Status of FASERν and Development of Neutrino Energy Reconstruction Algorithms

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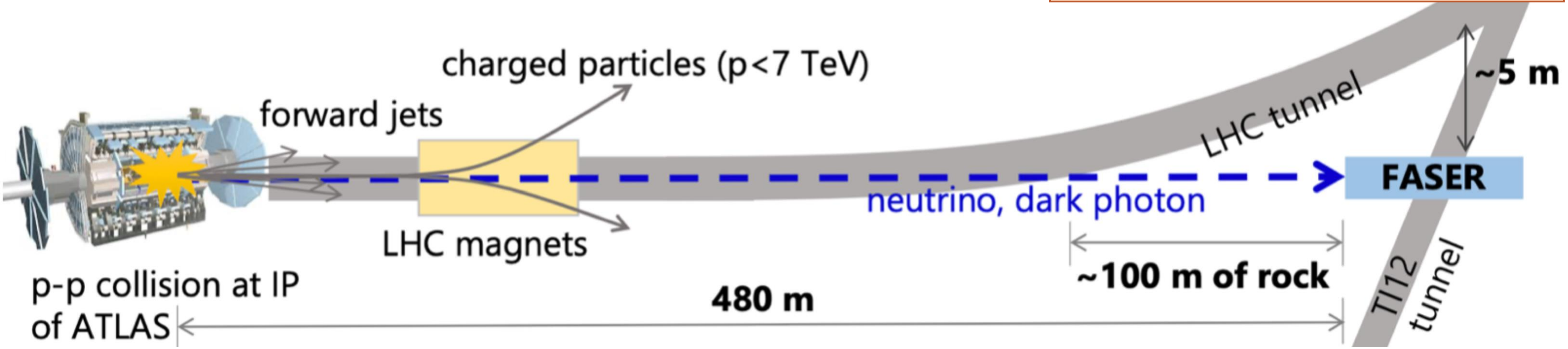
7th of September 2023, SPS / ÖPG 2023

ForwArd Search ExpeRiment

- New small experiment based at the LHC at CERN, taking data since 2022, investigating weakly-interacting light particles in the far-forward region.
- Aligned with the collision axis line-of-sight, maximising both the number and energy of neutrino interactions of all 3 flavours.
- First collider neutrino experiment!

See also Anna Sfyrla’s Plenary Talk on 05/09: “Looking forward to new physics with the LHC”

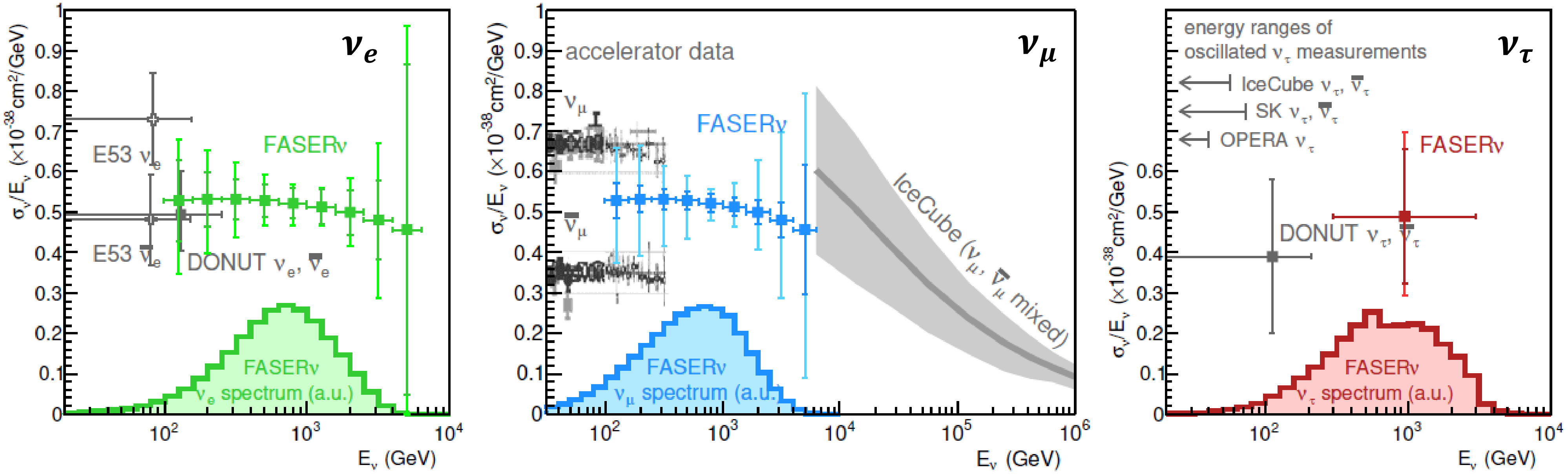


High Energy Neutrinos in FASER

- FASER takes advantage of the intense forward hadron production in proton-proton collisions to produce a collimated neutrino beam.
- 3-flavour cross-section measurement for previously unexplored energy range → highest E_ν from artificial source.
- Expect **> 10 000** neutrino interactions in FASER in LHC Run 3 (2022 - 2025) → 250 fb^{-1}.

For 250 fb^{-1}	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
Main source	Kaon/Charm decay	Pion/Kaon decays	Charm decay
№ expected CC events in FASERν	~ 2850	~ 9600	~ 70

(Based on PhysRevD.104.113008)

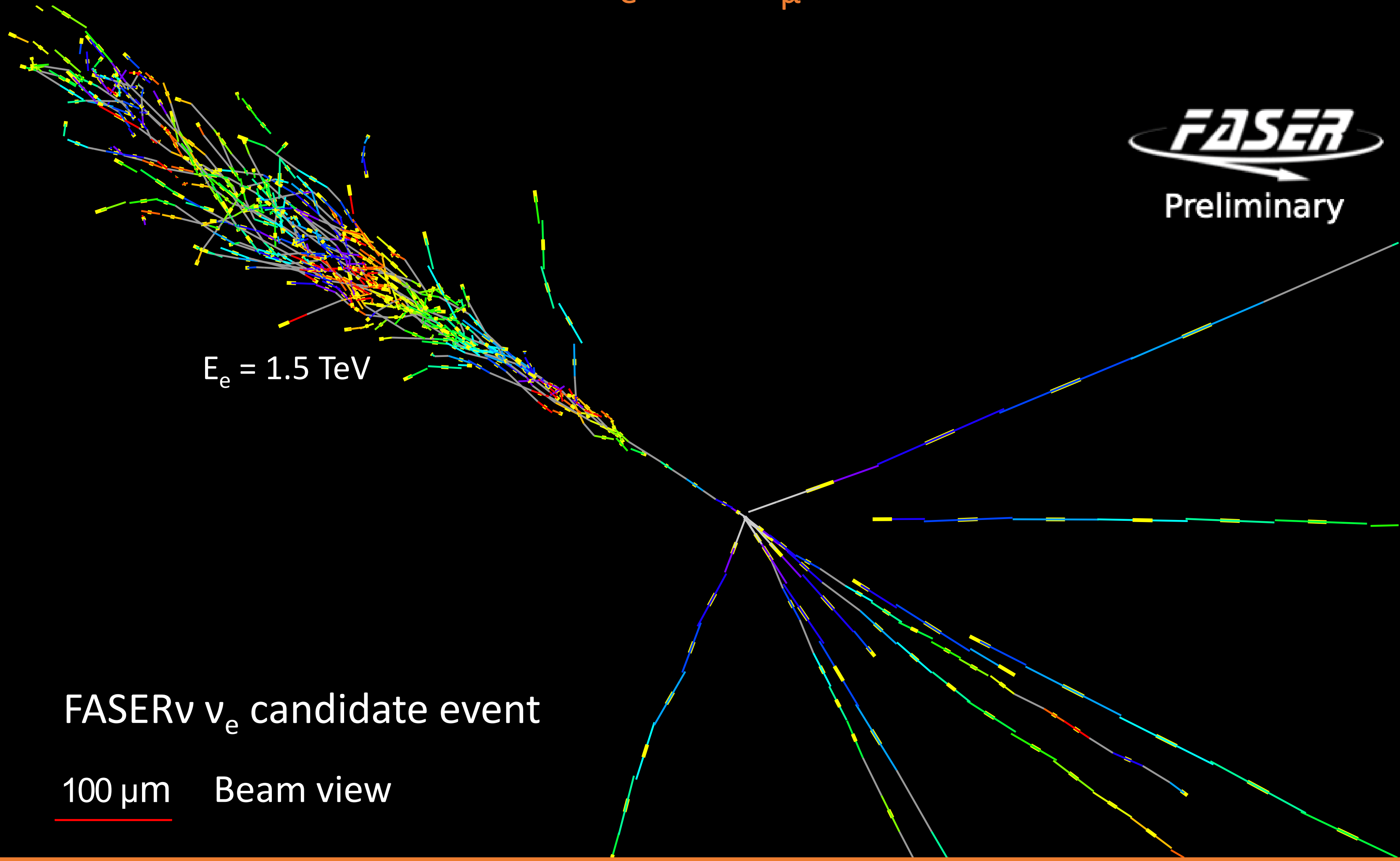


Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})

- Inner error bars: statistical uncertainties.
- Outer error bars: uncertainties from neutrino production rate.

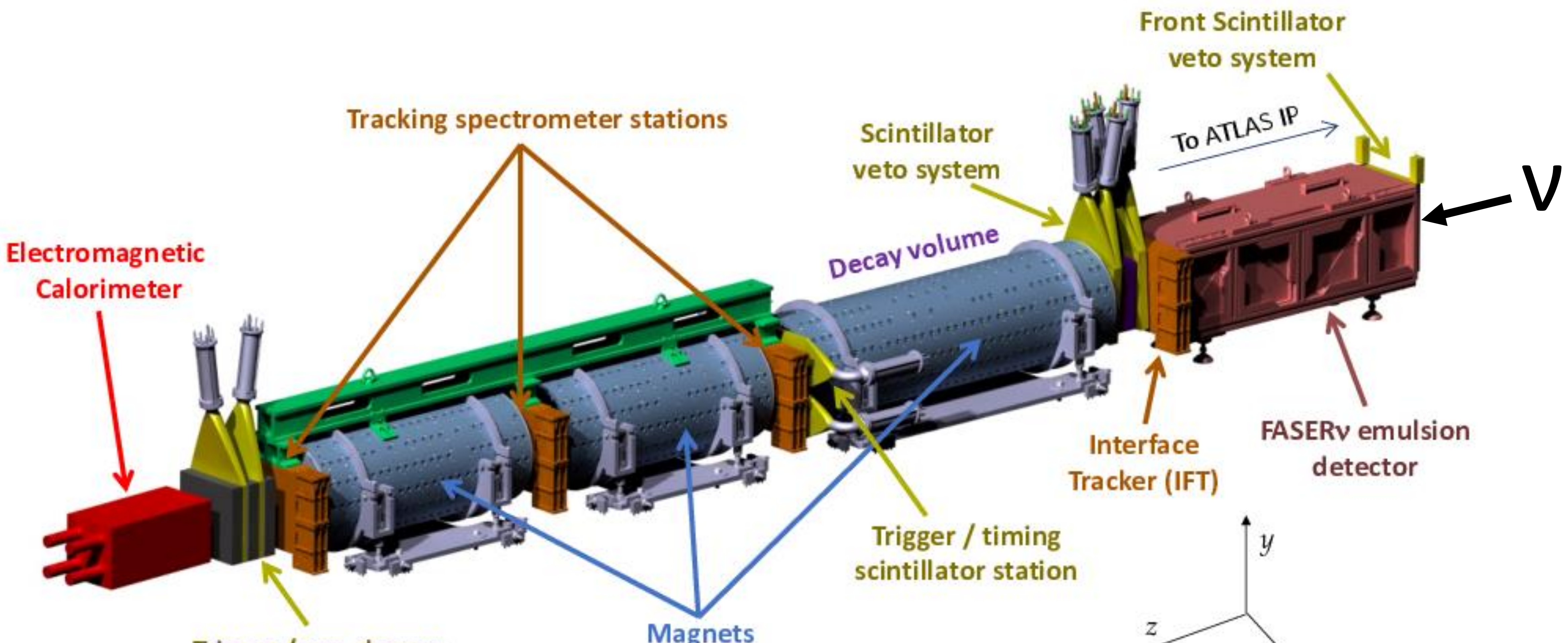
FASER: First Direct Observation of Collider Neutrinos

- FASER reported the first direct observation of collider ν_e and ν_μ .
  - ν_μ with 16σ significance;
    (Phys. Rev. Lett. 131, 031801)
  - ν_e with 5σ significance.
    (CERN-FASER-CONF-2023-002)



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

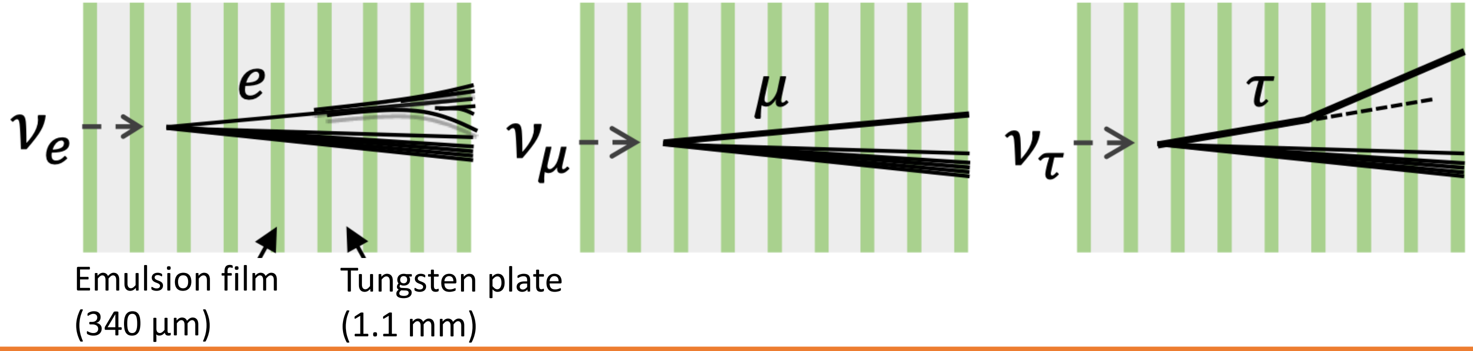
The FASER Detector



0.57 T permanent magnet, 10 cm aperture radius, 1.5 m decay length

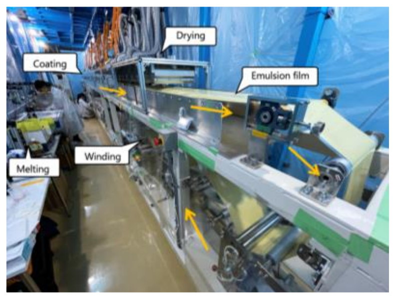
The FASERν Sub-Detector

- Module: 730 alternating FASERν emulsion films and 1.1 mm thick tungsten plates (25 x 30 cm^2).
- Target mass 1.1 tonnes; 1.1 m (220 X_0, 8λ).
- Module replaced 3 times per year every 20fb^{-1} to keep track occupancy < 10^6/cm^2.
- Neutrino events can be flavour tagged using topological and kinematical variables.



