Assembly, test and analysis development of the T2K upgrade

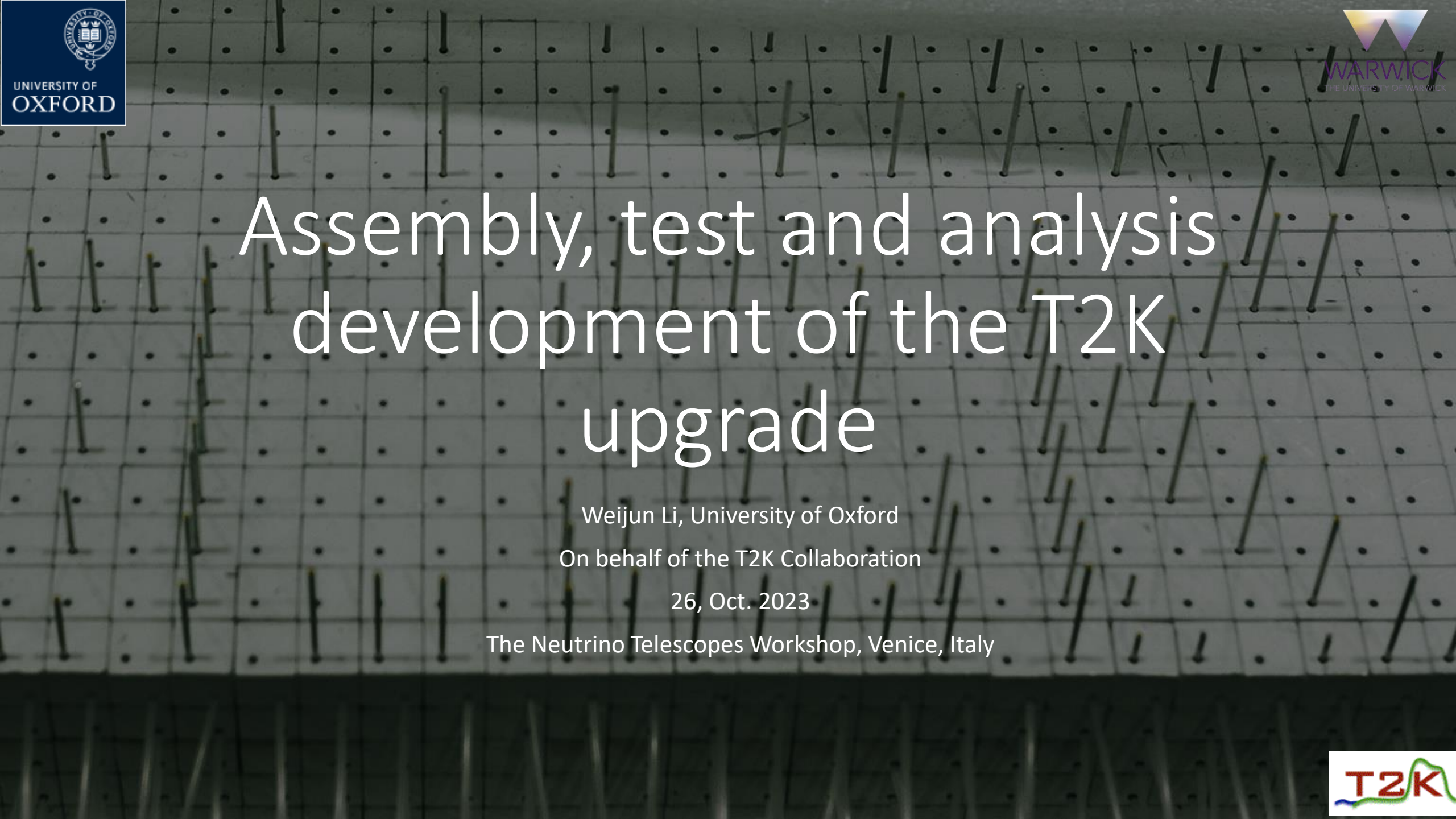
Weijun Li (University of Oxford) on behalf of the T2K Collaboration

Abstract

The near detector of T2K is undergoing a major upgrade. A new scintillator tracker, named superFGD, with fine granularity and 3D-reconstruction capabilities has been installed. The new Time Projection Chambers are based on the innovative resistive Micromegas technology and a field cage made of extremely thin composite walls. New scintillator panels with precise timing capability have been built to allow precise Time of Flight measurements.

Most of the upgrade has been assembled, installed and would be ready to take beam data in November 2023. The detailed characterization of detectors and multiple test results of the detectors were presented.

These innovative technologies bring significant improvements in phase space acceptance and resolution. A preliminary $\nu_\mu CC0\pi$ sample is selected with 94% purity, out of which a sub-sample with Elastically Contained and Scattered (ESC) protons achieves a proton momentum reconstruction resolution of 3.2%. The ESC sample is used to reconstruct and analyze Transverse Kinematic Imbalance (TKI) variables. Moreover, the pion decay topology is exploited in the new pion trackless reconstruction, which significantly improves efficiency for low momentum pions and is combined with the ESC protons to produce a $\nu_\mu CC1p1\pi$ sample to investigate TKI. Moreover, we devised a new nuclear-model-independent Final State Interaction probe, the pion decay angle in the centre-of-momentum frame of reconstructed hadrons. Neutron kinetic energy is reconstructed for the first time and novel colorimetric variables are also under development. Additionally, the GENIE Heavy Neutral Lepton (HNL) generator, BeamHNL, has been interfaced with the T2K simulation to explore the impact on HNL sensitivity.



Assembly, test and analysis development of the T2K upgrade

Weijun Li, University of Oxford

On behalf of the T2K Collaboration

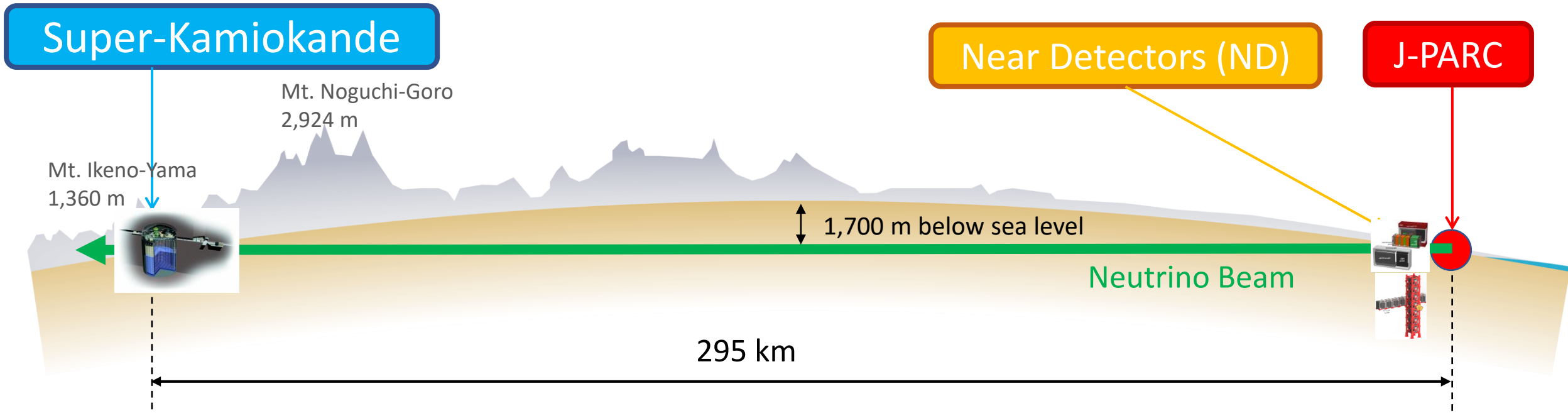
26, Oct. 2023

The Neutrino Telescopes Workshop, Venice, Italy

Outline

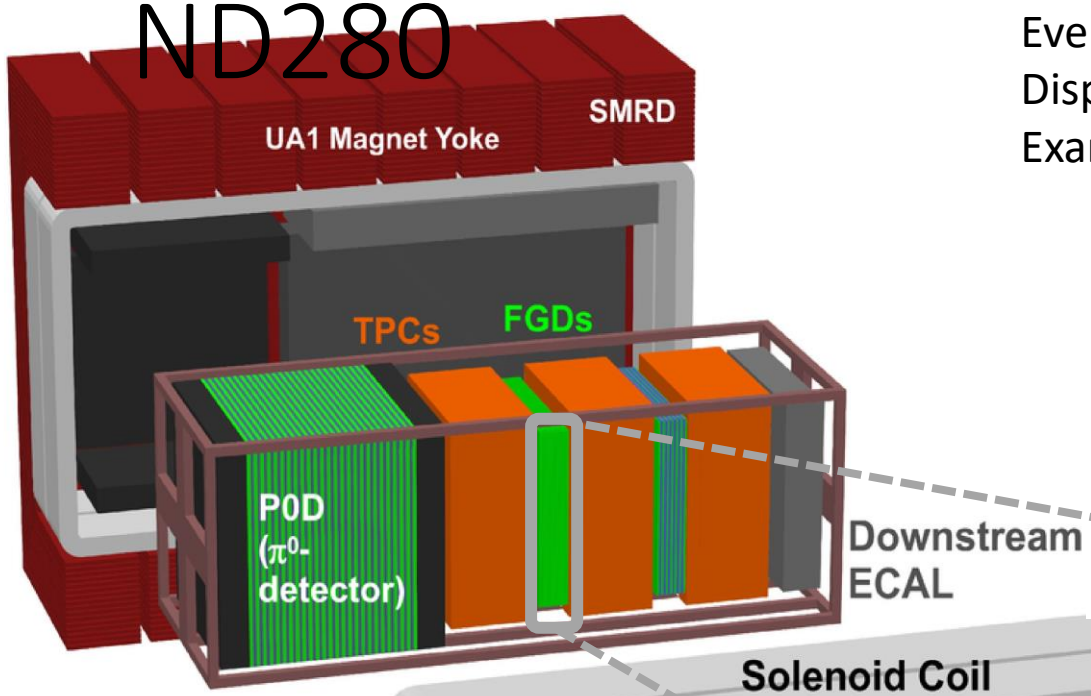
- Motivation
- Hardware – the new detectors
- Software – New analyses and samples selection

