Particle identification in highly segmented neutrino detector SuperFGD of the T2K neutrino experiment

29th International Scientific Conference of Young Scientists and Specialists

Shvartsman Alexandr
INR RAS

supported by RSF grant 24-12-00271

T2K experiment

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

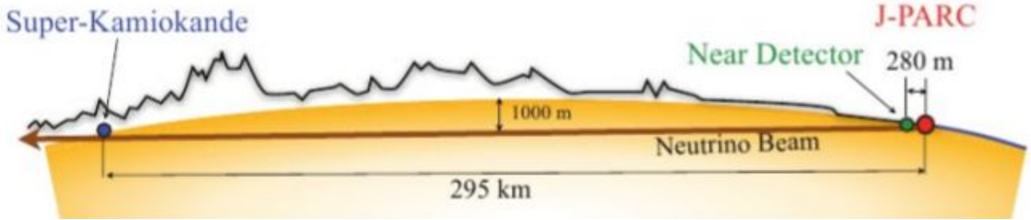
T2K (Tokai to Kamioka) is an experiment with a long baseline for searching for neutrino oscillations

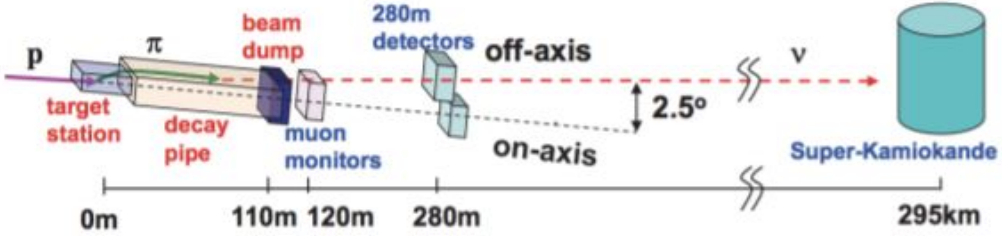
Observations: $\nu_\mu \longrightarrow \nu_e$

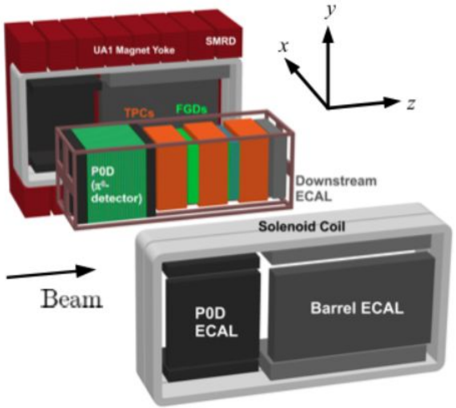
T2K conducts very precise measurements of the probability of oscillations and the difference between the masses of two types of neutrinos.

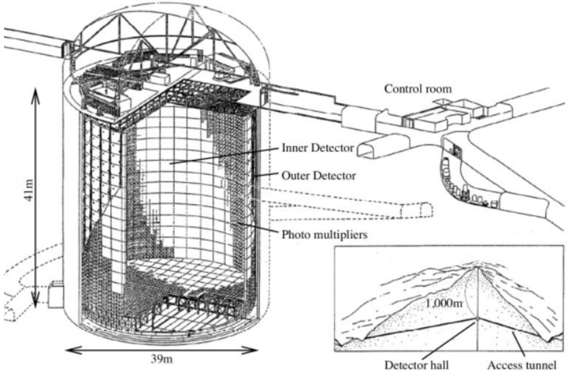
2.5° off-axis angle peaks ν_μ energy spectrum at ~600 MeV

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

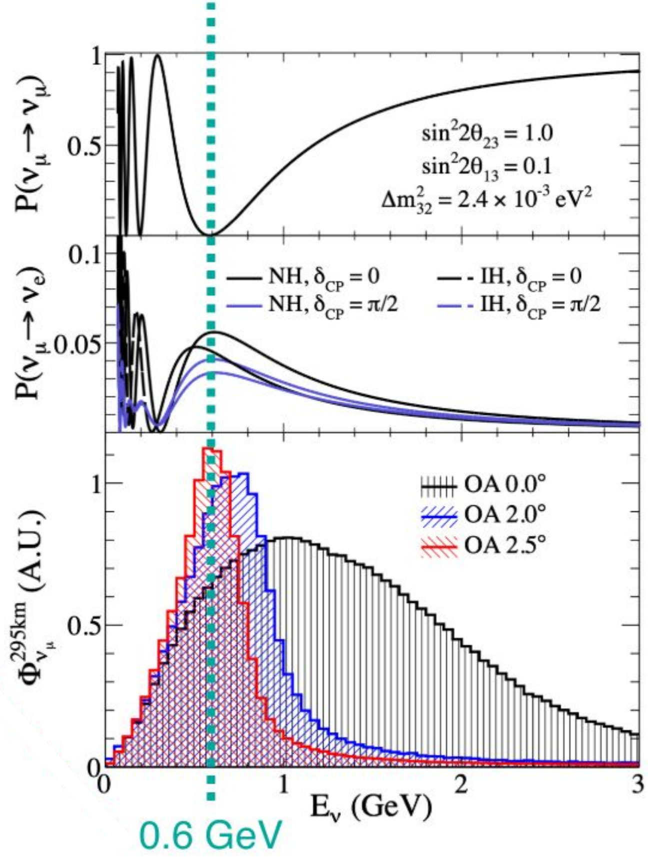








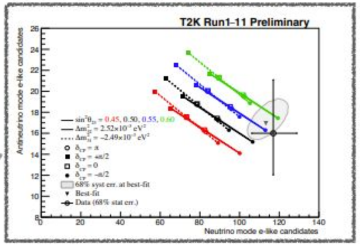
T2K experiment: CP-violation search results



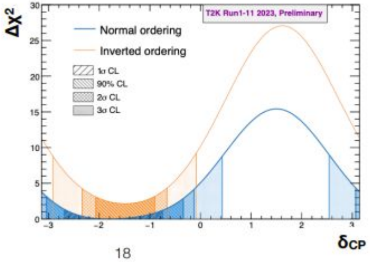
Oscillation analysis results

T2K

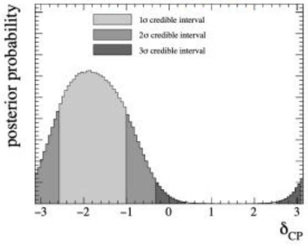
Sample	δCP=-π/2	δCP=0	δCP=π/2	δCP=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
ν̄-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
ν̄-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
ν̄-mode 1Re	17.6	20.0	22.2	19.7	16



