Combined ν_μ and $\bar{\nu}_\mu$ CC0π Cross Section Measurement in the T2K Near Detector Complex

NuFact 2021, Cagliari, Italy

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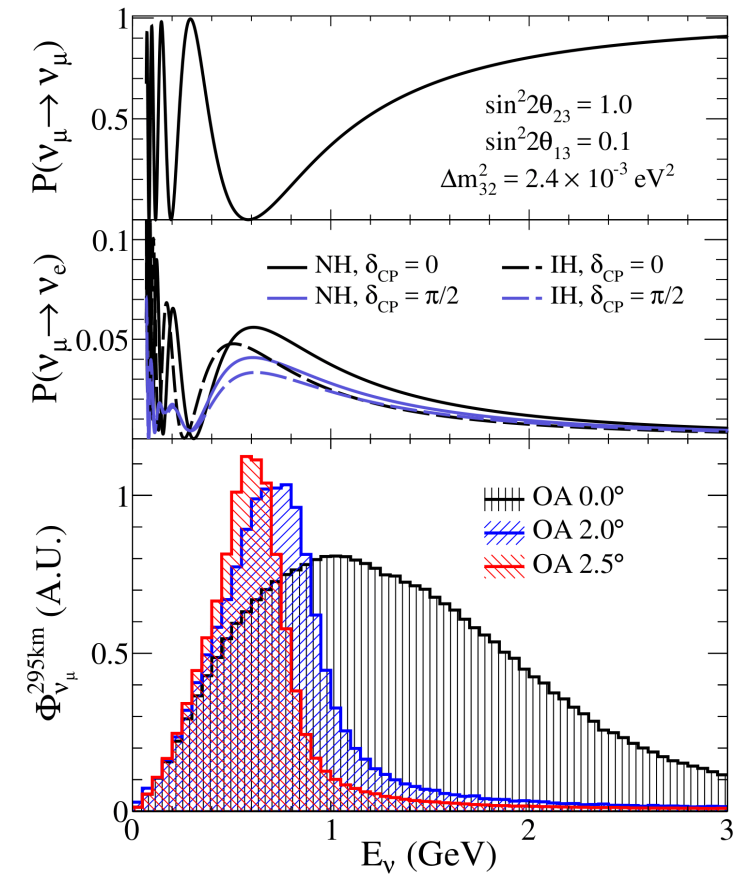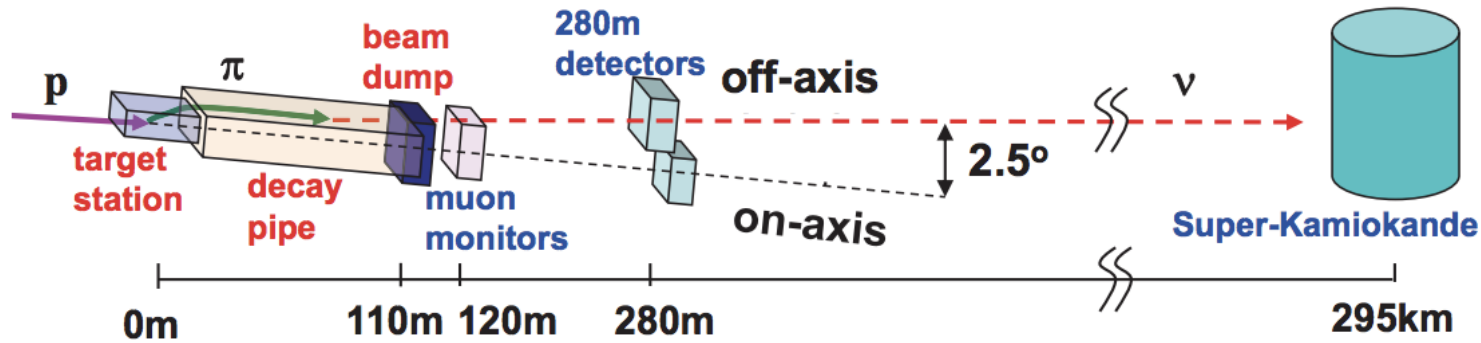IPA   ETH *zürich*   T2K

Caspar Schloesser

The T2K Experiment

- Long-baseline neutrino oscillation experiment

- $\nu_\mu \to \nu_\mu$ / $\overline{\nu}_\mu \to \overline{\nu}_\mu$ disappearance and $\nu_\mu \to \nu_e$ / $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance

- First experiment to use off-axis technique

$\sin^2 2\theta_{23} = 1.0$
$\sin^2 2\theta_{13} = 0.1$
$\Delta m^2_{32} = 2.4 \times 10^{-3}\ eV^2$

NH, $\delta_{CP} = 0$ IH, $\delta_{CP} = 0$
NH, $\delta_{CP} = \pi/2$ IH, $\delta_{CP} = \pi/2$

OA 0.0°
OA 2.0°
OA 2.5°

E_ν (GeV)

ETH zürich   T2K

Cross Section Measurements at T2K

$$\text{Event rate} = \Phi_\nu(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times P(\nu_\mu \to \nu_{\mu,e})$$

Near Detector

Far Detector

Neutrino Flux   Interaction Cross Section   Detector Efficiency   Oscillation Probability

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interaction	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

- Errors on SK reduced from:
  $\sim 15\%$ to $\sim 5\%$

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arXiv:1807.07891

- Different flux, target and acceptance for near and far detectors
- Φ_ν, σ constrained by near detector → reduce far detector systematics
- Interaction cross section uncertainty is dominant one for oscillation analysis
- Need for reliable model and better understanding of neutrino interactions
  - Neutrino physics is entering high precision era

