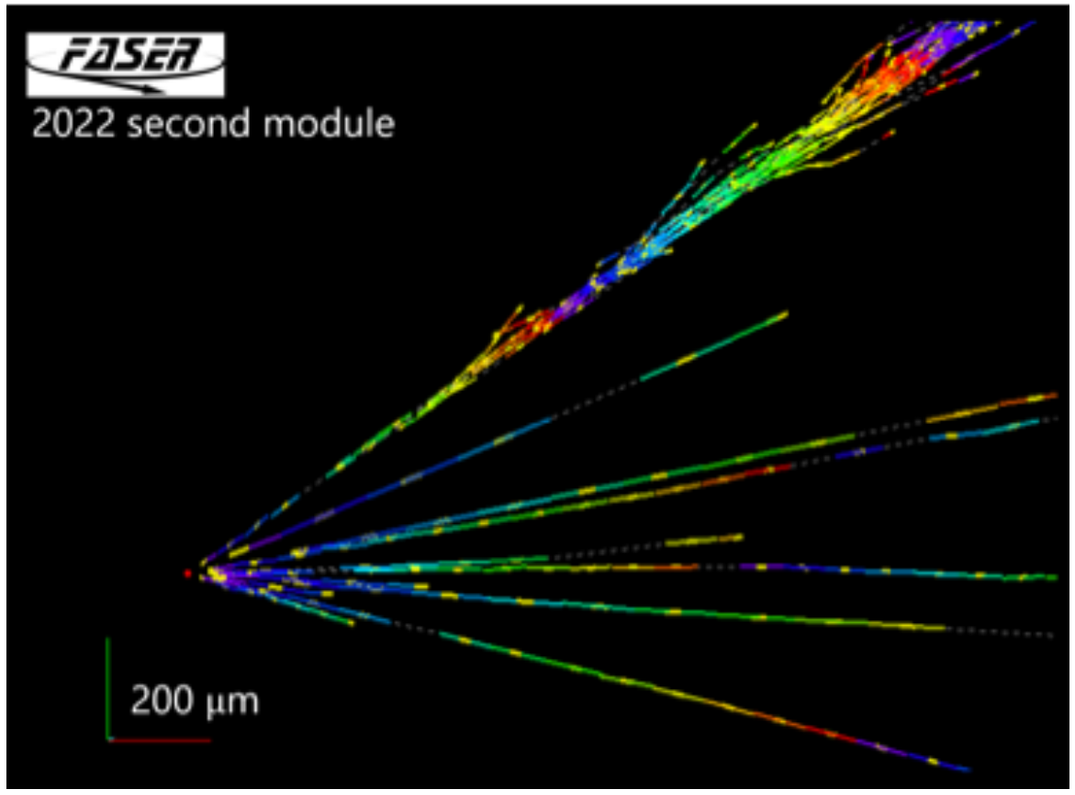
Neutrino Physics with the FASER experiment

Enrique Kajomovitz Ken
Technion

Outline

- Neutrinos at the LHC
- FASER detector
  - Emulsion detector
- FASER neutrino measurements
  - Electronic detector
  - Emulsion detector
- Summary



LHC neutrinos

- LHC's *pp* inelastic cross section is huge:

  $\sigma_{\text{inel}}(13\text{TeV}) \sim 75\text{mb}$

  - Wealth of pions, kaons, Hyperions, and other hadrons produced in the very forward direction $\theta \sim \Lambda_{\text{QCD}}/E$

- Hadron decays produce a beam of high-energy neutrinos in the very forward direction around the IPs 1908.02310

  - All neutrino species

- Carry QCD information

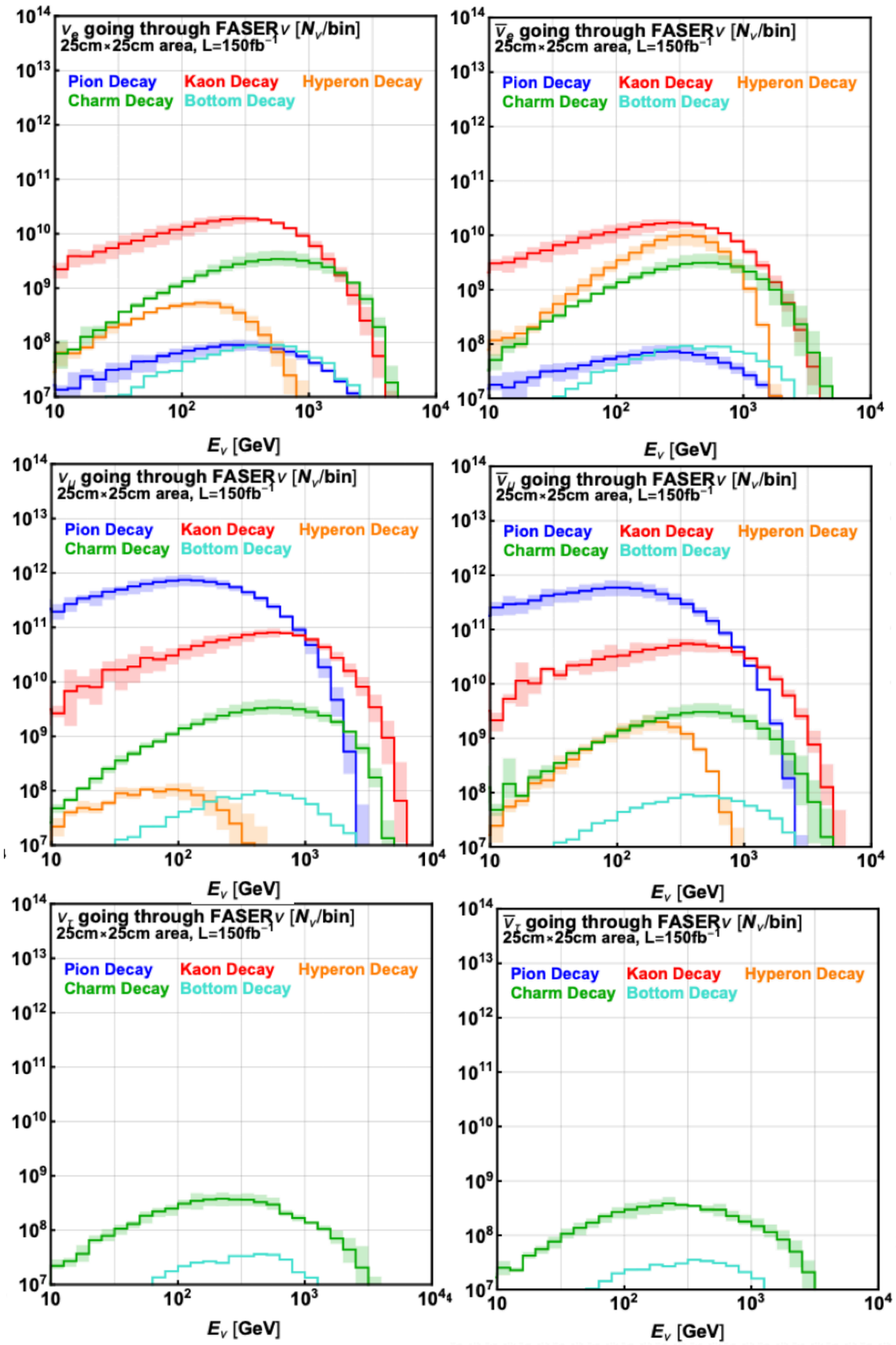
  - Constraints to proton PDF

- Unexplored cross sections range

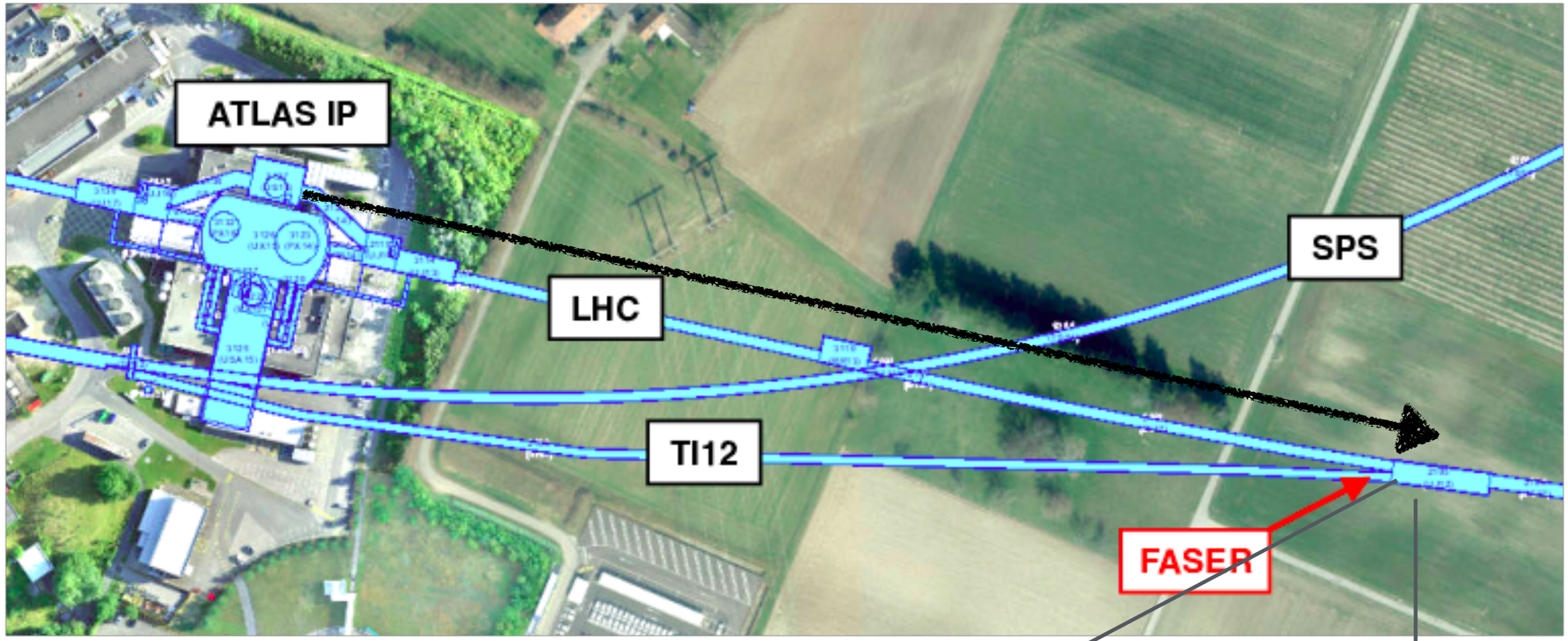
  - Neutrino cross sections in for TeV neutrinos

