High-energy neutrino measurements with FASERν at the LHC

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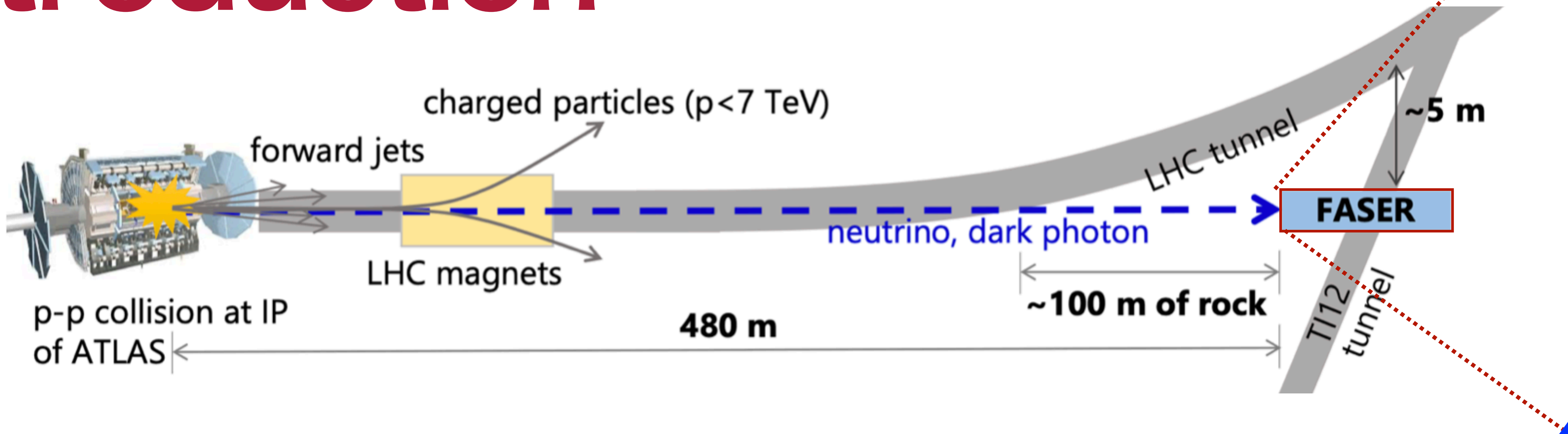
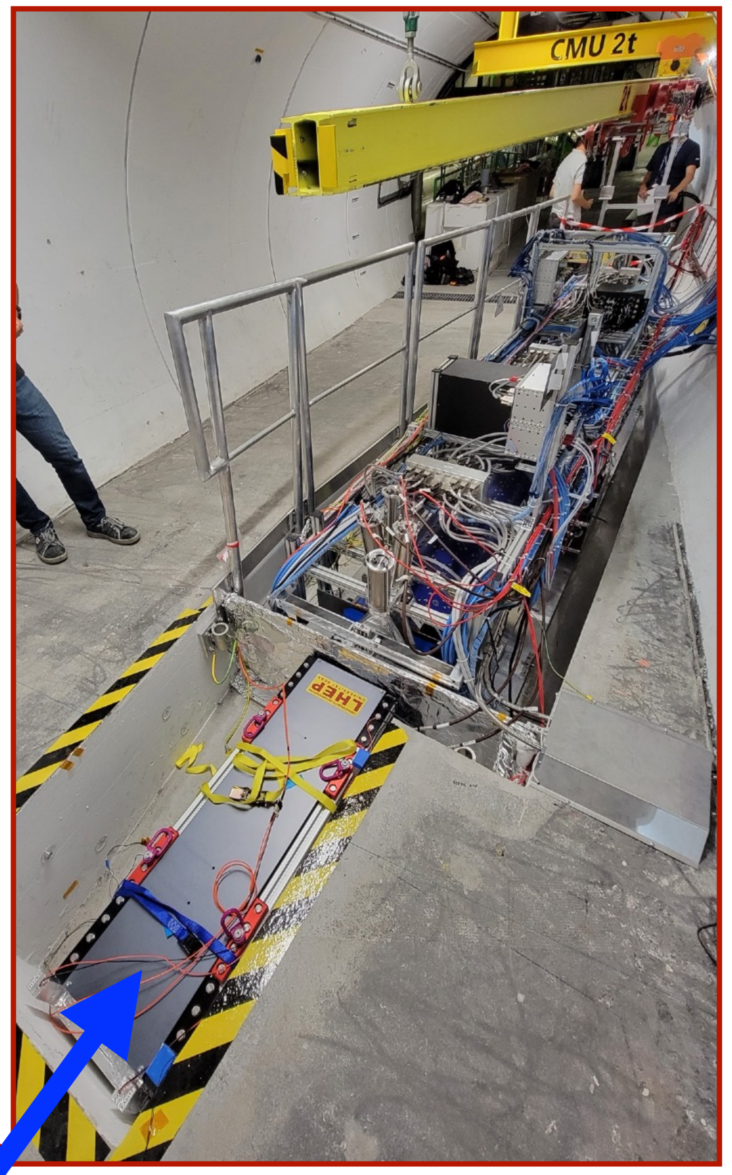
on behalf of the FASER collaboration

CHIBA UNIVERSITY

Introduction



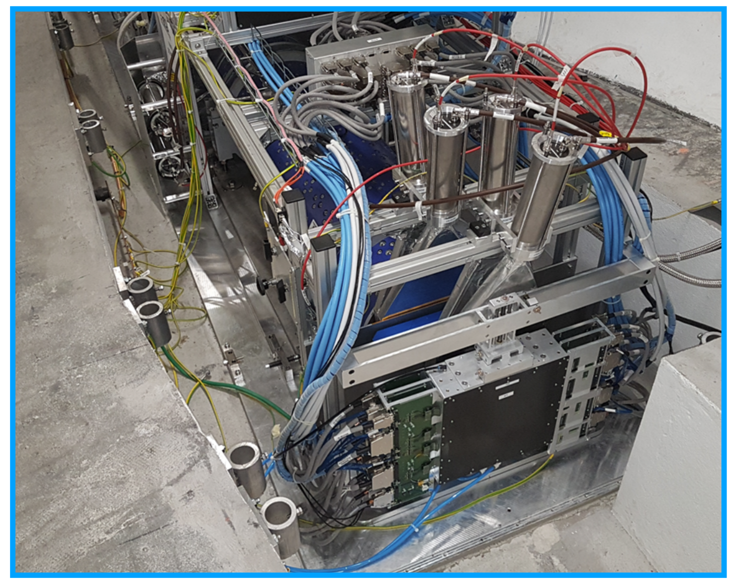


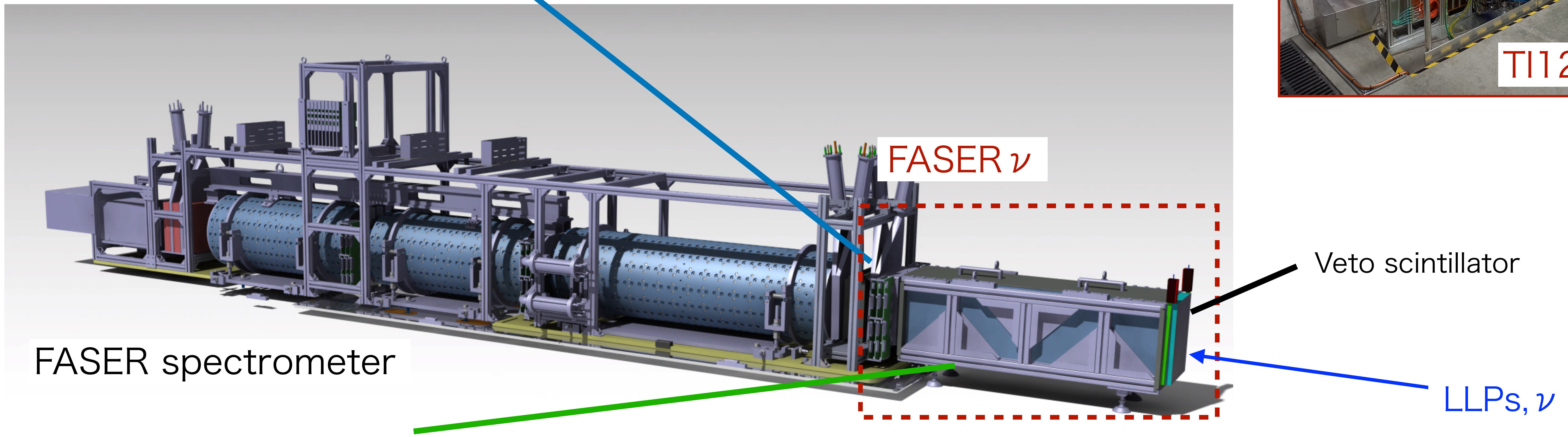
- Large Hadron Collider (LHC): 27 km ring collider, 13.6 TeV proton-proton collisions
- Energetic particles produced in the far-forward direction of the collisions
- **FASER** (**F**orw**A**rd **S**earch **E**xpe**R**iment) is a new experiment at the LHC to search for new, light, long-lived particles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

FASERν: neutrino program of the FASER experiment
Three flavor neutrino cross section measurements at TeV energy ranges

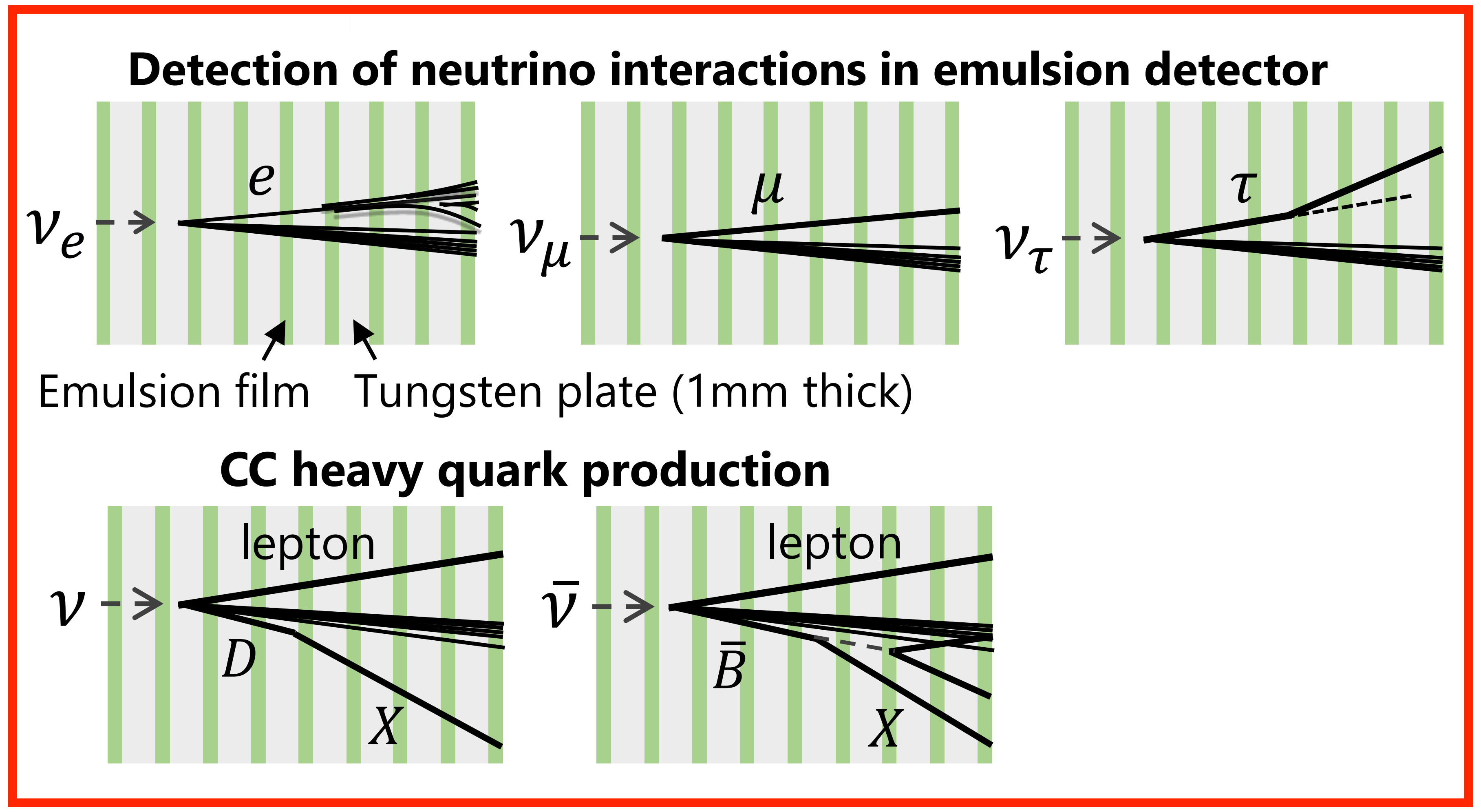
FASERν Detector

Interface Silicon Tracker: 3 layer siliconstrip tracker

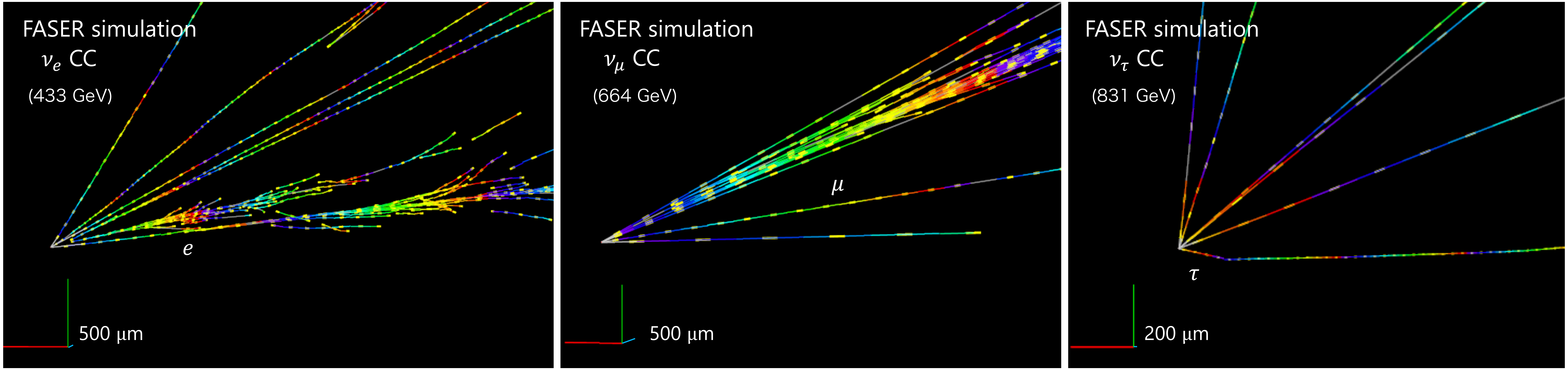




- **FASERν emulsion detector**
  - 730 × [tungsten (~1.1 mm thickness) + emulsion film]
  - 250 mm × 300 mm, 1 m long, 1.1 tons (220 X_0)
  - **Spatial (angular) resolution: 0.4 μm (0.1 mrad for 10 mm tracks)**
- ν flavor tagging with topological/kinematical informations
- Muon charge identification by FASER spectrometer with 0.55 T magnets (ν_μ)

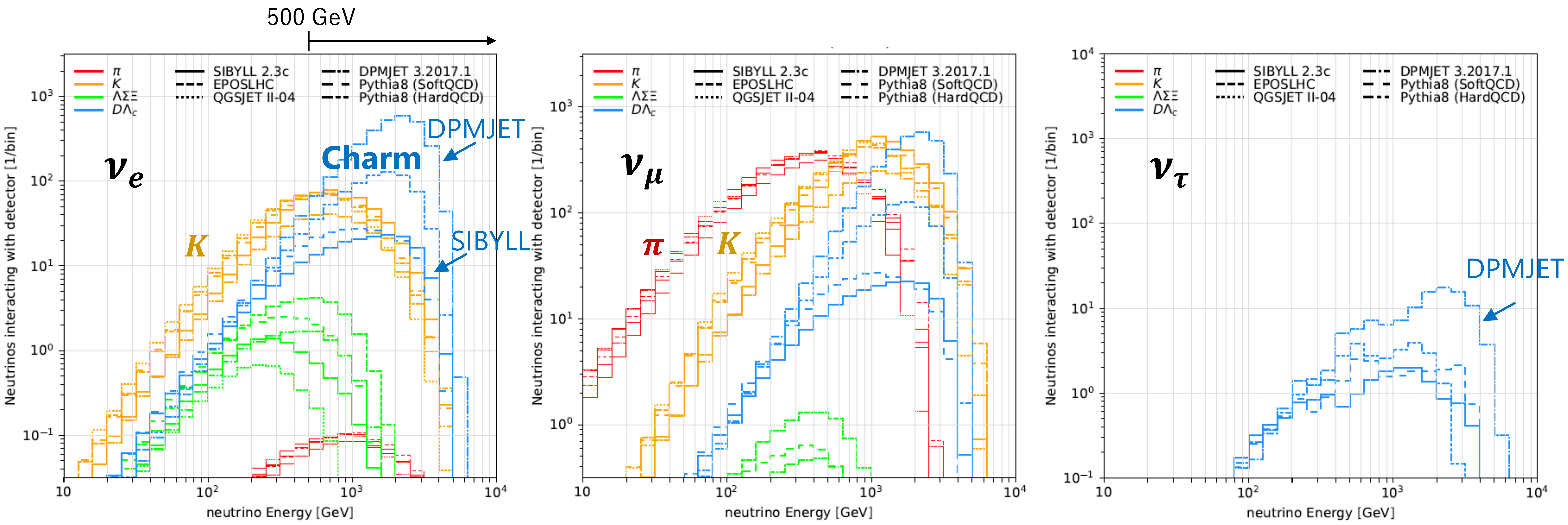


Neutrino Interaction Events (MC)



- Generator: GENIE
- MC simulation with FASER simulation framework based on Geant4
- Reconstructed particle hits in emulsion detector

Expected Number of Events



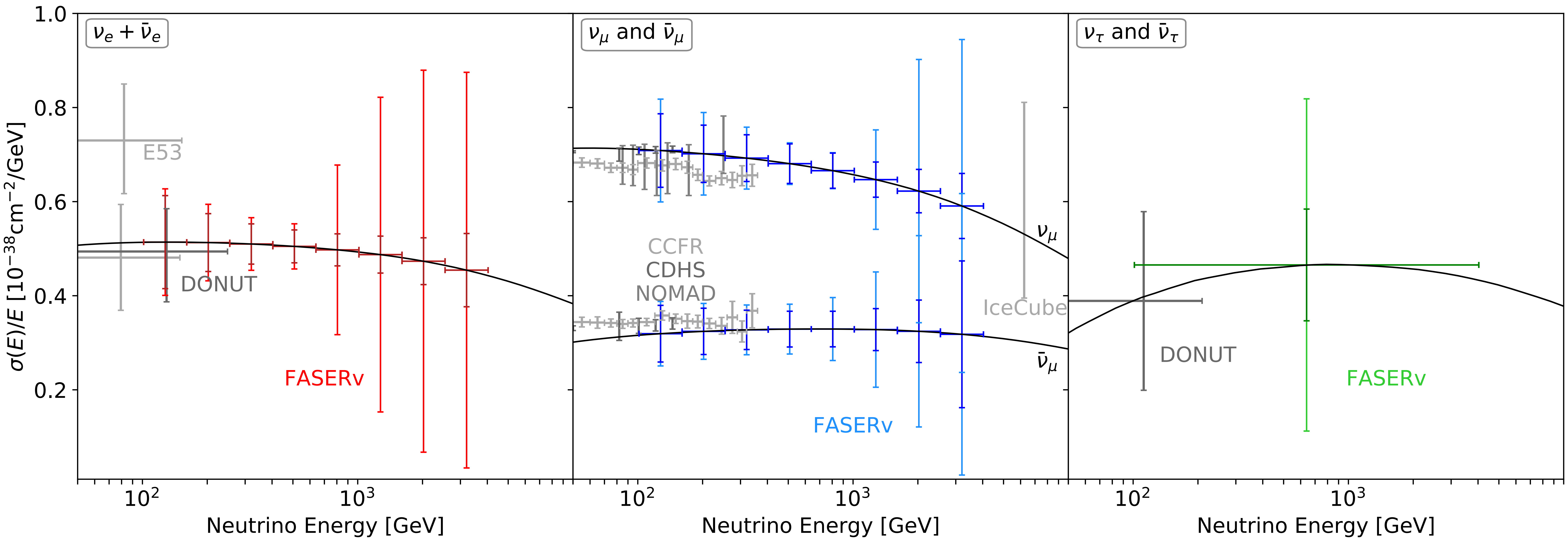
Expected CC interaction events **(250 fb^{-1})**

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

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

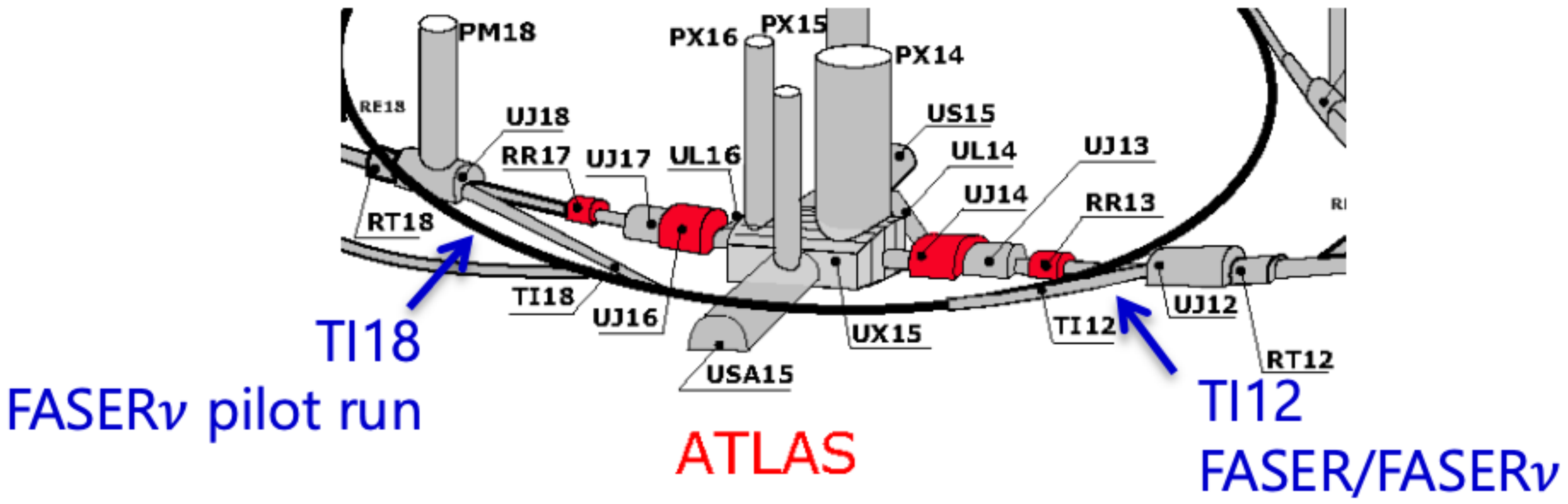
Cross-Section Sensitivity

(150 fb^{-1})

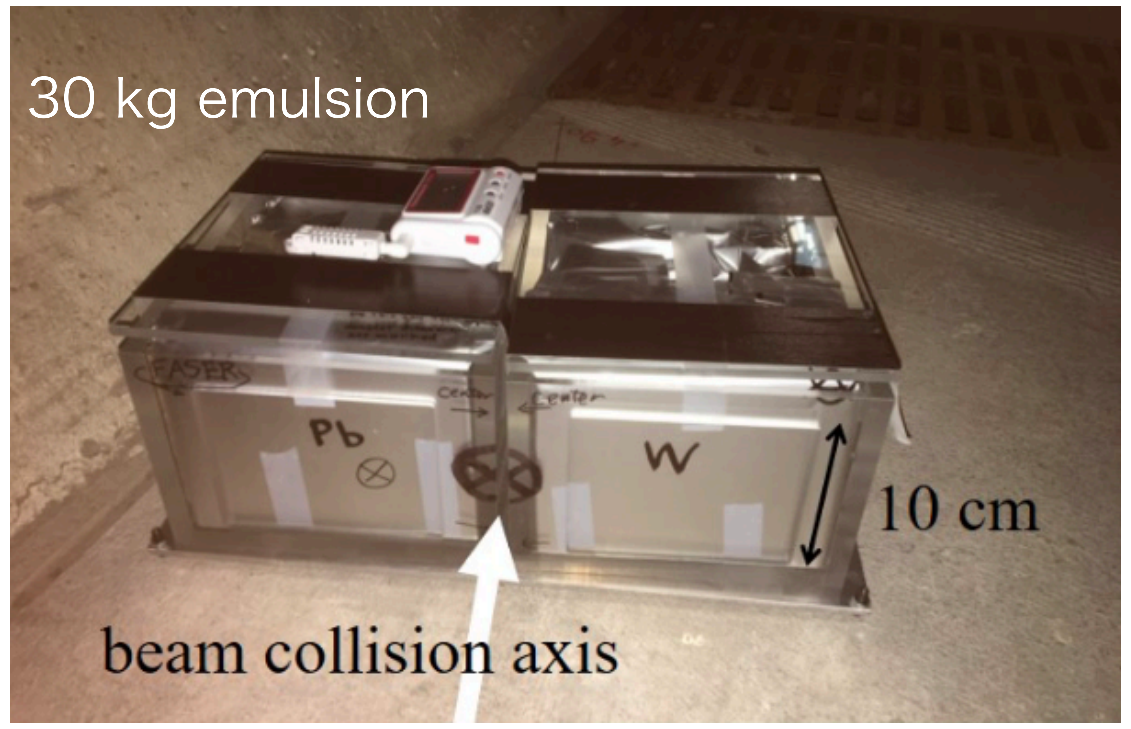


- Three flavors neutrino cross-section measurements for unexplored energy ranges
- Neutrino energy reconstruction with resolution 30% expected from simulation studies

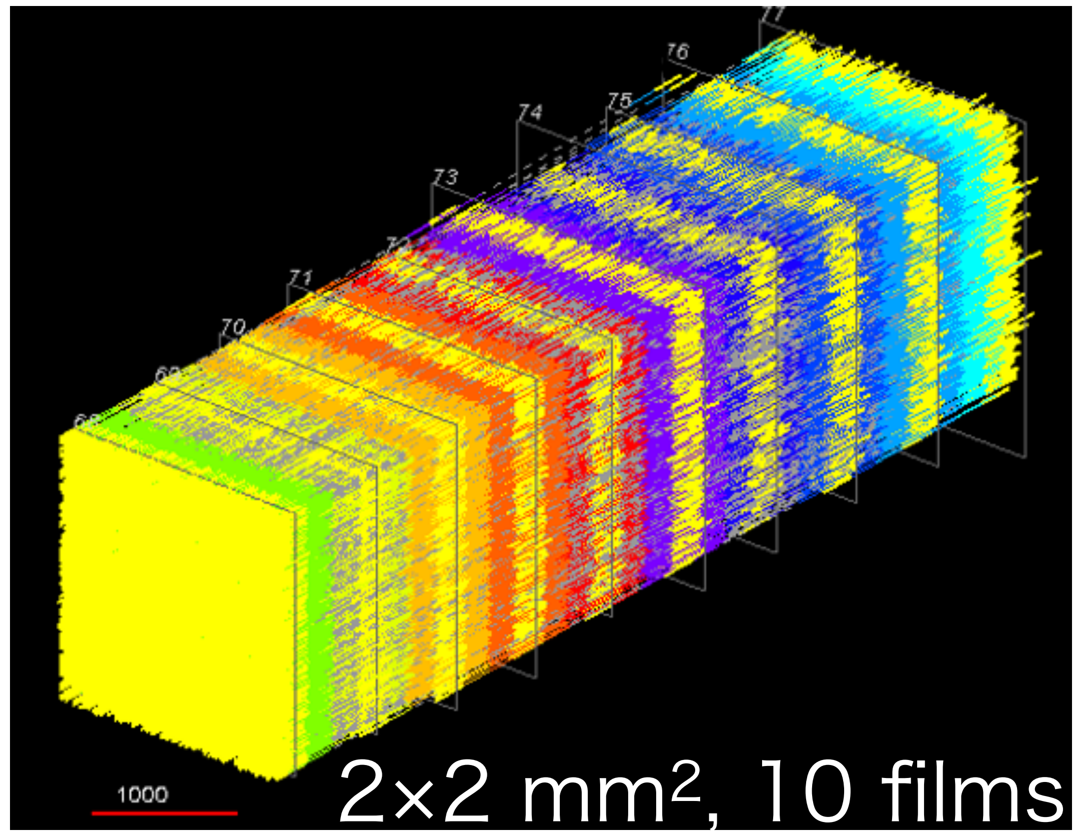
Pilot Run (2018)



