Particle identification in highly segmented neutrino detector SuperFGD

22nd Lomonosov conference on elementary particle physics

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T2K experiment

Nucl. Instrum. Methods A, 659 (2011)
arXiv:1910.03887 **[hep-ex]**

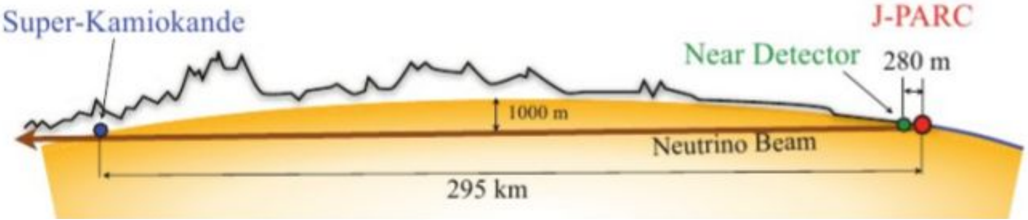
T2K (Tokai to Kamioka) is an experiment with a long baseline for searching for neutrino oscillations

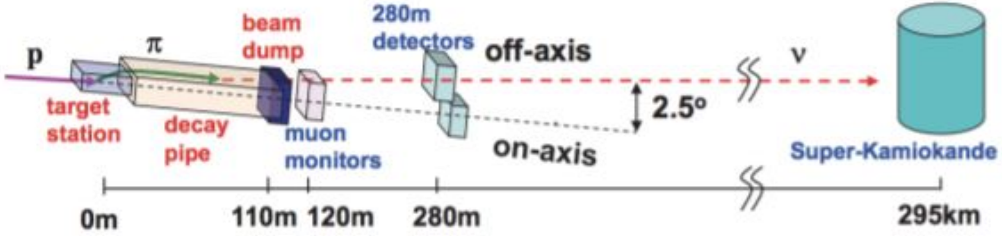
Observations: $\nu_\mu \longrightarrow \nu_e$

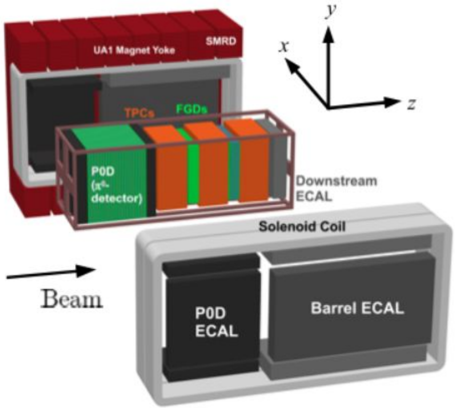
T2K conducts very precise measurements of the probability of oscillations and the difference between the masses of two types of neutrinos.

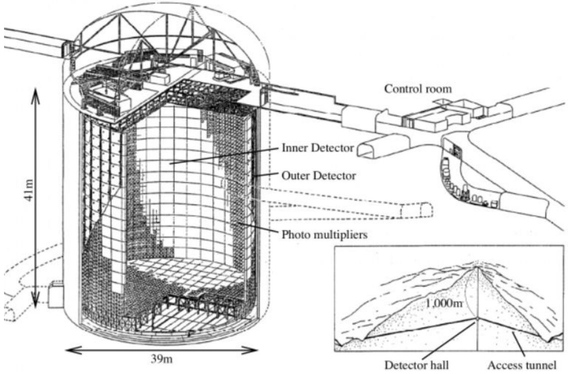
2.5° off-axis angle peaks ν_μ energy spectrum at ~600 MeV

The main goal of the experiment is a search for CP-violation in neutrino oscillations.

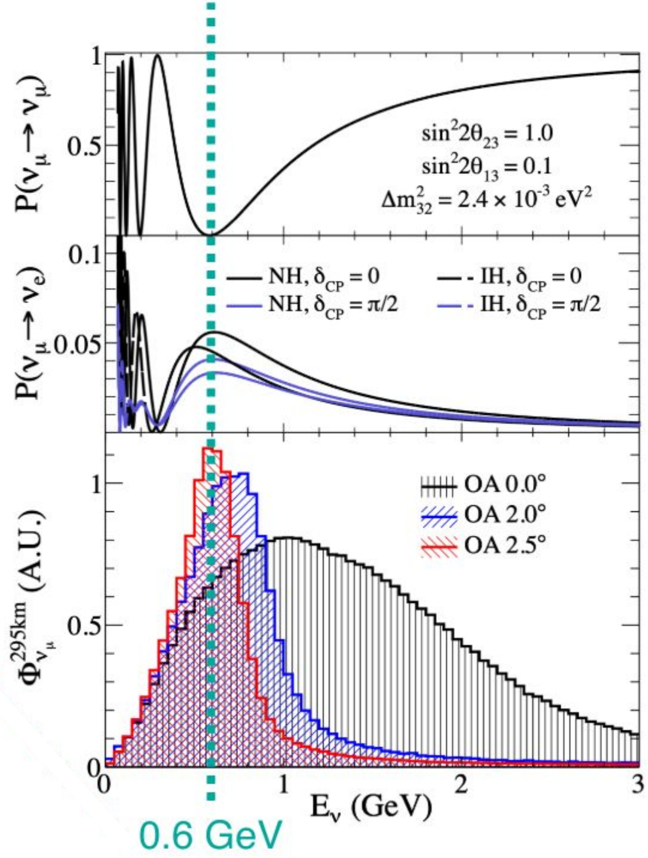






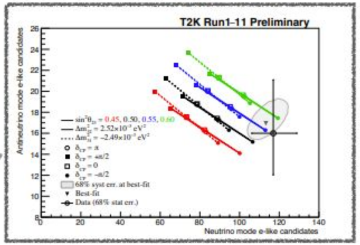


T2K experiment: CP-violation search results

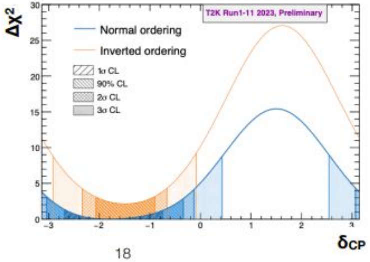


Oscillation analysis results

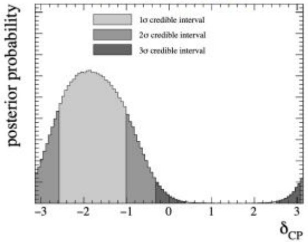
Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