Measurement

- Joint $\nu_\mu / \overline{\nu}_\mu$ cross section measurement on carbon

- Charged current with zero pions in the final state

- Using the T2K on- and off-axis near detectors

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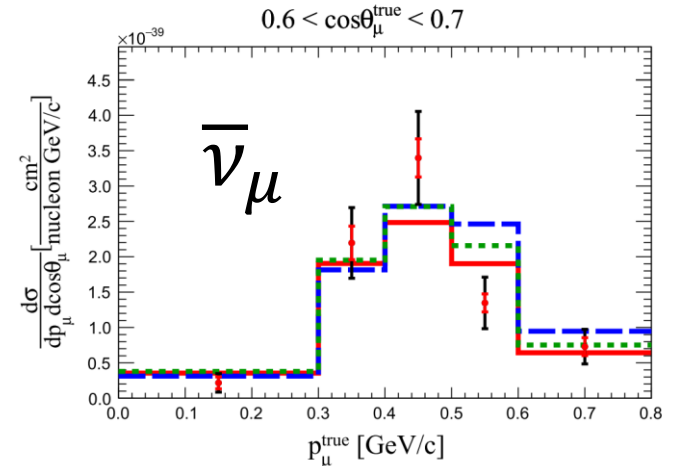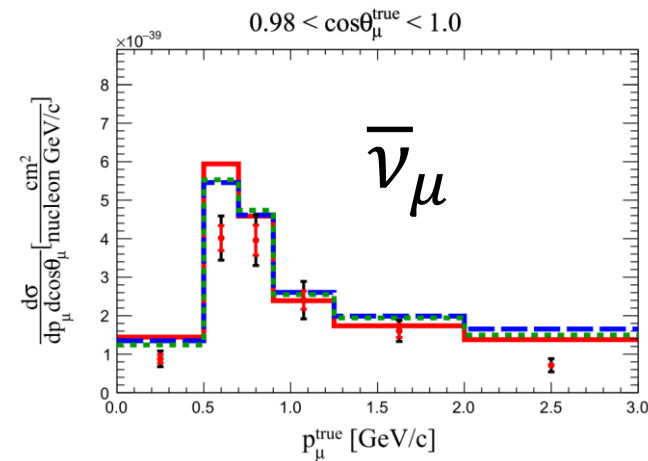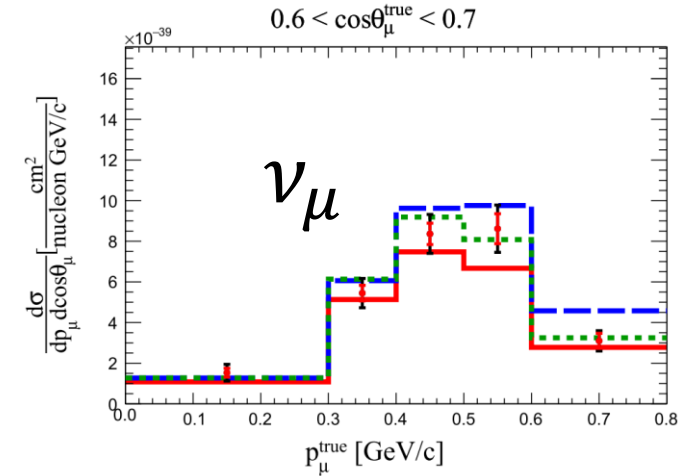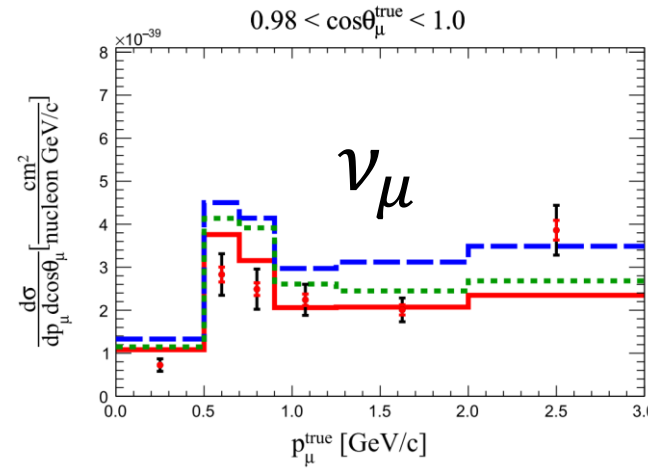
- Using the T2K on- and off-axis near detectors

Joint $\nu_\mu / \bar{\nu}_\mu$ cross section measurement

- $\nu_\mu / \bar{\nu}_\mu$ cross sections differ by sign of axial-vector interference term
- Multinucleon excitations enter in this term
  - These can be tested by taking the difference between ν and $\bar{\nu}$ cross sections
- CP violation analyses measure the asymmetry between $\nu/\bar{\nu}$ oscillations
 - Important to account for neutrino-nucleus interaction asymmetry

$$
\begin{aligned}
\frac{d^2\sigma}{d\cos\theta\, d\omega} = \ & \frac{G_F^2 \cos^2\theta_c}{\pi} |\mathbf{k}'| E_l' \cos^2\frac{\theta}{2} \left[\frac{(\mathbf{q}^2 - \omega^2)^2}{\mathbf{q}^4} G_E^2\, R_\tau(\mathbf{q},\omega) \right. \\
& + \frac{\omega^2}{\mathbf{q}^2} G_A^2\, R_{\sigma\tau(L)}(\mathbf{q},\omega) \\
& + 2\left(\tan^2\frac{\theta}{2} + \frac{\mathbf{q}^2 - \omega^2}{2\mathbf{q}^2}\right) \left(G_M^2 \frac{\mathbf{q}^2}{4M_N^2} + G_A^2\right) R_{\sigma\tau(T)}(\mathbf{q},\omega) \\
& \pm 2\frac{E_\nu + E_l'}{M_N} \tan^2\frac{\theta}{2} G_A G_M\, R_{\sigma\tau(T)}(\mathbf{q},\omega) \left. \vphantom{\frac{(\mathbf{q}^2)^2}{\mathbf{q}^4}} \right]
\end{aligned}
$$

ETH zürich   T2K

Joint $\nu_\mu / \overline{\nu}_\mu$ cross section measurement

- Simultaneous fit to $\nu_\mu / \overline{\nu}_\mu$ events (off-axis only)