The T2K Experiment

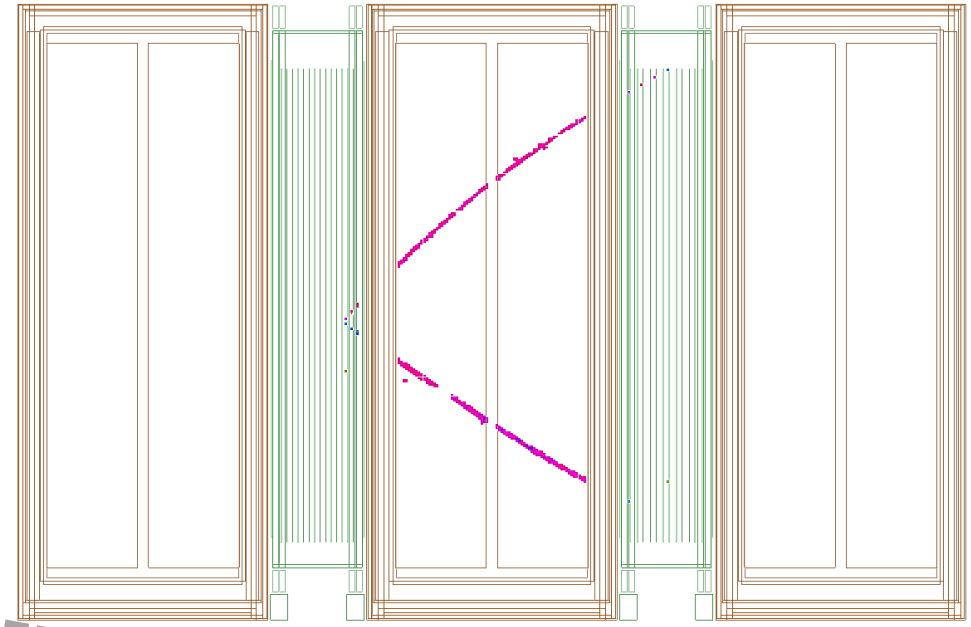


See Tom Holvey's talk

ND280



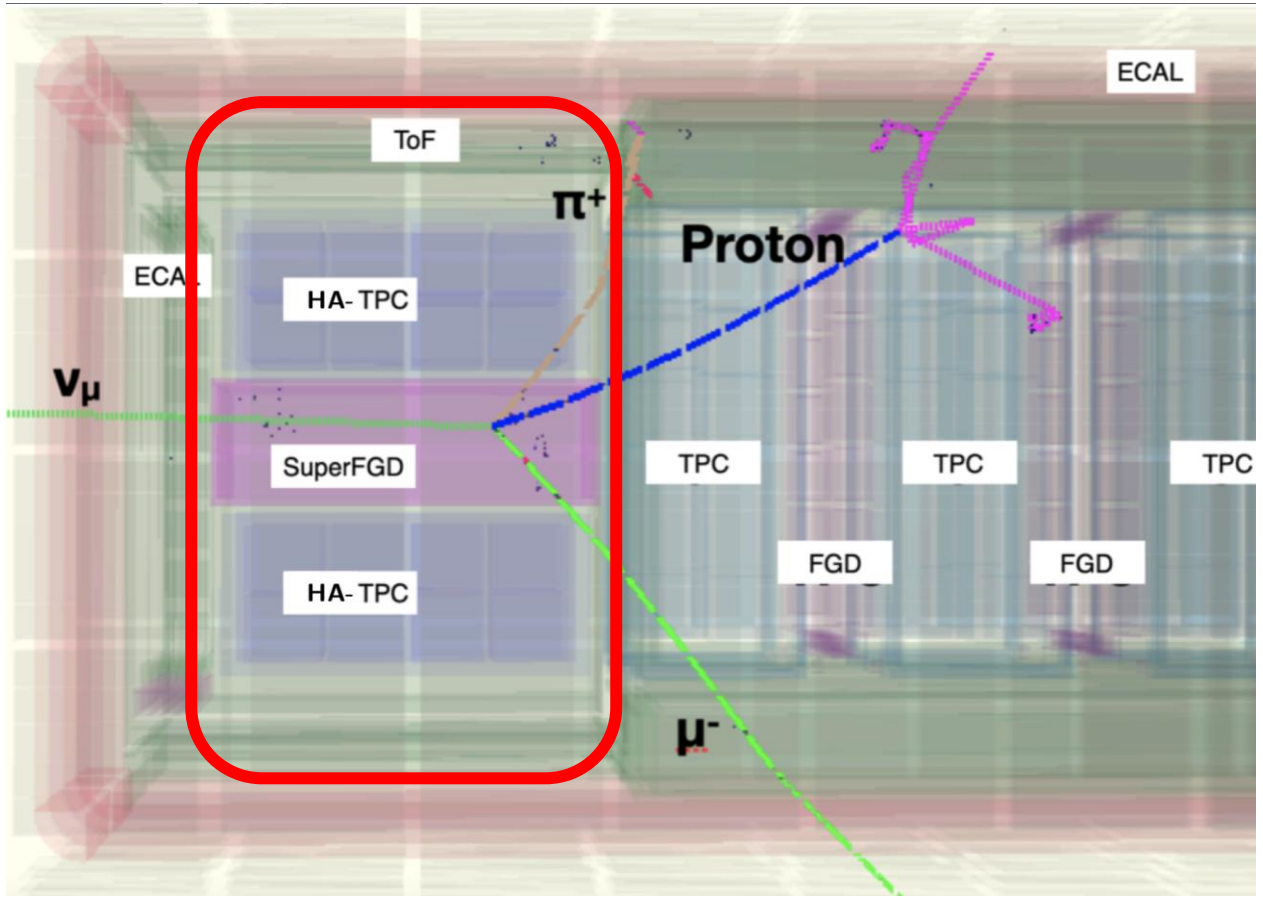
Event Display Example



Problem: low high-angle acceptance!

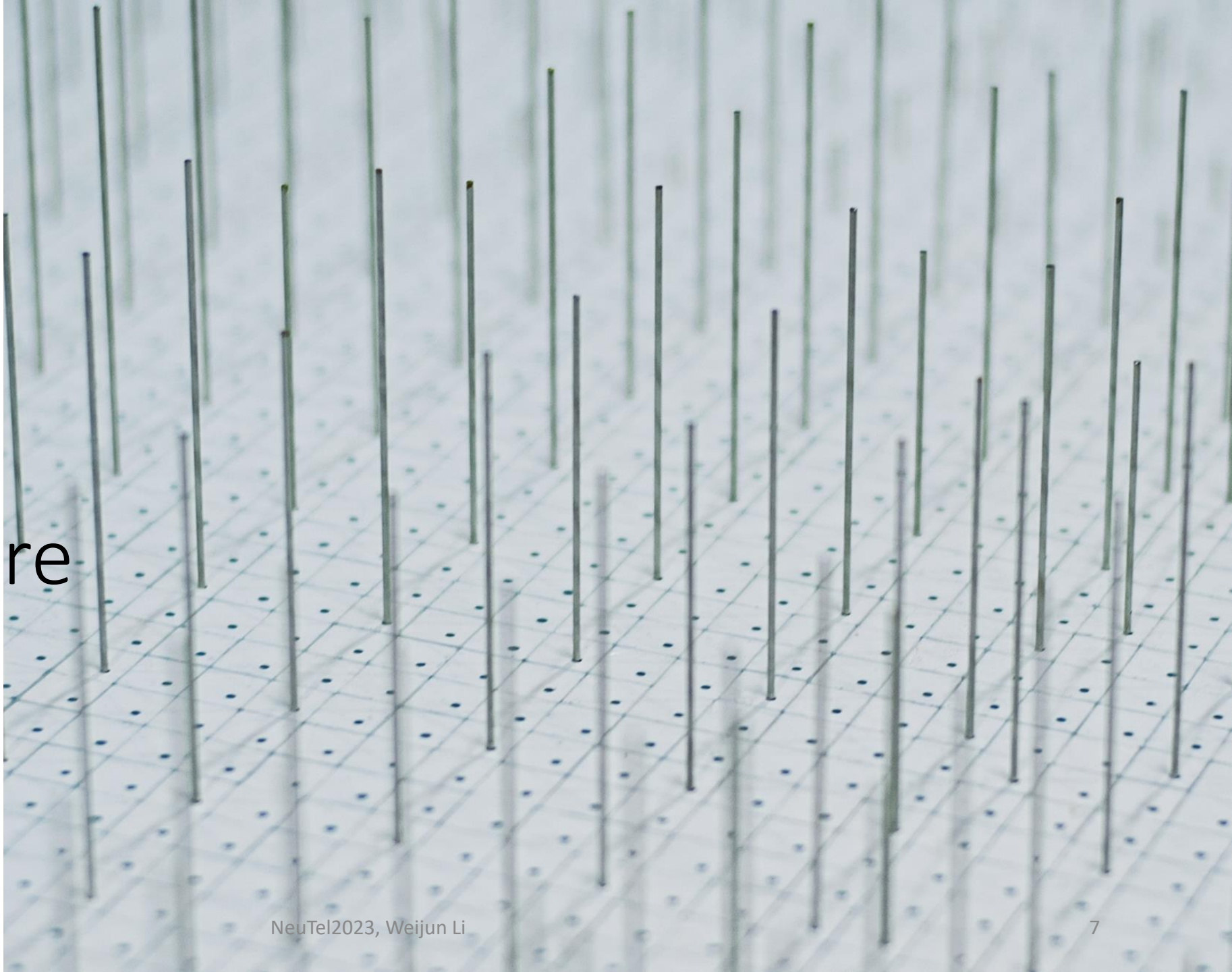
Motivation

- The scintillation bars has poor high angle acceptance and limited resolution
- The upgrade is designed to solve these problems



