[NU_10] Neutrino cross-section measurements with the current and upgraded T2K near detectors

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Joint Workshop of TYL/FJPPN and FKPPN
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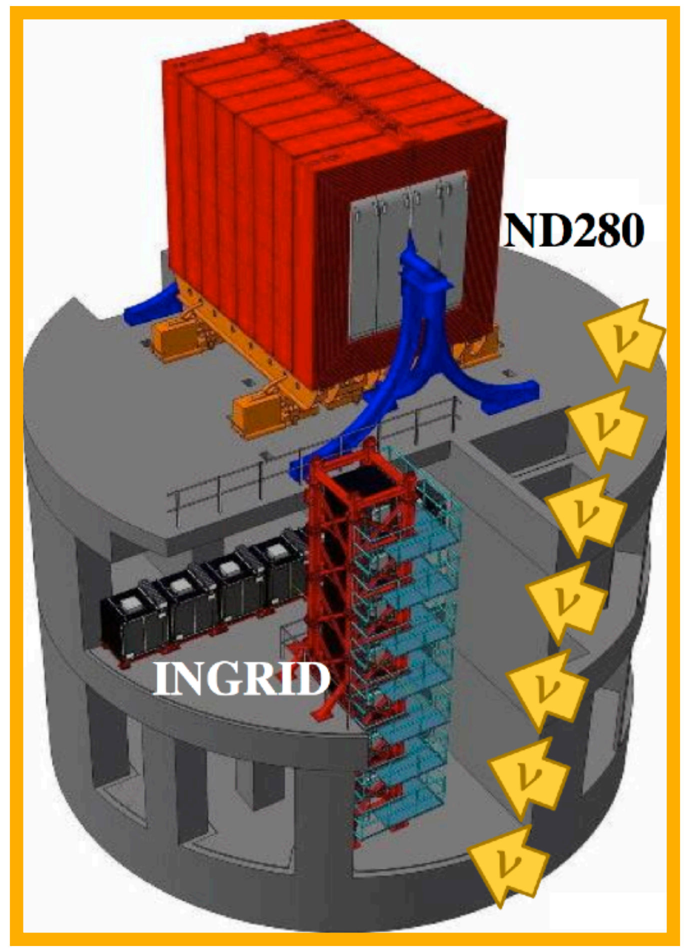
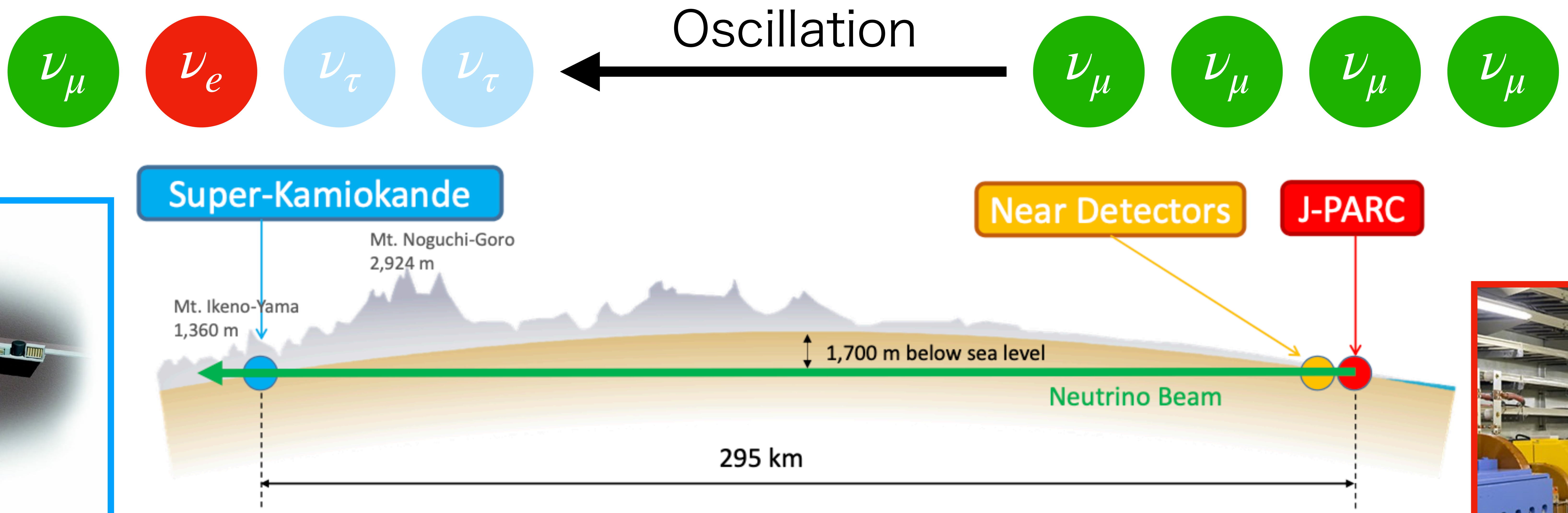
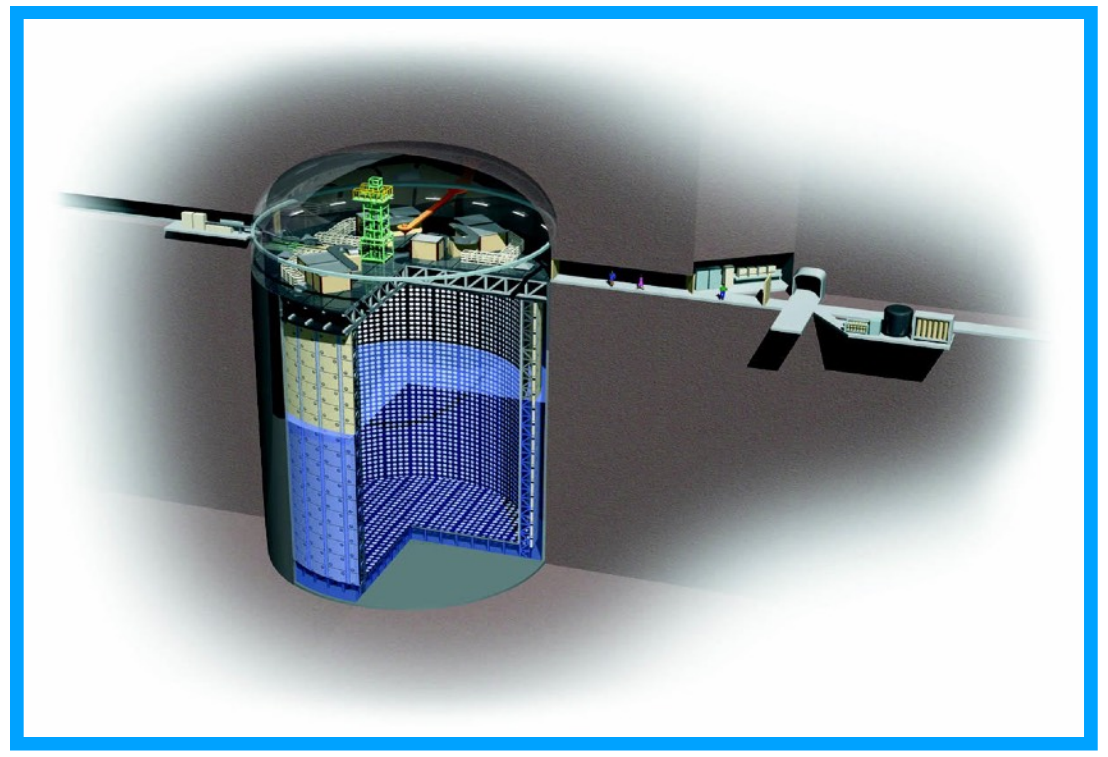
T2K (Tokai-to-Kamioka) experiment

- Long baseline neutrino oscillation experiment in Japan
- $\nu_\mu/\bar{\nu}_\mu$ beam produced at J-PARC, measured at Super-Kamiokande
  - $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance
- Constrain systematics with near detectors

Near detectors







Super-Kamiokande (SK)

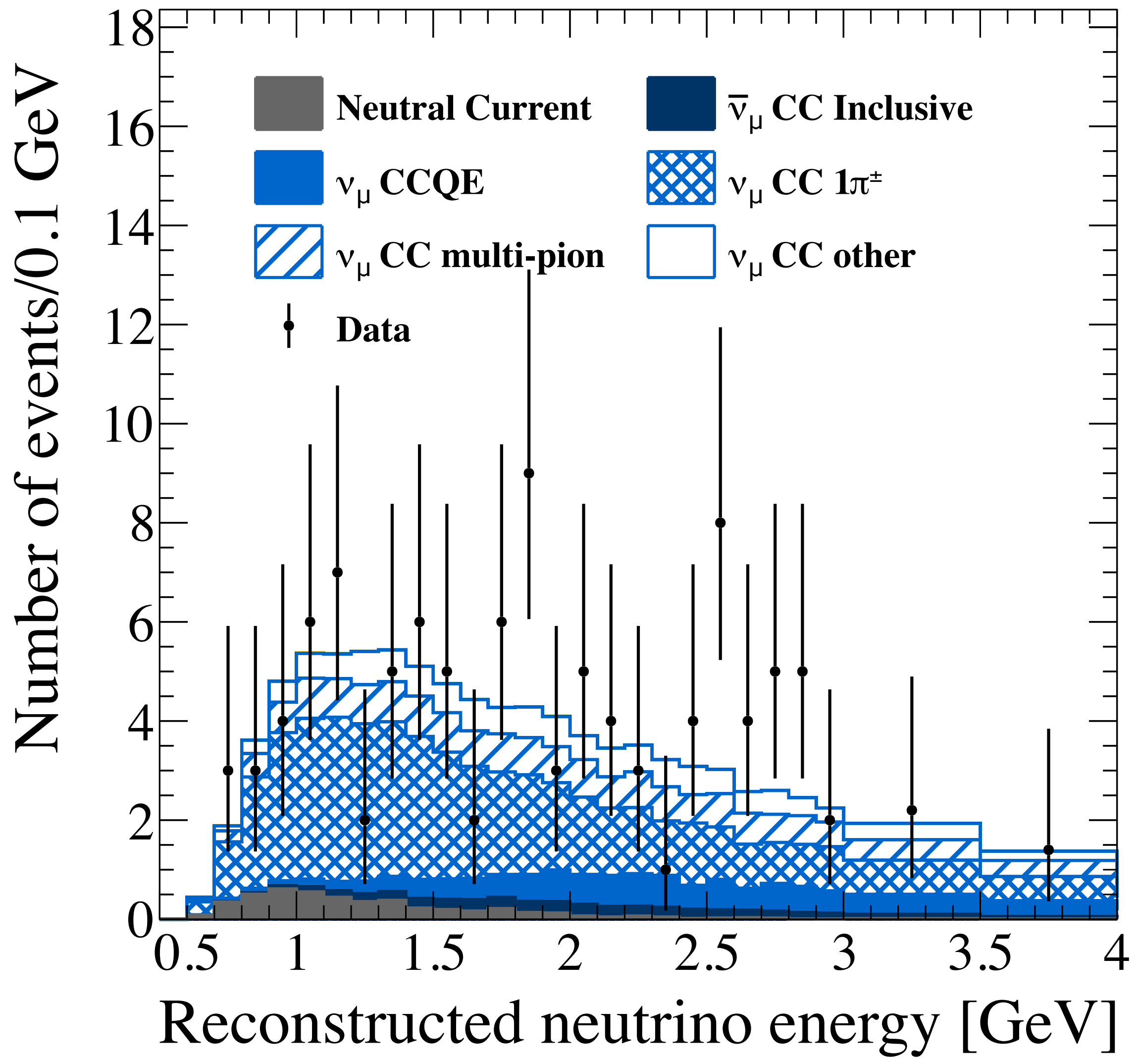
J-PARC Main Ring

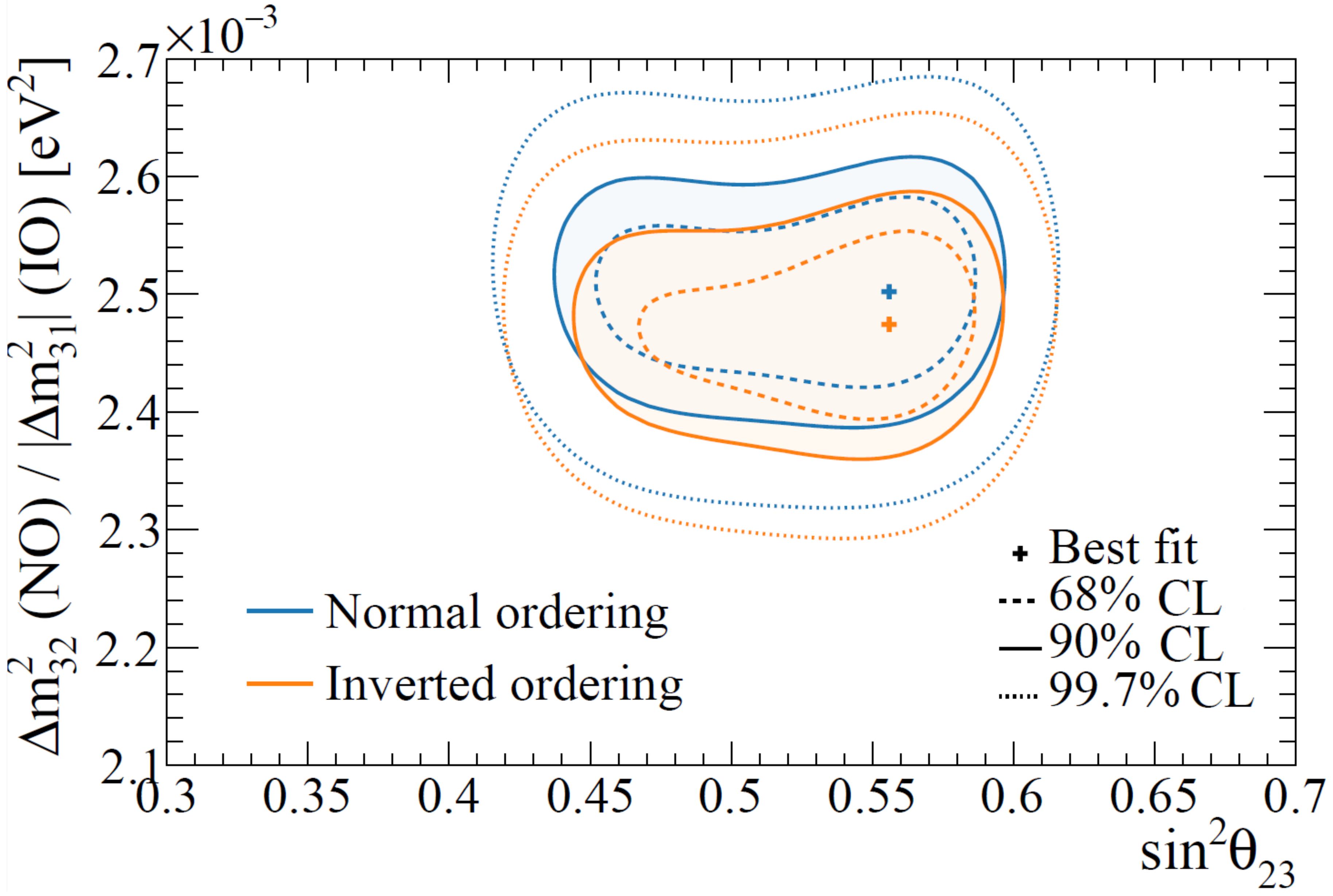
Recent results

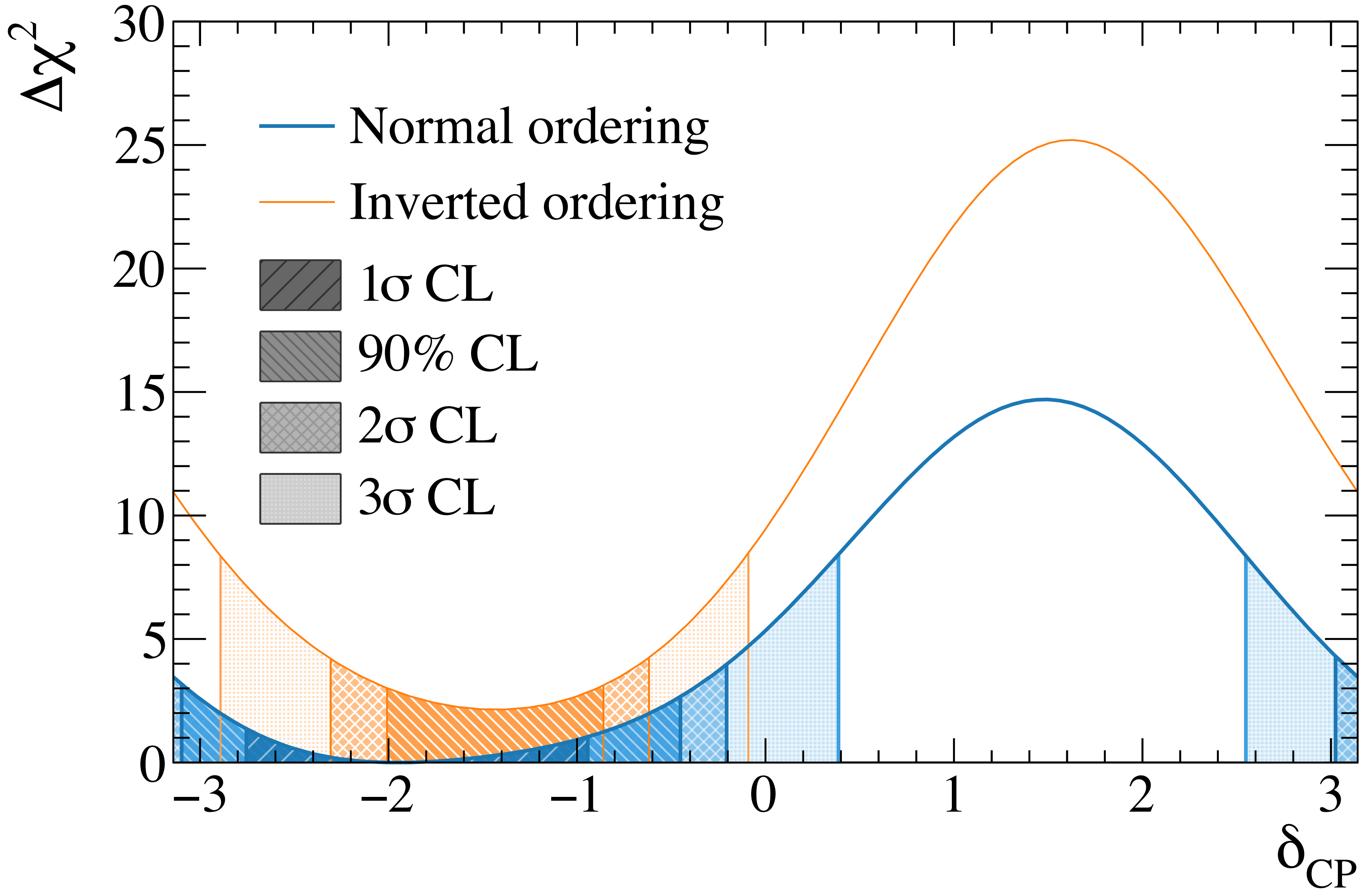
Phys. Rev. Lett. 135, 261801

- Analyzed 3.6×10[21] POT data (Jan. 2010 to Feb. 2020)
- $\sin^2\theta_{23} = 0.559^{+0.018}_{-0.078}$, $\Delta m^2_{32} = (+2.506^{+0.039}_{-0.052}) \times 10^{-3}\ \mathrm{eV}^2$
- $\delta_{CP} = 0$ was excluded at a 90% C.L.