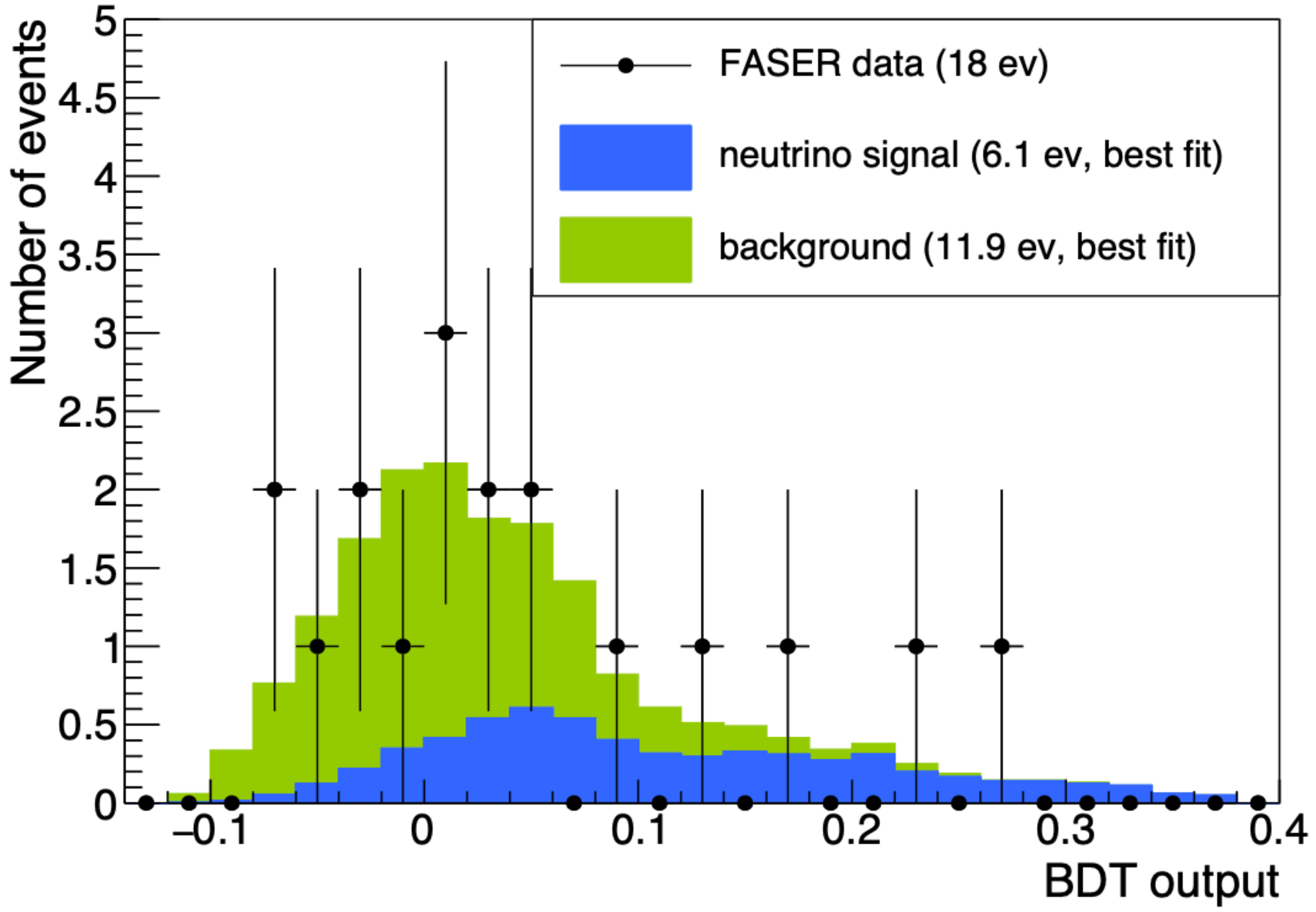
Detector at TI18 in 2018



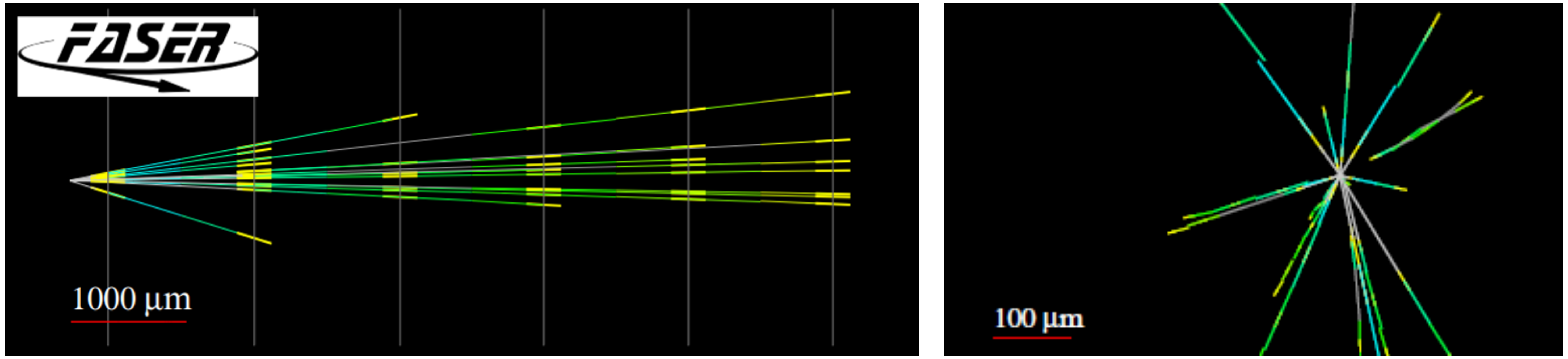
Reconstructed tracks



BDT analysis result



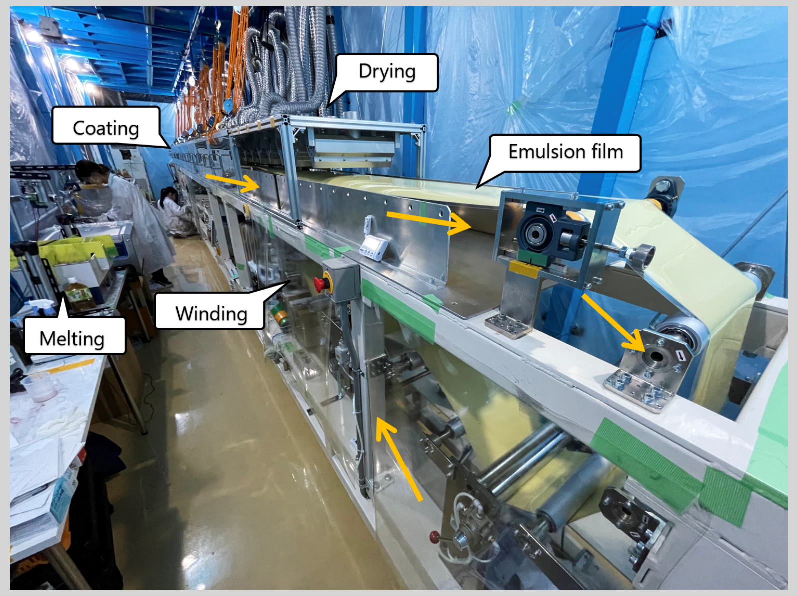
Neutrino candidate



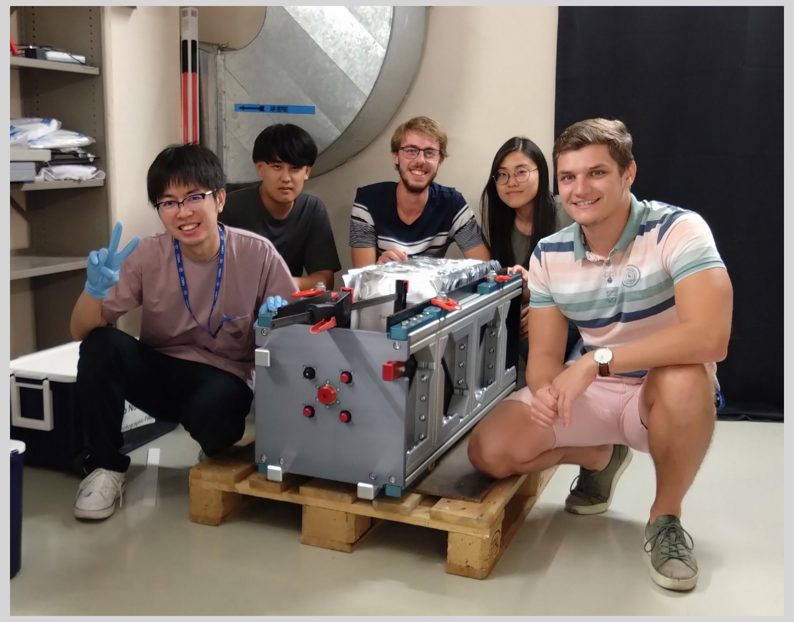
- Pilot run in 2018, 1 month exposure (12.2 fb^{-1})
- Statistical significance: 2.7 σ from null hypothesis
- Phys. Rev. D 104, L091101

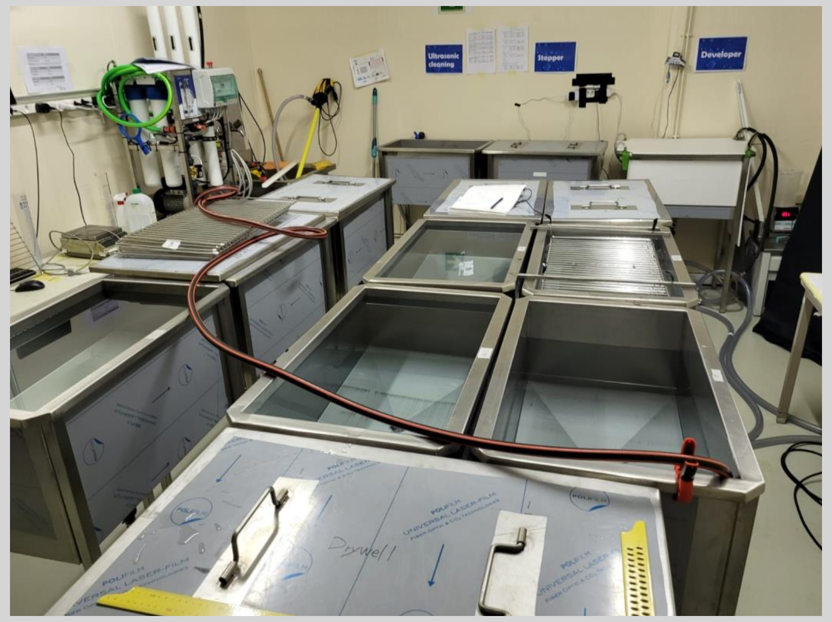
FASERν Emulsion Detector

Japan

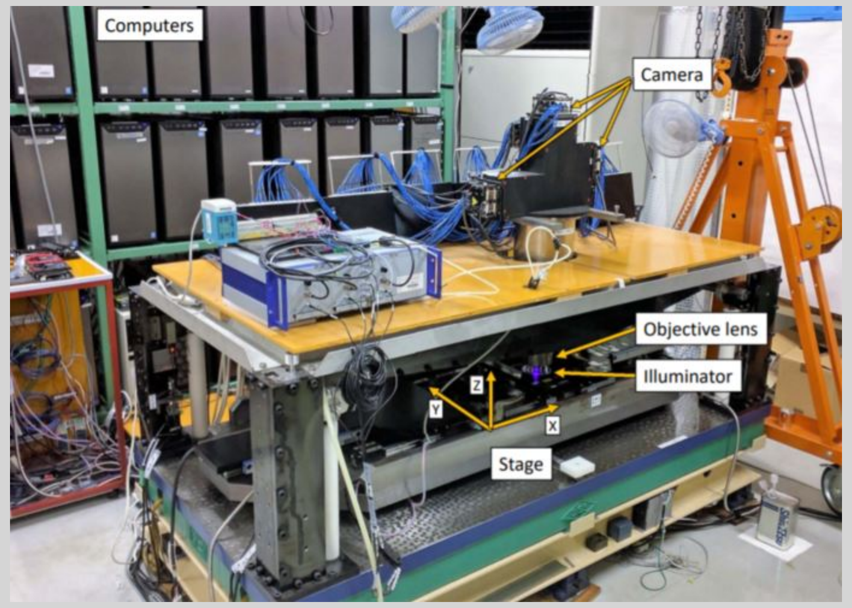


CERN





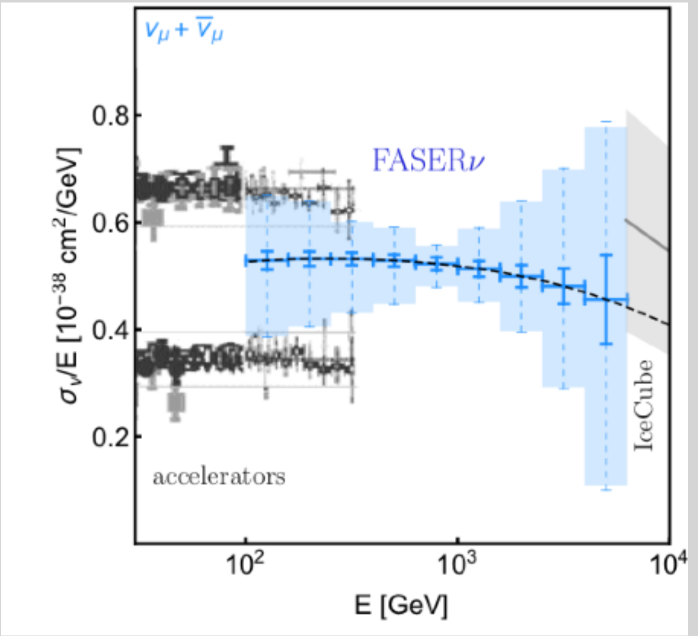
Japan

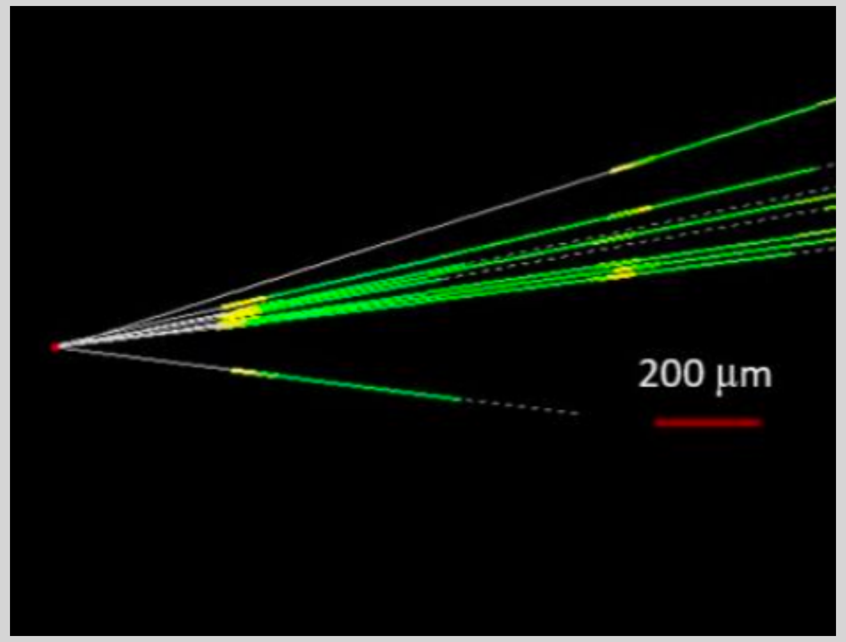


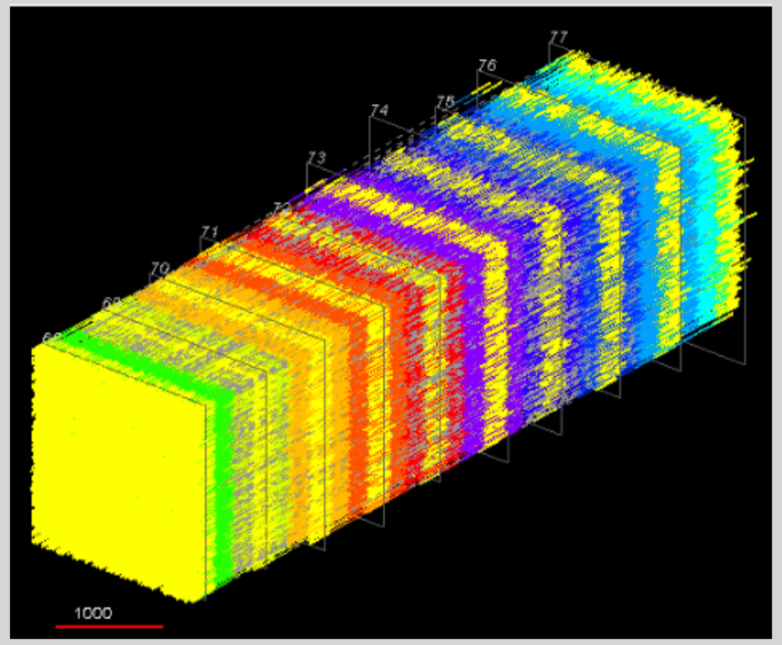
Film production → Assembly → Exposure → Disassembling → Development → Readout

