FASERν2

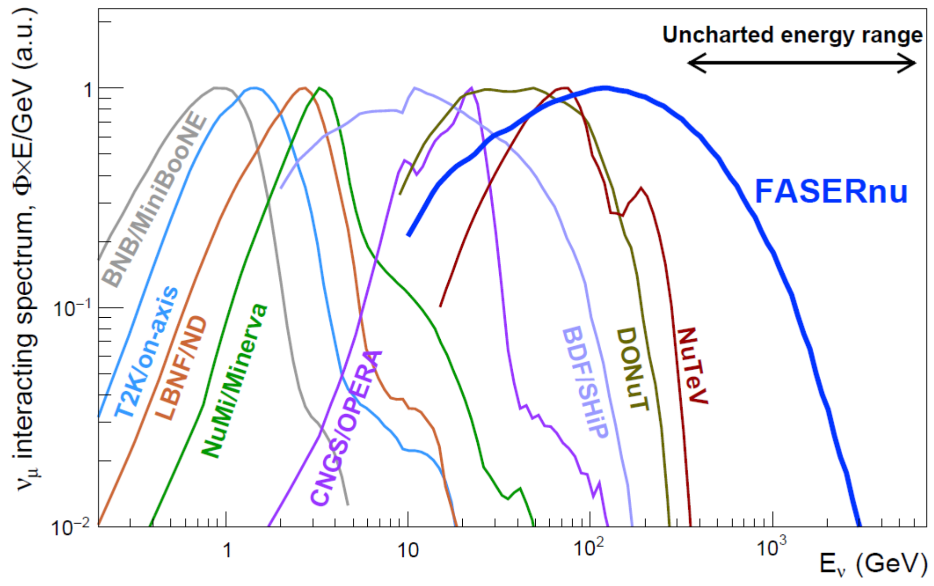
Tomoko Ariga (Kyushu University)

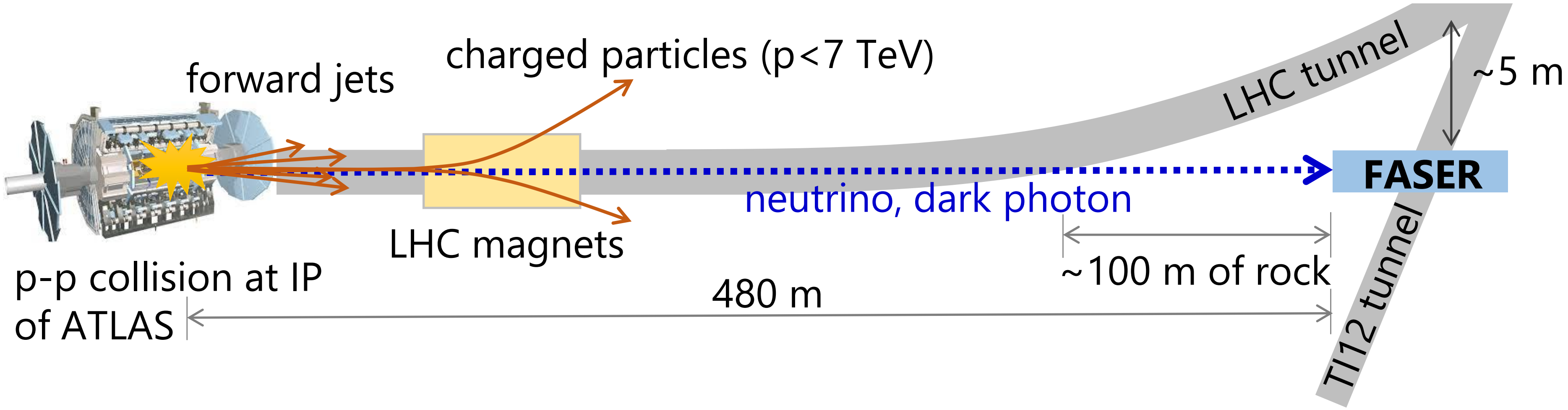
Thanks to those who have contributed to this activity,
mainly from the FASER Collaboration

Neutrinos from the LHC:

High energy frontier of man-made neutrinos

- Cross section measurements of different flavors at high energy
- Probing neutrino-related models of new physics
- Measurements of forward particle production





FASERν/FASERν2 schedule

FASERν pilot run in 2018

FASERν physics run will start in 2022

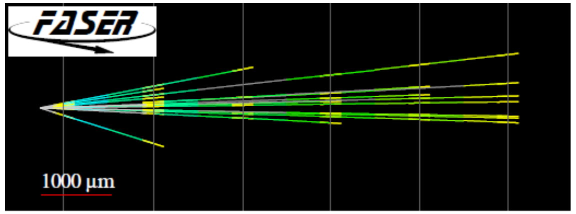
FASERν2 in HL-LHC

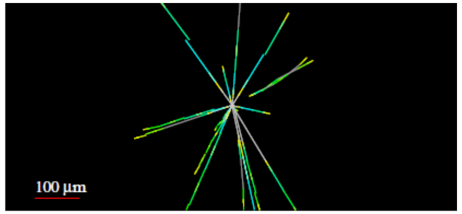
First neutrino interaction candidates at the LHC

FASER Collaboration, Phys. Rev. D 104, L091101 (2021)

Cross section measurements of different flavors at TeV energies

Precision ν_τ measurements and heavy flavor physics studies





FASERν2 physics potential

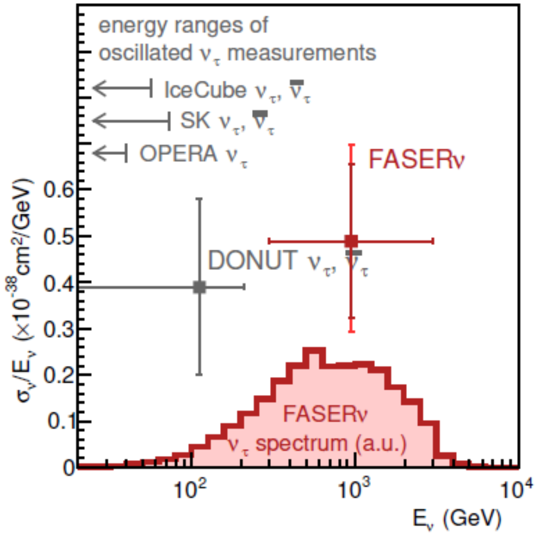
- Precision measurements of high-energy neutrinos (especially tau neutrinos)
  - Tau neutrino is one of the least studied particles
  - Only a few measurements
    - Direct ν_τ beam: DONuT
    - Oscillated ν_τ: OPERA, Super-K, IceCube
  - In FASERν2, 2.3k ν_τ interactions are expected using Sibyll (20k events using DPMJET)

- Neutral-current measurements
  - constraining neutrino non-standard interactions (NSI)

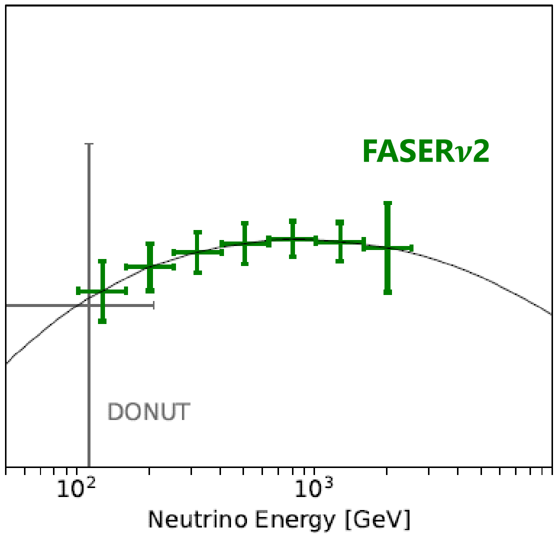
A. Ismail, R.M. Abraham, F. Kling, Phys. Rev. D 103, 056014 (2021)

