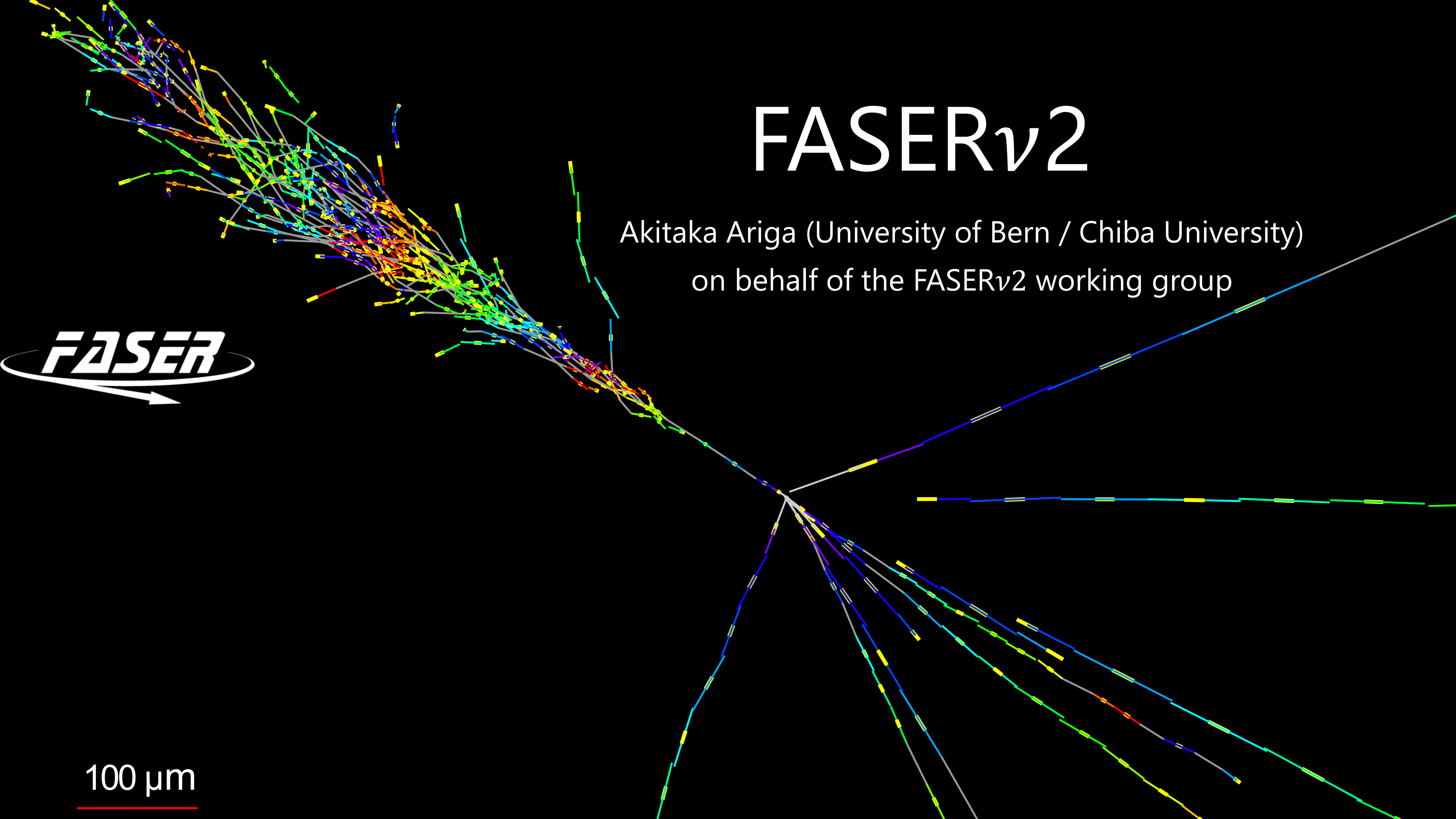
FASERν2

Akitaka Ariga (University of Bern / Chiba University)
on behalf of the FASERν2 working group



FASERν and FASERν2

Now ↓

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC Run 2				LHC Run 3							LHC Run 4				
						PBC review	LOI	TDR	Construction				Commissioning	Data taking	

11 kg x 12 fb^{-1}

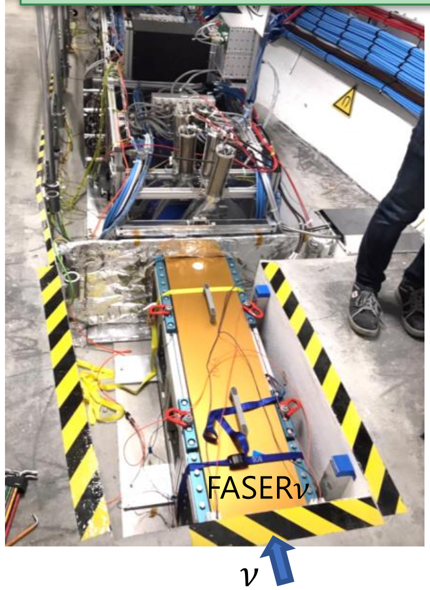
FASERν pilot run

First neutrino interaction candidates at the LHC

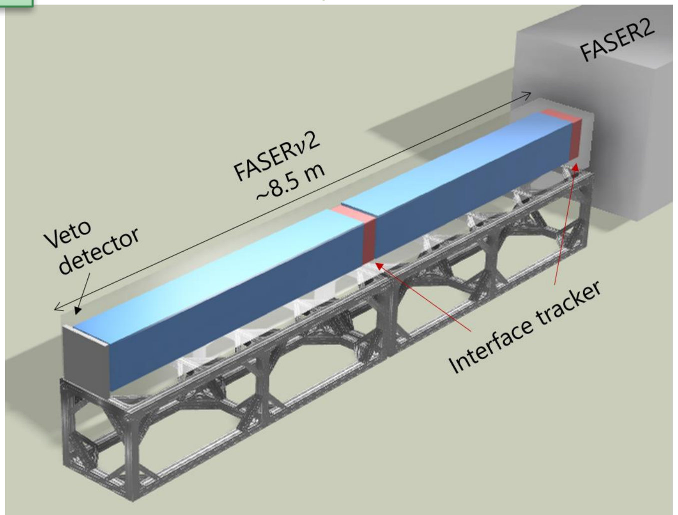
FASER Collaboration,
Phys. Rev. D 104, L091101 (2021)

1.1 tons x 250 fb^{-1}

FASERν physics run



CONF note, Aug. 2023,
https://cds.cern.ch/record/2868284/files/ConferenceNote.pdf



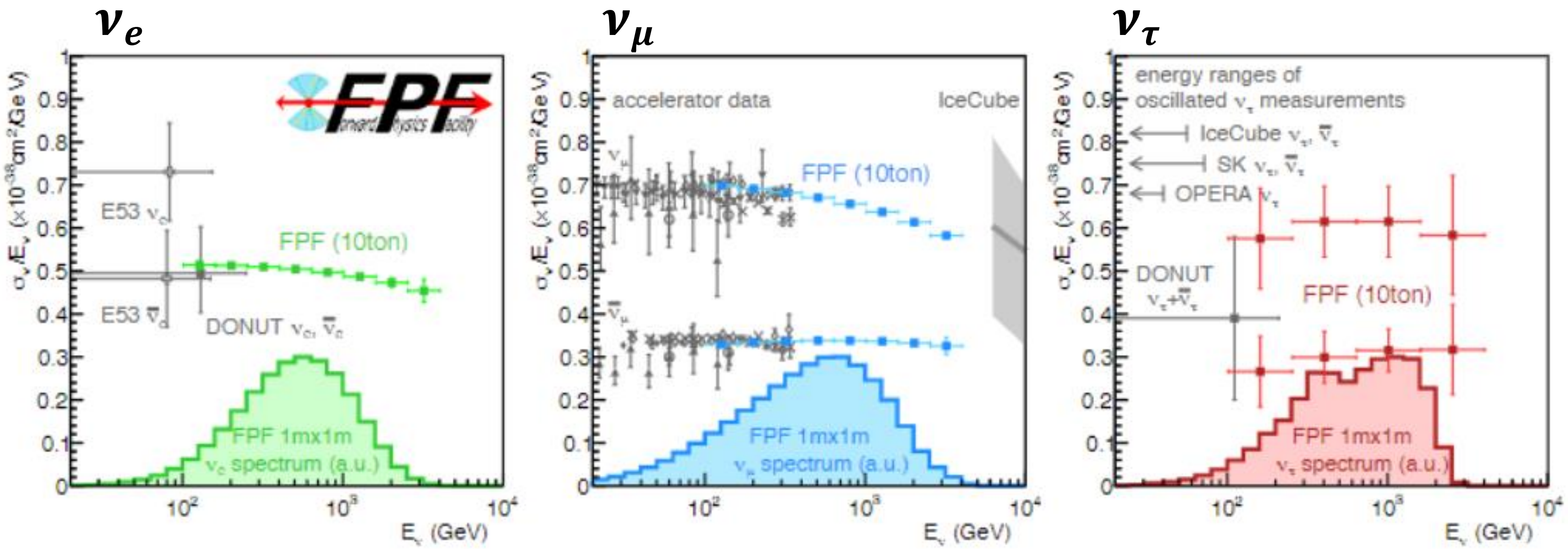
10-20 tons x 3 ab^{-1}

FASERν2

Precision ν_τ measurements
and heavy flavor physics studies
$10^3 - 10^4$ ν_τ interactions

Motivations

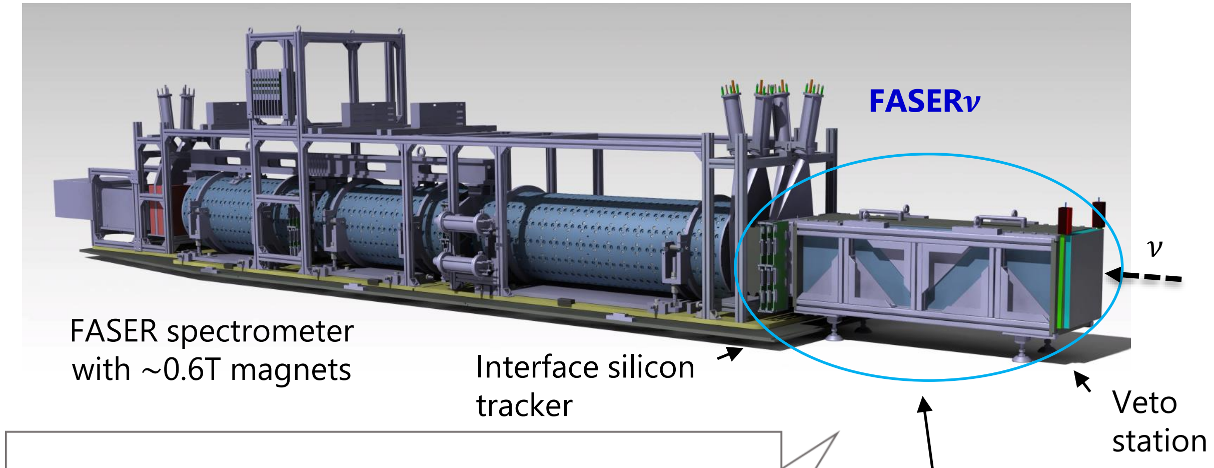
- FASERν @LHC-Run 3 (1.1 ton)
  - First study of collider neutrinos at TeV energies
  - ν_e/ν_μ universality in cross sections and charm production, QCD
- FASERν2 @HL-LHC (~20 ton)
  - Tau neutrino physics, precise measurement of cross sections, Lepton Flavor Universality, NSI, rare processes
  - QCD, saturation, cosmic rays