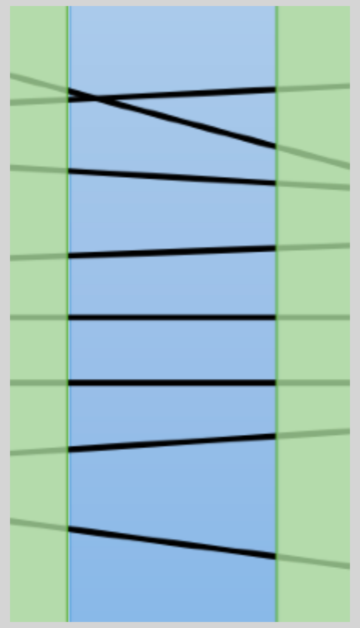
Offline analysis

Alignment → Track reconstruction → Vertex reconstruction → Physics analysis

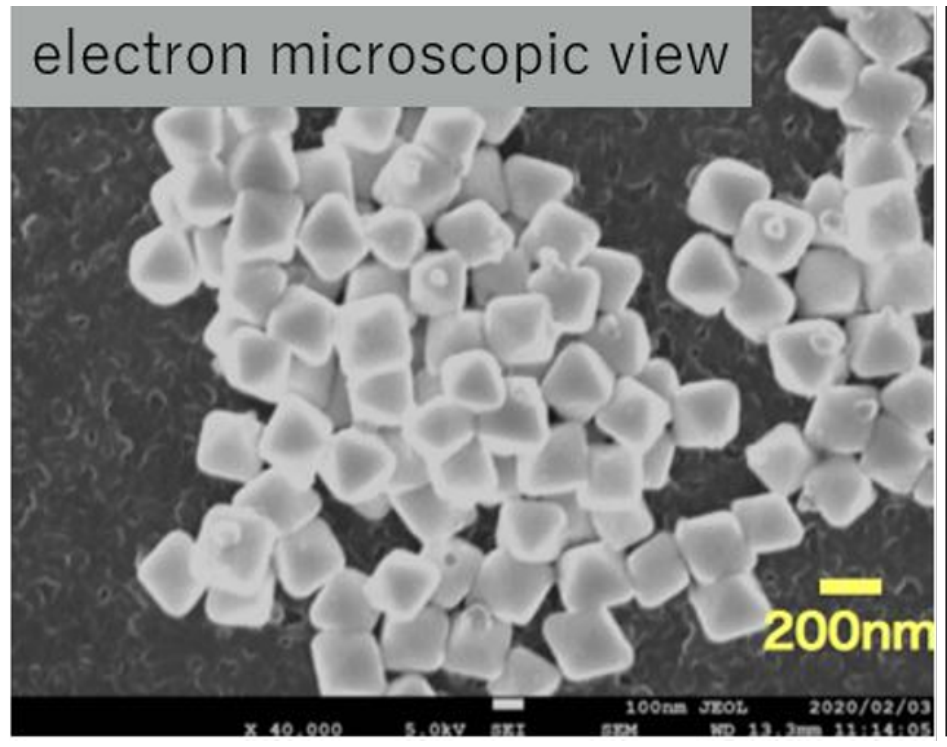


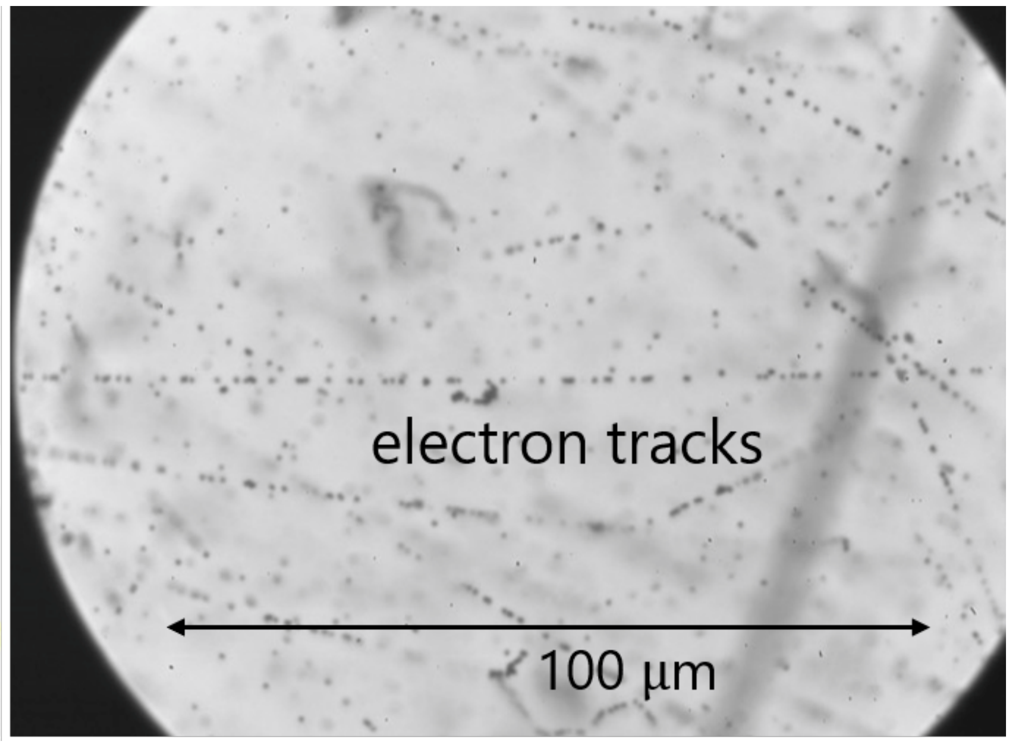


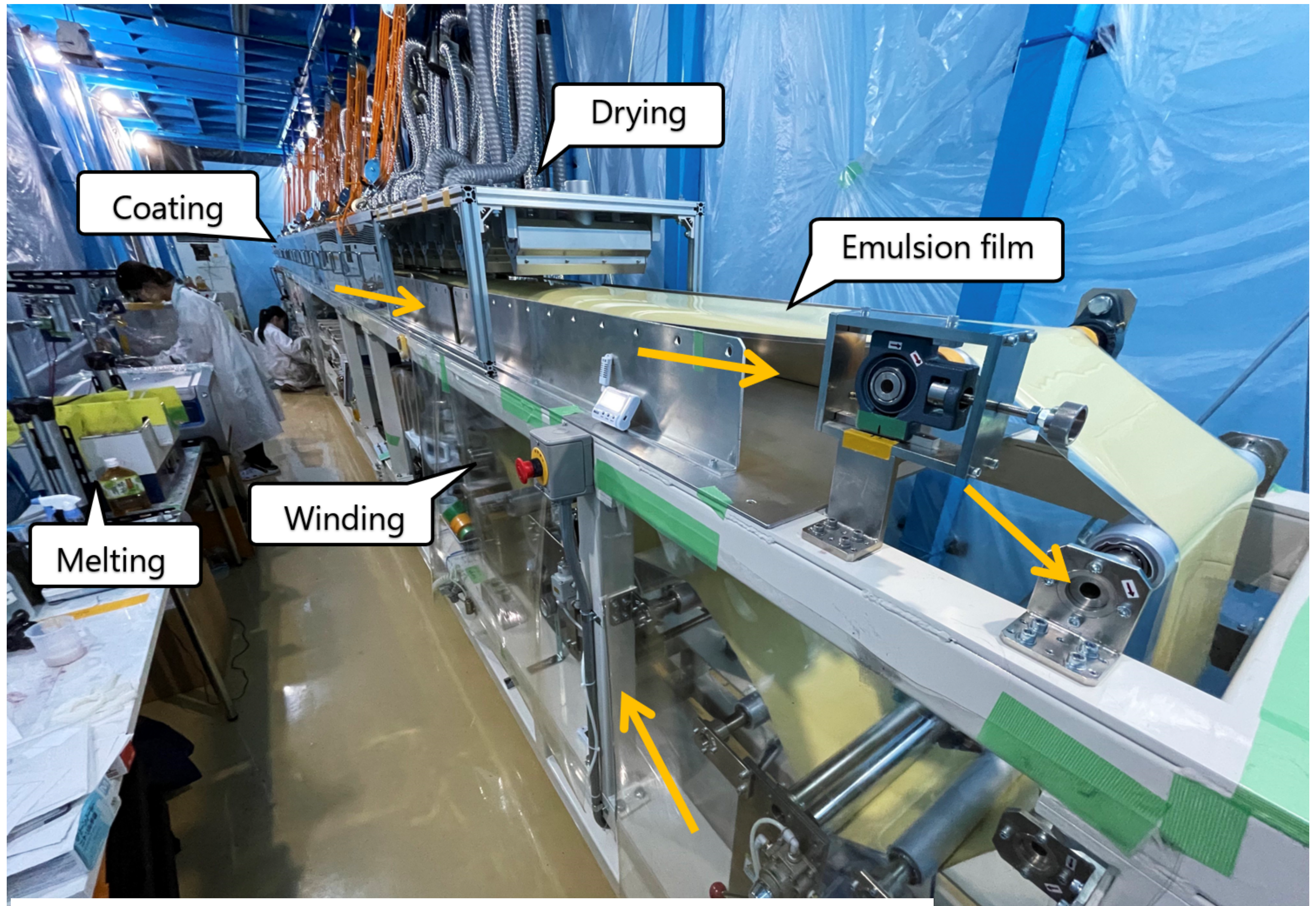




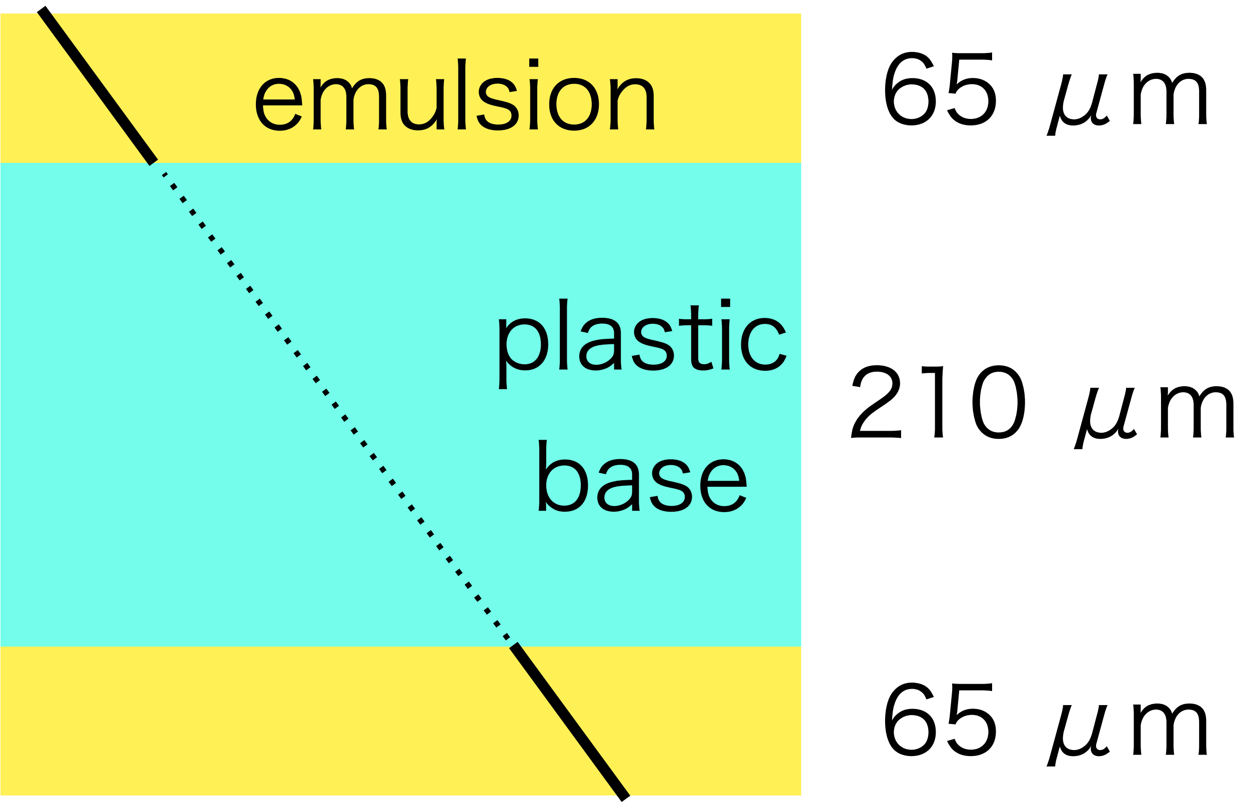
Film Production







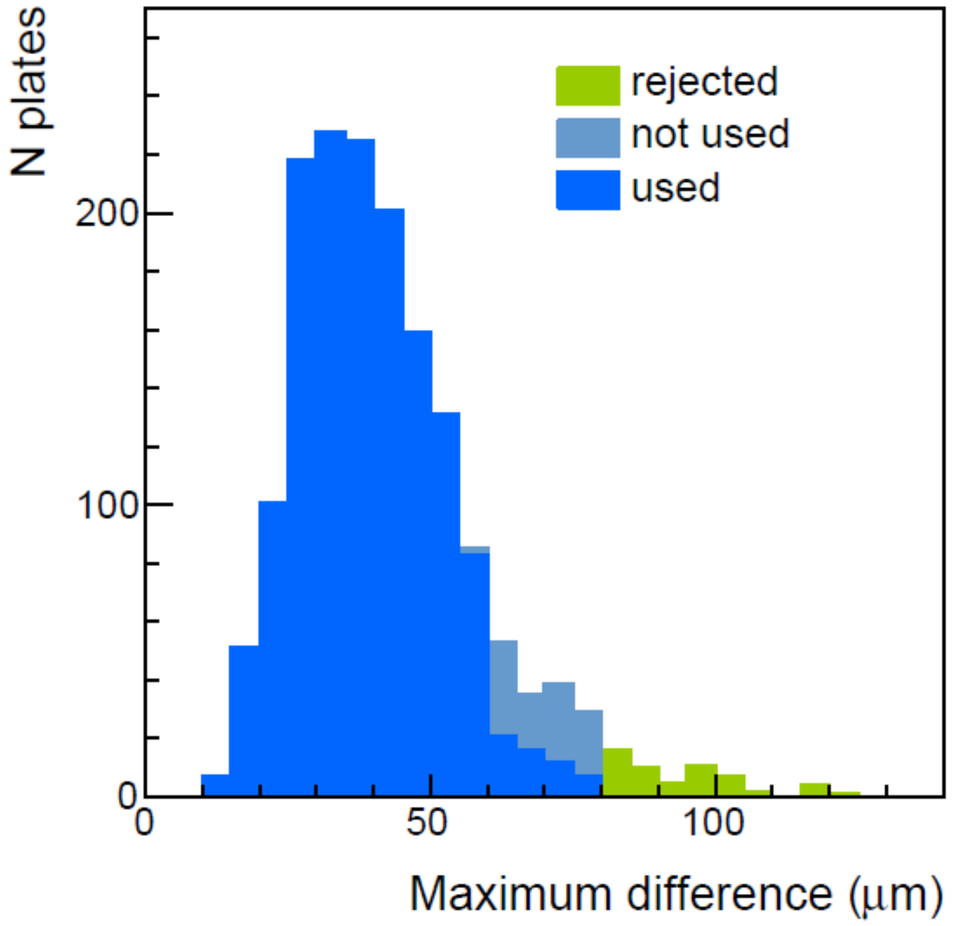
Emulsion film coating system

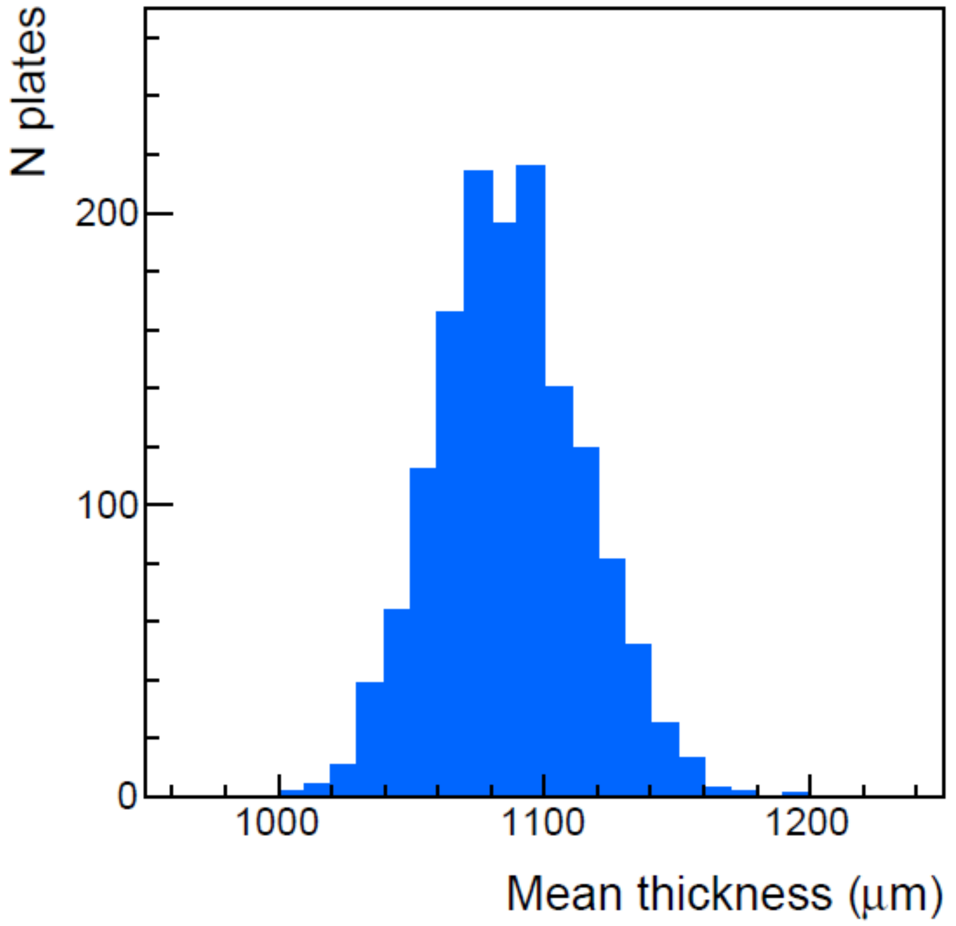


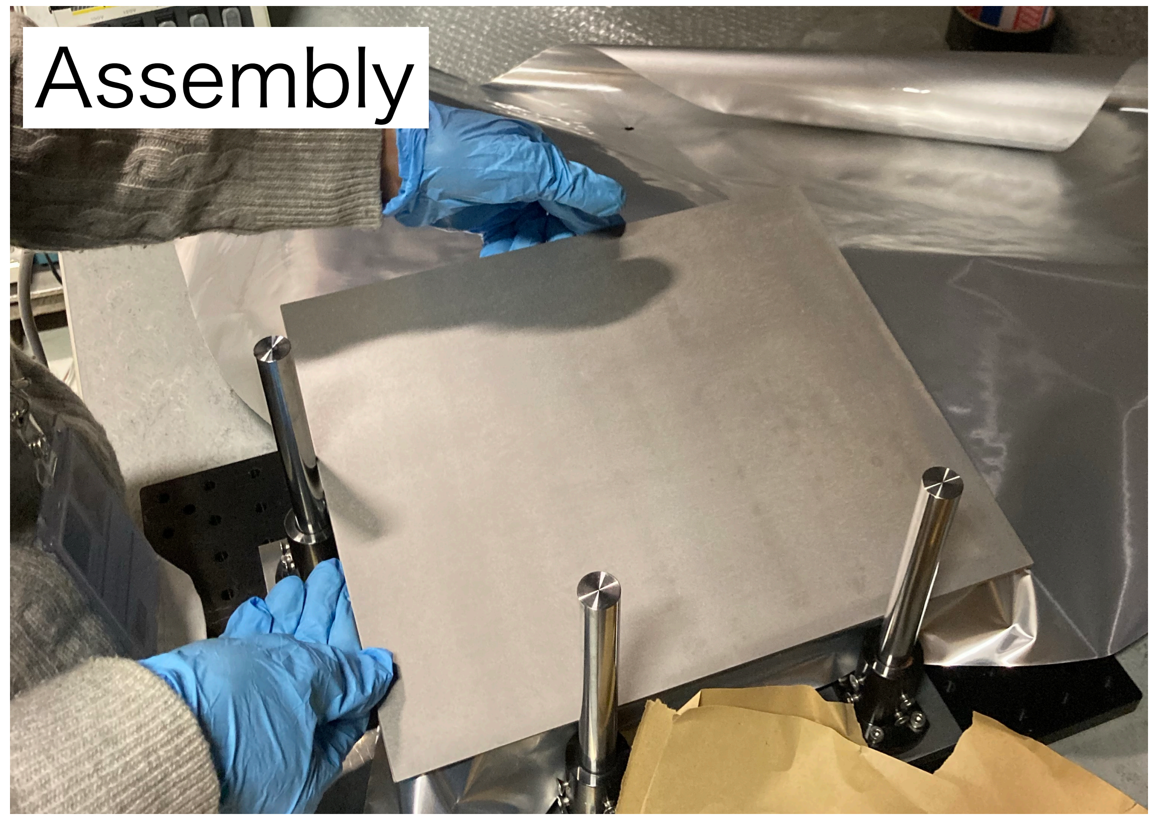
- 200 nm diameter crystals
- Double sided emulsion coating
- Total area of 730 films: ~55 m^2
- Produce emulsion gel and film a few months before module assembly

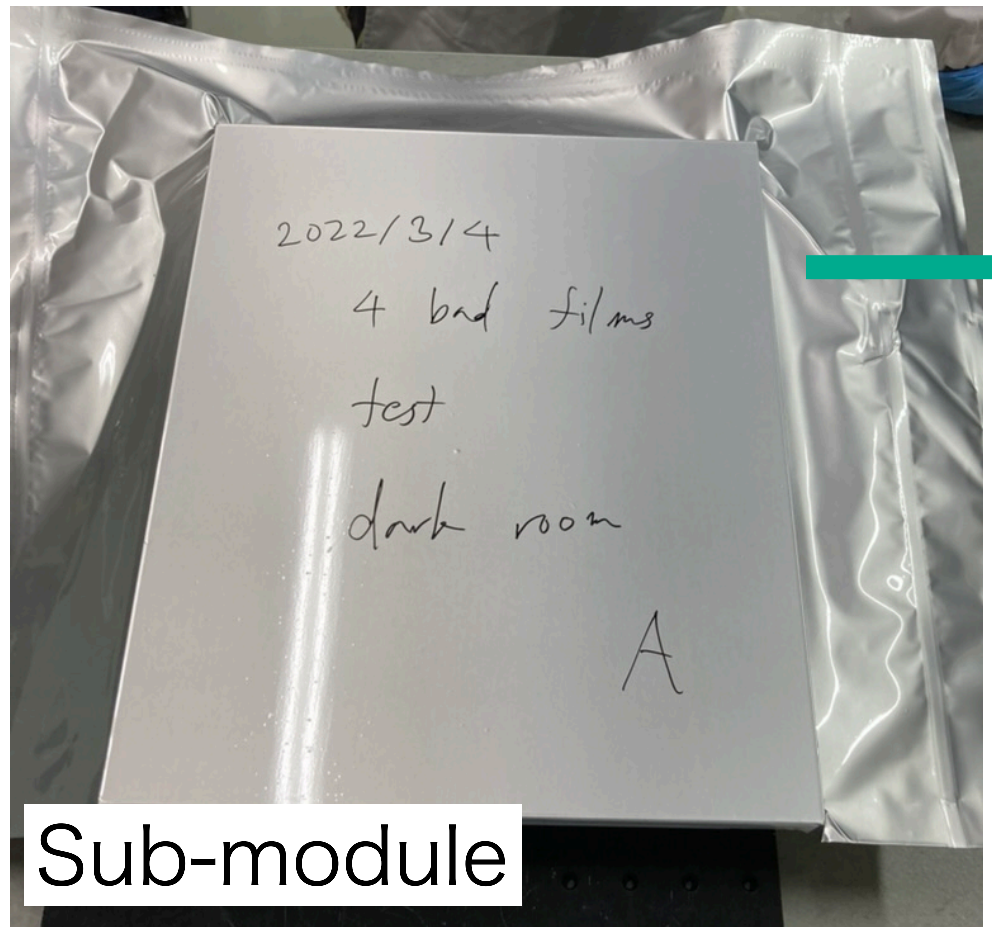
Assembly

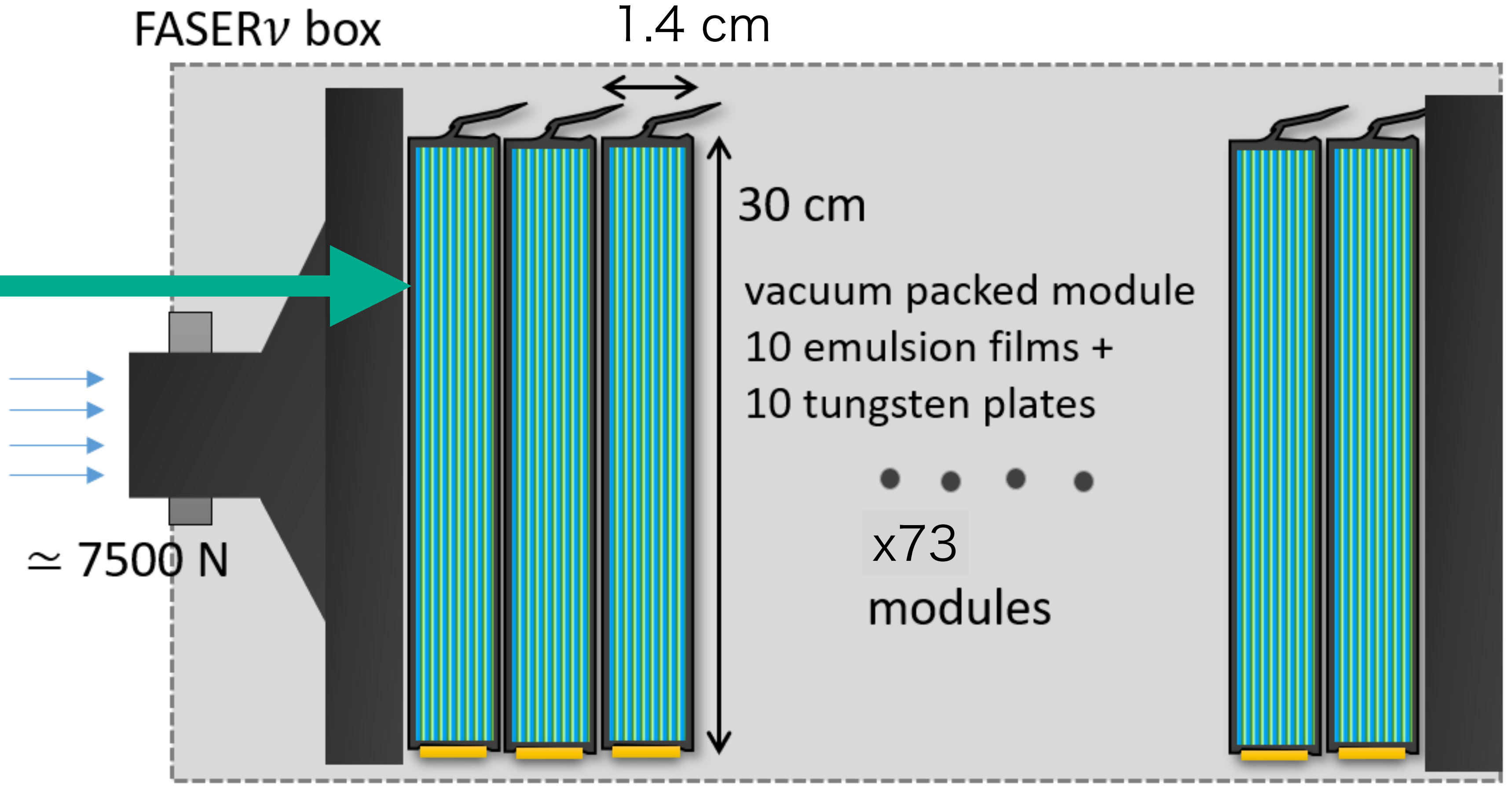
Tungsten measurement/washing

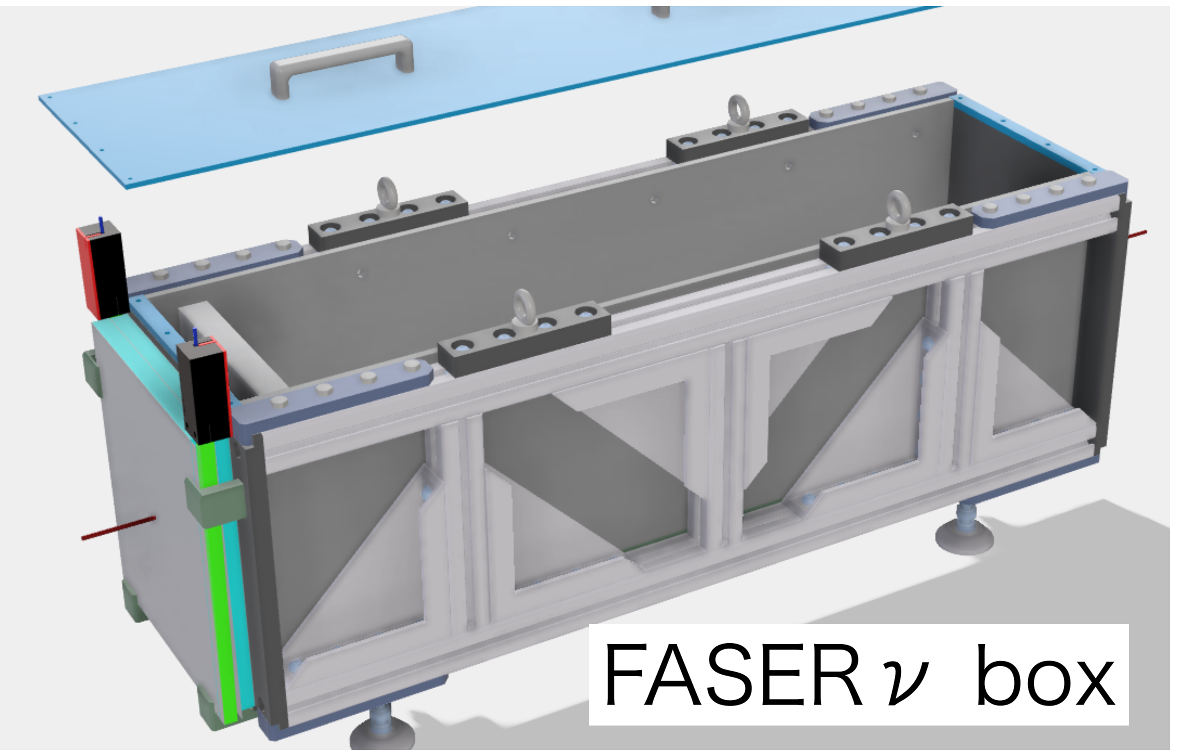






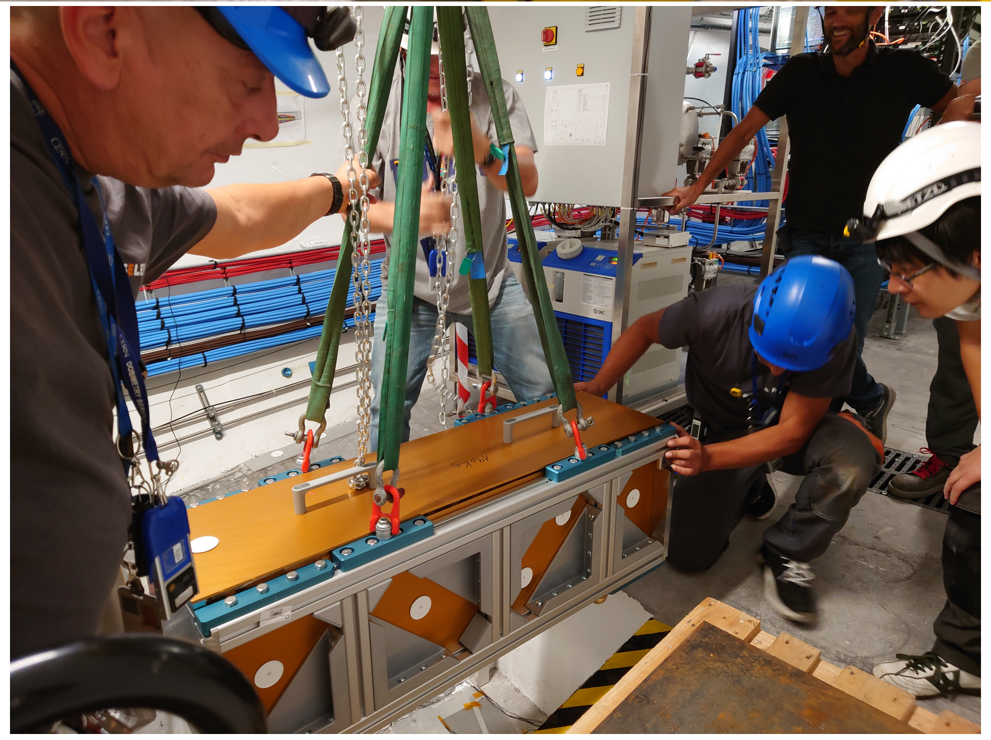


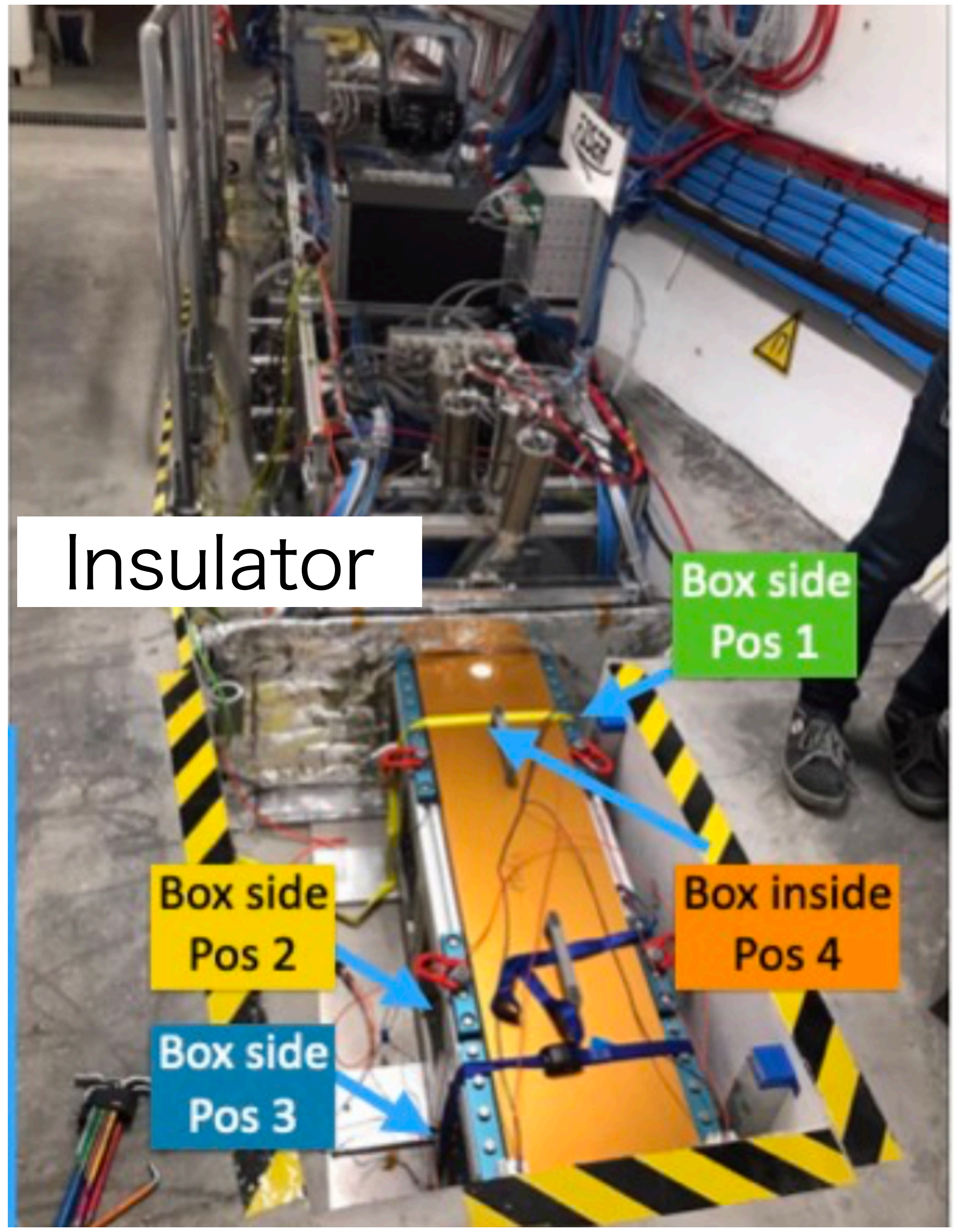




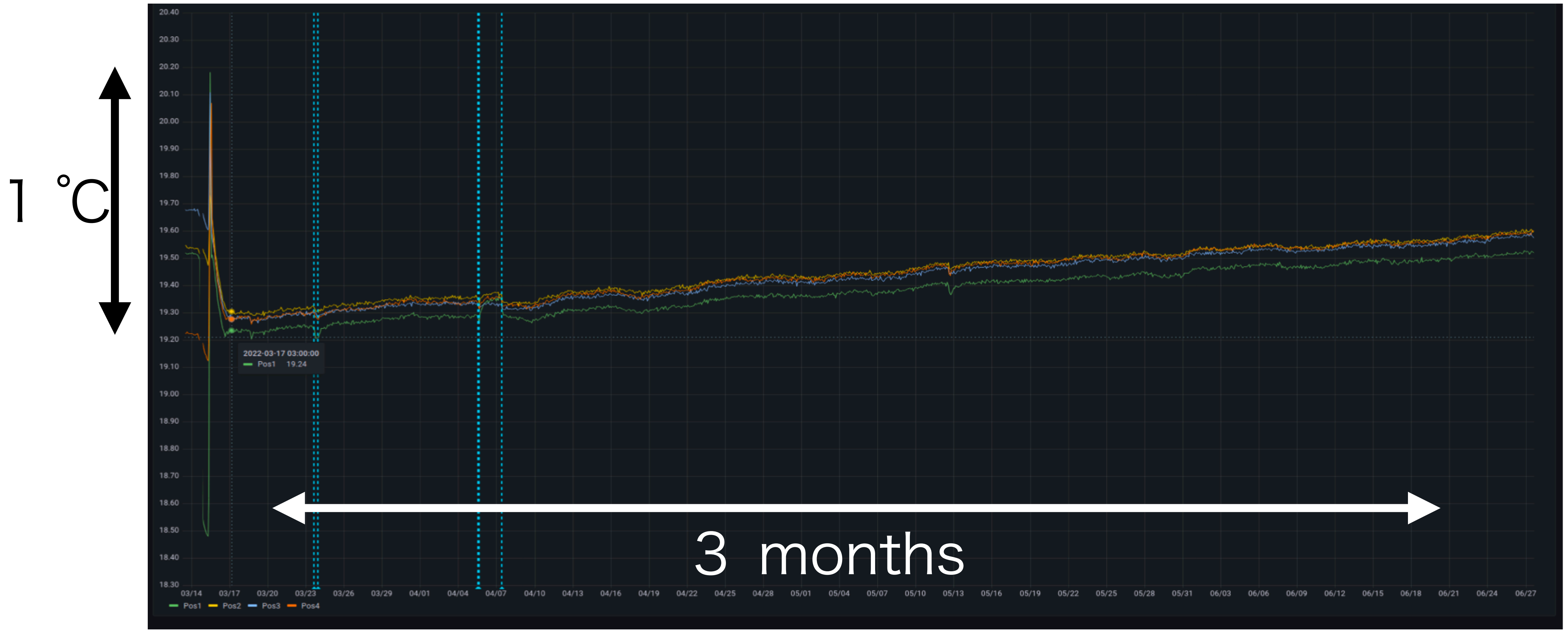
- Screening of tungsten target plates
  - Require thickness difference < 80 μm in each plate (1562/1622 plates)
- Sub-module: vacuum packed 10 films + 10 tungsten plates
- Apply external force (equivalent to 1 bar) to 73 sub-modules in the FASERν box

Installation and Data-taking





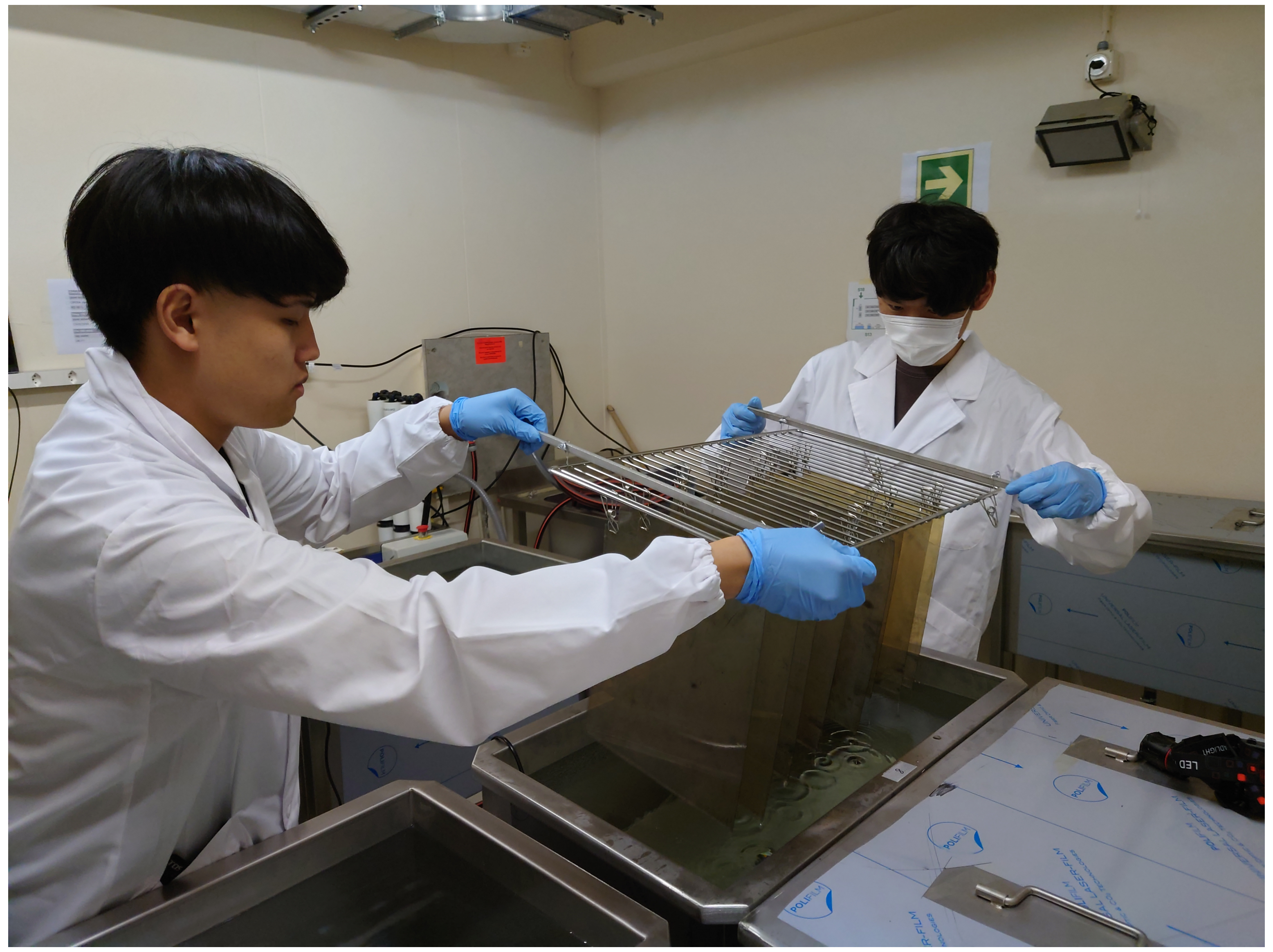
- In order to keep the track multiplicity in the detector manageable, the detector is exchanged during LHC Technical Shutdowns (3 times per year)
- The measured multiplicity corresponds to ~2.3×10^{4} cm^{-2}/fb^{-1}

