Results from TeV Neutrinos at the FASER Experiment

Sergey Dmitrievsky on behalf of the FASER Collaboration

42nd International Conference on High Energy Physics
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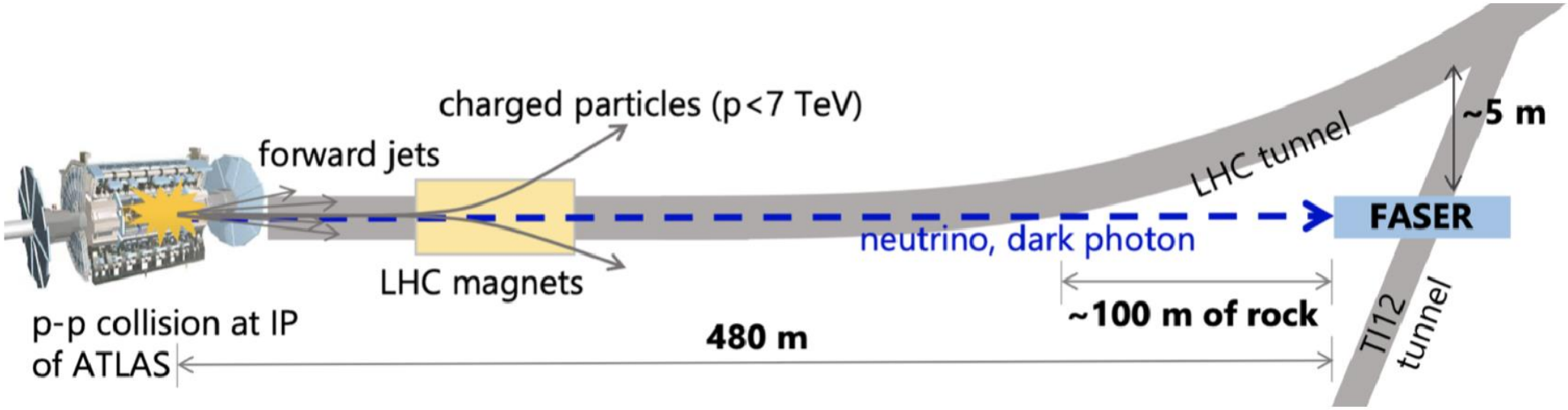
ForwArd Search ExpeRiment



FASER is a small LHC based experiment designed to search for light, weakly interactive particles produced in the far-forward region of proton-proton collisions at the ATLAS interaction point (IP):

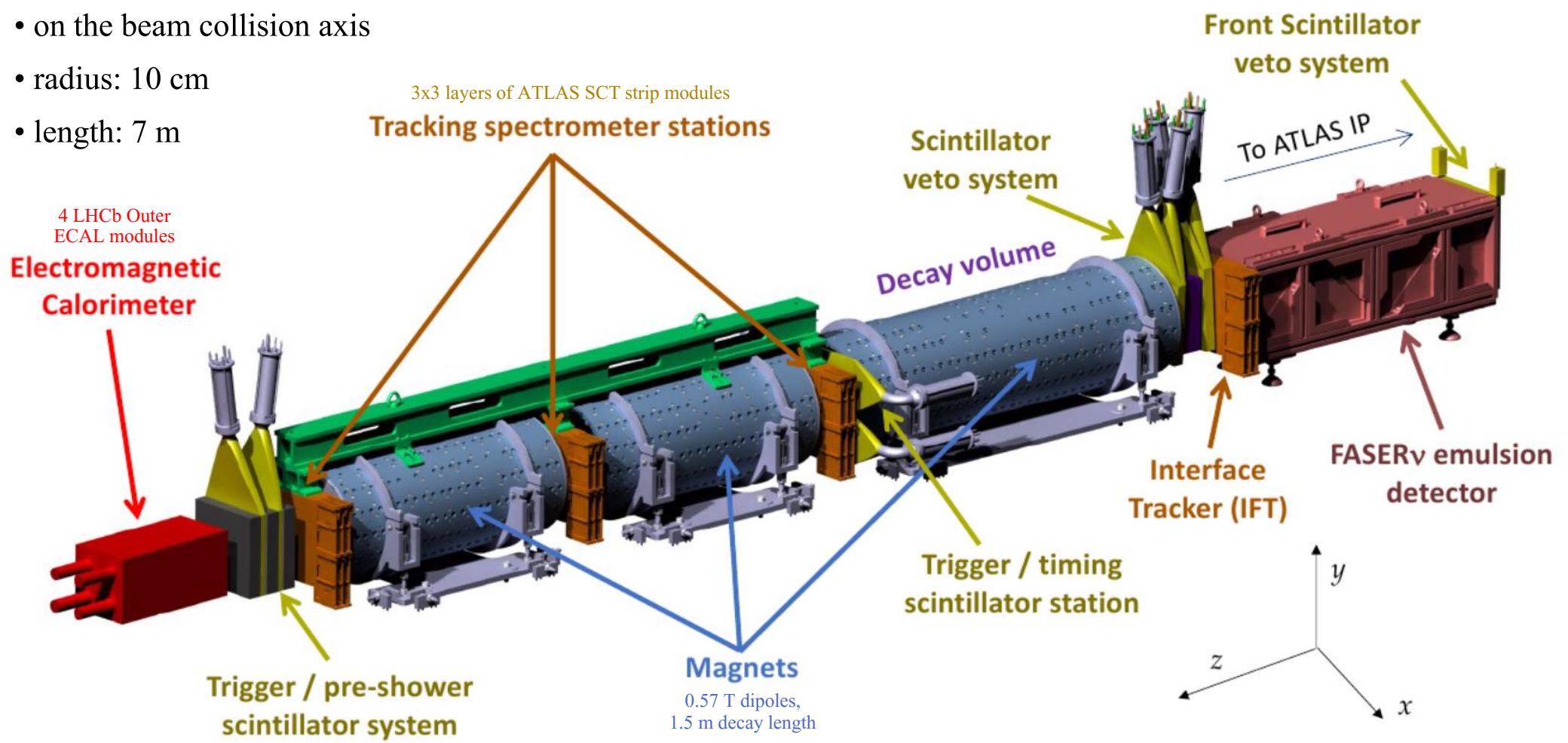
- long-lived BSM particles (dark photons, axion-like-particles (ALPs))
- TeV neutrinos