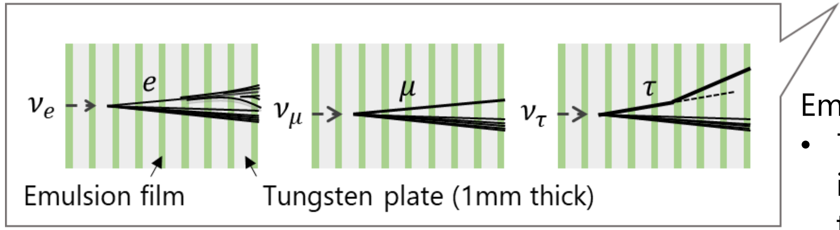


Statistical error only

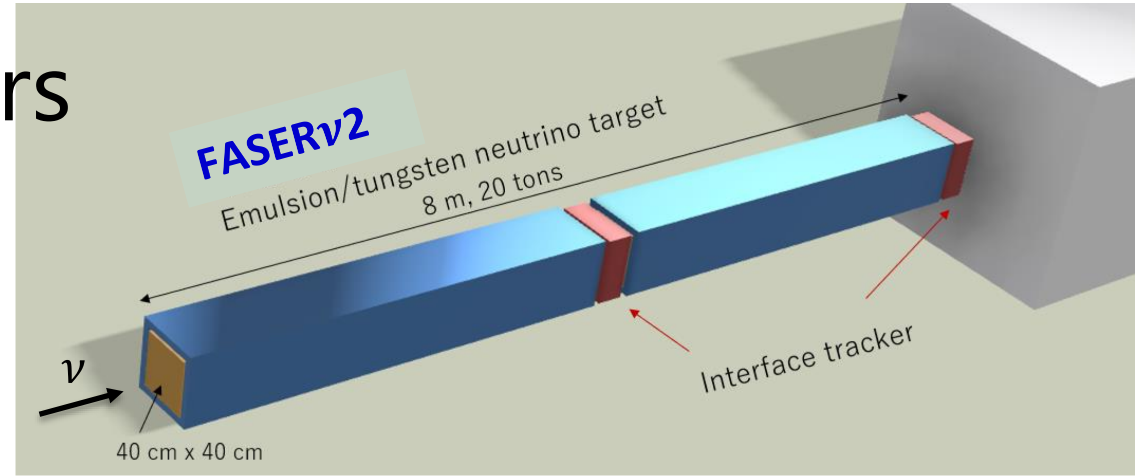
FASERν and FASERν2 detectors

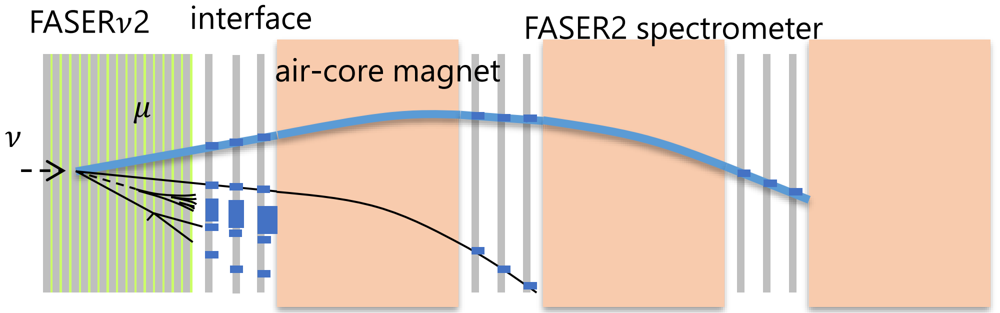
- On-axis, to maximize # of neutrino interactions
- Flavor sensitivity
- Charge ID for muons ($\nu_\mu/\bar{\nu}_\mu$ separation, $\nu_\tau/\bar{\nu}_\tau$ separation)





Emulsion/tungsten detector
- 730 emulsion layers interleaved with 1.1-mm-thick tungsten plates
- 25x30 cm^2, 1.1 m long, 1.1 tons
- 3 installations per year



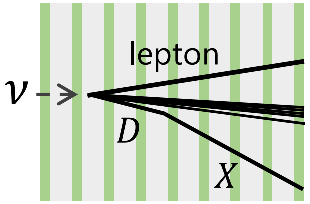


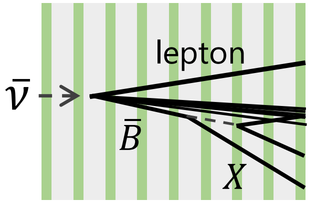
- FASERν2 detector: 3300 emulsion layers interleaved with 2 mm-thick tungsten plates
- Veto and interface detectors to the FASER2 spectrometer.
- The total volume of the tungsten target is 40 cm $\times$ 40 cm $\times$ 6.6 m, and the mass is 20 tons.
  - One replacement per year with muon BG reduction
  - 3 or more if muon BG is not reduced

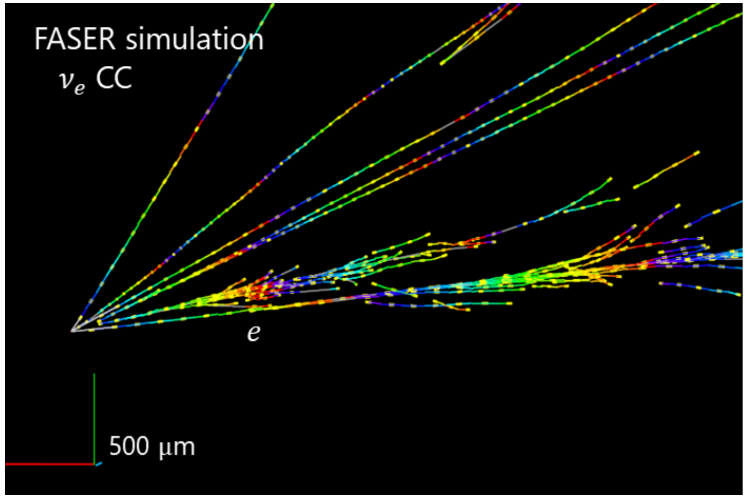
FASERν and FASERν2: expected number of events

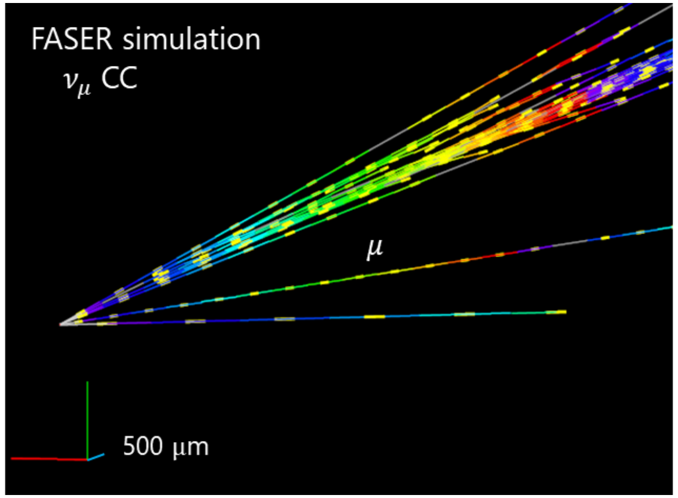
Based on "F. Kling and L.J. Nevay, Forward Neutrino Fluxes at the LHC, [Phys. Rev. D 104, 113008](#)"
and "J.L. Feng et al., The Forward Physics Facility at the High-Luminosity LHC, [arxiv:2203.05090](#)"

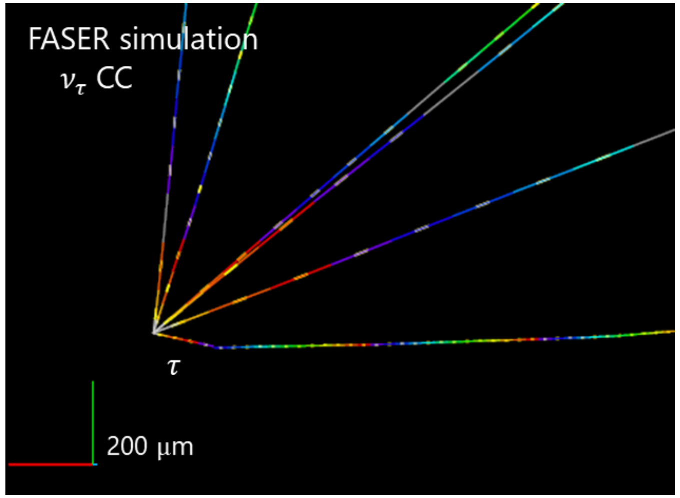
		(ν int. rate estimated using **Sibyll 2.3d**)			(**DPMJET 3.2017**)		
		$\nu_e+\overline{\nu_e}$ CC	$\nu_\mu+\overline{\nu_\mu}$ CC	$\nu_\tau+\overline{\nu_\tau}$ CC	$\nu_e+\overline{\nu_e}$ CC	$\nu_\mu+\overline{\nu_\mu}$ CC	$\nu_\tau+\overline{\nu_\tau}$ CC
FASERν (1.1 tons, 150 fb^{-1})	**ν int.**	**0.9k**	**4.8k**	**15**	**3.5k**	**7.1k**	**97**
	ν int. with charm	~0.1k	~0.5k	~2	~0.4k	~0.7k	~10
	ν int. with beauty	-	~0.05	-	-	~0.1	-
FASERν2 (20 tons, 3 ab^{-1})	**ν int.**	**178k**	**943k**	**2.3k**	**668k**	**1400k**	**20k**
	ν int. with charm	~20k	~90k	~0.2k	~70k	~100k	~2k
	ν int. with beauty	~2	~10	~0.02	~7	~10	~0.2











Emulsion film

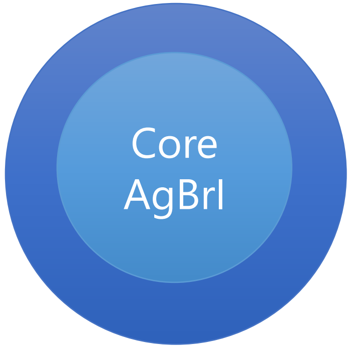
A minimal detector:

Silver bromide (AgBr) Cristal

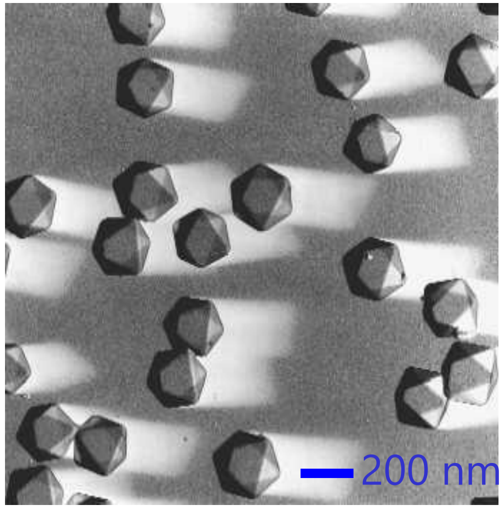
- diameter = 200 nm
- detection eff. = 0.16/crystal
- noise rate = 0.5×10^{-4}/crystal
- volume occupancy = 30%

10^{14} detection channels per cm^3

Core-shell structure



Shell AgBr (+Fe)

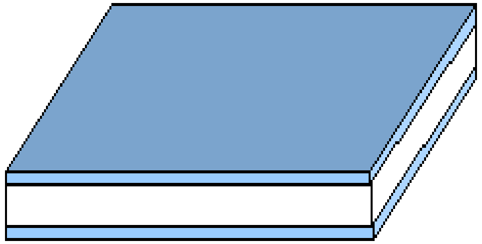


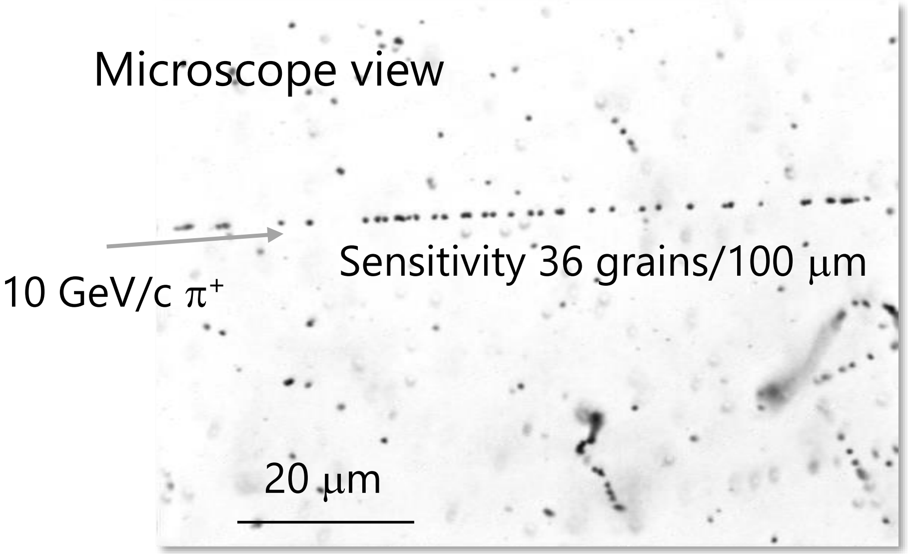
AgBr crystals of 200 nm diameter

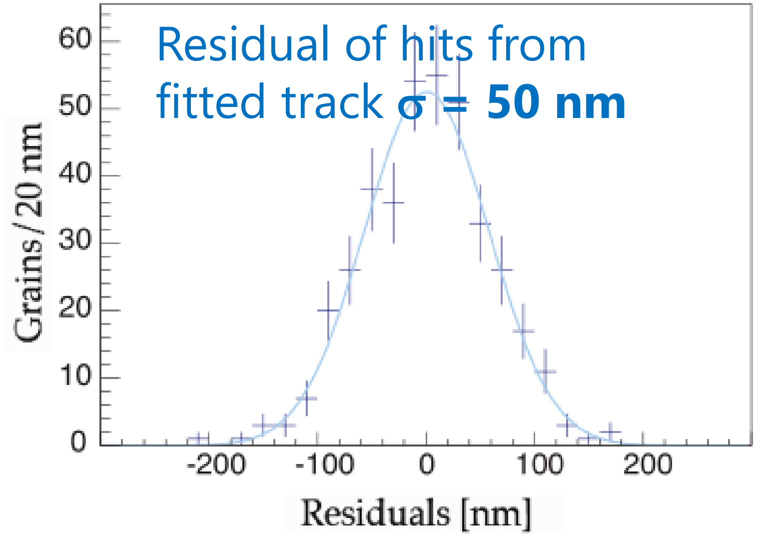
"Nuclear Emulsions", https://link.springer.com/chapter/10.1007/978-3-030-35318-6_9

