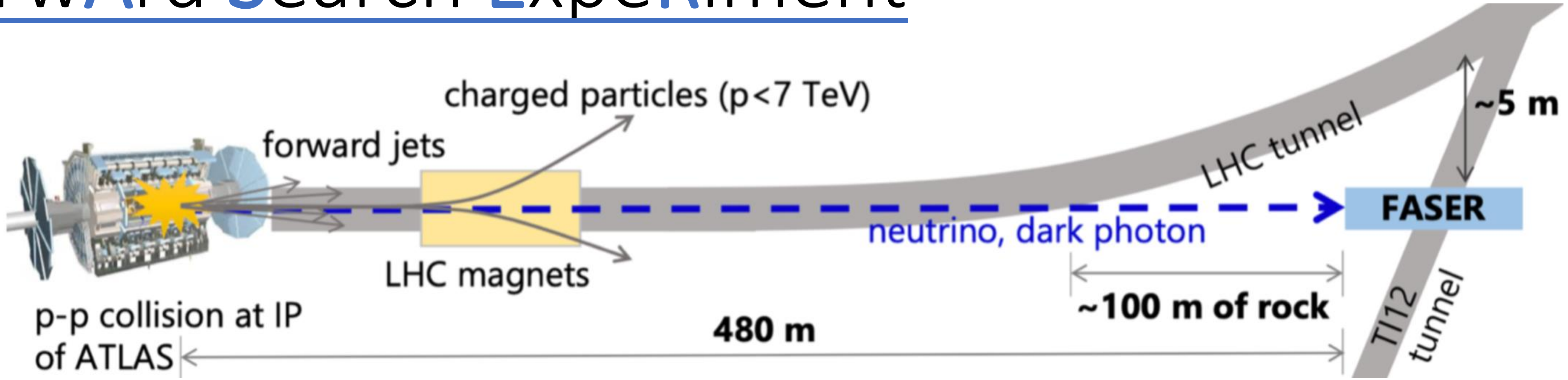
# Neutrinos at the LHC – Results from FASER

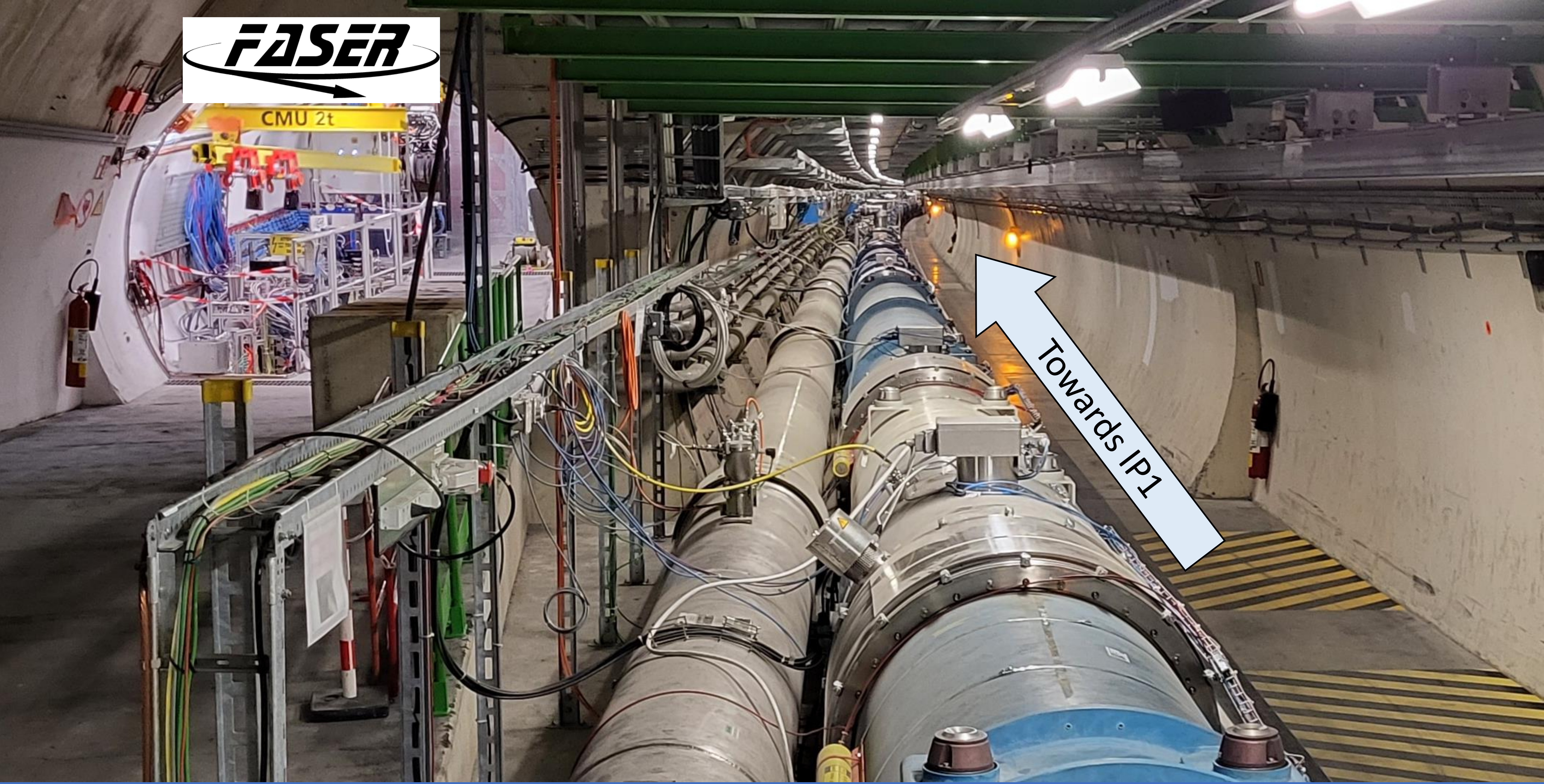
Jeremy Atkinson (Universität Bern) on behalf of the FASER Collaboration

9th of April 2024, DIS2024, Grenoble

# ForwArd Search ExpeRiment

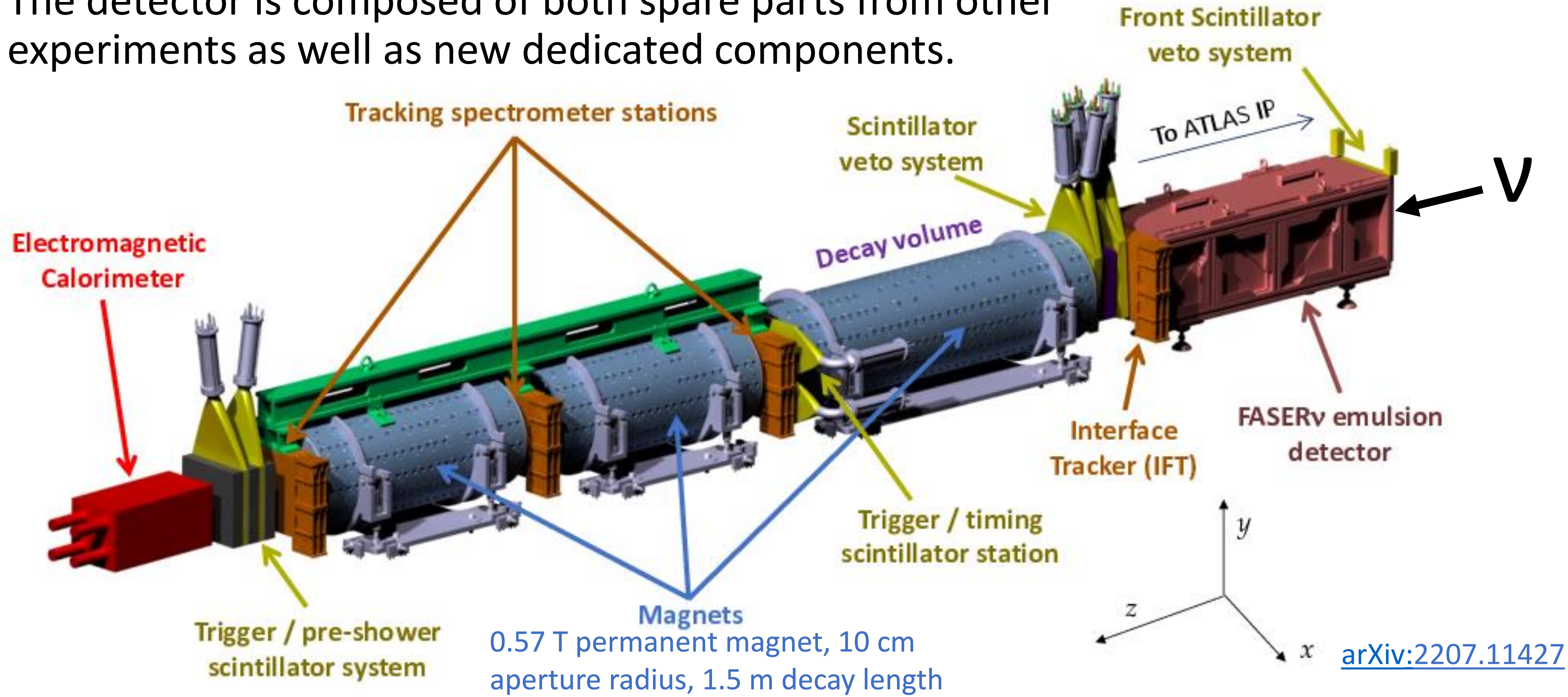


- Small experiment based at the LHC at CERN, taking data throughout Run 3 (2022 – 2025).
- Light, long-lived, weakly-interacting particles are produced in the far-forward region of 13.6 TeV proton-proton collision at the ATLAS collision point (IP1).
- The detector is aligned with the collision axis line-of-sight, maximising both the number and energy of neutrino interactions of all 3 flavours.
- First collider neutrino experiment!
    - First neutrino interaction candidates at the LHC [Phys. Rev. D 104, L091101 (2021)].
    - First direct observation of $\nu_\mu$ CC interactions at the LHC [Phys. Rev. Lett. 131, 031801 (2023)].


FASER
CMU 2t
Towards IP1

# The FASER Detector

- The detector is composed of both spare parts from other experiments as well as new dedicated components.



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

arXiv:2207.11427

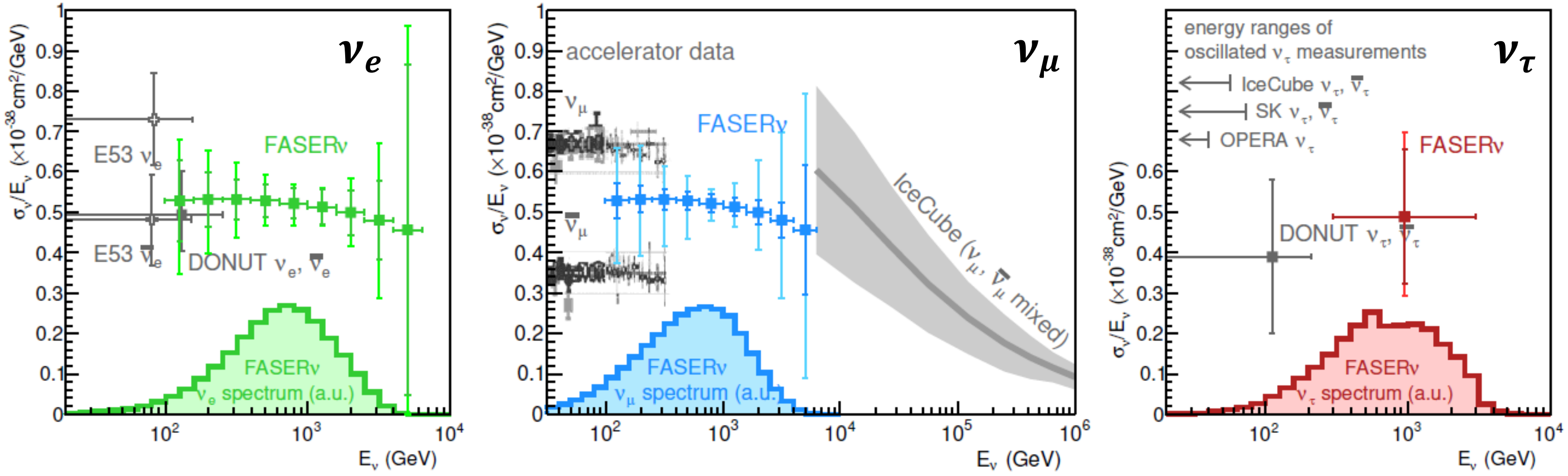
# Neutrinos at FASER

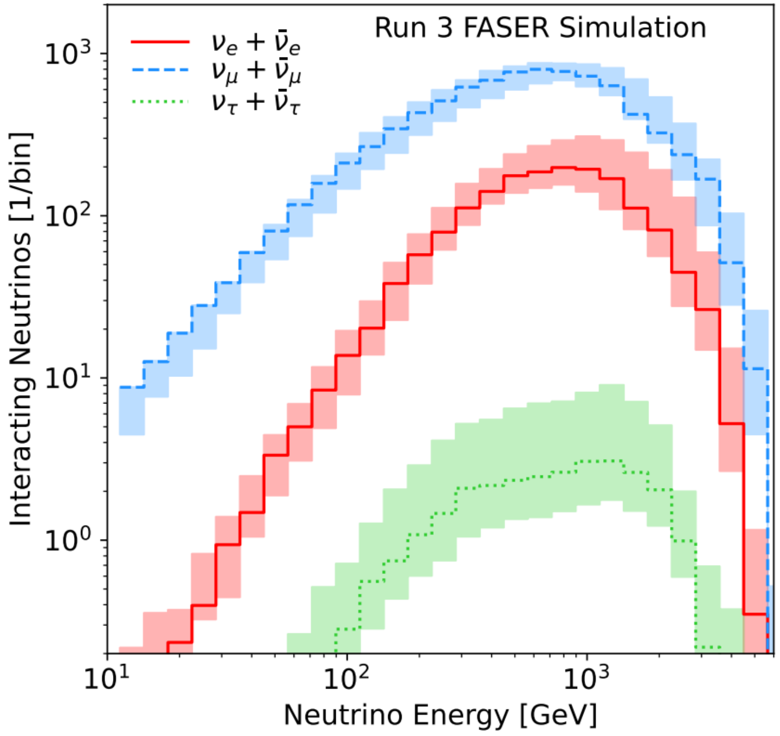
- The decay of hadrons produced in the forward region produces a collimated neutrino beam.
- >10 000 neutrinos expected to interact in FASER throughout Run 3 (250 fb$^{-1}$).
- 3-flavour cross-section measurement for previously unexplored energy range → highest $E_\nu$ from artificial source.
- Expect $\mathcal{O}(1000)$ events via charm production channels → neutrino induced heavy quark production.
- For more on neutrino DIS with FASER, see Juan Rojo's talk on 09/04: "Deep-inelastic scattering with collider neutrinos at the LHC and beyond"

| 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 | ~ 1700 | ~ 8500 | ~ 30 |

arXiv:2402.13318

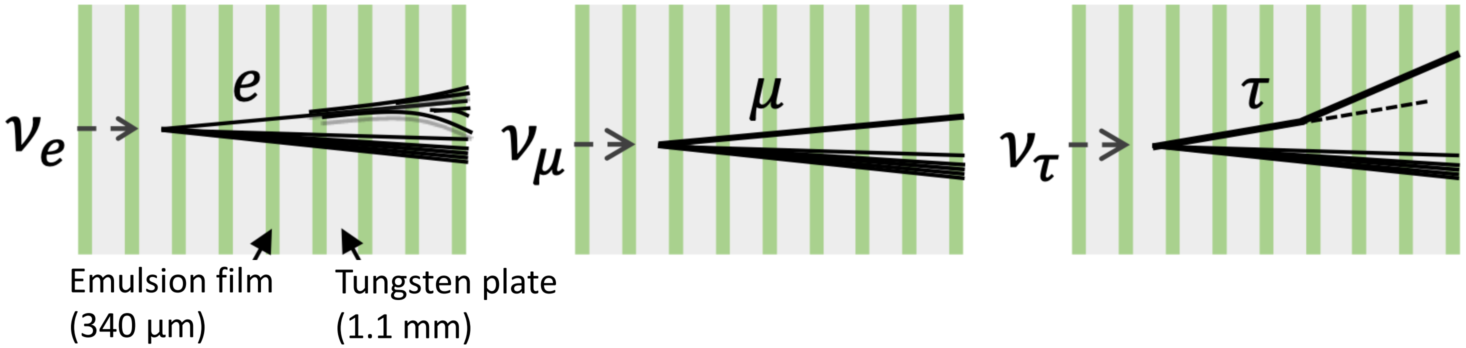
**Projected precision of FASERν measurement at 14-TeV LHC (150 fb$^{-1}$)**





# The FASERν Detector

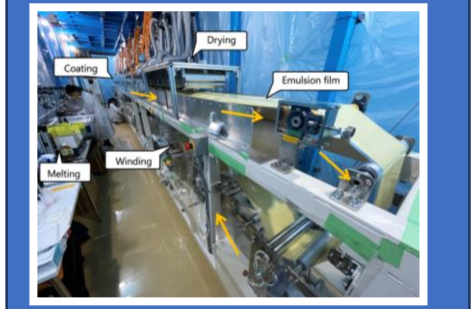
- Module: 730 alternating FASERν emulsion films and 1.1 mm thick tungsten plates (25 x 30 $\text{cm}^2$).
- Target mass 1.1 tonnes; 1.1 m (220 $X_0$, 8λ).
- 3 modules irradiated each year to keep track occupancy $< 10^6/\text{cm}^2$ (around 30$\text{fb}^{-1}$).
- Temperature kept constant at 0.1°C level with dedicated cooling system.
- Position can be adjusted to compensate for changing ATLAS IP crossing angle.
- Neutrino events can be flavour tagged using topological and kinematical variables.



