FASERCal: High Energy Neutrino Measurements at FASER

8th Forward Physics Facility Meeting

21st January 2025

Lottie Cavanagh on behalf of FASERCal group

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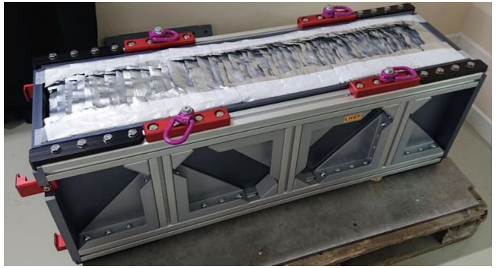
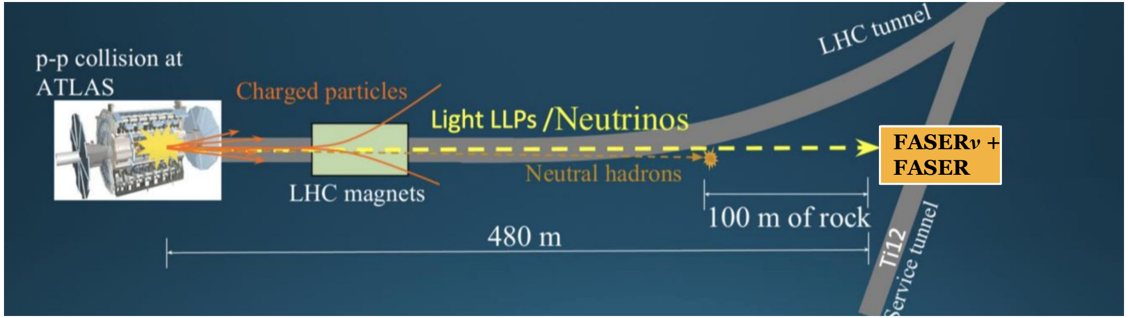
Physics Motivation

- A higher beam rate will be challenging for existing FASERν detector
- A finely-segmented detector is required, capable of exploiting the large numbers of neutrinos expected in Run 4 and HL-LHC era

Current FASERν emulsion/tungsten box:





- Opportunity to place a detector in addition to FASER that can provide important data for current and future high-energy neutrino telescope projects
  - Study neutrino energy spectra for simulation and background studies
  - Will allow the study of QCD at low-x
  - Giving insight into intrinsic charm measurements

Physics Motivation Continued

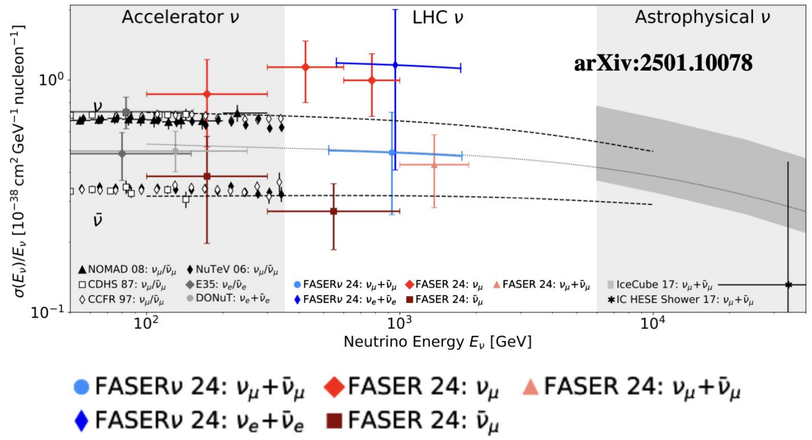
- ***Goal: A detector capable of detecting ν_e CC, ν_μ CC interactions and identifying the tau lepton***
  - ν_e and ν_μ cross section measurements at TeV energy
  - ν_τ CC interaction studies ongoing

- FASERCal will act as a target for neutrino interactions, functioning as a calorimeter for energy measurements
  - Both CC and NC interactions will be targeted

- Shower containment and energy reconstruction for neutrino interactions deep within the detector
  - Reconstruction of ν_e critical for studying neutrino energy spectrum in combination with neutrino flux

Expected neutrino interactions in FASERν:
(1 tonne detector, on beam axis line of sight)

	Luminosity	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
Run 3	250 fb^{-1}	1700	8500	30
Run 4	680 fb^{-1}	4900	25000	90



See also Felix Kling's talk: Collider Neutrinos: Opportunities and Perspectives

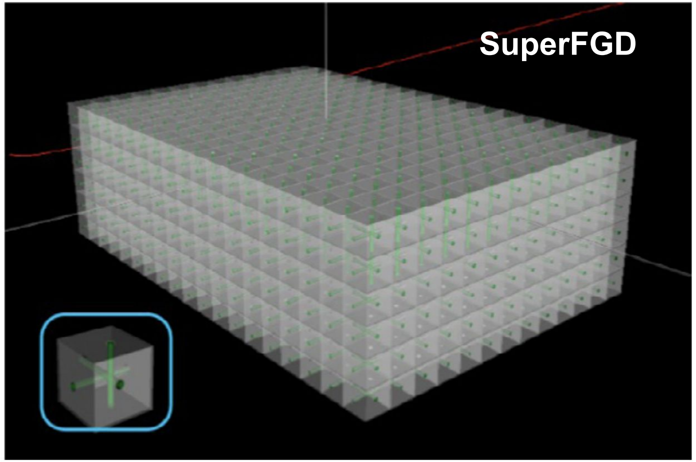
Evolution of design concept

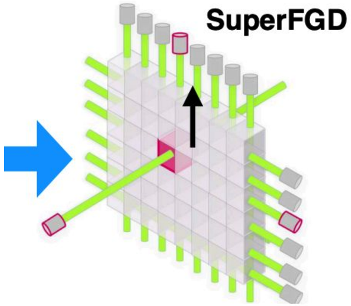
- FASERCal will provide simultaneous 3D tracking of particles in addition to precise and accurate reconstruction of particle trajectories