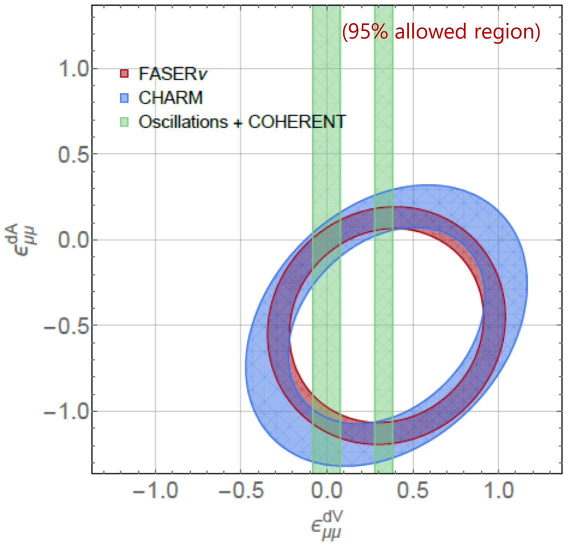
FASERν → FASERν2

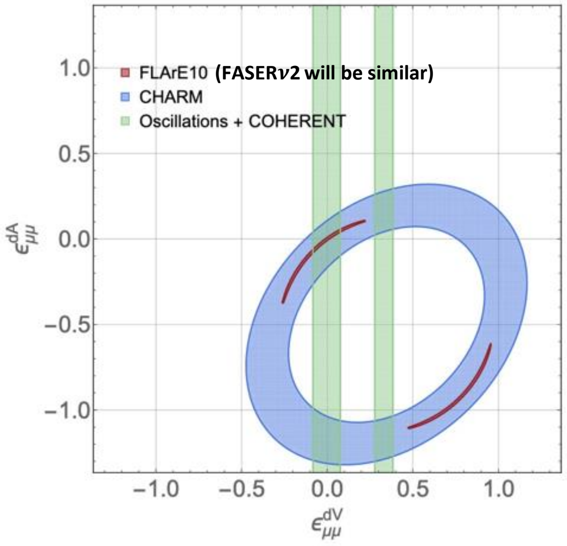
ν_τ and $\overline{\nu_\tau}$



ν_τ and $\overline{\nu_\tau}$

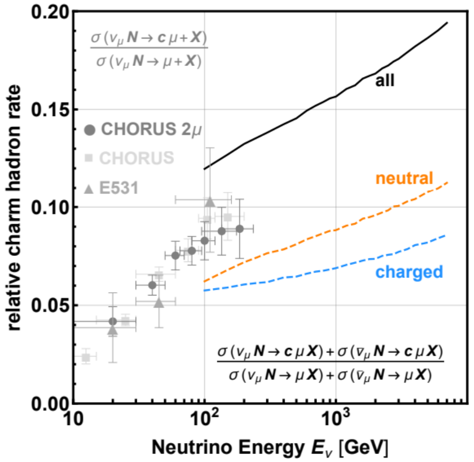


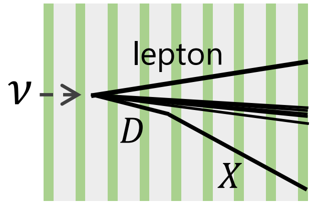


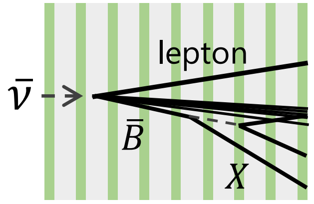


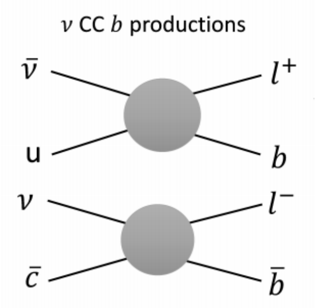
FASERν2 physics potential (cont.)

- Neutrino CC interaction with charm production ($\nu s \rightarrow lc$)
  - Study the strange quark content
- Neutrino CC interaction with beauty production
  - Has never been detected.
- Tests of lepton universality in the heavy-flavor-associated channels









(ν int. rate estimated using Sibyll 2.3d)

		$\nu_e+\bar{\nu}_e$ CC	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_\tau+\bar{\nu}_\tau$ CC
FASERν (1.1 tons, 150 fb^{-1})	**ν int.**	**1.3k**	**6.1k**	**21**
	ν int. with charm	~0.1k	~0.6k	~2
	ν int. with beauty	-	~0.1	-
FASERν2 (20 tons, 3 ab^{-1})	**ν int.**	**178k**	**943k**	**2.3k**
	ν int. with charm	~20k	~90k	~0.2k
	ν int. with beauty	~2	~10	~0.02

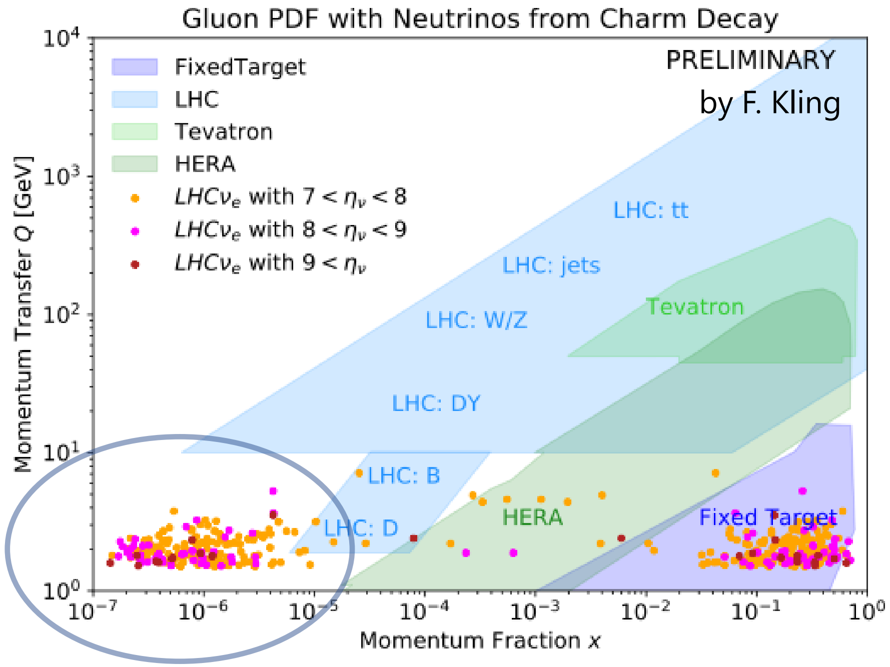
(DPMJET 3.2017)

$\nu_e+\bar{\nu}_e$ CC	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_\tau+\bar{\nu}_\tau$ CC
4.6k	**9.2k**	**131**
~0.5k	~0.9k	~10
-	~0.1	-
668k	**1400k**	**20k**
~70k	~100k	~2k
~7	~10	~0.2