CP-symmetry is excluded at 90% confidence level

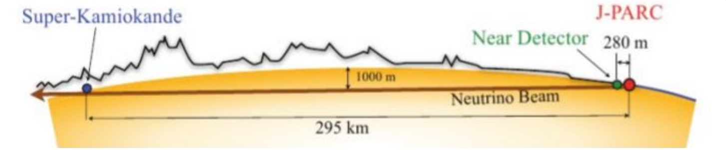


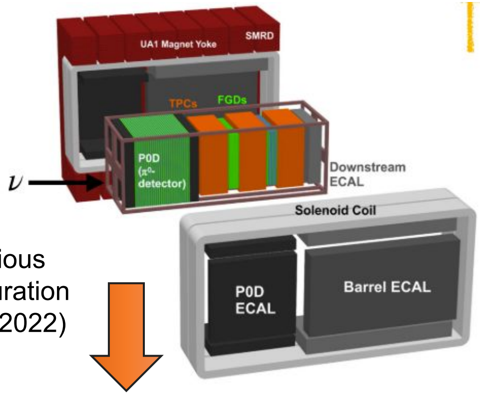
Credible intervals marginalized over both hierarchies



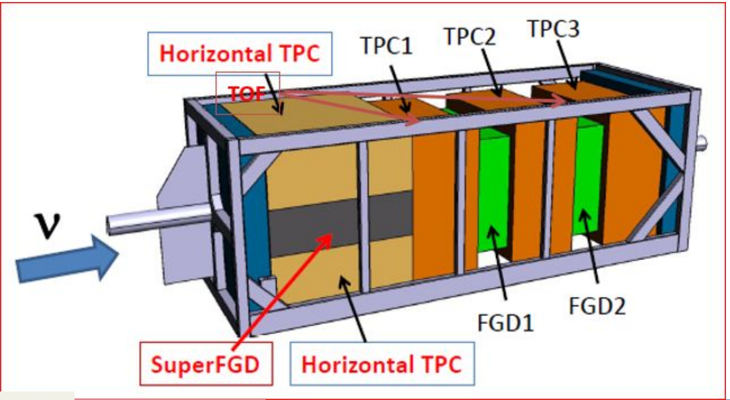
C. Giganti's talk at Neutrino-2024, 2024.06.17

Near Detector





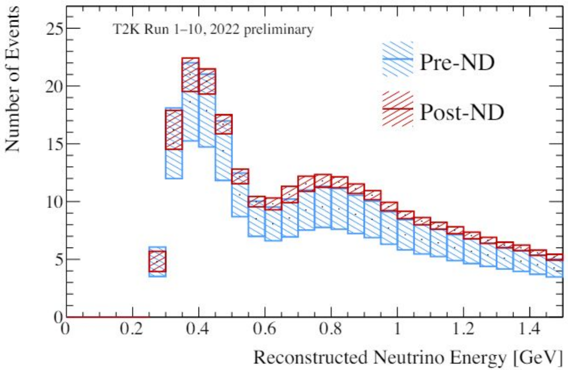
Previous configuration (2010-2022)

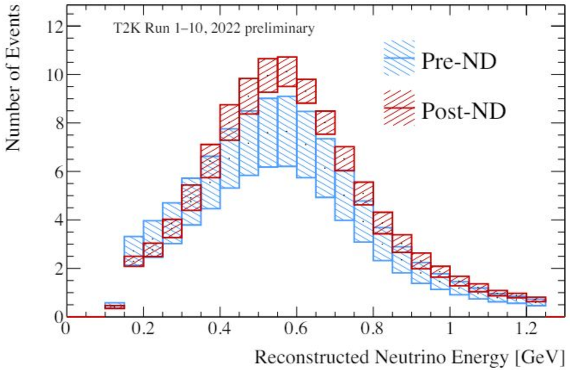


Systematic uncertainty is contrained by the measurements of the Near Detector

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

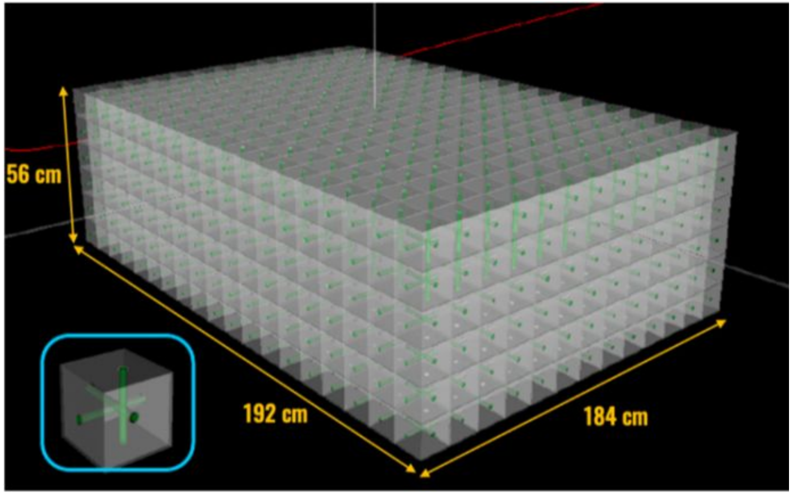
Super-Kamiokande systematics reduced from 15% to ~5-6% with ND280