$\nu_\mu CC1\pi^+$ sample at SK



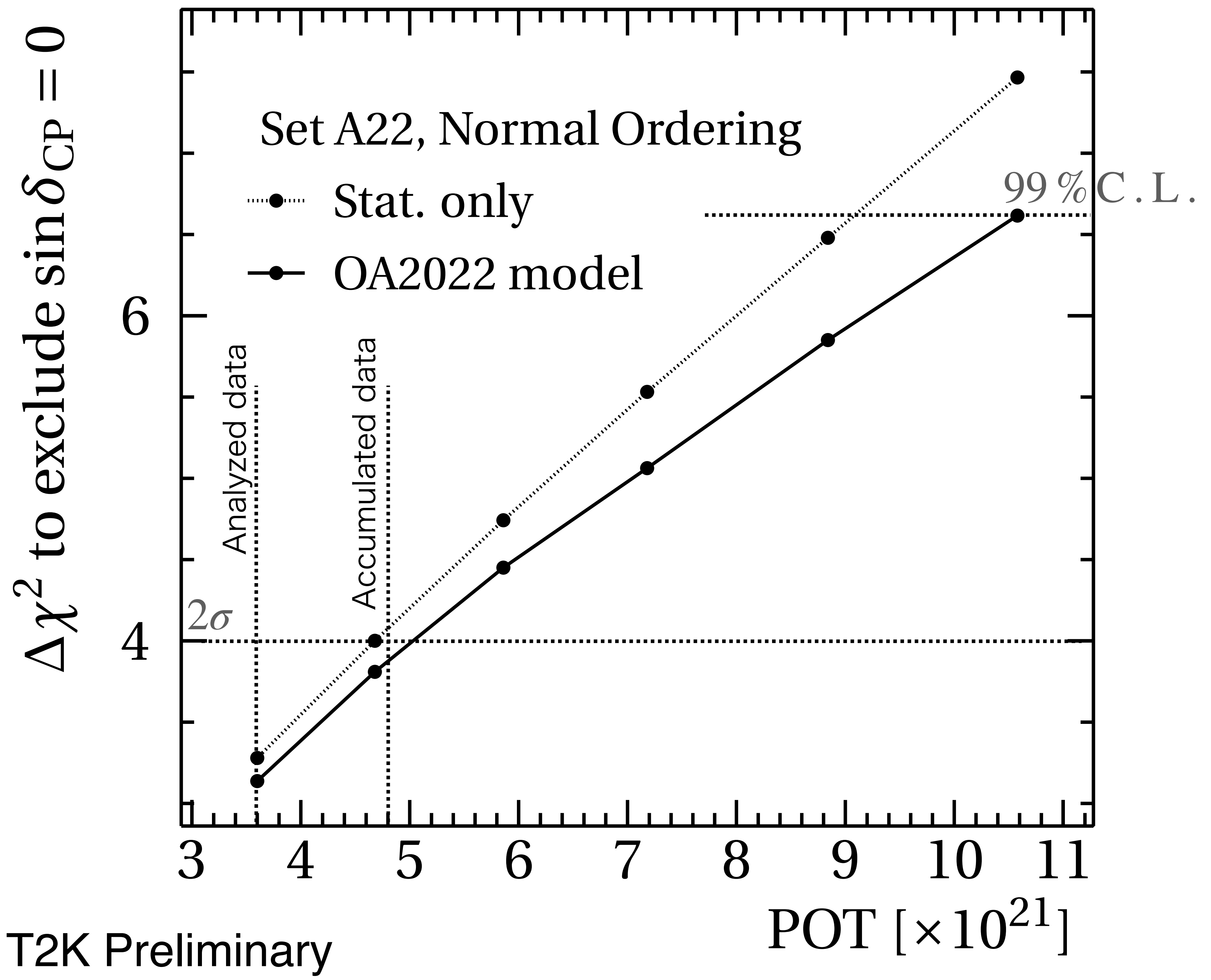




Project overview

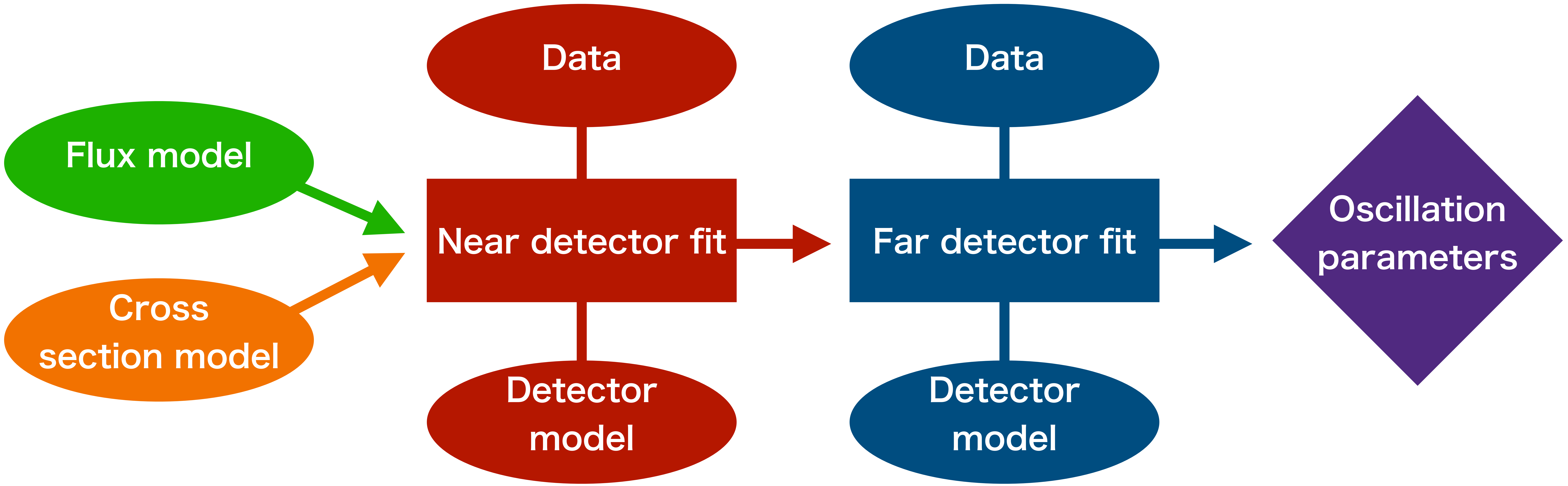
- Data taking/analysis with the ND280 upgraded detectors
- Neutrino cross-section measurements with current/upgraded detectors
  - ND280 ・INGRID ・WAGASCI-BabyMIND
- Reduce the systematics related to neutrino-nucleus interactions
  - Maximize the oscillation sensitivity of the T2K experiment
  - Provide inputs for future experiments (e.g. Hyper-Kamiokande)

Improving systematics will become important



T2K Preliminary

Importance of cross-section analysis



- By constraining cross-section model uncertainty with the near detector, the oscillation sensitivity becomes dramatically better

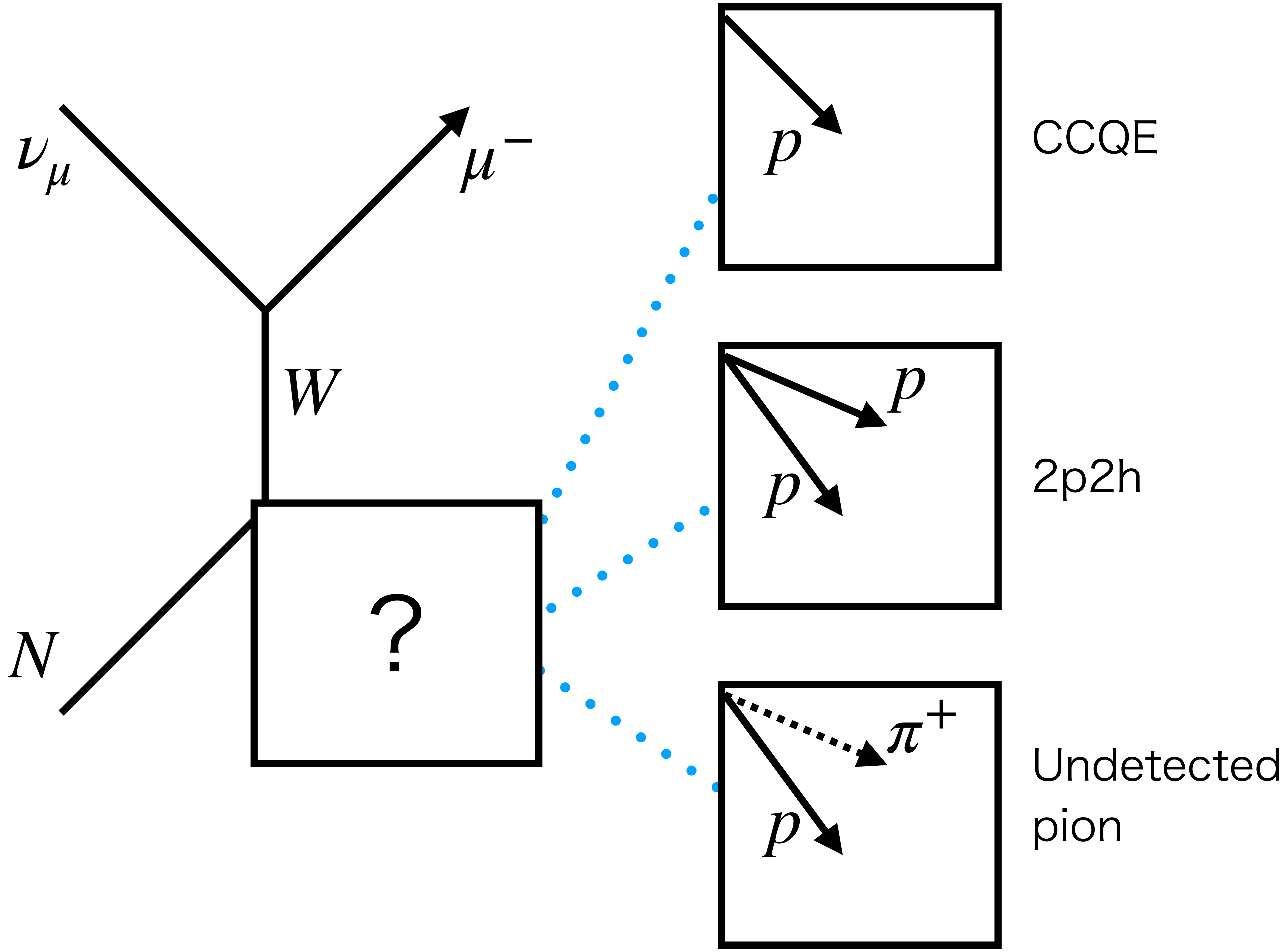
Event number uncertainty at SK

		w/o NDfit	w/ NDfit
ν_μ candidate	ν	13.0%	3.0%
	$\bar{\nu}$	12.0%	4.0%
ν_e candidate	ν	13.8%	4.7%
	$\bar{\nu}$	12.7%	5.9%

The European Physical Journal C, 83(9)

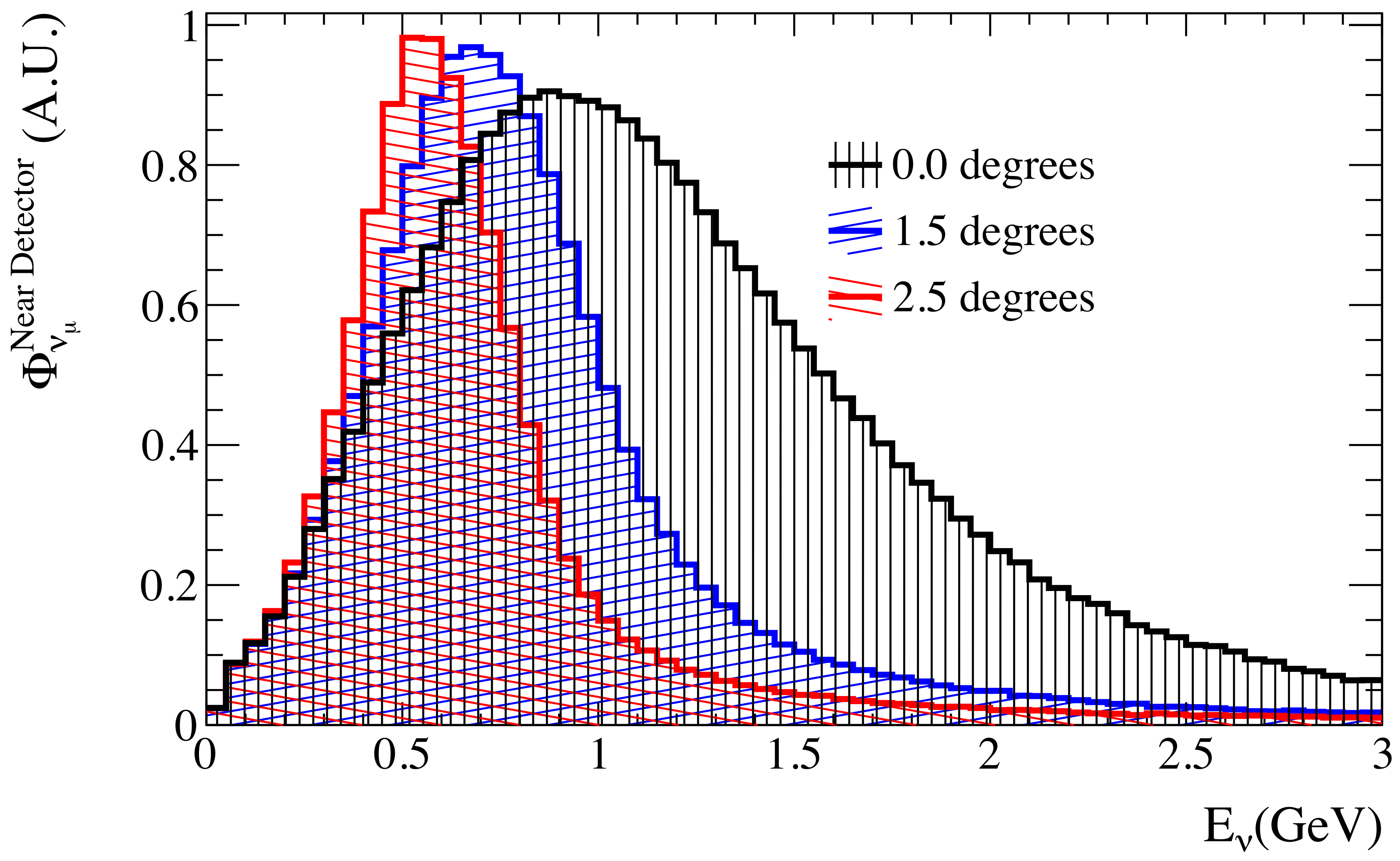
Neutrino interaction

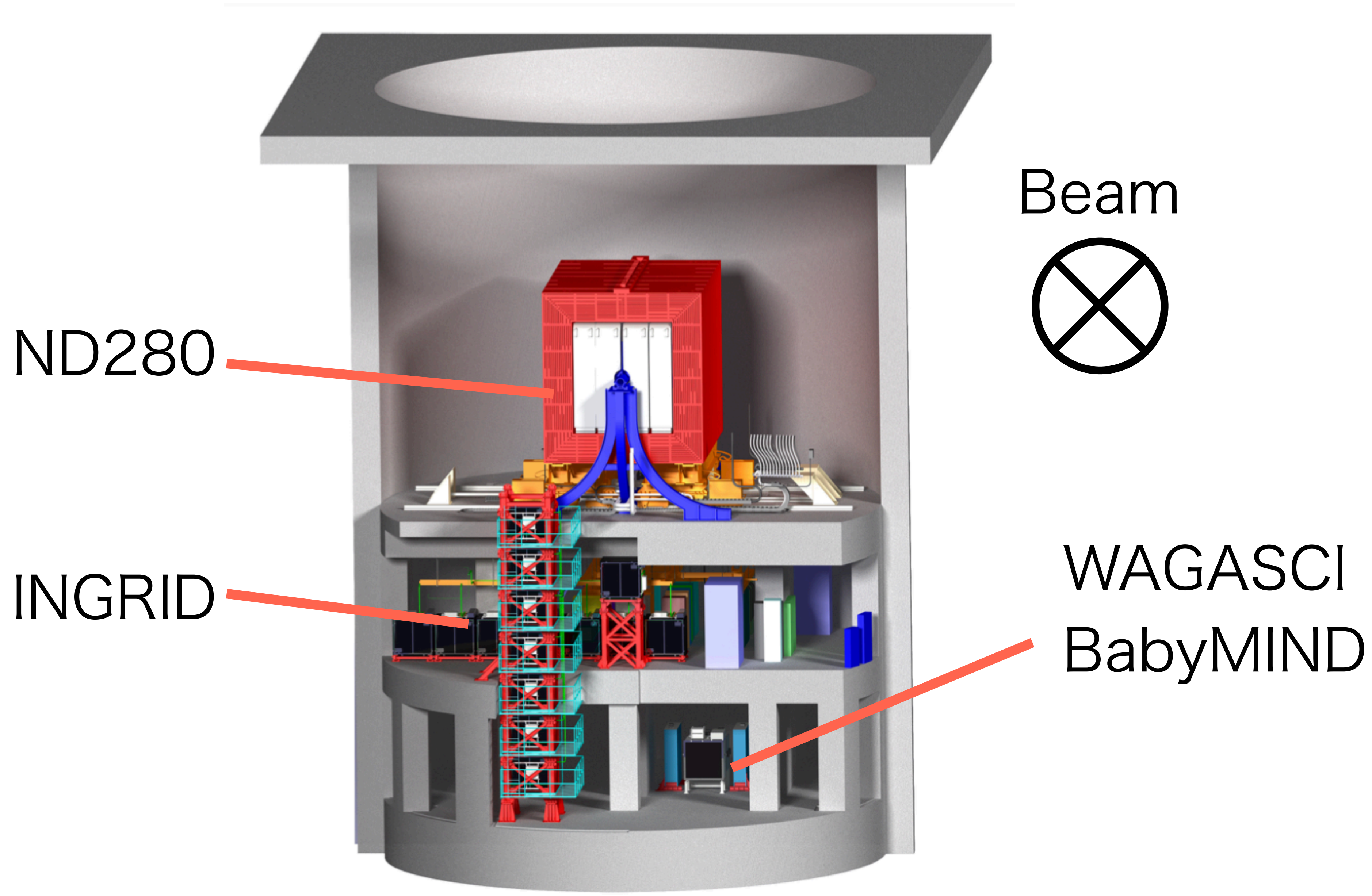
- Dominant process: Charged-current quasi-elastic (CCQE)
- In SK, a neutrino energy is reconstructed with a charged lepton
  - Cannot detect protons
- The energy is smeared by:
  - Non-QE interaction
  - Final state interaction
  - Fermi motion
- Must understand the effects
  - Near detector analysis!



Near detectors

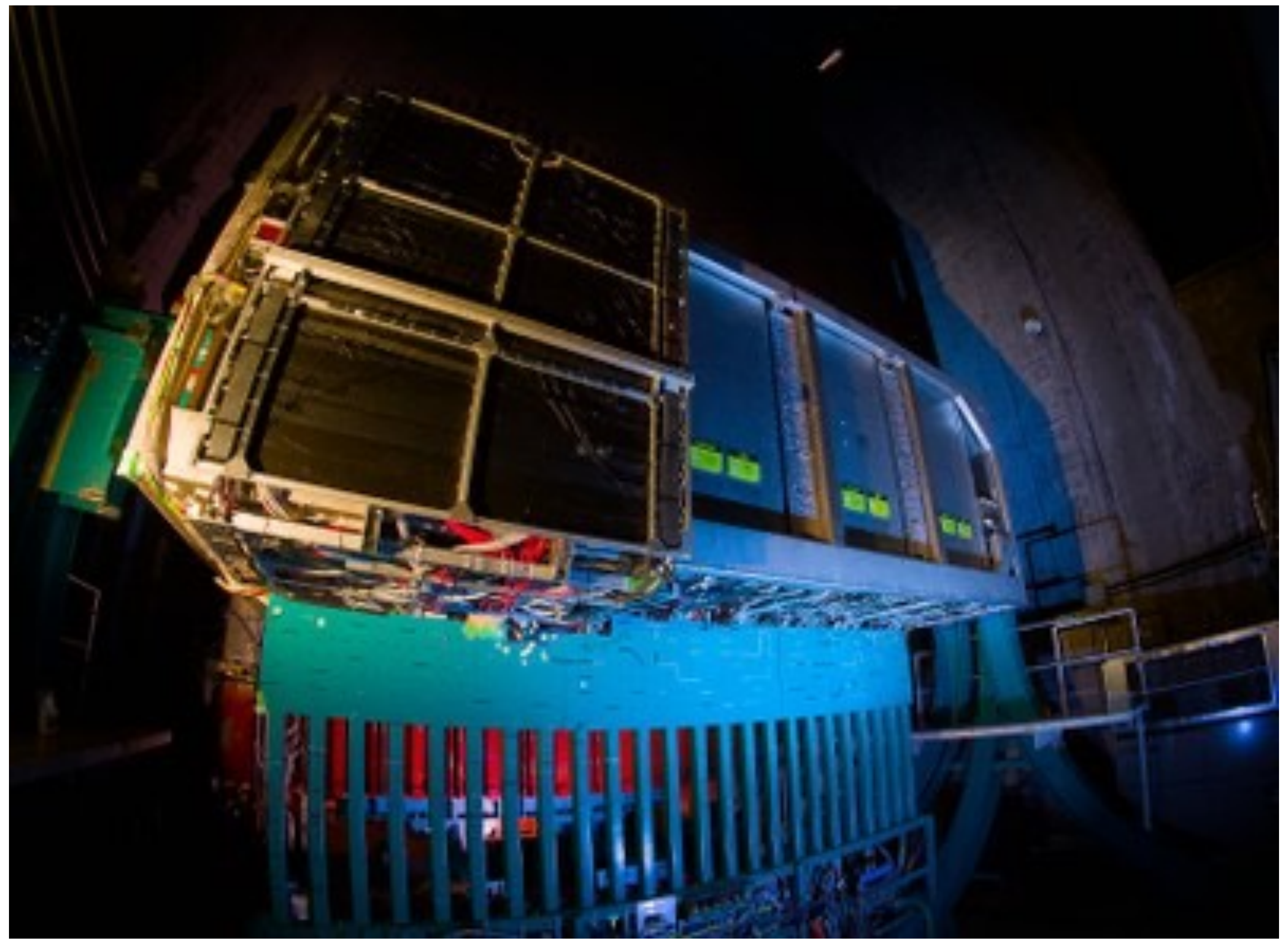
- INGRID (on-axis): Beam monitor
- ND280 (2.5° off-axis): Flux, cross-section measurement (Magnetized)
- WAGASCI-BabyMIND (1.5°): neutrino interaction with water