- Nuclear matter interaction

  - Shed light nuclear matter interaction during hadronization

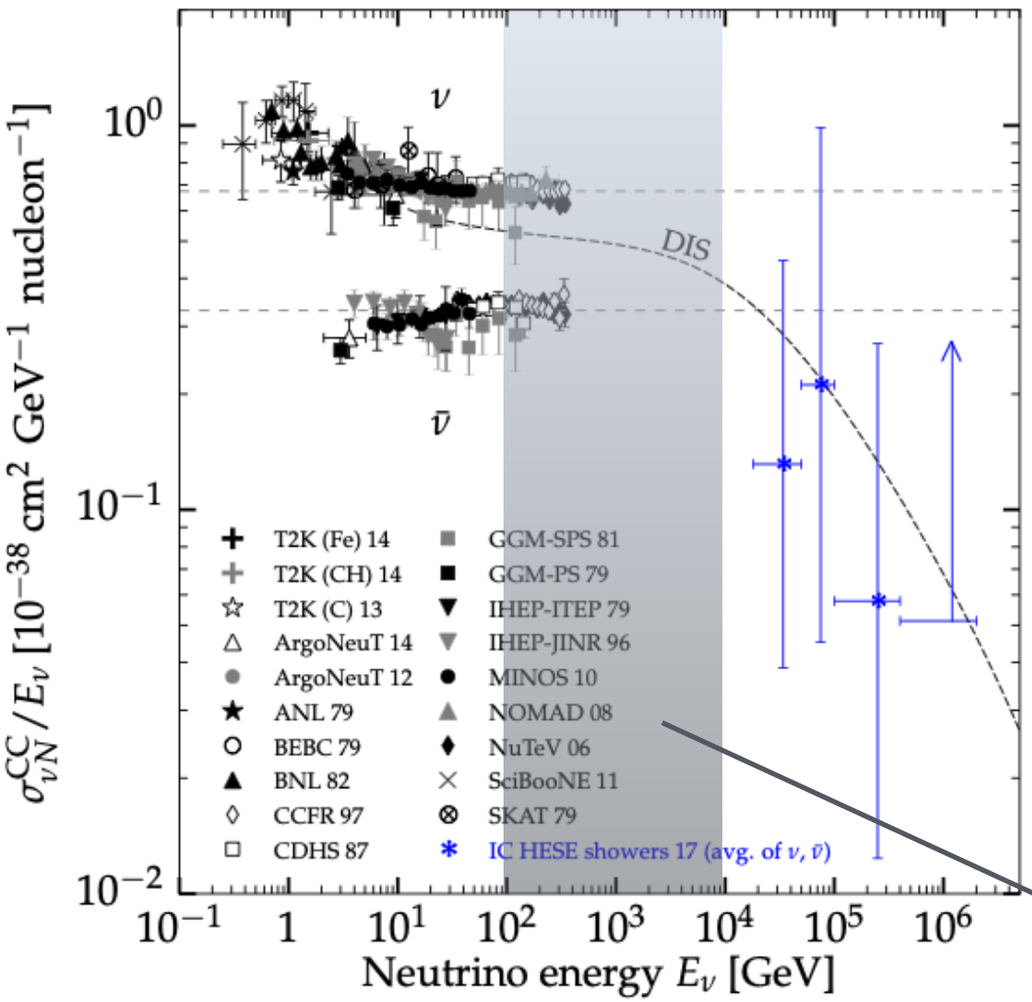


Detecting forward neutrinos



1.1 ton Instrumented target

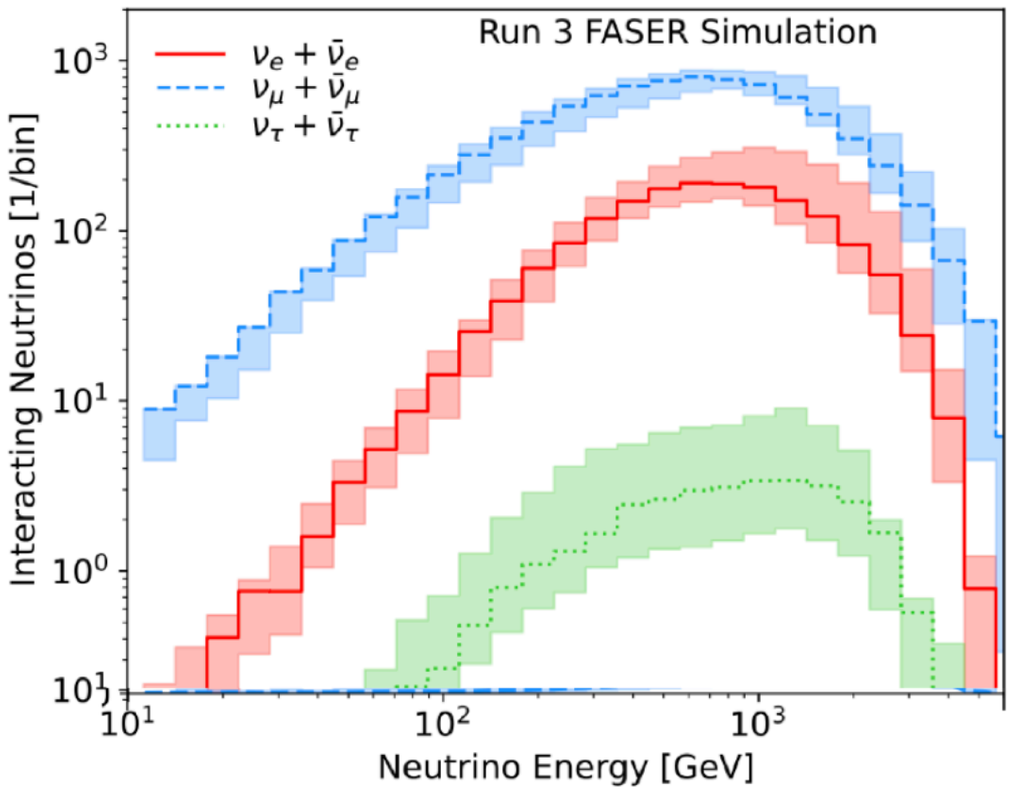
TeV neutrino interactions - an unexplored regime



1711.11043

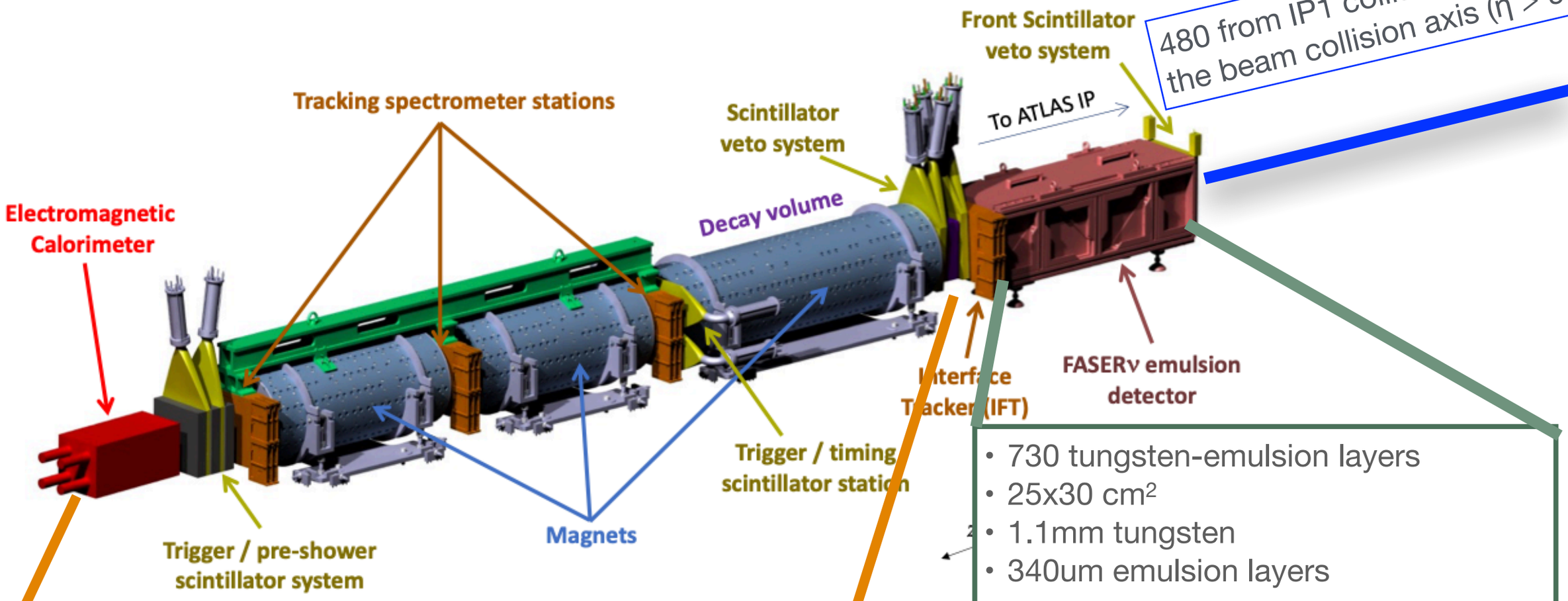
Run-3 expected (250/fb)

- 8500 muon neutrino interactions
- 1700 electron neutrino interactions
- 30 tau neutrino interactions



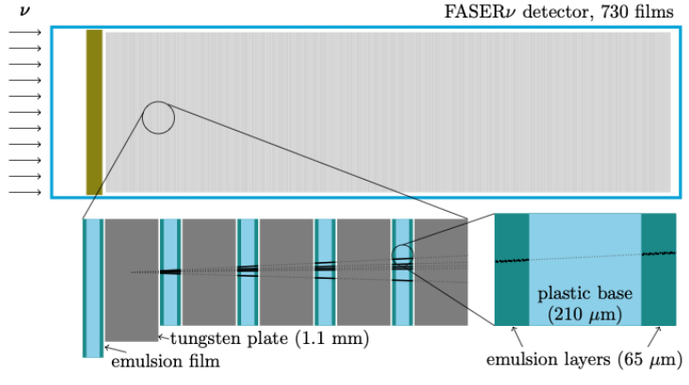
2402.13318

The FASER experiment

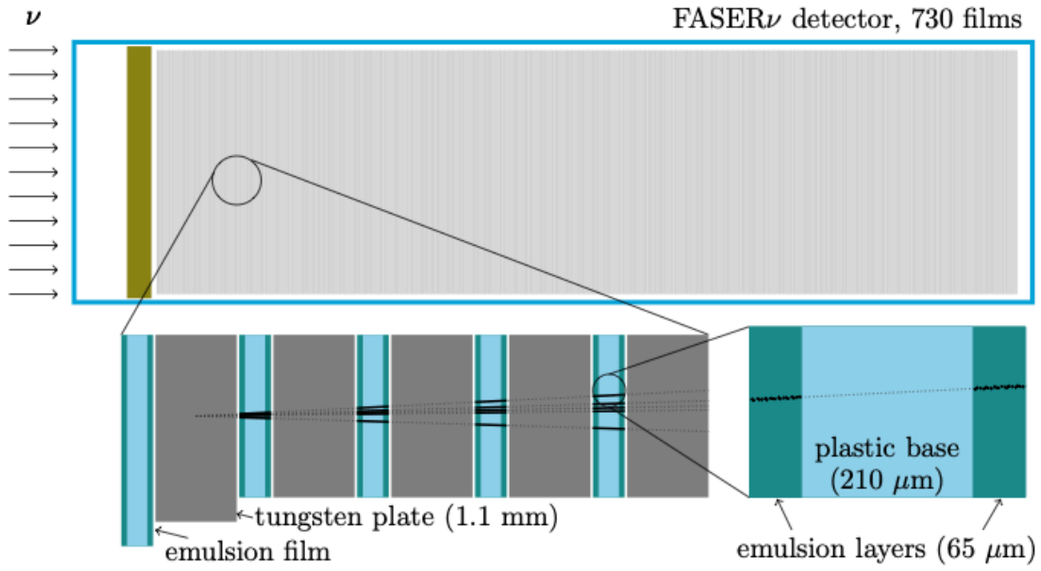


- 0.6T permanent dipole magnets
- 1.5m long decay volume
- 2.5m long tracker (96 ATLAS SCTs)
- Scintillators for veto, trigger, and
- Preshower (particle ID)
- 4 LHCb calorimeter modules