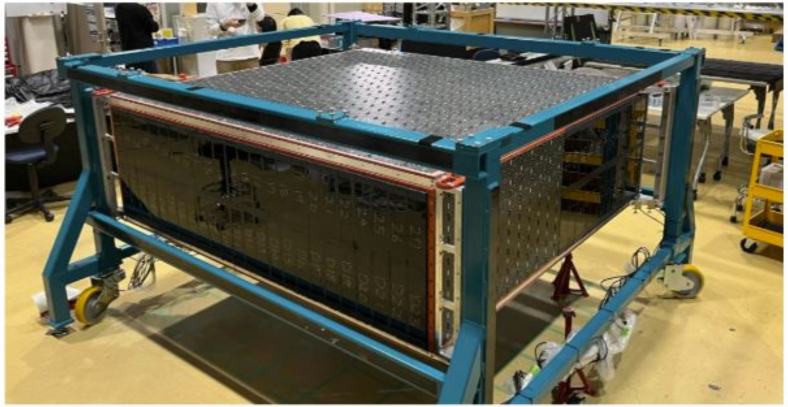




Upgrade: goal – reduce systematics downto 2-3%

P0D -> SuperFGD, HighAngleTPC, TOF





SuperFGD

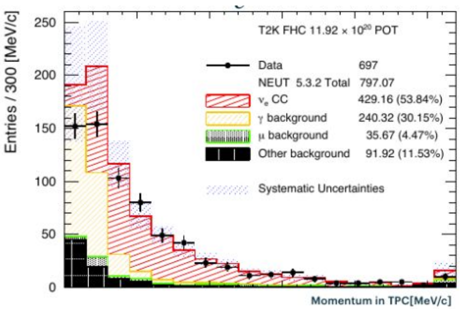
arXiv: 2005.11048

Characteristics

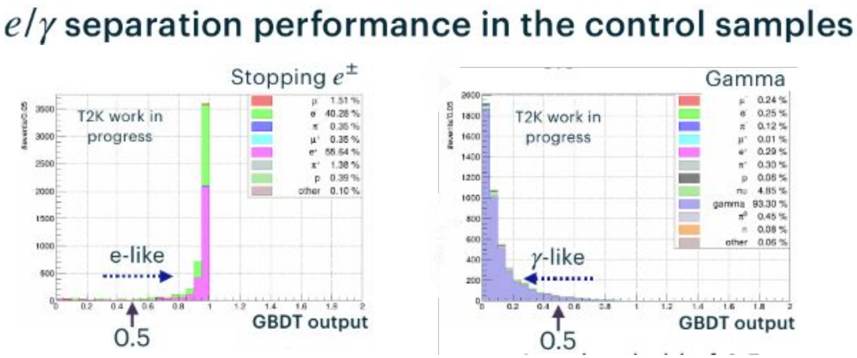
- ➢ Volume 192 x 56 x 182 cm^3
- ➢ **~2 x 10^6** scintillation cubes 1 x 1 x 1 cm^3
- ➢ 3 orthogonal holes with 1.5 mm diameter each
- ➢ 3D (x,y,z) WLS readout – about **56000** readout WLS/MPPC channels
- ➢ Active weight **2 tons** (like FGD1+FGD2)

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.

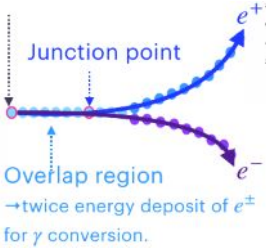


- T2K beam is muon beam, the mixture of electron neutrino is about 1%;
- Main background for electron neutrino events is from photons (T2K analysis, Abe. K. J. High Energ. Phys., 114 (2020))



Neutrino events selection:

- select a primary vertex
- group tracks into cones to capture tree-like structure
- Identify cones: Gradient Boosting Decision Trees
- find lepton from the primary vertex



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

talk by H.Kobayashi at NuFact 2025

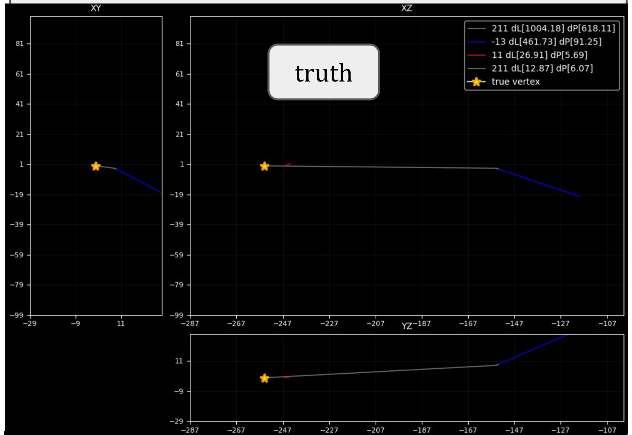
Control samples: purity of 80% at an efficiency of 20%

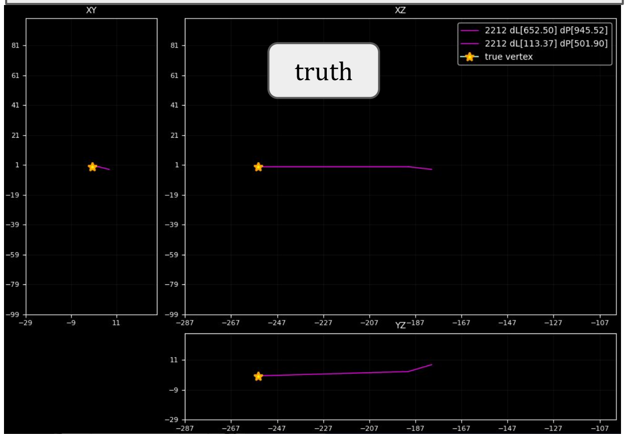
Deep neural network models can be applied. Monte-Carlo simulated in the SuperFGD electrons, photons, muons, pions, protons with energies up to 1 GeV were used for testing and evaluation.