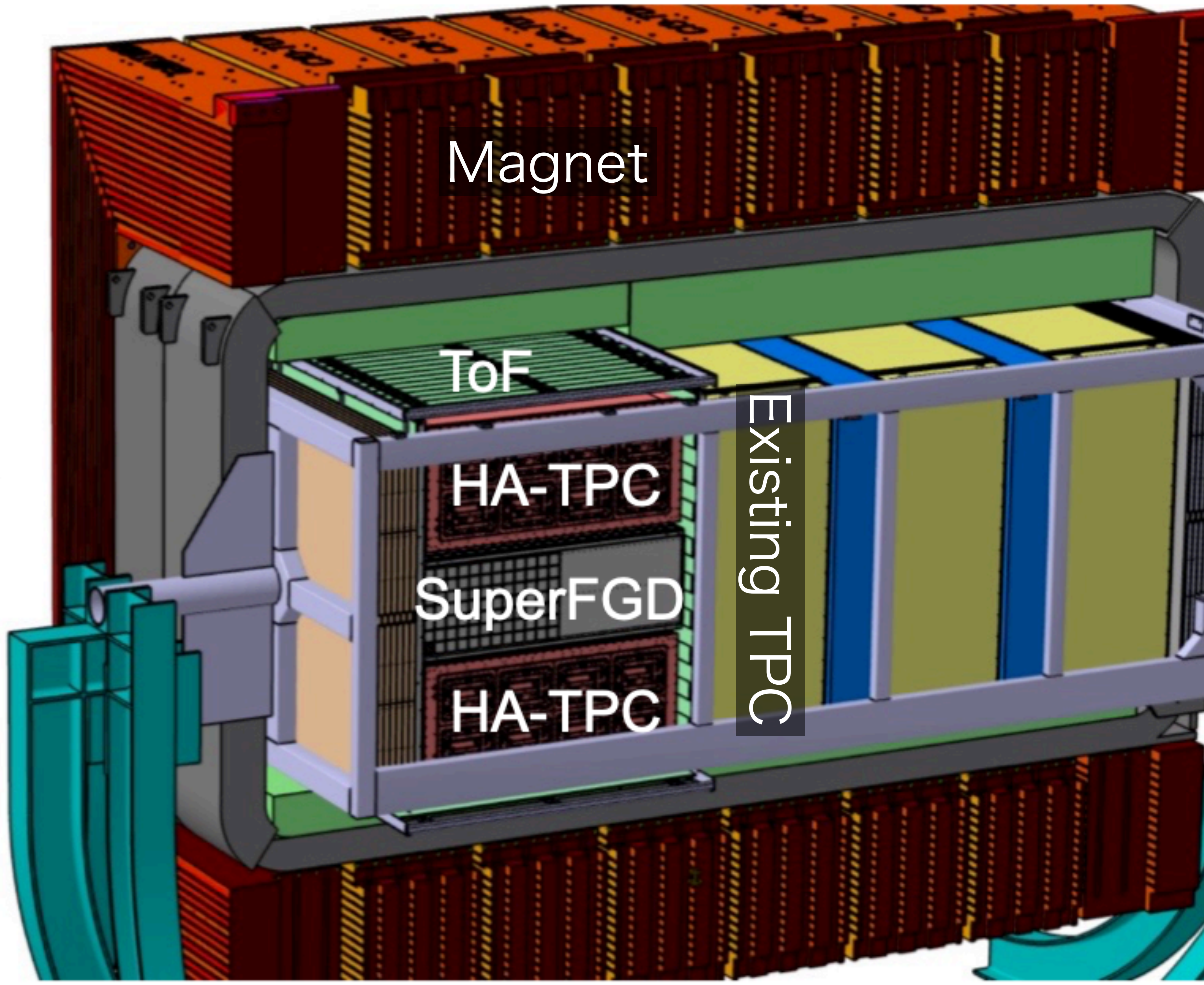




ND280 upgrade

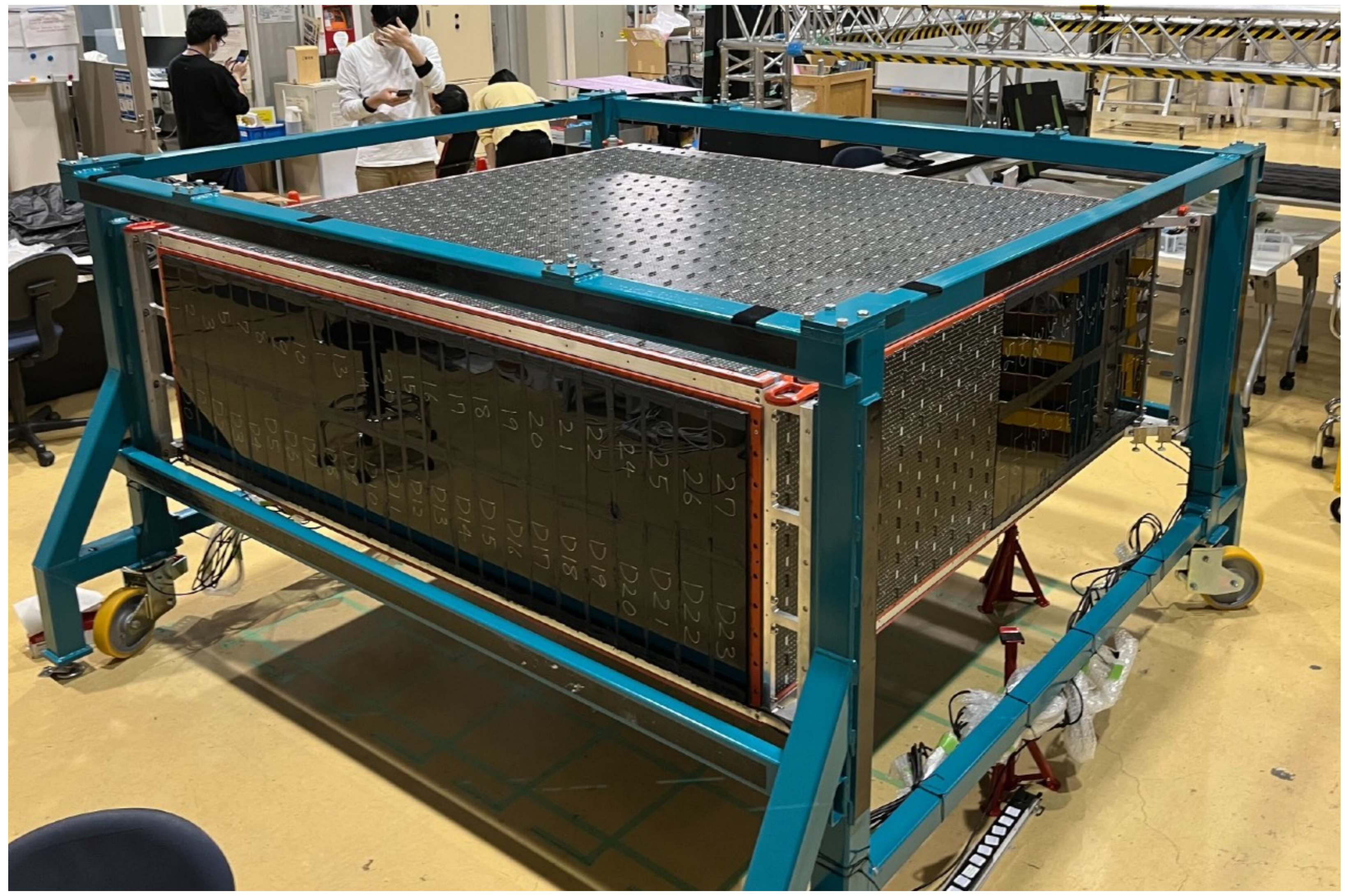
- ND280 upgrade was completed in 2024
- **SuperFGD**
  - 2 ton active neutrino target (scintillator cubes)
- **High-Angle TPC**
  - Measure particles with large scattering angle
- **Time-of-Flight detectors**
  - Timing information to reject backgrounds
  - 150 ps timing resolution

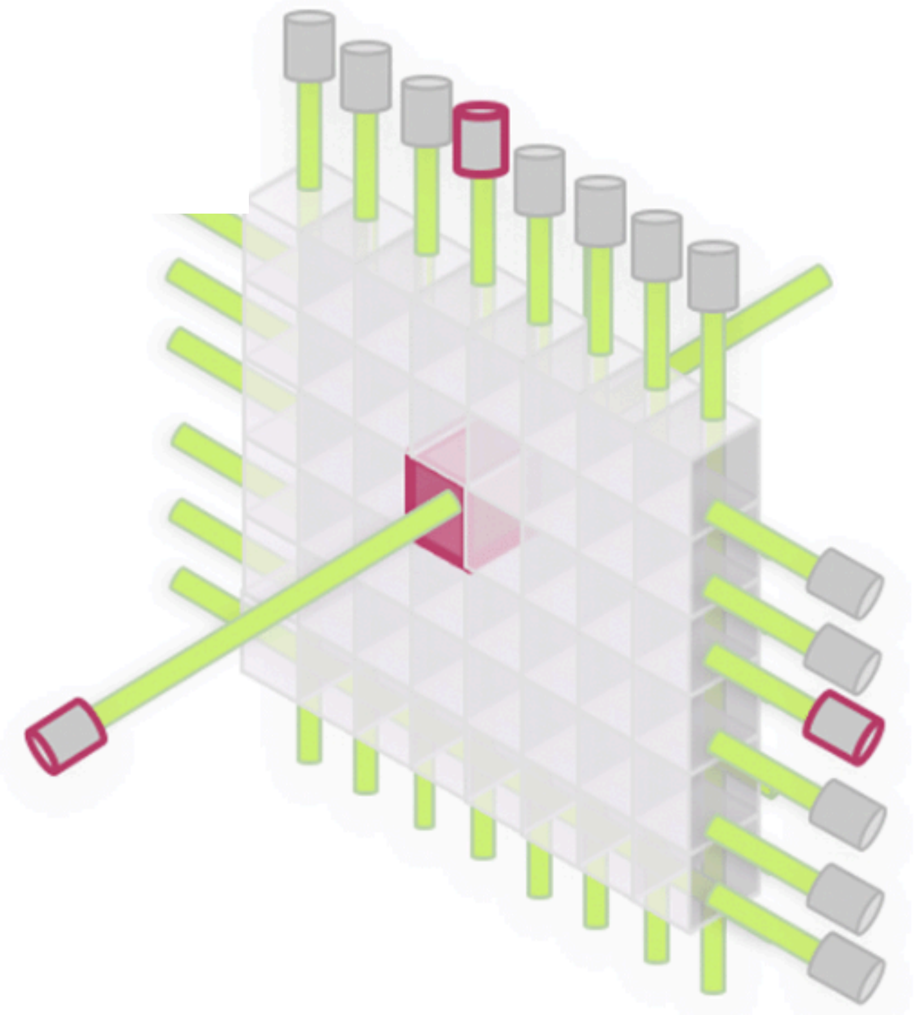


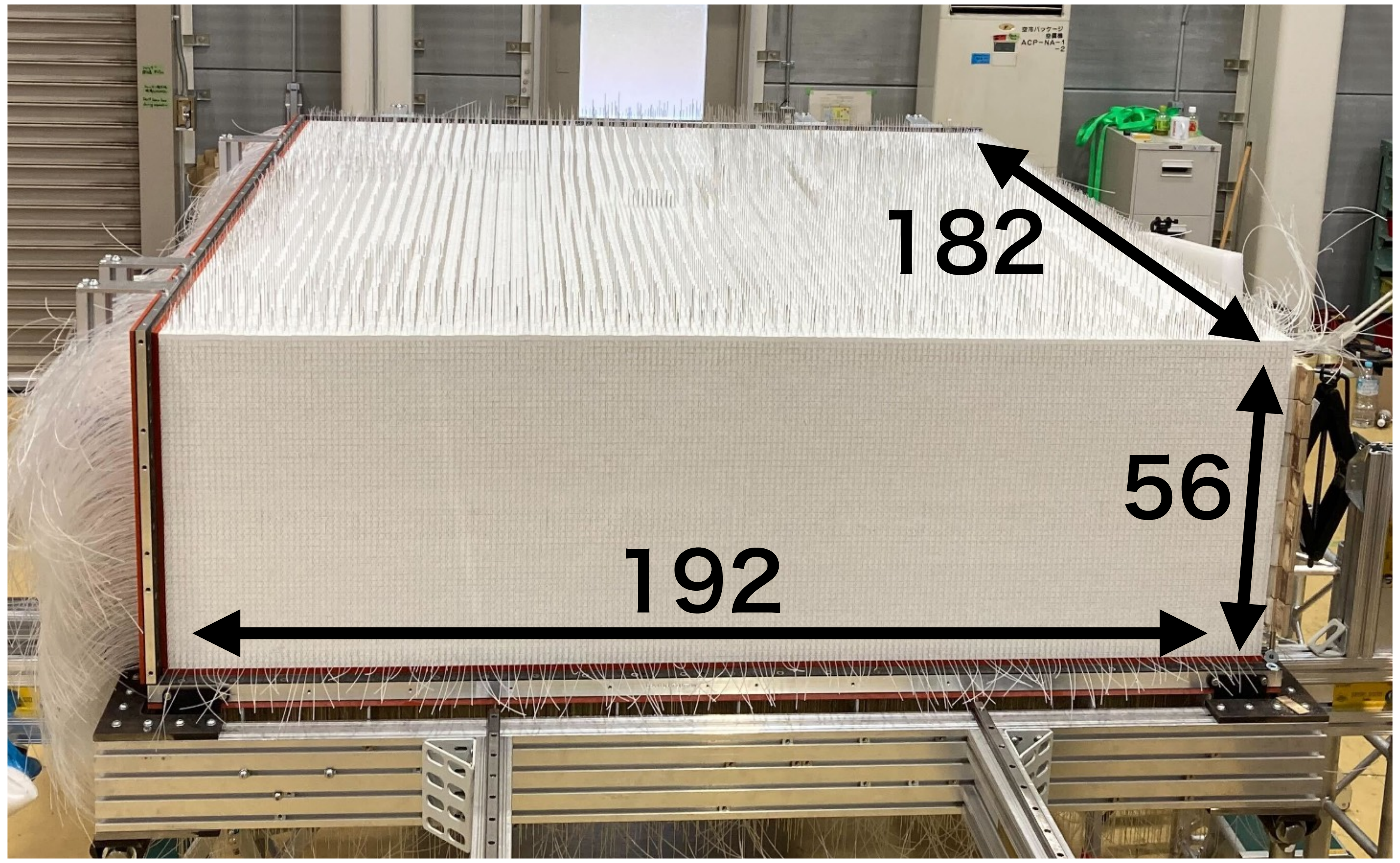


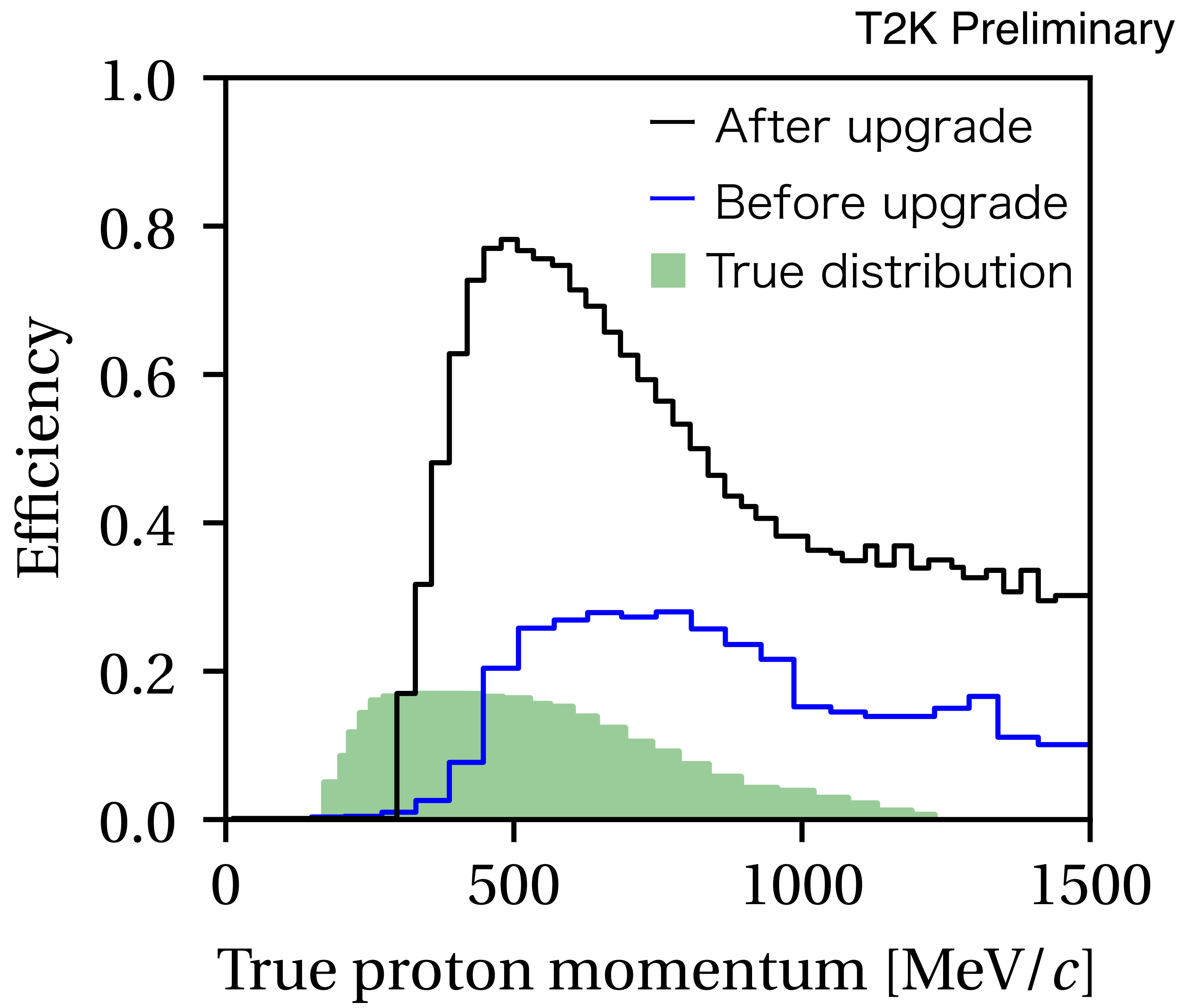
SuperFGD overview

- Active neutrino target
- 1 cm^3 scintillator cubes, 192×182×56
- Readout of 2D × 3 directions (X, Y, and Z planes)
  - 4π acceptance
  - Proton tagging threshold ~350 MeV/c