- Based on the **SuperFGD** detector operating at T2K
  - Modules consisting of tungsten plates and layers of optically isolated plastic scintillator cubes
  - Readout by WLS fibres and SiPM
    - Allows sub-nanosecond tracking and calorimetry
    - Allows very fine granularity

SuperFGD: A fully active fine grain detector (2018) *JINST*
3D SuperFGD detector at T2K (2022) *NIMA*

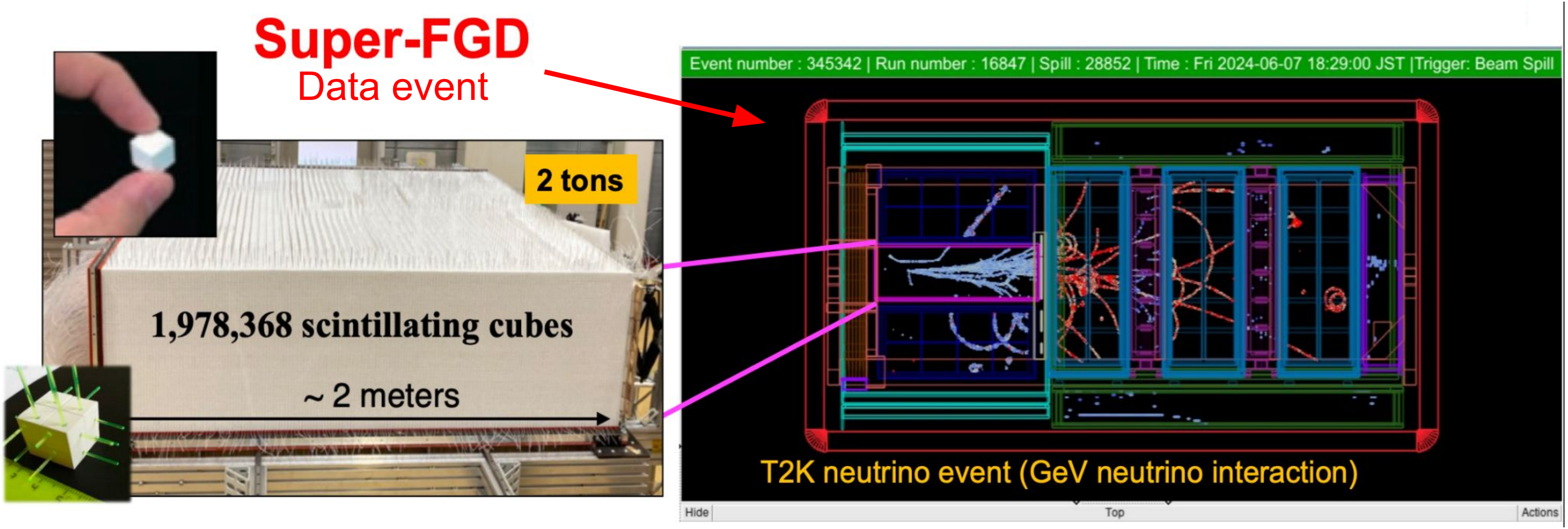
Proof of concept: Demonstrating a 3D segmented plastic scintillator detector (2021) *JINST*





SuperFGD: Neutrino interaction event display

CERN Seminar: Super-FGD at T2K



FASERCal detector: conceptual design

3DCAL

- Scintillator voxels + high precision tracker
- 15 modules making up the main target
- Highly granular (1 cm^3) 3D tracking
- Precise and accurate reconstruction of particle trajectories