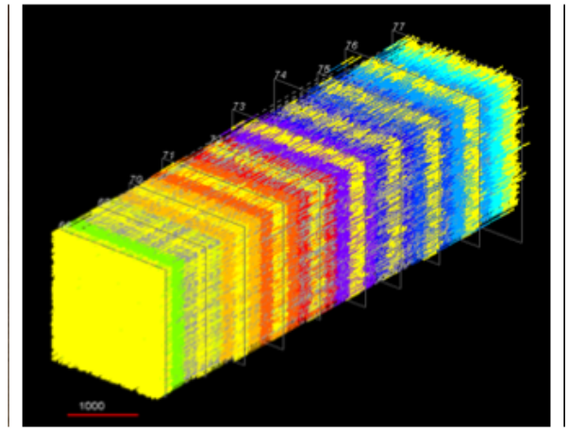
- 730 tungsten-emulsion layers
- 25x30 cm^2
- 1.1mm tungsten
- 340um emulsion layers

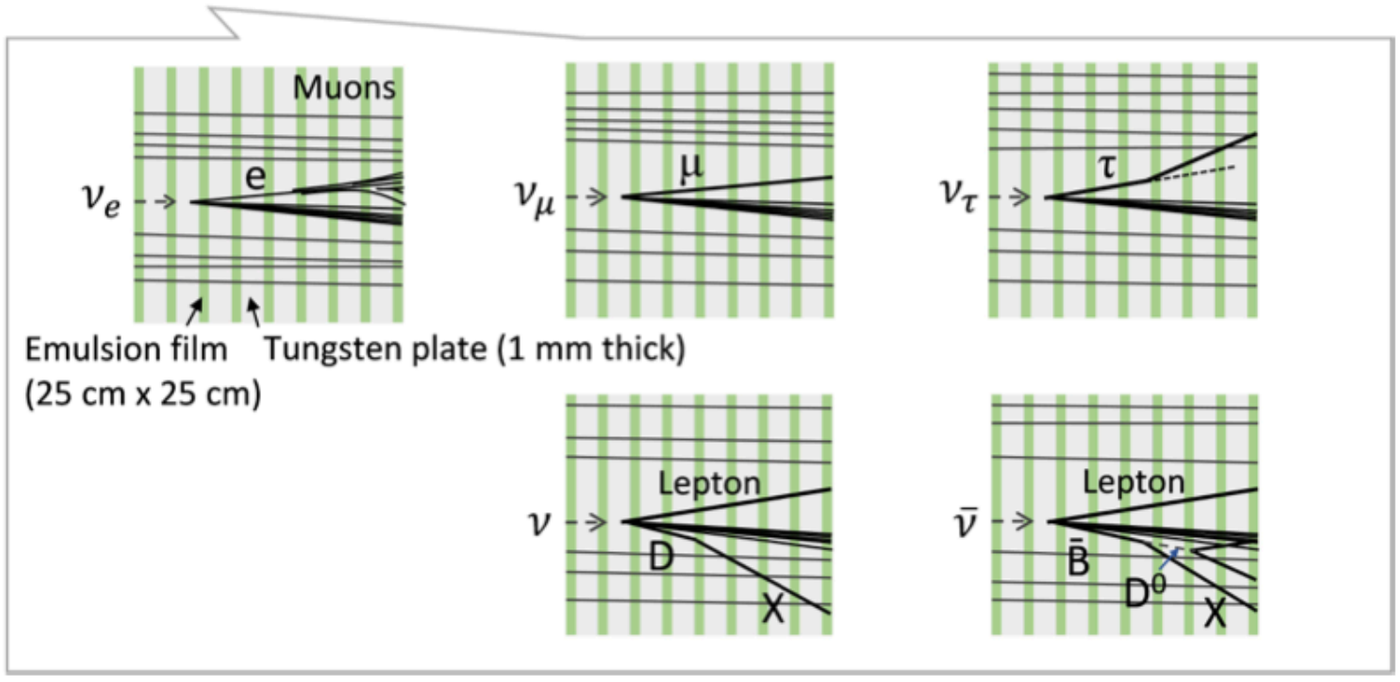


FASERν - Emulsion detector



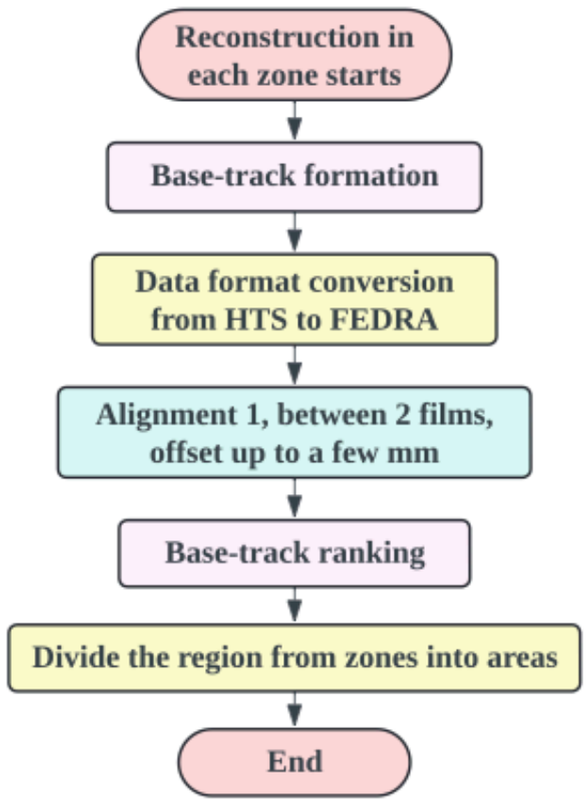
- 730 tungsten-emulsion layers
- 25x30 cm^2
- 1.1mm tungsten
- 65+210+65 (um) emulsion layers
- Pros:
  - Extremely precise in spatial resolution (0.3um)
  - Neutrino flavor tagging
- Cons:
  - No time resolution
  - Needs to be changed every 3 months
  - Long processing time

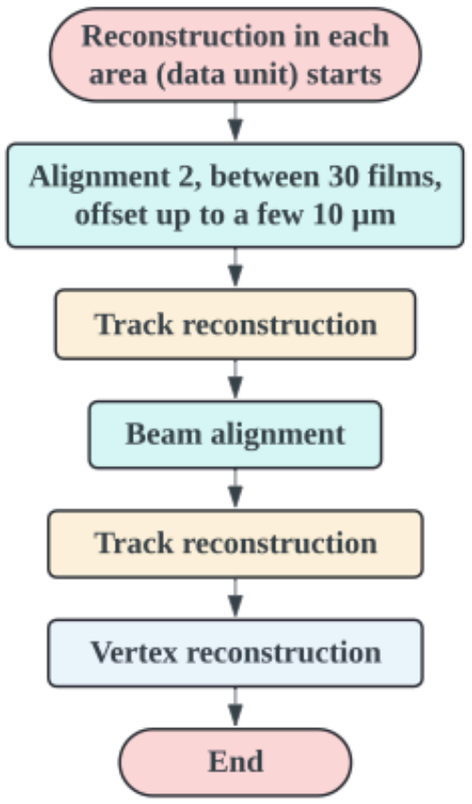


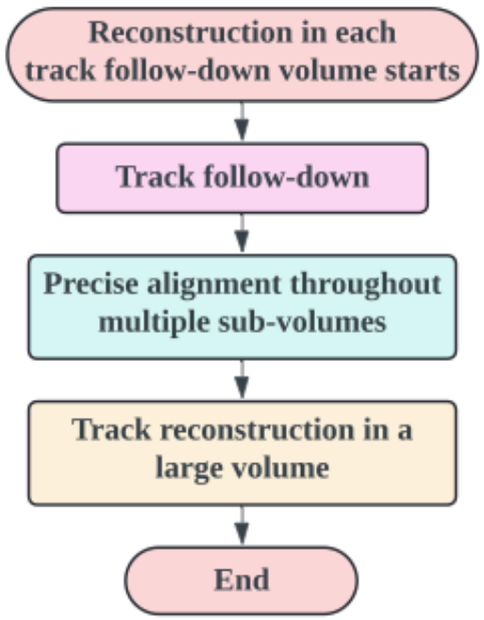


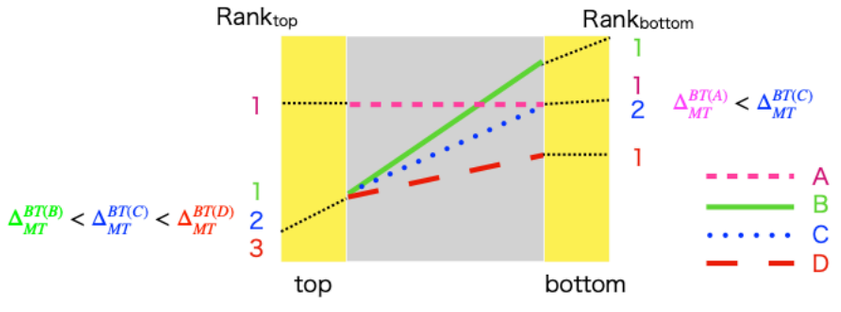
Reconstruction with the emulsion detector

