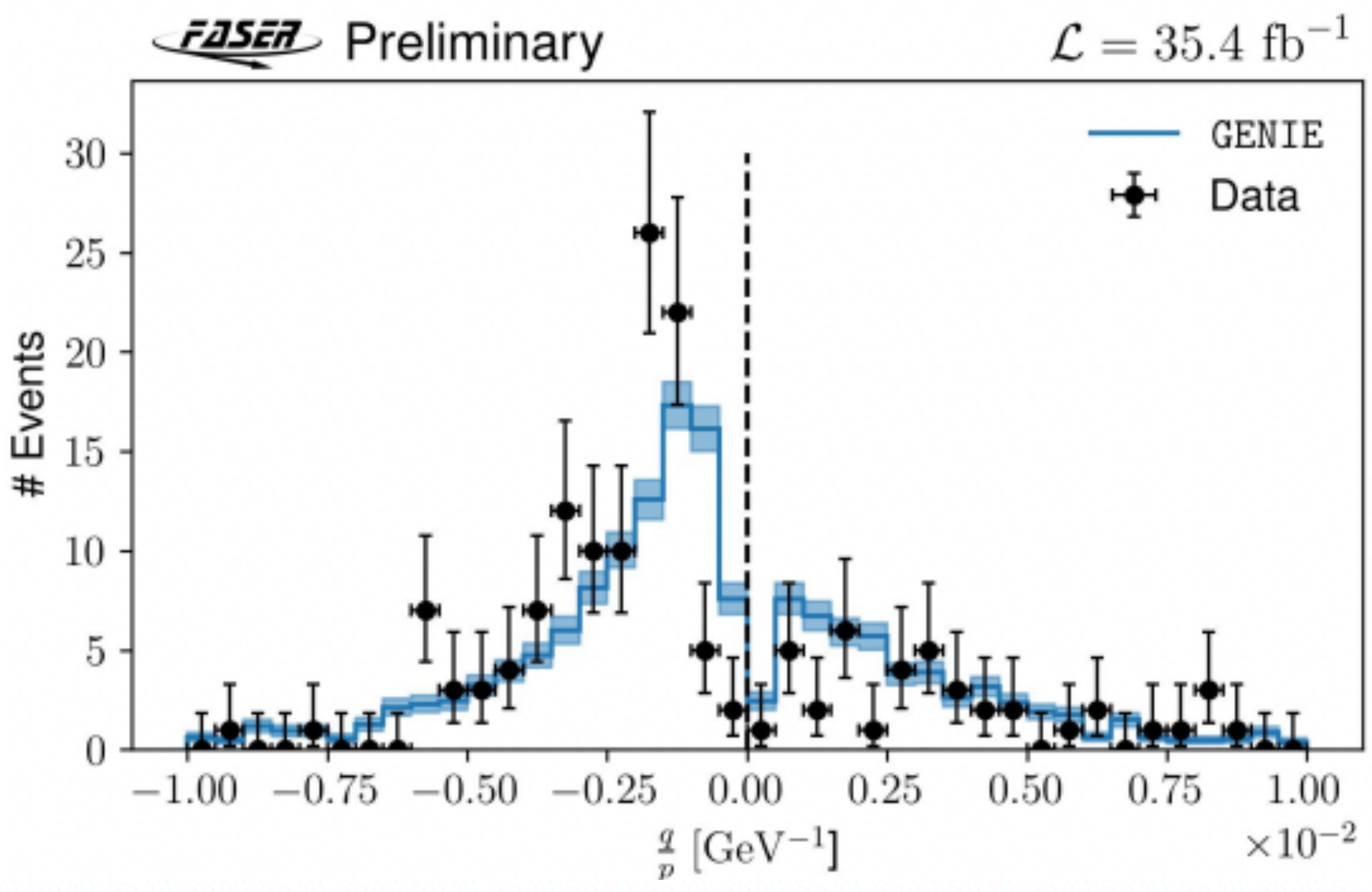


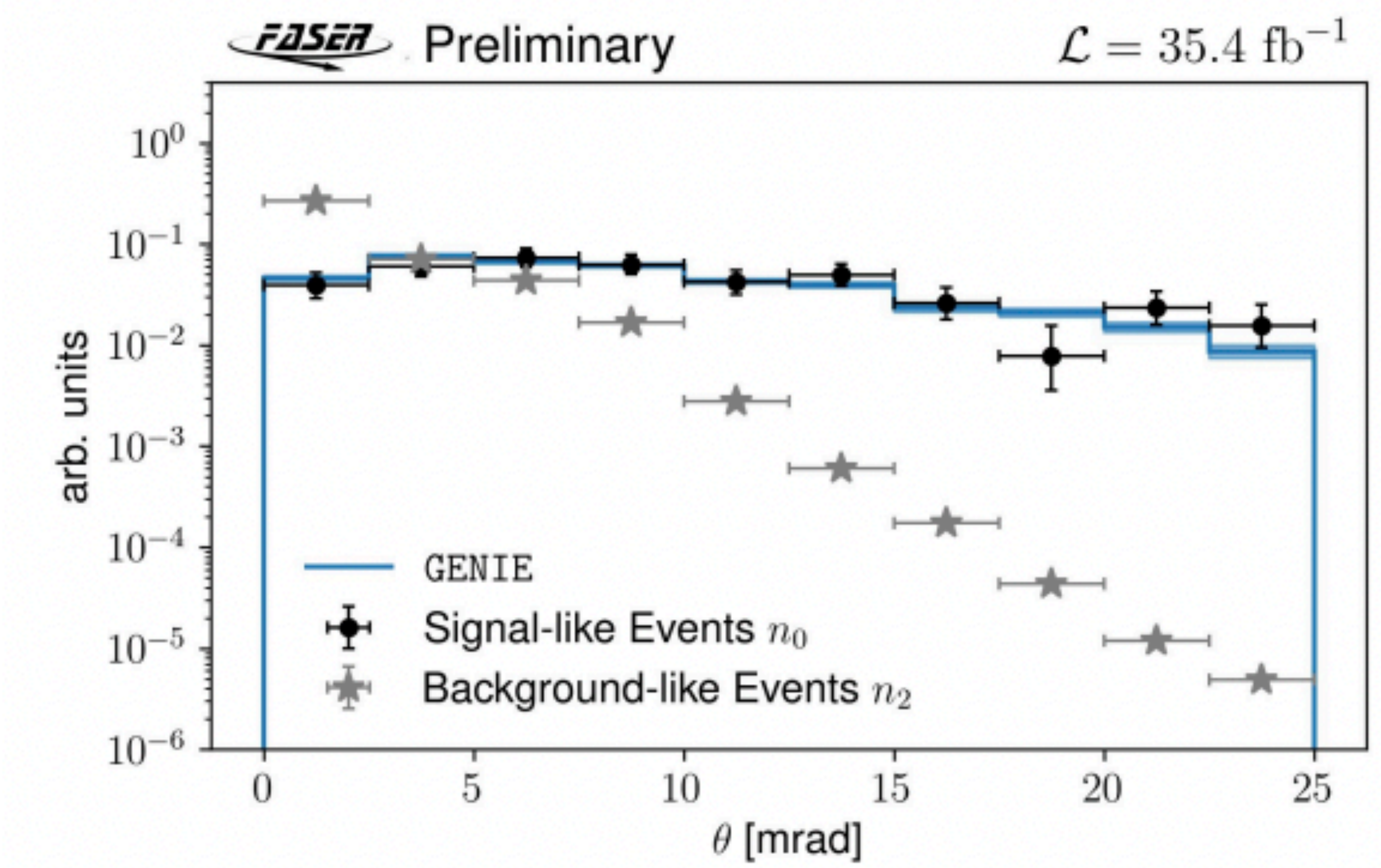


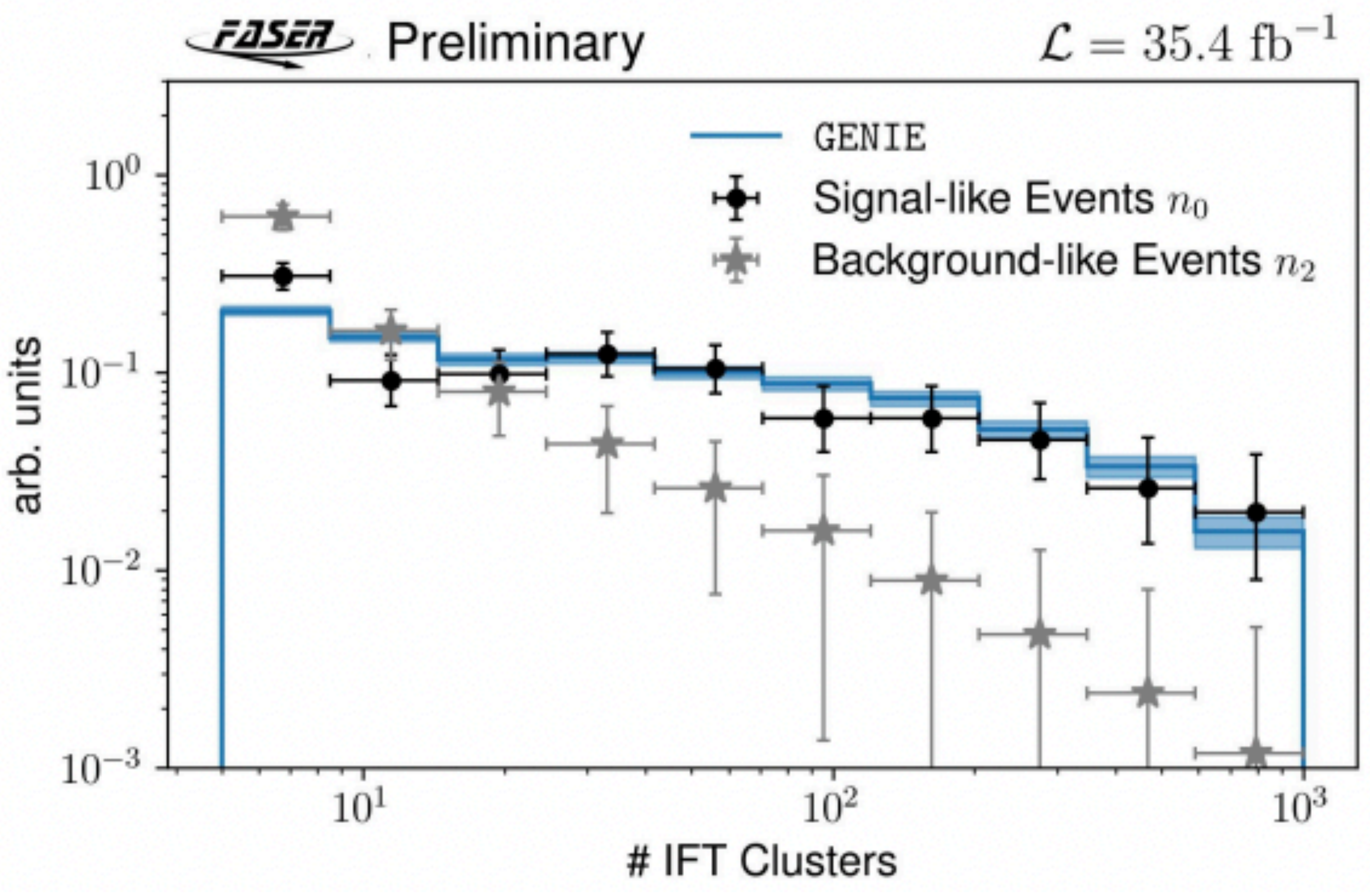
r_{VetoNu} [mm]	r_{IFT} [mm]	$r_{Tracker}$ [mm]	θ [mrad]	p [GeV]	q	clusters IFT
57.2	55.8	54.6	2.5	843.8	−1	57

Neutrino Characteristics

- Well-matched between observed events and simulation
  - Dominated by high momentum events (E_μ > 200 GeV)
  - More ν_μ than $\bar{\nu}_\mu$
  - High occupancy (clusters) in the front tracker (the IFT)
  - Large angle distribution
- Note that no experimental uncertainties included







