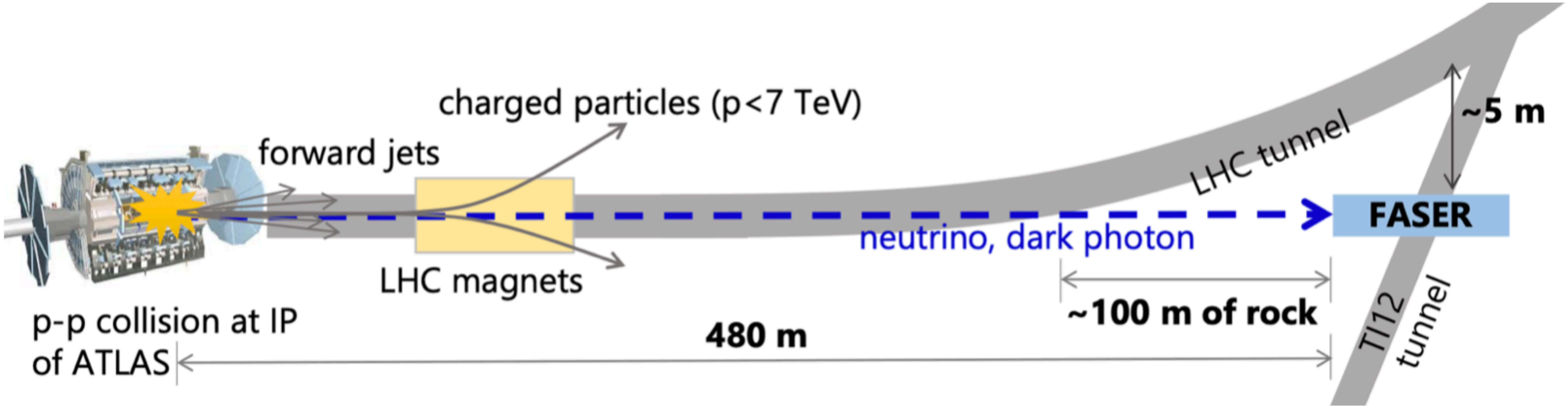
FASER Neutrino Results and Future Prospects

19th of July 2023, Neutrino Workshop at IFIRSE (NuIF)

Daiki Hayakawa (Chiba University) on behalf of the FASER collaboration

The FASER Experiment

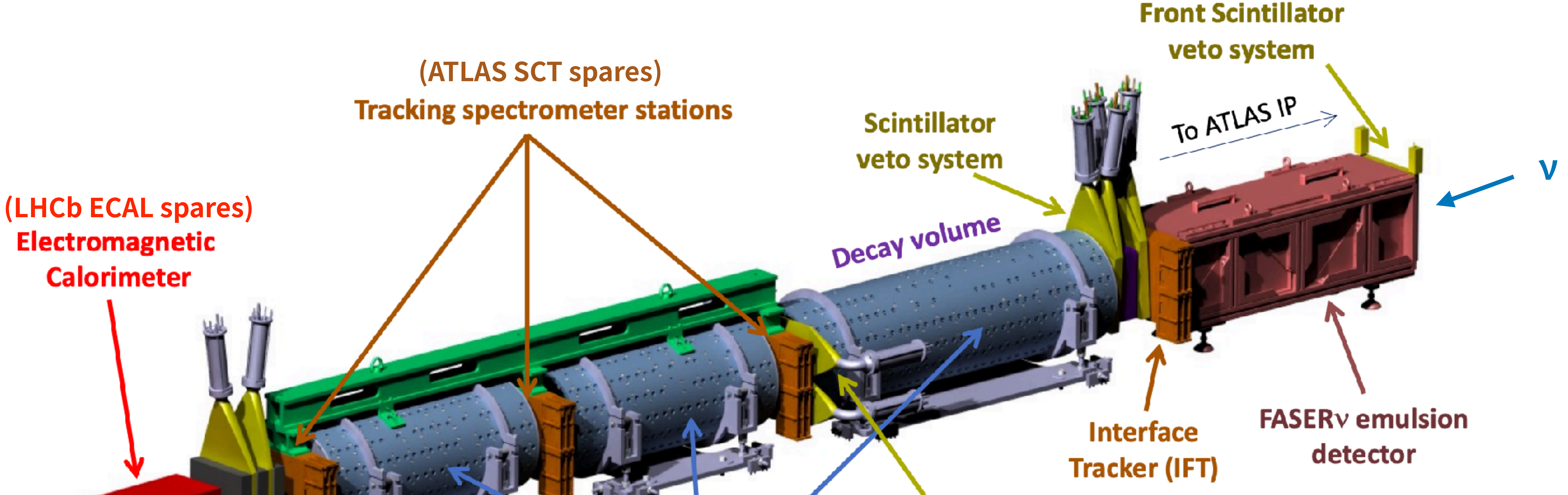


- **Large Hadron Collider (LHC)**: 27 km ring collider, 13.6 TeV proton-proton collisions
- Energetic particles produced in the **far-forward direction** of the collisions
- **FASER**(**F**orw**A**rd **S**earch **E**xpe**R**iment) is a new experiment at the LHC
  to search for long-lived BSM particles (dark photon, axion-like-particles)
  and study **neutrinos**

FASER at TI12 Tunnel

FASER Detector

arXiv:2207.11427

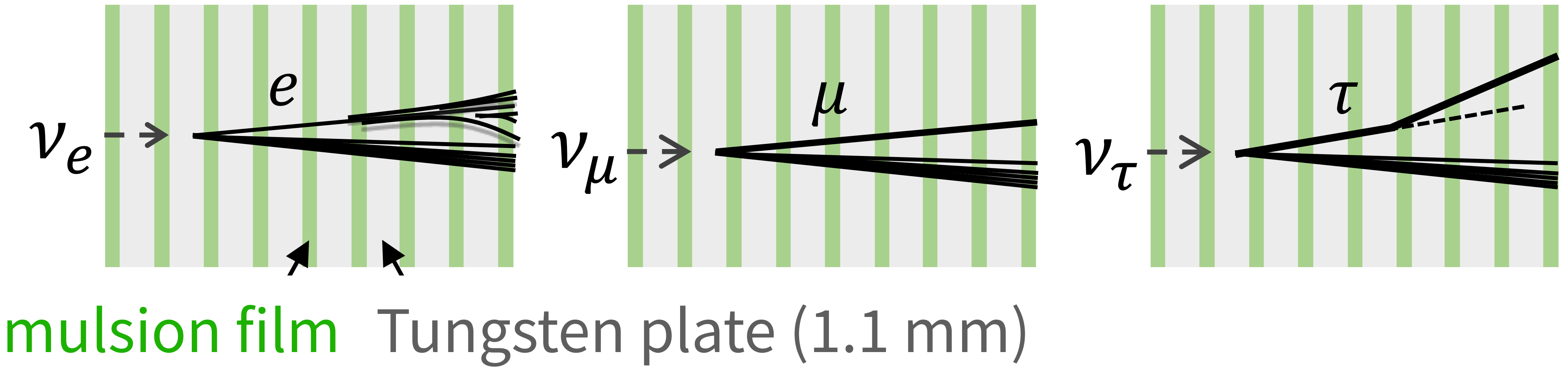


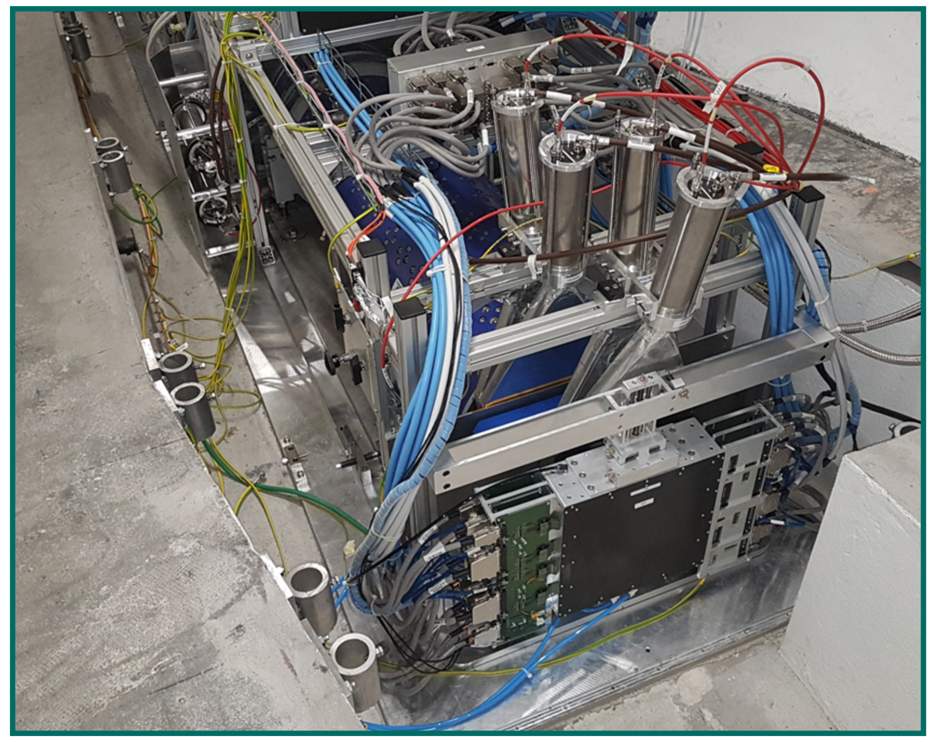
Length: ~7 m

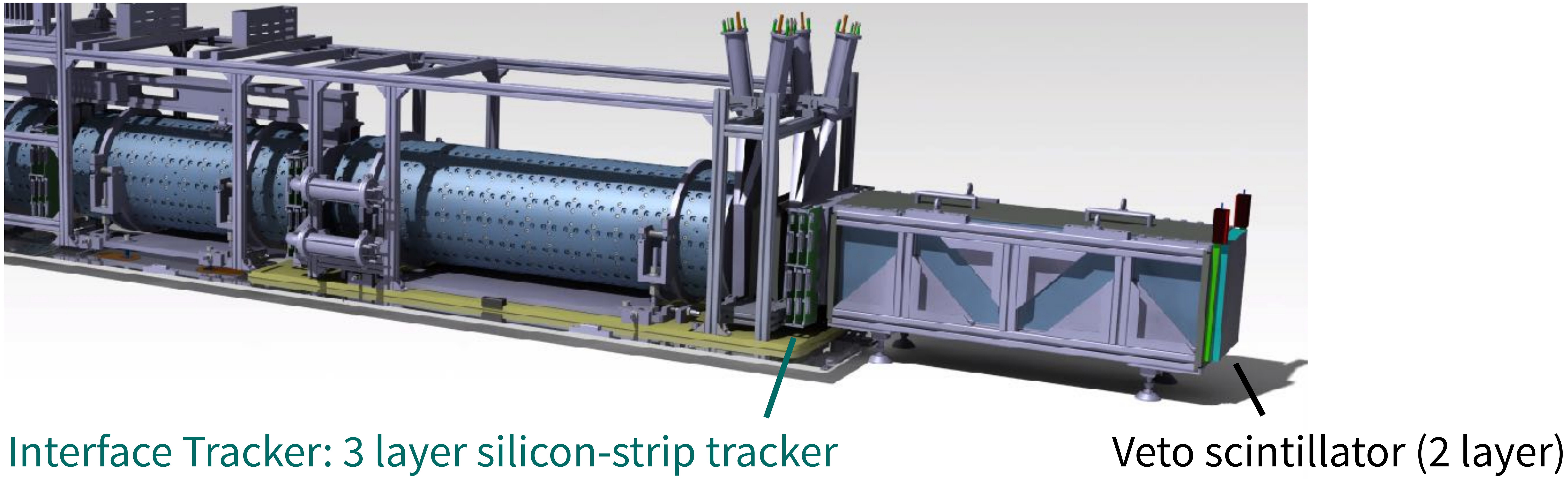
FASERν Neutrino Detector

- Emulsion-based detector
  - 730 × [tungsten (1.1 mm thickness) + emulsion film]
  - 250 mm × 300 mm, 1 m long, 1.1 tons (220 X_0)
  - Install (exchange) emulsions 3 times a year

- ν flavor tagging with topological/kinematical informations

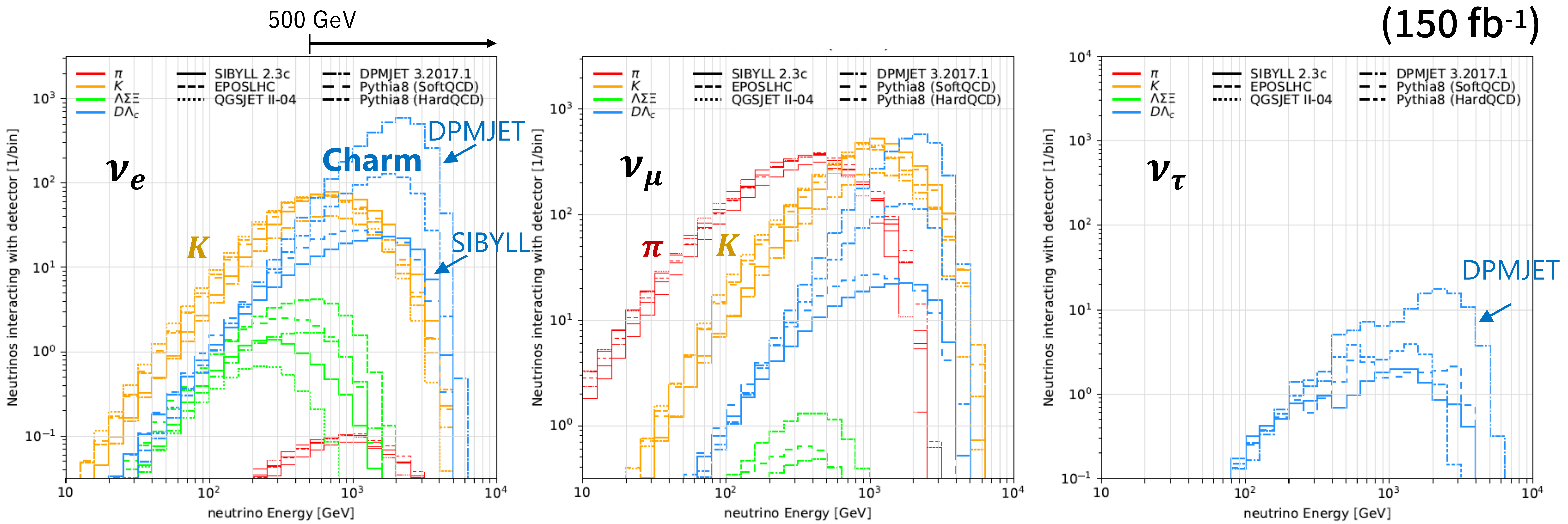






- Global reconstruction with FASER spectrometer
- Muon charge identification (ν_μ)

FASERν Expected Number of Interactions



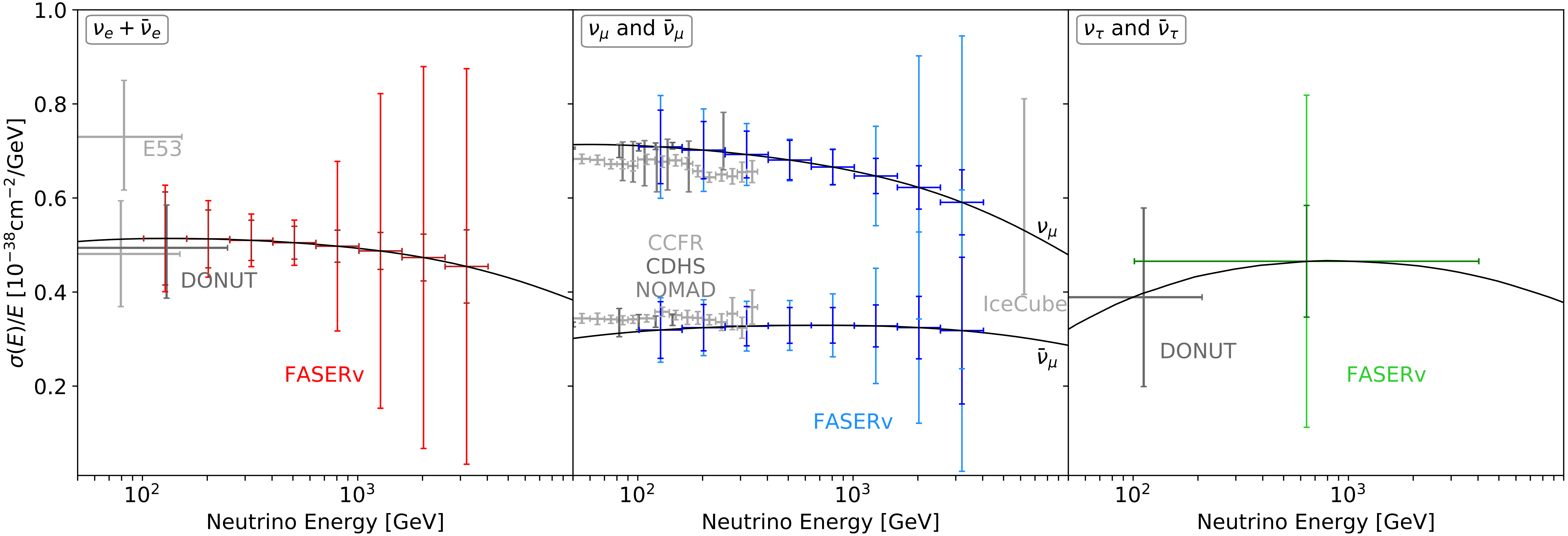
Expected CC interaction events (250 fb⁻¹) (based on PhysRevD.104.113008)

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}	$36^{+20.8}_{-11.5}$

- **Discrepancy between generators for charm production**
- **~10,000 ν interactions expected in LHC Run 3 (2022-2025)**

FASERν Cross-Section Sensitivity

(150 fb^{-1})

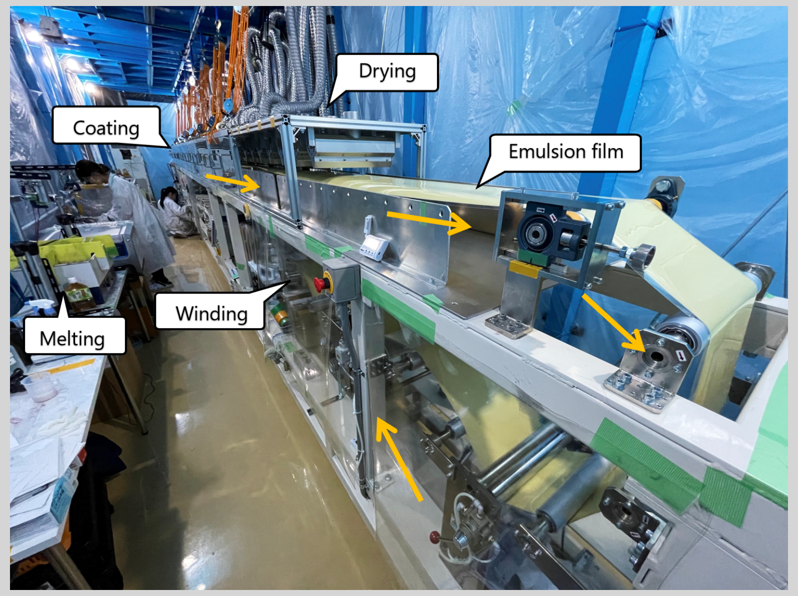


(inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate)

- Three flavors neutrino cross-section measurements for unexplored energy ranges
- Neutrino energy reconstruction with resolution of 30% expected from simulation studies

