LHC Neutrinos at FASERν and Neutrino Energy Reconstruction Methods

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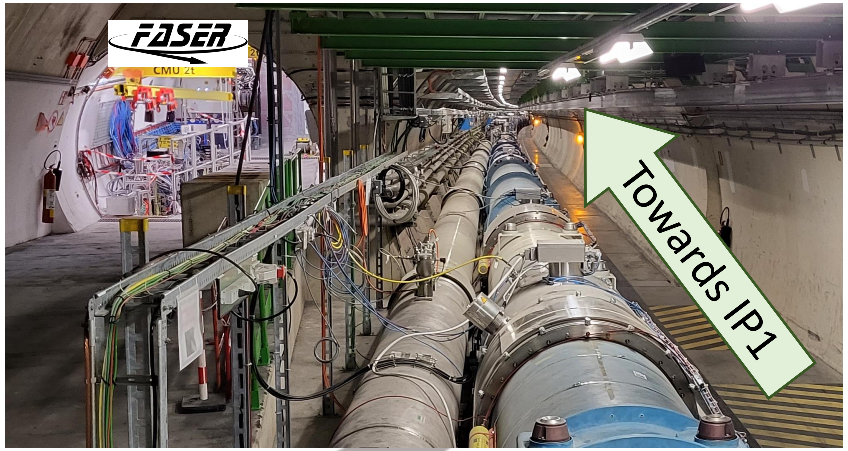
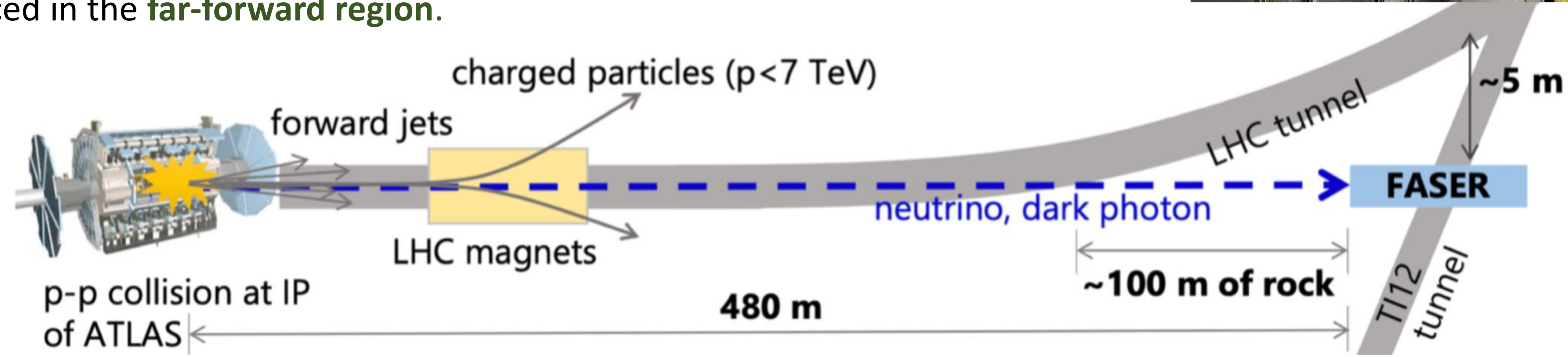
12th of September 2024, SPS Annual Meeting, ETH Zürich

ForwArd Search ExpeRiment



- First collider neutrino 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**.



The detector is aligned with the collision axis line-of-sight → maximises the number and energy of **neutrino** interactions of all 3 flavours.

Neutrino results!

- First neutrino interaction candidates at the LHC [Phys. Rev. D 104, L091101 (2021)].
- First direct observation of ν_μ CC interactions at the LHC [Phys. Rev. Lett. 131, 031801 (2023)].
- First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector [Phys. Rev. Lett. 133, 021802 (2024)]

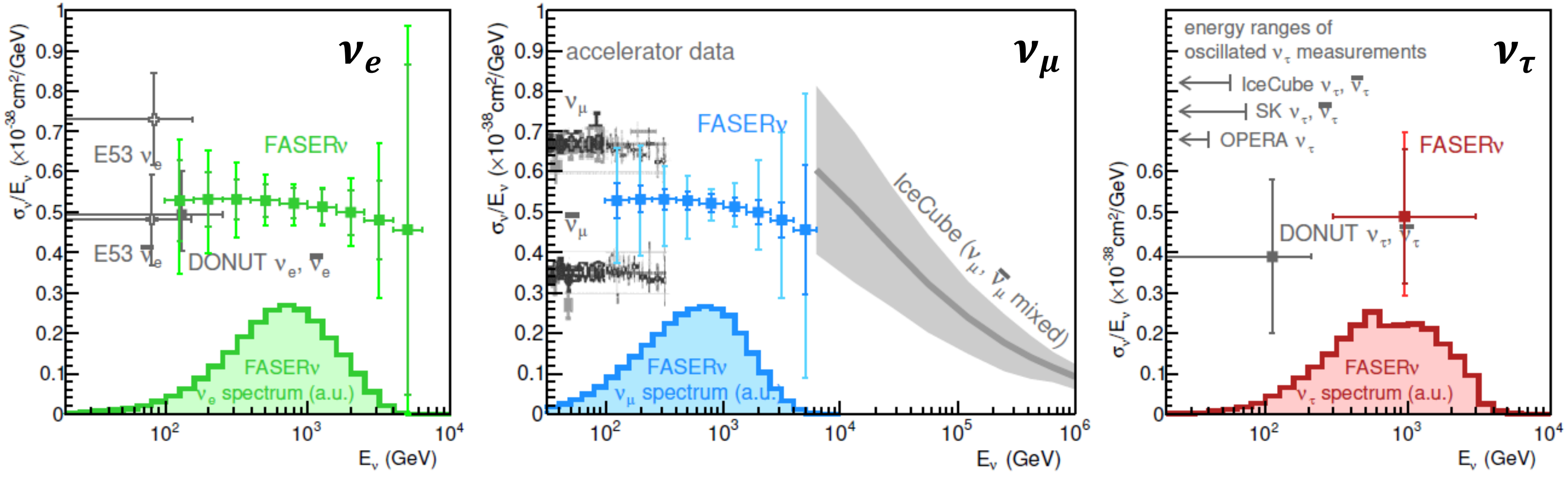
Neutrinos at the LHC

- There are no neutrino cross-section measurements in the TeV regime.
- The decay of hadrons produced in the forward region of collider experiments produces a collimated neutrino beam.

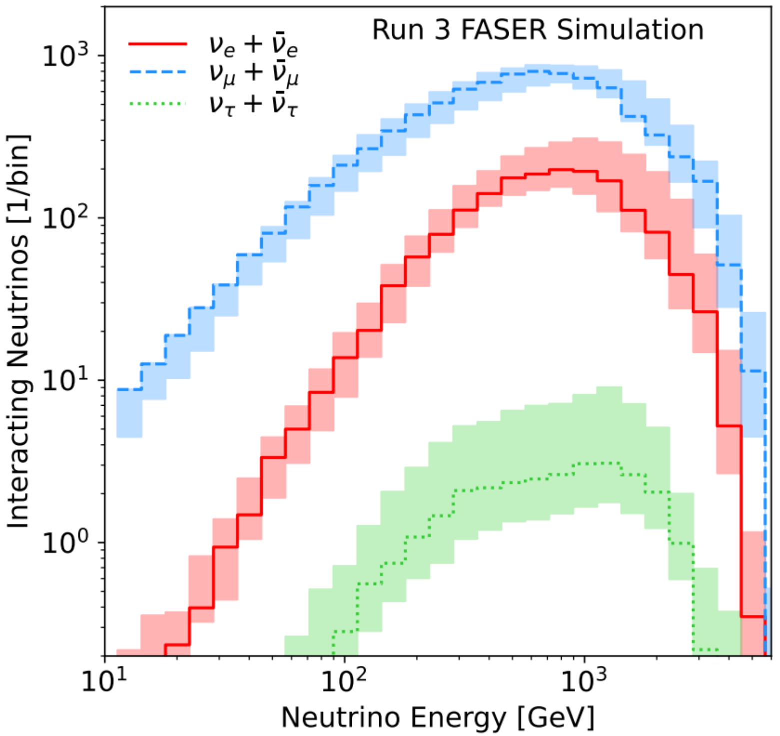
For 250 fb^{-1}	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
Main source	Kaon/Charm decay	Pion/Kaon decays	Charm decay
№ expected CC events in FASERν	~ 1700	~ 8500	~ 30

- FASER can measure the cross-section for all 3 flavours in this previously unexplored energy range → highest E_ν from artificial source.

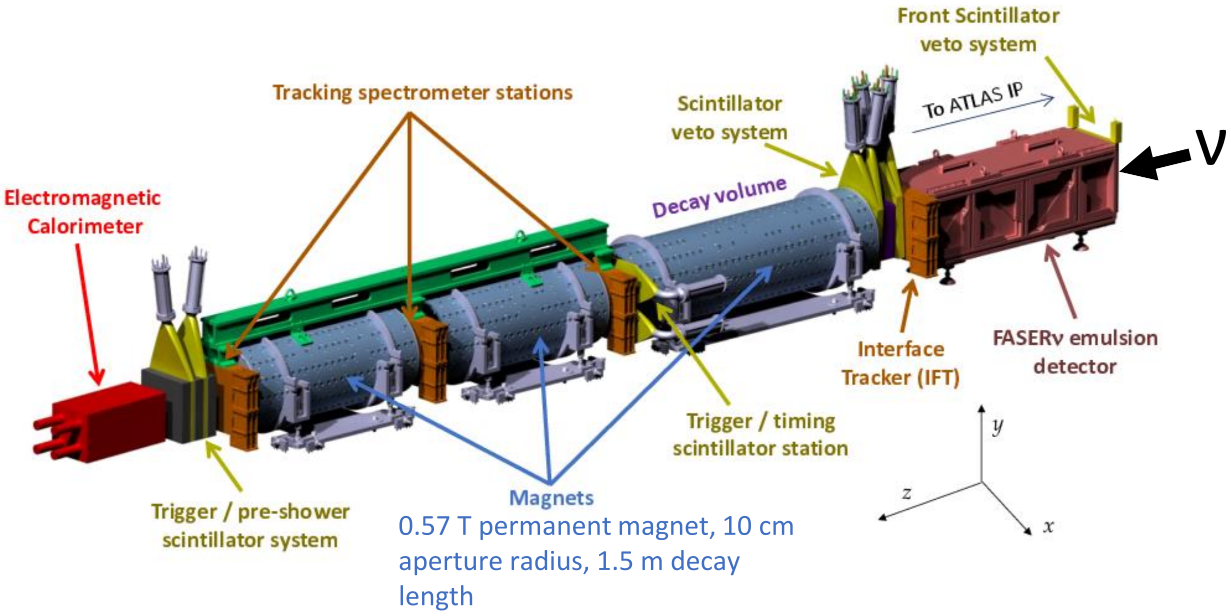
Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})



[Phys. Rev. D 110, 012009 (2024)]

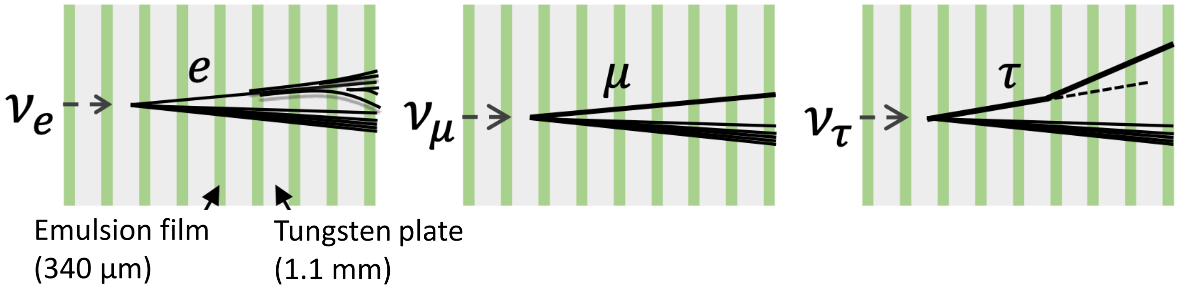


The FASERν Detector



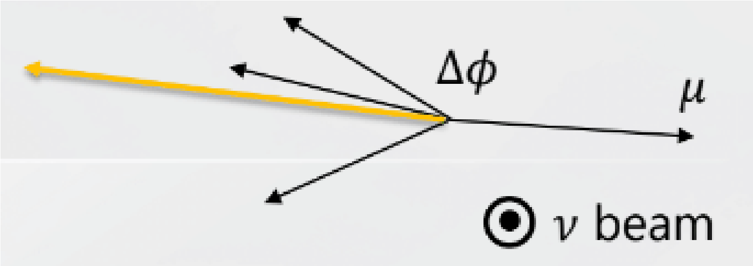
- The FASERν detector is specifically designed to study neutrinos of all 3 flavours.
  - Module: 730 alternating FASERν emulsion films and 1.1 mm thick tungsten plates (25 x 30 cm^2).
  - Target mass 1.1 tonnes; 1.1 m (220 X_0, 8λ).
  - 3 modules irradiated each year to keep track occupancy < 10^6/cm^2 (around 30fb^{-1}).
  - Neutrino events can be flavour tagged using topological and kinematic variables.

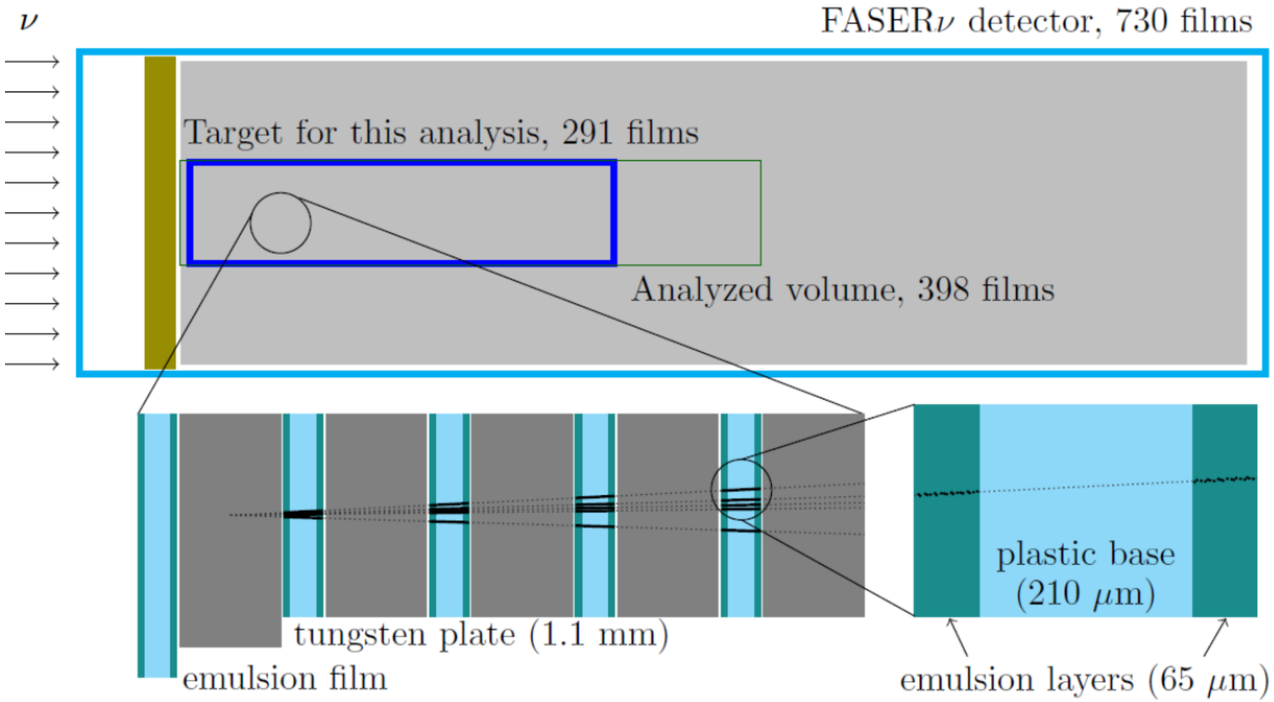
73 sub-modules installed

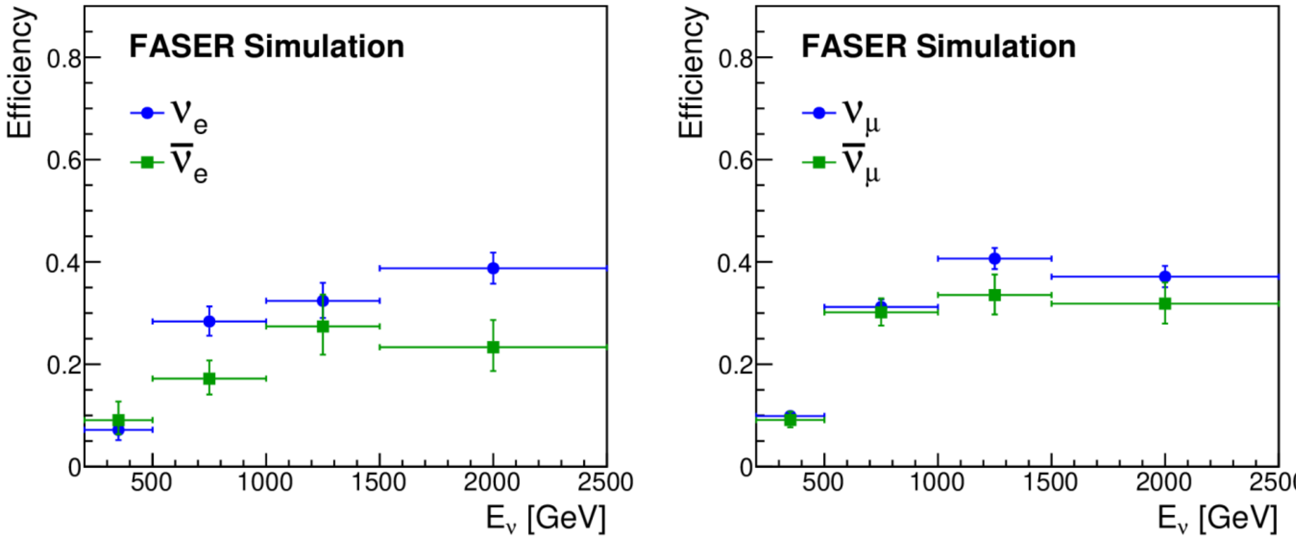


Latest FASERν Analysis

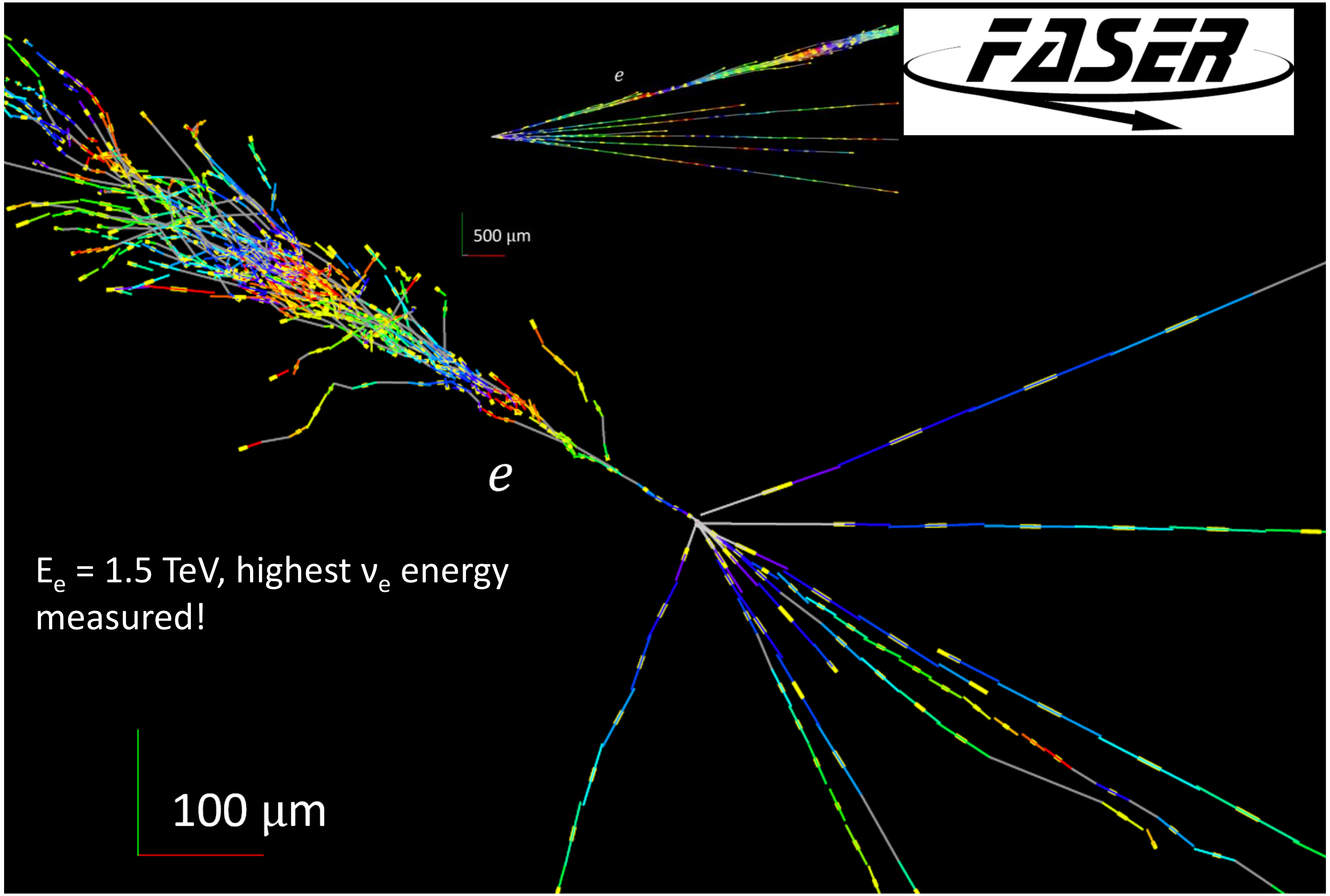
- Data set:
  - 2022 second module → 9.5 fb^{-1};
  - Target mass: 128.6 kg;
  - ~ 1.7% of data collected to date.
- Selection criteria:
  - Vertex reconstruction:
    - $N_{track} \geq 5$
    - $N_{track}(\tan\theta \leq 0.1) \geq 4$
  - Lepton requirements:
    - E_e or $p_\mu > 200$ GeV
    - $\tan\theta_e$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