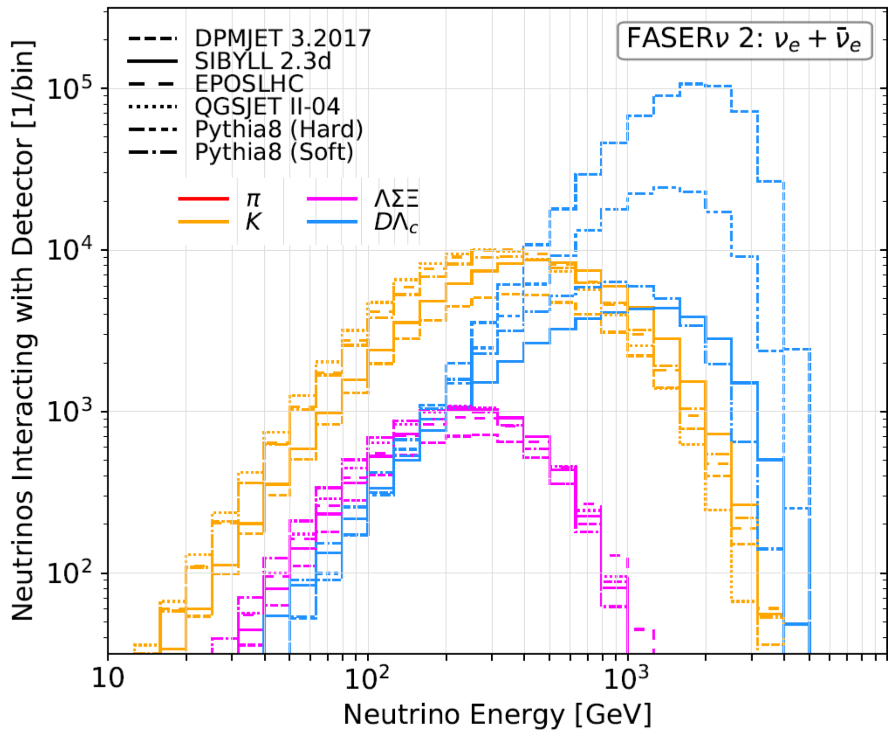
FASERν2 physics potential (cont.)

- Neutrinos produced in the forward direction at the LHC originate from decays of hadrons, mainly pions, kaons, and charm particles.
- With the capability to distinguish neutrinos of different flavors, FASERν2 can provide experimental data on forward particle production with much higher statistics than FASERν.
  - Especially ν_e and ν_τ events to study forward charm and kaon production.

FASERν: η>8.8
FASERν2: η>8.8 or η>8.6



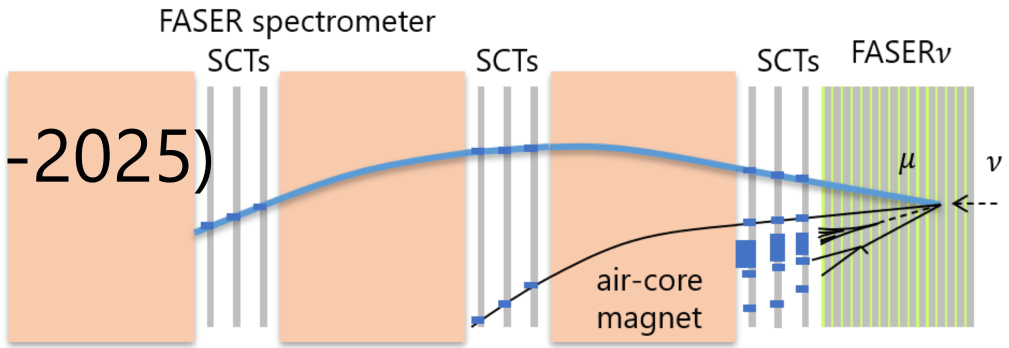
ν_e and $\overline{\nu_e}$ interacting with FASERν2



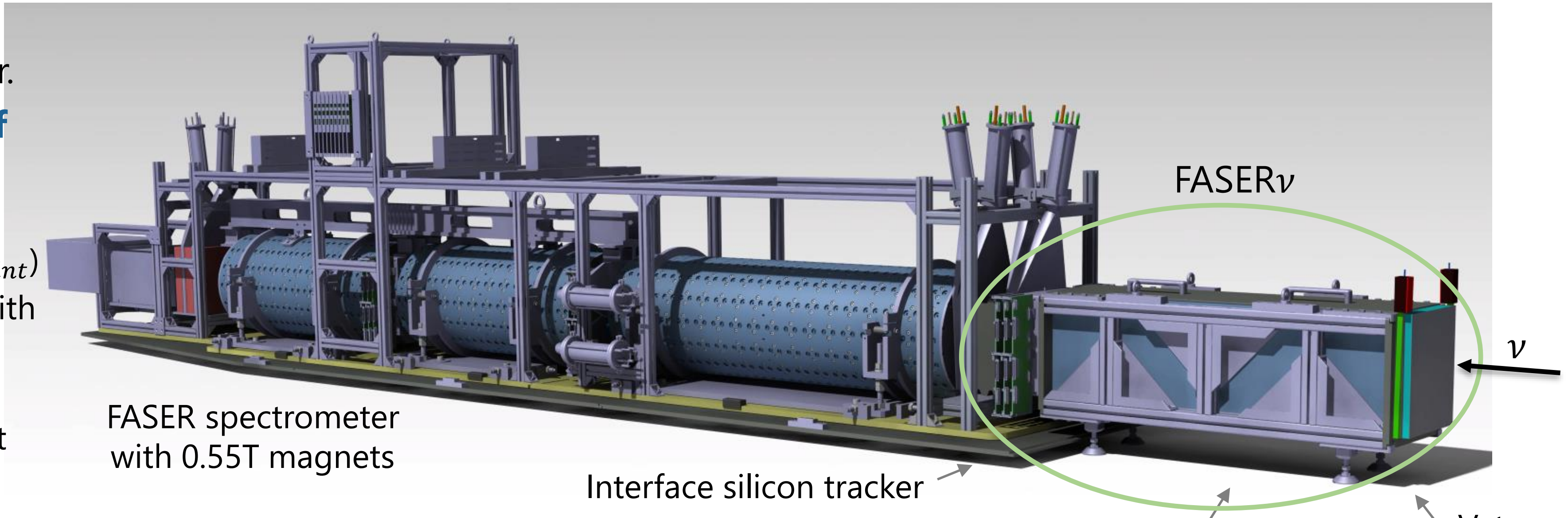
The Forward Physics Facility: Sites, Experiments, and Physics Potential, arXiv: 2109.10905

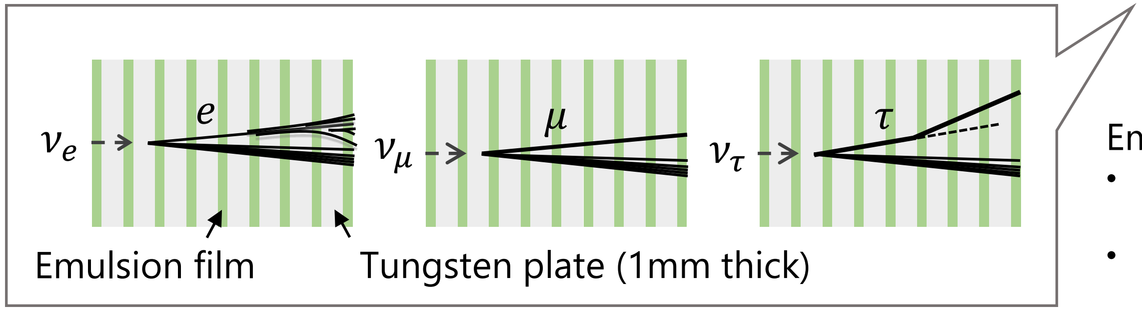
Reminder:

The FASERν detector for LHC Run 3 (2022-2025)



- **Emulsion/tungsten detector, interface silicon tracker, and veto station** will be placed in front of the main FASER detector.
- Allow to distinguish **all flavor of neutrino interactions**.
  - **Muon identification** by their track length in the detector ($8\lambda_{int}$)
  - **Muon charge identification** with hybrid configuration → distinguishing ν_μ and $\bar{\nu}_\mu$
  - **Neutrino energy** measurement with ANN by combining topological and kinematical variables





Emulsion/tungsten detector

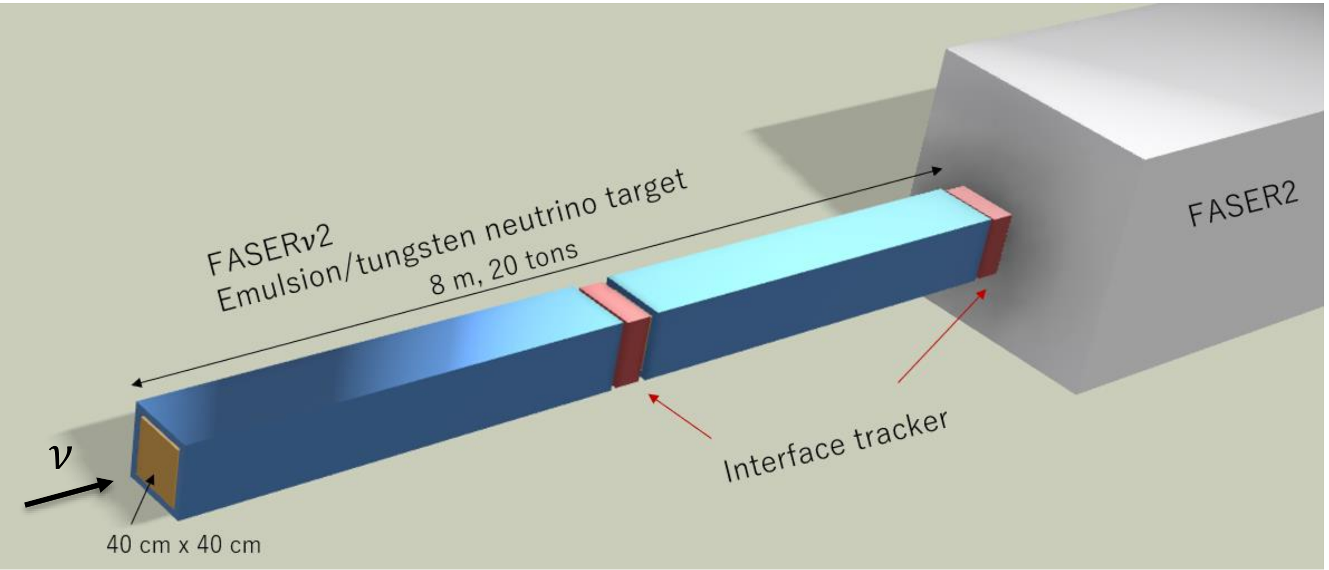
- 770 1-mm-thick tungsten plates, interleaved with emulsion films
- 25x30 cm^2, 1.1 m long, 1.1 tons detector ($220X_0$)

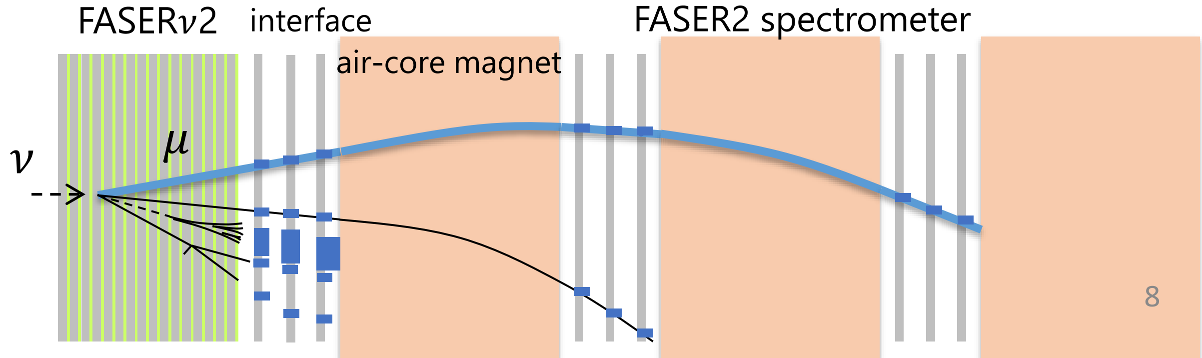
The FASERν2 detector for HL-LHC

Requirements

- **On-axis**
  - to maximize the neutrino interaction event rate of all three flavors and also to maximize neutrino energy
- **Large mass**
  - to gain statistics
- **Flavor sensitivity**
  - to identify different lepton flavors (electron, muon, tau) and charm/beauty decays
- **Energy reconstruction**
  - to measure muon and hadron momenta, energy of electromagnetic showers, and estimate neutrino energy
- **$\nu_\tau/\overline{\nu_\tau}$ separation**
  - Charge measurement of tau daughters → A global analysis that combines information from FASERν2 with the FASER2 spectrometer, with a help of an interface detector, is required.

- **The FASERν2 detector** is envisioned to be composed of 3300 emulsion layers interleaved with 2 mm-thick tungsten plates.
- It will also include a veto detector and interface detectors to the FASER2 spectrometer.
- The total volume of the tungsten target is 40 cm × 40 cm × 6.6 m, and the mass is 20 tons.