FASER
Towards ATLAS IP

The FASER detector

JINST 19 (2024) P05066

- on the beam collision axis
- radius: 10 cm
- length: 7 m



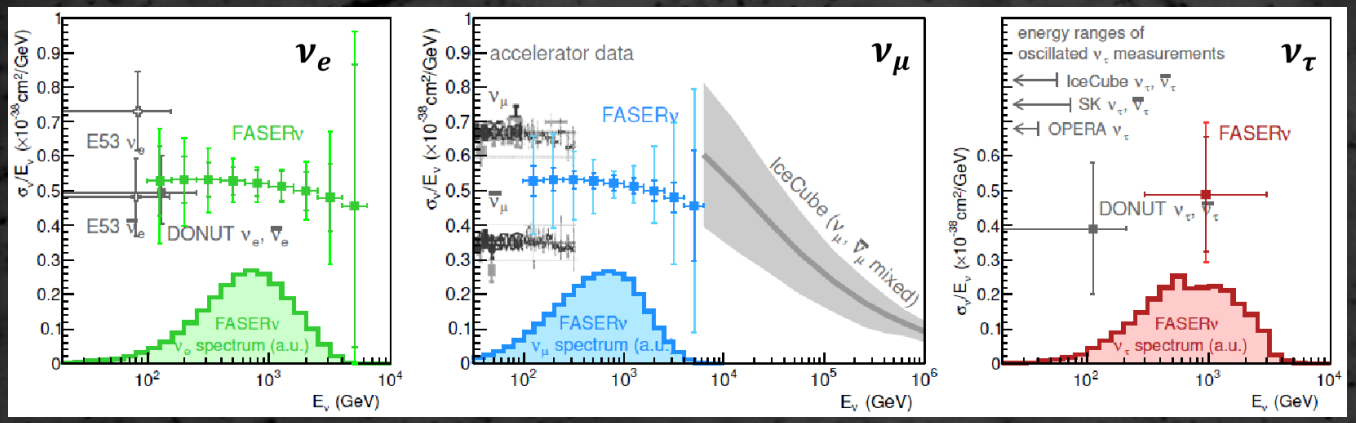
Collider neutrinos at FASER

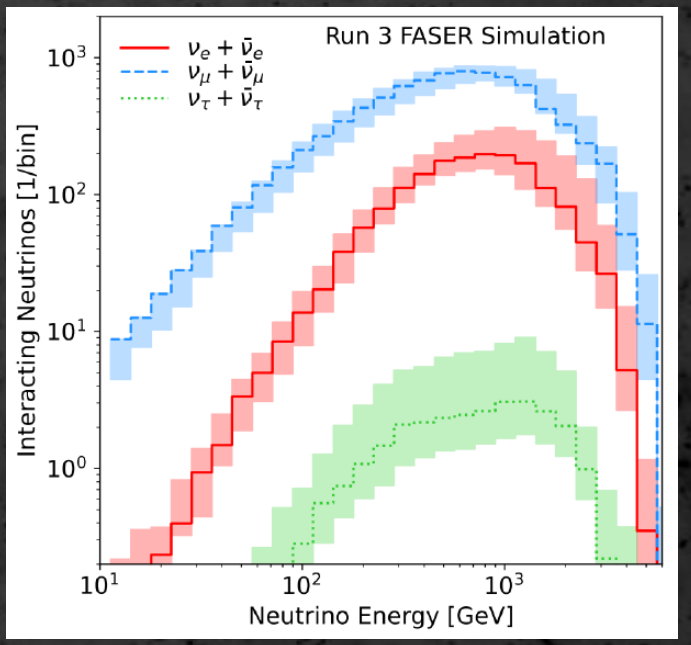
- >10 000 neutrinos expected to interact in FASER throughout LHC Run 3 (~250 fb^{-1})
- 3-flavour cross-section measurement for previously unexplored energy range ➔ highest E_ν from artificial source
- $\mathcal{O}(1000)$ events via charm production channels – allows to measure forward charm production
- High statistics allows to study neutrino induced heavy quark (charm) production

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/charm decays	Charm decay
№ expected CC events in FASERν	~1700	~8500	~30

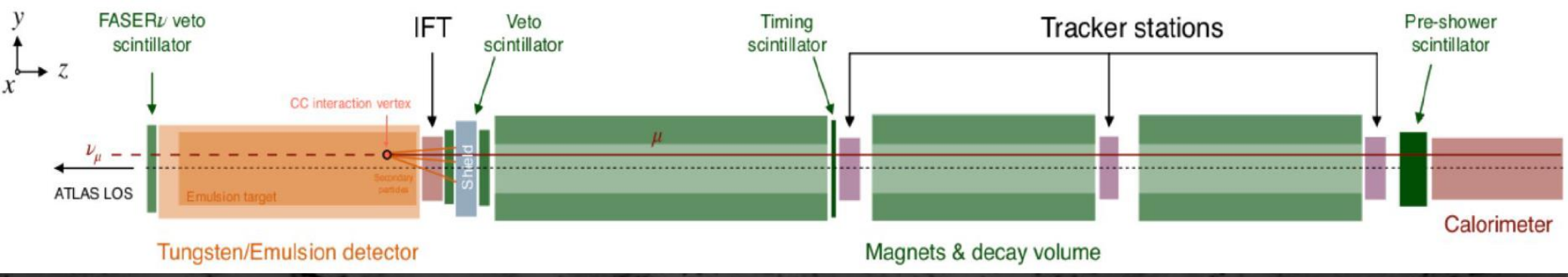
Phys.Rev.D 110, 012009 (2024)

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





Neutrino measurements with FASER



Using tungsten/emulsion detector

- Sensitive to all neutrino flavours
- High spatial and angular resolution
- Analysis is time intensive due to scanning and processing of emulsion films

Using electronic detectors

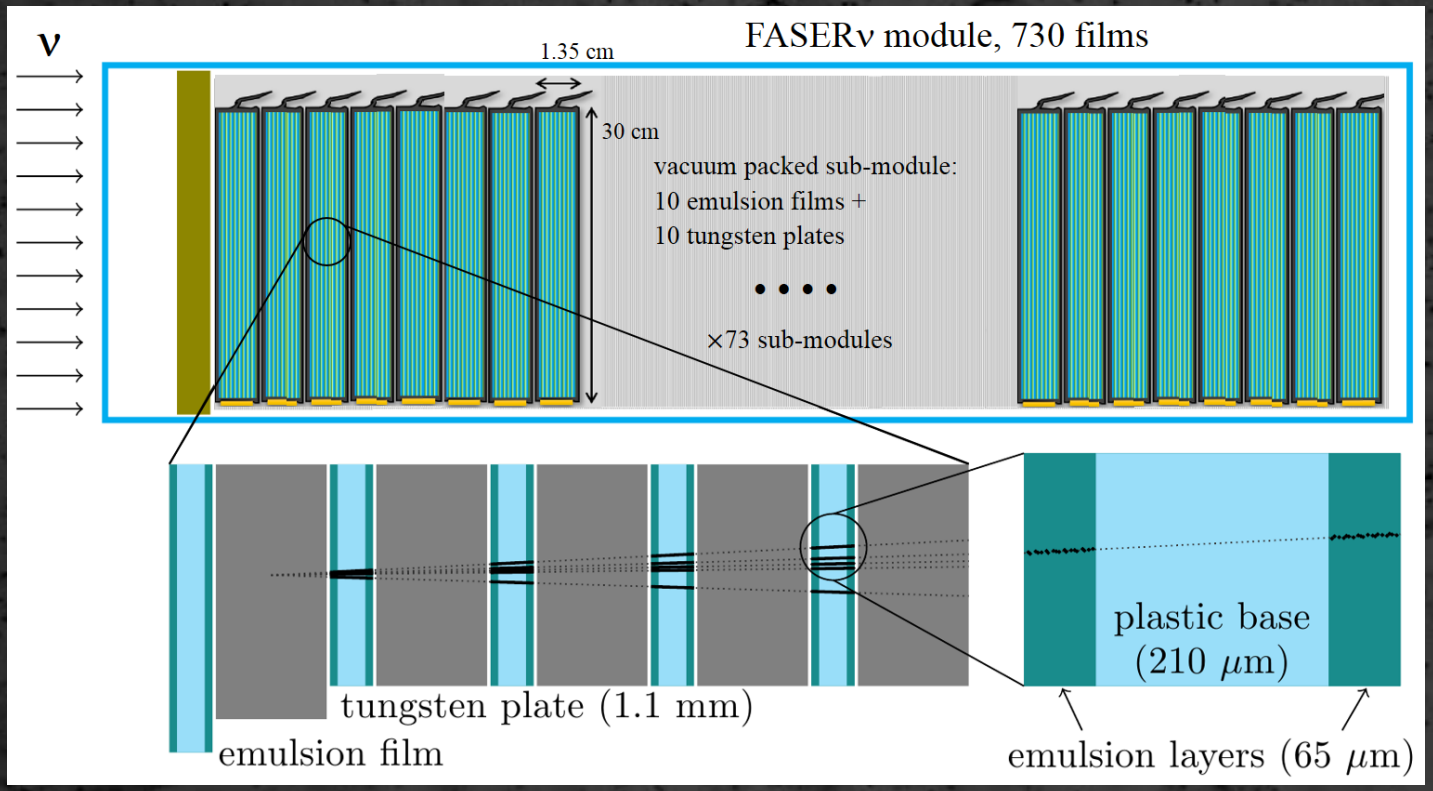
- FASERν as target (1.1 t) – detection of muons from ν_μ CC interactions
- Can separate ν and $\bar{\nu}$
- Fast analysis of data possible
- Only sensitive to muon neutrinos