2504.13008



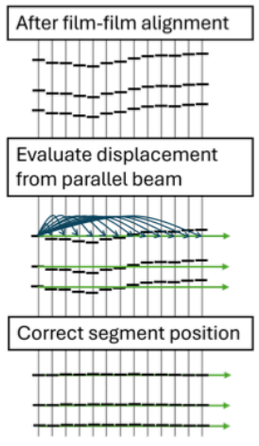


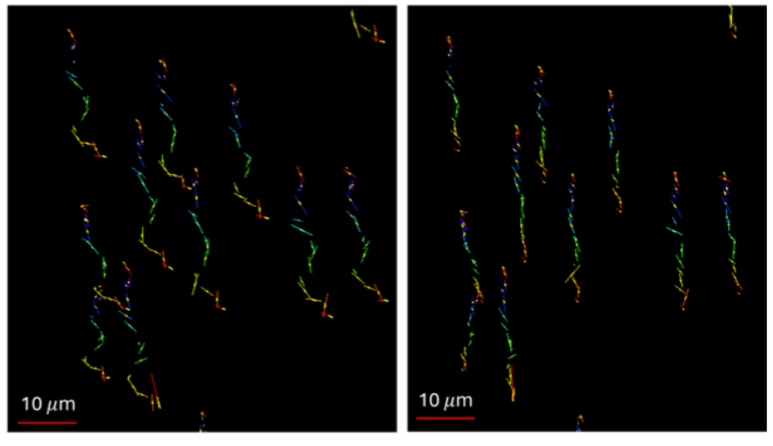




$$\begin{pmatrix} x_{2\,\mathrm{on}\,1} \\ y_{2\,\mathrm{on}\,1} \end{pmatrix} = \begin{pmatrix} a_{2\to1} & b_{2\to1} \\ c_{2\to1} & d_{2\to1} \end{pmatrix} \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} + \begin{pmatrix} p_{2\to1} \\ q_{2\to1} \end{pmatrix},$$

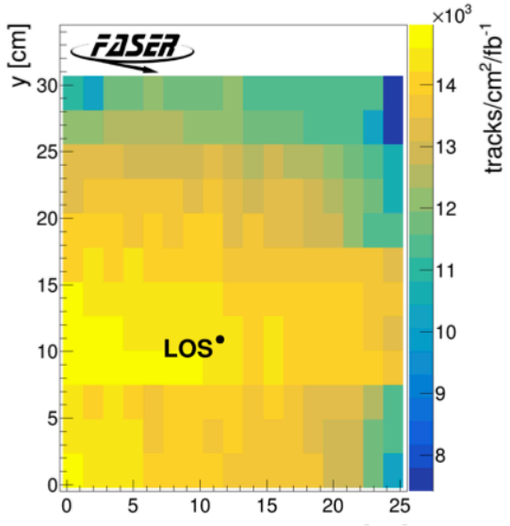
$$z_{2\,\mathrm{on}\,1} = z_2 + \Delta z_{2\to1}.$$

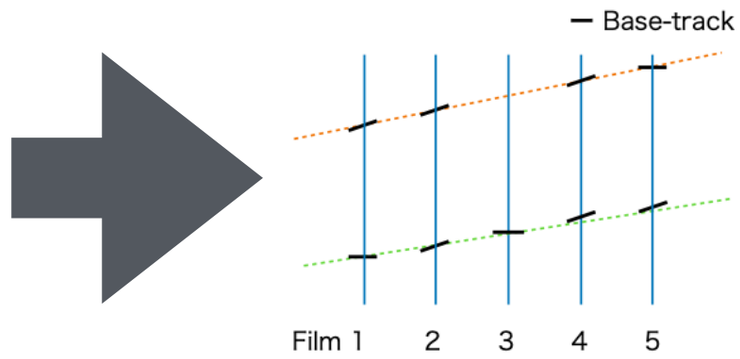


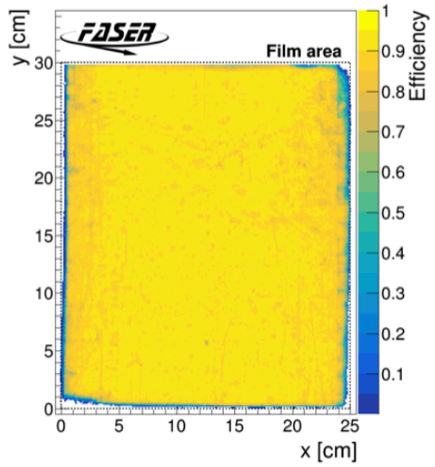


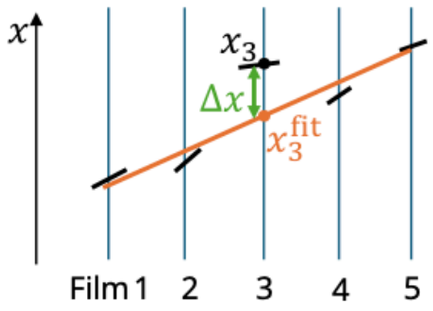
Performance

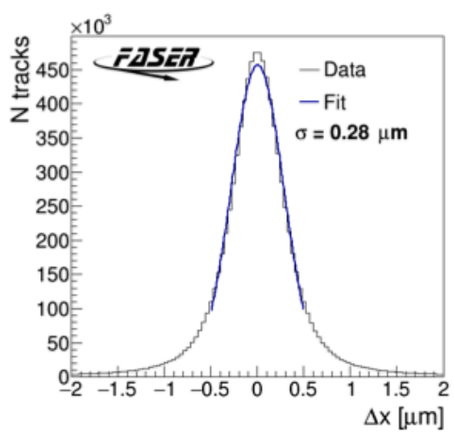
2504.13008

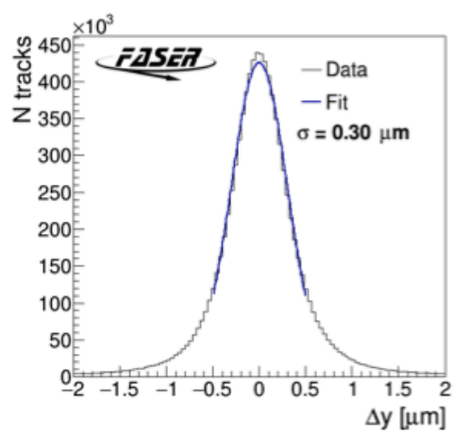


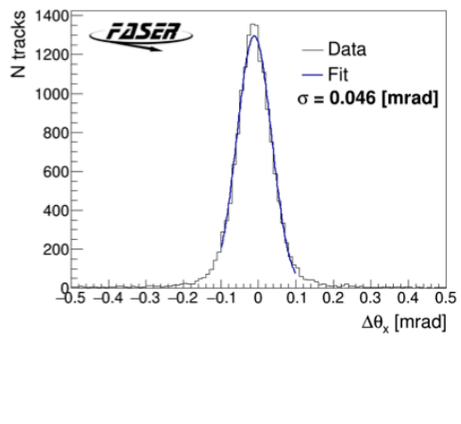


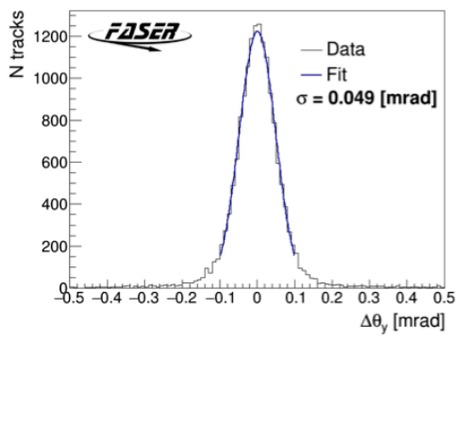










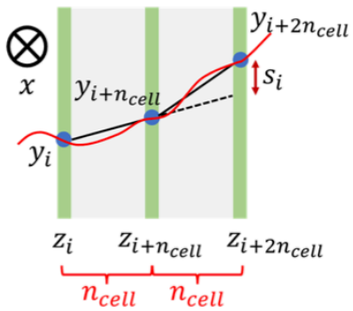


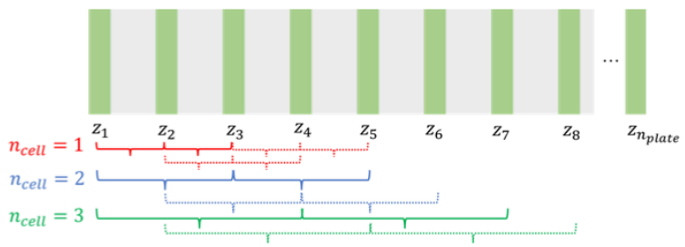
Momentum reconstruction in the emulsion detector

2602.17575

Based on multiple coulomb scattering

$$\theta_{\text{plane}}^{\text{RMS}} = \frac{0.0136\ \text{GeV}}{\beta pc}\sqrt{\frac{z}{X_0}}\left\{1 + 0.038\ln\left(\frac{z}{X_0\beta^2}\right)\right\}.$$

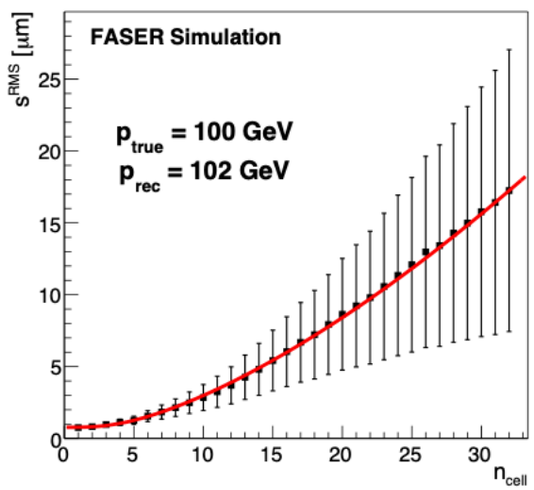


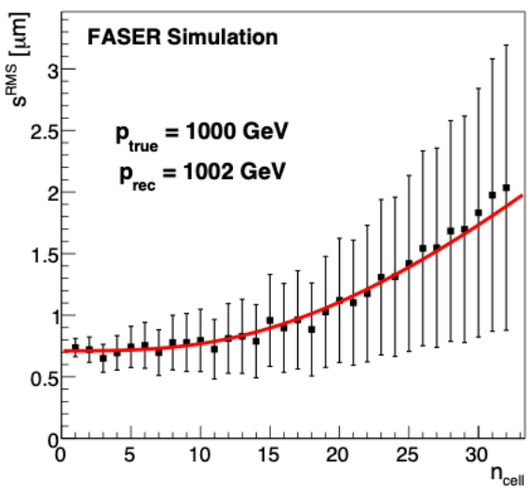


$$s_{\text{MCS}}^{\text{RMS}}(p, n_{\text{cell}}) = \sqrt{\frac{2}{3}}\cdot\frac{0.0136\ \text{GeV}}{\beta pc}\cdot z_{n_{\text{cell}}}\sqrt{\frac{z_{n_{\text{cell}}}}{X_c}}\left\{1 + 0.038\ln\left(\frac{z_{n_{\text{cell}}}}{X_c\beta^2}\right)\right\}.$$