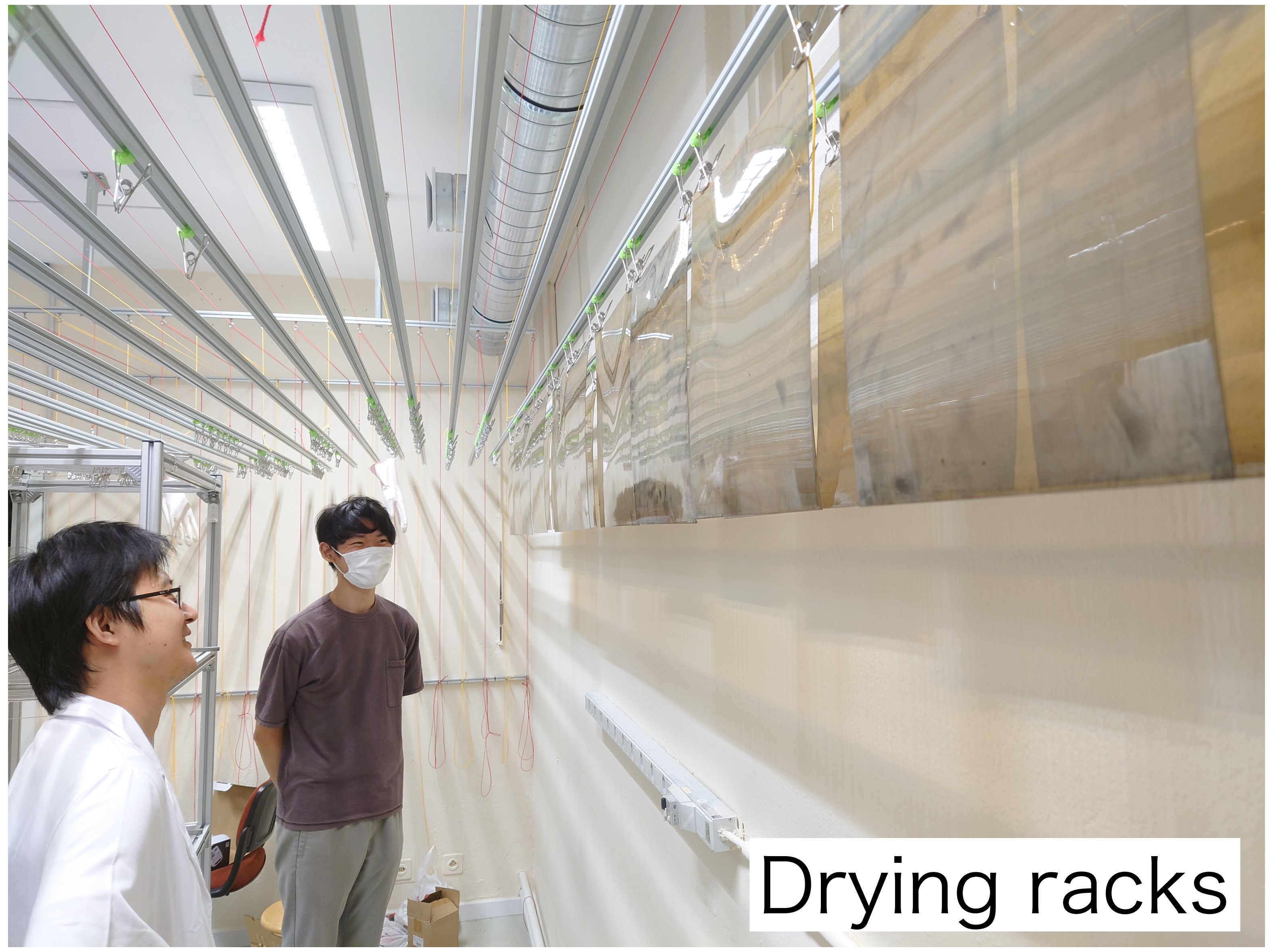


- Installed a thermal insulator between the FASERν module and IFT
- Temperature monitoring
  - ~0.1 ℃/1 month variation will not affect to the position alignment of the emulsion films

Development

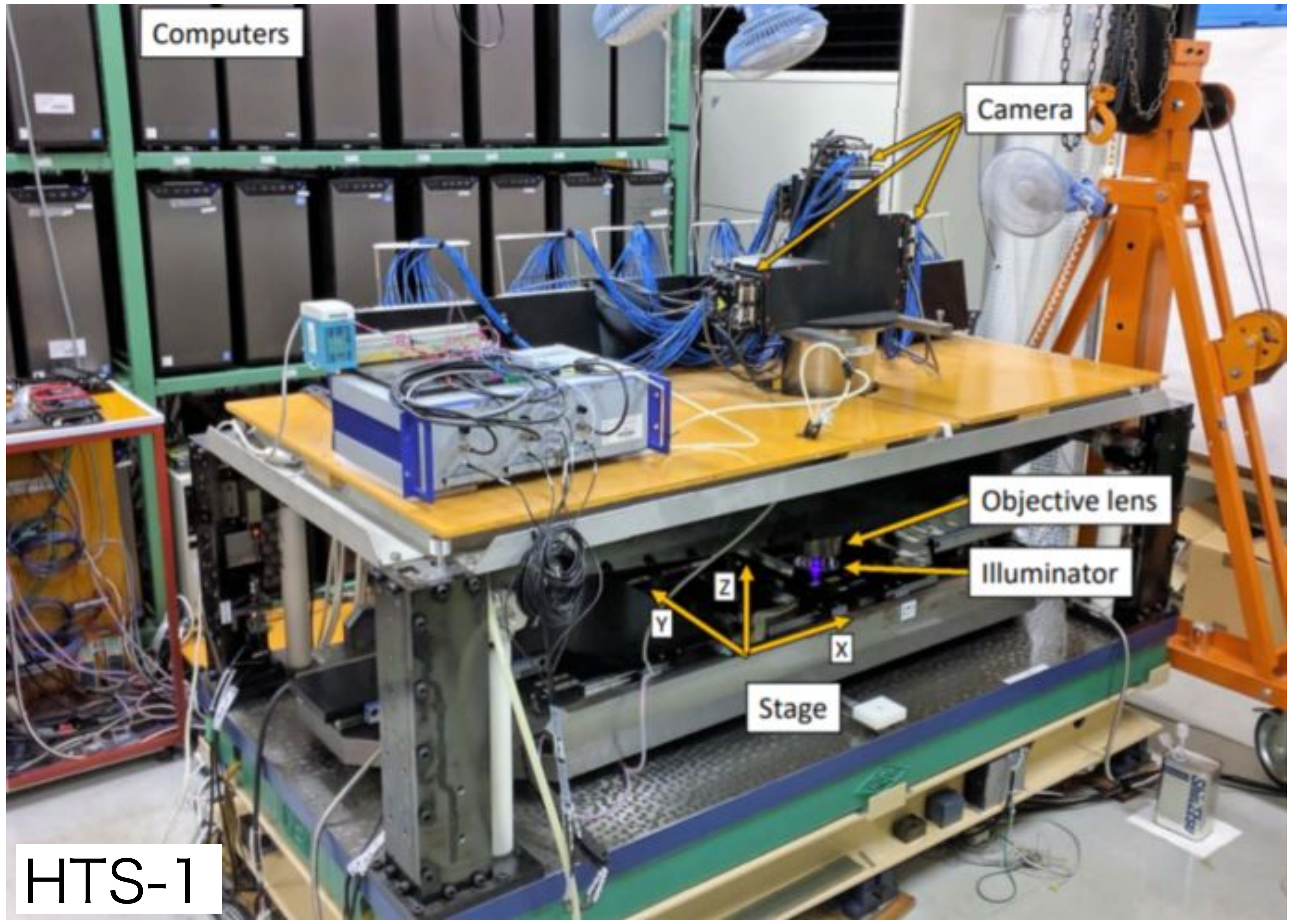

Development chains

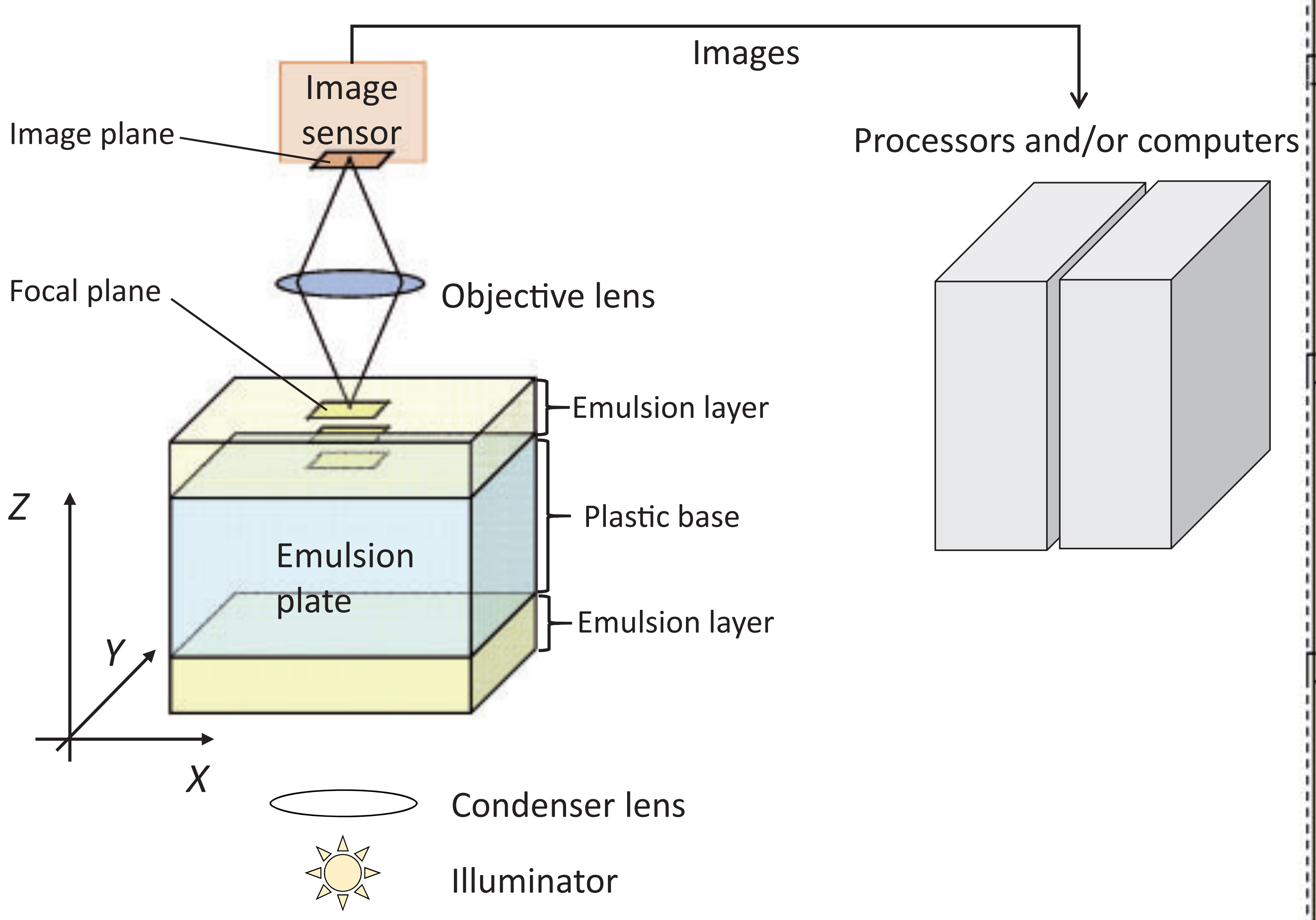


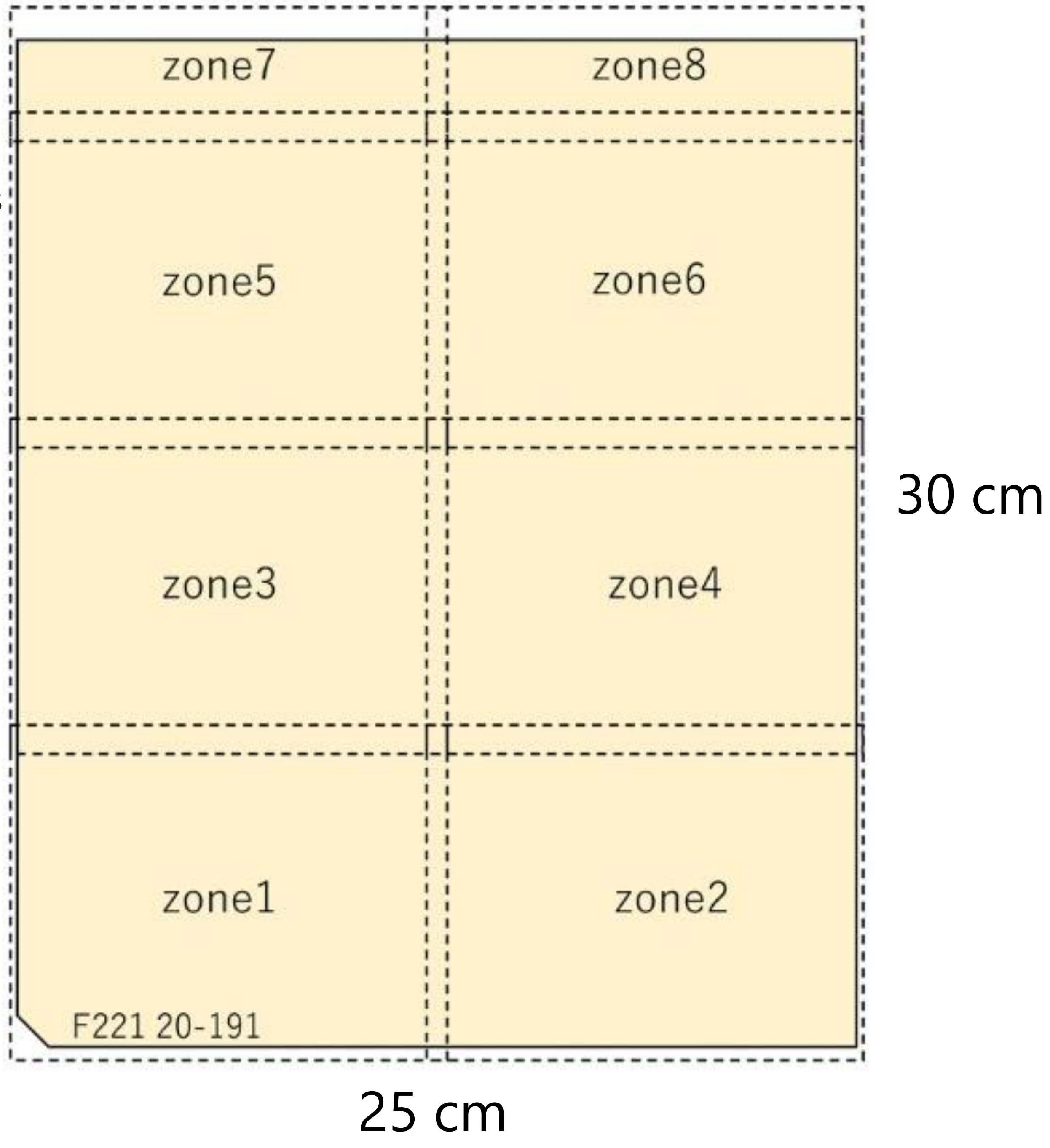

Drying racks

- Installed new development chains and drying racks at CERN darkroom facility
- 10-12 days to complete 730 films
- Developed 2 FASERν modules so far

Readout

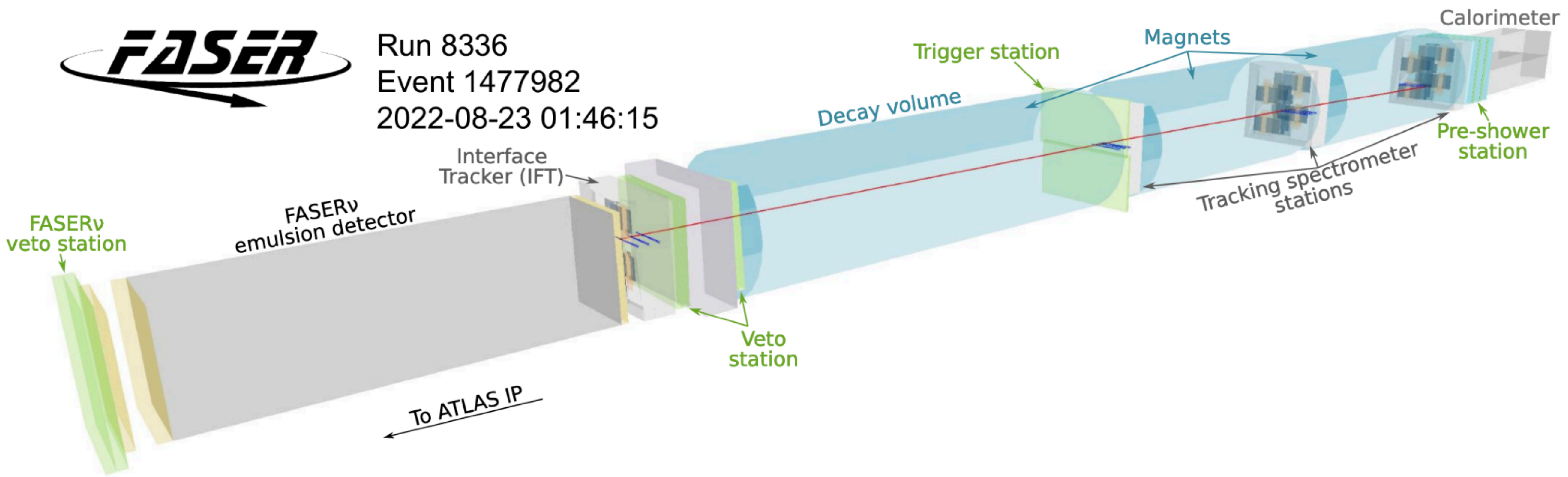


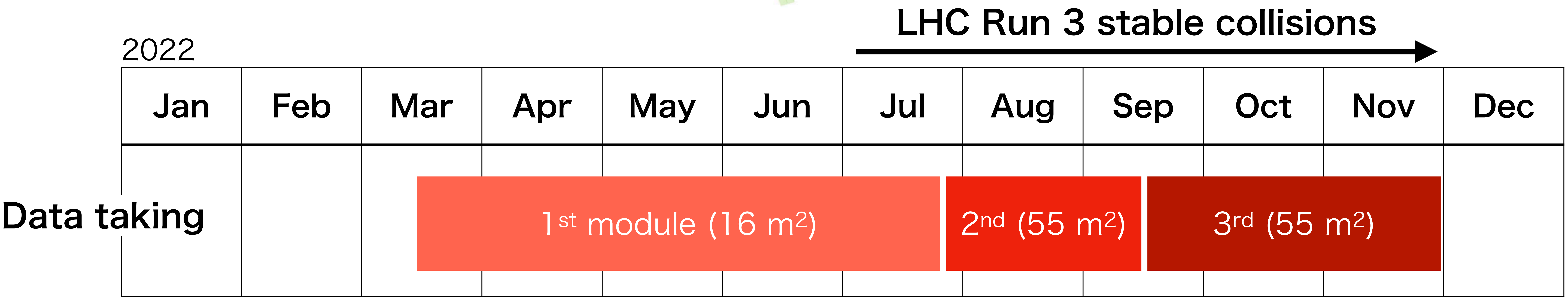




- Transport films to Japan after development
- Readout by Hyper Track Selector-1 (HTS-1)
- Field of view: 5.1 mm × 5.1 mm
- ~3 months to readout 1 FASER ν module (5 hours/day)
- Fast enough to readout in parallel with data taking

Run 3 (2022)

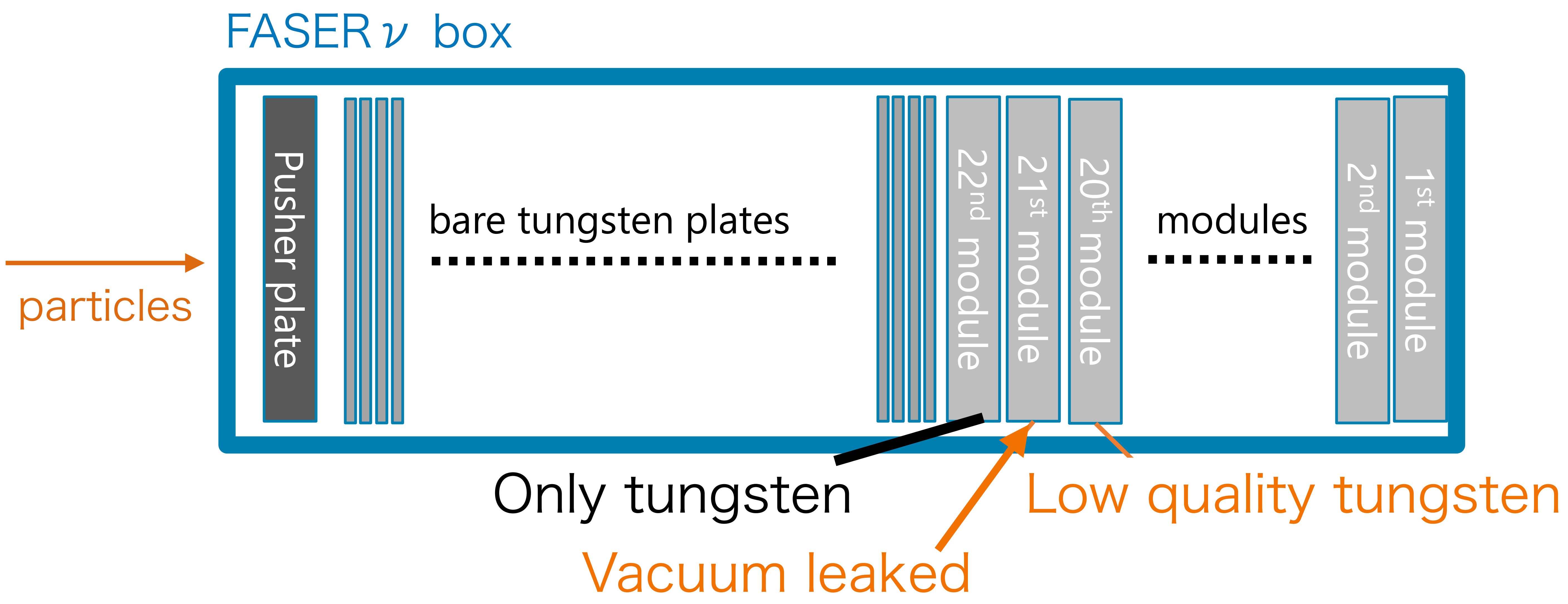




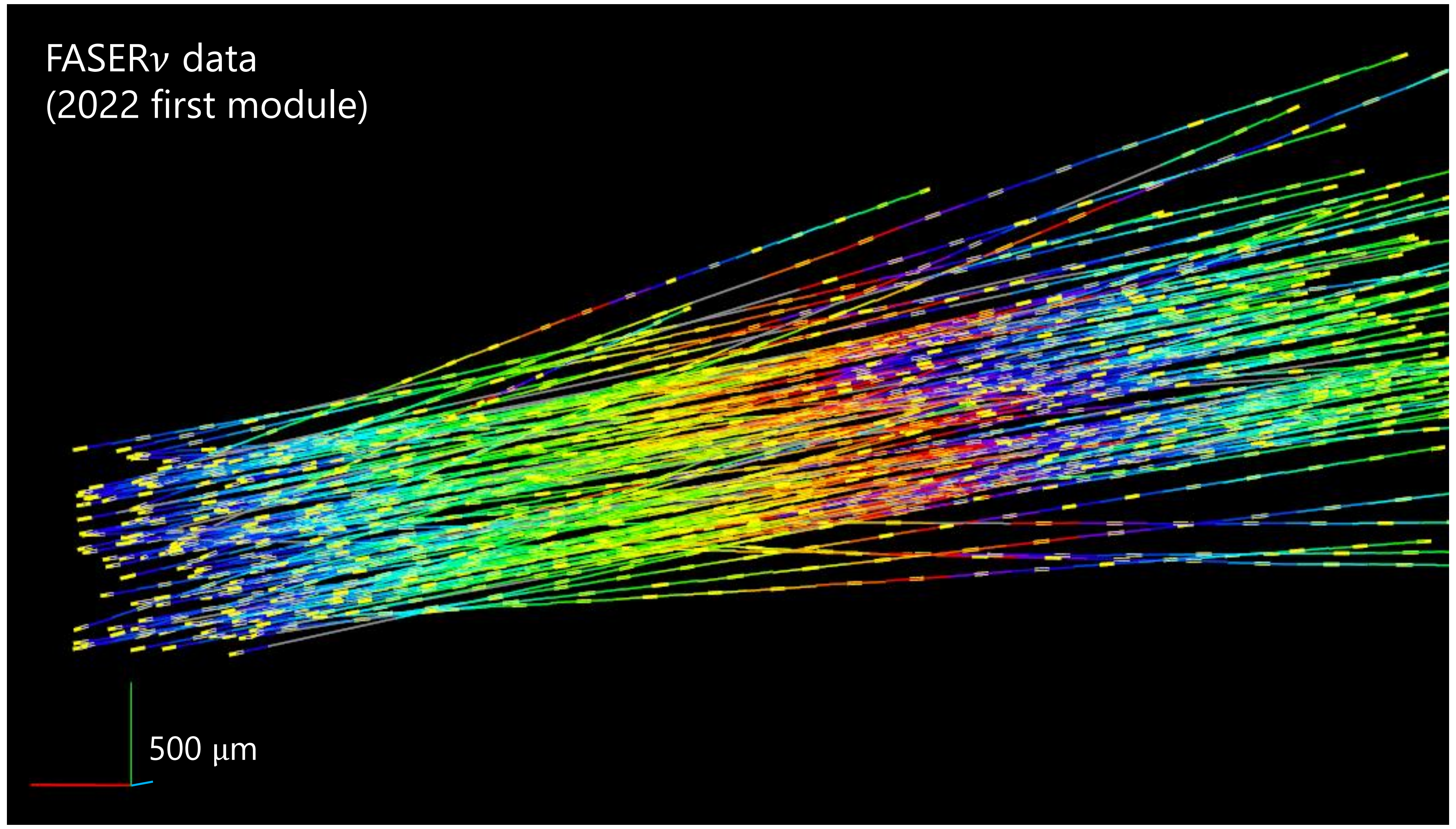
		Integrated luminosity per module (/fb)	N ν int. expected
2022 1st emulsion	Mar 15 – Jul 26	0.5	25 ×29%
2022 2nd emulsion	Jul 26 – Sep 13	10.6	530
2022 3rd emulsion	Sep 13 – Nov 29	(~20)	(~1000)

- Assembled 3 modules in 2022
- The 2nd module should have enough statistics to observe neutrinos!