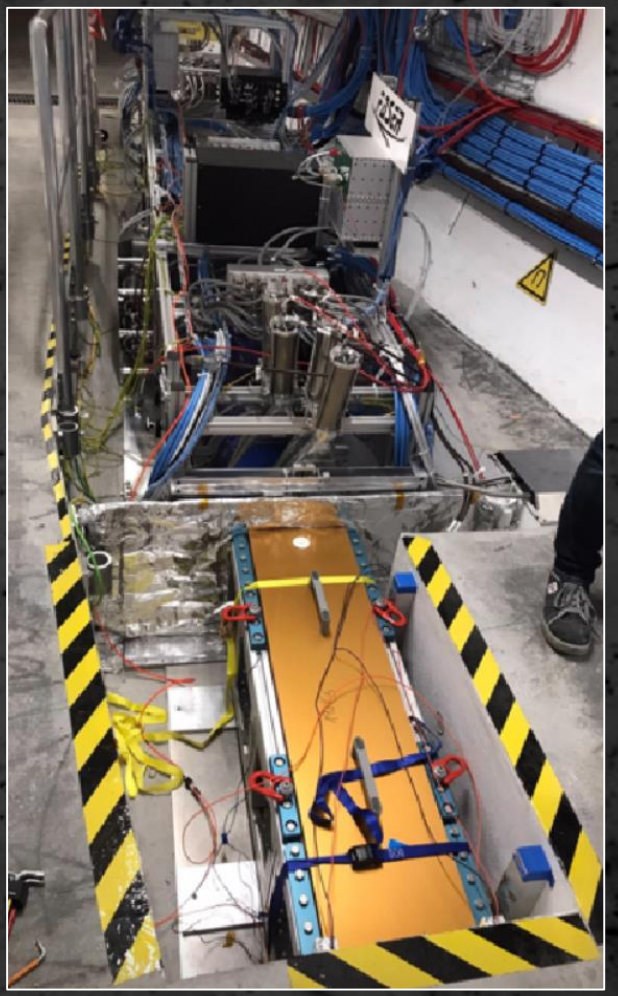
Recent physics results:

First Neutrino Interaction Candidates at the LHC (Phys.Rev.D 104, L091101 (2021))

First Direct Observation of Collider Neutrinos with FASER at the LHC (Phys.Rev.Lett. 131, 031801 (2023))

The FASERν tungsten/emulsion detector





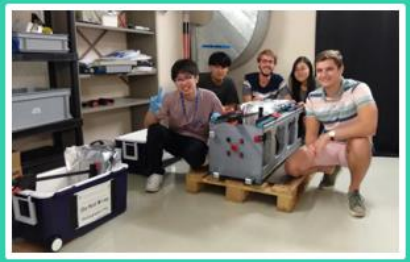
- 730 alternating emulsion films and 1.1 mm thick tungsten plates (25×30 cm^2)
- Target mass: 1.1 tonnes; length: 1.05 m (220 X_0, 8λ)
- 3 modules irradiated each year to keep track occupancy <$10^6/cm^2$ (~30 fb^{-1})

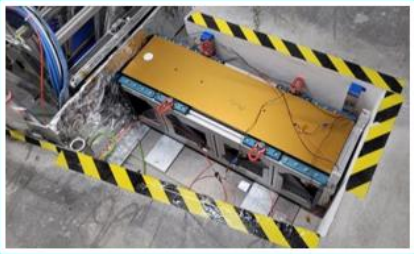
FASERν processing and analysis chain

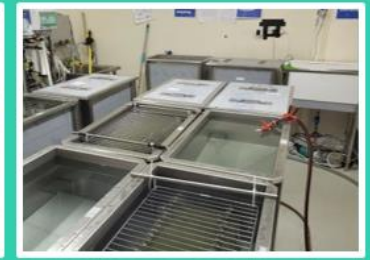
From emulsion production to exposure at the LHC and the subsequent event analysis steps to physics results

Japan

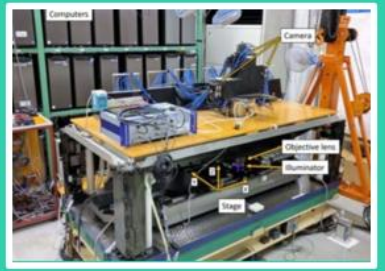
CERN







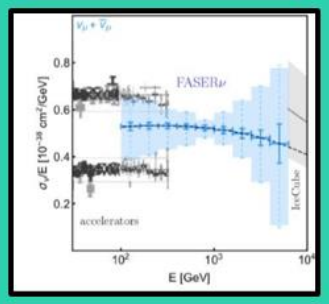
Japan

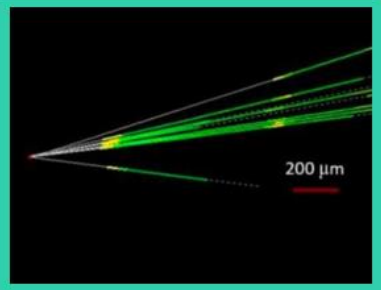


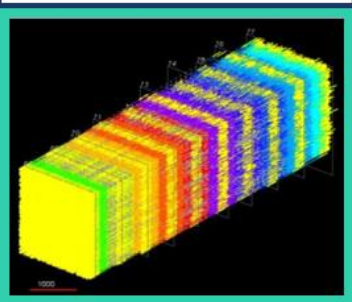
Film production → Assembly → Exposure → Disassembling → Development → Readout

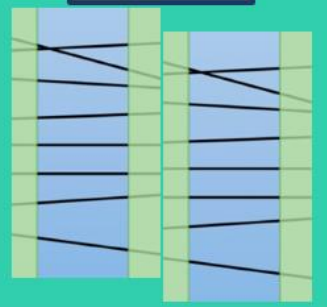
Offline analysis

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





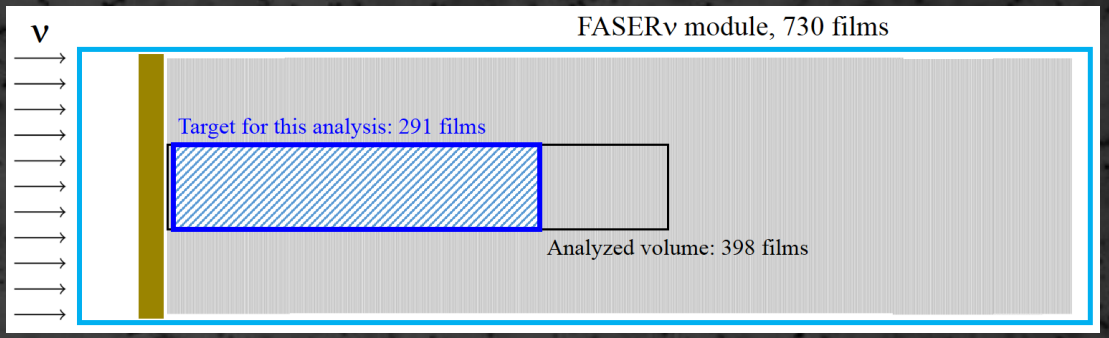




New FASERν analysis

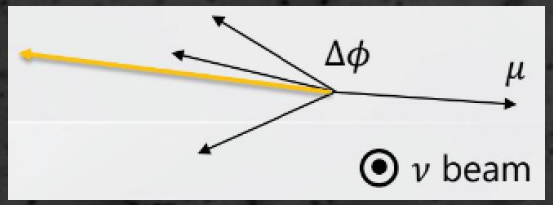
Data set analyzed:

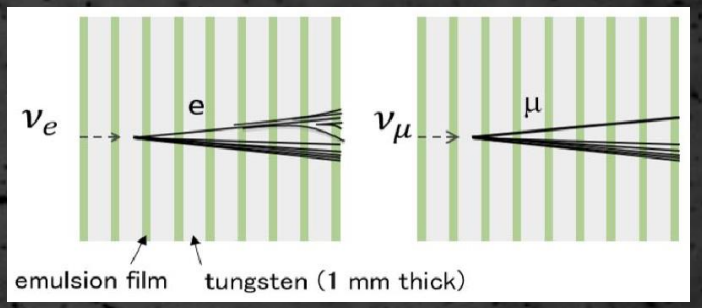
- 2022 2nd module ➔ 9.5 fb^{-1}
- Target mass: 128.6 kg
- 1.7% of data collected today



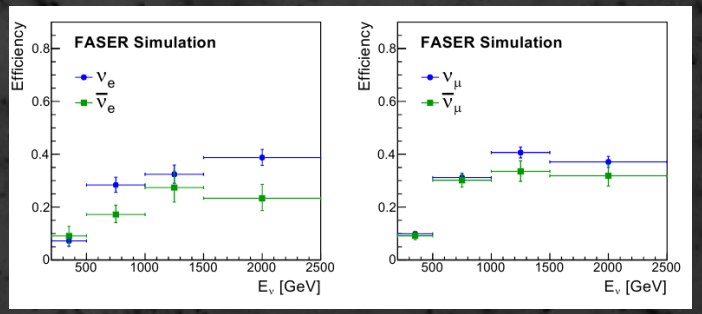
ν event selection criteria:

- Vertex reconstruction:
  - N_{track} (tanθ ≤0.5) ≥ 4
  - N_{track} (tanθ ≤0.1) ≥ 3
- Lepton requirements:
  - E_e or p_μ > 200 GeV
  - $\tan\theta_e$ or $\tan\theta_\mu$ > 0.005
- Back-to-back topology: $\Delta\phi$ > 90°





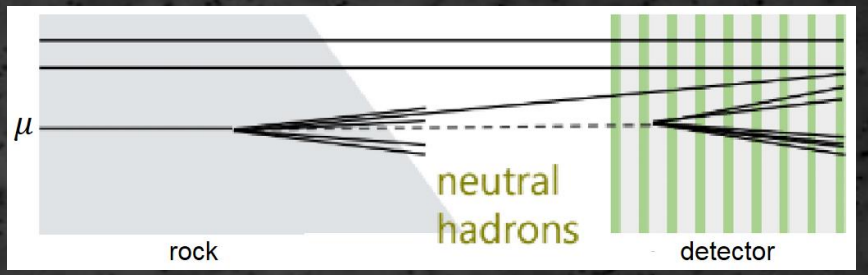
Track resolution in emulsion is 0.3 μm



E_e – from counting track segments at EM shower maximum (resolution: ~25% at 200 GeV)
p_μ – from track spread due to multiple Coulomb scattering (resolution: ~30% at 200 GeV/c, validated with test beam)

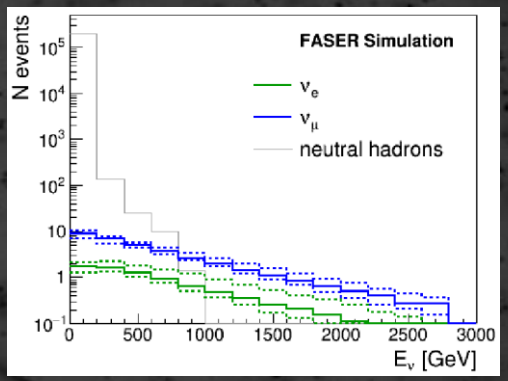
Study of neutral-hadron background

- Neutral hadrons are produced in interactions of muons within the rock in front of the FASER detector or within the FASERν detector material.

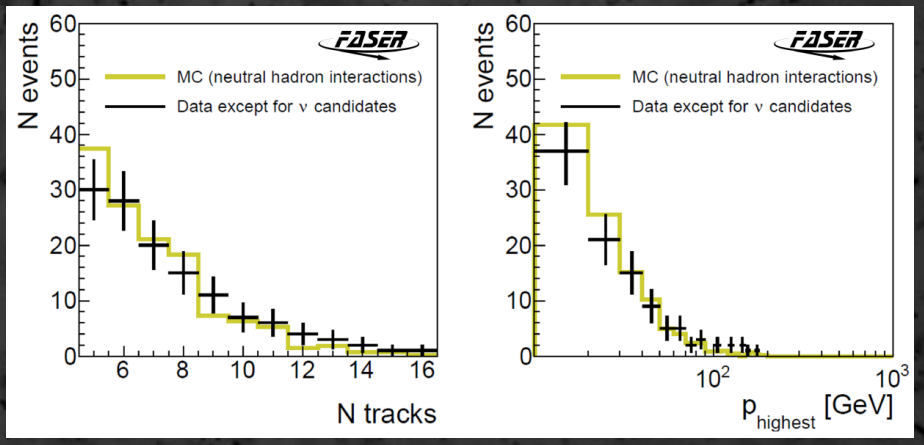


- Estimated using simulation.

- The simulation was validated with study of low-energy neutral-vertex data sample from a part of the analyzed volume (150 tungsten plates ➔ target mass = 68.2 kg).



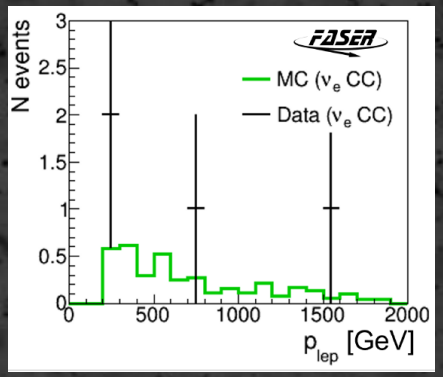
- Expected: 246 vertices ($K_S, K_L, n, \bar{n}, \Lambda, \bar{\Lambda}$ interactions).
- Reconstructed: 139 vertices.
- Lies within 50% uncertainty.

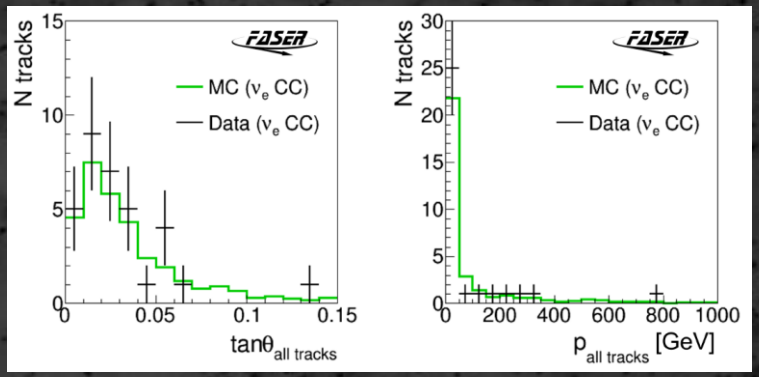


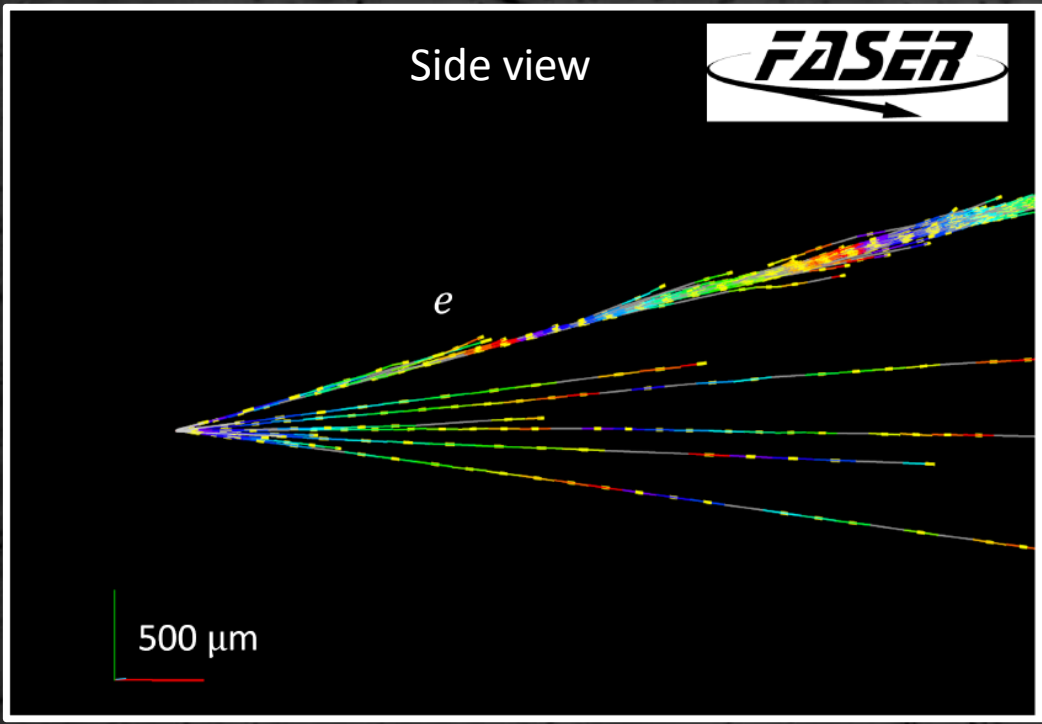
MC is normalized to the number of data events