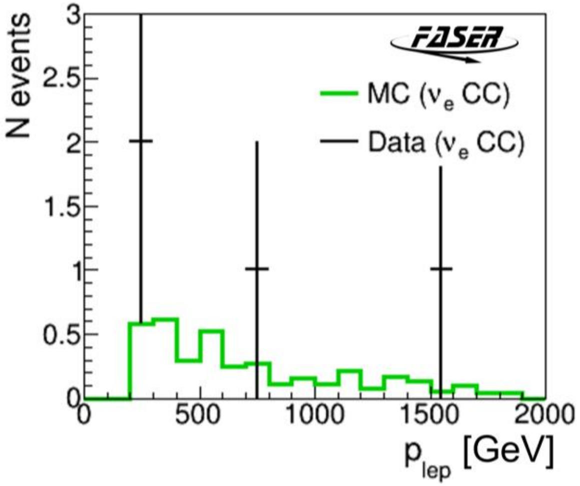


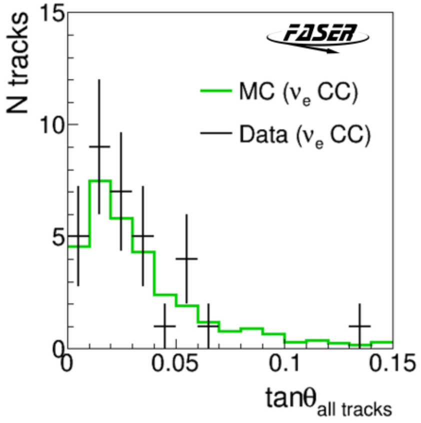


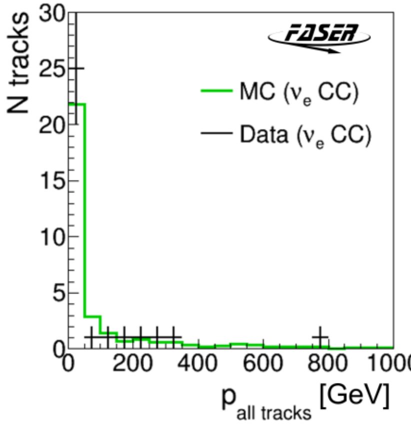


ν_e events in FASERν



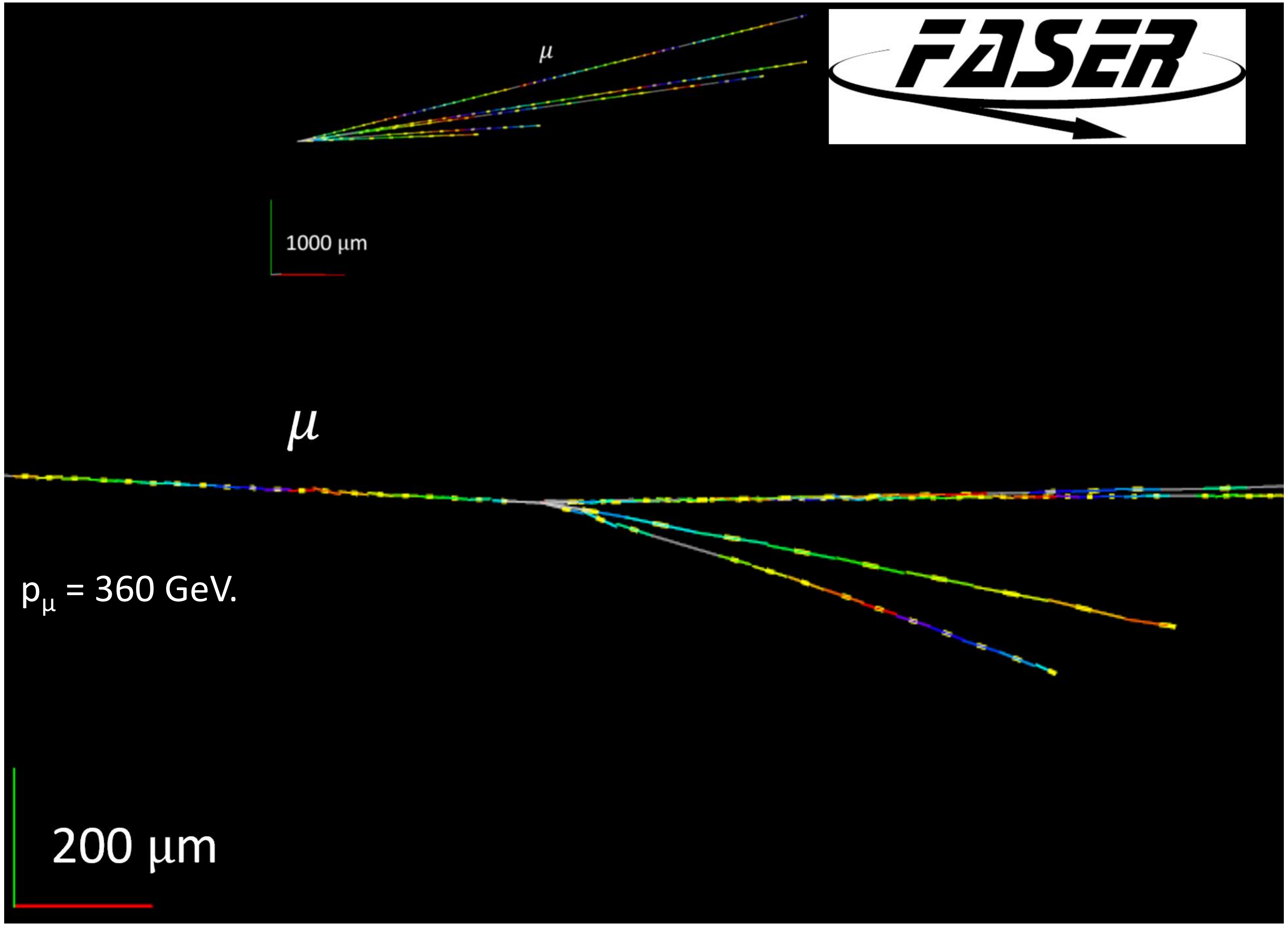


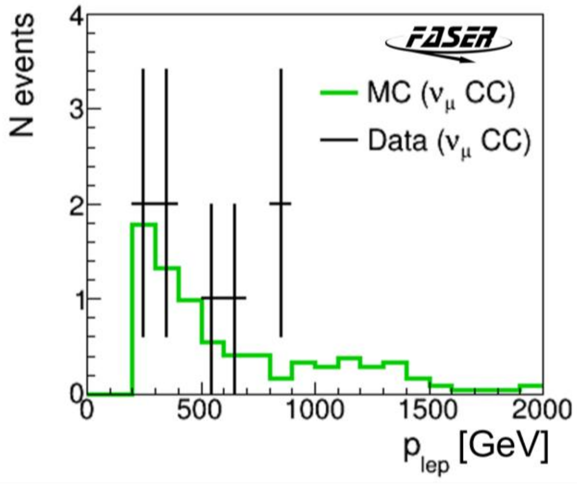


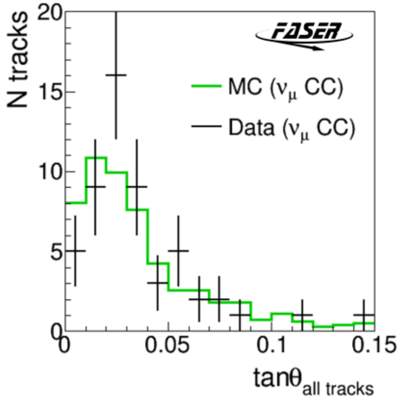


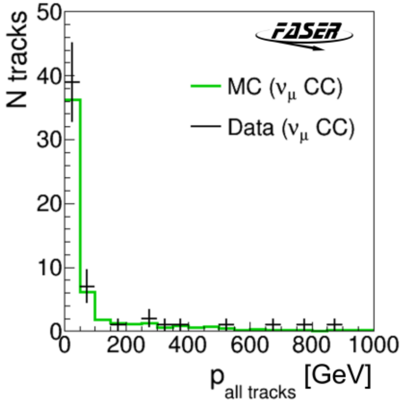
MC normalized to number of observed events.

ν_μ events in FASERν









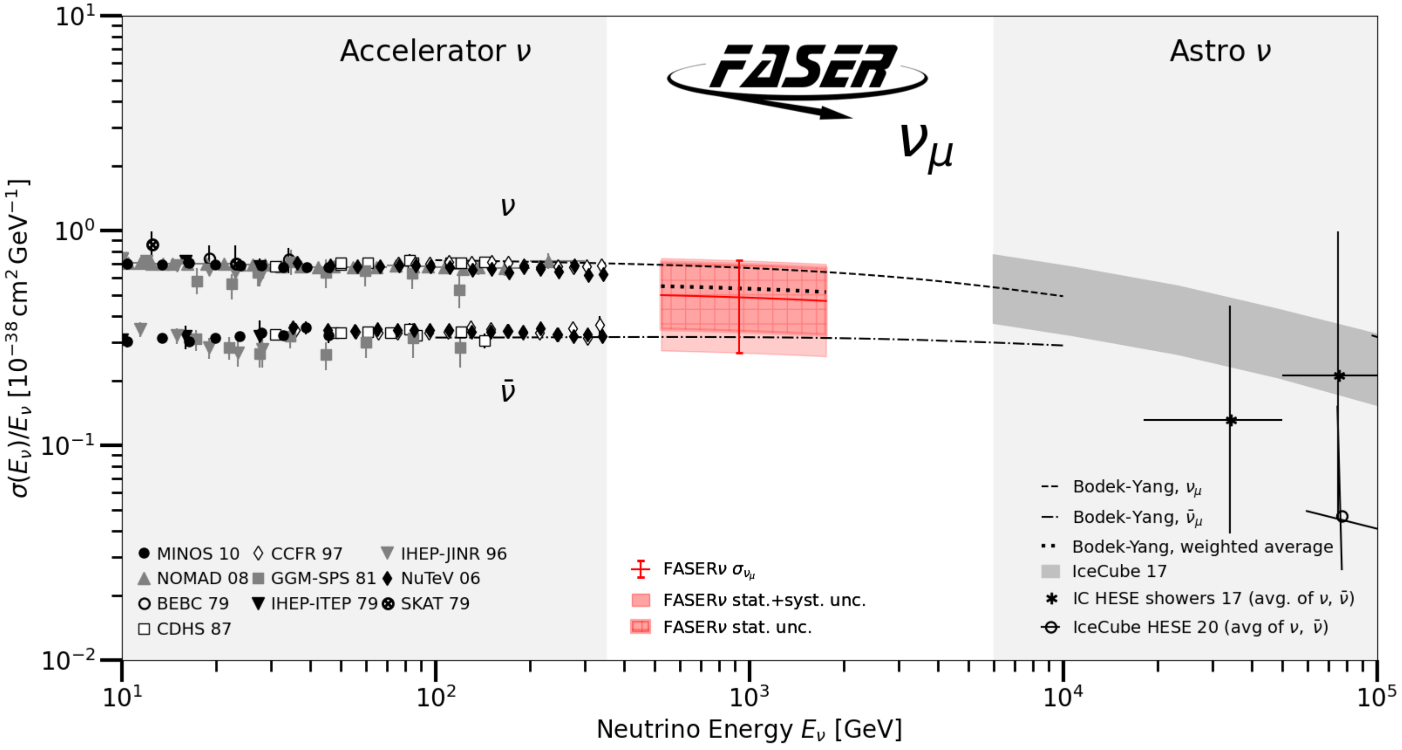
MC normalized to number of observed events.

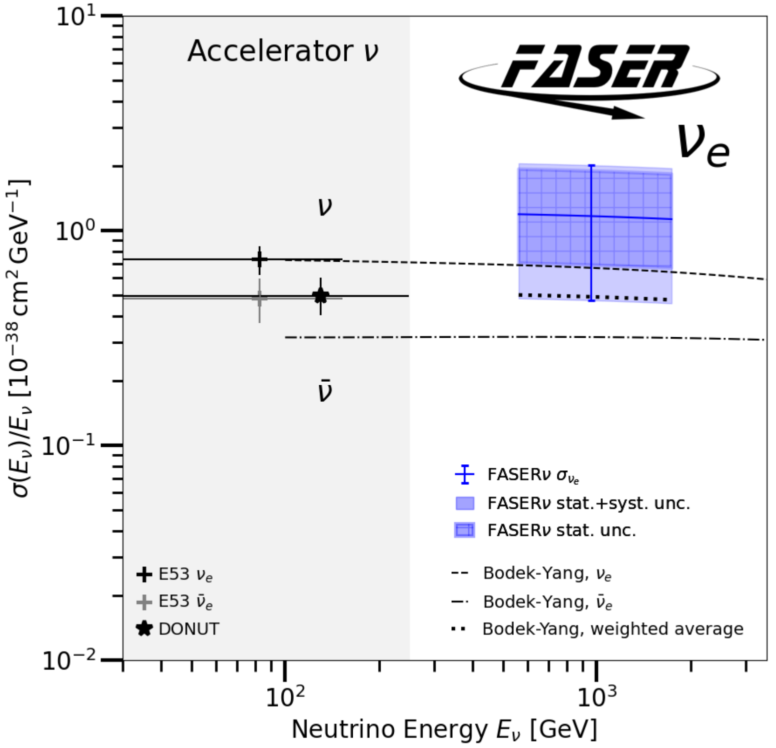
Results from FASERν

Interaction	Expected background	Expected signal	Observed	Significance
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1 – 3.3	4	**5.2σ**
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5 – 12.4	8	**5.7σ**

- First observation of ν_e at the LHC!
- First neutrino cross-section measurement in the TeV range!

[Phys. Rev. Lett. 133, 021802 (2024)]



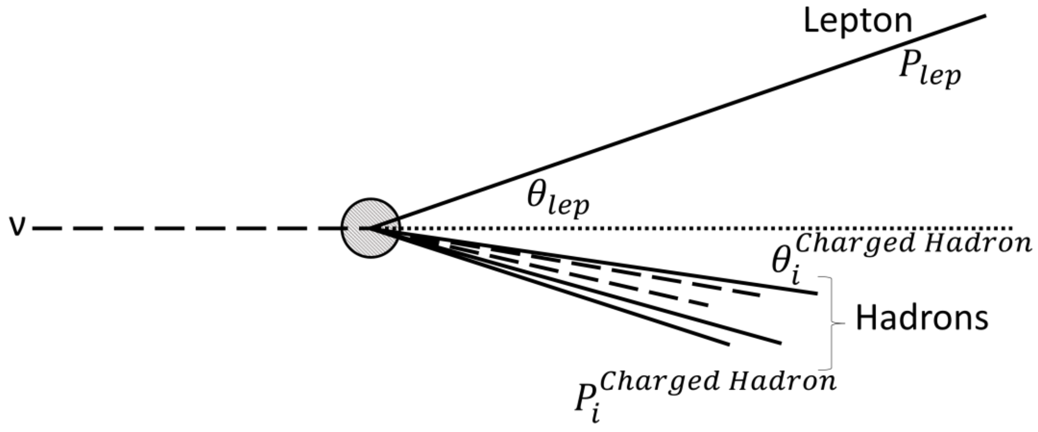


- Measurement relative to theoretical curve.
- Uncertainty dominated by neutrino flux.

Neutrino Energy Reconstruction

- For the next FASERν cross-section analysis, the incident neutrino energy needs to be reconstructed.
- First estimate: sum of visible momenta $\Sigma P_{vis} = P_{lep} + \Sigma P_{had}$ scaled to compensate for missing neutral particle momenta.
- This can further be improved by implementing machine learning methods.

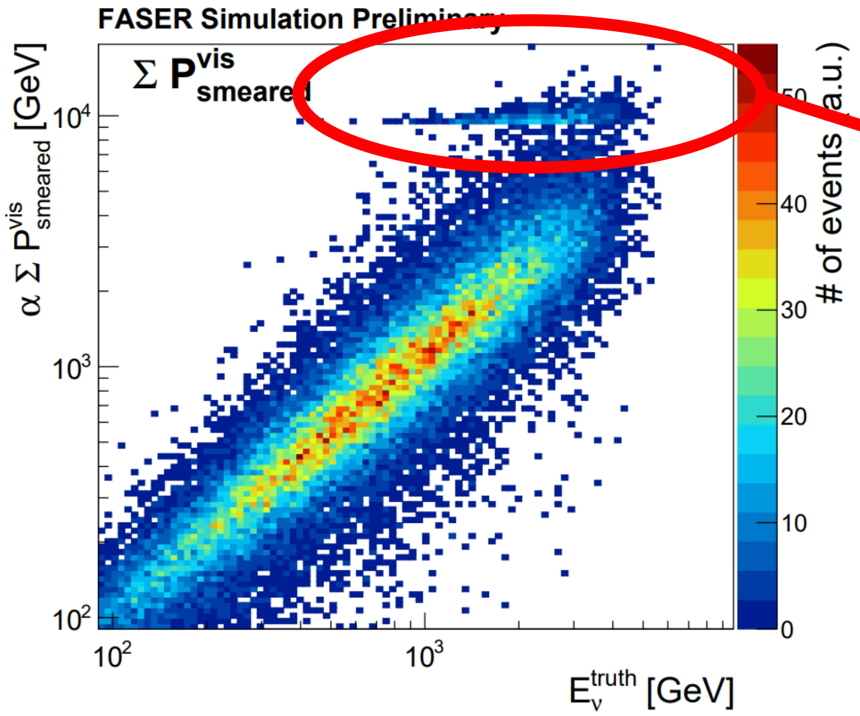
- Variables of interest for this neutrino energy reconstruction study are particle momenta and angles (tanθ generally used).



- Dataset: GENIE simulation using realistic neutrino fluxes at FASER, with momentum and angular smearing to emulate FASERν conditions.
  - Event cuts: charged current ν_μ interactions; number of charged particles > 1 (muon + 1 hadron minimum); E_ν truth < 7 TeV.
  - Track cuts: P > 1 GeV; tanθ < 0.5.

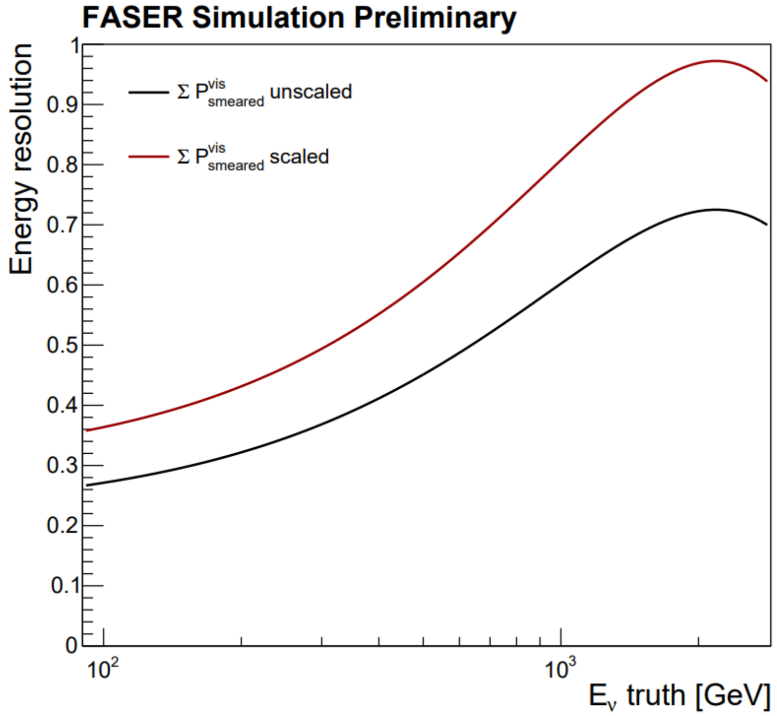
First estimate: Visible momenta (scaled)

- DIS regime → standard neutrino energy calculation using lepton kinematics does not work.
- Using $\Sigma P_{vis} = P_{lep} + \Sigma P_{had}$ and scaling by $< \alpha > = \frac{1}{N_{events}} \Sigma \frac{E_\nu^{truth}}{\Sigma P_{vis}} = 1.34.$
- E_γ under development, to be added in the future.
- Resolution = r.m.s.(ΔE/E) ; $\frac{\Delta E}{E} = \frac{(E^{reco} - E_\nu^{truth})}{E_\nu^{truth}}$



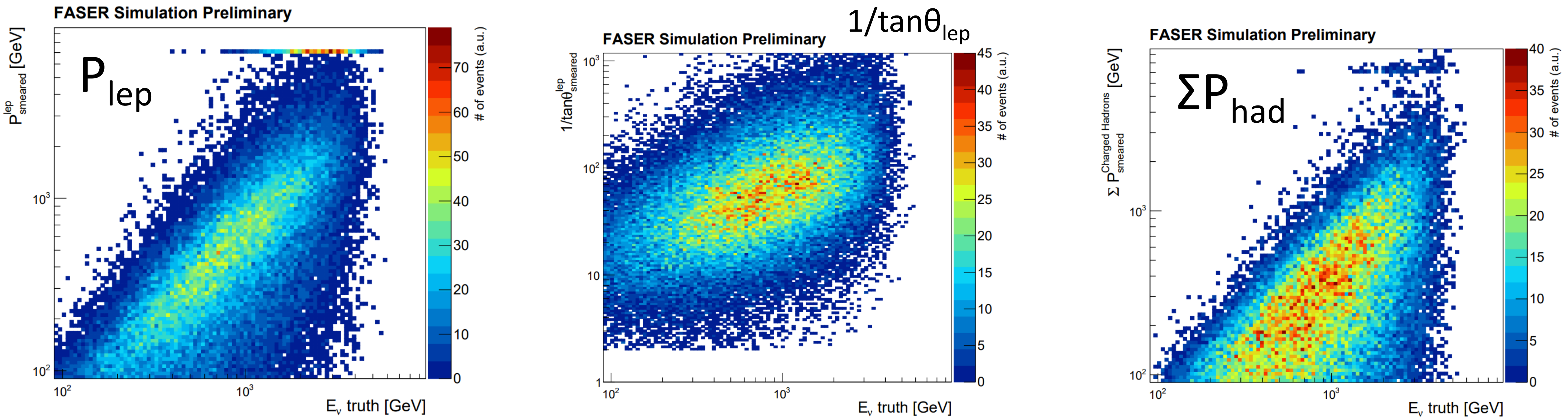
<u>Overflow</u>

Due to the MCS method, when the muon momentum is too high, it is severely overestimate → all particles with P > 7 TeV are assigned P = 7 TeV.