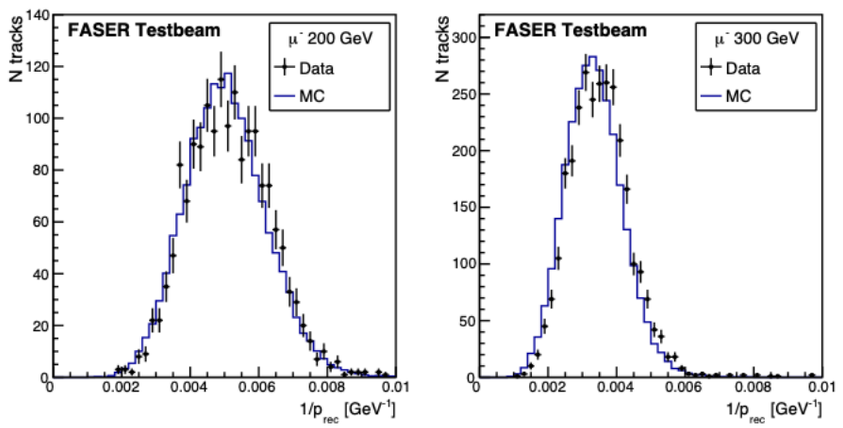
Measure: $s^{\text{RMS}} = \sqrt{\left(s_{\text{MCS}}^{\text{RMS}}(p, n_{\text{cell}})\right)^2 + 6\,\sigma_{\text{pos}}^2}.$

$$w(n_{\text{cell}}) = \frac{\sqrt{(n_{\text{plate}} - 1)/n_{\text{cell}}}}{s^{\text{RMS}}}.$$





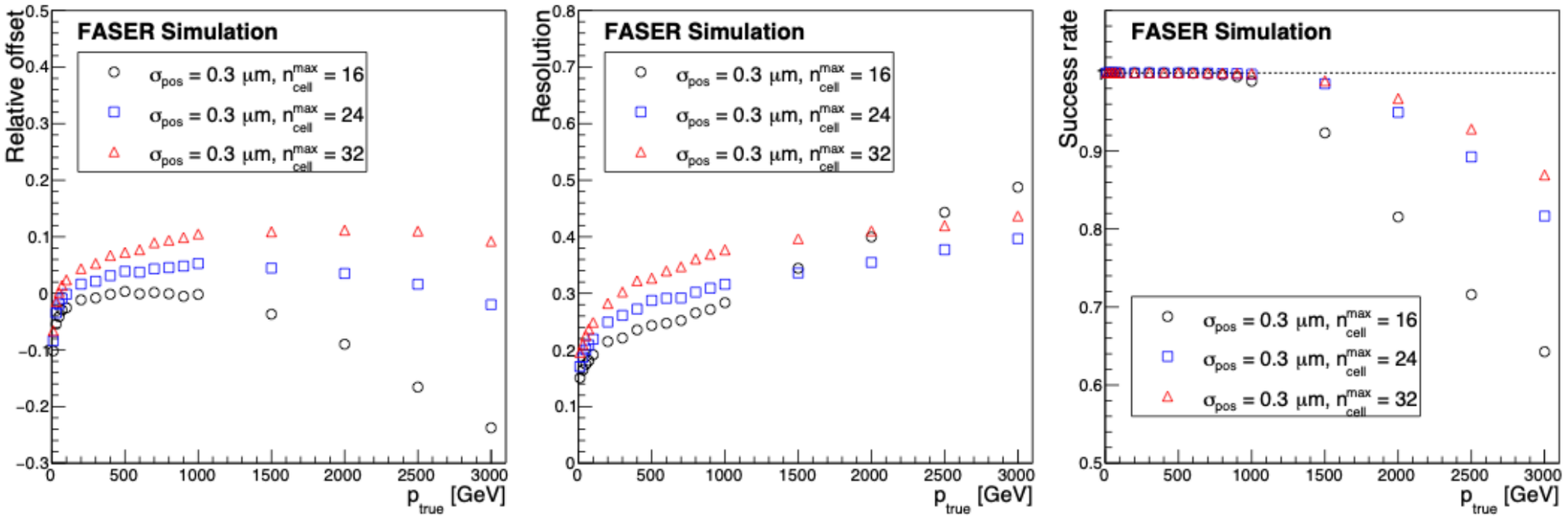
Test beam



Beam momentum	p_{center} [GeV] (Data)	p_{center} [GeV] (MC)	Resolution [%] (Data)	Resolution [%] (MC)
100 GeV	$98.1^{+4.6}_{-4.3}$	$98.4^{+0.1}_{-0.1}$	20.7±0.6	20.7±0.1
200 GeV	$195.2^{+9.3}_{-8.5}$	$198.7^{+0.2}_{-0.2}$	22.7±0.6	22.6±0.1
300 GeV	$286.6^{+13.5}_{-12.4}$	$299.7^{+0.4}_{-0.3}$	23.2±0.4	24.2±0.1

Momentum reconstruction performance with the emulsion detector

2602.17575

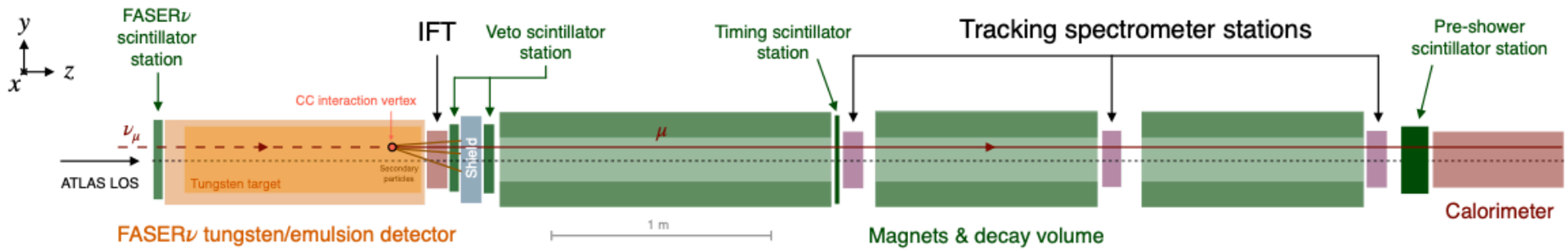


Neutrino measurements with FASER

Electronic detector

Muon neutrino with FASER's electronic detector

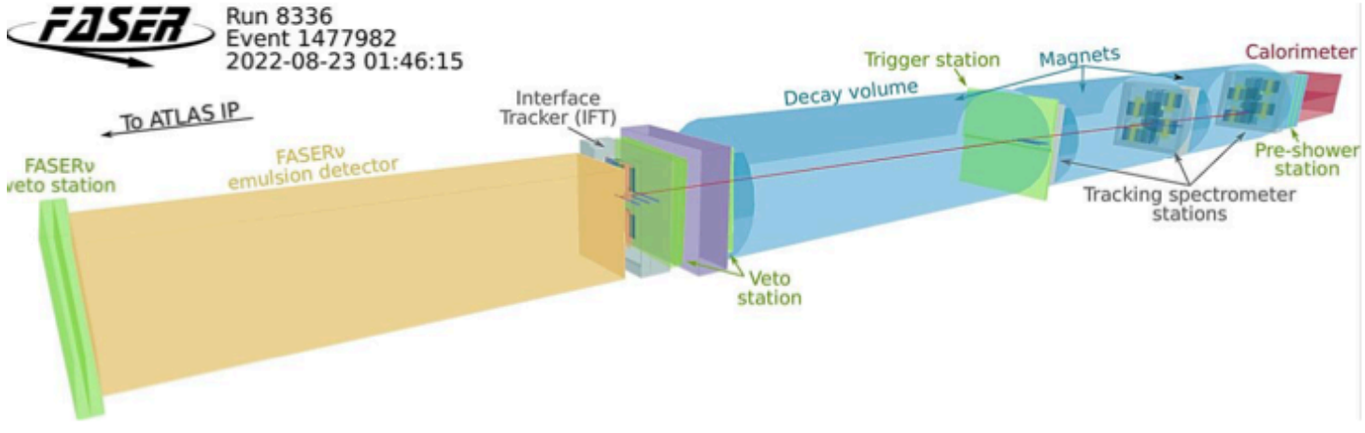
2303.14185



Only for $\nu\mu$ interactions

- No hit in veto planes
- Good spectrometer track
- MIP-like signal in downstream scintillators

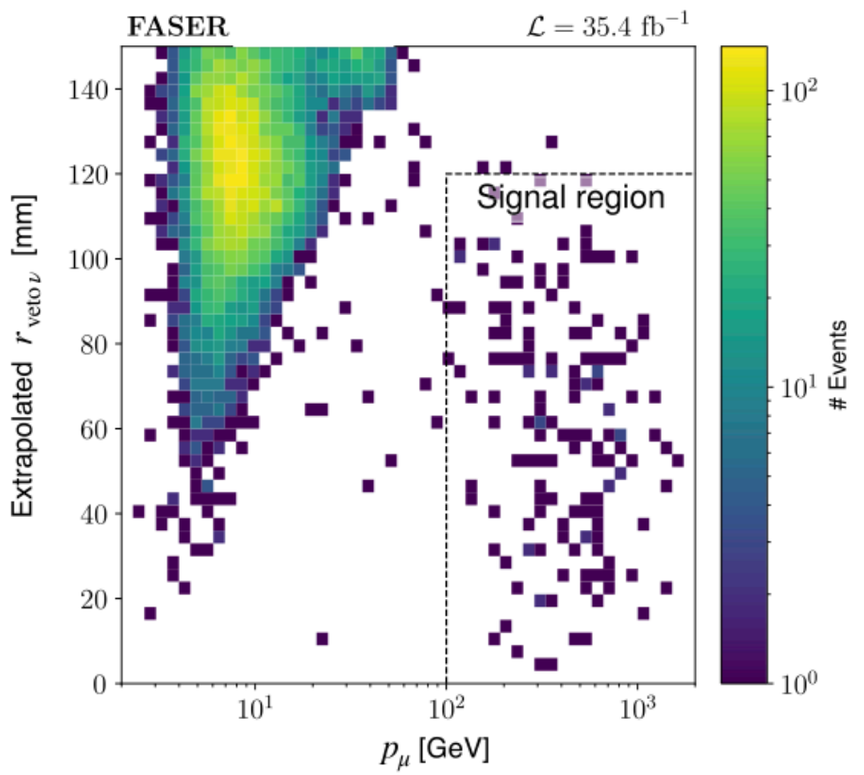
- Interface Tracker (IFT) designed to match events observed with vertices in FASERν
- Can distinguish between neutrinos and anti-neutrinos

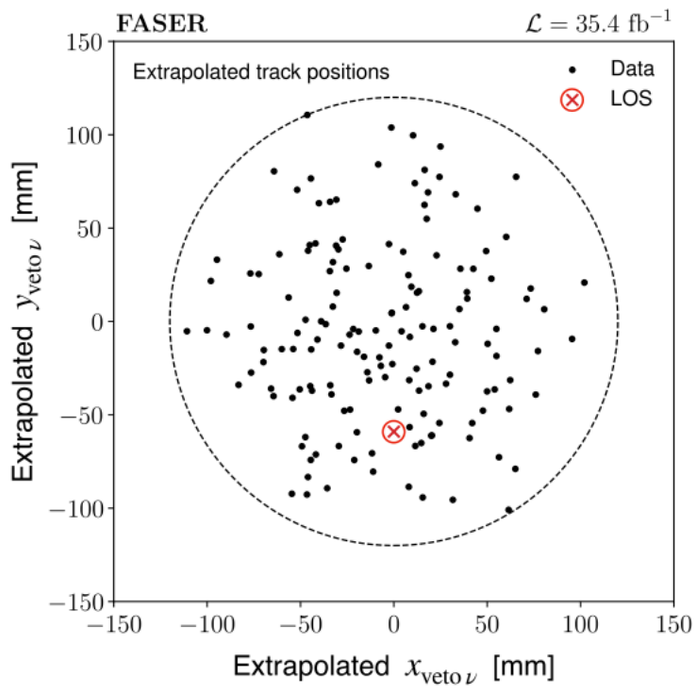


Muon neutrino with FASER's electronic detector

2303.14185

- Simulation: Expected 151 +/- 41 events
  - Error is the difference between two generators
- Observed: 153 $^{+12}_{-13}$
- Backgrounds
  - Neutral hadrons decaying to muons within FASER volume (0.11 +/- 0.08)
  - Scattered muons into FASER volume (0.08 +/- 1.83)
  - Veto inefficiency (negligible)