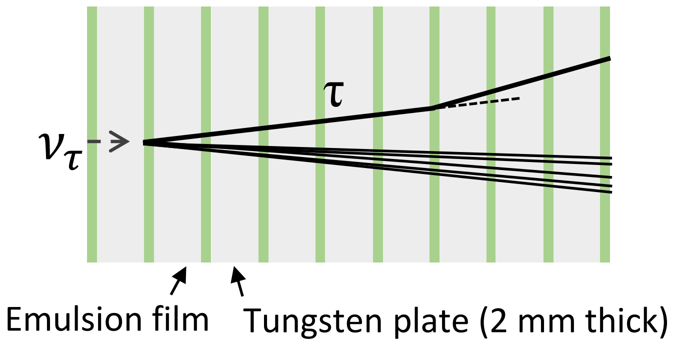


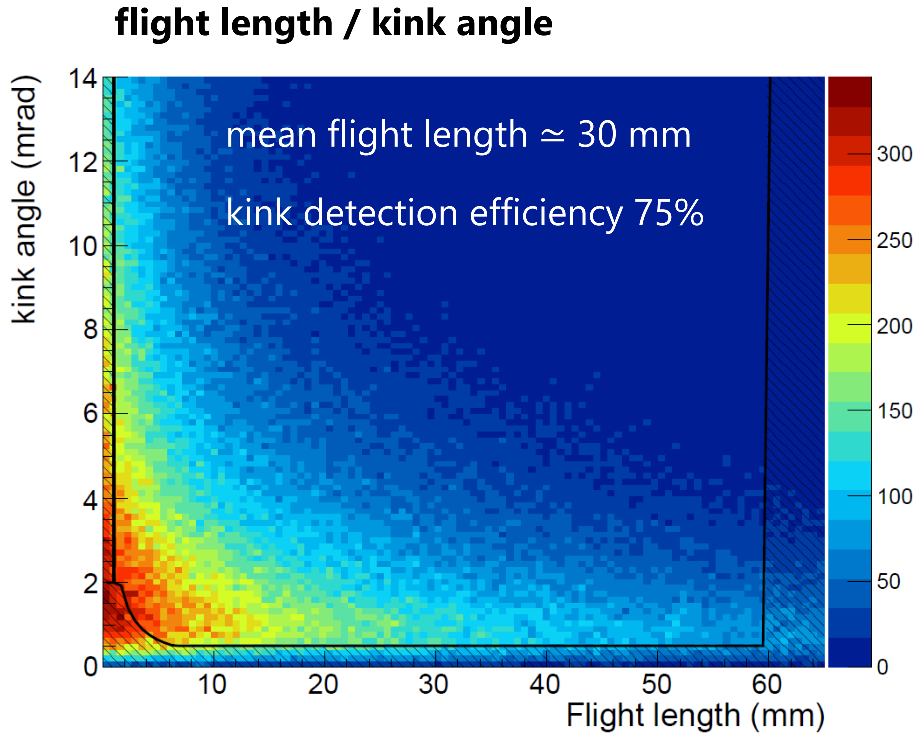
Detection of tau decays

- Special resolution of hits in the emulsion
  - 0.5 μm (measured in the FASERν pilot run data)

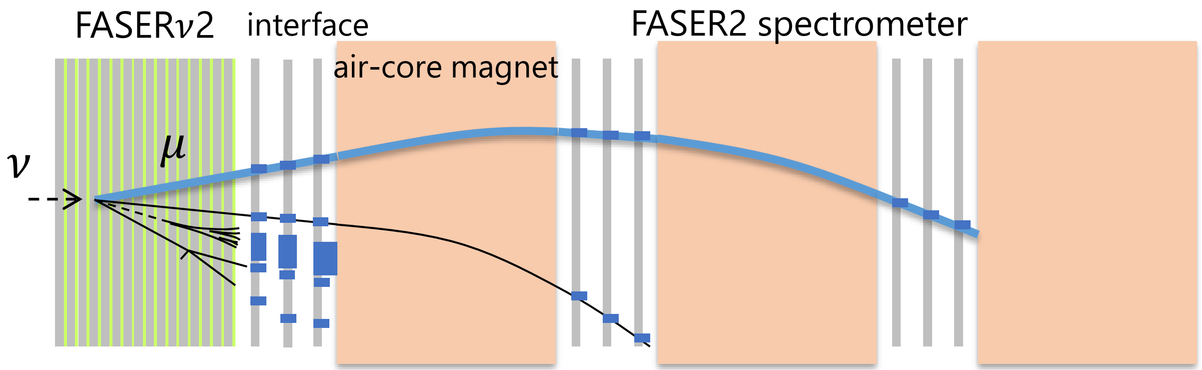
- → Angular resolution with the arm length of 10 mm
  $= 0.5\times\sqrt{2}/10000 = \sim 0.1$ mrad

- To detect a kink,
  - tau should cross at least one emulsion layer,
  - kink angle should be larger than four times the angular resolution and more than 0.5 mrad
  - → reasonable efficiency for τ decays (75% for 1-prong decays)



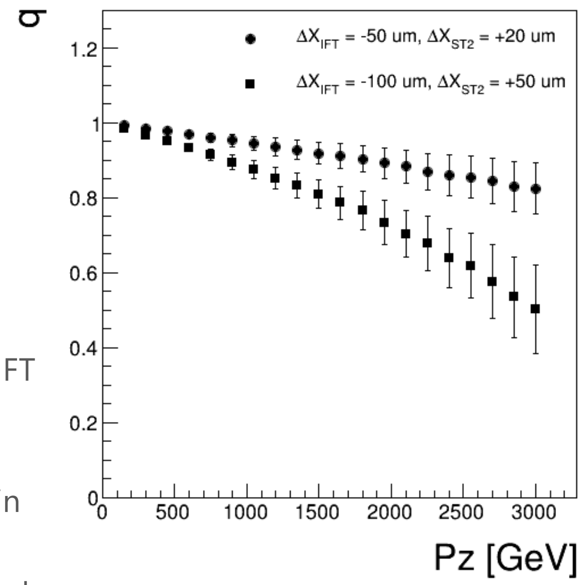


ν_τ / $\bar{\nu}_\tau$ separation



- So far $\bar{\nu}_\tau$ has not been studied separately from ν_τ.
- Charge measurements can be performed for muons.
  - Tau branching fraction decaying into a muon ($\tau^- \to \mu^- \nu_\mu \nu_\tau$) = 17.4%
- Charge ID capability
  - For FASERν: FASER spectrometer length ~4 m, 0.55T
  - For FASERν2: FASER2 spectrometer length ~4m/~20 m, 1T(?)
  - Similar or better performance (w.r.t. FASERν) is expected.
    - Alignment requirements should be considered in FASER2 detector design as charge ID performance at high energy is very sensitive to tracker alignment.

Charge ID capability in FASER



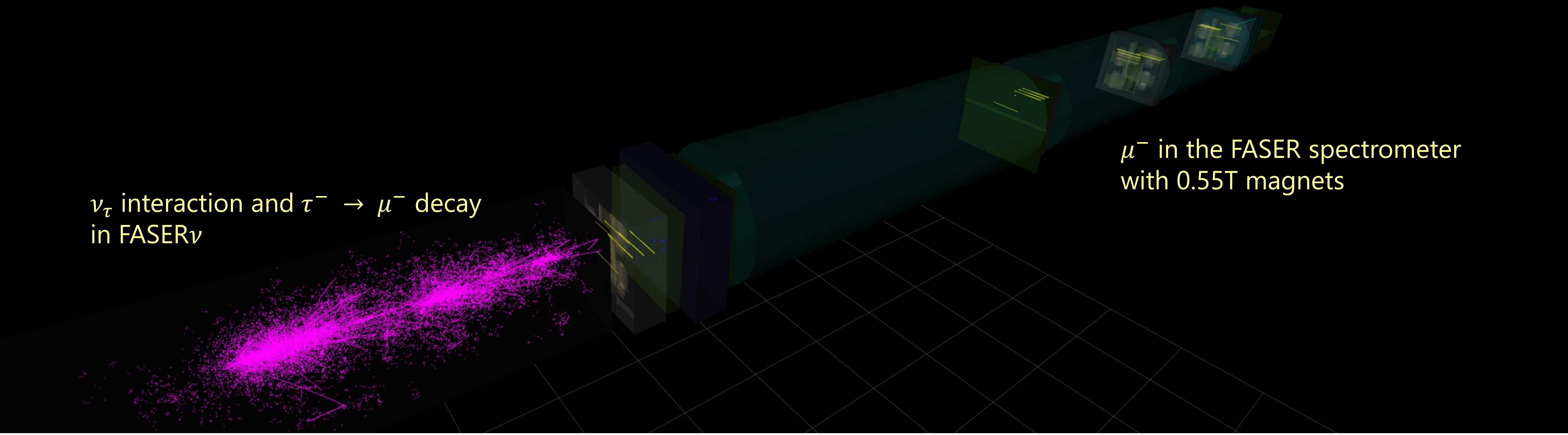
- Tracking performance with IFT/veto was evaluated with mathematical calculation, including alignment shifts of IFT and FASER tracker stations.
- Particle charge can be identified up to ~1.7 TeV with 3σ even with alignment shift of 200 μm in IFT and 100 μm in the second tracker station in FASER.
  - Uncertainty on q was checked when fixing x on each layer with q and r as $q(r - \sqrt{r^2 - z^2}) + \alpha z + \beta$