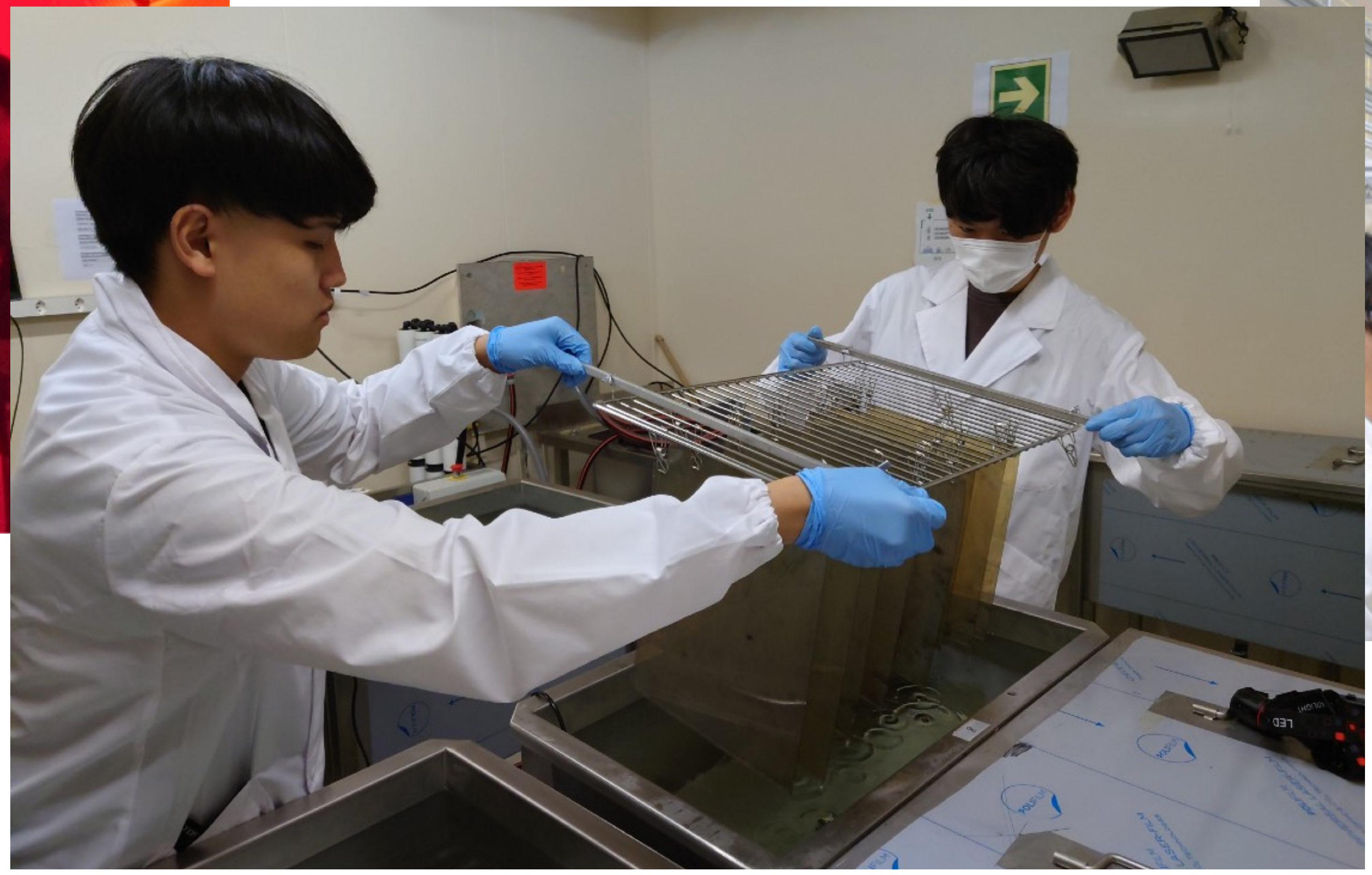
Neutrino study with Emulsion detectors

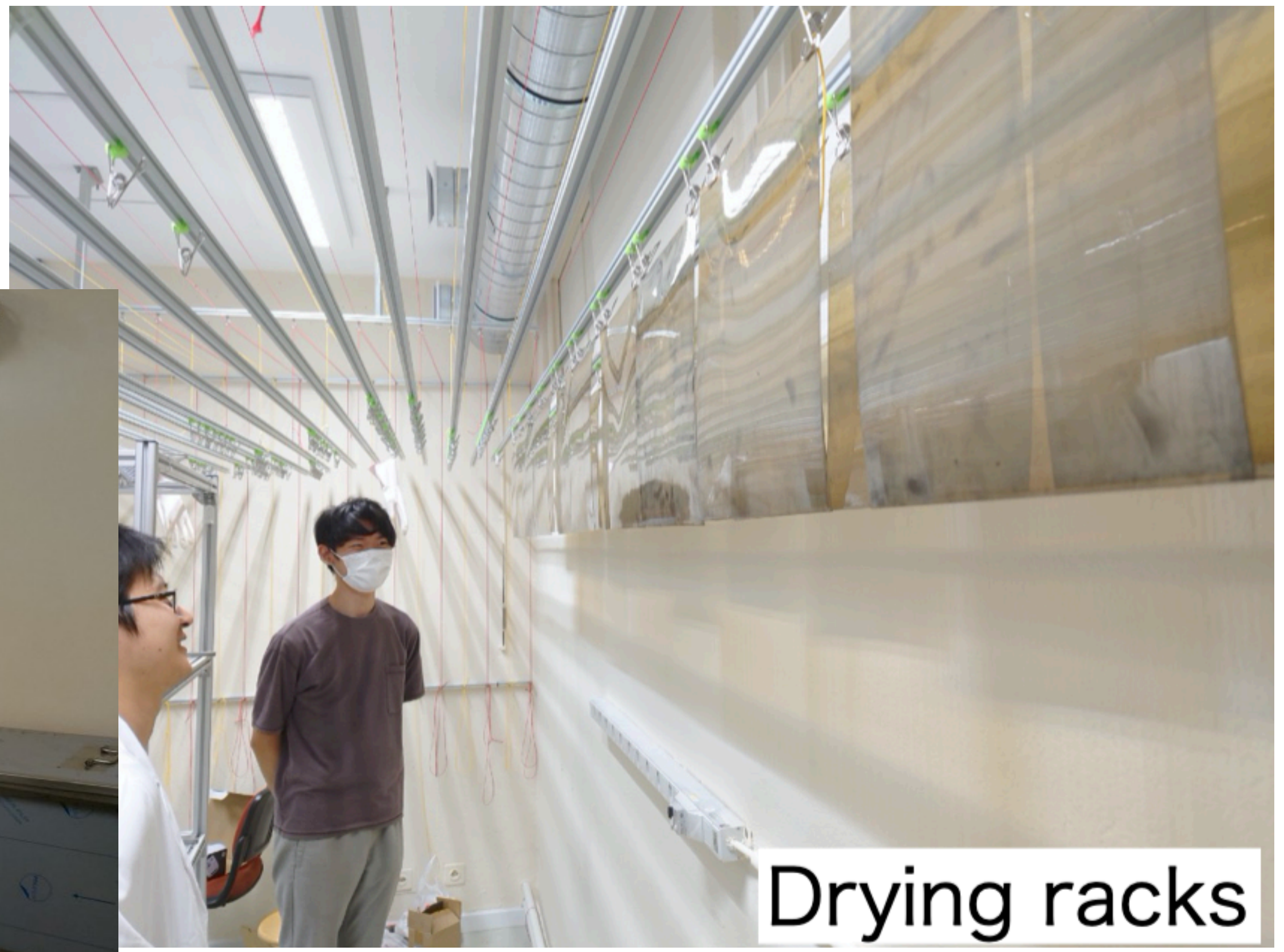
FASERν installation, operation and readout

Since March 2022, we keep collecting data with FASERν

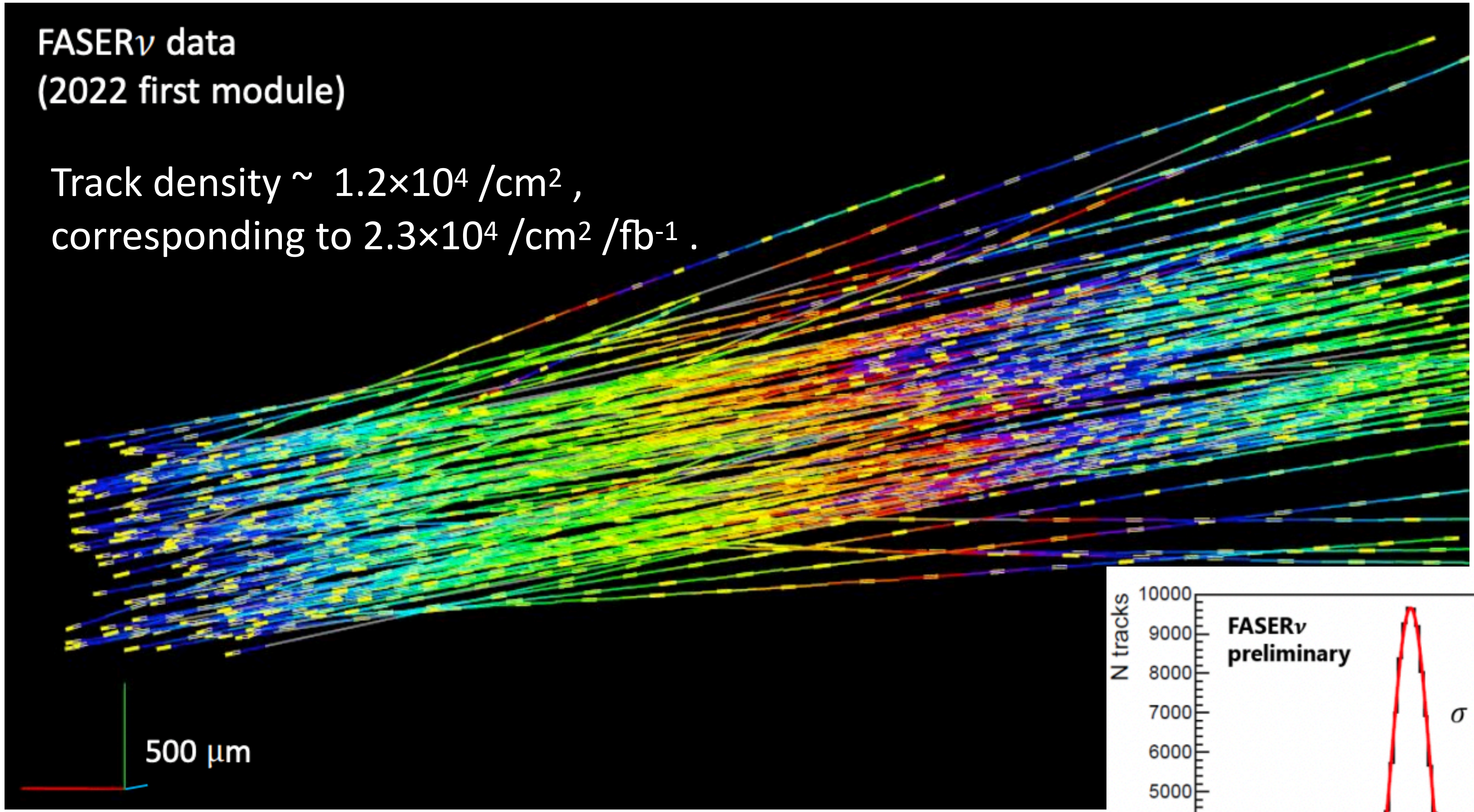
- Detector is assembled in dark room **at the emulsion facility in CERN**
- Installation to TI12 can be done within ~ 4hours
- After exposures, **films are developed and dried at CERN**
- **Scanning films** are performed by the facility at Nagoya University in Japan after transportation