1st FASER ν Module

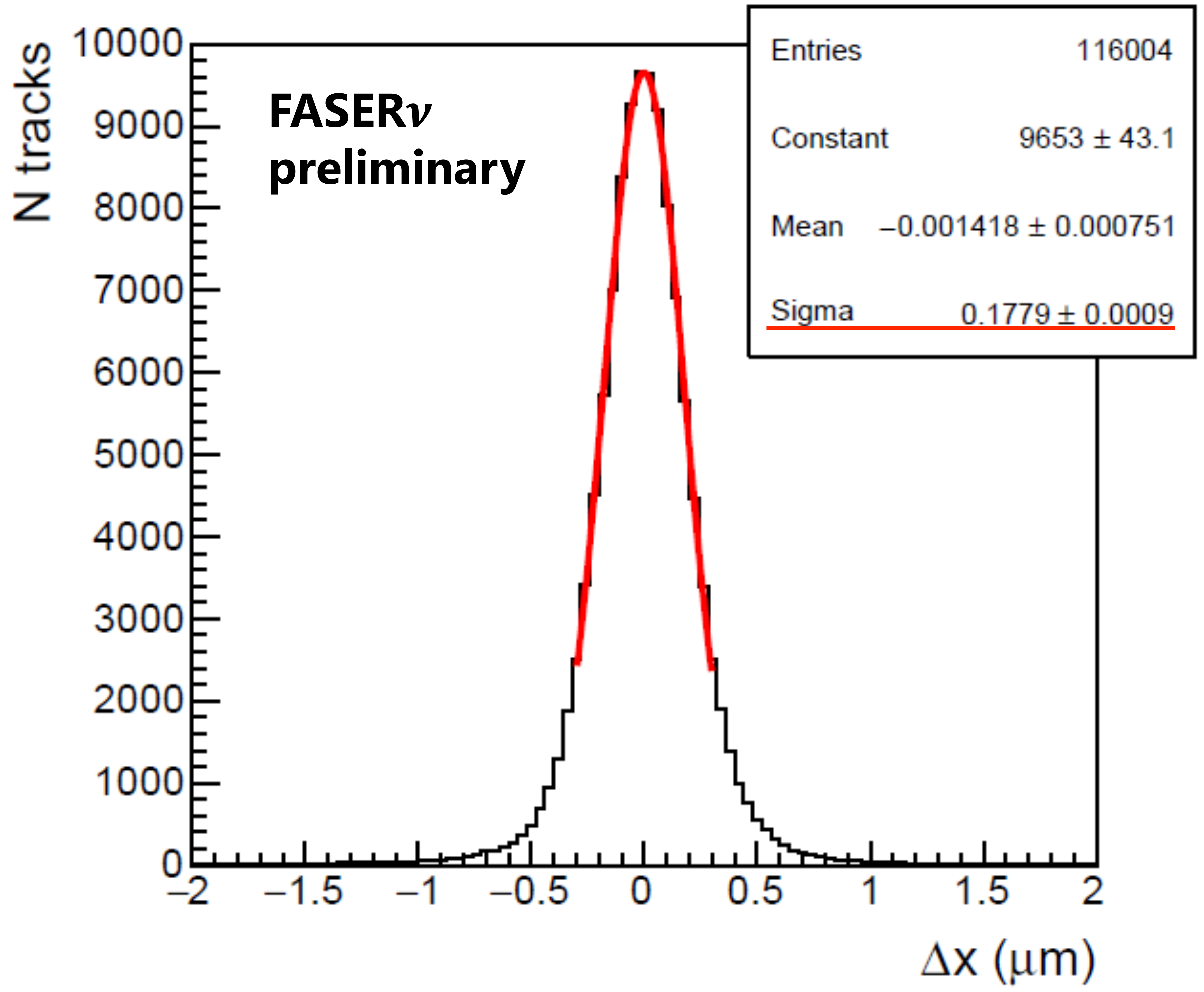


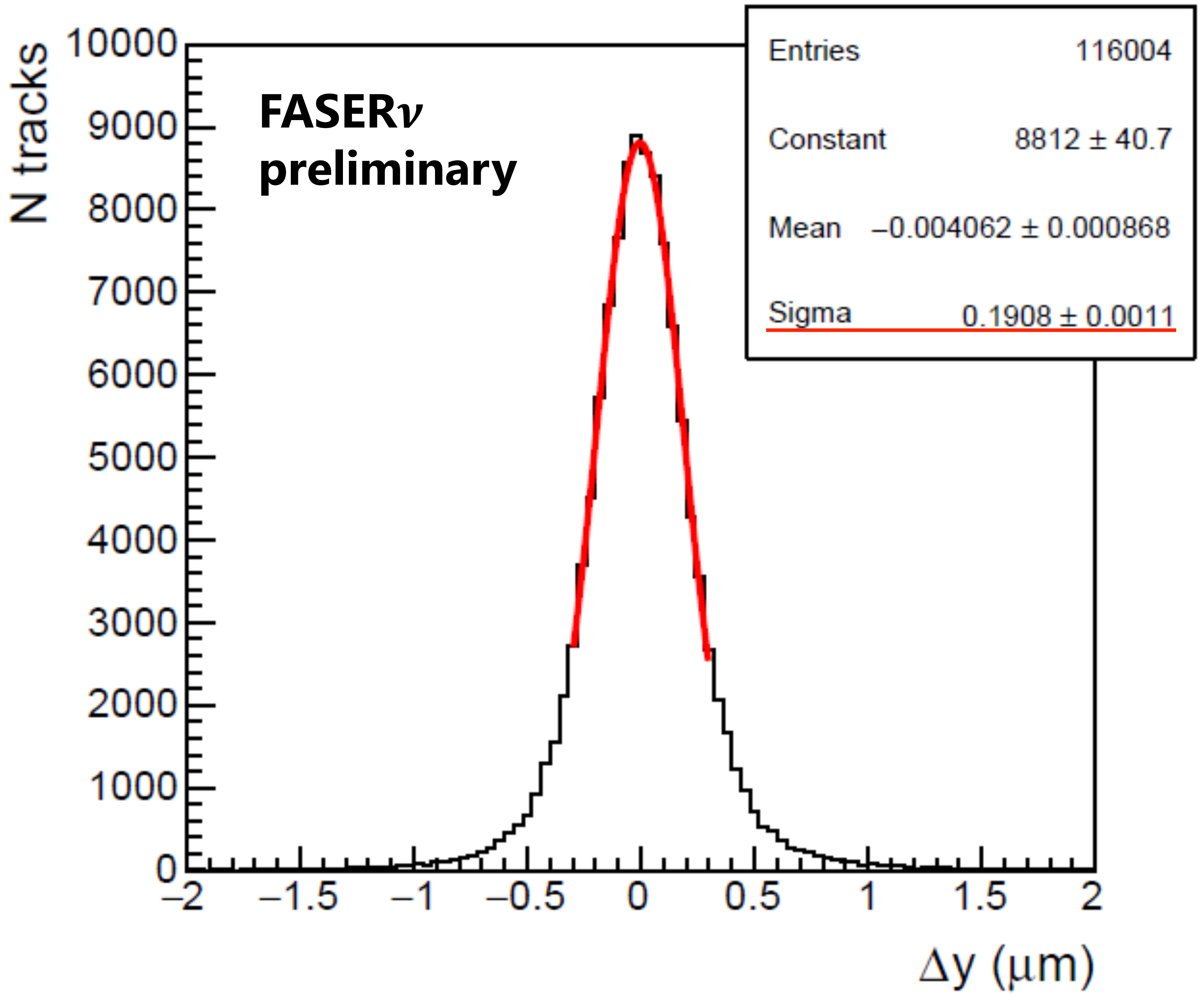
Reconstructed tracks (20 emulsion films)



- Installed the 1st FASER ν module on March for detector performance study
  - Integrated luminosity: 0.5 fb^{-1}
  - 21 sub-modules (**29%** of full detector)
  - 2 special sub-modules for alignment study
- Performed development on 30th-31st of July. Film scan is ongoing
- Reconstructed tracks in 20 emulsion films look very good
- **Successfully performed the whole sequence of the 1st FASER ν detector**

Position Accuracy

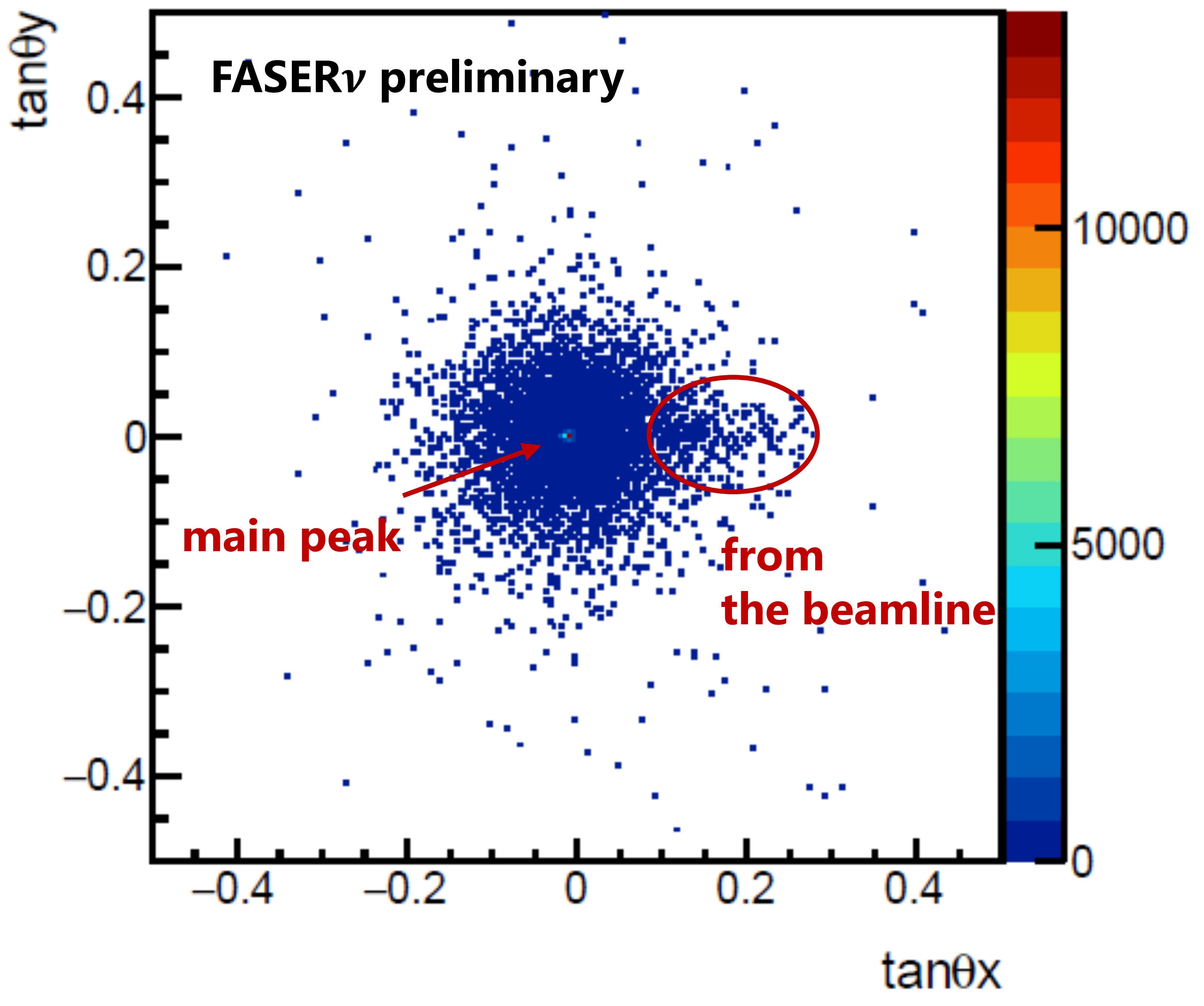


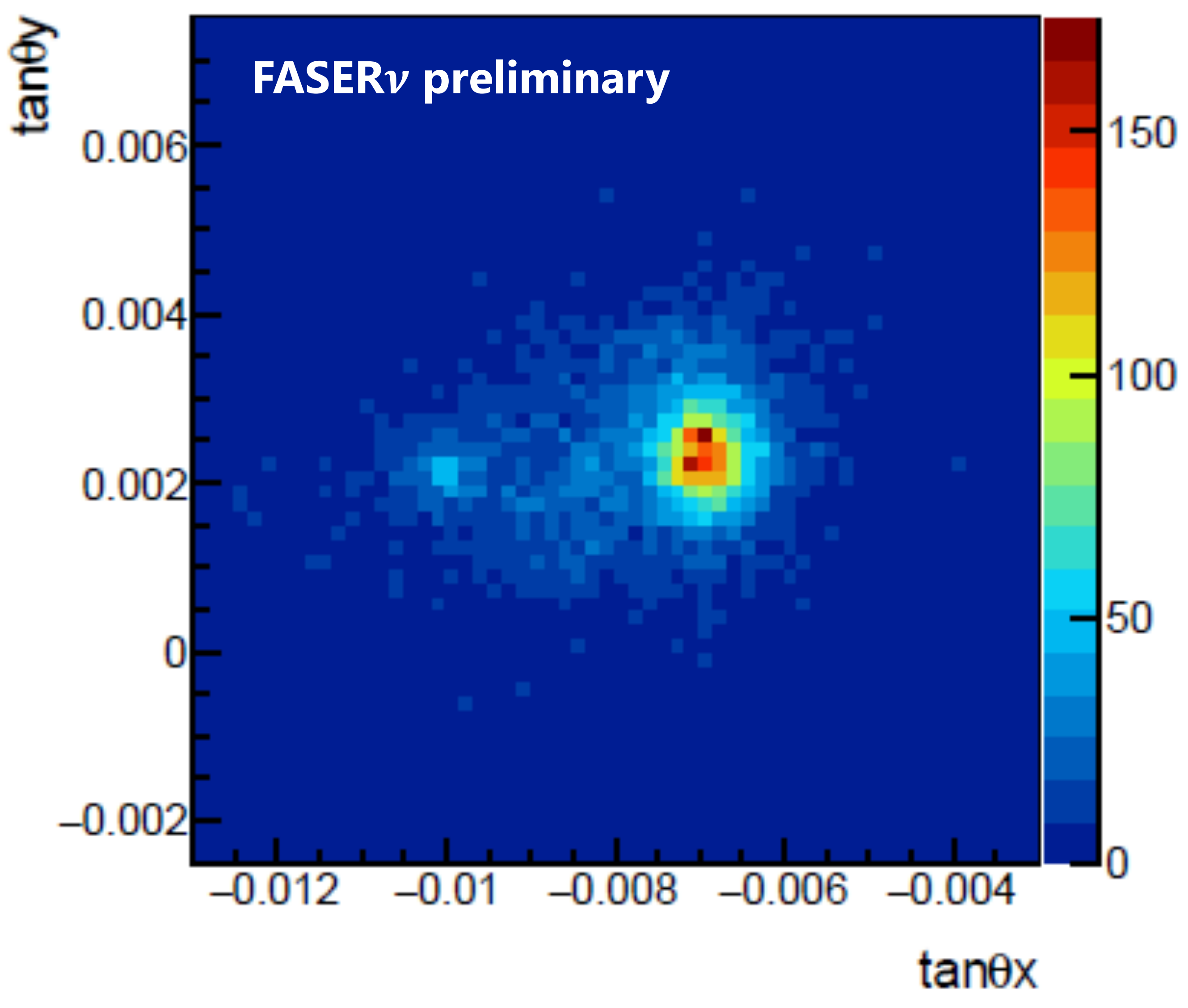


- Position deviation between hits and the straight-line fits to the reconstructed tracks
- Dataset: most downstream 10 emulsion films of the 1st FASERν module
- Observed **~0.2 μm position accuracy** with dedicated alignment using high momentum muon tracks

Angular Distributions

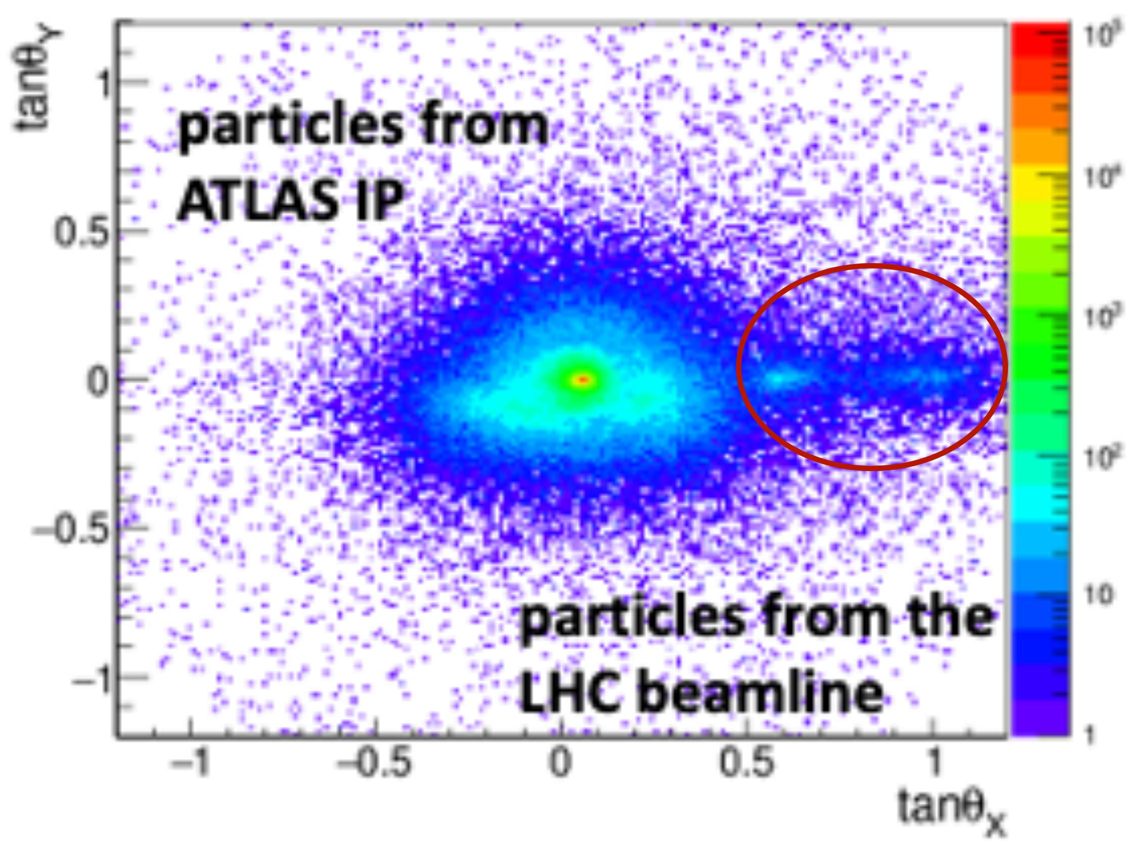
1st module (2022)

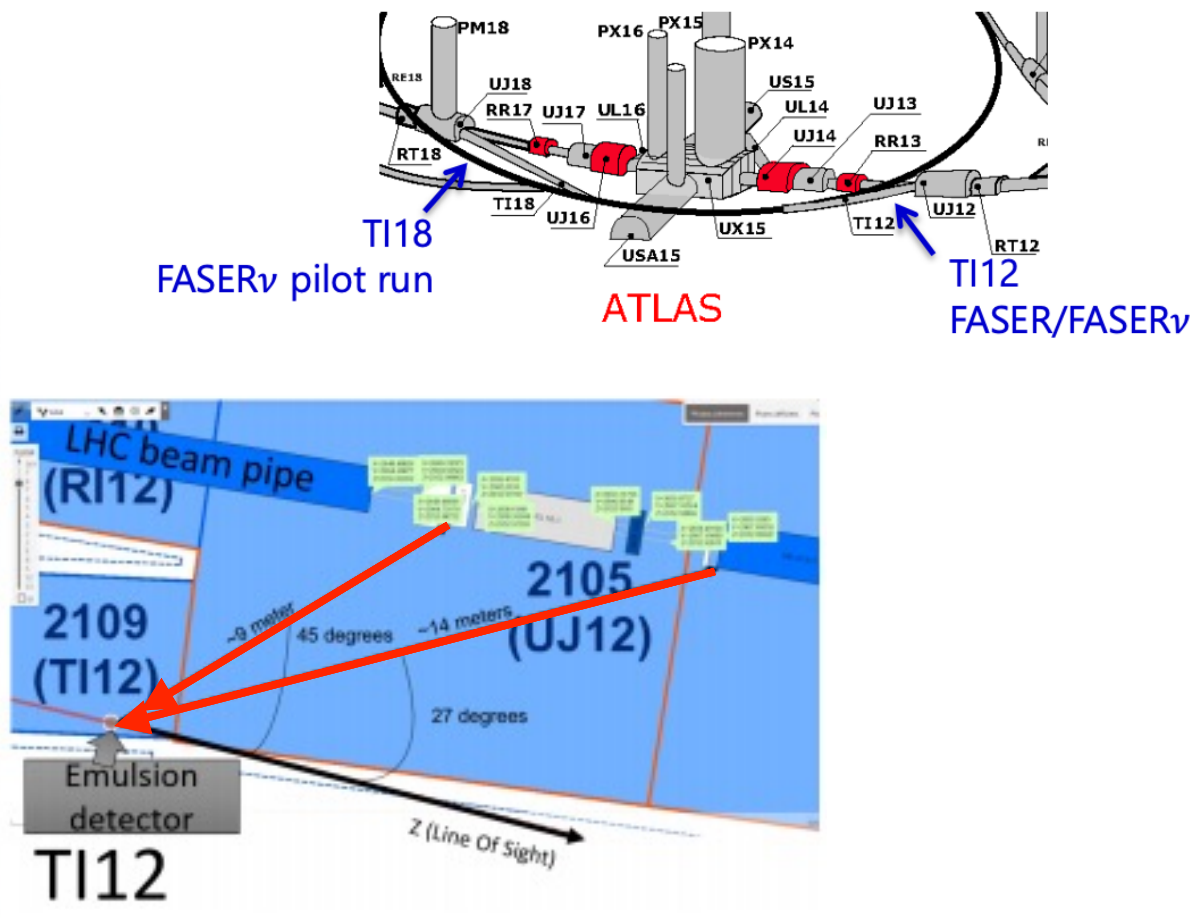




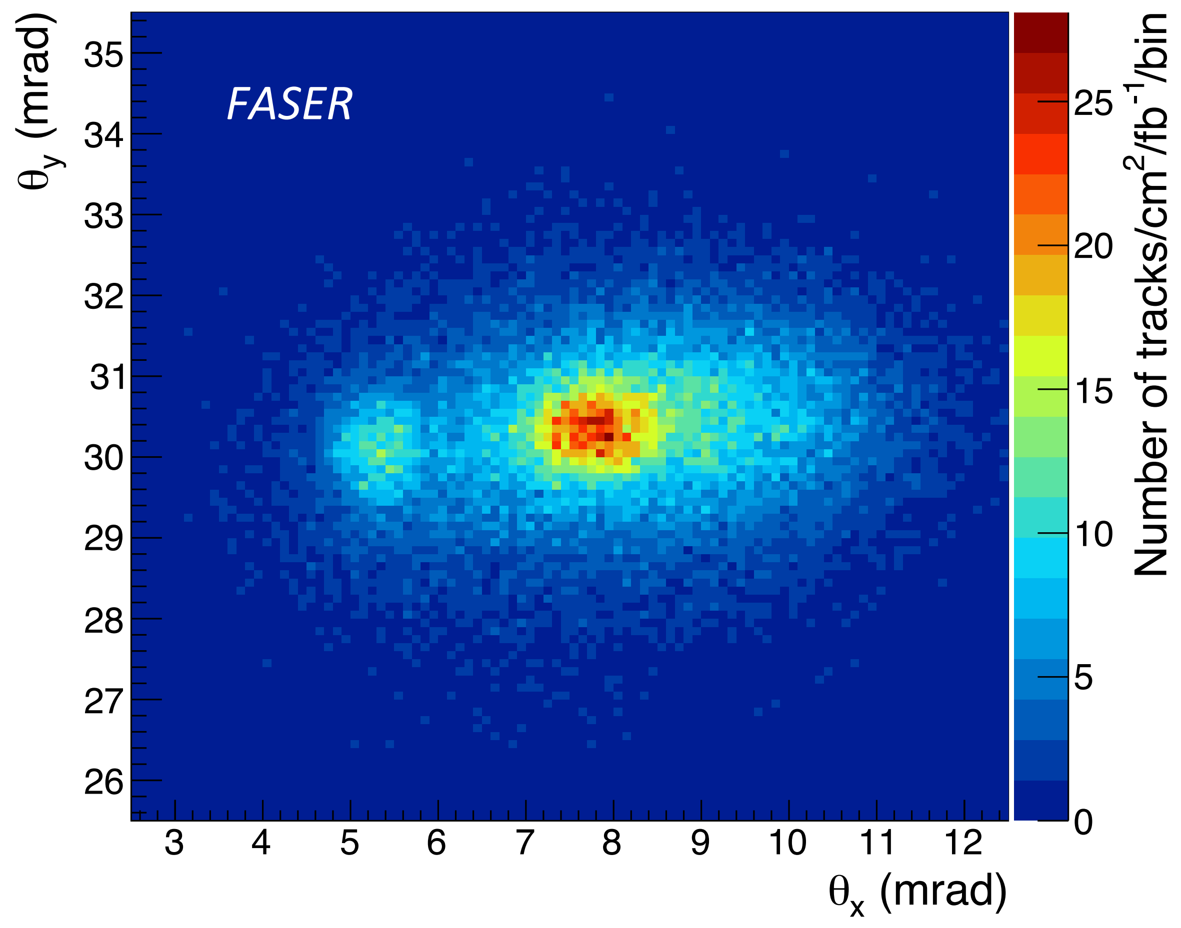
- Observed large angle particles
  - Cosmic rays
  - Backward tracks from the beam line
- Observed double-peak structure
  - Consistent with particles arriving from the LHC beam line in the vertical plane
  - The origin of the structure is under investigation with simulation studies

In-situ measurement (2018)



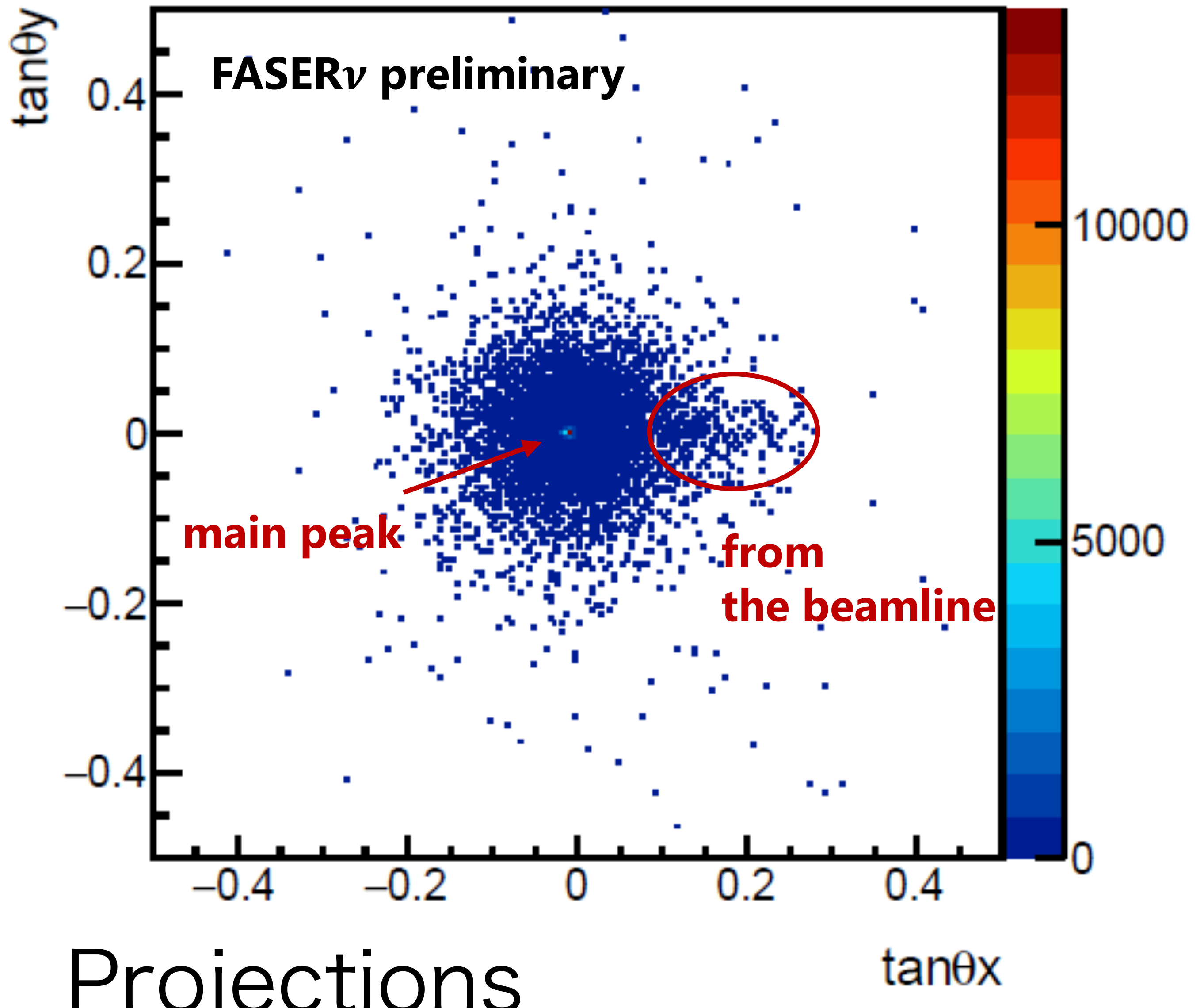


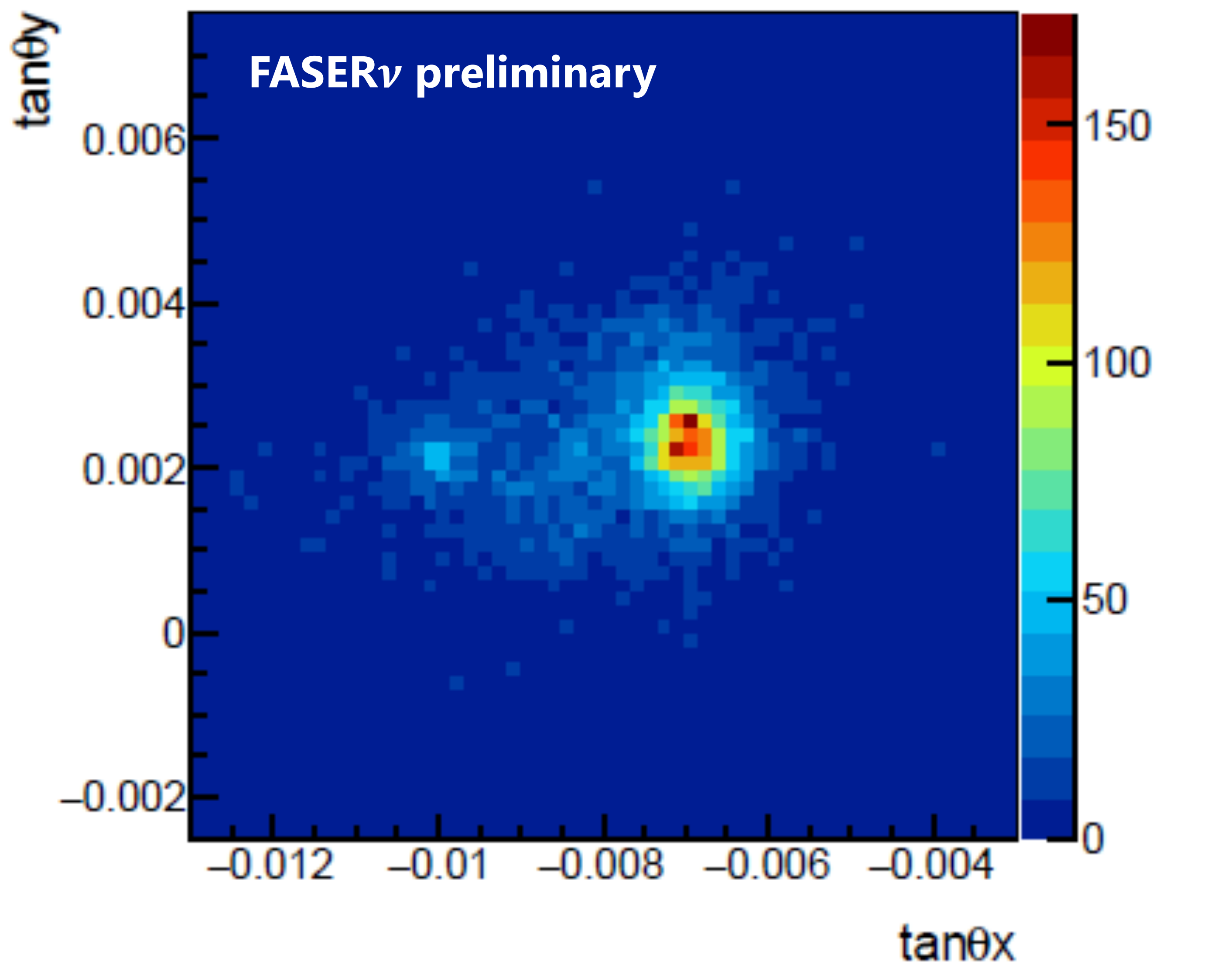
Pilot run (2018)