Emulsion gel = composite of AgBr crystals and gelatin

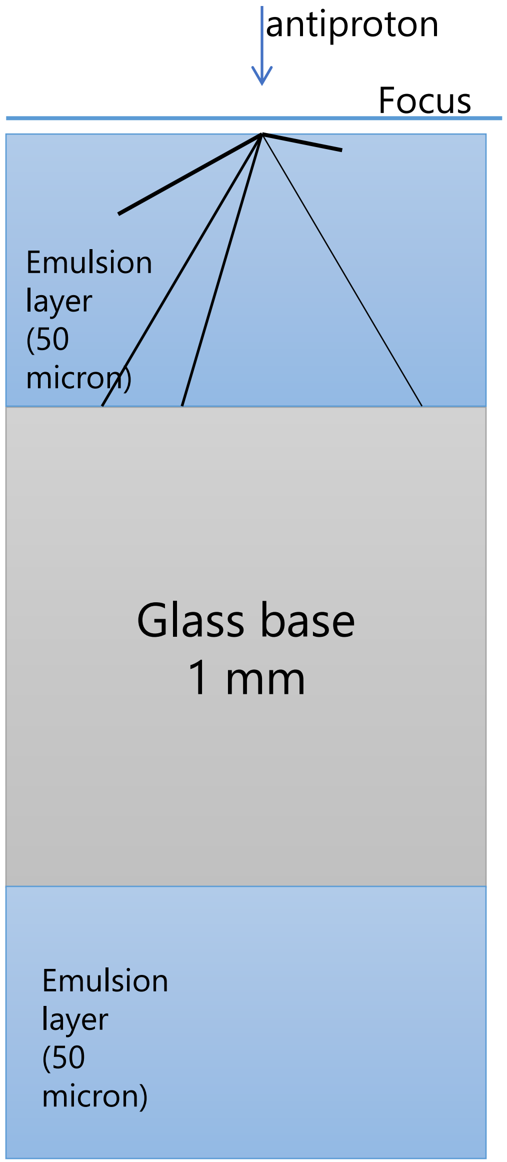
Emulsion film has two layers of 65-μm-thick emulsion layer on both sides of 210-μm plastic base







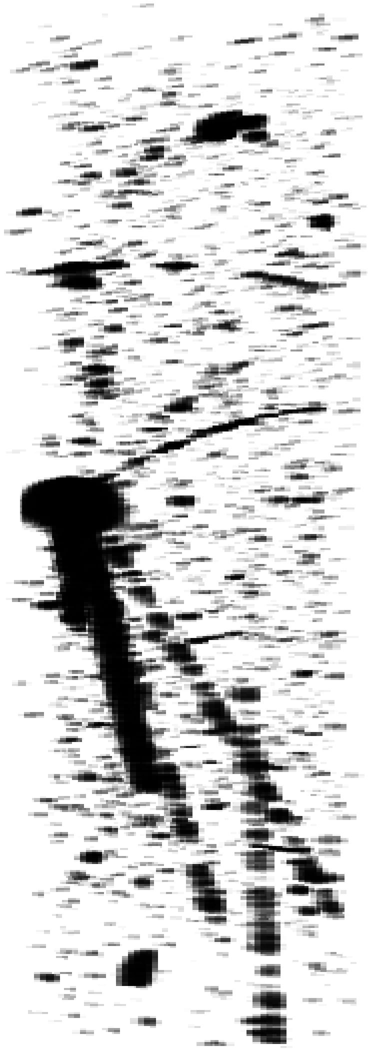
Microscope view in an emulsion detector



Antiproton annihilation taken in AEgIS

200 microns

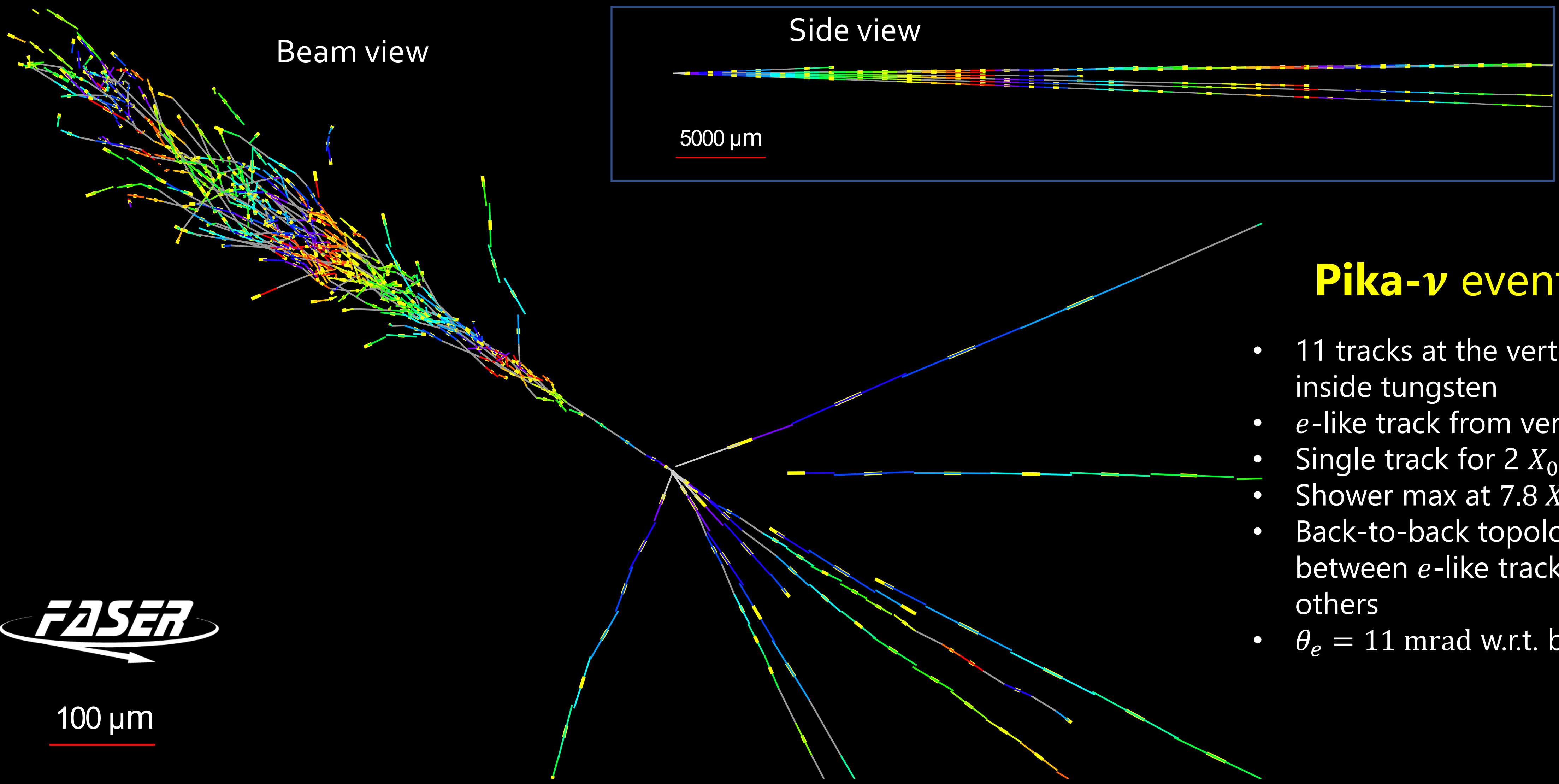
3D view of emulsion detector



150 μm x 120 μm x 50 μm

- 3D high resolution hits
- Work as tracker
- dE/dx proportional to darkness (Number of grains)

Observed ν_e candidate in FASERν



Pika-ν event

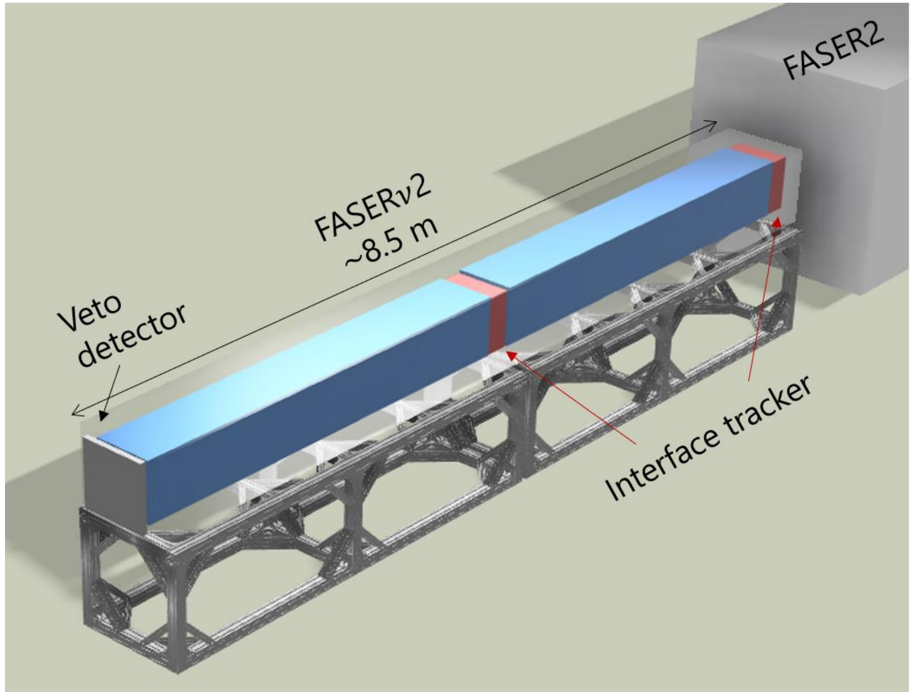
- 11 tracks at the vertex, 615 μm inside tungsten
- e-like track from vertex
- Single track for 2 X_0
- Shower max at 7.8 X_0
- Back-to-back topology, 175° between e-like track and others
- $\theta_e = 11$ mrad w.r.t. beam

Status of FASERν2 tasks

as of 29/2/2024

Bold lines are discussed in next slides

- **Emulsion films**
  - Film production of ~550 m^2 per year
  - **Film shape still to be defined**
  - Emulsion production facility in Nagoya University
  - **Performance tests in realistic conditions (long-term performance)**
- **Tungsten target**
  - 2-mm-thick tungsten plates, purity>99.95%
  - Will purchase sample plates and start testing them
- **Mechanical structure, assembly method, cooling system**
  - Mechanical structure to hold 20-ton emulsion-tungsten target
  - Keep temperature as low as possible to prevent "fading"
  - **Prototype test is under preparation**
- **Emulsion facility**
  - Dark room for assembling and development
  - Further investment may be needed depending on the film shape, etc.
- **Emulsion readout system**
  - Development of HTS3 in Nagoya University
  - Considering 2nd facility in Chiba University



- **Veto, interface tracker and charge ID**
  - Combined analysis with FASER2
  - **Detector technology yet to be defined**
- **Performance, physics sensitivity studies**
  - Simulation studies to be done
  - **Test reconstruction with real data in FASERν with FASERν2 configuration**
- **Muon background reduction**
  - Sweeping magnet

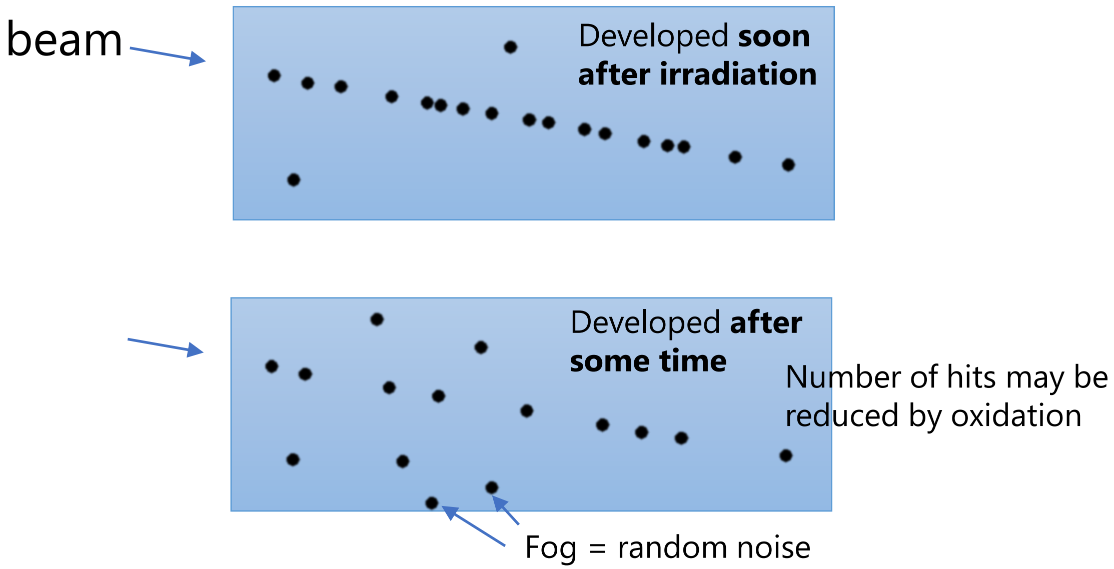
Hiroaki Kawahara (Kyushu), Tomoko Ariga (Kyushu)

Long-term performance test of emulsion

To check if the emulsion perform well when developed after long-term exposure.