73 sub-modules installed

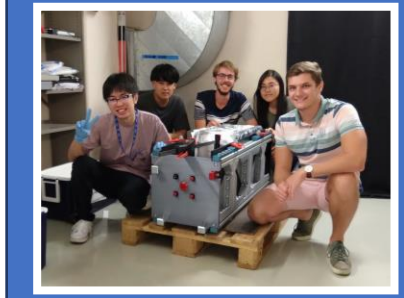
# FASERν Process

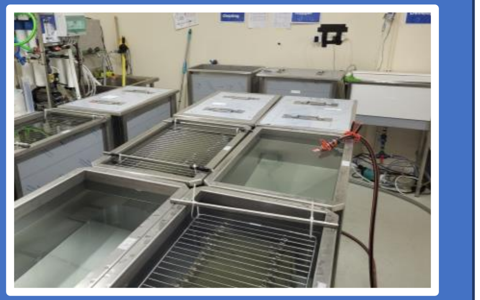
## Japan



Film production

## CERN





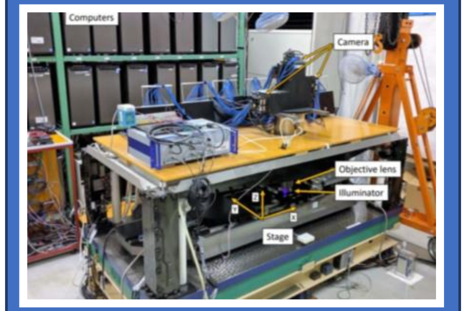
Assembly

Exposure

Disassembling

Development

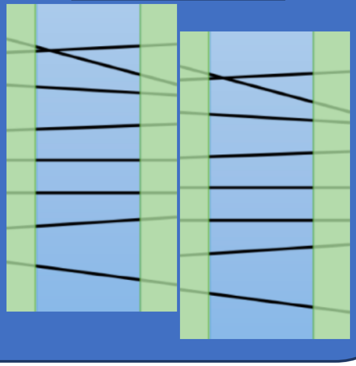
## Japan



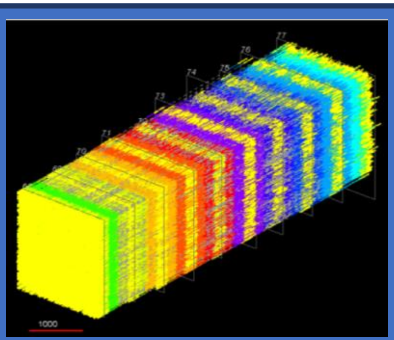
Readout

## Offline analysis

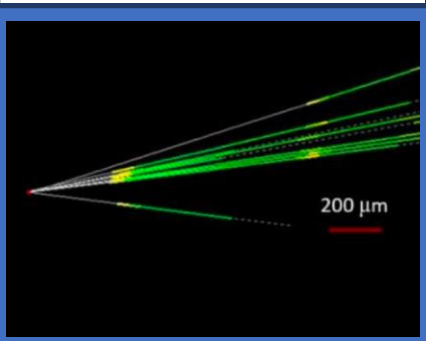
Alignment



Track reconstruction

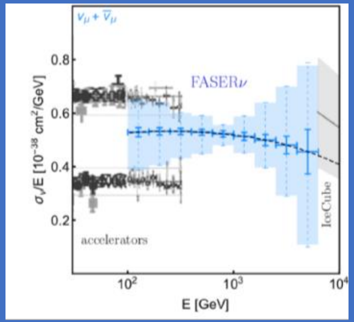


Vertex reconstruction

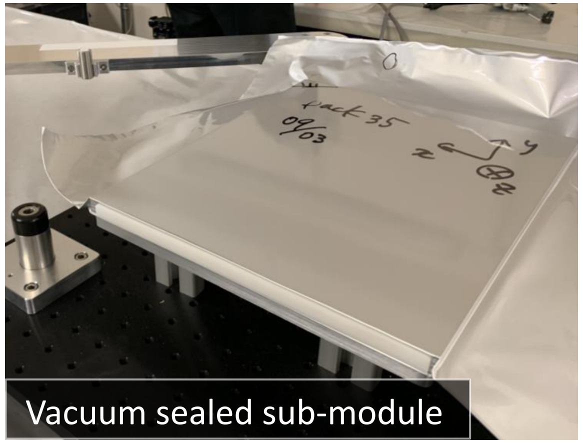


$e, \mu$ ID
$\tau$ decay search
charge ID
etc…

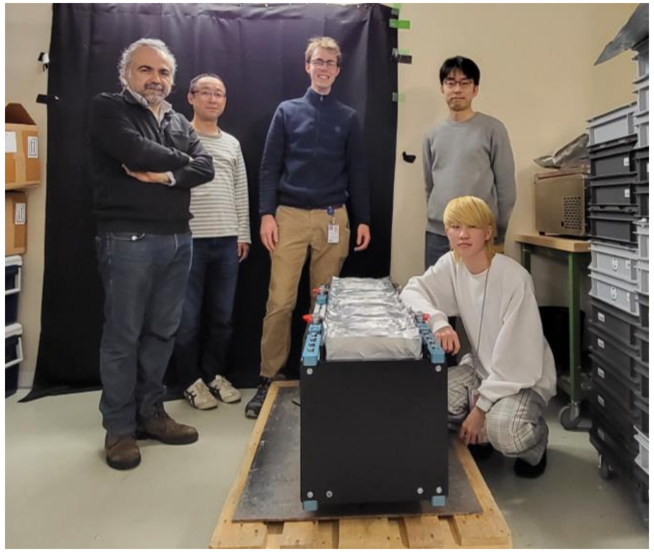
Physics analysis

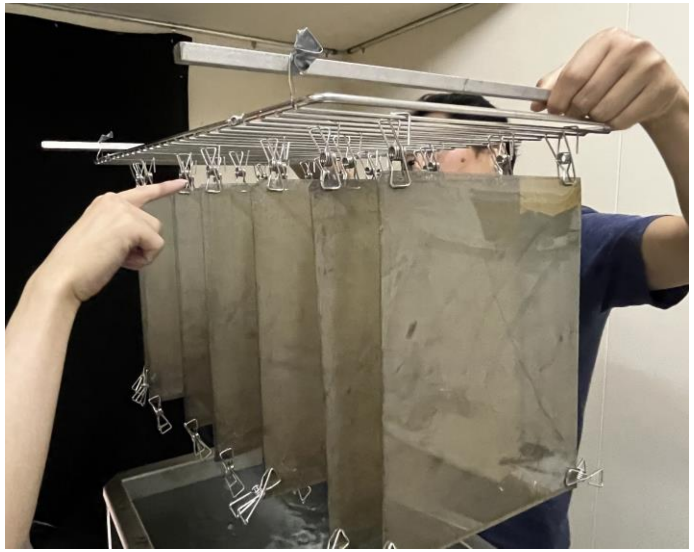


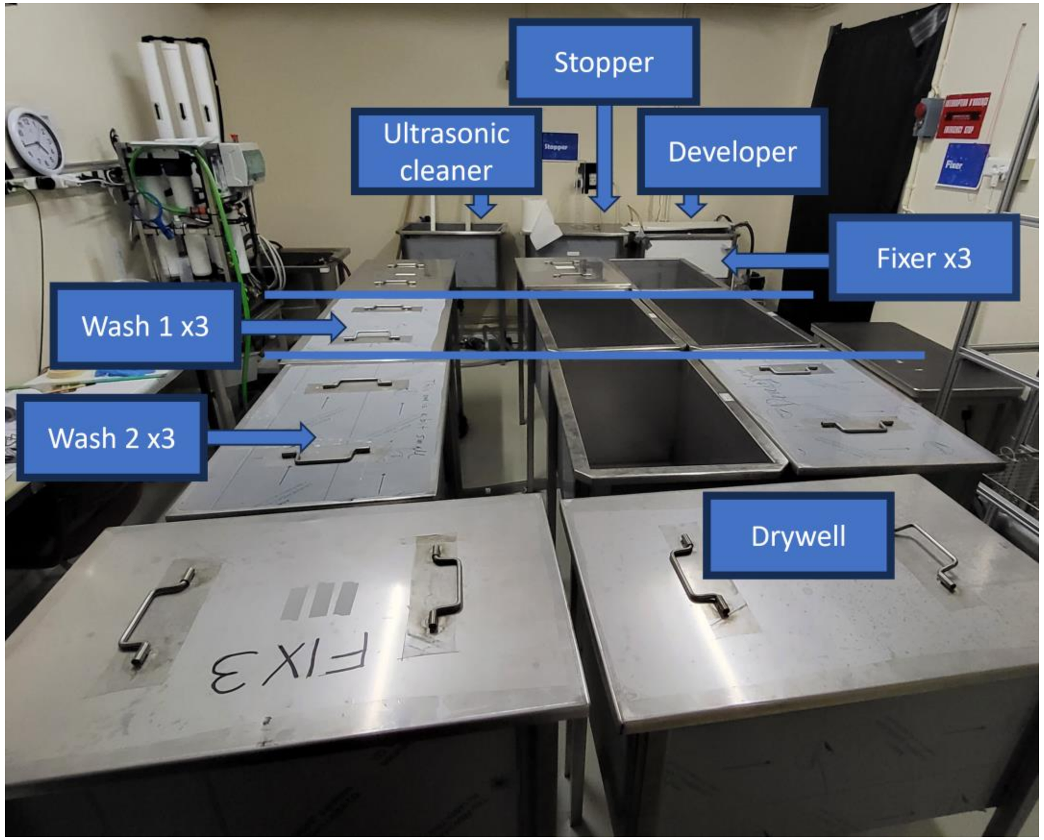
# FASERν Assembly and Development


Vacuum sealed sub-module

- FASERν sub-modules: 10 alternating emulsion films and tungsten plates.
- Pressure is applied to keep the alignment between sub-modules inside the FASERν module.
- Development campaign lasts ~ 12 days.
    - Films are extracted and labelled.
    - 200 films developed every 3 days.
    - 25 films developed together → 3.5 hours + 1 day dry.



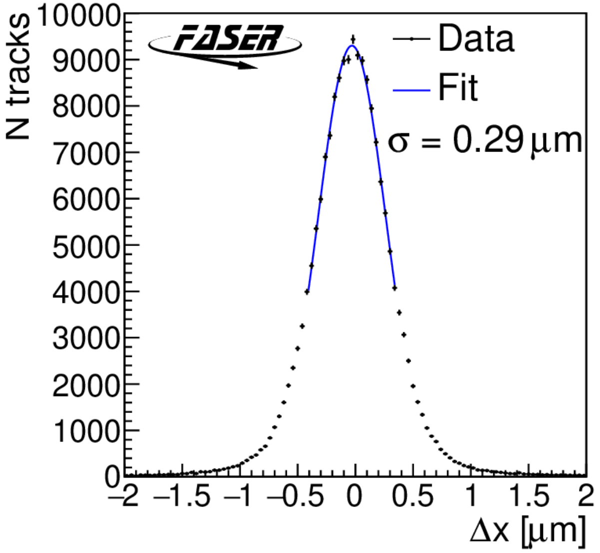


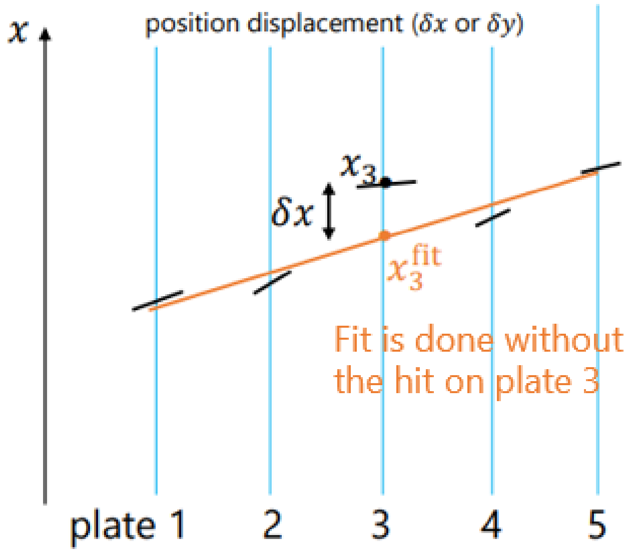


# FASERν Performance

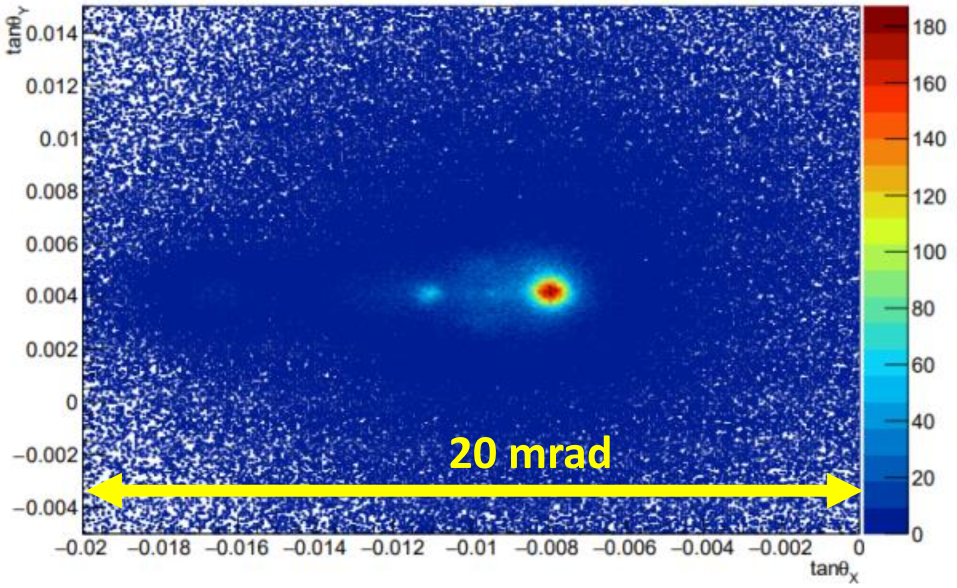
- Position resolution is determined using the position displacement between a hit and the linear fit of a track.
- Hit resolution ~ 300 nm after dedicated film alignment using high-momentum muon tracks ($\mathcal{O}(10^5)$ tracks/cm²).

- Angular resolution for track of length ~1 cm is ~ 0.04 mrad.
- Angular spread of muon peaks ~ 0.4 mrad.





Fit is done without the hit on plate 3

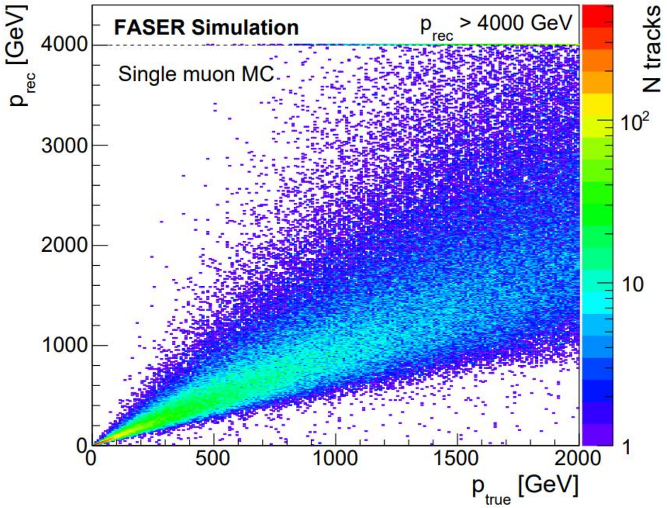


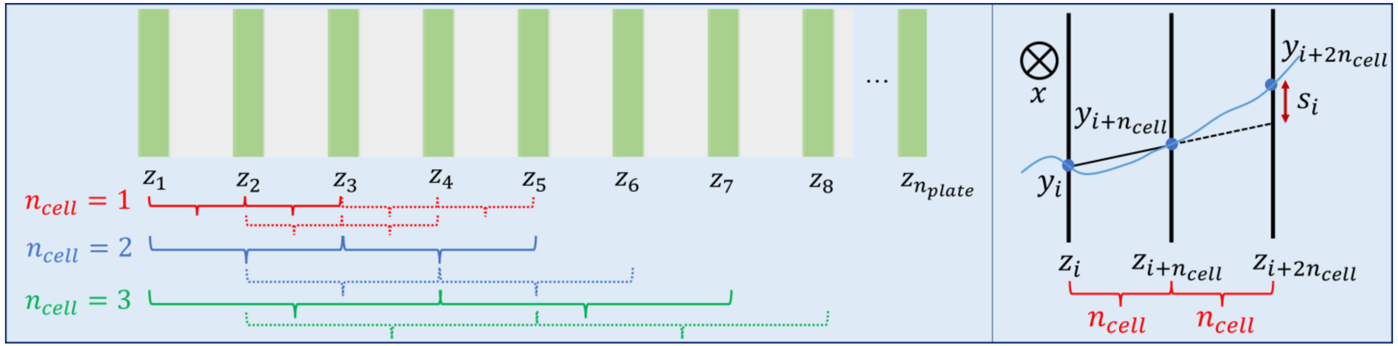
Background muons (data).

FASER preliminary

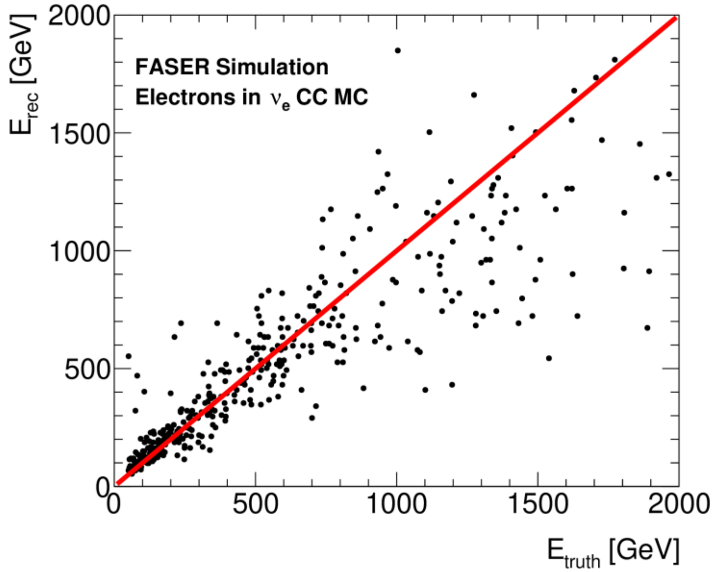
# Kinematical measurements

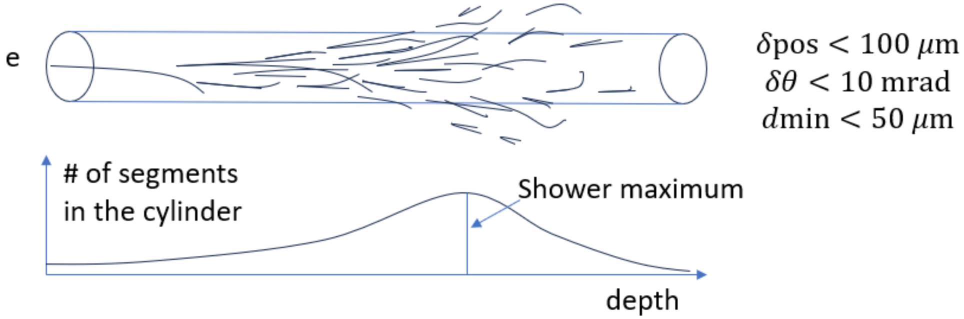
- Particle momenta calculated using Multiple Coulomb Scattering (MCS) via the Coordinate Method (works well even > 1 TeV).
- Muon momentum: $\Delta P^{RMS}/P \approx 0.3$ at 200 GeV.





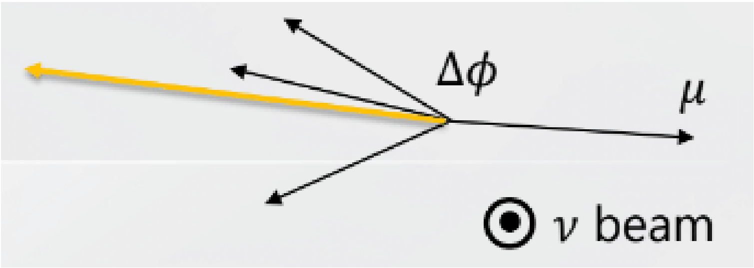
- EM shower energy found using track multiplicity.
- Reconstructed electron energy: $\Delta E/E \approx 0.25$ at 200 GeV.

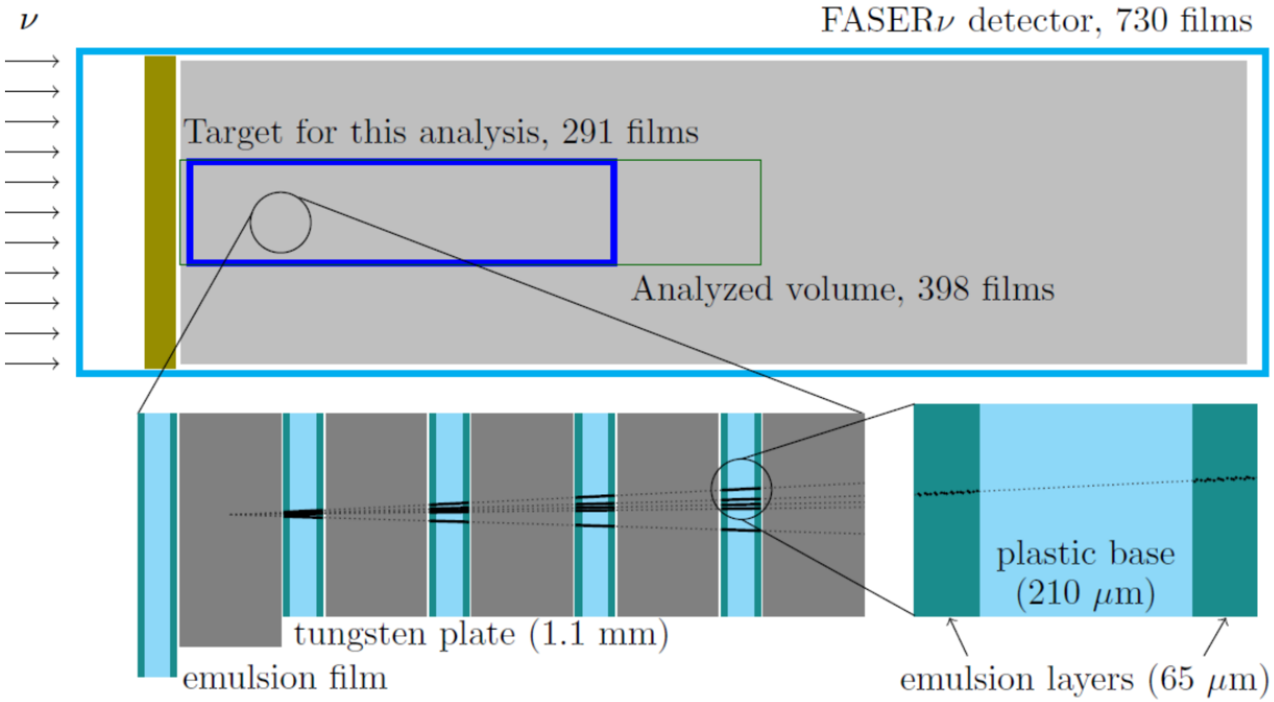


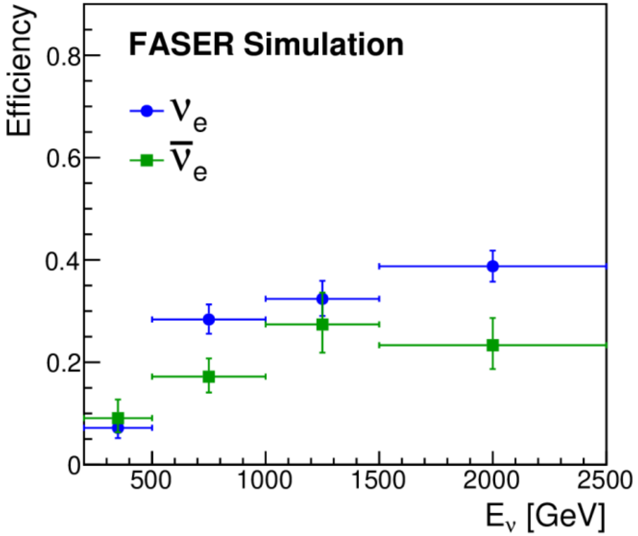


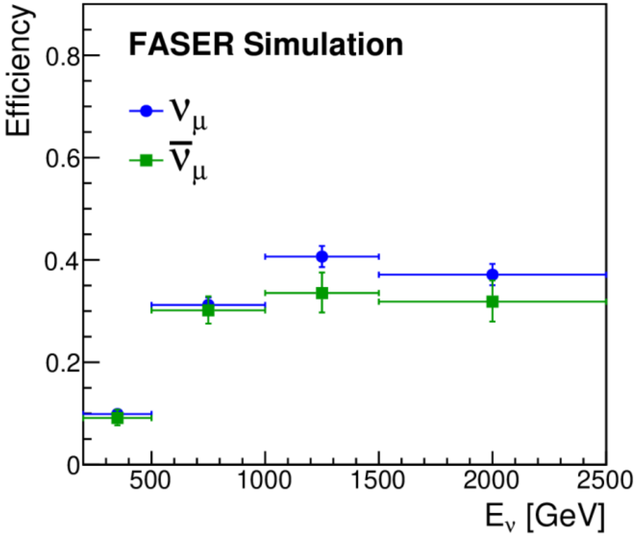
# New FASERν Analysis

- Data set:
  - 2022 second module → 9.5 fb$^{-1}$;
  - Target mass: 128.6 kg;
  - ~ 1.7% of data collected to date.
- Selection criteria:
  - Vertex reconstruction:
    - $N_{track} \geq 5$
    - $N_{track}(\tan\theta \leq 0.1) \geq 4$
  - Lepton requirements:
    - $E_e$ or $p_\mu > 200$ GeV
    - $\tan\theta_e$ or $\tan\theta_\mu > 0.005$
  - Back-to-back topology: $\Delta\phi > 90°$