- MC overestimates cross section in forward direction at medium momentum

- MC underestimation in for high angles and low momentum

- No model describes the data well

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Measurement

- Joint $\nu_\mu / \overline{\nu}_\mu$ cross section measurement on carbon

- **Charged current with zero pions in the final state**

- Using the T2K on- and off-axis near detectors

Signal Definition

Interaction Modes
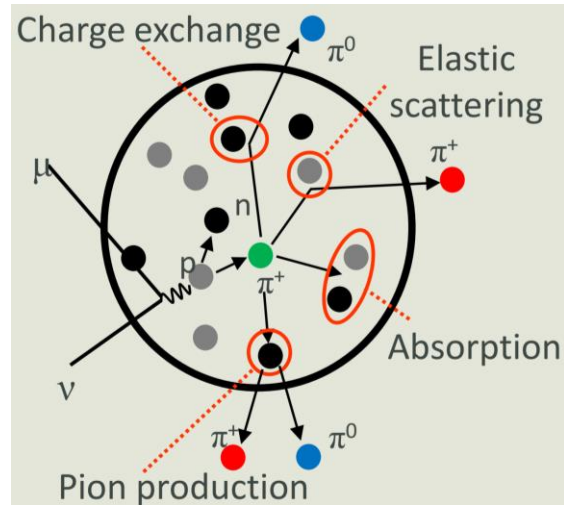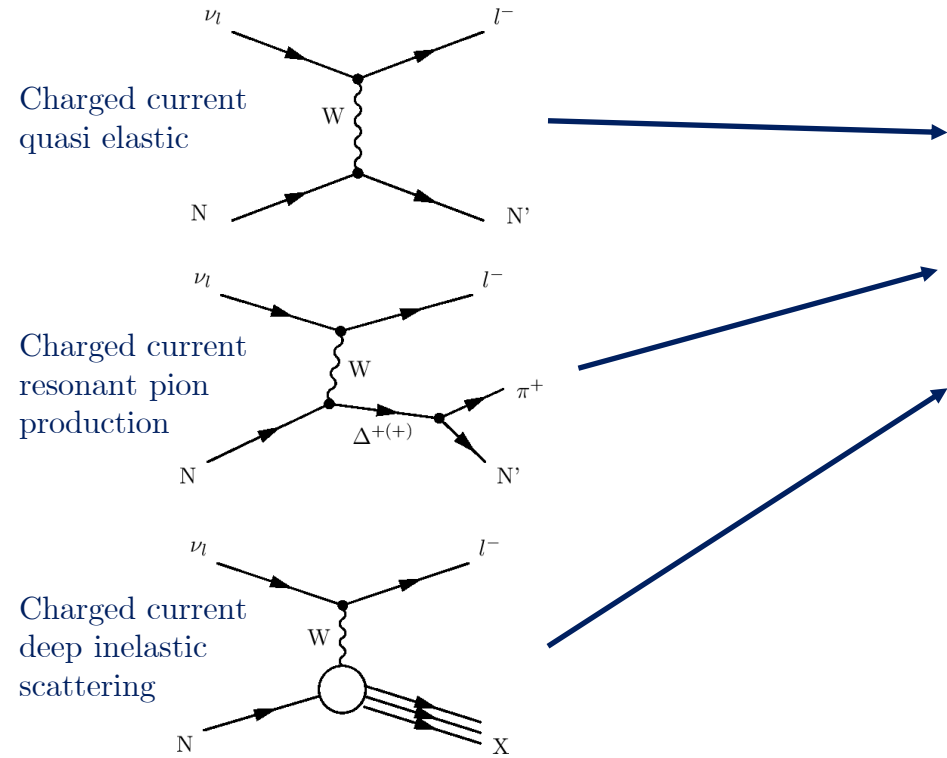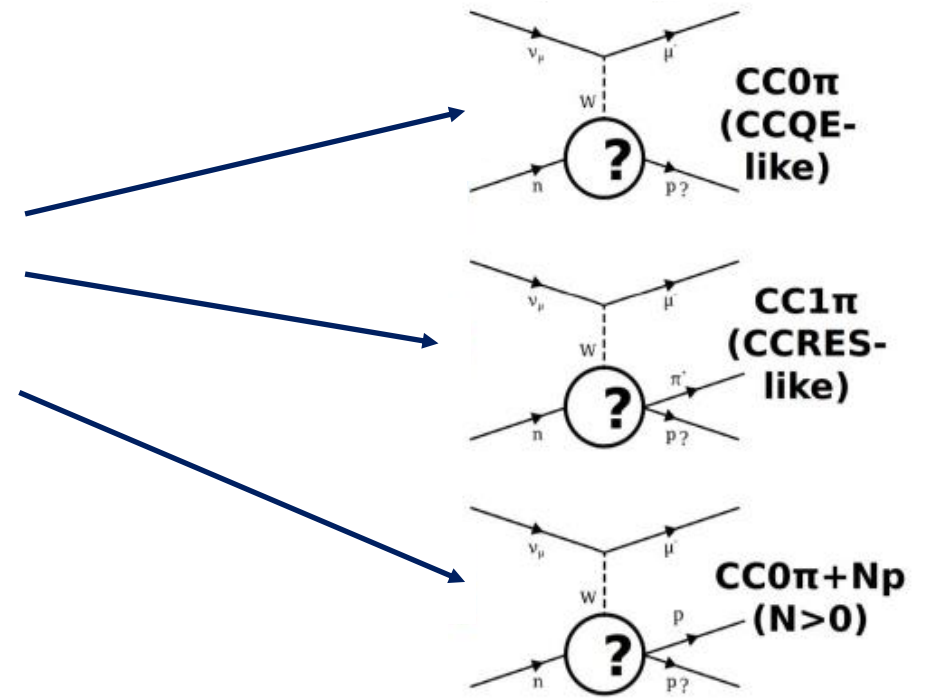
- Underlying interaction is obfuscated by nuclear effects and final state interactions
- Need model independent samples using final state signals
  - CC0π: 1 muon, 0 pions
  - most CCQE-like signal (most important channel for T2K)
- Increased detector acceptance of signal

Cross Section Extraction

Number of signal events from statistical fit
(includes background constraints and unfolding)

Differential cross section
as a function of kinematic
variable x in truth bin i

$$\frac{d\sigma}{dx_i} = \frac{N_i}{\epsilon_i \; T \; \Phi \; \Delta x_i}$$

Bin width correction

Efficiency correction in
analysis binning

Number of target nuclei

Integrated flux at
detector

Measurement

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- Charged current with zero pions in the final state