- Track recognition efficiency with HTS
- Noise density

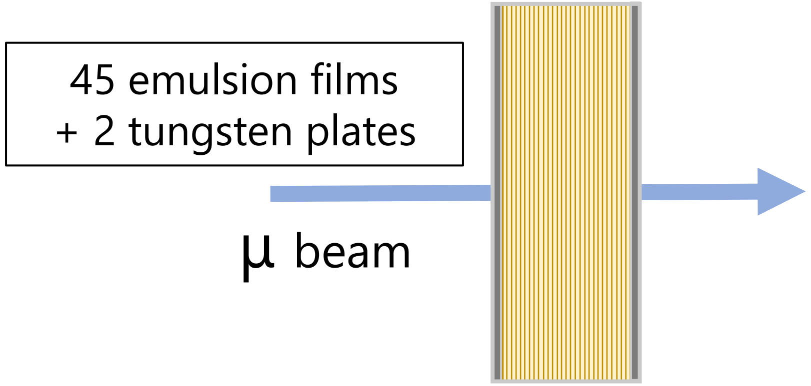
Concerned "Fading effect" and "Fog increase"



Fading & noise increase are both accelerated by high temperature

2023 test beam in Augst

- 45 emulsion films, exposed to muon beam



Delayed photo-development
to study the long-term performance

- 45 films → 9 groups of 5 films
- 7 groups are put in 21℃ and 2 groups in 12℃ until the development.

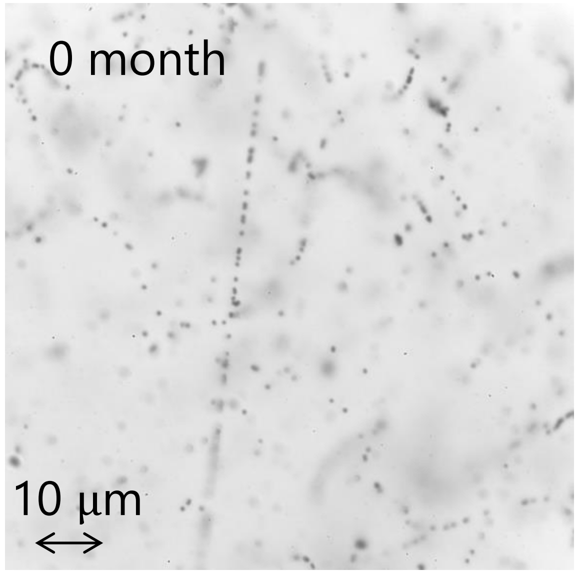
Hiroaki Kawahara, Tomoko Ariga

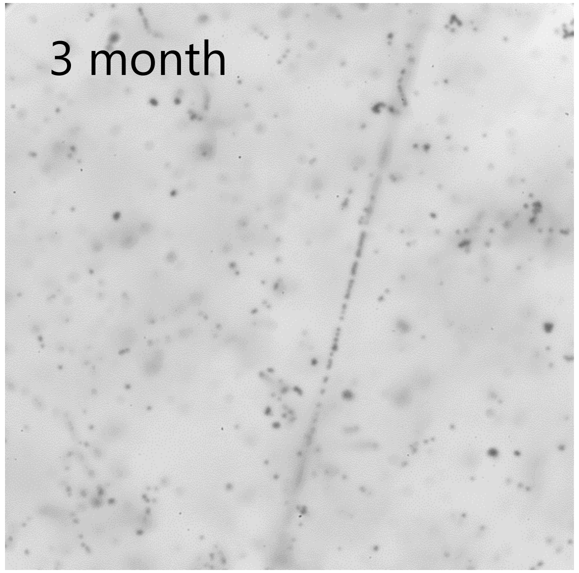
- The evaluation is in progress for the samples up to 3 months.
- No significant increase in the noise density is observed. The sensibility / efficiency will be checked.

N films	**Films**	**Time until development**	**Storing temperature**	**Fog density** (/(10 μm)^3)	**Efficiency**
5 films	Cutting and resetting in Japan	0	21℃	3.1±0.3	Will be checked
5 films		1 month	21℃	3.1±0.3	
5 films		3 months	21℃	2.8±0.3	
5 films		9 months	21℃	To be developed	
5 films		3 months	12℃	2.7±0.3	
5 films		9 months	12℃	To be developed	
5 films	Without resetting	0	21℃		
5 films		3 months	21℃	3.3±0.3	
5 films		9 months	21℃	To be developed	

9-month sample will be processed in May-June 2024.

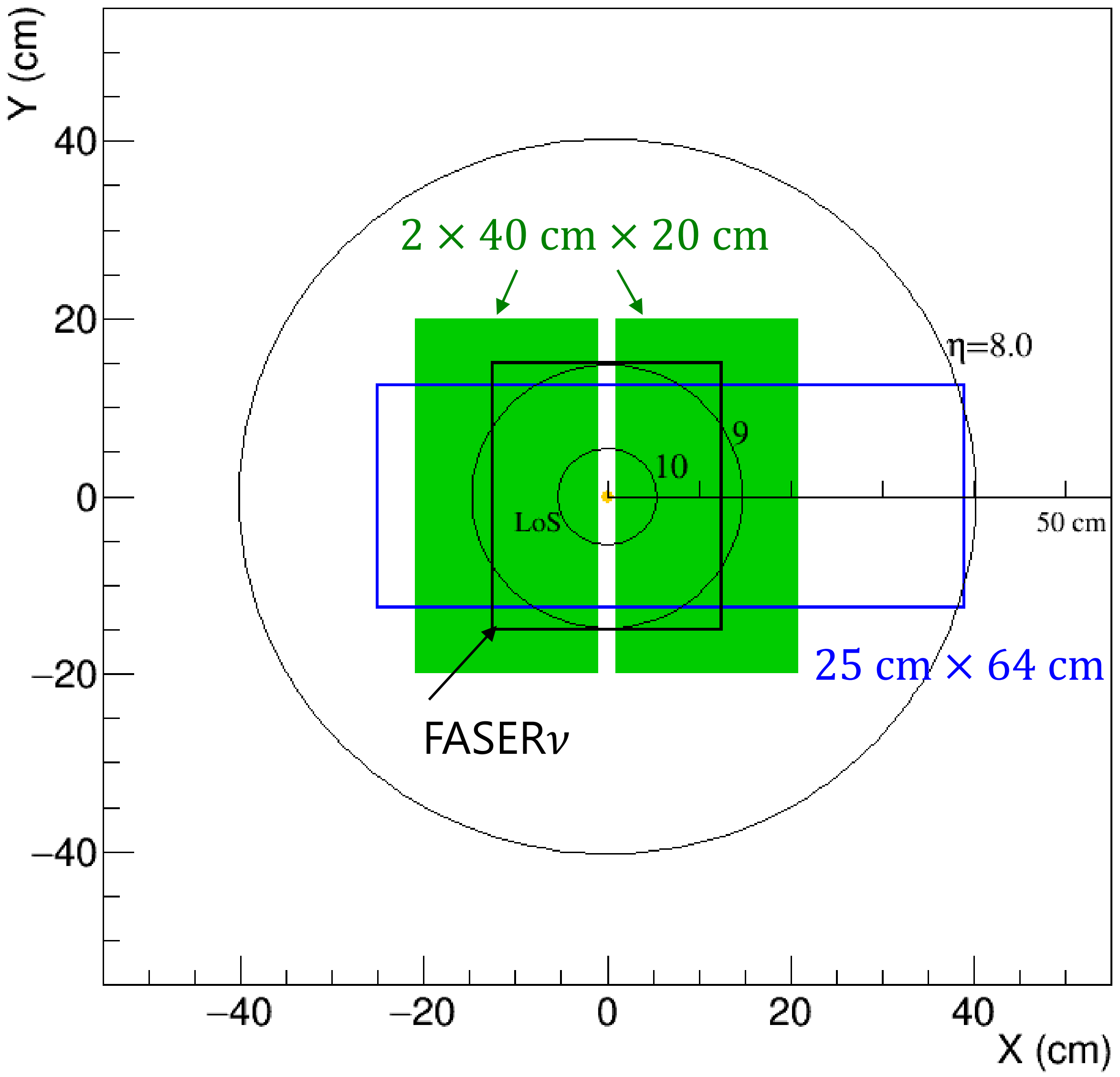
No fog increase is observed in 3 months scale



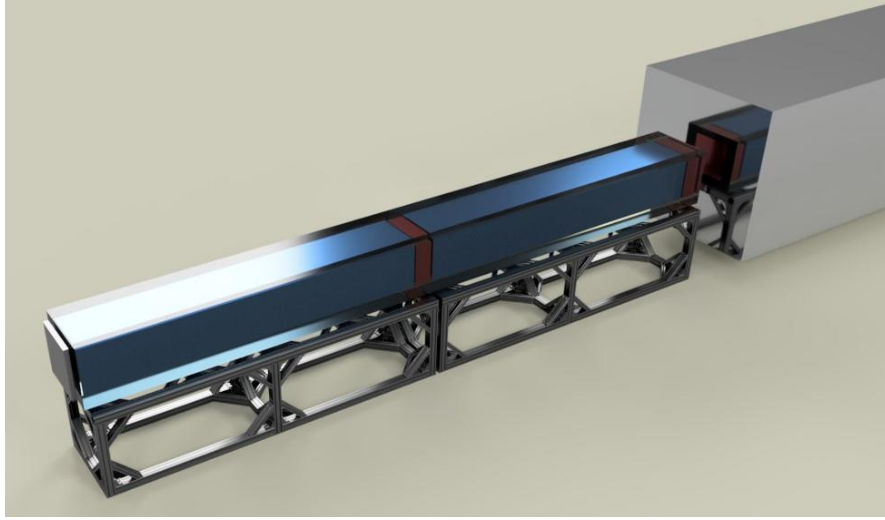


Film shape

- 40 cm × 40 cm film cannot be produced by the current film production machine
- Two options
  - 2 × 40 cm × 20 cm
    - Stay close to LoS ☺
    - Dead area in the middle ☹
    - Double the number of films ☹
  - 25 cm × 64 cm
    - Keep number of films and area ☺
    - Cover wider η range ☺
    - No dead area ☺
    - Decrease # of interactions ☹
- Both options are to be considered wrt physics performances



Detector assembling

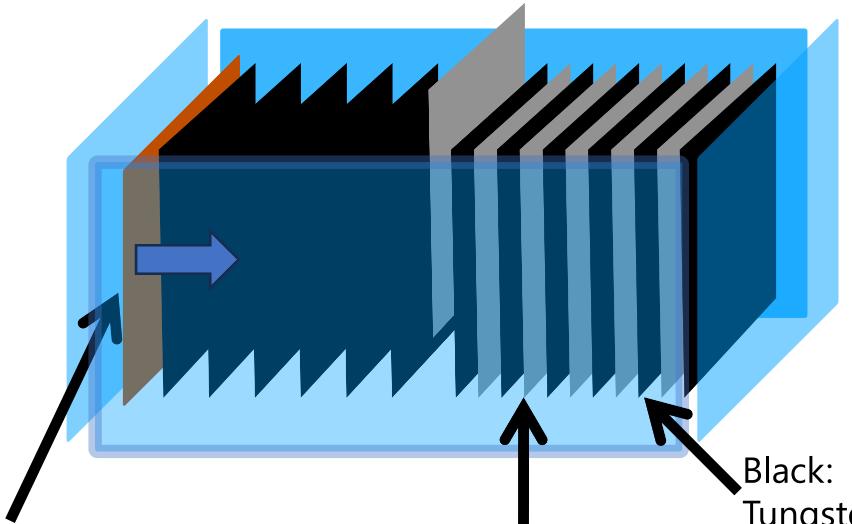


- Currently in FASERν
  - Assembling in surface lab, ~12 days
  - Transport an underground buffer area to avoid cosmic rays, 1 day
  - Transport 1.3-ton detector to the LHC tunnel, 1 day
  - After irradiation, bring again to the surface lab, 1 day
  - Disassemble and development, ~ 10 days
- For FASERν2, how can we assemble 20 times bigger detector?
- Can we bring up and down 20 tons of tungsten? or 20 boxes of FASERν?
- The support structure should apply 1 atm equivalent pressure to keep an alignment between films

Ken Ohashi (Bern), Akitaka Ariga (Bern/Chiba)