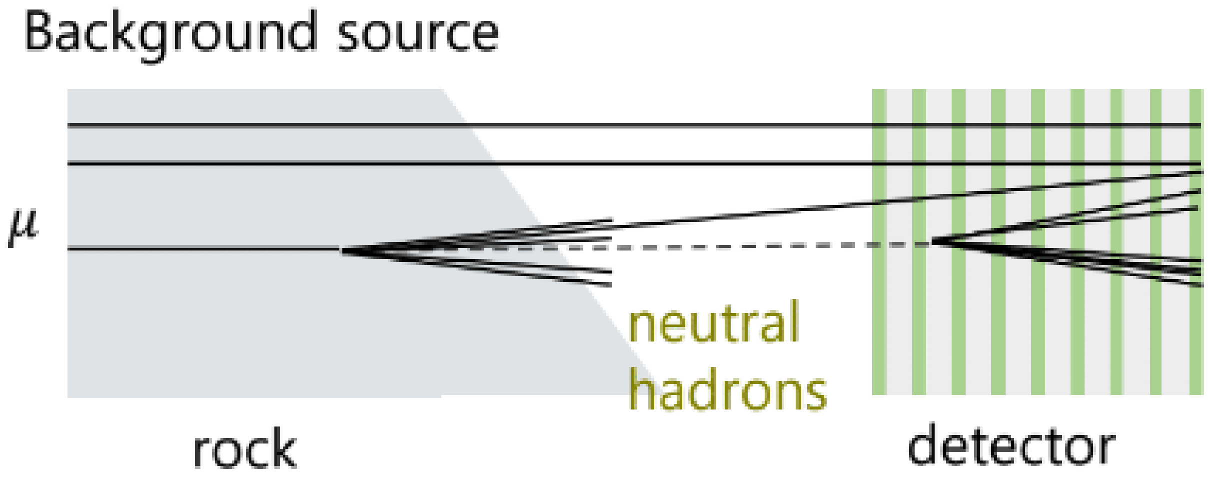


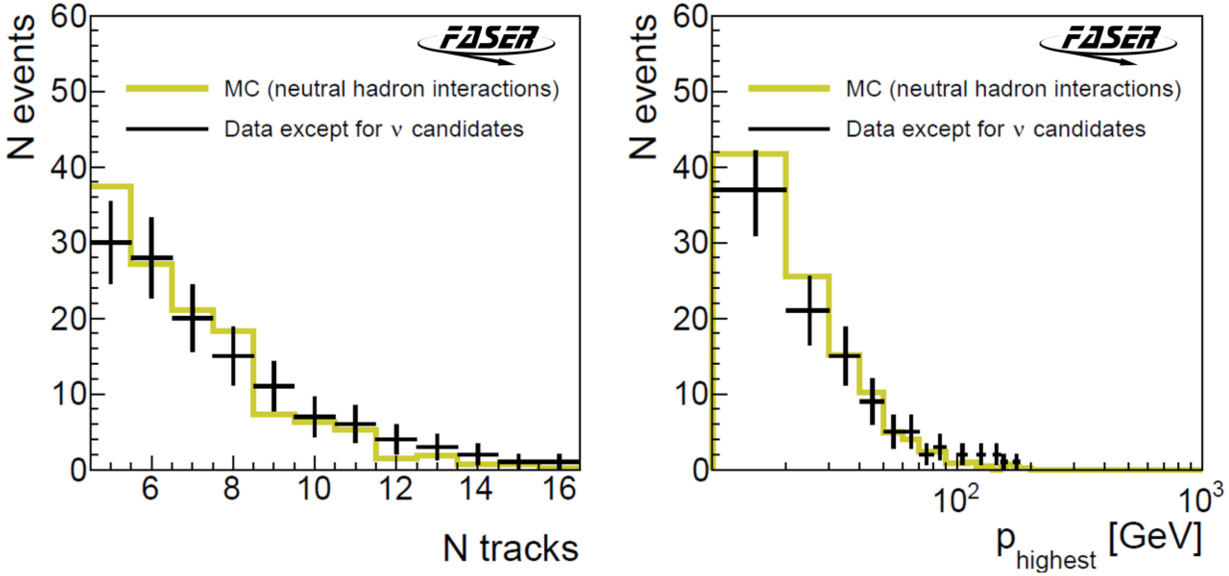


# Results from FASERν: Neutral Hadron Study

- Detected neutral vertices before high-energy lepton selection are dominated by neutral hadron interactions.
- Validation study: interactions occurring in 150 tungsten plates → target mass = 68.2 kg.

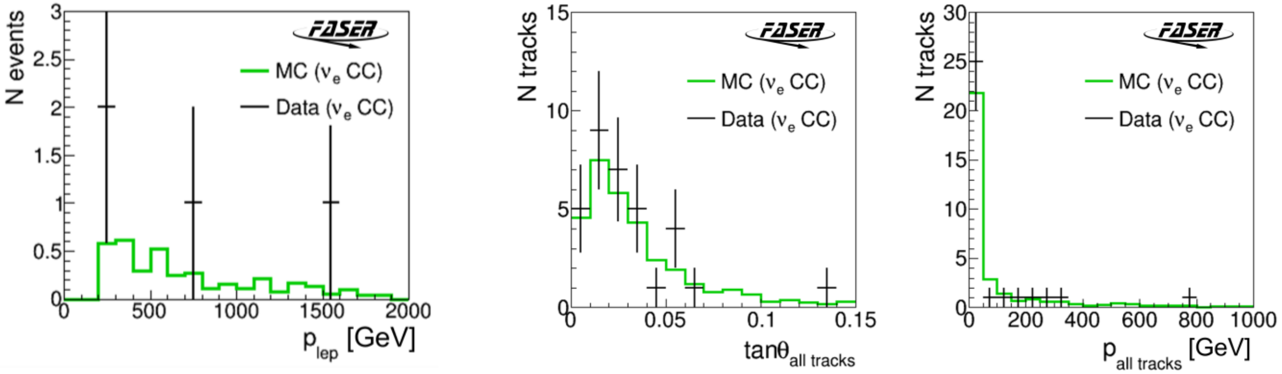
- Expectation: 246 vertices ($K_s, K_L, n, \overline{n}, \Lambda, \overline{\Lambda}$ interactions).
- Data: 139 vertices detected.
- Lies within 50% uncertainty.

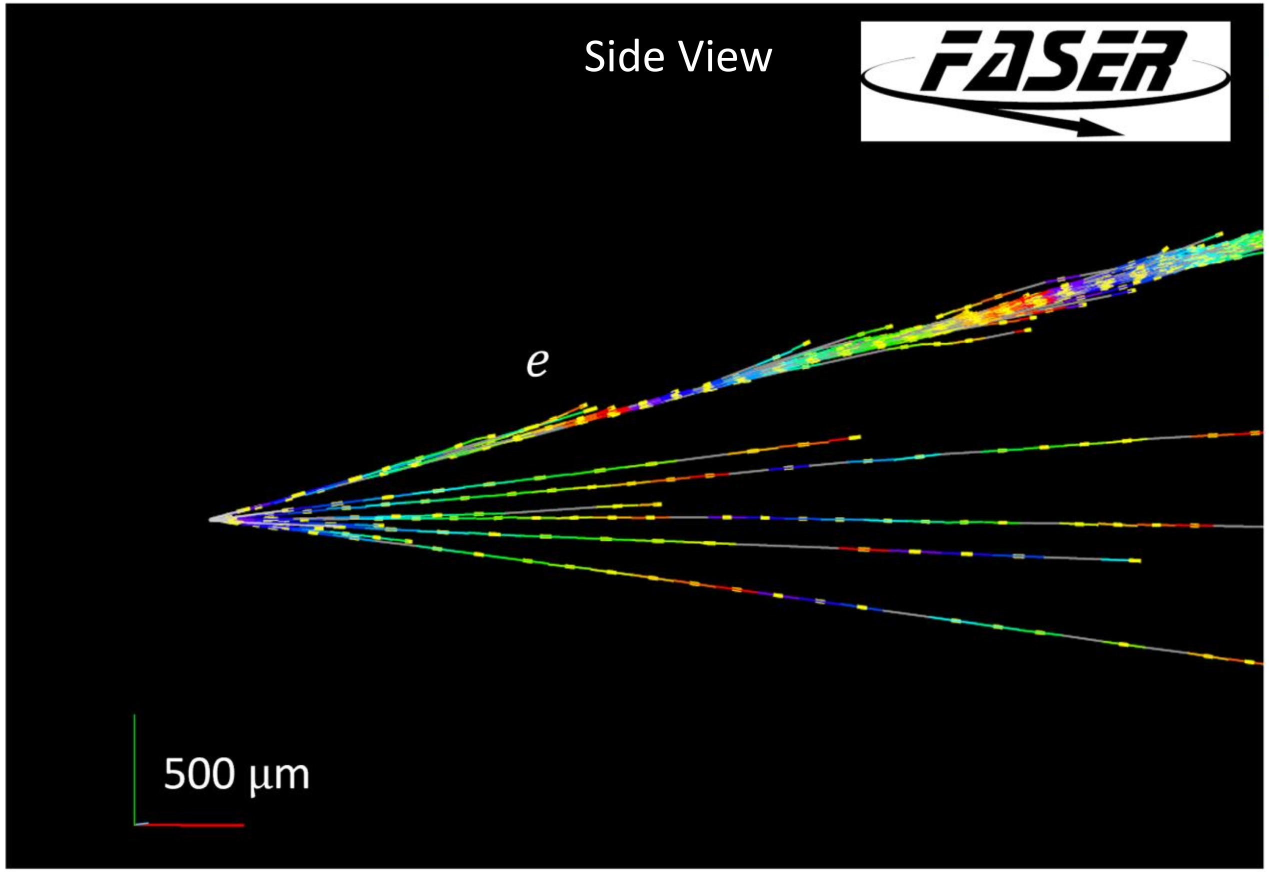


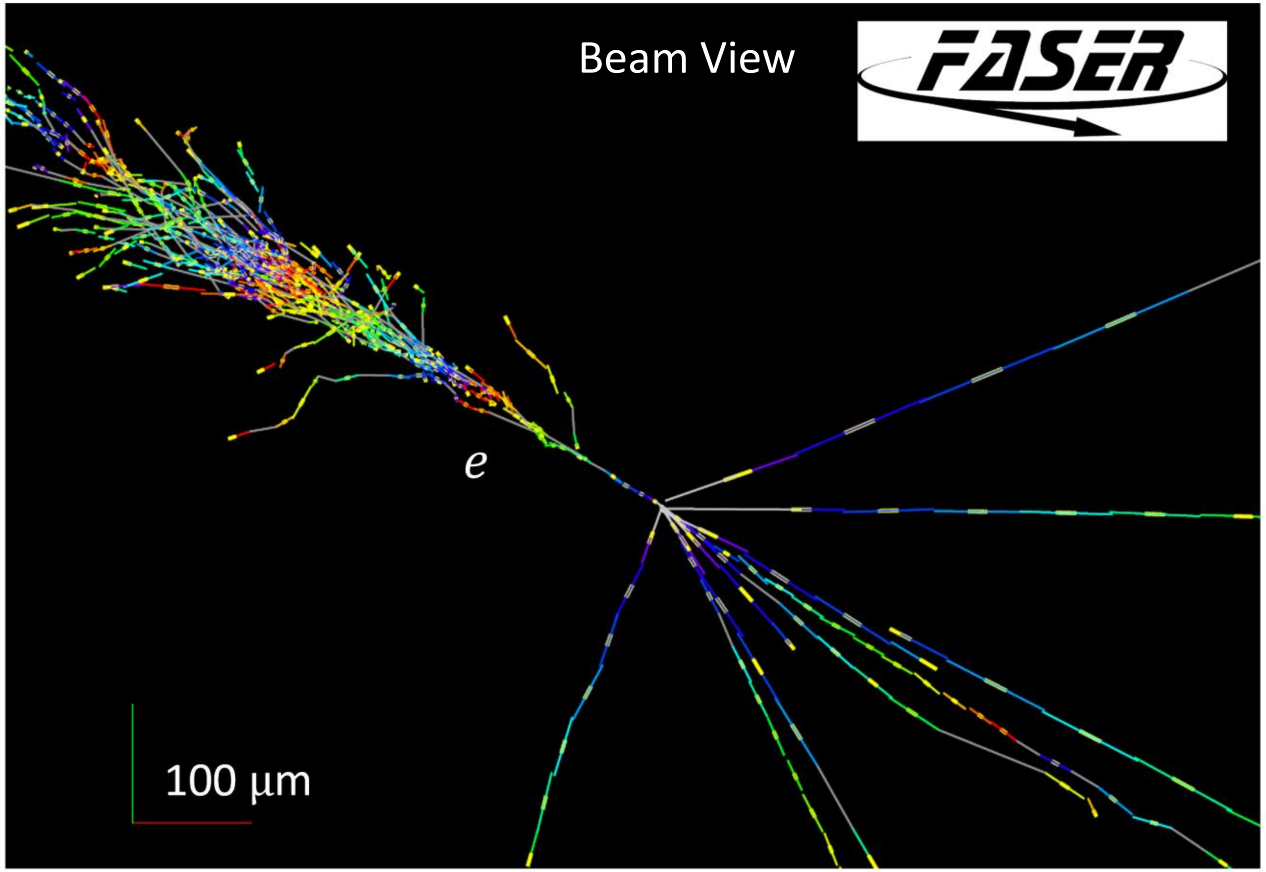


# $\nu_e$ events

- $E_e$ = 1.5 TeV, highest $\nu_e$ energy measured!
- MC normalized to number of observed events.

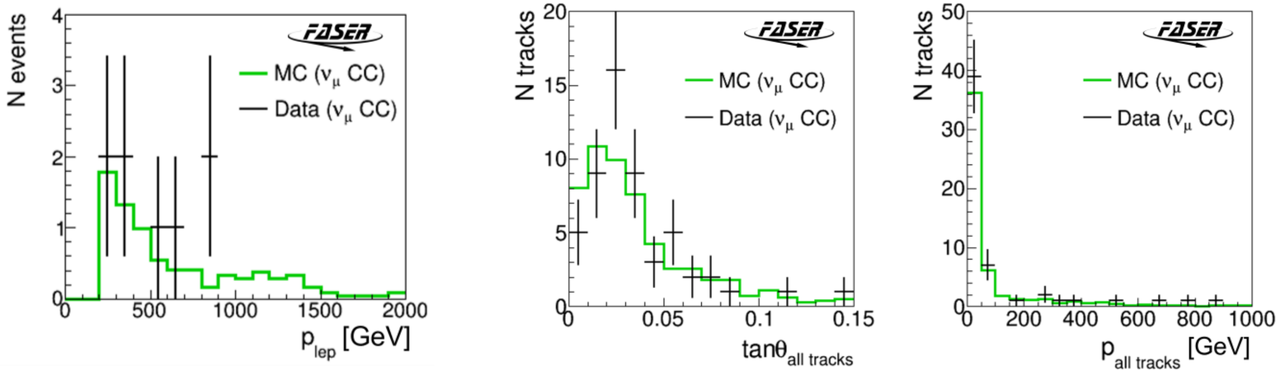


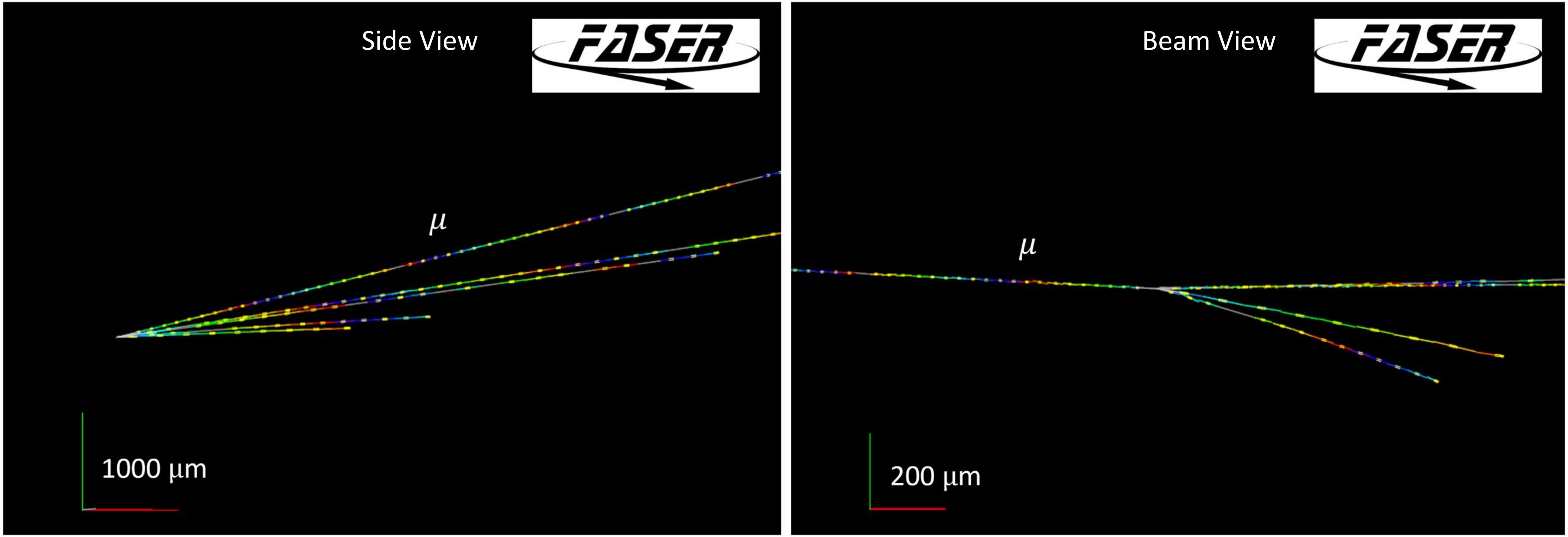




# $\nu_\mu$ events

- $p_\mu$ = 360 GeV.
- MC normalized to number of observed events.