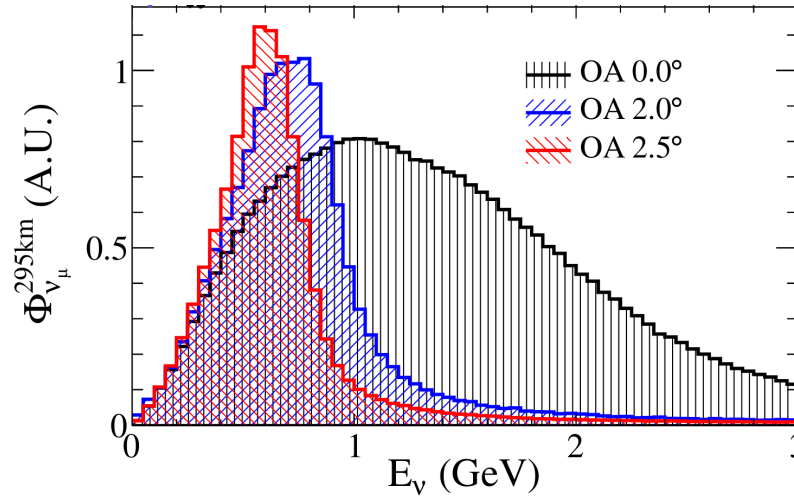- Using the T2K on- and off-axis near detectors
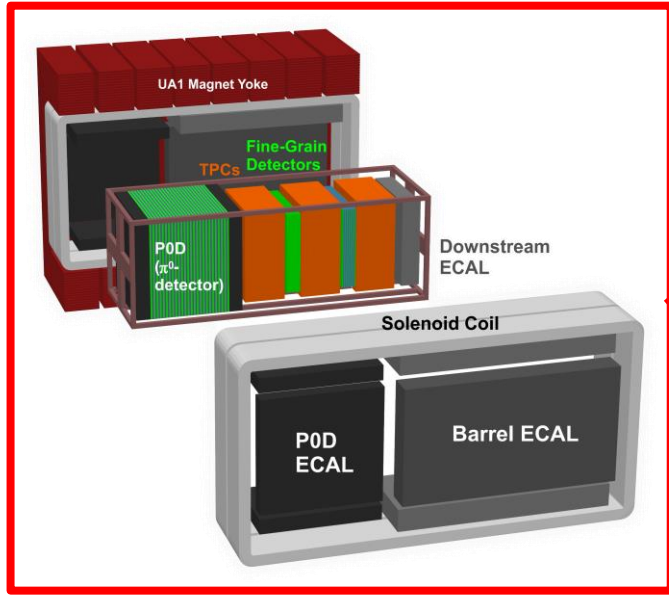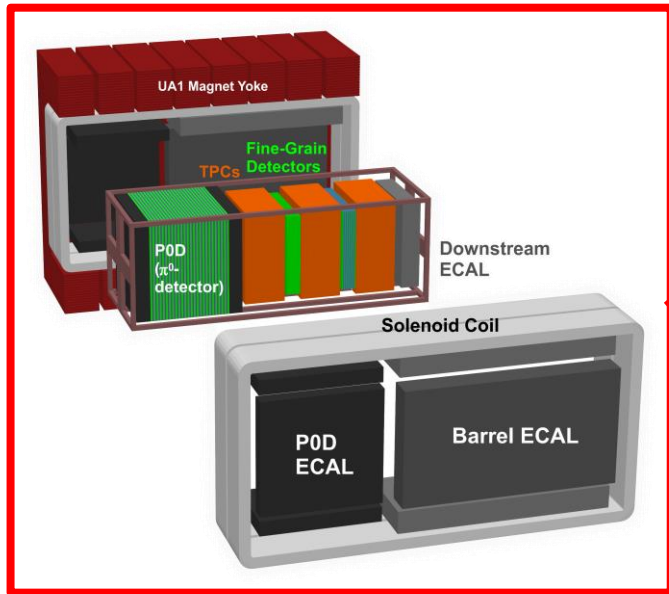
The Near Detectors
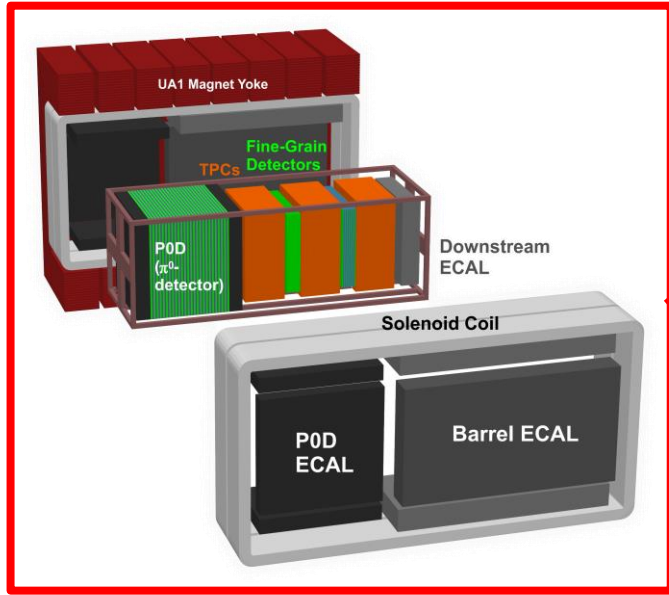
ND280 off-axis