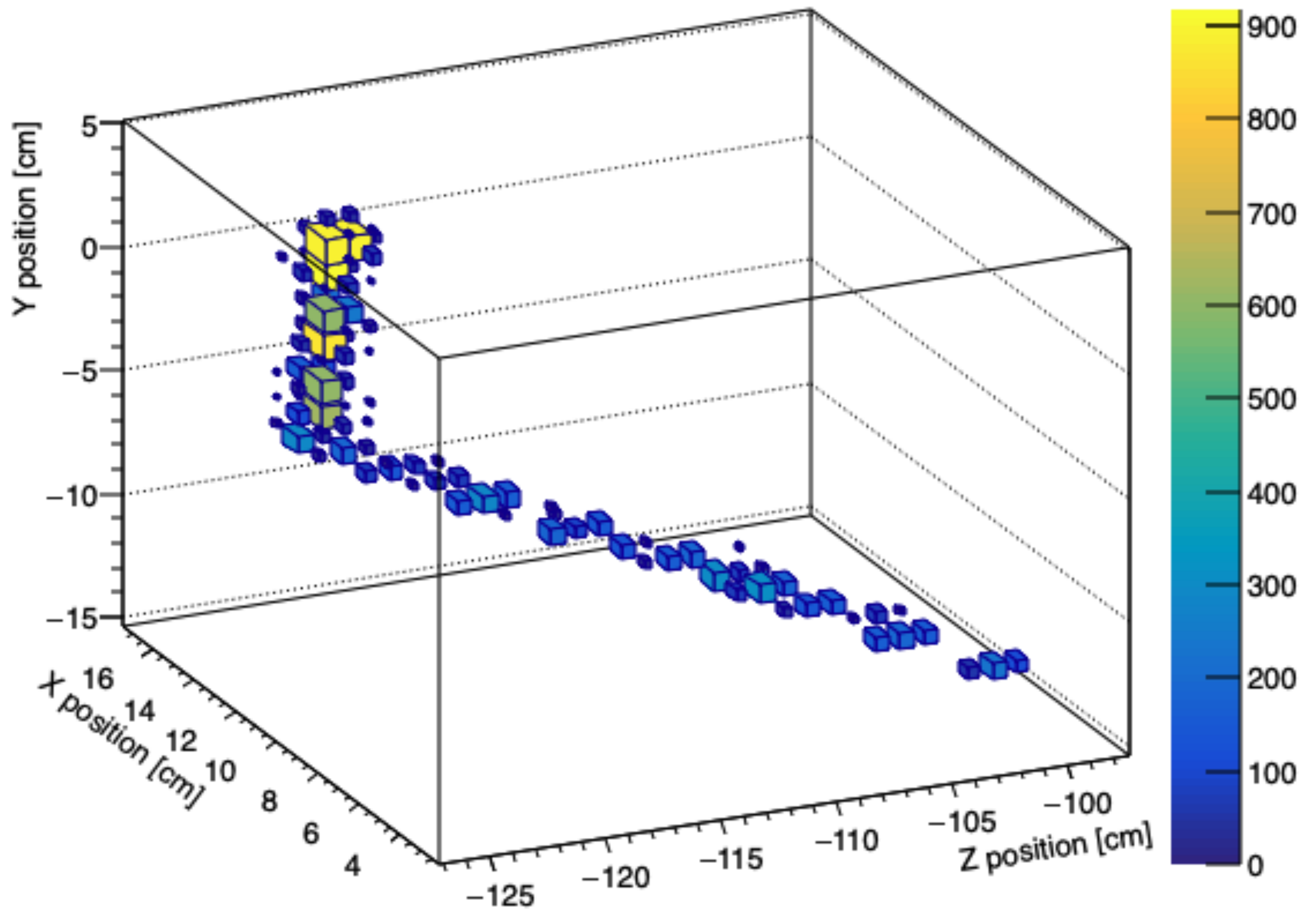


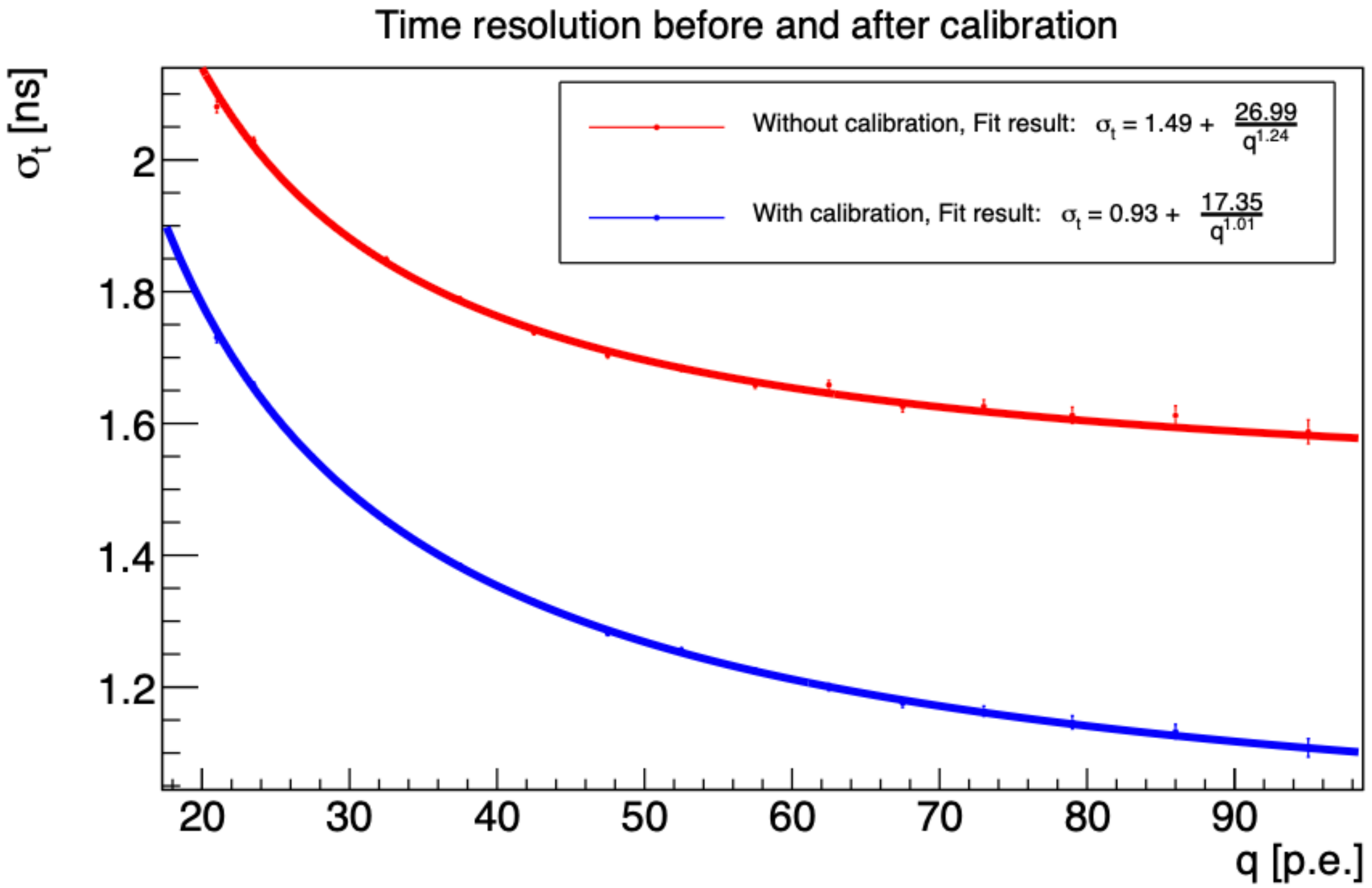




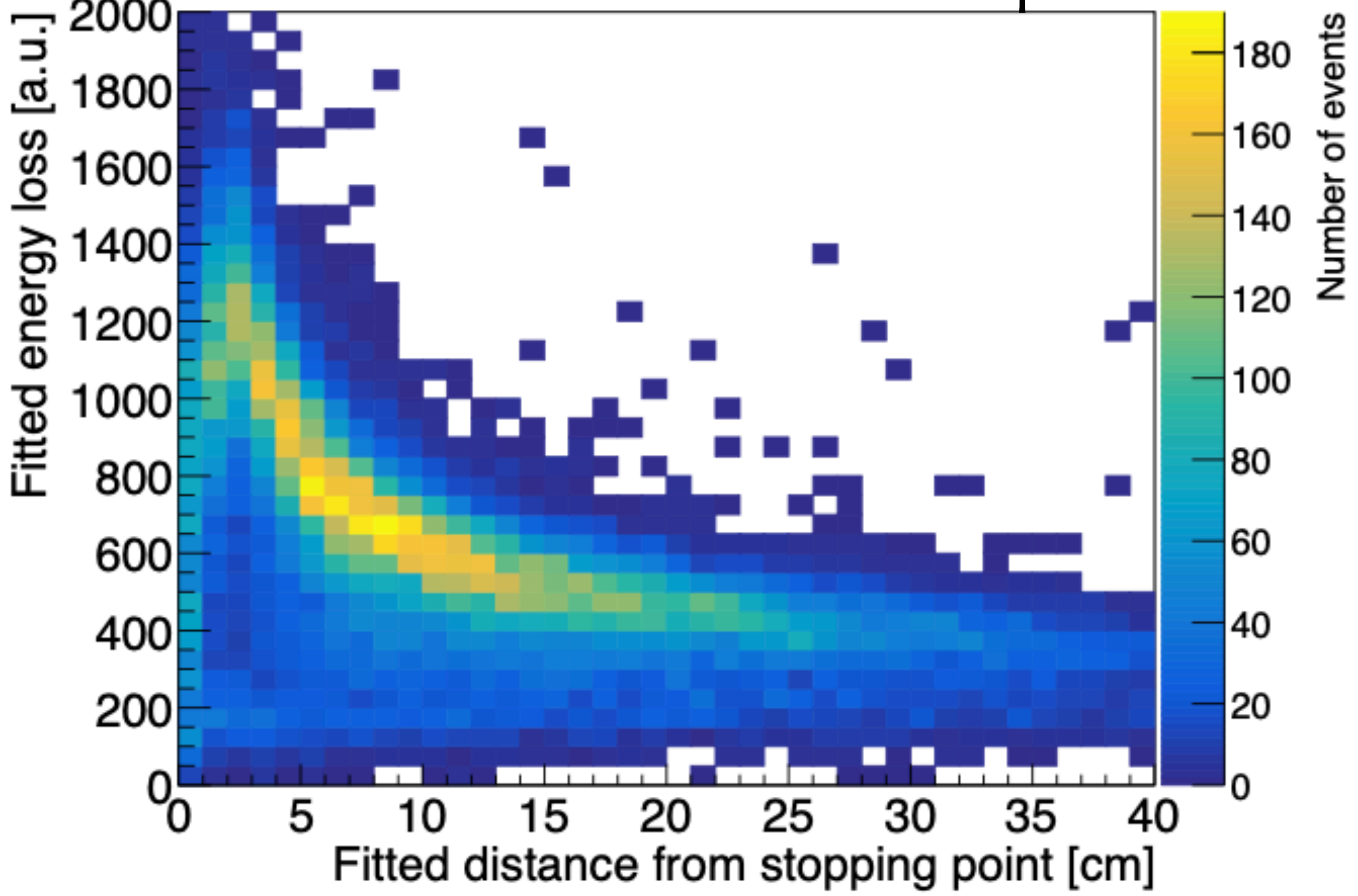
SuperFGD performance

- 3D track reconstruction with good resolution
  - Better understanding of the vertex
- The timing resolution improved after calibration
- A clear proton Bragg peak was seen in data
- Detector paper was submitted (arXiv:2603.14921)



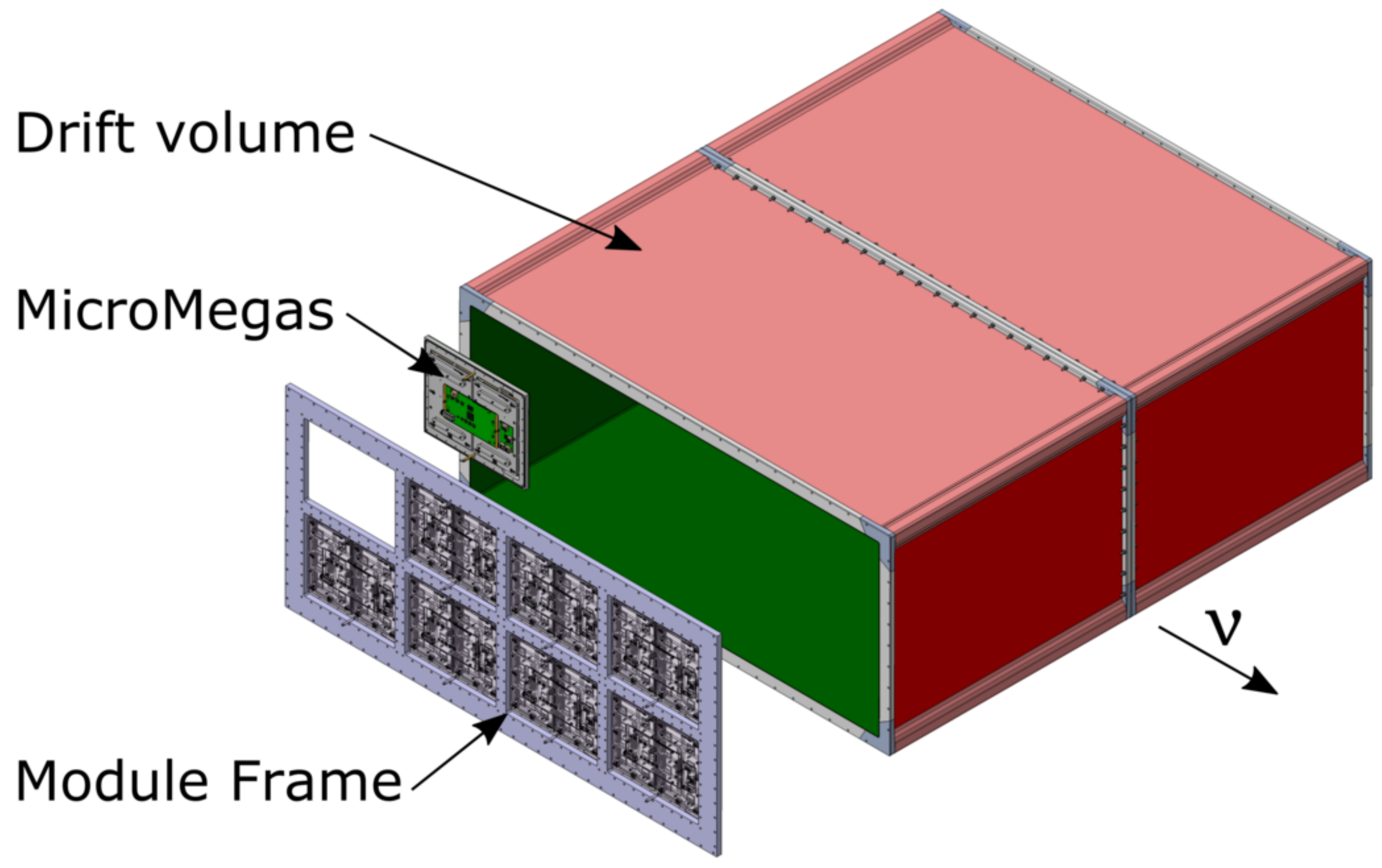


Proton control sample

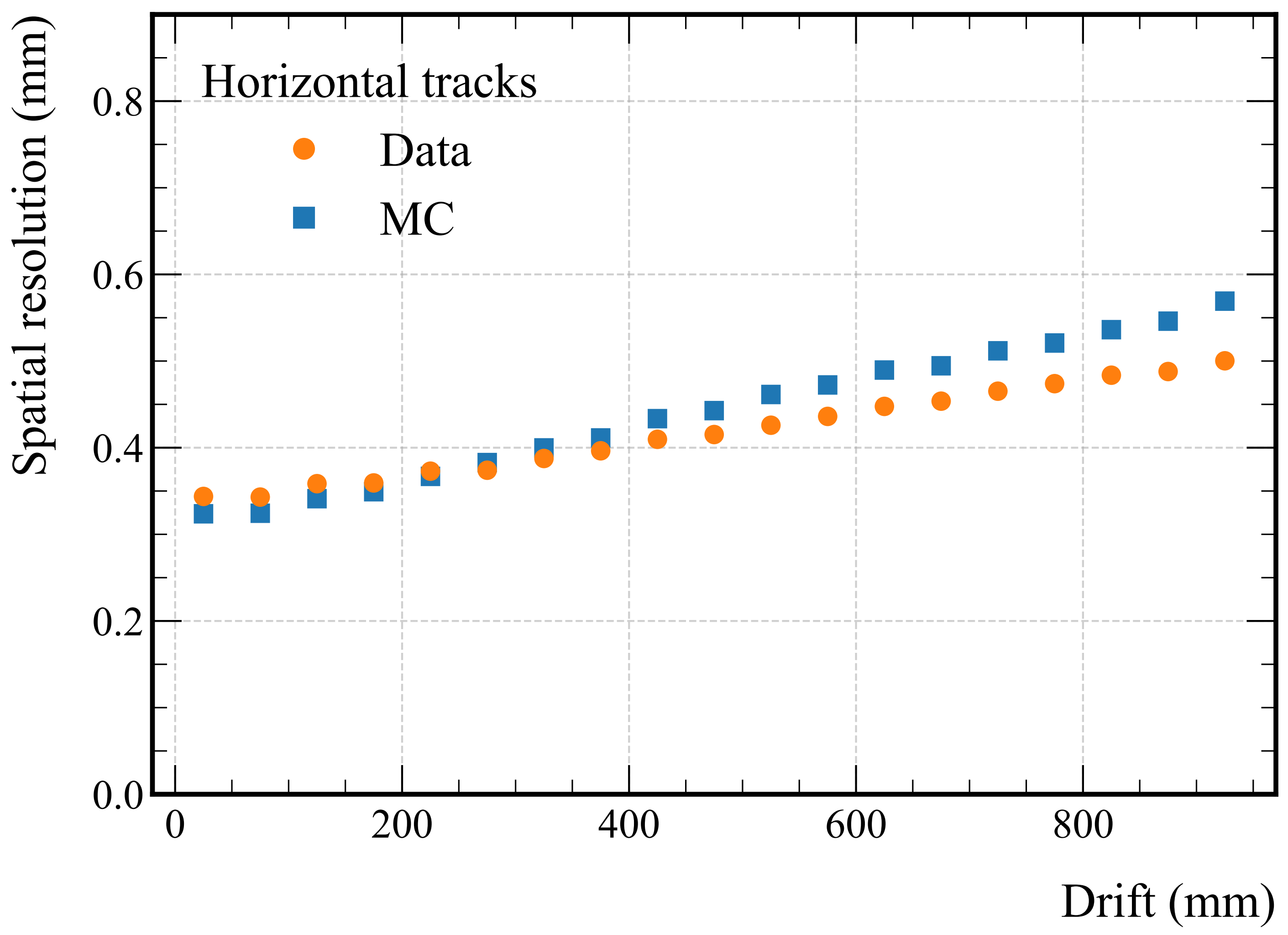


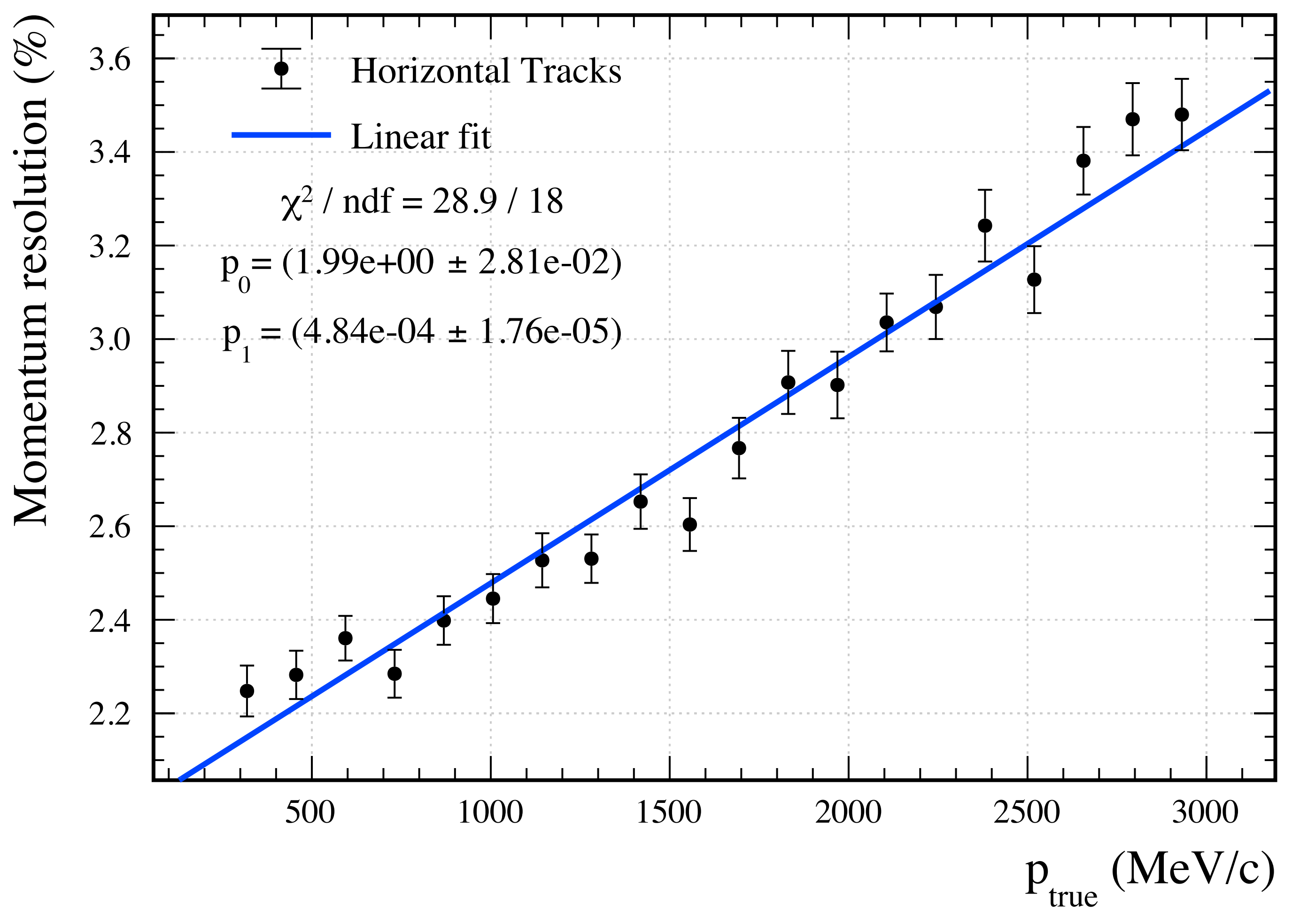
High-Angle TPC

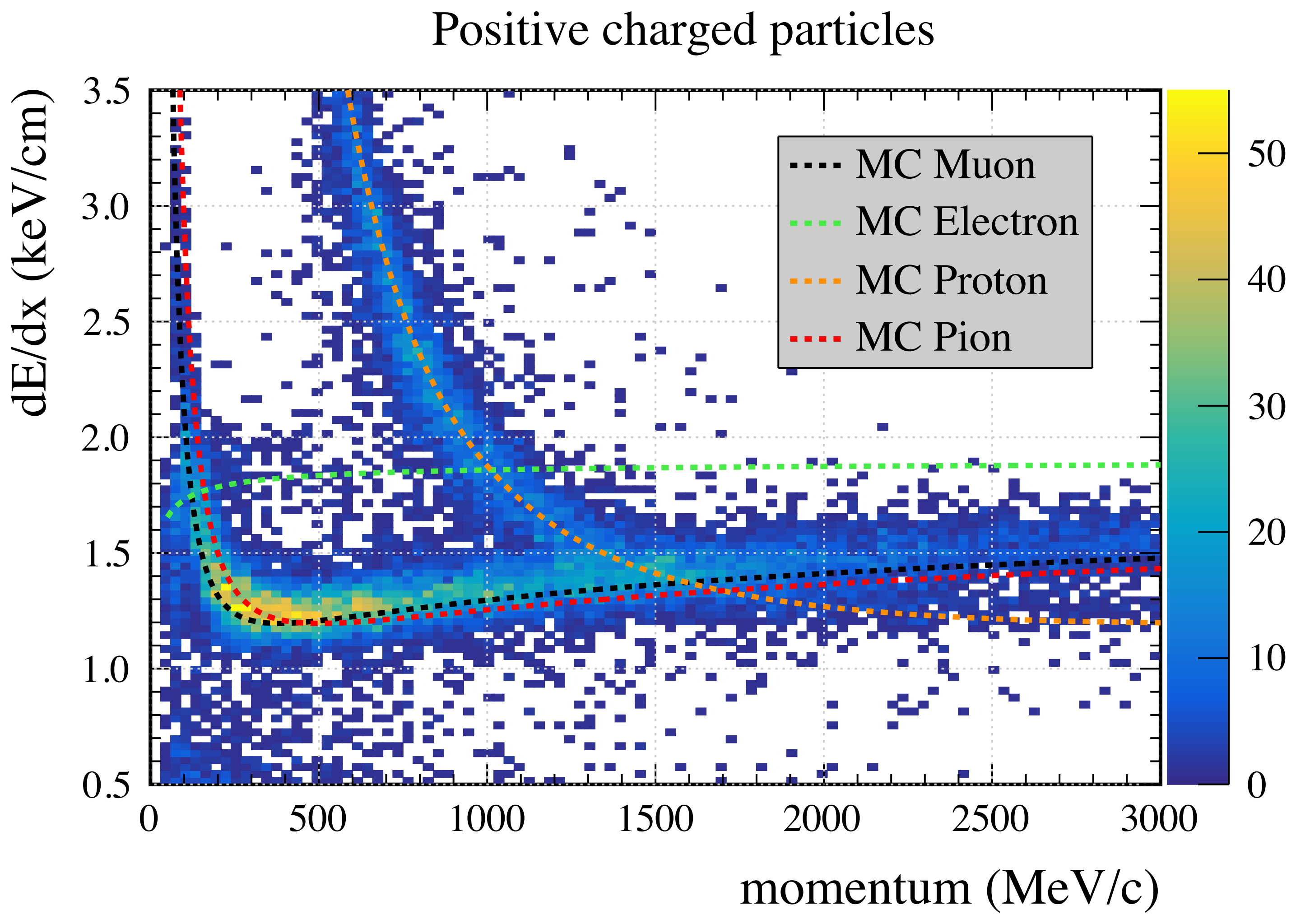
- Measure particles with large scattering angle
  - 0.2 T magnetic field
- ~0.4 mm spatial resolution
- Capable of PID with momentum vs dE/dx