CP-symmetry is excluded at 90% confidence level

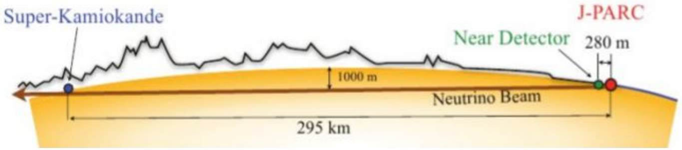


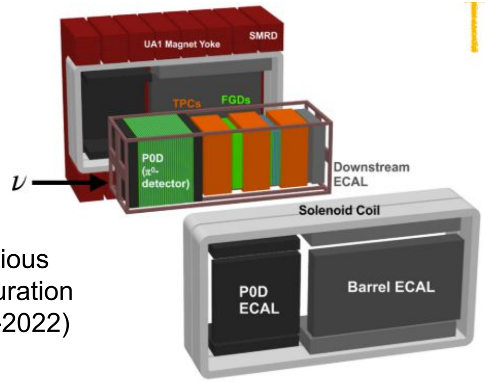
Credible intervals marginalized over both hierarchies



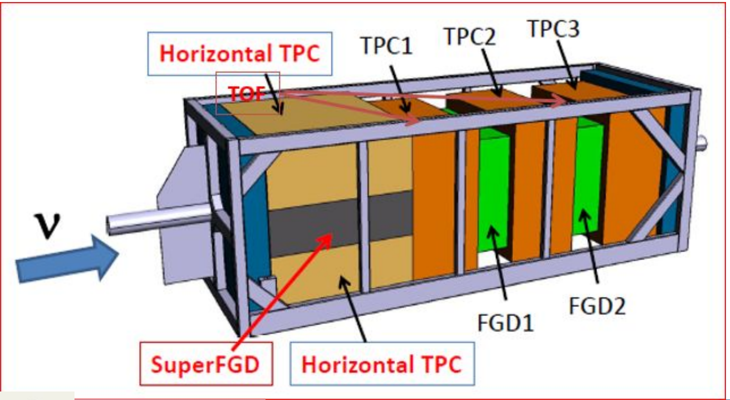
C. Giganti’s talk at Neutrino-2024, 2024.06.17

Near Detector





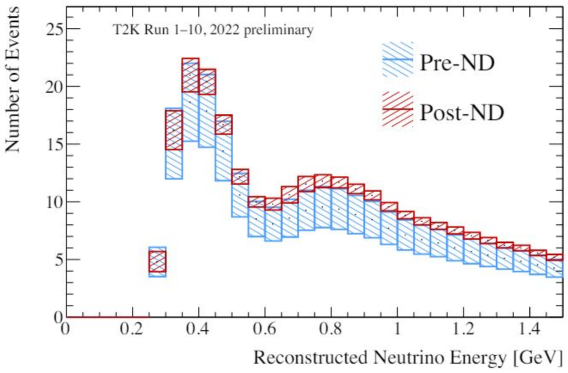
Previous configuration (2010-2022)

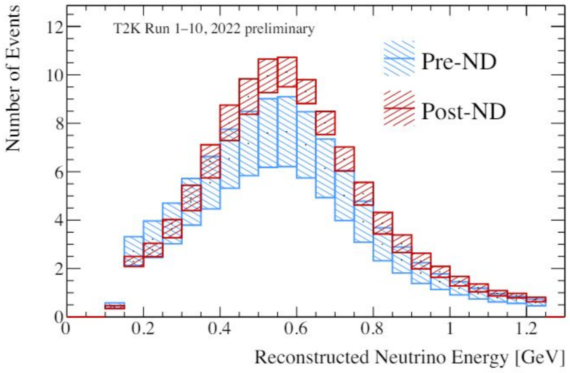


Systematic uncertainty is contrained by the measurements of the Near Detector

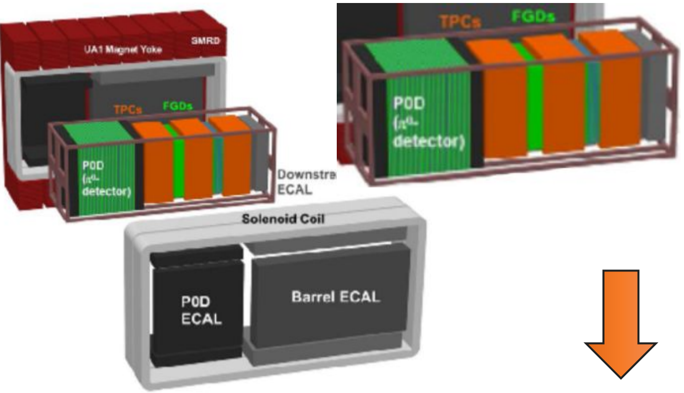
- ➔ Neutrino flux
- ➔ Neutrino spectrum
- ➔ Neutrino interaction cross sections

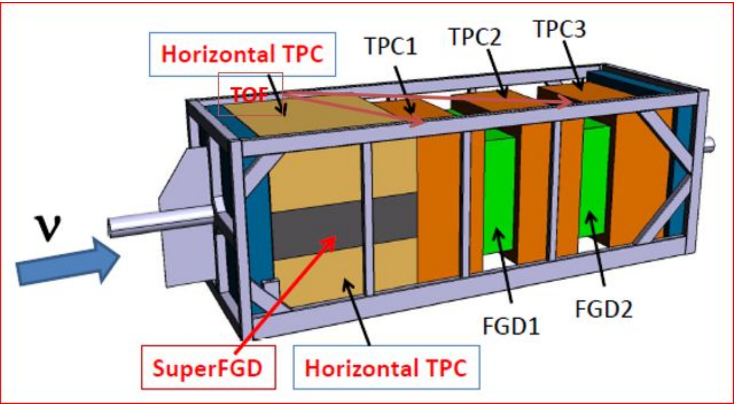
ND280 helps to reduce Super-Kamiokande systematics from 15% to ~5-6%