		Integrated luminosity per module (fb^{-1})	**N ν int. expected**
2022 1st module	Mar 15 – Jul 26	0.5	~7
2022 2nd module	Jul 26 – Sep 13	10.6	~530
2022 3rd module	Sep 13 – Nov 29	(~20)	(~1000)



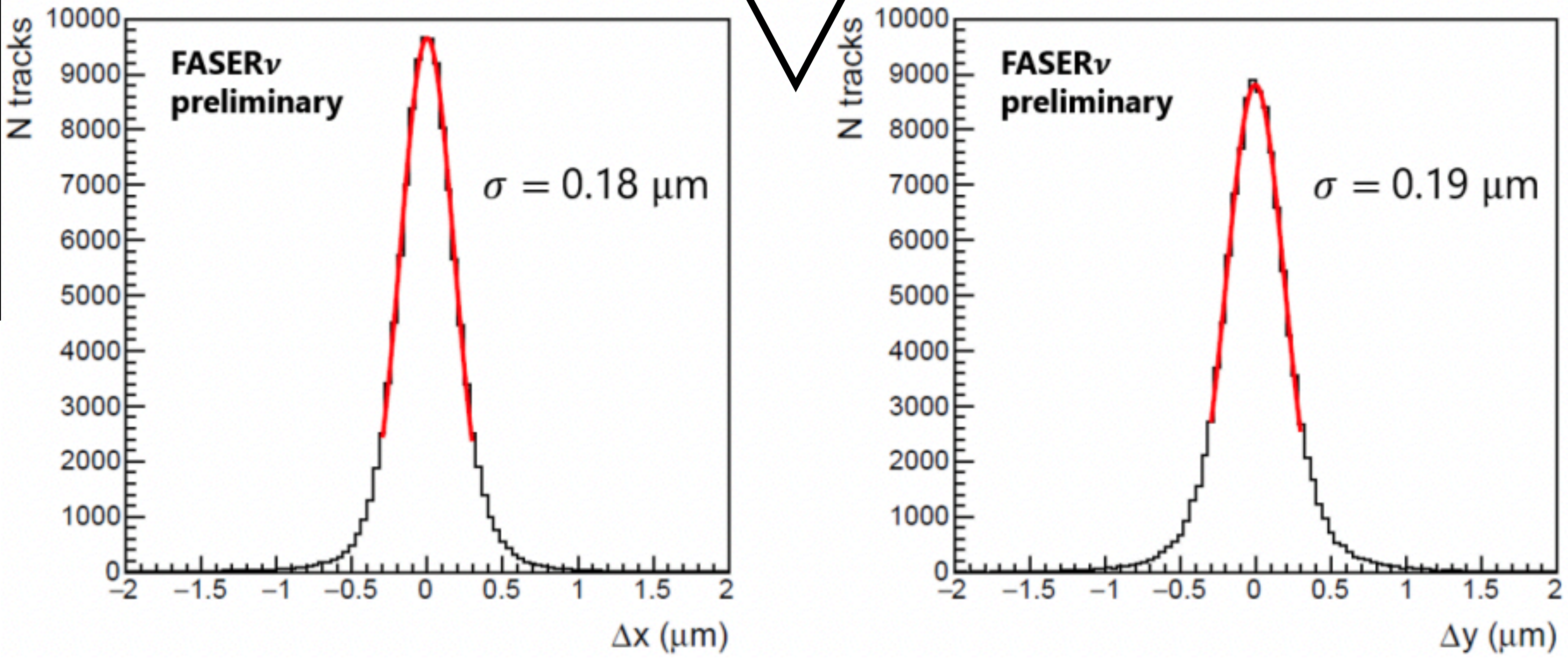


FASERν performance



Distributions of the position deviation between the track hits and the straight-line fits to reconstructed tracks.

The distributions show position resolutions of **~0.2 μm** for the case dedicated alignment is applied to 10 emulsion films.