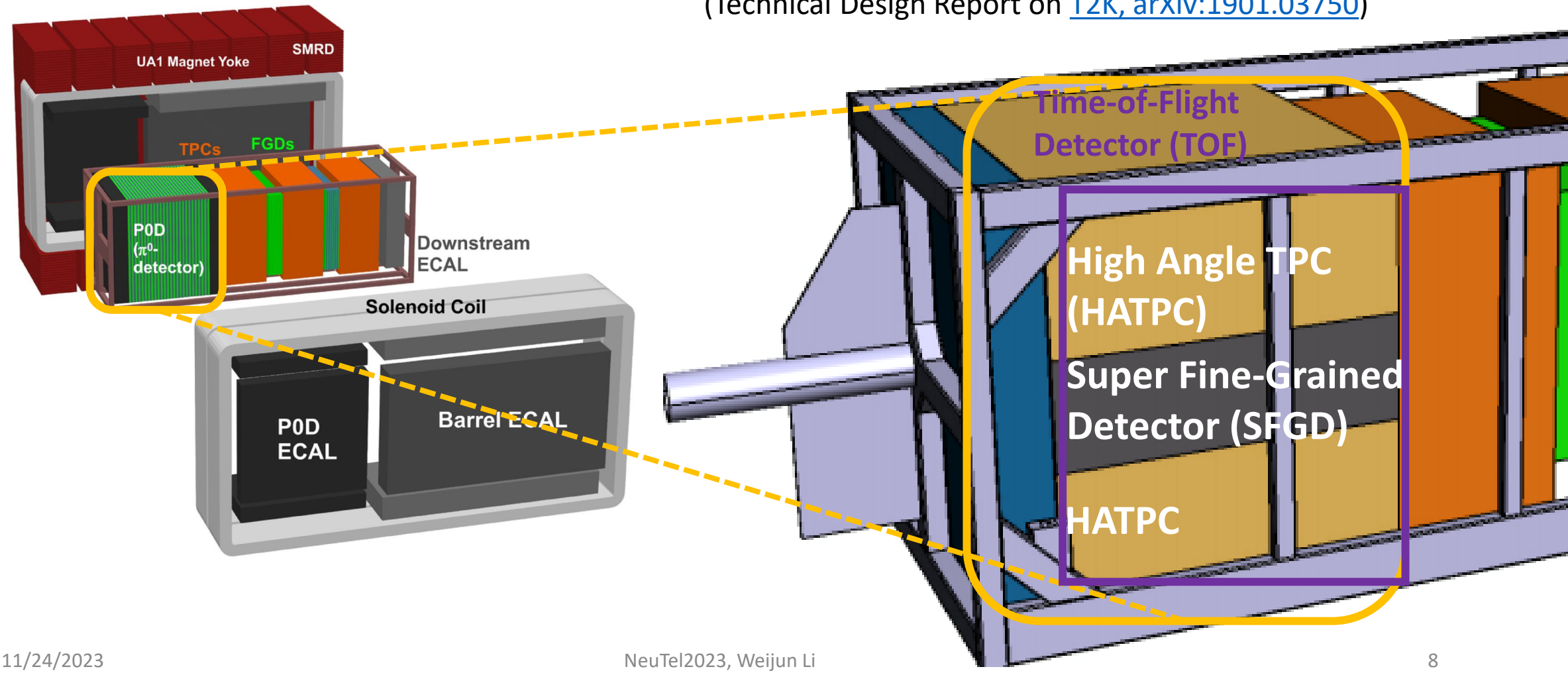
The Hardware

- Tests and Assembly

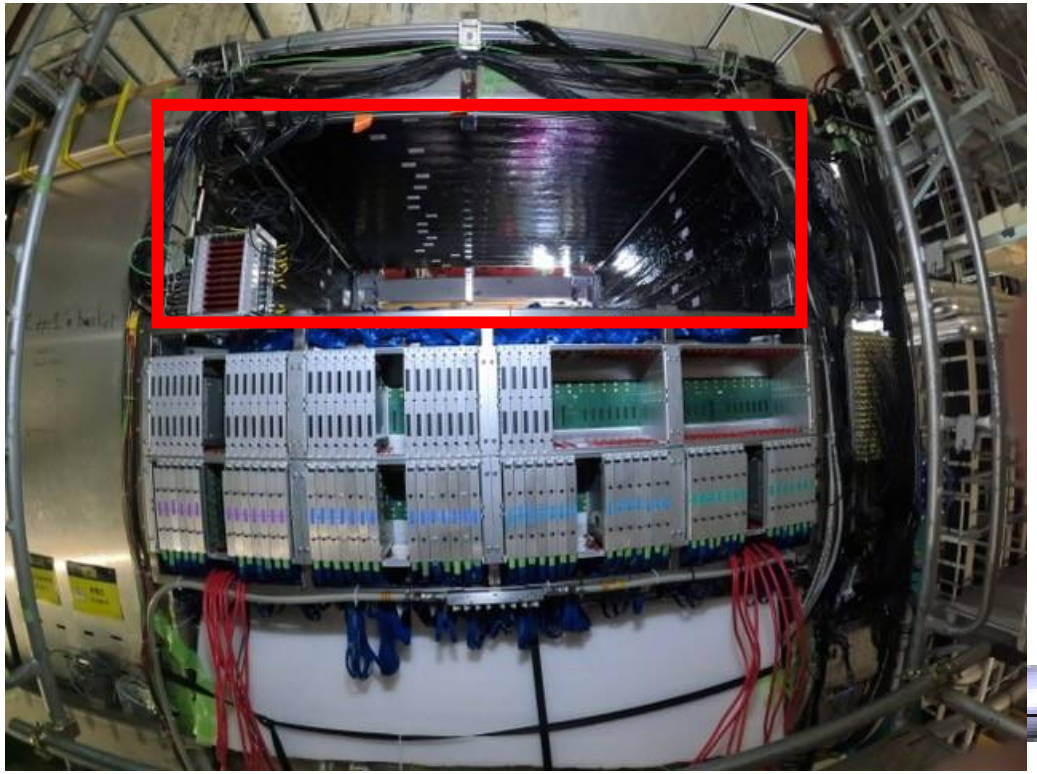


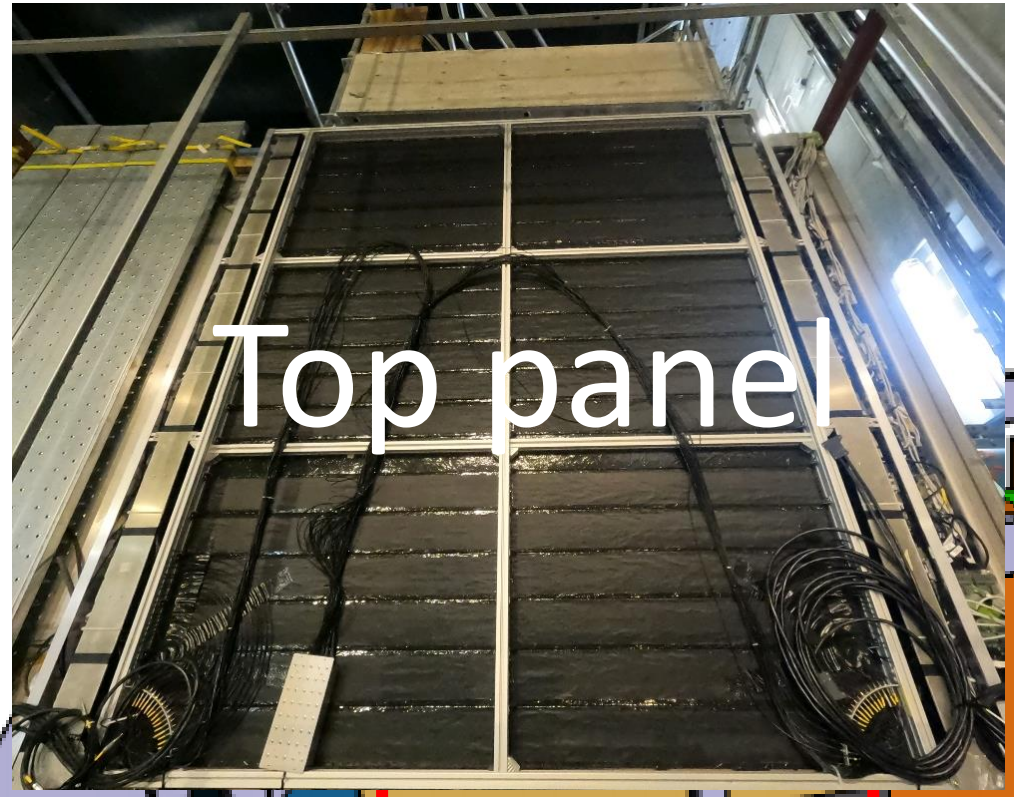
Near Detector

(Technical Design Report on T2K, arXiv:1901.03750)