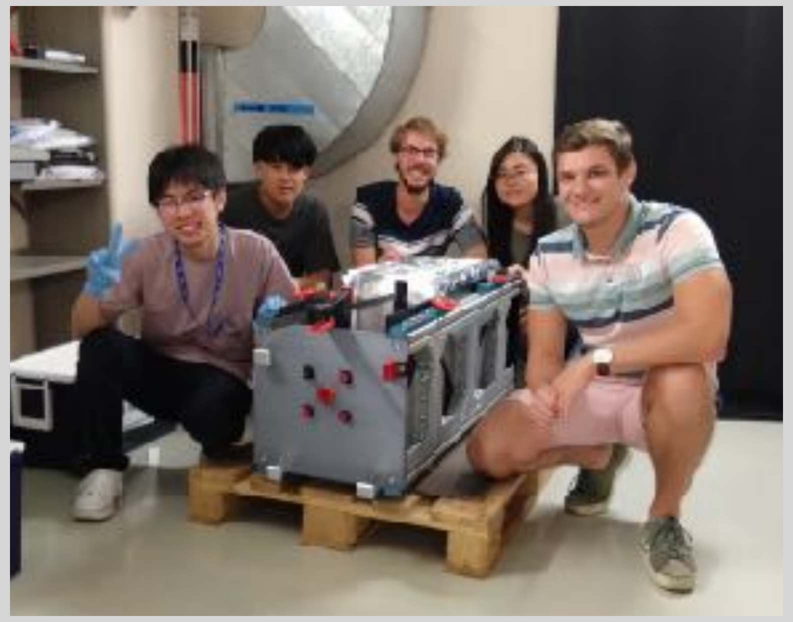
FASERν Emulsion Detector

Japan



Film production →

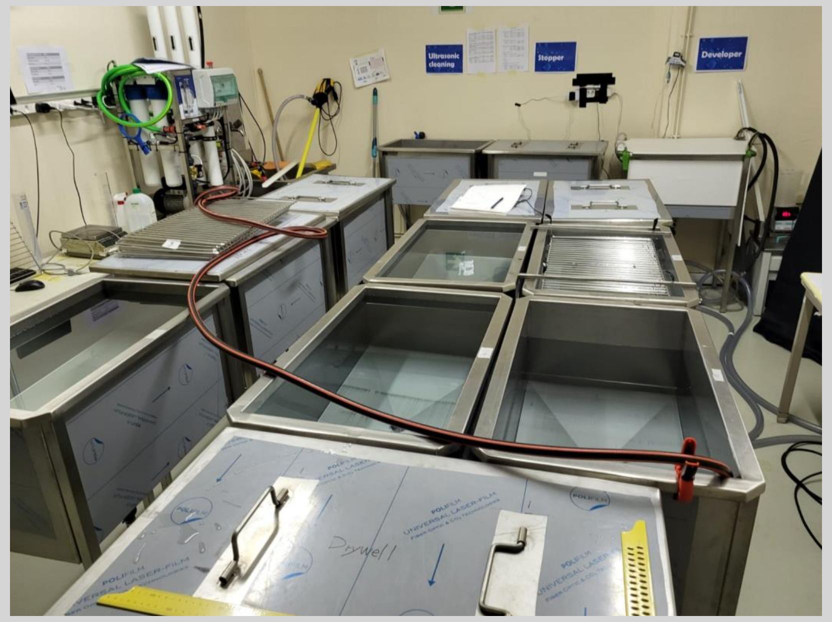
CERN



Assembly →

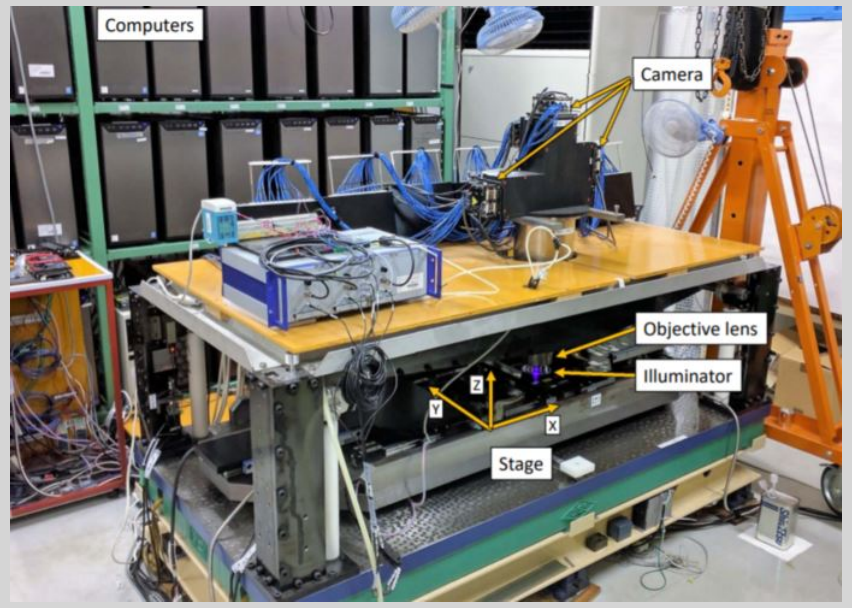
Exposure →

Disassembling →



Development →

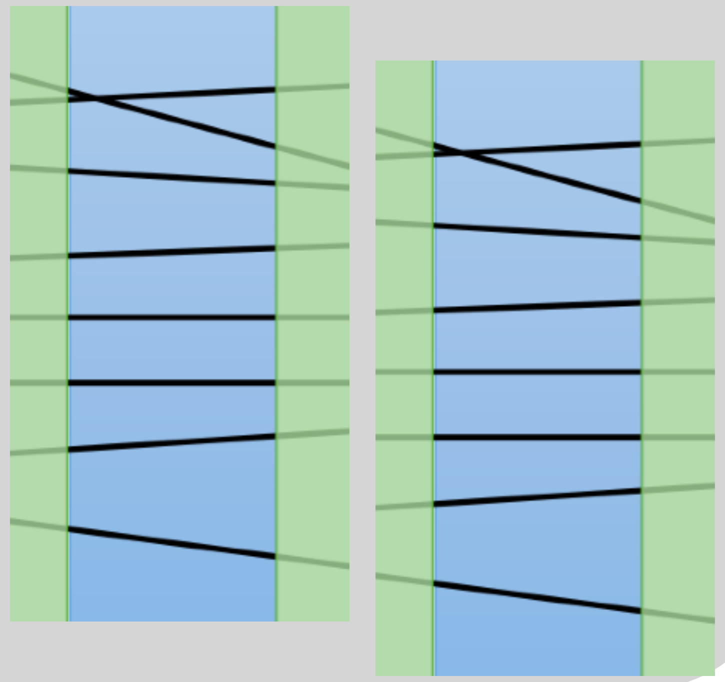
Japan



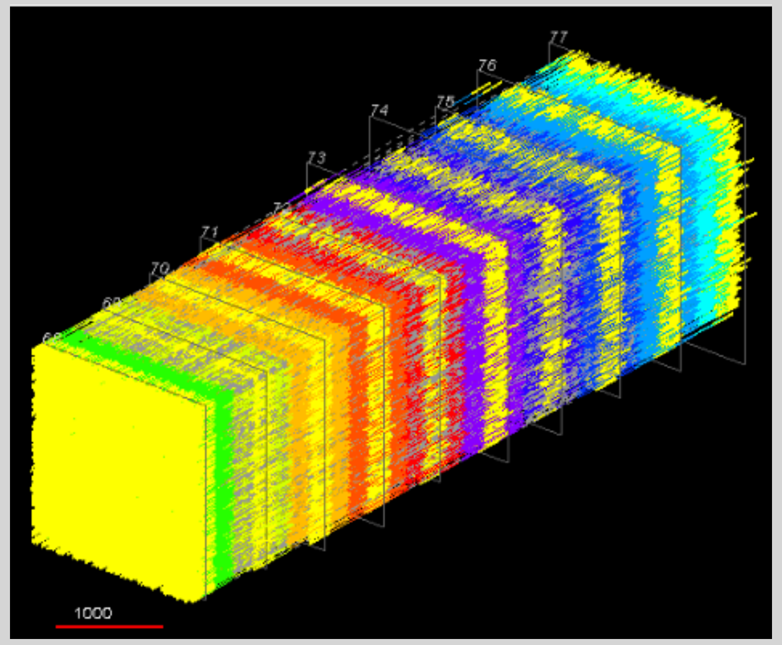
Readout ↓

Offline analysis

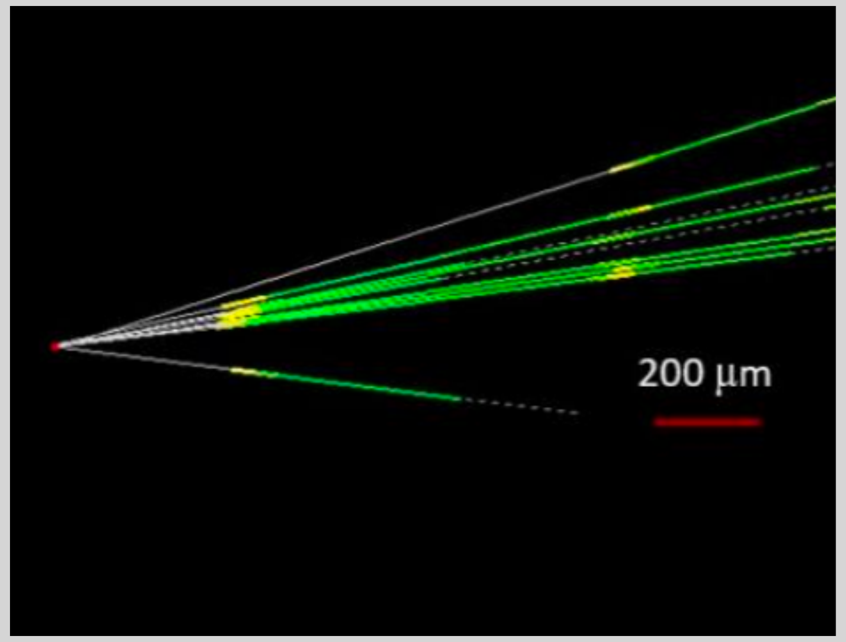
Alignment →



Track reconstruction →

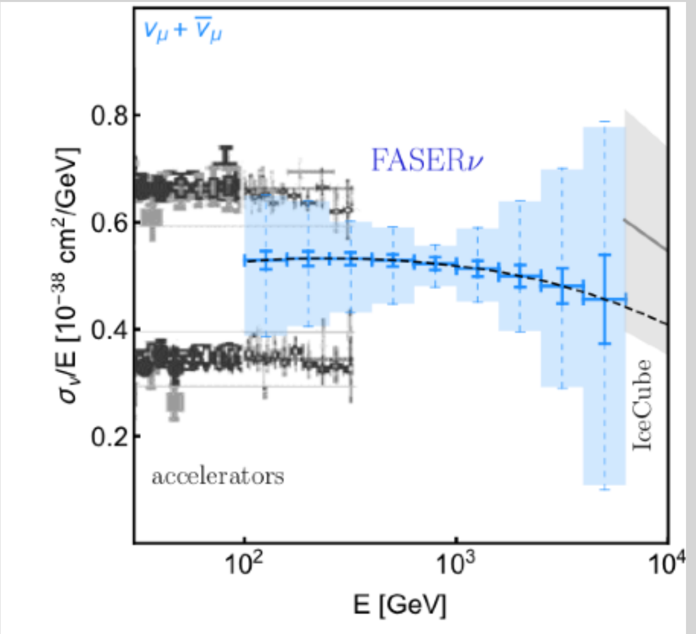


Vertex reconstruction →



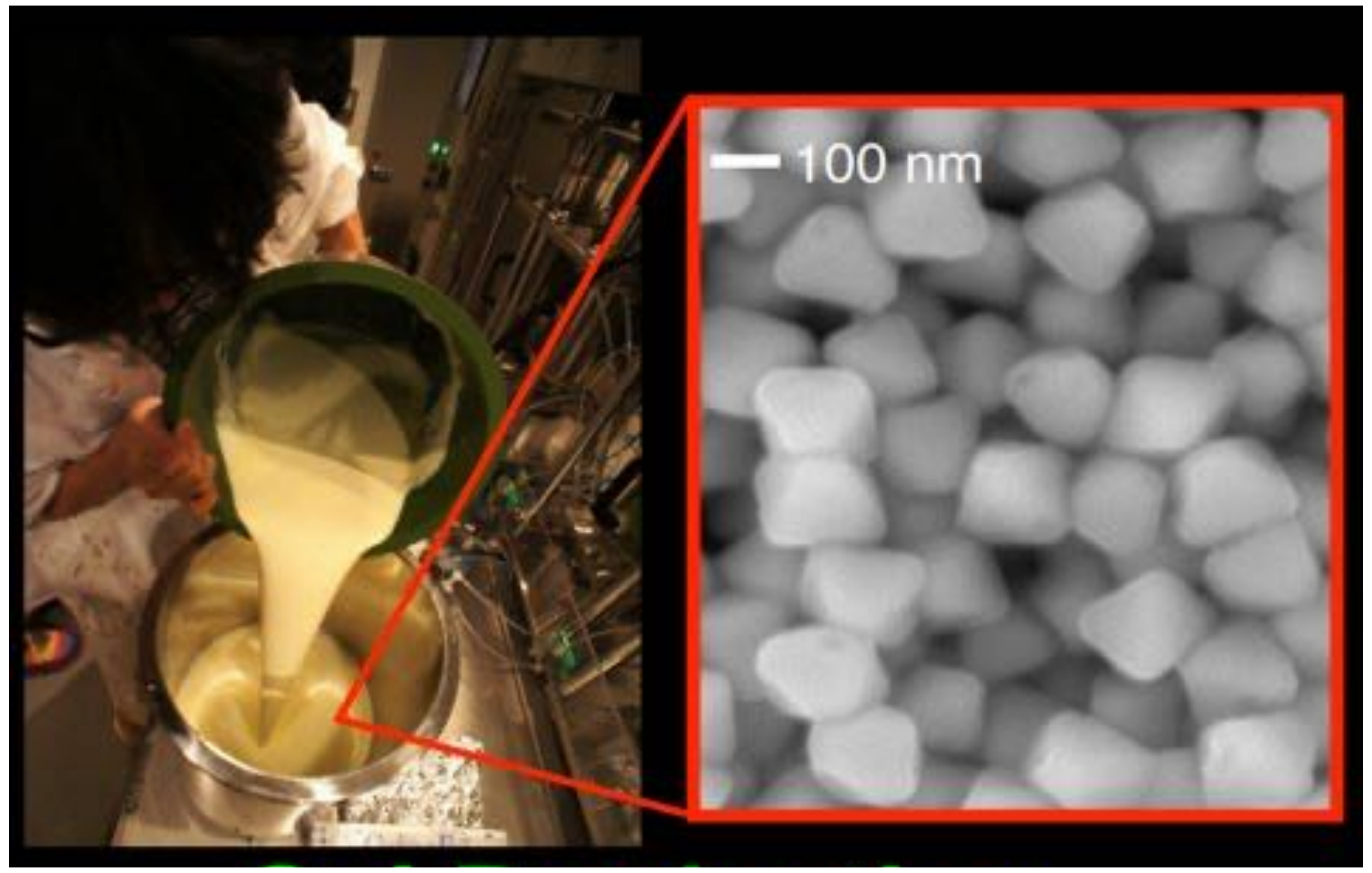
Kinematical analysis, Lepton ID, etc →

Physics analysis

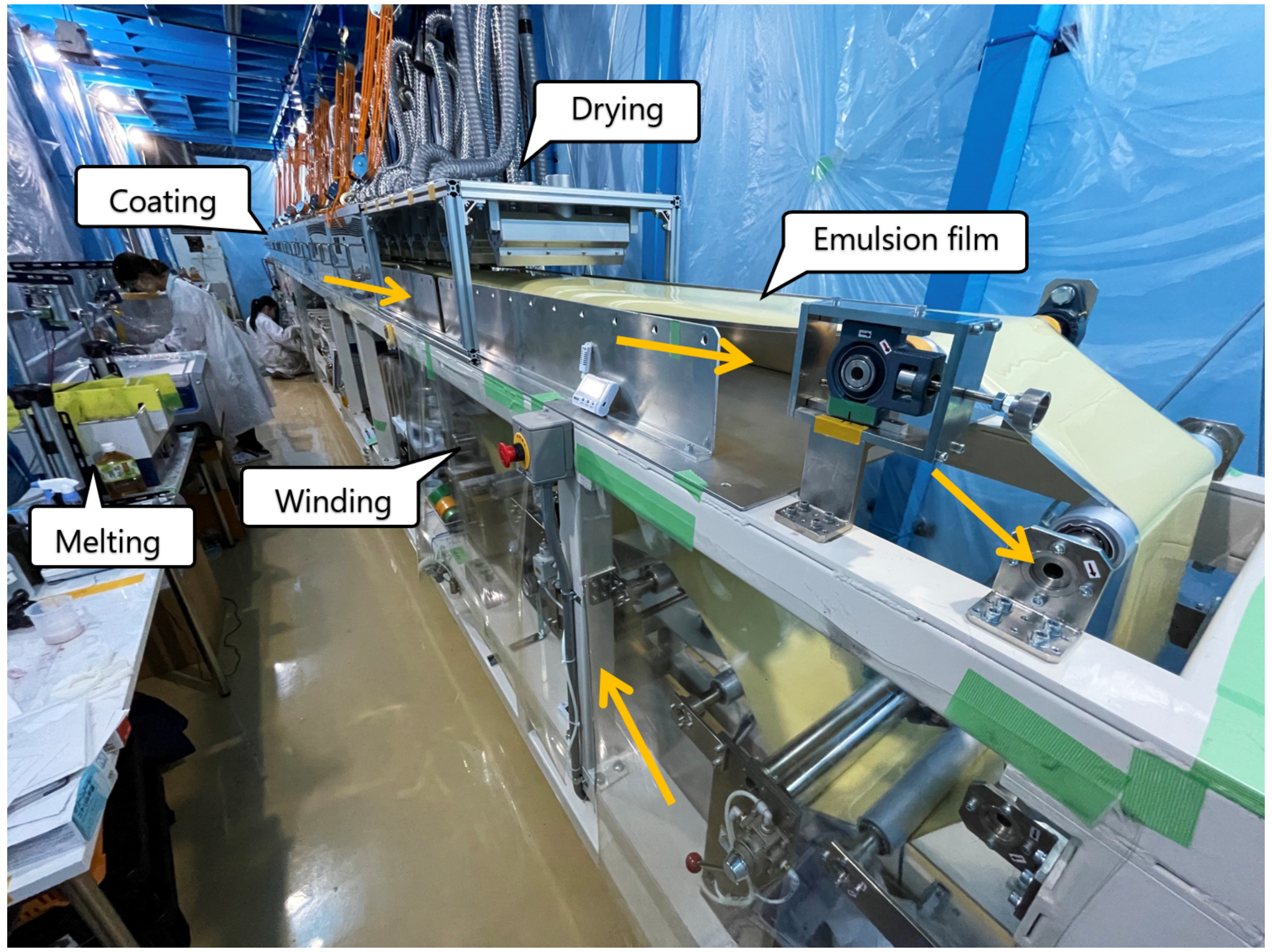


Film Production

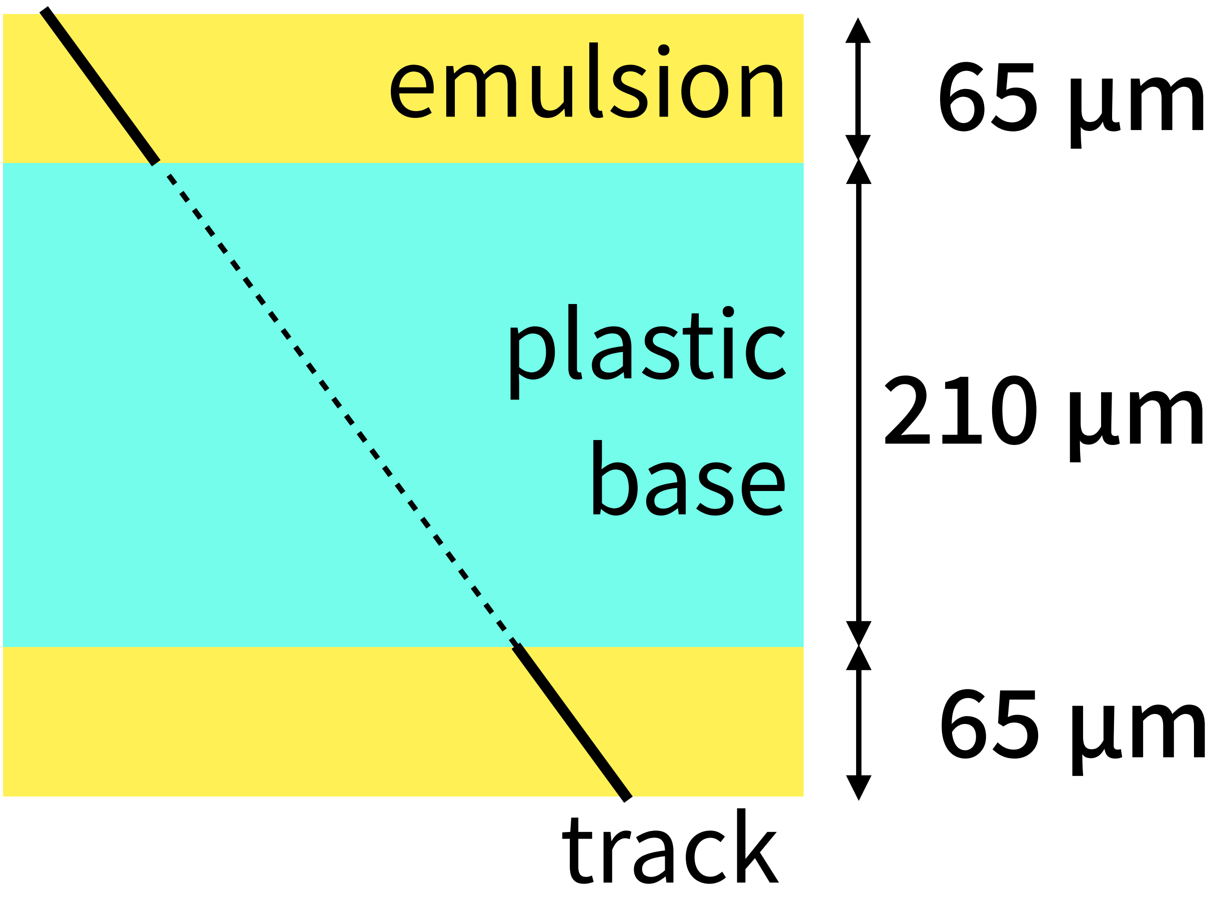
Gel production



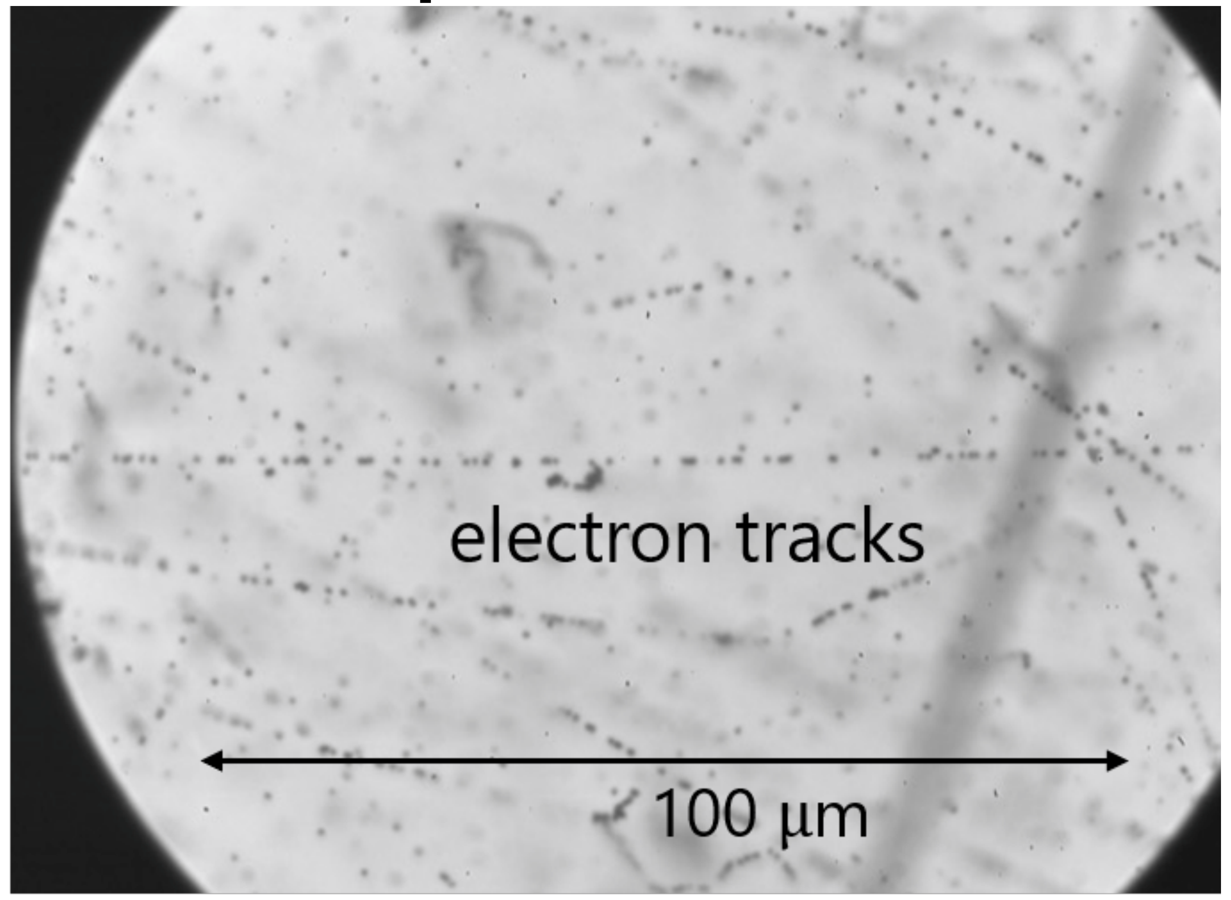
Emulsion film coating system



Double sided emulsion coating

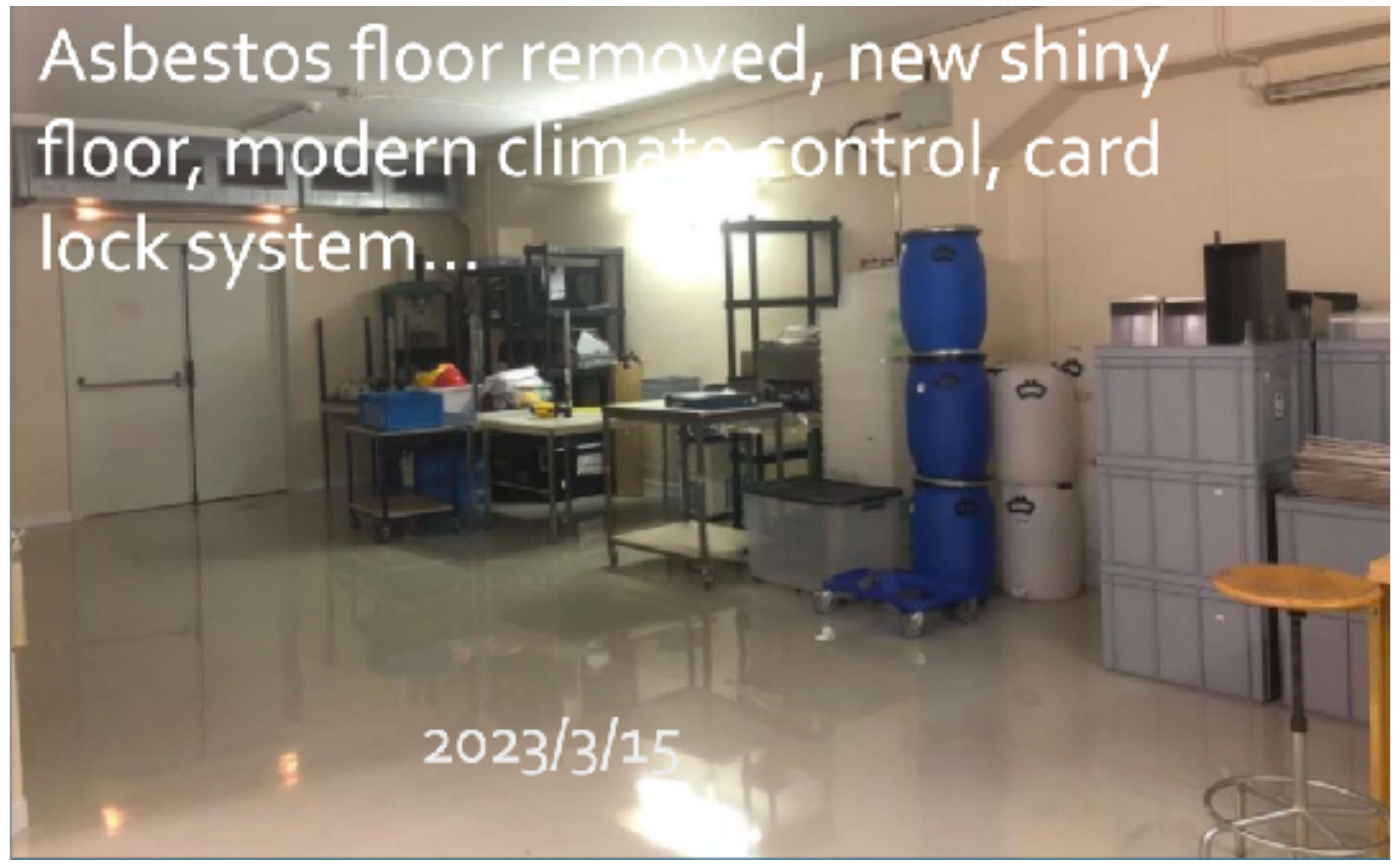


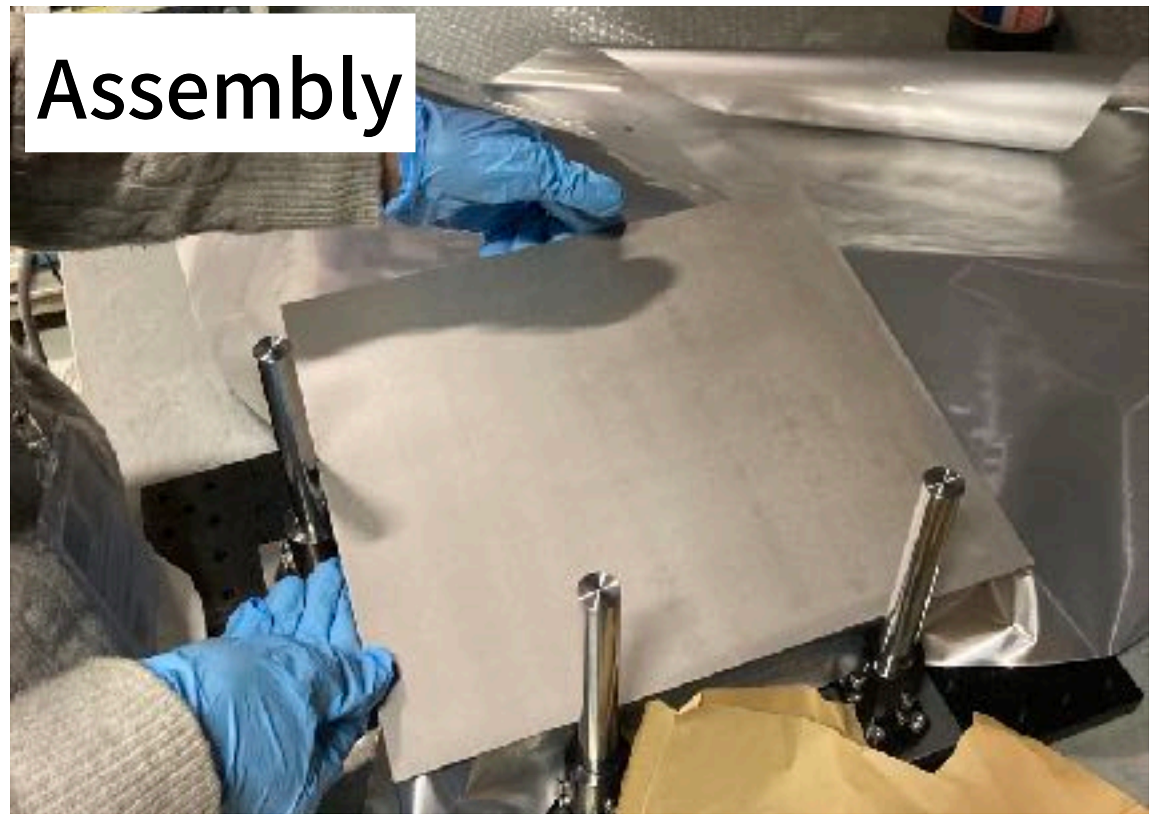
Microscopic view

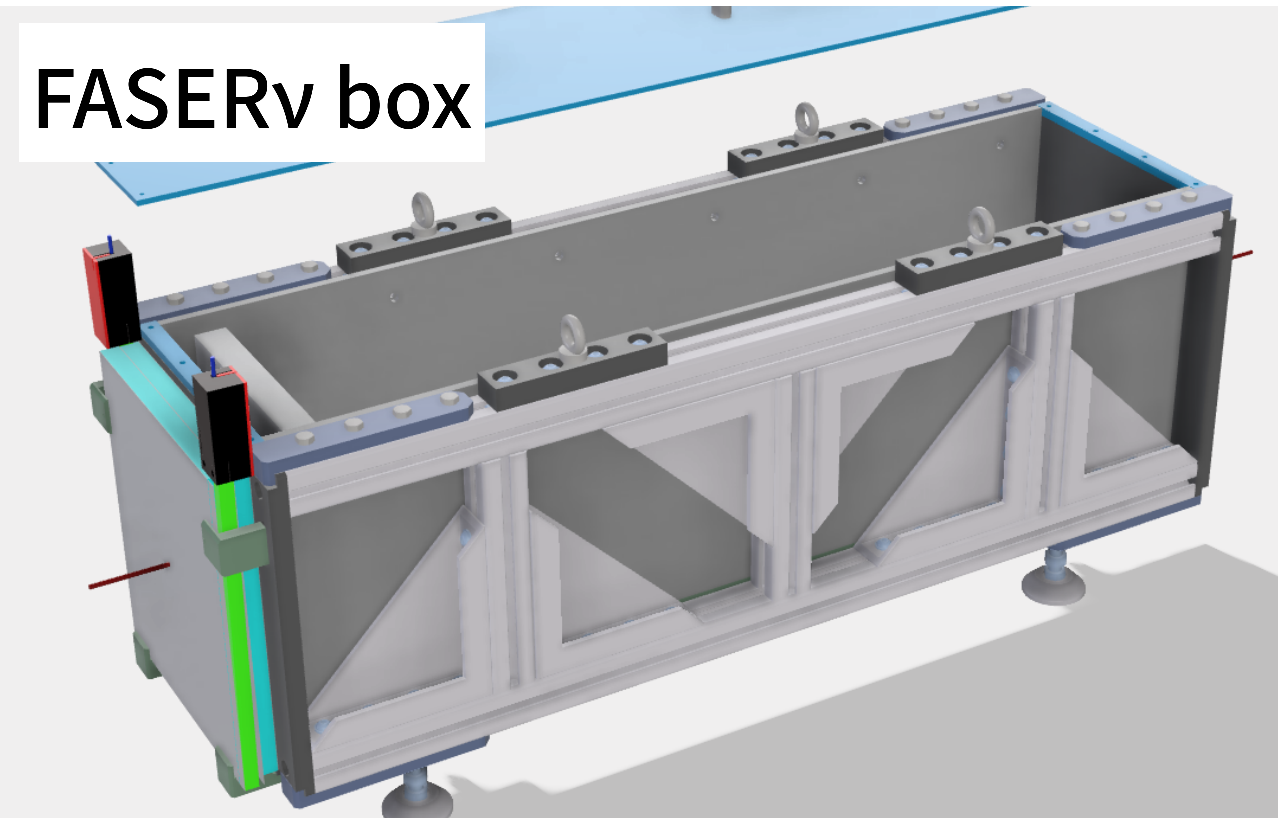


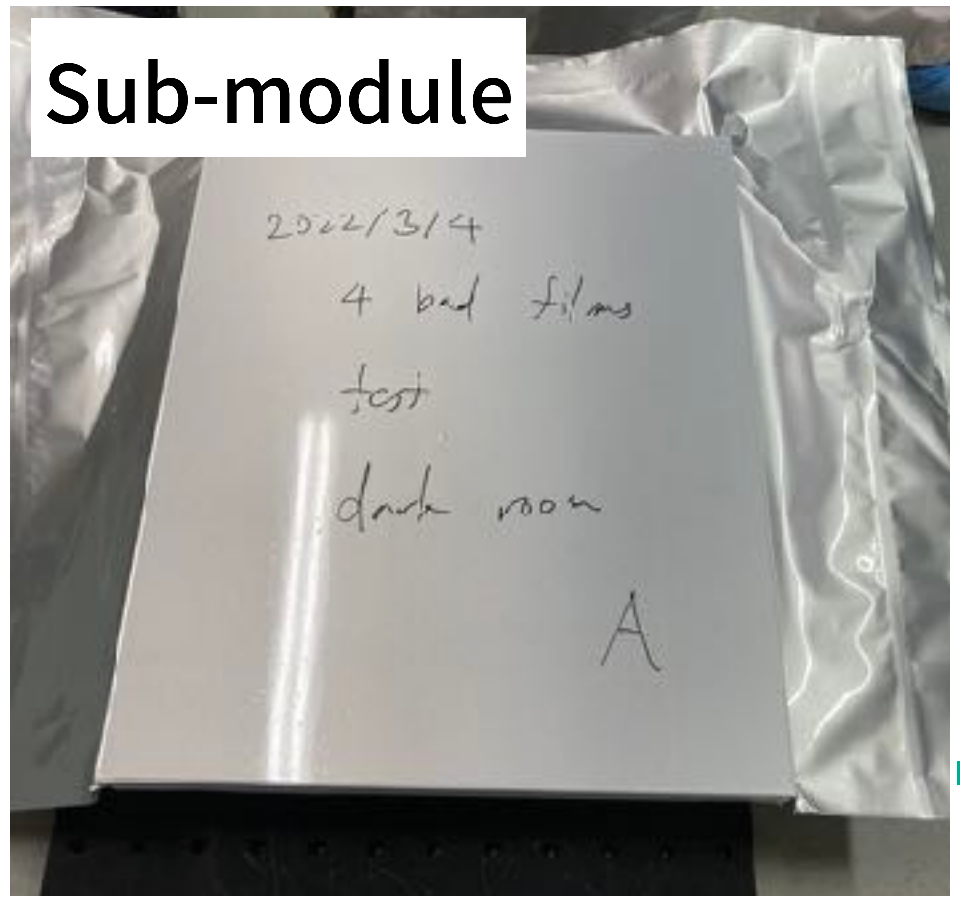
- 200 nm diameter silver halide crystals dispersed in gelatin
- Produced gel and film at Nagoya University
- Total area of 730 films: ~55 m^2 per replacement