Event display of a simulated ν_τ event

Thanks to
D. Casper

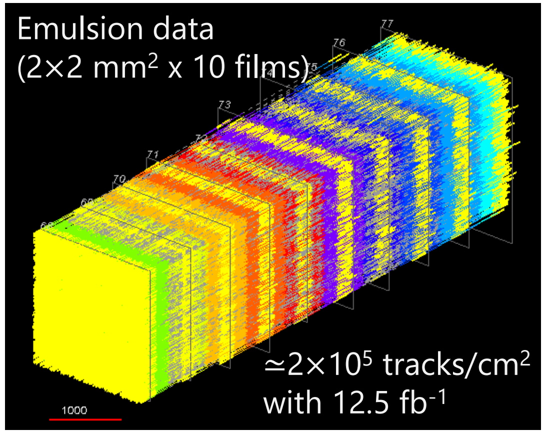
A ν_τ event with the tau decaying into a muon and the muon passing through the FASER spectrometer

(Will perform a similar simulation for FASERν2+FASER2 geometry)

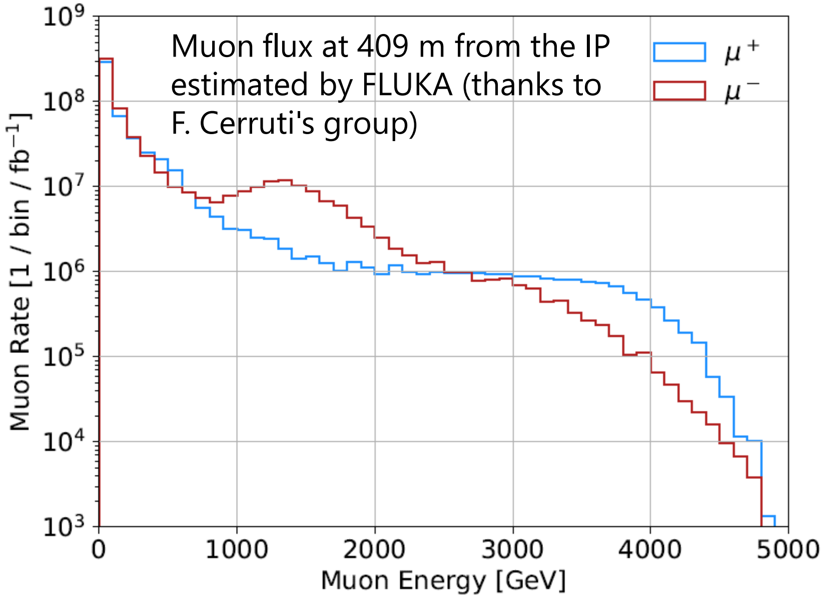


Key issue for the emulsion detector:

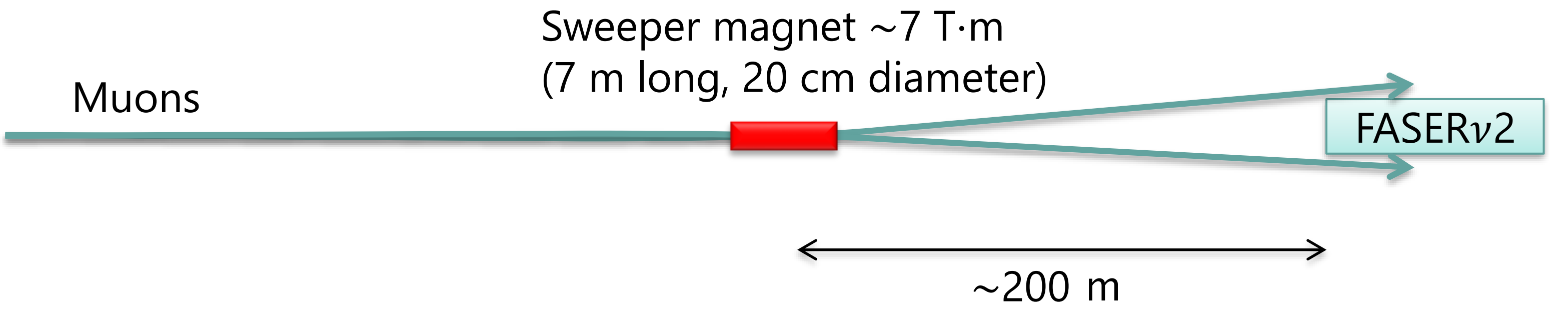
Reducing the muon rate with a sweeper magnet



- The background muon rate may be able to be reduced with a sweeper magnet.
- The feasibility of such a sweeper magnet is under study.

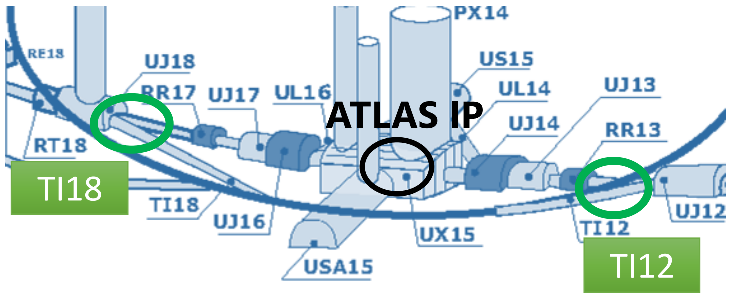


Jamie Boyd, "FPF Sweeper Magnet", 3rd FPF workshop

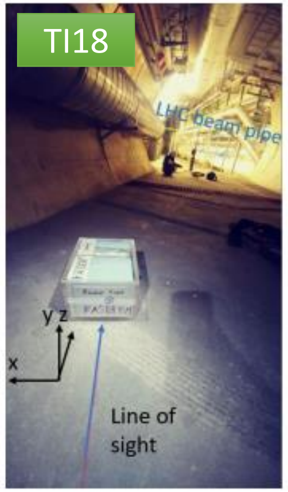


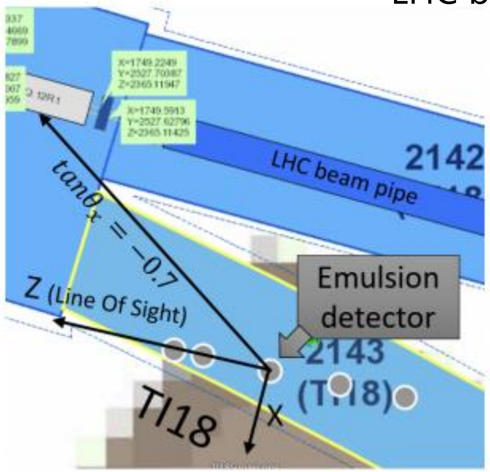
- Assuming a field integral of 7 T·m for the sweeper magnet, this would sweep a 100 GeV (500 GeV) muon 4.2 m (0.8 m) from the LoS at the FPF (200 m away).
  - Still needs to be studied with simulation if the magnet would also sweep muons into the LoS, and if so what the overall reduction of the background along the LoS would be.
  - If we have such a sweeper magnet, it will be enough to replace emulsion films once per year. If we don't have a sweeper magnet, we need to replace them every ~50 fb^{-1}.