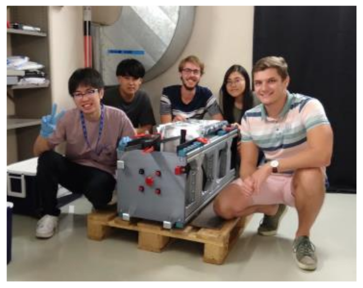
FASERν Process

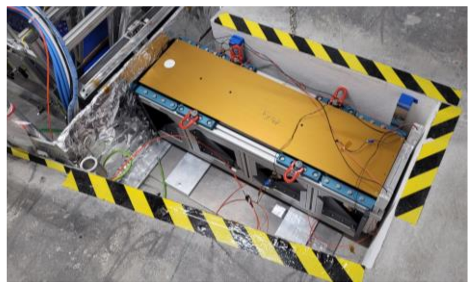
Japan

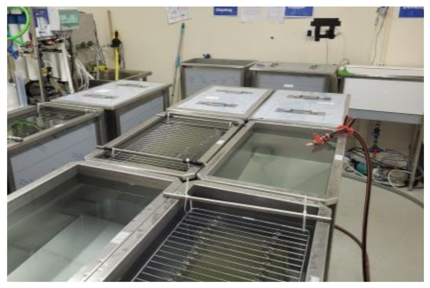


Film production

CERN

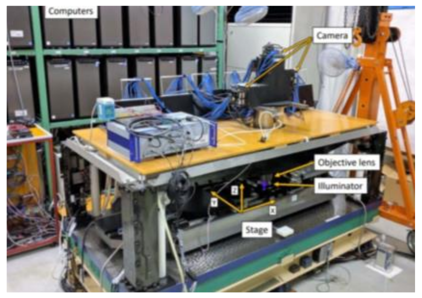






Assembly → Exposure → Disassembling → Development

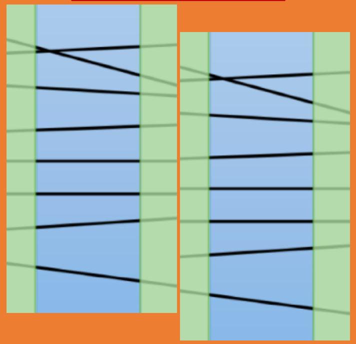
Japan



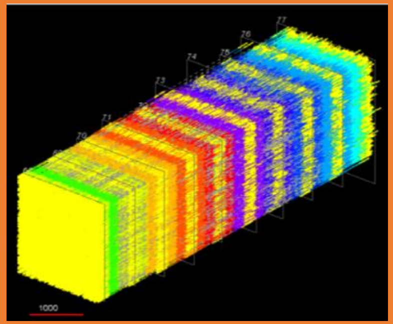
Readout

Offline analysis

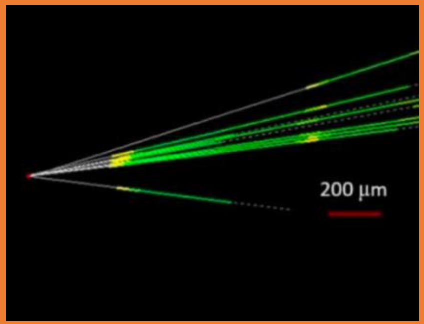
Alignment



Track reconstruction

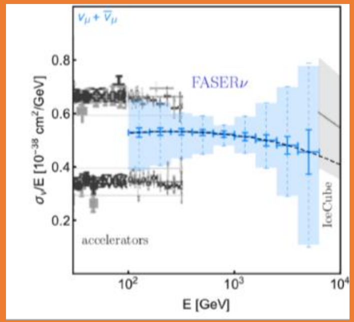


Vertex reconstruction



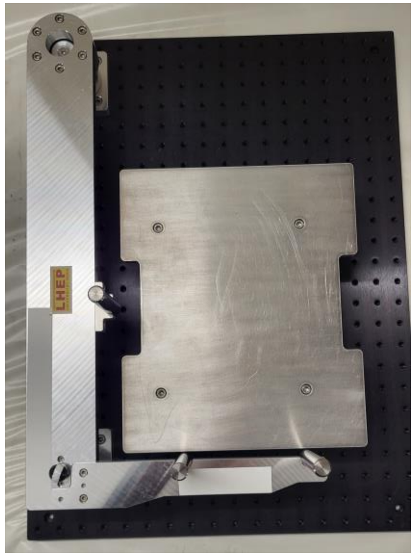
e, μ ID
τ decay search
charge ID
etc…

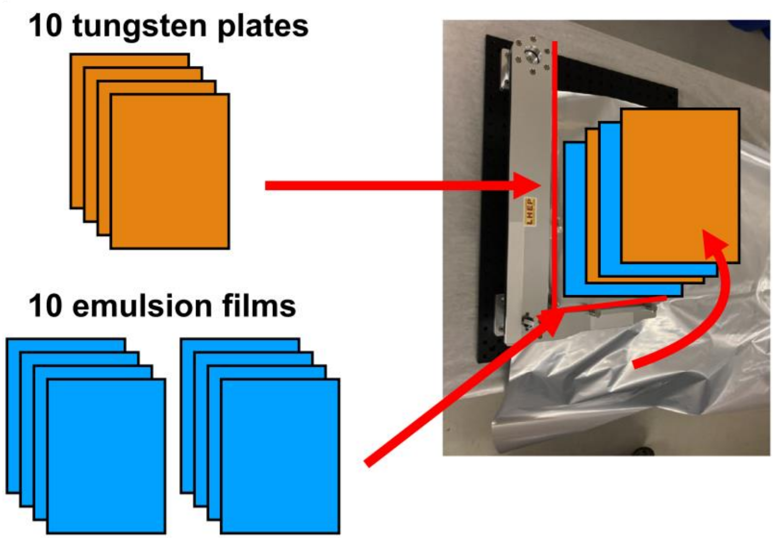
Physics analysis

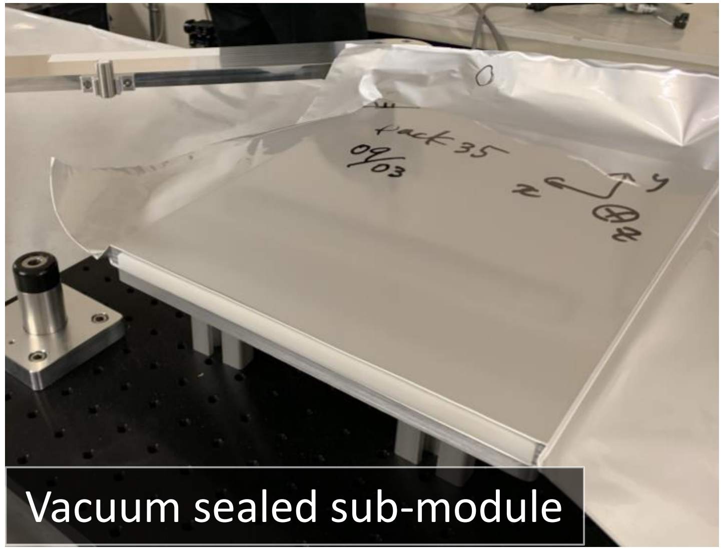


FASERν Assembly at CERN

- FASERν sub-modules: 10 alternating emulsion films and tungsten plates.
- 2 dedicated assembly table for parallel assembly.
- Pressure is applied to keep the alignment between sub-modules inside the FASERν module.

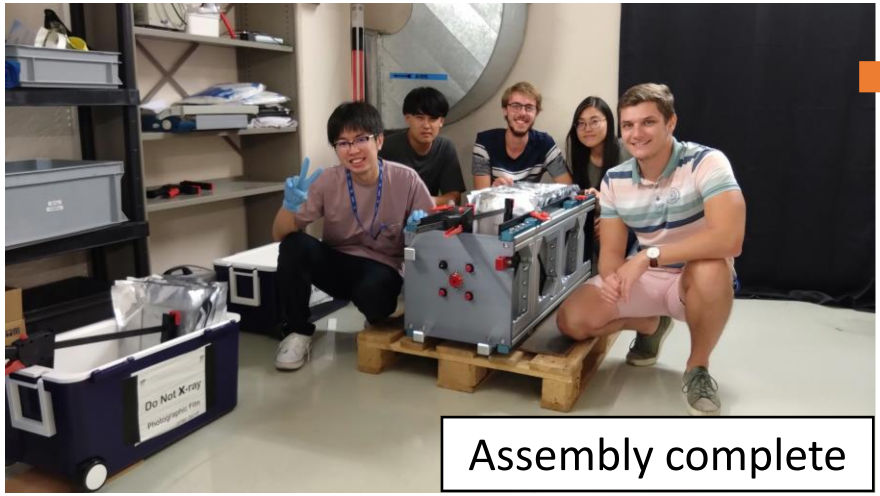


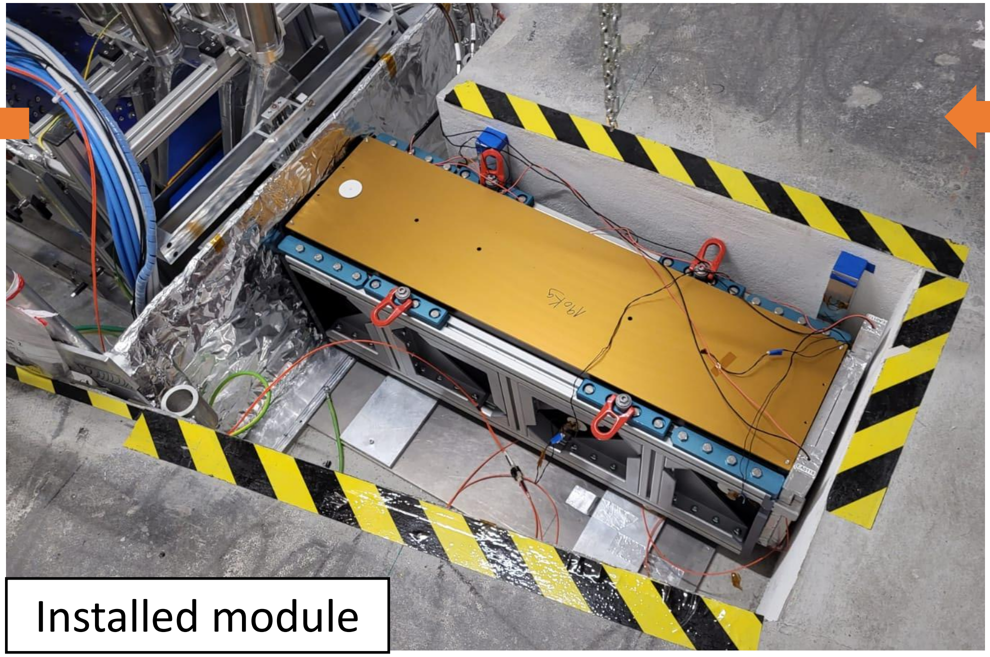


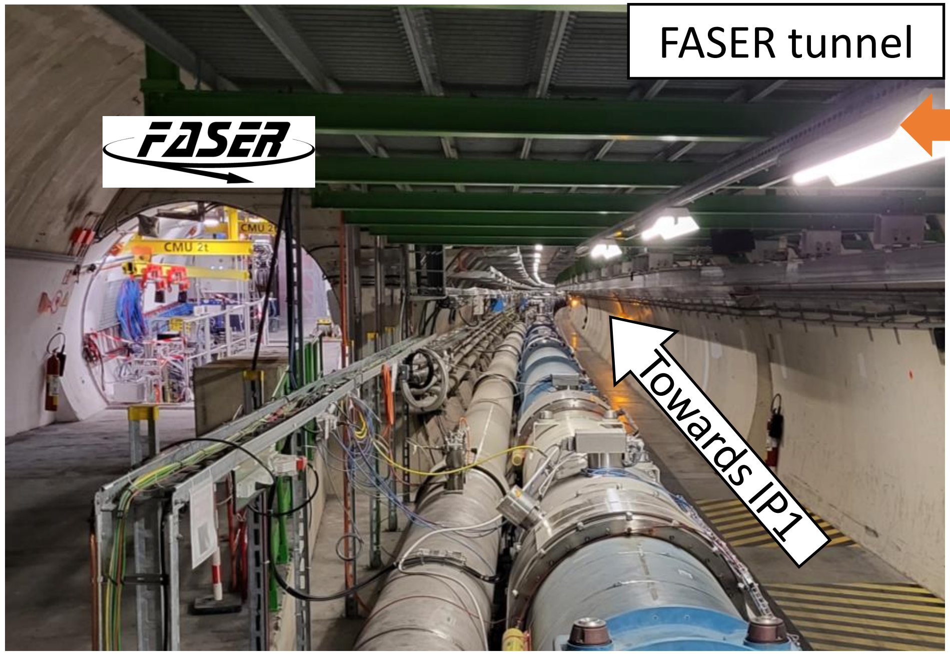

Vacuum sealed sub-module

FASERν Exchange

- Irradiated module extracted, and new module installed.
- Performed by FASER members with CERN technical teams.

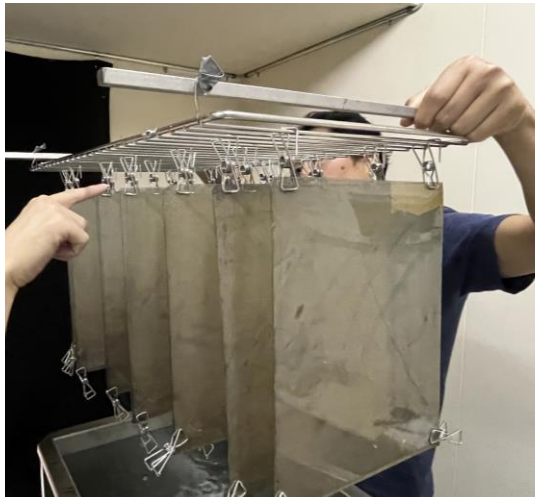


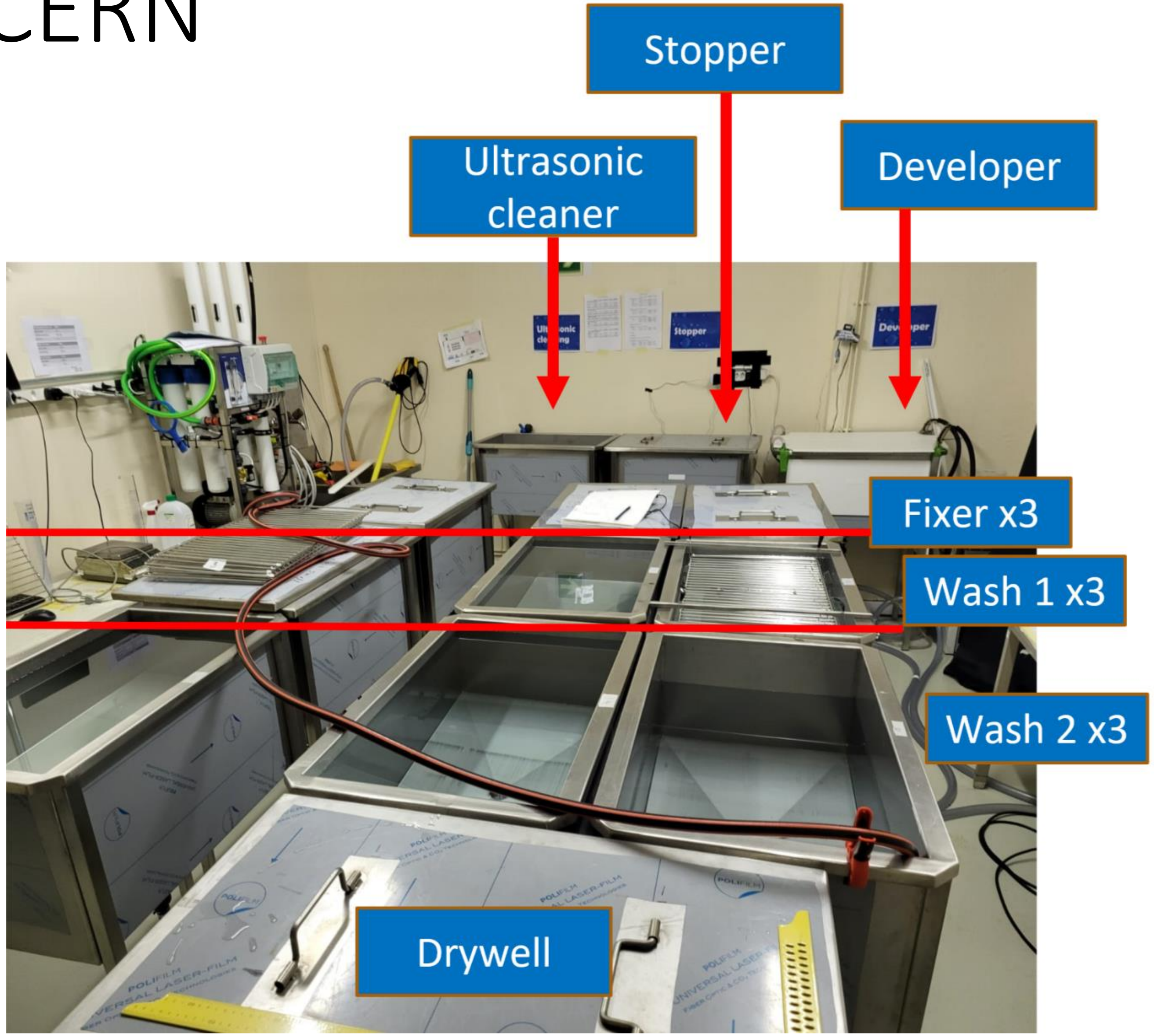




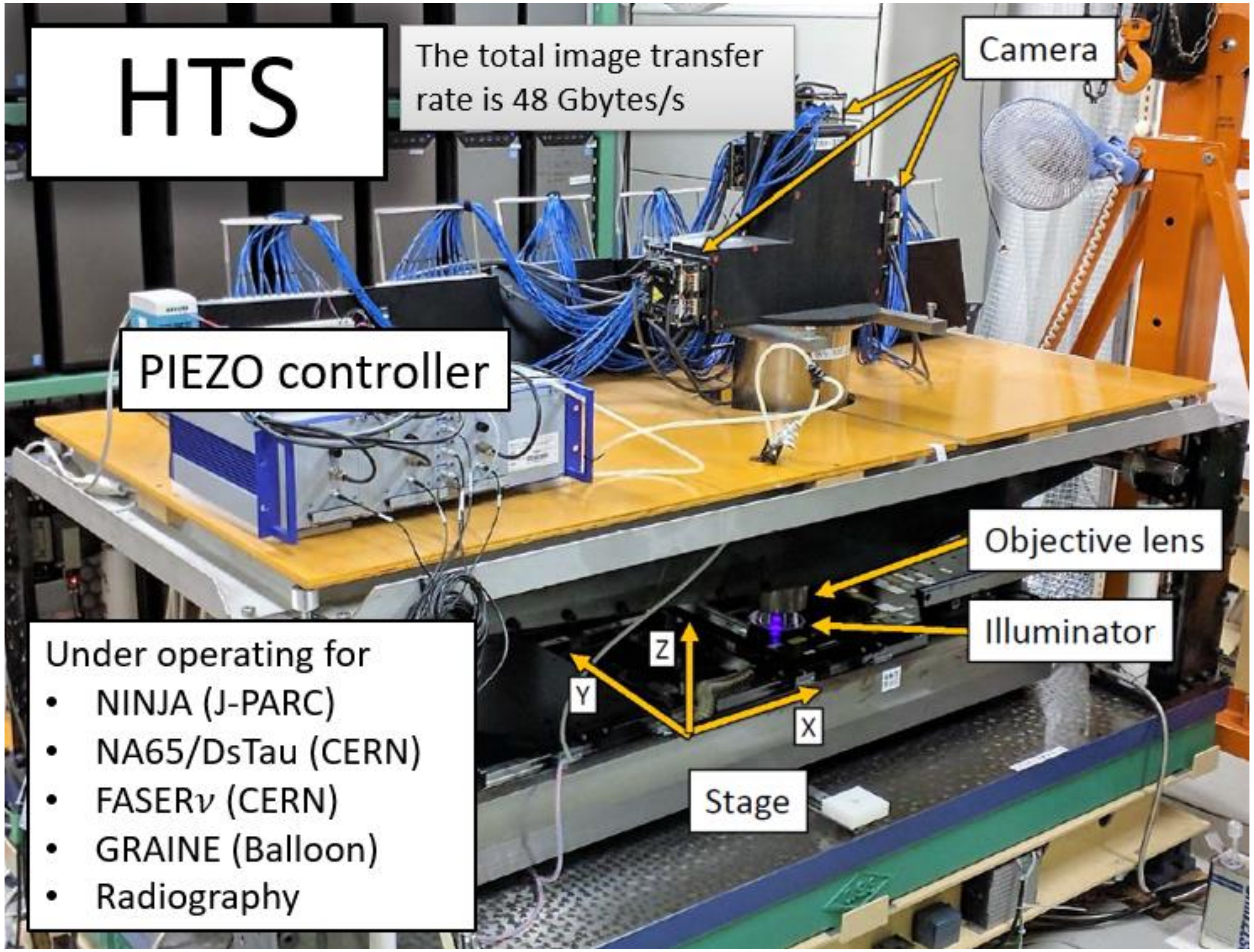
FASERν Development at CERN

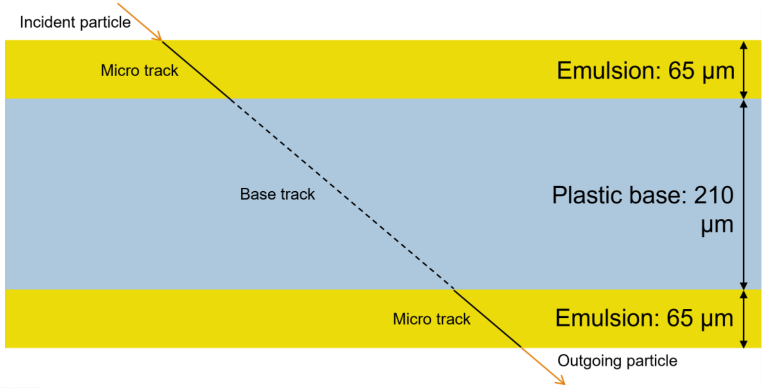
- Development campaign lasts ~12 days.
- Films are extracted and labelled.
- 200 films developed with one set of chemicals in 3 days (1 cycle).
- 25 films developed together (1 chain) → 3.5 hours + 1 day drying.
- 25-minute shift between chains.