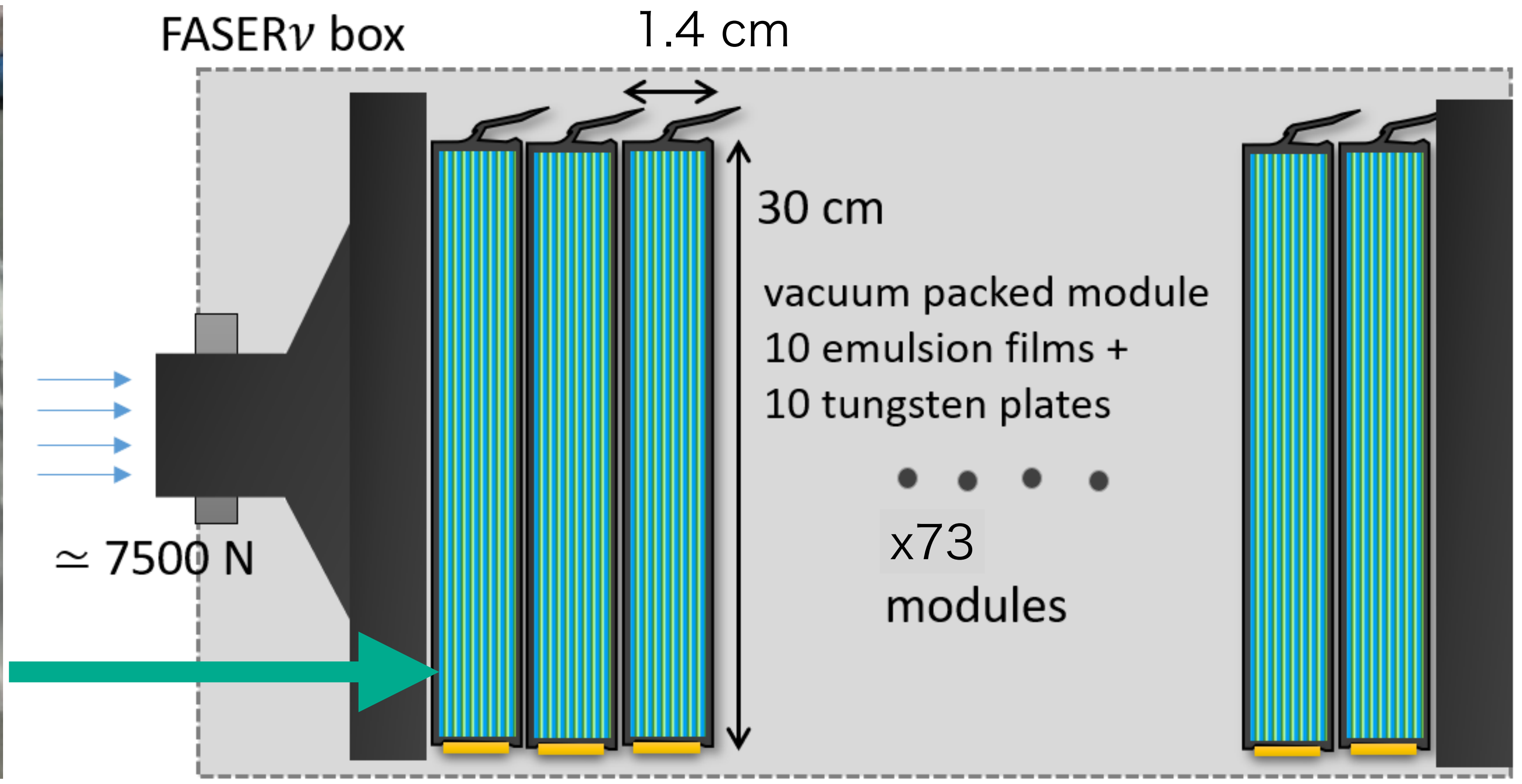
Module Assembly







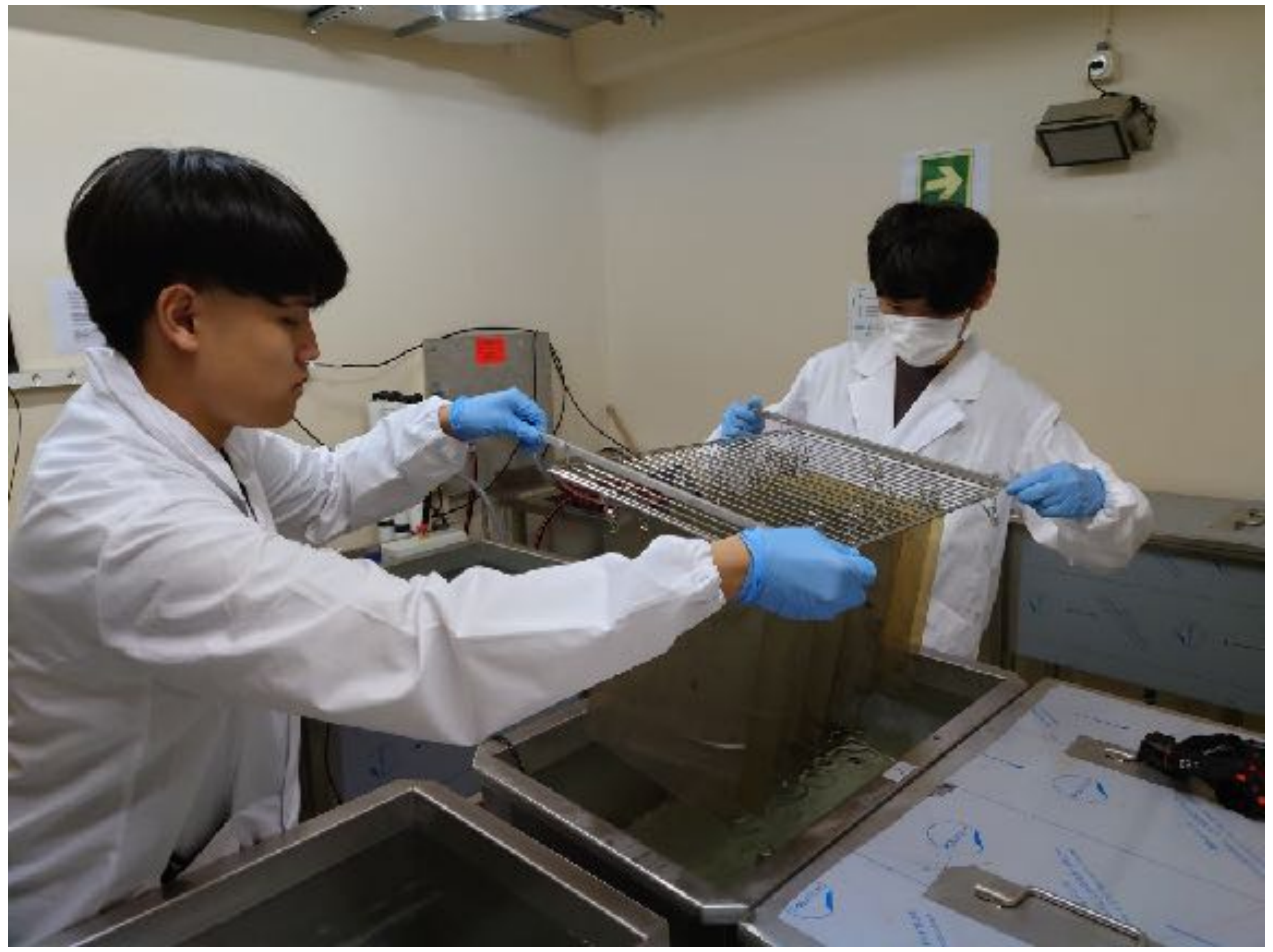


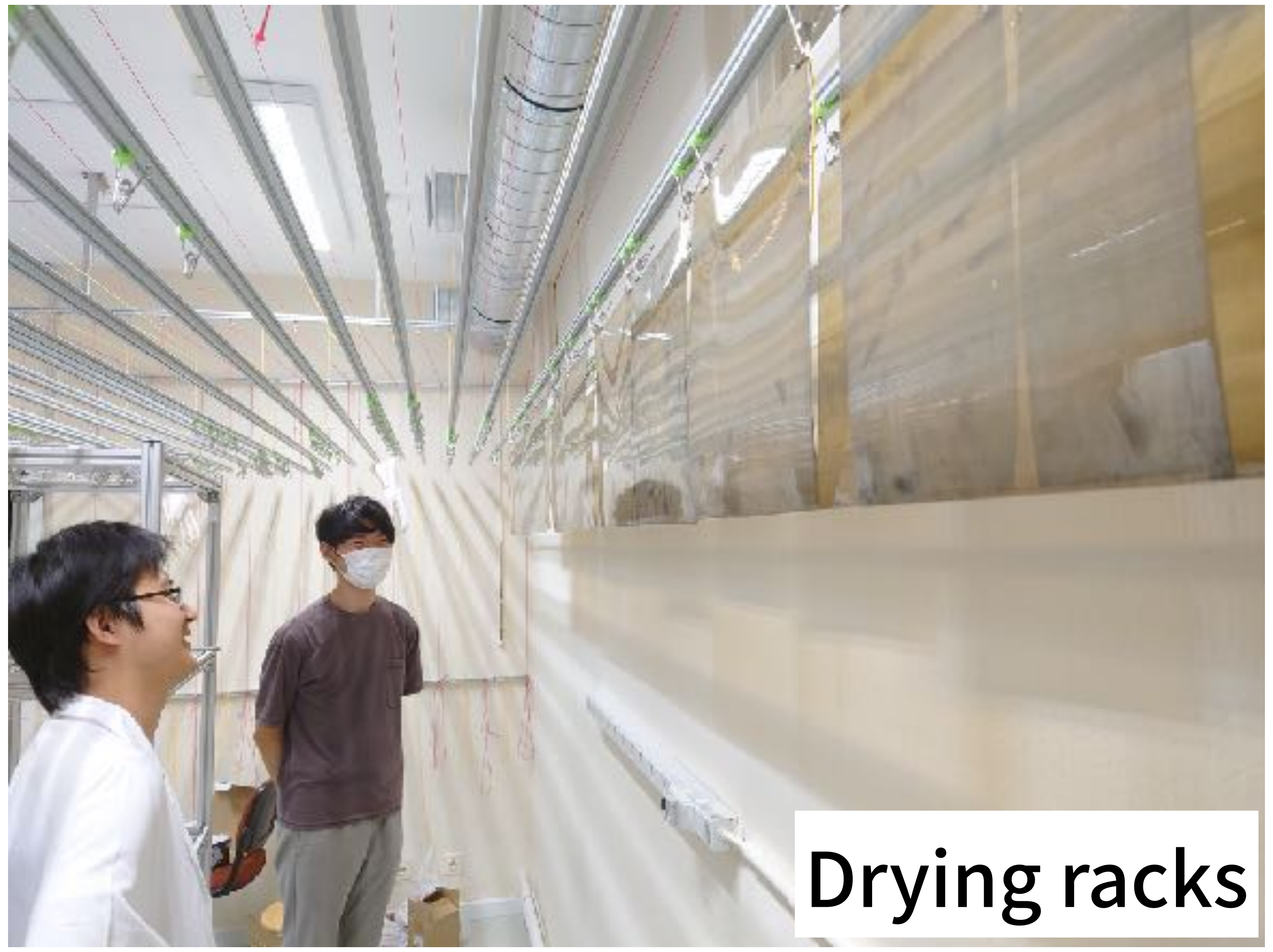


- Sub-module: vacuum-packed 10 films + 10 tungsten plates
- ~14 days to complete 73 packs
- Apply external force (equivalent to 1 bar) to the sub-modules in the FASERν box

Film Development

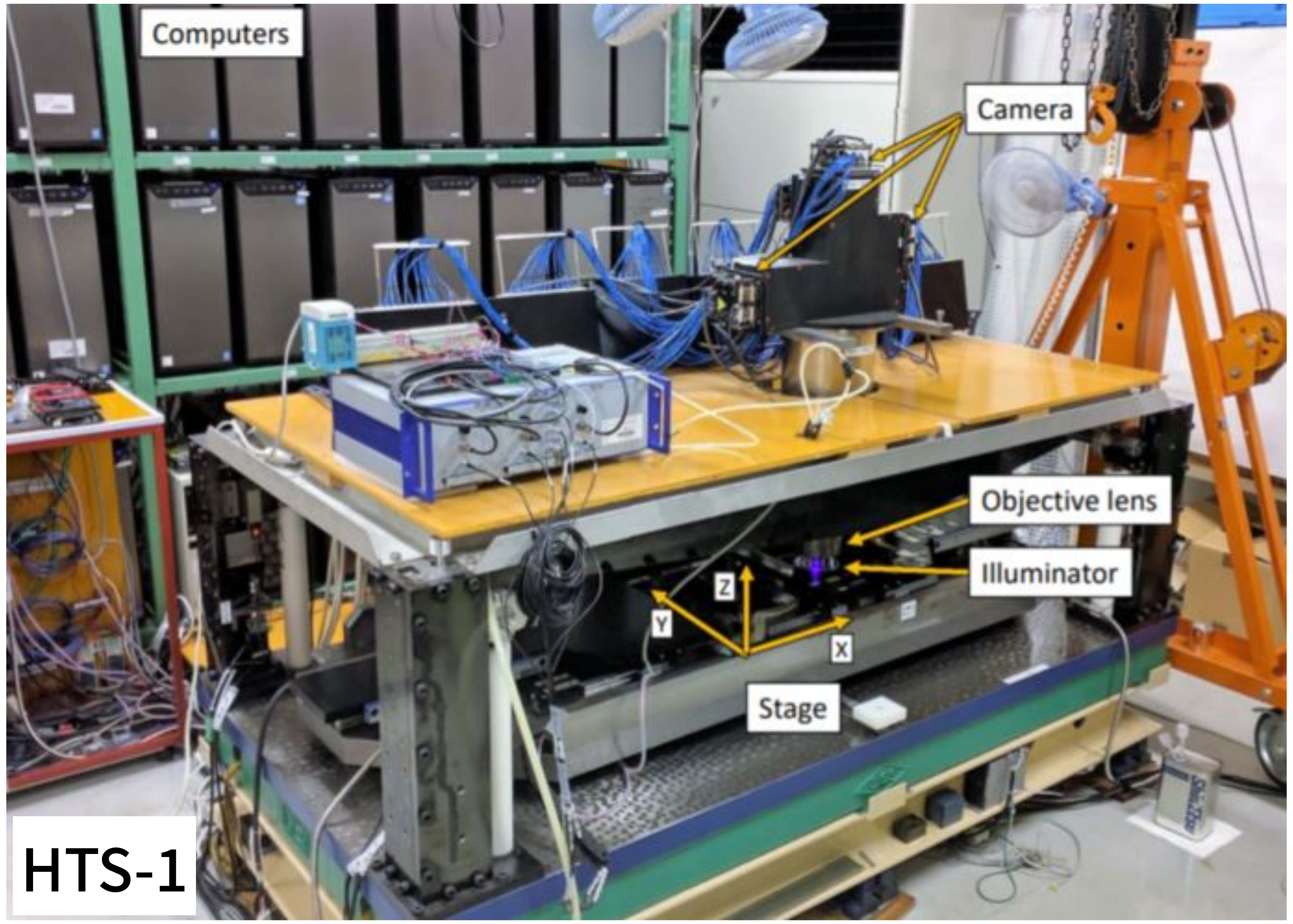

Development chains

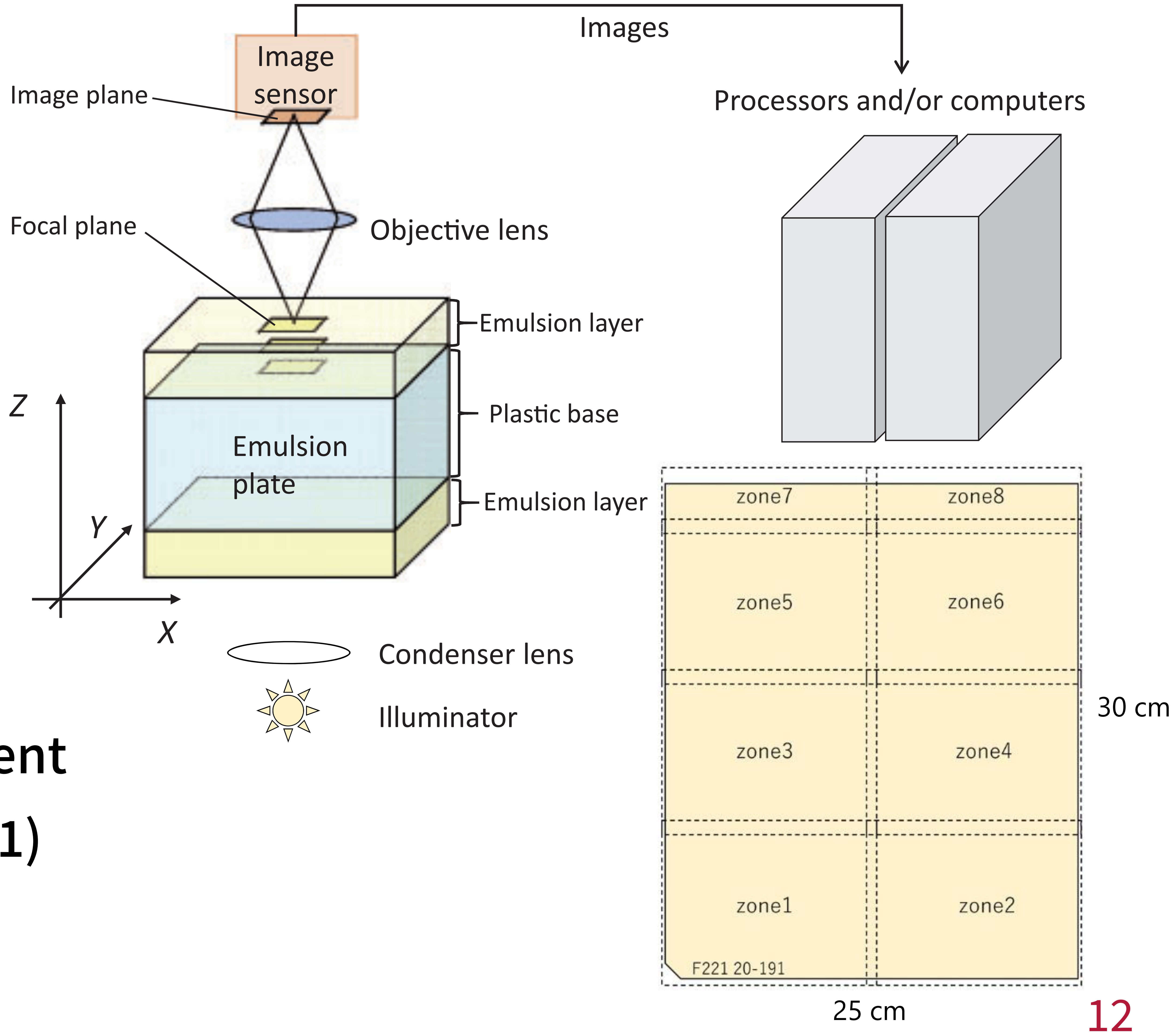



Drying racks

- Installed new development chains and drying racks at the renovated CERN darkroom facility
  - Sharing the facility with other emulsion experiments: NA65/DsTau, SND@LHC, etc
- 10-12 days to complete 730 films

Readout

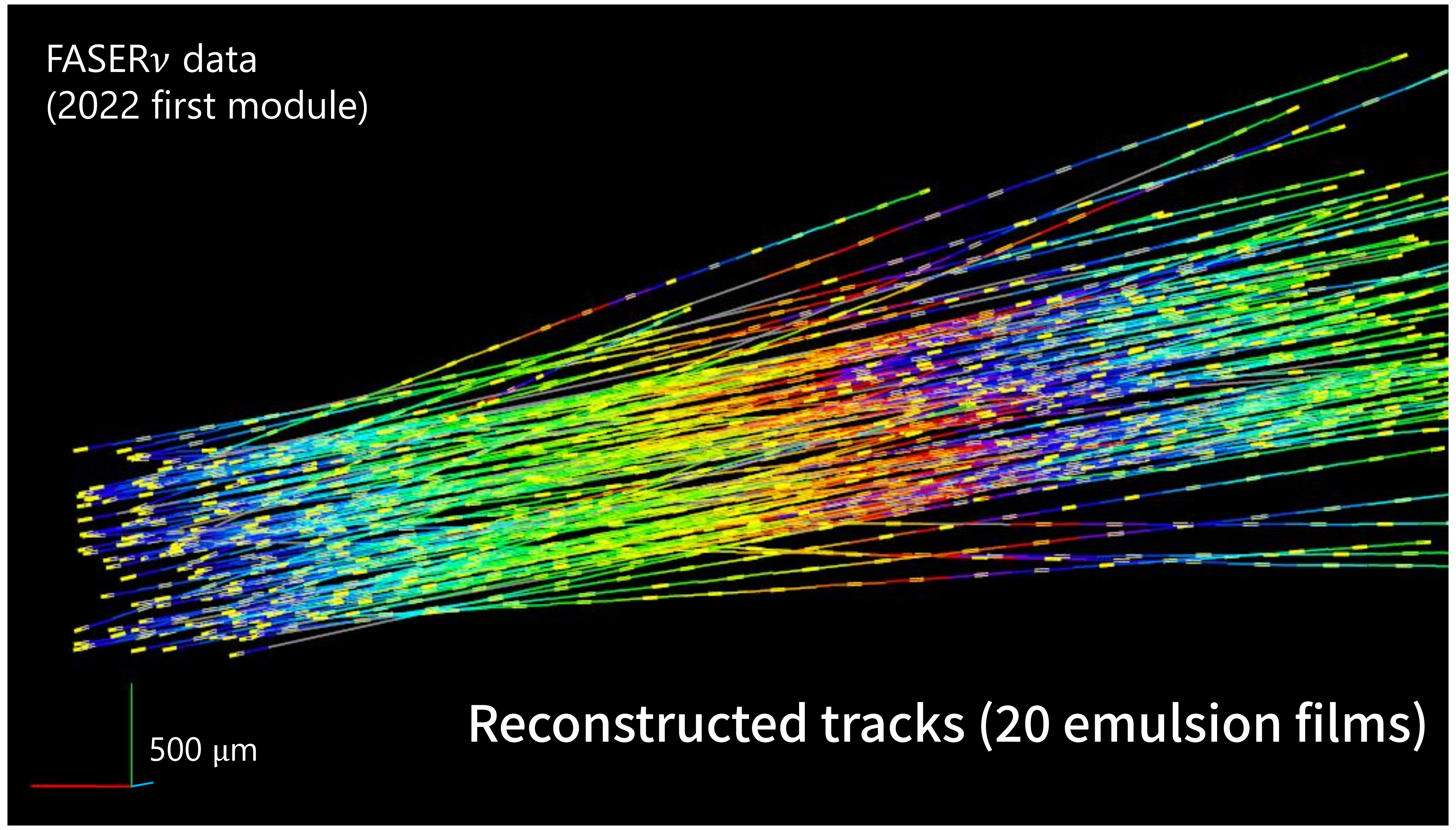


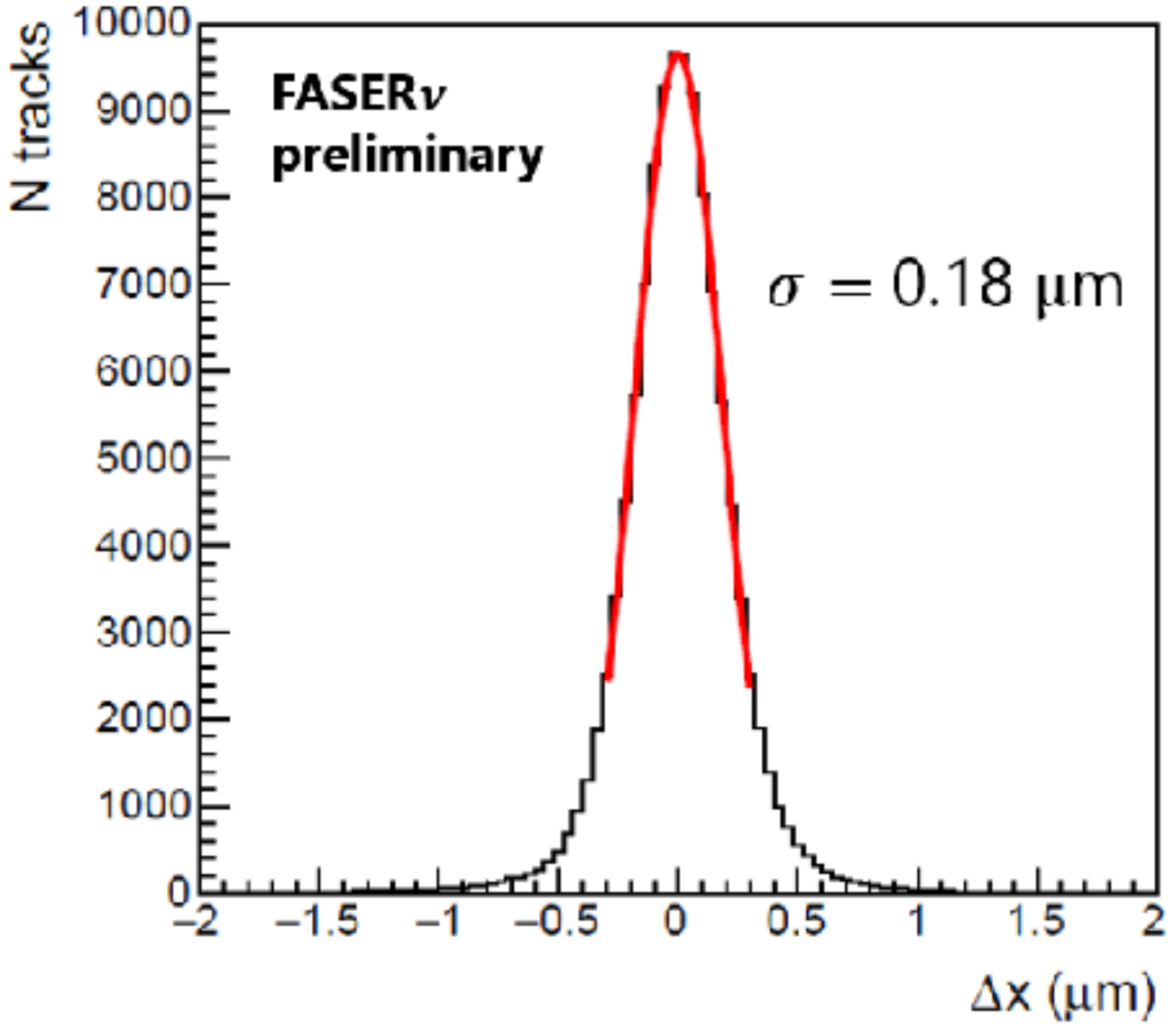


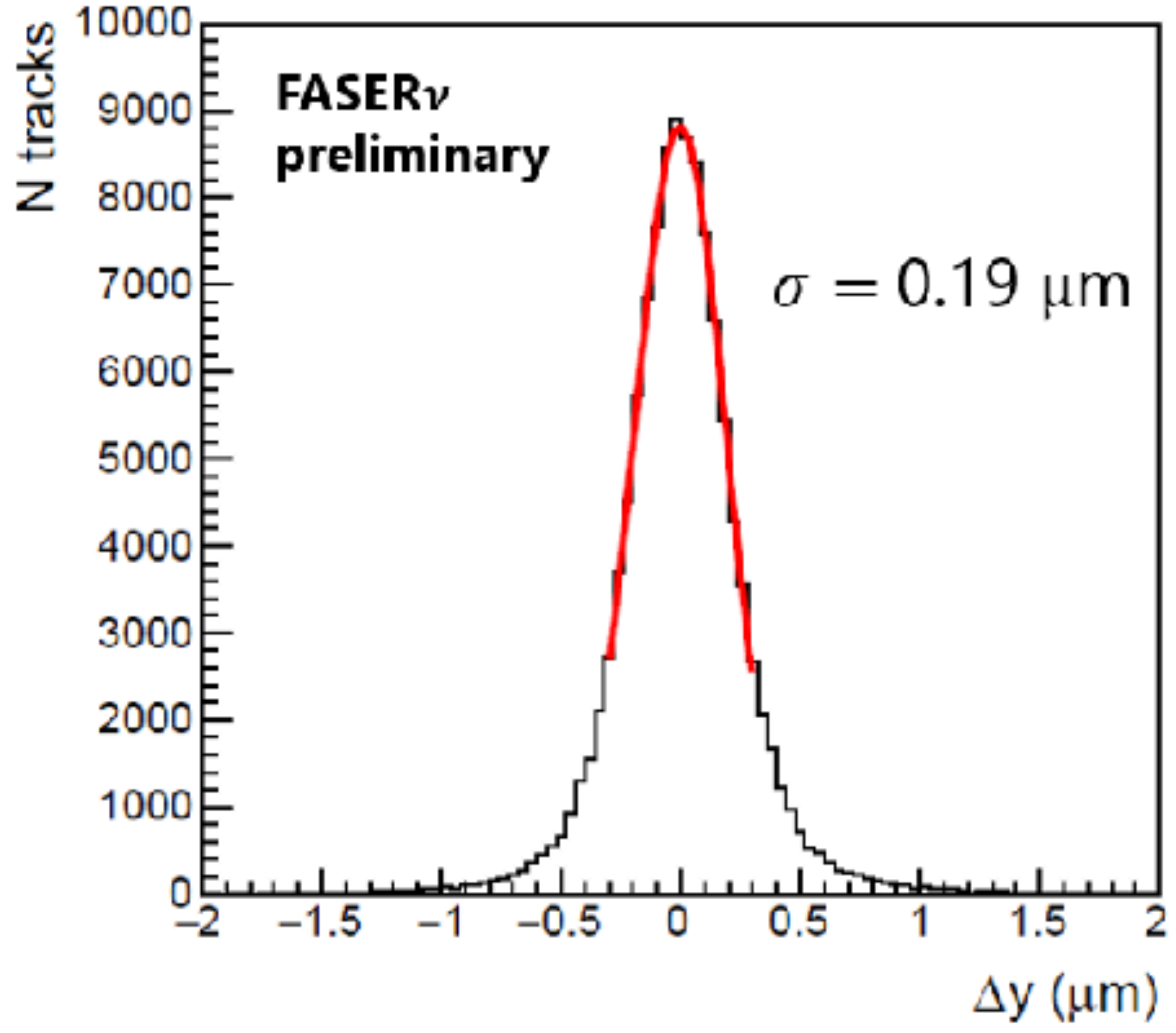
- Transport films to Japan after development
- Readout by Hyper Track Selector-1 (HTS-1)
  - Field of view: 5.1 mm × 5.1 mm
  - 60-80 minutes per a film

FASERν Performances

- Dataset: most downstream 10 emulsion films of the 1st FASERν module
  - From March to July 2022, integrated luminosity: 0.5 fb^{-1}
- Position deviation between hits and the straight-line fits to the reconstructed tracks