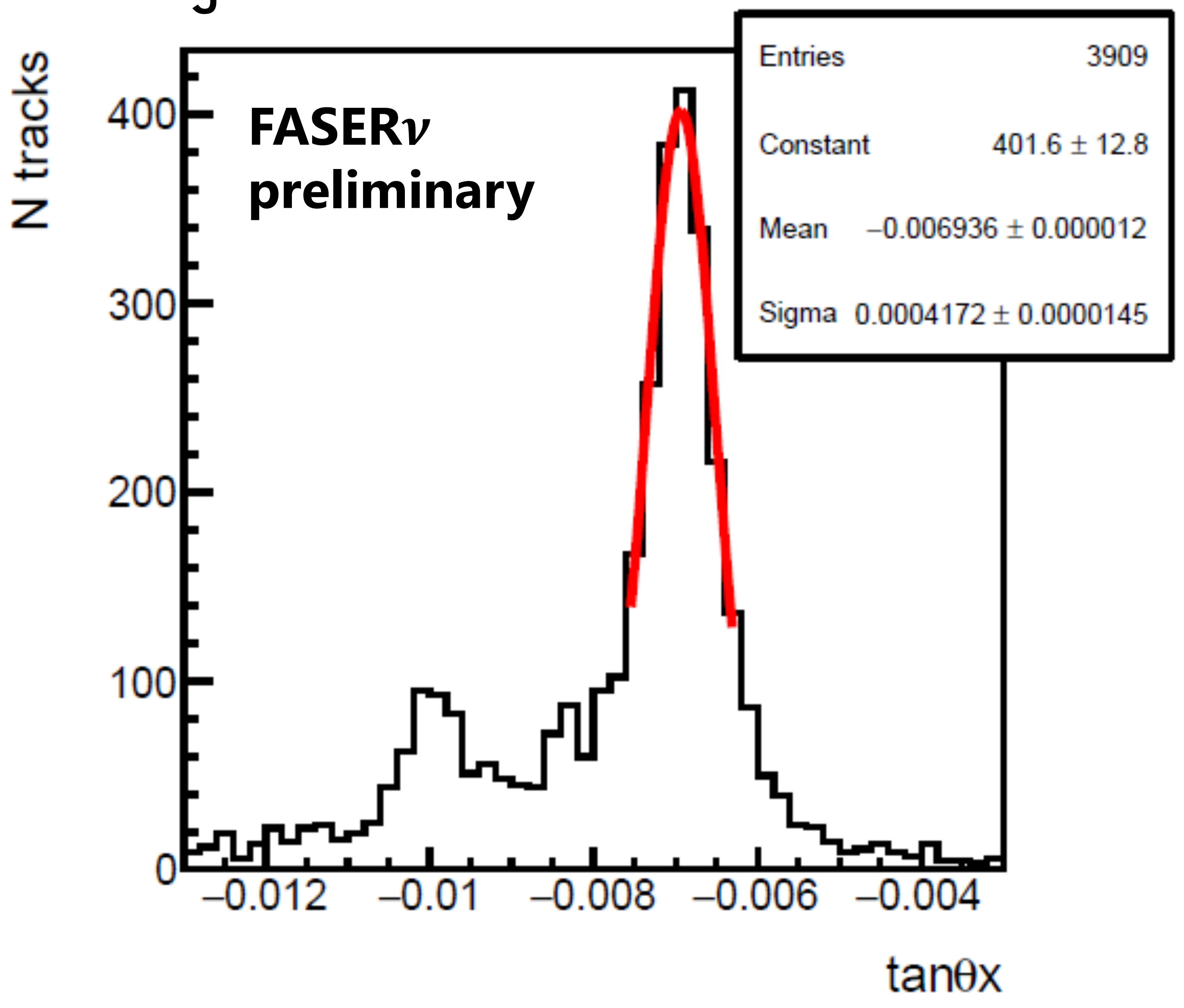
Angular Distributions

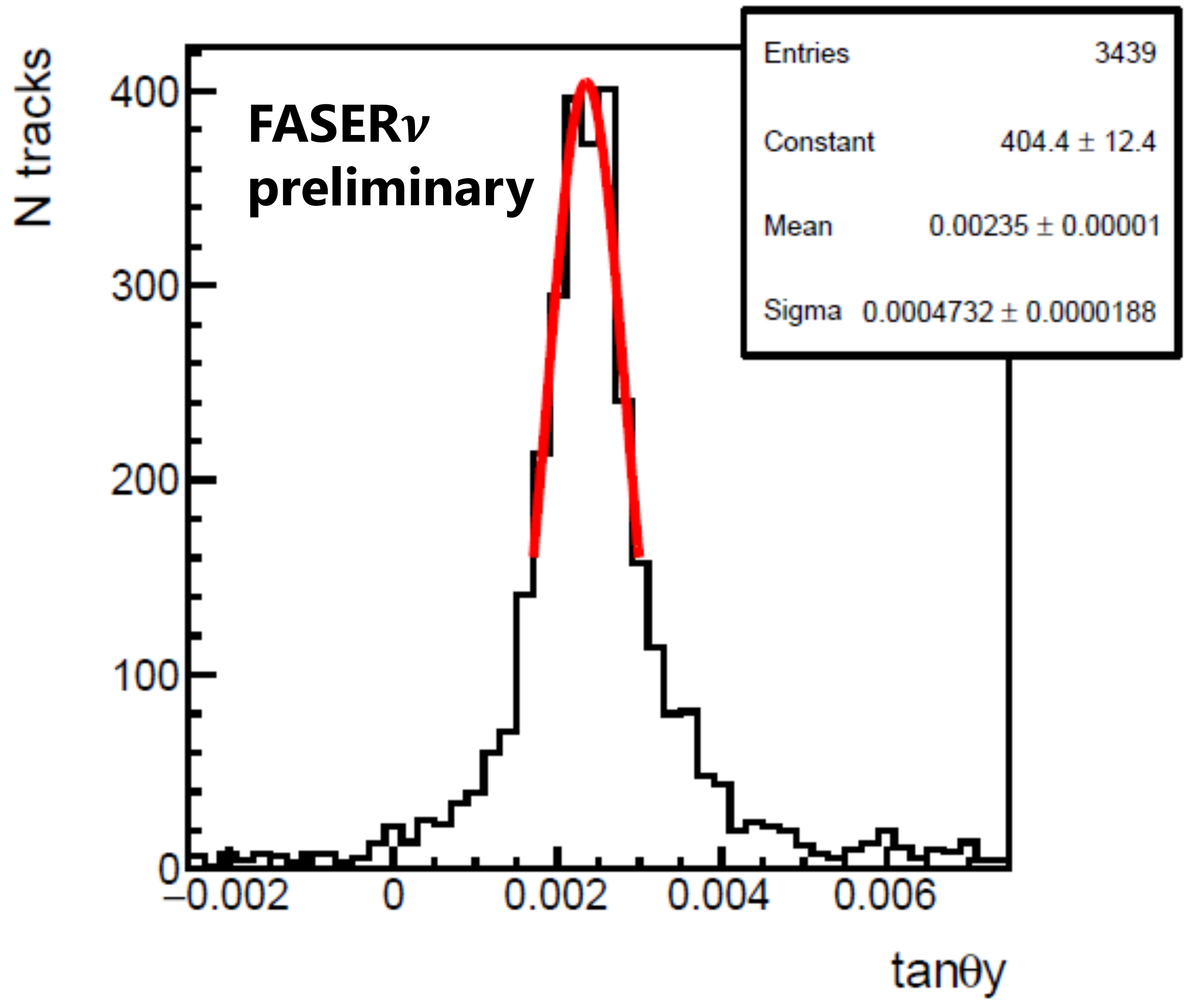
1st module (2022)





Projections



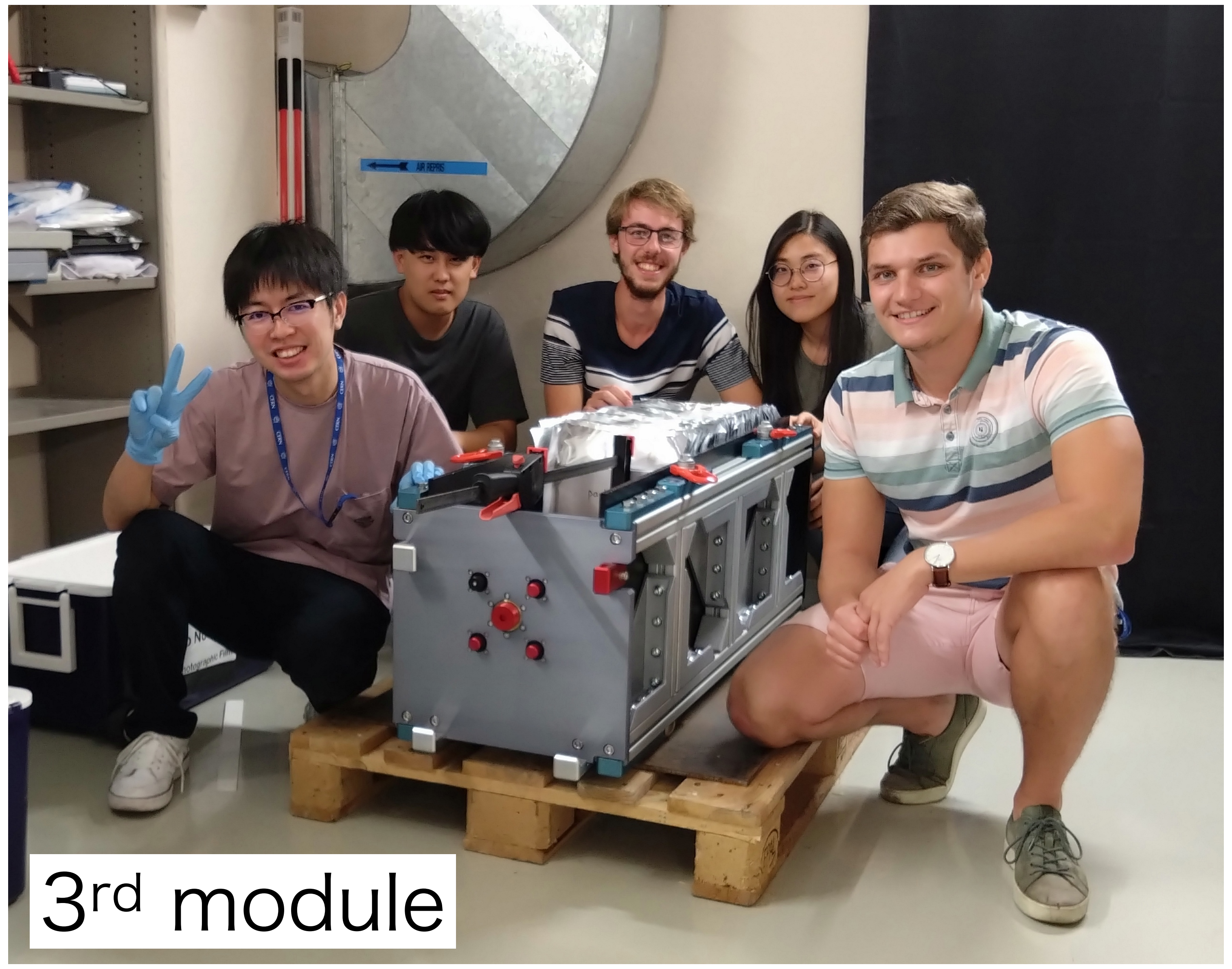


- The angular spread of the projected peaks is approximately 0.5 mrad due to MCS through 100 meters of rock

(Angular resolution is expected to be ~0.1 mrad with 10 films)

2^{nd}/3^{rd} FASERν Module

2^{nd} module



3^{rd} module

- Installed the 2^{nd} module on 25^{th} of July
  - Data-taking and development were successfully done
  - Physics analysis in parallel with film scan
  - Looking forward to observing neutrinos!

- Installed the 3^{rd} module on 14^{th} of September
  - Development will be done by the end of this year

Conclusions

- FASERν studies three flavor neutrinos at the high energy frontier
  - ~10,000ν interactions in LHC Run 3 (2022-2025, 250 fb^{-1})
- Data-taking is on track
  - 3 FASERν modules were assembled and installed this year
  - Performed development of the 2 modules. Film scan is being done
- Successfully performed the whole sequence of the 1st FASERν detector
  - ~0.2 μm position accuracy observed on the 10 emulsion films
  - First results with the LHC beam show an excellent performance of the FASERν detector
- Physics analysis has began towards the first physics results

- Starting to discuss a larger, O(10 tonne), FASERν2 detector for the HL-LHC, as part of the proposed **Forward Physics Facility (FPF)**
  - Ref: https://arxiv.org/abs/2203.05090

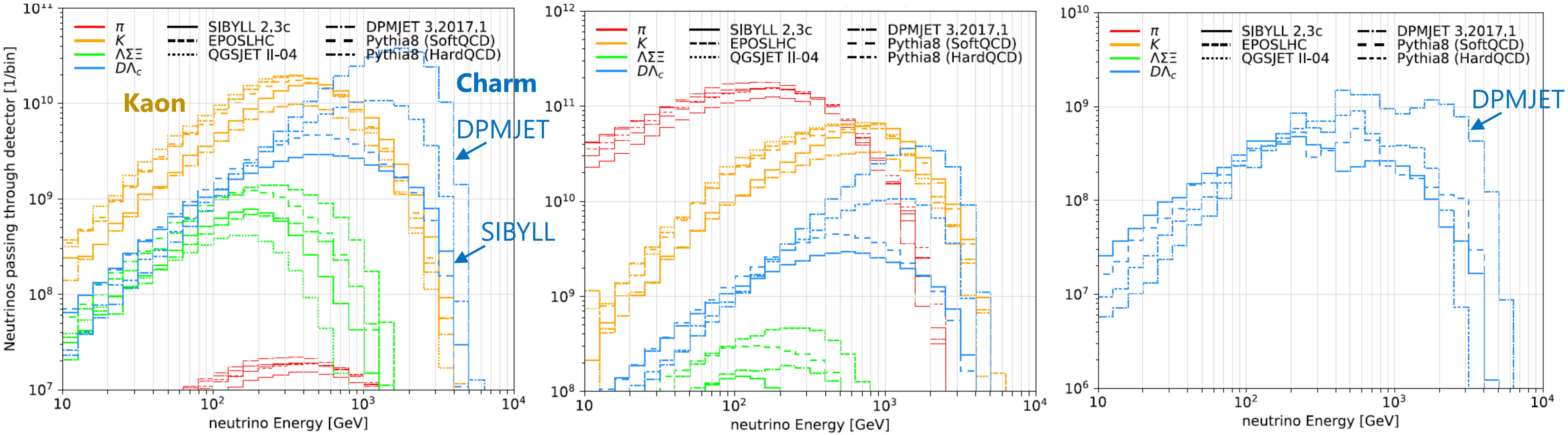
Backup

Collaboration

CERN
UNIVERSITÉ DE GENÈVE
KYUSHU UNIVERSITY
UC IRVINE
UNIVERSITÄT BERN
Technion Israel Institute of Technology
NAGOYA UNIVERSITY
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE
KEK
UNIVERSITY OF OREGON
UNIVERSITÄT BONN
INFN
清華大学 Tsinghua University
MANCHESTER 1824 The University of Manchester
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
CHIBA UNIVERSITY
UNIVERSITY OF SUSSEX
DESY.
JINR

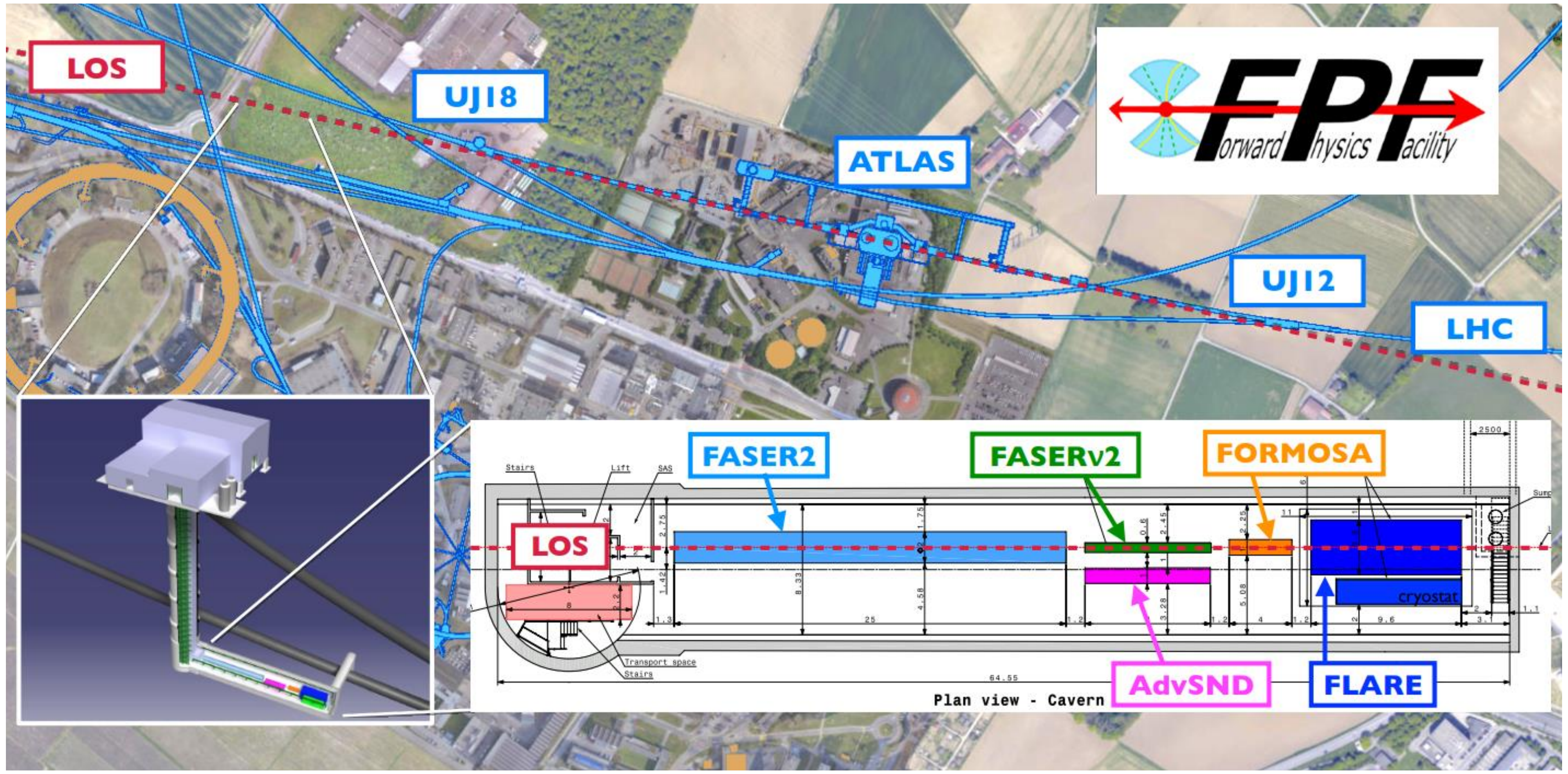
83 members from 22 institutions and 9 countries

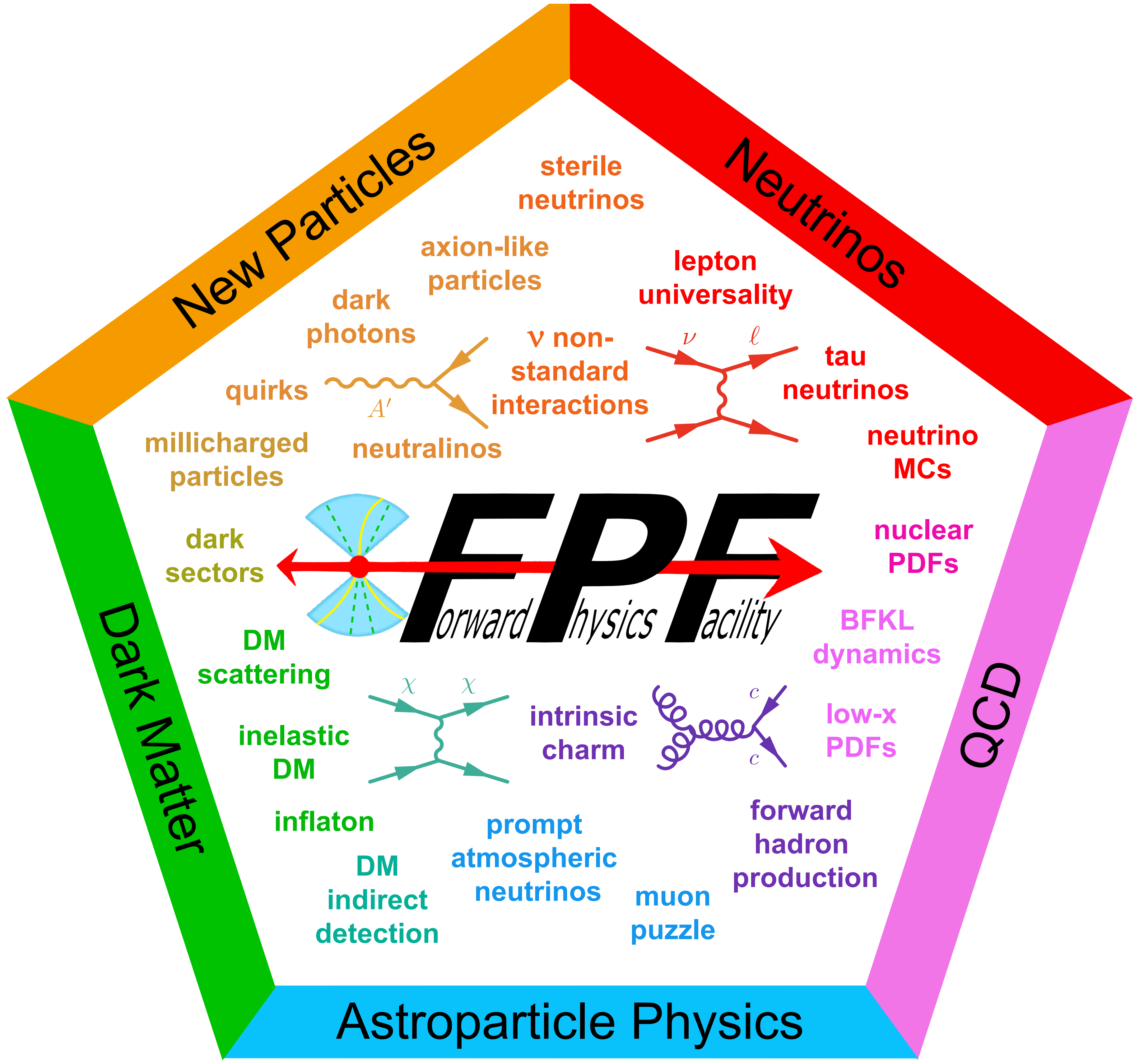
Neutrino Production



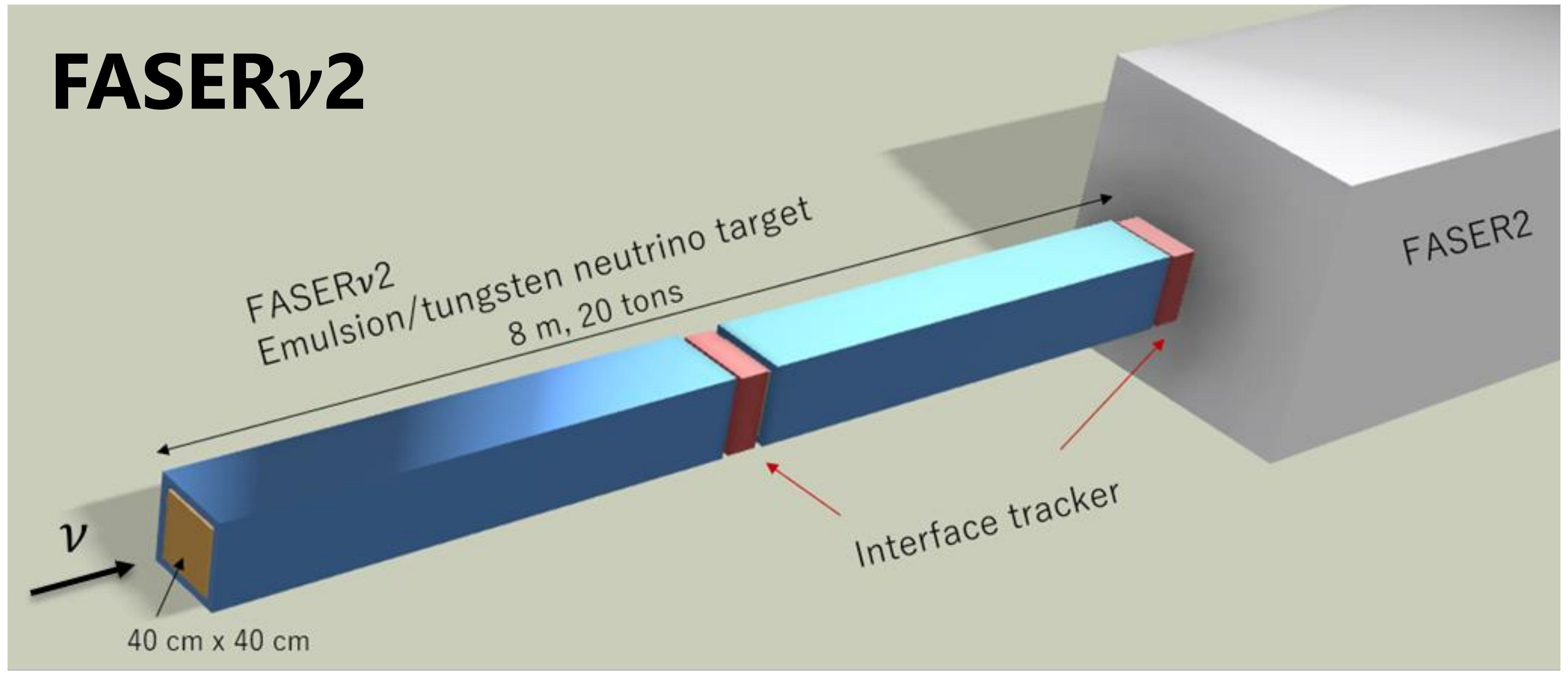
passing through the detector

Forward Physics Facility





- New facility for forward physics at HL-LHC
- Dedicated sweeper magnet for muon background rejection
- Expected of tau neutrino interactions: ~2300 (SIBYLL) / ~20000 (DPMJET)