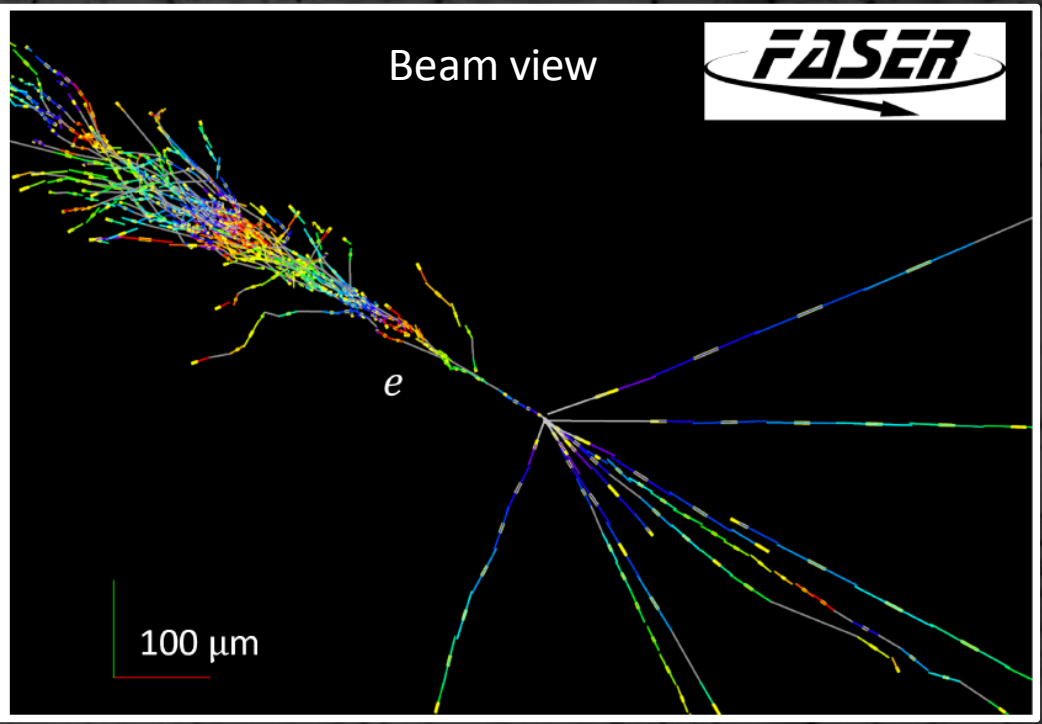
ν_e-candidate events

MC normalized to number of observed events.





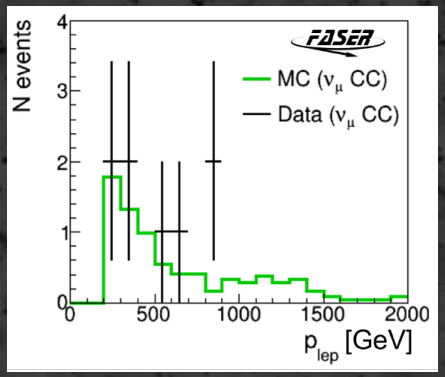


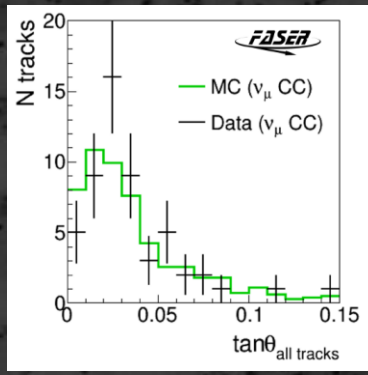


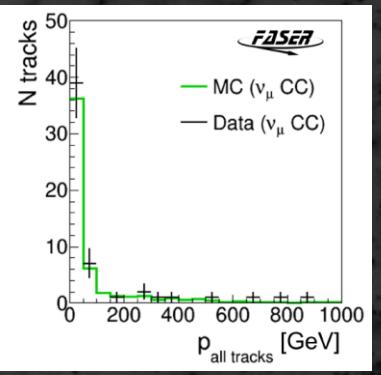
E_e=1.5 TeV, highest ν_e energy measured in accelerator-based experiments

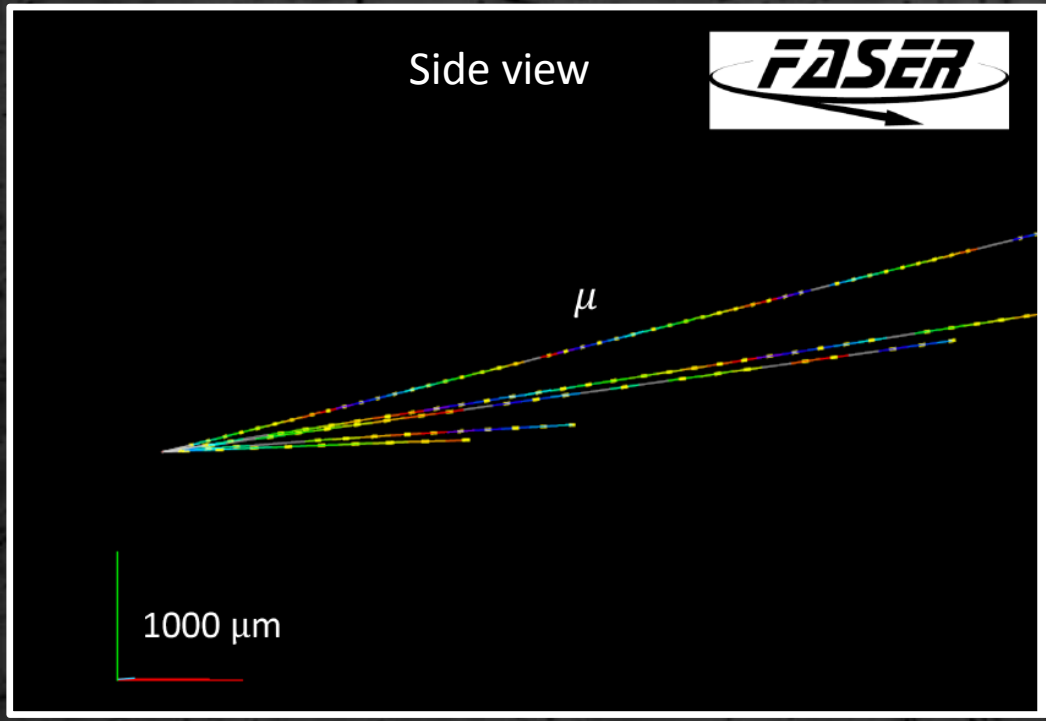
ν_μ-candidate events

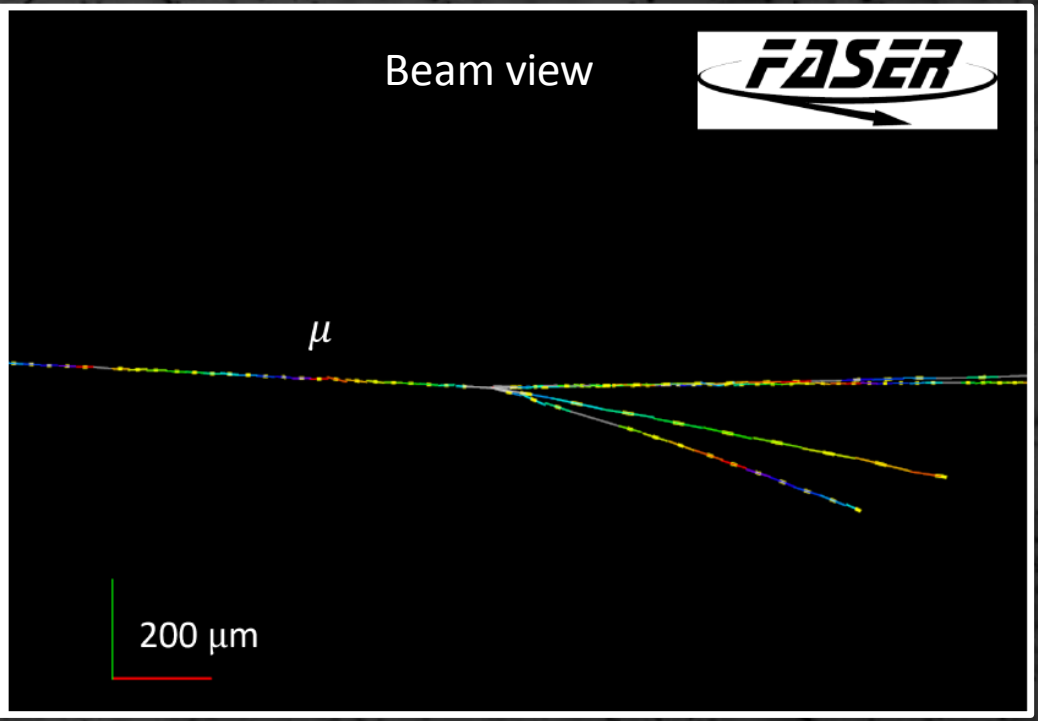
MC normalized to number of observed events.