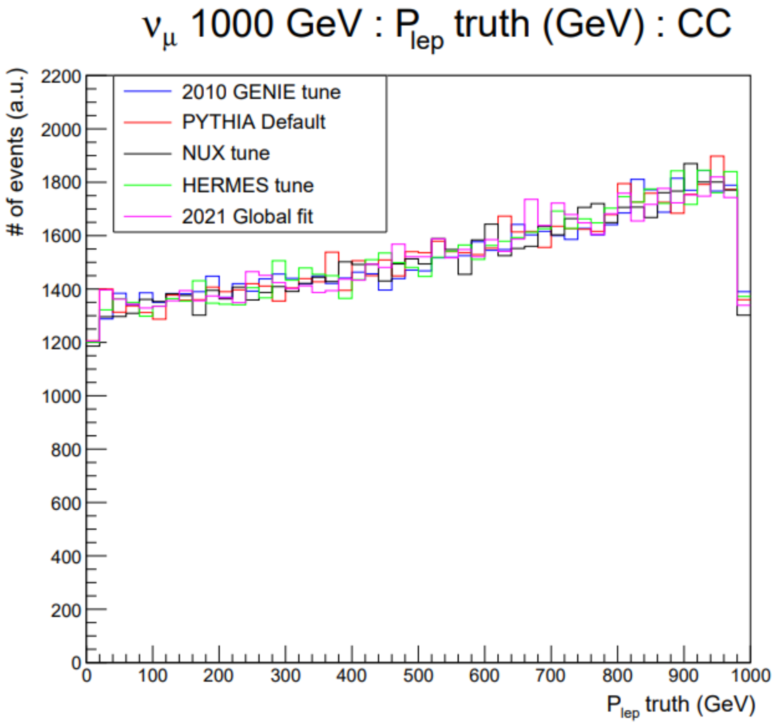
Machine Learning

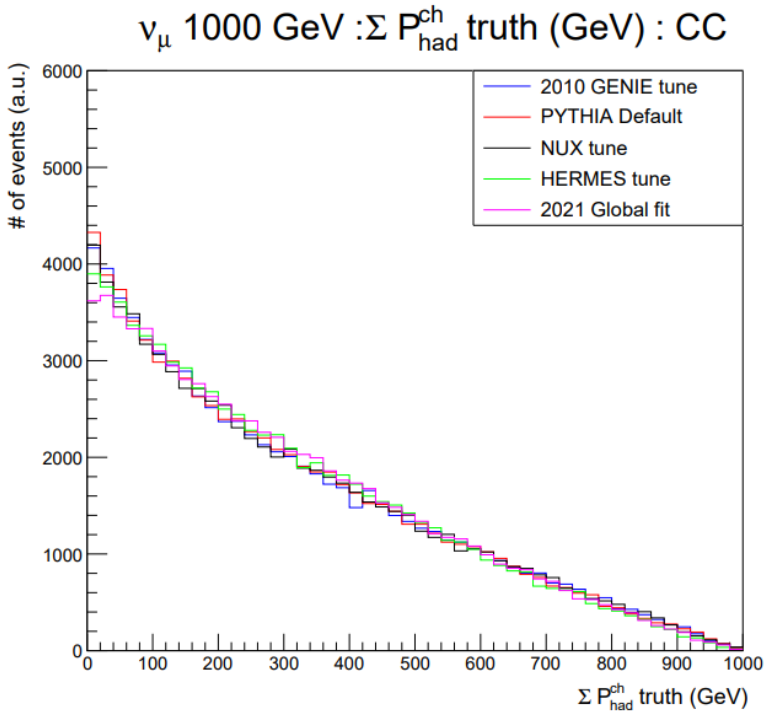
- To improve upon on the visible energy estimate, machine learning methods are implemented.
- No calibration data for TeV neutrinos interacting with tungsten → large uncertainty in the hadronization:
  - GENIE is implements final state interactions at high energies using PYTHIA.
  - Different hadronization tunes in PYTHIA yield varying results.
- Interested in variables that correlate well with neutrino energy and are stable across hadronization tunes.

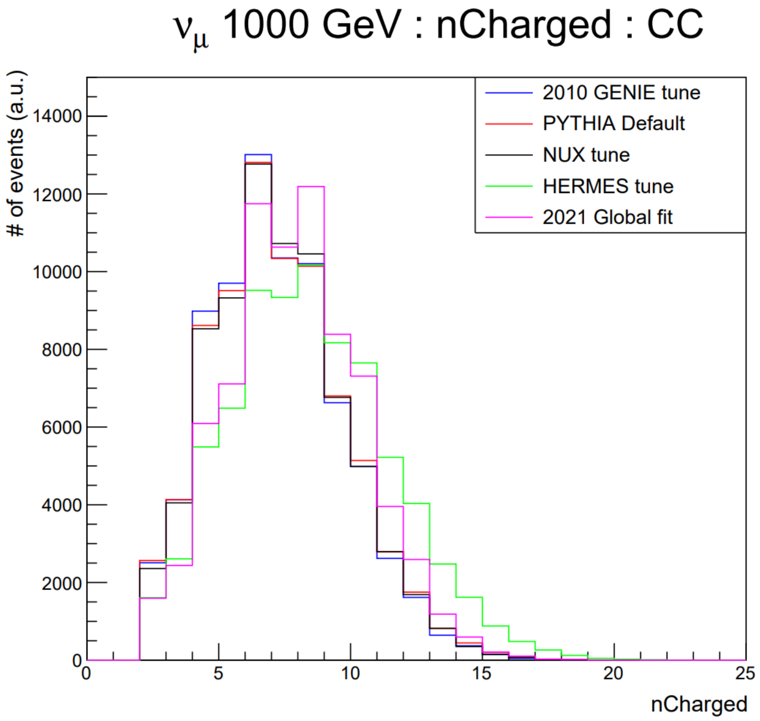


Monochrome GENIE simulation

- Dataset: muon neutrino interactions with GENIE for 5 PYTHIA hadronization tunes for 100 GeV, 500 GeV, 1 TeV and 5 TeV.
- Same event selection as defined before (CC, nCharged > 1) → compared variables at truth level.
- Best variables: lepton momentum; lepton angle; sum of hadronic momenta.

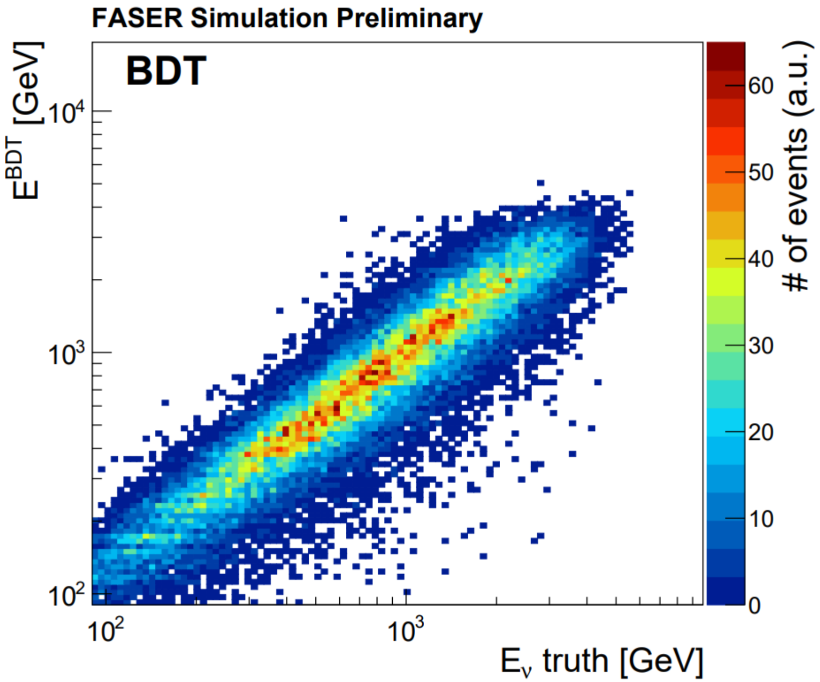


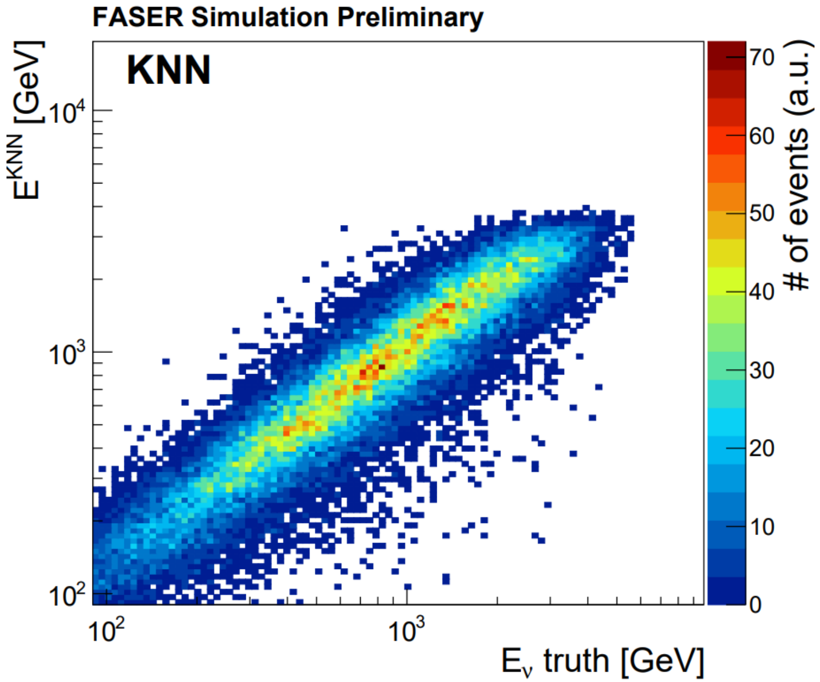


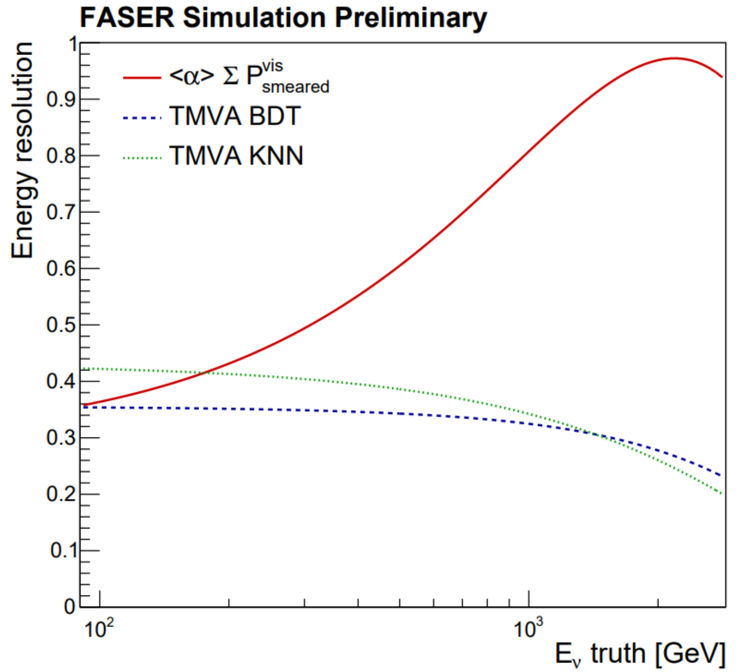


TMVA

- TMVA package in ROOT offers **Regression** techniques → such as BDT and KNN.
- Both show clear correlation with true neutrino energy.
- Resolution for both TMVA methods lies roughly between 0.35 and 0.45 in the range 100 GeV < E_ν < 1 TeV.



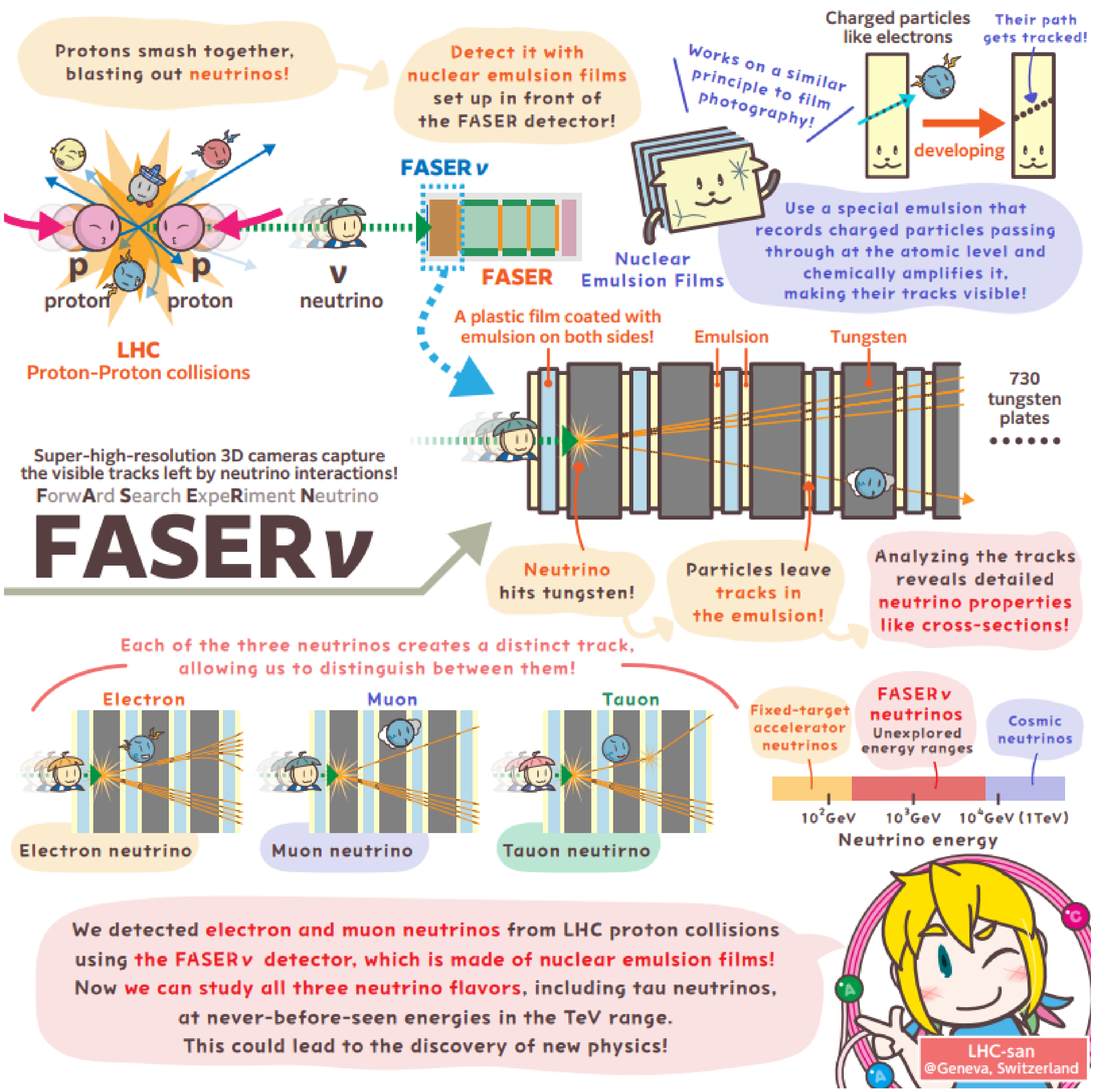




Summary

- FASER measures TeV-scale neutrinos of all 3 flavours → First collider neutrino experiment!
- FASER is successfully operating during CERN LHC Run 3.
- 7 FASERν modules have been irradiated, collecting around 85 fb^{-1} to date → 8^{th} module ready to be installed.
- Results from FASERν → First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector!
- Neutrino energy reconstruction using machine learning techniques shows promising results.
- 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…

Thank you!



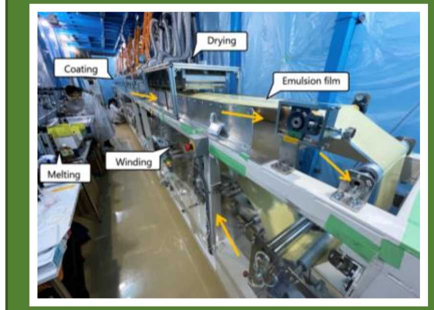
Protons smash together, blasting out neutrinos!
Detect it with nuclear emulsion films set up in front of the FASER detector!
Works on a similar principle to film photography!
Charged particles like electrons
Their path gets tracked!
developing
p
proton
p
proton
ν
neutrino
LHC
Proton-Proton collisions
FASERν
FASER
Nuclear Emulsion Films
Use a special emulsion that records charged particles passing through at the atomic level and chemically amplifies it, making their tracks visible!
A plastic film coated with emulsion on both sides!
Emulsion
Tungsten
730 tungsten plates
Super-high-resolution 3D cameras capture the visible tracks left by neutrino interactions!
ForwArd Search ExpeRiment Neutrino
FASERν
Neutrino hits tungsten!
Particles leave tracks in the emulsion!
Analyzing the tracks reveals detailed neutrino properties like cross-sections!
Each of the three neutrinos creates a distinct track, allowing us to distinguish between them!
Electron
Muon
Tauon
Electron neutrino
Muon neutrino
Tauon neutirno
Fixed-target accelerator neutrinos
FASERν neutrinos
Unexplored energy ranges
Cosmic neutrinos
10²GeV
10³GeV
10⁴GeV (1TeV)
Neutrino energy
We detected electron and muon neutrinos from LHC proton collisions using the FASERν detector, which is made of nuclear emulsion films! Now we can study all three neutrino flavors, including tau neutrinos, at never-before-seen energies in the TeV range. This could lead to the discovery of new physics!
LHC-san
@Geneva, Switzerland

Backup

FASER

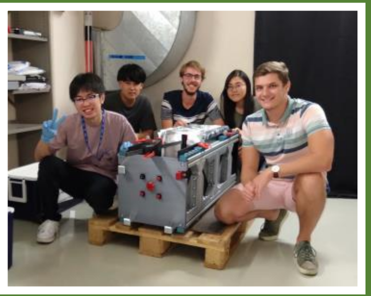
FASERν Process

Japan



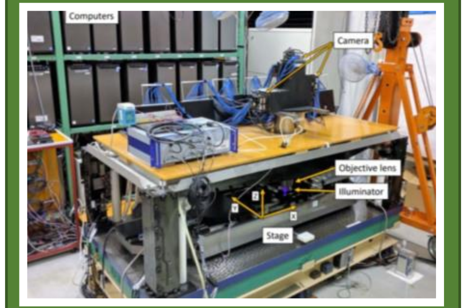
Film production

CERN



Assembly → Exposure → Disassembling → Development

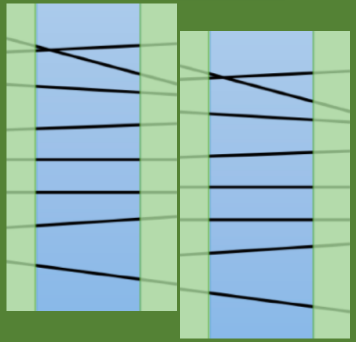
Japan

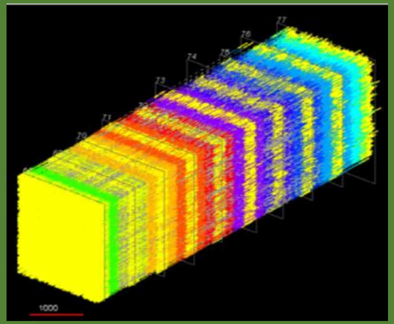


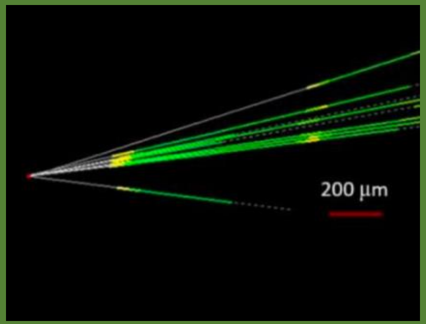
Readout

Offline analysis

Alignment → Track reconstruction → Vertex reconstruction → e, μ ID, τ decay search, charge ID, etc… → Physics analysis