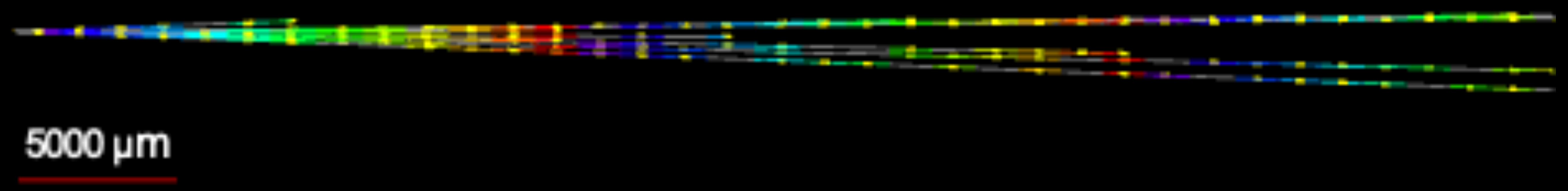


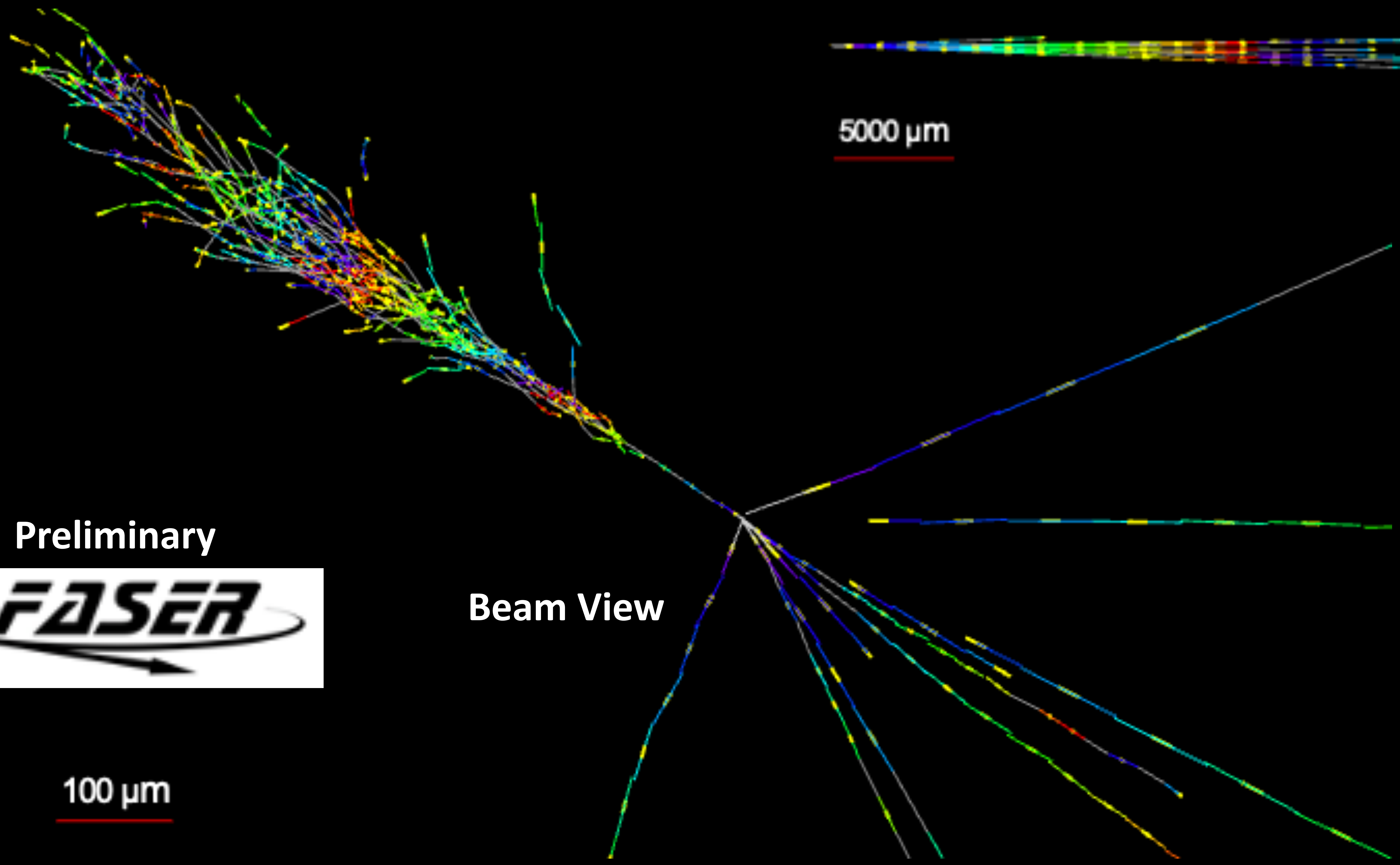
Reconstructed tracks (above ~1 GeV) in 1 mm × 1 mm × 20 emulsion films from the 2022 1st module of the FASERν detector, which collected 0.5 fb^{-1} of data.

Electron Neutrino Event "Candidate"

- **Analysis of FASERν emulsion detector underway**
  - Have multiple candidates including highly ν_e like event

Side View





Preliminary

Beam View

- **Vertex with 11 tracks**
- **e-like track from vertex**
  - Single track for $2X_0$
  - Shower max at $7.8X_0$
  - Θ_c = 11mrad to beam
- **Back-to-back topology**
  - 175° between e & rest

Summary

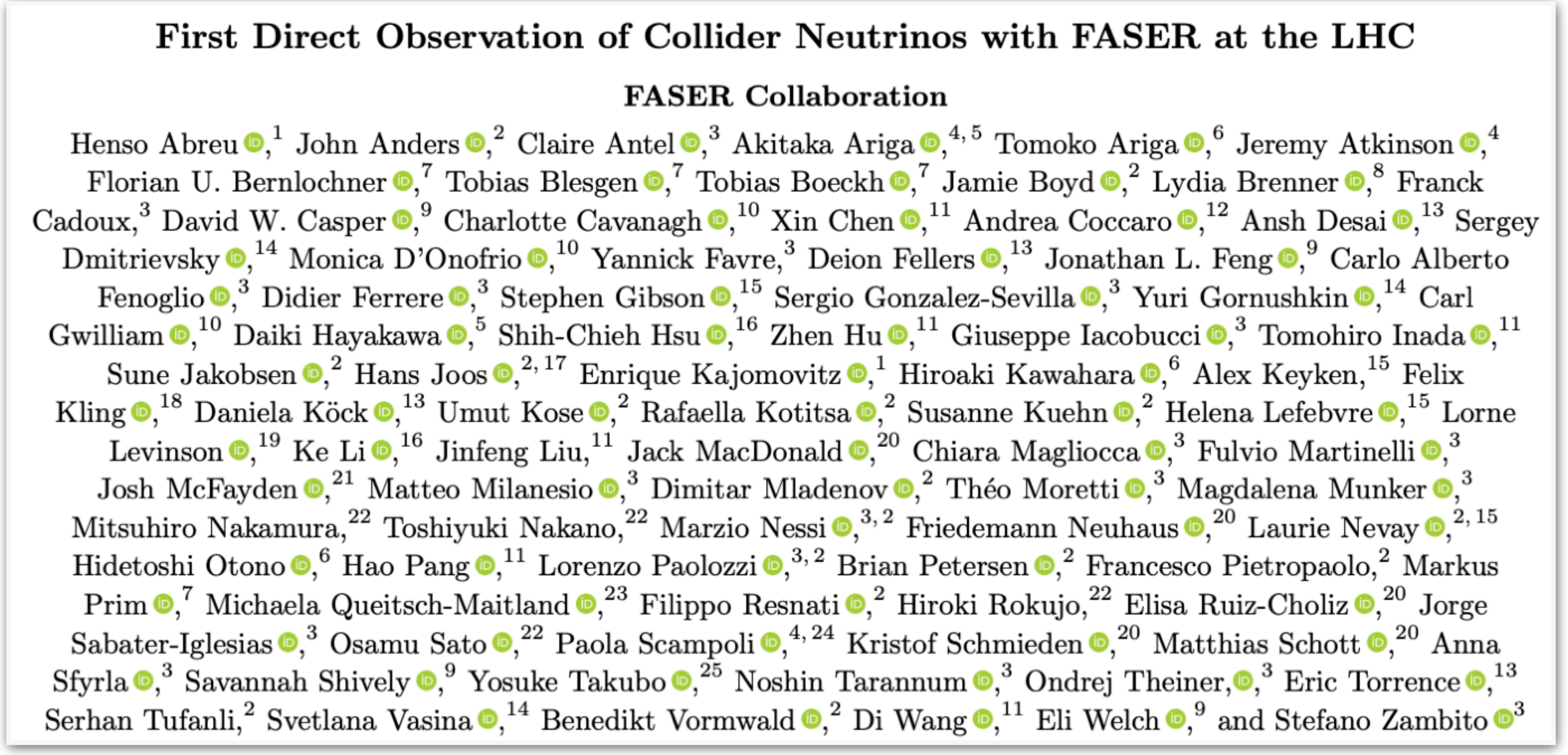
- FASER successfully took data in first year of Run 3
  - Running with fully functional detector and very good efficiency

- FASER is running very well in 2023 data taking with more than 20 fb-1 of data collected so far

- First direct detection of collider neutrinos (~150 ν_μ CC interactions)
  - Opens new window for high-energy ν study arXiv:2303.14185
  - Plan to measure cross-section and flux in future

- **More searches and neutrino measurements** to come with **FASERν**
  - **Flavors, energy spectra, cross-section, flux** etc

- **Larger upgrades of FASER and FASERν are discussed** in the context of the proposed Forward Physics Facility with ~100x measurement of more neutrino interactions possible (O(10x) Run 3 lumi and O(10x) target mass))
  - - see talk by J. Boyd for more details.