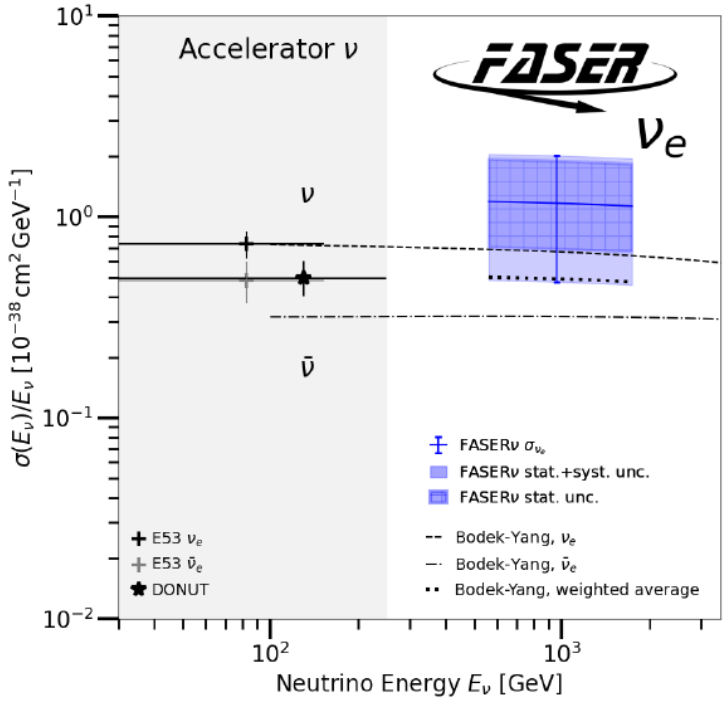
p_μ=360 GeV

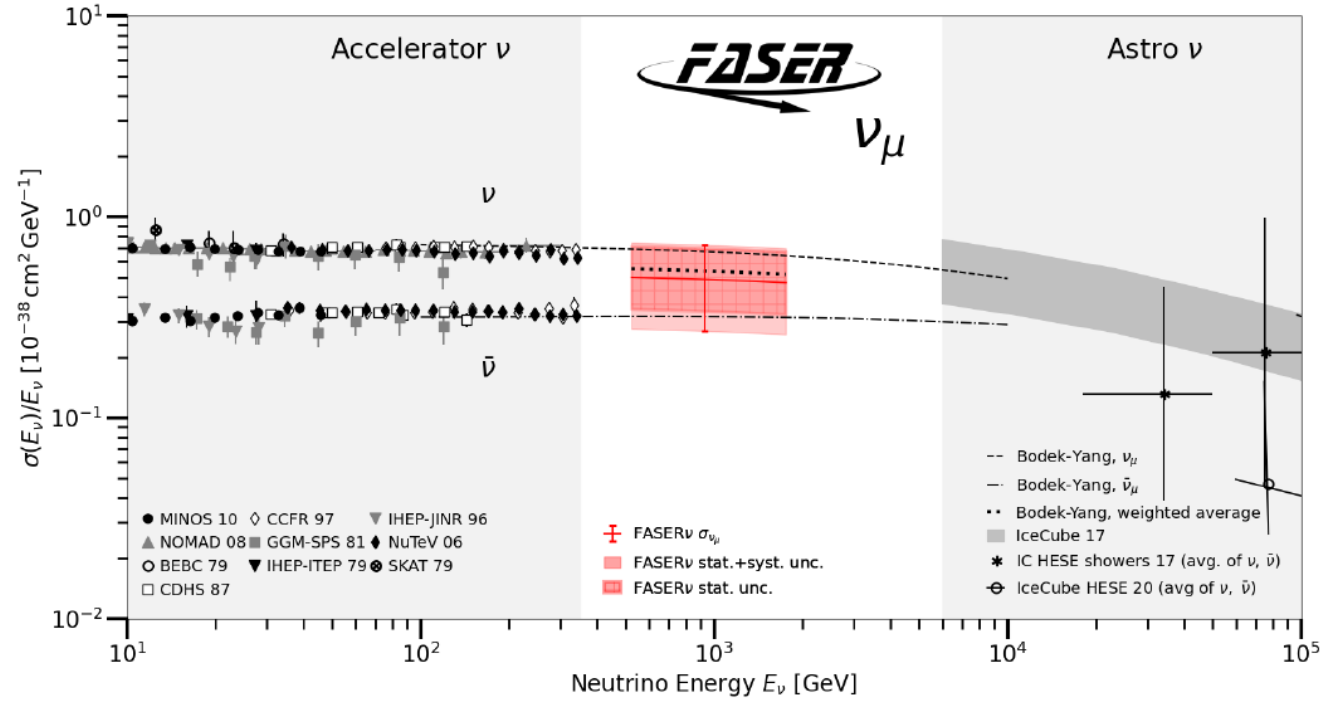
ν_e and ν_μ cross section measurements

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

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	$0.02^{+0.09}_{-0.07}$	6.5 – 12.4	8	5.7σ

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





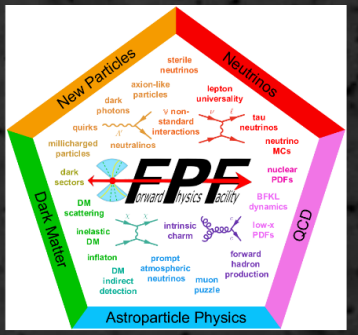
- The uncertainties dominated by neutrino flux and by data statistics (for the ν_e channel).
- Both measurements are consisted with the Standard Model.

Conclusions and outlook

- FASER is aimed to detect TeV-scale neutrinos of all 3 flavours ➔ First collider neutrino experiment!
- FASER has been successfully operating at CERN since 2022:
  - 7 FASERν modules have been irradiated, ~110 fb^{-1} collected to date, with ~140 fb^{-1} more collision data expected until the end of LHC Run 3.
- New physics results from FASERν presented ➔ First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector! These results demonstrate the ability to carry out ν measurements with emulsion-based detectors in the challenging conditions at the LHC.

Perspectives:

- FASER was approved for HL-LHC (Run 4).
- Search for signatures of physics beyond the Standard Model with FASER. See talk about new physics results by Jack MacDonald.
- Upgrade of FASER's preshower detector. See talk by Andrea Pizarro Medina.
- 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. See talk by Alan Barr.