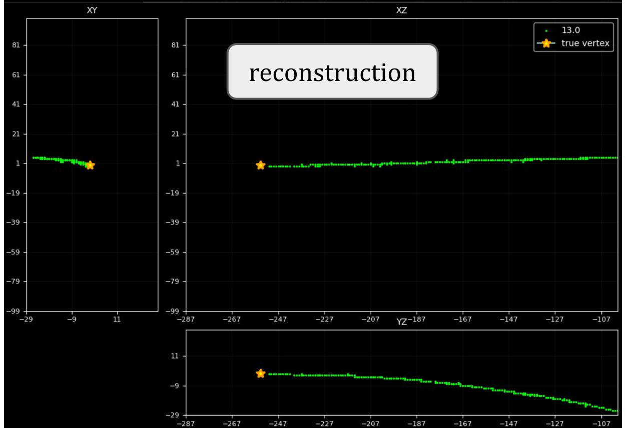
for different models see talk by A. Chalumeau at EPS-HEP

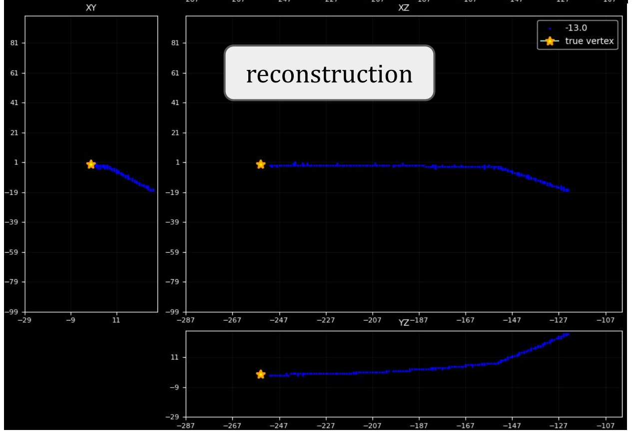
Events examples

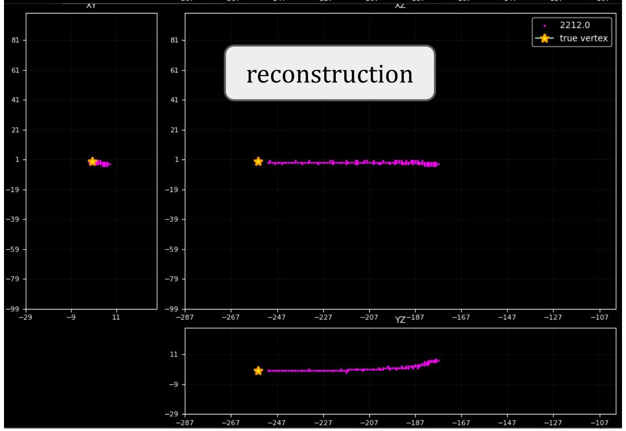
muon event	pion event	proton event







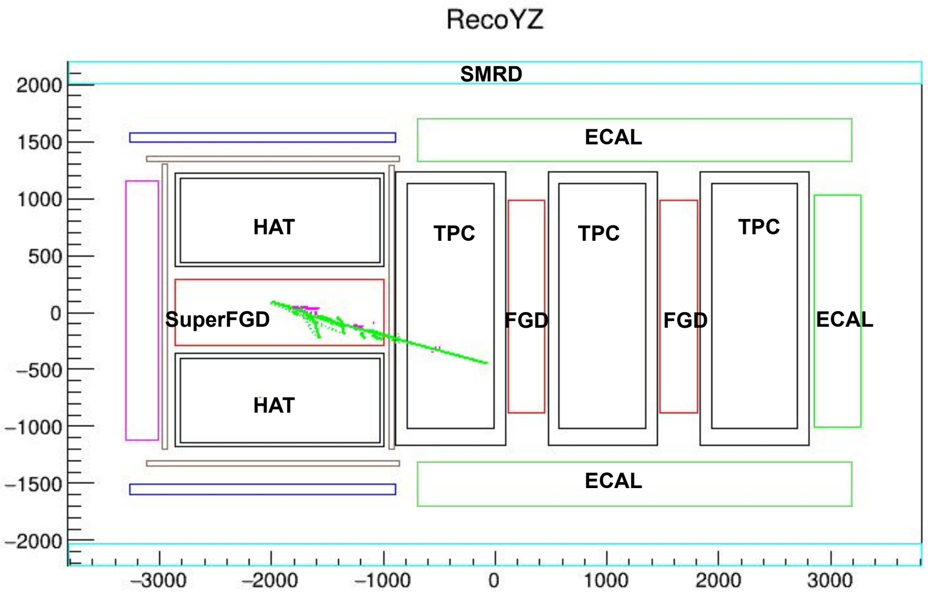


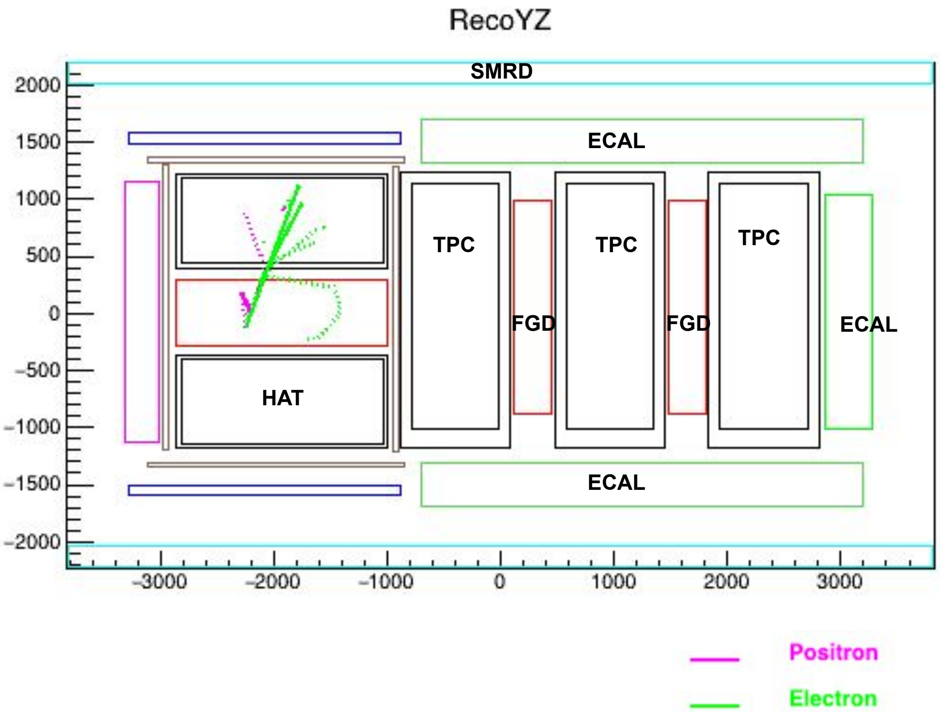


Events examples

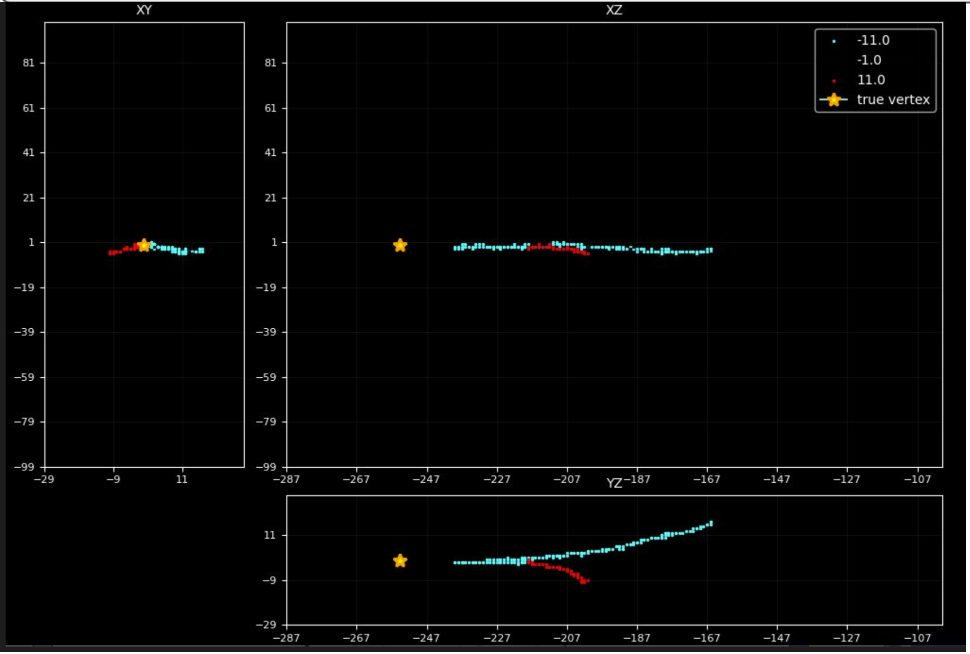
T2K beam is muon beam, the mixture of electron neutrino is about 1%. Photons are background for electron neutrino interactions