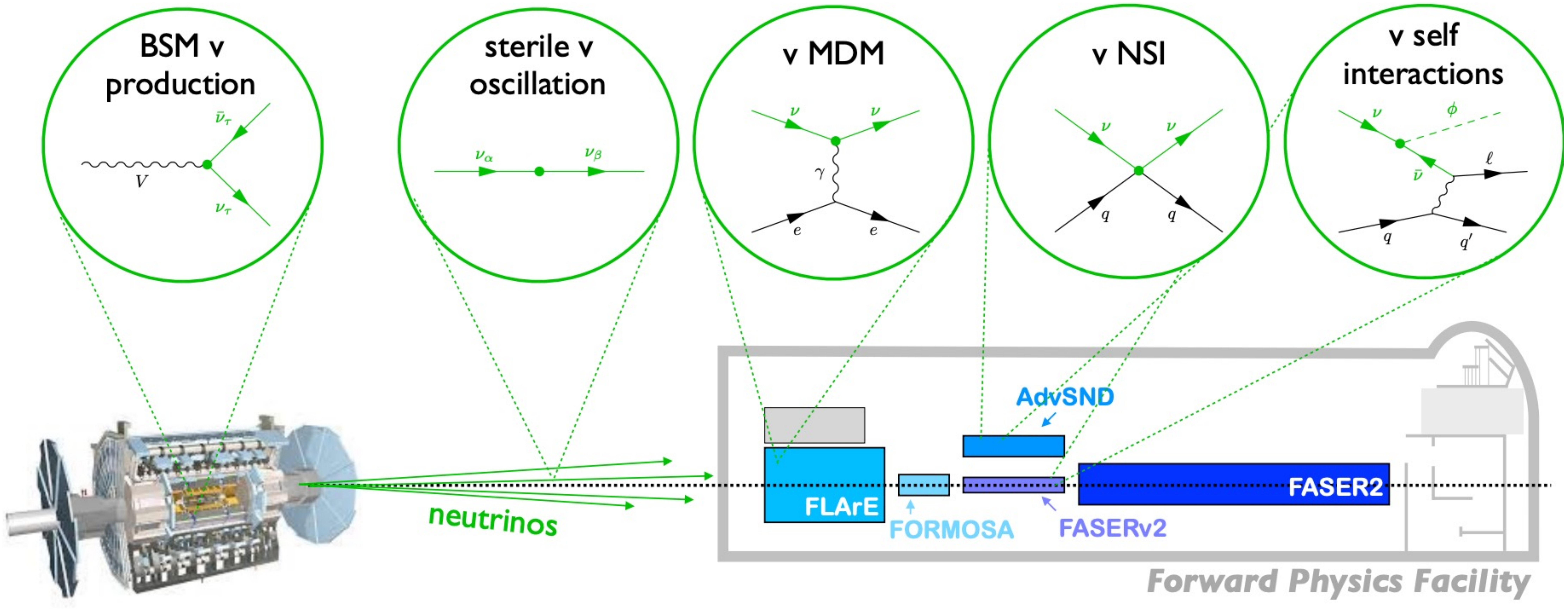


Neutrino Event Rates

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

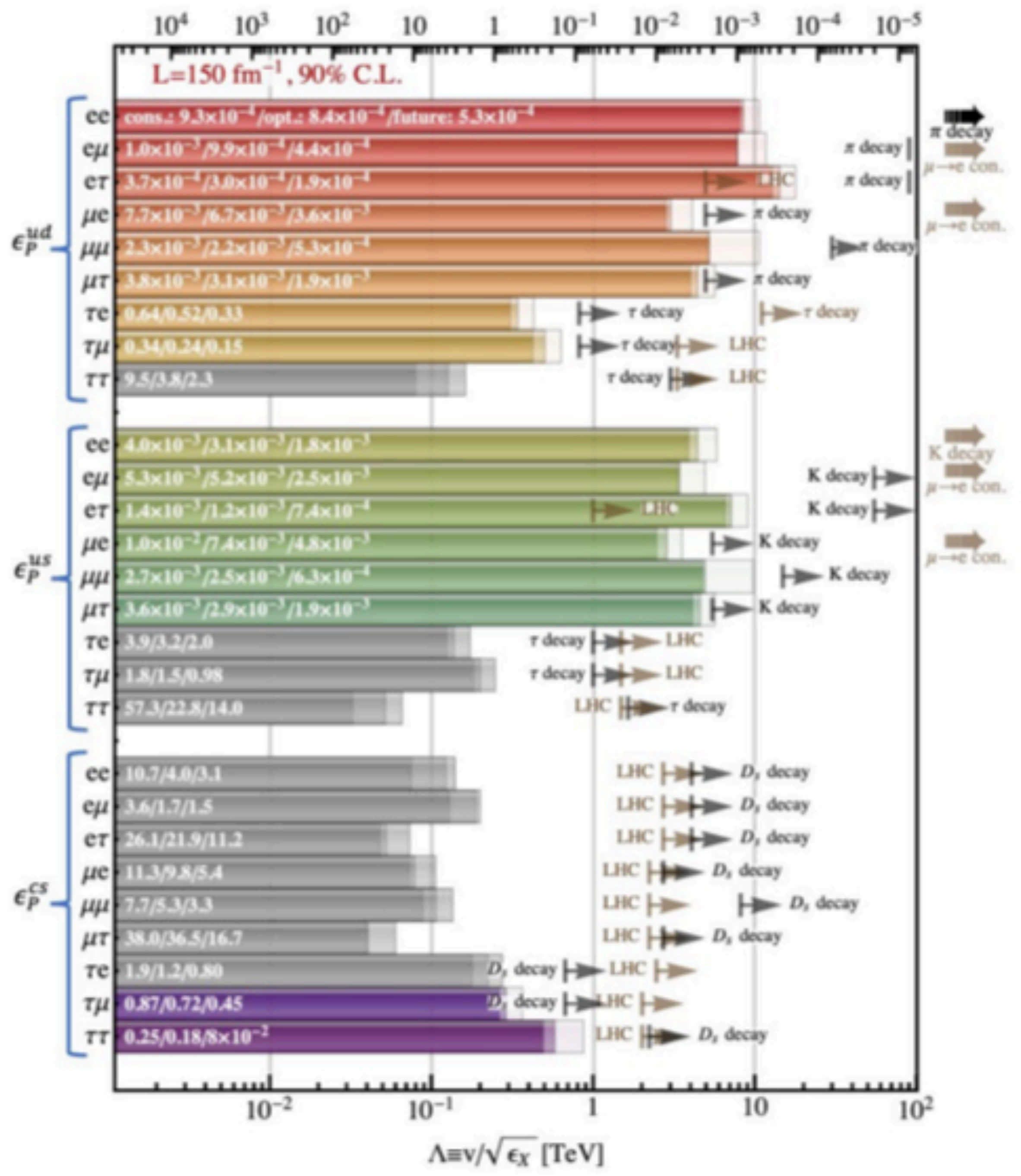
Table 7.1: Detectors and neutrino event rates: The left side of the table summarizes the detector specifications in terms of the target mass, pseudorapidity coverage and assumed integrated luminosity for both the LHC neutrino experiments operating during Run 3 of the LHC as well as the proposed FPF neutrino experiments. On the right, we show the number of charged current neutrino interactions occurring the detector volume for all three neutrino flavors as obtained using two different event generators, `Sibyll 2.3d` and `DPMJet 3.2017`.

Neutrino (BSM) at the FPF

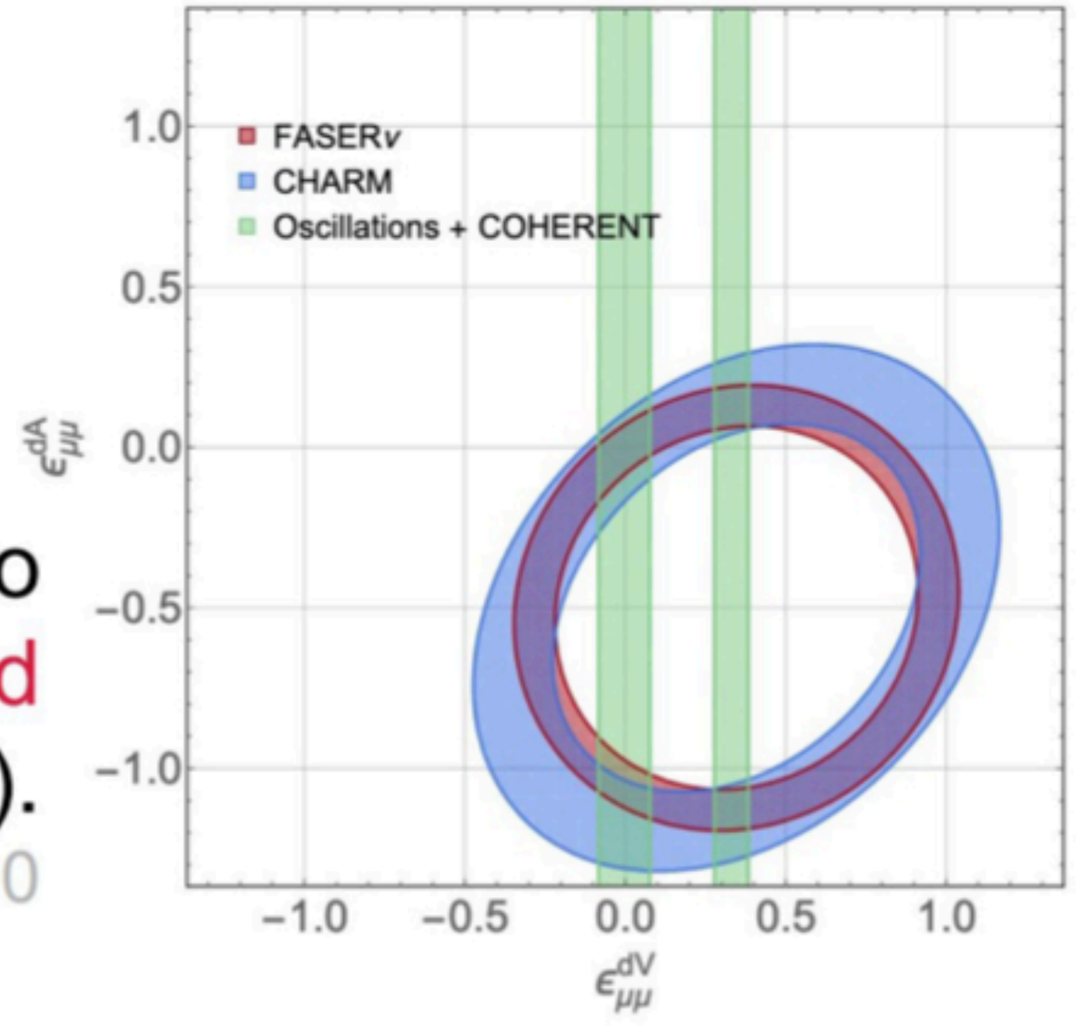


New Physics

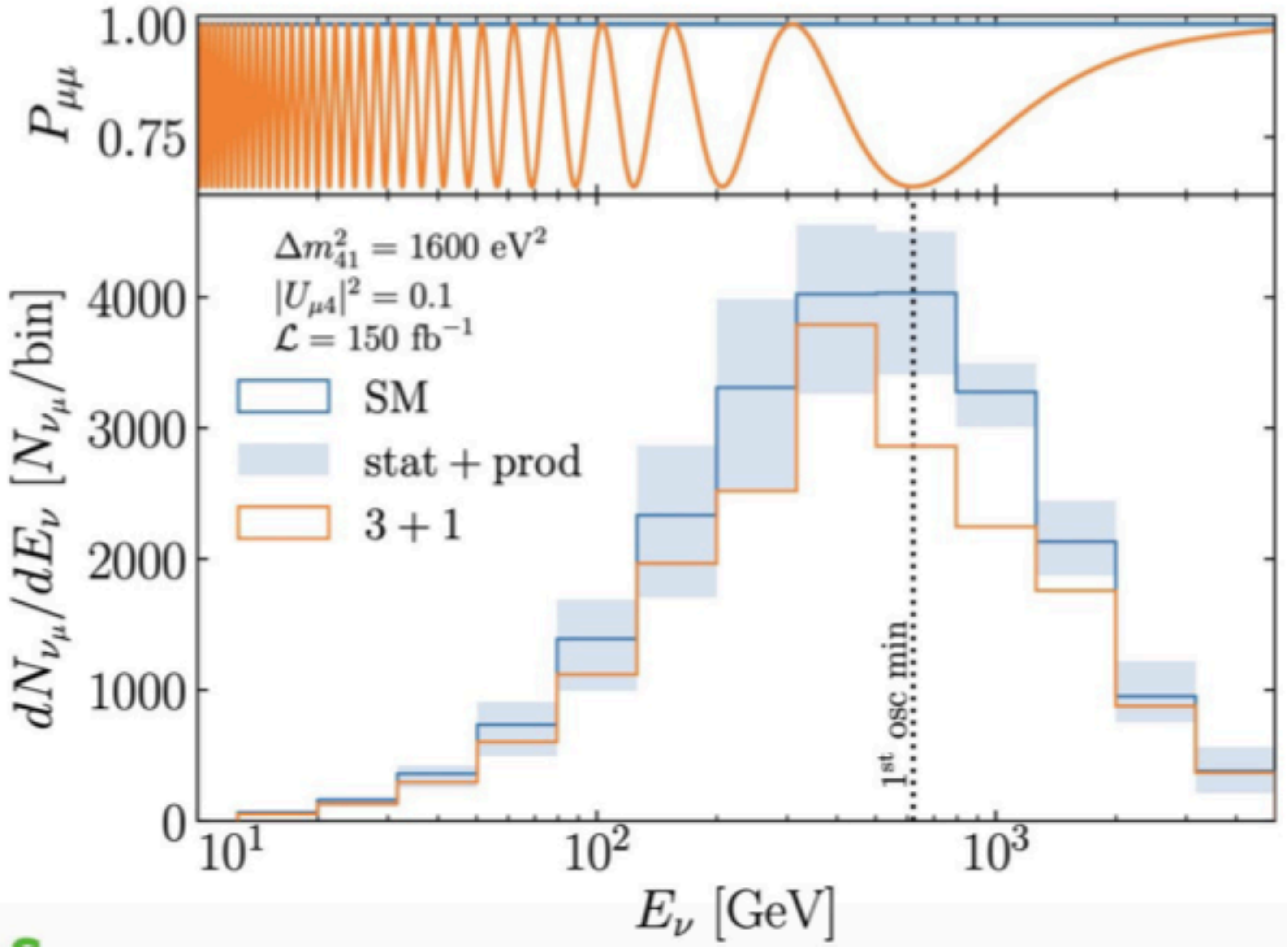
Interactions of LHC neutrino can also be used to constrain SM EFT coefficients
Falkowski, González-Alonso, Kopp, Soreq, Tabrizi 2105.12136



NC measurements could also constrain neutrino non-standard interactions (NSI).
Abraham, Ismail, Kling 2012.10500

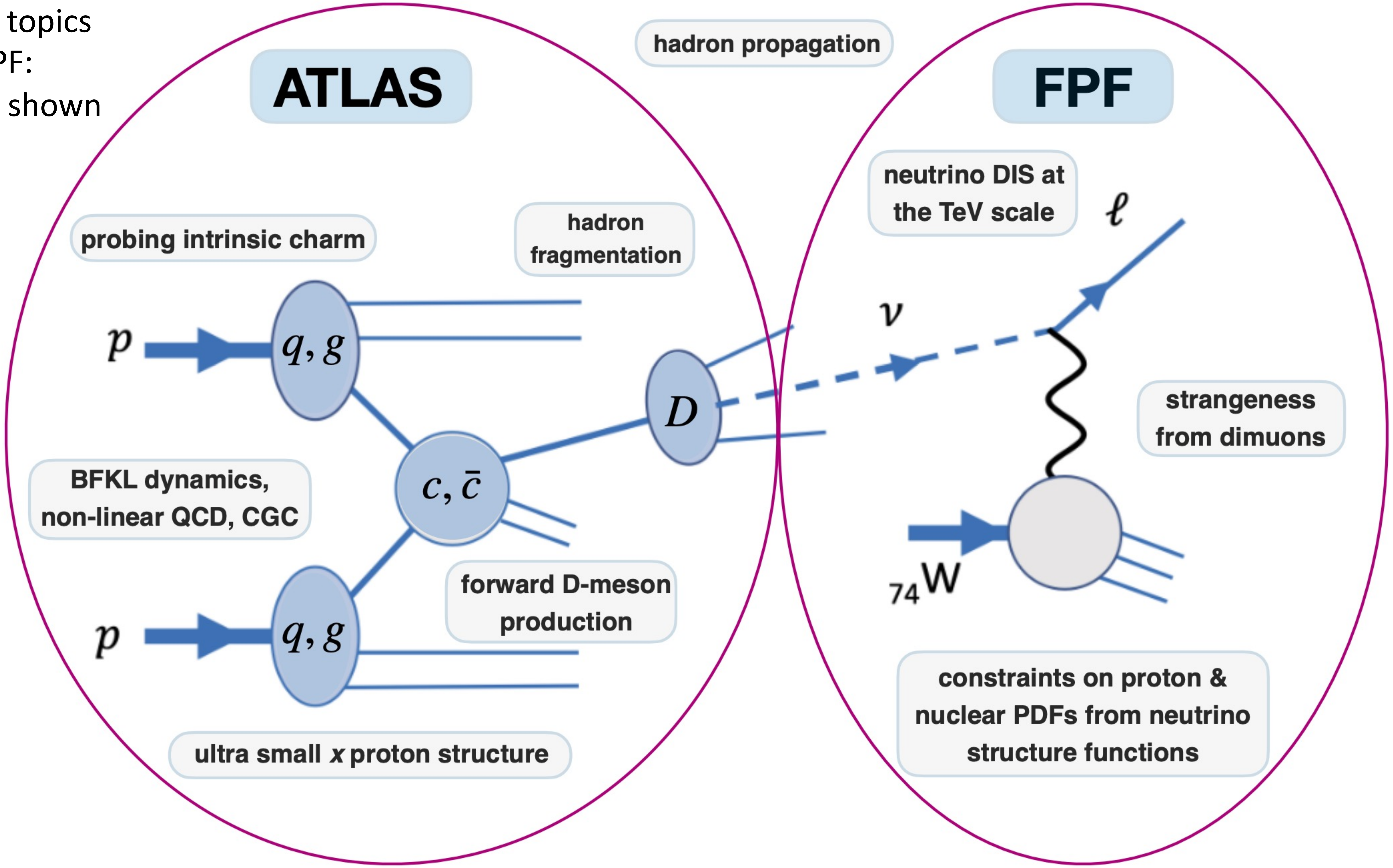


SM neutrino oscillations are expected to be negligible at FASERv. However, sterile neutrinos with mass ~40eV can cause oscillations. FASERv could act as a short-baseline neutrino experiment.



QCD at the FPF

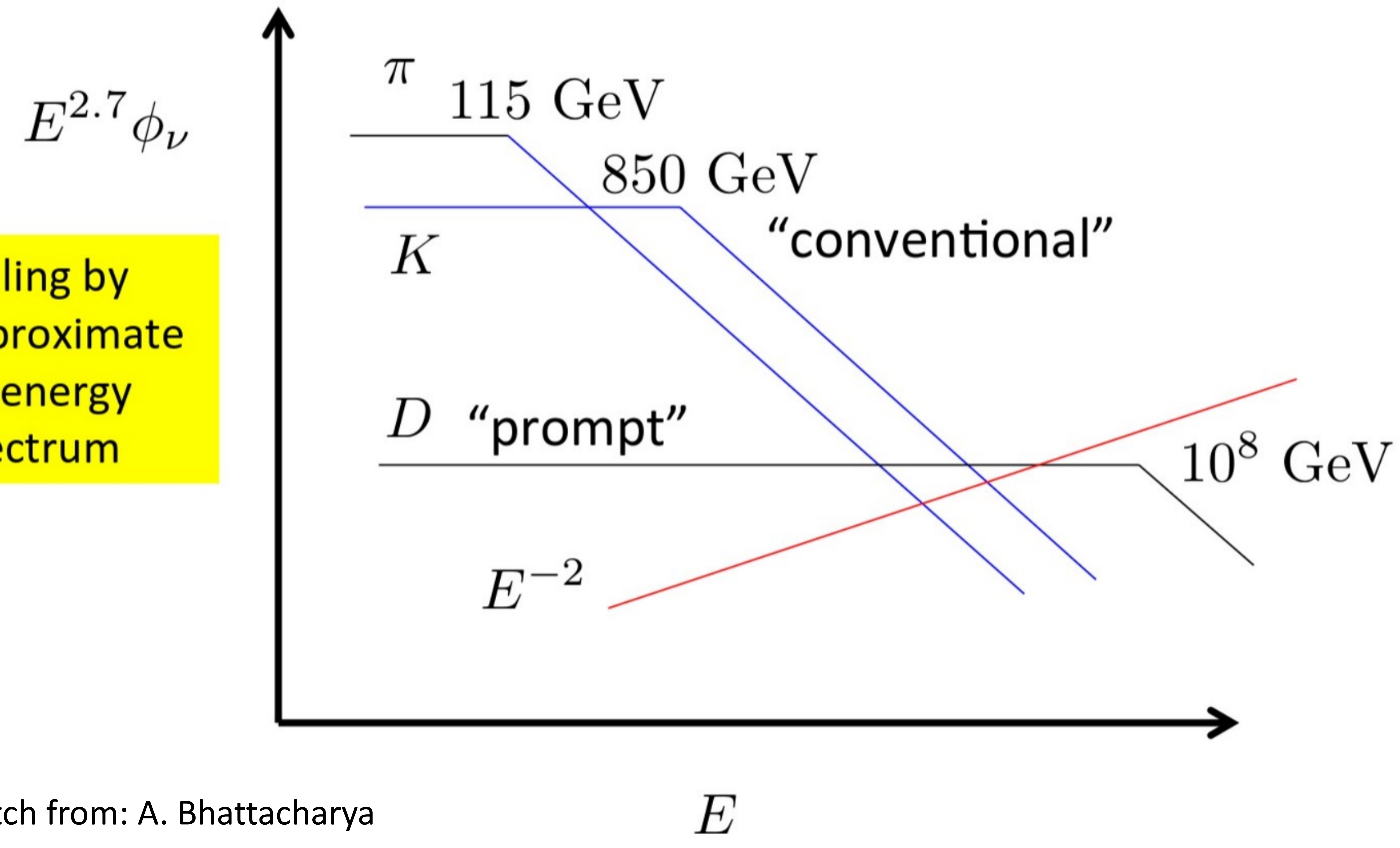
Many interesting QCD topics to be studied at the FPF:
(A couple of examples shown on next slides)



Input for astroparticle experiments

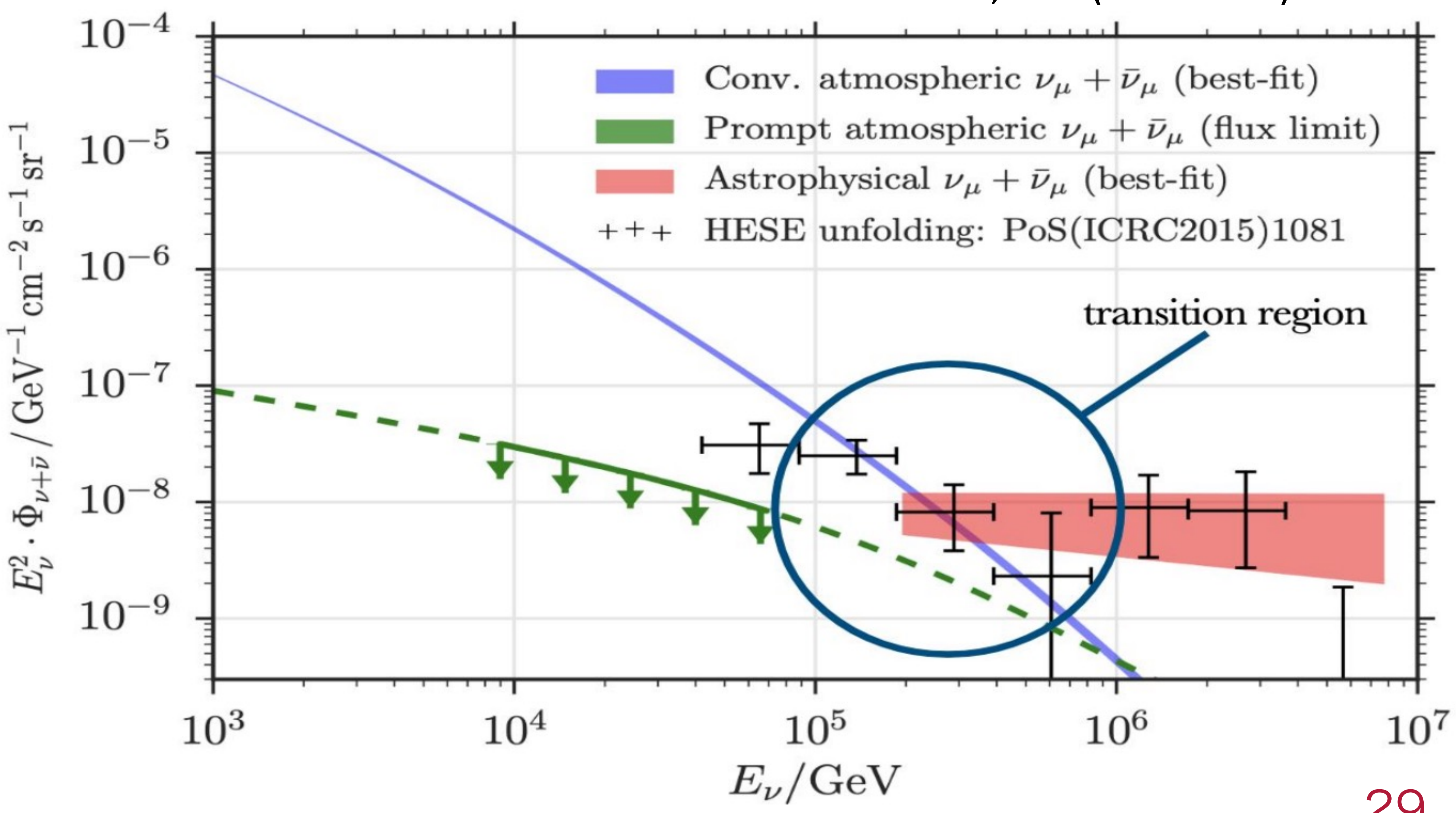
Studies of high-energy astrophysical neutrinos with large-scale neutrino telescopes (e.g. IceCube), suffer from backgrounds from atmospheric neutrinos from charm-decay (charm produced in hadronic shower initiated by cosmic rays hitting the atmosphere).
At ultra high-energy light hadrons travel far through 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.