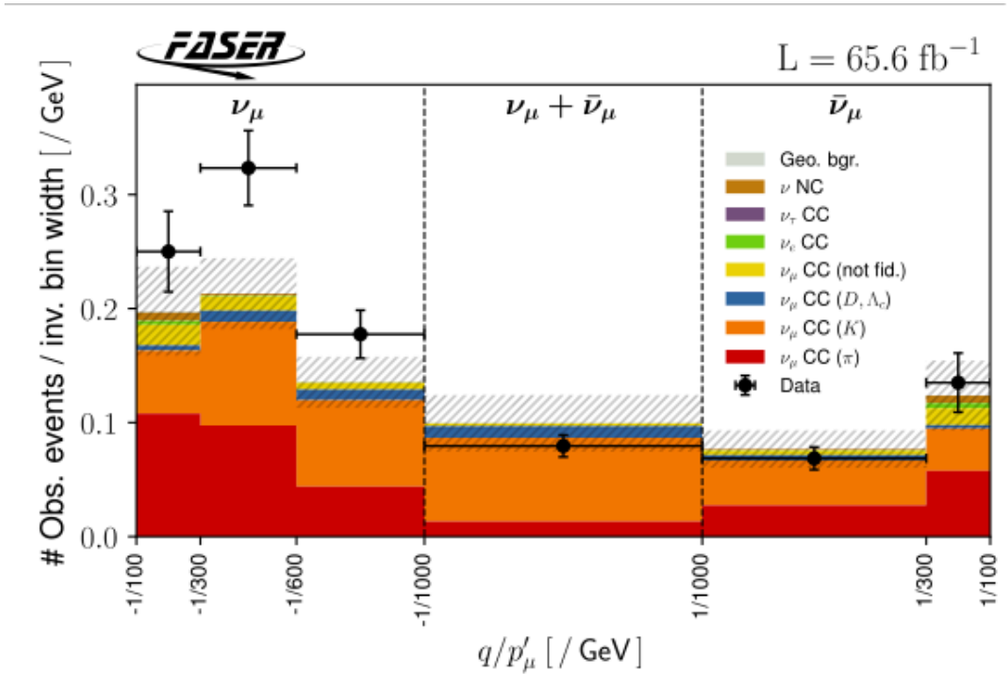


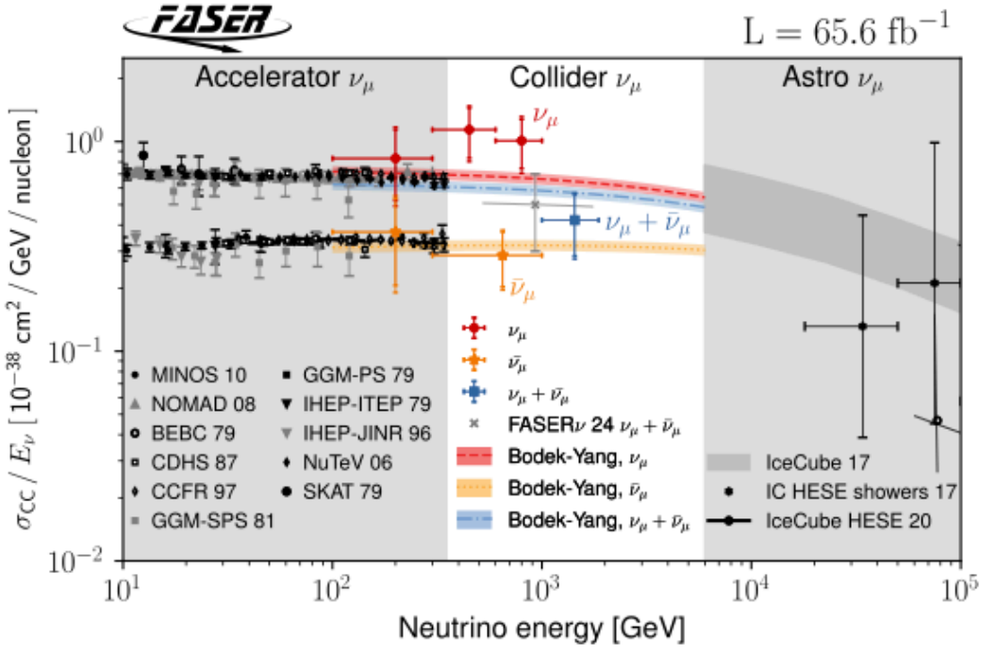


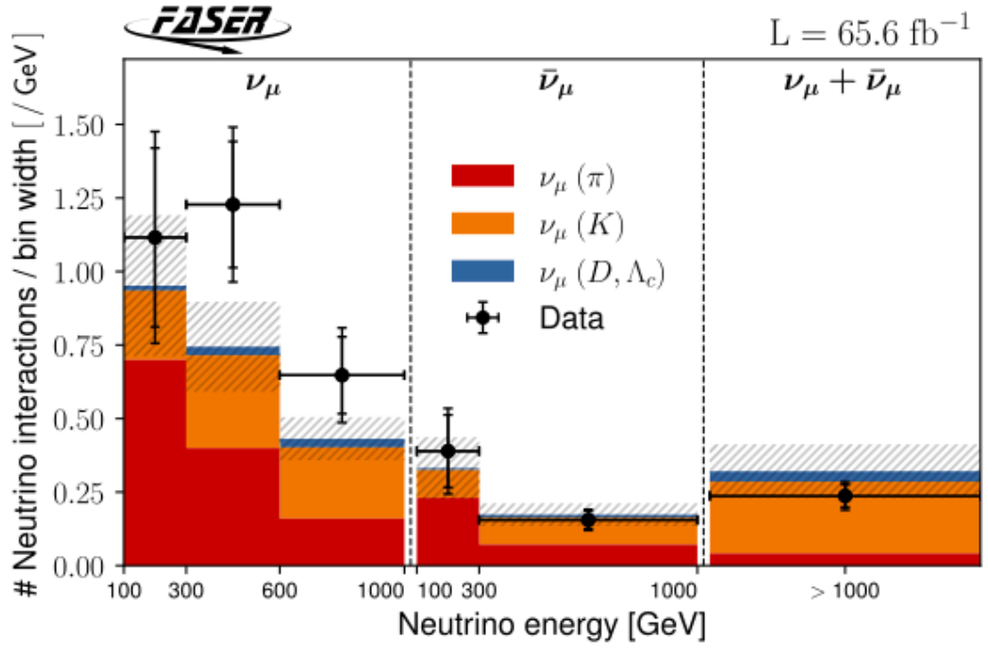
Muon neutrino interaction and flux as a function of energy

2412.03186

- Differential cross section measurement using electronic detector
- Integrated Luminosity 65.1/fb
- Unfolds muon energy to obtain original neutrino energy
- Nobs = 338 +/- 19 (stat) +/- 8.8 (syst)