Upgrade: goal – reduce systematics downto 2-3%



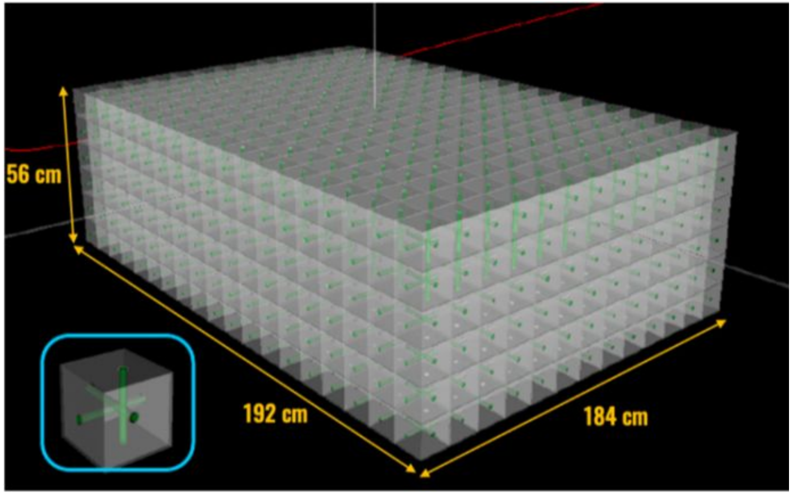


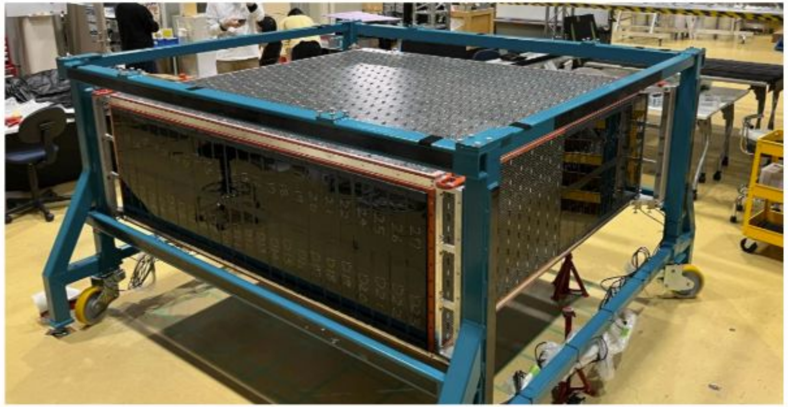
Requirements for a scintillation detector

- ➔ Significant mass to ensure a large number of neutrino interactions (comparable to the mass of two FGDs).
- ➔ 4π registration of charged leptons.
- ➔ Study of electron neutrino reactions.
- ➔ Ability to reconstruct and identify short tracks of low-energy hadrons around the interaction vertex.
- ➔ Differentiation between electrons and photons.
- ➔ Registration of neutrons.

P0D was replaced with: SuperFGD, 2 High-angle TPCs, 6 TOFs

- High-Angle TPCs allow to reconstruct muons at any angle with respect to beam
- SuperFGD allows to fully reconstruct the tracks issued by ν interactions in 3D $\rightarrow$ lower threshold and excellent resolution to reconstruct protons at any angle
- Neutrons will also be reconstructed by using time of flight between vertex of $\overline{\nu}$ interaction and the neutron re-interaction in the detector
- PID for proton/muon and electron/photon





SuperFGD

arXiv: 2005.11048

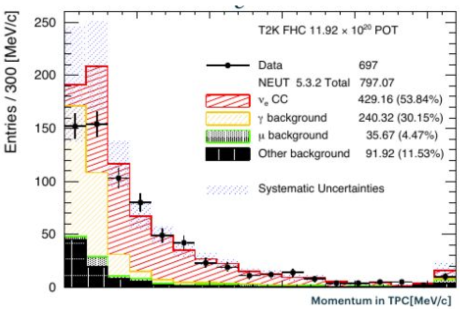
Characteristics

- Volume 192 x 56 x 182 cm^3
- **~2 x 10^6** scintillation cubes 1 x 1 x 1 cm^3
- 3 orthogonal holes with 1.5 mm diameter each
- 3D (x,y,z) WLS readout – about **56000** readout WLS/MPPC channels
- Active weight **2 tons** (like FGD1+FGD2)

Advantages

- A sufficiently large mass (2 tons) provides a significant number of neutrino events.
- It has good sensitivity to charged particles at large angles.
- It can reconstruct and identify short tracks of low-energy hadrons around the interaction vertex.
- It measures charged particles tracks in all 3 projections.

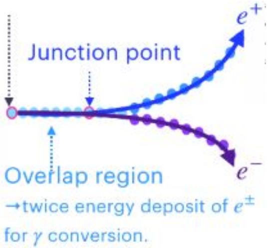
Applying to neutrino events



- T2K beam is muon beam, the mixture of electron neutrino is about 1%;
- Main background for electron neutrino events is from photons (T2K analysis, Abe. K. J. High Energ. Phys., 114 (2020))

Electron neutrinos selection:

- selection of primary vertex
- group tracks/hits into cones
- Particle identification: Gradient Boosting Decision Trees applied to first 15 hits to determine cone type: electron/photon-induced



At a threshold of 0.5
~96% of γ rejected
while keeping ~94% of $e^{\pm}$.
by the GBDT discriminator.

Control samples: purity of 80% at an efficiency of 20%

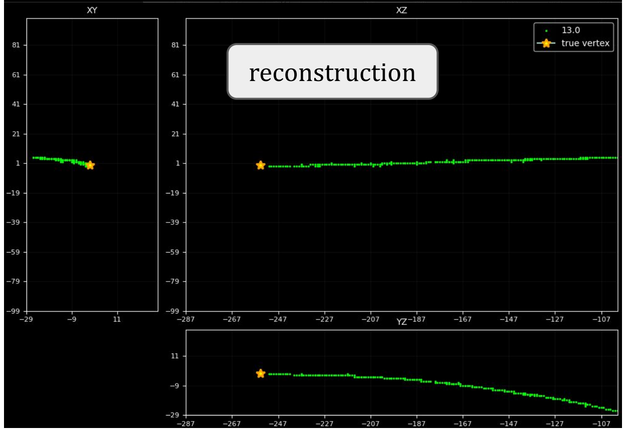
talk by H.Kobayashi at NuFact 2025

Deep neural network models can be applied. Monte-Carlo simulated in the SuperFGD electrons, photons, muons, pions, protons with energies up to 1 GeV were used for testing and evaluation