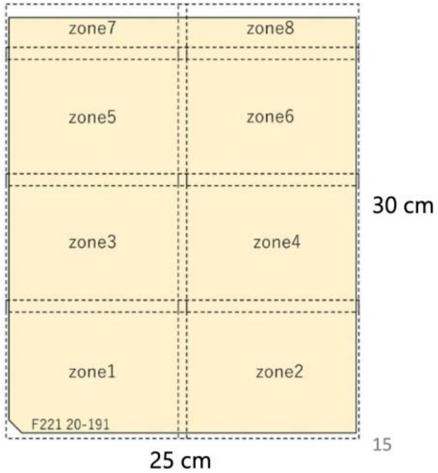


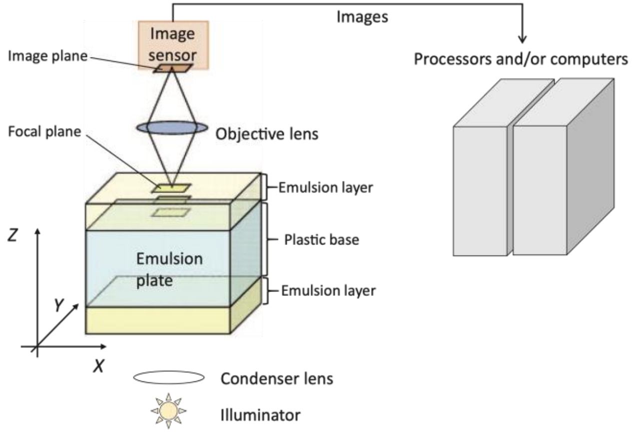


Film Readout in Nagoya







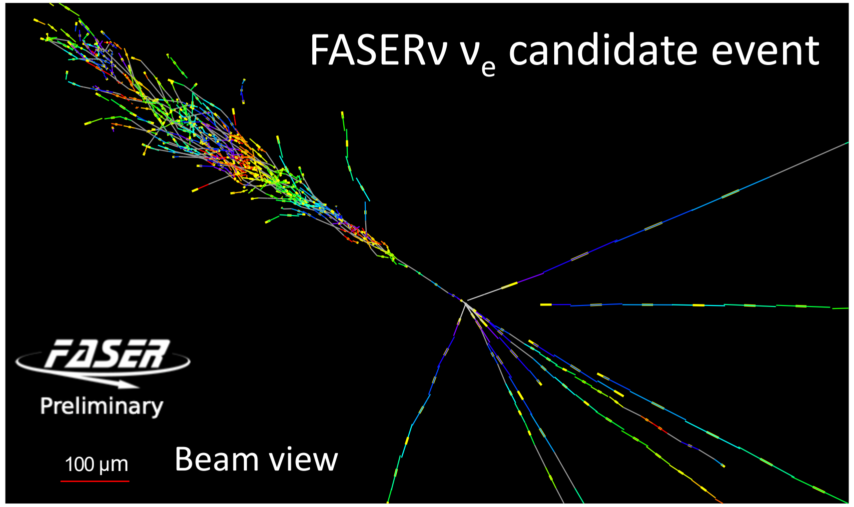


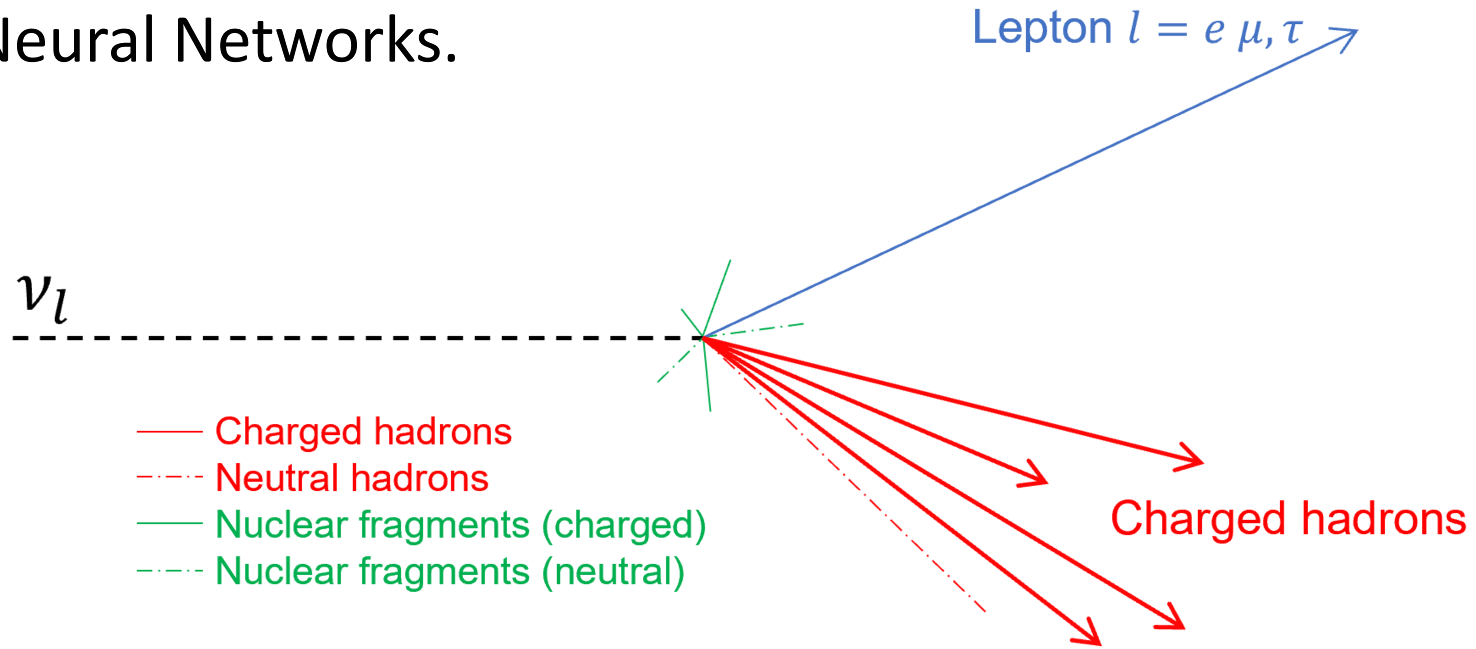
Hyper Track Selector (HTS): complex microscope system scans films for digital readout.

- Images made at different focal depths in emulsion;
- 5.1 x 5.1 mm^2 field of view;
- Each film scanned in 8 zones;
- 60 – 80 minutes for each film.

Neutrino Energy Reconstruction

- To perform cross-section measurements for neutrino interactions, the neutrino energy, E_ν, must be first reconstructed.
- Dataset – GENIE Monte Carlo ν_μ :
  - Flat E_ν spectrum before interaction → higher statistics at higher energies after;
  - Smearing applied to all momenta and angles.
- First estimate – sum of leptonic and hadronic visible energy.
- Further study – application of Neural Networks.



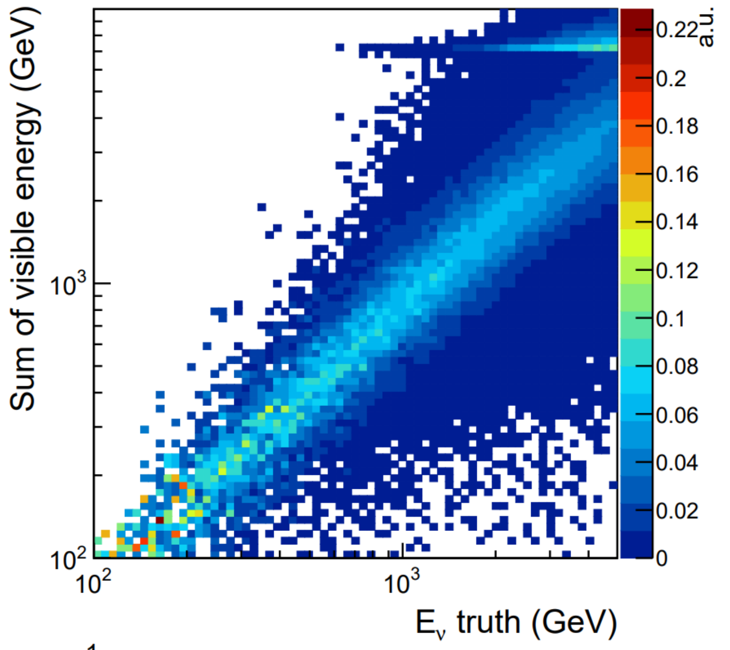


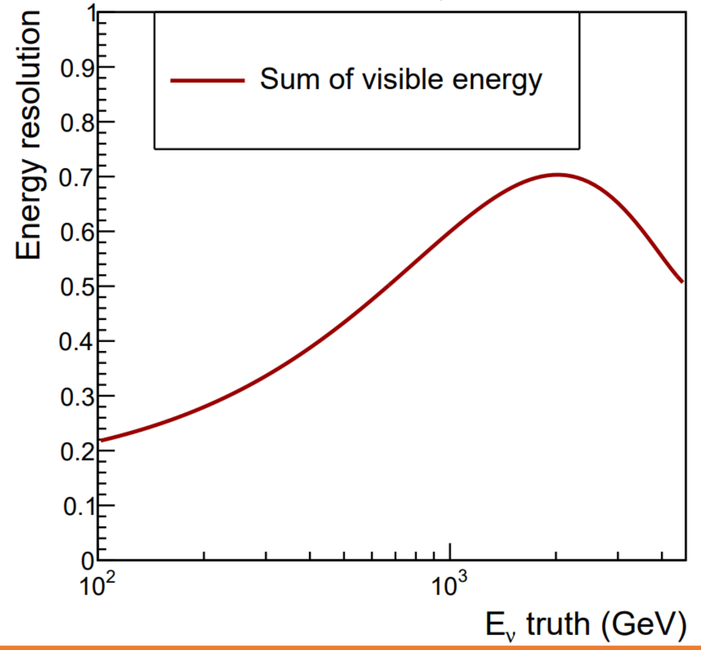
E_ν Reconstruction – Visible Energy

- Initial energy estimate found using sum of measured momenta of charged particles:
  - Lepton energy;
  - Sum of hadronic energy;
  - Sum of EM energy → currently being developed, to be implemented.

- Energy is slightly underestimated, as expected (EM energies not used, neutral hadrons).

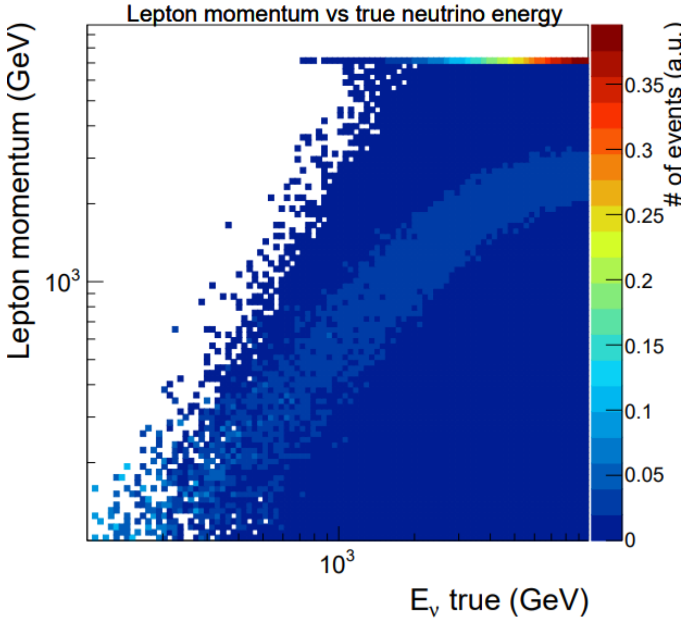
- Energy resolution defined as $\frac{E_{rec} - E_{true}}{E_{true}}$ → want to minimise.

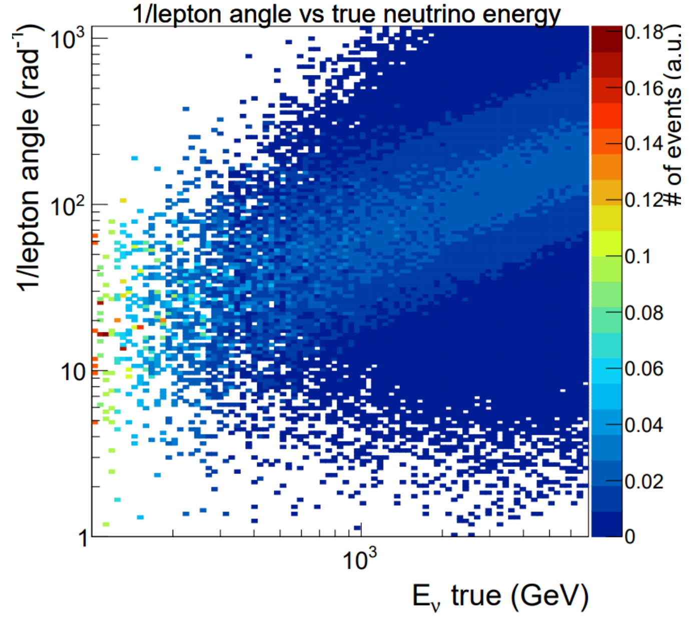


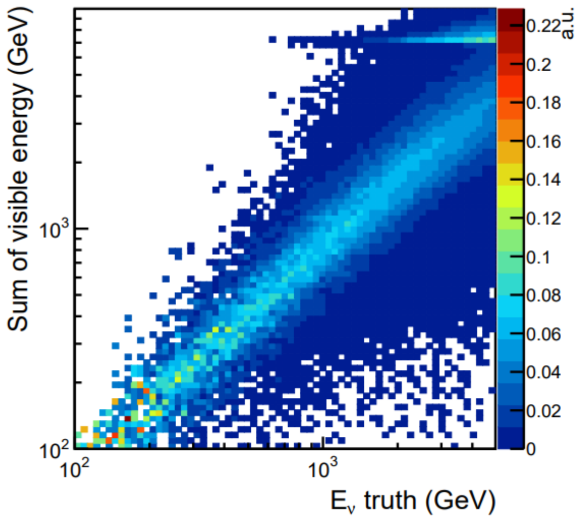


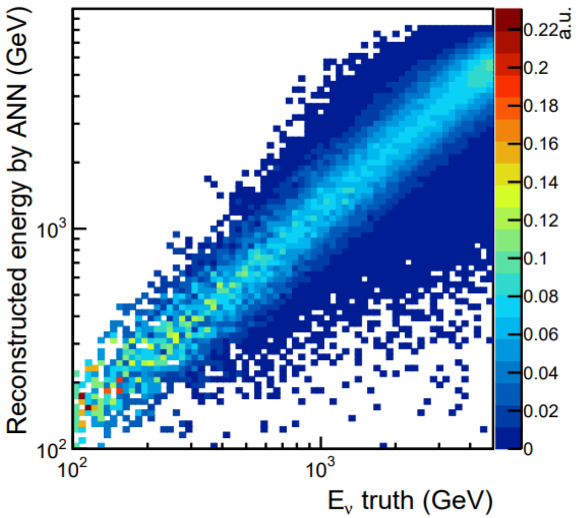
E_ν Reconstruction – Neural Network

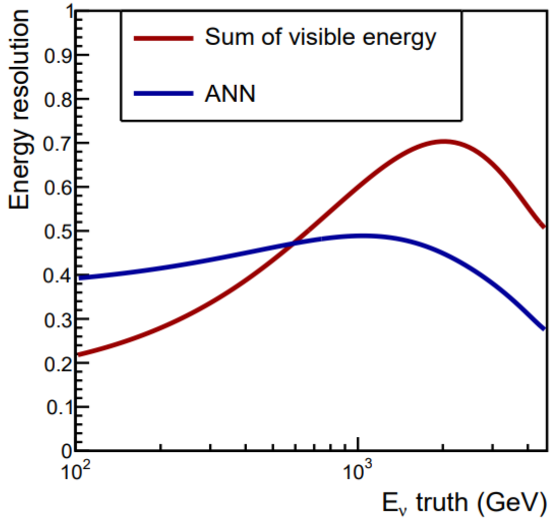
- Applying Neural Network techniques to improve E_ν reconstruction → Multi Layer Perceptron (MLP).
- Input variables investigated:
  - Lepton kinematics: momentum, angle, pseudorapidity;
  - Hadronic system kinematics: sum of momenta, angle averages, rapidity;
  - Interaction variables: charged particle multiplicity.







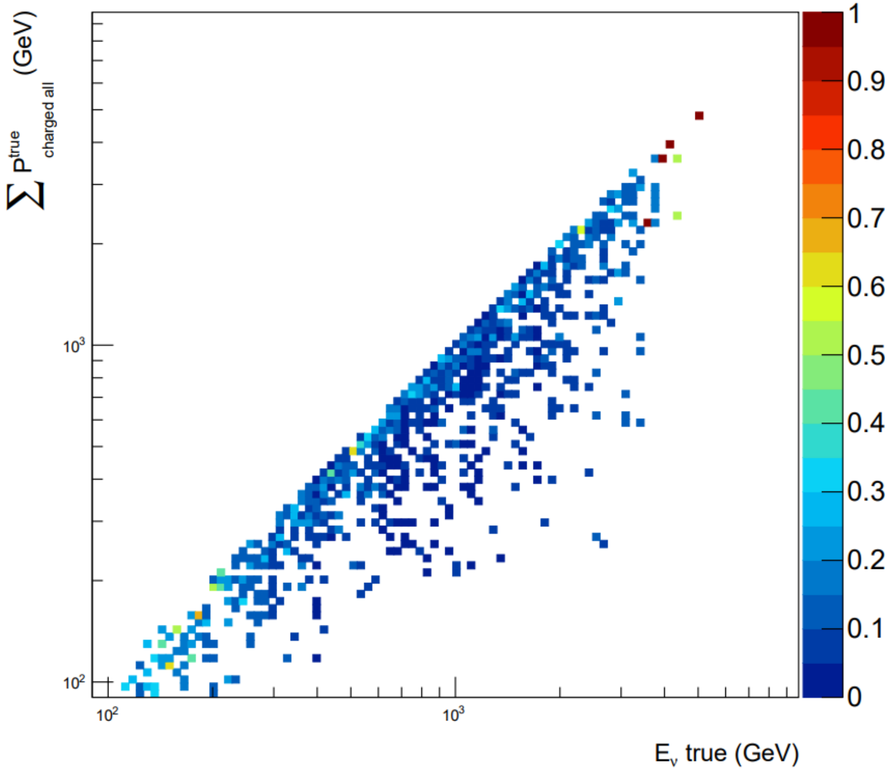




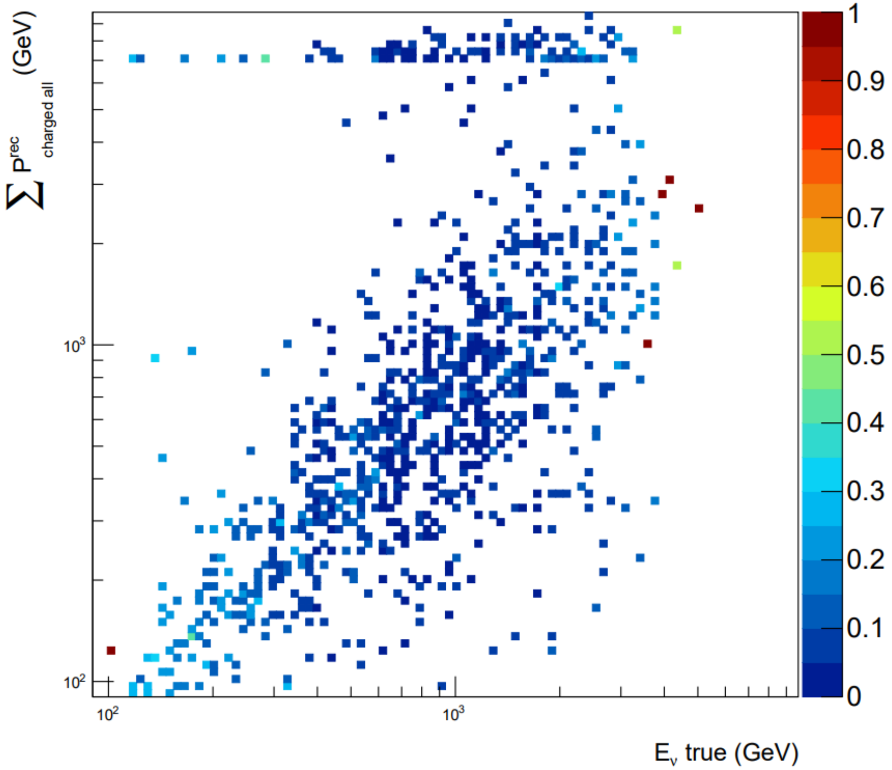
Reconstructed GENIE MC – Visible Energy

- Dataset of GENIE MC reconstructed using the analysis performed on data.
- Currently low statistics, but results are consistent with expectations.