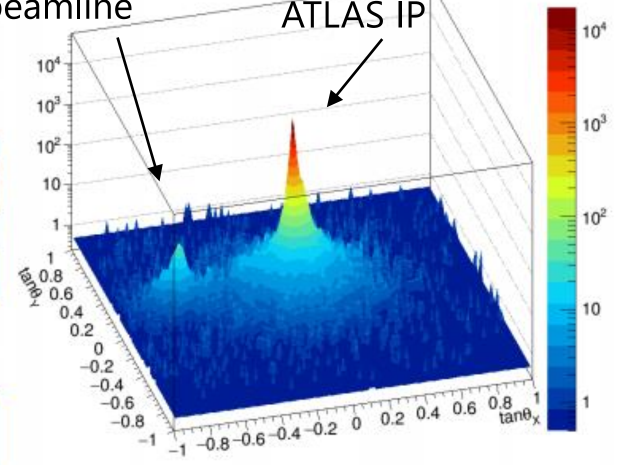
Muon flux measurements on site



- Measurements performed in 2018



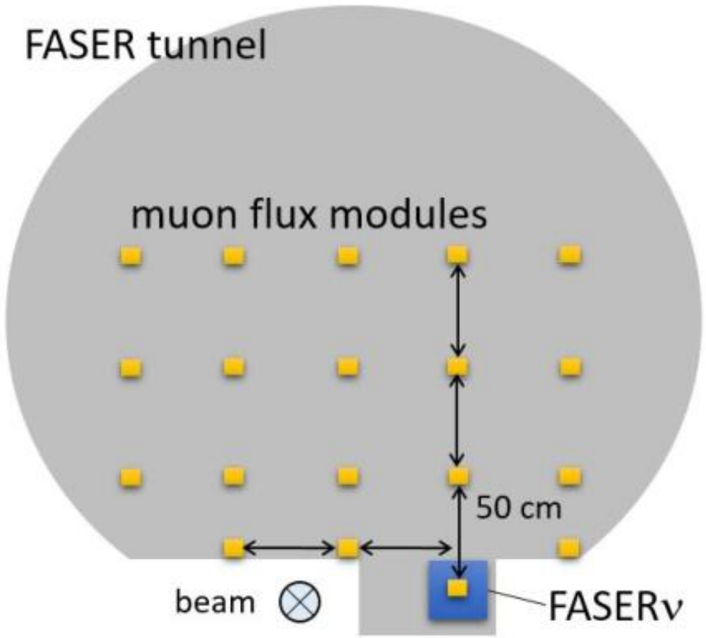




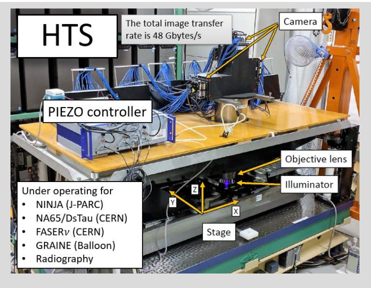
  - The charged particle flux within 10 mrad of the angular peak (dominated by energetic muons) is $(1.7\pm0.1)\times10^4$ tracks/cm^2/fb^{-1}

Reported by the FASER Collaboration,
First neutrino interaction candidates at the LHC,
Phys. Rev. D 104, L091101 (2021)

- Planning to measure the flux and position profile in 2022
  - Emulsion-based beam monitor (installing several small modules at various positions)



Emulsion detector preparation and processing chain



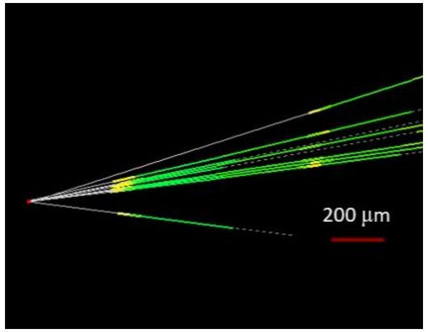
In Japan: **Emulsion film production** → **At CERN**: **Detector assembling** → **Exposure** → **Disassembling** → **Development** → **In Japan**: **Full area readout**

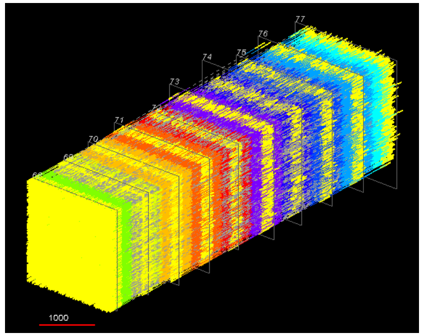
Off-line analysis: Alignment → Track reconstruction → Vertex reconstruction → μ / e ID → Search for tau/charm decays → Kinematical analysis

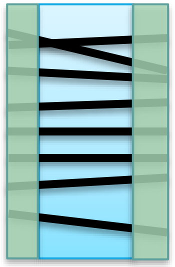
Interface tracker (IFT) data

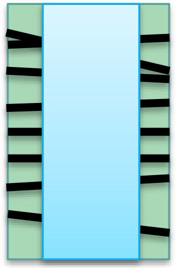
Spectrometer data

~300 TB/year (FASERν, LHC Run3)
~1000 TB/year (FASERν2, HL-LHC)