The current idea: Assembling on site

Keep the box and tungsten plates always underground, but exchange films only



Orange:
Push system to keep alignment

Gray:
Emulsion pack,
~0.5mm thickness
Removed and inserted once per year

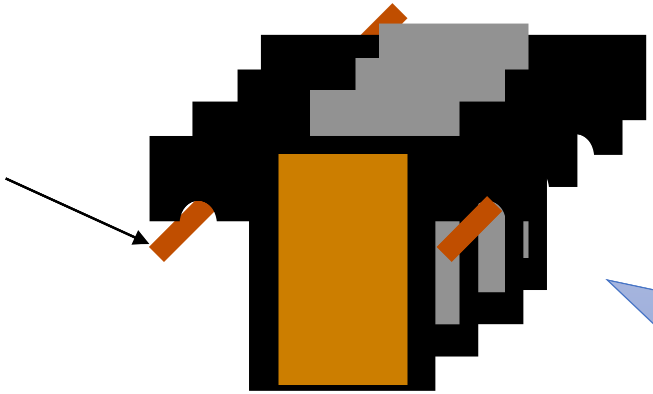
Black:
Tungsten plate, 2mm thickness

Emulsion film packs

1 film per pack

T-shorts shaped tungsten plates hanged on rails

Stainless steel rail



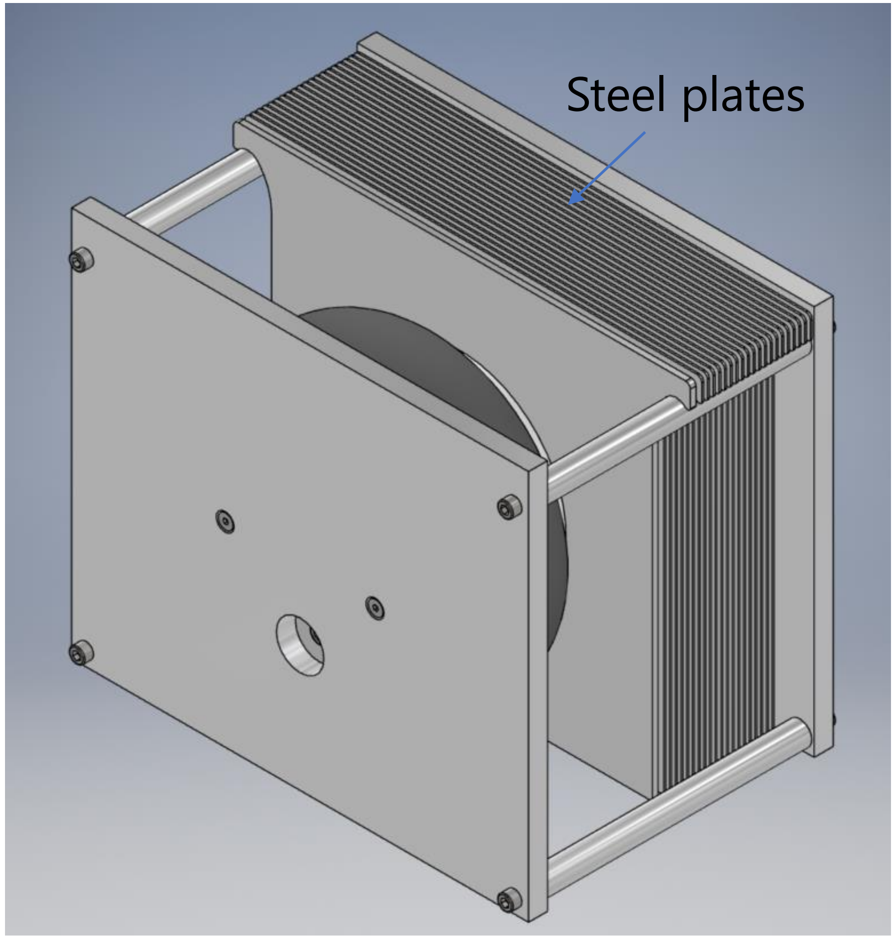
Pusher plate at the end
(One pushing plate for 1650 layers)

Can O(100) plates slide on the rails?
→ Test with a small prototype

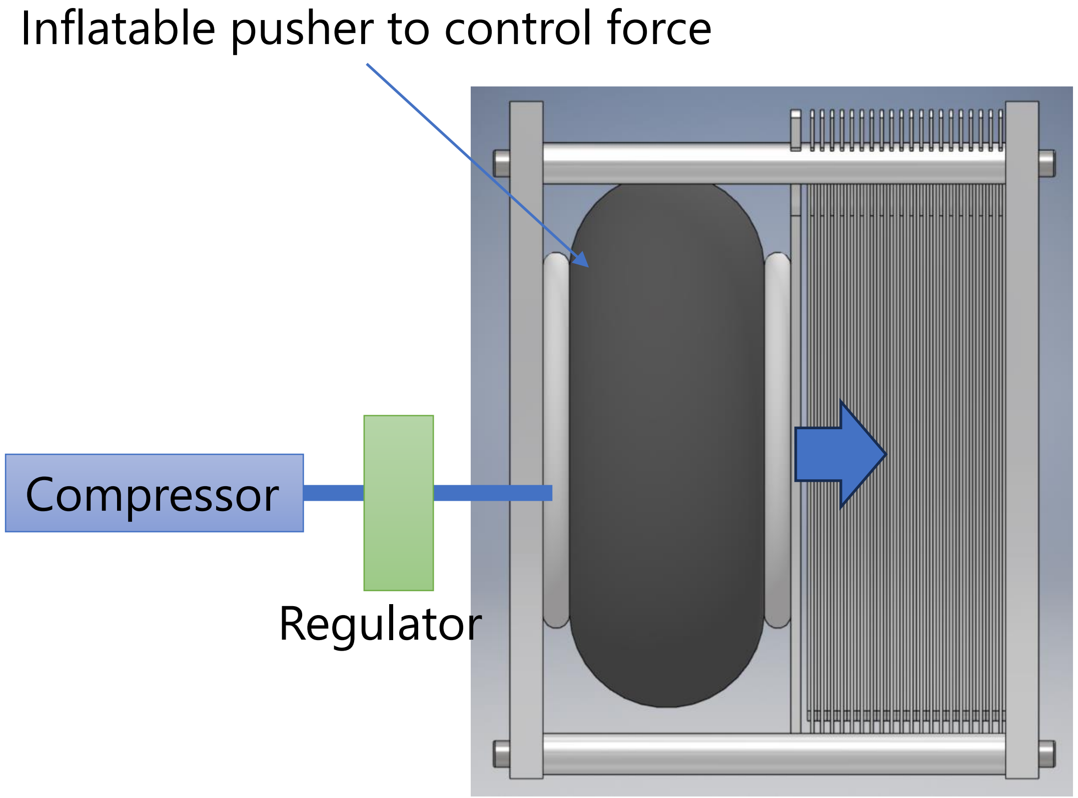
3 m, 10-ton boxes, 1650 layers per box

Ken Ohashi, Akitaka Ariga

Prototype



6kg Steel plates x 20
Total ~160 kg



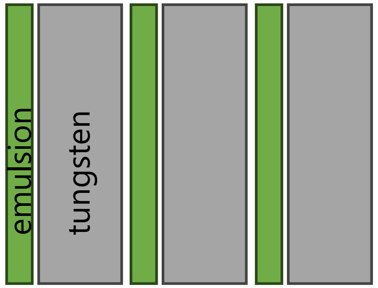
Change pressure and test the mechanism

Prototype production / test in Spring – Summer 2024

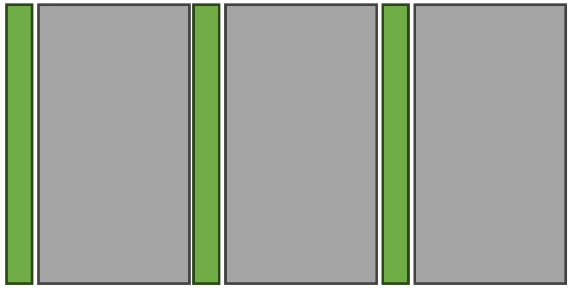
Tomoko Ariga (Kyushu), Sergey Dmitrievsky (JINR)

Increase tungsten thickness to reduce emulsion film cost

- FASERν2 plans to use **2-mm-thick tungsten plates** instead of **1-mm-thick plates to reduce the emulsion cost (2MCHF/year -> 1MCHF/year)**.
- Need to make sure a reconstruction will work in high track density environment.
- We are testing feasibility using one film every two (only odd film number) in the FASERν data (1-mm-thick tungsten).