Sum of all charged particle **TRUTH** momenta vs true neutrino energy (GeV)



Sum of all charged particle **RECONSTRUCTED** momenta vs true neutrino energy (GeV)



Neutrino Energy Reconstruction – Future

- Going forward with Neural Networks:
  - Testing further parameters and variables for MLP;
  - Incorporate EM variables;
  - Generalise to all (anti-)neutrino flavours;
  - Investigate other Neural Network techniques.

- Jets:
  - Low energy nuclear fragments emitted isotropically;
  - 300 GeV minimum momentum cut applied, but some may pass selection;
  - Aim to group hadronic components into single forward jet.

Summary

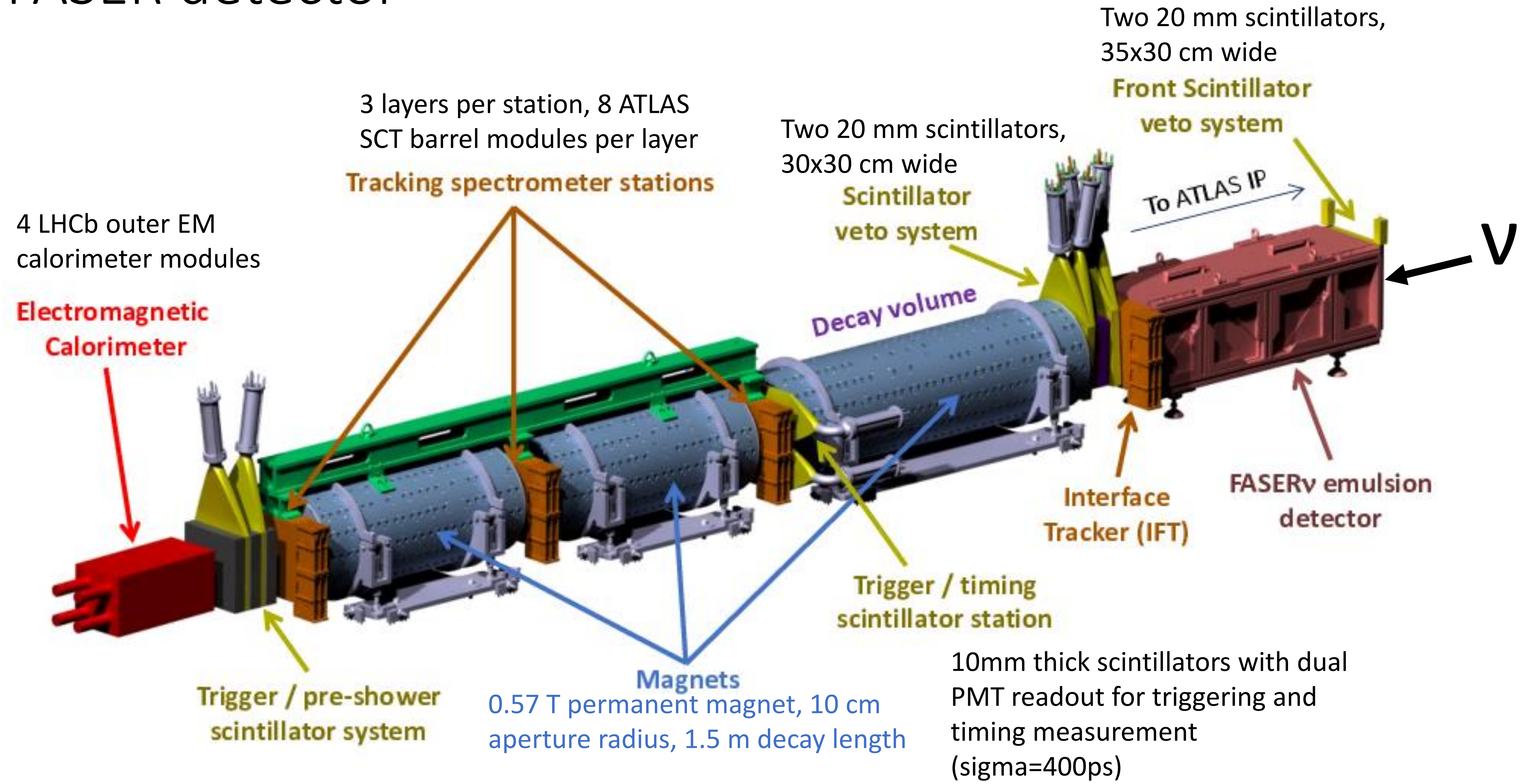
- The FASERν emulsion detector measures TeV-scale neutrinos of all 3 flavours → First collider neutrino experiment!
- FASER is successfully operating during CERN LHC Run 3.
- 5 FASERν modules have been irradiated, collecting 60 fb^{-1}, with another ~120 fb^{-1} expected in Run 3.
- FASERν operations include:
  - Emulsion film production;
  - Detector assembly and development;
  - Developed film scanning using HTS microscope.

- Currently developing neutrino energy reconstruction methods using Neural Network techniques.

- First observation of collider ν_μ and ν_e CC interactions by FASER.
- First physics results with FASERν demonstrate the ability to carry out neutrino measurements with emulsion-based detectors in the challenging conditions at the LHC → a lot more physics to come…

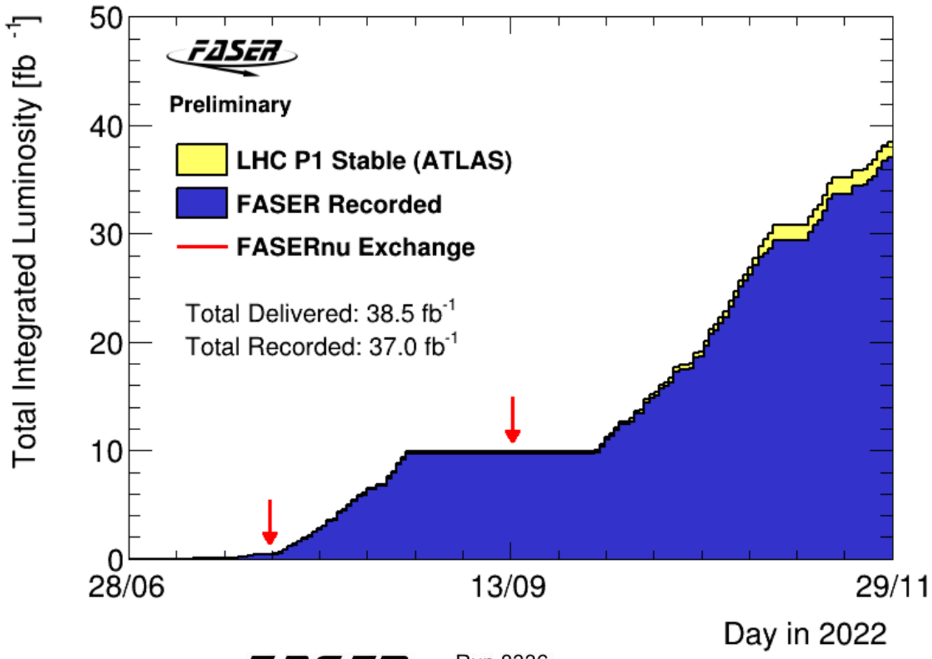
Backup

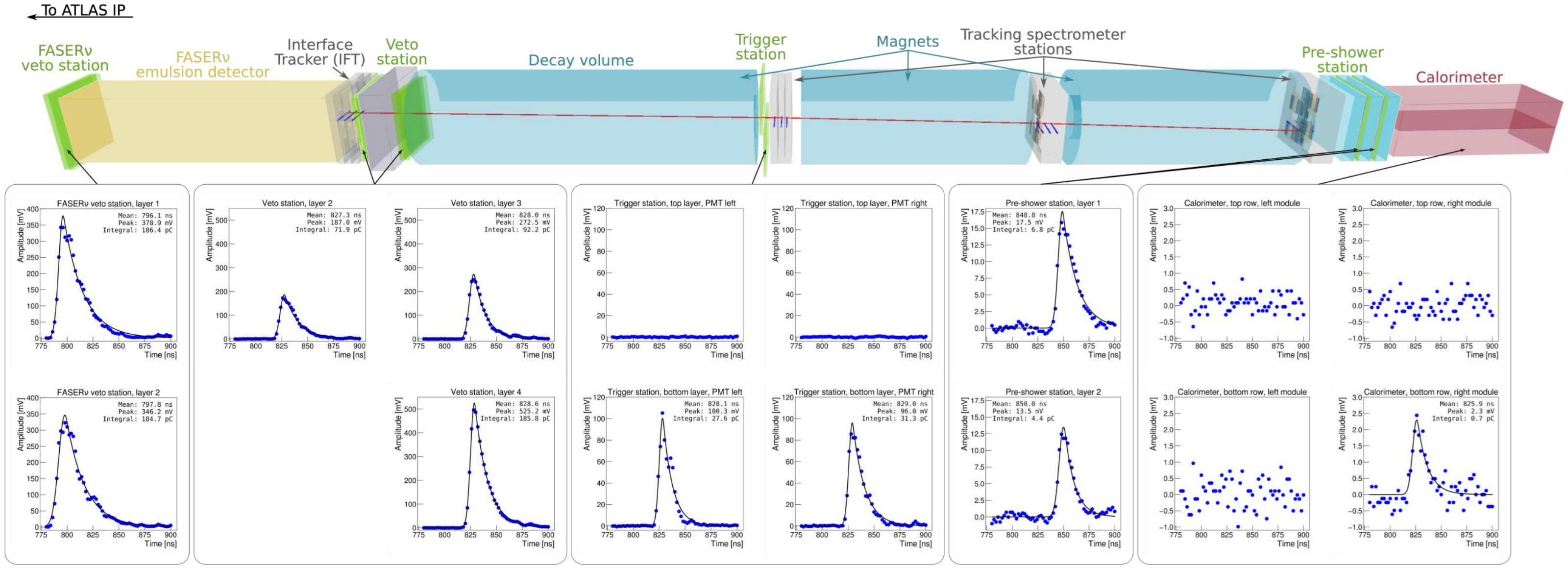
FASER detector

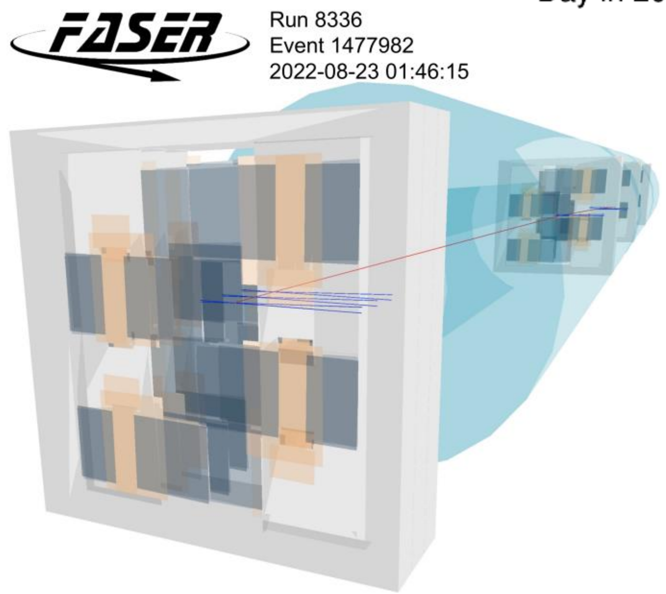


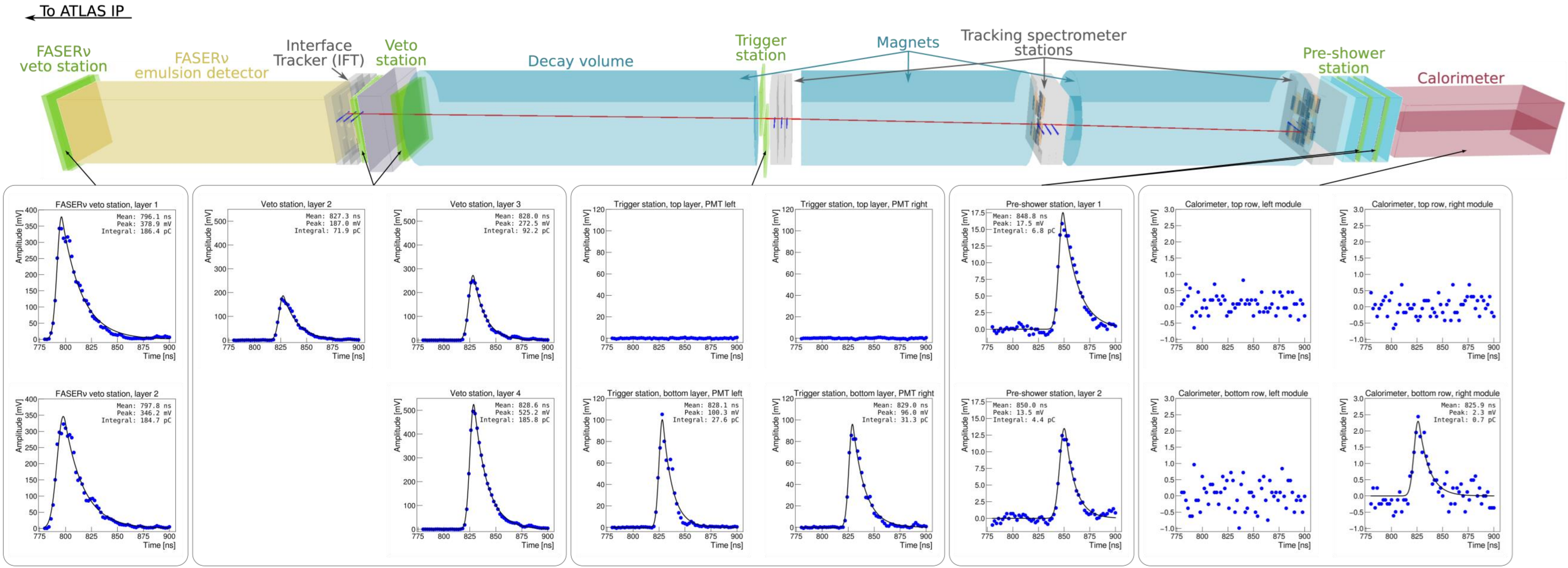
FASER Operations

- Successful running in 2022.
- Recorded **96%** of delivered luminosity → > 35 fb^{-1} .
- FASERν module exchanged twice due to occupancy in emulsion.
- Example event: muon leaving track in full detector → all detector components working well.





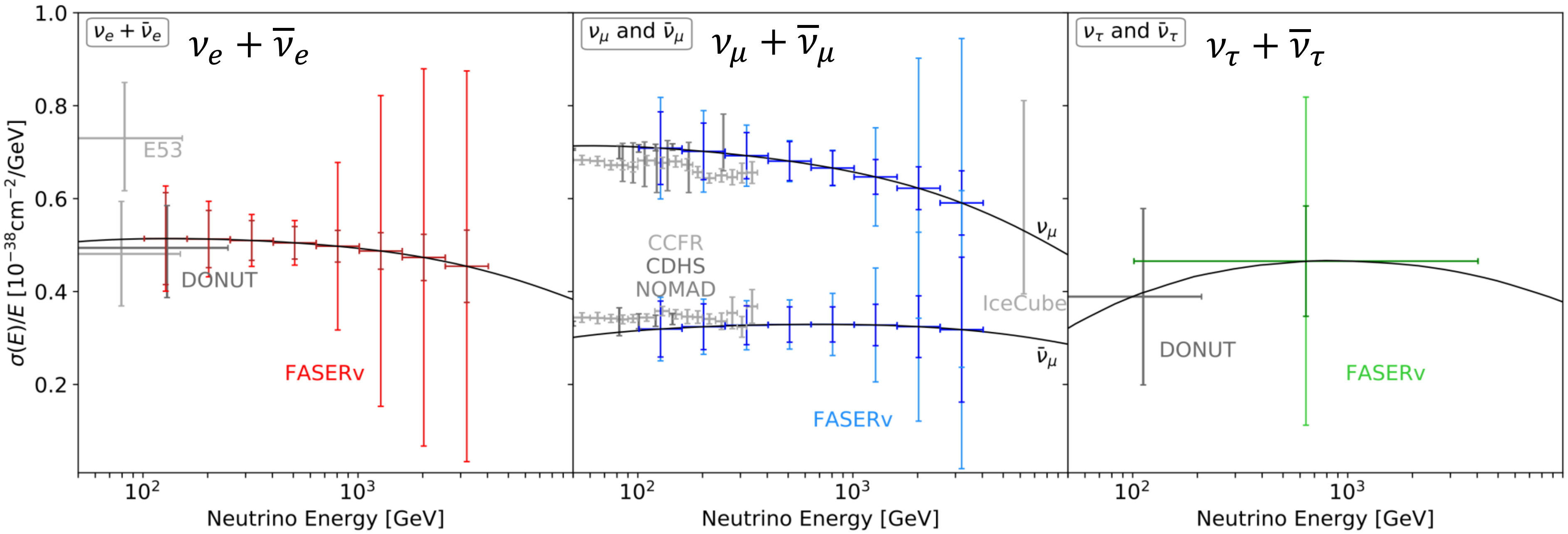



To ATLAS IP
FASERν veto station
FASERν emulsion detector
Interface Tracker (IFT)
Veto station
Decay volume
Trigger station
Magnets
Tracking spectrometer stations
Pre-shower station
Calorimeter
FASERν veto station, layer 1
Mean: 796.1 ns
Peak: 378.9 mV
Integral: 186.4 pC
FASERν veto station, layer 2
Mean: 797.8 ns
Peak: 346.2 mV
Integral: 184.7 pC
Veto station, layer 2
Mean: 827.3 ns
Peak: 187.0 mV
Integral: 71.9 pC
Veto station, layer 3
Mean: 828.0 ns
Peak: 272.5 mV
Integral: 92.2 pC
Veto station, layer 4
Mean: 828.6 ns
Peak: 525.2 mV
Integral: 185.8 pC
Trigger station, top layer, PMT left
Trigger station, top layer, PMT right
Trigger station, bottom layer, PMT left
Mean: 828.1 ns
Peak: 100.3 mV
Integral: 27.6 pC
Trigger station, bottom layer, PMT right
Mean: 829.0 ns
Peak: 96.0 mV
Integral: 31.3 pC
Pre-shower station, layer 1
Mean: 848.8 ns
Peak: 17.5 mV
Integral: 6.8 pC
Pre-shower station, layer 2
Mean: 850.0 ns
Peak: 13.5 mV
Integral: 4.4 pC
Calorimeter, top row, left module
Calorimeter, top row, right module
Calorimeter, bottom row, left module
Calorimeter, bottom row, right module
Mean: 825.9 ns
Peak: 2.3 mV
Integral: 0.7 pC
Amplitude [mV]
Time [ns]