electron shower	photon shower



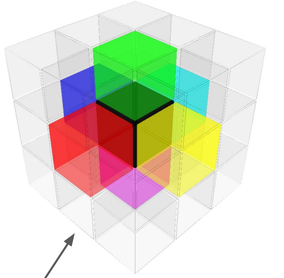


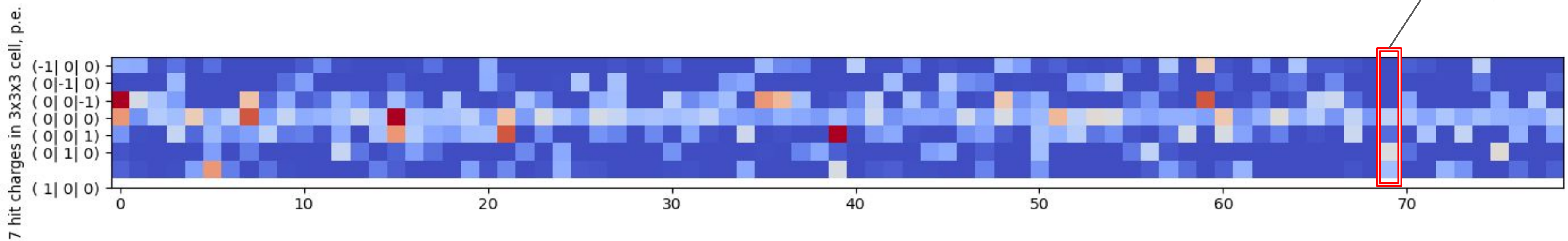
SuperFGD events representation



- **~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

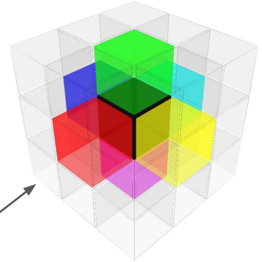


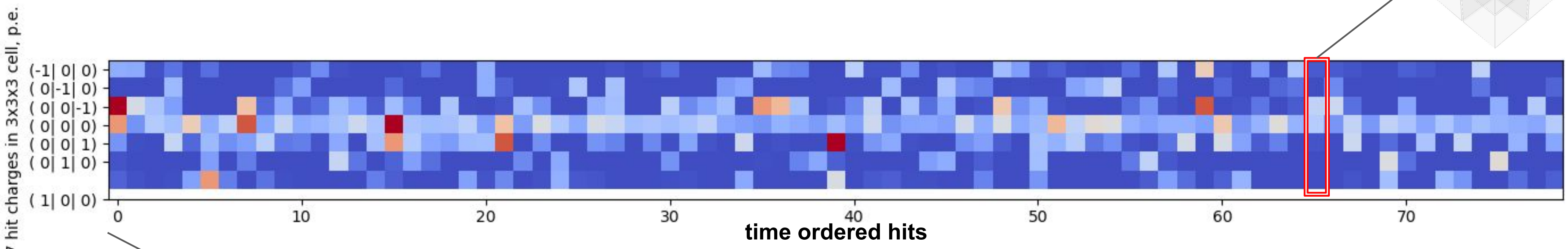


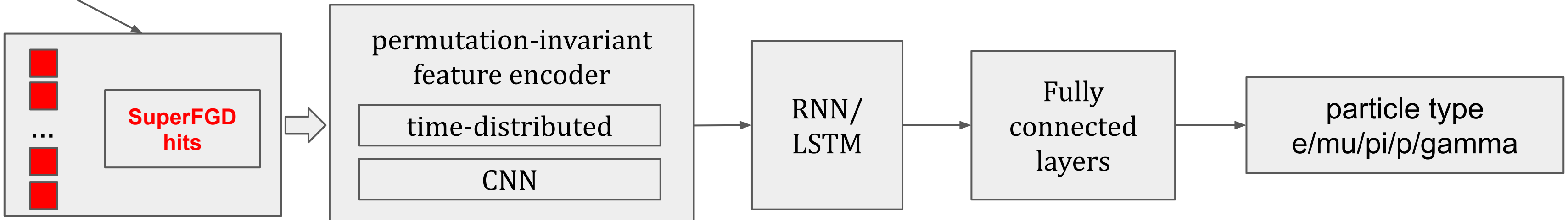
Model architecture for particle identification