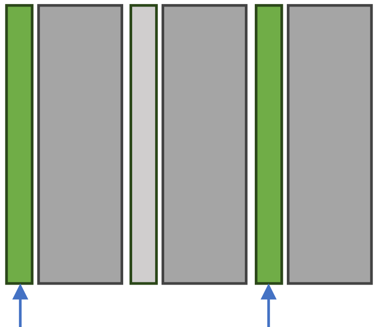


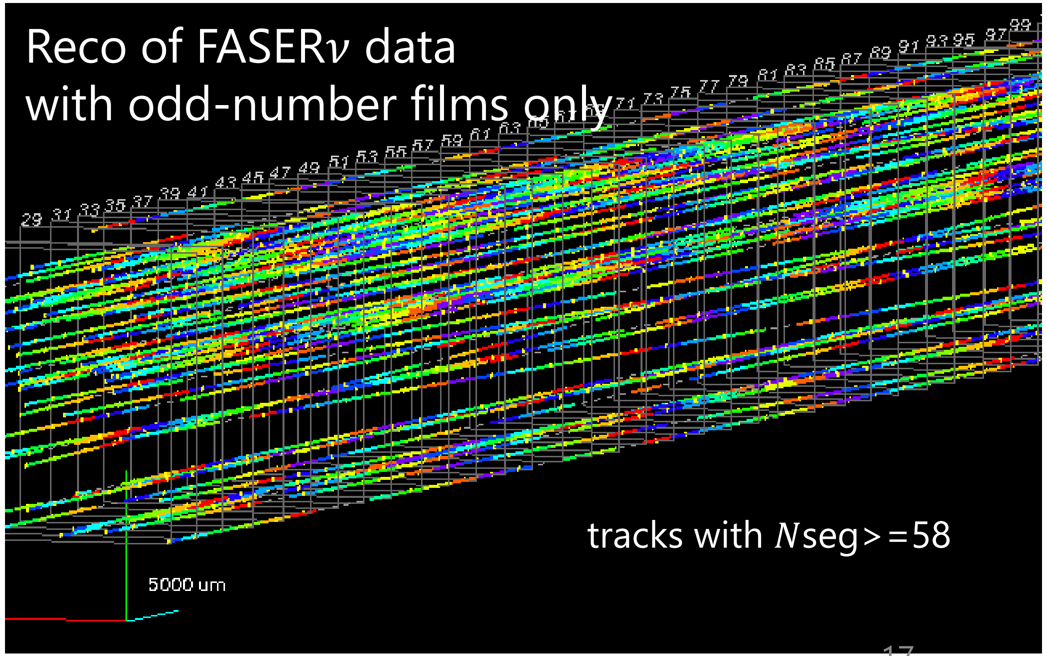
FASERν, 1.1 mm thick



FASERν2, 2 mm thick

Test reco with FASERν data only odd-number films

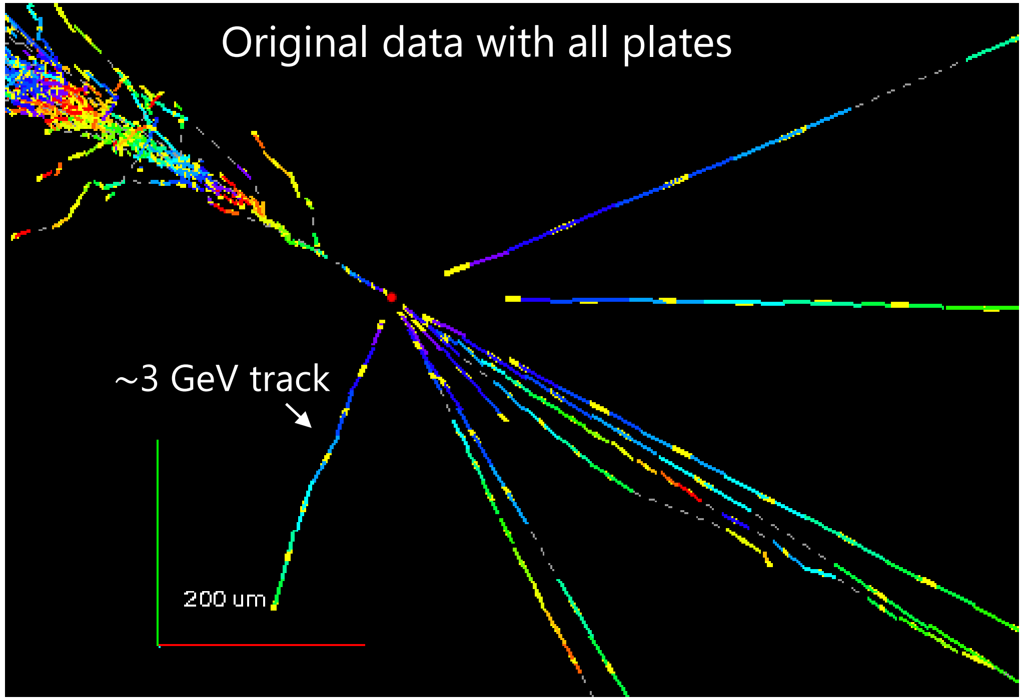


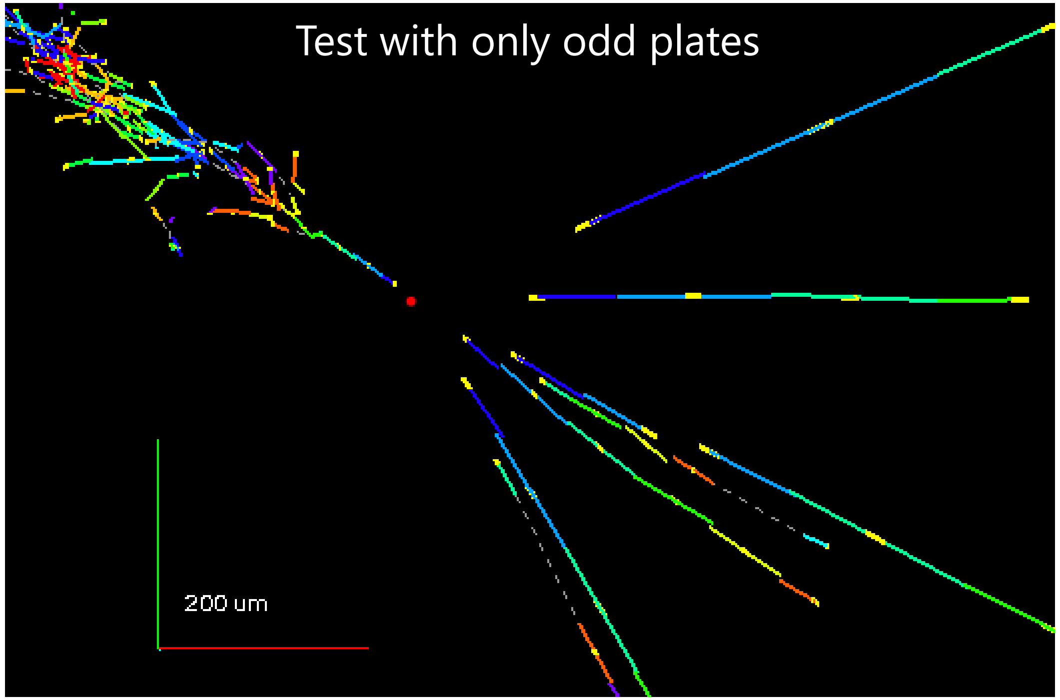


Tomoko Ariga, Sergey Dmitrievsky

Demonstration of reconstruction using one in every two films in the FASERν data

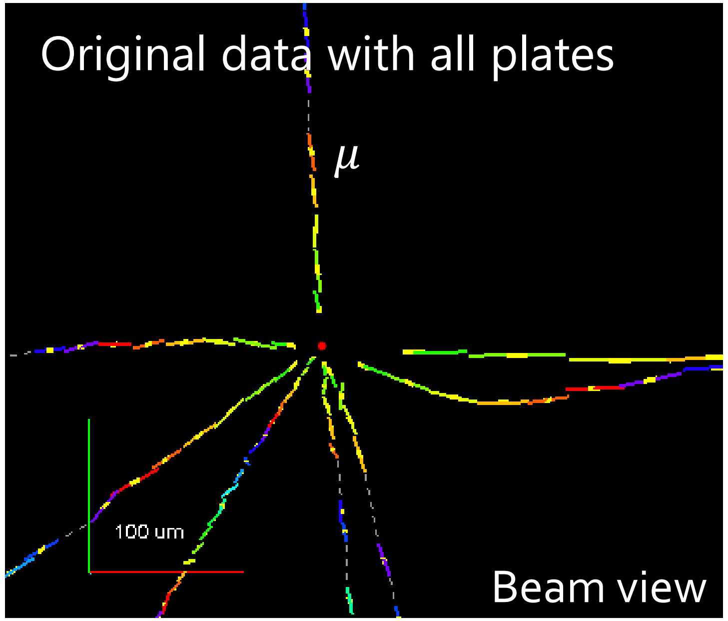
- A ν_e candidate in the FASERν data was reconstructed using only odd plates.
  - The vertex and the primary electron candidate are successfully found.
  - Most of tracks at the vertex are found except for a track with a few GeV.
- Preliminary conclusion: Reconstruction with 2.2-mm-thick tungsten plates in the muon background (at ~10^5 muons/cm^2) seems feasible.
- Further studies with MC and tunings are needed.

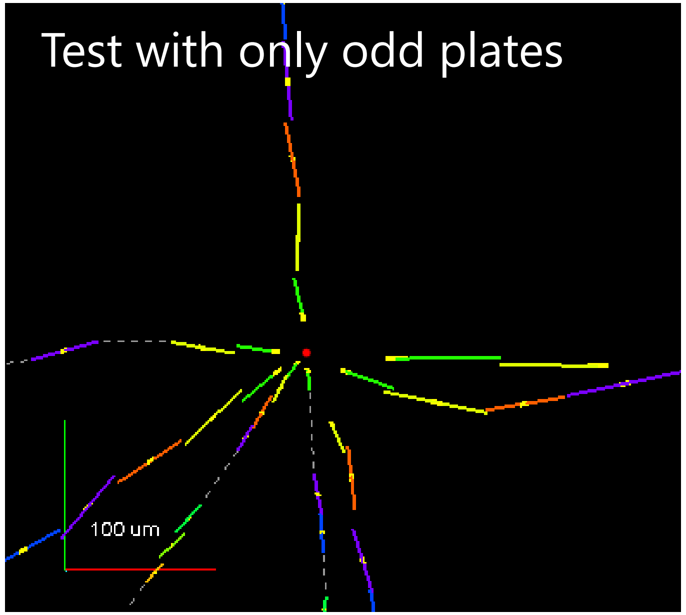




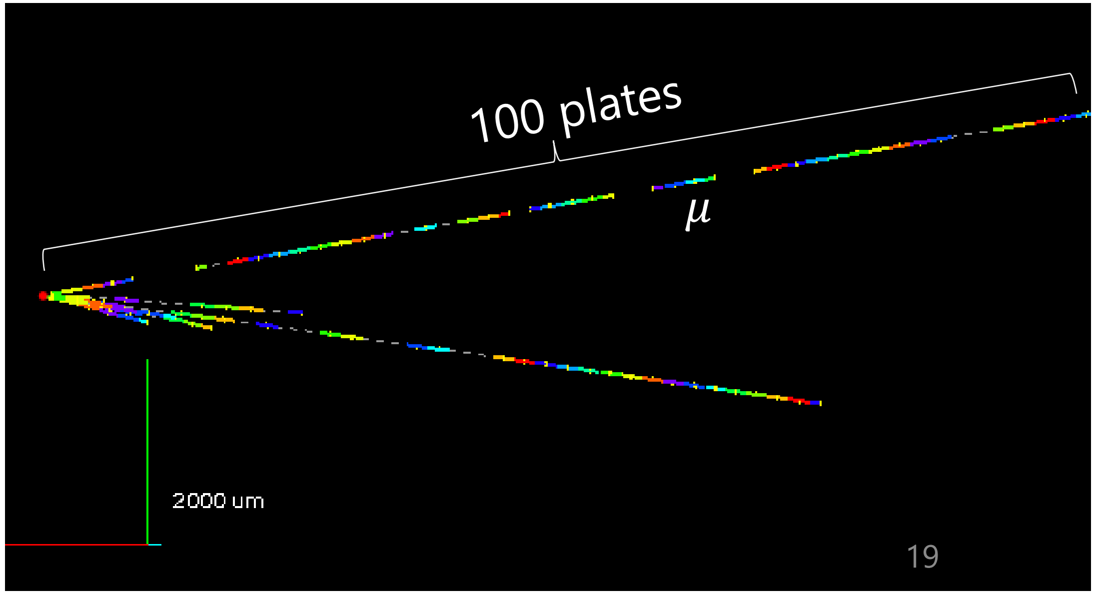
Demonstration using another neutrino event in the FASERν data

- Another ν_μ candidate event in FASERν was reconstructed using only odd plates.
  - The vertex and the primary muon candidate are found.
  - All the primary tracks are found.





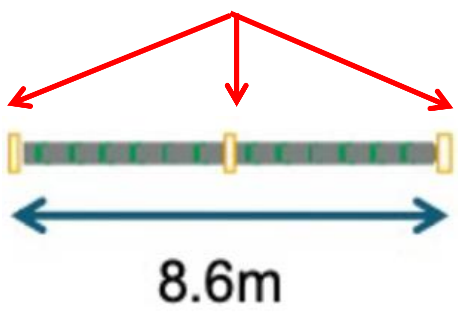
Test with
only odd plates



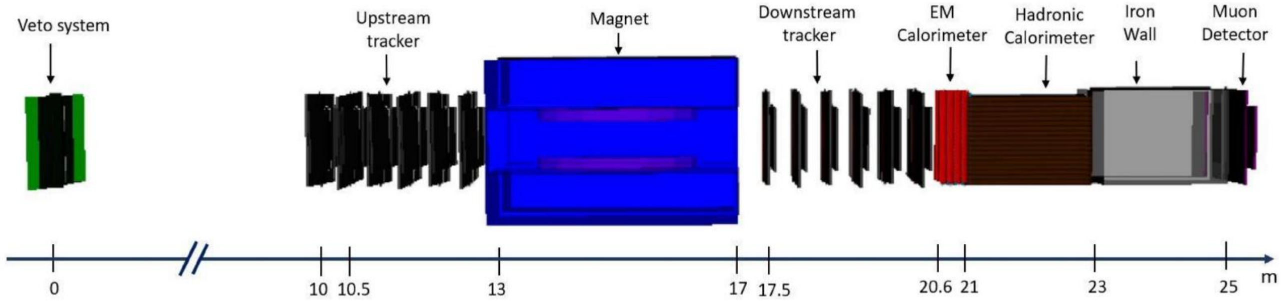
Yosuke Takubo (KEK), Hidetoshi Otono (Kyushu)

Interface Tracker (IFT) for FASERν2

- Interface Tracker (IFT) is needed to identify charge of muons → $\nu_\mu, \nu_\tau \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$
    - Interface FASERν2 and FASER2
- Three technical options are currently considered:
    - SciFi: scintillating fiber with O(100 um) diameter (LHCb: 250 um)
    - Gas detector: Micro-Megas, GEM, etc
    - Silicon strip detector: consisting of ATLAS SCT modules as the current IFT
- The performance of track matching with emulsion and FASER2 tracker has to be studied with the realistic geometry
- The technical decision will also strongly depend on the tracker design of FASER2



FASERν2

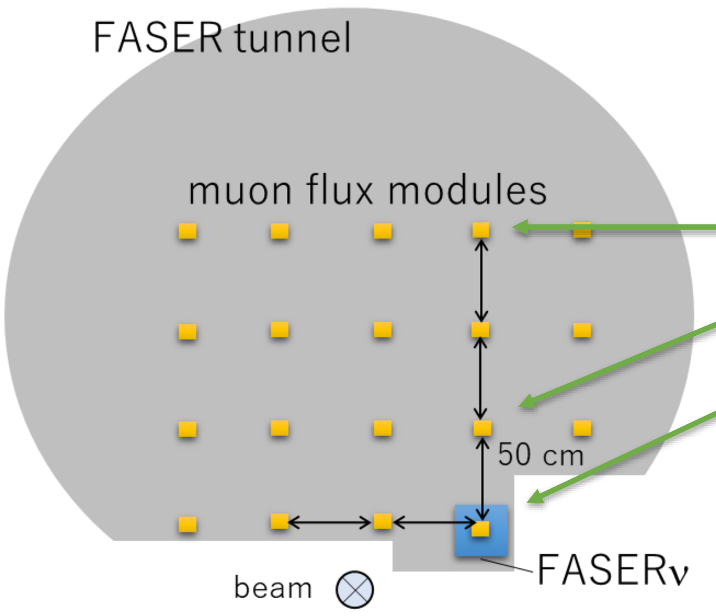


FASER2

Kanai Takumi (Chiba), Ken Ohashi (Bern)