High Energy Neutrinos in FASER

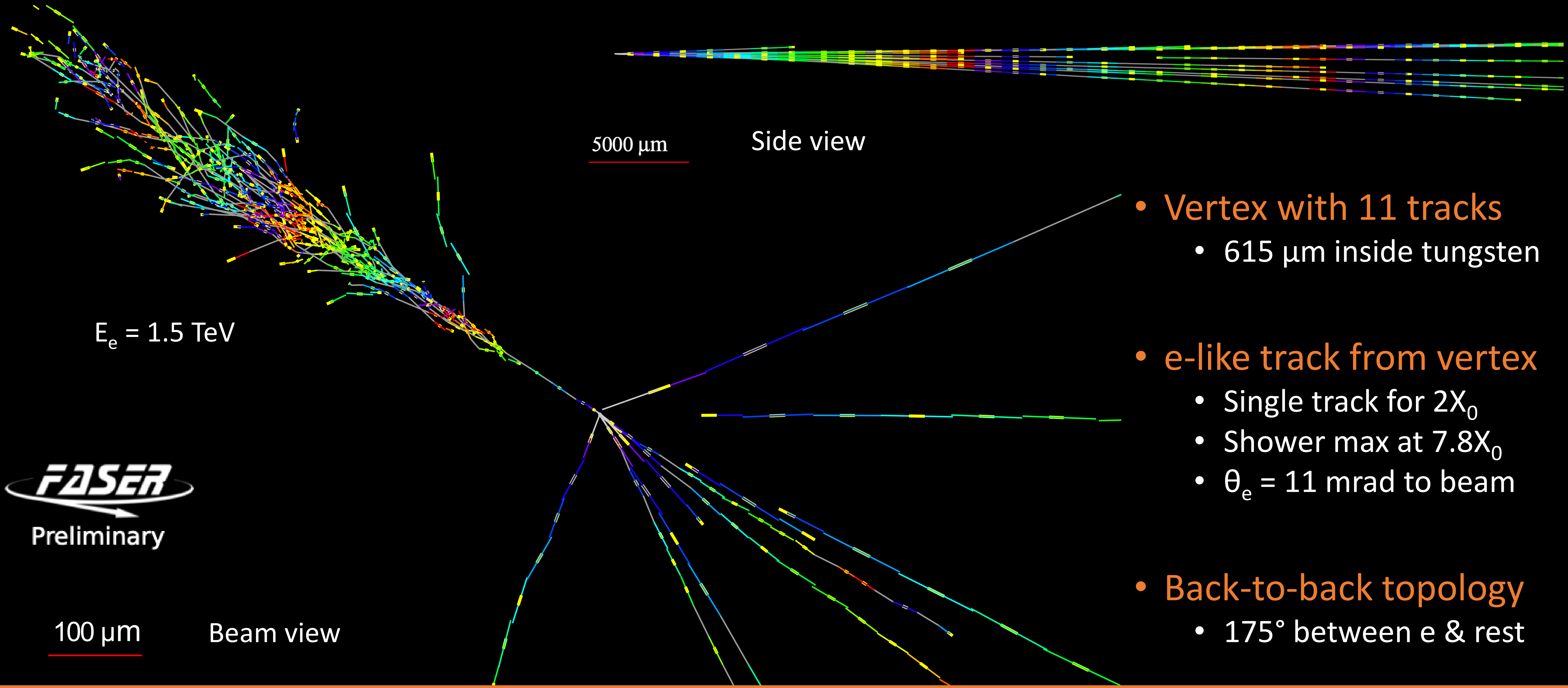
- FASER takes advantage of the intense forward hadron production in proton-proton collisions to produce a collimated neutrino beam.
- 3-flavour cross-section measurement for previously unexplored energy range → highest E_ν from artificial source.

FASER expected sensitivity



- Inner error bars: statistical uncertainties.
- Outer error bars: uncertainties from neutrino production rate.

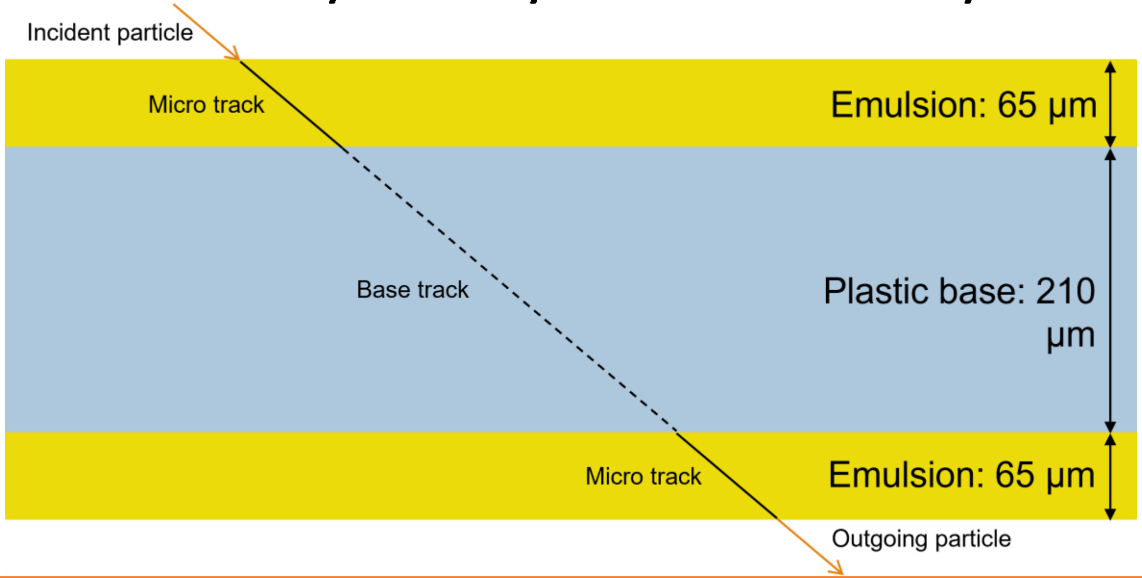
FASERν ν_e candidate event

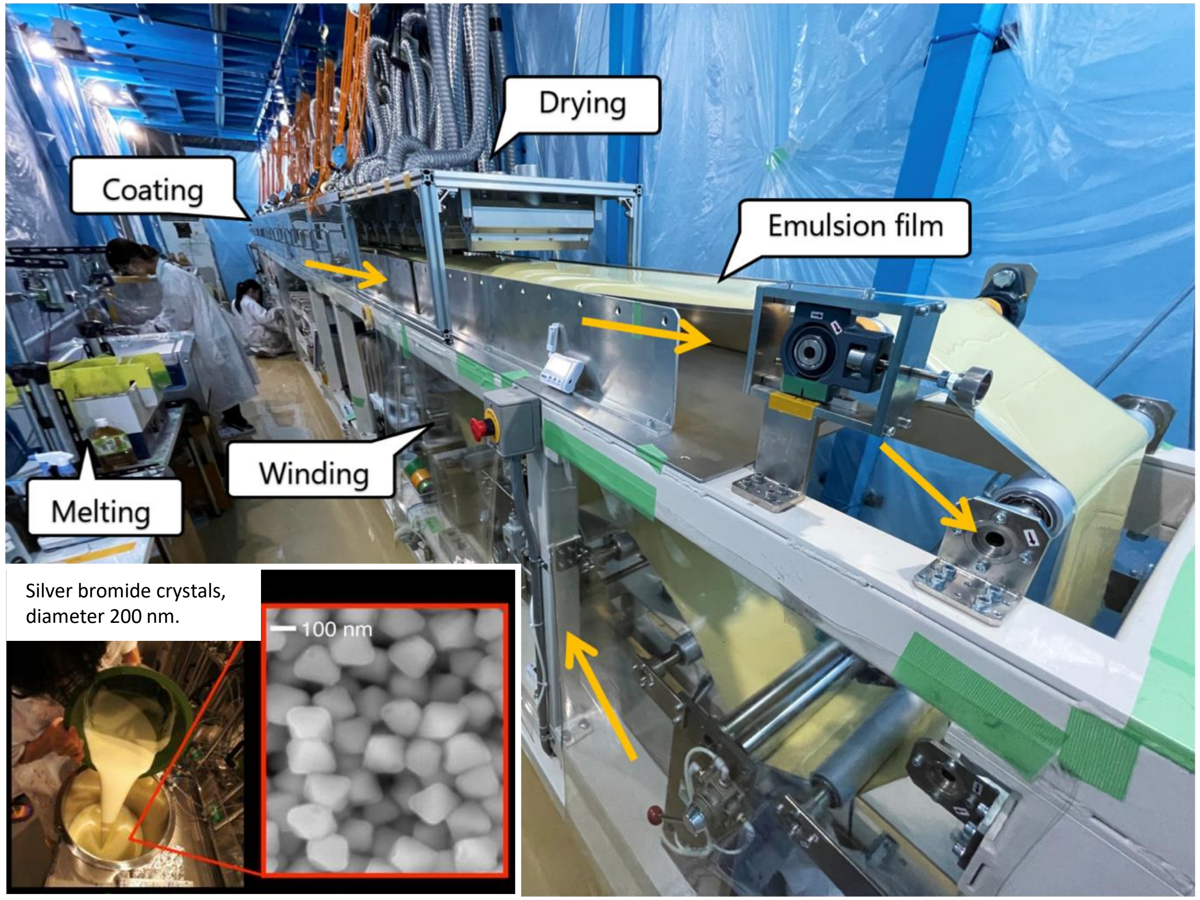


- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max at $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

Film production

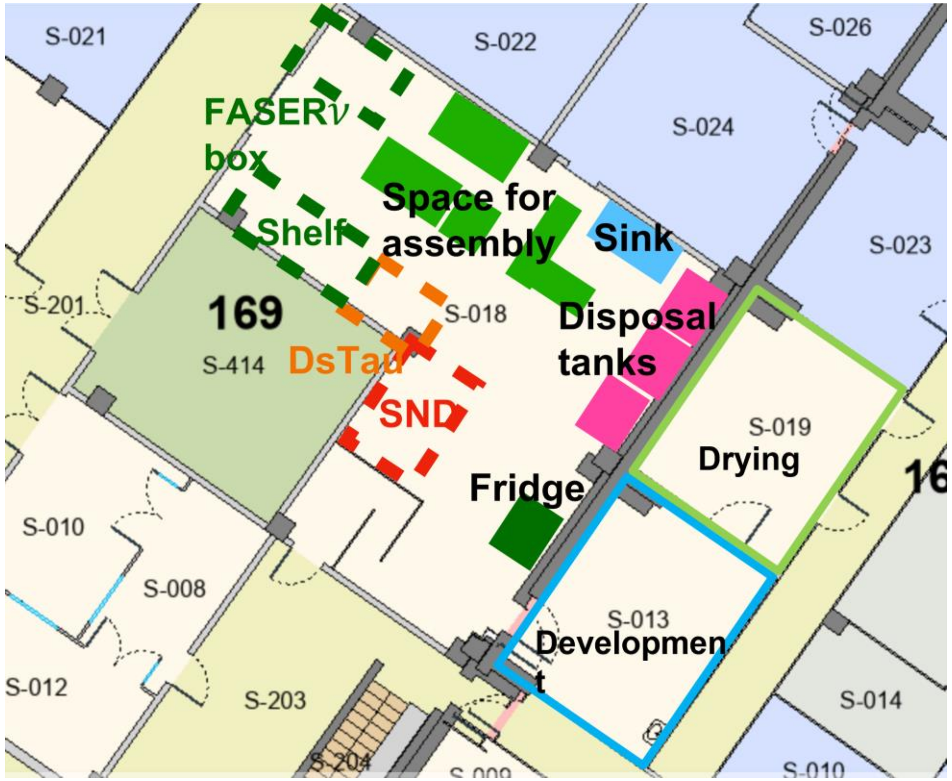
- Emulsion gel and films produced at Nagoya University in dedicated facility.
- Silver bromide crystals, diameter 200 nm.
- 110 m^2 of emulsion for every module.
- Resetting procedure performed in Nagoya University and Kyushu University.





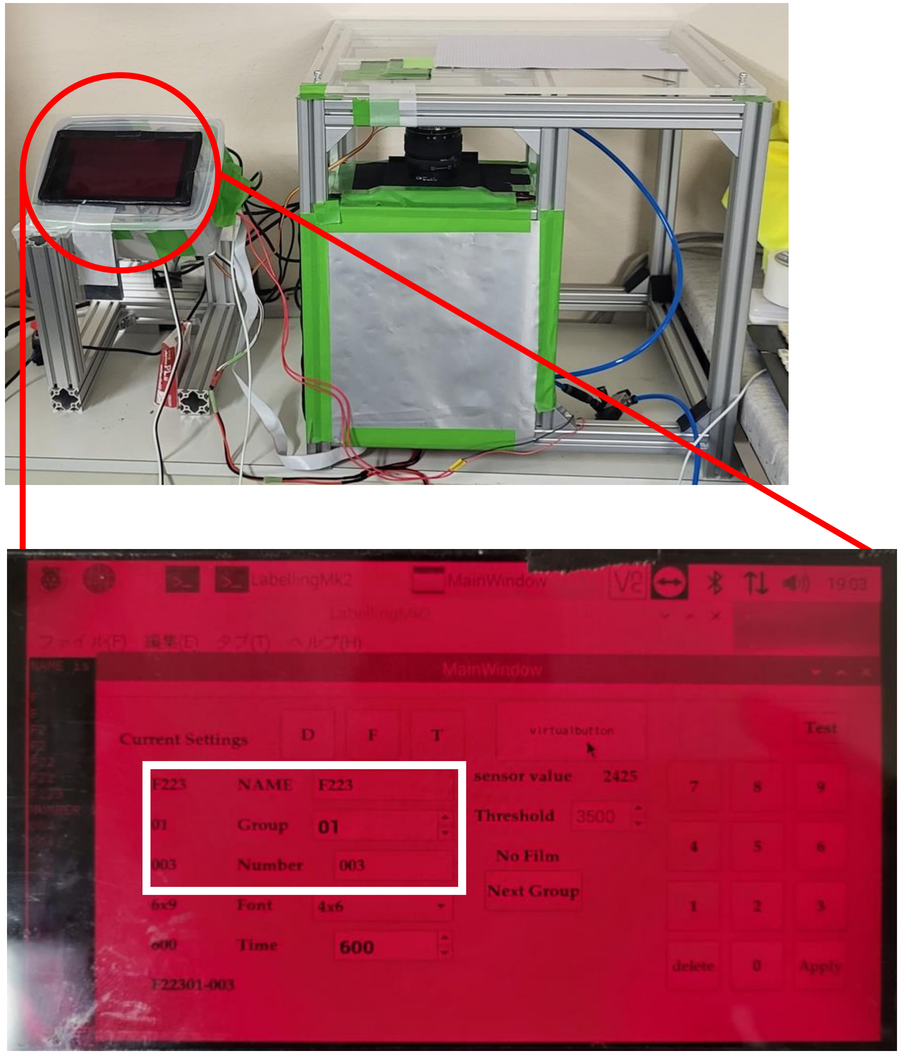
Emulsion Facility at CERN

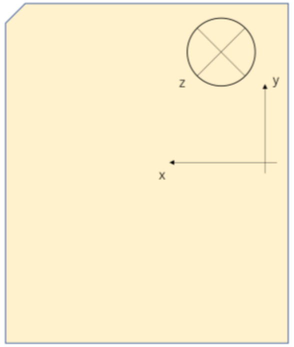
- New facility set up at CERN for emulsion experiments – includes modern climate control and ventilation system, access card entry, and full dark room capabilities for emulsion handling.
- 3 dedicated room: assembly, development and drying.
- Shared with NA65/DsTau, SND@LHC and SHiP Collaborations.
- Darkroom operations: module assembly and development.

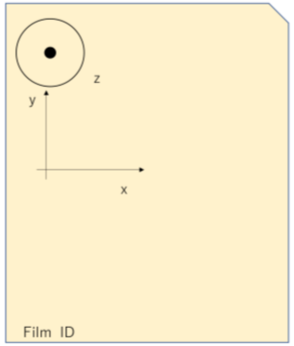


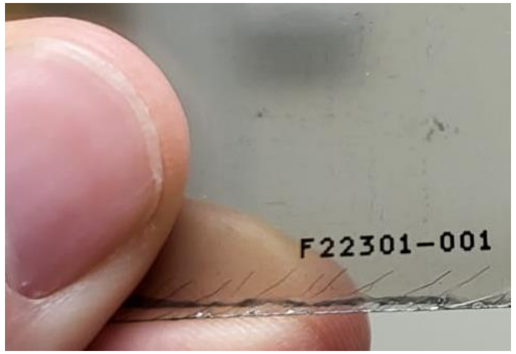
Development

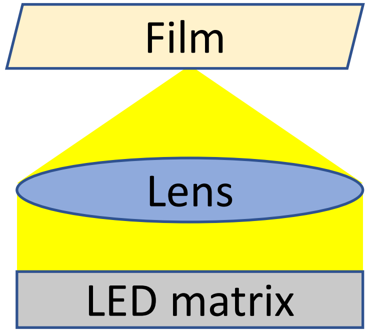
- FASERν module disassembly is performed in darkroom conditions by 2 people.
- 5 sub-modules (50 films) are extracted, disassembled, labelled and sorted into 2 packs of 25 films → Odd and Even films are separated and are developed in different batches of chemicals.
- Labelling is performed using a digital label maker.