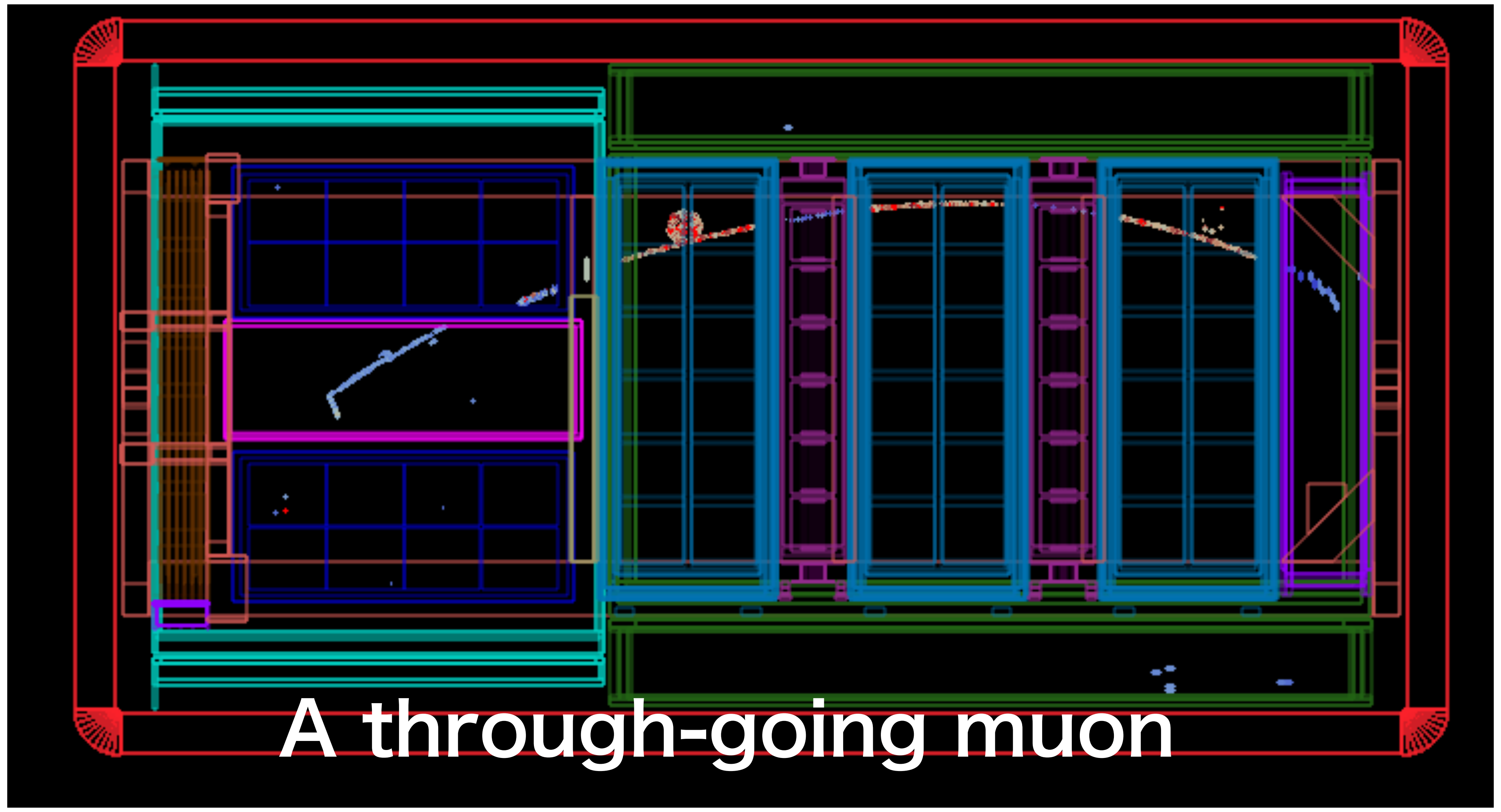
arXiv:2511.18650



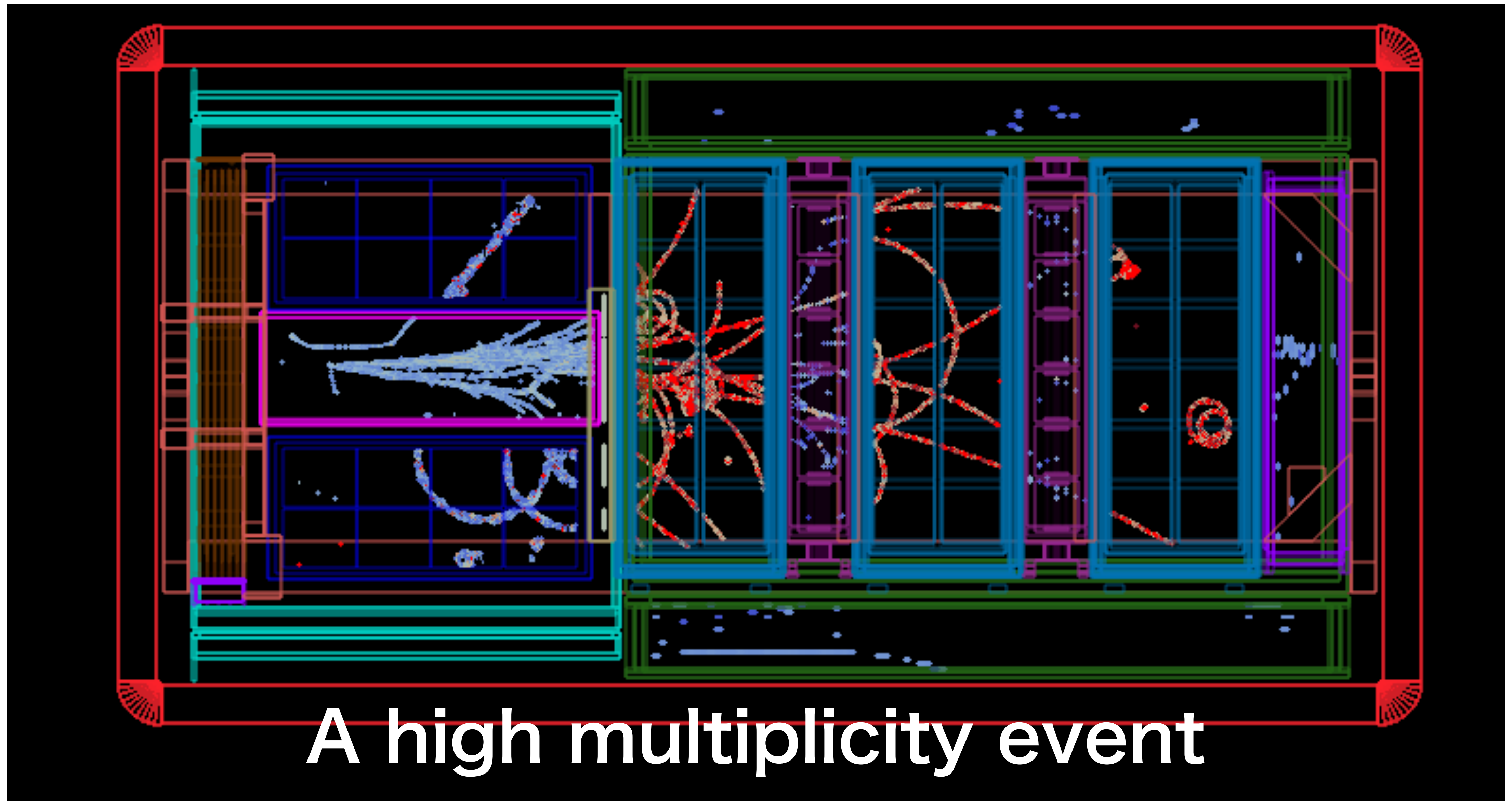




Event displays

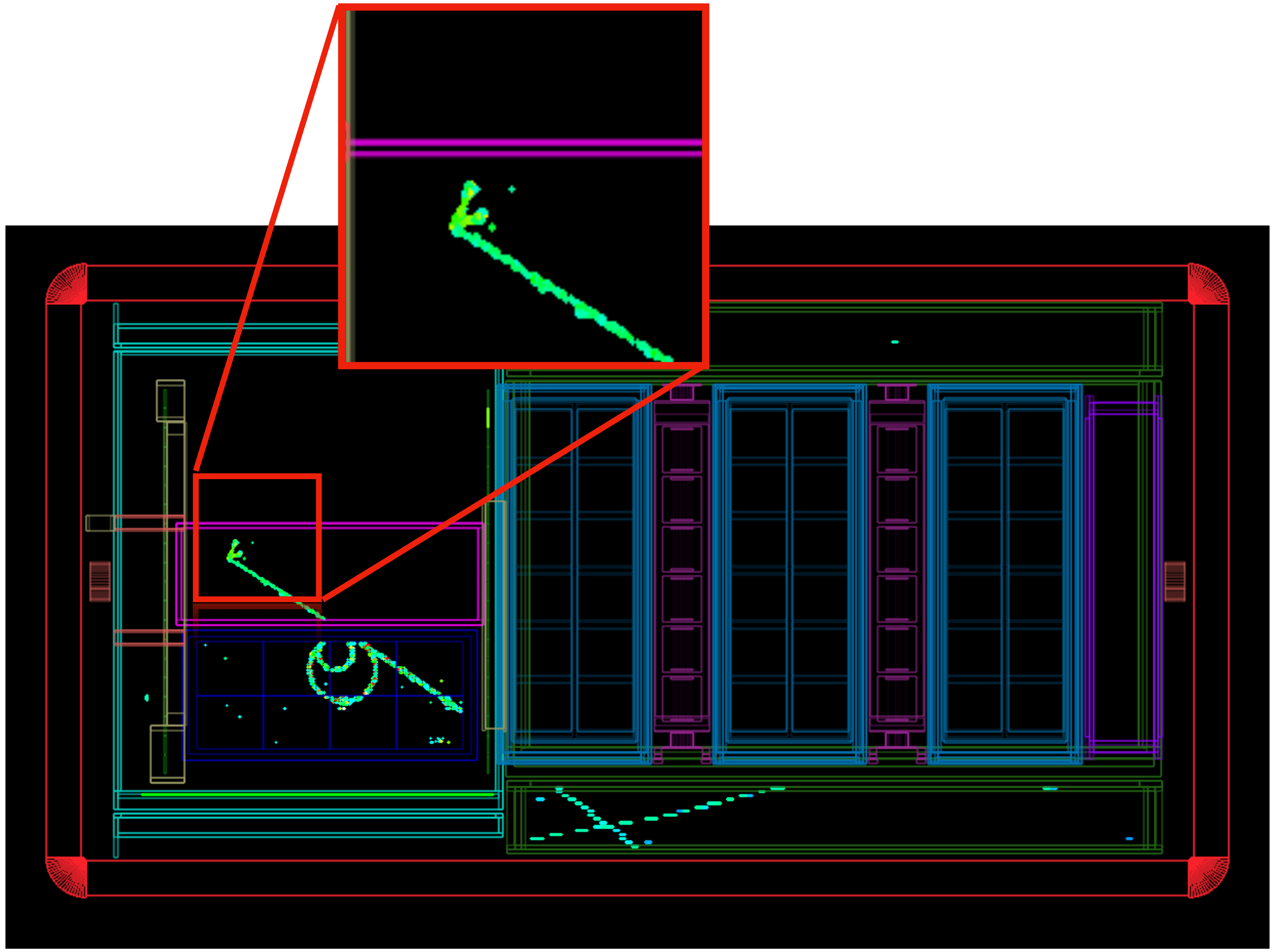


A through-going muon



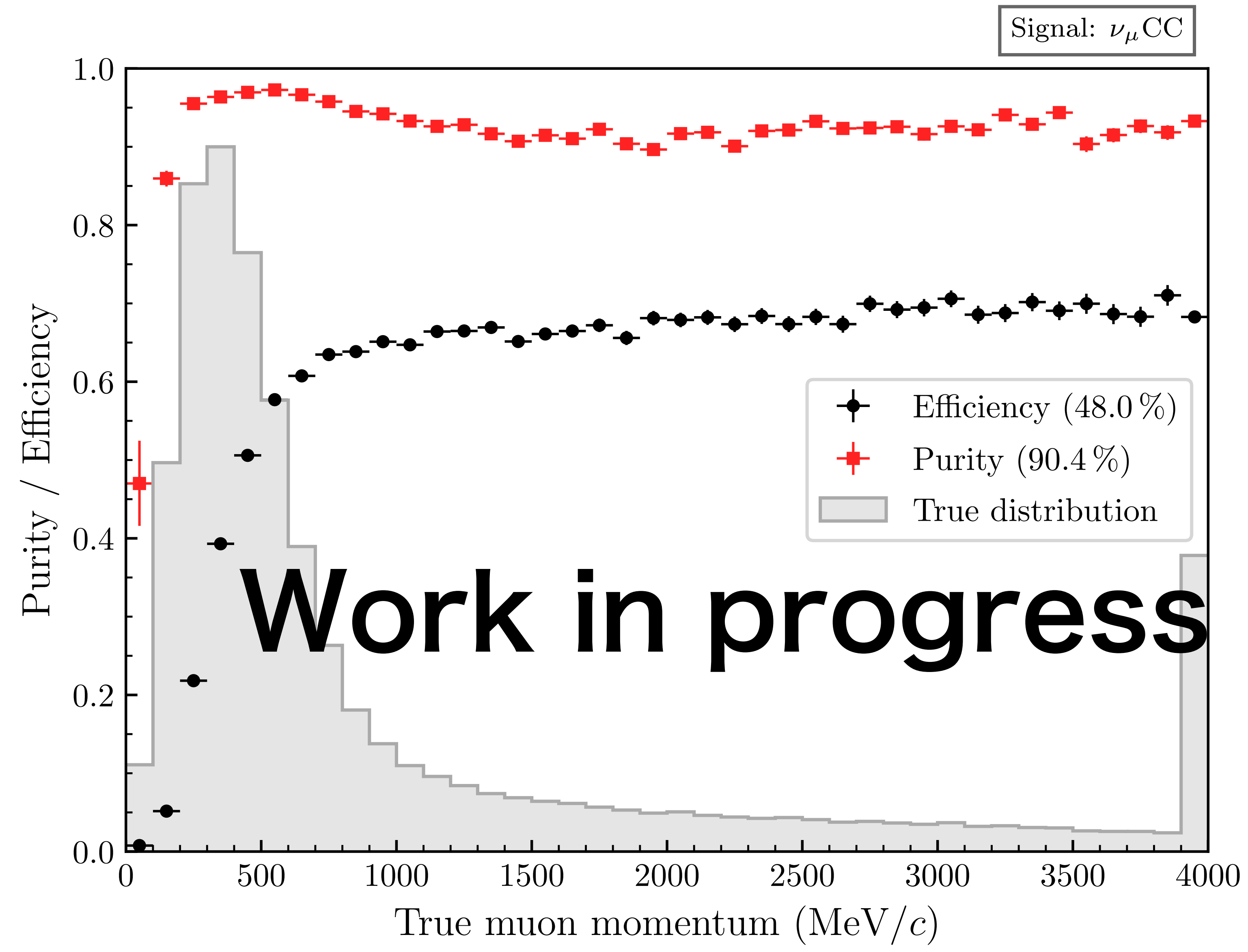
A high multiplicity event

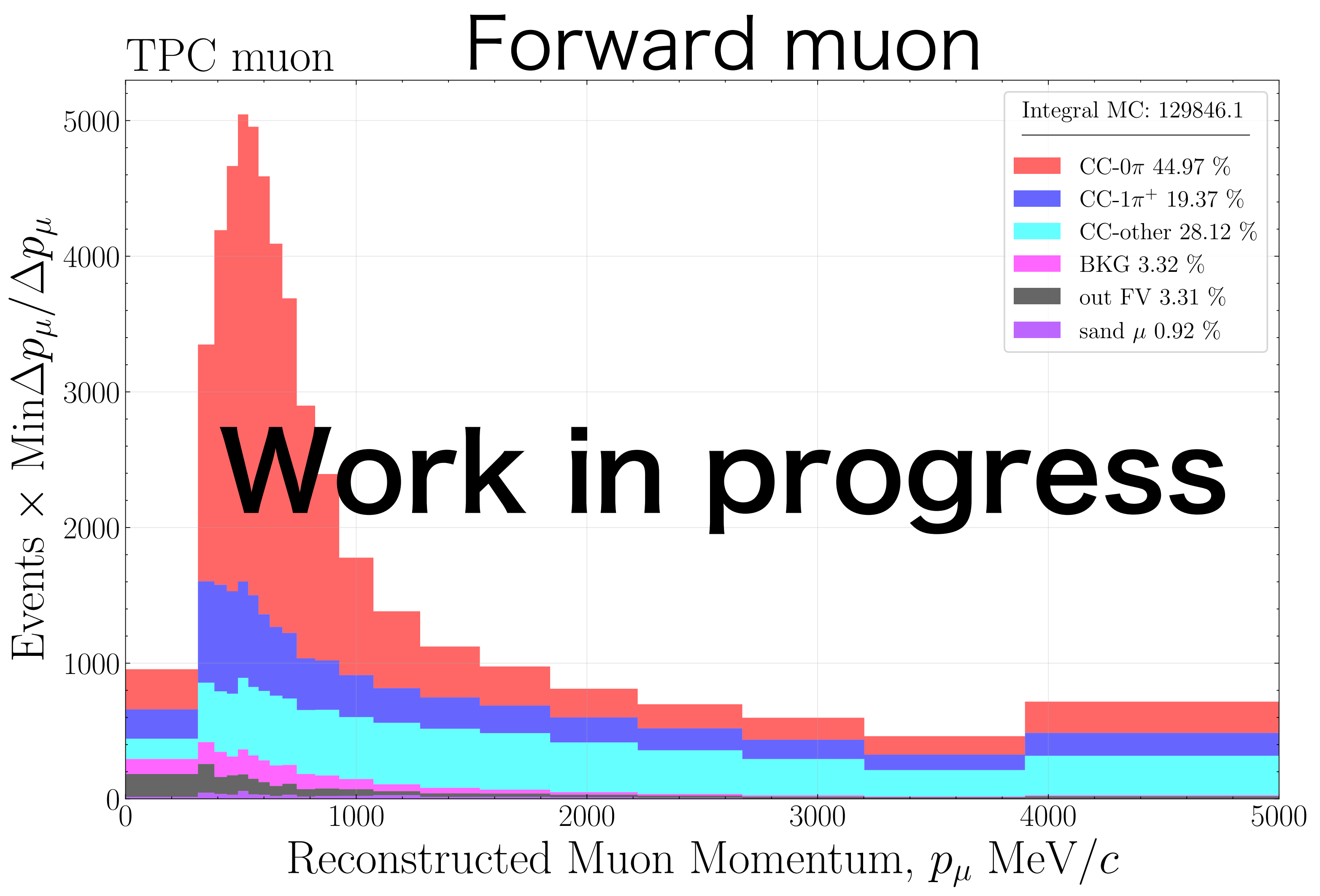
Two short range protons

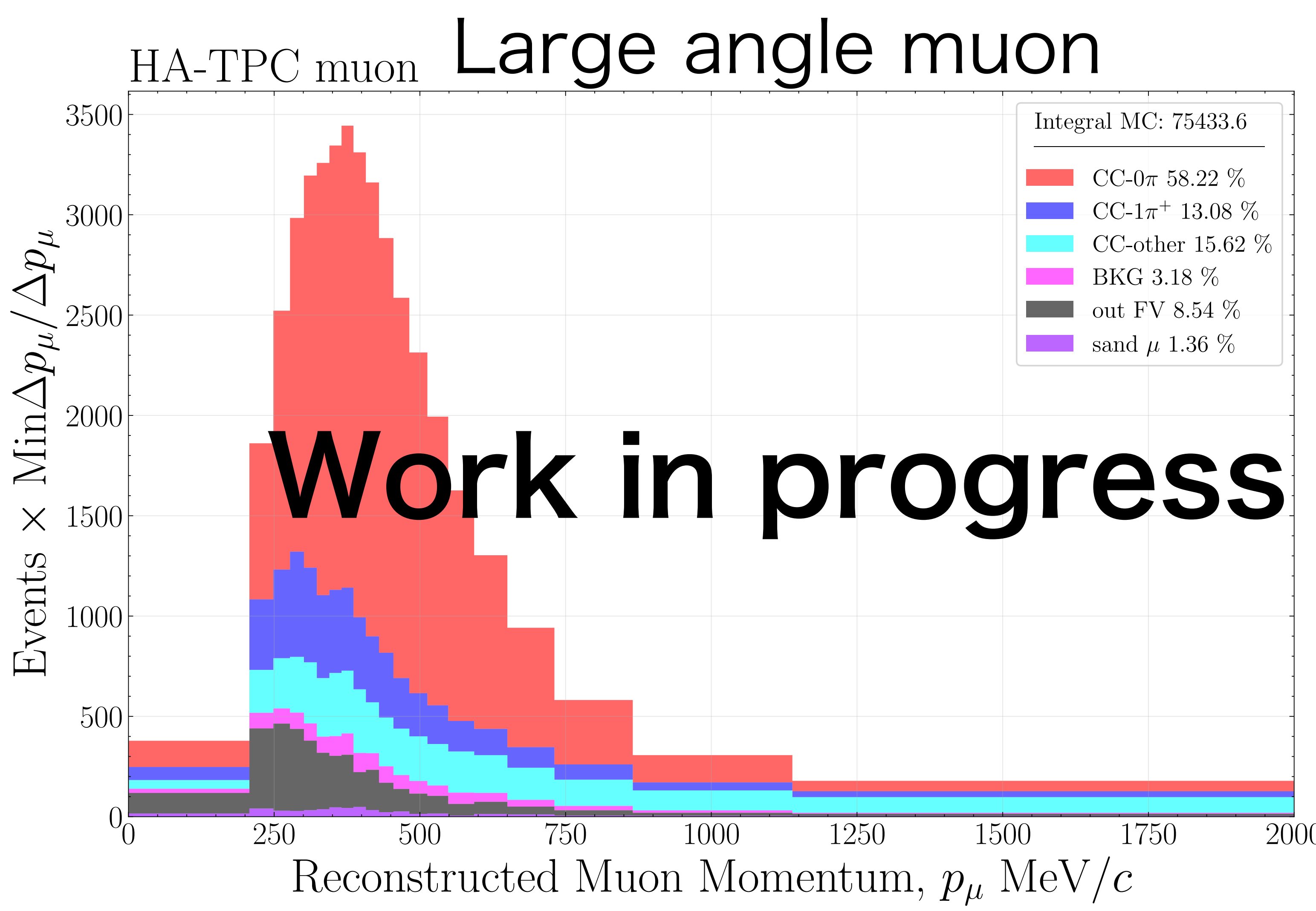


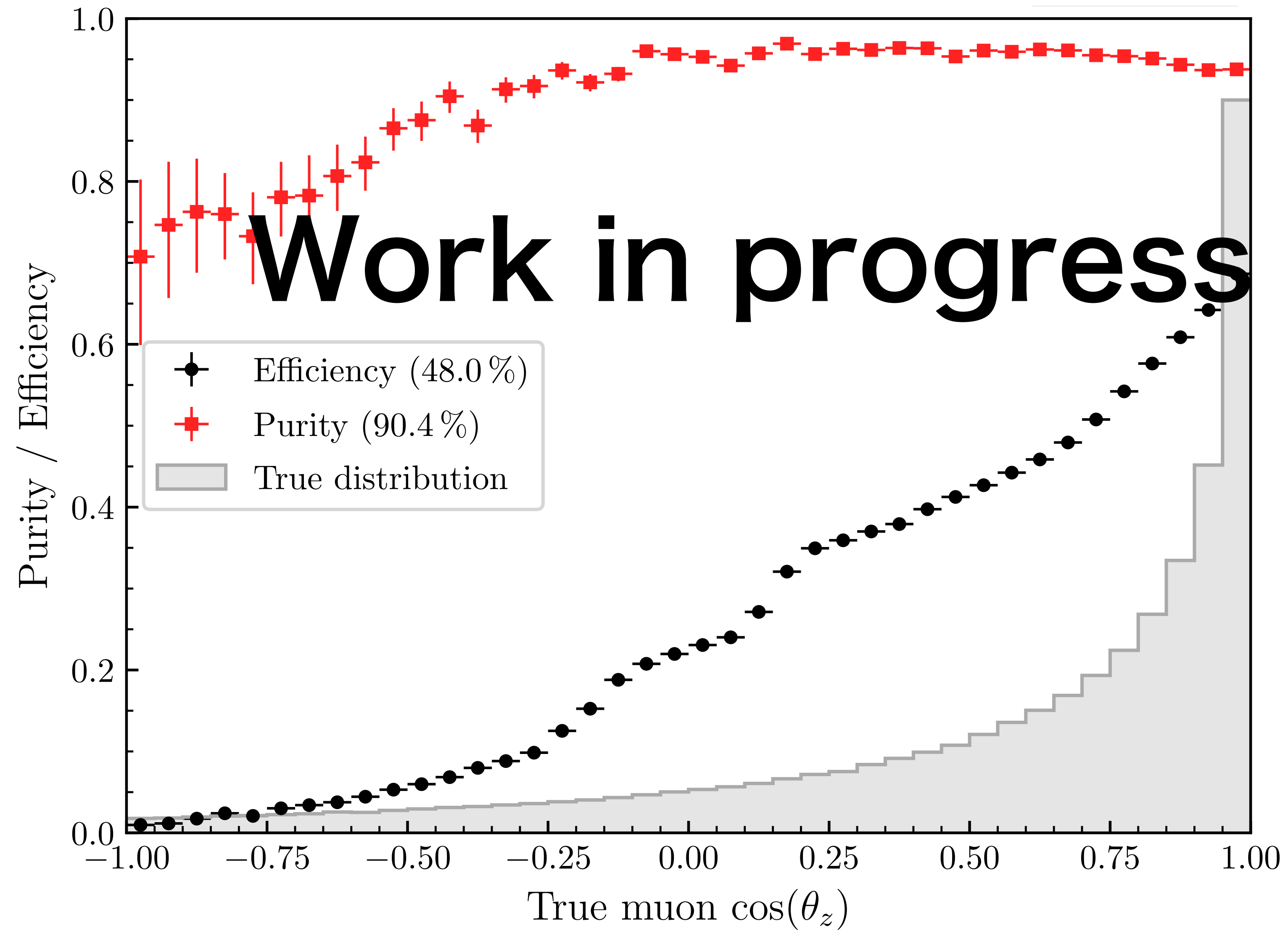
Upgrade ND280 (inclusive)

- Inclusive numuCC sample
  - Detect muons with TPCs
- Selection efficiency ~48% with purity ~90%
- Low efficiency at low energy/backward muons