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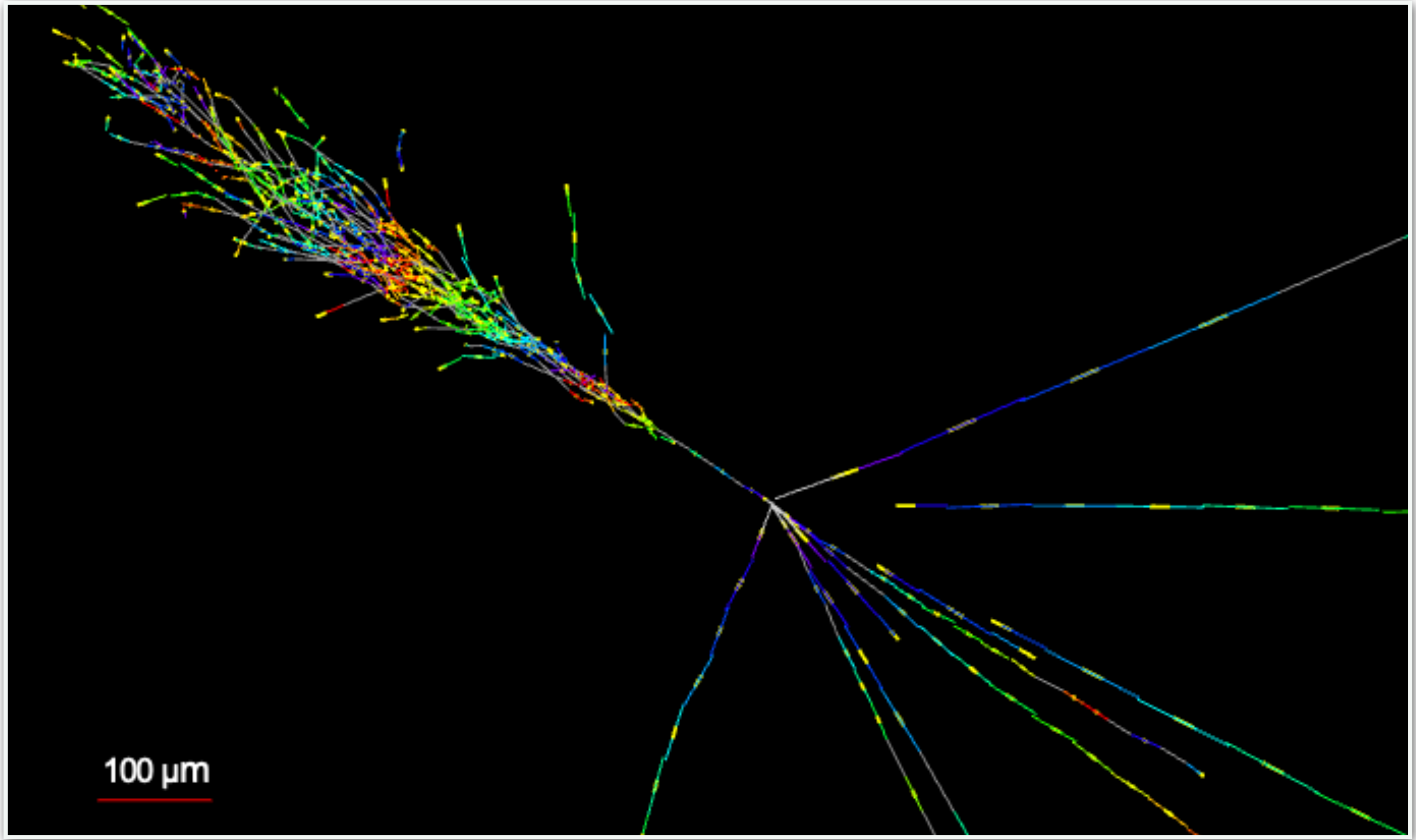

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科研費 KAKENHI

- And would additionally like to thank
  - LHC for the excellent performance in 2022
  - ATLAS for providing luminosity information
  - ATLAS for use of ATHENA s/w framework
  - ATLAS SCT for spare tracker modules
  - LHCb for spare ECAL modules
  - CERN FLUKA team for background sim
  - CERN PBC and technical infrastructure groups for excellent support during design construction and installation

Back

Up

Neutrinos: fit

- Fit to events with 0, 1 or 2 front veto hits
  - Splitting those were 1 hit is in1st/2nd layer
- Construct likelihood as product of Poissions
- With additional 3 Gaussian constraints for Neutral hadron background, Geometric background and the extrapolation factor

$$\mathcal{L} = \prod_{i}^{4} \mathcal{P}(\underset{\text{obs}}{n_i} | \underset{\text{exp}}{\nu_i}) \cdot \prod_{j}^{3} \mathcal{G}_j$$

- Determine number of in each category
  - Along with inefficiencies of 2 forward vetos, which are found to be close to expected vals.

Inefficiencies:
$6 / 9 \times 10^{-8}$

1 - p1 = 99.999994(3)%
1 - p2 = 99.999991(4)%

n_0: A neutrino enriched category from events that pass all event selection steps.