Development

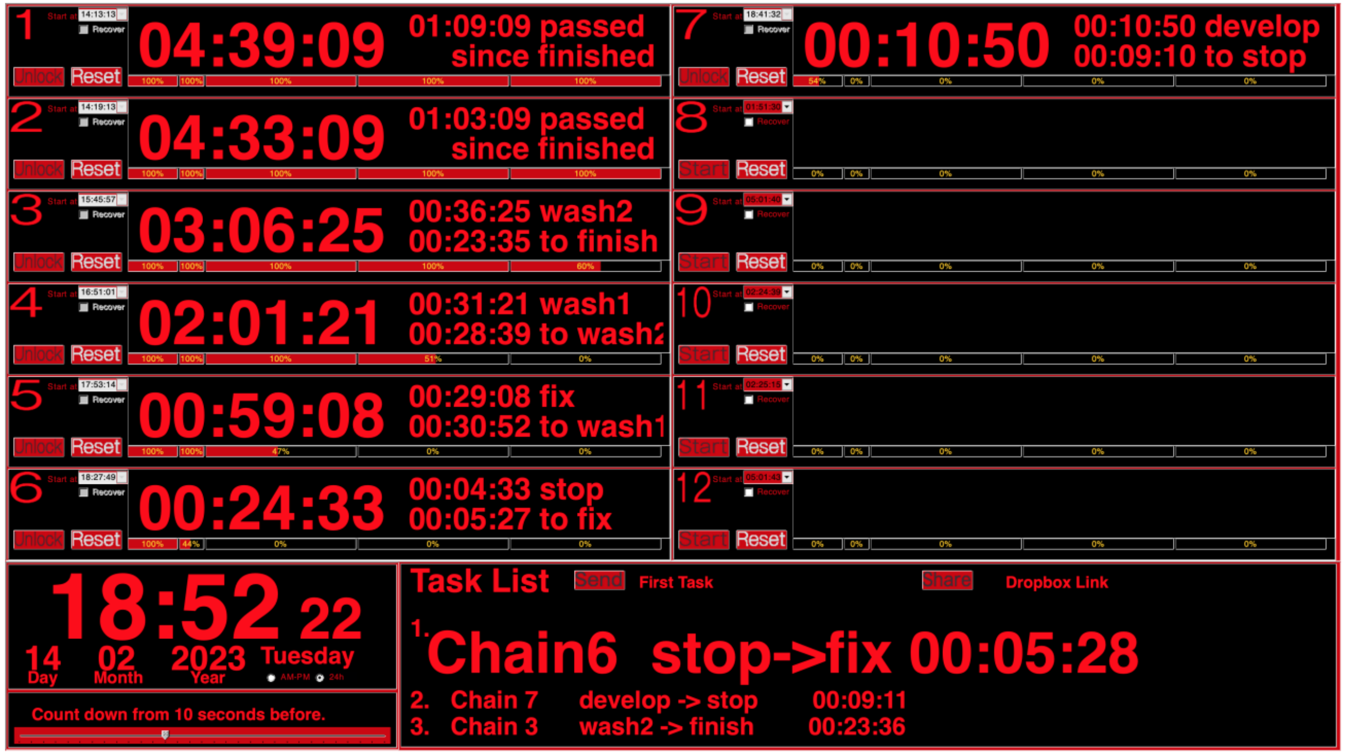
- 730 FASERν films in one FASERν module.

- 200 FASERν films → one cycle.
- 25 FASERν films hung using clips per rack → one chain.
- 4 cycles of 9 chains → each cycle takes approximately 3 days.
- Can have 3 chains going in parallel with around 25 minute shift.

- Approximately same number of films per chain in sets of 3 chains.
- Odd and Even films from the same sub-module are never developed in the same cycle.

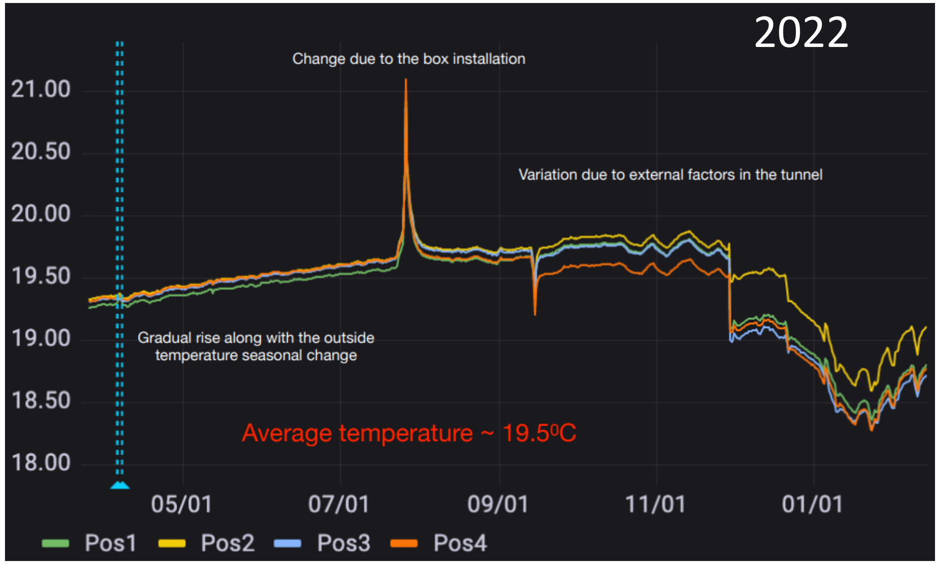
Cycle	Day 1	Day 2	Day 3
08:00			
09:00			
10:00	Chemical preparation		
11:00			3 chains
12:00			
13:00		6 chains	
14:00	Test		
15:00	Development		Chemical
16:00			disposal
17:00			
18:00			
19:00			

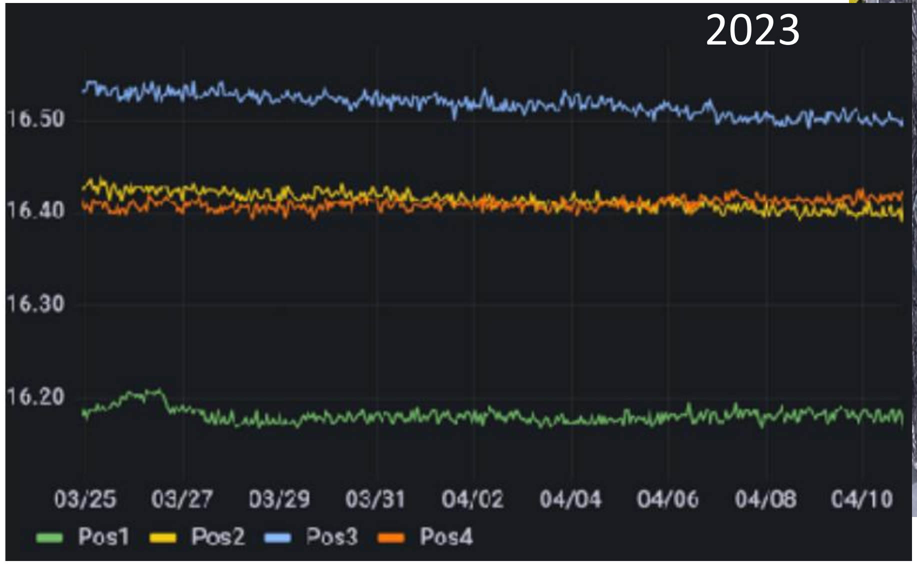
Solution	Time	№ tanks
Developer	20 minutes	1
Stopper	10 minutes	1
Fixer	1 hour	3
Wash 1	1 hour	3
Wash 2	1 hour	3
Drywell	10 seconds	1
Total	3.5 hours + 1 day drying	

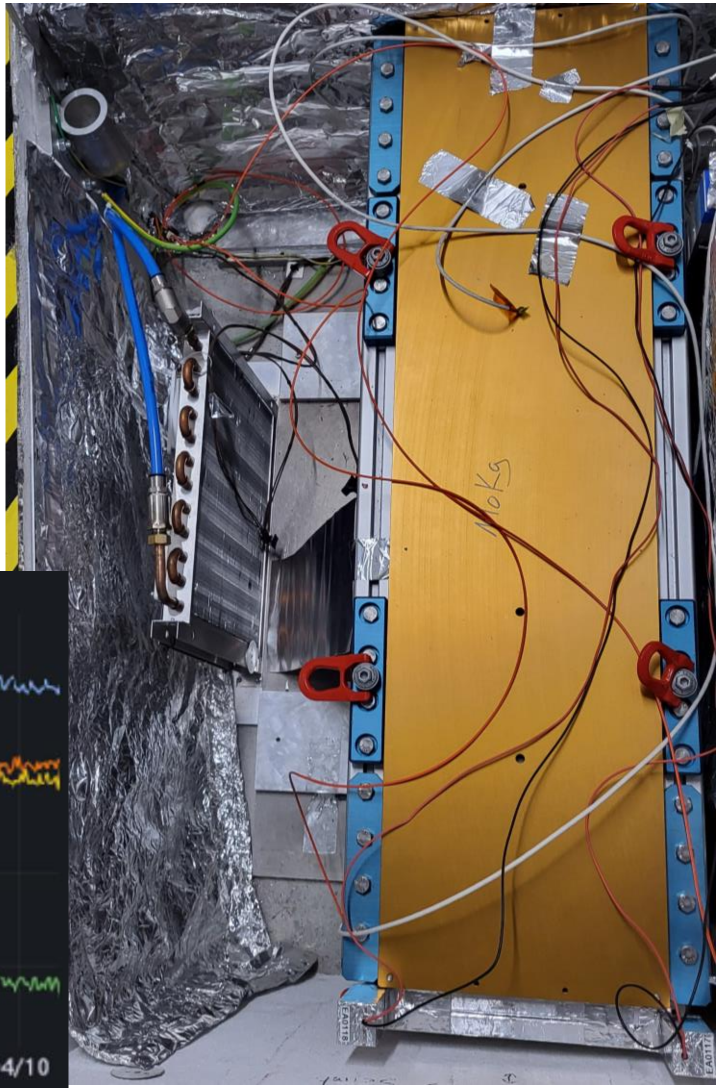


Module temperature control

- Temperature of the FASERν module is kept constant at 0.1°C level with dedicated cooling system.
- Water in heat exchanger is kept at 15°C, and a fan system mixes the air in the FASERν trench, with a slanted perforated plate which helps further mix the air on all sides of the module.
- An insulating layer is placed between the FASERν module and rest of FASER, and the trench is closed with an insulated metal cover → this is to ensure temperature stability which both increases alignment and minimises the fading effect of emulsion, as well as to understand the long-term properties.
- 4 temperature sensors are placed in and around the module to monitor the temperature.

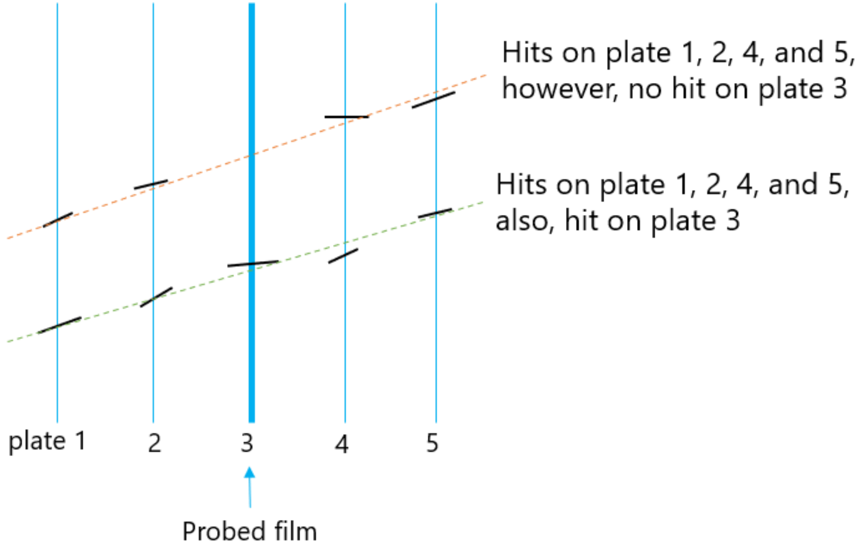


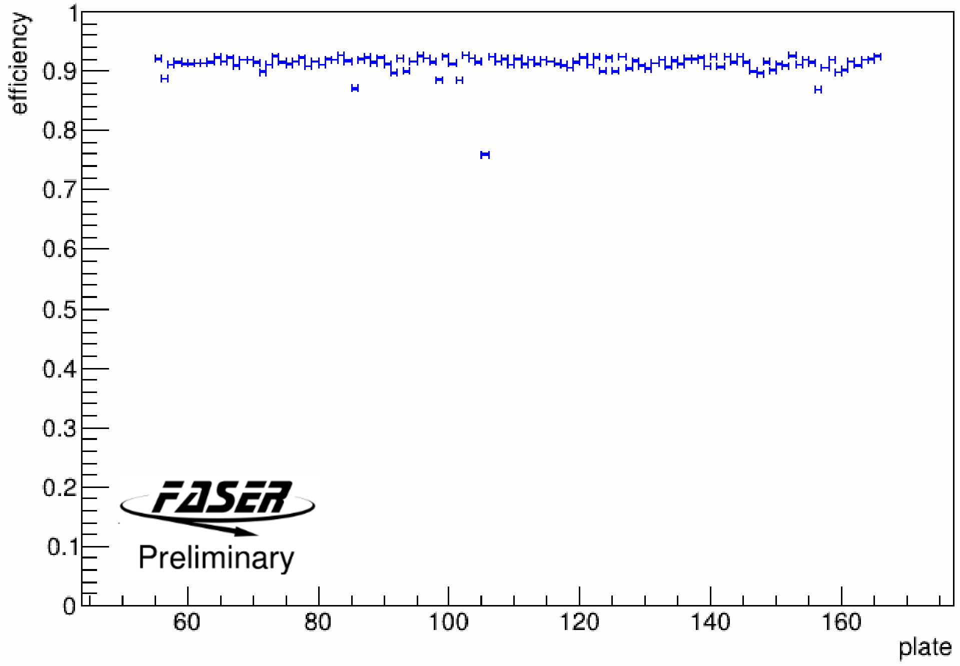




FASERν Event Reconstruction

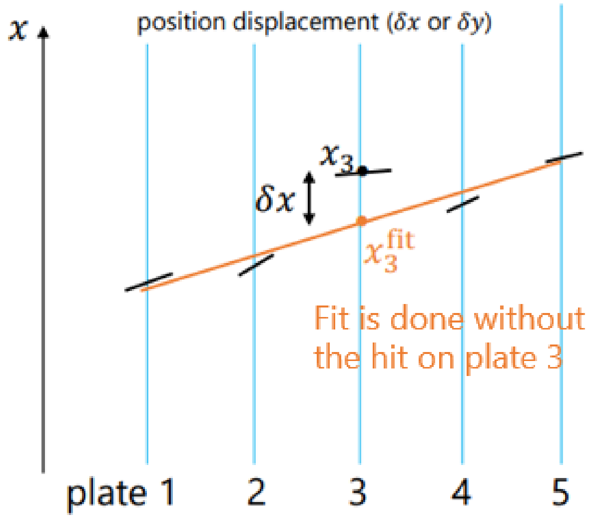
- Dedicated film alignment is performed using high-momentum muon tracks ($\mathcal{O}(10^5)$ tracks/cm^2).
- Track reconstruction links base-tracks on different films using position and angular information.
- Single film hit efficiency if found by considering whether a selected film has a hit given that 2 films either side have hits → observed efficiency > 90%.

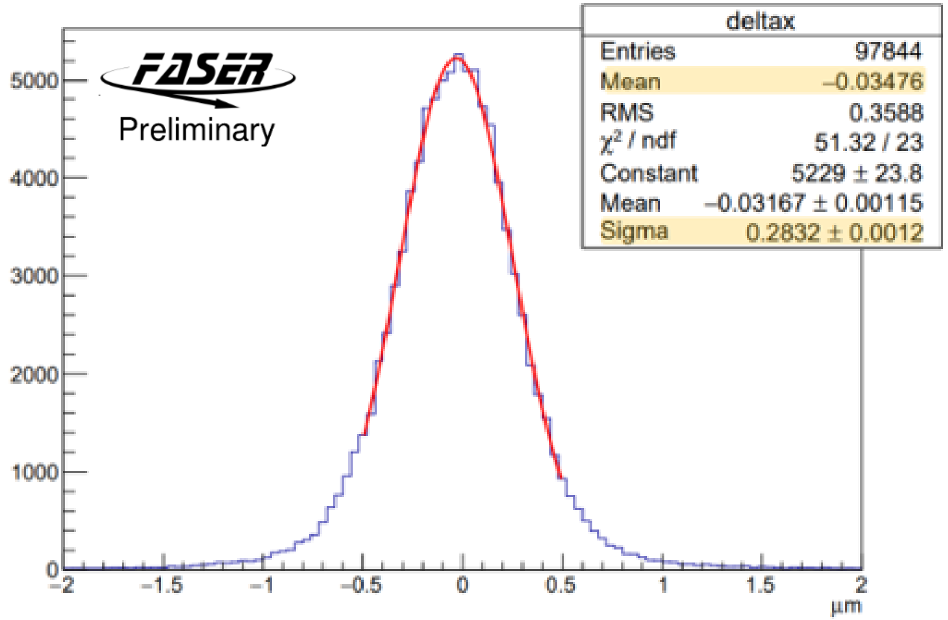




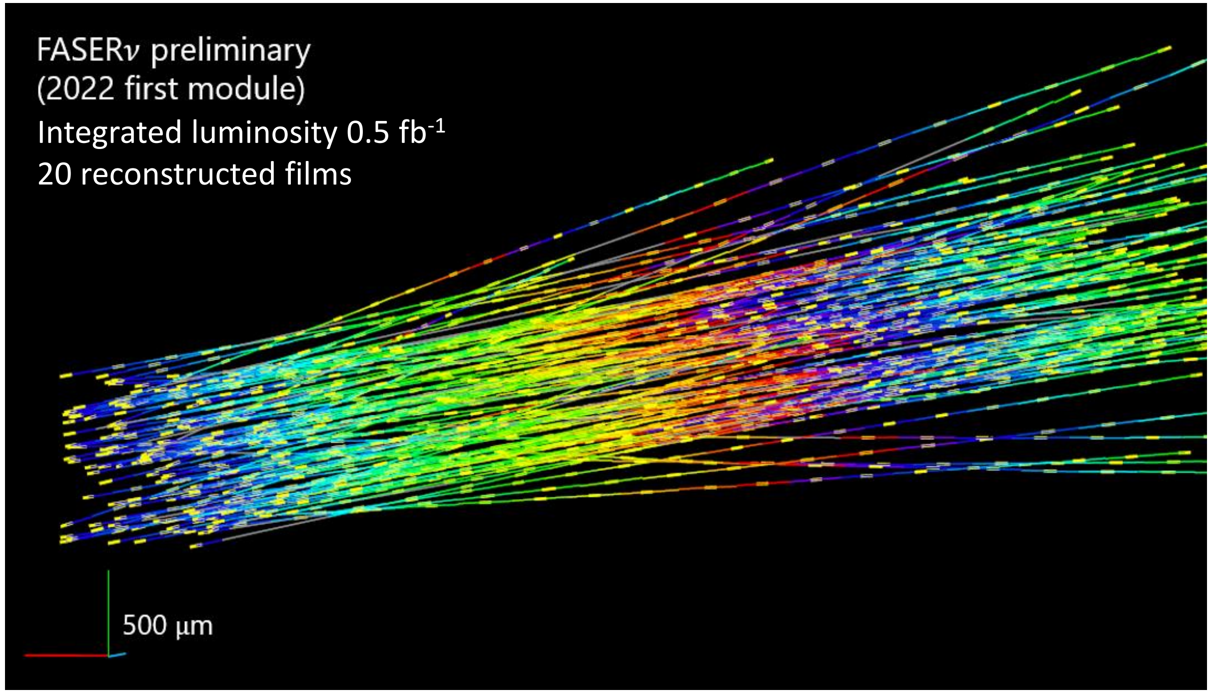
FASERν Performance

- Position resolution found using position displacement between hit and linear track fit.
- Observed <0.3 μm hit resolution after dedicated film alignment.