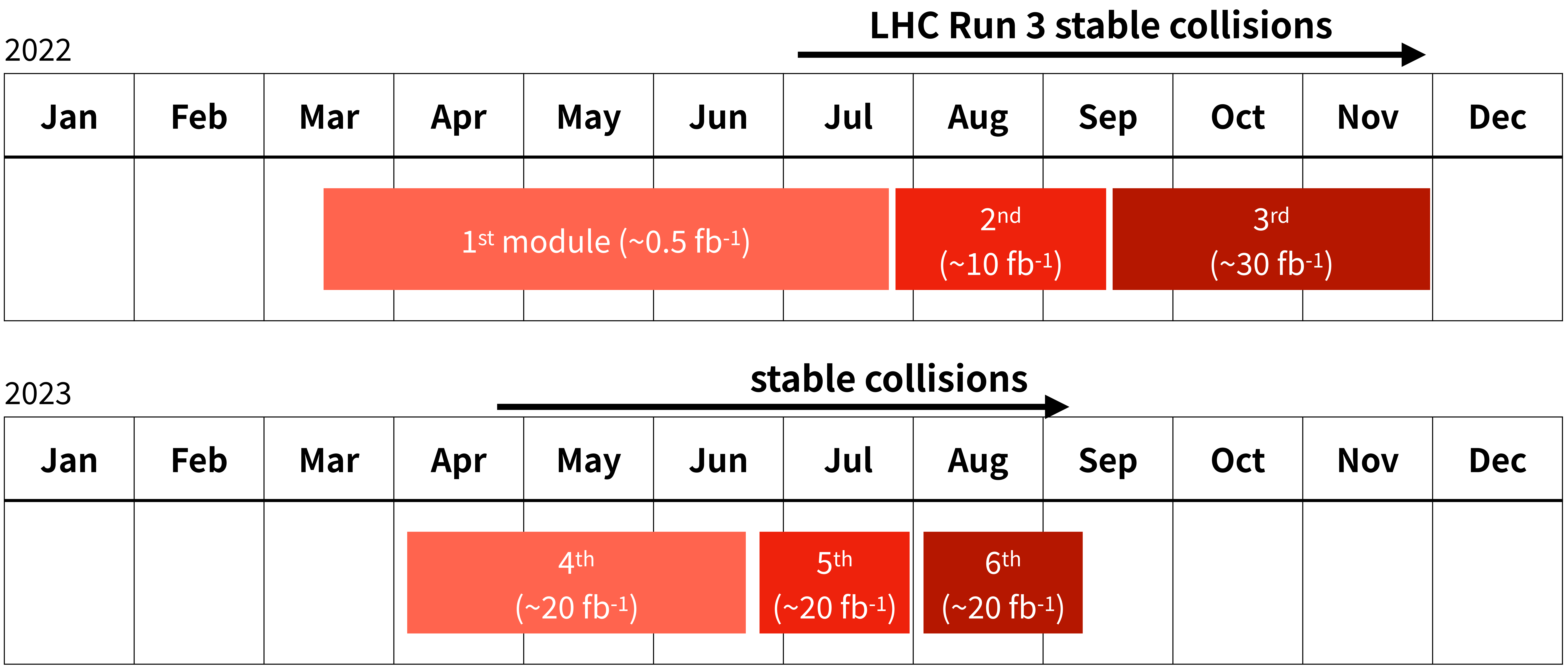






- Observed **~0.2 μm position accuracy** with dedicated alignment using high momentum muon tracks

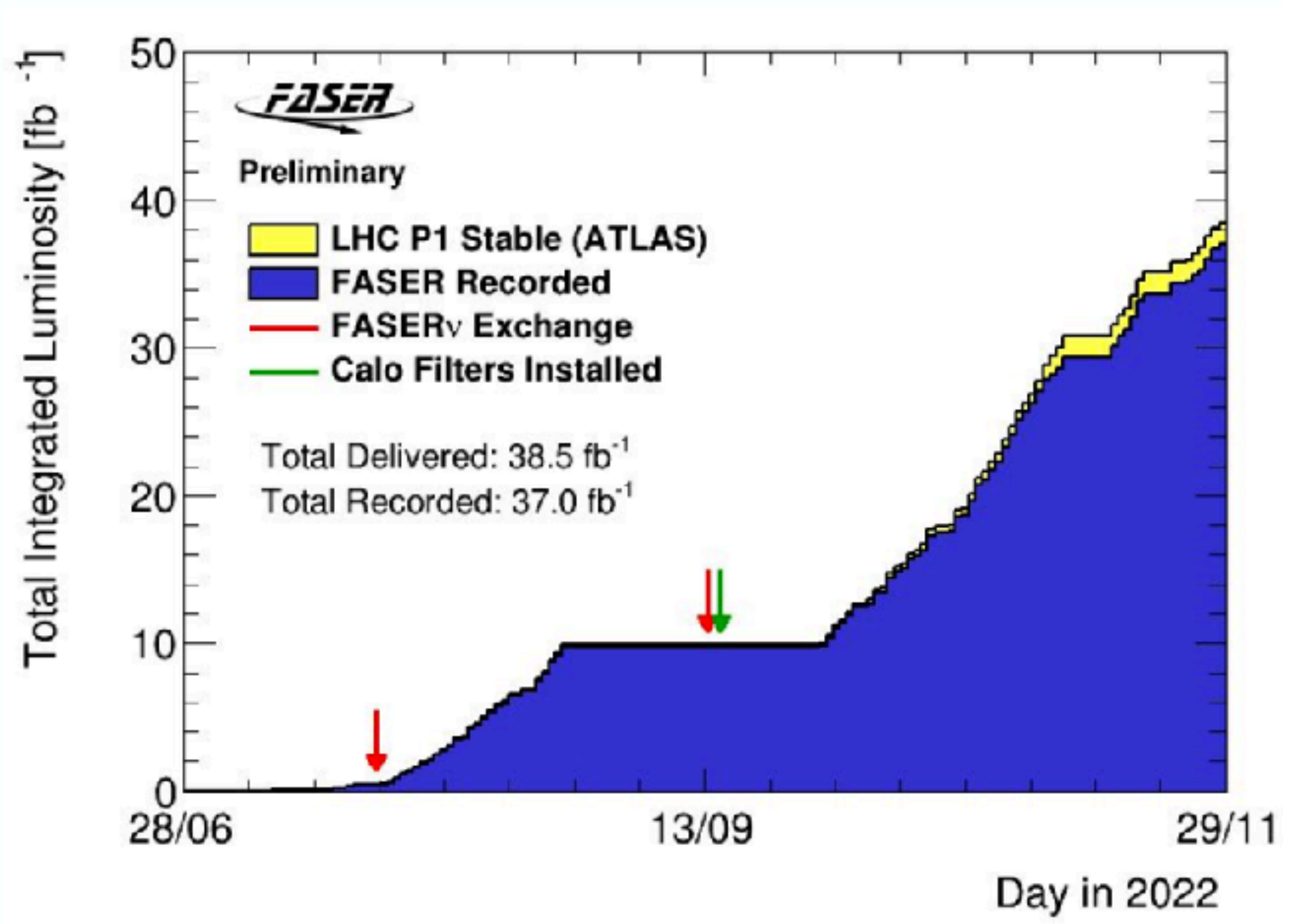
Emulsion Detector Replacement in LHC Run 3



- Physics data taking from the 2nd module
- Exchange every 20-30 fb^{-1} integrated luminosity from 2023

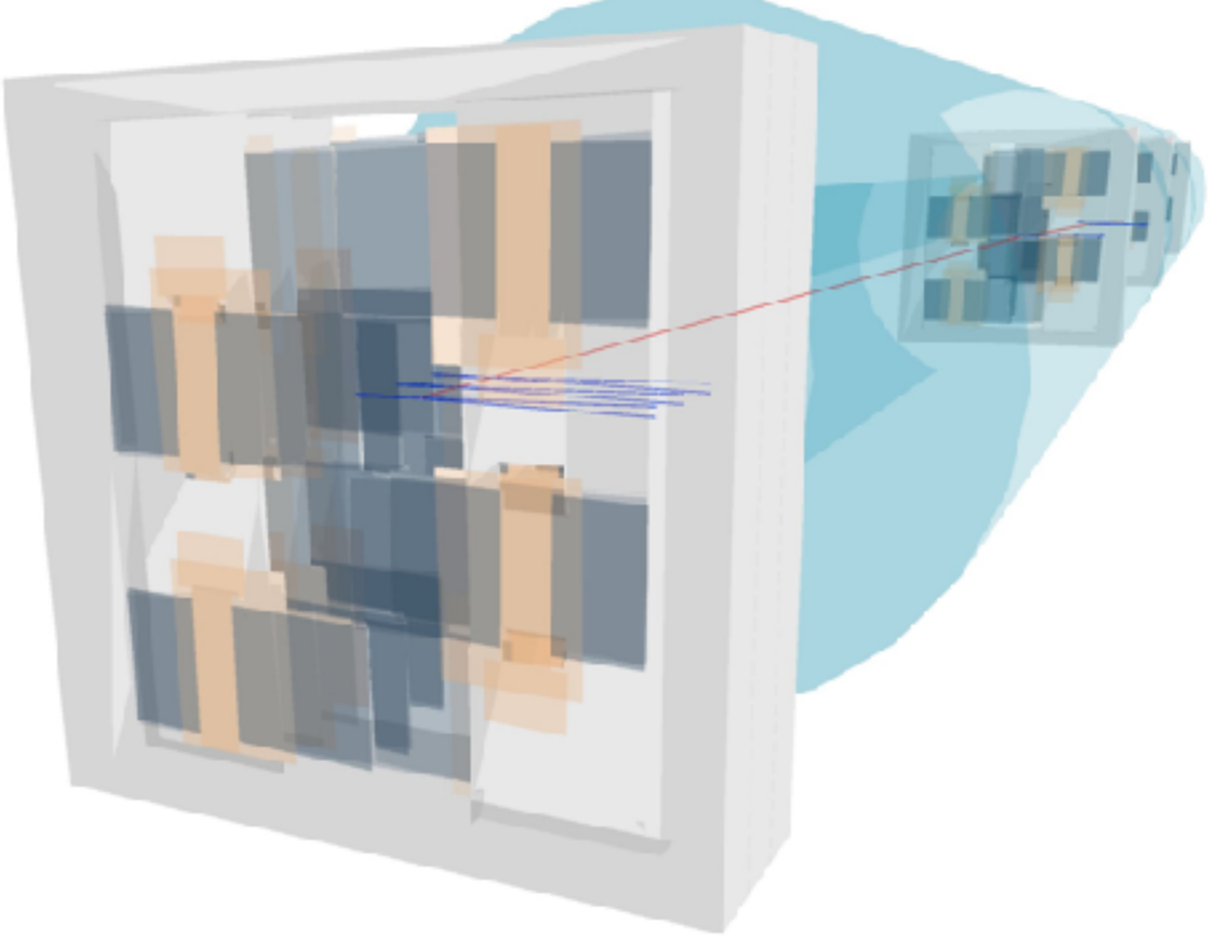
FASER Operations

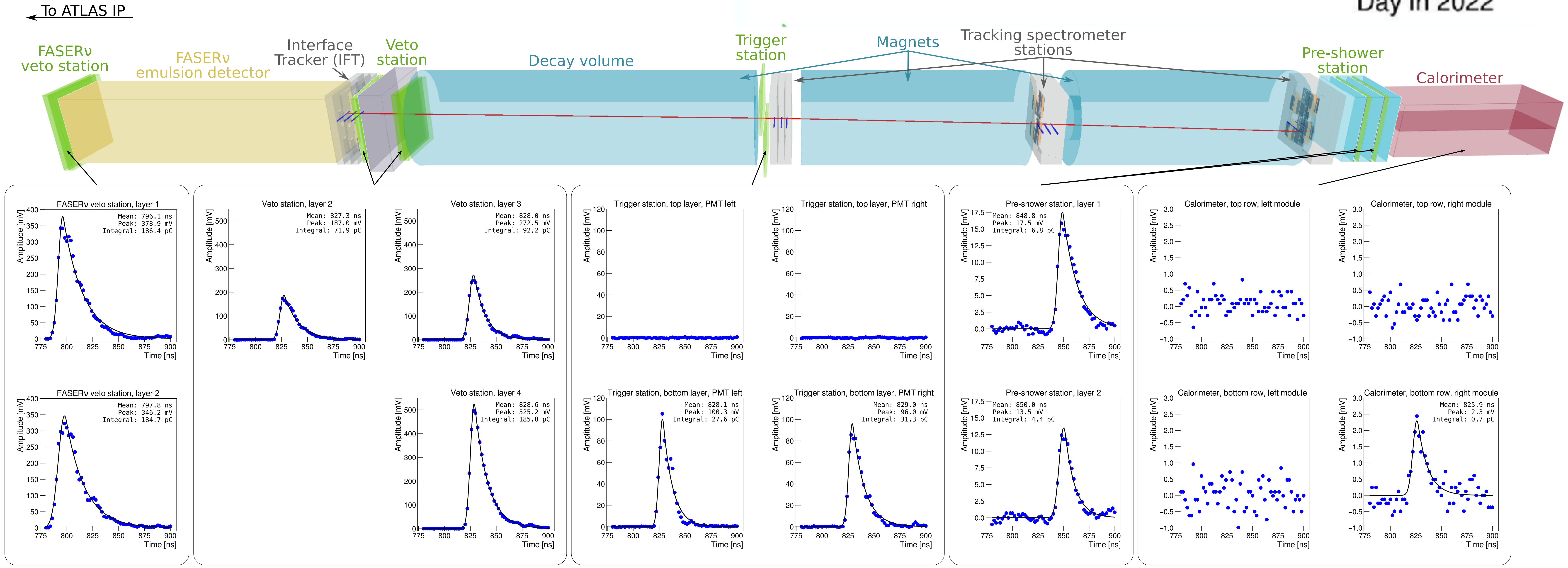
- Successfully operated throughout 2022
  - FASER recorded 96% of delivered luminosity
- FASER operating very well in 2023 data taking with >30fb-1 of data recorded so far



Muon leaving track passing through full detector

Run 8336
Event 1477982
2022-08-23 01:46:15



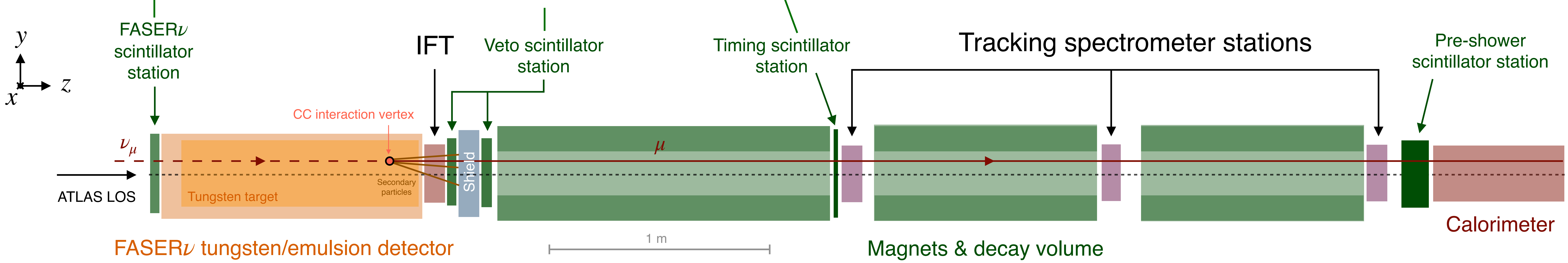


consistent with MIP

"Electronic" Neutrino Search

ariv:2303.14185
(accepted by PRL)

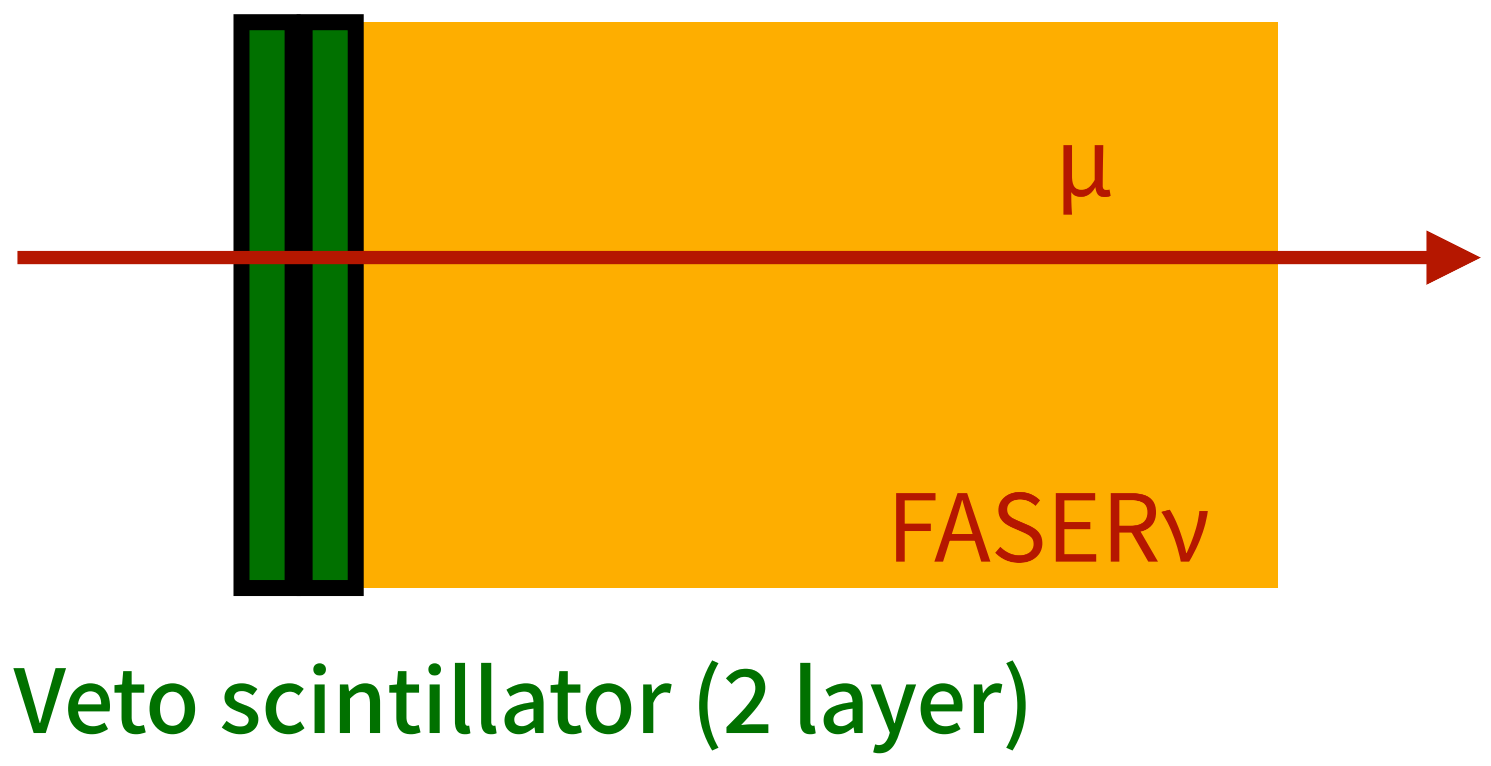
- Collision event with good data quality (35.4 fb^{-1})
- No signal (<40 pC)
- Signal (>40 pC)



- Timing and pre-shower consistent with $\geq$ 1MIP
- Exactly 1 good fiducial (r < 95 mm) track
  - p > 100 GeV and θ < 25 mrad
  - Extrapolating to r < 120 mm in front veto
- Expect **151 ± 41** events from GENIE simulation
  - Uncertainty from DPMJET vs. SIBYLL
  - No experimental errors

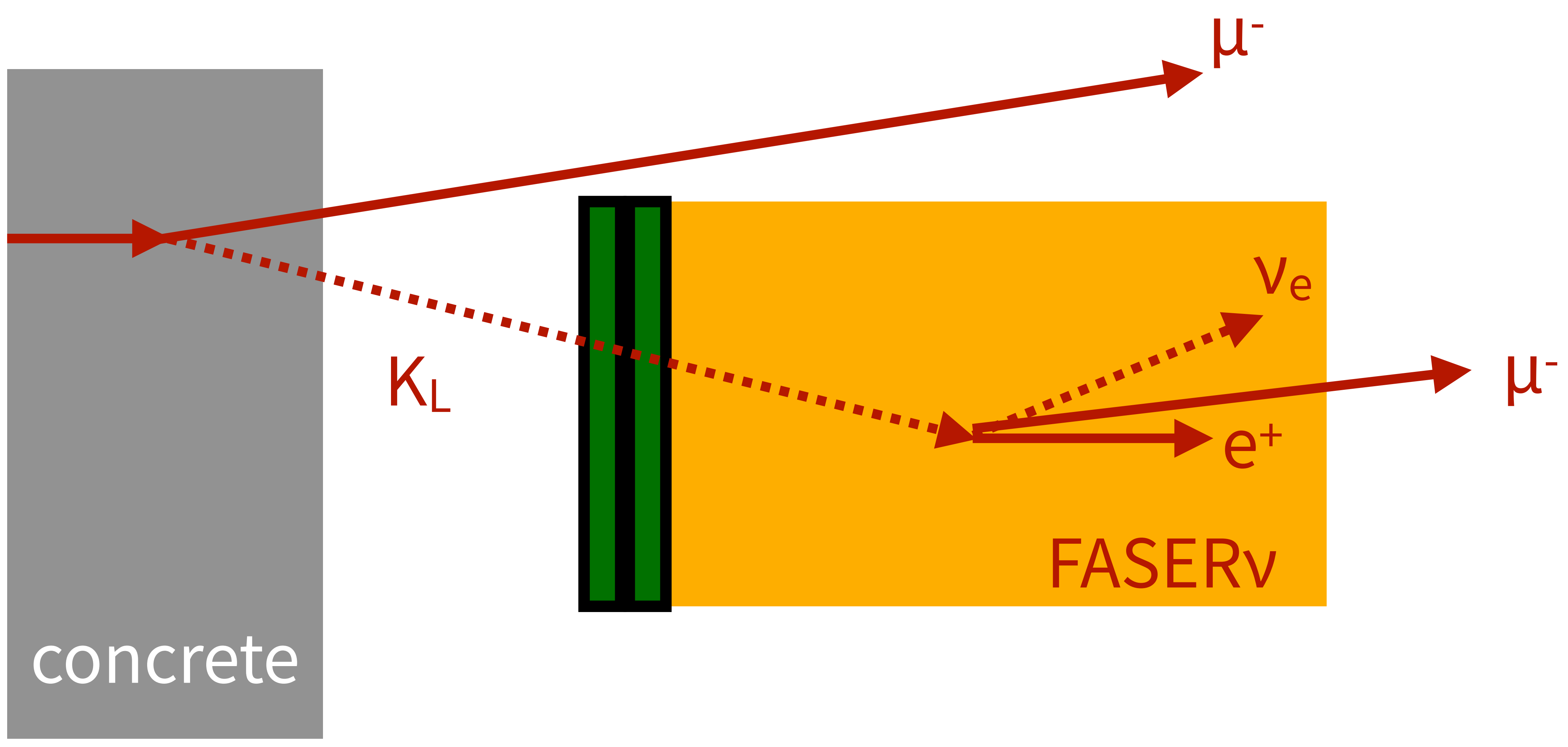
Background Estimation (1)

Veto inefficiency



- Estimated from events with just one veto scintillator firing
- Negligible background expected due to very high veto efficiency

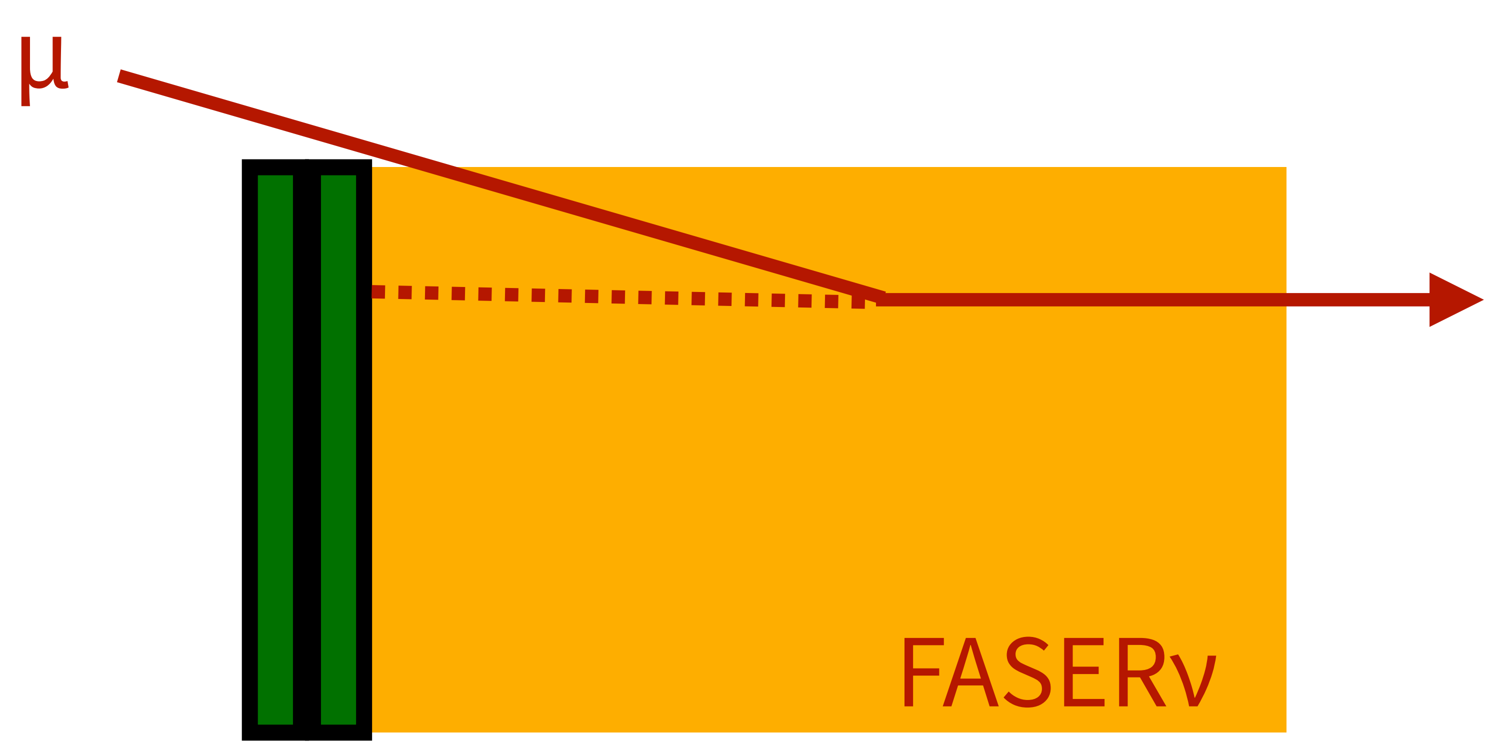
Neutral hadrons

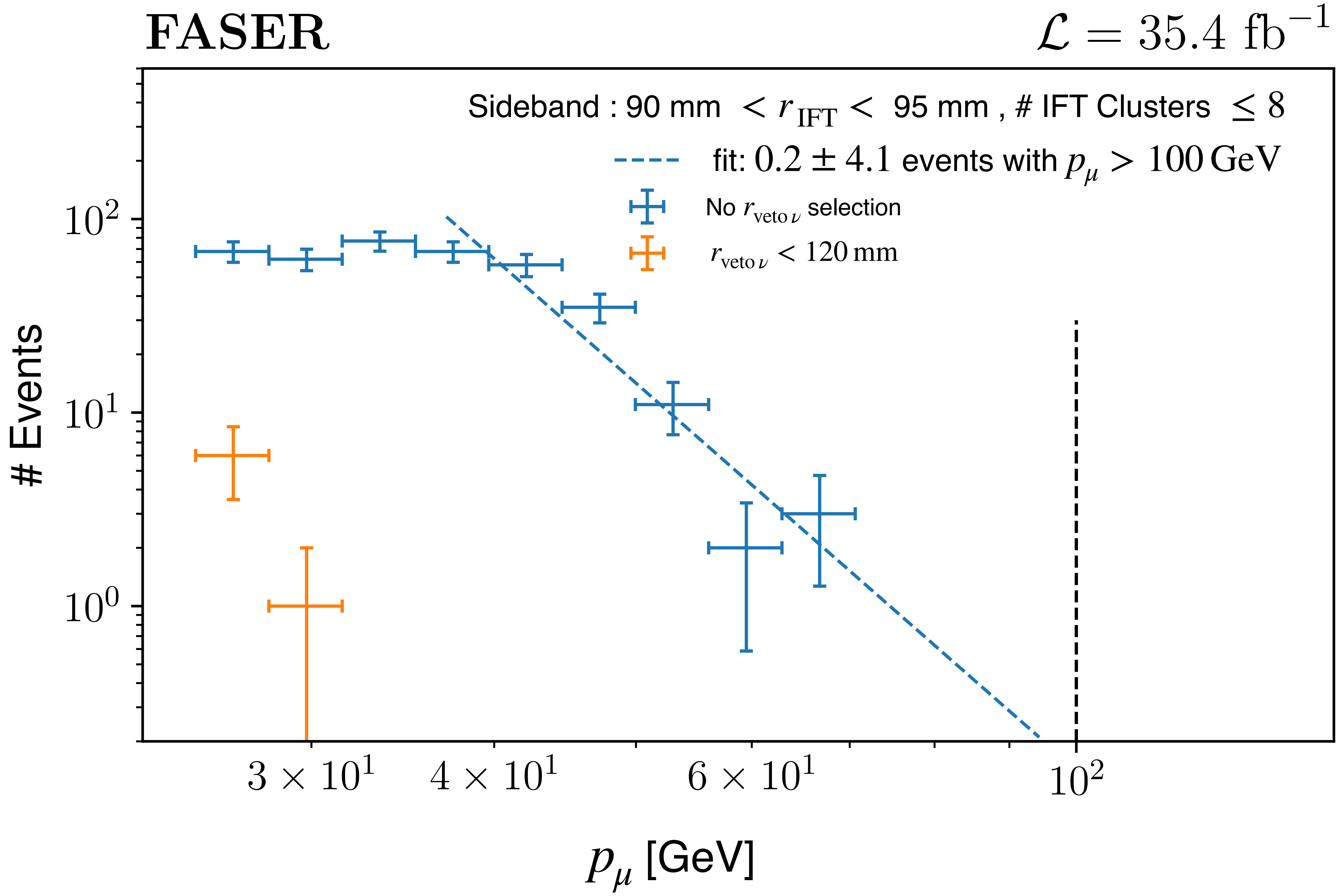


- Expect ~300 neutral hadrons with E>100 GeV
- Most are absorbed in tungsten
- Estimated from 2-step MC simulations
- Estimate 0.11±0.06 events

Background Estimation (2)