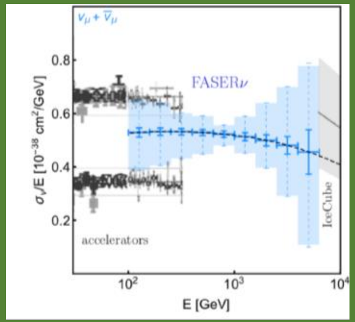






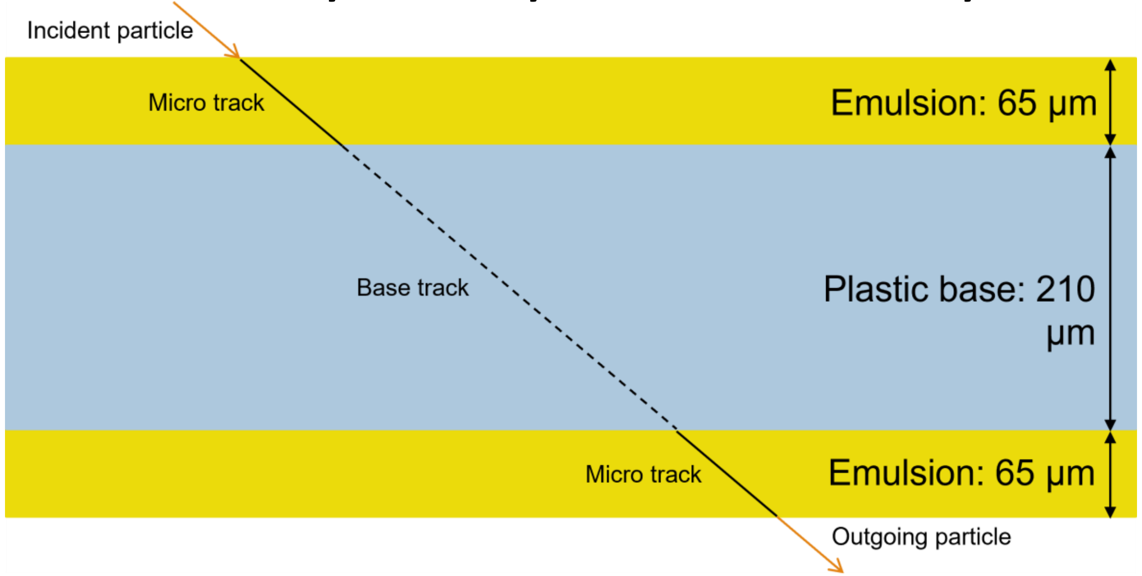
e, μ ID
τ decay search
charge ID
etc…

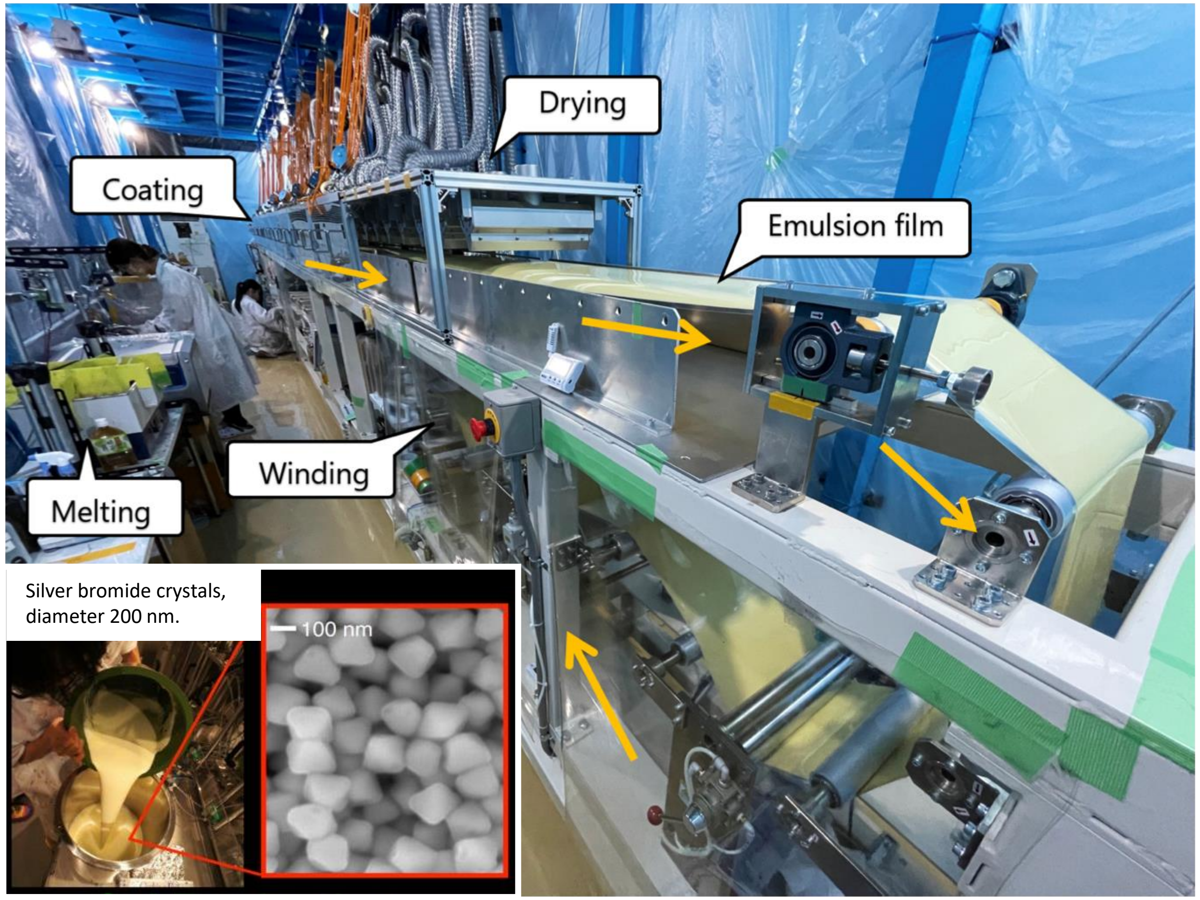
Physics analysis



Film production

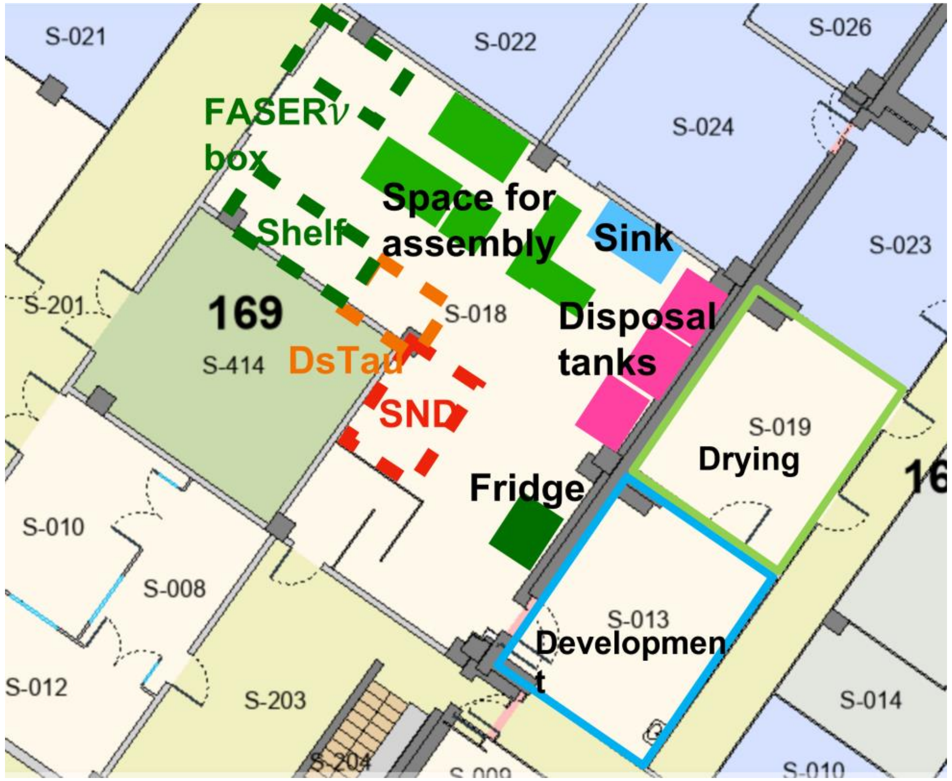
- Emulsion gel and films produced at Nagoya University in dedicated facility.
- Silver bromide crystals, diameter 200 nm.
- 110 m^2 of emulsion for every module.
- Resetting procedure performed in Nagoya University and Kyushu University.



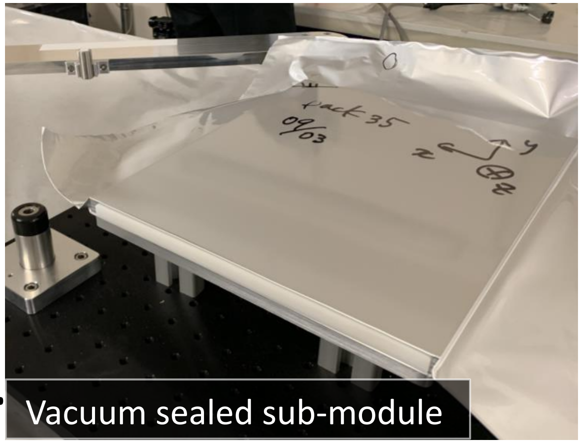


Emulsion Facility at CERN

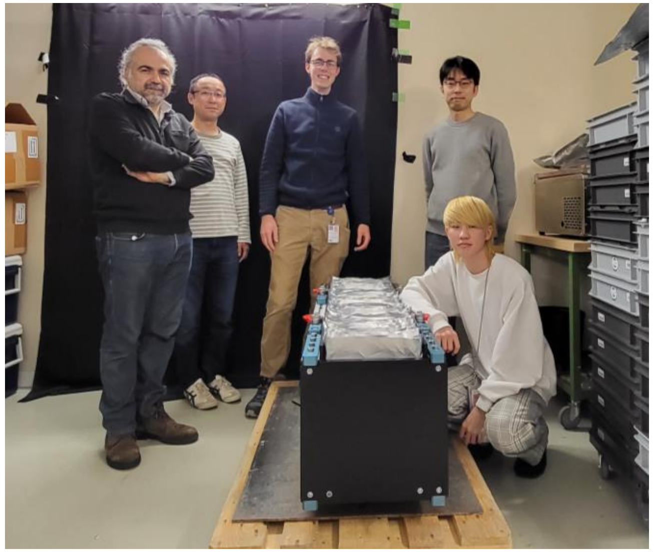
- New facility set up at CERN for emulsion experiments – includes modern climate control and ventilation system, access card entry, and full dark room capabilities for emulsion handling.
- 3 dedicated room: assembly, development and drying.
- Shared with NA65/DsTau, SND@LHC and SHiP Collaborations.
-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

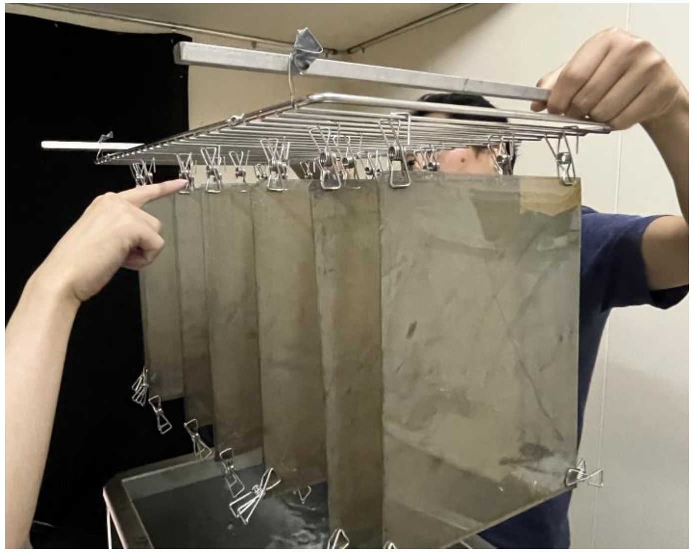


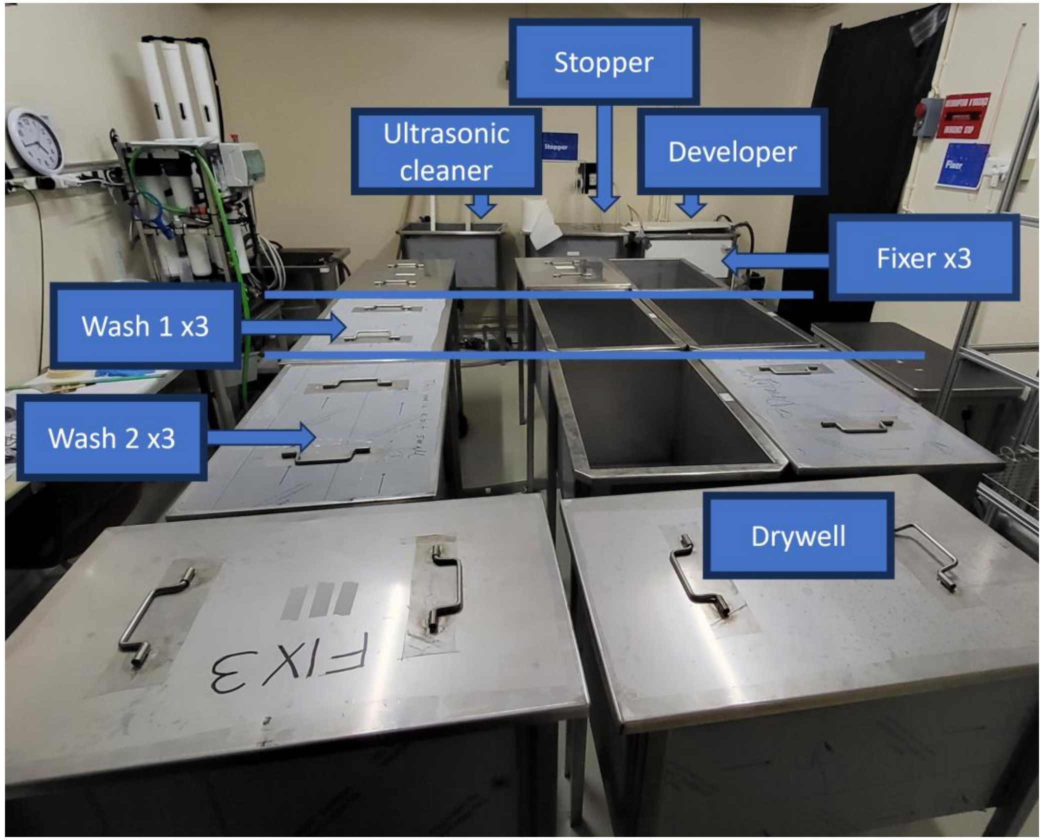
FASERν Assembly and Development


Vacuum sealed sub-module

- FASERν sub-modules: 10 alternating emulsion films and tungsten plates.
- Assembly campaign lasts ~ 12 days → 73 submodules assembled.
- 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.

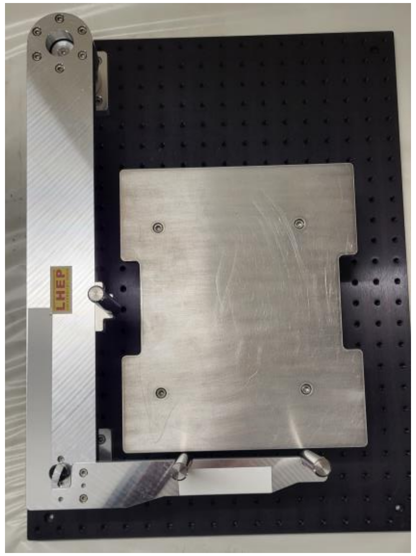


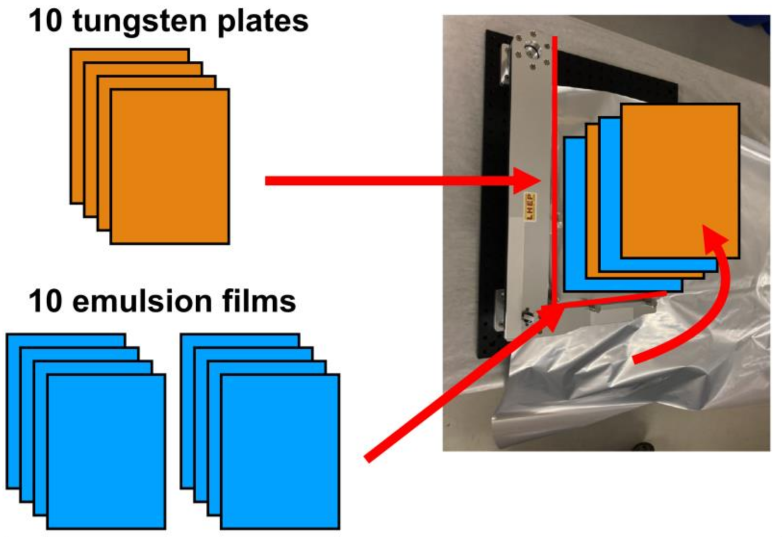


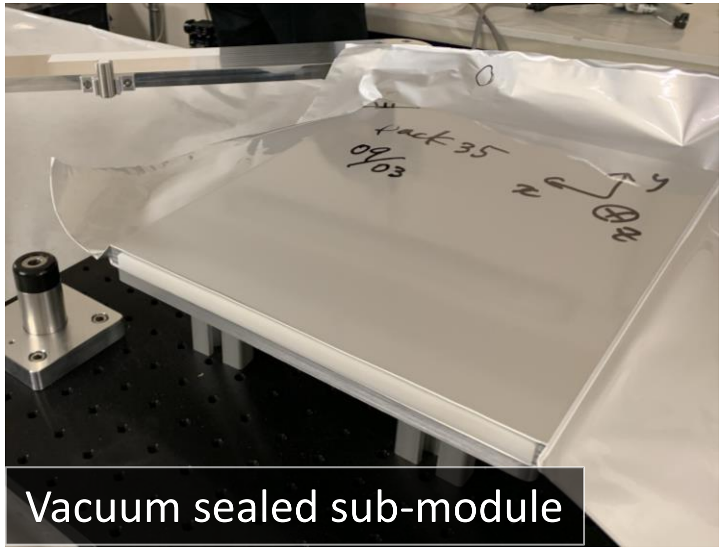


FASERν Assembly at CERN

- 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.

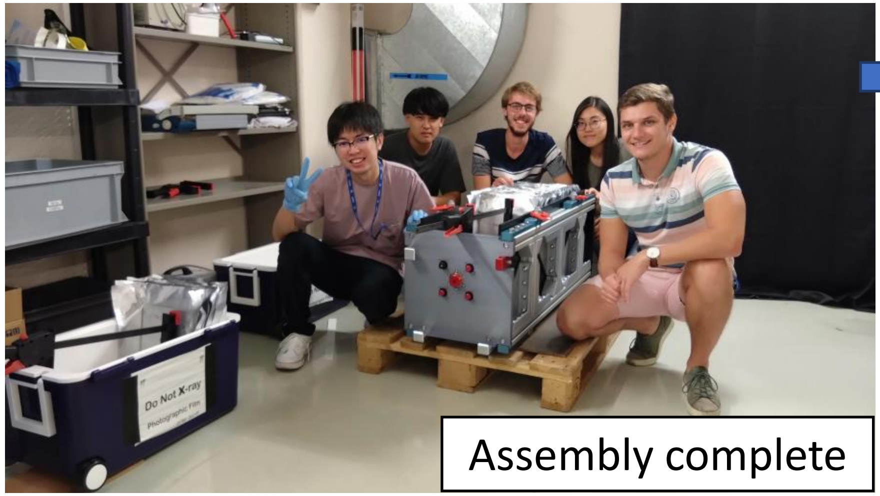






FASERν Exchange

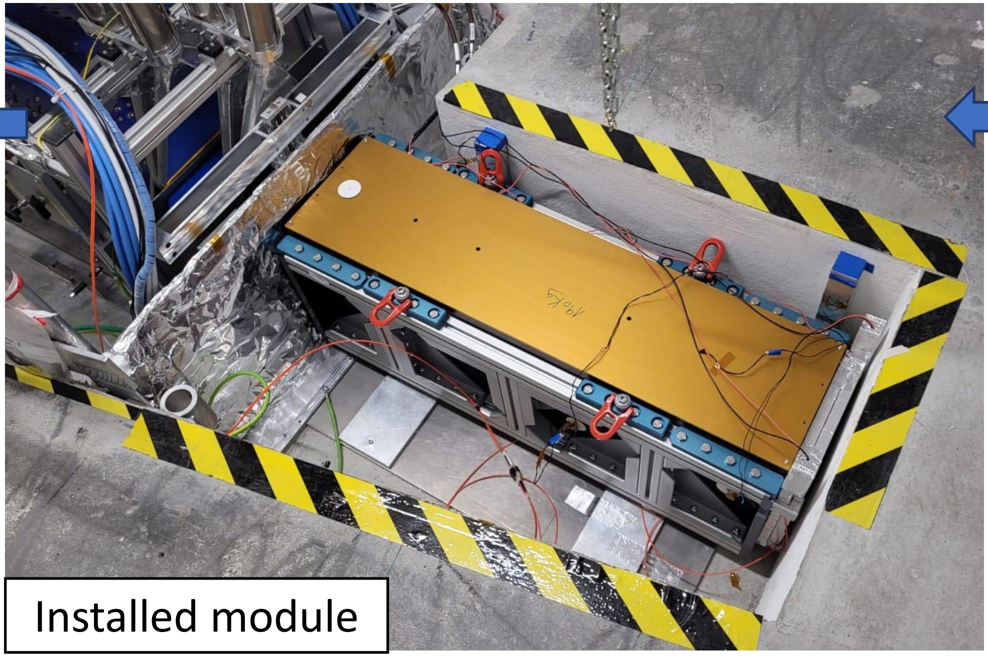
- Irradiated module extracted, and new module installed.
- Performed by FASER members with CERN technical teams.