INGRID on-axis
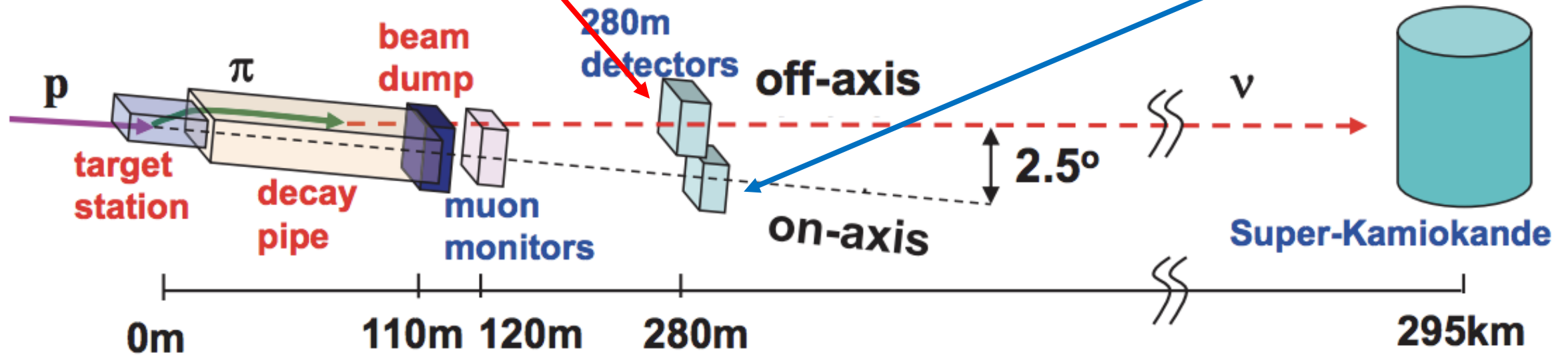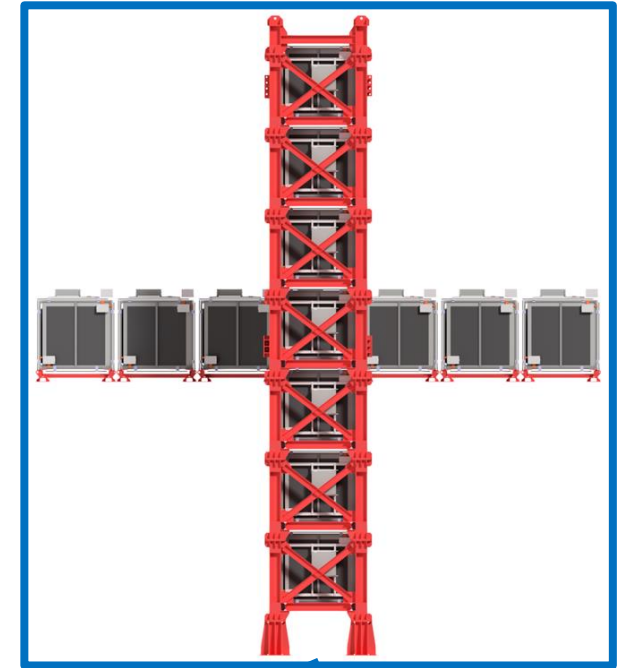
The Near Detectors
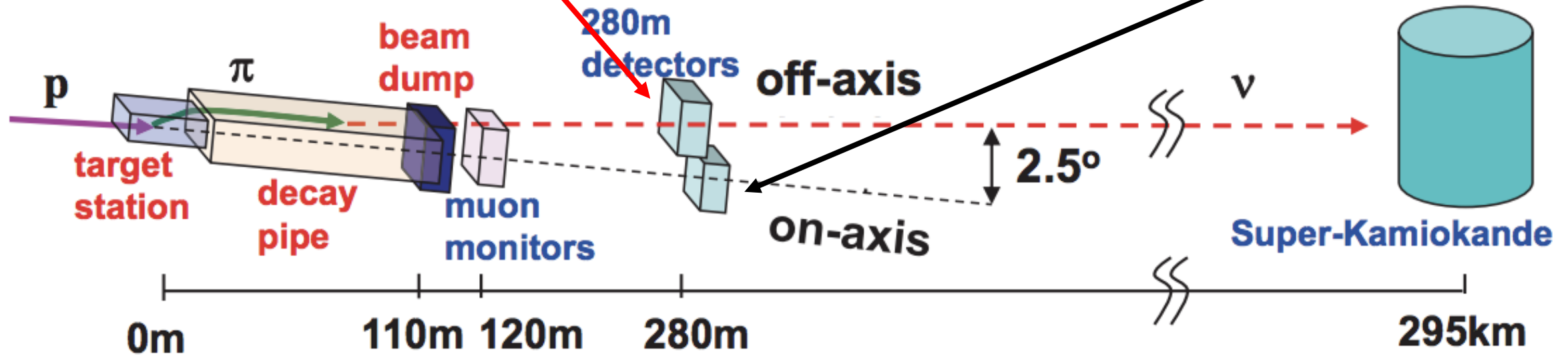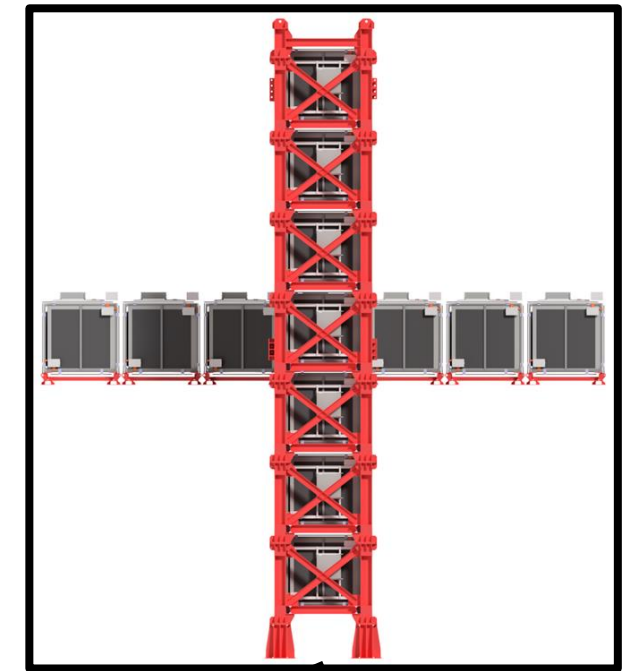
The Near Detectors