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

- timesteps:
  - hit in SuperFGD: charge

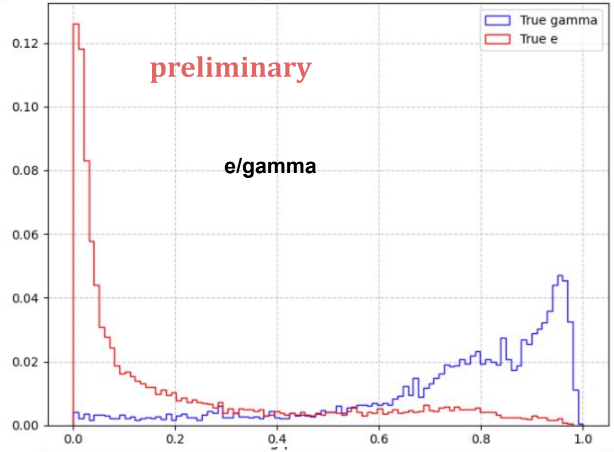


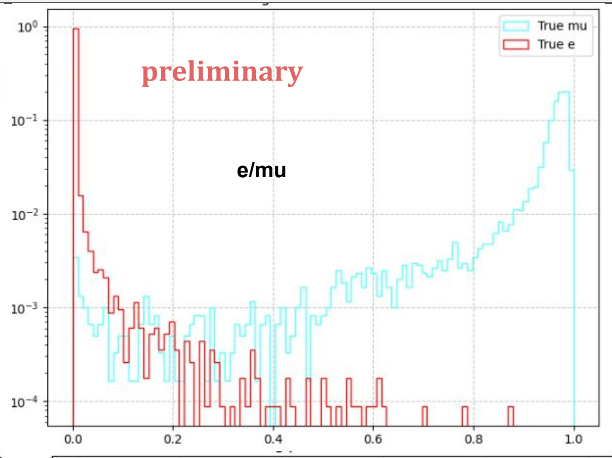


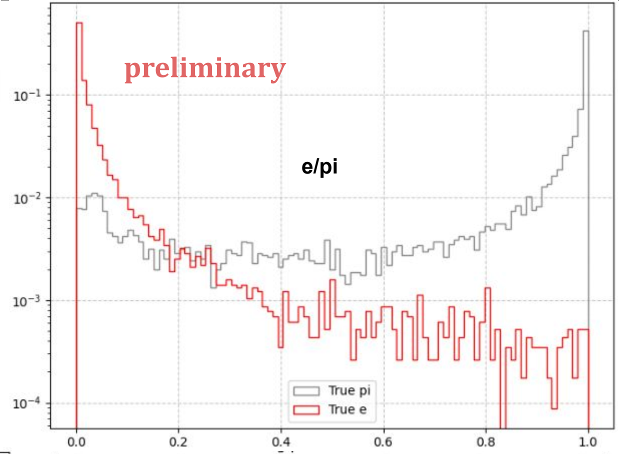


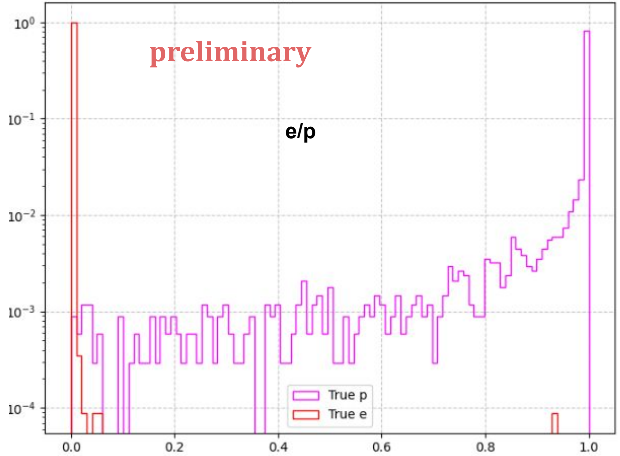
Sequence of “timesteps”