RearCAL

- Electromagnetic calorimeter
- Measurement and identification of EM showers

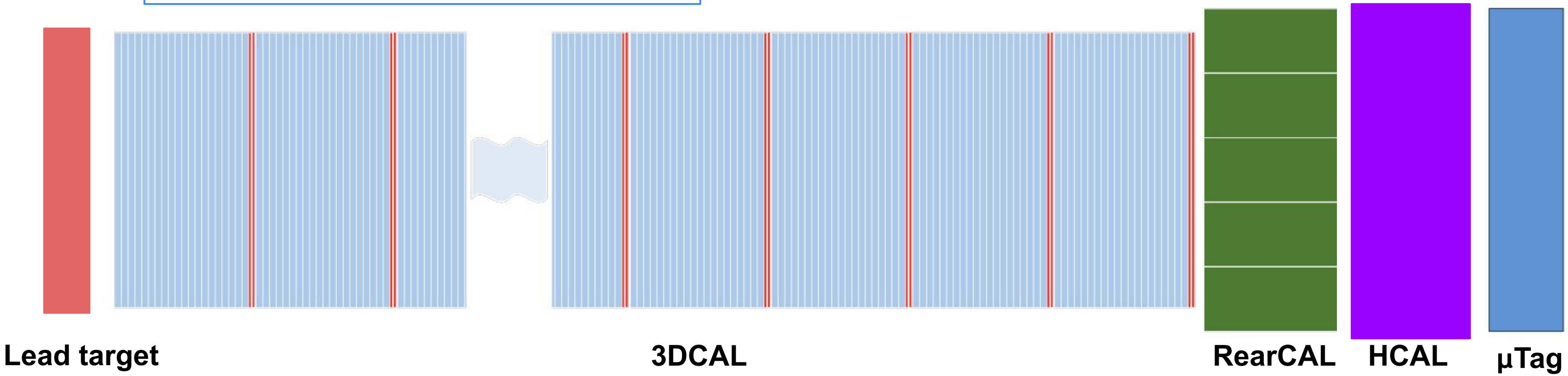
μTag

- Muon ID for ν_μ CC interactions
- Reduce background and provide clean signal
- Plastic scintillator

Necessary components:

- Effective calorimetry ✓
- Tracking ✓
- 3D segmentation ✓

Optimisation of geometry ongoing



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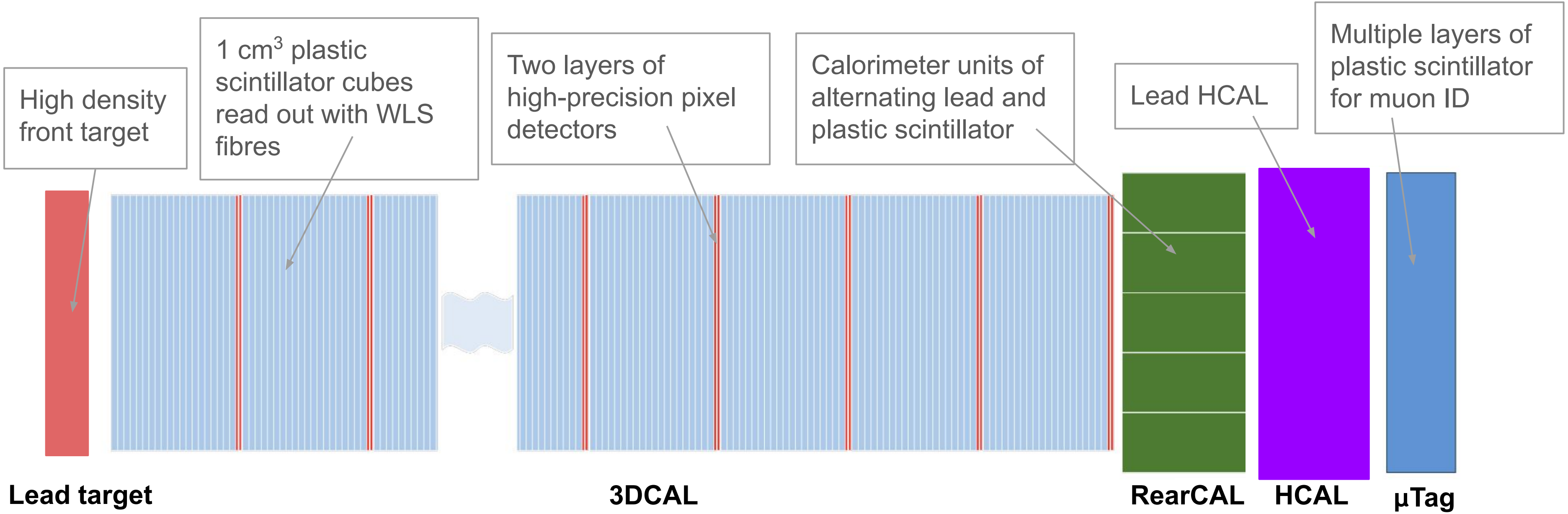
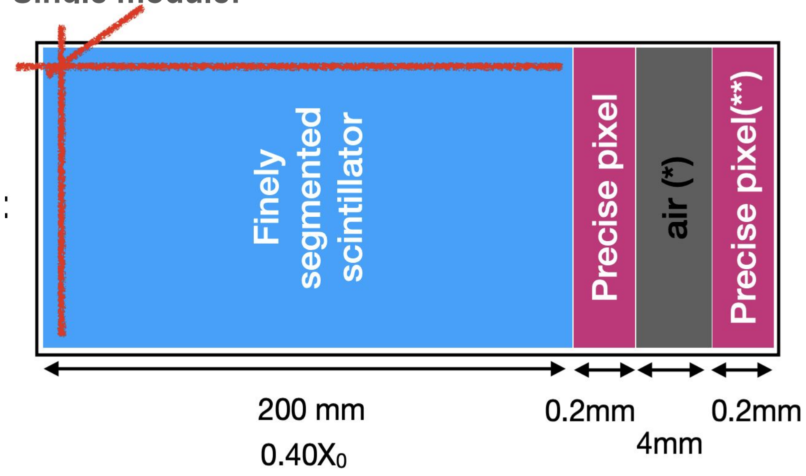