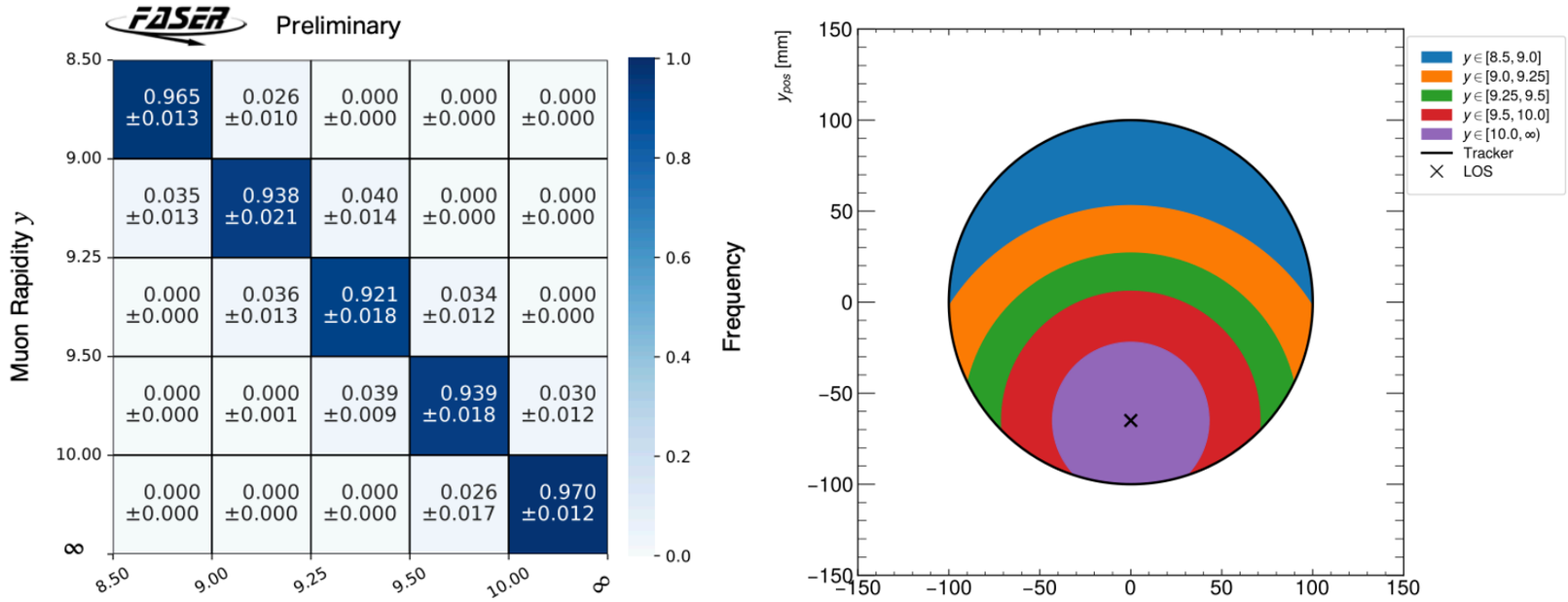




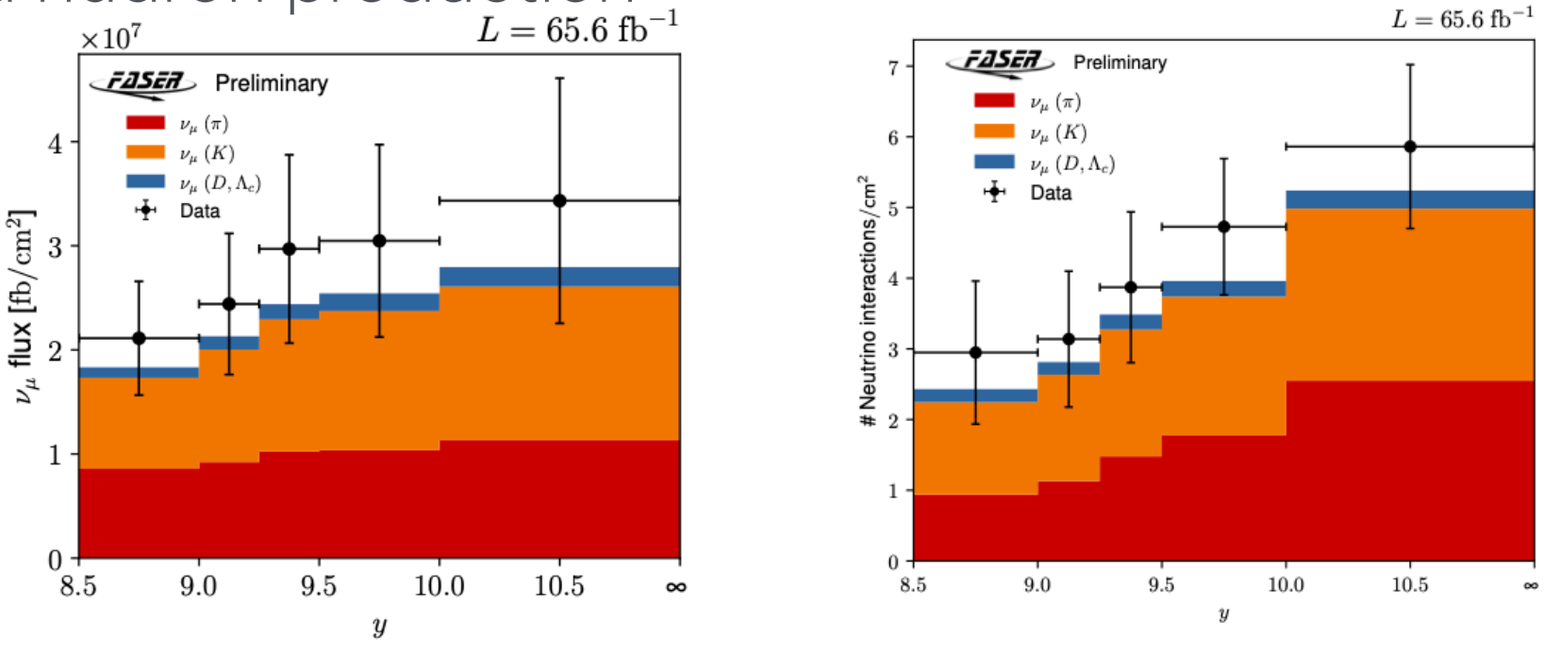
Muon neutrino flux as a function of rapidity

Preliminary result

Muon angle is mapped to the neutrino production rapidity



With current data can already begin constraining models for forward hadron production



Neutrino measurements with FASER

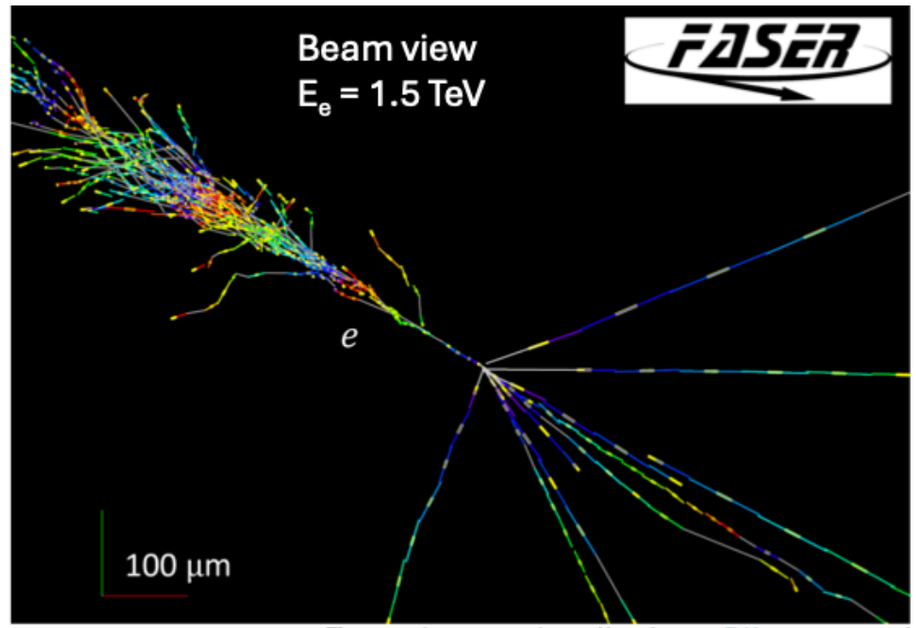
Emulsion detector

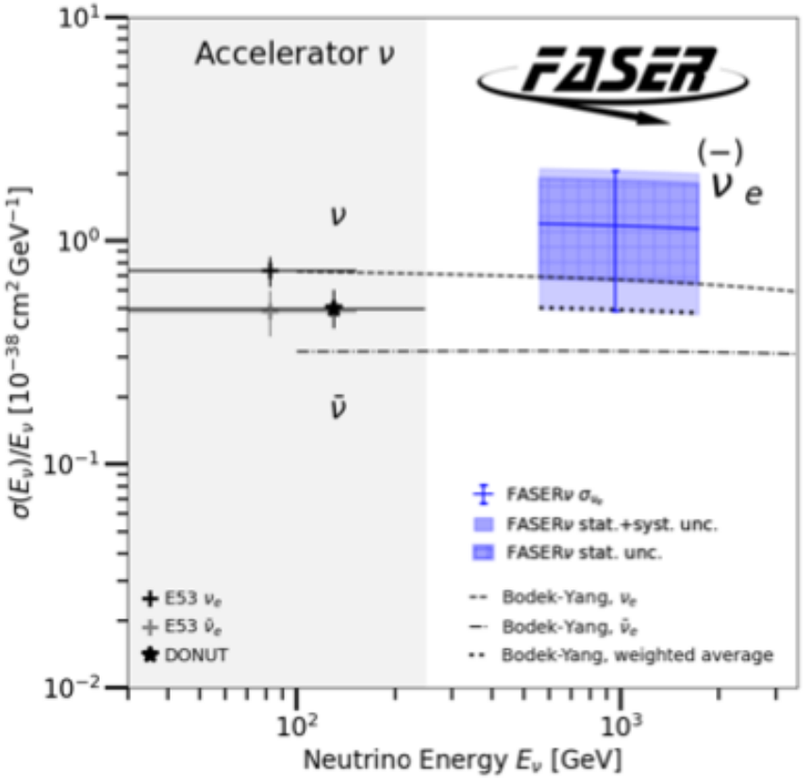
First ν_e observation

2403.12520

- Dataset:
  - Second module from 2022 → 9.5/fb
  - Target mass = 128.6 kg
- Selection Criteria:
  - CC neutral vertices with >4 tracks
  - $E_{electron}$ > 200 GeV
  - Back-to-back topology
- Background events rejected by kinematic variables

Background: $0.025^{+0.015}_{-0.010}$
Expected: 1.1-3.3
Observed: 4



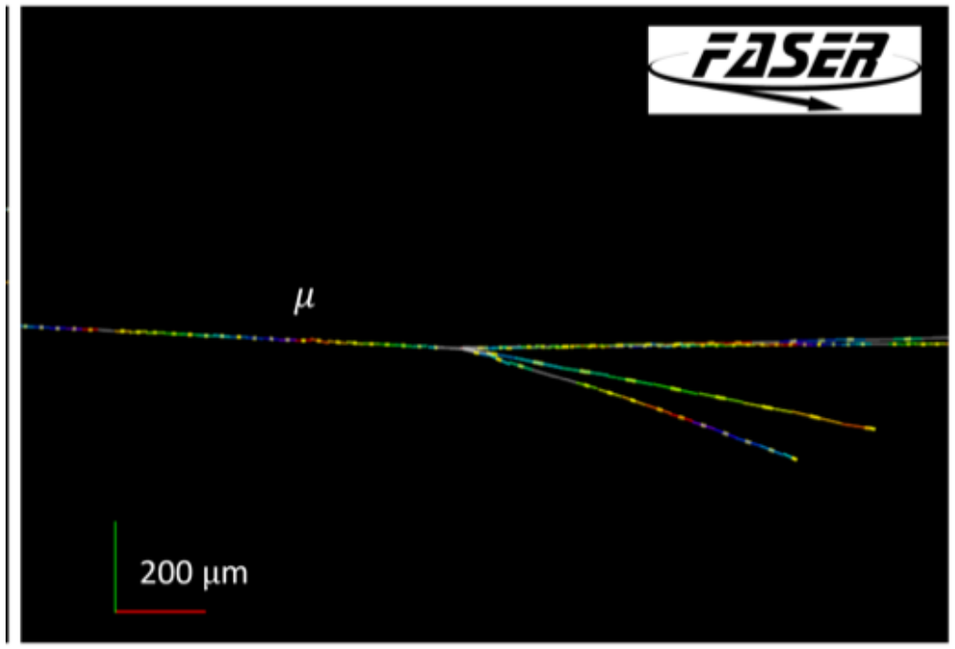


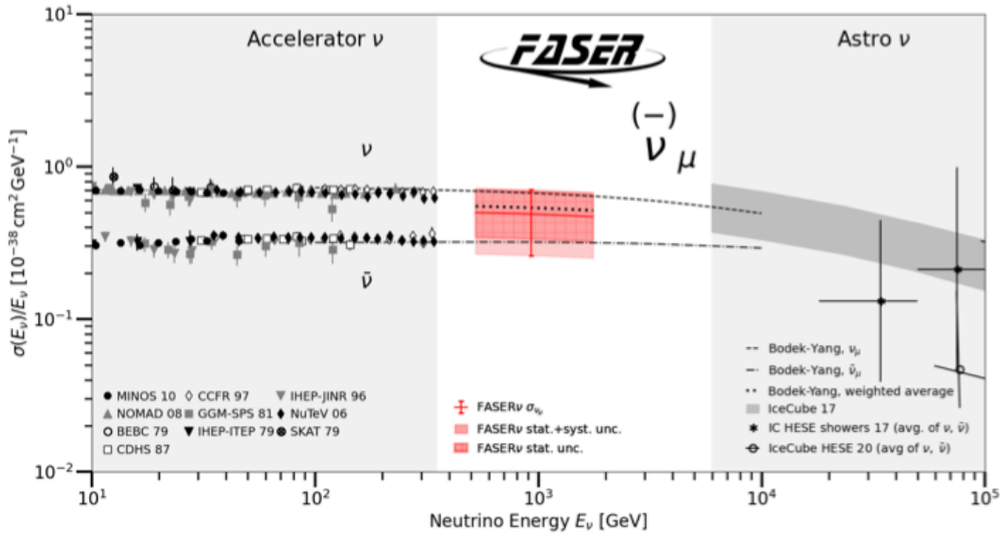
First measurement of ν_μ cross section with the emulsion detector