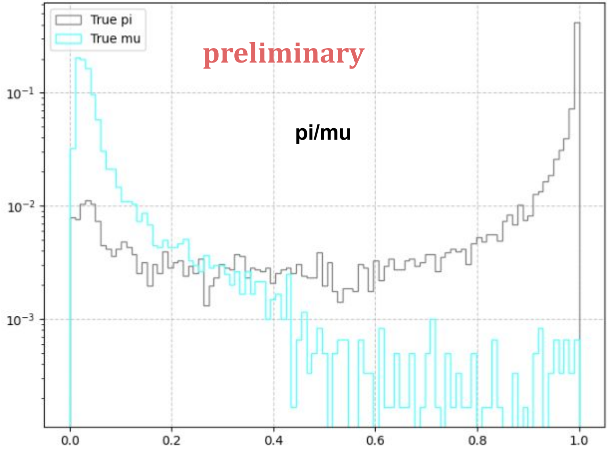
Results

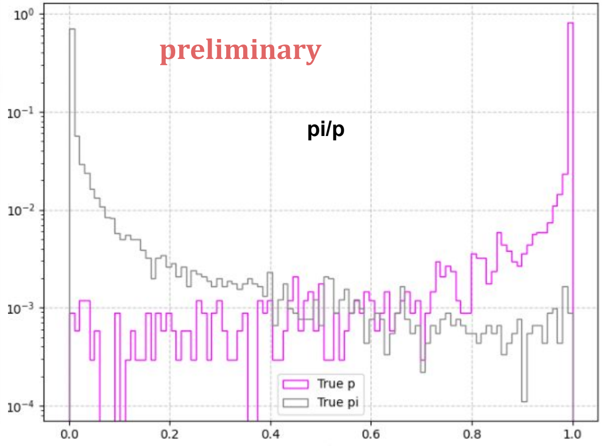

True gamma
True e
preliminary
e/gamma


True mu
True e
preliminary
e/mu

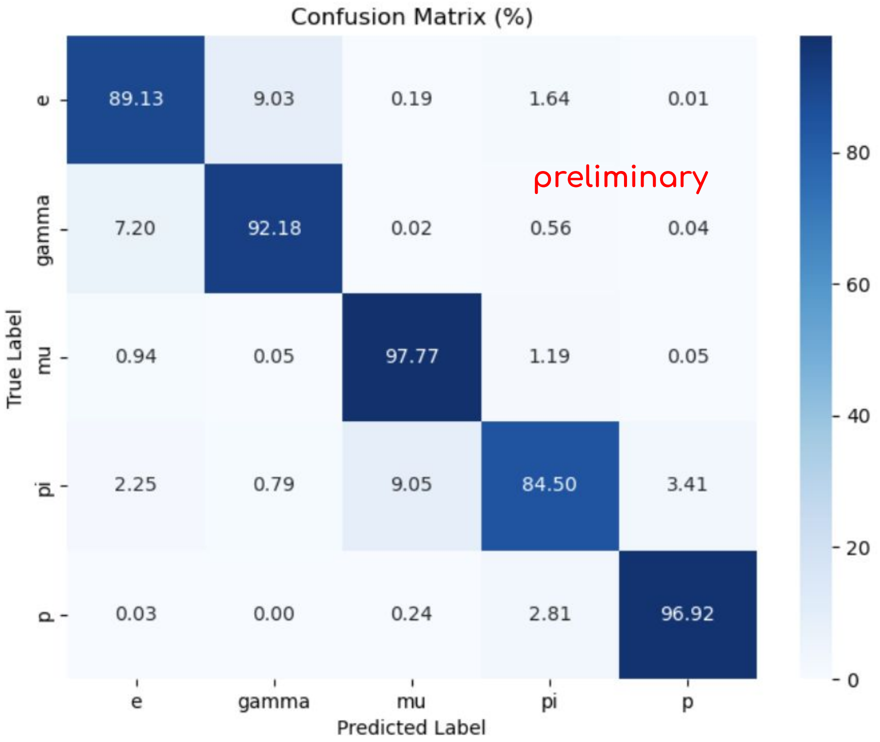

preliminary
e/pi
True pi
True e


preliminary
e/p
True p
True e

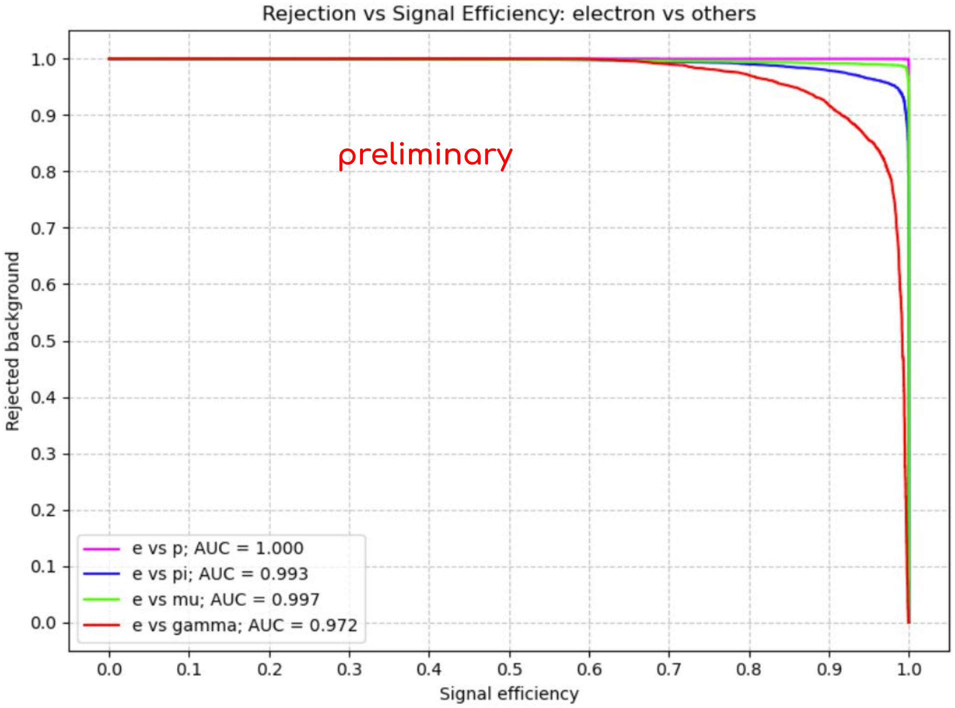

True pi
True mu
preliminary
pi/mu


preliminary
pi/p
True p
True pi

Results-2



Confusion Matrix (%)
True Label
Predicted Label
e
gamma
mu
pi
p
89.13 9.03 0.19 1.64 0.01
7.20 92.18 0.02 0.56 0.04
0.94 0.05 97.77 1.19 0.05
2.25 0.79 9.05 84.50 3.41
0.03 0.00 0.24 2.81 96.92
0
20
40
60
80
preliminary