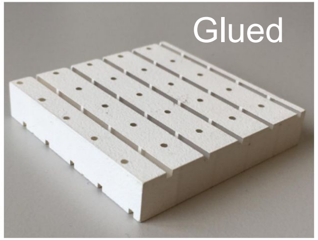
3DCal modules

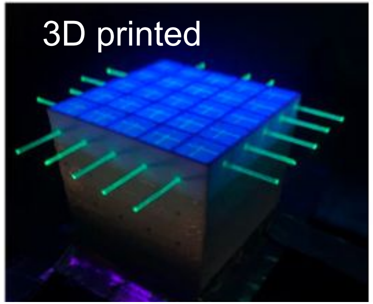
- 15 modules made up of scintillator voxels and pixel detector
    - 1 cm^3 granularity 3D voxels
    - 6 x 10^7 pixels per tracker layer

Single module:



Scintillator voxels





- Optically isolated 1 cm^3 cubes, readout fibres arranged in three planes to collect light from multiple cubes
- 3D voxel reconstruction implemented from 2D views
- One end of each WLS fibre read out by SiPM (silicon photomultiplier)

Two options for production:

- Glued cubes
  Well understood procedure
  Demonstrating a single-block 3D-segmented plastic-scintillator detector
- 3D printed cubes
  R&D ongoing with 3Det collaboration hosted by CERN
  Additive manufacturing of a 3D-segmented plastic scintillator detector (2023)
  Beam test results of a fully 3D-printed plastic scintillator particle detector prototype (2024)

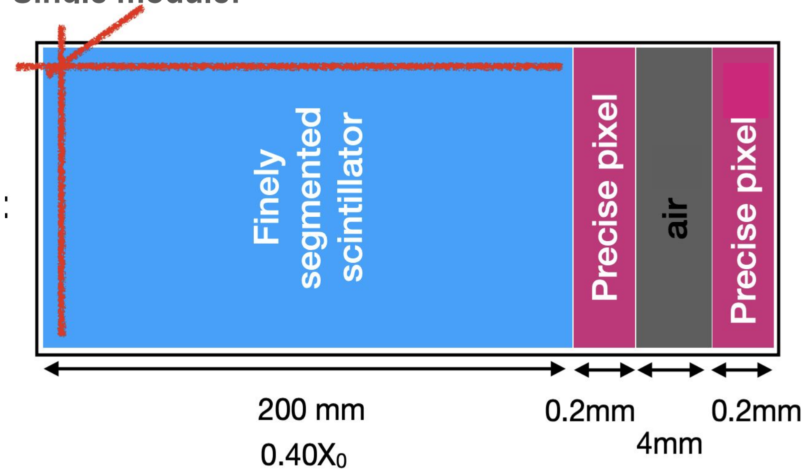
3DCal modules

- 15 modules made up of scintillator voxels and pixel detector
  - 1 cm^3 granularity 3D voxels
  - 6 x 10^7 pixels per tracker layer

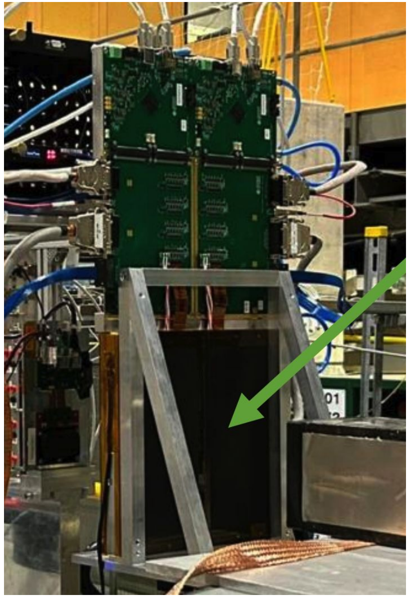
High precision pixel-based tracker

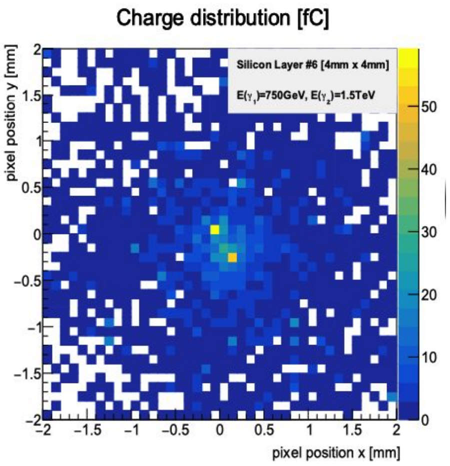
- Pixel detector
- Two layers for reconstruction of track segments
- Combine with 3D voxel reconstruction to complete 3D track reconstruction

Single module:



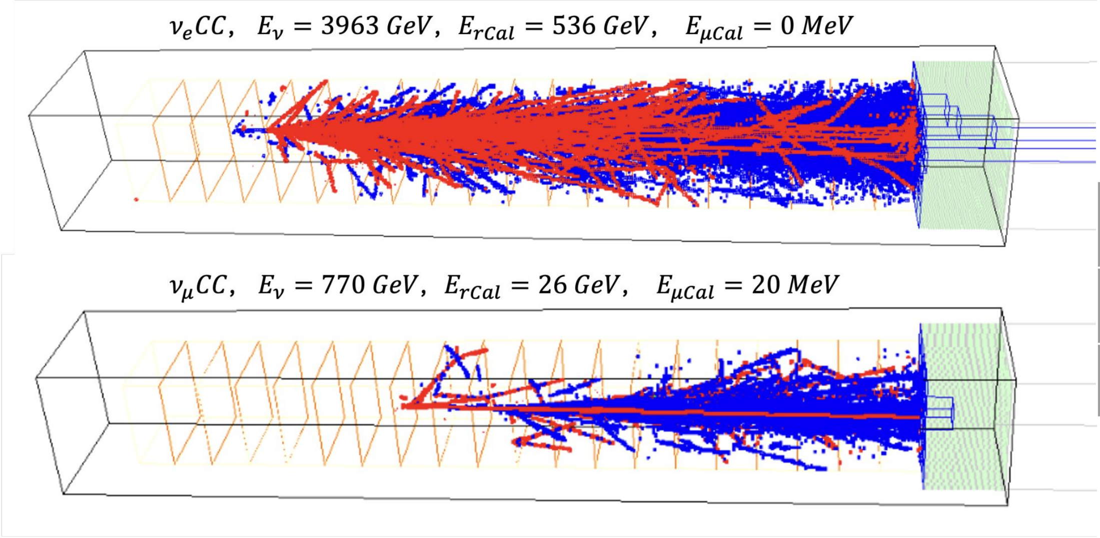
- Air gap and material not finalised





FASERCal event display

- Simulated ν_e CC and ν_μ CC interactions in the FASERCal detector
  - Electromagnetic shower component shown in blue
  - Hadronic component shown in red

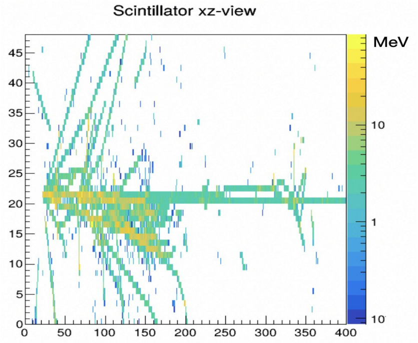


	True ν_e	True ν_μ	True NC	Purity
Pred. ν_e	**4,640**	142	175	**92%**
Pred. ν_μ	264	**15,662**	1,6	**89%**
Pred. NC	269	1,365	**5,703**	**77%**

FASERCal event display: 3D voxel reconstruction

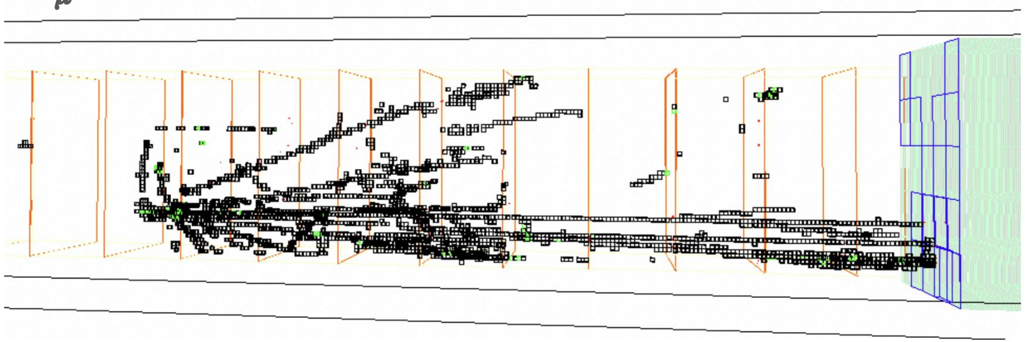
- Full FASERCal simulation implemented in Geant4
- Implementation of full 3D reconstruction of neutrino interaction constructed from 2D views
- Developing new deep learning tools for removal of ghosts

2D projection:

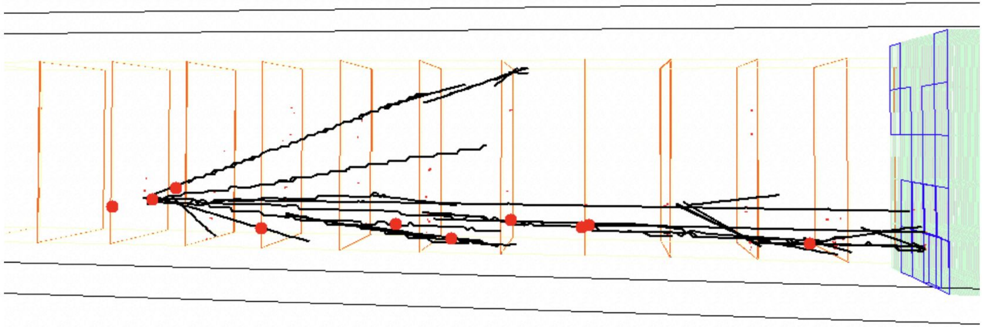


ν_μ CC

Reconstructed 3D voxels



Reconstructed tracks + vertices



The possibility of reconstructing the energy flow in 3D opens the door to measure exclusive final states and exploit the transverse kinematical variables with the possibility of using these features to identify charm and tau events.