2403.12520

- Dataset:
  - Second module from 2022 → 9.5/fb
  - Target mass = 128.6 kg
- Selection Criteria:
  - CC neutral vertices with >4 tracks
  - E_{muon} > 200 GeV
  - Back-to-back topology
- Background events rejected by kinematic variables

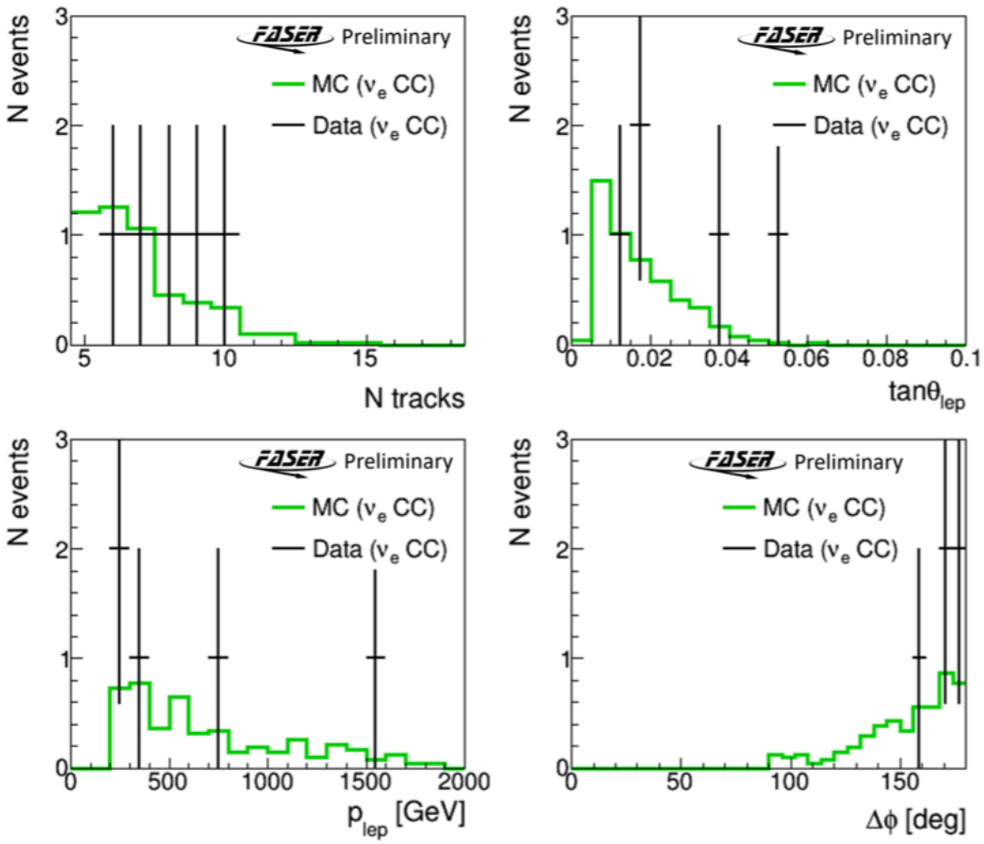
Background: $0.022^{+0.09}_{-0.07}$
Expected: 6.5-12.4
Observed: 8

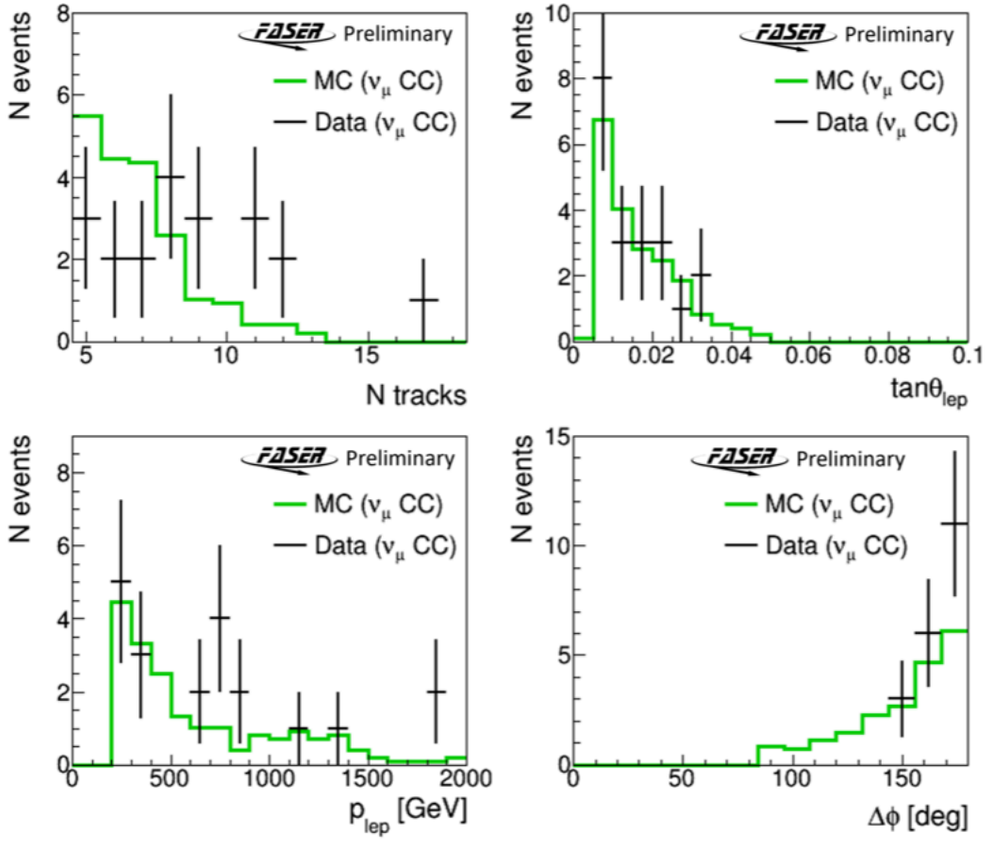




Updated statistics [CERN-FASER-CONF-2025-002]

- Dataset:
  - Second module from 2022 → 9.5/fb
  - Target mass = 314.7 kg



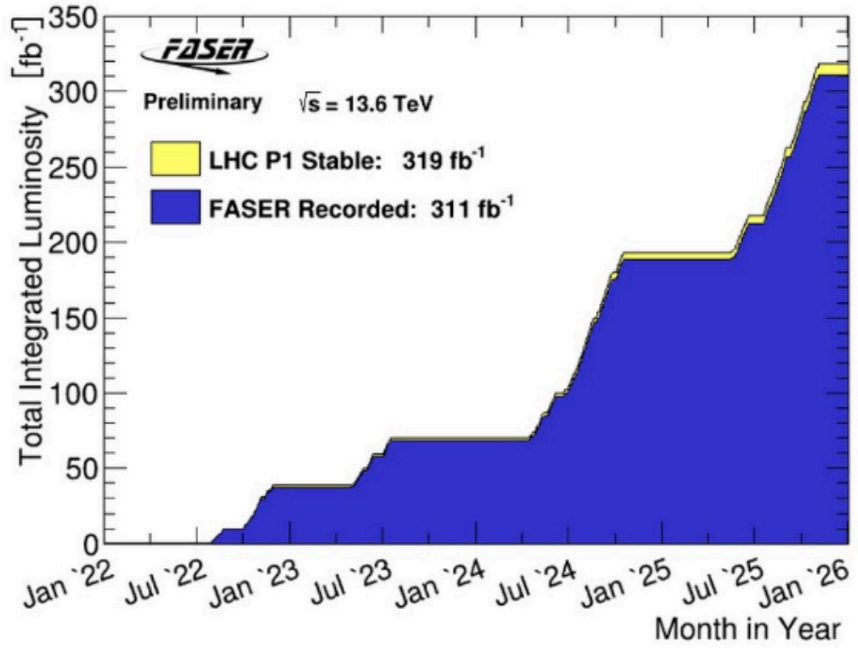


Outlook

We have already collected ~300/fb!

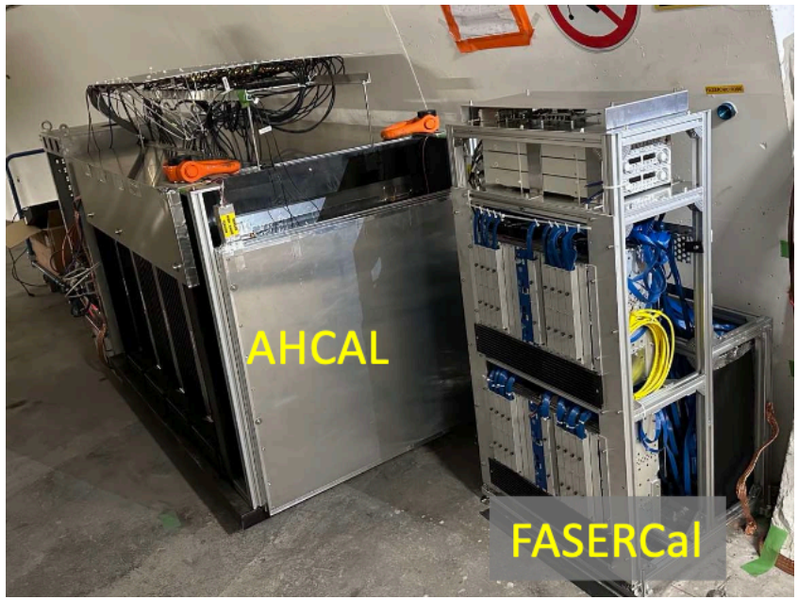
Analysis I've presented are just the beginning

- In the emulsion detector we have exposed and developed 205/fb, (1.1 tone)



Upgrades for Run-4

- Several detectors being considered
- Two prototypes:
  - Sampling calorimeter: AHCAL
  - 3D scintillating cube: FASERCal



Summary

- LHC with its large inelastic cross section and large luminosity makes possible to measure neutrinos in the forward direction
- FASER is located ~500m from the interaction point covering the very forward direction
  - Ideal for making neutrino measurements
- FASERν is an instrumented target where LHC neutrinos interact
  - We are sensitive to all neutrino flavors, with energies in TeV range
  - FASERν emulsion detector performance:
    - sub-micron spatial resolution
    - Momentum resolution is limited - since it is measured from multiple coulomb scattering
- FASER has observed neutrinos
  - Electronic detector
  - Emulsion detector
- First differential cross section measurements
- Stay tuned - many new interesting results to come

FASER

FASER COLLABORATION

123 collaborators, 27 institutions, 11 countries