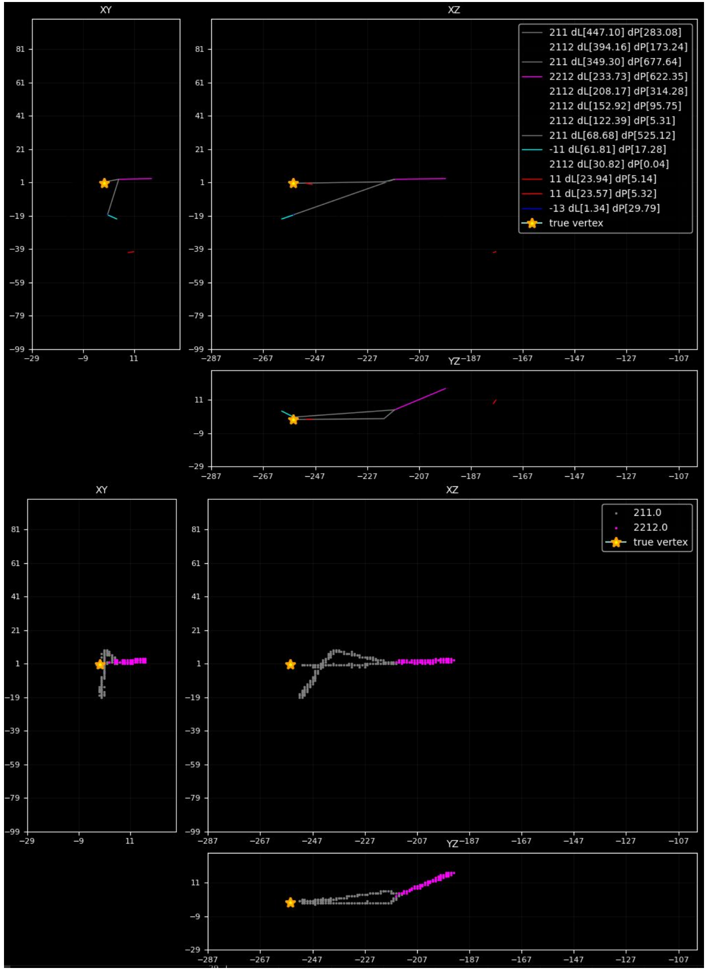


Rejection vs Signal Efficiency: electron vs others
Rejected background
Signal efficiency
preliminary
e vs p; AUC = 1.000
e vs pi; AUC = 0.993
e vs mu; AUC = 0.997
e vs gamma; AUC = 0.972

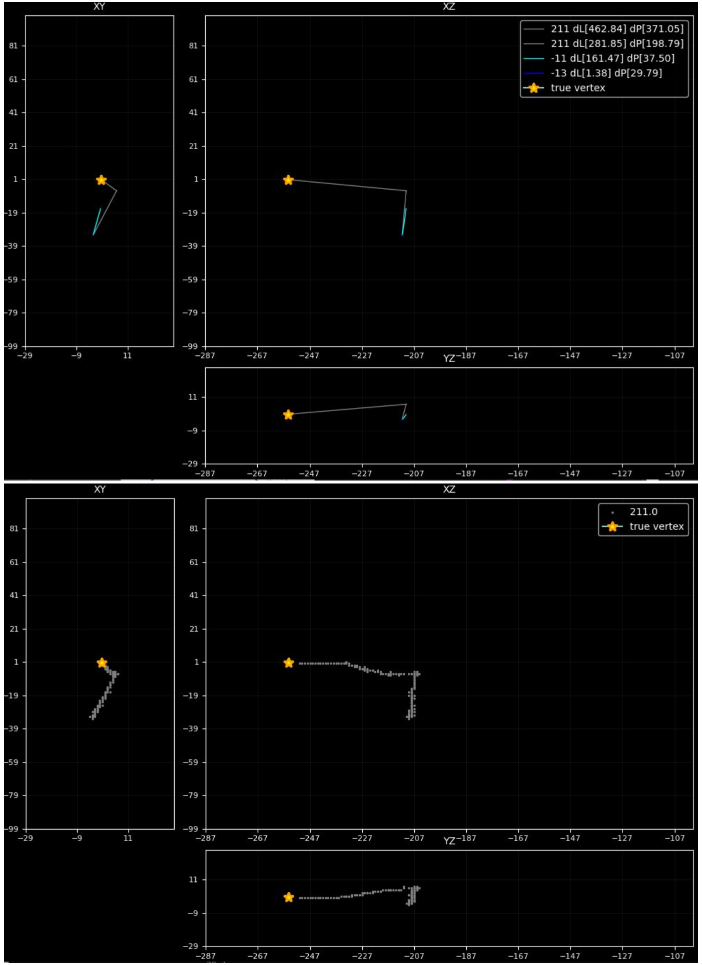
Conclusions

- 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;
- 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 98% and 97%;
- Due to similarly of energy deposit for pions and muons, accuracy for pions is 84%;
- electron-induced electromagnetic showers are separated from photon-induced with 89% accuracy.

Backups



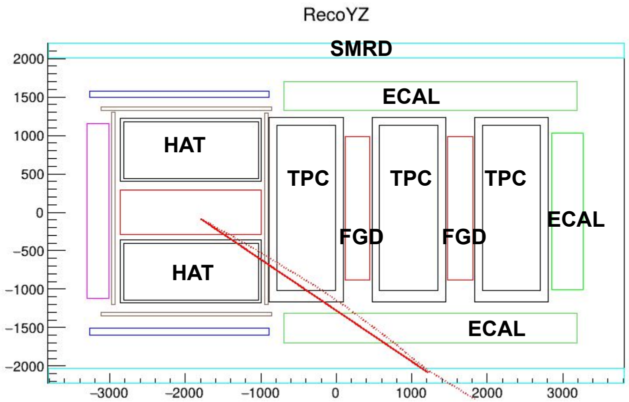
618.11 MeV/c



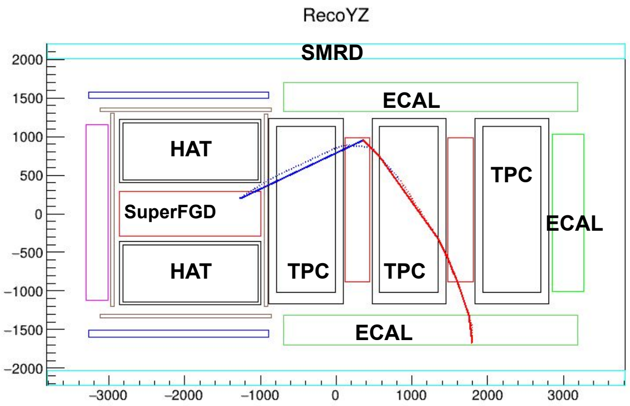
371.05 MeV/c; pion + decay, reconstructed as pion

Events examples

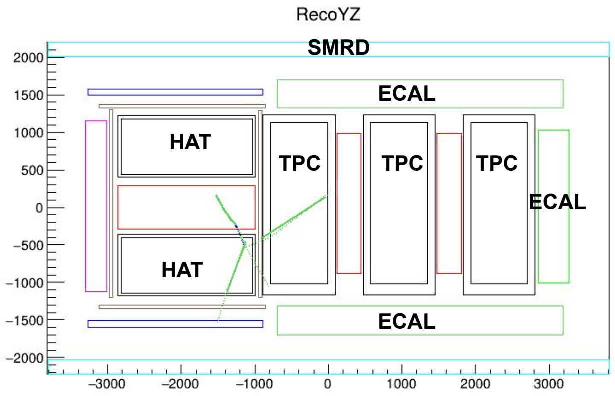
muon event	pion event	proton event



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