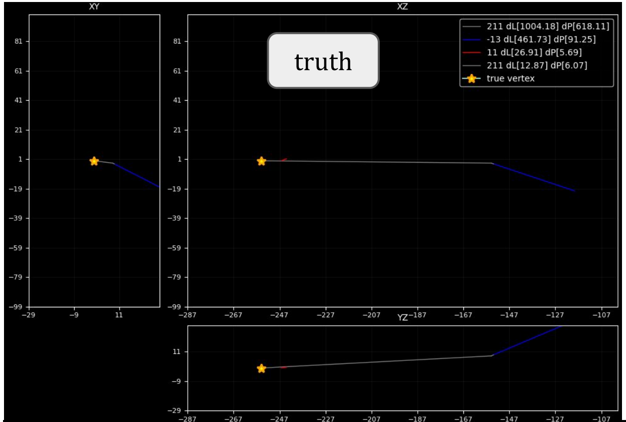
for different models see talk by A. Chalumeau at EPS-HEP

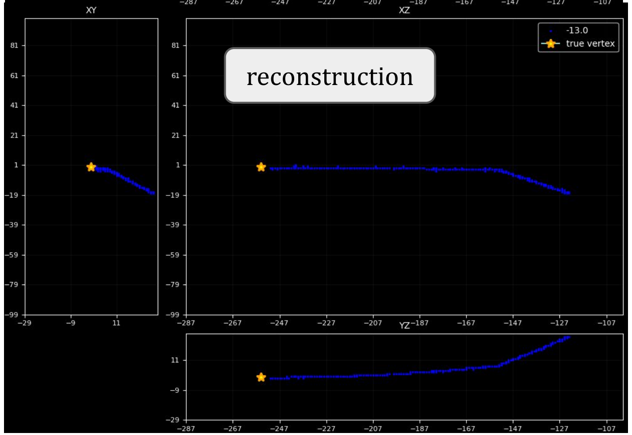
Events examples

muon event

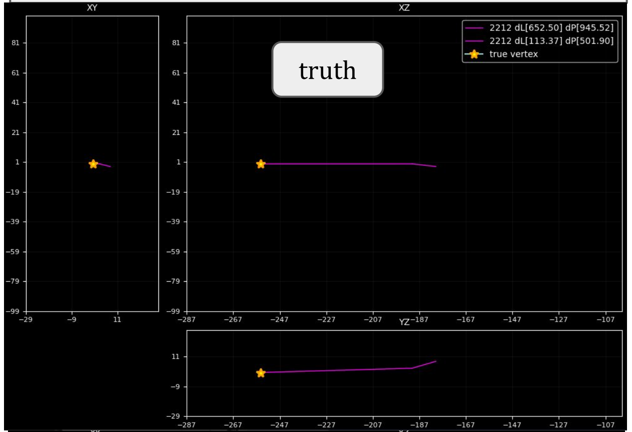


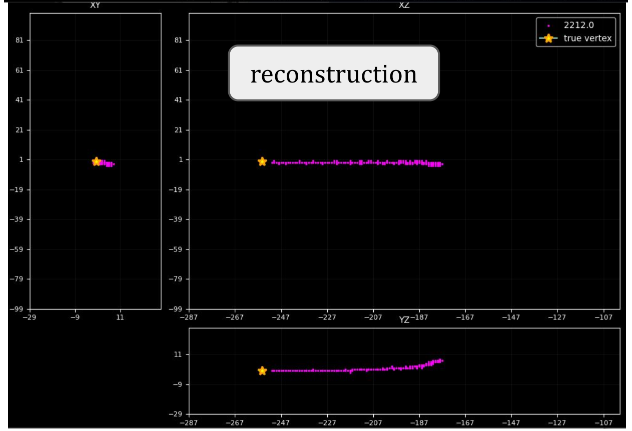
pion event





proton event

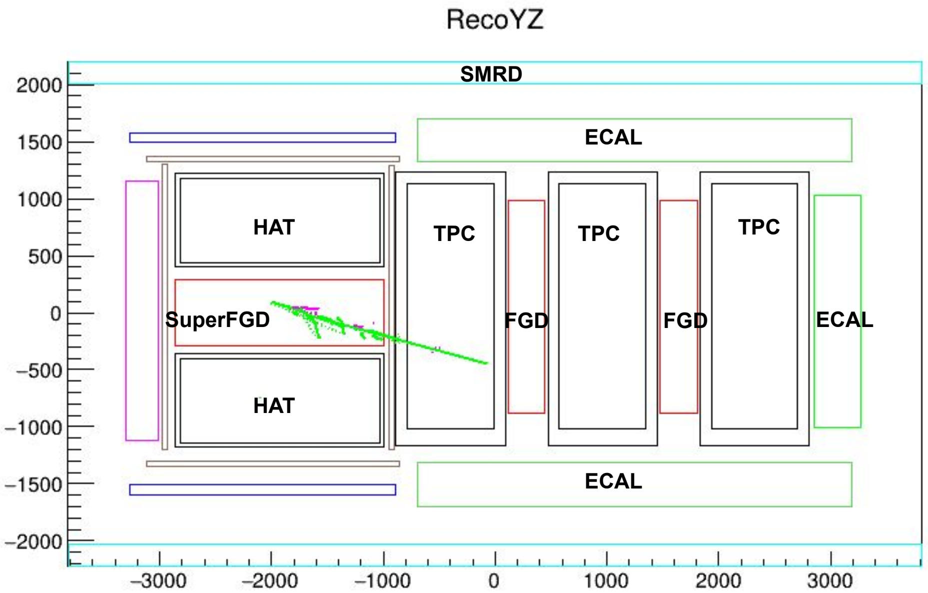


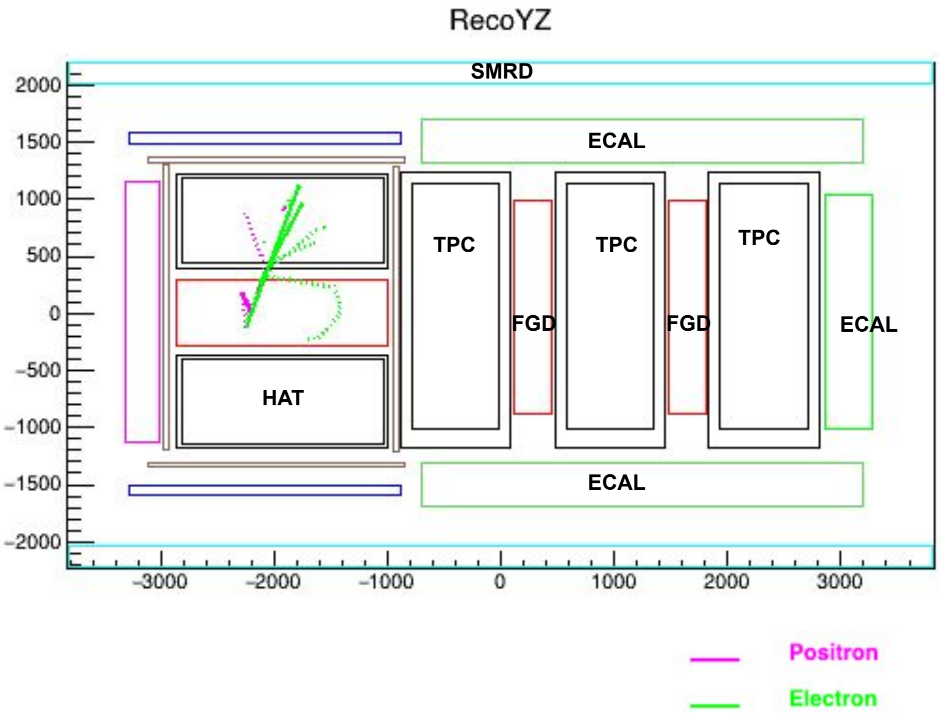


Events examples

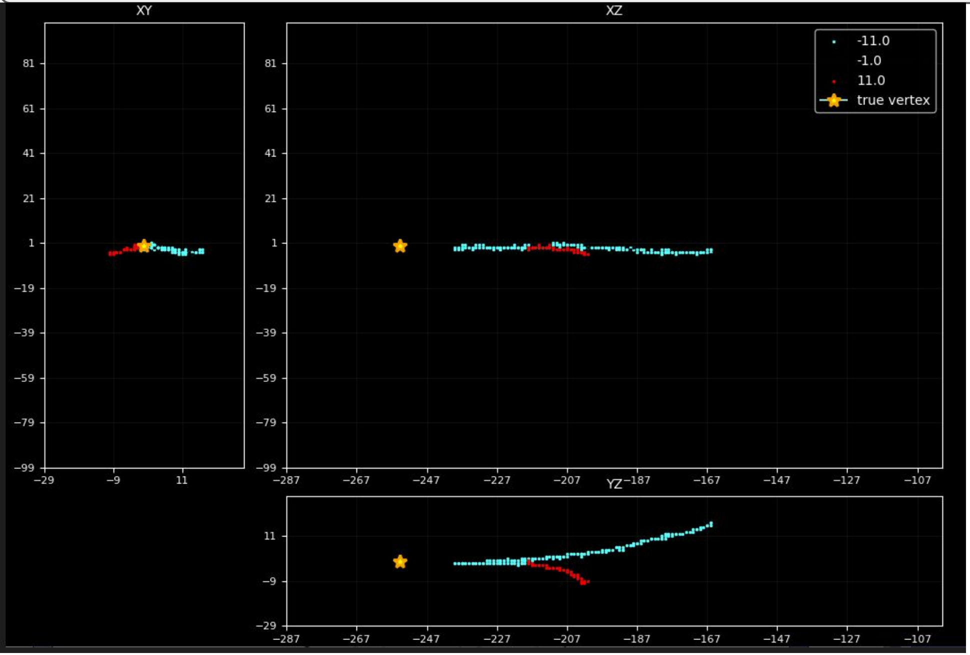
T2K beam is muon beam, the mixture of electron neutrino is about 1%. Photons are background for electron neutrino interactions