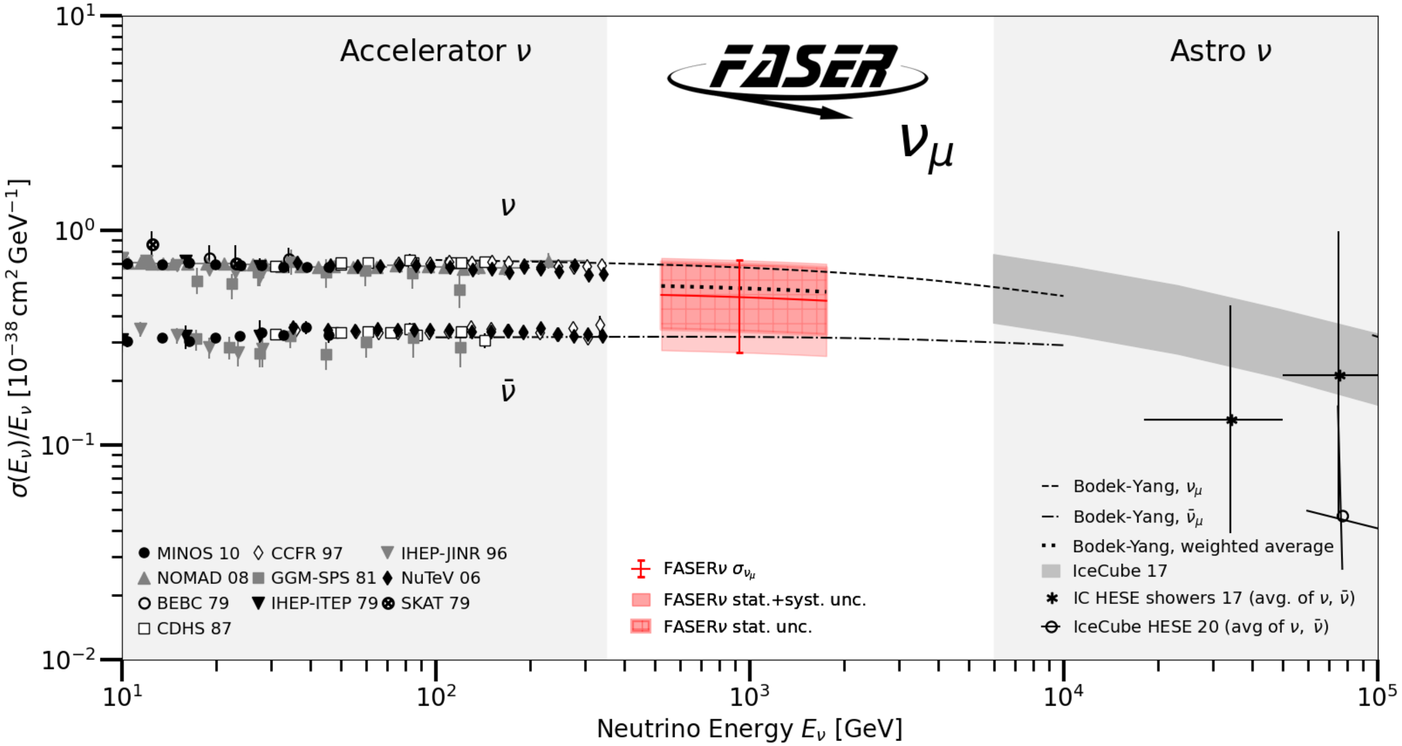


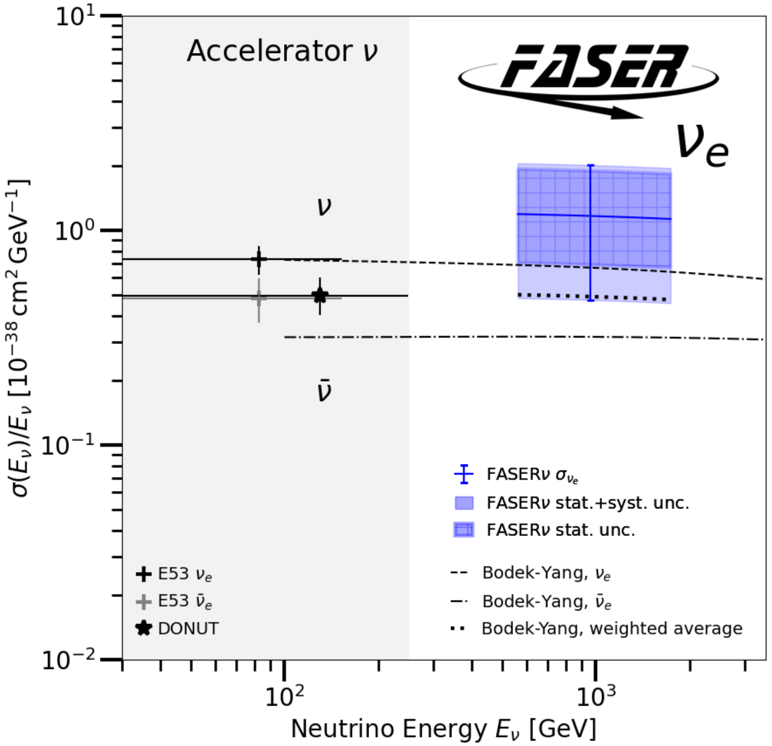
# Results from FASERν: $\nu_\mu$ and $\nu_e$ events!

| Interaction | Expected background | Expected signal | Observed | Significance |
|---|---|---|---|---|
| $\nu_e$ CC | $0.025^{+0.015}_{-0.010}$ | 1.1 – 3.3 | 4 | 5.2σ |
| $\nu_\mu$ CC | $0.22^{+0.09}_{-0.07}$ | 6.5 – 12.4 | 8 | 5.7σ |

- First observation of $\nu_e$ at the LHC!
- First neutrino cross-section measurement in the TeV range!

arXiv:2403.12520!!!





- Measurement relative to theoretical curve.
- Uncertainty dominated by neutrino flux.

# Summary

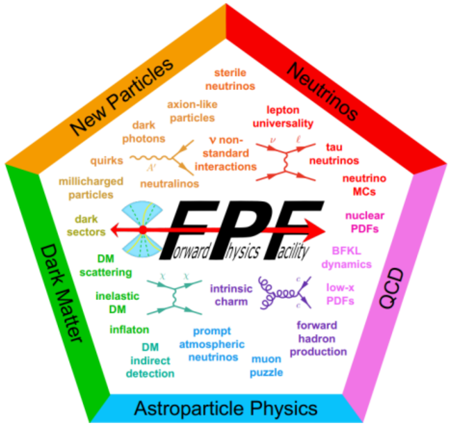
- The FASER measures TeV-scale neutrinos of all 3 flavours → First collider neutrino experiment!
- FASER is successfully operating during CERN LHC Run 3.
- 5 FASERν modules have been irradiated, collecting 60 $\text{fb}^{-1}$ to date, with another 180 $\text{fb}^{-1}$ expected in Run 3 → 6th module currently installed.

- New results from FASERν presented → First Measurement of the $\nu_e$ and $\nu_\mu$ Interaction Cross Sections at the LHC with FASER's Emulsion Detector!

- 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…

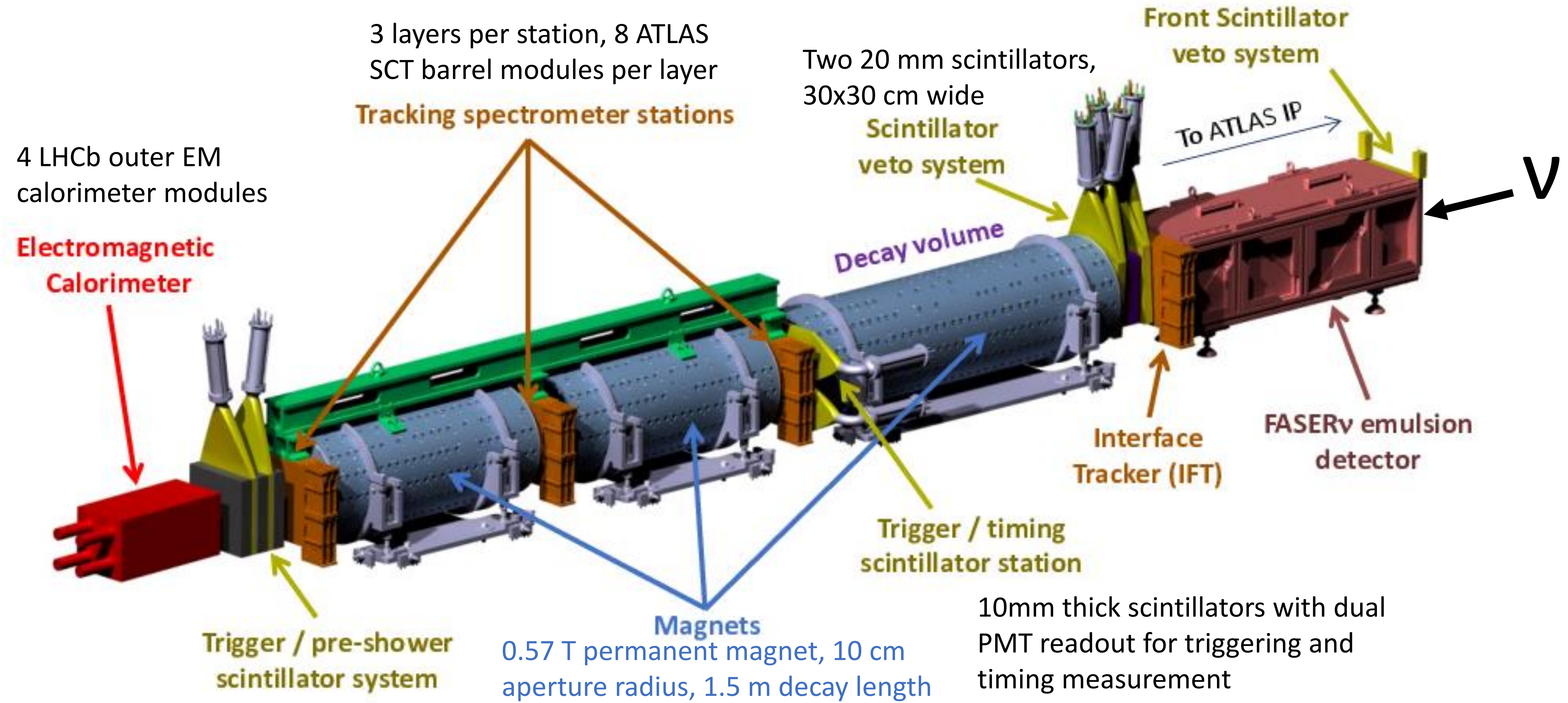
<u>Looking to the future:</u>

  - FASER in Run4 approved;
  - Forward Physics Facility (FPF) at CERN → planned project to build new experimental cavern in the HL-LHC era for an improved physics programme, including FASER2 and FASERν2



# Backup

# FASER detector



Two 20 mm scintillators, 35x30 cm wide

3 layers per station, 8 ATLAS SCT barrel modules per layer

Two 20 mm scintillators, 30x30 cm wide

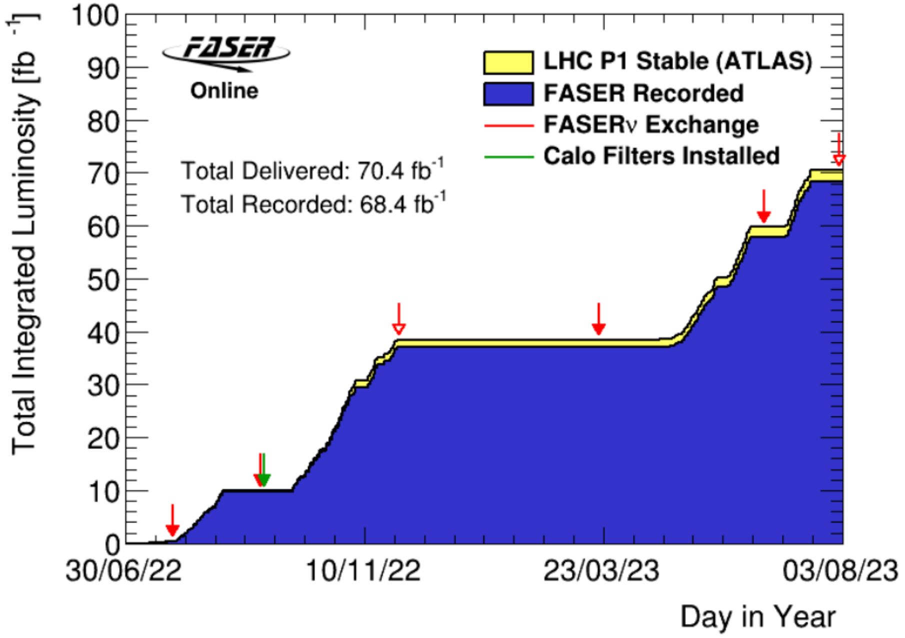
4 LHCb outer EM calorimeter modules

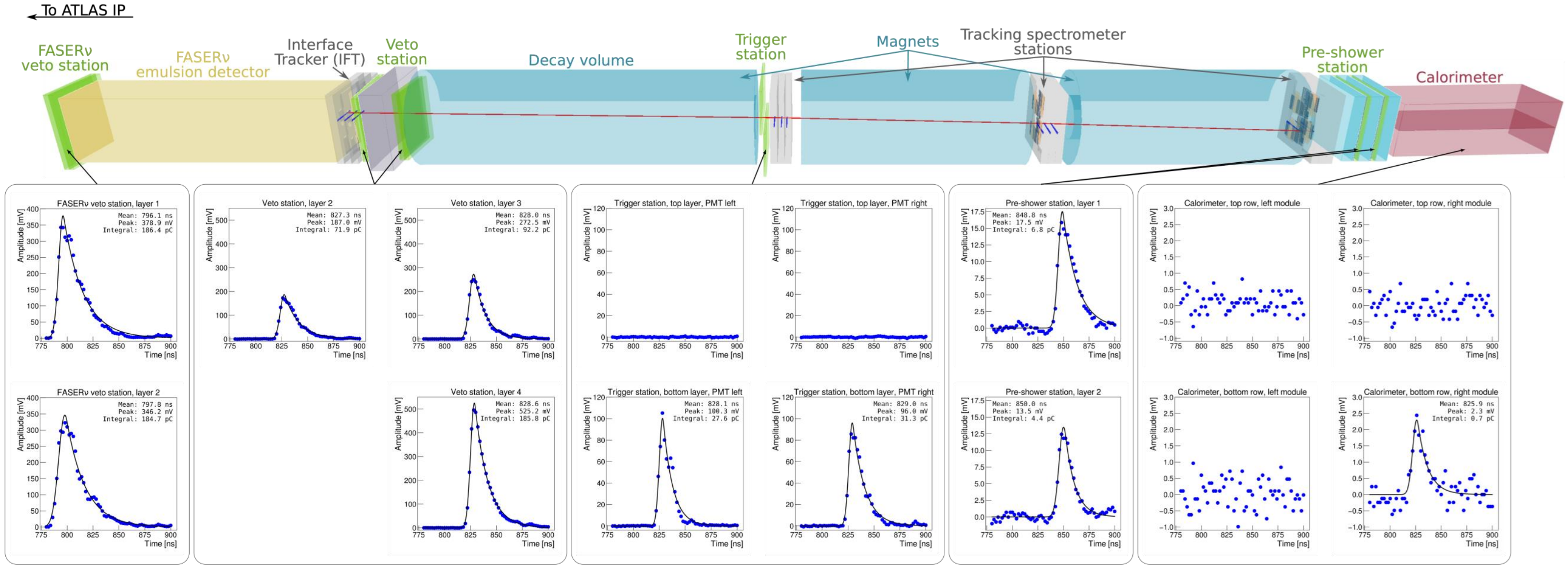
0.57 T permanent magnet, 10 cm aperture radius, 1.5 m decay length

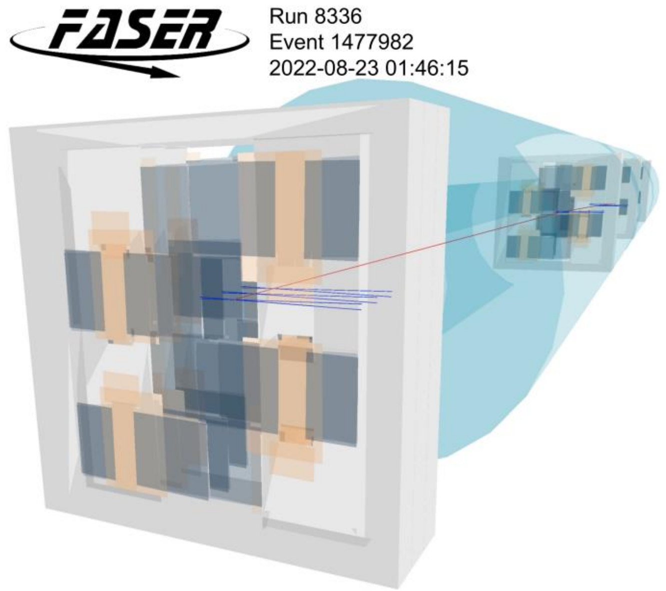
10mm thick scintillators with dual PMT readout for triggering and timing measurement (sigma=400ps)

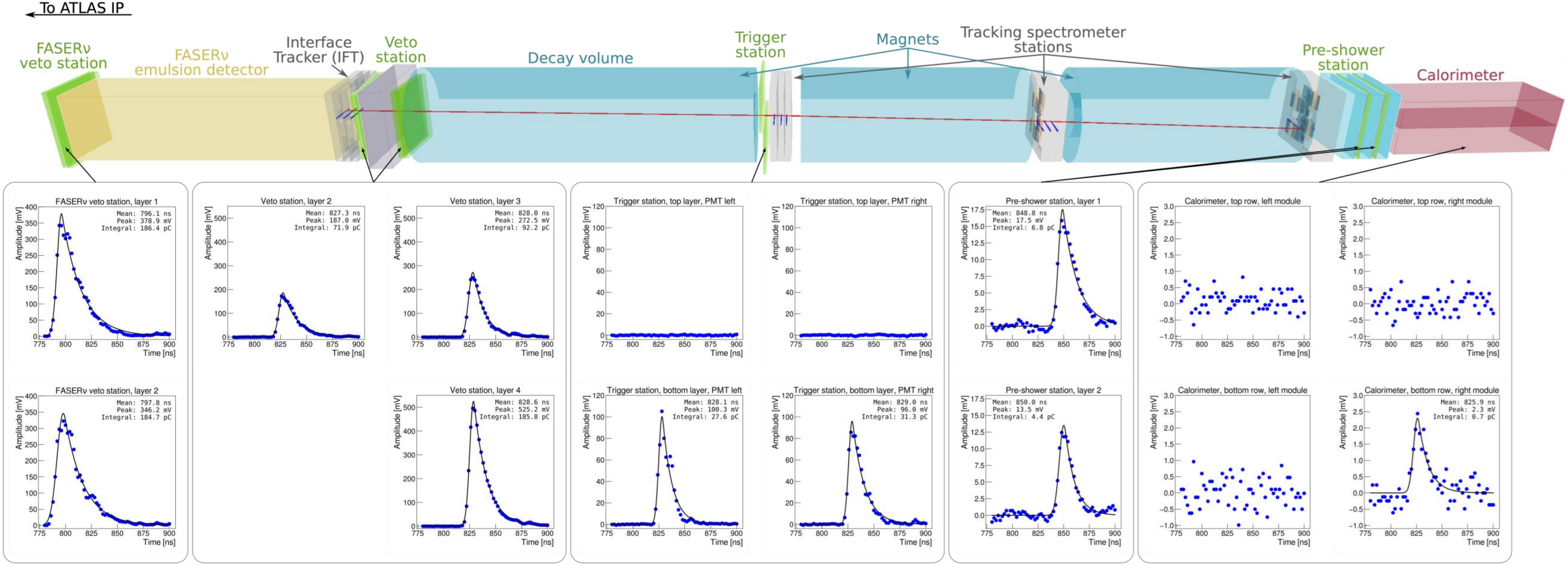
# FASER Operations

- Successful running in 2022 and 2023.
- Recorded **97%** of delivered luminosity → > 65 fb$^{-1}$ .
- FASERν module exchanged twice due to occupancy in emulsion.
- Example event: muon leaving track in full detector → all detector components working well.