Summary

- FASERCal plans to provide fine granularity and full energy flow reconstruction in 3D for future neutrino analyses
  - Potential measurements of exclusive final states and exclusive cross section analysis
  - Exploitation of transverse kinematical variables with the possibility to identify charm and tau events

- 3D voxel reconstruction
  - Preliminary physics studies underway including energy reconstruction and missing transverse momentum studies
  - Work in progress: studies exploring deep learning tools
  - Geometry optimisation in progress

- Prototyping for FASERCal is ongoing
  - Proof of concept demonstrated
  - Many R&D opportunities already being explored

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NSF
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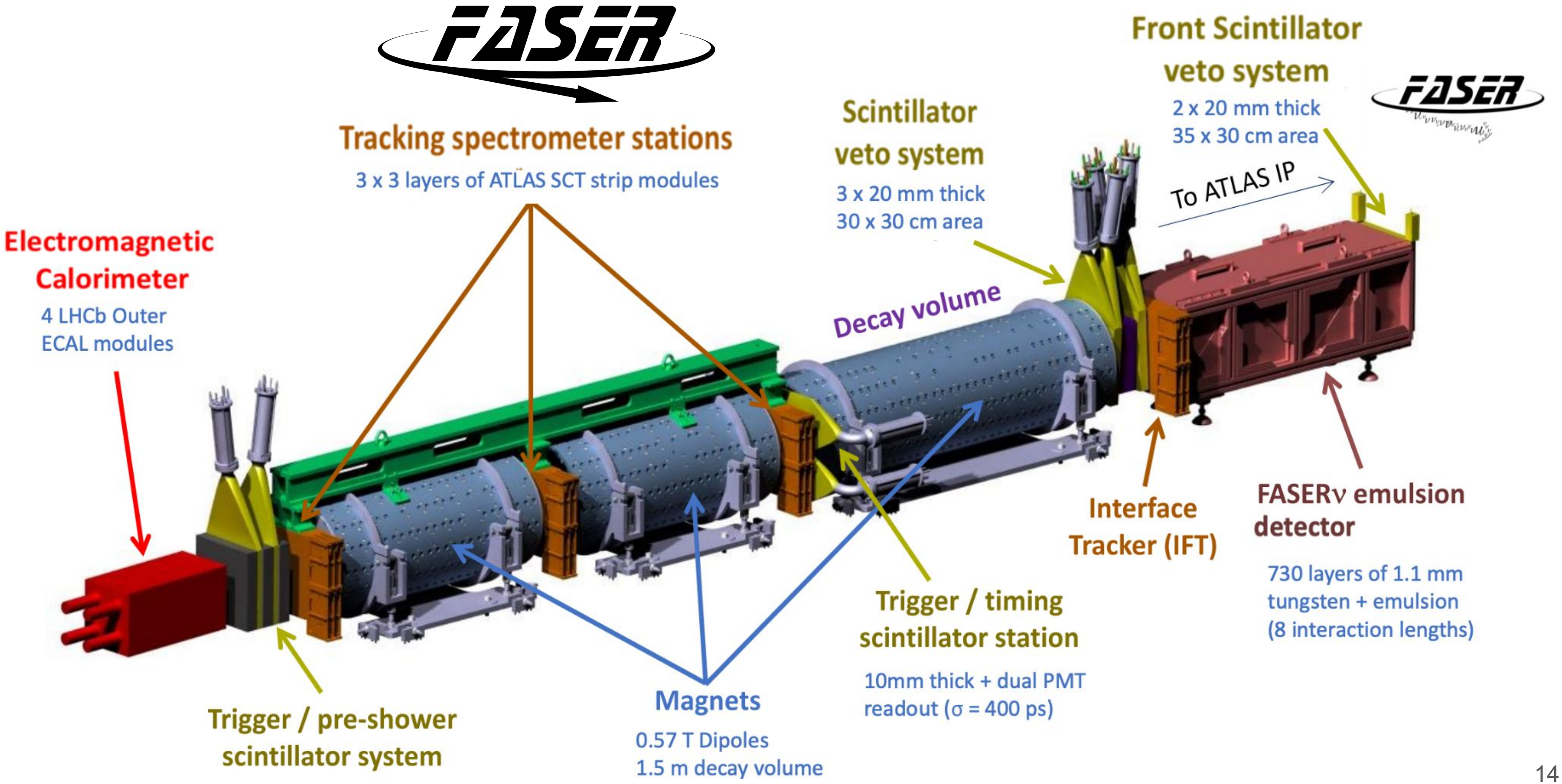
Backup Slides

FASER and FASERν



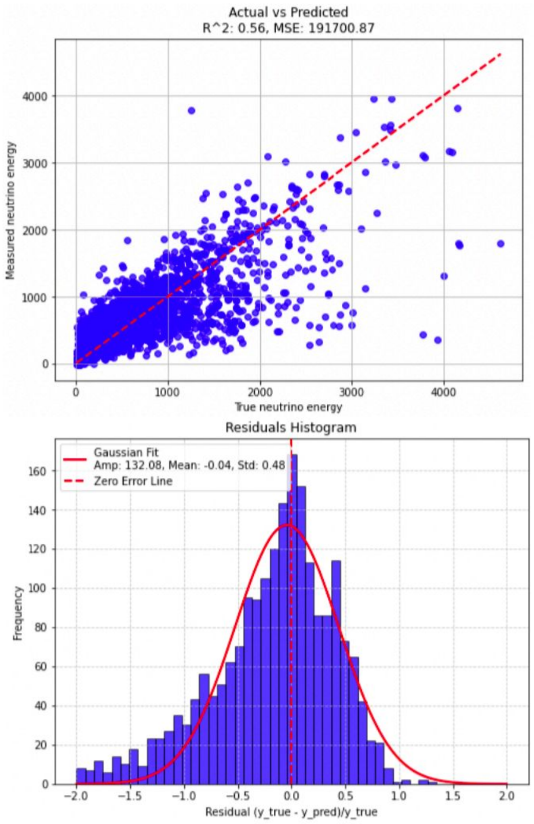
Expected neutrino interactions in FASERCal