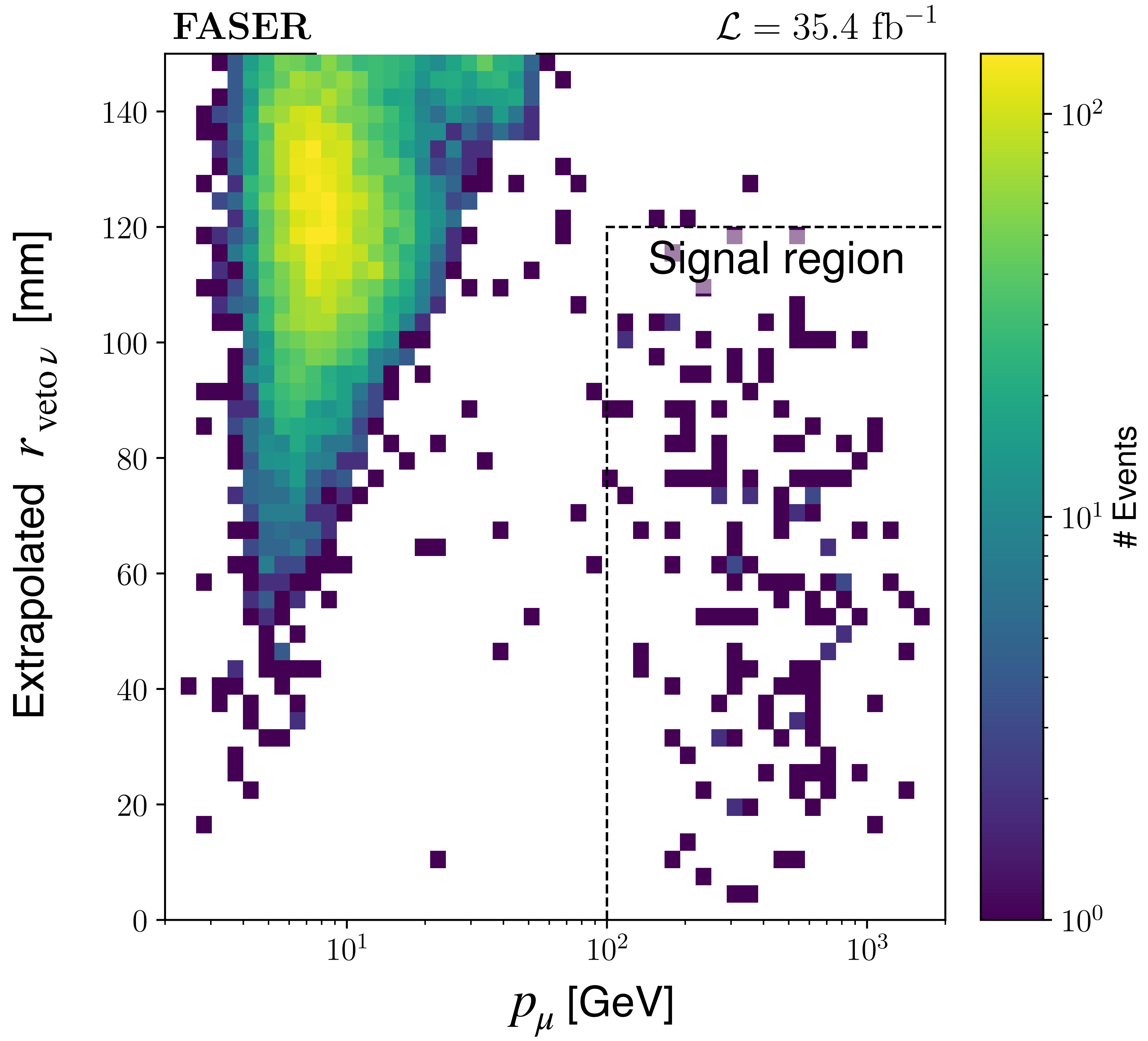
Scattered muons (geometric BG)

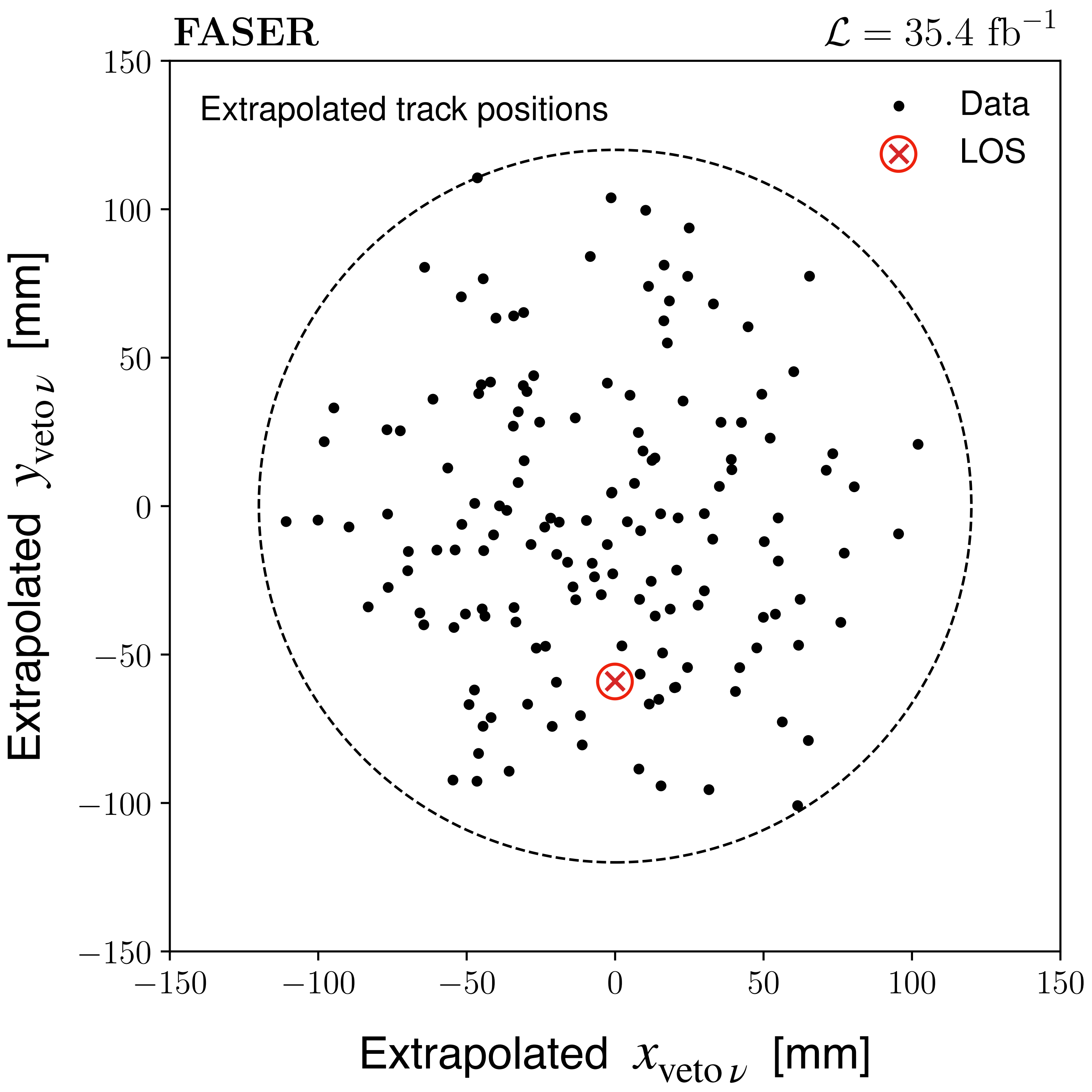




- Estimated from sideband
  - Fit to extrapolate to higher momentum
- Calculate scaling factor using MC simulations to extrapolate to signal region
- Estimate 0.08 ± 1.83 events (uncertainty from varying selection)

Results

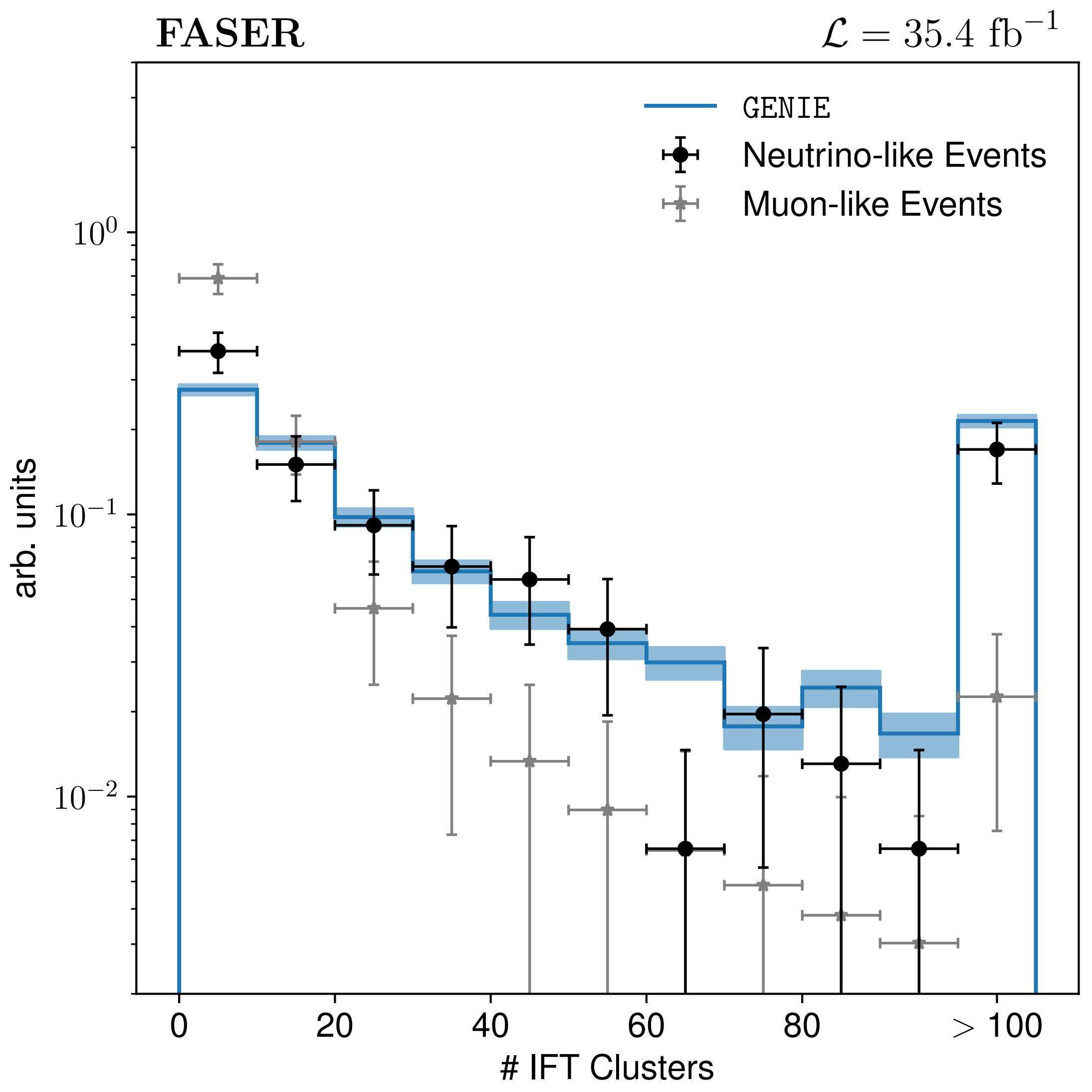




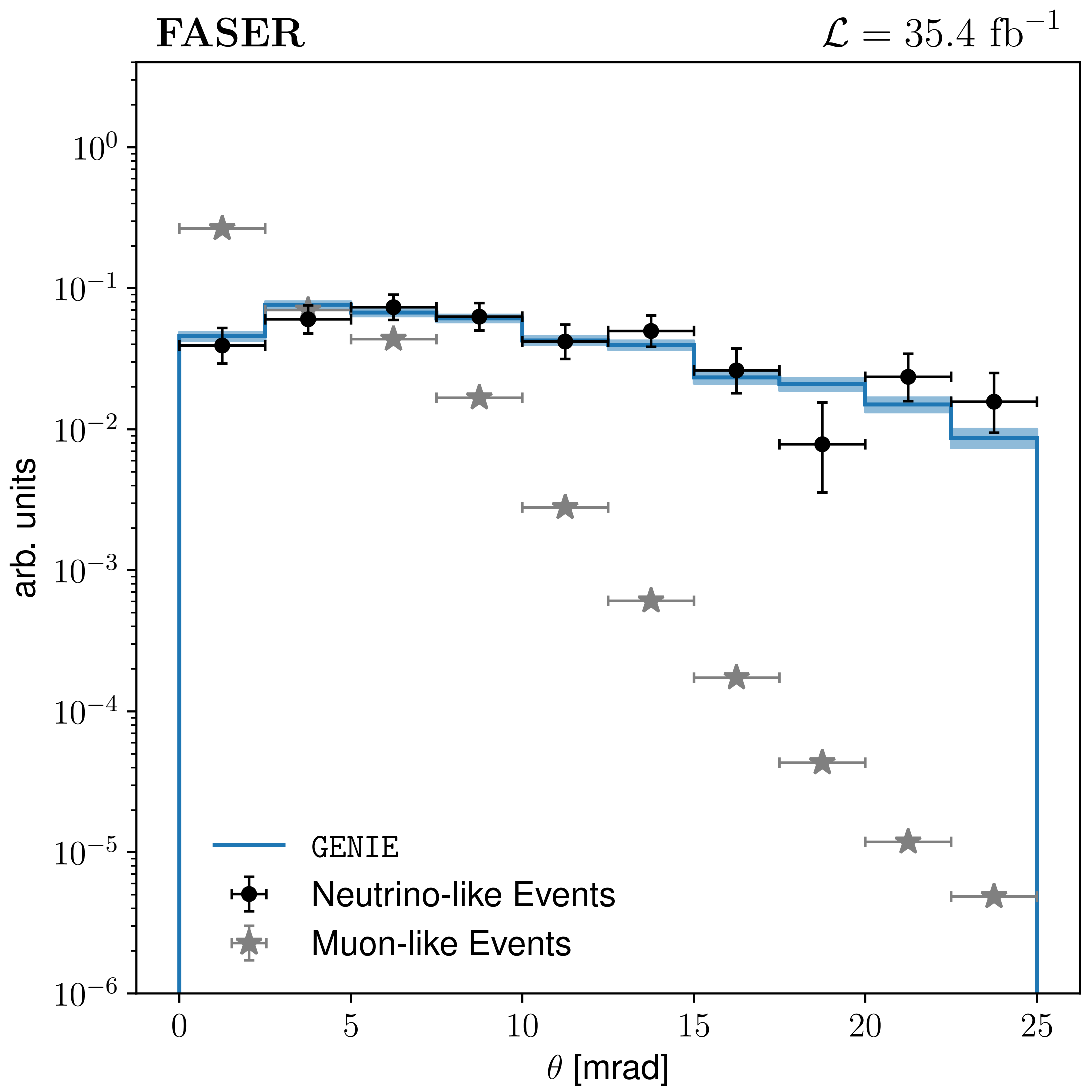
Category	Events
Signal	153
n_{10}	4
n_{01}	6
n_2	64014695

- Observed 153^{+13}_{-12} events (151 ± 41 events expected)
- Signal significance of **16σ**
- **First directory observation of collider neutrinos**

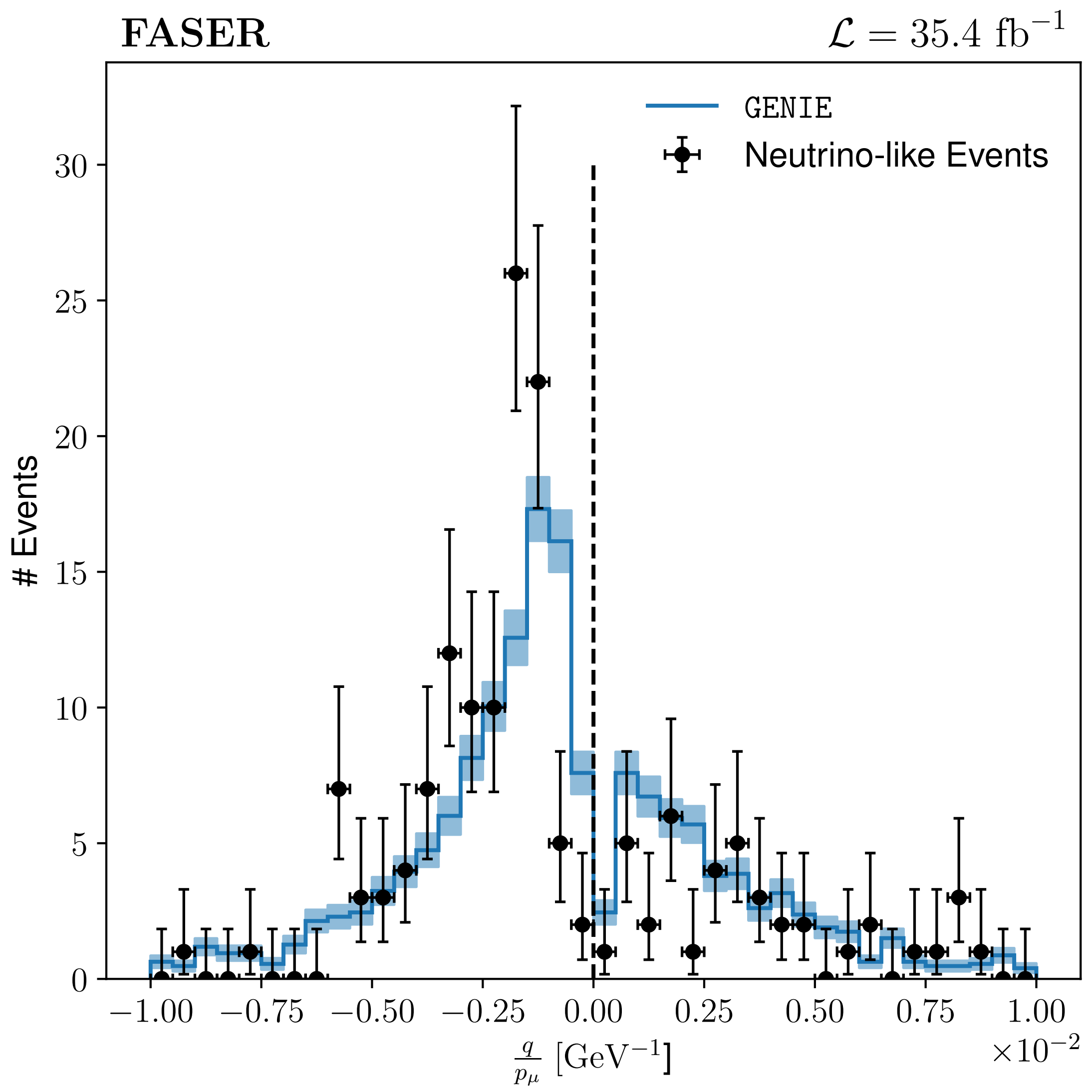
Neutrino Characteristics



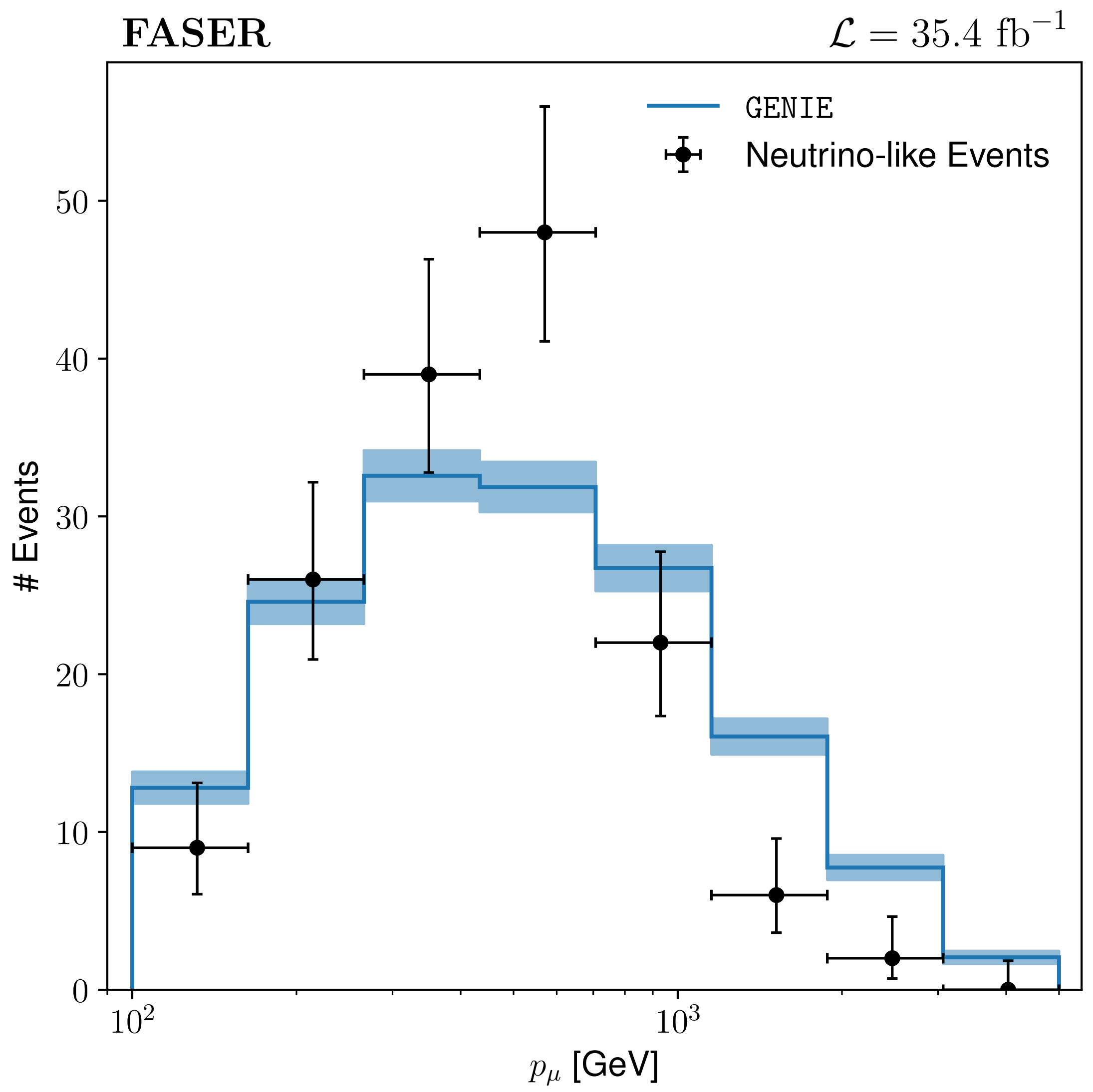
High occupancy in IFT



Large μ polar angle



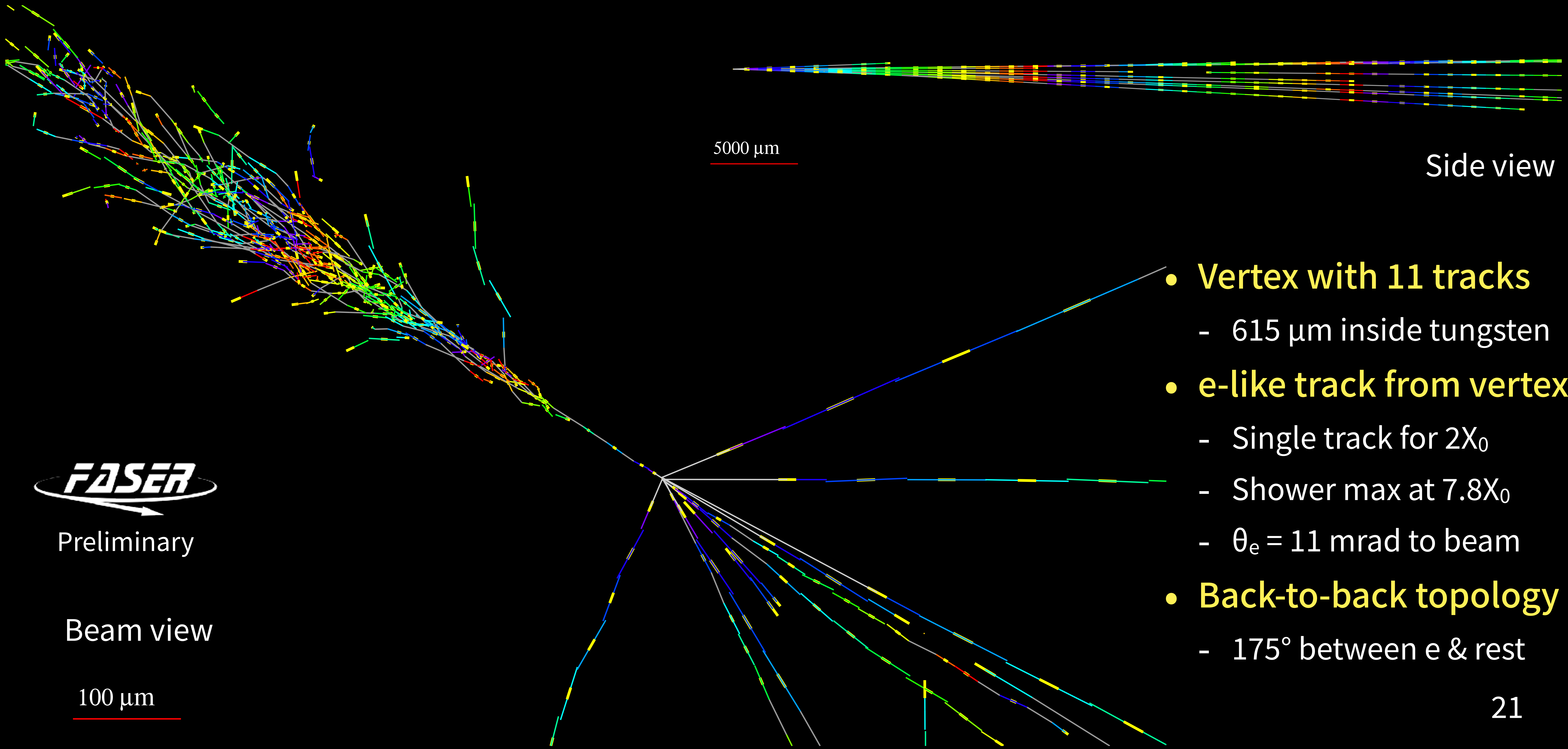
More ν_μ than $\bar{\nu}_\mu$



High μ momentum

- Only statistical errors are shown
- Most events at high momentum (E_μ > 200 GeV)
- **Good agreement with expectations from simulation**

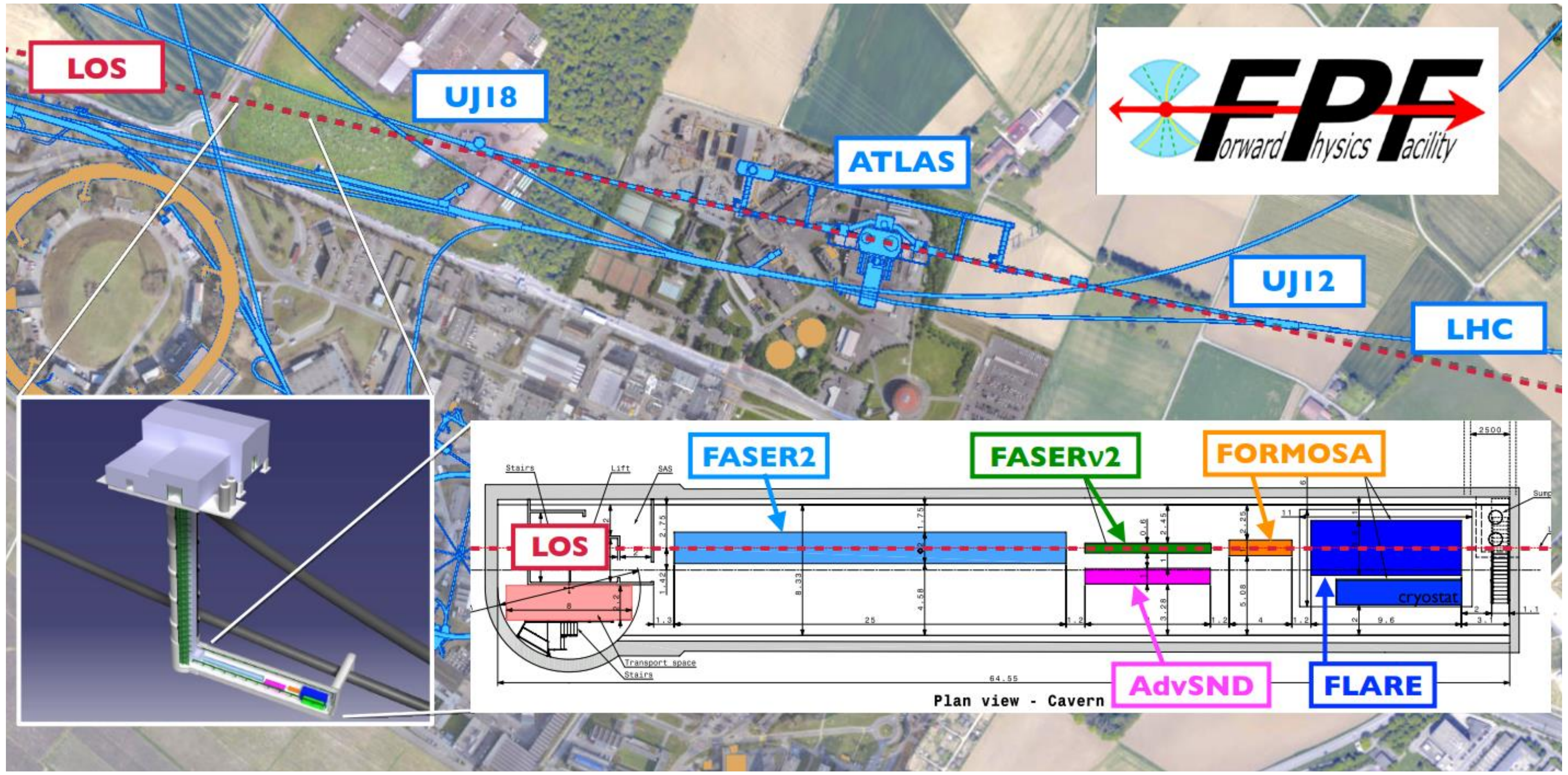
Observation of ν_e Candidate with FASERν