Time-of-Flight Detector

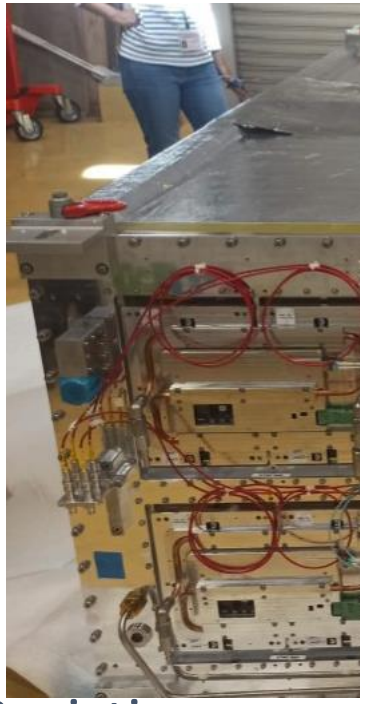


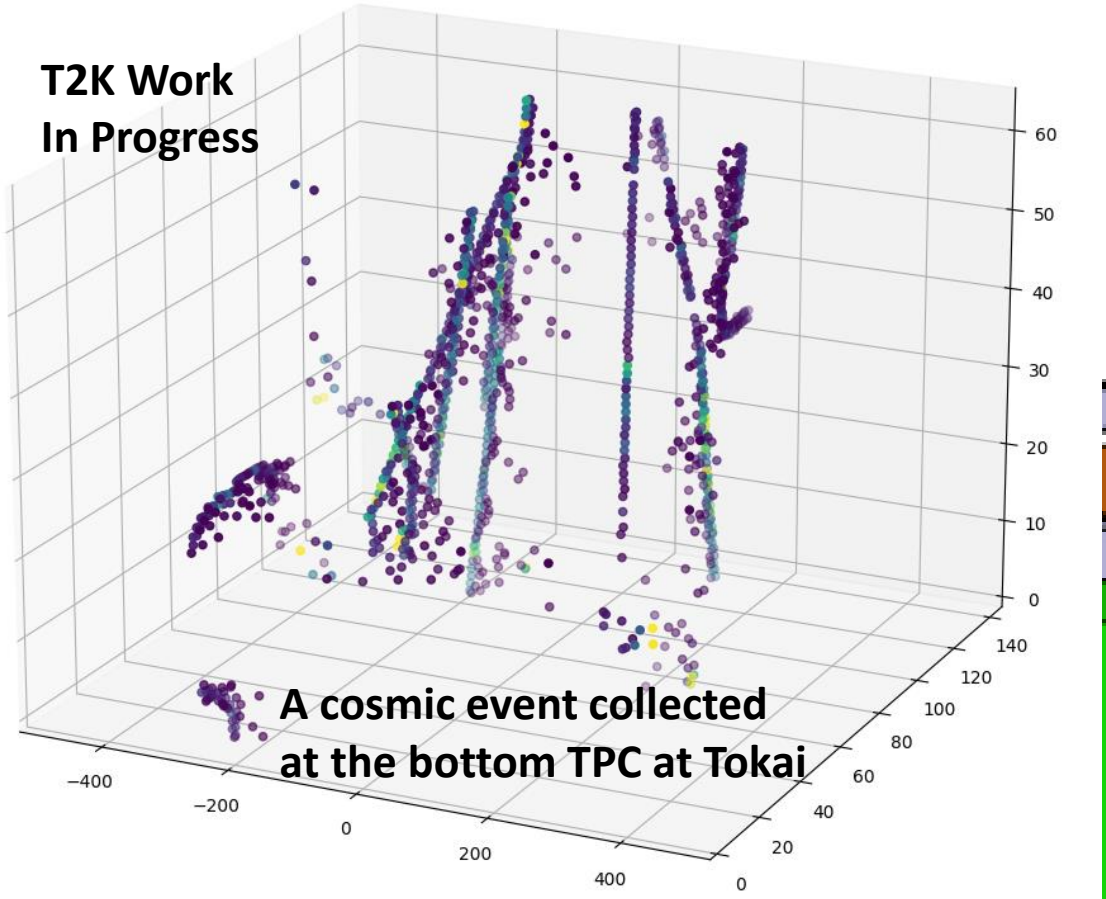


- 6 Planes of 20 Scintillation Bars
- Veto of outside particles & Cosmic triggers

-> Excellent timing resolution ~ 0.14ns (A. Korzenev et al., JINST 17 P01016 (2022))

High Angle TPC



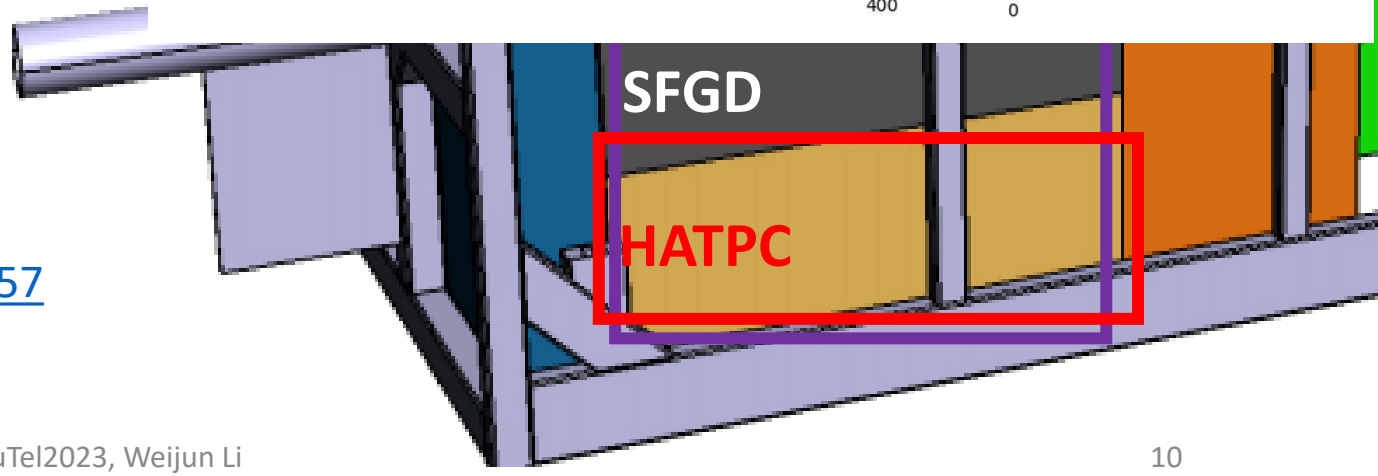


- New field cage design and Resistive MicroMegas

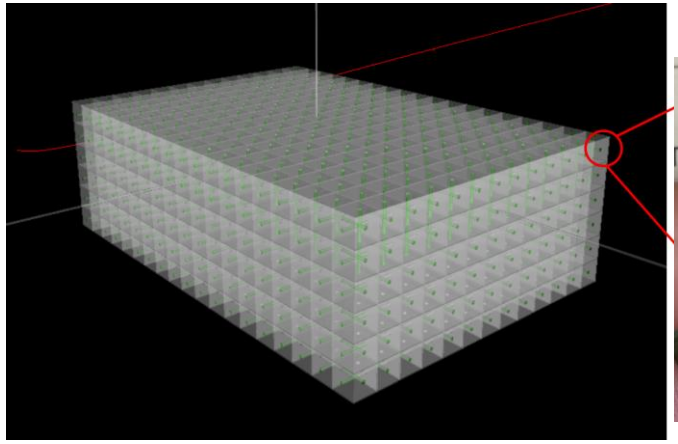
➔ Larger **tracking** volume and **better spatial resolution**

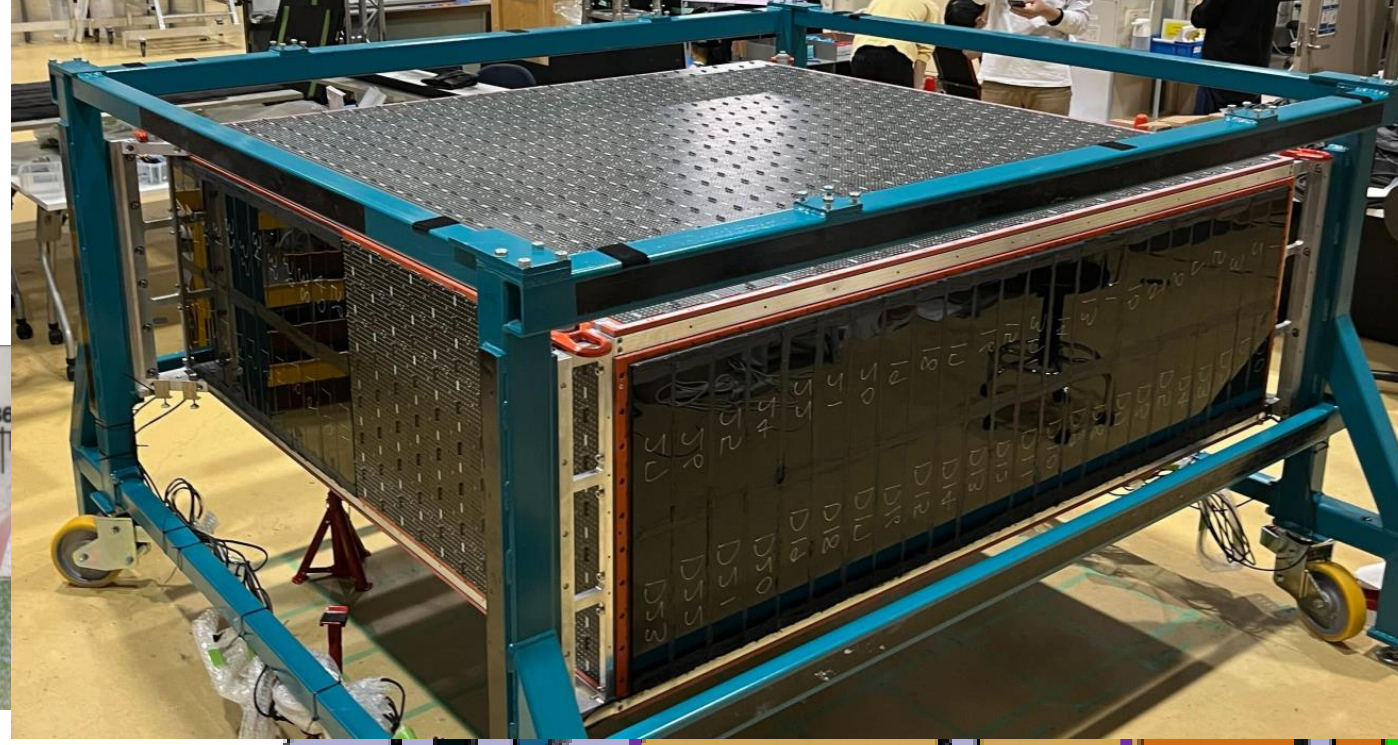
➔ Spatial resolution ~ 500 μm, dE/dx resolution < 10%

  - D. Attié et al., Nucl. Inst. and Methods, A 957 (2020) 163286
  - D. Attié et al., j.nima.2021.166109