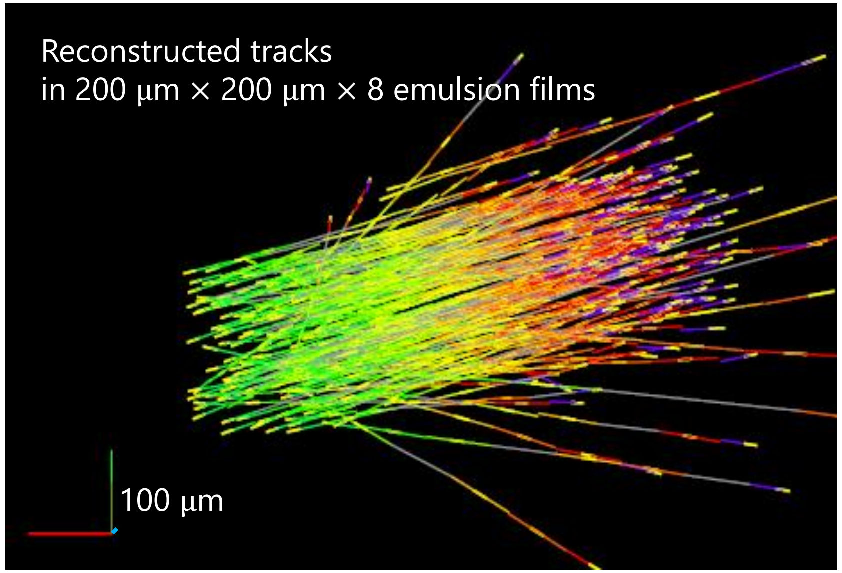
Muon flux map measurement

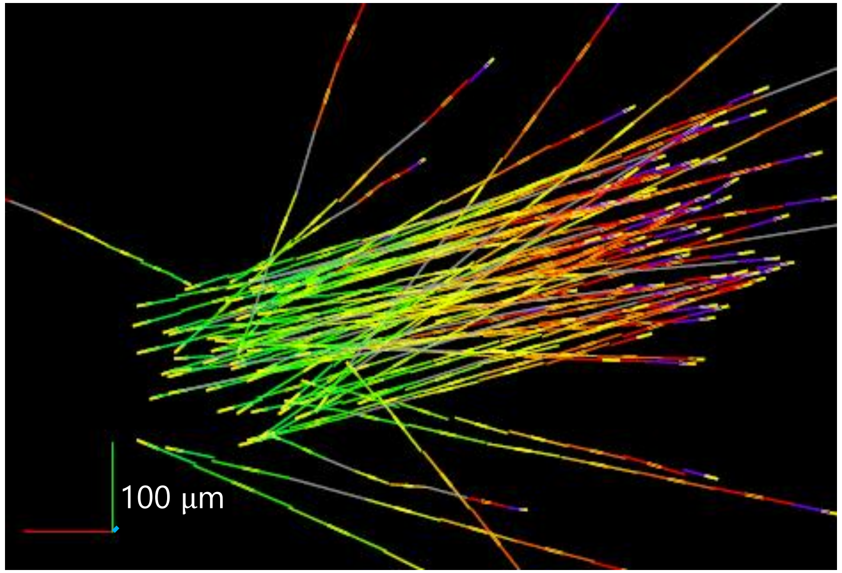
To validate the FLUKA/BDSIM simulations, 19 small emulsion detectors were installed in July-Sep 2022 in the region ~2 m from the LOS, collecting 9.5 fb^{-1} of data.
Data/MC comparison is ongoing.



FASERν preliminary

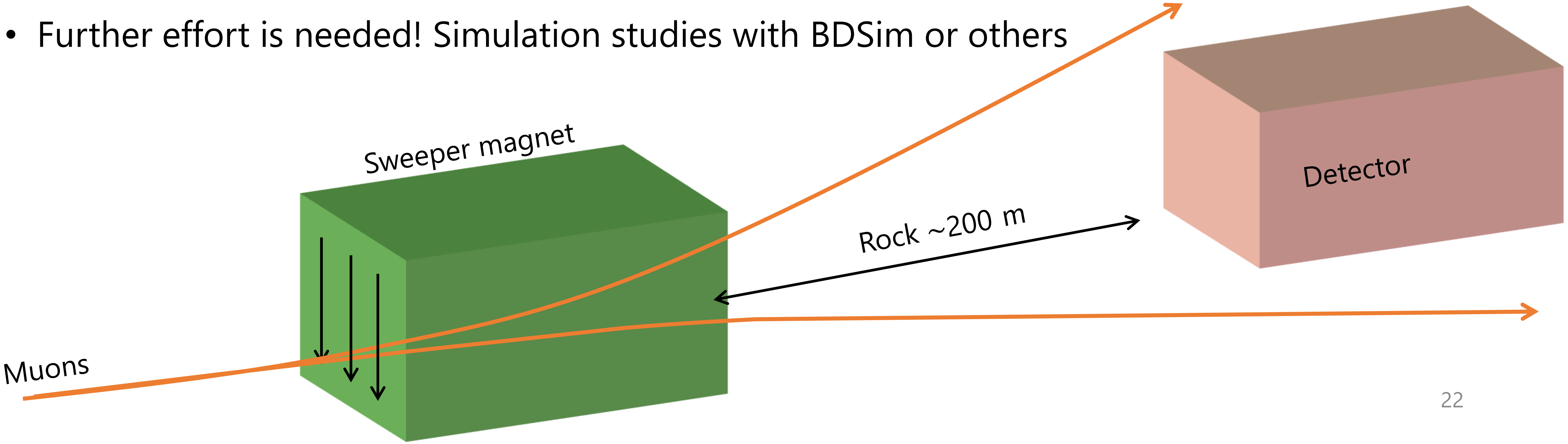
	track density (/cm²/fb⁻¹) (within 10 mrad from the peak)
height=150 cm	5.1×10^4
height=50 cm	1.5×10^4
height=0 cm	1.0×10^4
FASERν 1st module	1.2×10^4





Sweeper magnet to reduce BG muons

- To increase the duration of data taking with a FASERν2 detector, a reduction of muon rate is vital
- Maximum track density in emulsion should be kept below ~5×10^5 tracks/cm^2 → 2 months without muon reduction
- Install a sweeper magnet upstream to reduce the muon flux
- Previous studies by CERN-FLUKA team showed a pessimistic result ☹
- Further effort is needed! Simulation studies with BDSim or others



Cost estimate

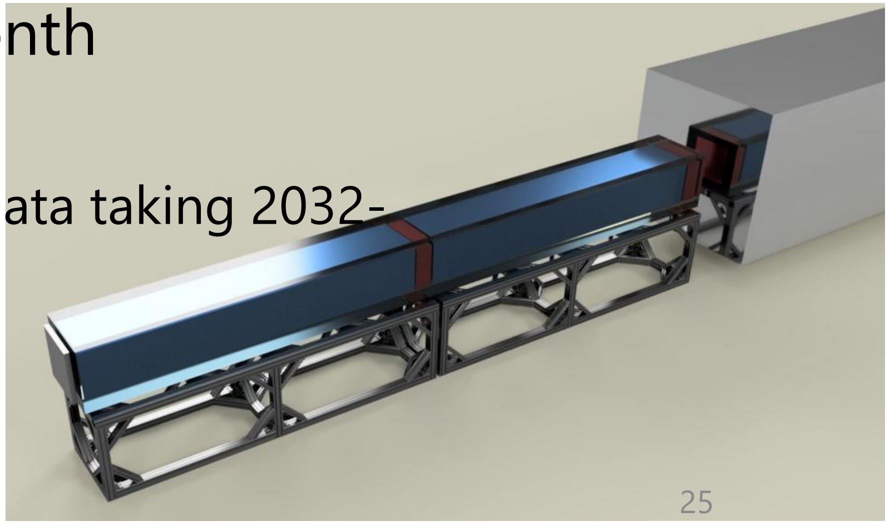
Item	Cost (kCHF)	How many years	Sub-total	Comments
Fixed costs				
Tungsten	2000		2000	2-mm-thick 40x40 cm^2, 3300 plates +10%
Emulsion readout	1700		1700	
Expert of the readout system	500		500	
Veto / interface detectors	200		200	
Support structure	400		400	
Cooling system	100		100	
Annual cost				
Emulsion	1000	10	10000	40x40 cm^2, 3300 films
Chemicals for development	50	10	500	
Personnel for scanning	50	10	500	
Total			15900	

FASERν2 schedule

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
	Run 3	Run 3	Run 3				Run 4	Run 4	Run 4 Year-1	Run 4 Year-2	
MC studies and documentation				TDR							
Detector support and cooling system	R&D				Construction						
Tungsten plates		Tests			Purchase and tests						
Readout system (HTS3?)		Development of HTS3			Dedicated system for Fnu2: production and tests						
Emulsion films		Stability study						Production	Production		
CERN darkroom facility for the assembly and development											
Construct the interface detector						Construction	Installation				
Construct the veto detector											
Cost					Tungsten ~2M Readout ~2.2M Support ~0.4M Cooling ~0.1M IFT+veto ~0.2M			Emulsion 1.1M (for 2031)	1.1M (for 2032)		1.1M/year during Run

Summary

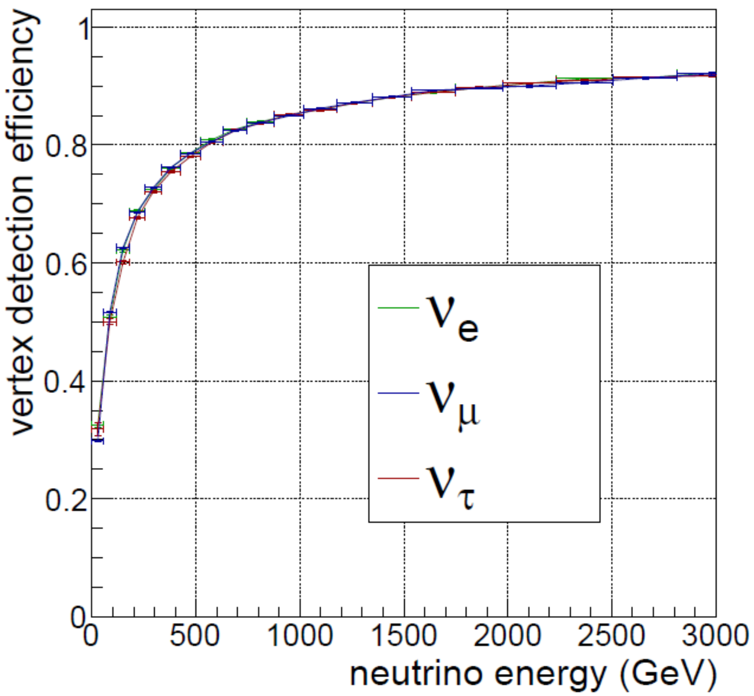
- FASERν2 aims $\sim O(100) \times$ FASERν in interaction statistics
- Demonstrating FASERν2 concepts with the ongoing FASERν analyses
- Several R&D are ongoing.
  - Long term performance test with Test Beam 2023 (also TB 2024)
  - Prototypes to test assembling scheme
  - Reconstruction with reduced segmentation demonstrated
  - Choice of interface detector
- FASERν2 working group regularly meets once a month
- The time scale fits with the global FPF timeline
  - LOI 2025, TDR 2026, funding 2027/28, construction 28-, data taking 2032-



Backup

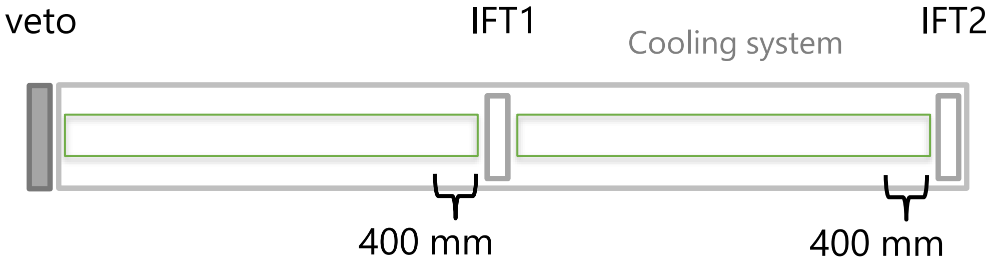
ν detection and acceptance

- **Vertex detection efficiency** after requiring at least 5 charged particles
  - Using charged tracks and γ rays with p > 0.3 GeV and $\tan\theta$ < 1 (relative to the neutrino direction)
  - → may change to p > 1 GeV and $\tan\theta$ < 0.5

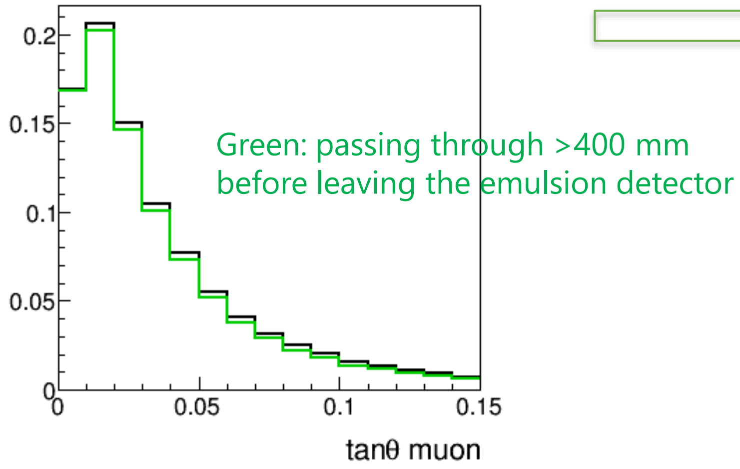


- **Additional inefficiencies for ν_μ**

1. 400 mm tungsten from the most downstream layer would be used for μ ID (400 mm/3300 mm = 12%).