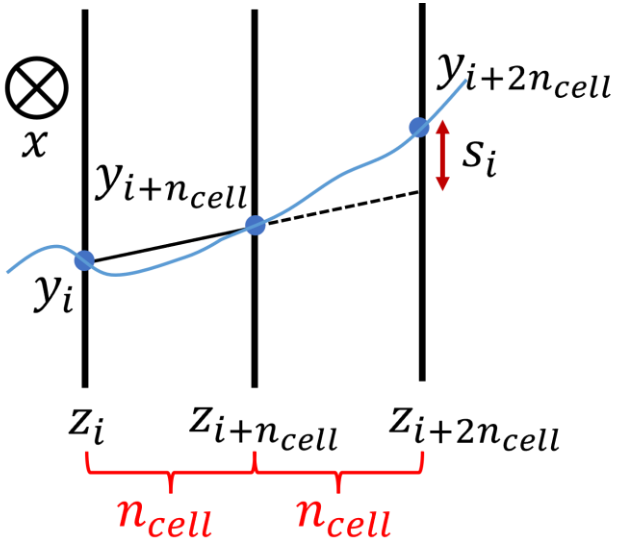


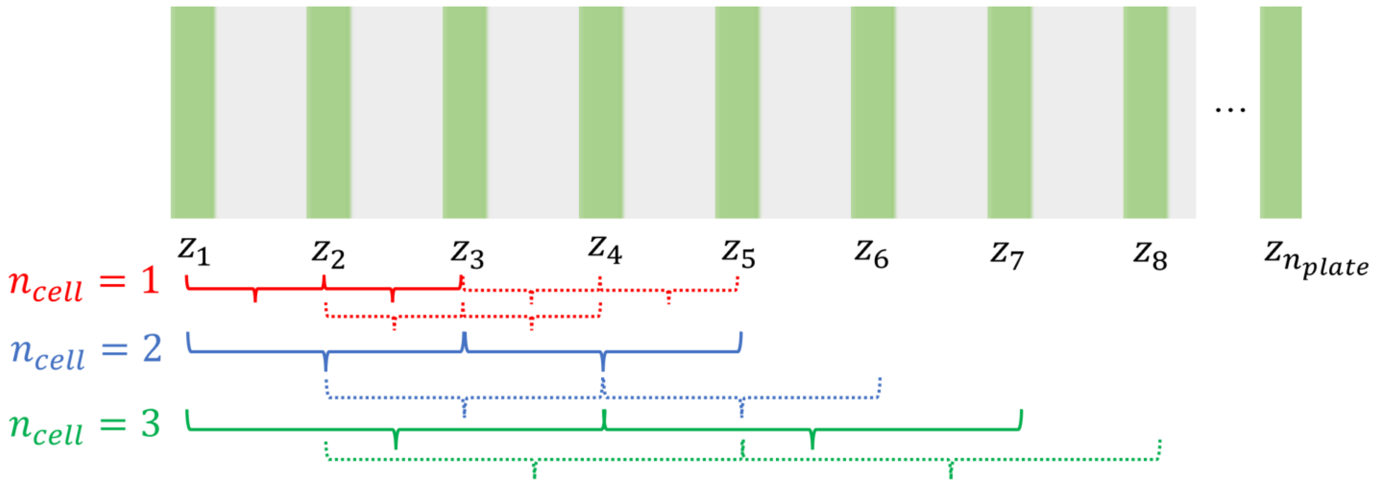
FASERν 2022 2^{nd} module (integrated luminosity 9.5 fb^{-1}).

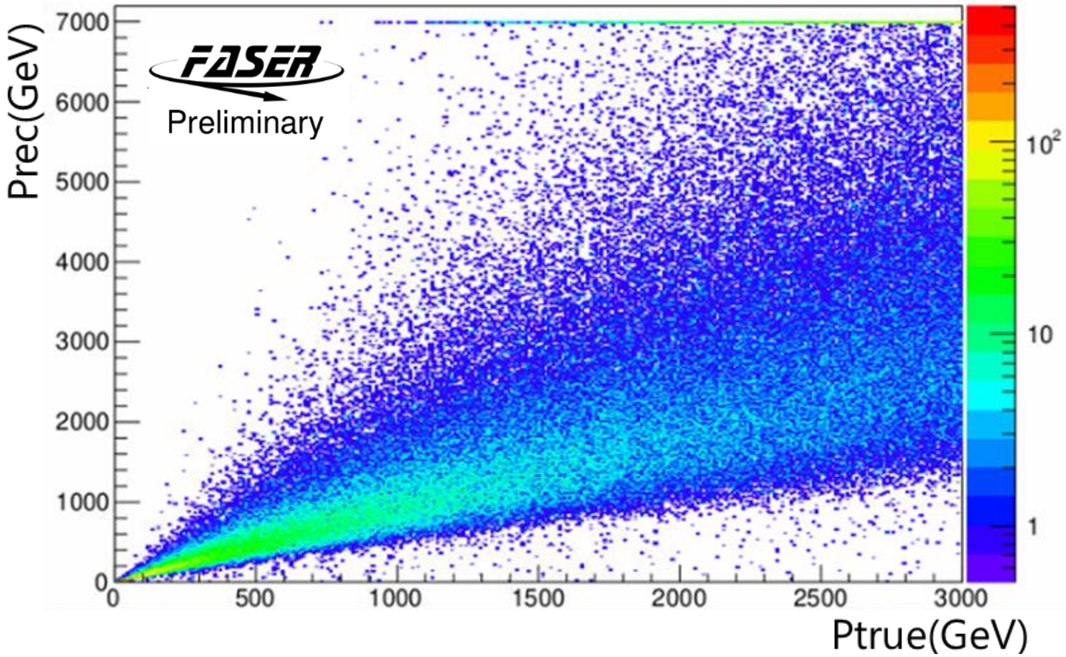


Momentum Measurement

- Particle momenta calculated using Multiple Coulomb Scattering (MCS) via the Coordinate Method.
- Allows particle momenta to be measured using MCS even for > 1 TeV.
- Momentum resolution ~ 20% at 200 GeV.

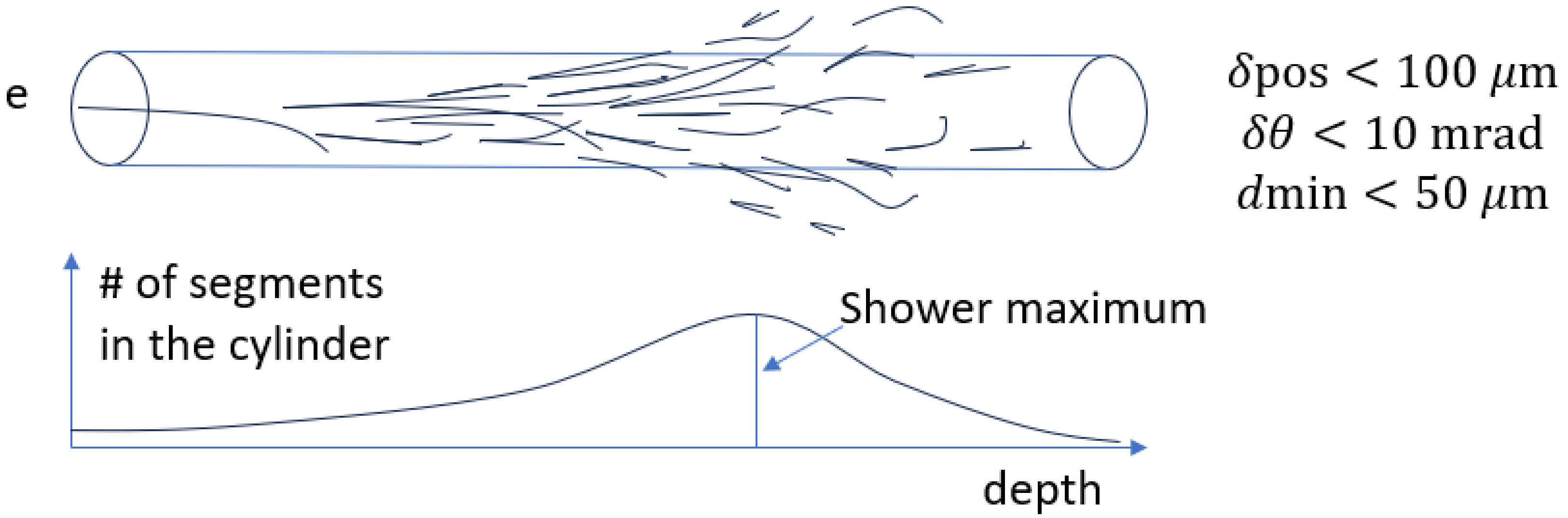






Shower Energy Measurement

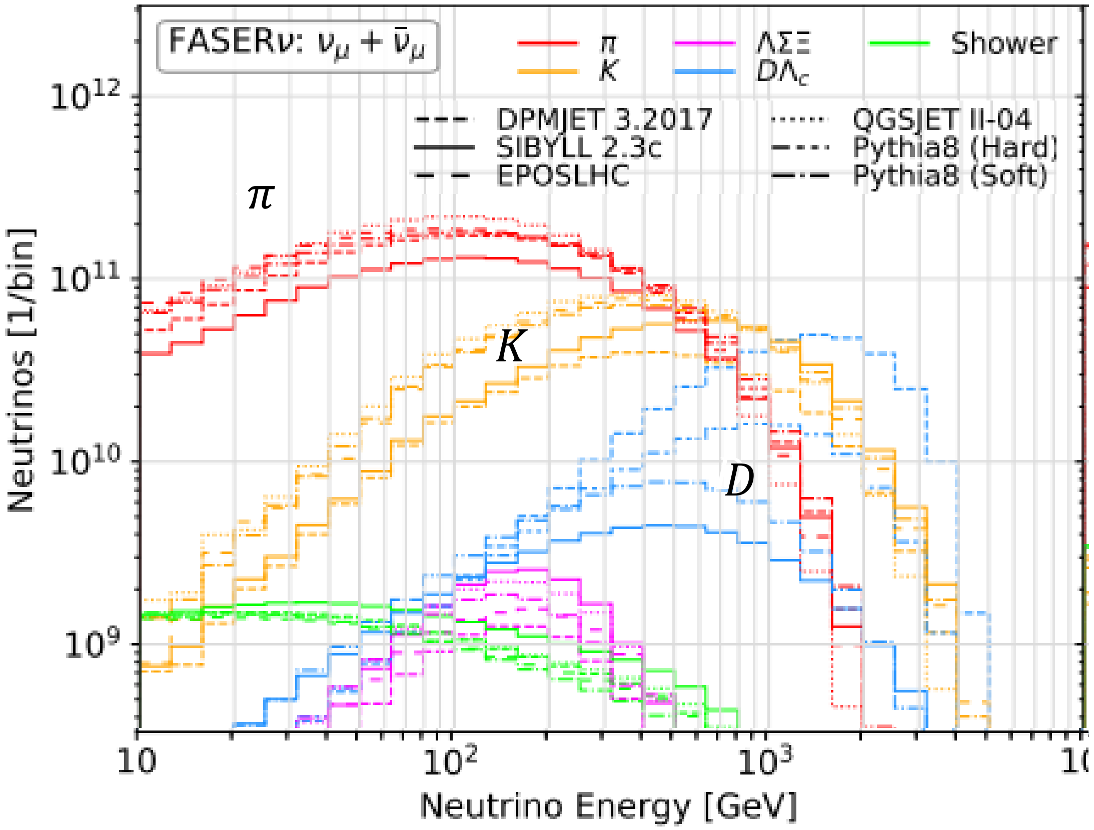
- Performed by counting number of segments within a cylinder along an electron candidate → shower maximum has the highest number of segments.
- Background segments are sizable → cylinder size limited to r = 100 µm, length = 8 cm; segment angle with respect to shower axis < 10 mrad; minimum distance to segment < 50 µm.
- Average background estimated by using random cylinders and subtracting from the shower before energy estimation.
- Resolution: approx. 25% for 200 GeV, 25-40% at higher energies (depending on electron angle).

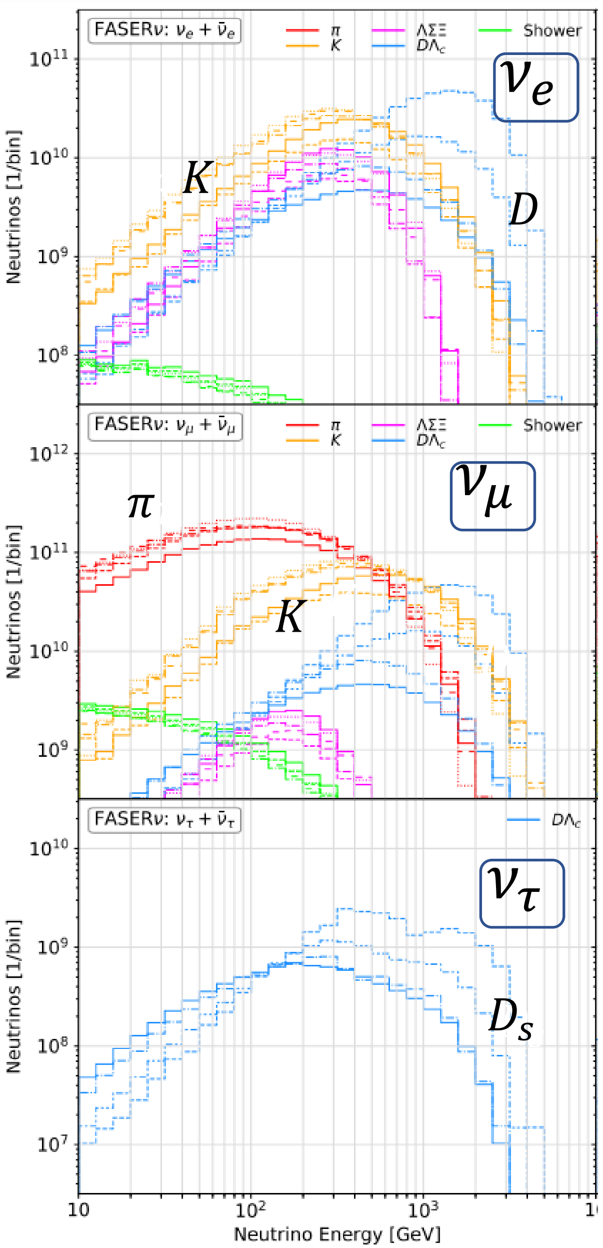


Generator flux uncertainty

- Uncertainties come from the difference between DPMJET and SIBYLL generators in modelling pp collisions.
- Mainly in the high-E range due to charm production.

- Charm hadrons produce ν_τ, high-E ν_μ, ν_e → by deconvolving charm contribution, this can help constrain neutrino flux.



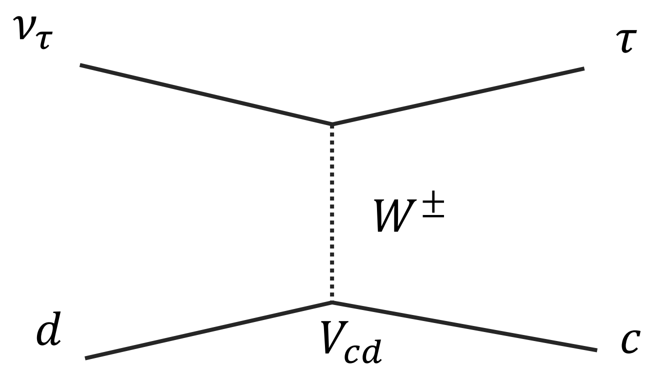


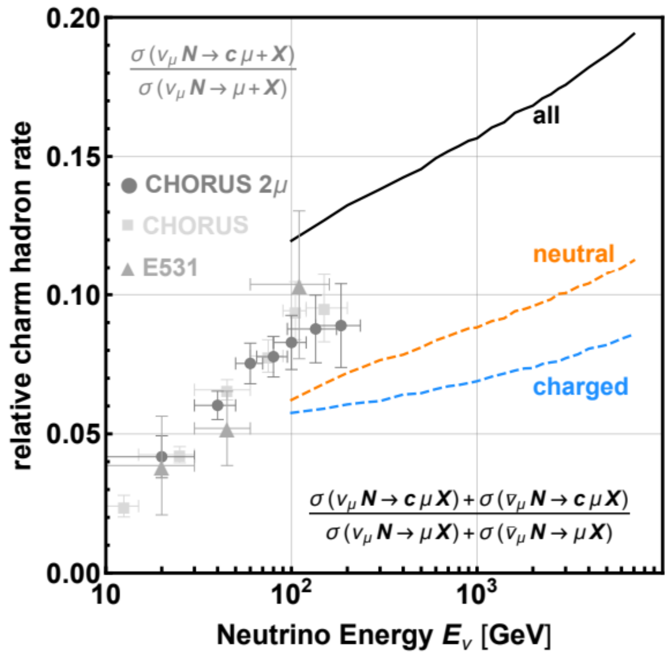
Heavy-flavour-associated channels

- Measure charm production channels:
  - ~10% ν CC event→ $\mathcal{O}(1000)$ events via charm production channels expected;
  - 1st measurement of ν_e induced charm production;
  - Can be observed in FASERν due to secondary charm decay vertex.

$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)} \qquad l = e, \mu$$

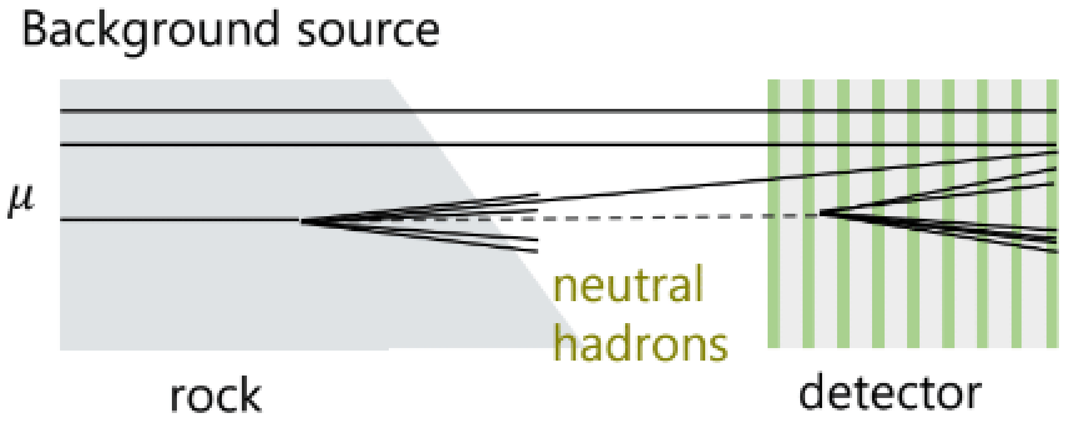
- Search for Beauty production channels
  - Expected SM events (ν_μ CC) $\mathcal{O}(0.1)$ in Run 3 → CKM suppression $V_{ub}^2 \approx 10^{-5}$.
  - BSM physics could amplify, such W' boson, charged Higgs boson, TeV scale leptoquark.