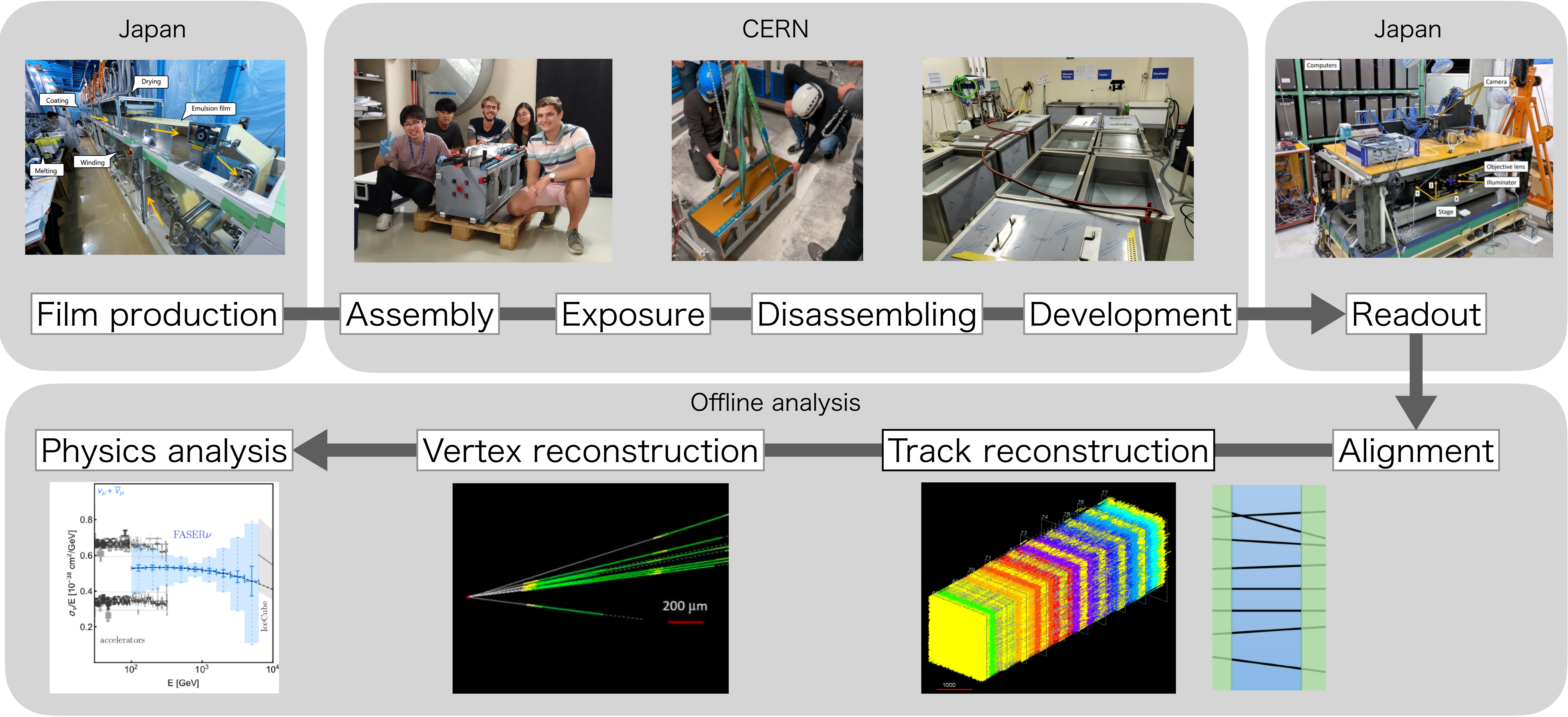
n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.

n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

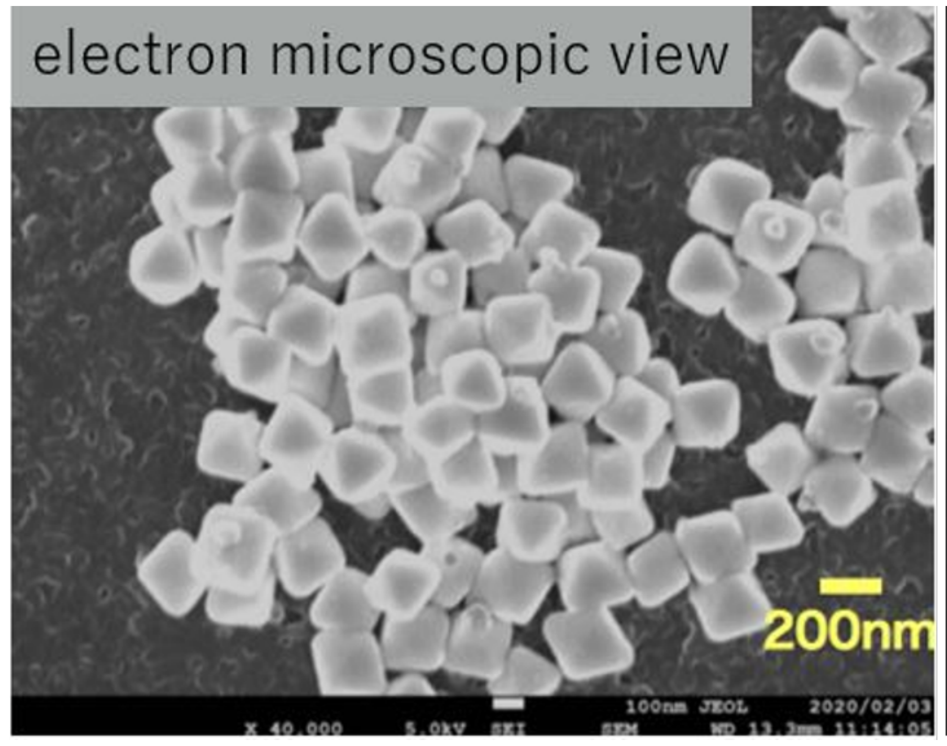
n_2: Events for which both layers observe more than 40 pC of charge.

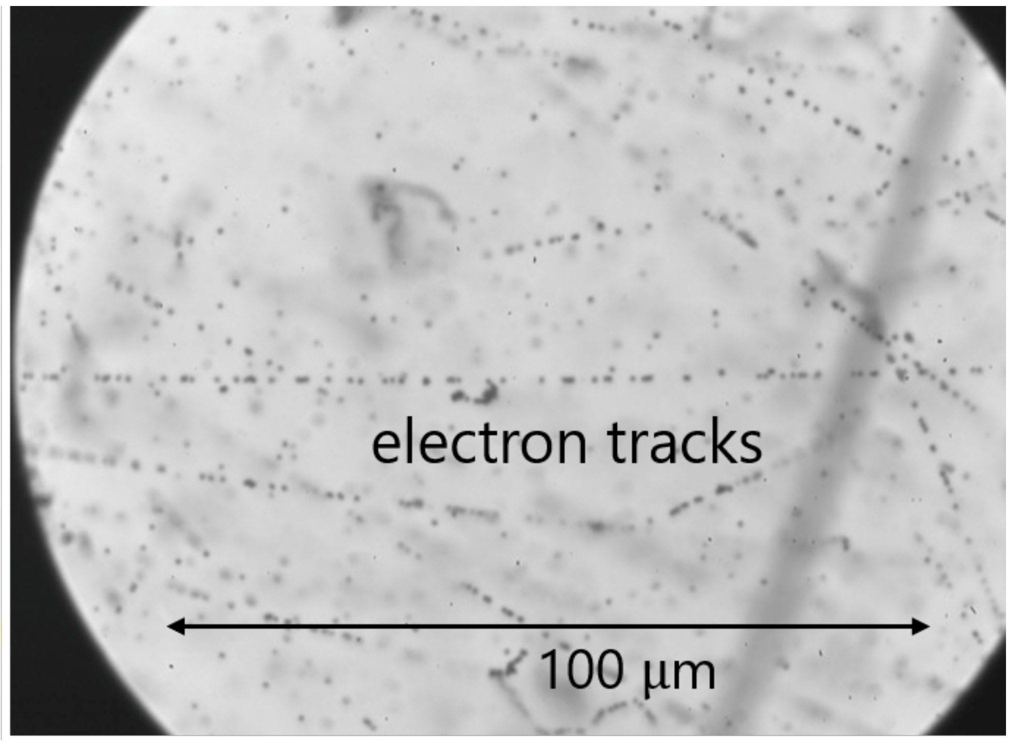
Category	Events	Expectation
n_0	153	$\nu_\nu + \nu_b \cdot p_1 \cdot p_2 + \nu_{\text{had}} + \nu_{\text{geo}} \cdot \eta_{\text{geo}}$
n_{10}	4	$\nu_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$\nu_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$\nu_b \cdot (1 - p_1) \cdot (1 - p_2)$