electron shower	photon shower



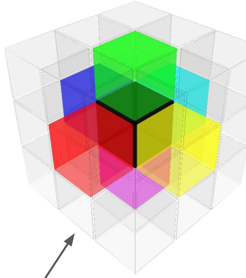


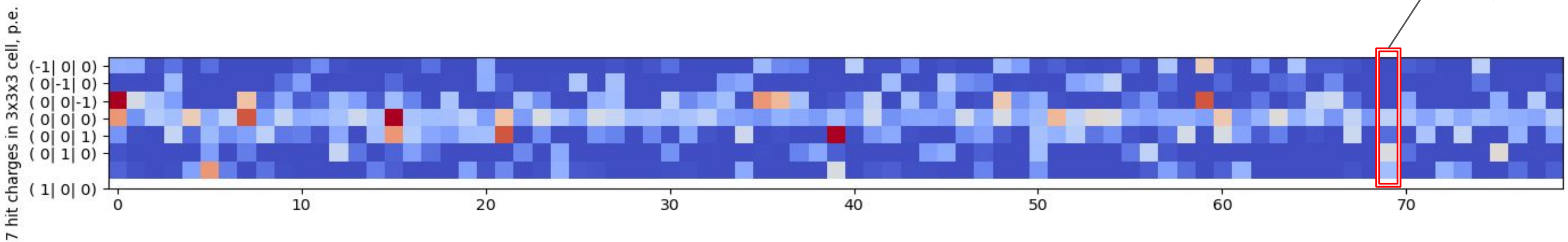
SuperFGD events representation



- **~2 x 10^6** scintillation cubes 1 x 1 x 1 cm^3
- each cube is a hit, where particle deposits energy
- hits are composed into tracks

- tracks are composed into a collection – shower-like or track-like object
- hits from each collection are considered
- spatio-temporal structure is flattened