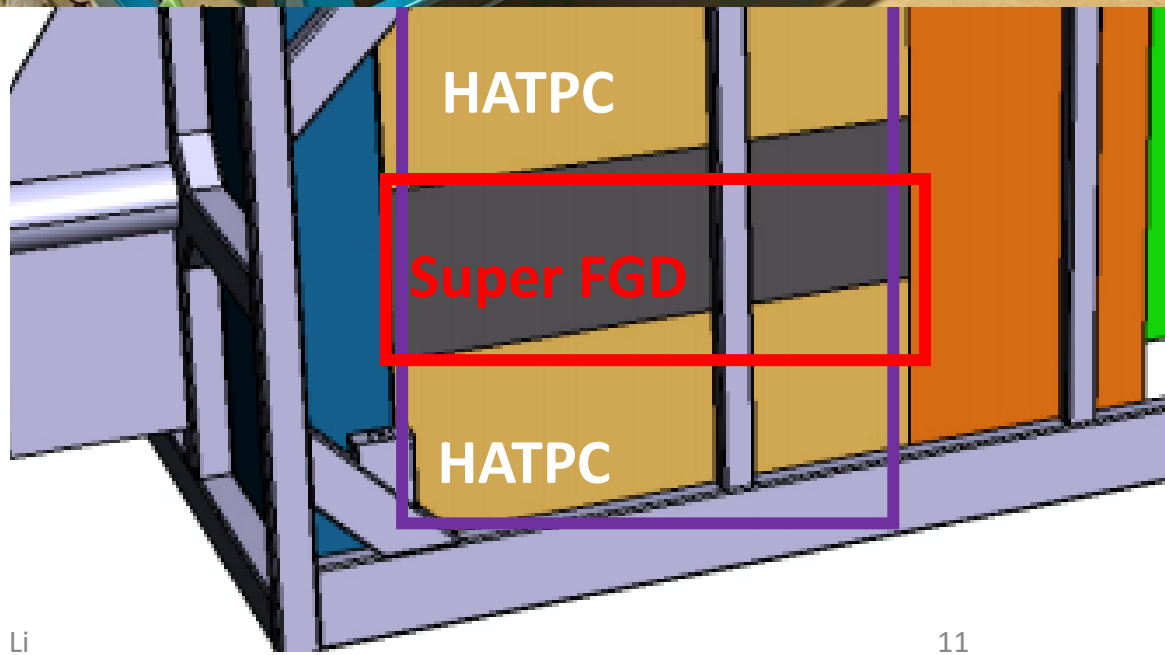


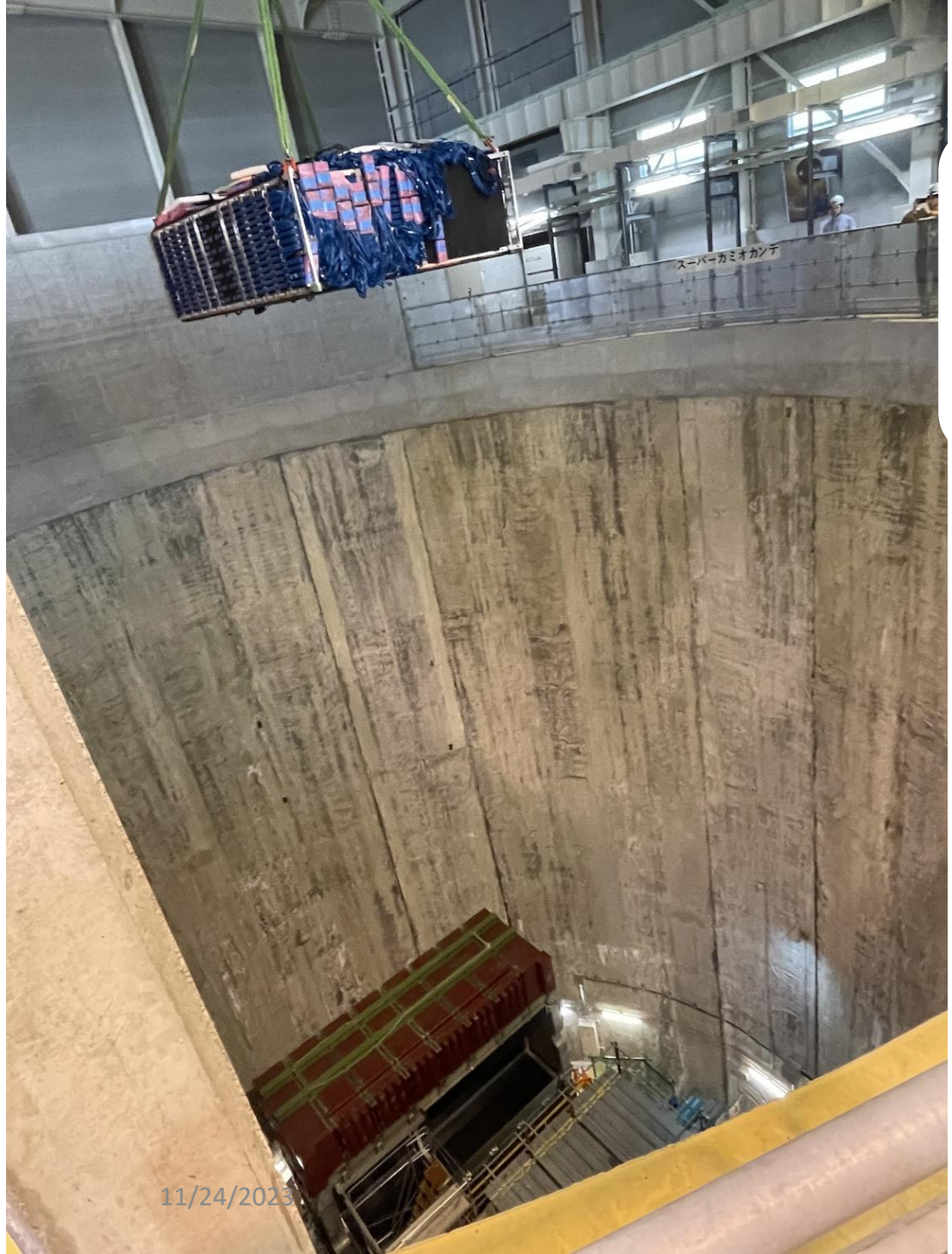
SFGD





- 3D plastic scintillator ~ 2 million 1.0 cm^3 cubes
- Active target (~2ton), tracking and PID
- Isotropic particle tracking, and together with HATPC -> better phase space match with Far Detector
- Excellent local dE/dx measurement and timing resolution ~ 1.14ns
  - Charged particle beam, A. Blondel et al., JINST 15 P12003 (2020)
  - Neutron beam, A. Agarwal et al., Phys. Lett. B 840 (2023) 137843

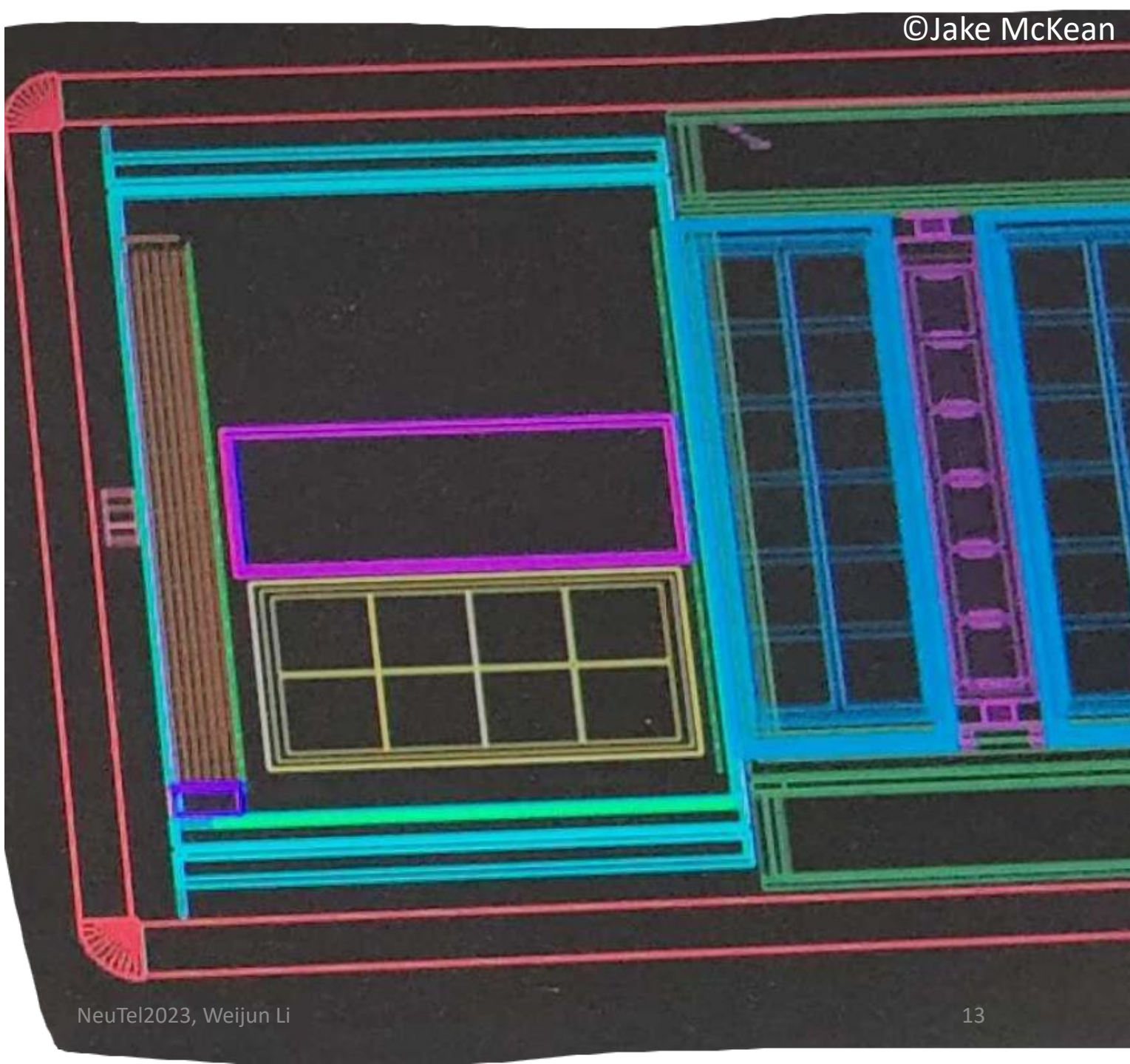





© Tsunayuki Matsubara
TOF
Top High Angle TPC
(coming next spring)
TOF
Ready for beam run
Super FGD
in November!!
Bottom High Angle TPC