Backup slides

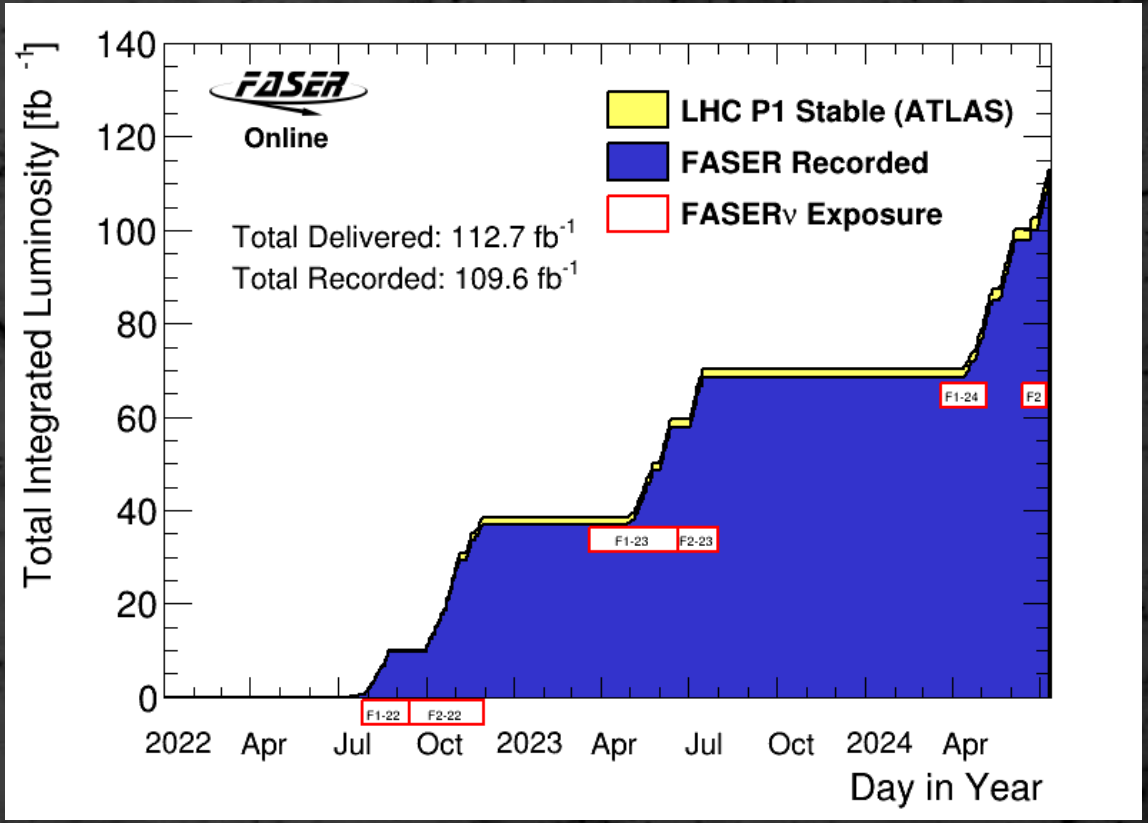
The FASER collaboration

101 collaborators, 27 institutions, 11 countries

6th FASER Collaboration meeting, 25-27 June 2024, Bonn, Germany

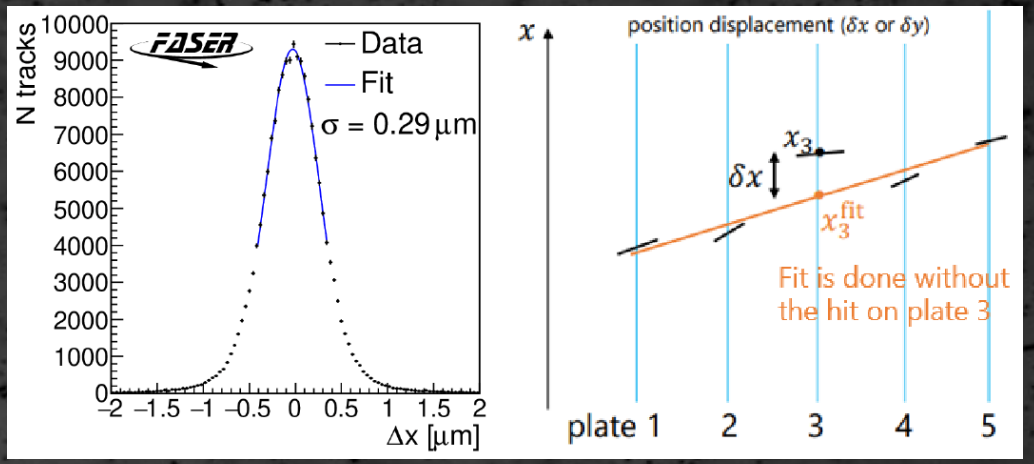
FASER during LHC Run 3

- Successful running since 2022.
- Very high (97%) data-taking efficiency and excellent detector performance.
- Exchanges of FASERν modules due to occupancy in emulsion: 7 times so far.



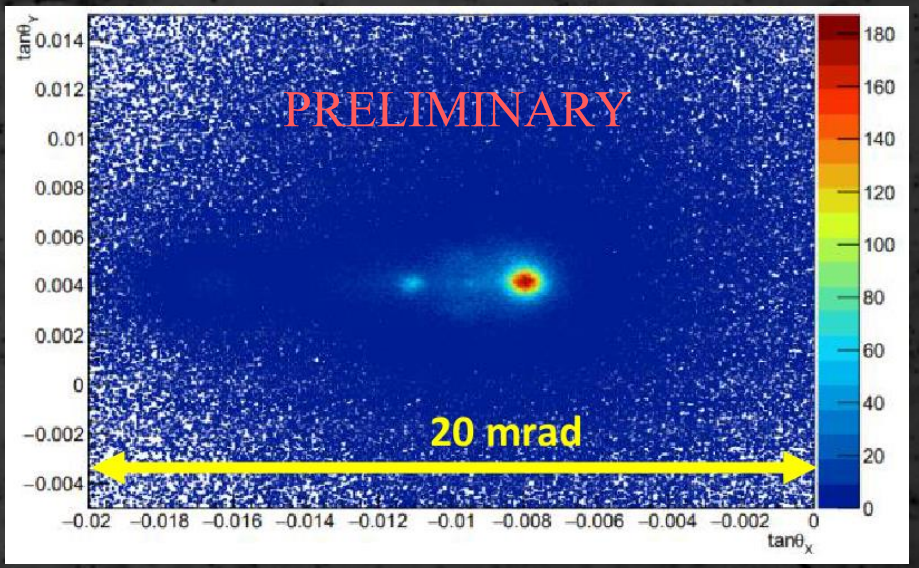
FASERν performance

- 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/cm^2).



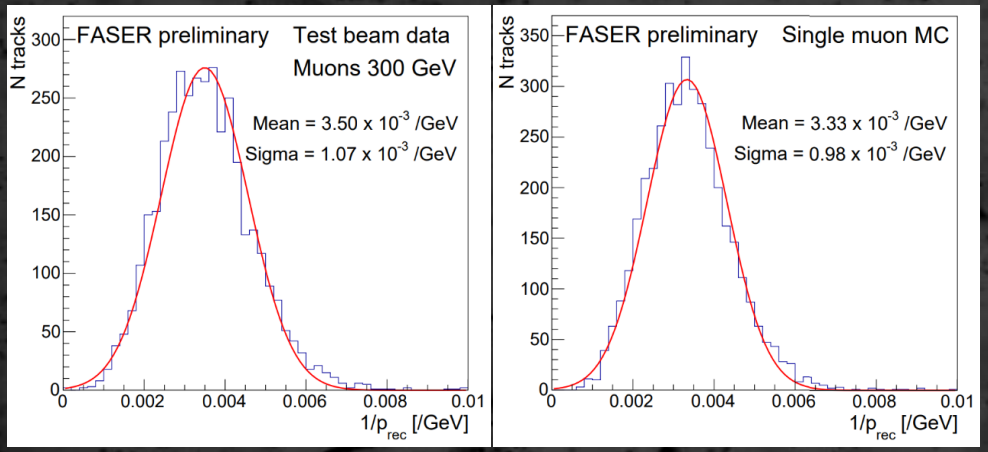
- Angular resolution for track of length ~1 cm: ~0.04 mrad.
- Angular spread of muon peaks: ~0.4 mrad.