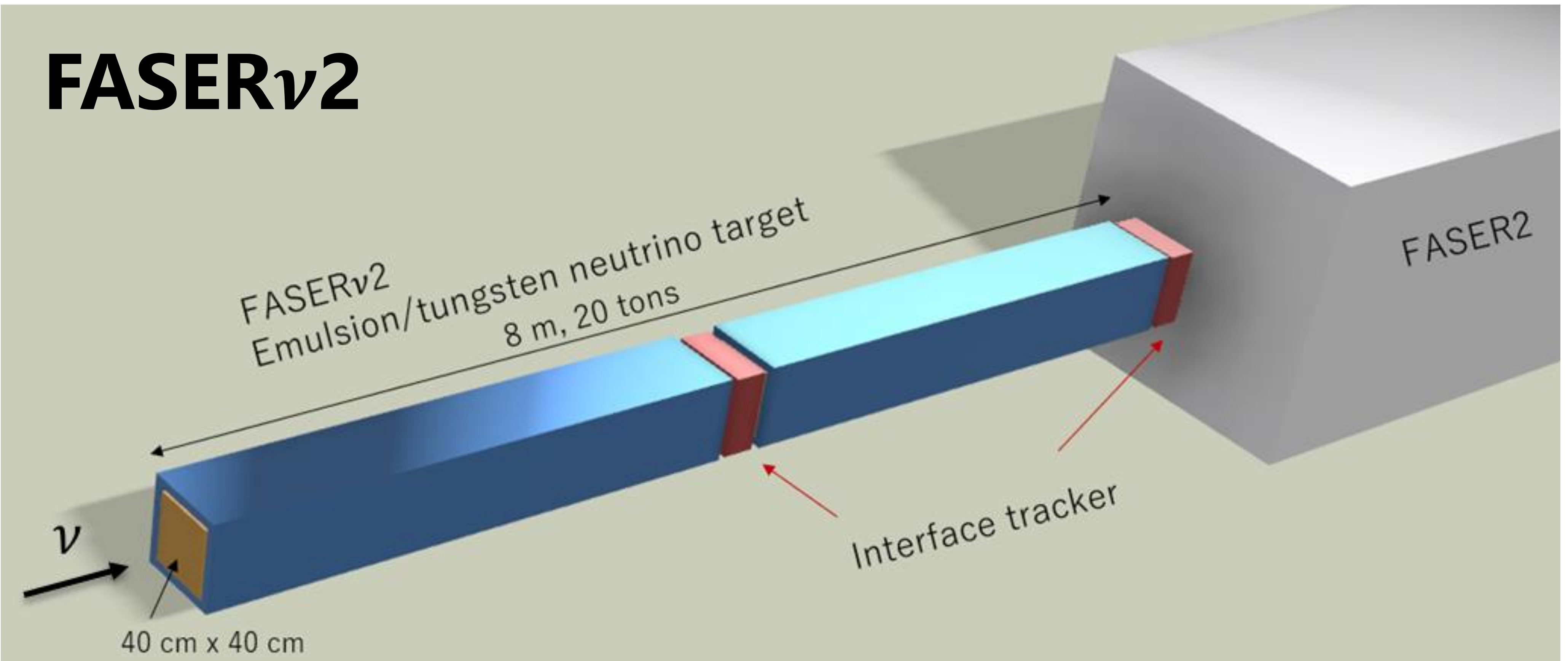


FASER
Preliminary

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

Forward Physics Facility



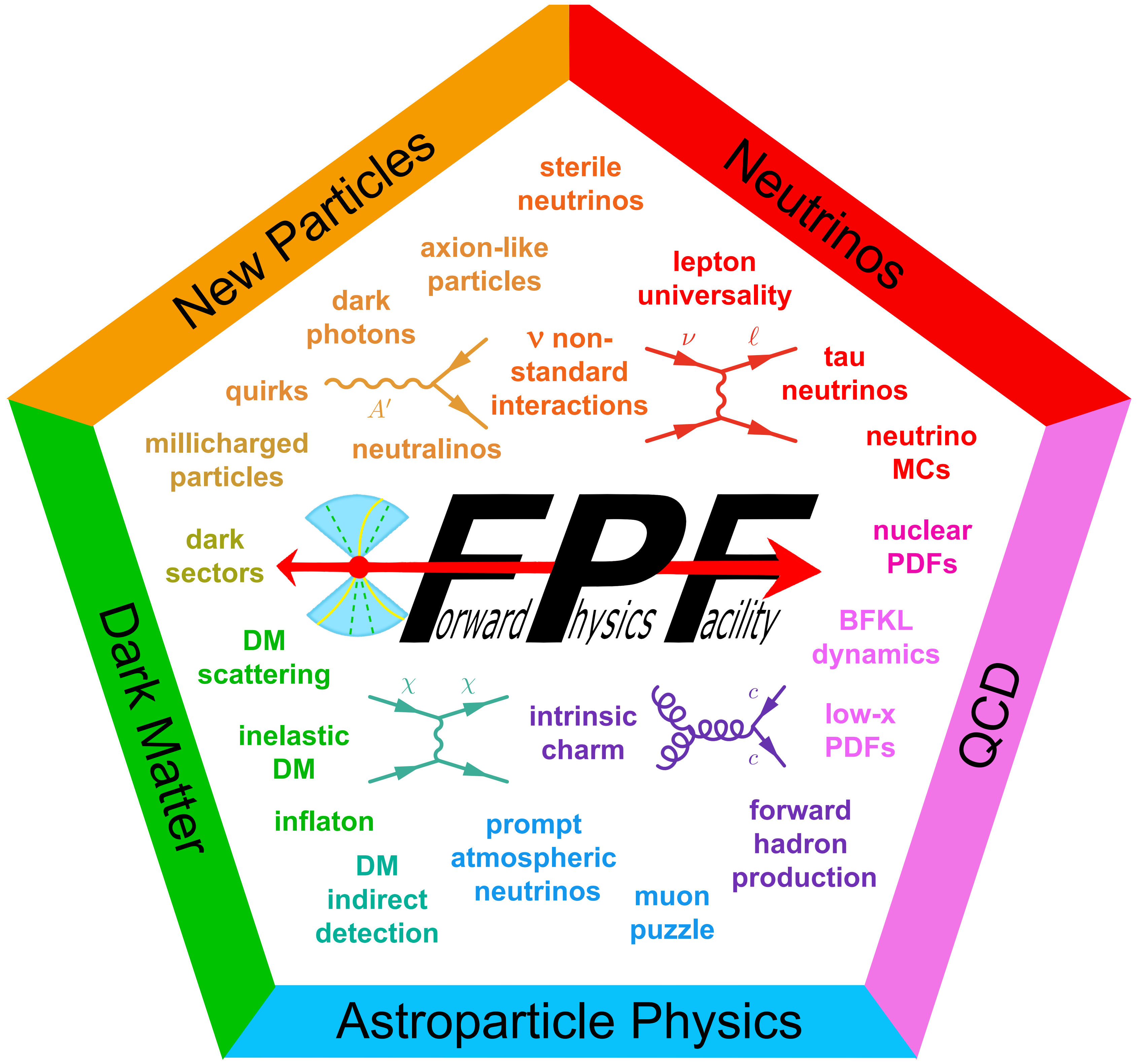


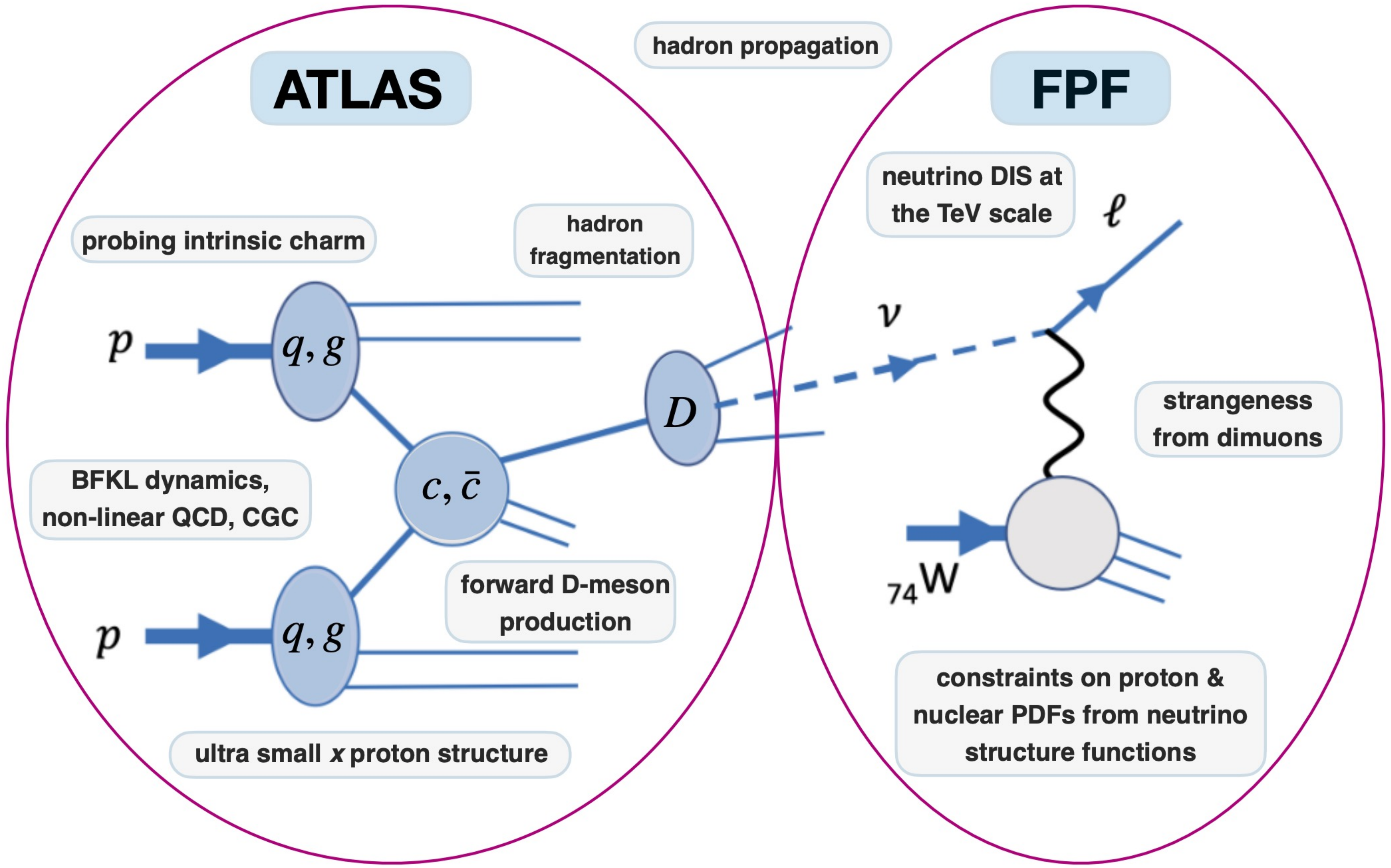
- **FASERν2** as part of the proposed **Forward Physics Facility (FPF) at HL-LHC**
  - target mass: 20 tons
- Studying possibility of installing a dedicated sweeper magnet to reduce muon background
  - Emulsion detector replacement: Once per a year

FPF Physics

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

- Expected tau neutrino interactions: ~2300 (SIBYLL) / ~20000 (DPMJET)
- Many interesting QCD topics as well as neutrino and BSM physics



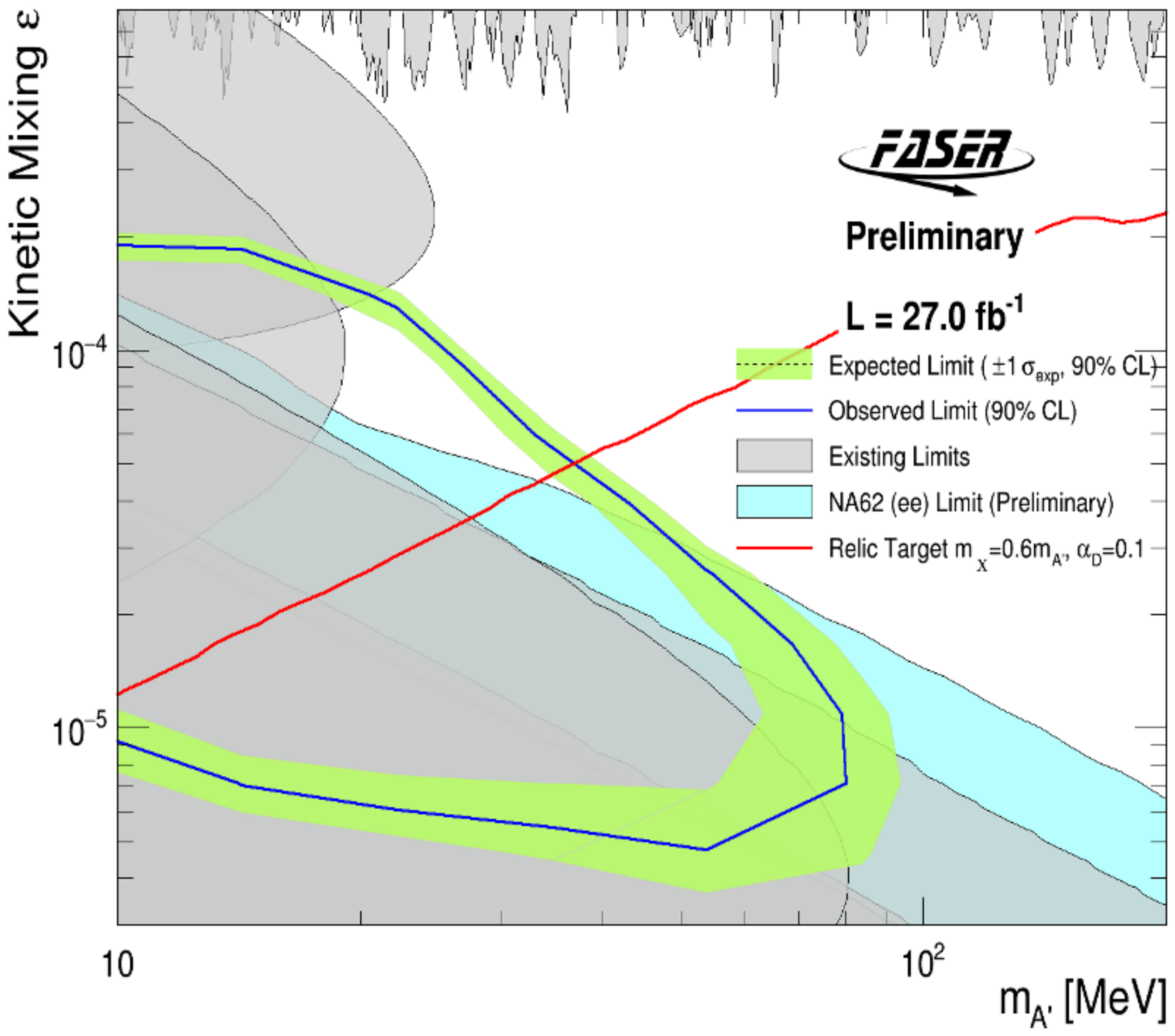


Summary

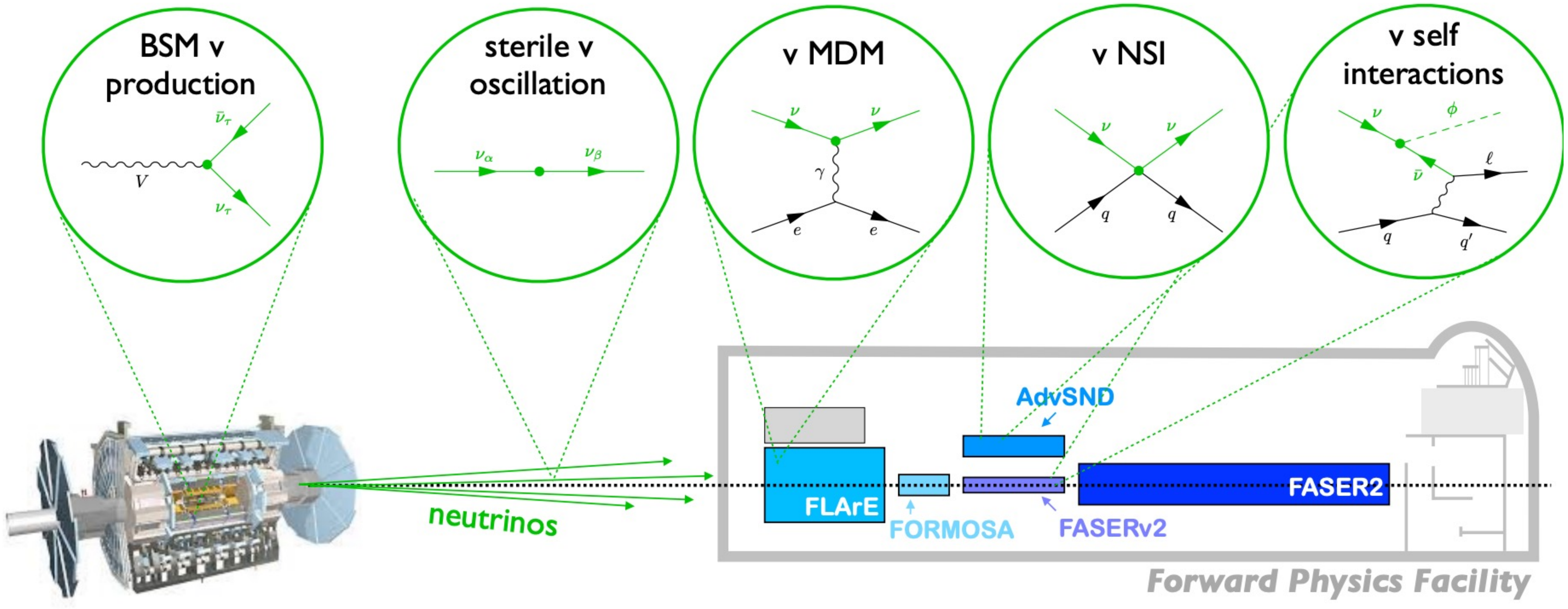
- **FASERν studies three flavor neutrinos at the high energy frontier**
  - **~10,000ν interactions** expected in LHC Run 3 (2022-2025, 250 fb^{-1})
- **Successfully taking data since the start of LHC Run 3**
  - **FASER recorded 96% of delivered luminosity in 2022**
  - **~0.2 µm position accuracy** observed on the 10 emulsion films
- **Observed 153 ν_μ CC interactions with FASER (signal significance of 16σ)**
  - **First direct observation of collider neutrinos**
  - Neutrino characteristics are in good agreement with expectations from simulation
- **FASERν observed ν_e candidate**
  - Emulsion analysis will follow soon
- **Starting to discuss a new forward physics facility at HL-LHC (FPF)**

Backup

Dark Photon Search



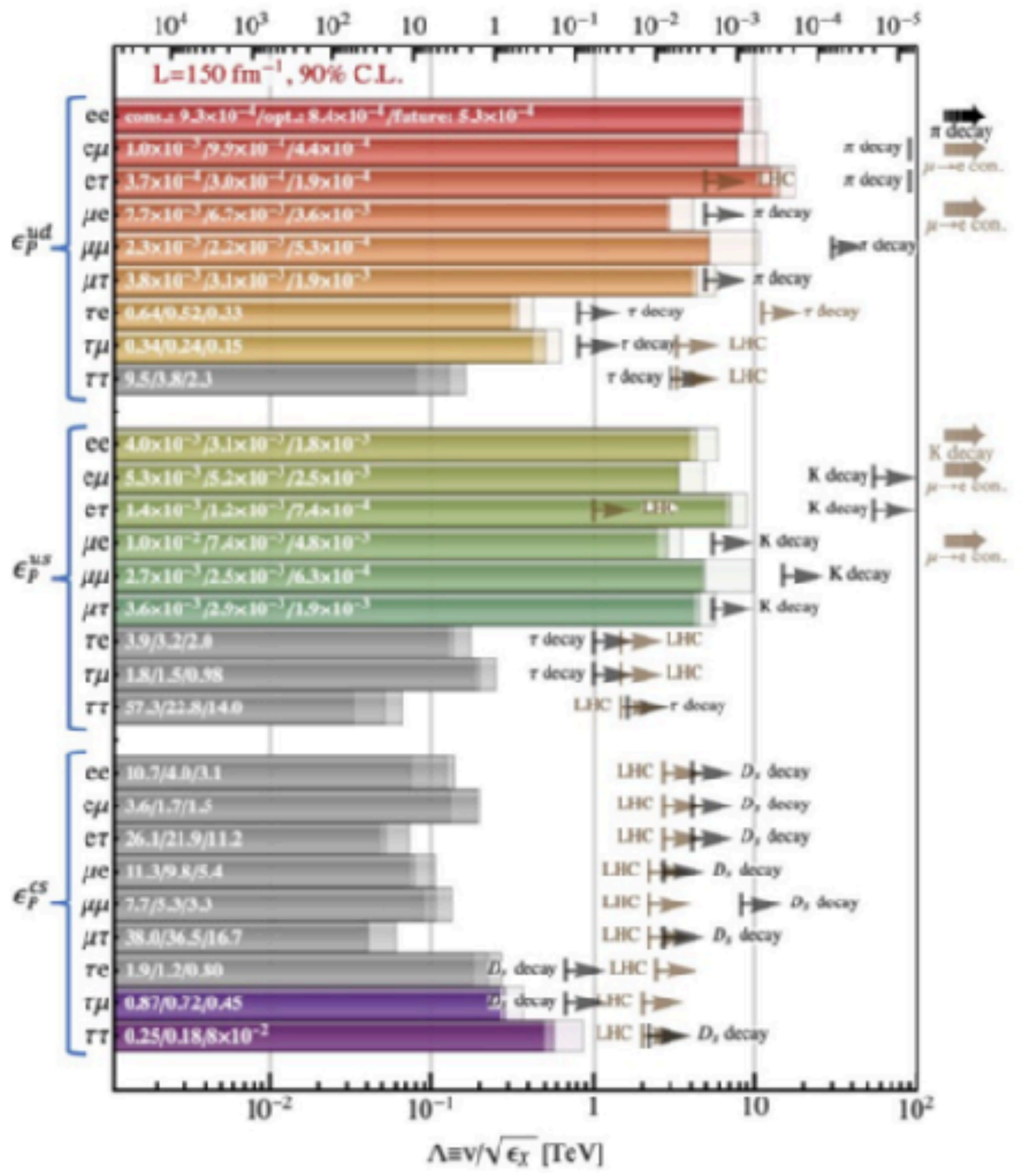
Neutrino (BSM) at the FPF



New Physics

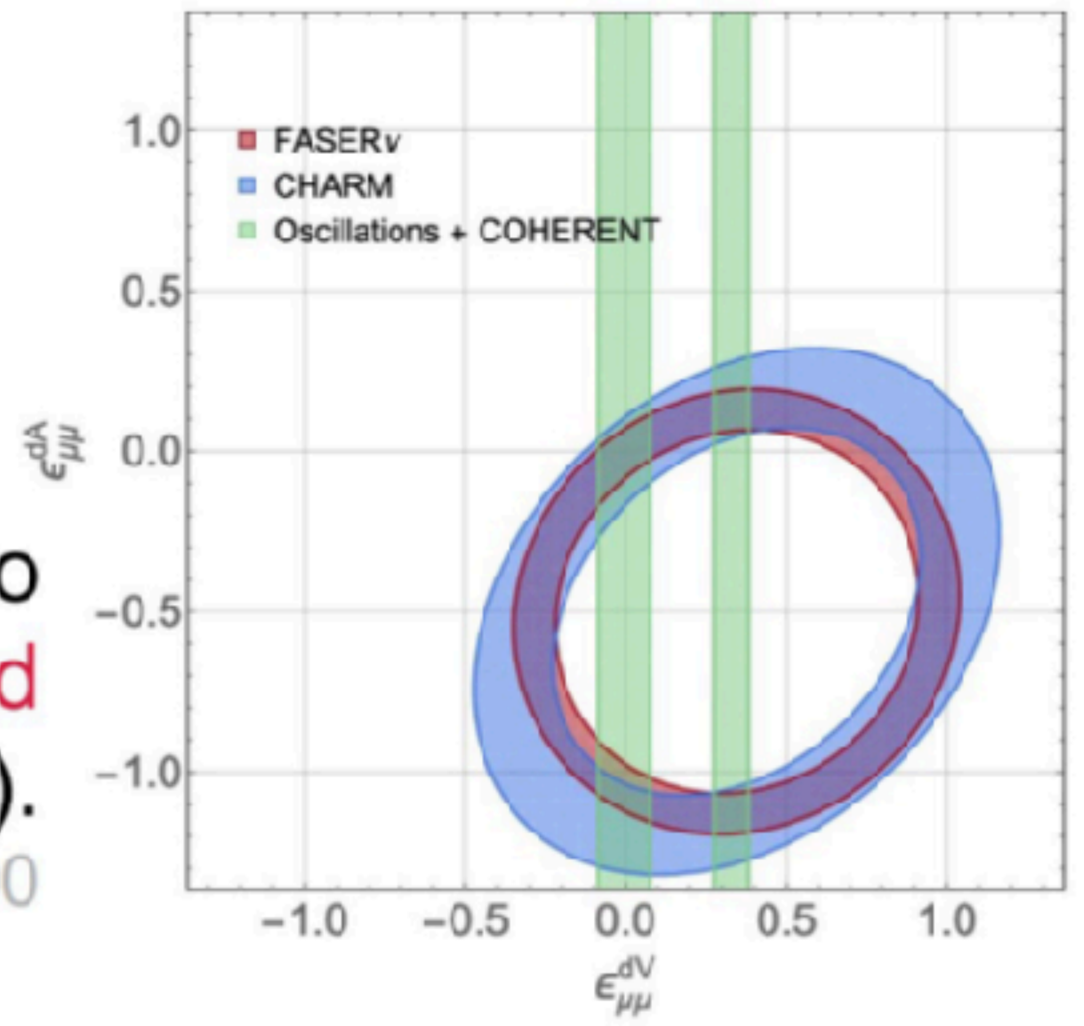
Interactions of LHC neutrino can also be used to constrain SM EFT coefficients

Falkowski, González-Alonso, Kopp, Soreq, Tabrizi 2105.12136

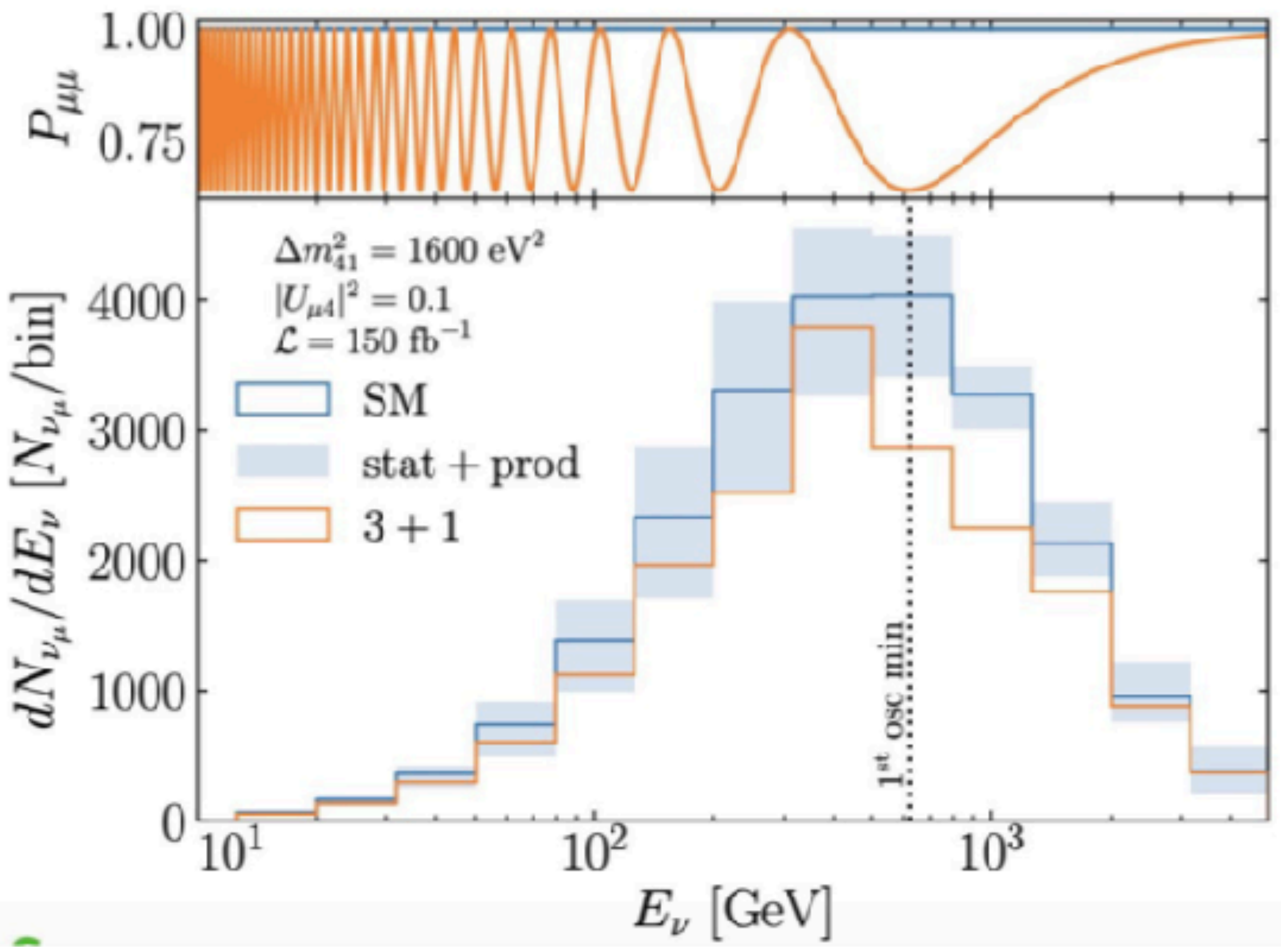


NC measurements could also constrain neutrino non-standard interactions (NSI).