The Software

- Analyses Development



List of Current Analyses

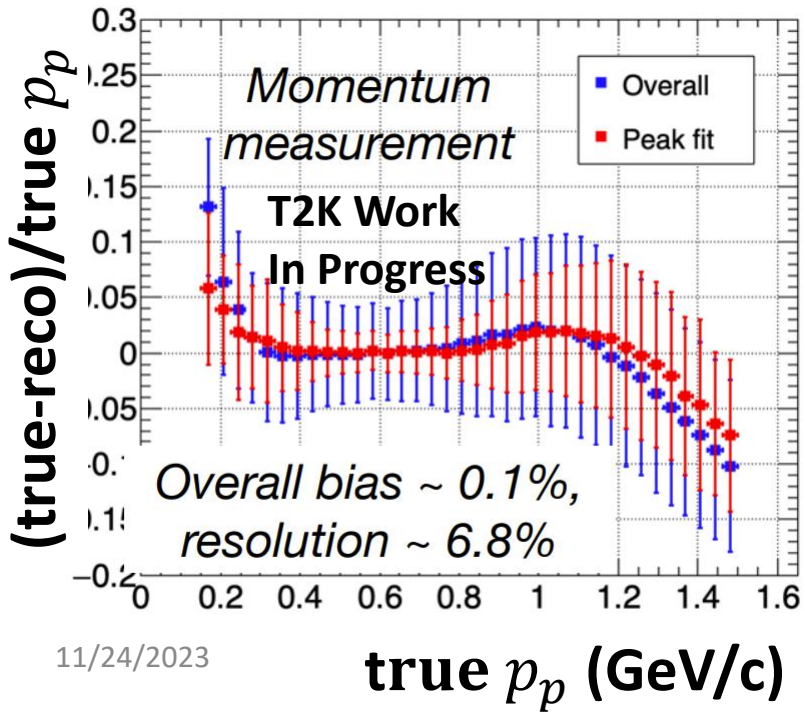
- ν_μCC0π
  - Inclusive, Elastically Scattered and Contained (ESC) protons
  - Transverse Kinematic Imbalance (TKI), Calorimetric Variables
- ν_μCC1π^+
  - Trackless pion selection, Double TKI
  - Proton- π^+ rest frame variables
- $\overline{\nu_\mu}$
  - Neutron Kinematics Reconstruction
- Exotics
  - Heavy Neutral Lepton (HNL)
- ν_e - Requires more validation

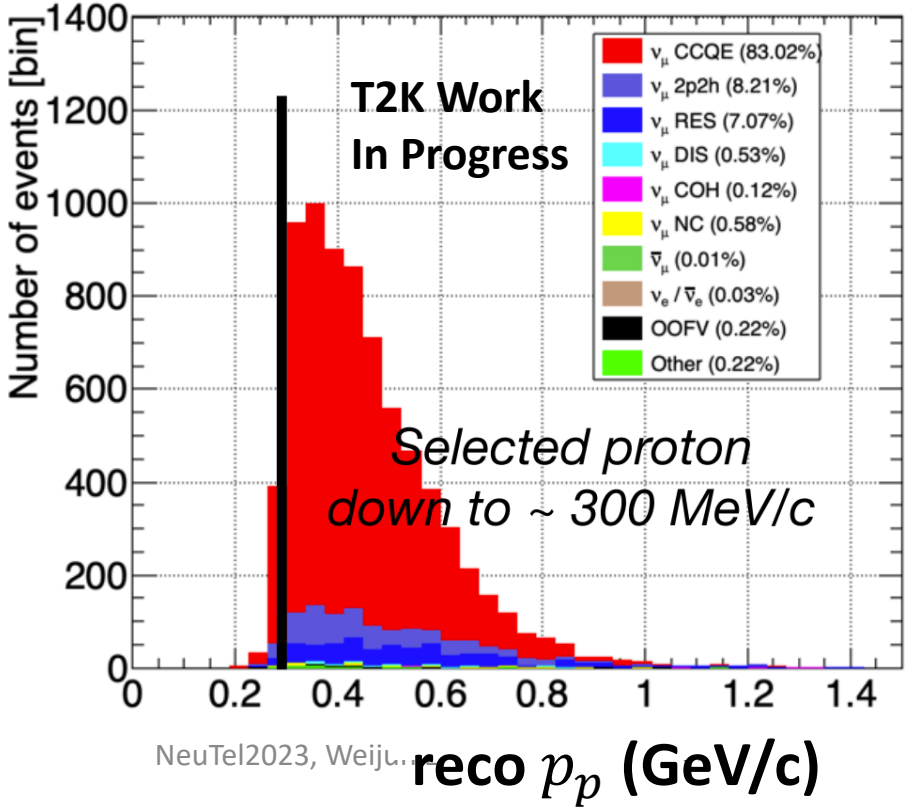
ν_μCC0π

High purity (~94%) CC0π sample

- Thanks to excellent dE/dx measurement and SFGD granularity
- Excellent proton momentum reconstruction

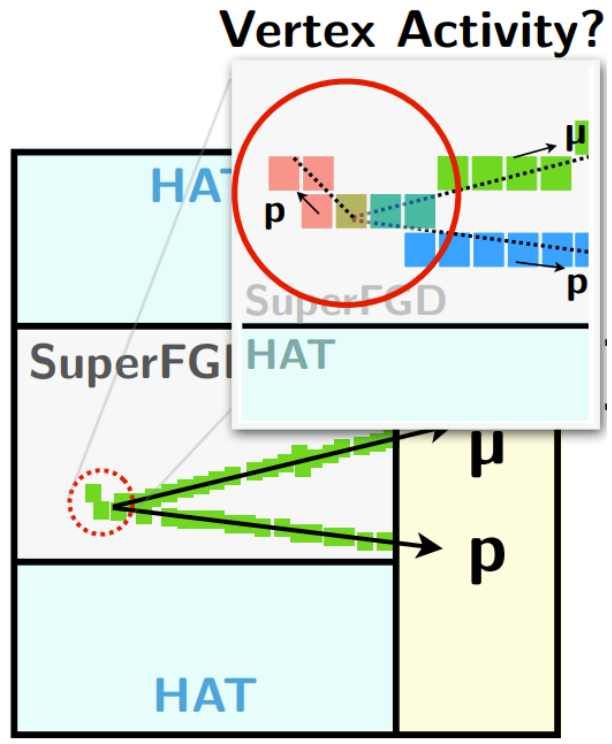
  Low proton threshold





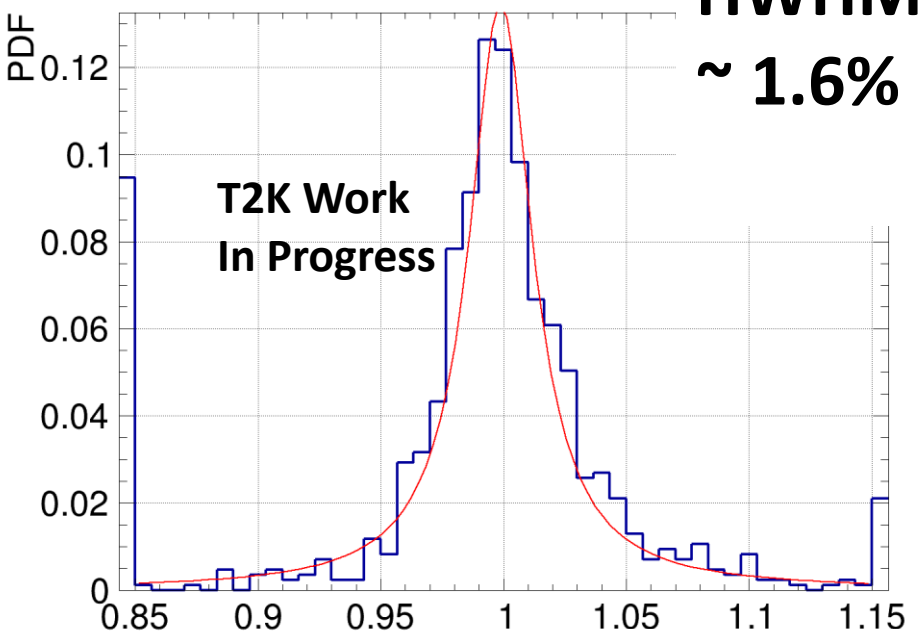
Calorimetric Variables

- Fine granularity -> E belongs to muon
- Reconstruction of visible and hadronic energy, vertex activity



ESC proton selection

- Exploits the Bragg peak feature (X.-G. Lu & M. Betancourt arXiv:1608.04655)
- A better-quality sample for TKI measurement

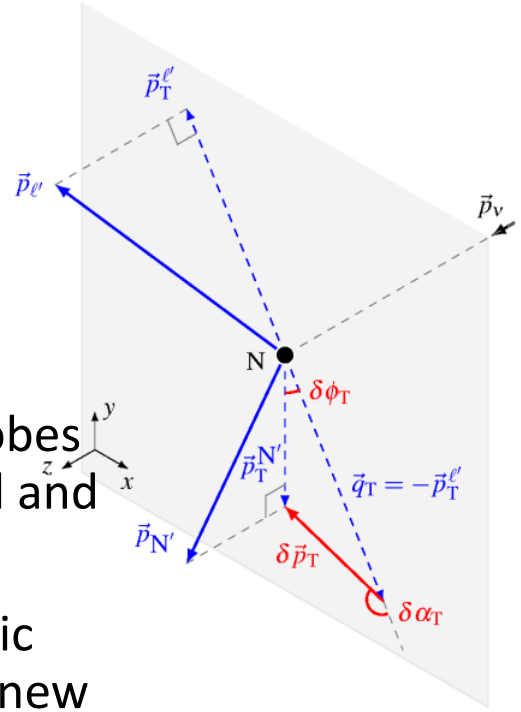


HWHM ~ 1.6%

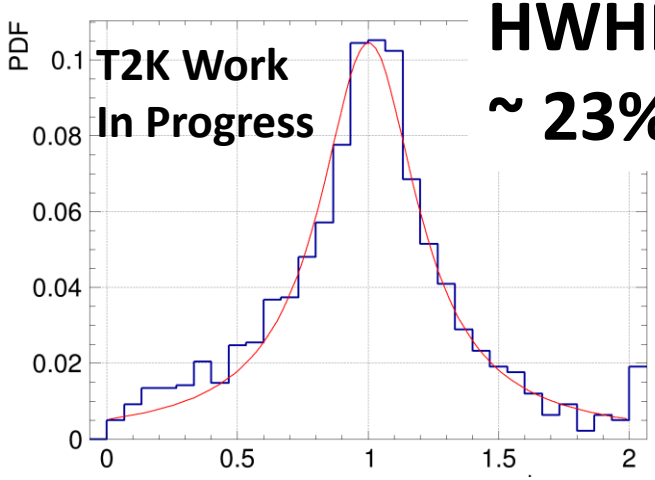
true/reco p_p

ν_μCC0π TKI

- TKI variables are important probes for investigating nuclear model and Final State Interactions (FSI).
- The improved particle kinematic reconstruction brought by the new detectors leads to high resolution of the TKI variables.