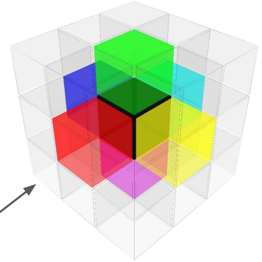


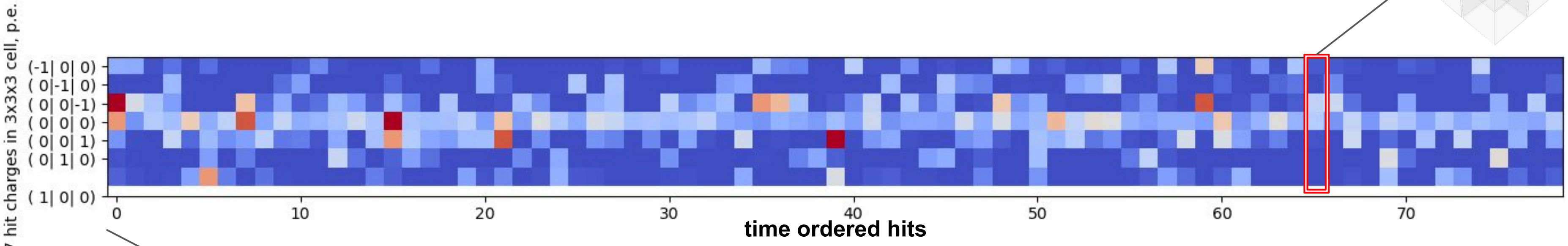


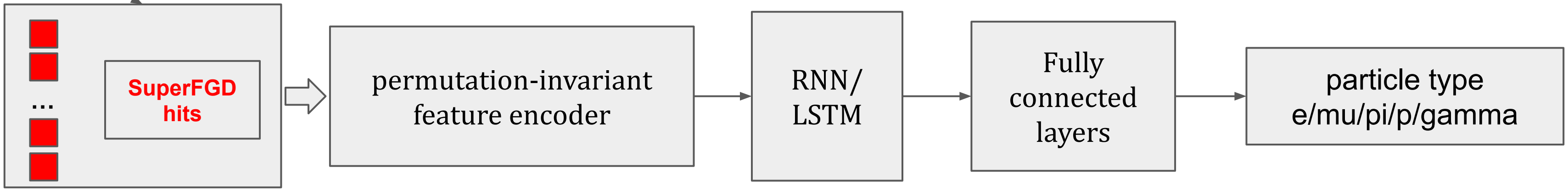
Model architecture for particle identification

Track can be represented as a collection of “timesteps” of variable length => Recurrent neural network architecture can be used

- timesteps:
  - hit in SuperFGD: charge

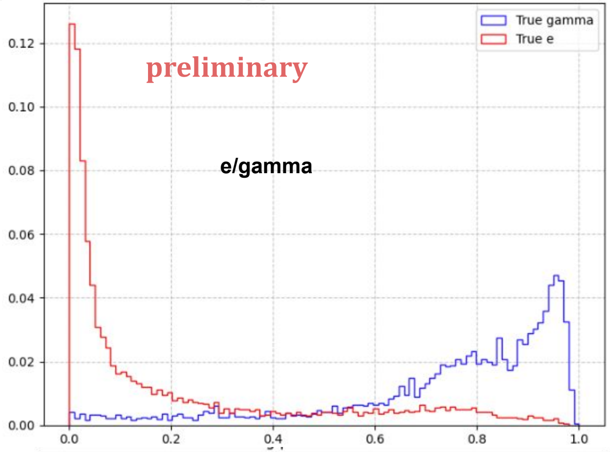




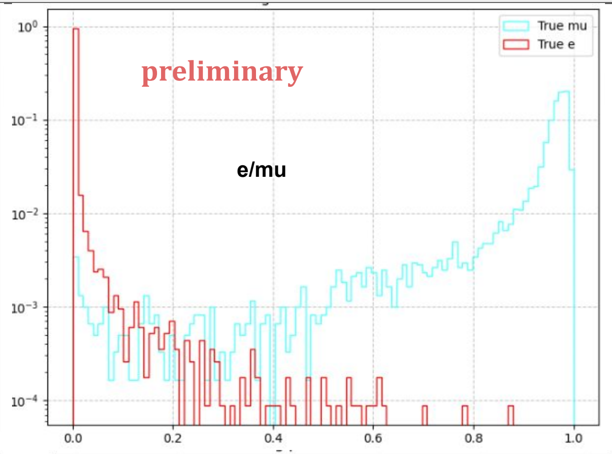


Sequence of “timesteps”