  - Will improve with contained muon selection





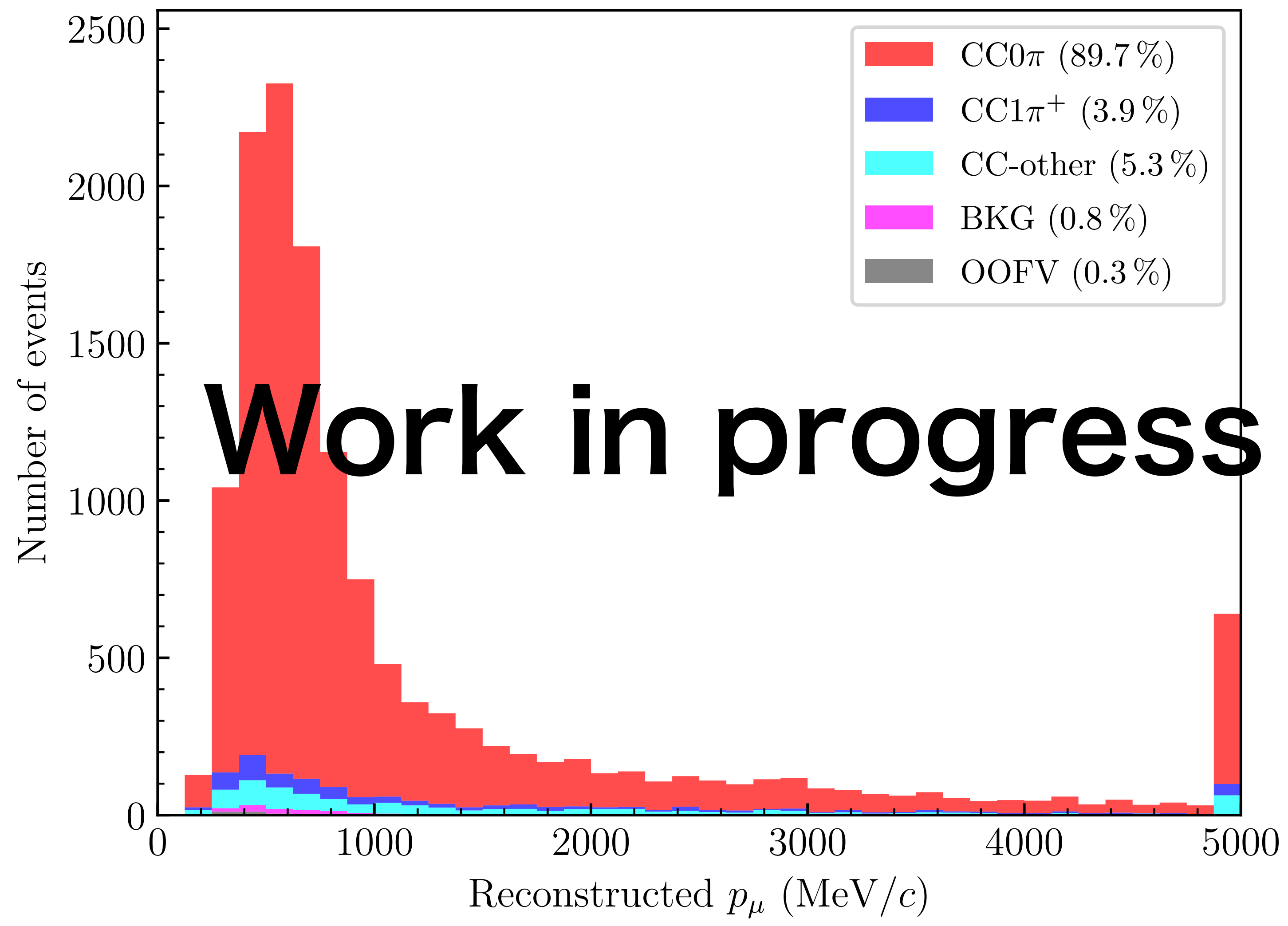




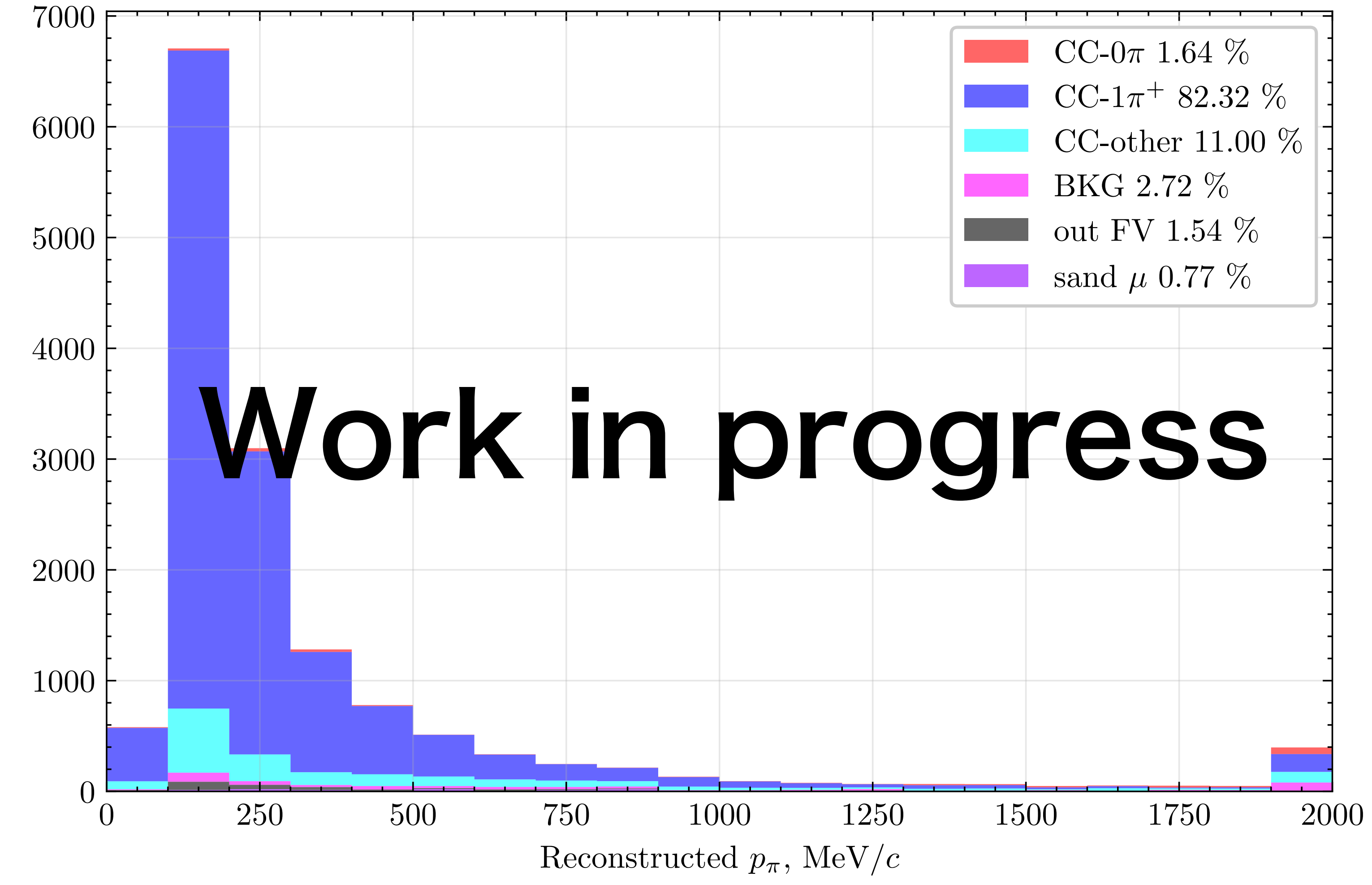
Upgrade ND280 (0pi/1pi)

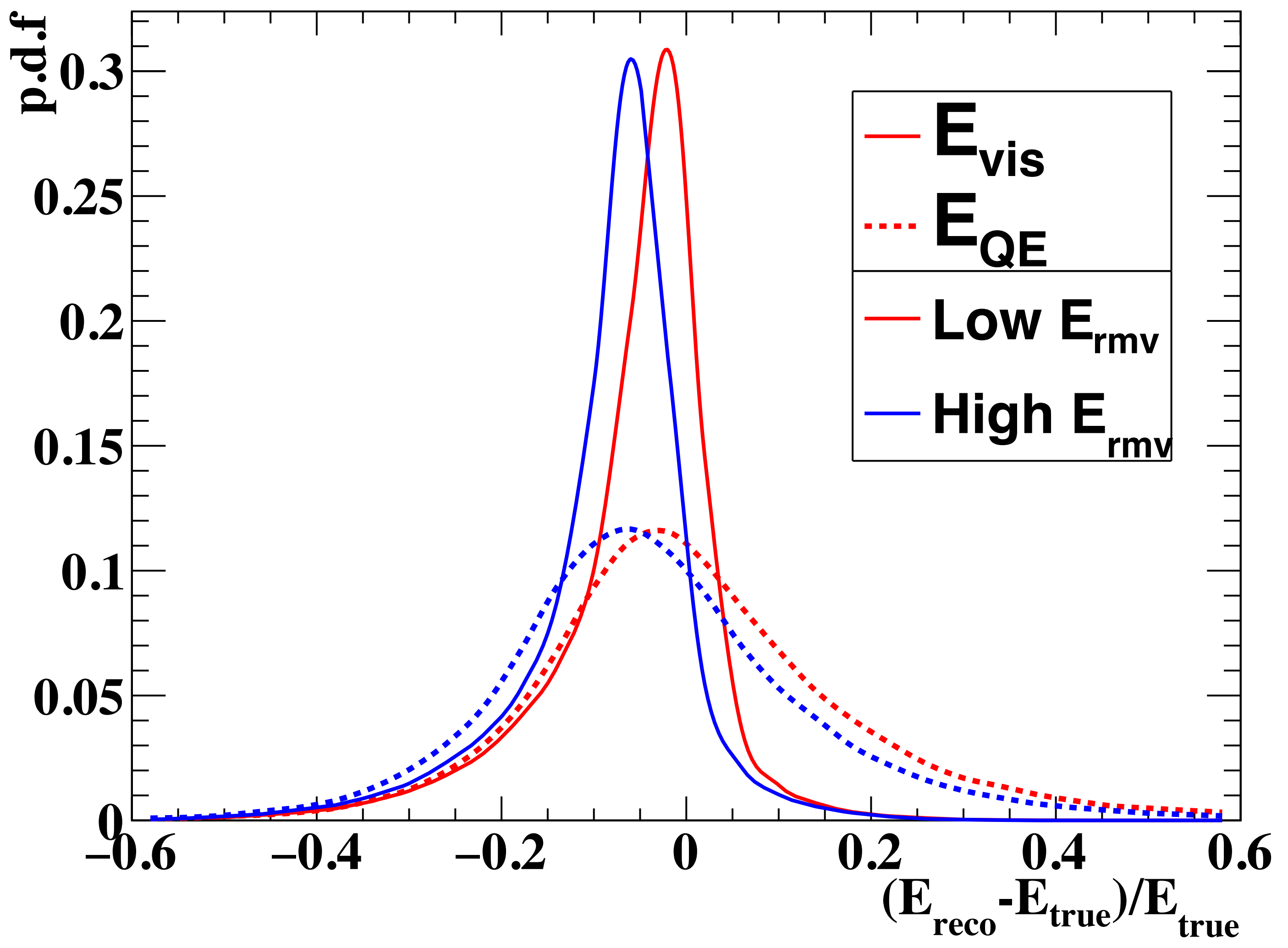
- A more precise hadron reconstruction is possible
  - Capable of probing nuclear effects etc.
- CC0pi/1pi events are selected with 80-90% purity

CC0pi_1proton



CC1pi

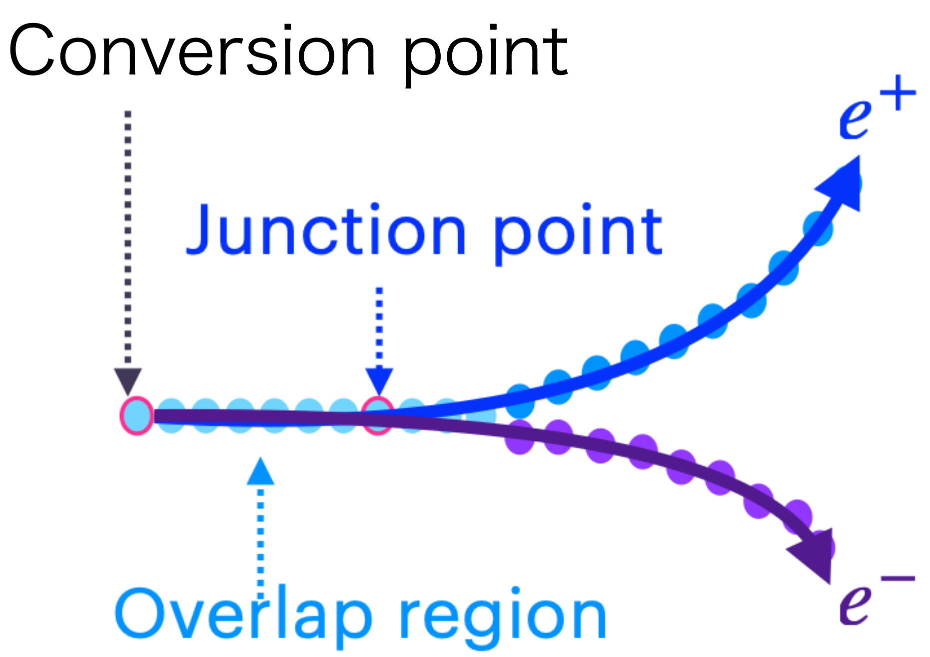




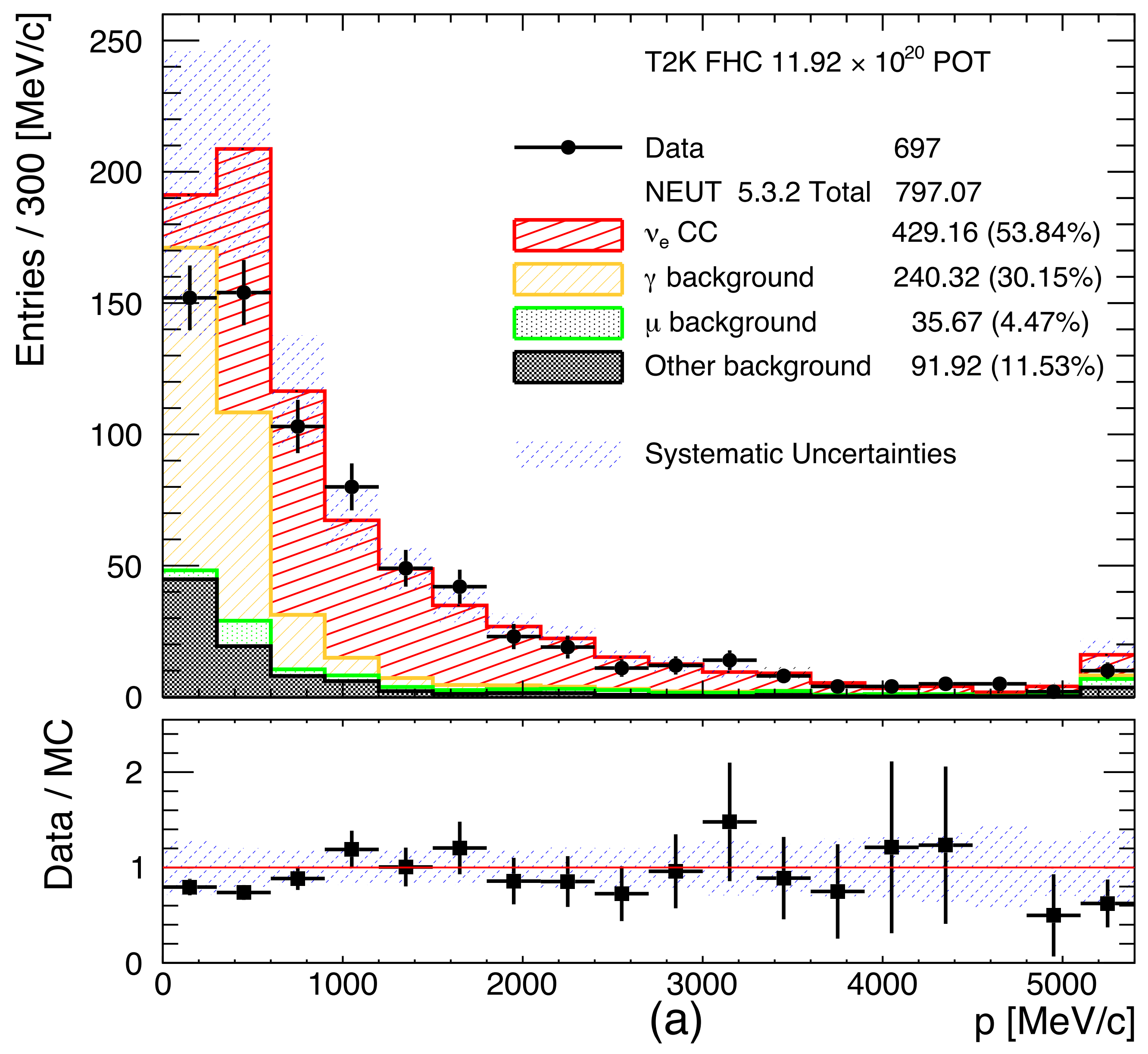
Neutrino energy resolution becomes better by adding hadron information