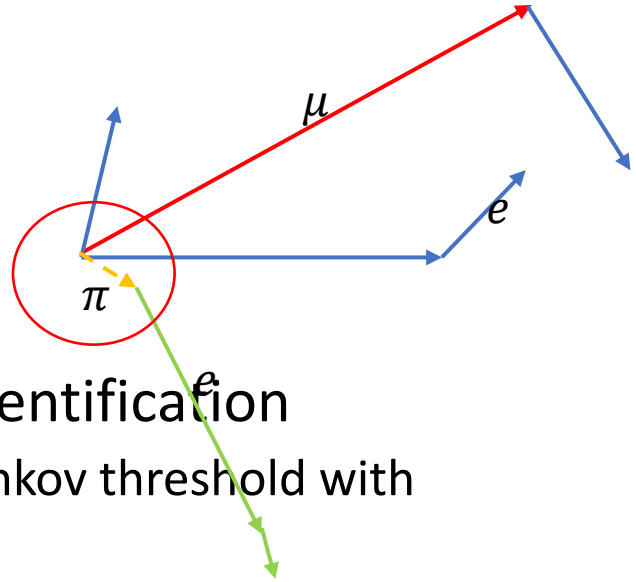
X.-G. Lu et al. Phys Rev C 94, 015503



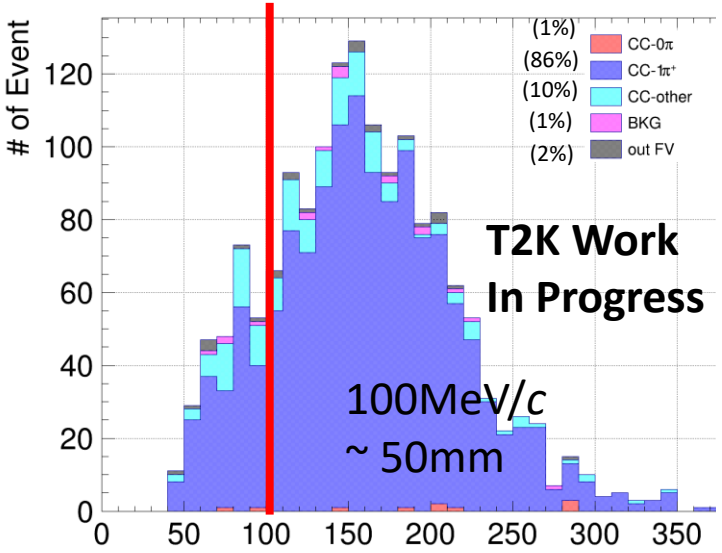
HWHM ~ 23%

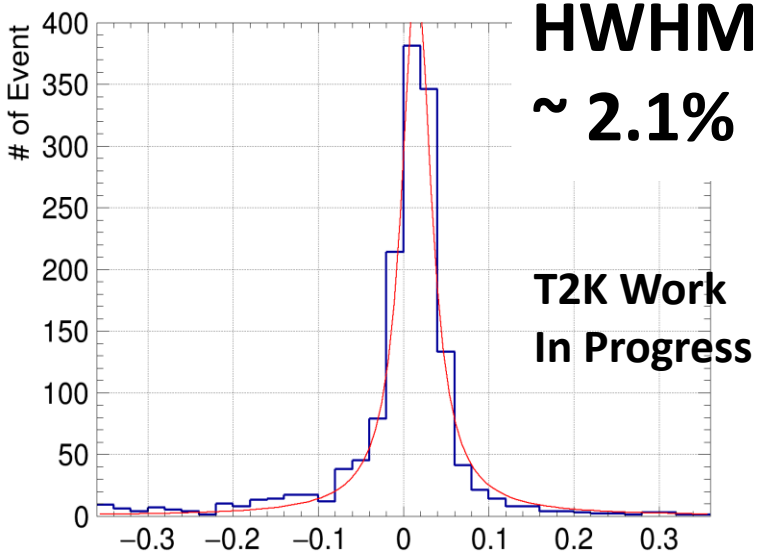
true/reco p_n

ν_μCC1π^+



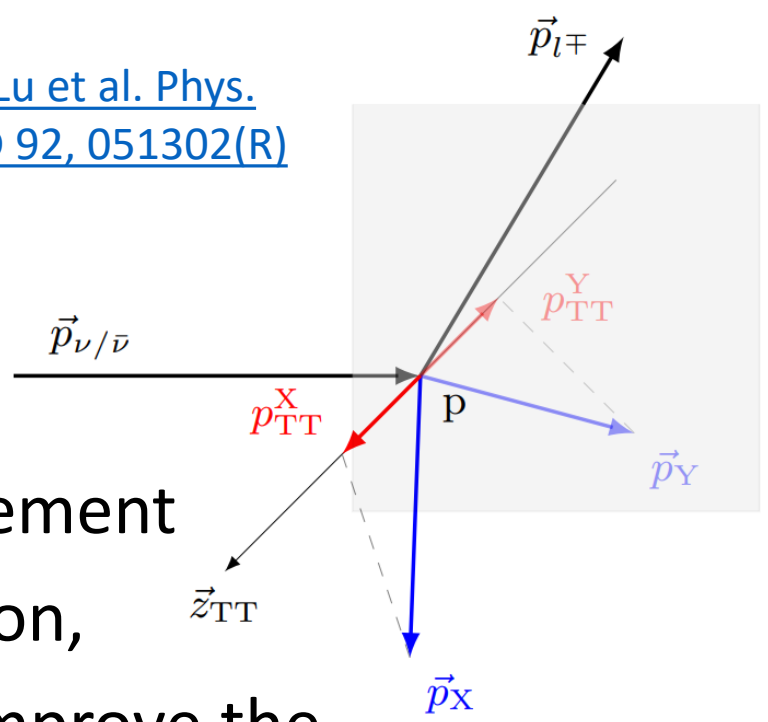
- Delayed particle tag is implemented to improve primary pion identification
  - ➔low pion threshold thanks to SFGD granularity -> below the pion Cherenkov threshold with good kinematics reconstruction
  - ➔important for reducing oscillation analysis systematics
- Novel trackless pion selection
  - ➔Transcend tracking threshold - could reconstruct pions with energy too low to leave a track



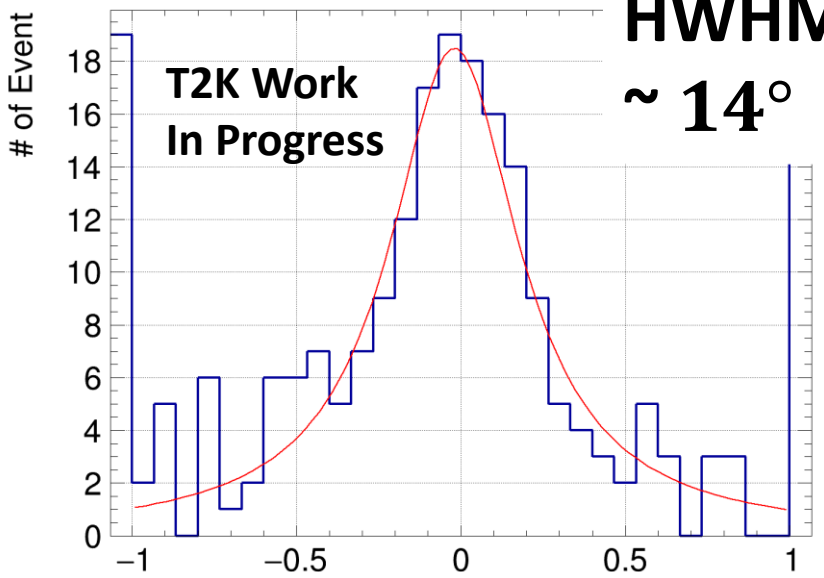


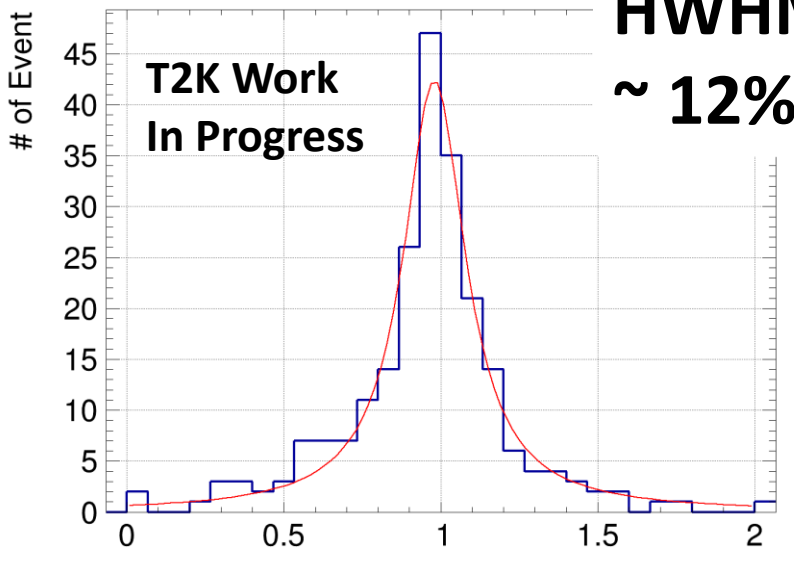
ν_μCC1p1π^+ TKI

X.-G. Lu et al. Phys. Rev. D 92, 051302(R)



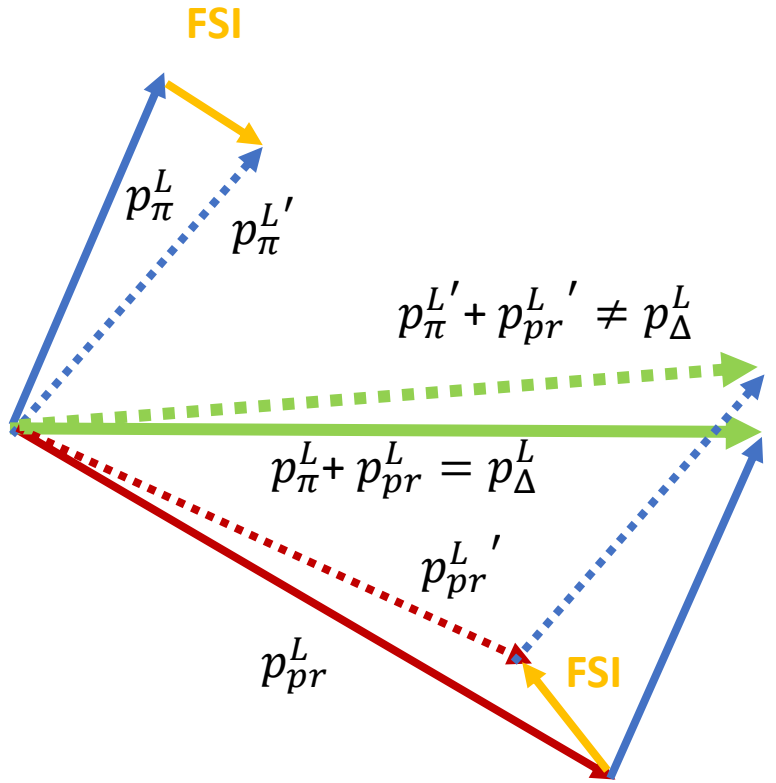
- Combined ESC proton selection and the pion trackless selection to obtain high quality TKI measurement
- Promising improvement in Hydrogen δp_{TT} resolution, which could be exploited on this sample to further improve the isolation of νH events.