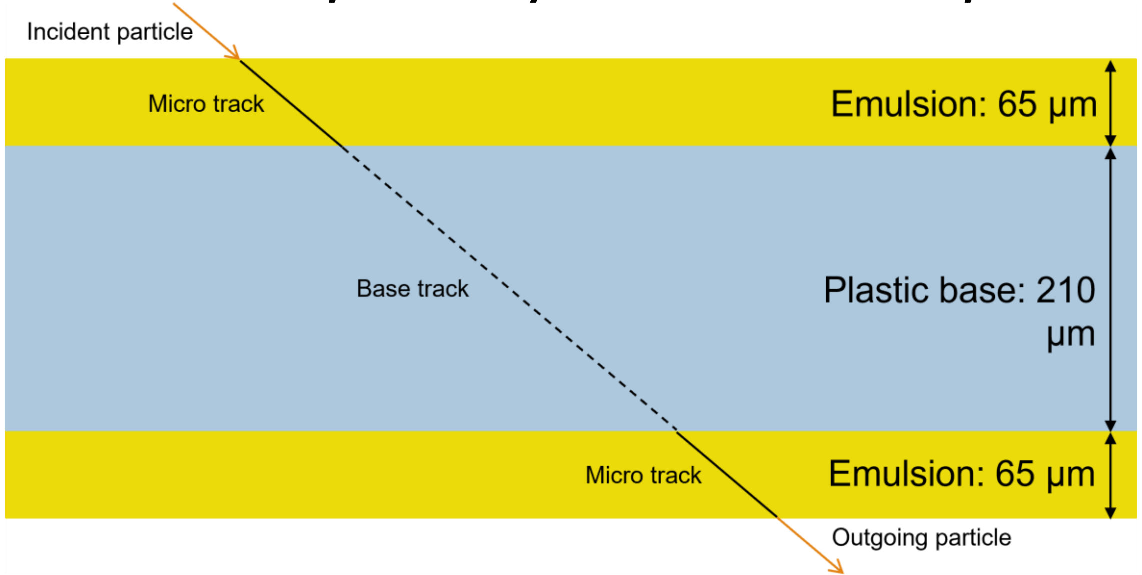


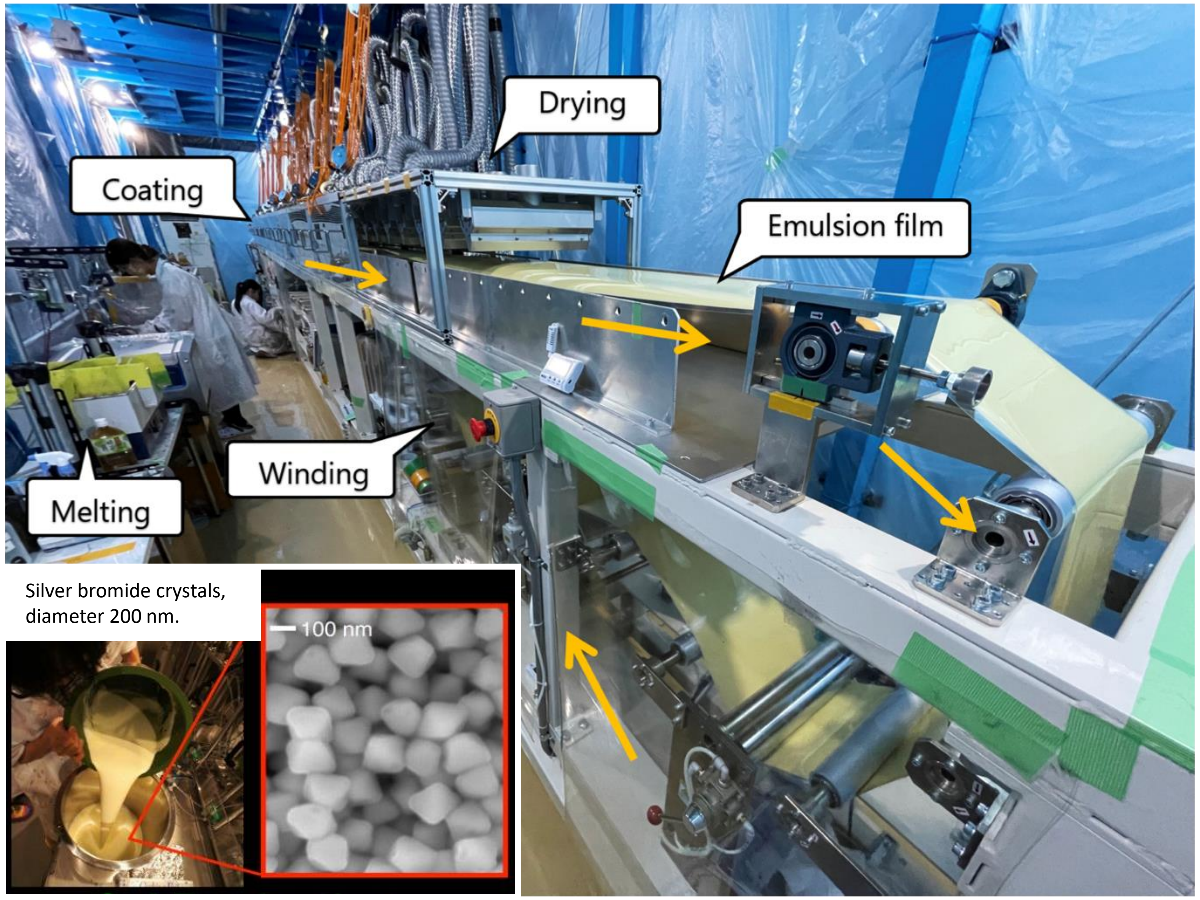



To ATLAS IP
FASERν veto station
FASERν emulsion detector
Interface Tracker (IFT)
Veto station
Decay volume
Trigger station
Magnets
Tracking spectrometer stations
Pre-shower station
Calorimeter
FASERν veto station, layer 1
Mean: 796.1 ns
Peak: 378.9 mV
Integral: 186.4 pC
FASERν veto station, layer 2
Mean: 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]
775
800
825
850
875
900

# 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.

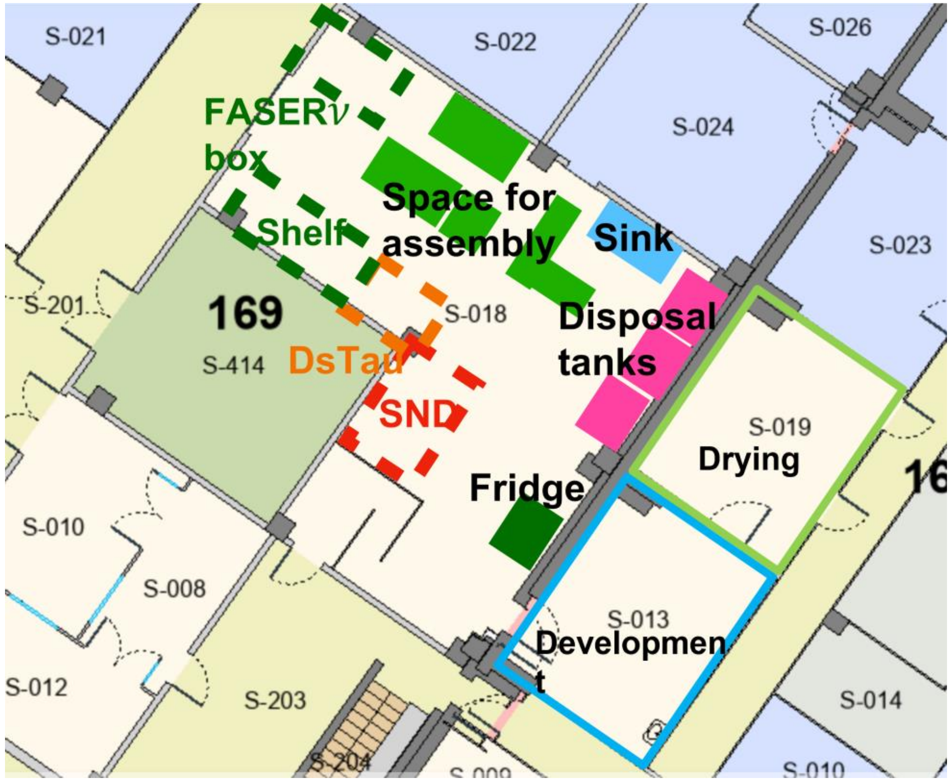




Silver bromide crystals, diameter 200 nm.

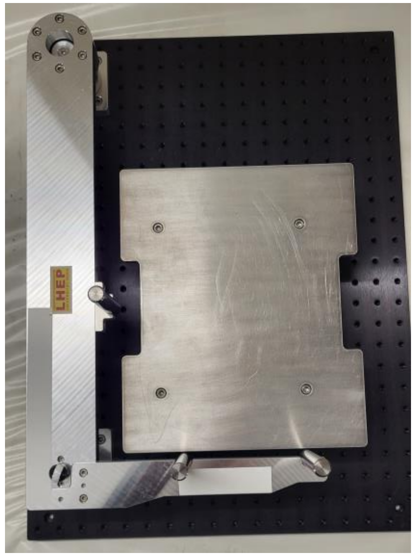
# Emulsion Facility at CERN

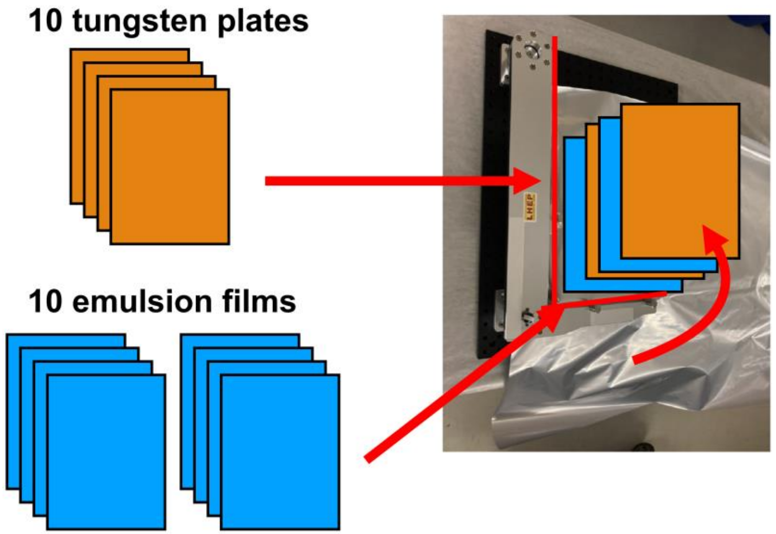
- New facility set up at CERN for emulsion experiments – includes modern climate control and ventilation system, access card entry, and full dark room capabilities for emulsion handling.
- 3 dedicated room: assembly, development and drying.
- Shared with NA65/DsTau, SND@LHC and SHiP Collaborations.
-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

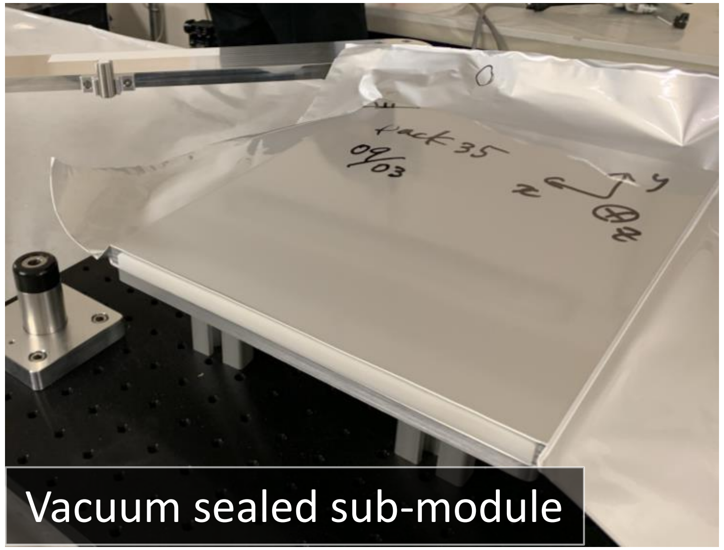


# FASERν Assembly at CERN

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



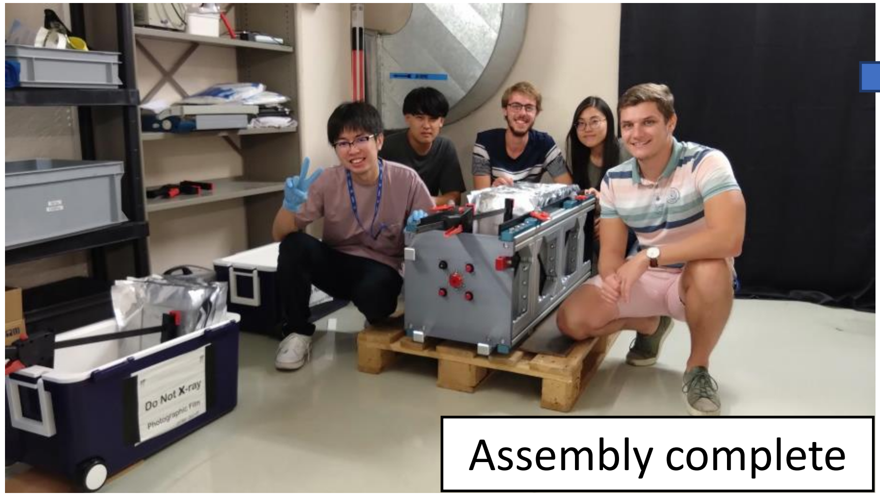




Vacuum sealed sub-module

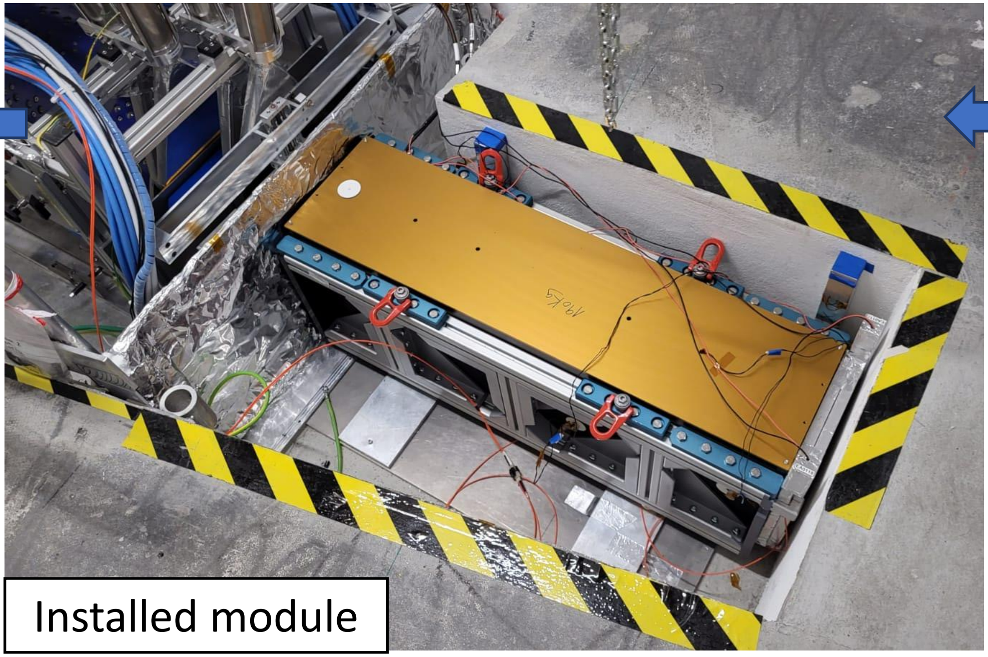
# FASERν Exchange

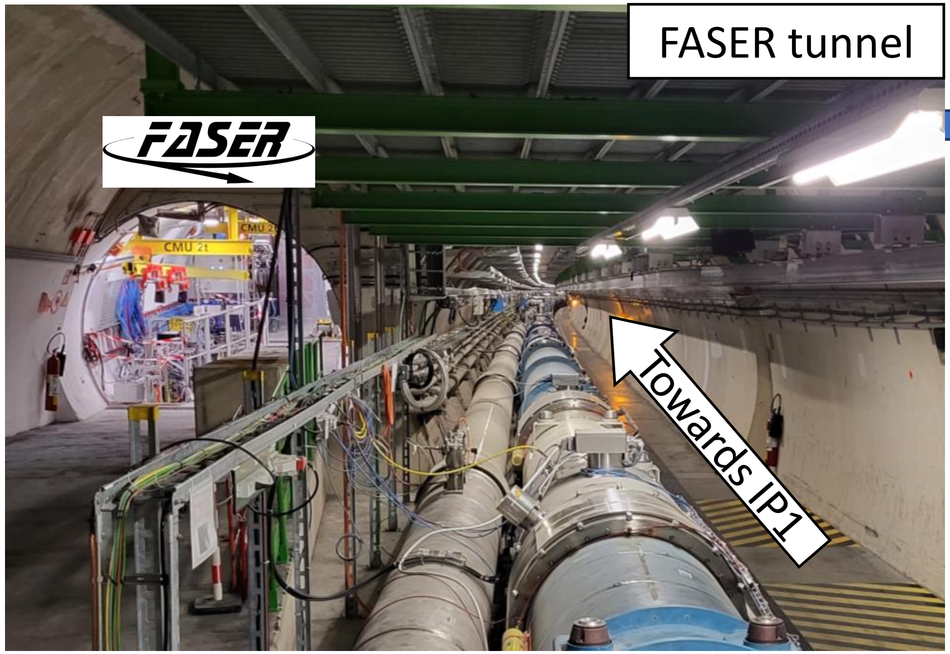
- Irradiated module extracted, and new module installed.
- Performed by FASER members with CERN technical teams.


Assembly complete


Moving modules over LHC

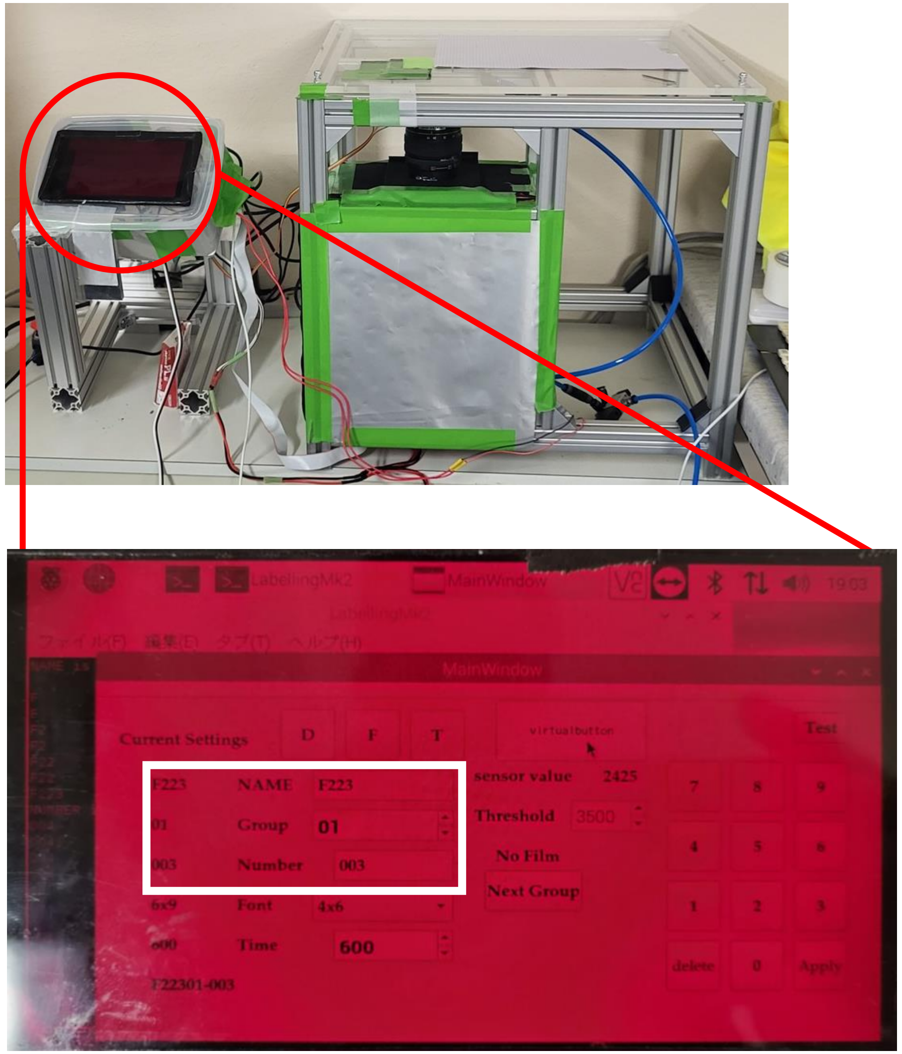

Exchange


Installed module


FASER tunnel

# 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.



Current Settings

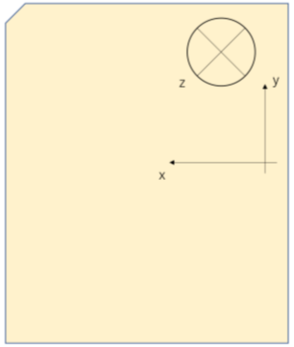
| | | |
|---|---|---|
| F223 | NAME | F223 |
| 01 | Group | 01 |
| 003 | Number | 003 |
| 6x9 | Font | 4x6 |
| 600 | Time | 600 |

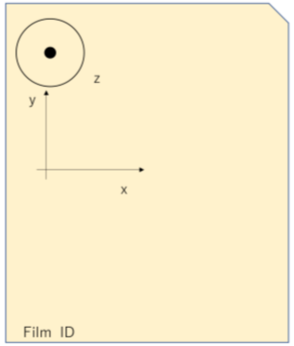
F22301-003

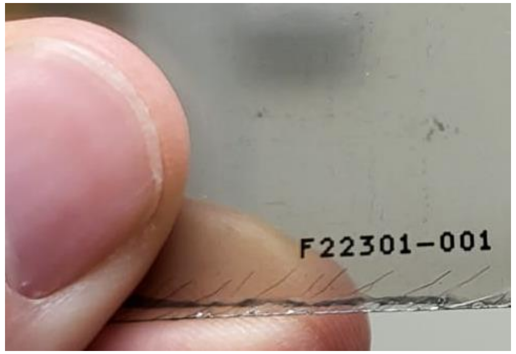
sensor value 2425

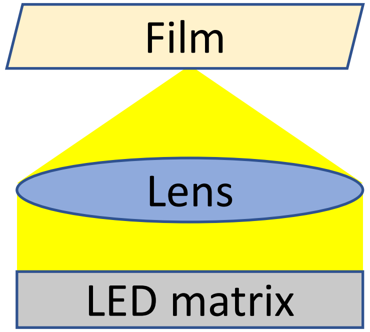
Threshold 3500

No Film







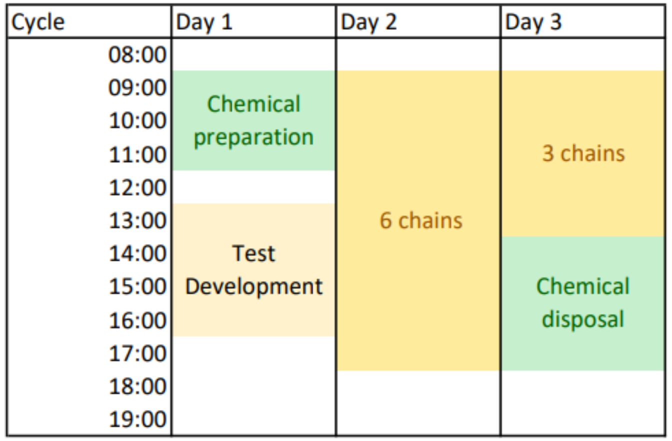


# Development

- 730 FASERv films in one FASERv module.