Upgrade ND280 (electron)

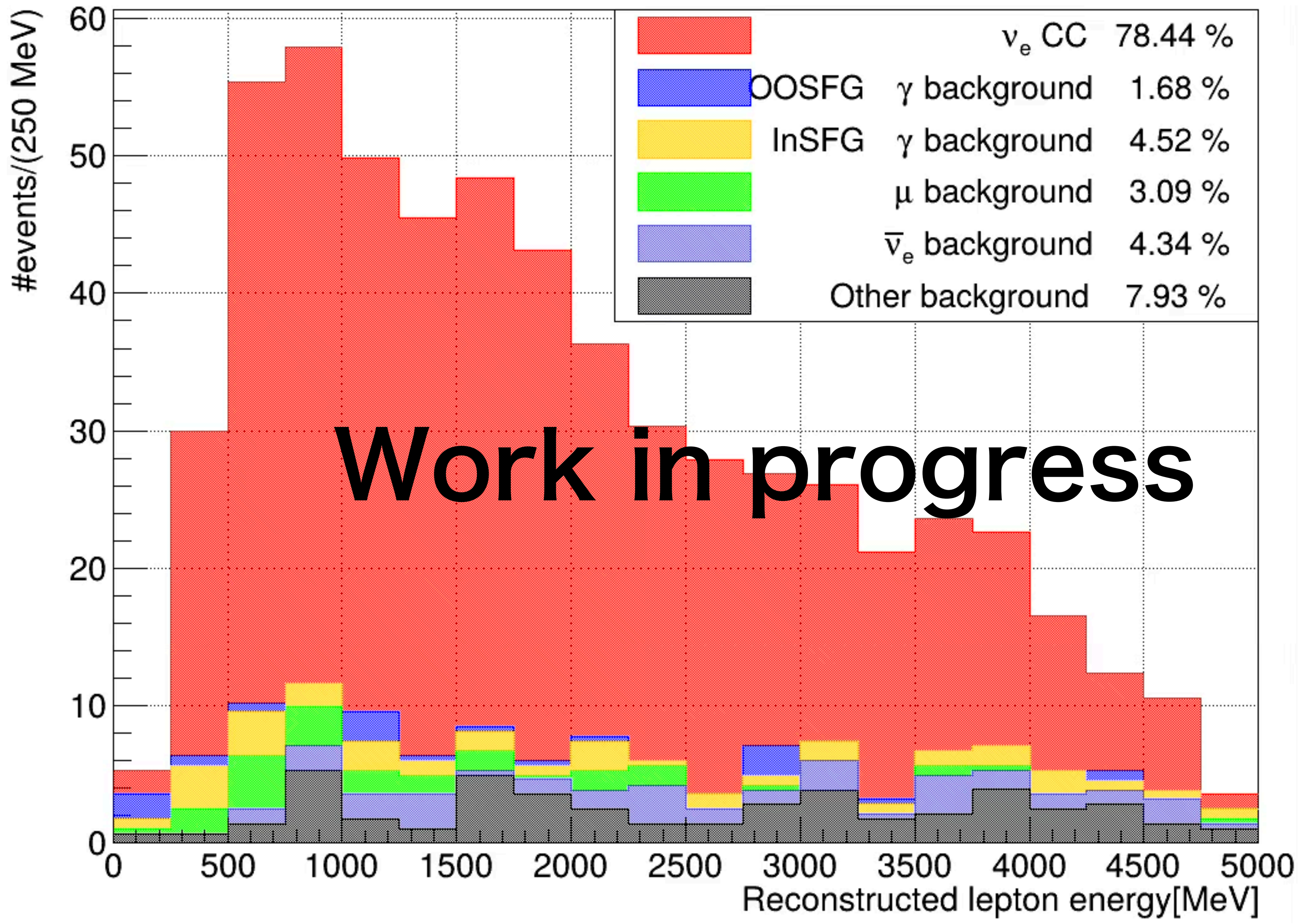
- Aiming to measure ν_e cross section with SuperFGD
  - Constrain ν_e/ν_μ cross section uncertainty
- Electron/gamma can be distinguished in SuperFGD
  - Measure the energy deposit at the e^+e^- overlap region



Pre-upgrade JHEP10(2020)114



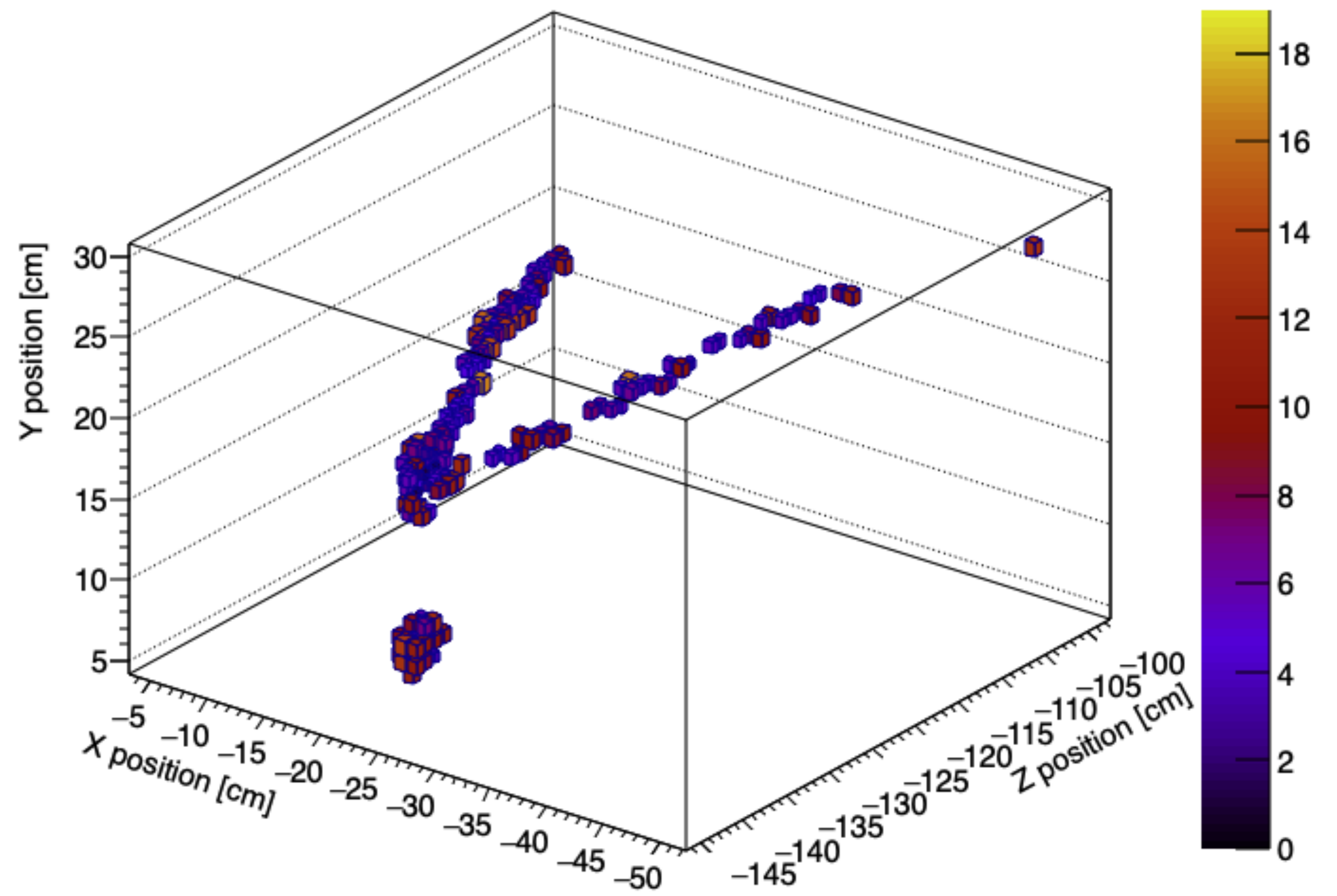
Upgraded ND280



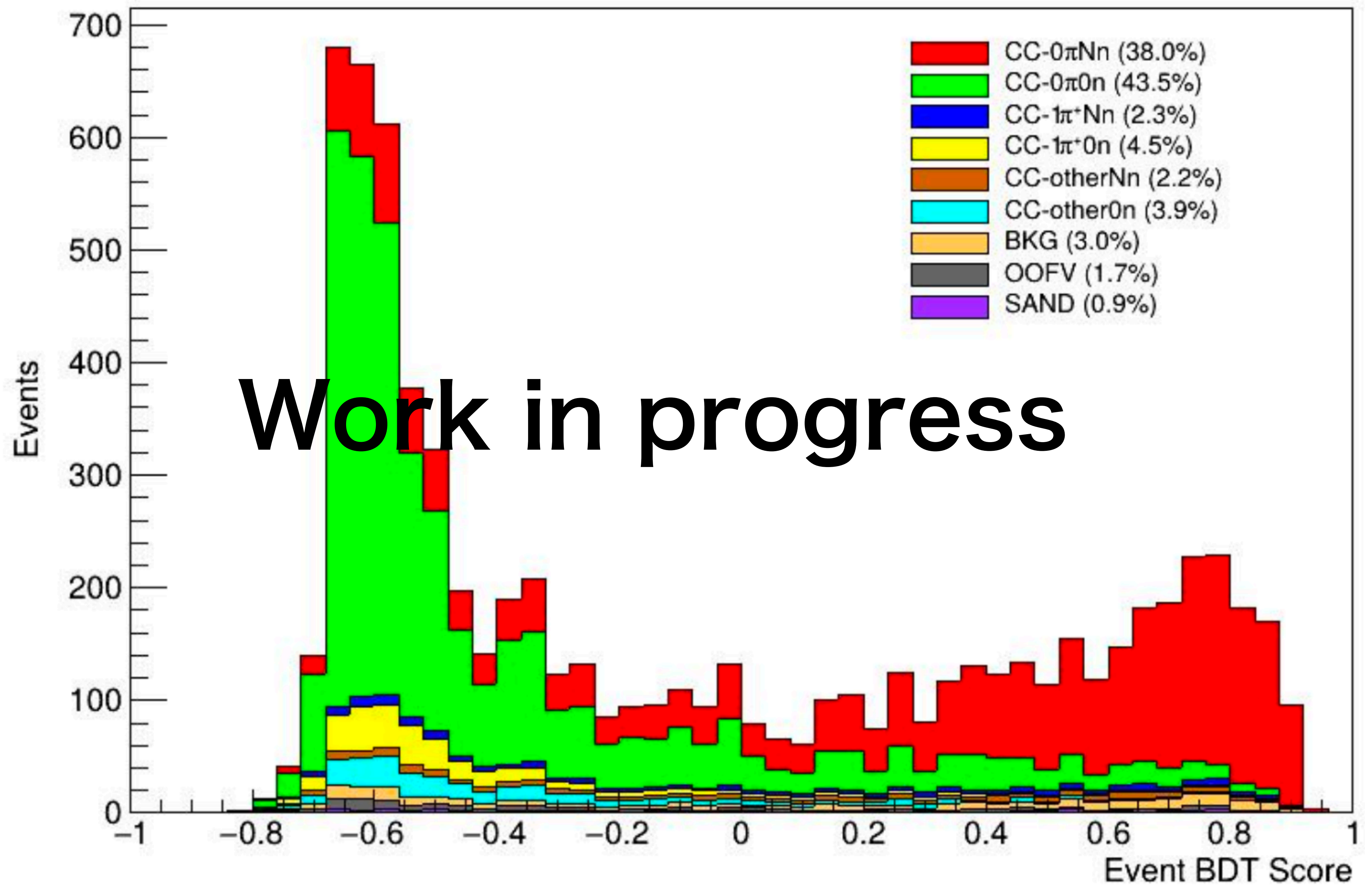
Upgrade ND280 (neutron)

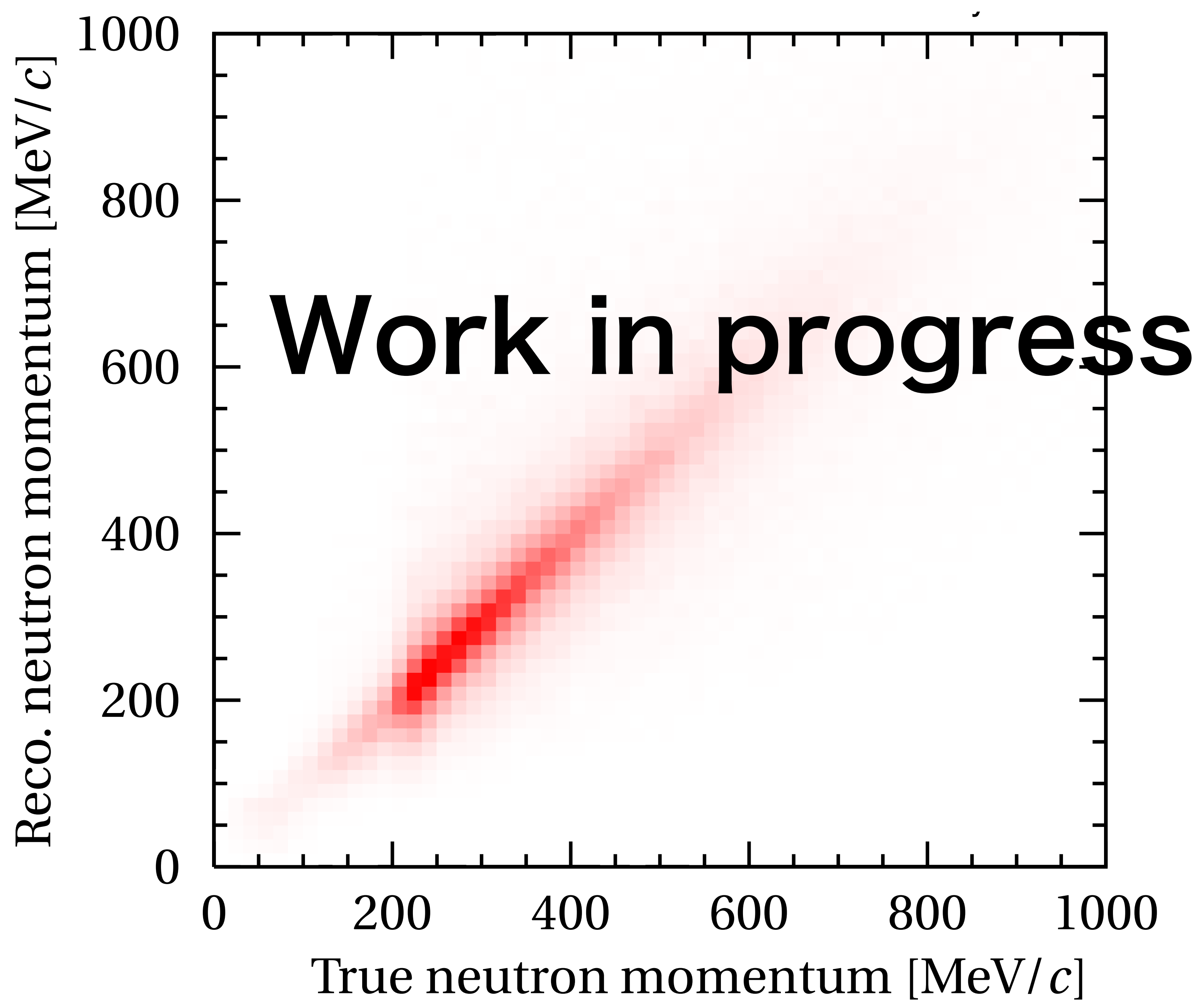
- SuperFGD can measure $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - Neutrons are detected with scattered protons
- The neutron energy is calculated from the time-of-flight