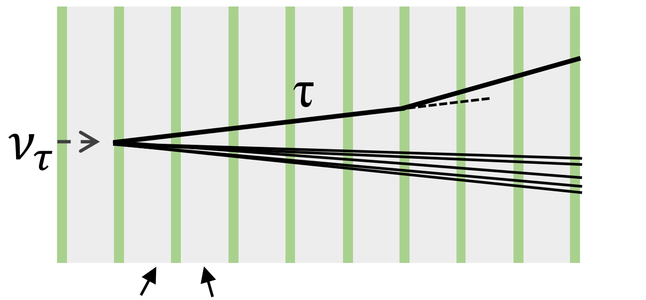


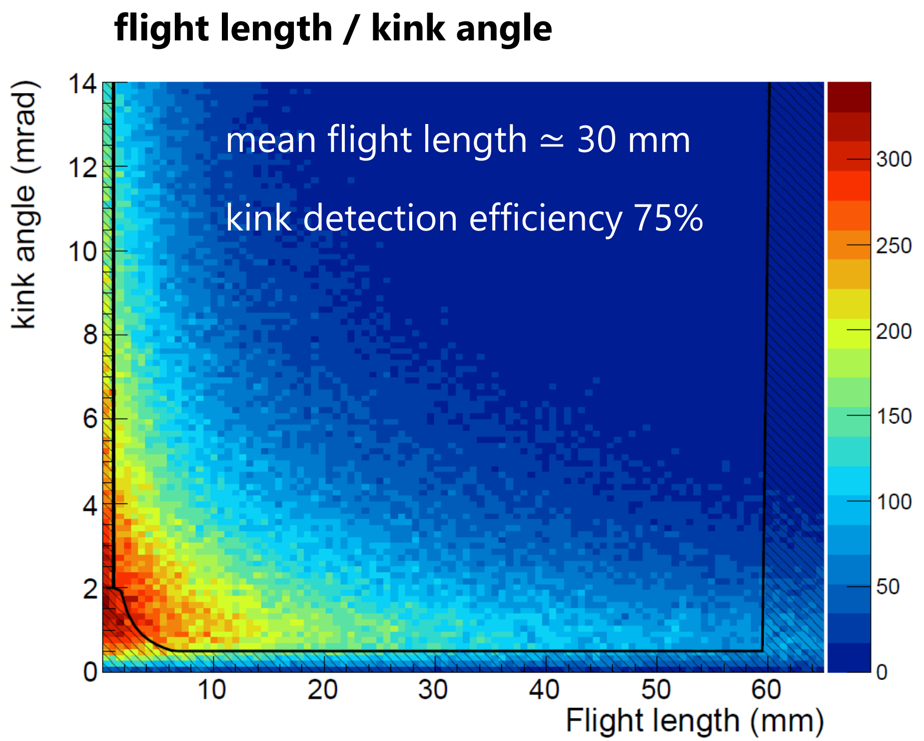
2. In addition, ~5.4% of μ^- (~3.5% of μ^+) will go side out before passing through enough material for the muon ID.



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 = $0.5 \times \sqrt{2}/10000$ = ~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)

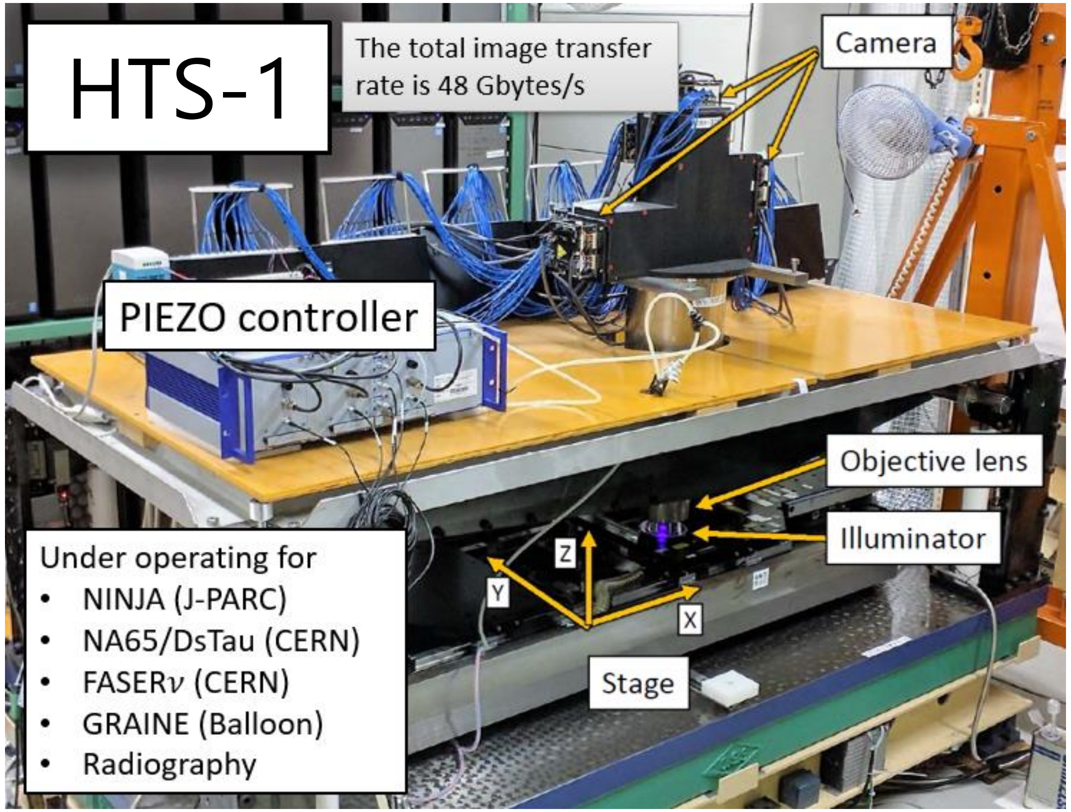




Emulsion readout systems

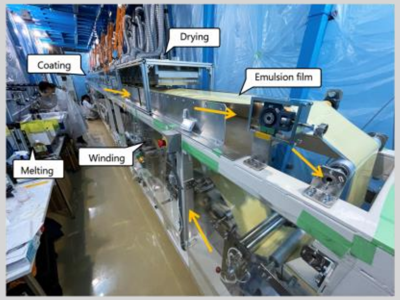
- Total emulsion film surface in FASERν2: ~530 m^2/year
  - ~2400 h/year with HTS
  - or ~420 h/year with HTS2

	Field of view (mm^2)	Readout speed (m^2/h/layer)
S-UTS	0.04	0.0072
HTS-1	**25**	**0.45**
HTS-2	**50**	**2.5**
HTS-3	**?**	**?**



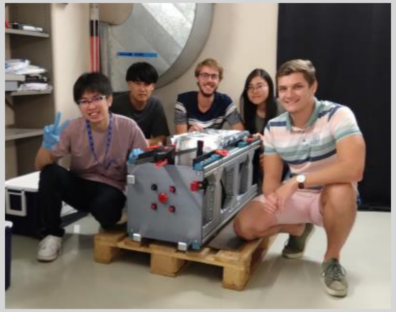
FASERν steps, 3 detectors per year

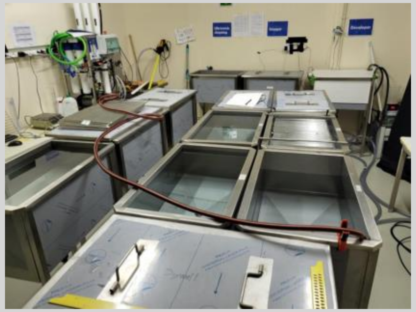
Japan



Film production

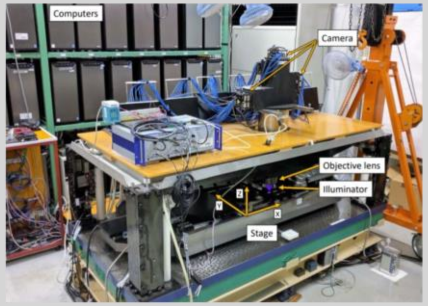
CERN





Assembly → Exposure → Disassembling → Development

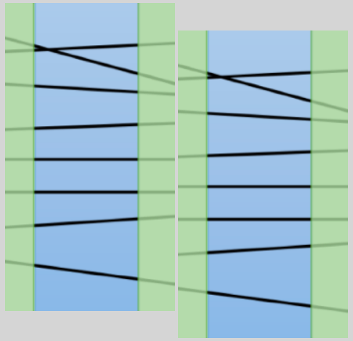
Japan

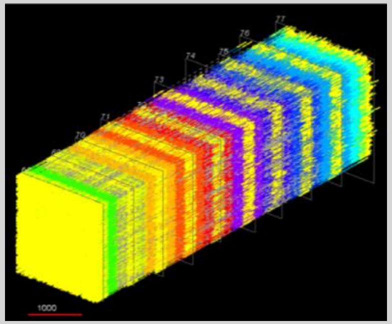


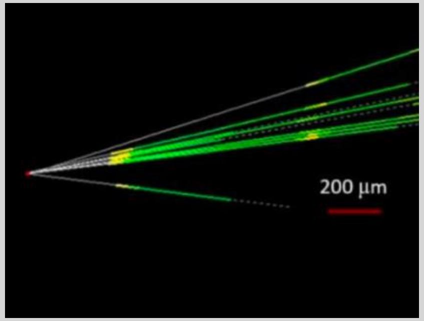
→ Readout

Offline analysis

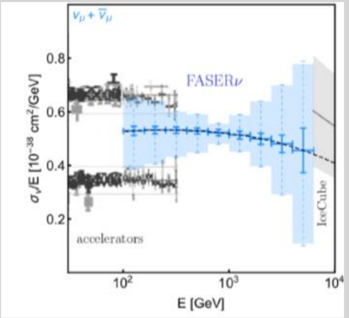
Alignment → Track reconstruction → Vertex reconstruction → e, μ ID → Physics analysis



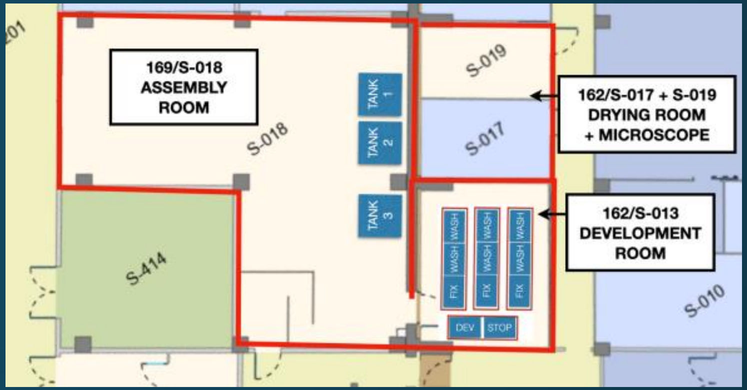




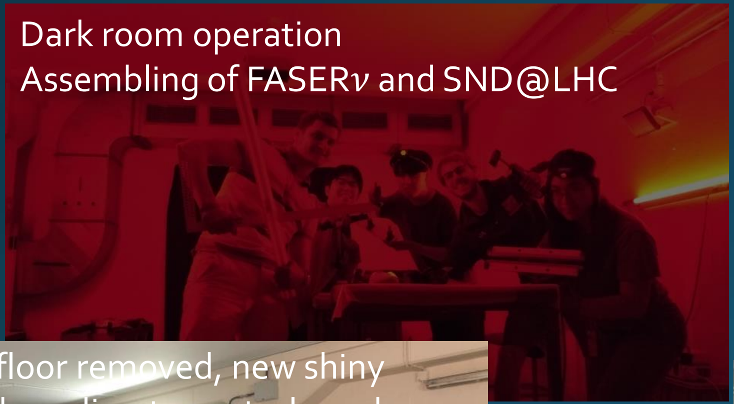
e, μ ID
τ decay search
charge ID
Eν reco
charm/beauty
etc.



CERN Emulsion Facility



- Dark room at CERN established in 80s → Obsolete
- Emulsion experiments are increasing: NA65/DsTau, FASERν, SND@LHC, SHiP, test beams…
- Refurbished recently, big thanks for supports from CERN!
- Experiments share installation and equipment



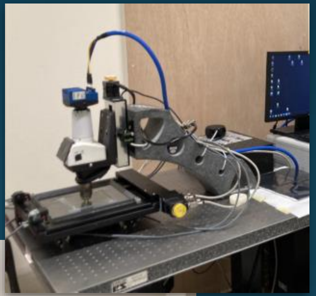
Dark room operation
Assembling of FASERν and SND@LHC

Temperature controlled developer bath

Development timer

Film drying

Microscope



Asbestos floor removed, new shiny floor, modern climate control, card lock system…

Development room
13 x 100L tanks
Easy disposal system

Disposal