Scaling by approximate CR energy spectrum

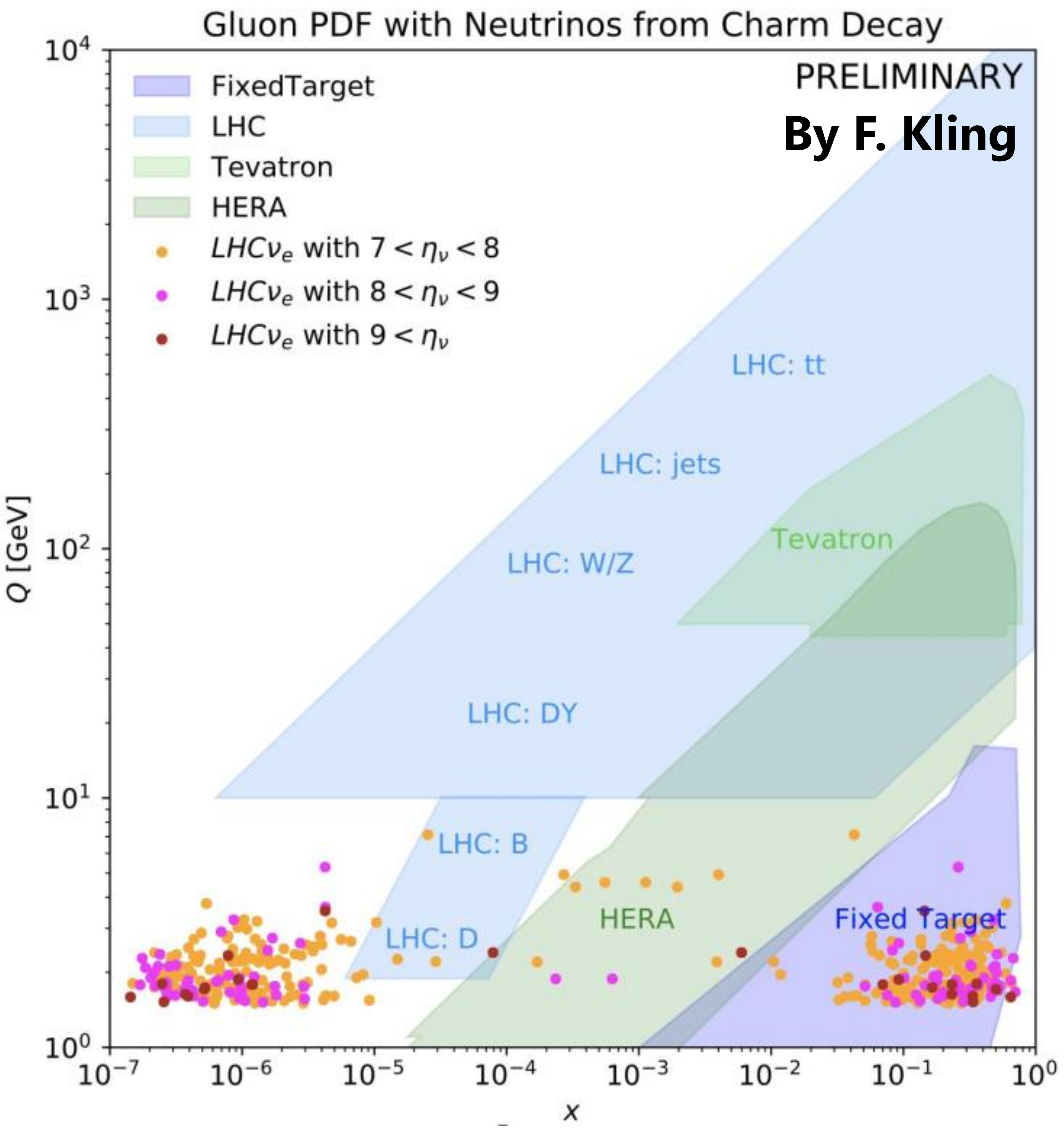


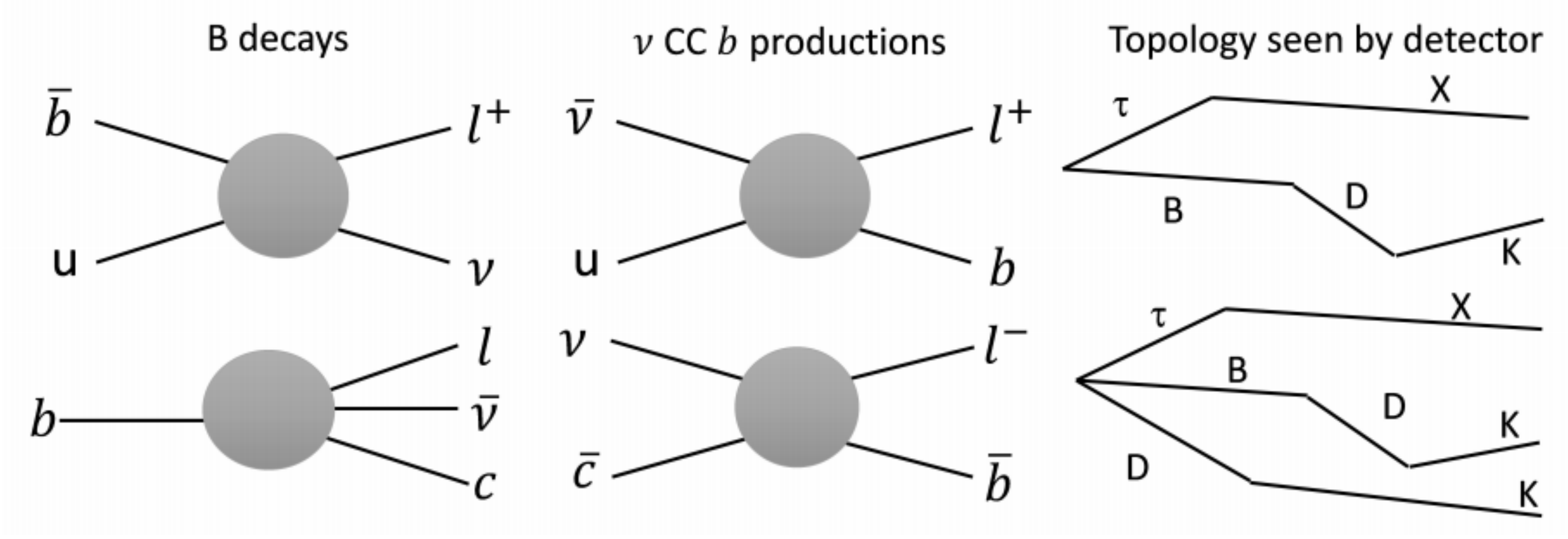
Sketch from: A. Bhattacharya

IceCube, PoS (ICRC2017) 1005



Physics

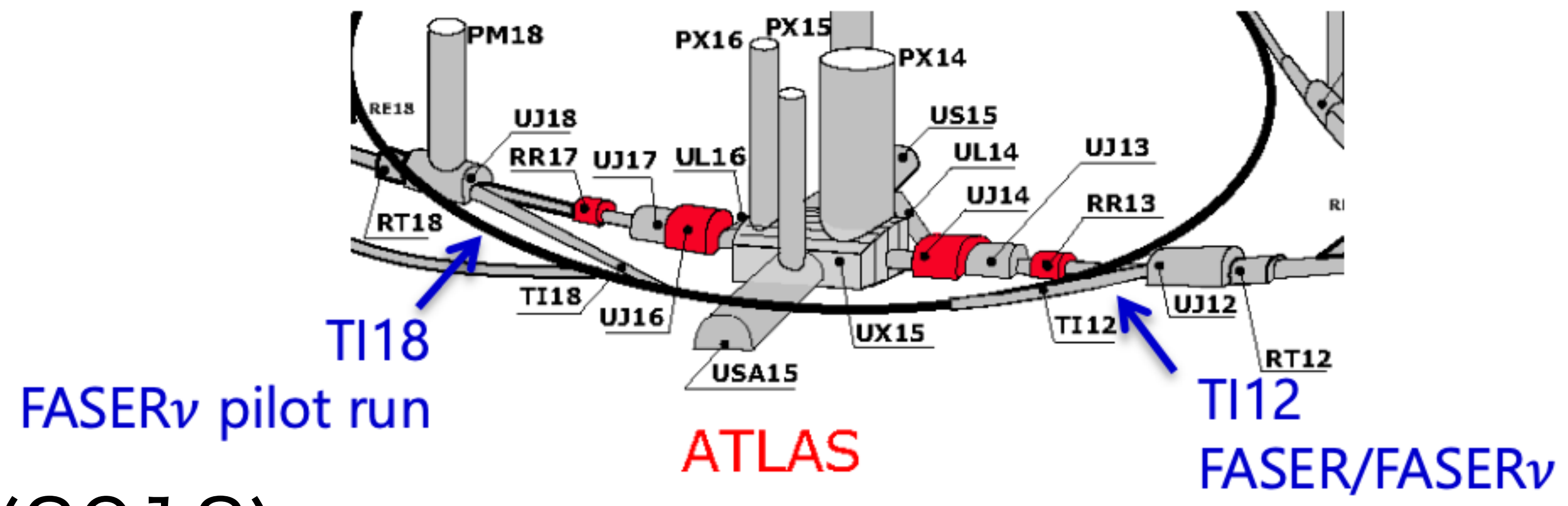




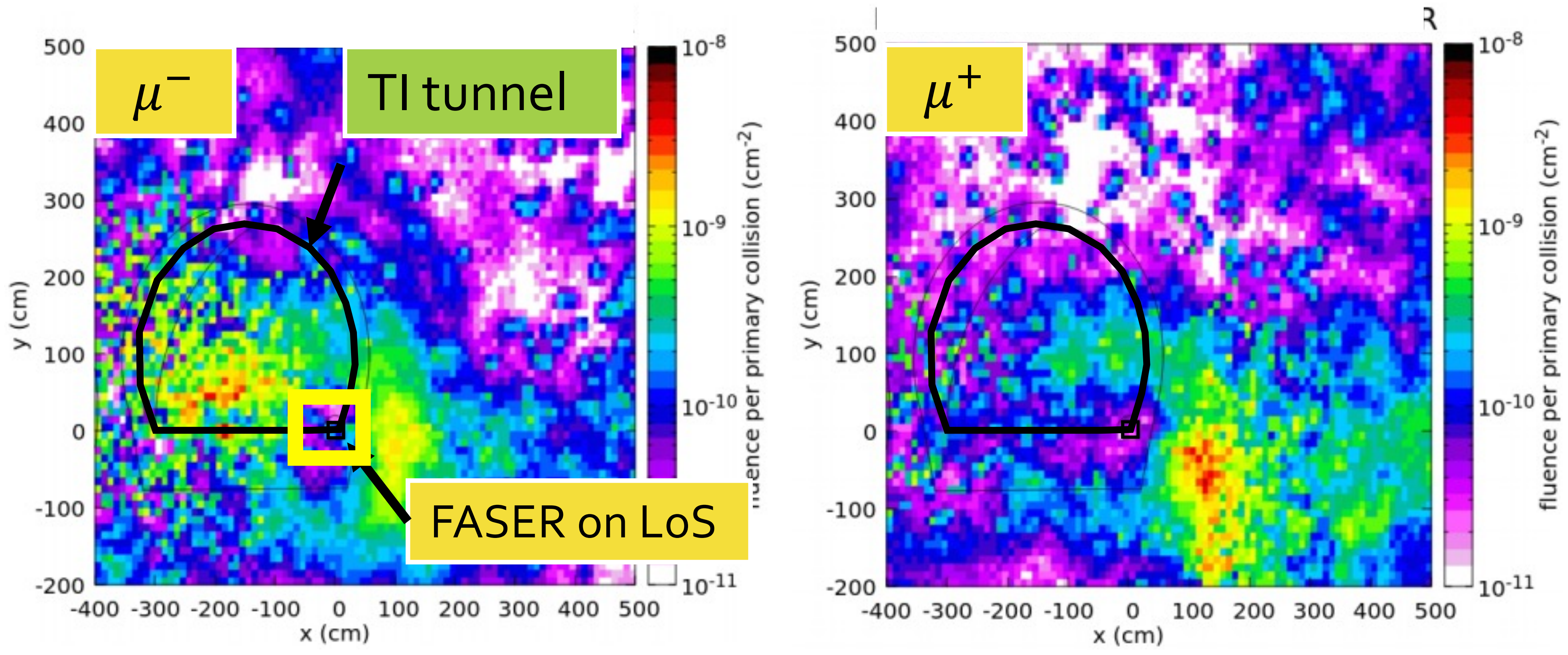
$$\bar{\nu}N \to \ell\bar{B}X$$

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

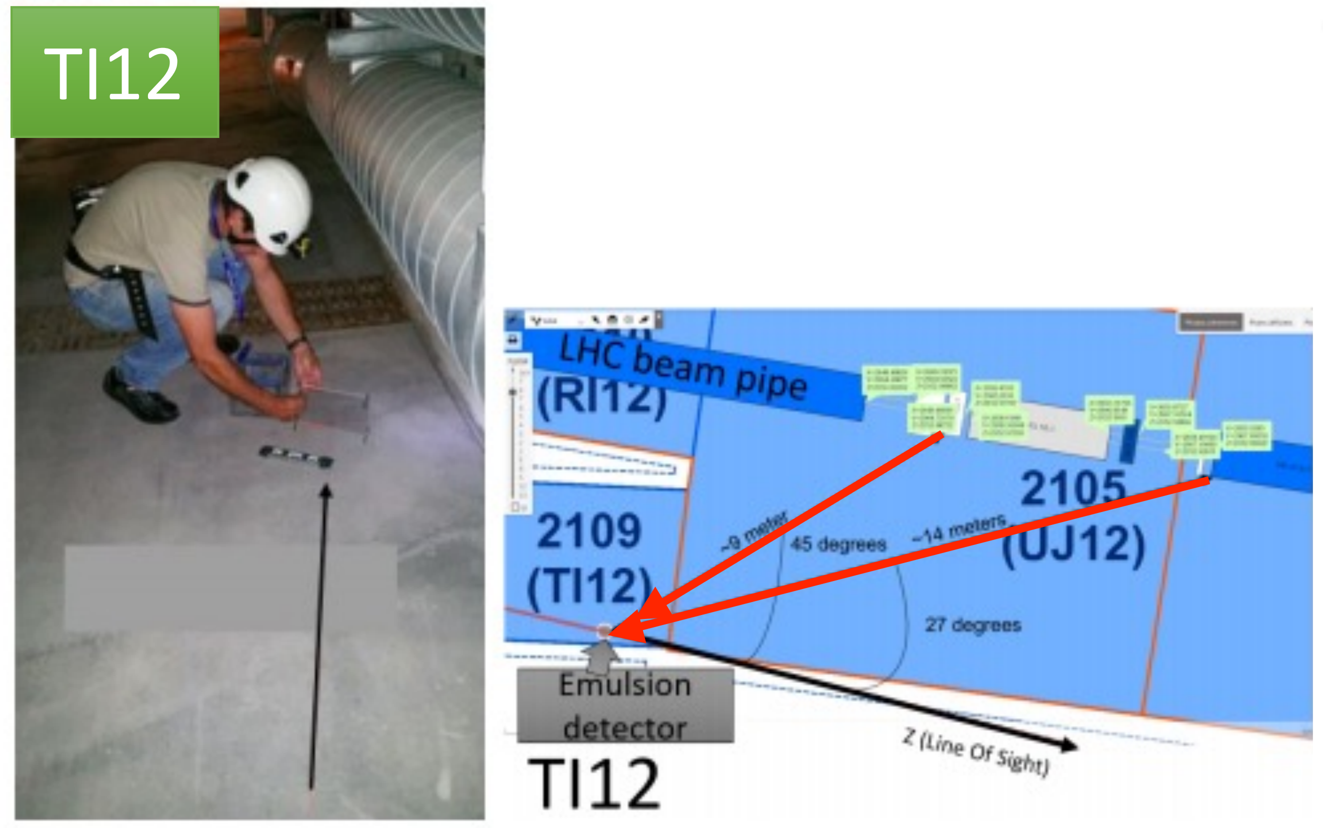
Detector Environment

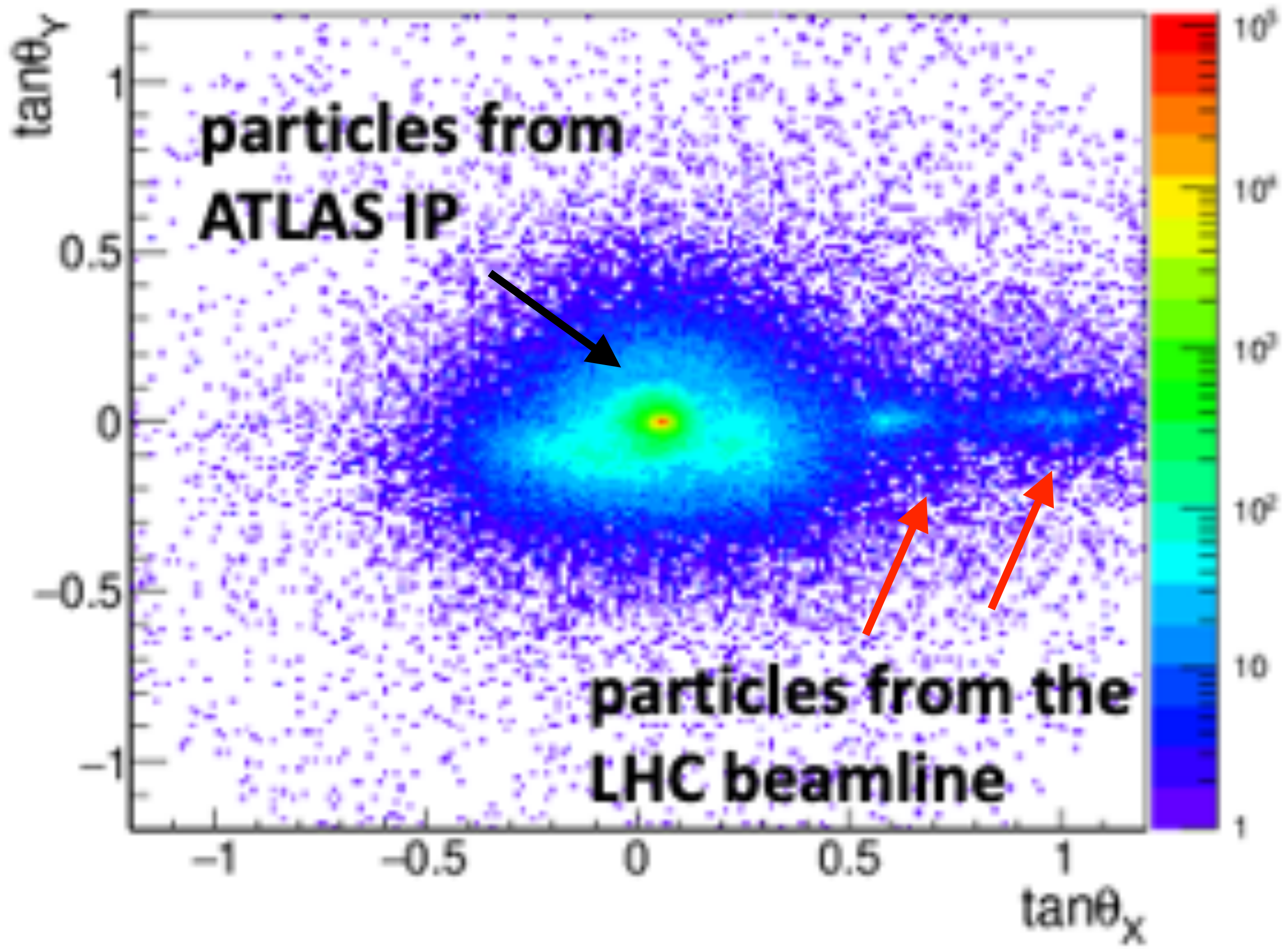


FLUKA simulations



In-situ measurements (2018)



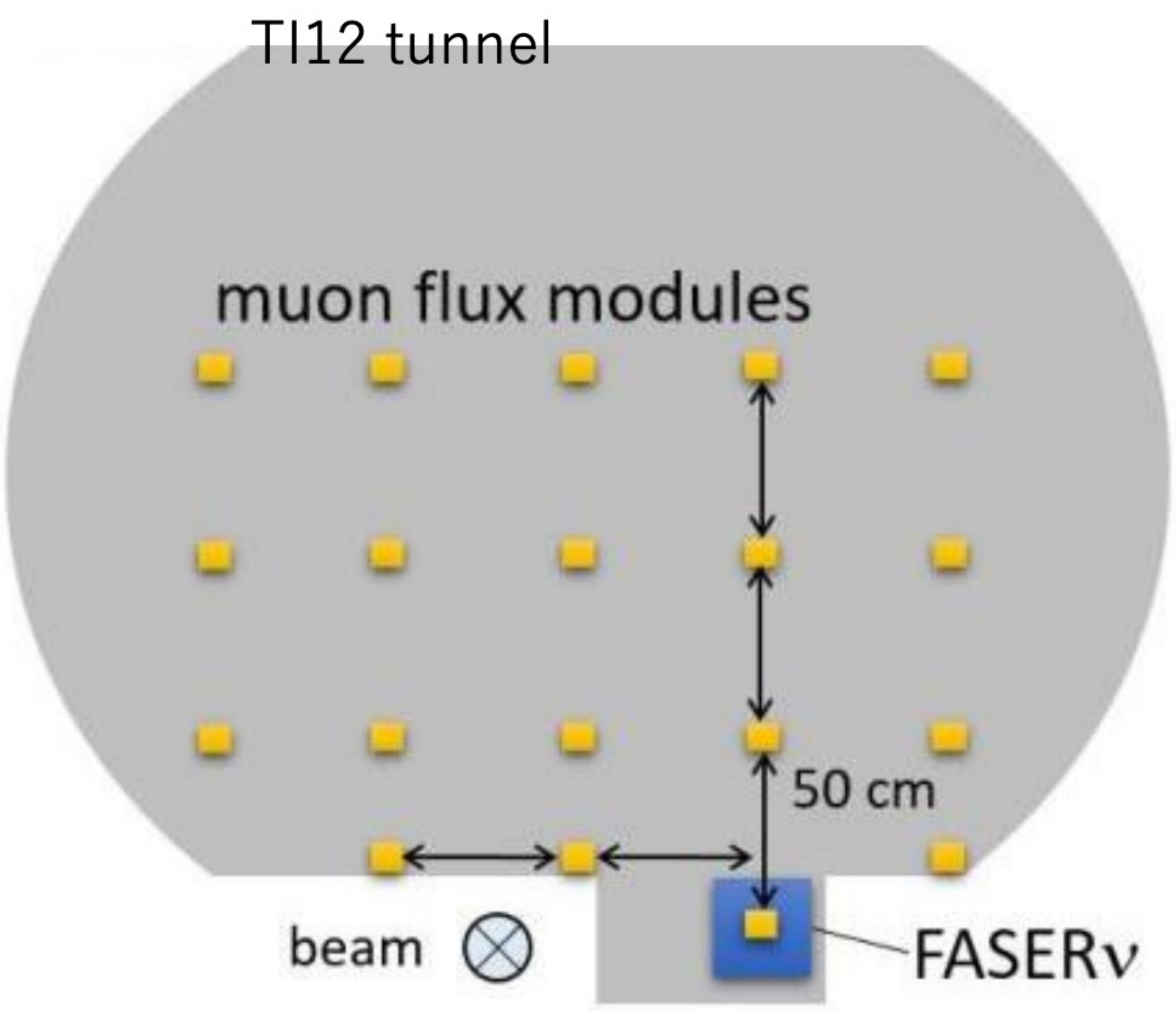


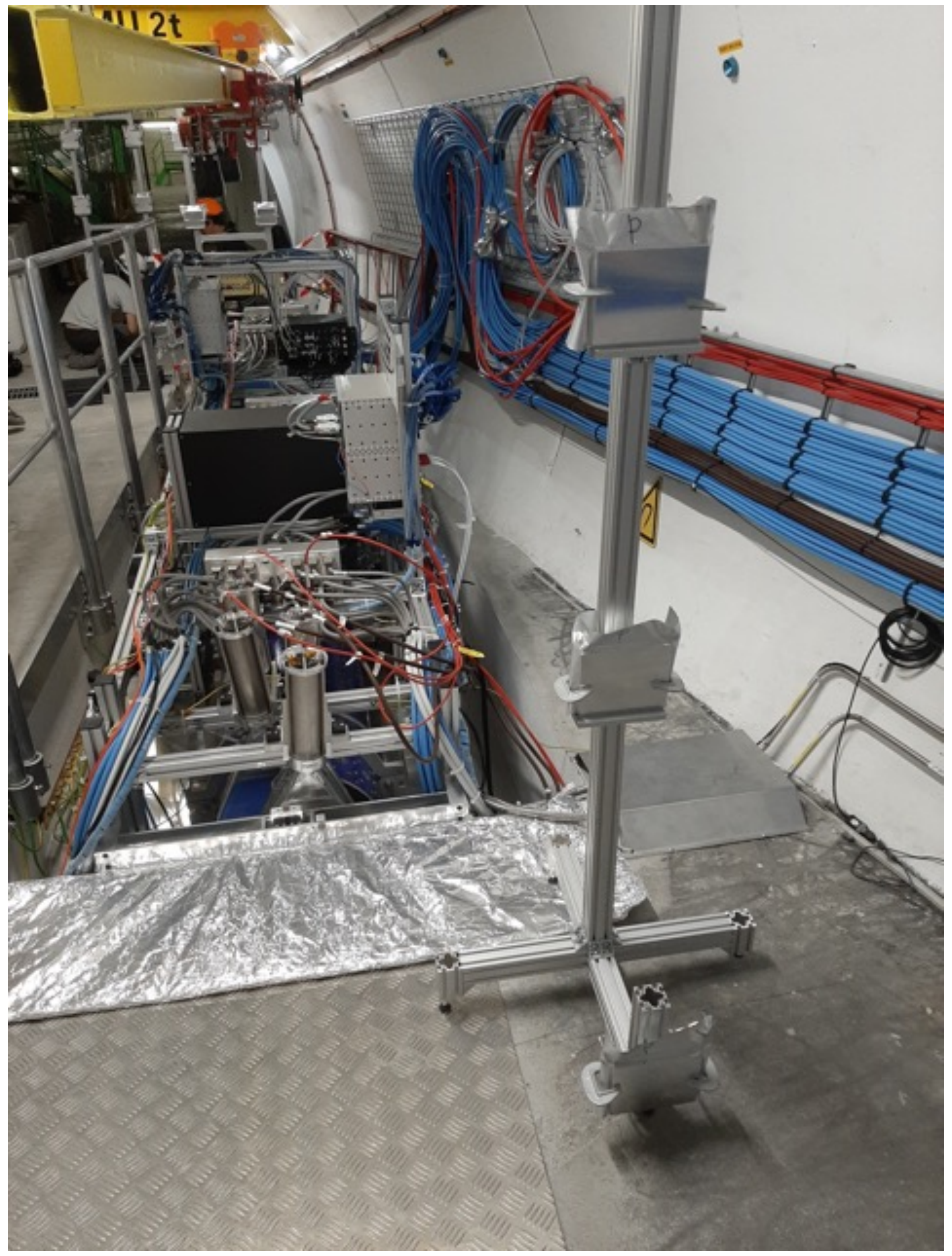
	Flux all [fb/cm^2]	Flux in main peak [fb/cm^2]
TI18 data	2.6±0.7 ×10^4	1.2±0.4 ×10^4
TI12 data	**3.0±0.3 ×10^4**	**1.9±0.2 ×10^4**
FLUKA MC		**2.0 ×10^4**

- 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

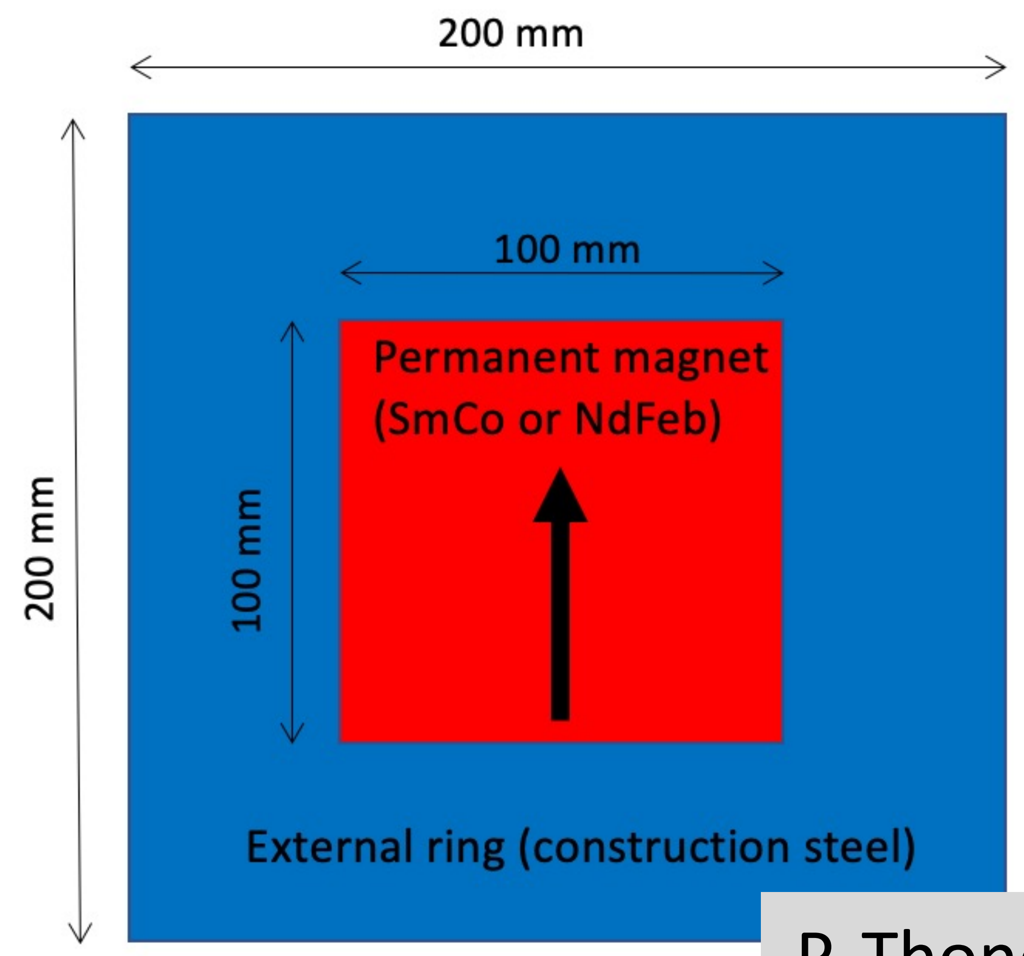
Muon Measurements

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.



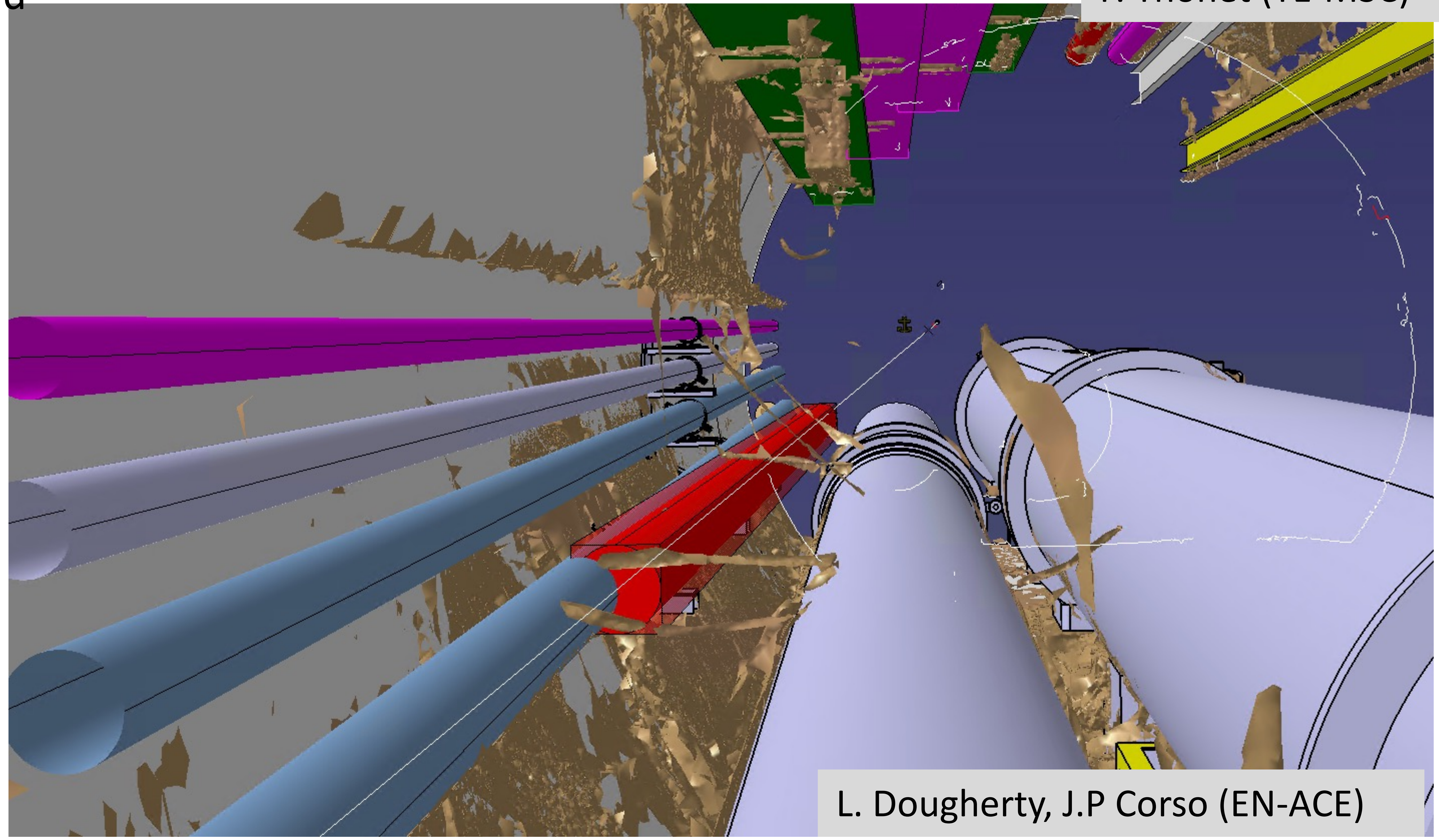


Sweeper Magnet: Ongoing Studies



P. Thonet (TE-MSC)

- 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



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