Abraham, Ismail, Kling 2012.10500

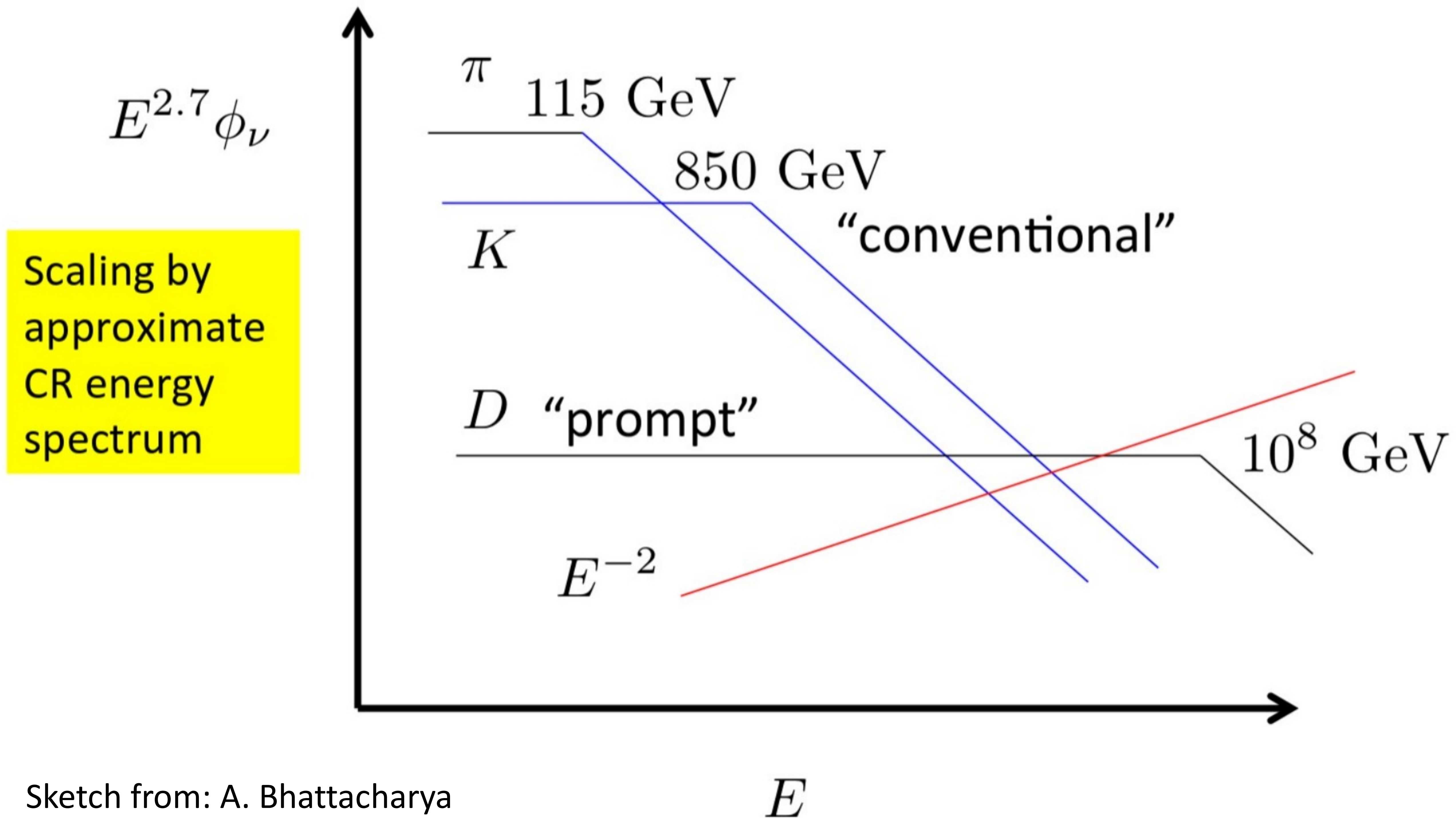


SM neutrino oscillations are expected to be negligible at FASERν. However, sterile neutrinos with mass ~40eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment.



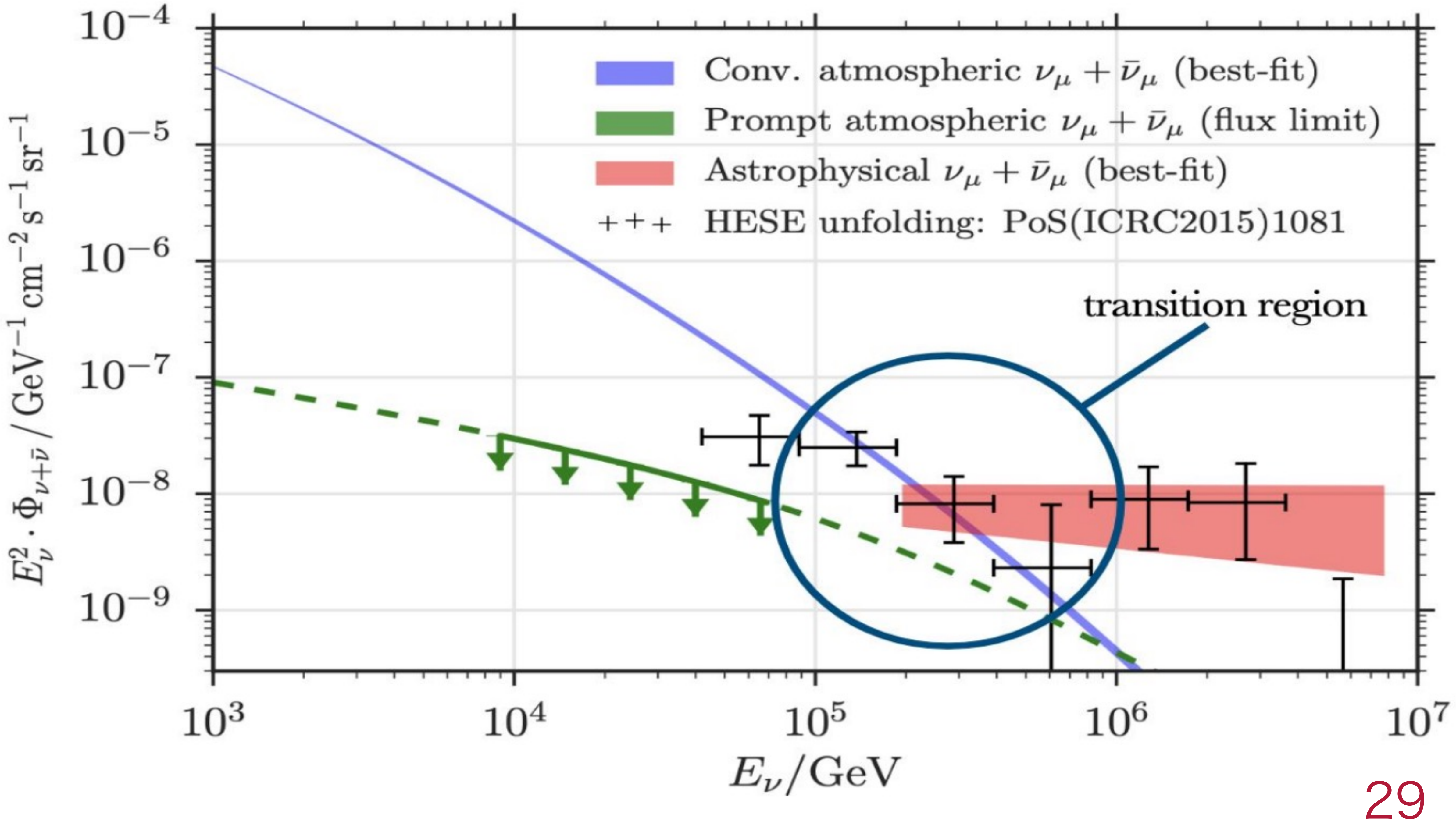
Input for astroparticle experiments

Studies of high-energy astrophysical neutrinos with large-scale neutrino telescopes (e.g. IceCube), suffer from backgrounds from atmospheric neutrinos from charm-decay (charm produced in hadronic shower initiated by cosmic rays hitting the atmosphere).
At ultra high-energy light hadrons travel far through the atmosphere, losing energy, and hence produce lower energy neutrinos. Neutrinos produced in charm decay ("prompt neutrinos") are therefore the key background at high energy.
This prompt background has a large associated uncertainty which limits the study of astrophysical neutrinos.
Measurements of neutrinos from charm at the FPF can provide important information to constrain this background.

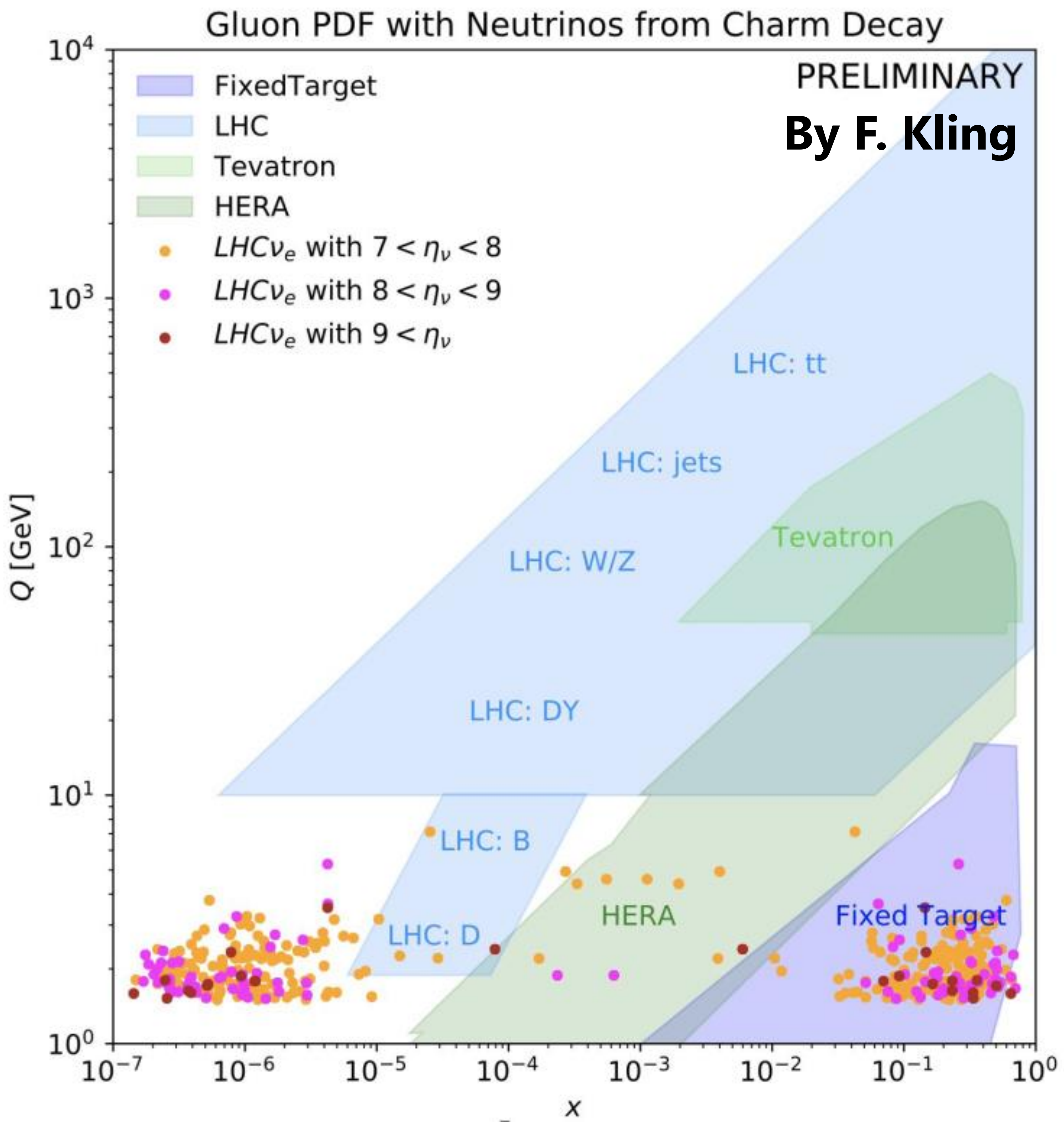


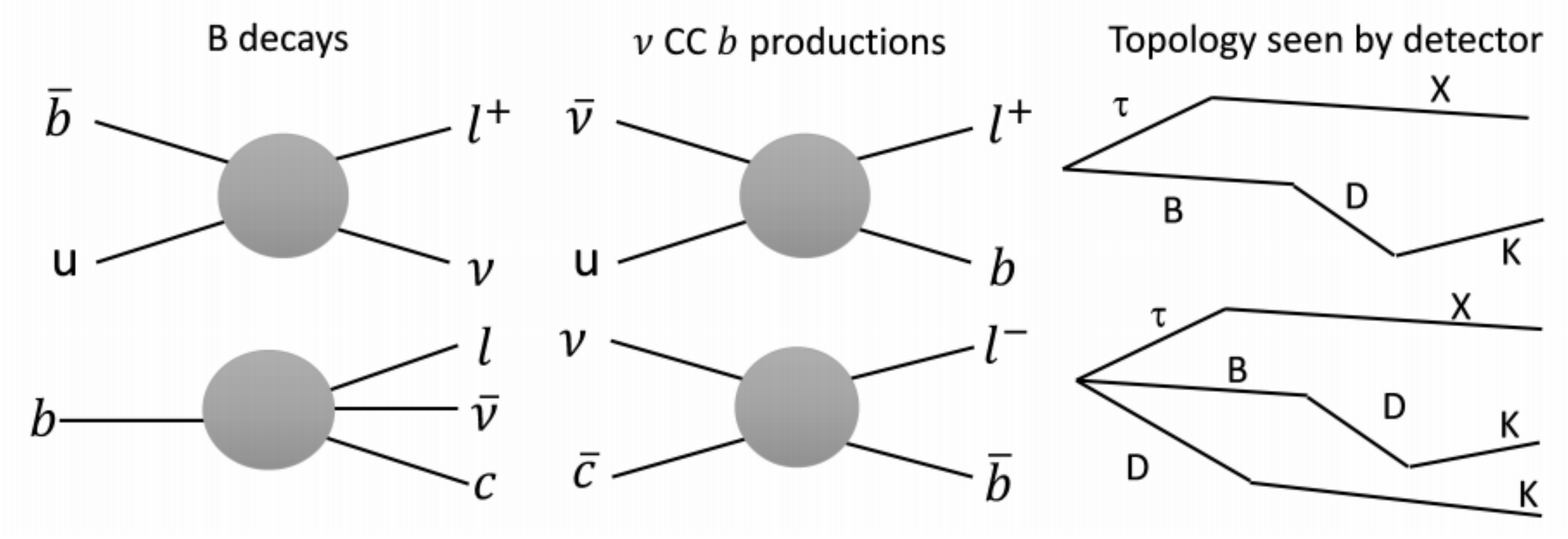
Sketch from: A. Bhattacharya

IceCube, PoS (ICRC2017) 1005



Physics

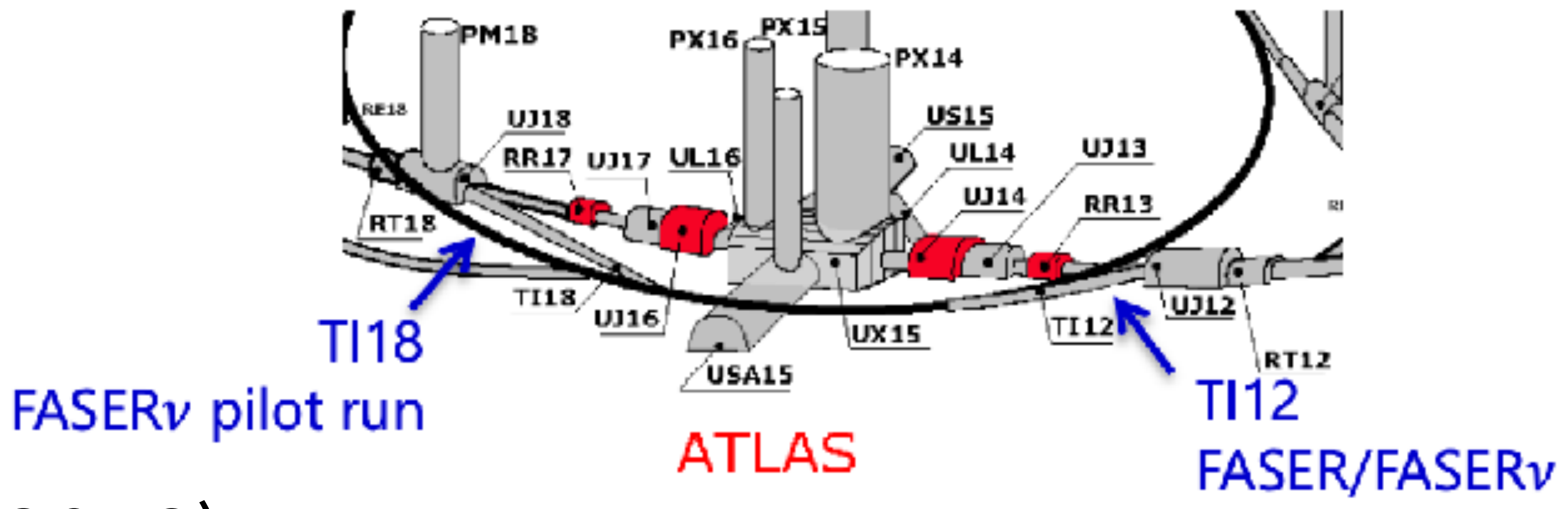




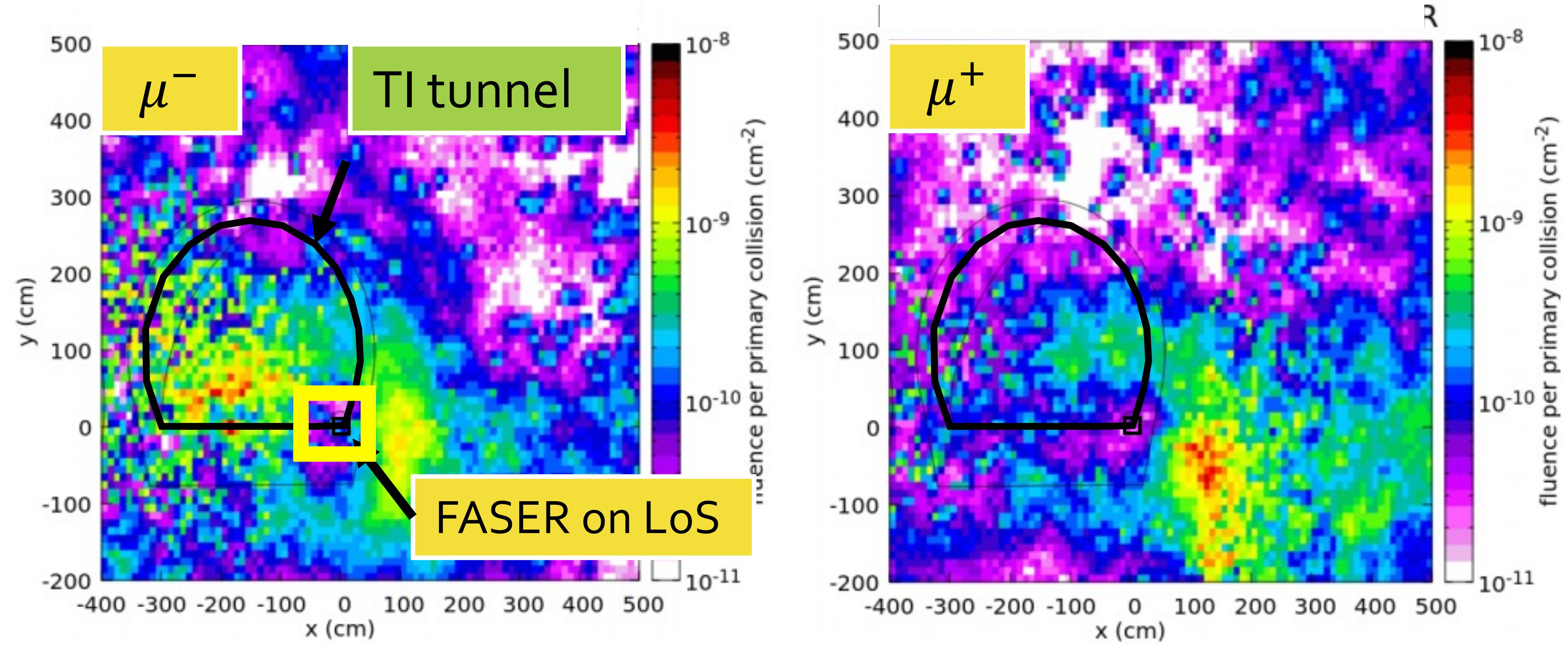
$$\bar{\nu}N \to \ell\bar{B}X$$

$$\nu N \to \ell BDX$$

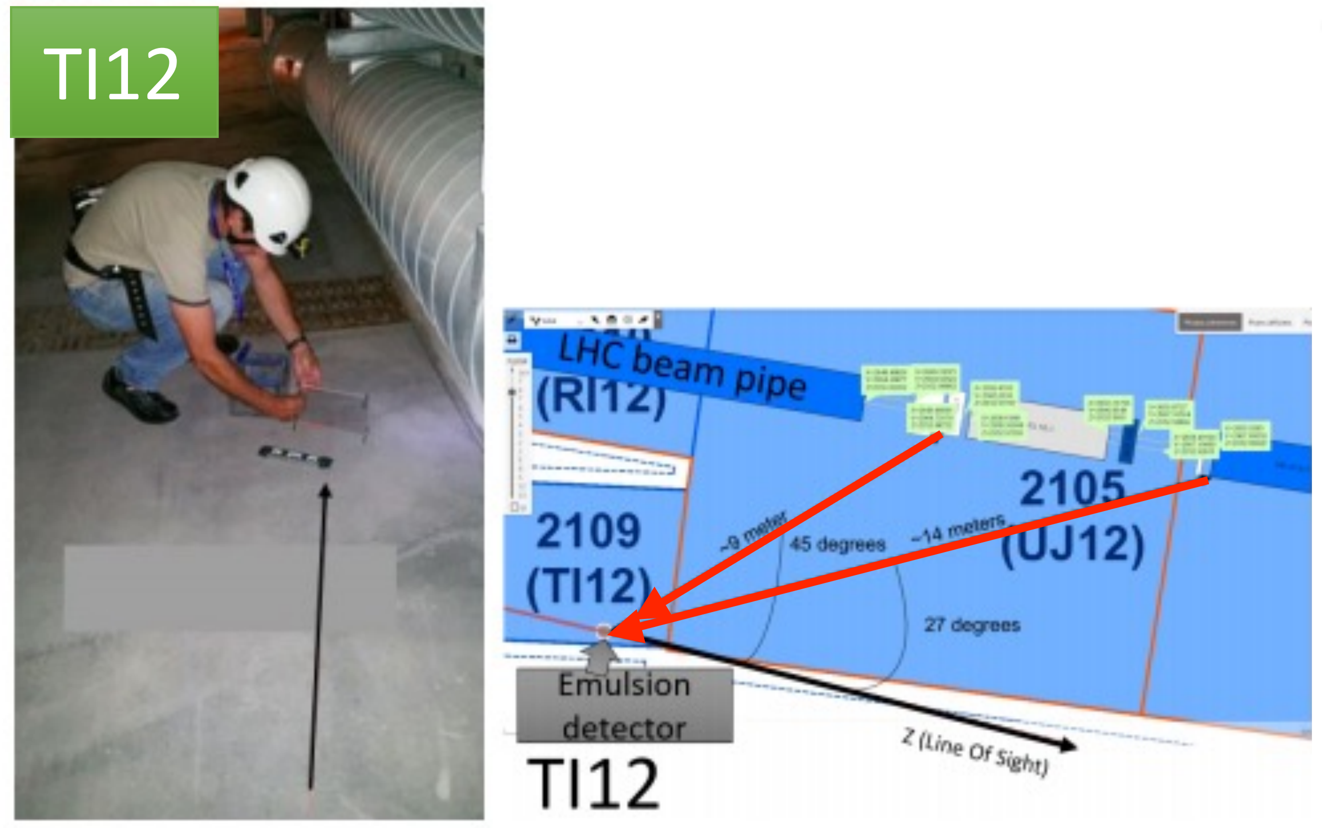
Detector Environment

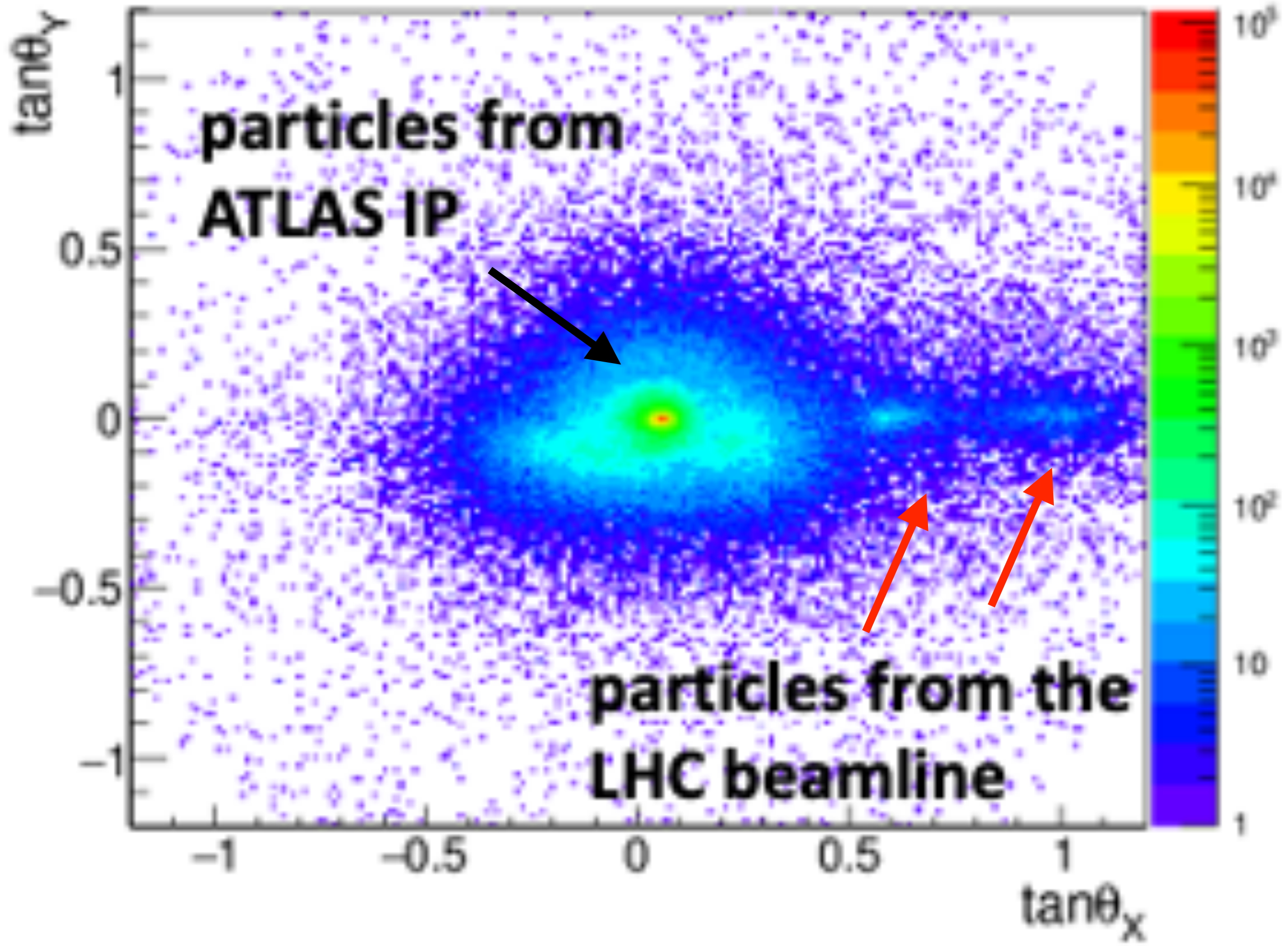


FLUKA simulations



In-situ measurements (2018)