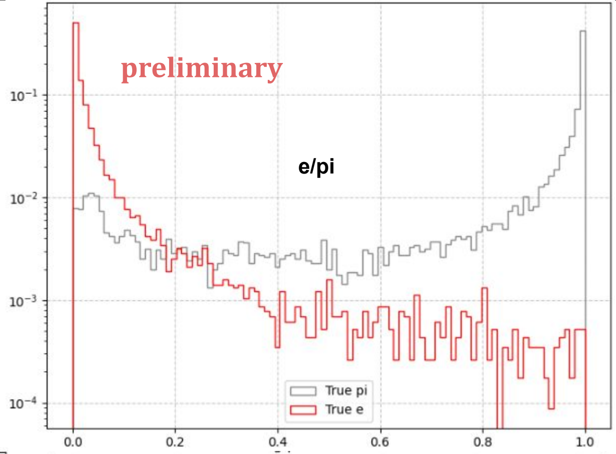
Results



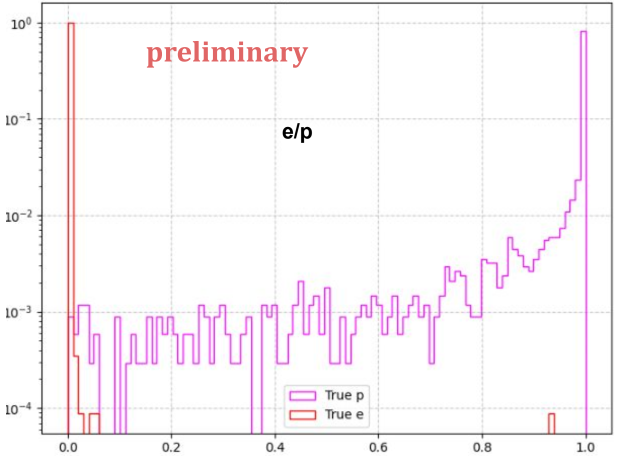
True gamma
True e
preliminary
e/gamma



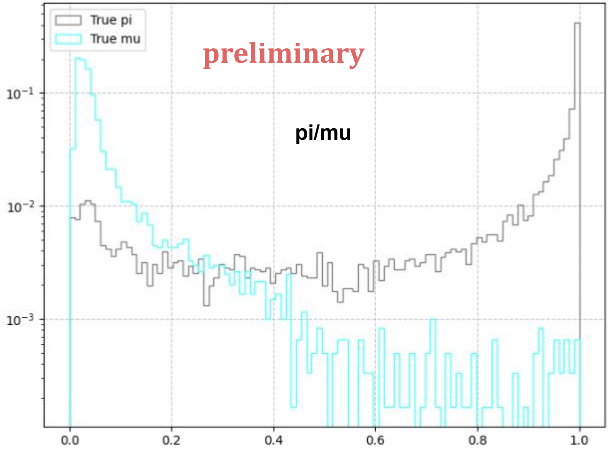
True mu
True e
preliminary
e/mu



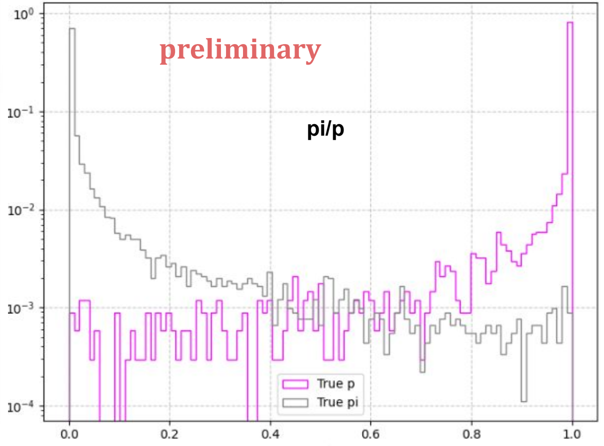
preliminary
e/pi
True pi
True e



preliminary
e/p
True p
True e

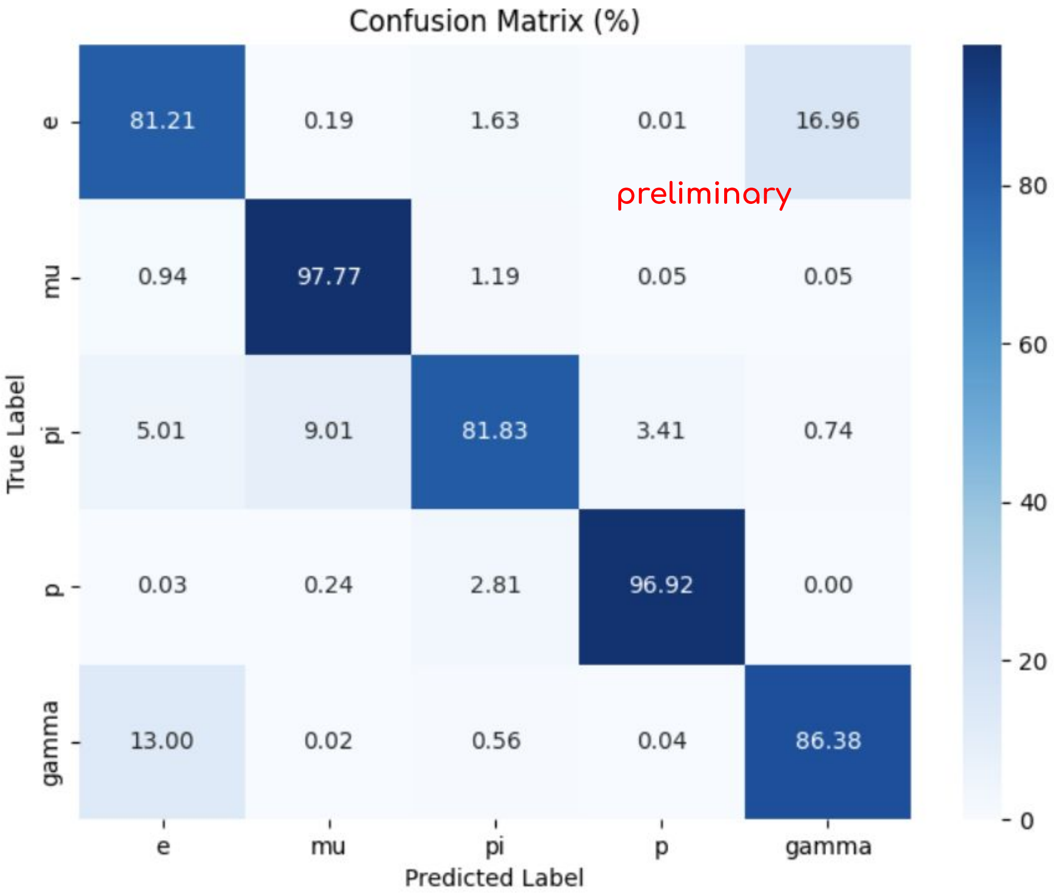


True pi
True mu
preliminary
pi/mu



preliminary
pi/p
True p
True pi

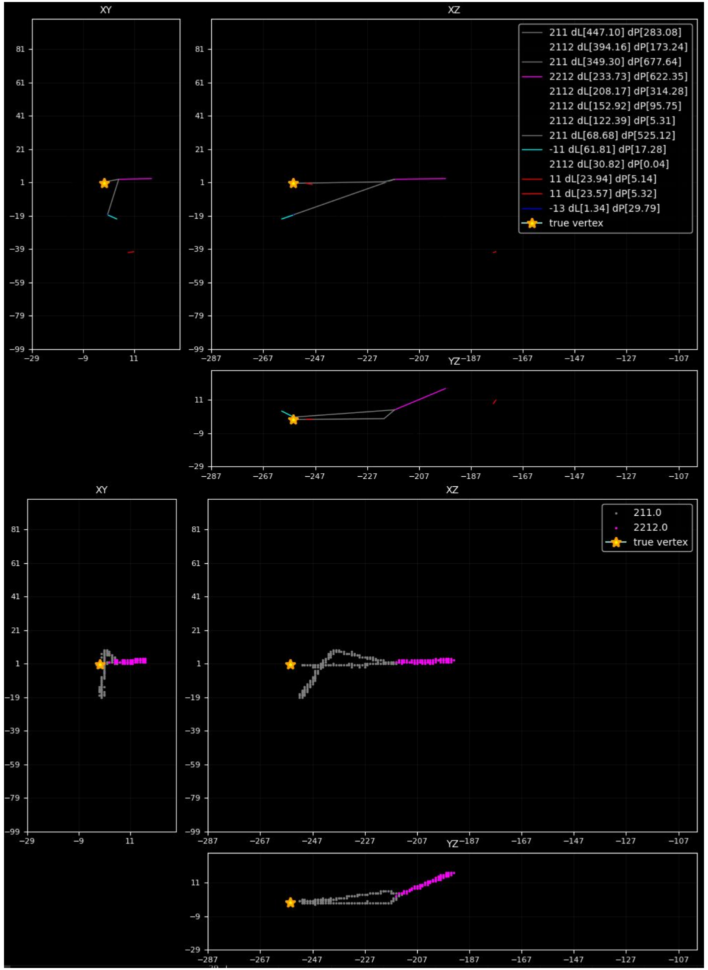
Results: confusion matrix



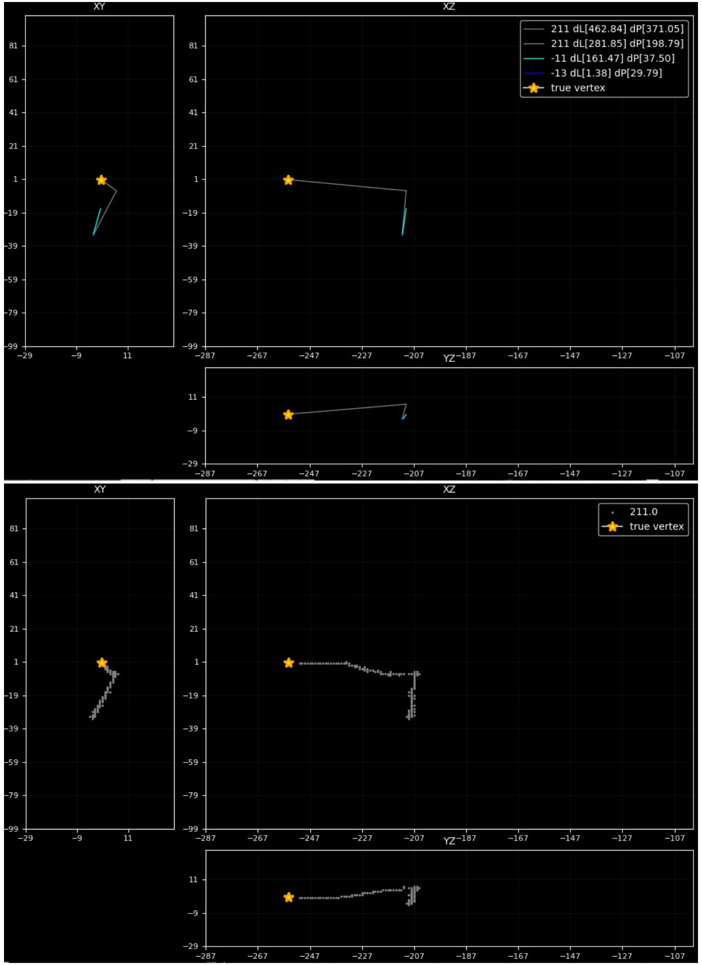
Conclusions

- SuperFGD is a novel detector, installed as a part of ND280 upgrade of the T2K experiment and now collects data
- Ability of SuperFGD to identify charged particles is studied with Monte-Carlo simulated electrons, muons, pions,protons, and photons;