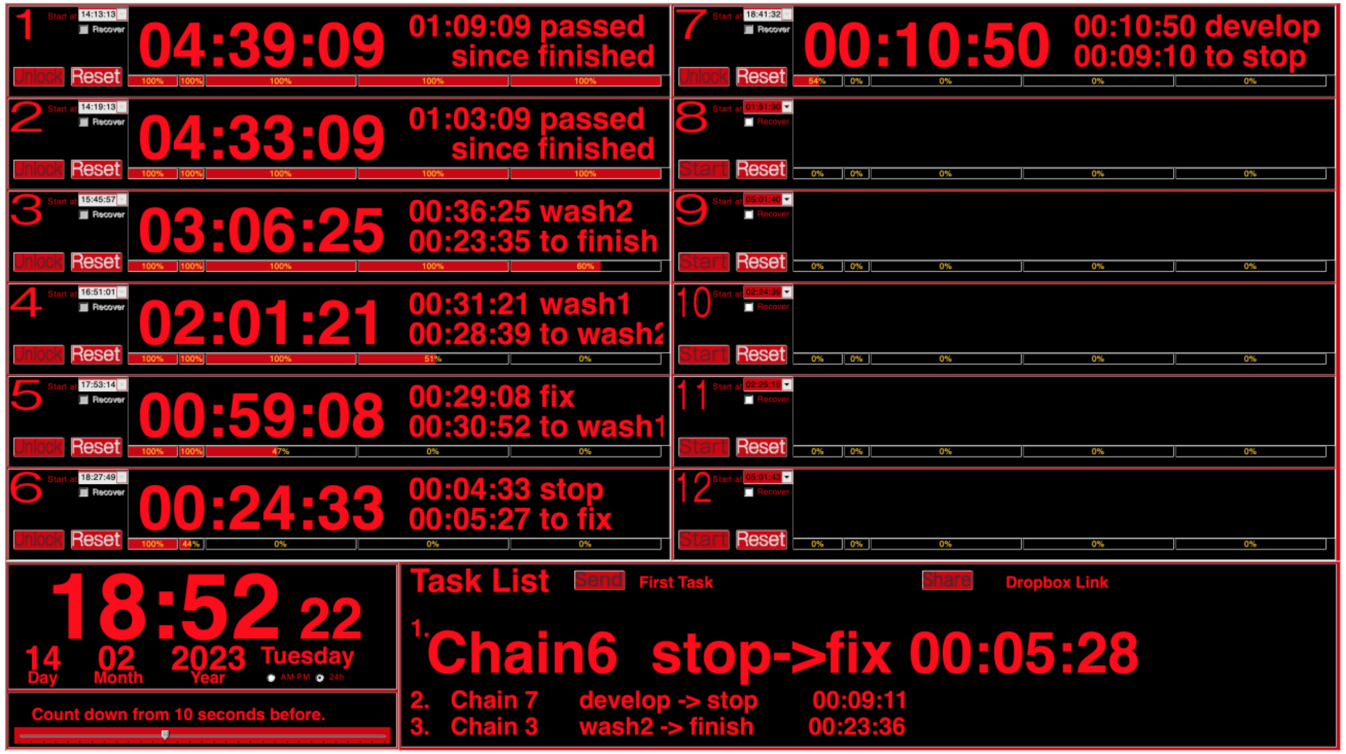
- 200 FASERv films → one cycle.
- 25 FASERv films hung using clips per rack → one chain.
- 4 cycles of 9 chains → each cycle takes approximately 3 days.
- Can have 3 chains going in parallel with around 25 minute shift.

- 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 | Chemical preparation | 6 chains | 3 chains |
| 10:00 | | | |
| 11:00 | | | |
| 12:00 | | | |
| 13:00 | Test Development | | |
| 14:00 | | | Chemical disposal |
| 15:00 | | | |
| 16:00 | | | |
| 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 | |



1 Start at 14:13:13 — 04:39:09 — 01:09:09 passed since finished

2 Start at 14:19:13 — 04:33:09 — 01:03:09 passed since finished

3 Start at 15:45:57 — 03:06:25 — 00:36:25 wash2 00:23:35 to finish

4 Start at 16:51:01 — 02:01:21 — 00:31:21 wash1 00:28:39 to wash2

5 Start at 17:53:14 — 00:59:08 — 00:29:08 fix 00:30:52 to wash1

6 Start at 18:27:49 — 00:24:33 — 00:04:33 stop 00:05:27 to fix

7 Start at 18:41:32 — 00:10:50 — 00:10:50 develop 00:09:10 to stop

8 Start at 01:51:30

9 Start at 05:01:40

10 Start at 02:24:39

11 Start at 02:25:15

12 Start at 05:01:43

18:52 22

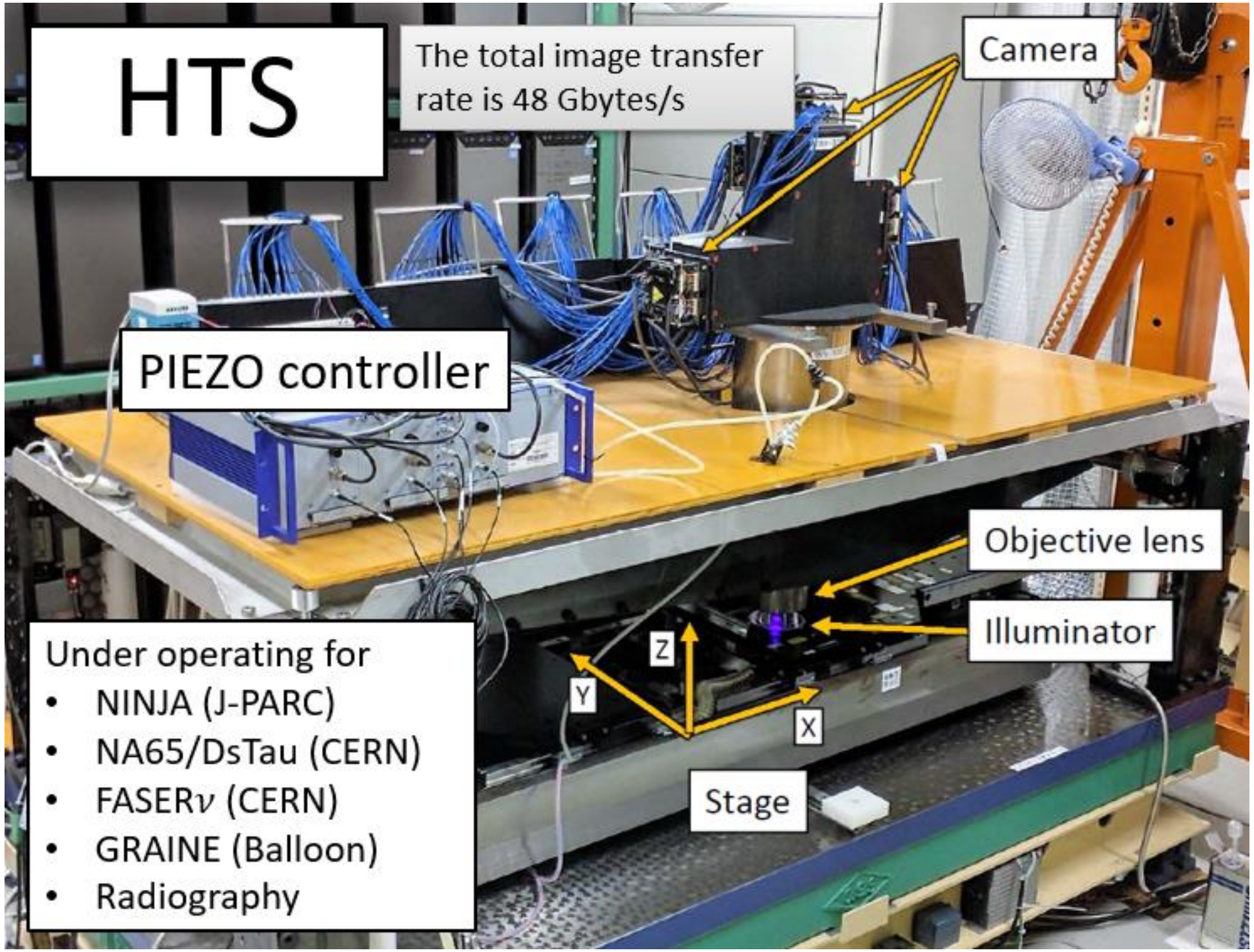
14 Day 02 Month 2023 Year Tuesday

Count down from 10 seconds before.

Task List — First Task

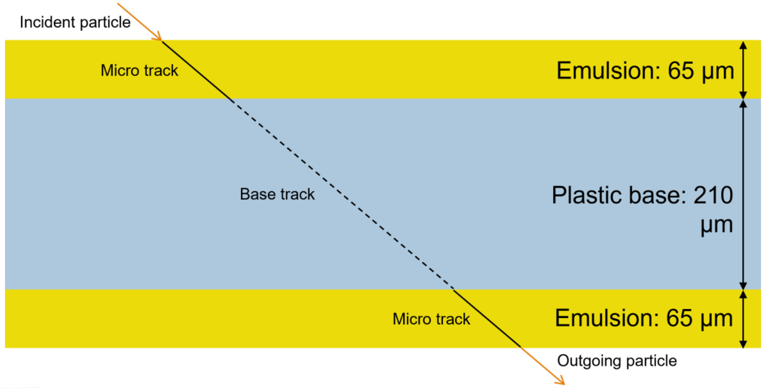
1. Chain6 stop->fix 00:05:28
2. Chain 7 develop -> stop 00:09:11
3. Chain 3 wash2 -> finish 00:23:36

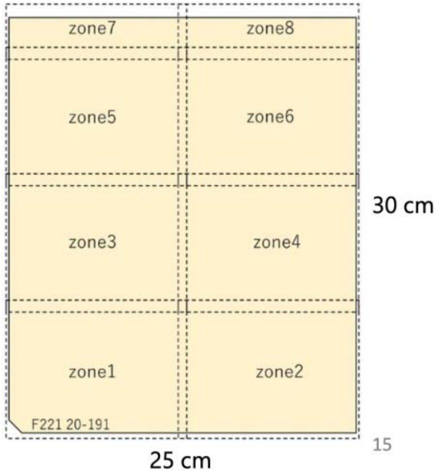
# Film Readout in Nagoya

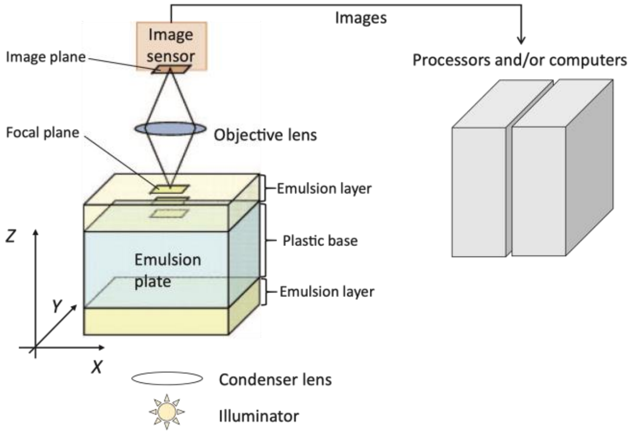


The total image transfer rate is 48 Gbytes/s

Under operating for
- NINJA (J-PARC)
- NA65/DsTau (CERN)
- FASER$\nu$ (CERN)
- GRAINE (Balloon)
- Radiography





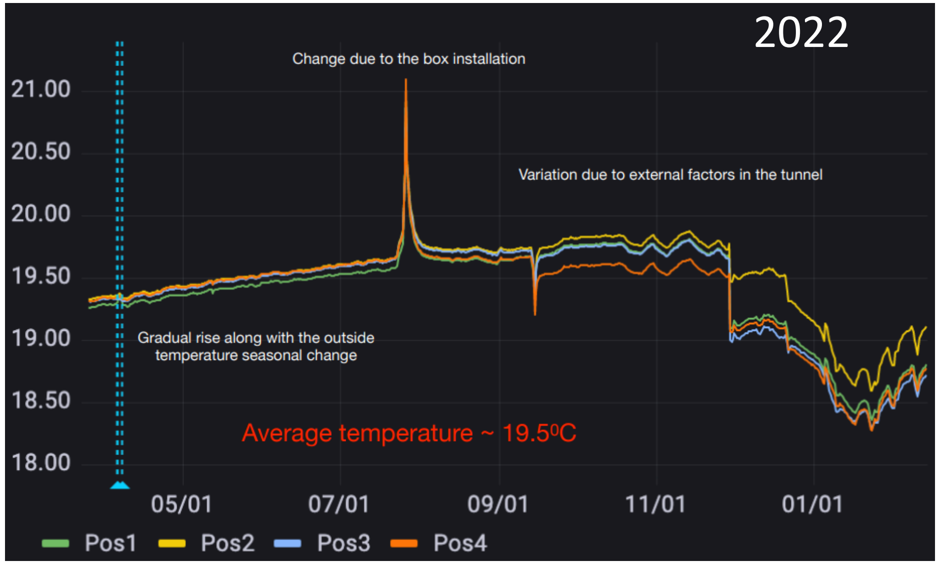


Hyper Track Selector (HTS): complex microscope system scans films for digital readout.

- 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.

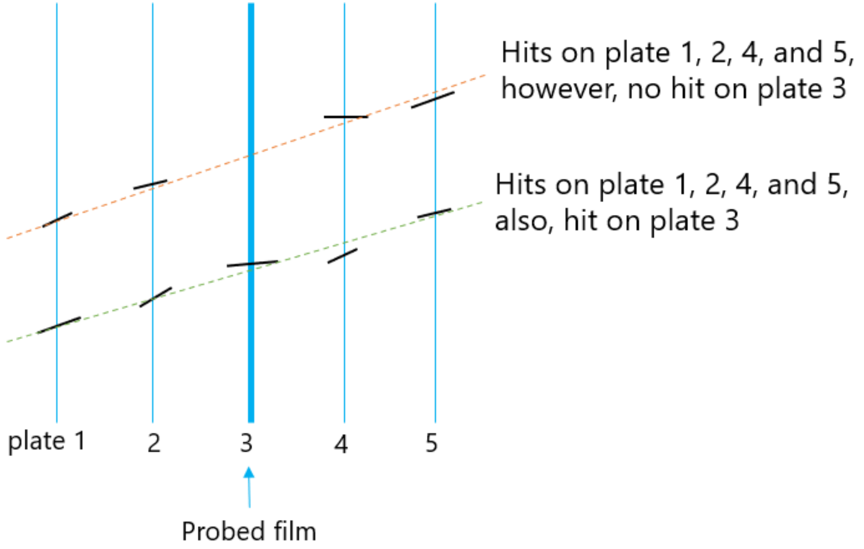
# Module temperature control

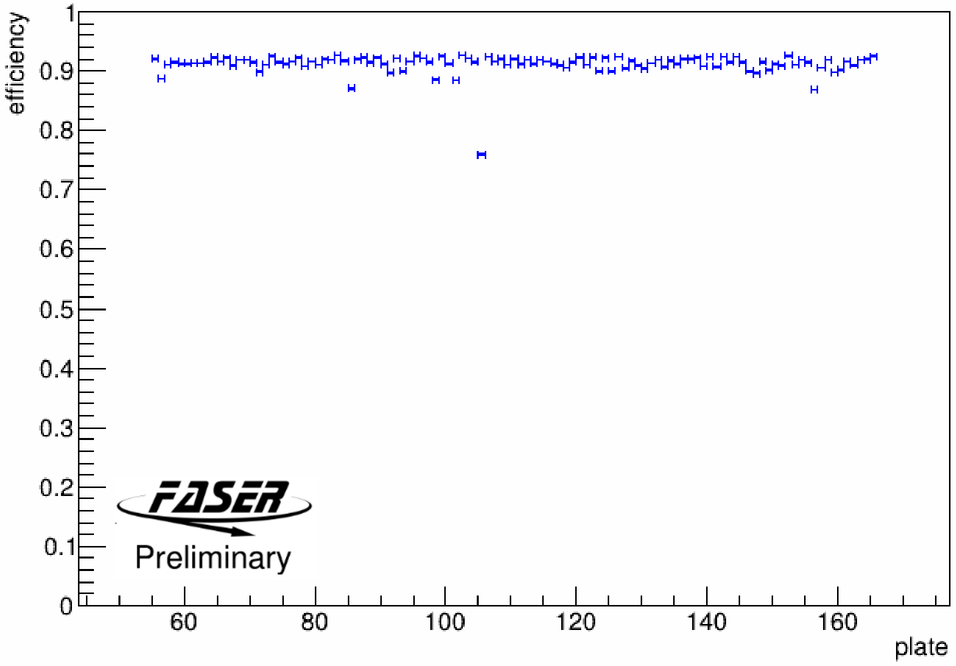
- Temperature of the FASERν module is kept constant at 0.1°C level with dedicated cooling system.
- Water in heat exchanger is kept at 15°C, and a fan system mixes the air in the FASERν trench, with a slanted perforated plate which helps further mix the air on all sides of the module.
- An insulating 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

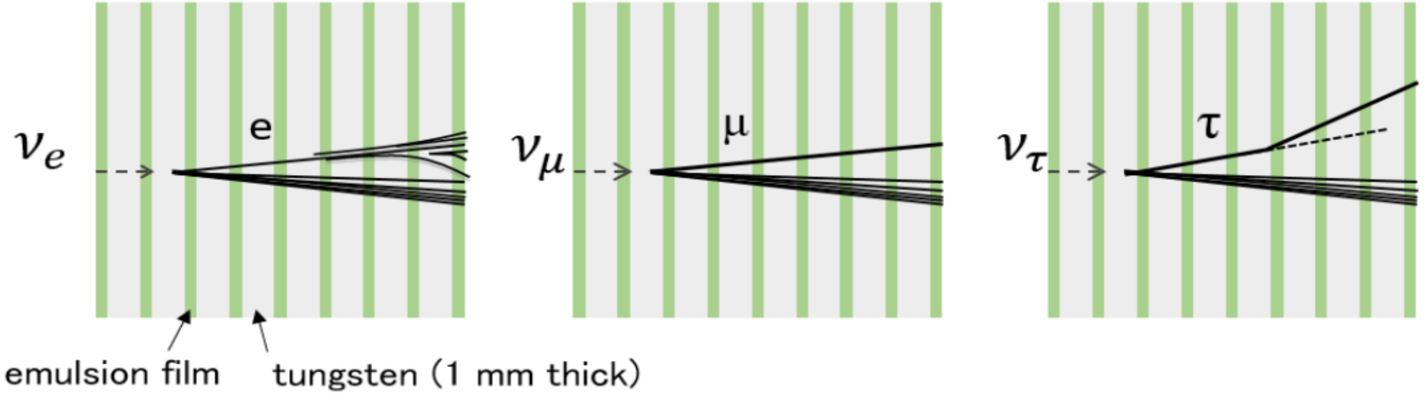
- Dedicated film alignment is performed using high-momentum muon tracks ($\mathcal{O}(10^5)$ tracks/cm$^2$).
- Track reconstruction links base-tracks on different films using position and angular information.
- Single film hit efficiency if found by considering whether a selected film has a hit given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

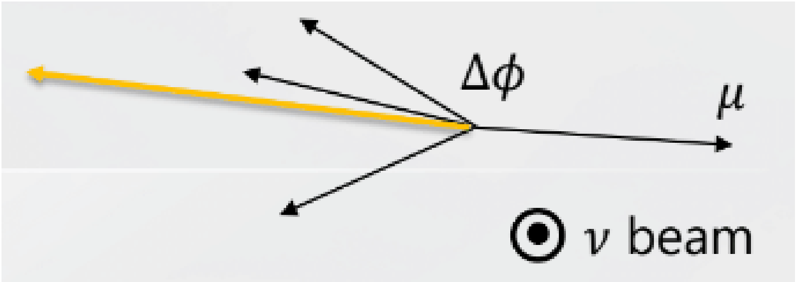


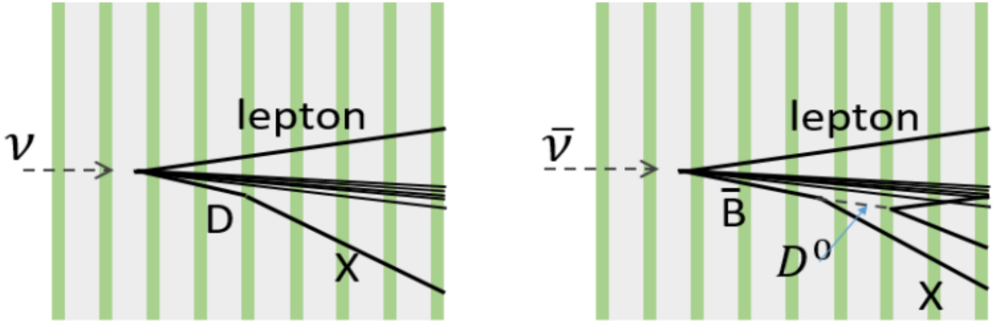


# Event Topology

- Neutrino events can be flavour tagged using topological and kinematical variables:
  - $\nu_e$ → outgoing electron initiating an EM shower;
  - $\nu_\mu$ → outgoing muon (identified by track length);
  - $\nu_\tau$ → tau lepton decay.
- For CC events, expect a back-to-back topology between lepton and hadrons in x-y plane → $\Delta\phi$ .