Background muon slopes (data)

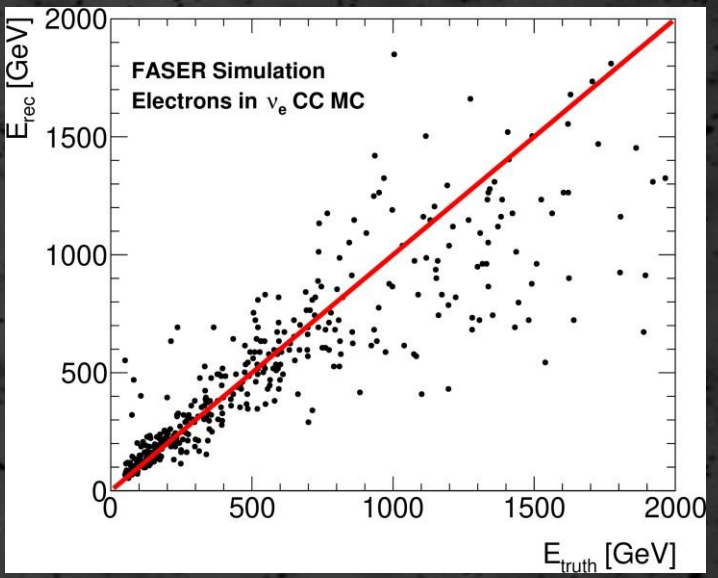


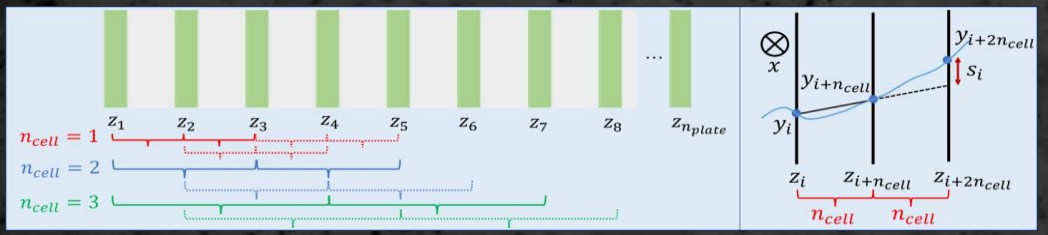
FASERν kinematical measurements

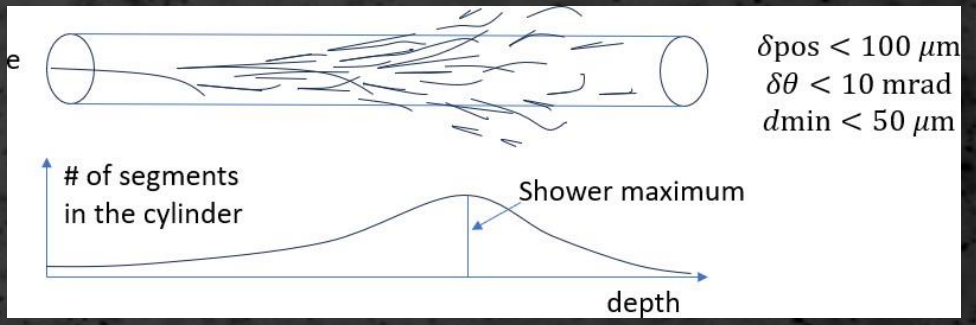
- Particle momenta calculated using multiple Coulomb scattering (MCS) via the Coordinate Method (works well even for P > 1 TeV/c).
- Muon momentum: $\Delta P^{RMS}/P \approx 0.3$ at 200 GeV/c.



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





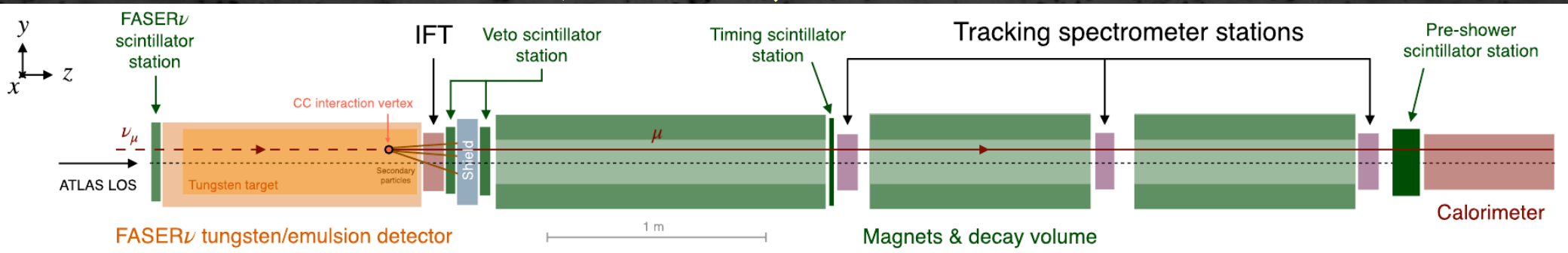


Search for neutrino using electronic detectors

Selection criteria:

- Collision events with good data quality (35.4 fb^{-1}) in 2022
- FASERν as target

- No signal (<40 pC)
- Signal (>40 pC)



- Timing and pre-shower consistent with ≥1 MIP
- Exactly 1 good track (r_{max} < 95 mm) in spectrometer fiducial tracking volume:
  - p > 100 GeV and θ < 25 mrad
  - Extrapolating to r < 120 mm in front veto station

151 ± 41 neutrino events expected from simulation:

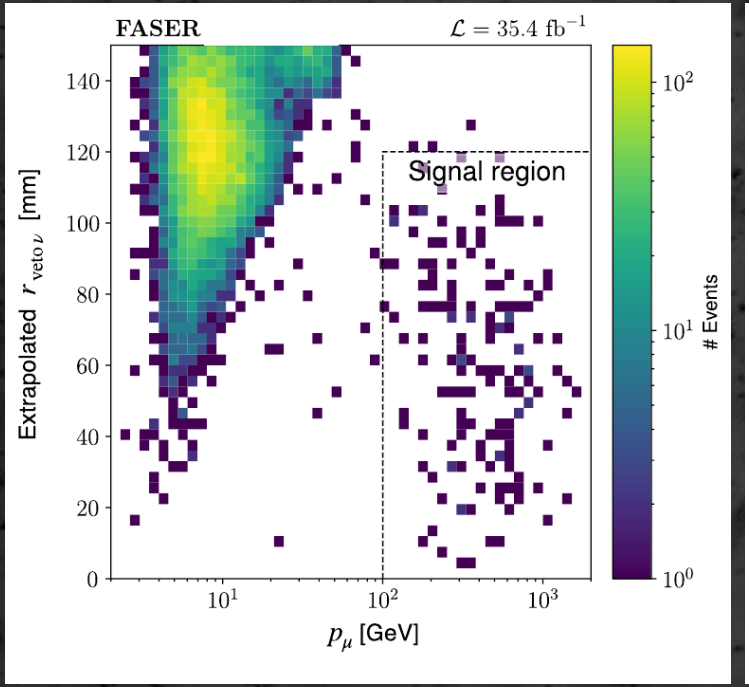
- Uncertainty from difference between generators (DPMJET & SIBYLL)
- No experimental errors were included

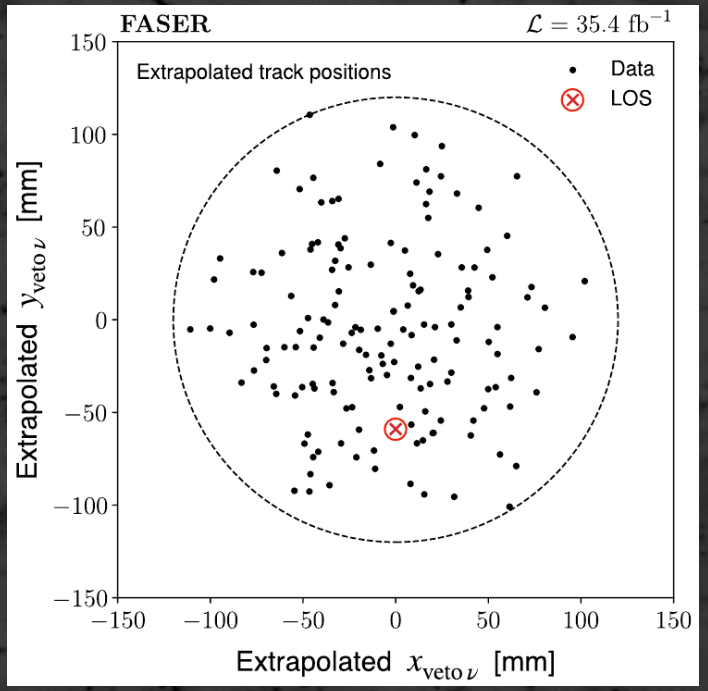
Search for neutrino using electronic detectors

Results:

- 153^{+12}_{-13} neutrino events observed (both ν_μ and $\bar{\nu}_\mu$):
  - Corresponds to 16σ
  - First direct observation of collider neutrinos

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





n_0: A neutrino enriched category from events that pass all event selection steps.

n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.

n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

n_2: Events for which both layers observe more than 40 pC of charge.

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