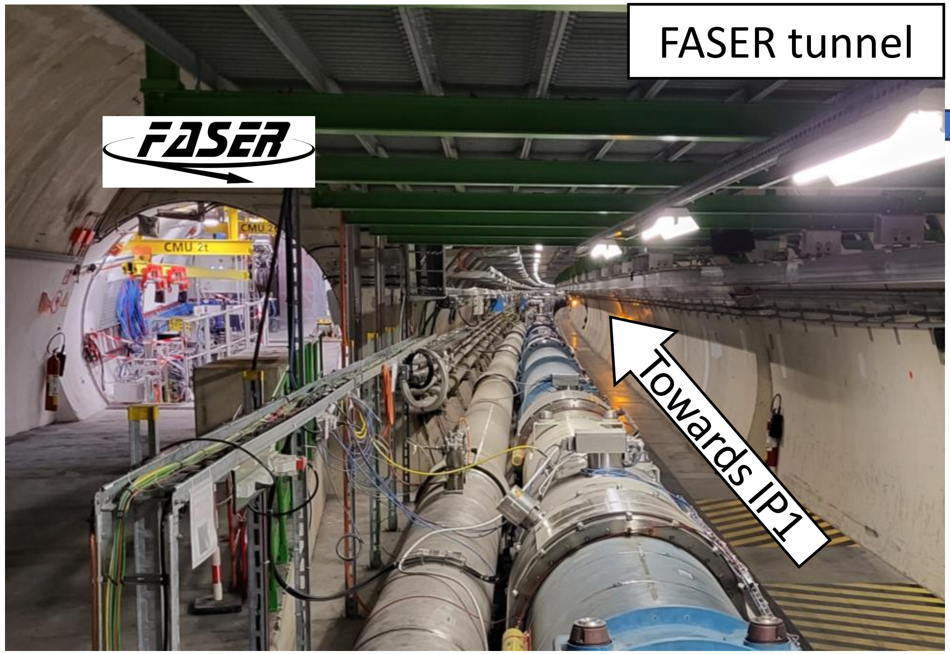
Assembly complete

Moving modules over LHC

Exchange



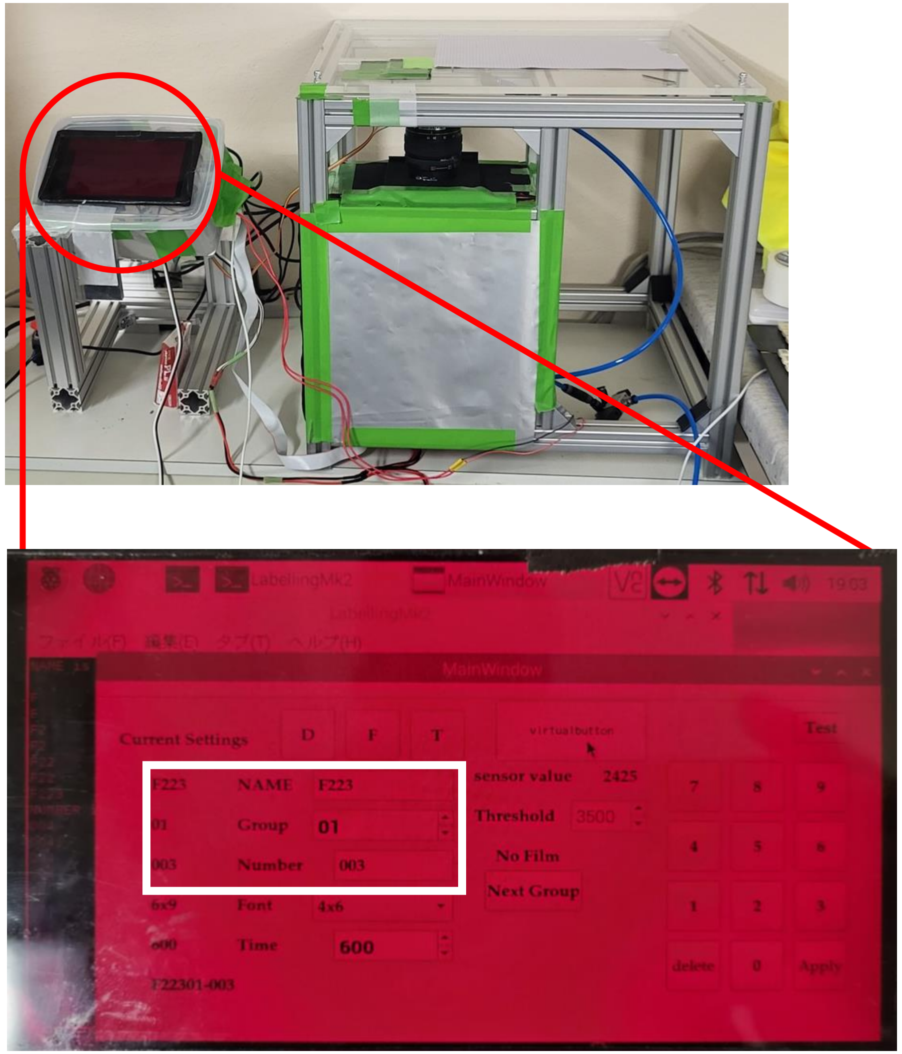
Installed module

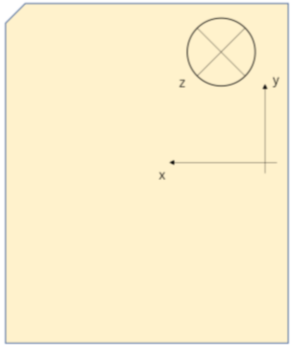


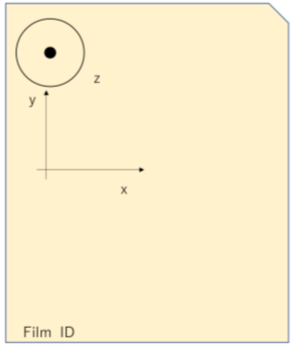
FASER tunnel

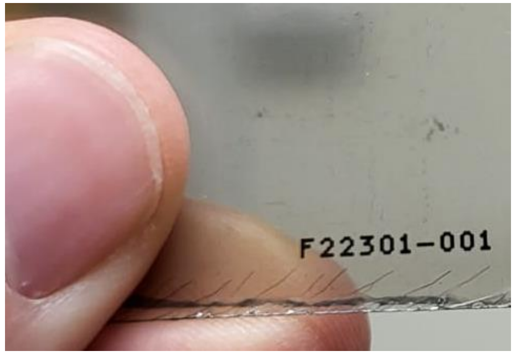
Development

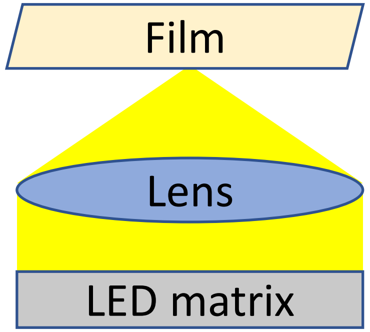
- FASERν module disassembly is performed in darkroom conditions by 2 people.
- 5 sub-modules (50 films) are extracted, disassembled, labelled and sorted into 2 packs of 25 films → Odd and Even films are separated and are developed in different batches of chemicals.
- Labelling is performed using a digital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











Development

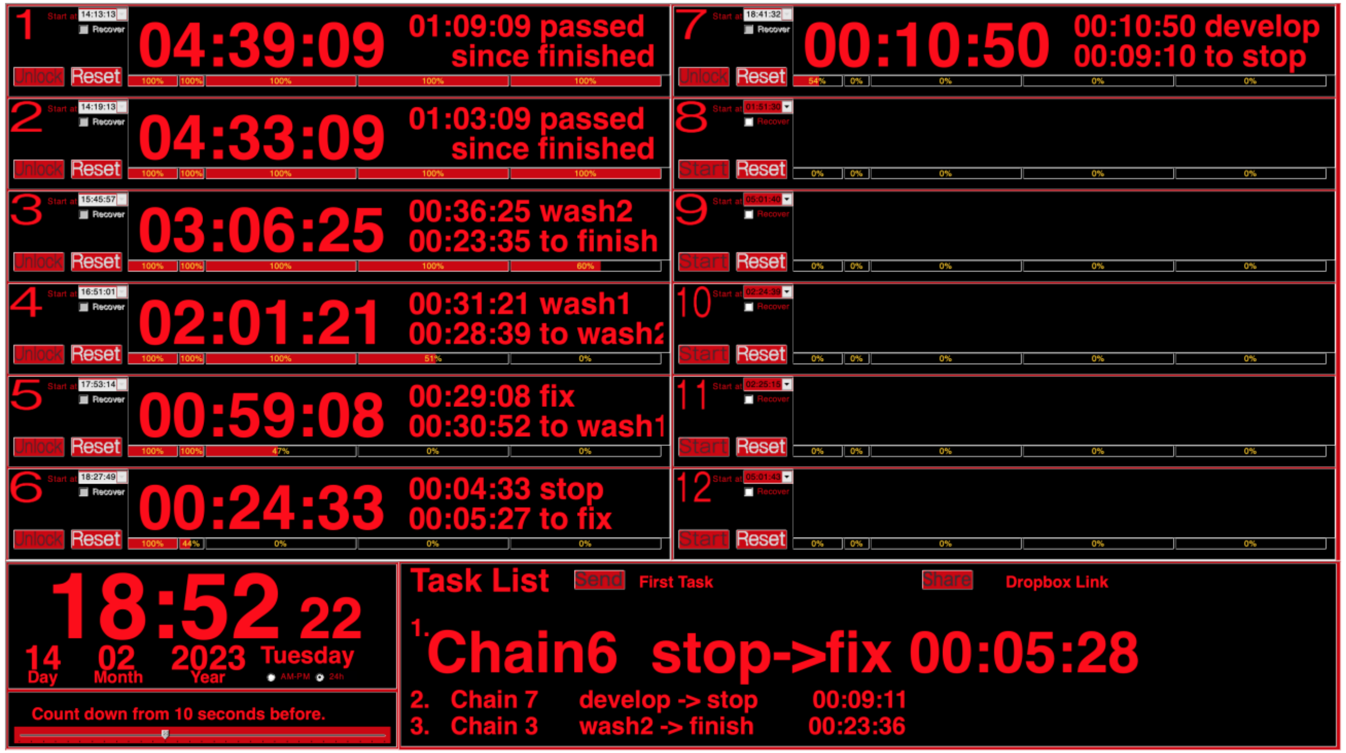
- 730 FASERν films in one FASERν module.

- 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.

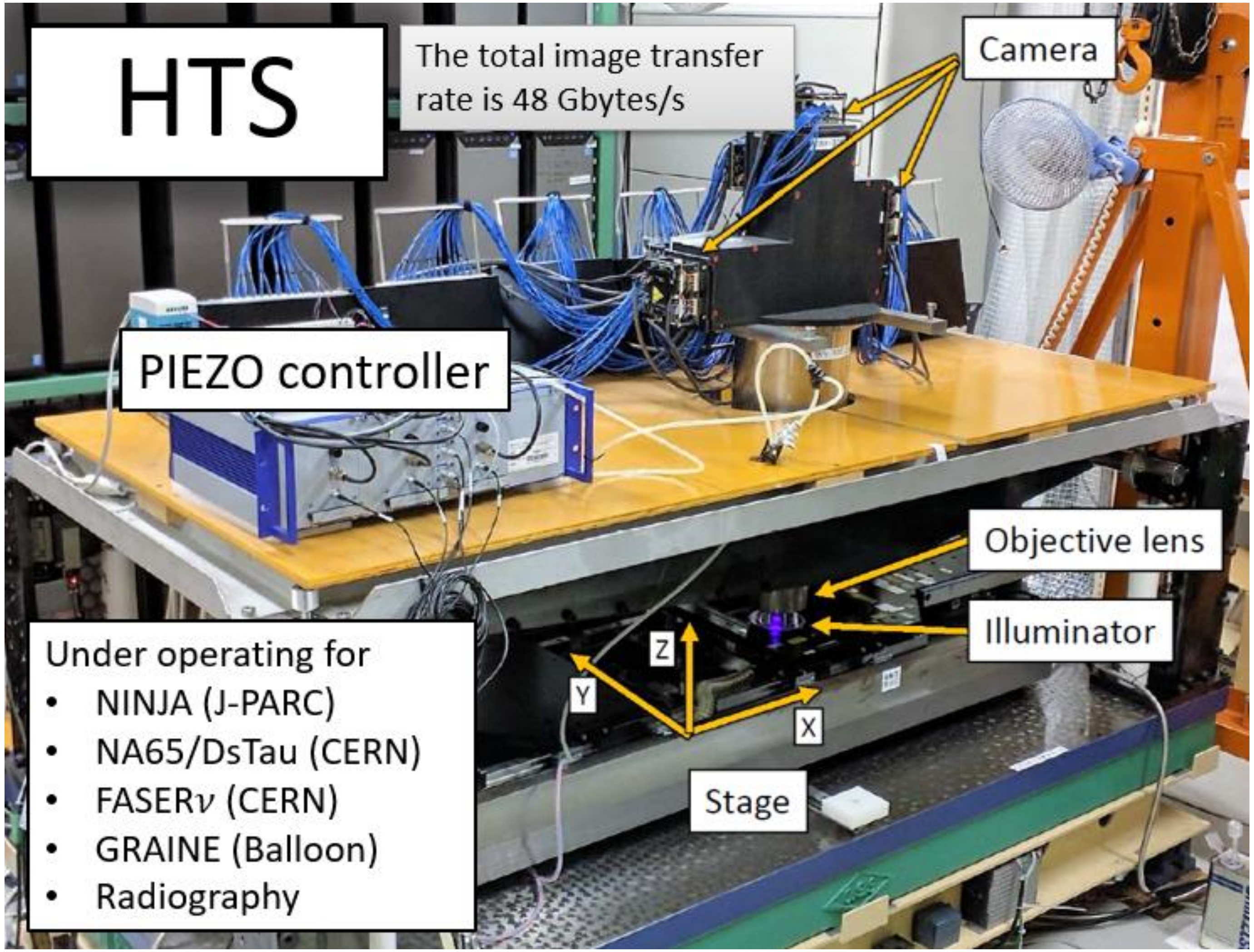
- Approximately same number of films per chain in sets of 3 chains.
- Odd and Even films from the same sub-module are never developed in the same cycle.

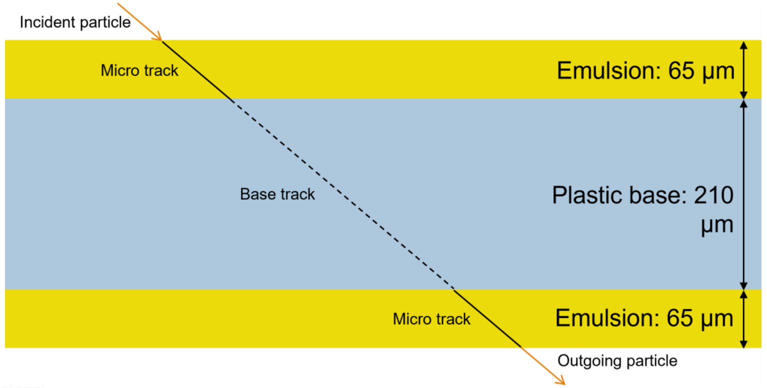
Cycle	Day 1	Day 2	Day 3
08:00			
09:00	Chemical preparation	6 chains	3 chains
10:00			
11:00			
12:00			
13:00	Test Development		
14:00			Chemical disposal
15:00			
16:00			
17:00			
18:00			
19:00			

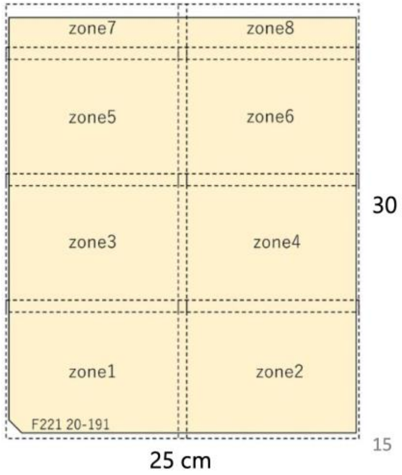
Solution	Time	№ tanks
Developer	20 minutes	1
Stopper	10 minutes	1
Fixer	1 hour	3
Wash 1	1 hour	3
Wash 2	1 hour	3
Drywell	10 seconds	1
Total	3.5 hours + 1 day drying	

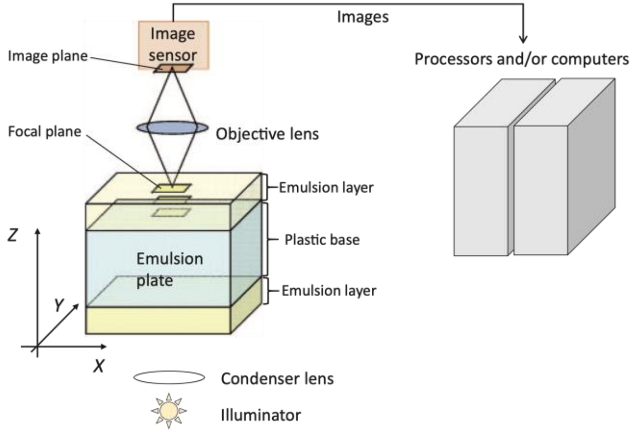


Film Readout in Nagoya







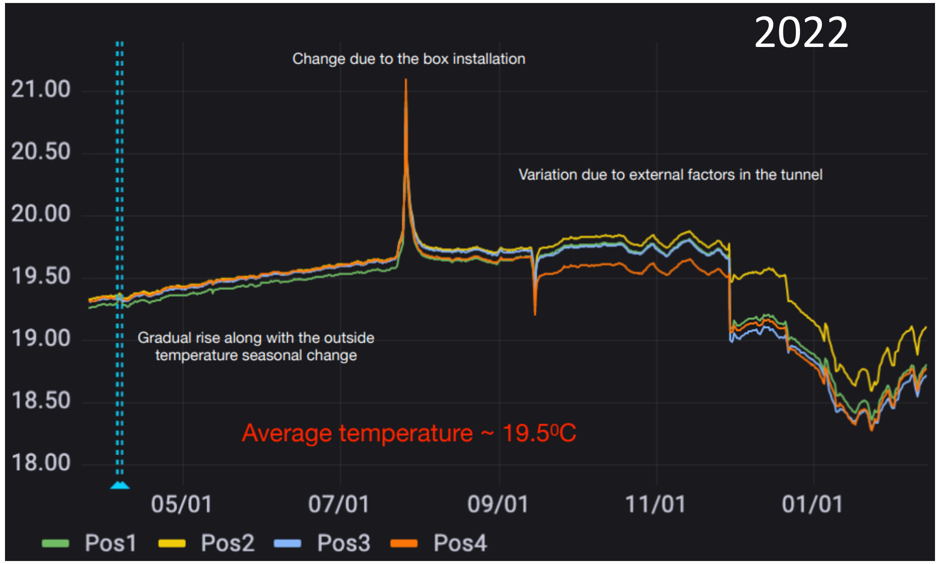


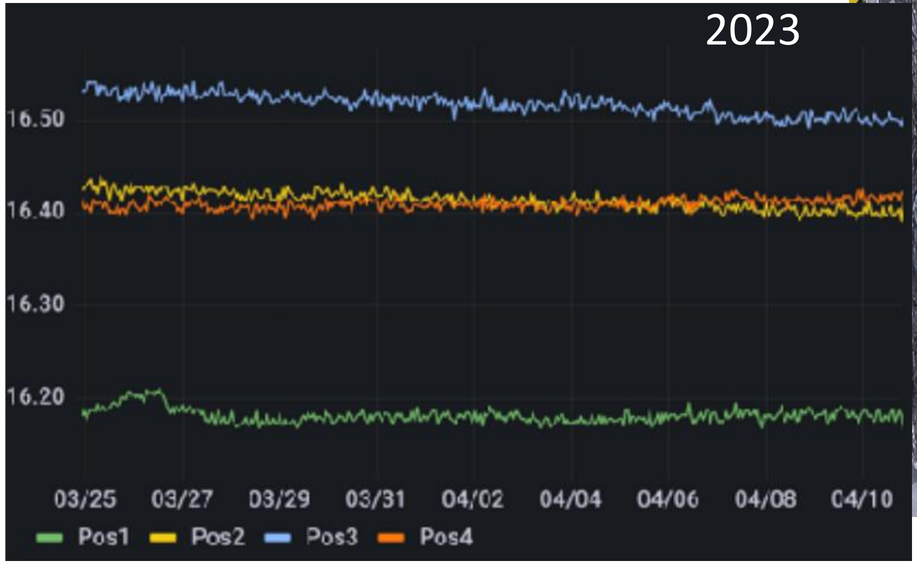
Hyper Track Selector (HTS): complex microscope system scans films for digital readout.

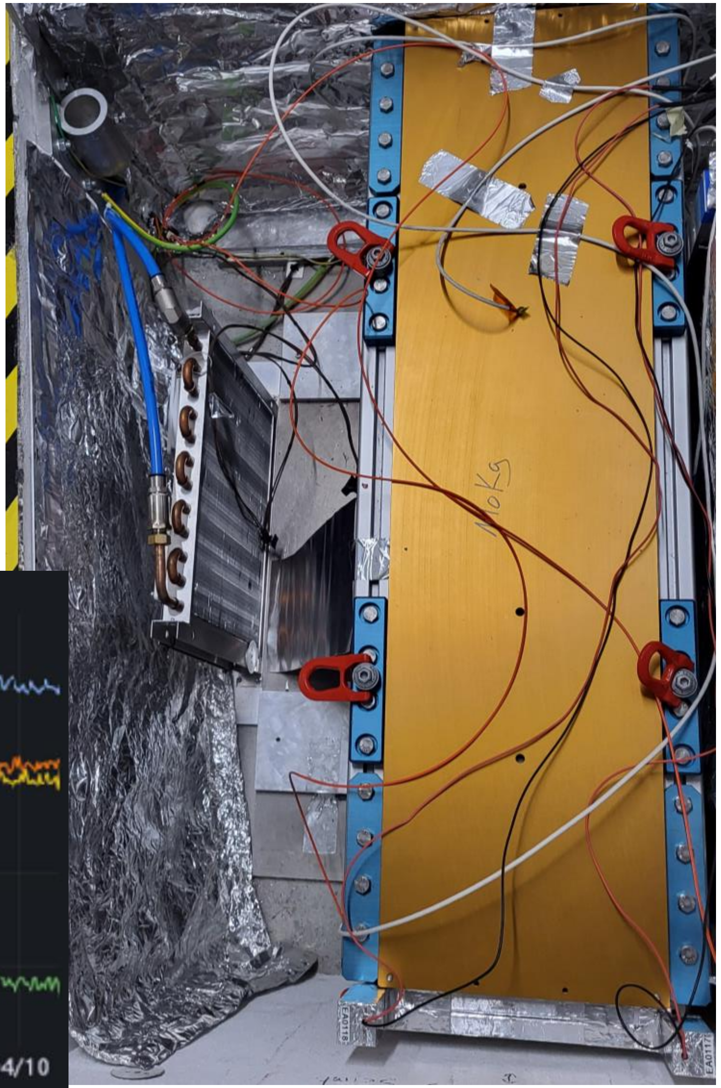
- Images made at different focal depths in emulsion;
- 5.1 x 5.1 mm^2 field of view;
- Each film scanned in 8 zones;
- 60 – 80 minutes for each film.

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.