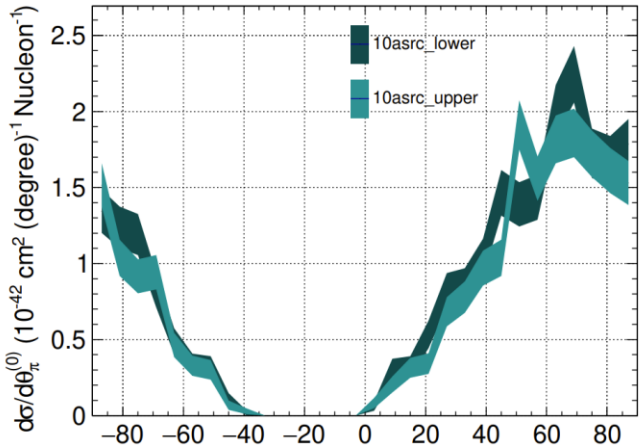


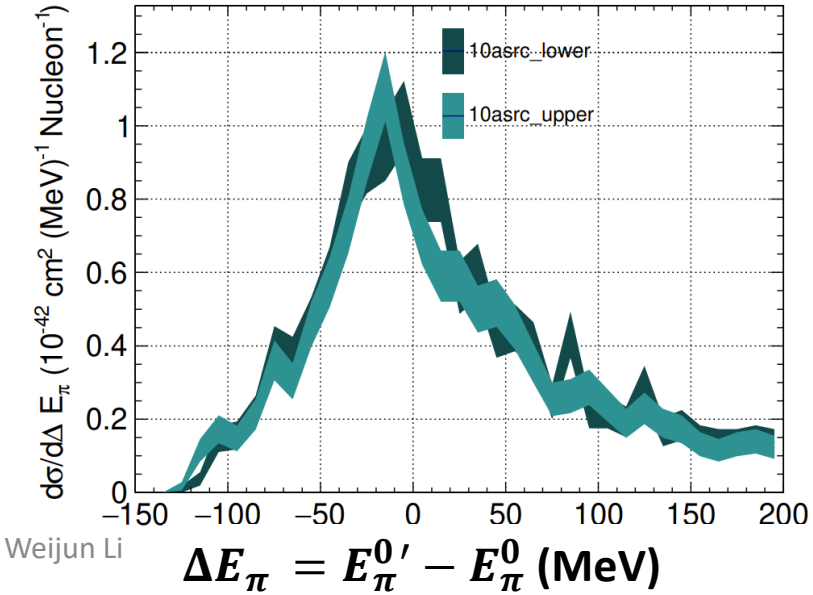
ν_μCC1p1π^+New FSI Probe

- Reconstruct the proton-π^+ rest frame variables using hadronic kinematics only thanks to excellent proton reco
  - π^+ decay angle
  - proton-π^+ invariant mass
- Promising application in H sample selection with TKI
- Nuclear model independent FSI probe



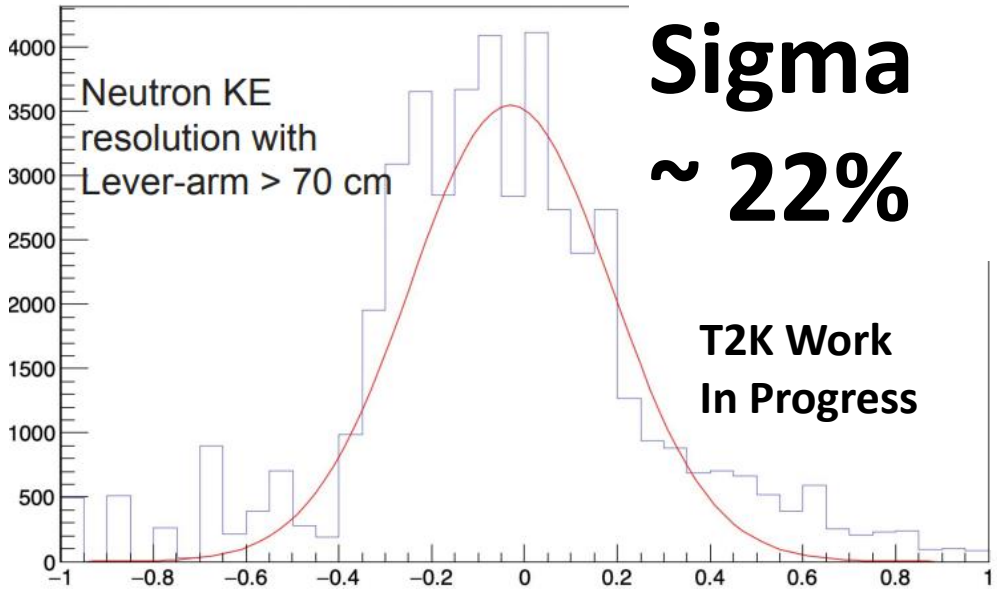
GENIE Truth Study (G18-10a-02-11b)





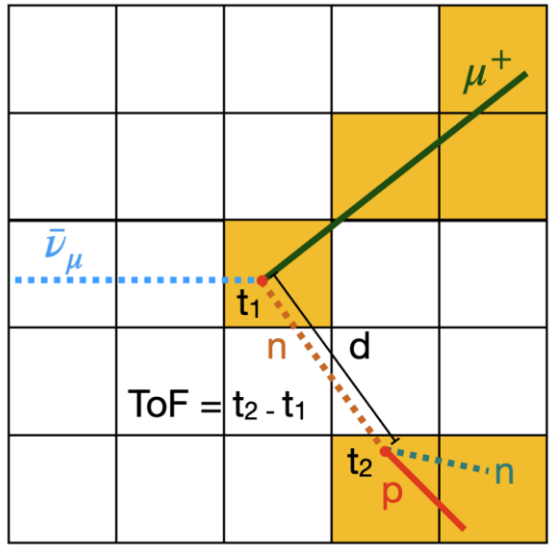
Neutron

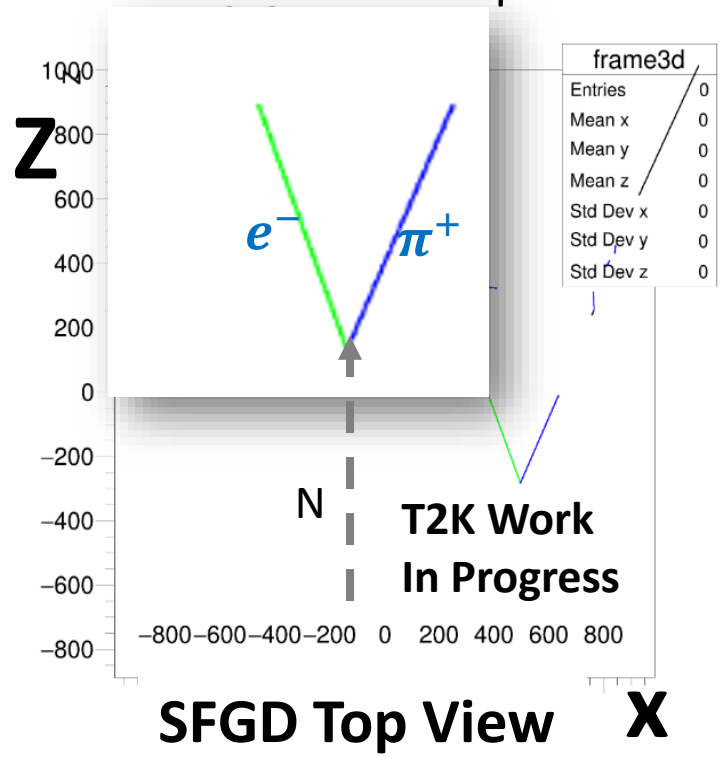
- Neutron energy from time-of-flight, kinematics reconstructed for the first time (L. Munteanu et al., Phys. Rev. D 101. 092003(2020))
- Neutron detection via proton recoil
- Prototype test (A. Agarwal et al., Phys. Lett. B 840 (2023) 137843)



HNL

- Interfaced with the GENIE HNL package, *BeamHNL* (K.-J. Plows & X.-G. Lu, Phys. Rev. D 107, 055003), to explore HNL sensitivity in SFGD, e.g. a N→$e^- + \pi^+$ simulated event display in SFGD is shown below.
- A preliminary selection has been developed.





Summary

- A large part of the upgrade detectors have been installed successfully and are being prepared for beam run in the coming November.
- Full ND upgrade (with Top HATPC) ready in Spring 2024.
- An extensive set of analyses have been developed.
- They demonstrate promising improvement in the kinematics reconstruction of the final state neutrino interaction profiting from the new detectors
- The analysis outcome could improve cross section measurement and reduce oscillation analysis systematics.
- New variables, p-π^+-rest-frame and Calorimetric, made possible by the upgrade, could shed new light on neutrino-nucleus interaction.
- Many more exciting analyses are under development.