- ND280: the off-axis near detector
- Situated 280 m from the target station
- Fully magnetized detector
  - Can differentiate between $\nu/\overline{\nu}$
- 2 fine-grained detectors (FGDs) act as target for neutrinos
- 3 argon time projection chambers (TPCs) act as tracker and measure particle momentum and charge
- Detector encased in electromagnetic calorimeters (Ecals)
- Goals: Measure unoscillated neutrino spectrum and neutrino-nucleus cross sections
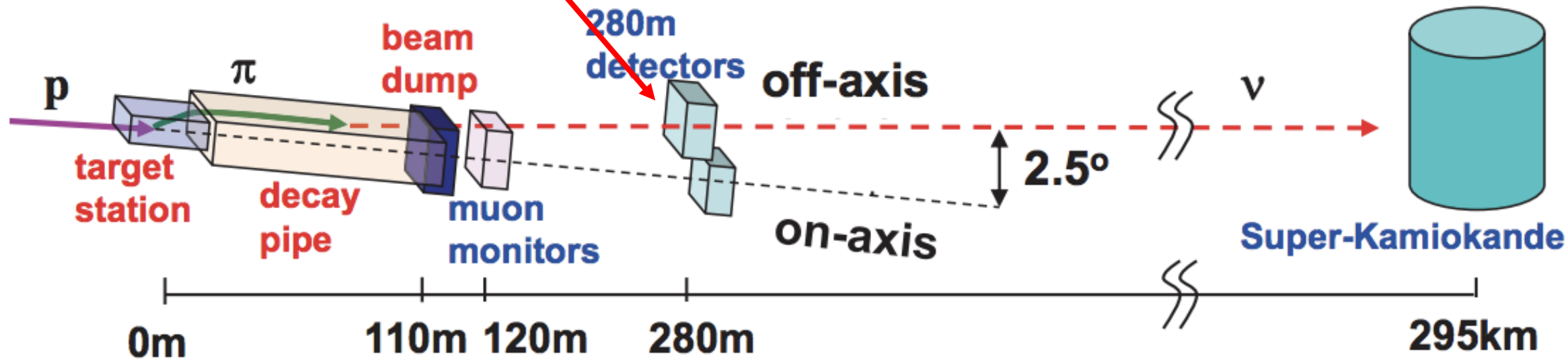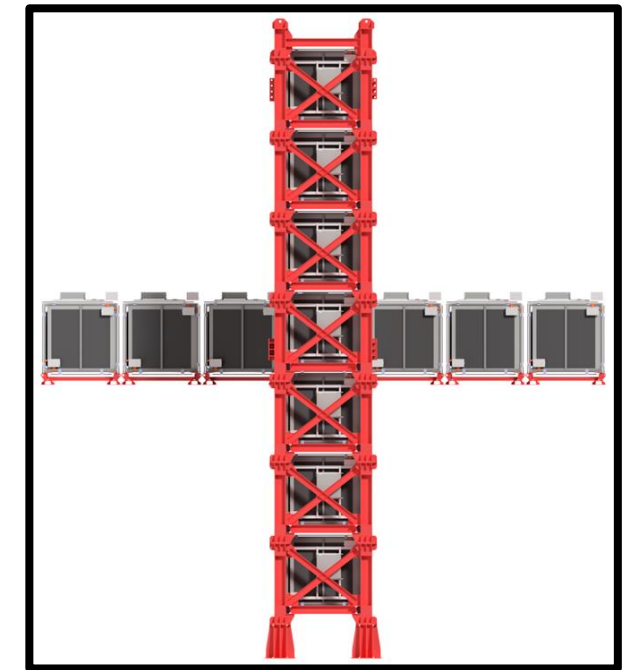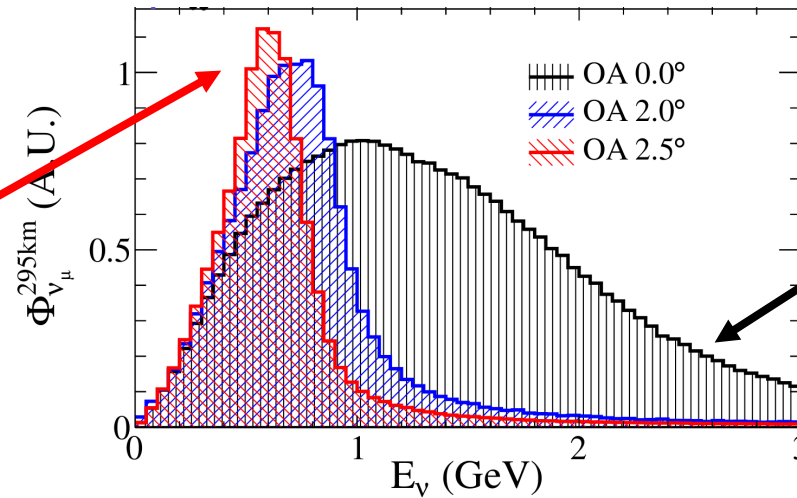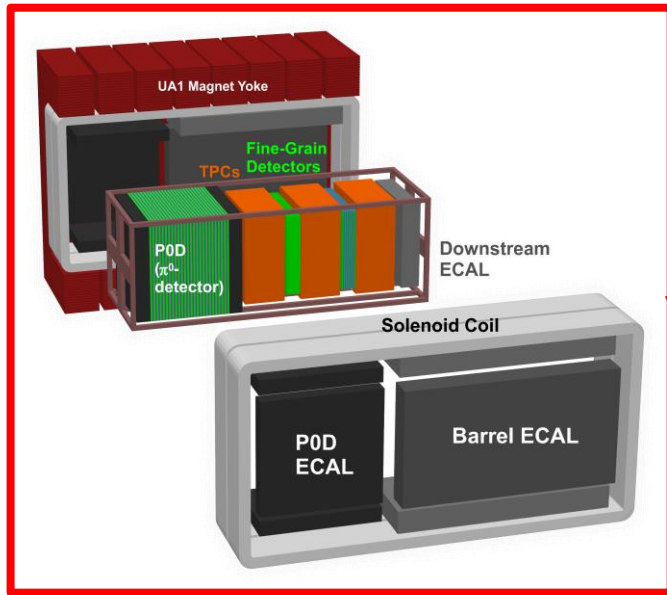
The Near Detectors