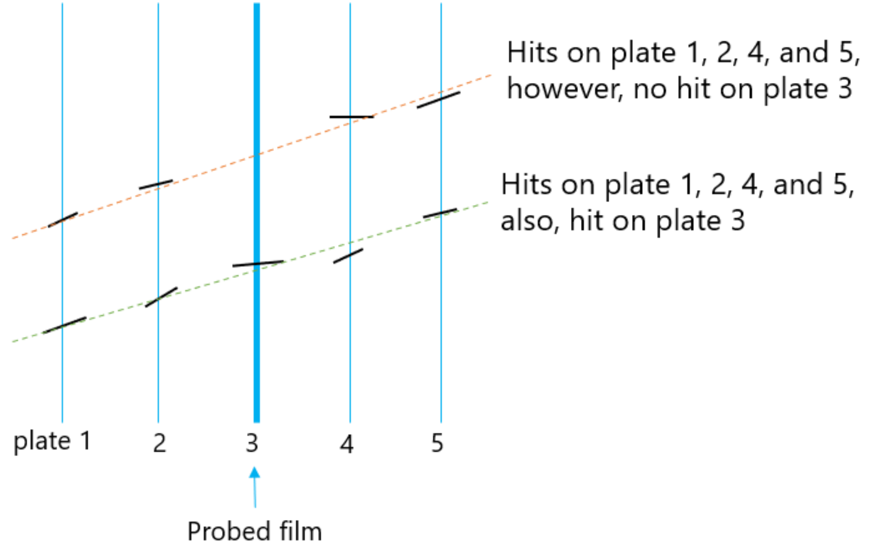


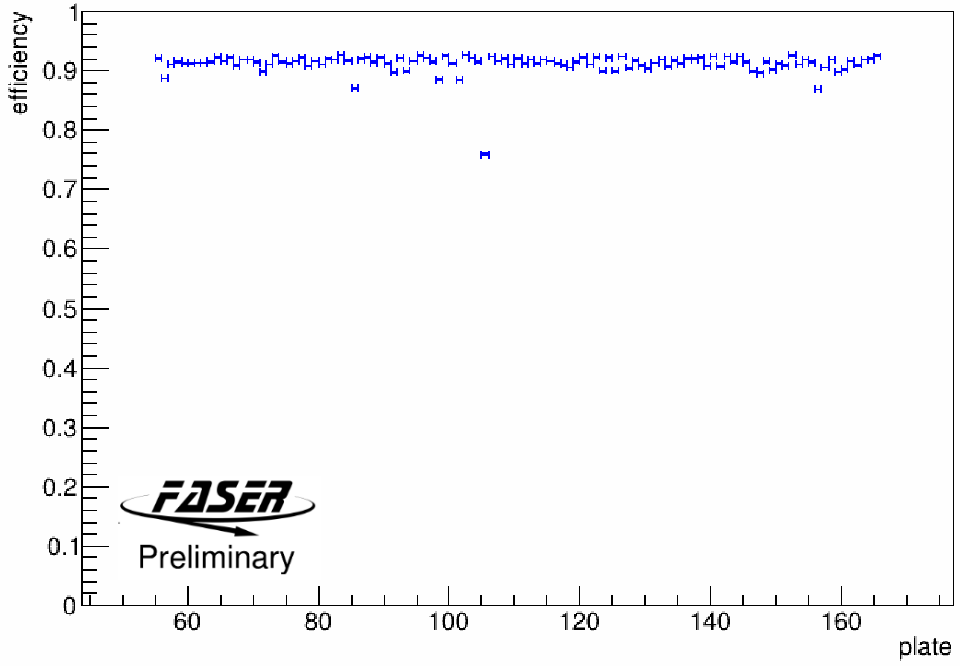




FASERν Event Reconstruction

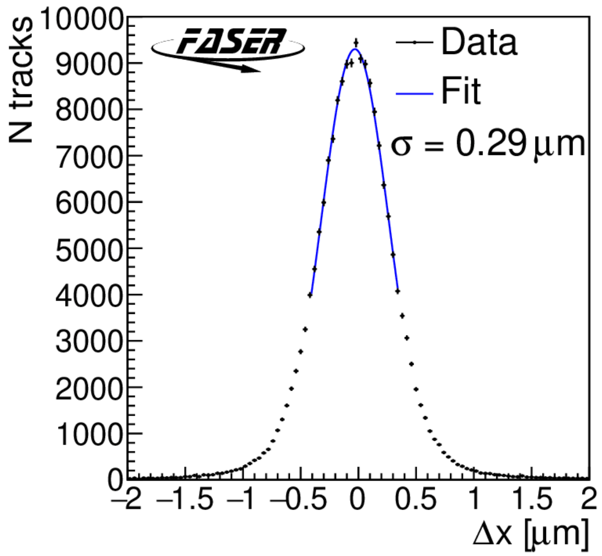
- Dedicated film alignment is performed using high-momentum muon tracks ($\mathcal{O}(10^5)$ tracks/cm^2).
- Track reconstruction links base-tracks on different films using position and angular information.
- Single film hit efficiency if found by considering whether a selected film has a hit given that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

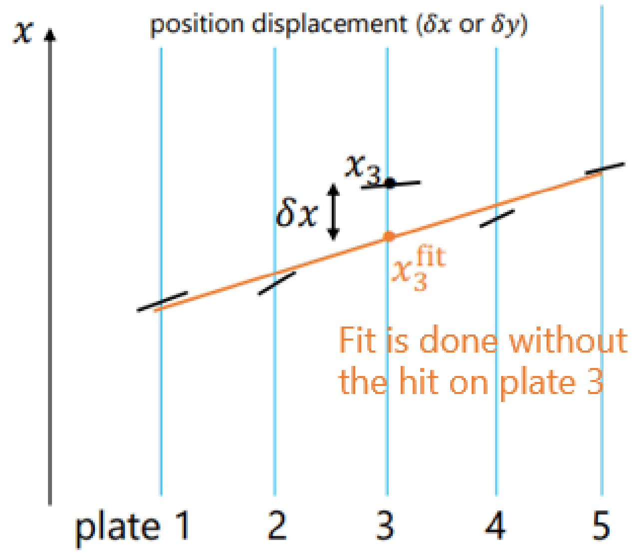




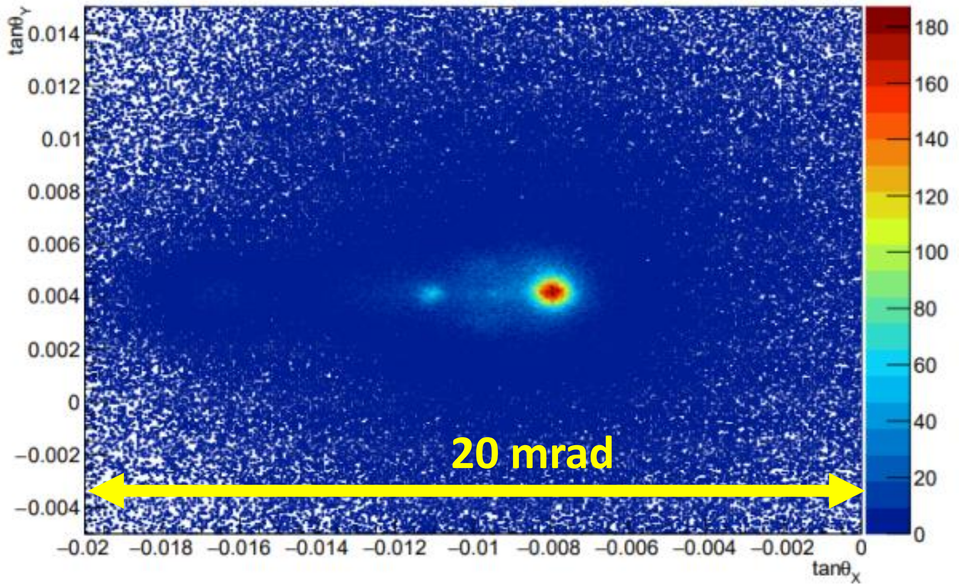
FASERν Performance

- Position resolution is determined using the position displacement between a hit and the linear fit of a track.
- Hit resolution ~ 300 nm after film alignment.





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

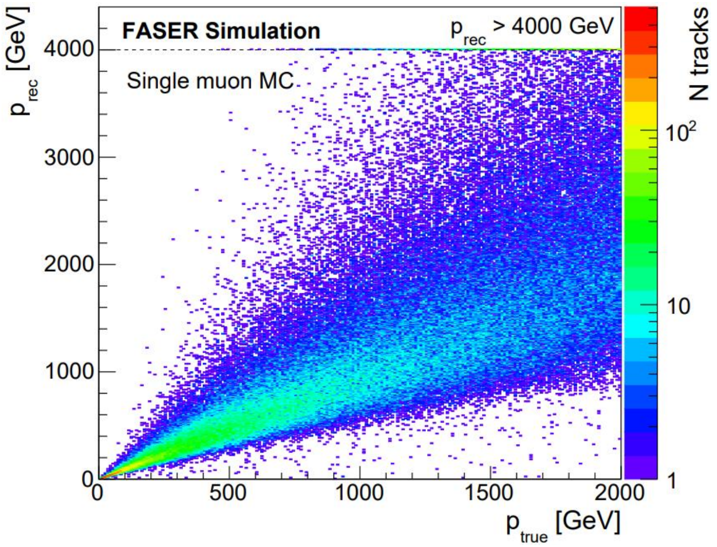


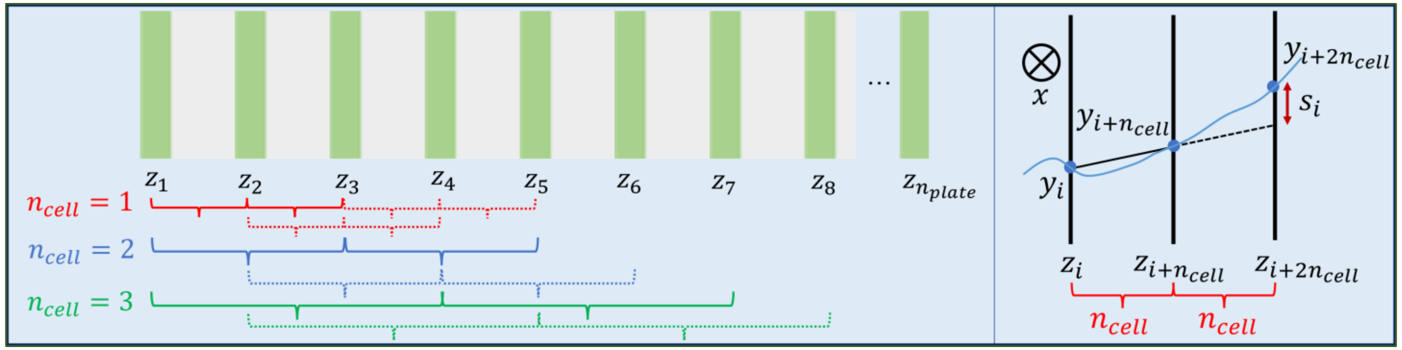
Background muons (data).

FASER preliminary

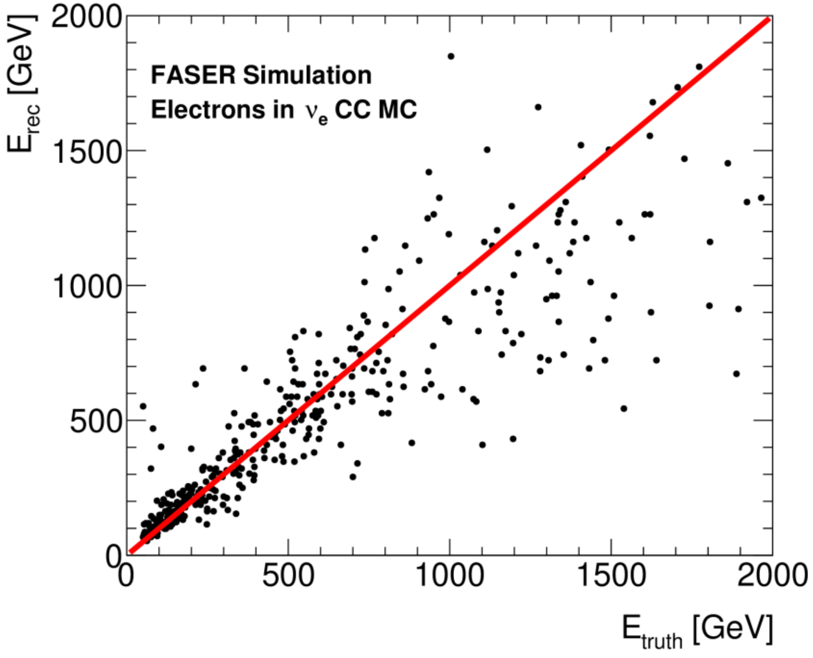
Kinematic measurements

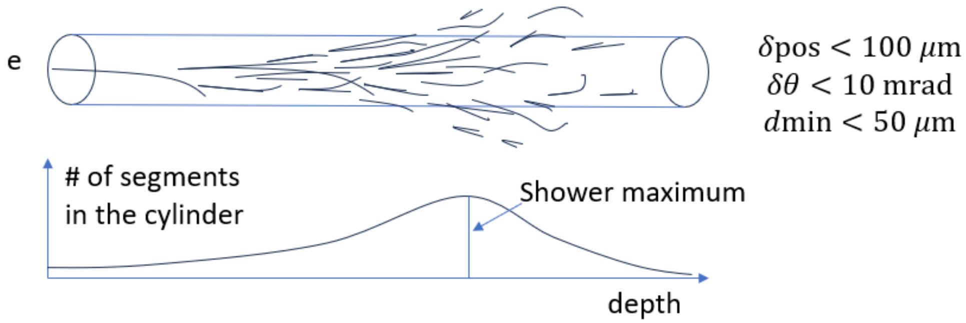
- Particle momenta calculated using Multiple Coulomb Scattering (MCS) via the Coordinate Method (works well even > 1 TeV).
- Muon momentum: $\Delta P^{RMS}/P \approx 0.3$ at 200 GeV.





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

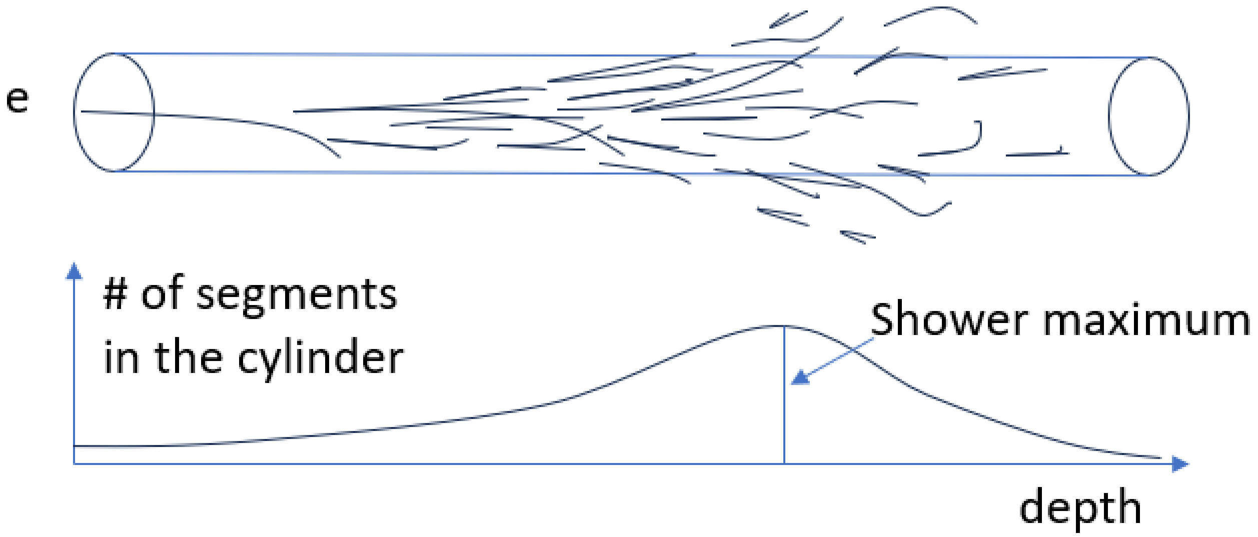




Shower Energy Measurement

- 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).