Predictions from 10 ab^{-1} GENIE MC in current FASERCal geometry :

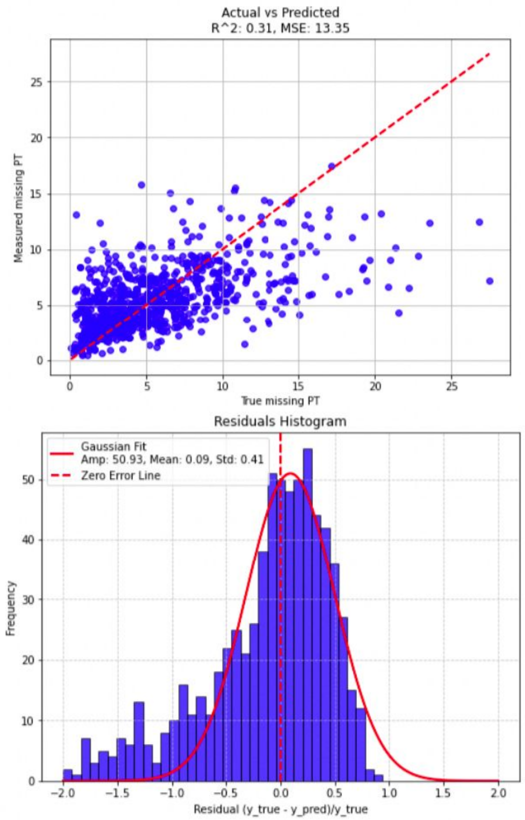
Interactions	FASERCal	FASERCal w/ no lead target
$\nu_e + \bar{\nu}_e$ CC	39575	22023
$\nu_\mu + \bar{\nu}_\mu$ CC	196646	107470
$\nu_\tau + \bar{\nu}_\tau$ CC	1050	583
ν NC	78551	45055
ES	326	182
Total	316148	175313

3D Voxel Reconstruction: ongoing studies

Neutrino energy reconstruction (CC events)



Missing p_T (NC events)



Neutrino interactions in FASERCal (10 ab^{-1})

	Interactions
$\nu_e + \bar{\nu}_e$ CC	39575
$\nu_\mu + \bar{\nu}_\mu$ CC	196646
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ν NC	78551
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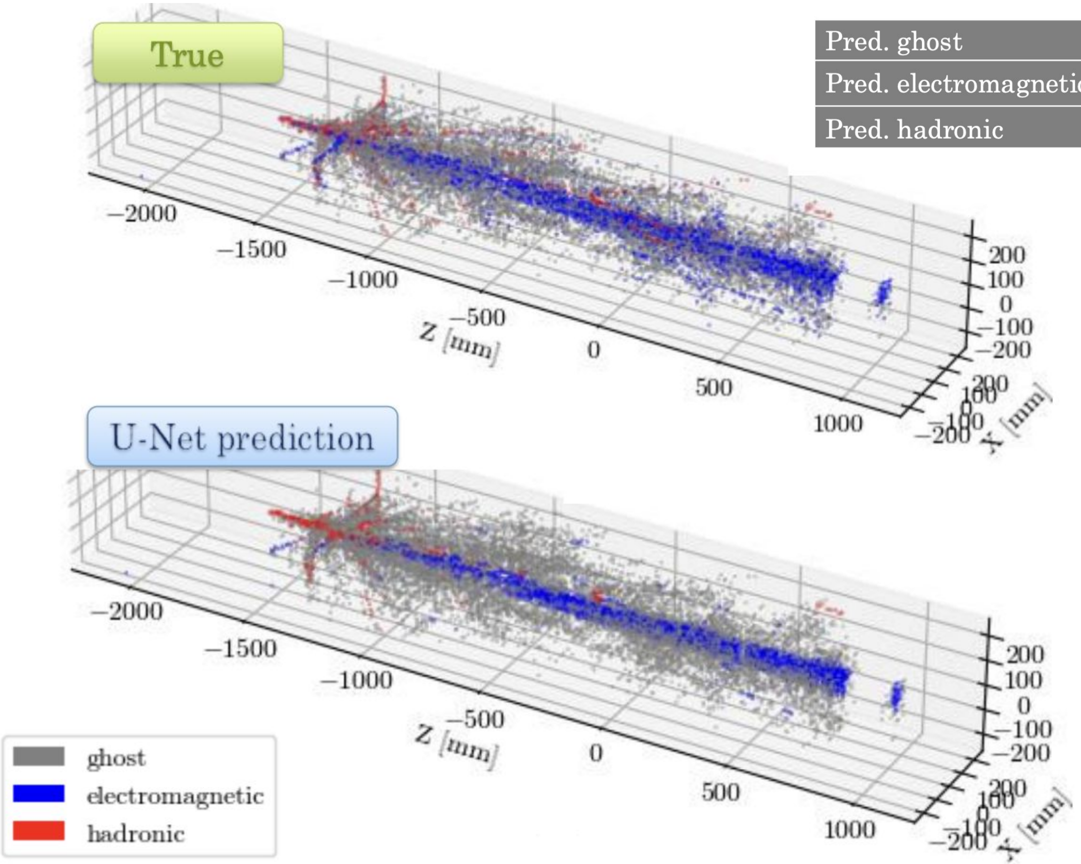
Total	316148