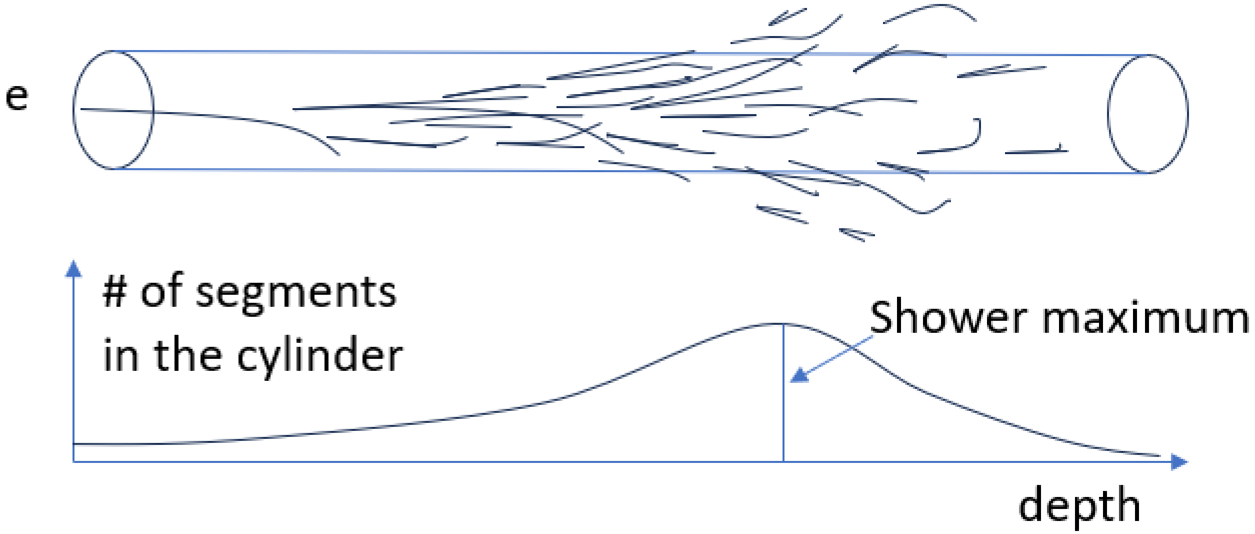






# Shower Energy Measurement

- 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).

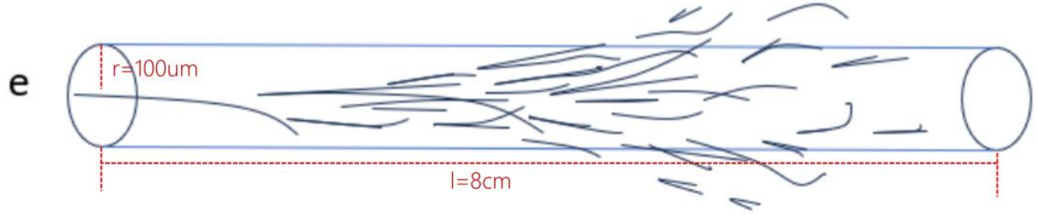


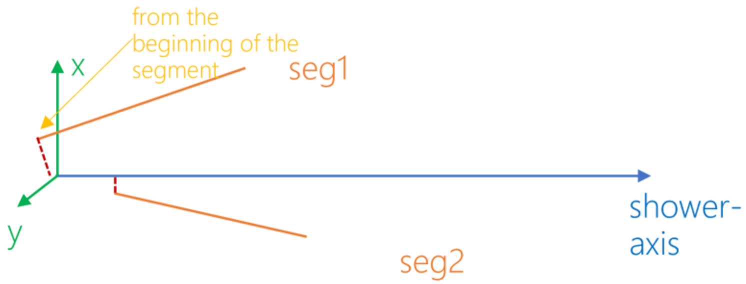
$\delta\text{pos} < 100\ \mu\text{m}$

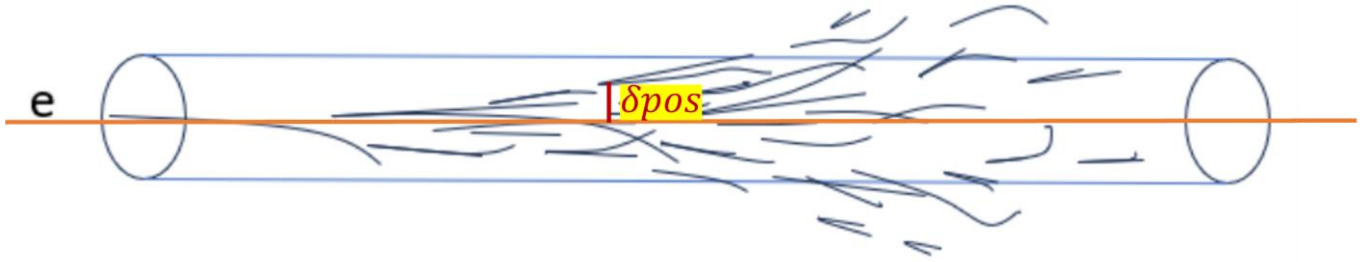
$\delta\theta < 10\ \text{mrad}$

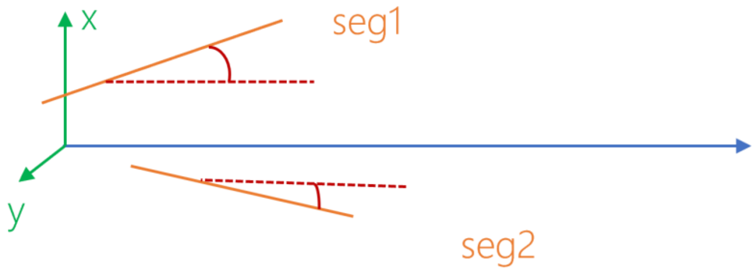
$d\text{min} < 50\ \mu\text{m}$

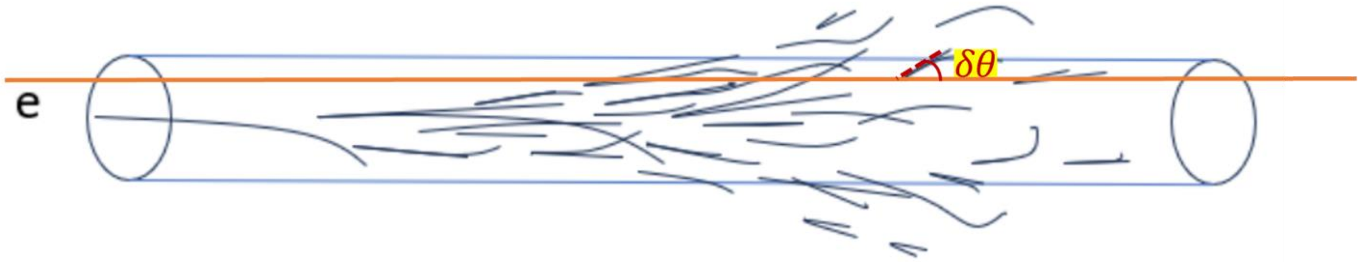
# Shower Energy Measurement

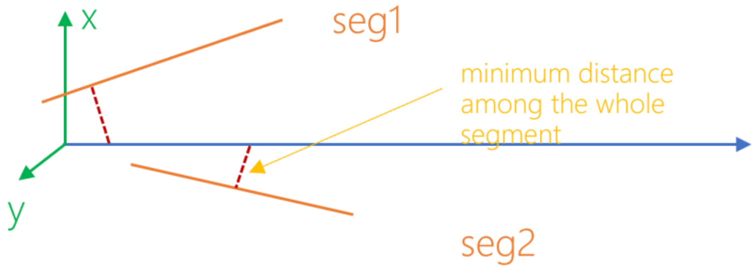


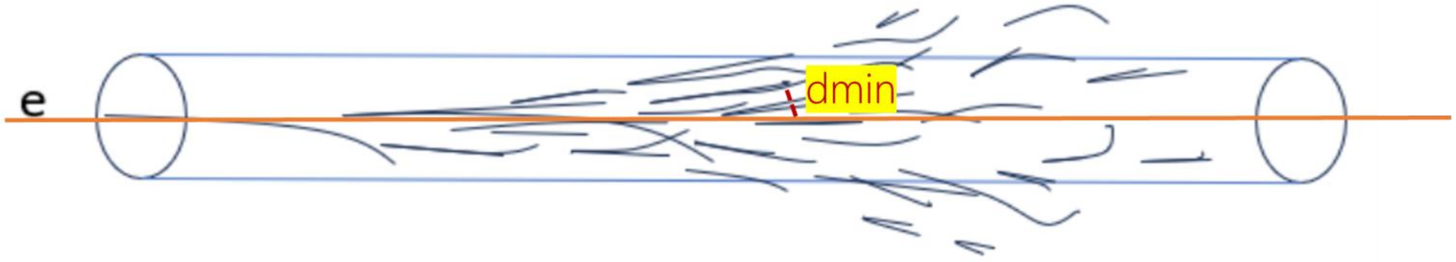




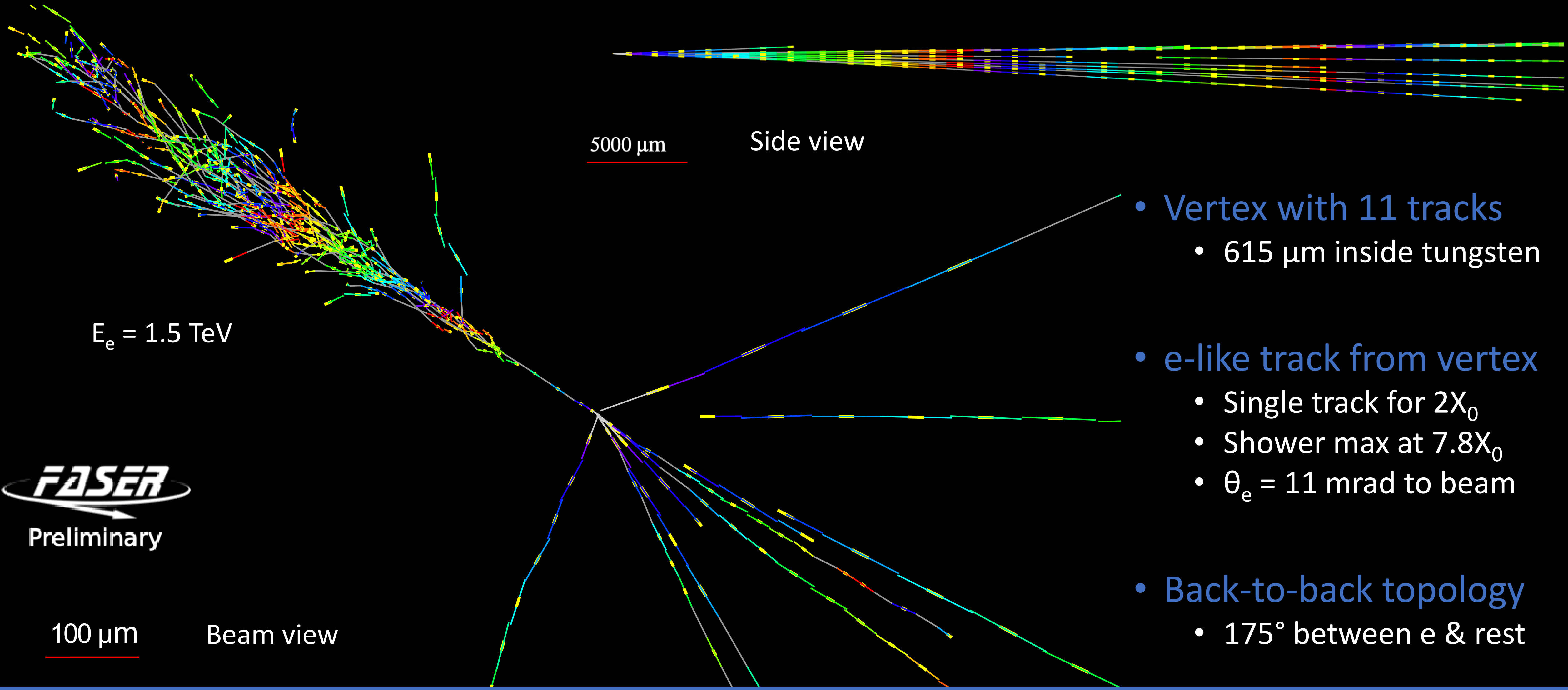








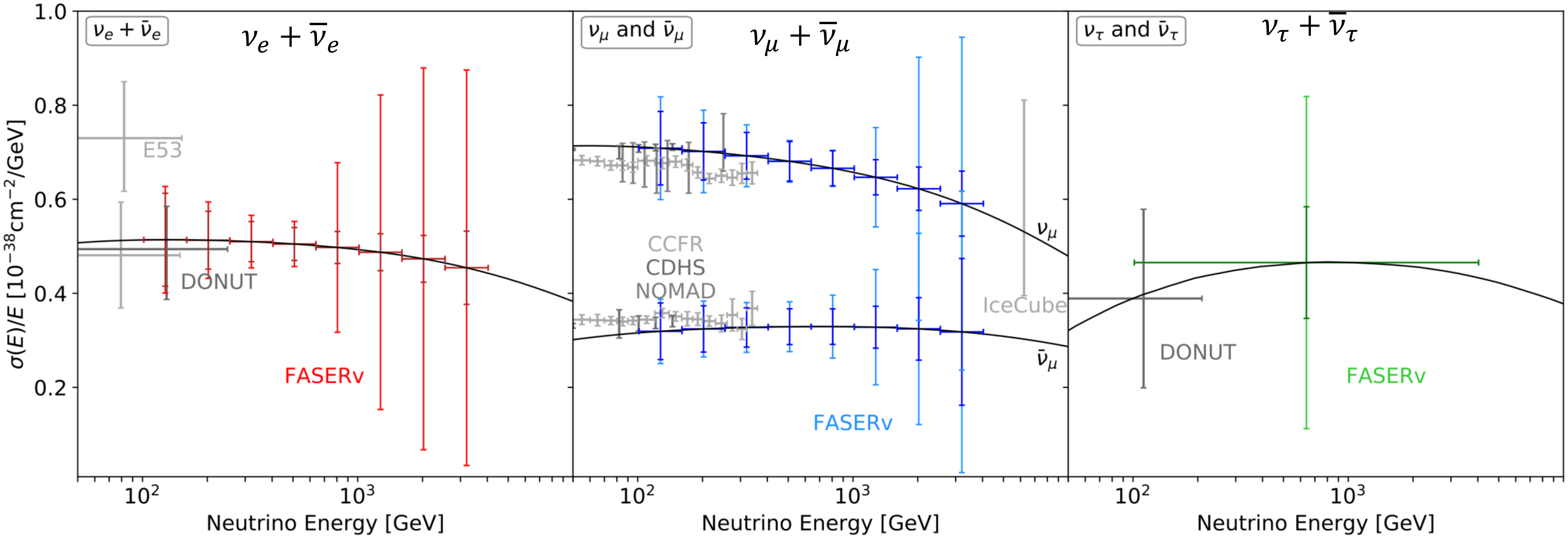
# FASERν $\nu_e$ candidate event



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

# FASER Expected Sensitivity

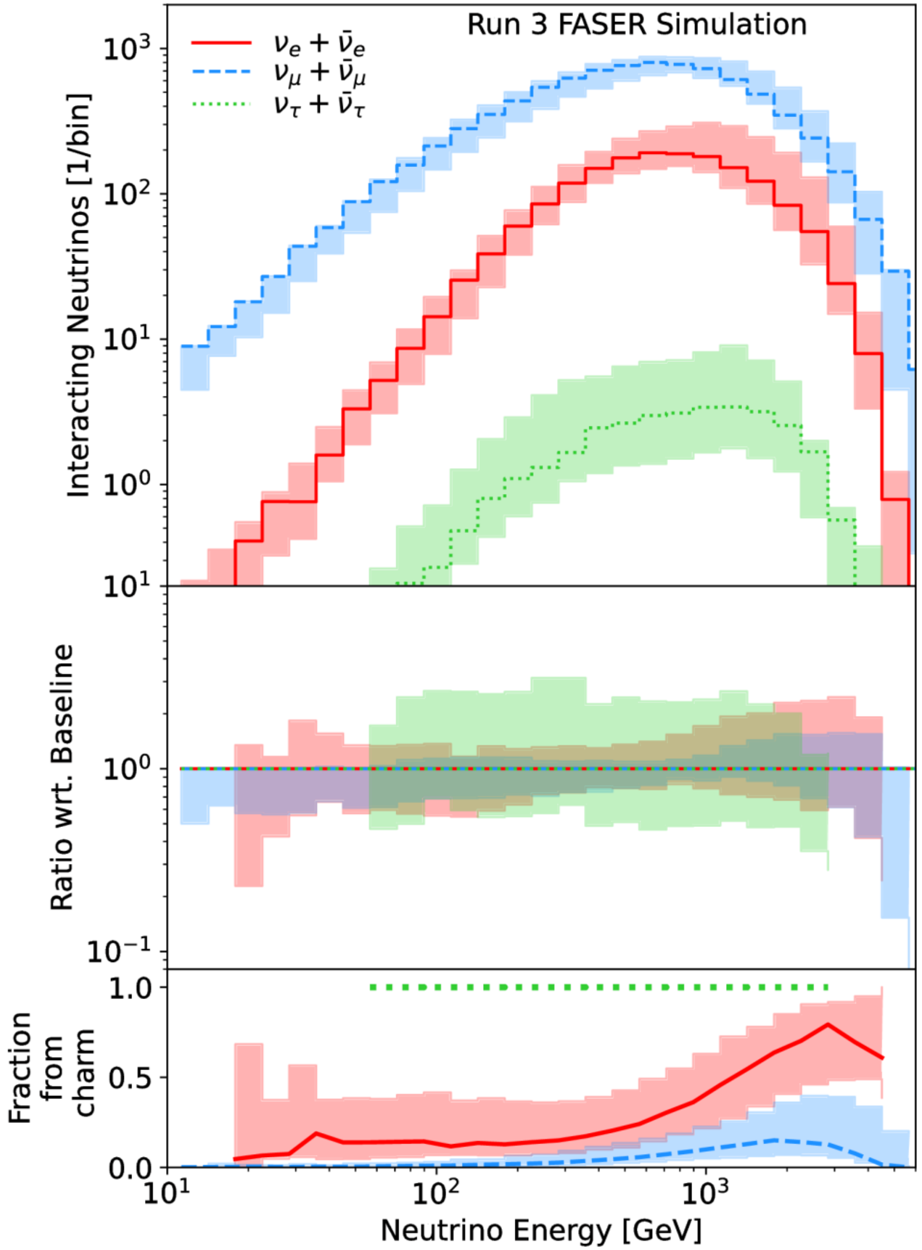
FASER expected sensitivity

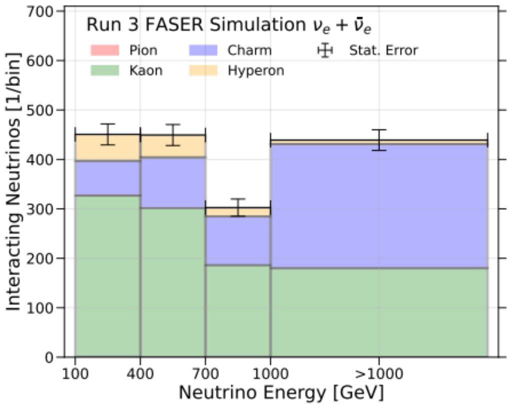


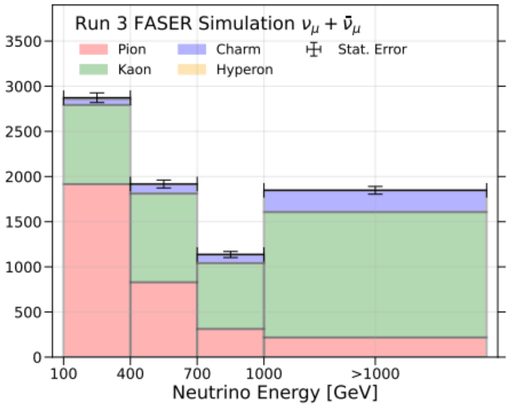
- Inner error bars: statistical uncertainties.
- Outer error bars: uncertainties from neutrino production rate.