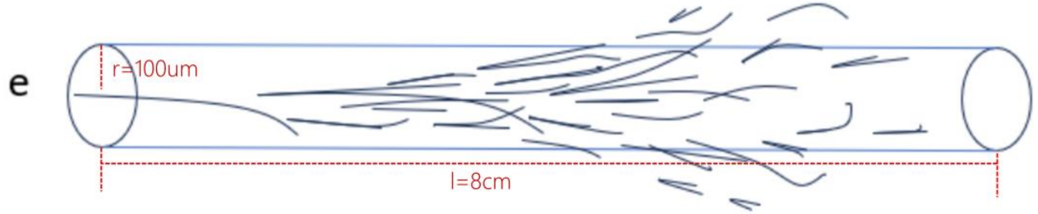


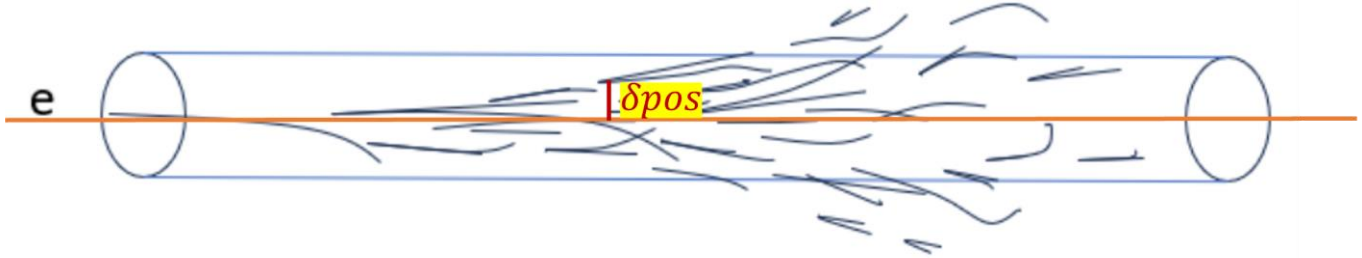
$\delta\text{pos} < 100\ \mu\text{m}$

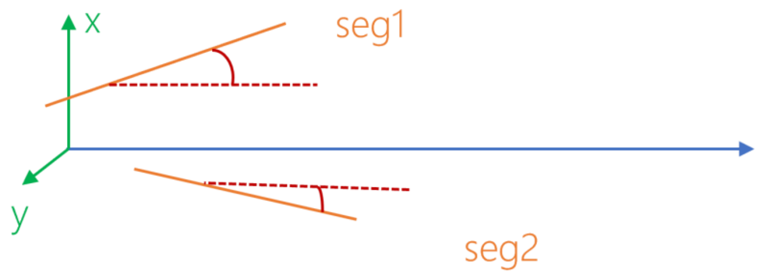
$\delta\theta < 10\ \text{mrad}$

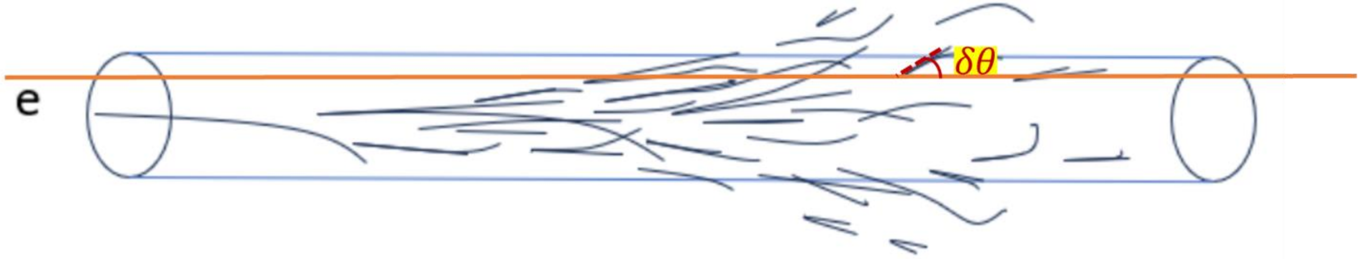
$d\text{min} < 50\ \mu\text{m}$

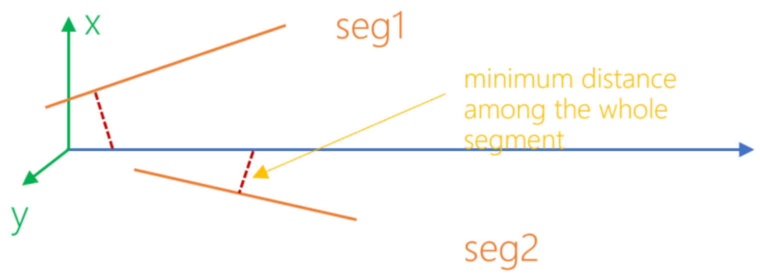
Shower Energy Measurement

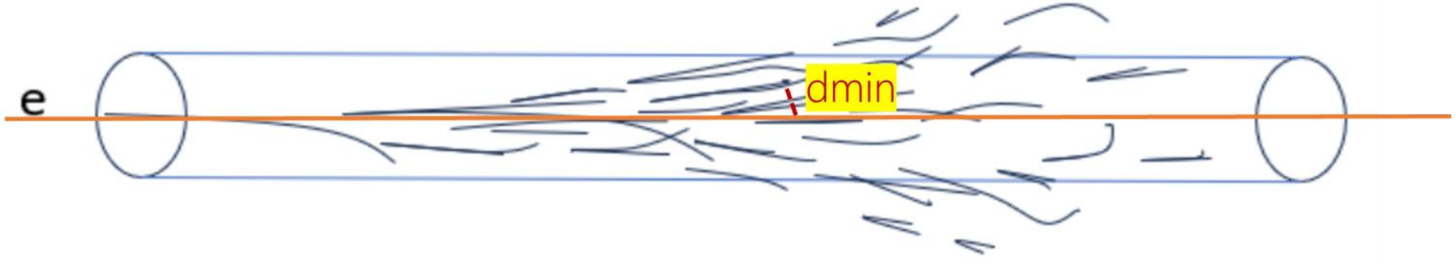






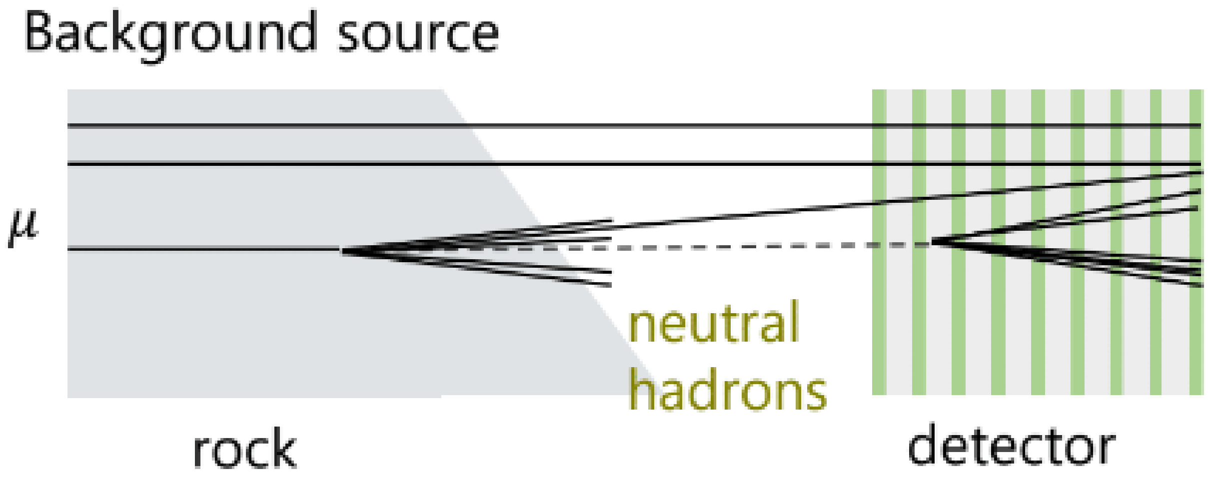




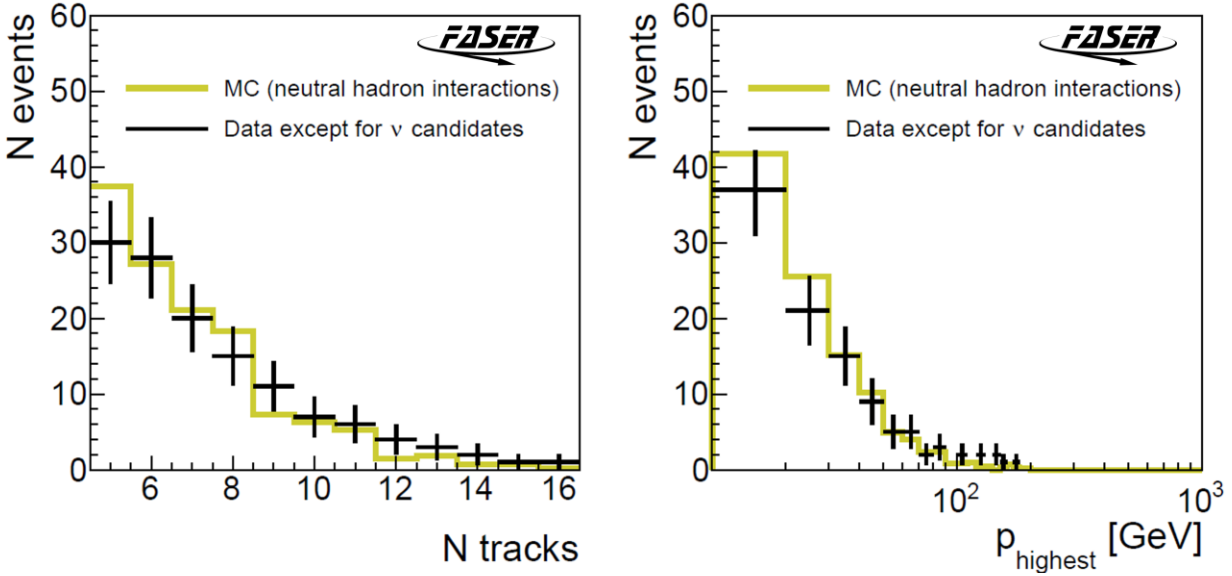


Results from FASERν: Neutral Hadron Study

- 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.

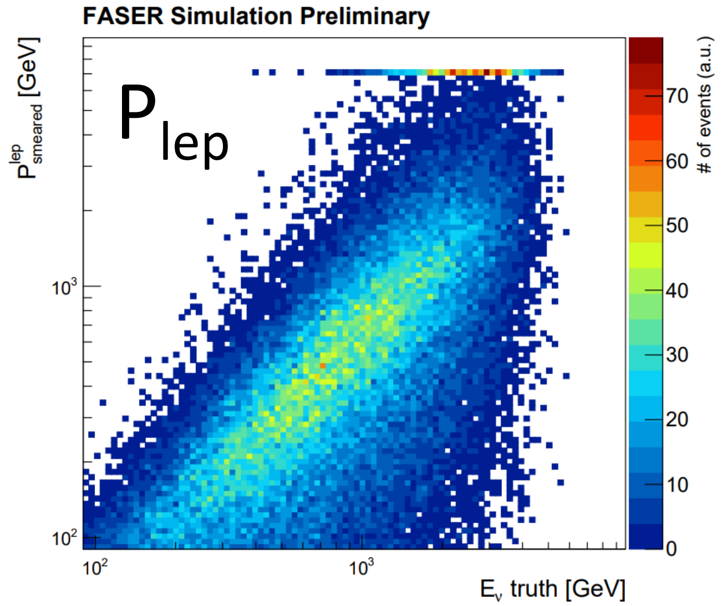


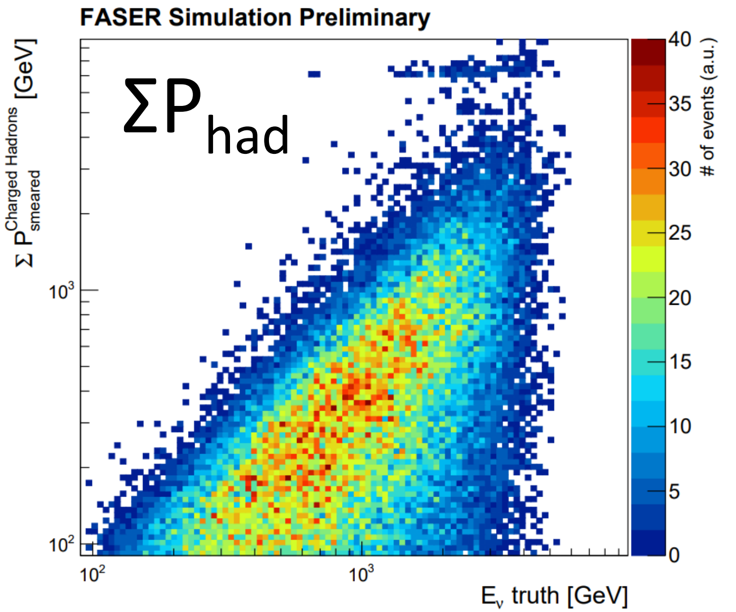
- Expectation: 246 vertices ($K_S, K_L, n, \overline{n}, \Lambda, \overline{\Lambda}$ interactions).
- Data: 139 vertices detected.
- Lies within 50% uncertainty.

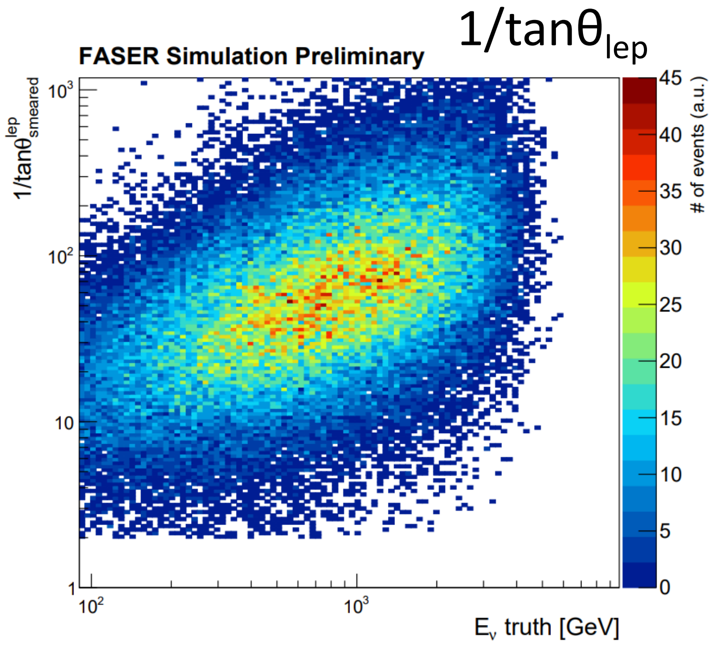


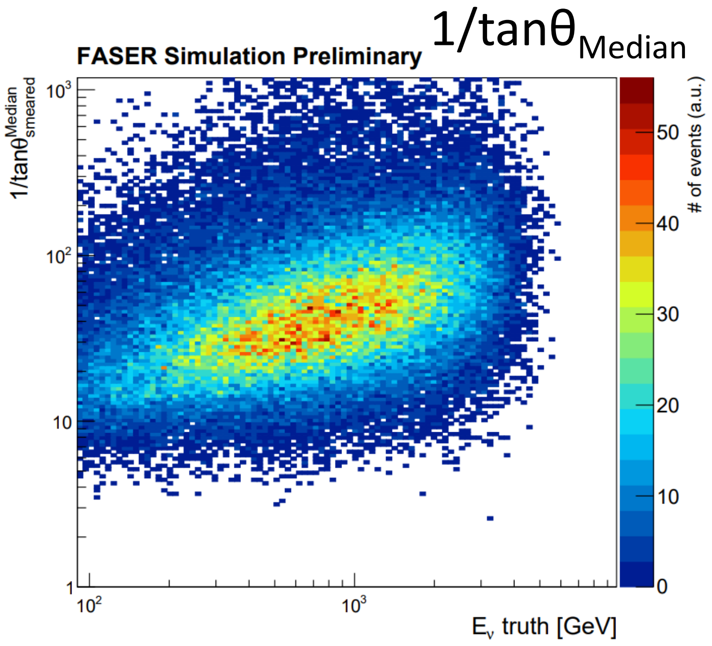
Correlation plots

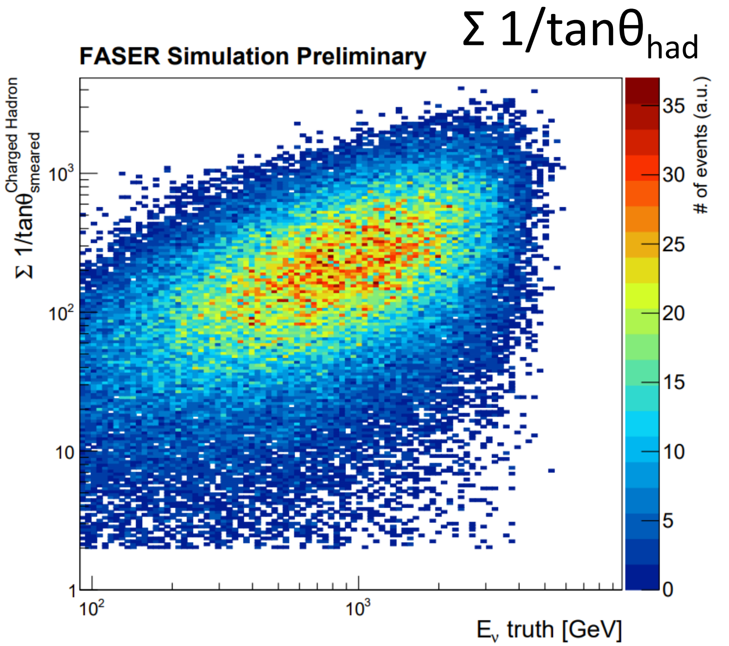
- For machine learning, interested in variables that correlate well with neutrino energy; e.g. momenta and angular variables.
- Correlation plots produced for variables of interest with respect to true neutrino energy.





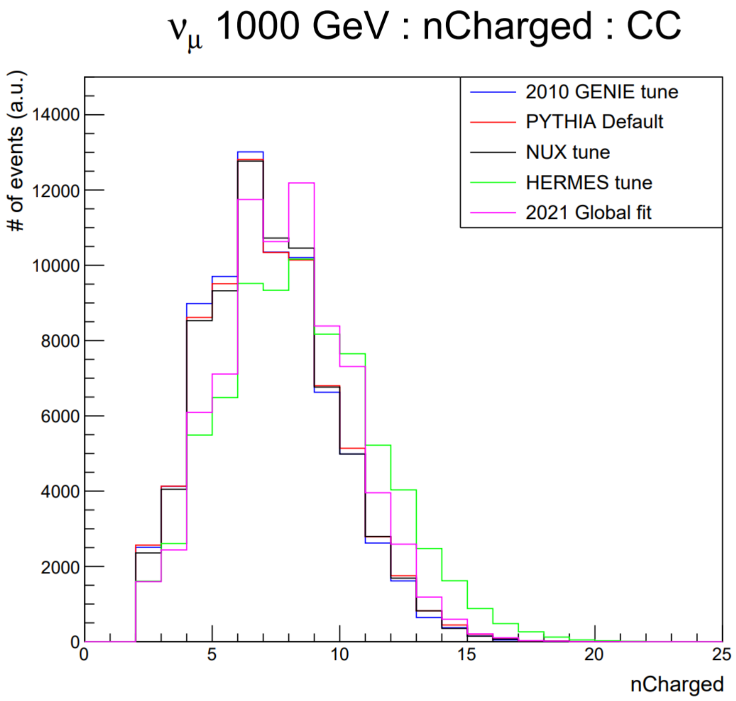


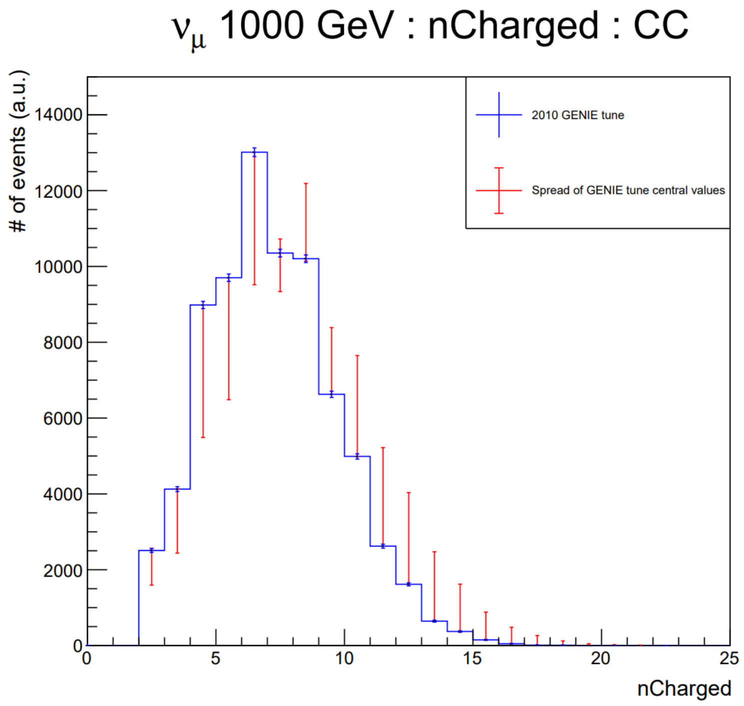




Monochrome GENIE Simulation

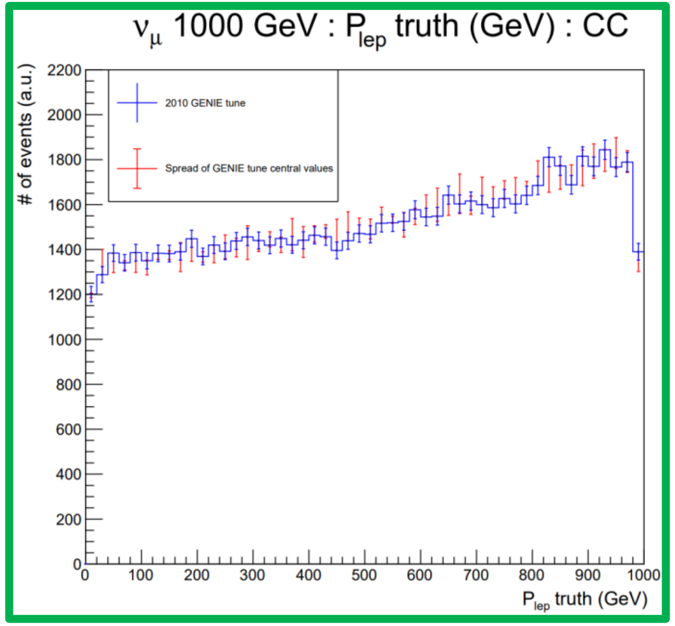
- Variables for machine learning → model-independent and stable against changing tunes.
- Produced 100 000 ν_μ interactions with GENIE for each hadronization tune for 100 GeV, 500 GeV, 1 TeV and 5 TeV.
- Same event selection as defined before (CC, nCharged > 1) → compared variables at truth level.
- Plotted distributions (left) and spread (right) – for the spread, the blue histogram corresponds to the default 2010 GENIE hadronization tune with its errors, and the red histogram shows the spread of central values for the different tunes.

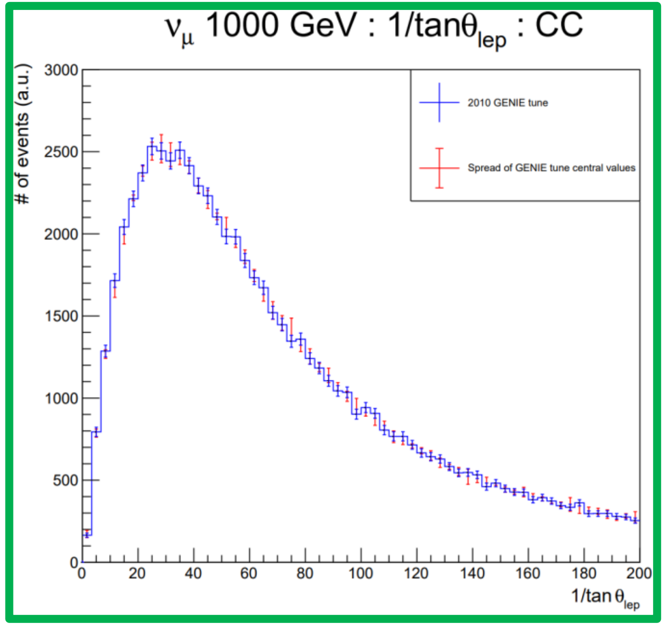


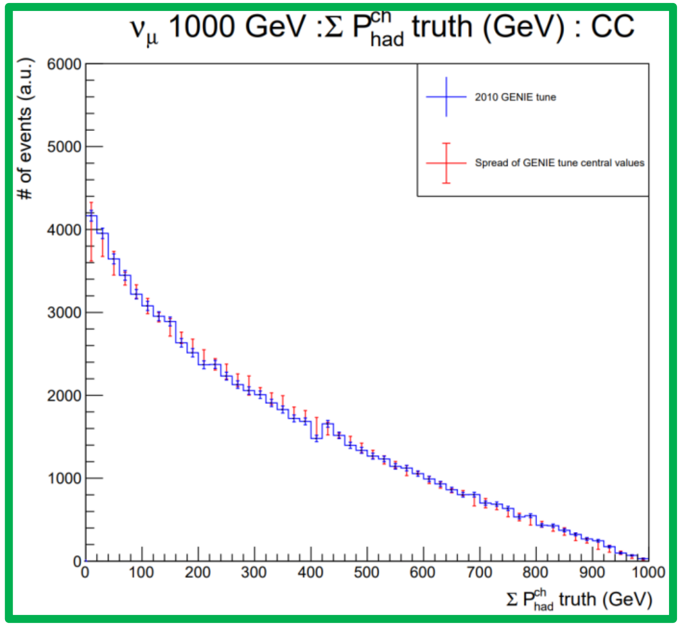


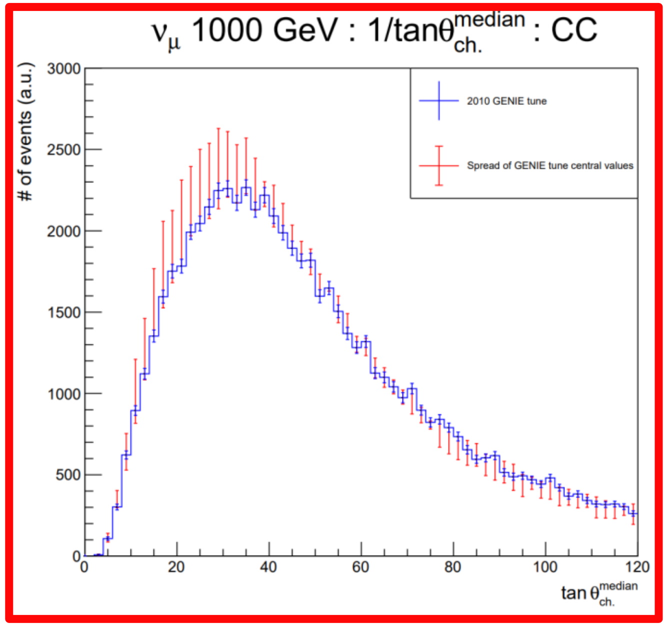
1 TeV case

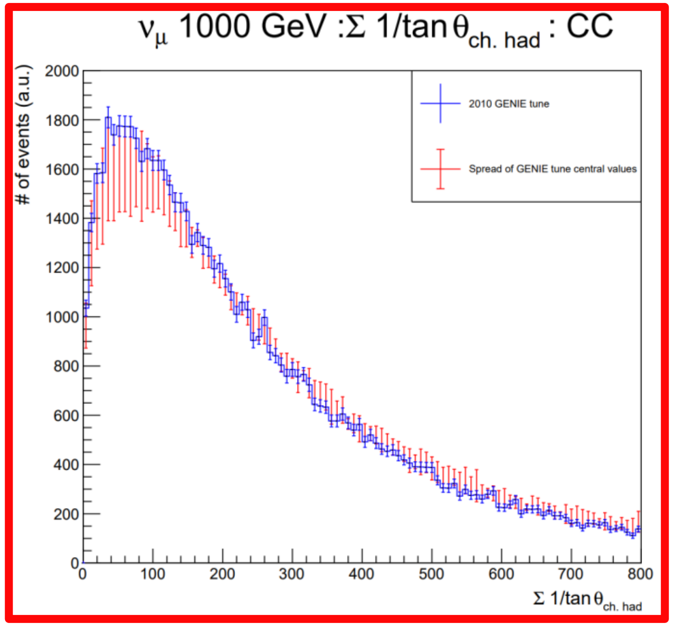
- Lepton variables are stable, as expected → variables selected.
- The sum of charged hadron momenta is stable→ variable selected.
- Angular variables dependent on charged hadrons perform poorly, possibly due to differences in charged hadron number → variables rejected.