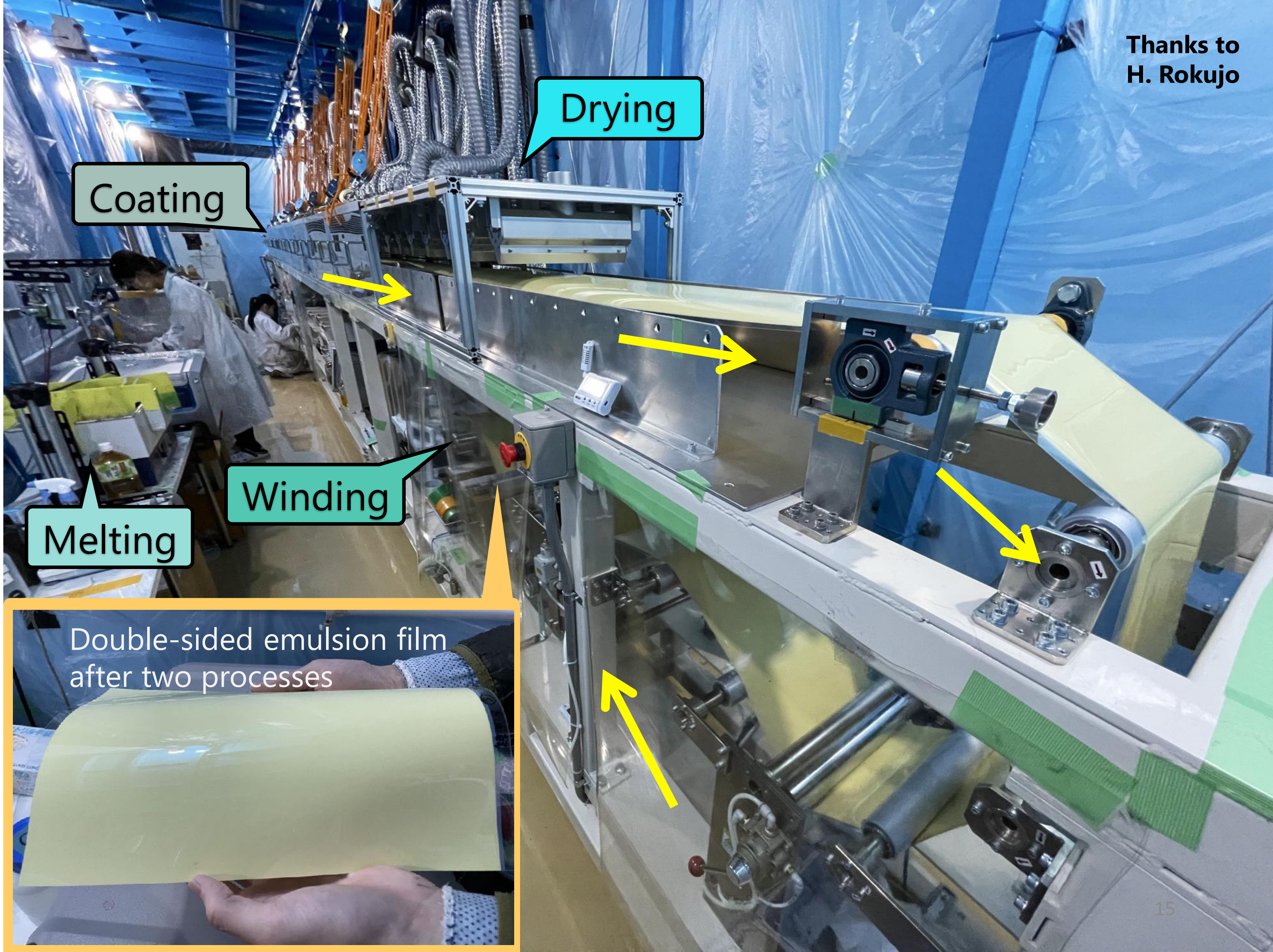






The new emulsion film coating facility

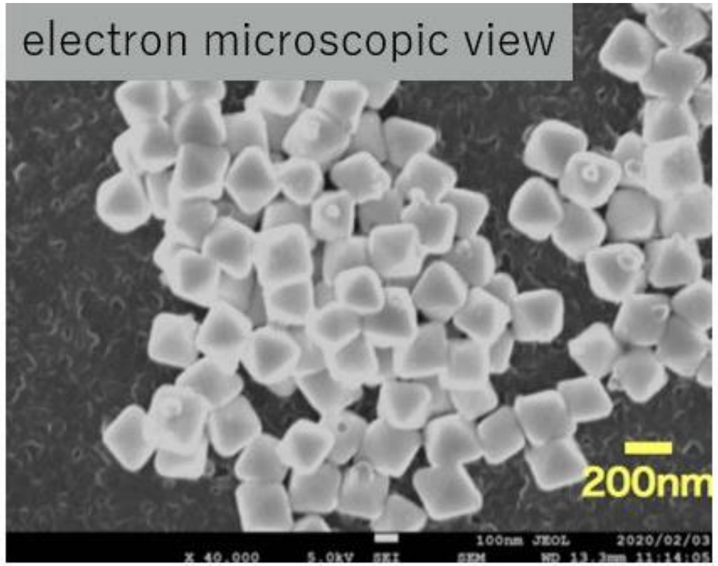
(operating
since May 2021)

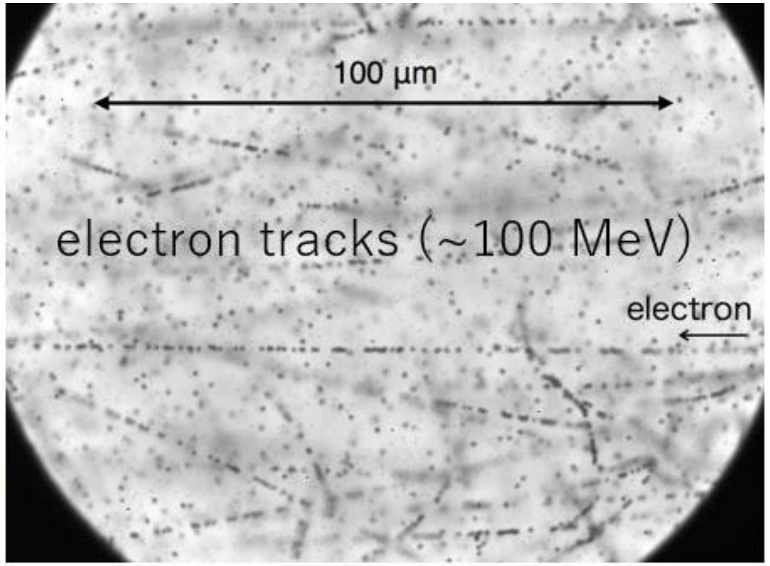


Emulsion production capacity

- The emulsion gel and film production facilities were set up in Nagoya in 2020.
- Mass production of the gel and films are ongoing for the running experiments.

- Prospects for FASERν2
  - Production capacity of the facility: ~2000 m^2/year
  - **Possible to produce ~500 m^2/year for FASERν2**

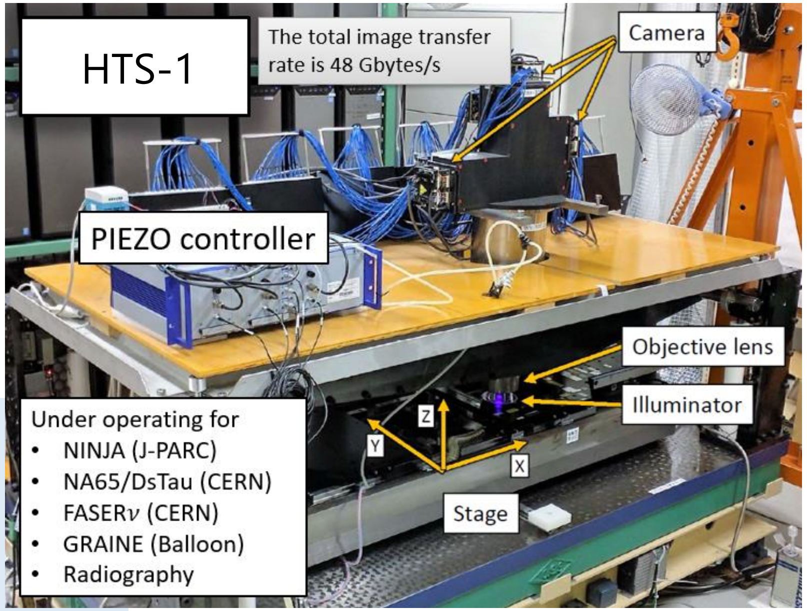




Emulsion readout systems

	Start year	Field of view (mm²)	Readout speed (cm²/h/layer)
S-UTS	2006	0.04	72
HTS-1	**2015**	**25**	**4500**
HTS-2	**2021**	**50**	**25000**

- **Fast readout of emulsion films**
  - Significant progress in the readout speed
  - ~100 times faster than OPERA
- **HTS-1** is under operation for several experiments.
- **HTS-2** is under commissioning.
- HTS-2 concept
  - Very large field of view: 9 x 5.5 mm2 (x2 cf. HTS-1)
  - Quick and continuous stage using the linear motors (good transfer characteristic) and counter stage.
  - GPGPU based image processing: <30 ms @tanθ<1.6 (total 72 Geforce RTX2080 will be used.)



Readout time for FASERν2
(1 replacement = 530 m^2)

~2400 hours/year with HTS-1 or
~420 hours/year with HTS-2

It will be **possible to finish reading the data taken in each year within a year** using either of the above systems.

Summary and prospects

- FASERν2 is designed to carry out **precision measurements of high-energy neutrinos (especially tau neutrinos)** and heavy flavor physics studies.
  - With an emulsion-based detector and interface detectors to the FASER2 spectrometer

- Based on recent developments on emulsion detector production and readout systems, it's feasible to conduct FASERν2, and further updates are foreseen.

- We expect to collect **>2000 tau-neutrino charged-current neutrino interactions in FASERν2**.
  - 2.3k ν_τ interactions expected using Sibyll (20k events using DPMJET)

- Further studies for defining the detector structure are in progress.

Thank you for your attention