- INGRID: the on-axis detector
- Consists of 14 identical modules arranged in a cross
- Each module consists of sandwiched iron plates and tracking scintillator plates
- Goals: measure neutrino beam profile and neutrino-nucleus cross sections
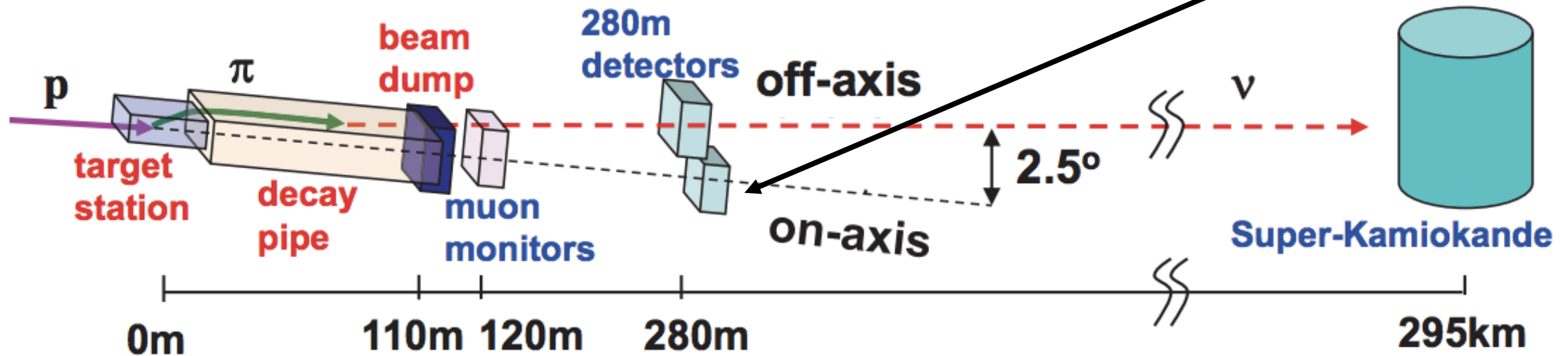
The Near Detectors

- Study cross section as a function of neutrino energy
- Measured ν interaction rate is product of flux and cross section → Degeneracy
- Difference in flux at the 2 near detectors can break this degeneracy
- Fluxes between detectors are correlated → Reduction of the flux uncertainty in the analysis
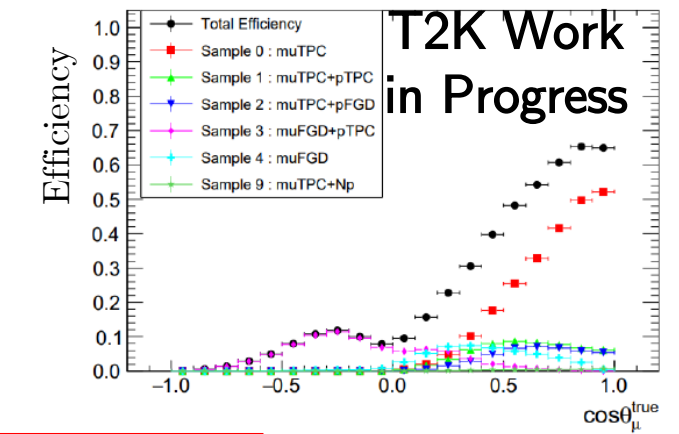- Important step towards planned future multi-axis measurements with Hyper-K, DUNE
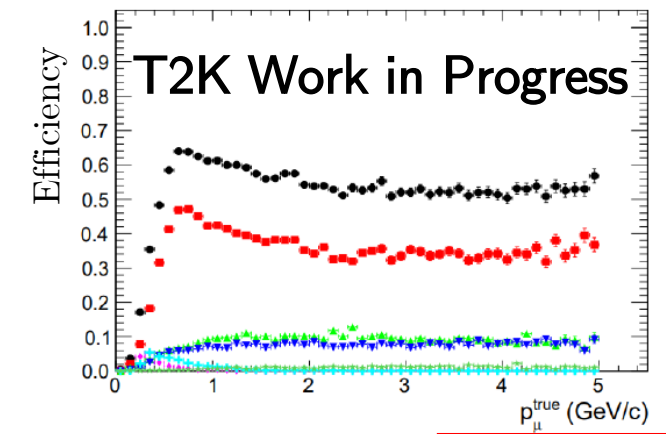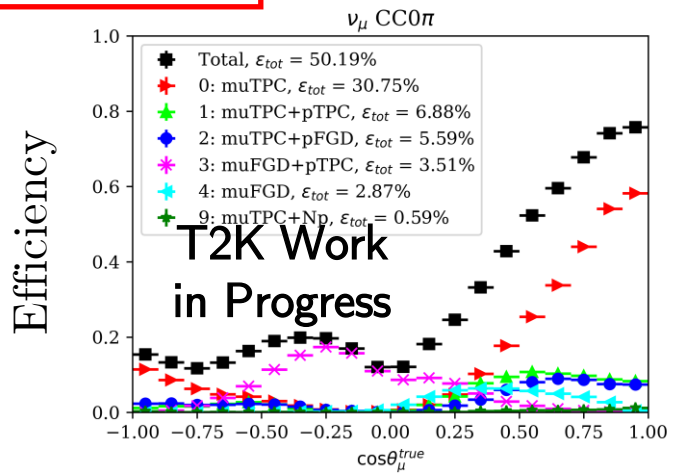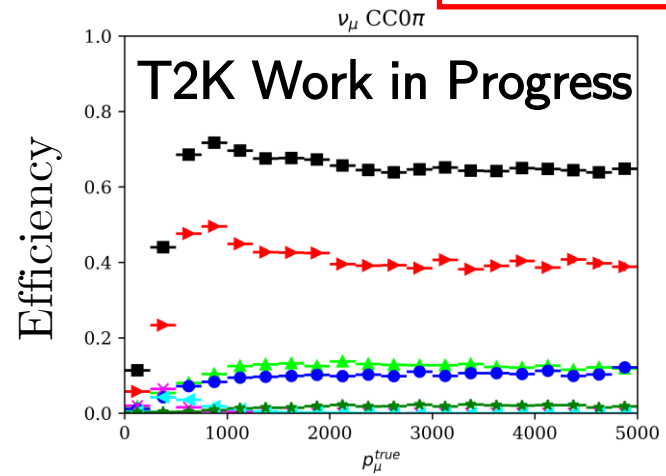
Event Selection