- A new LSTM-based architecture of neural network for identifying particle type in the SuperFGD is proposed;
- The proposed network efficiently separates electromagnetic particles from adronic;
- Identification of muons and protons reach 97% and 96%;
- Due to similarly of energy deposit for pions and muons, accuracy for pions is 81%;
- electron-induced electromagnetic showers are separated from photon-induced with 80% accuracy.

Backups



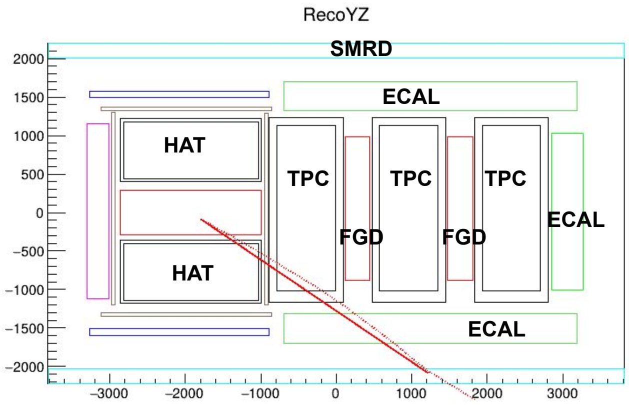
618.11 MeV/c



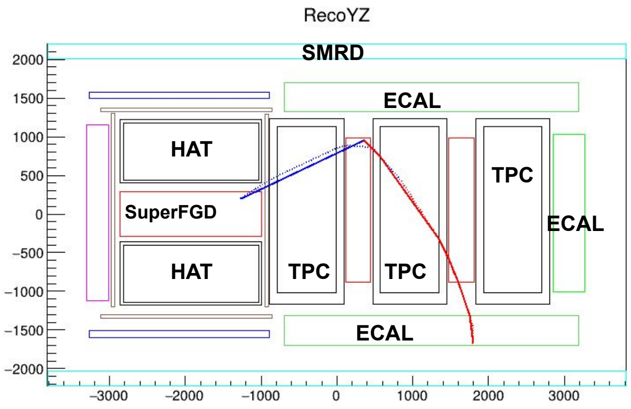
371.05 MeV/c; pion + decay, reconstructed as pion

Events examples

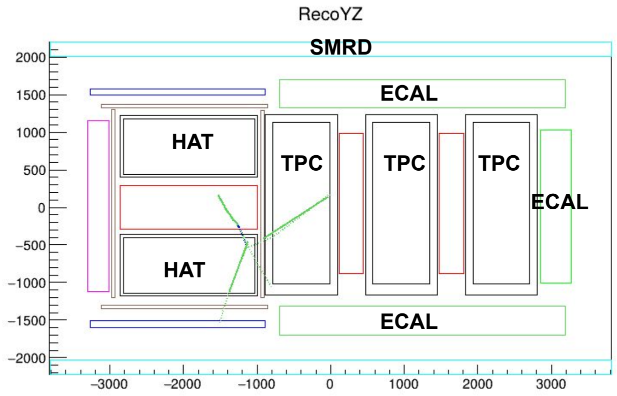
muon event	pion event	proton event



SuperFGD+HAT+TPC+ECAL for muon ECAL



SuperFGD+TPC+FGD for primary pion



SuperFGD+HAT for primary proton

dashed lines – true tracks
solid lines – reconstructed tracks