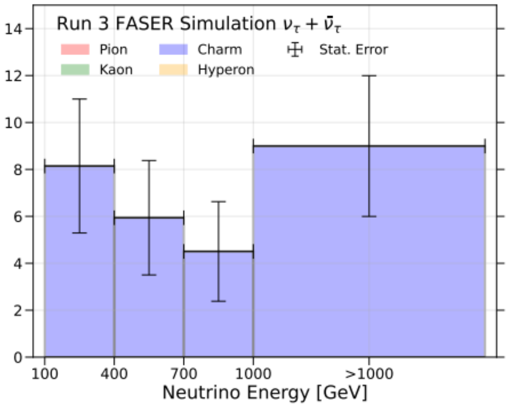
# Neutrino Flux at FASER

- Neutrinos are produced from the decay of light and charm hadrons.
- Light hadron production is generated using EPOS-LHC.
- Charm hadron production is generated using POWHEG + Pythia 8.3.
- Charm hadrons produce $\nu_\tau$, high-E $\nu_\mu$, $\nu_e$ → by deconvolving charm contribution, this can help constrain neutrino flux.

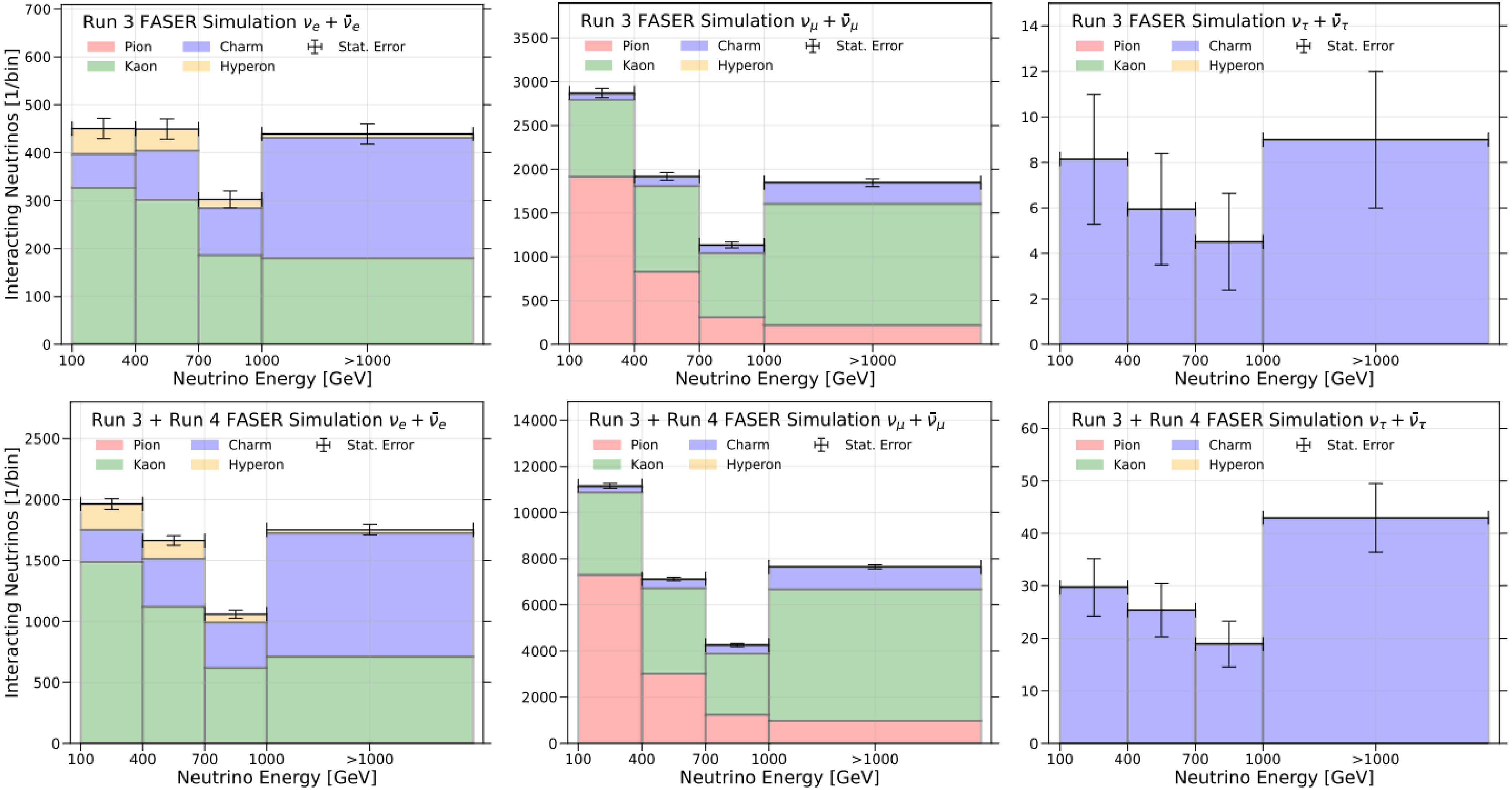






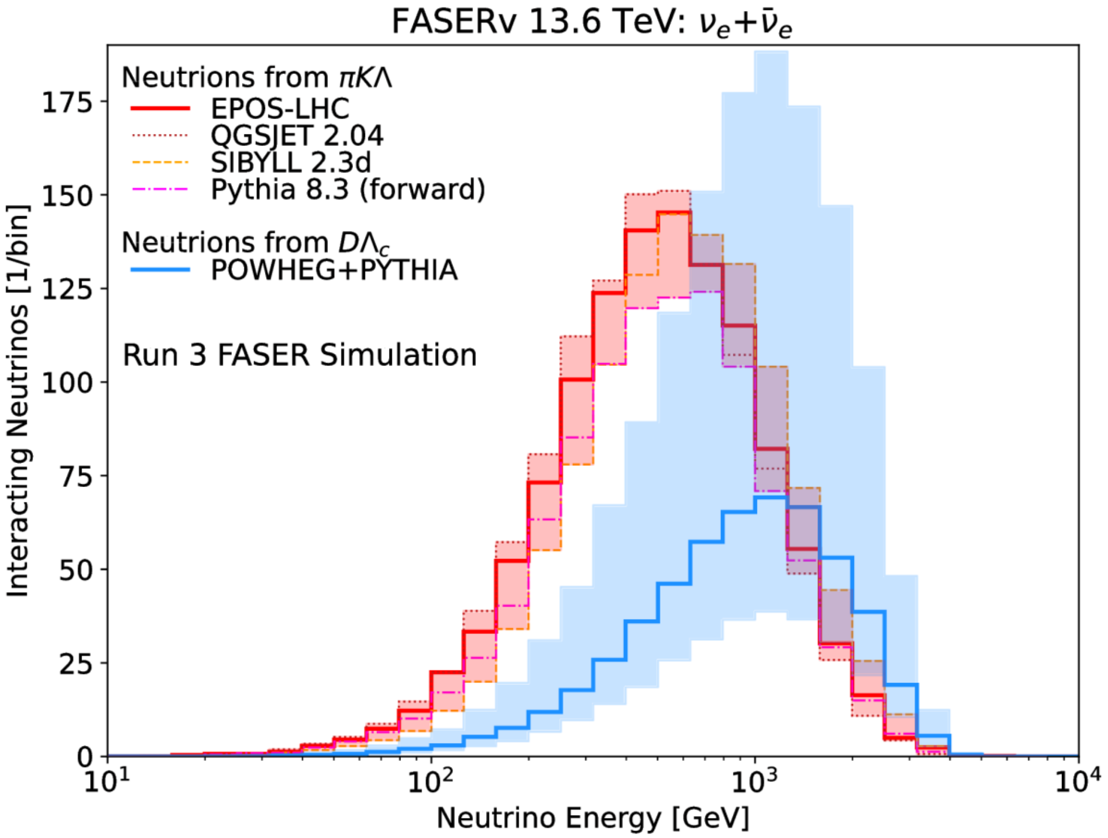


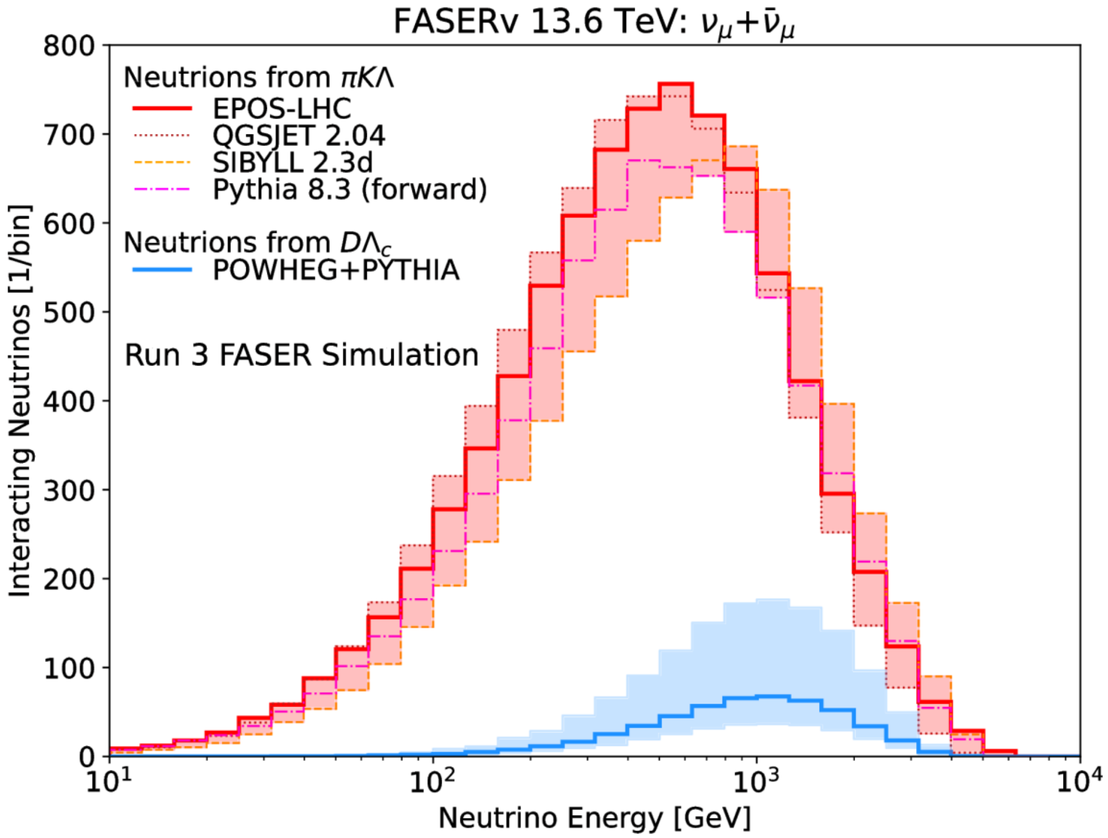
# Neutrino Flux at FASER



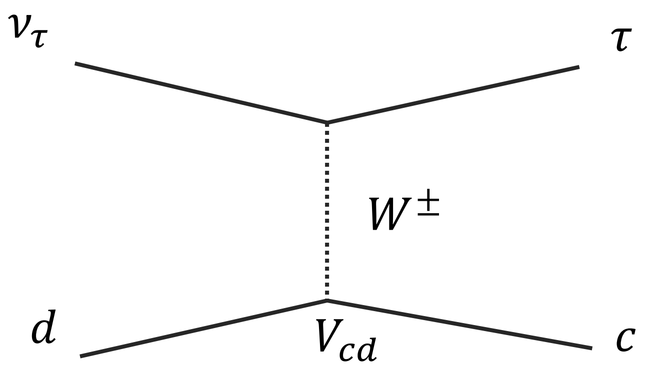
# Generator flux uncertainty

- Uncertainties for neutrinos from light hadron production come from spread of generators.
- Uncertainties for neutrinos from charm hadron decays come from varying internal parameters of charm hadron production by factor 2.
- Total uncertainty in the high-E range dominated by charm production.





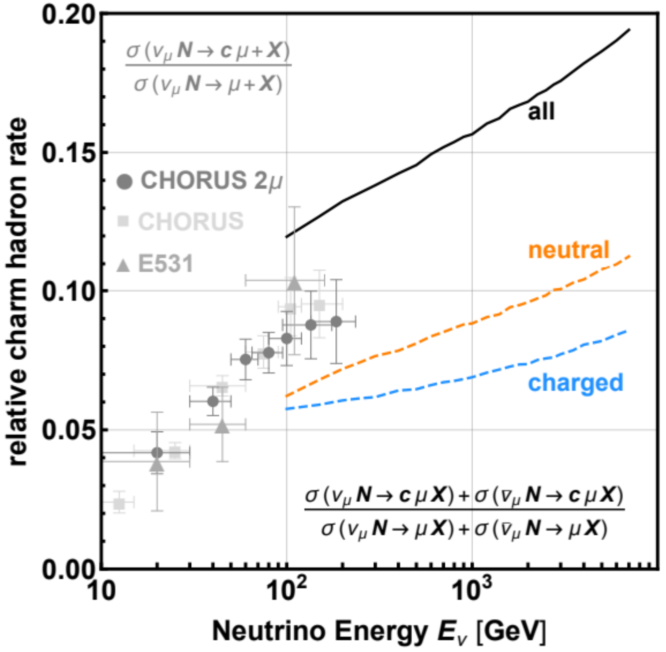
# Heavy-flavour-associated channels



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

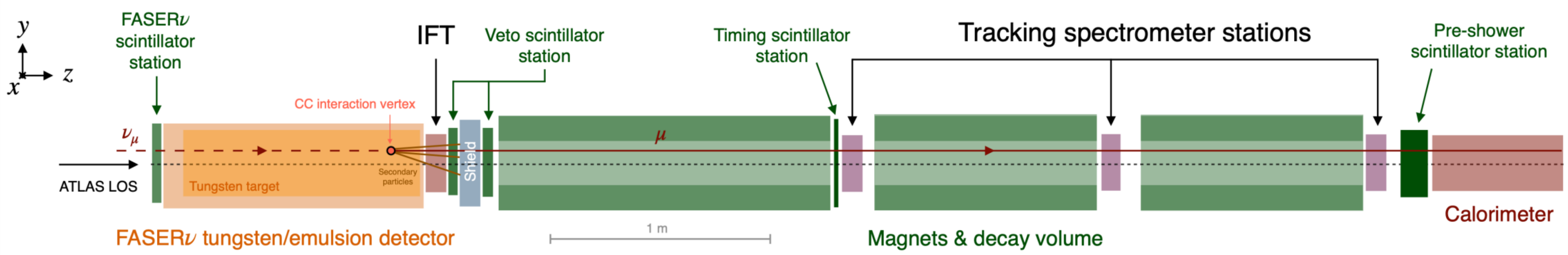
$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)} \qquad l = e, \mu$$

- Search for Beauty production channels
  - Expected SM events ($\nu_\mu$ 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.



# FASER "Electronic" Neutrino Search

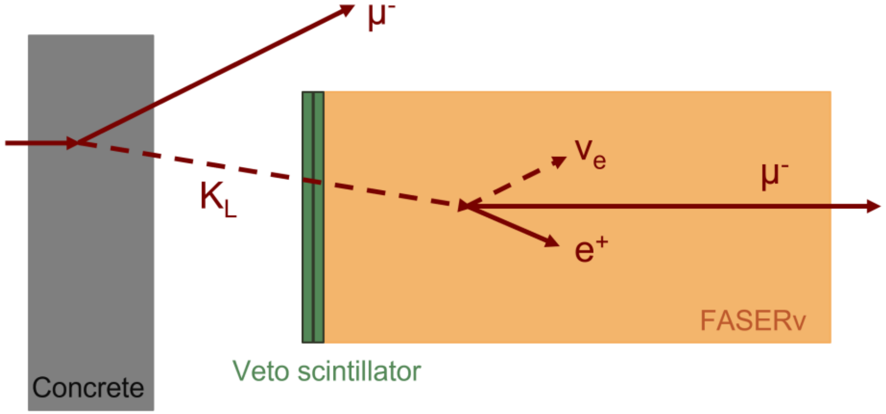
- Selection criteria:
  - Collision event in good data periods (35.4 $\text{fb}^{-1}$);
  - No signal in front 2 veto scintillators (<40 pC);
  - Signal in last 2 veto stations (>40 pC);
  - Signal in timing and pre-shower scintillators consistent with >= 1 MIP;
  - Exactly 1 good spectrometer track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



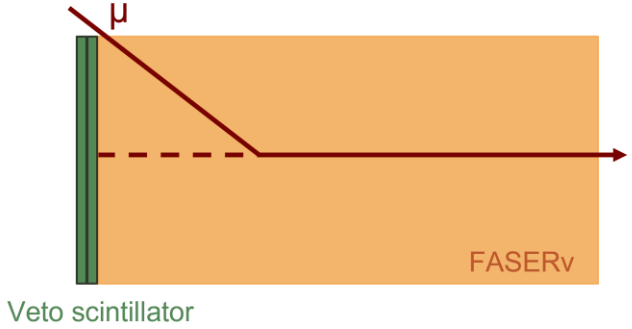
- 151 ± 41 neutrino events expected from simulation:
  - Uncertainty from difference between generators (DPMJET & SIBYLL).
  - No experimental errors were included.

# Background estimation

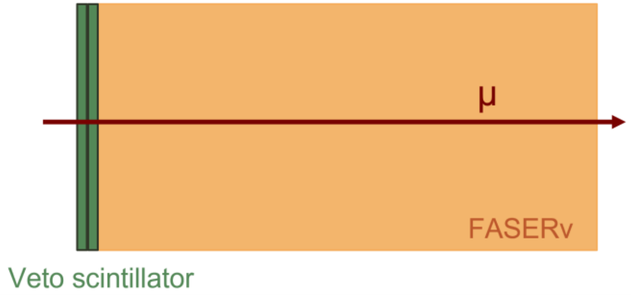
- Neutral hadrons 0.11 ± 0.06:
  - Expect approx. 300 with E > 300 GeV;
  - Tungsten absorbs the majority;
  - Estimated from 2-step simulation.



- 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.



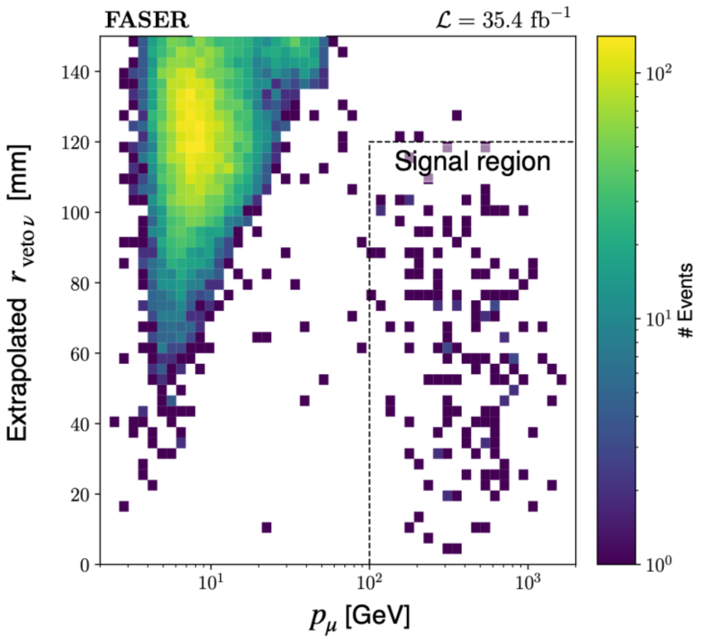
- Veto inefficiency negligible:
  - Estimated from events where only 1 veto scintillator fired;
  - Very high veto efficiency.

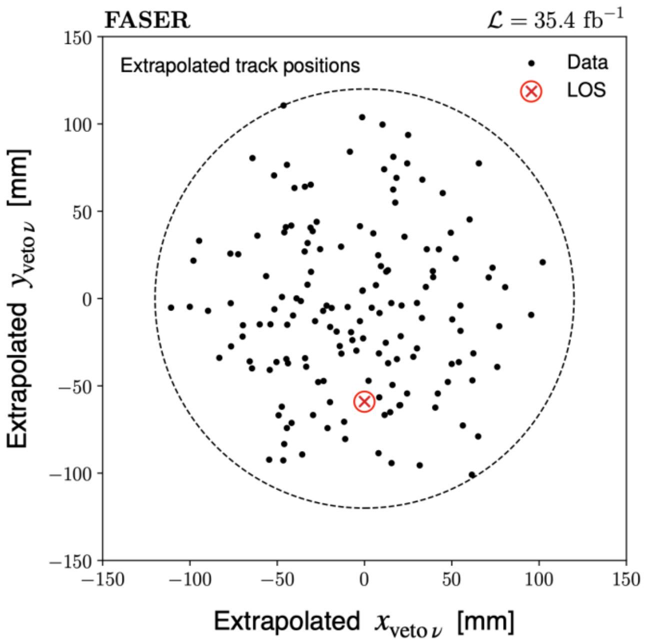


# Results

Phys. Rev. Lett. 131, 031801 (2023)

- **$153^{+12}_{-13}$** 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 |