Neutron event candidate



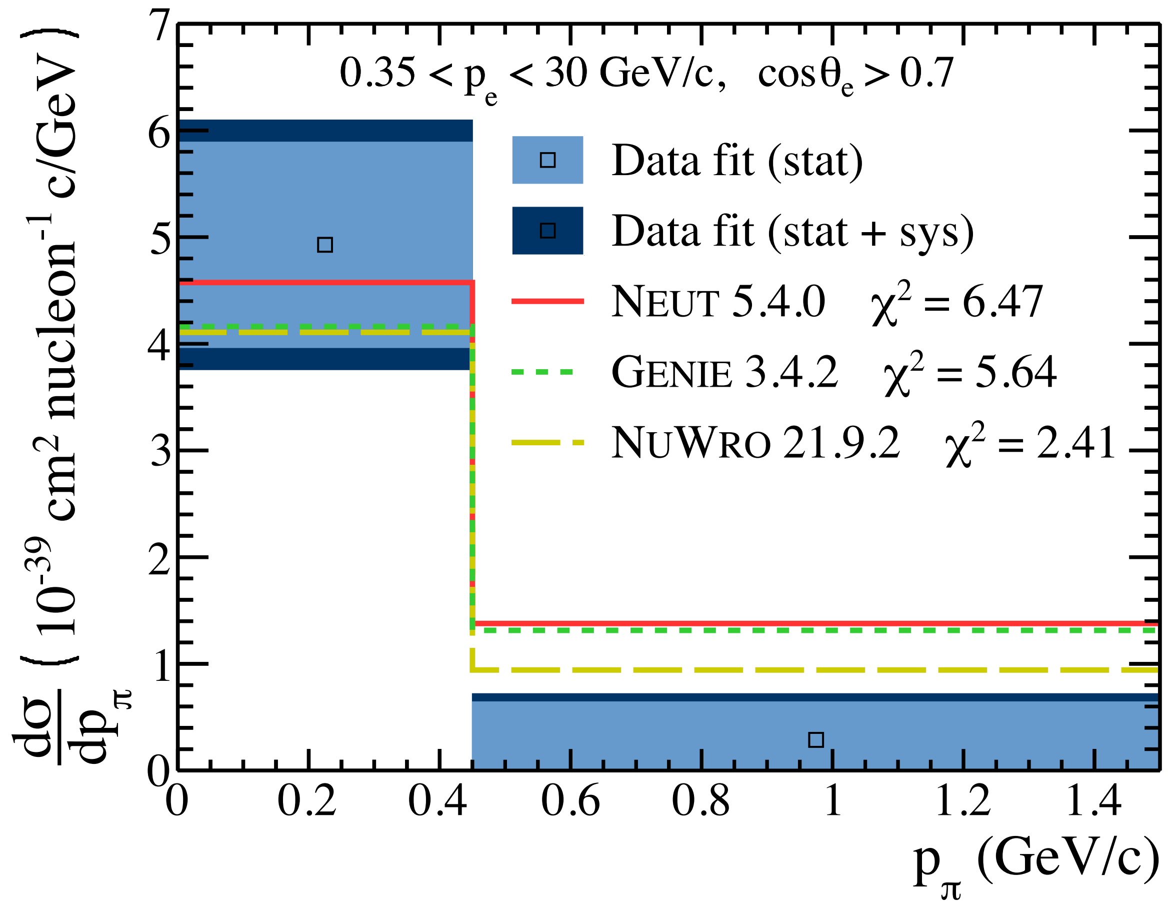
Neutron BDT score



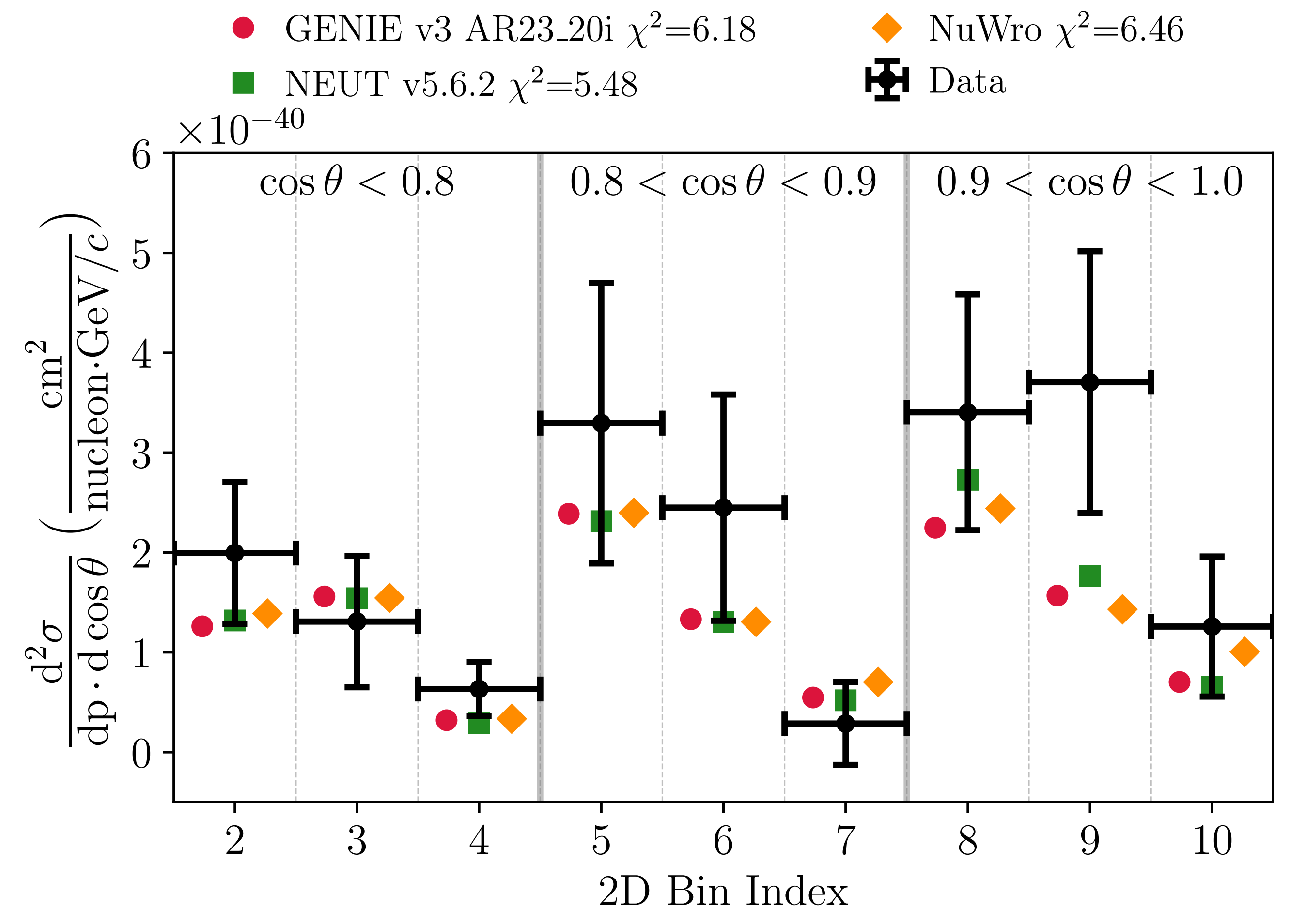


Pre-upgrade ND280 analysis

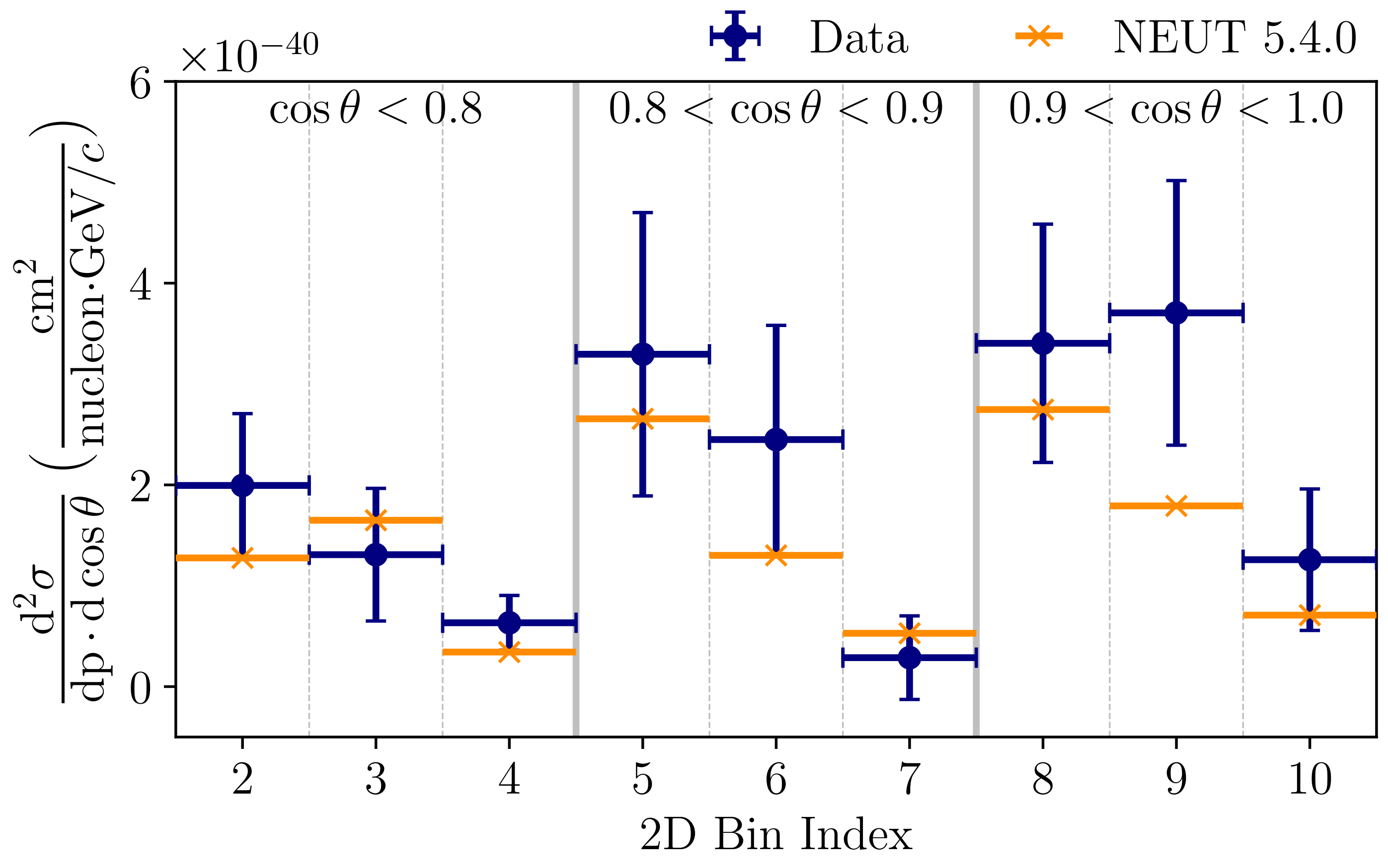
- Three new cross section publications:
  - First Measurement of the Electron-Neutrino Charged-Current PionProduction Cross Section on Carbon with the T2K Near Detector (Phys. Rev. Lett. 135, 151802)
  - First Differential Measurement of the Single π^+ Production Cross Section in Neutrino Neutral-Current Scattering (Phys. Rev. Lett. 135, 171803)
  - Signal selection and model-independent extraction of the neutrino neutral-current single π^+ cross section with the T2K experiment (Phys. Rev. D 112, 072008)



Phys. Rev. Lett. 135, 151802

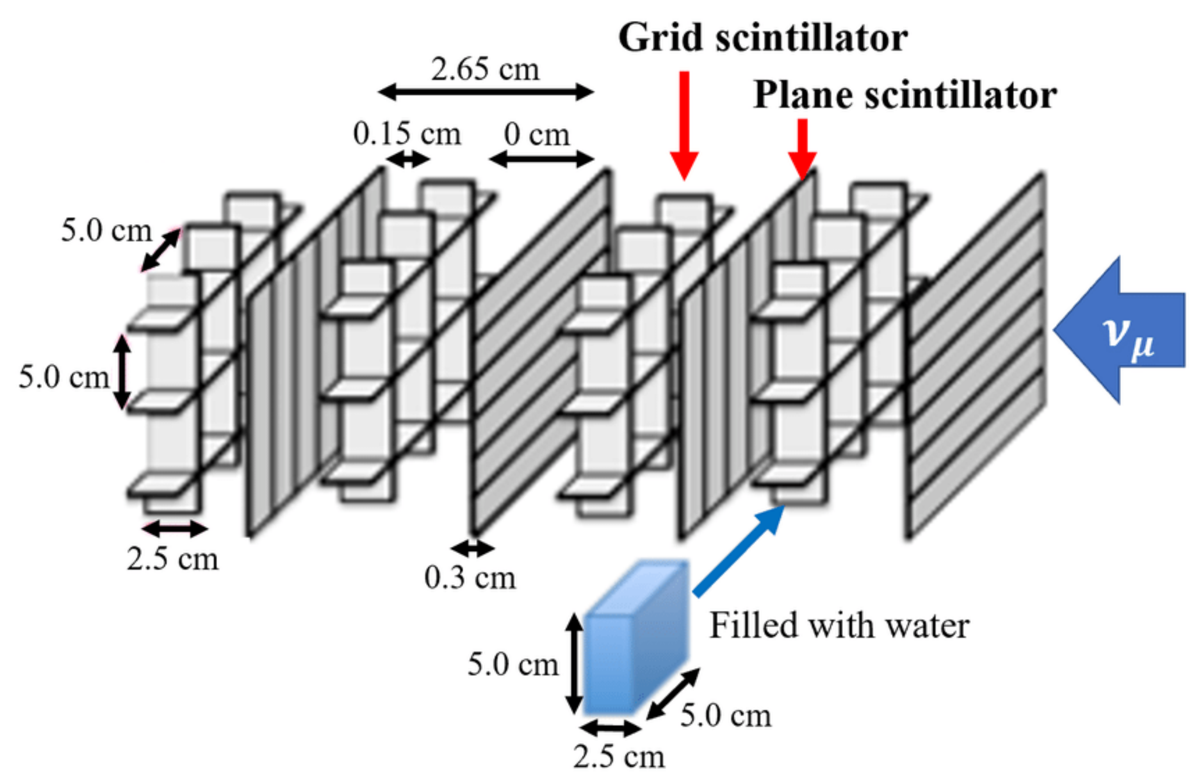


Phys. Rev. Lett. 135, 171803



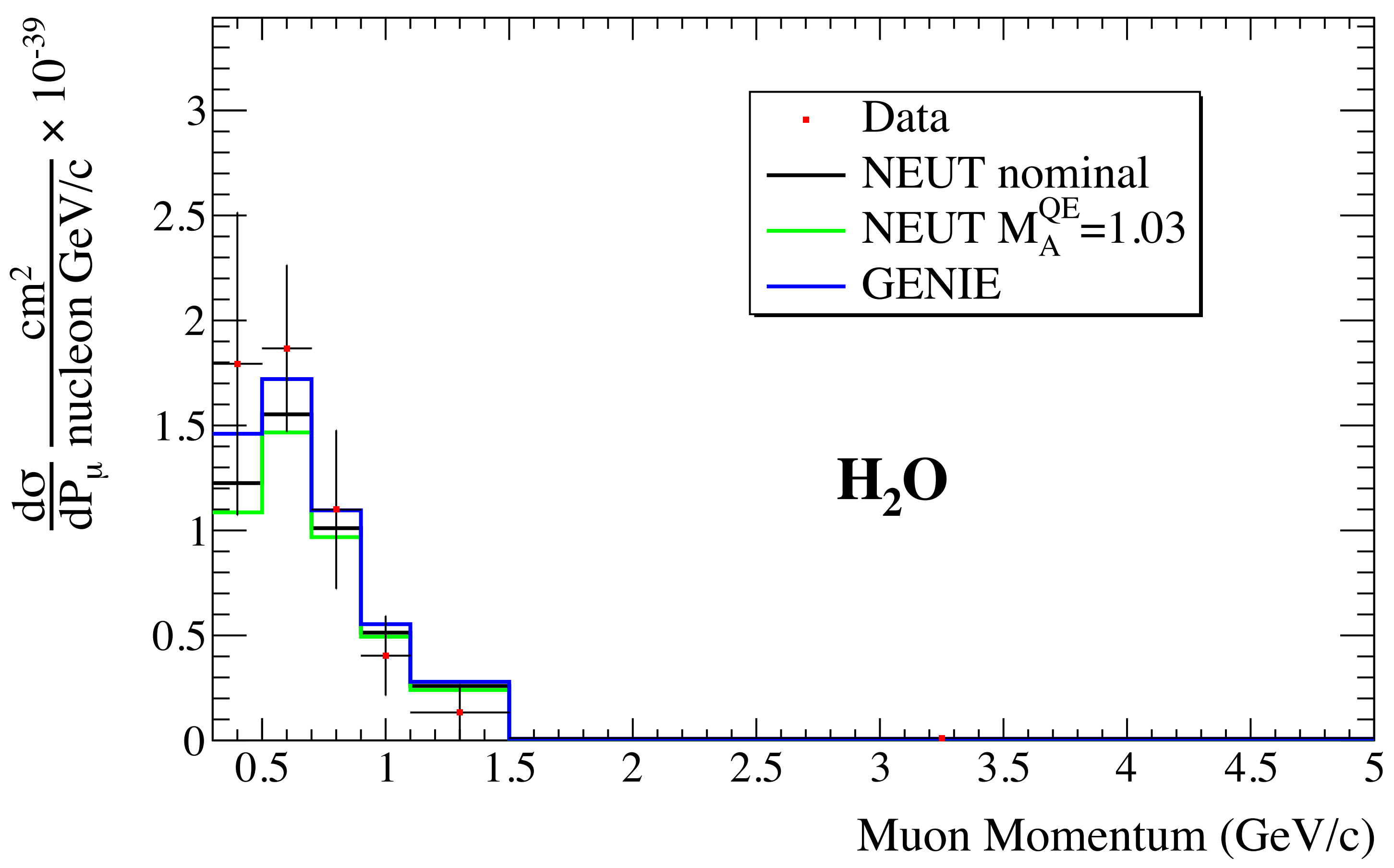
Phys. Rev. D 112, 072008

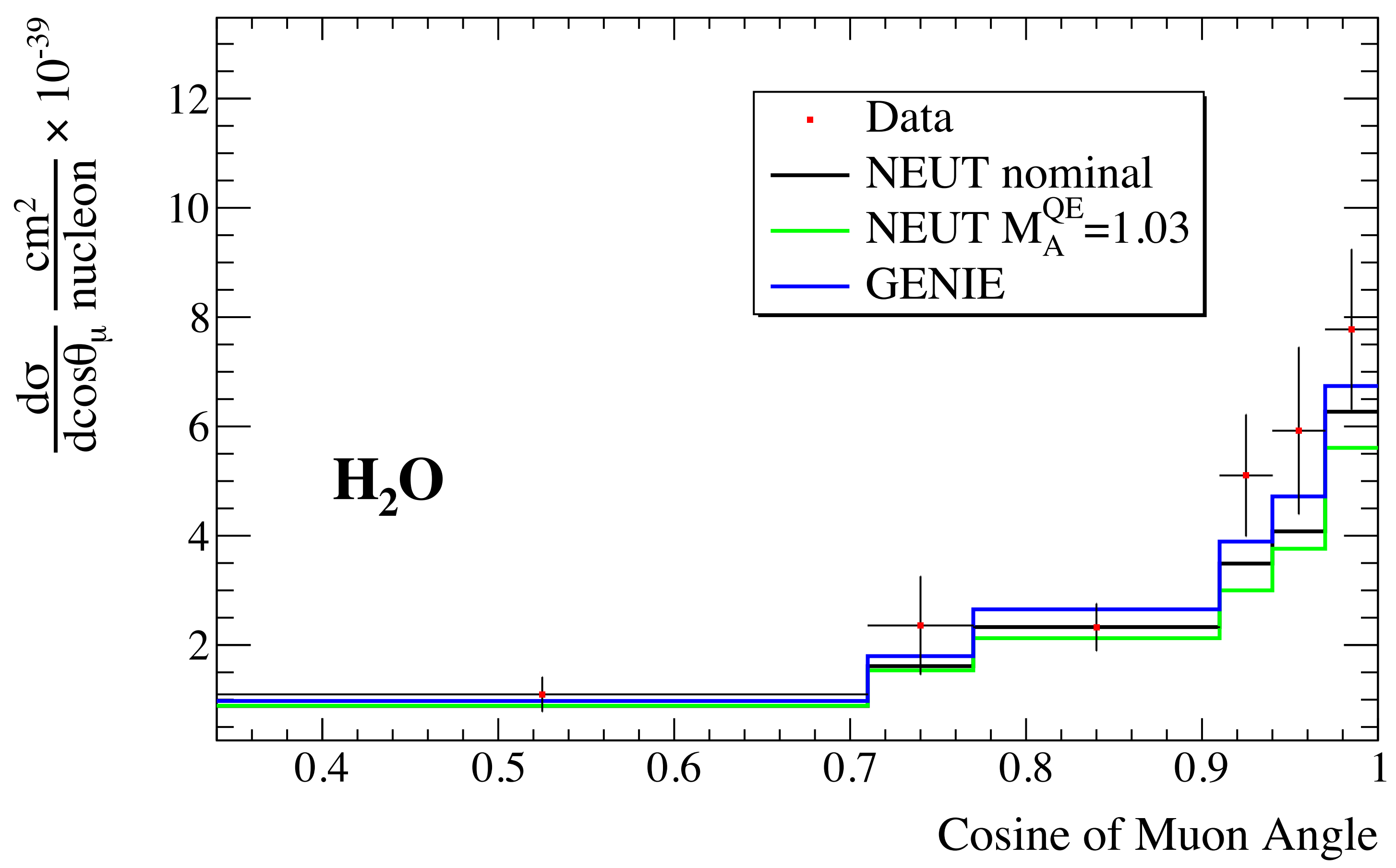
WAGASCI-BabyMIND



- **WAGASCI** is a tracker with water target
  - Constrain CH/H_2O cross section uncertainty
- **BabyMIND** tracks the muon range for momentum reconstruction
- CC0pi cross section measurement was published

Phys. Rev. D 112, 112020





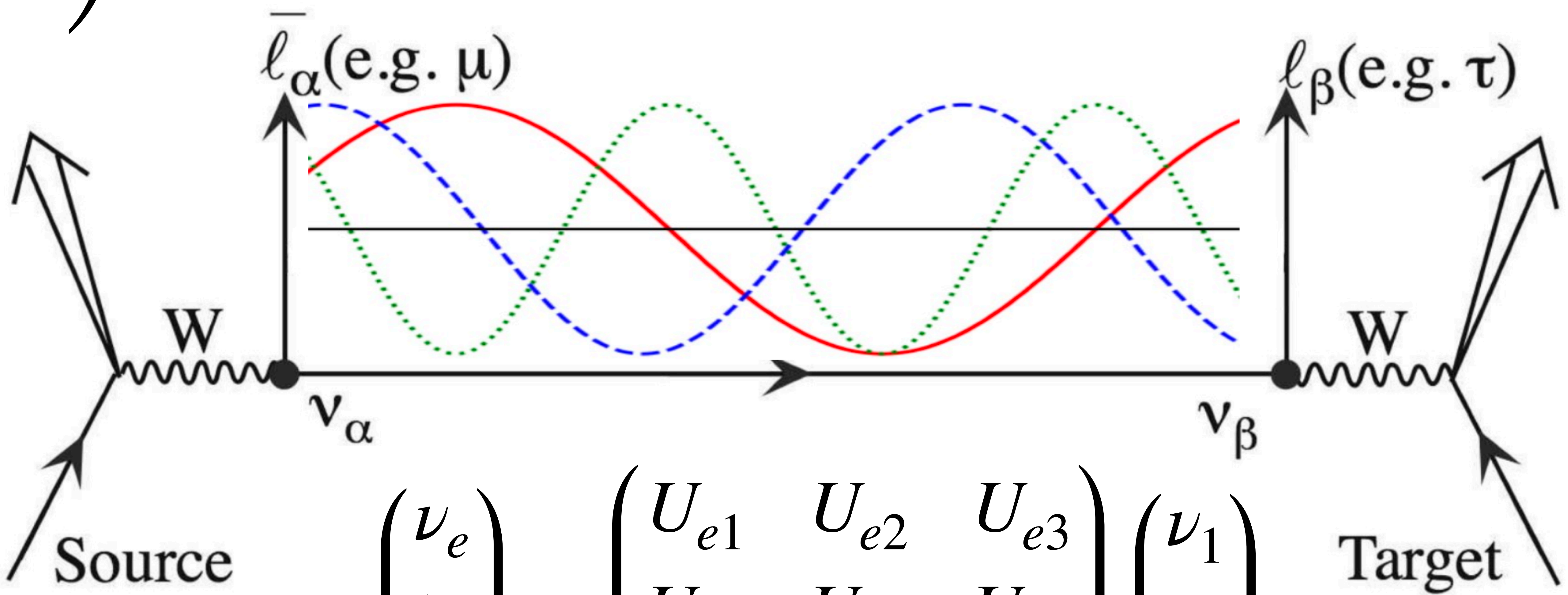
Conclusion

- This project aims to constrain neutrino interaction uncertainties via cross section analysis
  - Crucial for future experiments such as Hyper-Kamiokande
- Recent cross section papers:
  - Phys. Rev. Lett. 135, 151802,
  - Phys. Rev. Lett. 135, 171803,
  - Phys. Rev. D 112, 072008,
  - Phys. Rev. D 112, 112020
- ND280 has been upgraded, analyzes are well progressing
  - First physics results are coming soon

Backup

Neutrino oscillation

- Flavor states can be described as superpositions of mass states
  - Produced and detected as flavor states, propagate as mass states
- PMNS matrix $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$
- $P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$
  - $\Delta m^2_{32} > 0$ or $\Delta m^2_{32} < 0$?
  - $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$?
- $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin\delta_{CP}$
  - $\sin\delta_{CP} \neq 0$?



$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$