Machine Learning reconstruction study



	True ghost	True electromagnetic	True hadronic
Pred. ghost	**183,710,669**	49,885,184	15,051,598
Pred. electromagnetic	46,576,946	**298,401,577**	19,913,688
Pred. hadronic	5,932,741	12,501,237	**52,332,336**

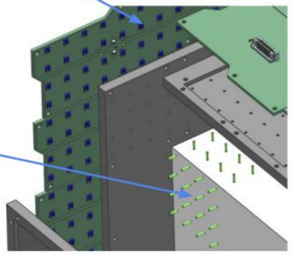
- Voxel tagging using machine learning
  - Training, validation and testing on 100k events
  - Good purity and efficiency
  - Performance improved further close to the primary vertex
- Flavour identification using deep learning
  - Achieved using RearCAL information
  - Overall accuracy (purity) of 87%

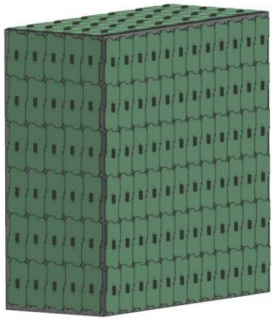
Location of FASERCal prototype

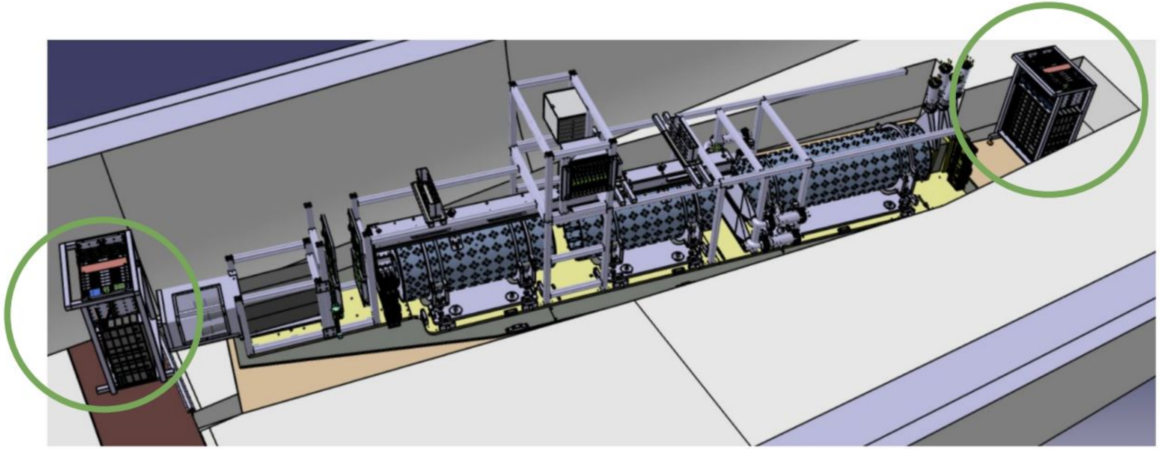
Two potential locations studied for the placement of a FASERCal prototype

SiPM for read out

Scintillator cubes and WLS fibres



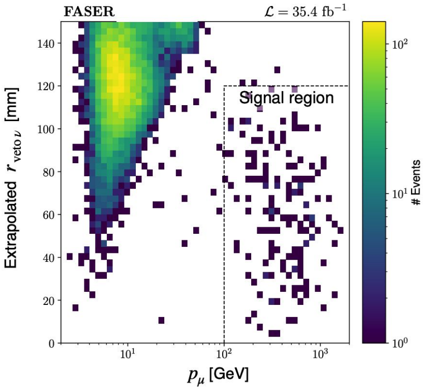




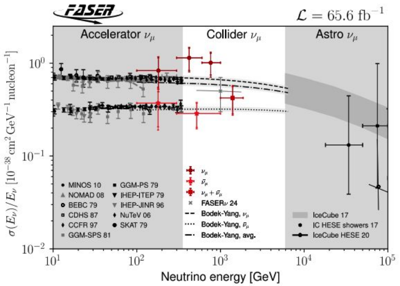
ν_e and ν_μ measurements in FASER electronic detector

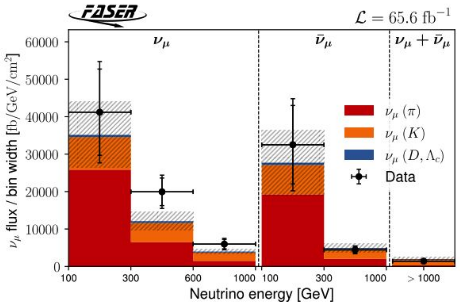
Existing results:

- First direct observation of collider neutrinos with FASER
  [August 2023]



- First measurement of muon neutrino interaction cross section and flux as a function of energy with FASER
  [December 2024]





ν_e and ν_μ measurements in FASER electronic detector

Planned analysis:

- ν_e measurement with FASER's electromagnetic calorimeter