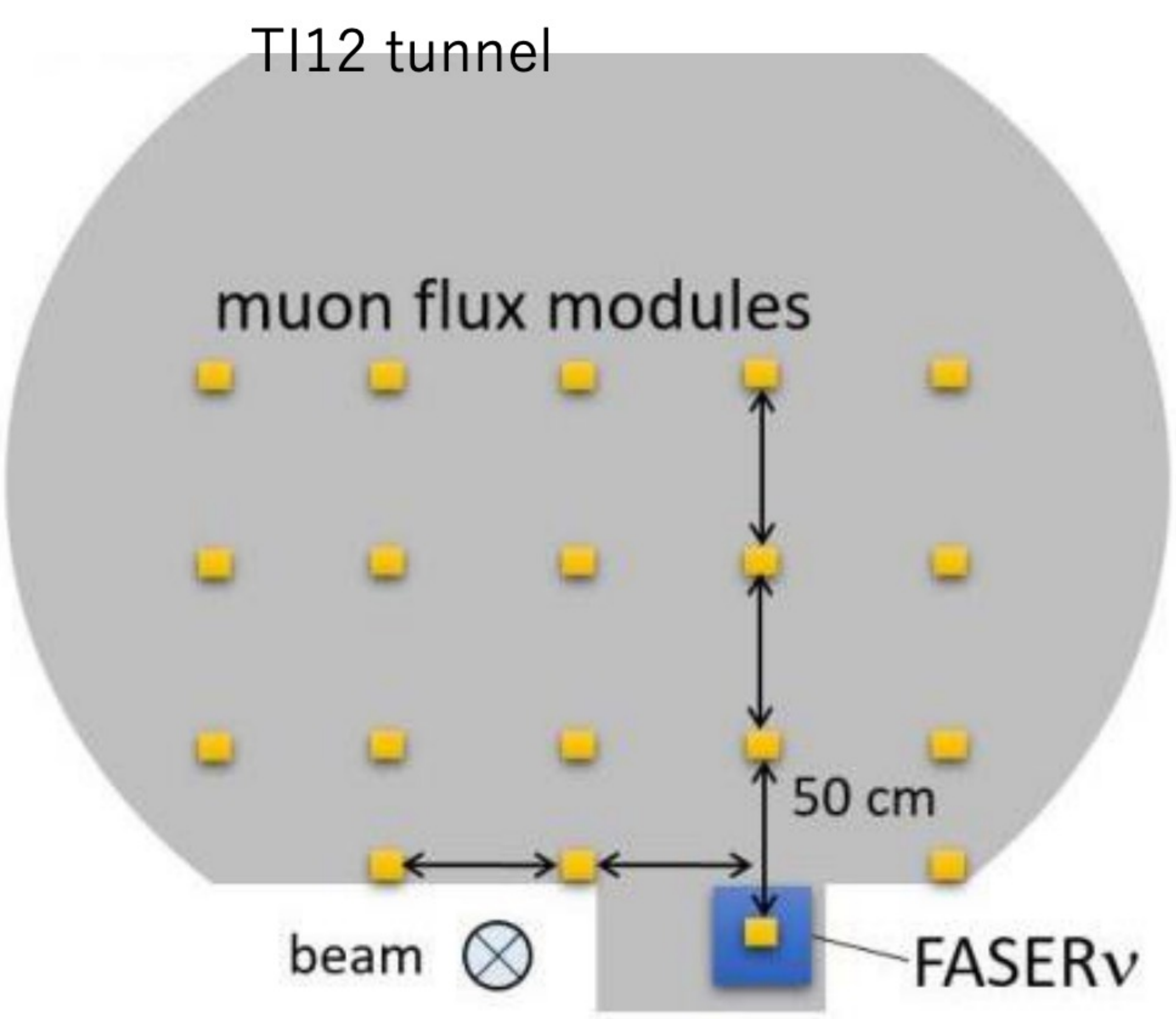


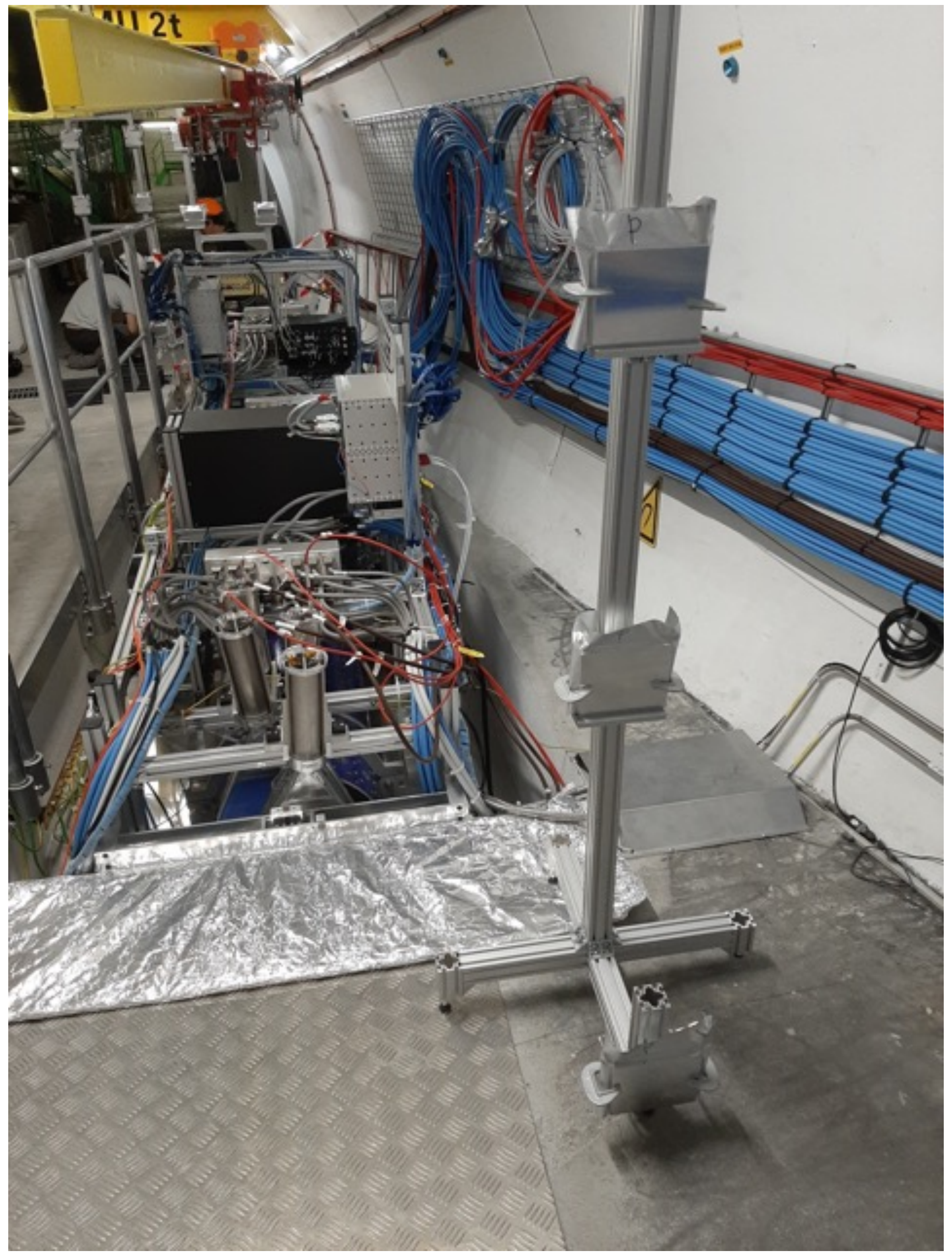
	Flux all [fb/cm²]	Flux in main peak [fb/cm²]
TI18 data	2.6±0.7 ×10⁴	1.2±0.4 ×10⁴
TI12 data	**3.0±0.3 ×10⁴**	**1.9±0.2 ×10⁴**
FLUKA MC		**2.0 ×10⁴**

- Muon flux simulations/measurements
- MC prediction is in good agreement with data
- The expected muon flux is low enough to use the emulsion detector in the tunnel

Muon Measurements

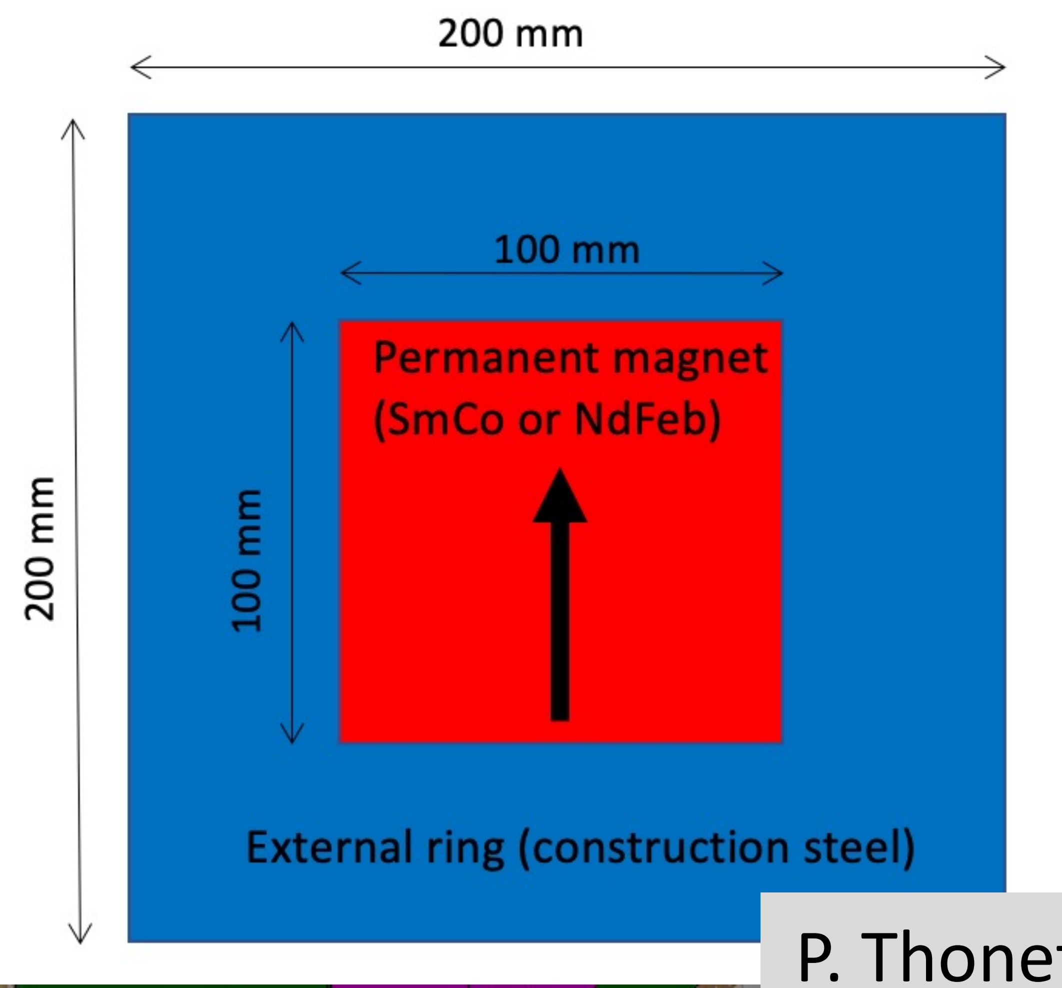
In order to measure the muon rate away from the LOS in Run 3, we recently installed 20 small emulsion detectors within 2m of FASER. These were installed on 23/7 and removed on 2/9, having been exposed to ~10/fb of data. They will provide a useful validation of the FLUKA estimate further from the LOS.



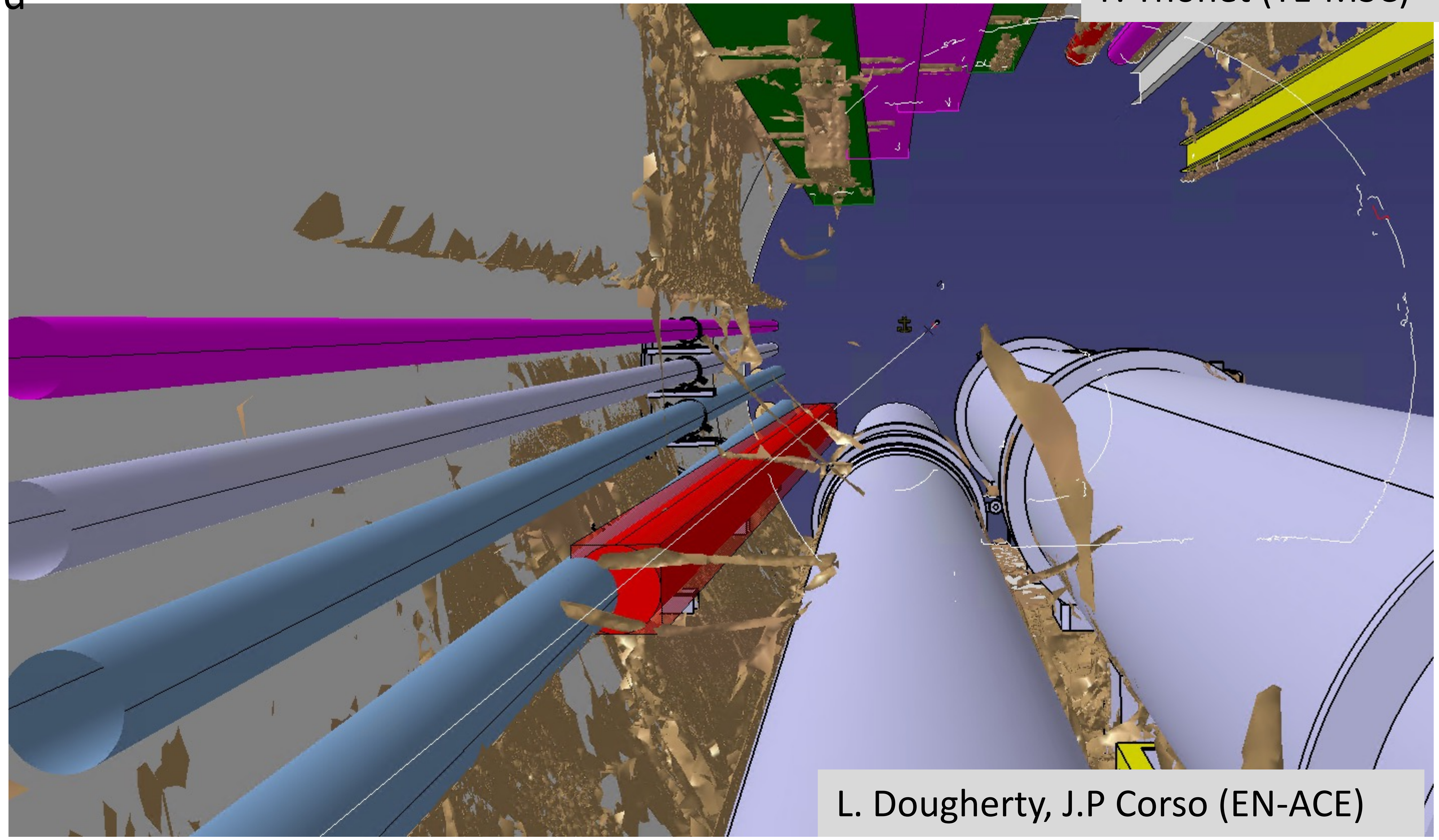


Sweeper Magnet: Ongoing Studies

- Preliminary design of sweeper magnet by TE-MSC
  - Based on permanent magnet to avoid power converter in radiation area
  - Consider 7m long (20x20cm^2 in transverse plane) magnet, 7Tm bending power
- To install such a magnet would require some modifications to cryogenic lines in relevant area
  - Possibility of modifications to be investigated with LHC cryo
  - Integration/installation aspects to be studied
- FLUKA and BDSIM studies ongoing to assess effectiveness of such a magnet in reducing the muon background in the FPF

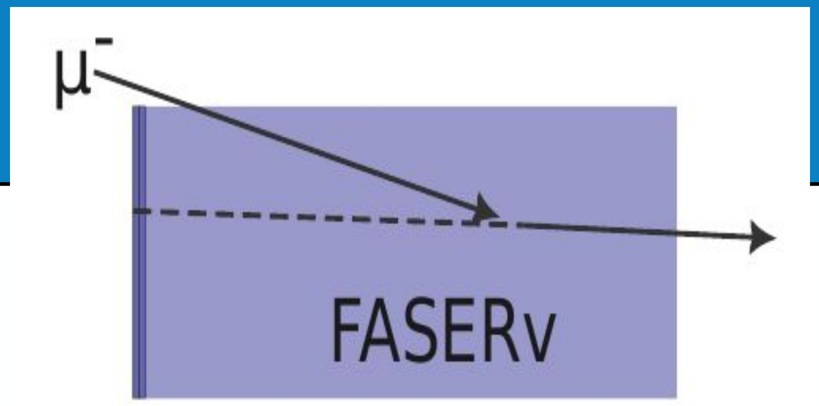


P. Thonet (TE-MSC)

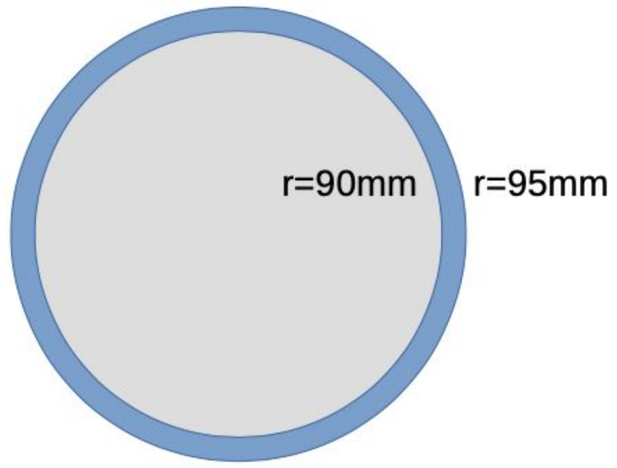


L. Dougherty, J.P Corso (EN-ACE)

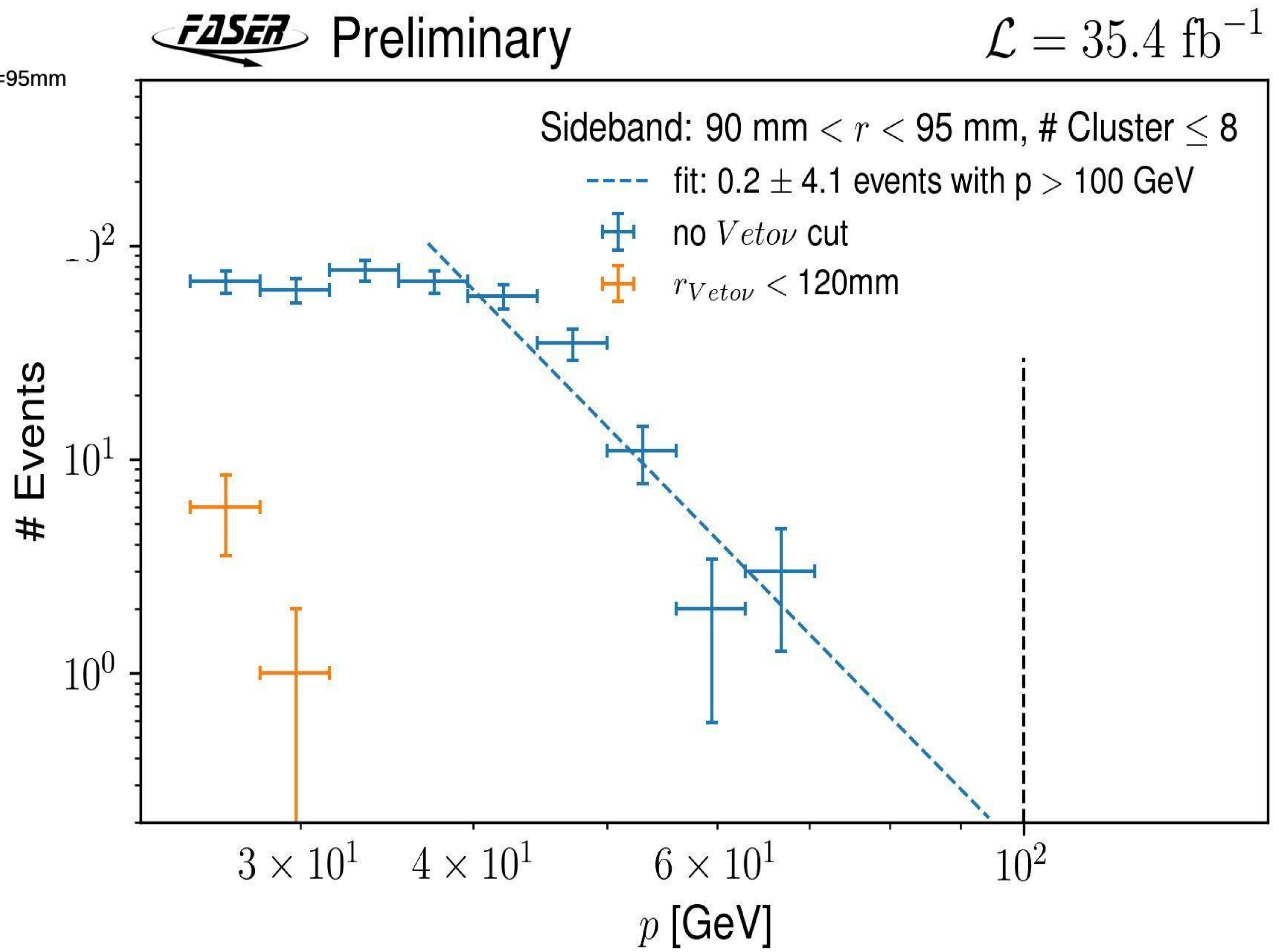
Neutrinos: Geometric Background



- 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
  - Negligible neutrino background

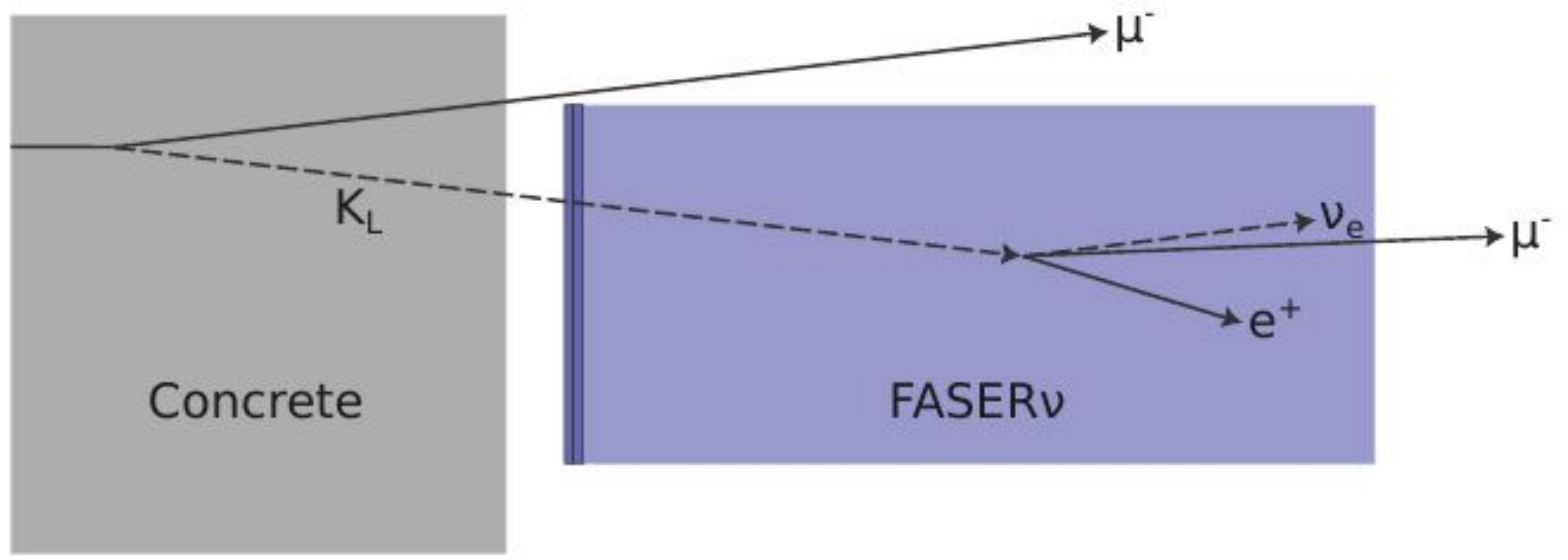


- Fit mom. to extrapolate to p > 100 GeV
- Scale to rate of events with r_{VetoNu} < 120 mm
  - 0 events so use 5.9 events as 3σ upper limit
- Scale from anulus to full acceptance
  - Using large angle muon simulation
- Expect 0.08 ± 1.83 events



Neutrinos: Neutral Hadron Background

- Simulated 10^9 μ^+ and μ^- events
  - Start from FLUKA Spectra
  - G4 propagation through last 8 m of rock
  - Number of hadrons with $p > 100$ GeV reaching FASER ≈ 300.
- Estimate fraction of these passing event selection
  - Simulate kaons (Ks/Kl) and neutrons with $p > 100$ GeV following expected spectra
  - Most are absorbed in tungsten with no high-momentum track only small fraction pass



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

Neutrinos: fit

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

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

obs exp

- 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.

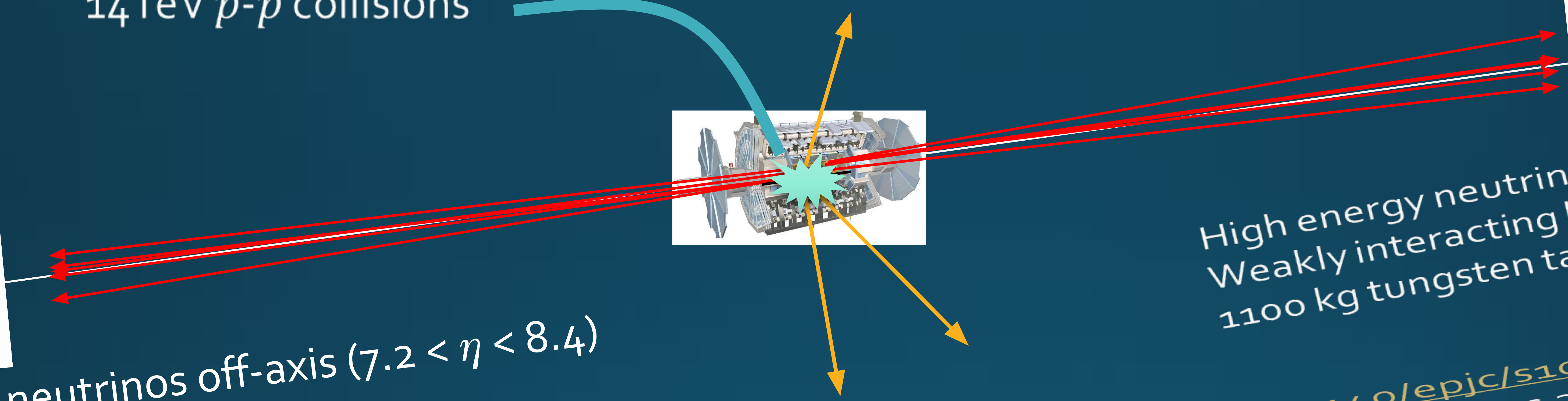
n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

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	$\nu_b \cdot (1 - p_1) \cdot (1 - p_2)$

Neutrino experiments at the LHC

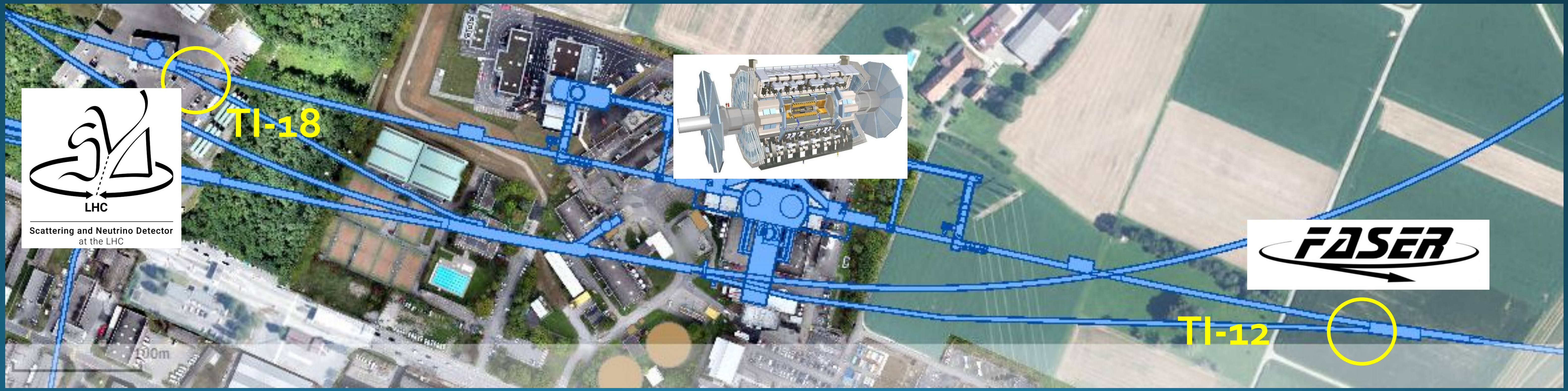
14TeV p-p collisions



Mid-high energy neutrinos off-axis ($7.2 < \eta < 8.4$)
800 kg tungsten target
SND@LHC was approved in Mar 2021,
TP arXiv:2002.08722

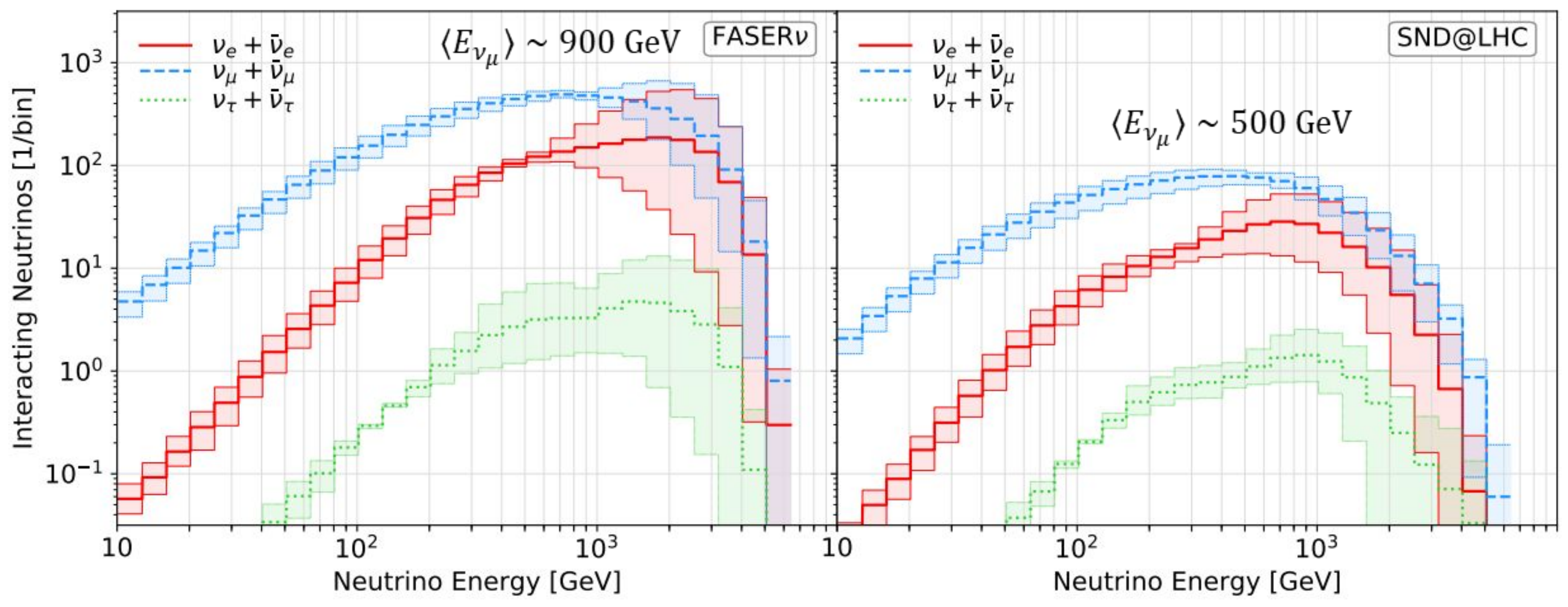
High energy neutrinos at on-axis ($\eta > 8.8$)
Weakly interacting light particles (A', ALP)
1100 kg tungsten target

FASERν paper 10.1140/epjc/s10052-020-7631-5
FASERν was approved in Dec 2019, TP arXiv:2001.03073



Expected neutrino spectra

Expected CC interactions with 150 fb^{-1}



		SND@LHC
Target mass	1100 kg	800 kg
Location	On axis	Off axis
Features	High energy & high statistics	More neutrinos from charm decay

10.1103/PhysRevD.104.113008