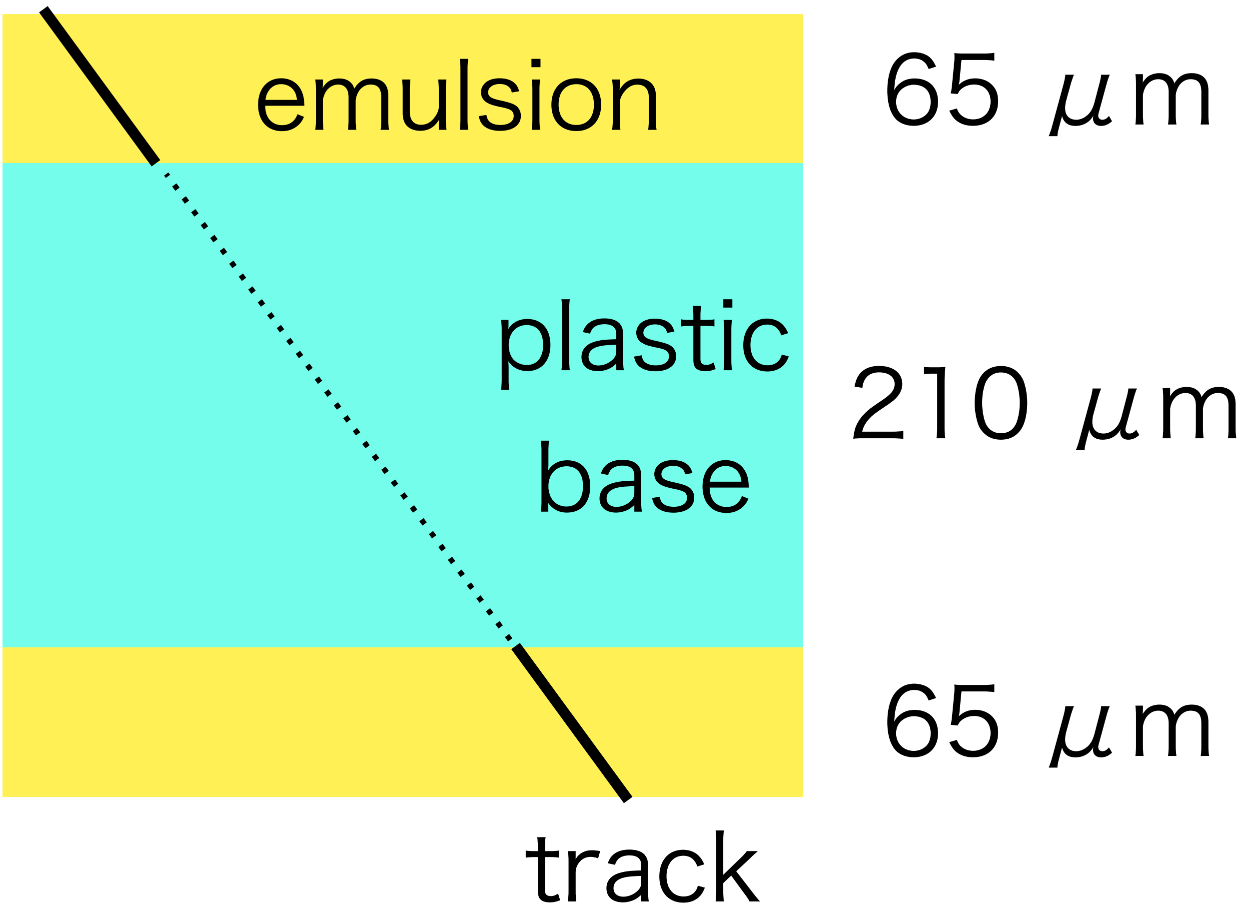
Emulsion work flow

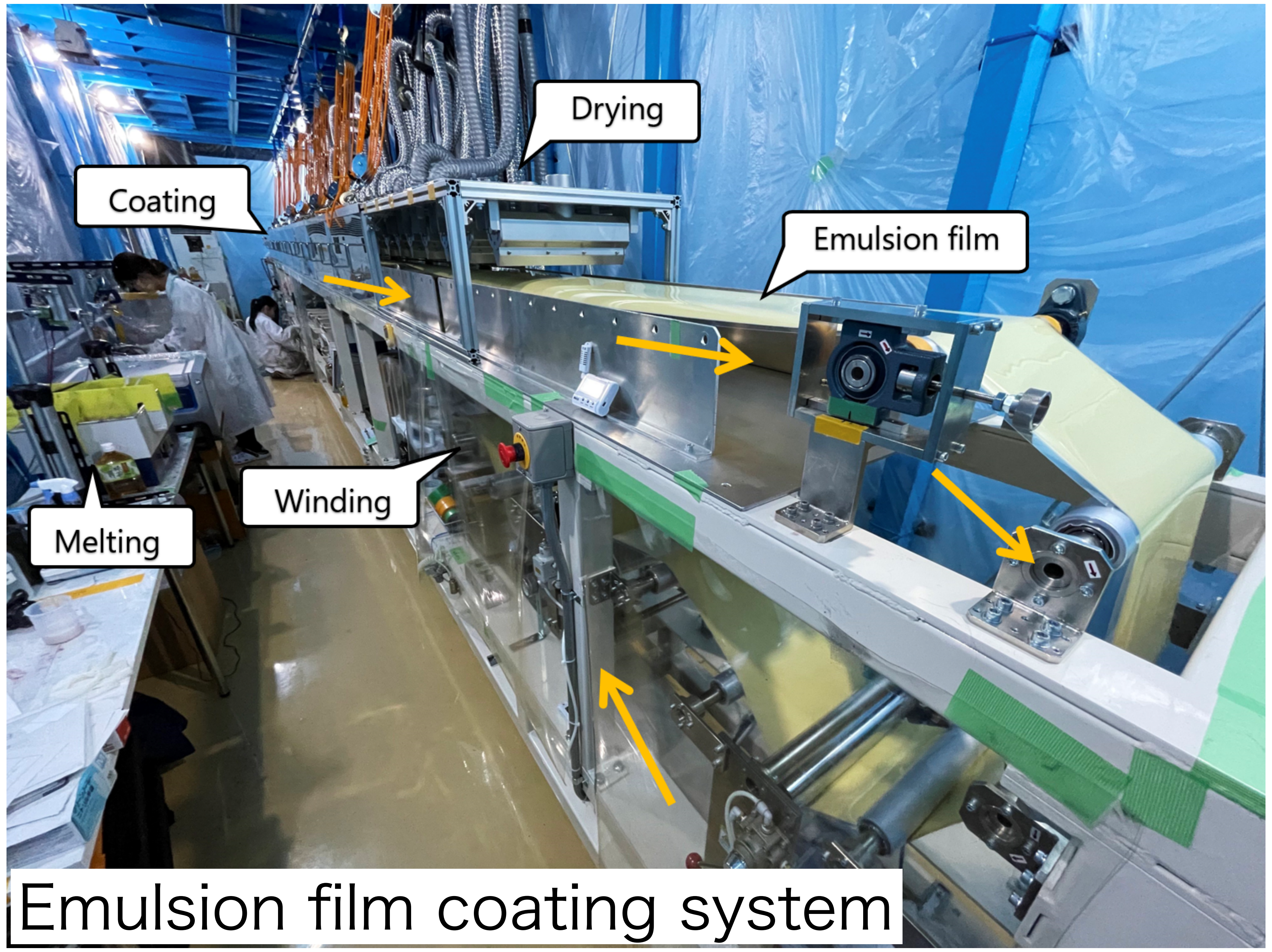


Film production









Emulsion film coating system

- 200 nm diameter crystals
- Double sided emulsion coating
- Total area of 730 files: ~55 m^2
- Produce emulsion gel and film a few months before module assembly