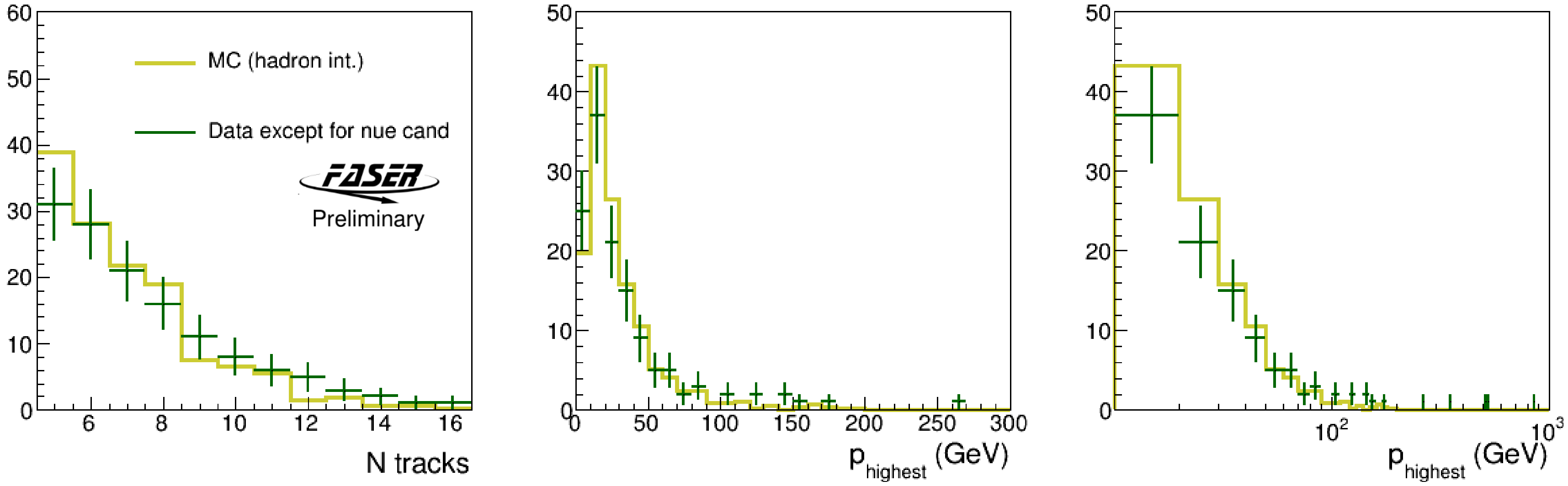


New FASERν Results – Background Study using Data

- First analysis: interactions occurring in 150 tungsten plates (target mass = 68.2 kg).
- Detected vertices before high-energy selection dominated by neutral hadron interactions.



- Expectation: 216 vertices ($K_S, K_L, n, \overline{n}, \Lambda, \overline{\Lambda}$ interactions)
- Data: 133 vertices → 140 detected; 7 ν CC candidates.
- Lies within 50% uncertainty.

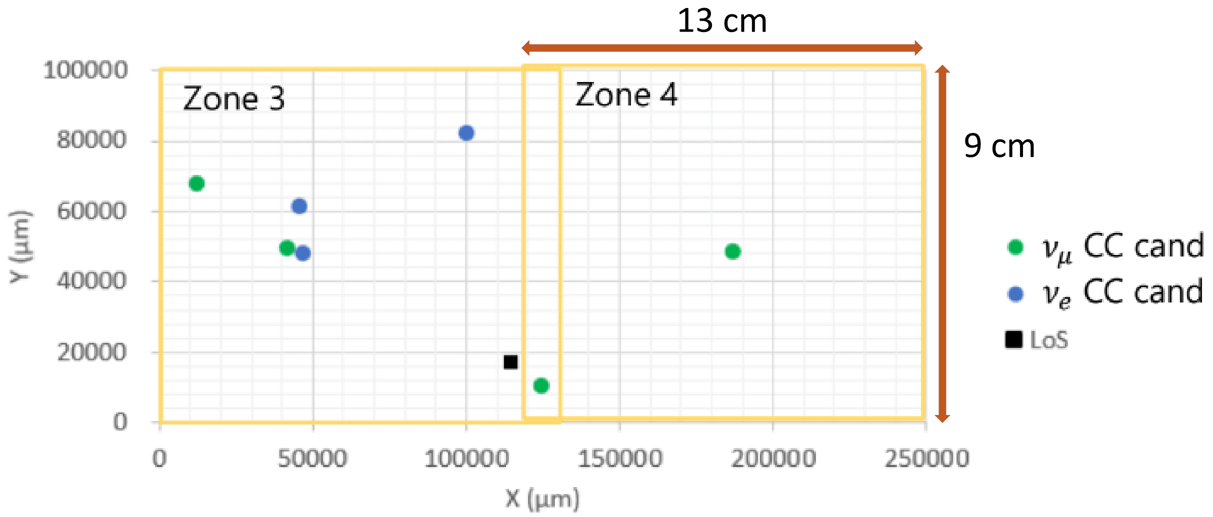


MC normalized to number of observed events.

New FASERν Results – Observed Events

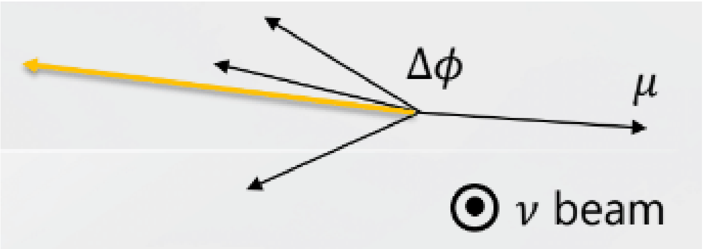
- 7 selected ν CC events after applying kinematic selection (p_{lep} > 200 GeV) .
- 3 ν_e CC → 5σ exclusion of the background-only hypothesis.
- Highest energy ν_e observed!
- First direct observation of ν_e CC interactions at the LHC!

Interaction	Expected background		Expected signal	Observed
	Hadron interactions	ν NC interactions		
ν_e CC	0.002 ± 0.002	-	$1.2^{+4.0}_{-0.6}$	3
ν_μ CC	0.32 ± 0.16	0.19 ± 0.15	$4.4^{+4.2}_{-1.4}$	4

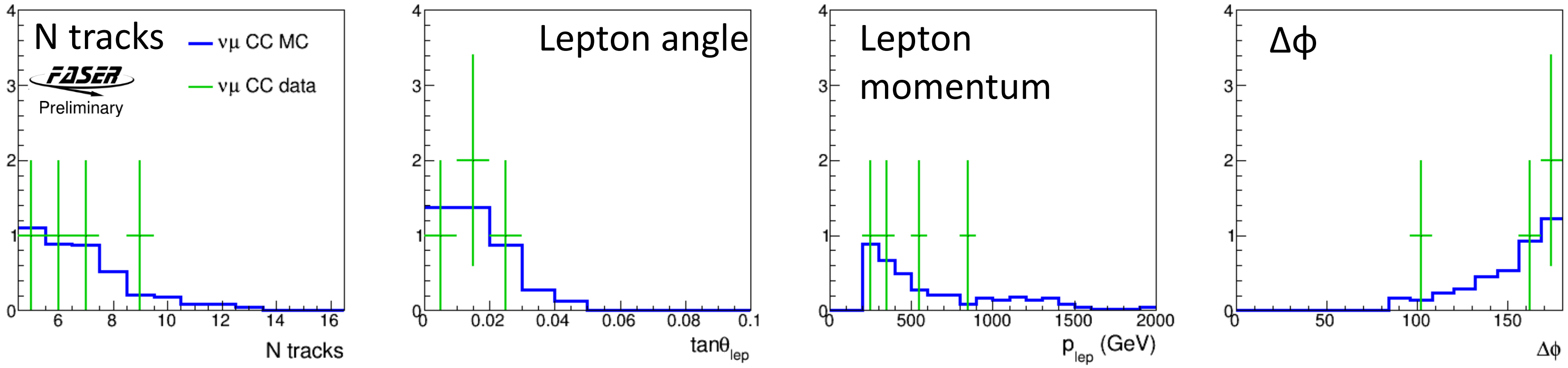


See also Tomoko Ariga's Plenary talk at NuFACT 2023 on 21/08: "New results on LHC neutrinos from the FASER experiment"

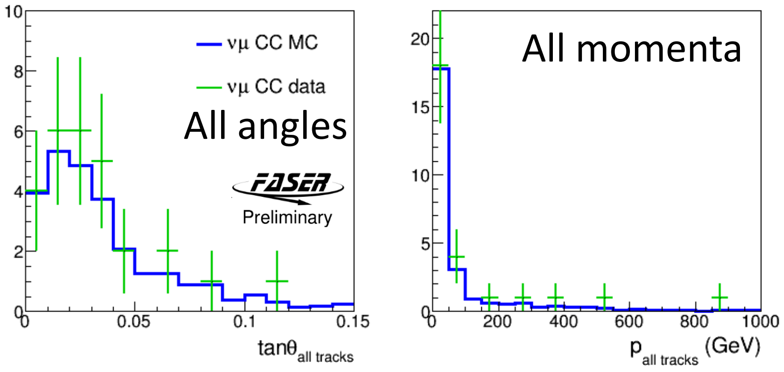
New FASERν Results – Data/MC Comparison



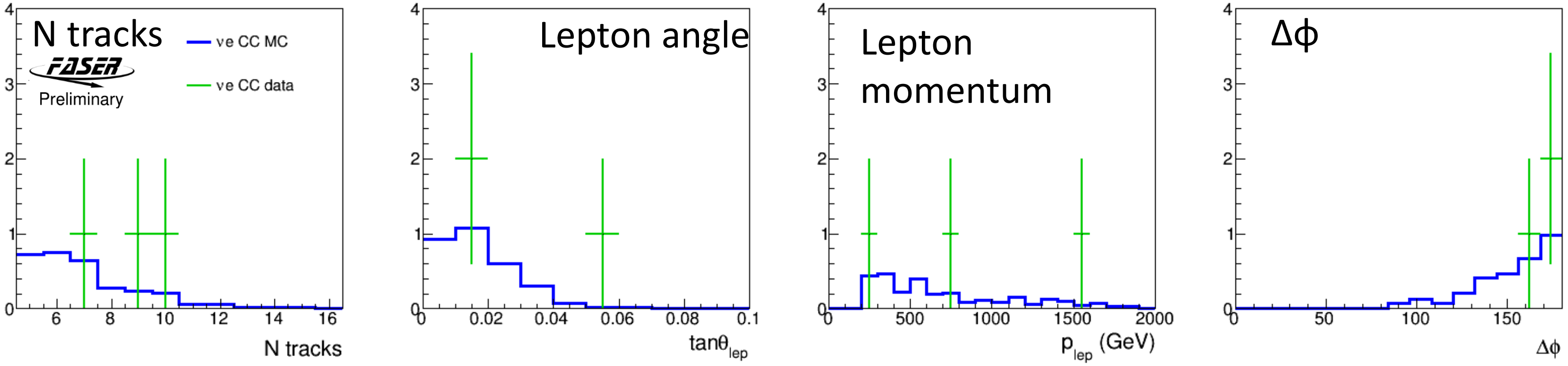
Vertex information of the ν_μ CC candidates.



Tracks from the vertices.



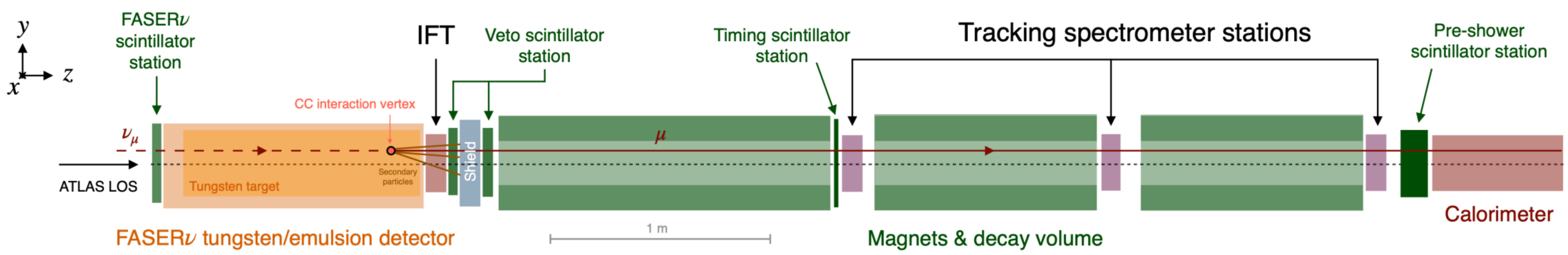
Vertex information of the ν_e CC candidates.



MC normalized to number of observed events.

FASER “Electronic” Neutrino Search

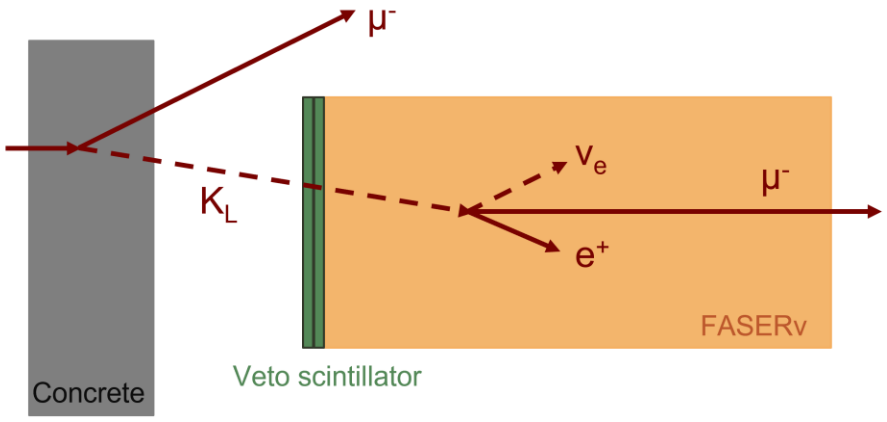
- Selection criteria:
  - Collision event in good data periods (35.4 fb^{-1});
  - No signal in front 2 veto scintillators (<40 pC);
  - Signal in last 2 veto stations (>40 pC);
  - Signal in timing and pre-shower scintillators consistent with >= 1 MIP;
  - Exactly 1 good spectrometer track with p > 100 GeV;
  - r_{max} < 95 mm in fiducial tracking volume;
  - Extrapolating to front veto station, r < 120 mm;
  - θ < 25 mrad.

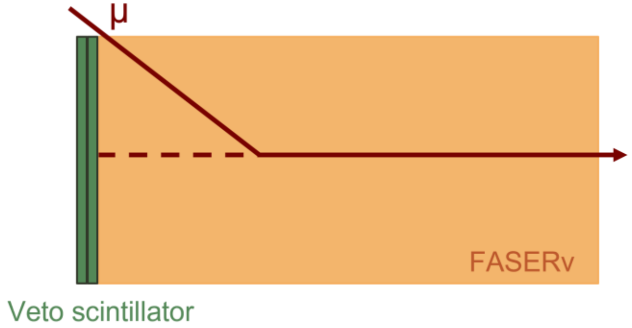


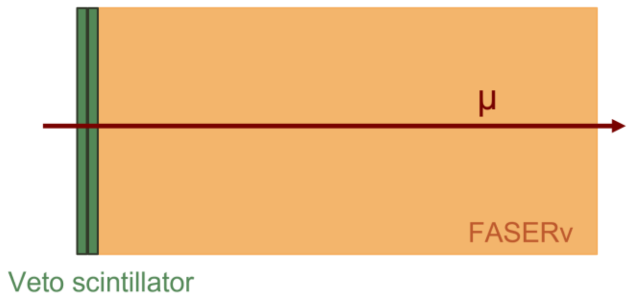
- 151 ± 41 neutrino events expected from simulation:
  - Uncertainty from difference between generators (DPMJET & SIBYLL).
  - No experimental errors were included.

Background estimation

- Neutral hadrons 0.11 ± 0.06:
  - Expect approx. 300 with E > 300 GeV;
  - Tungsten absorbs the majority;
  - Estimated from 2-step simulation.
- Scattered muons 0.08 ± 1.83:
  - Extrapolated from sideband control region;
  - Single track in the front tracker station;
  - Scaled to full detector volume using simulation.
- Veto inefficiency negligible:
  - Estimated from events where only 1 veto scintillator fired;
  - Very high veto efficiency.

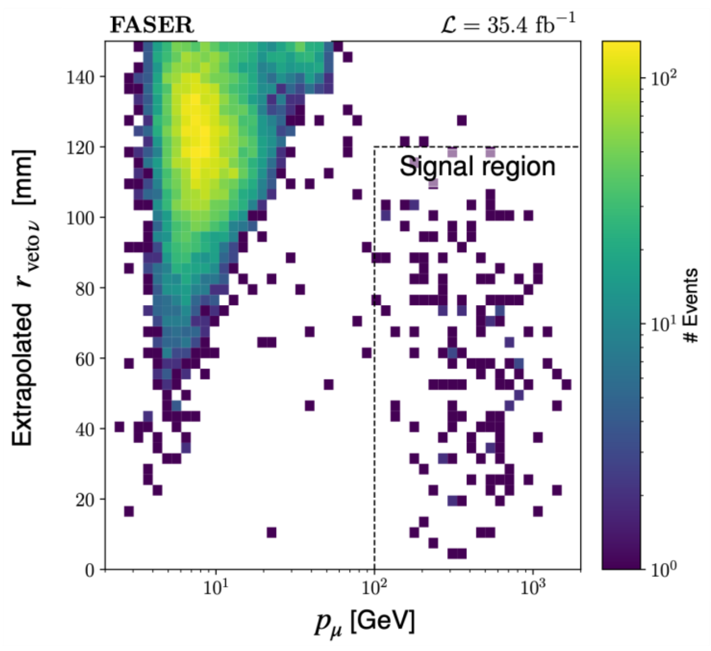


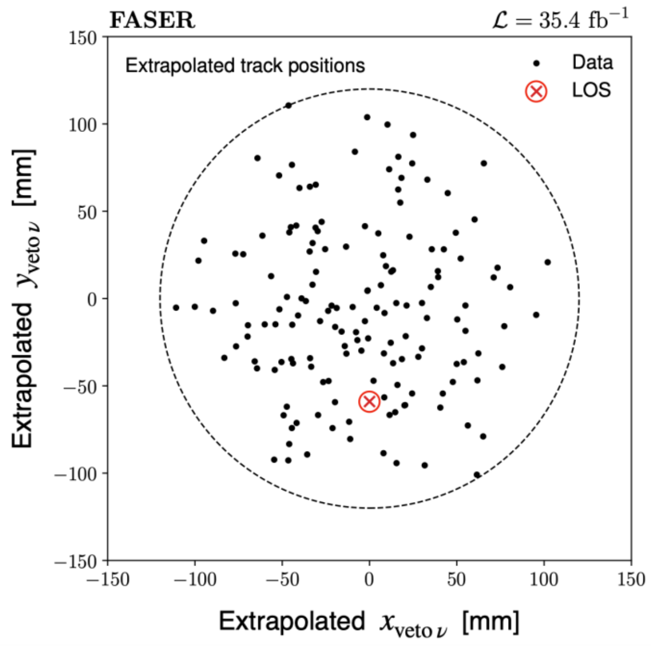




Results

- **153^{+12}_{-13}** neutrino events observed.
- Corresponds to **16σ**.
- **First direct observation of collider neutrinos.**





Category	Event
Signal (n_0)	15
n_{10}	4
n_{01}	6
n_2	64014695