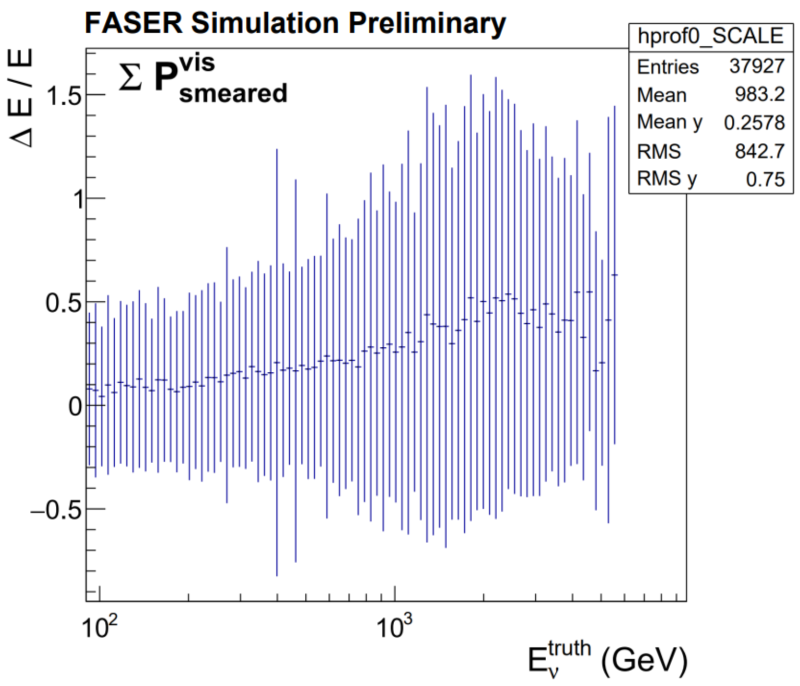


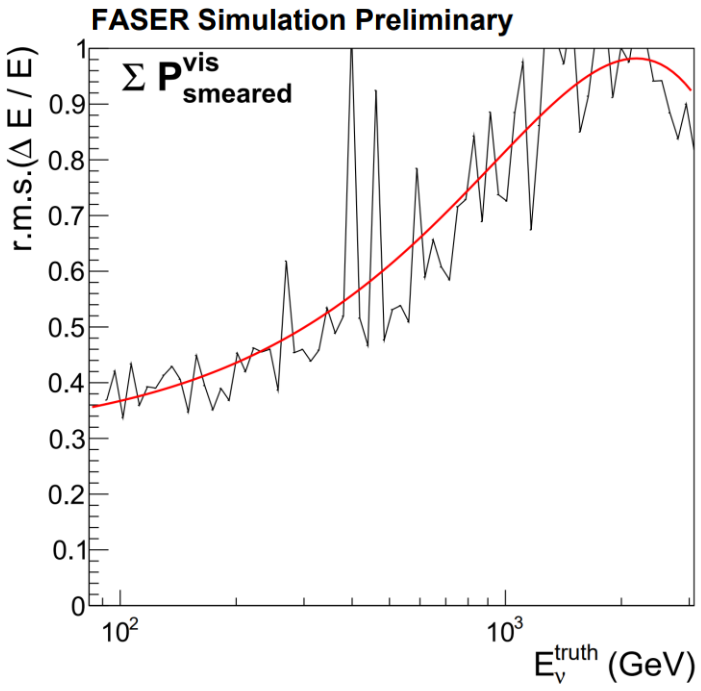




Reconstructed Energy Resolutions

- Resolution = r.m.s.(ΔE/E) ; $\frac{\Delta E}{E} = \frac{(E^{reco} - E_{\nu}^{truth})}{E_{\nu}^{truth}}$
- Graph of r.m.s. plotted and fitted to give resolution curve.
- Produced a Profile histogram for delta E/E to get mean and r.m.s.
- Plot r.m.s. and fit.





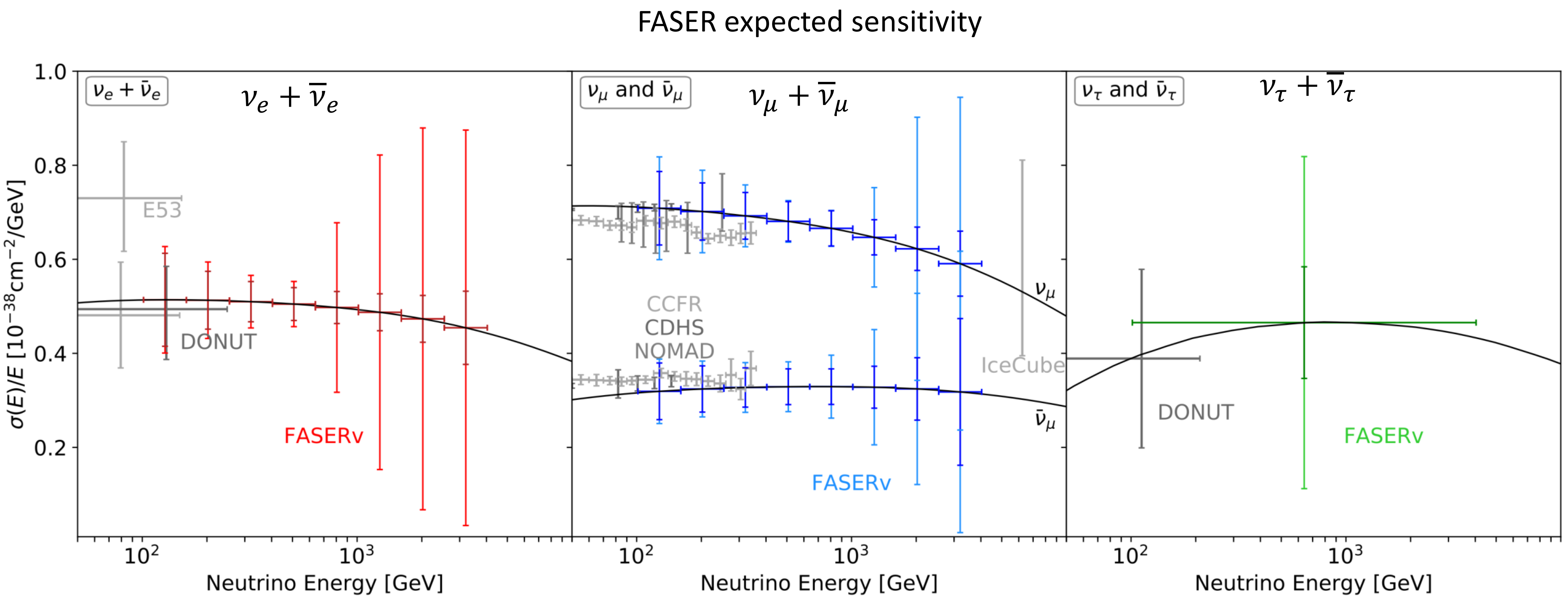
TMVA techniques

- TMVA package in ROOT (TMVA Users Guide)
  - Classification: tries to find a decision boundary (e.g. Signal vs. Background).
  - **Regression**: aims to map an initial set of variables to a target, in this case E_{ν}^{truth}.

- Boosted decision tree (BDT): repeated yes/no decisions are take on a single variable at time, aiming to decrease the error when attributing a value to the target variable; boosting extends this to several trees, which are then combined to give a weighted average.

- k-Nearest Neighbour (KNN): k-nearest neighbours are found from the training sample, and the returned value is the weighted average of the regression values of the k-nearest neighbours.

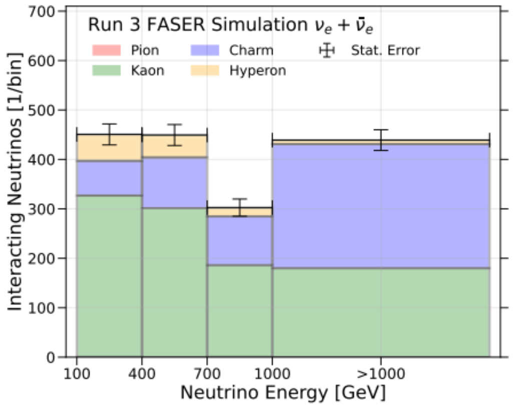
FASER Expected Sensitivity

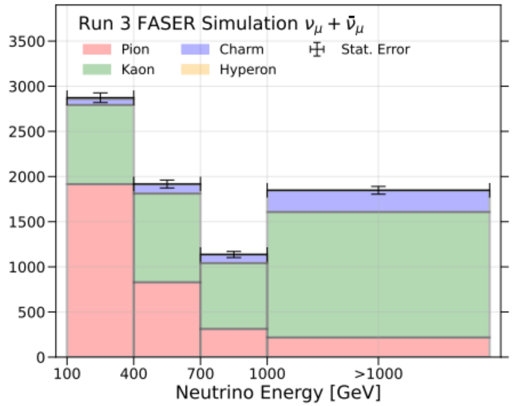


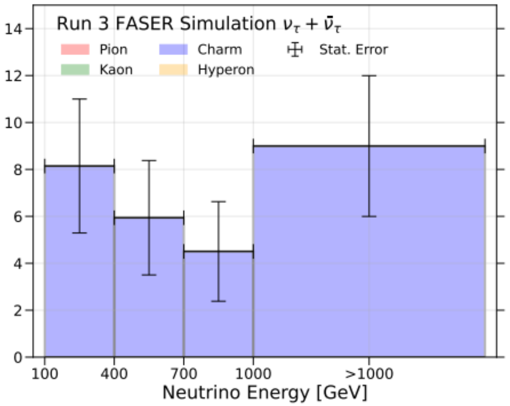
- Inner error bars: statistical uncertainties.
- Outer error bars: uncertainties from neutrino production rate.

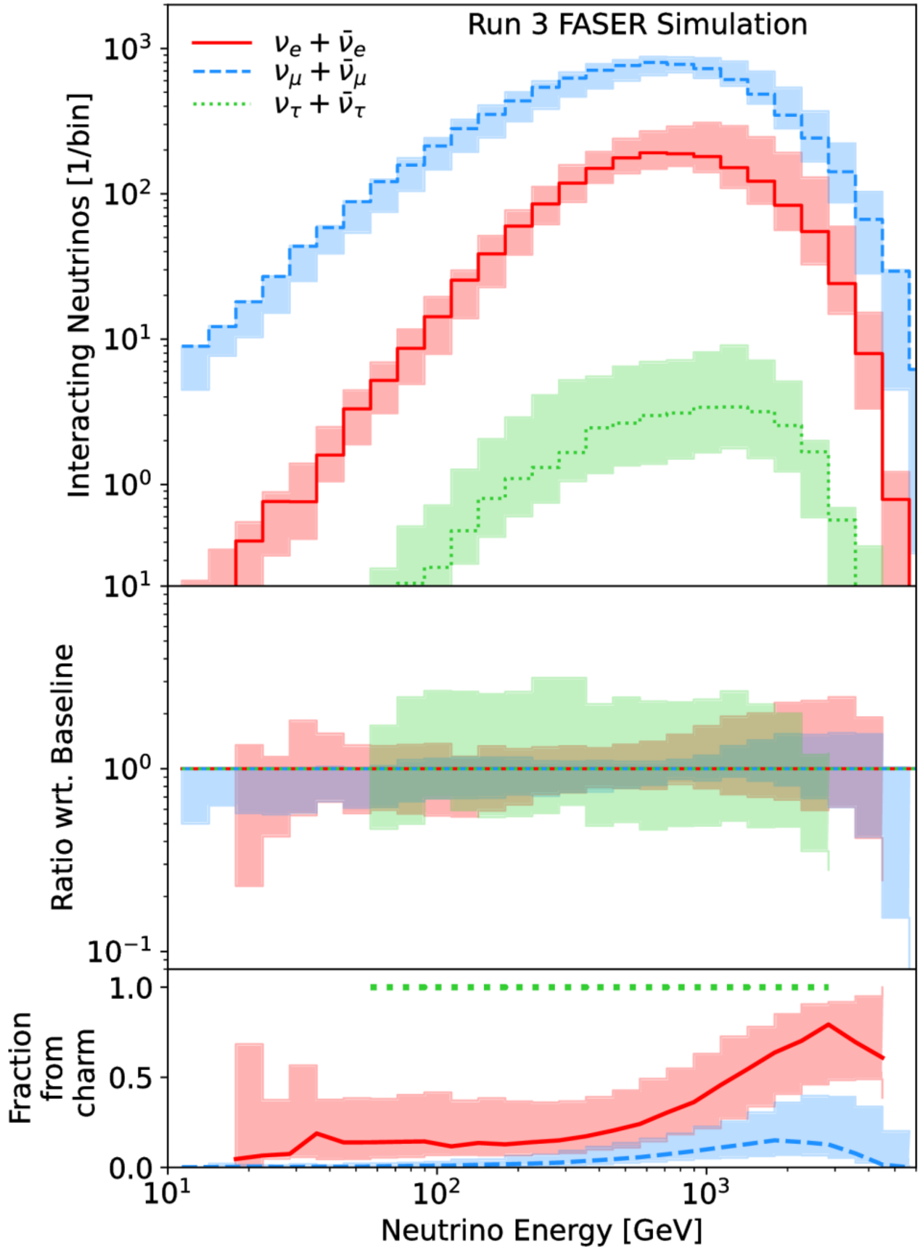
Neutrino Flux at FASER

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



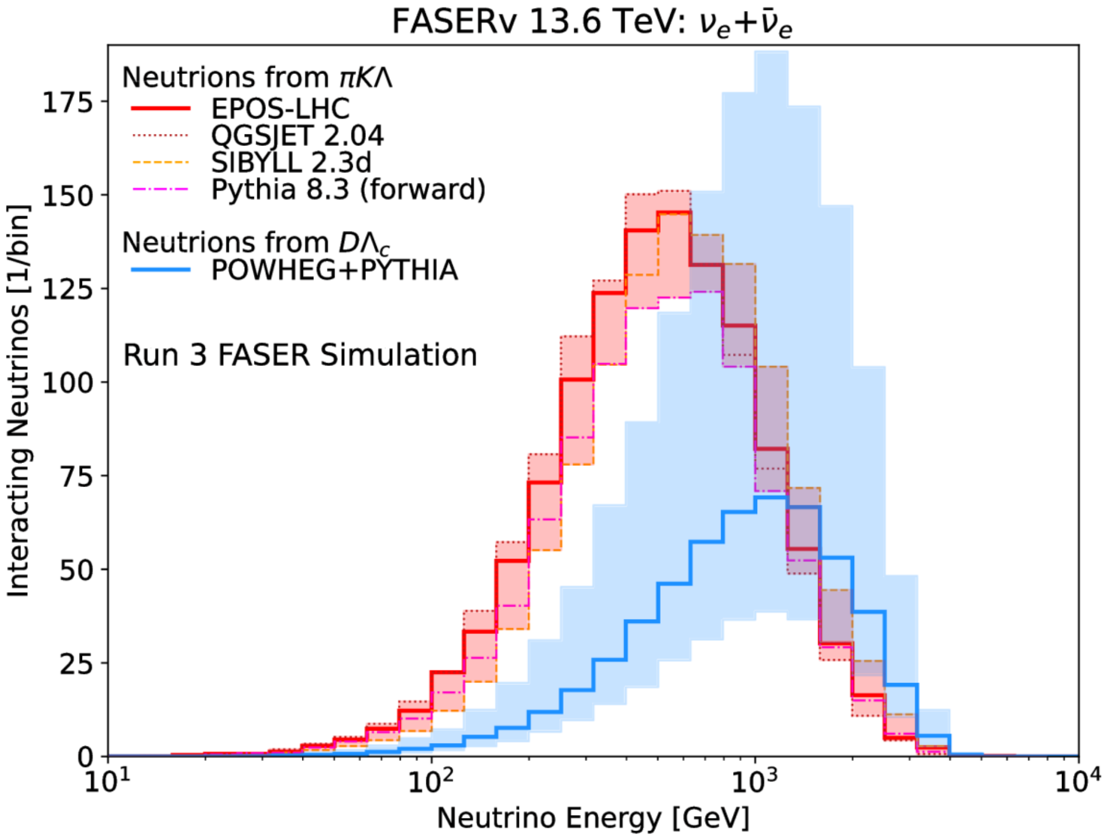


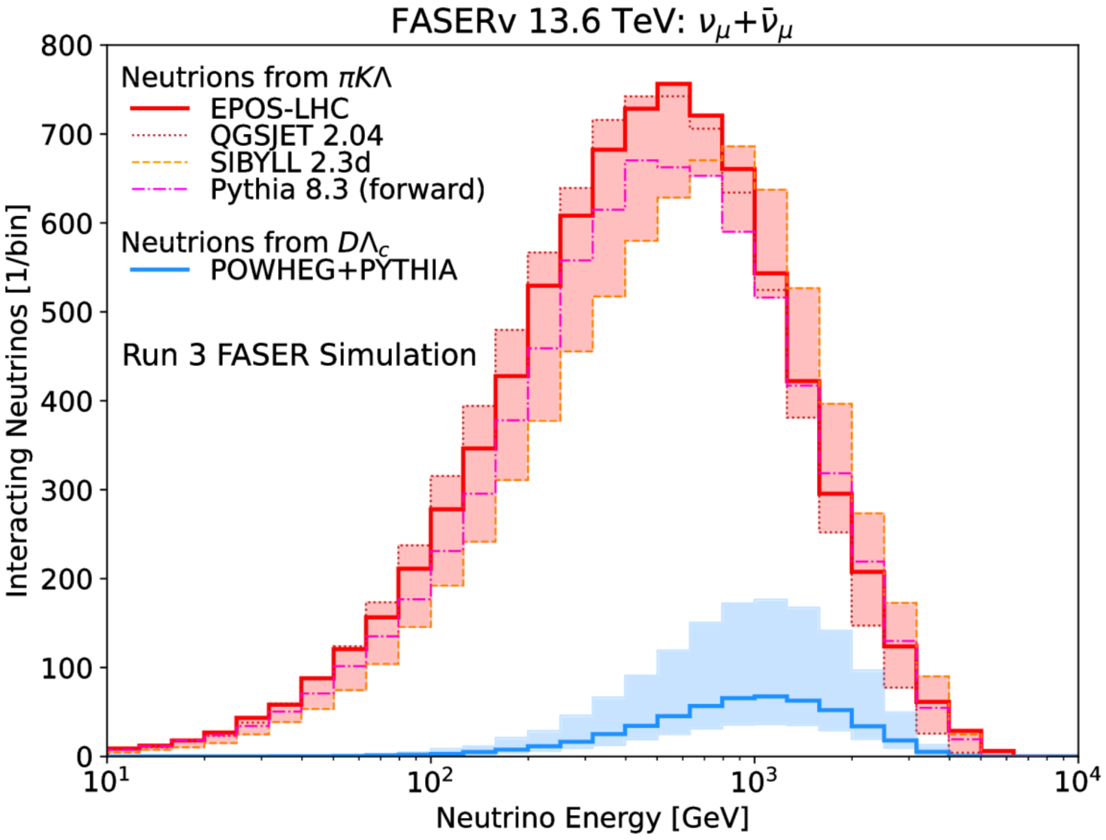




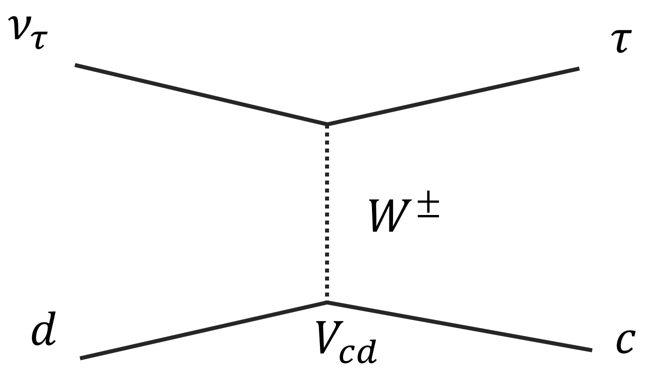
Generator flux uncertainty

- 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.



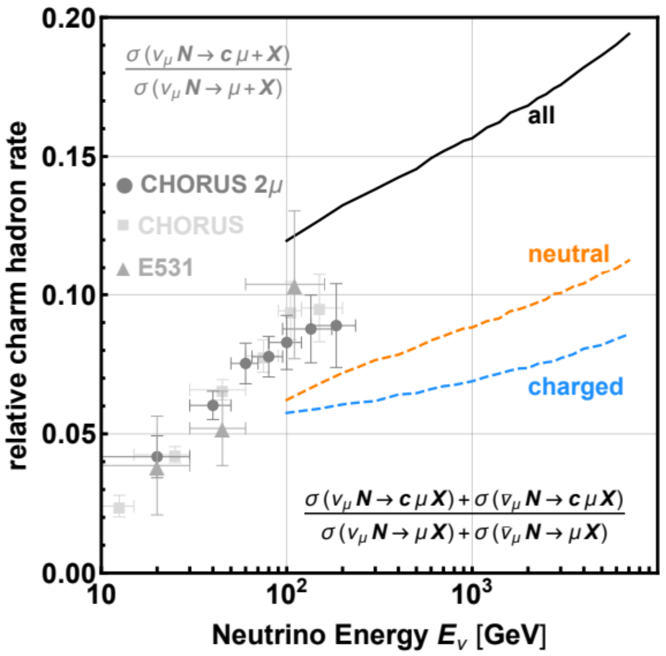


Heavy-flavour-associated channels



- Measure charm production channels:
  - ~10% ν CC event→ $\mathcal{O}(1000)$ events via charm production channels expected;
  - 1st measurement of 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.