- Strategy: define multiple samples and bin events in outgoing muon momentum and angle

Signal

Sidebands: used to constrain fit parameters and break degeneracies
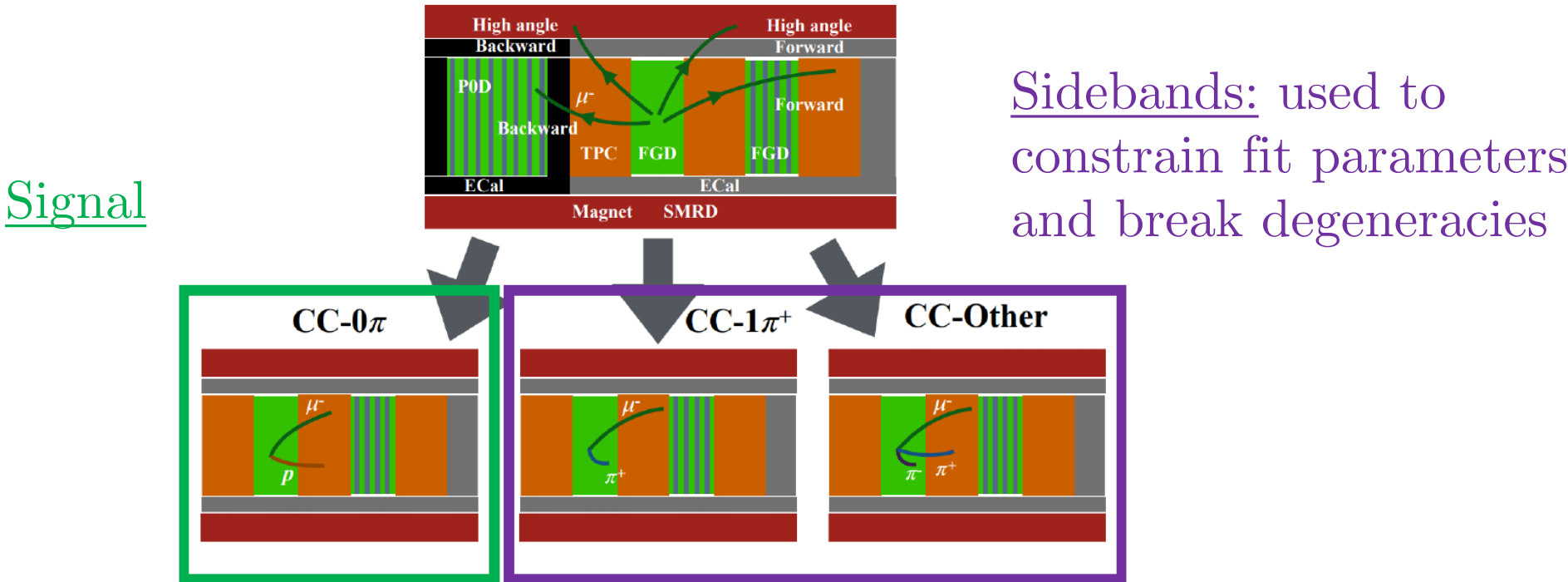
Event Selection - Improvements

New selection

Off-axis ν_μ Selection
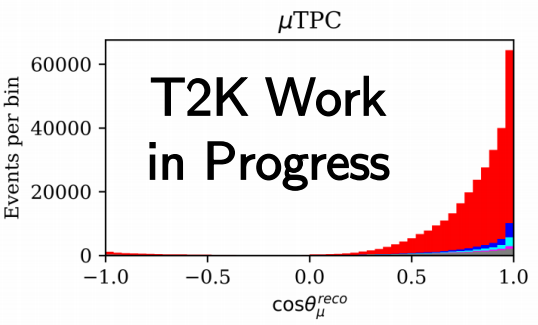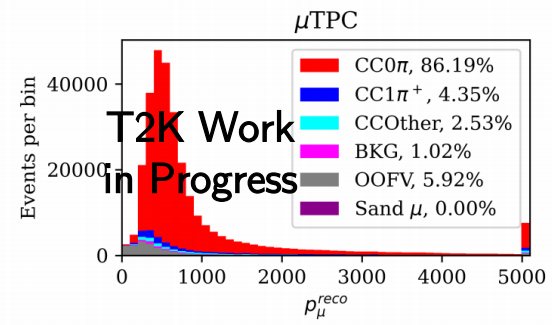
Off-axis $\overline{\nu}_\mu$ Selection

Previous selection
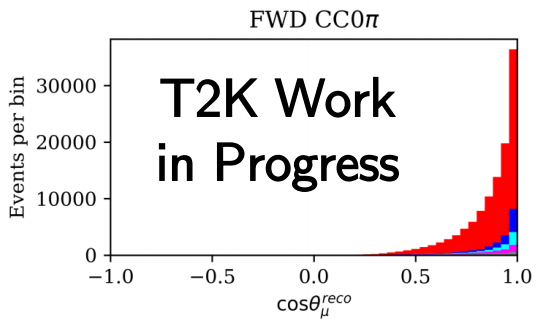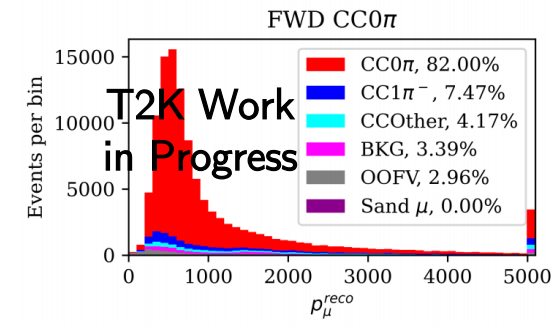
- Very similar purity for previous and improved selection
- But efficiency is greatly improved for high angle and backwards going tracks

Summary

- Joint measurements are the future of T2K's cross section group
- First doubly-joint cross section measurement at T2K is being completed
    - Multiple detectors
    - ν_μ and $\overline{\nu}_\mu$
- Working on minimizing model dependence and gain better handle on systematic uncertainties
- So far, all theoretical models hard pressed to accurately predict multiple data sets
- Further improvements from upgrade of ND280 planned in 2022

THANK YOU!