Measurements at the Water Cherenkov Test Experiment in support of T2K & SK

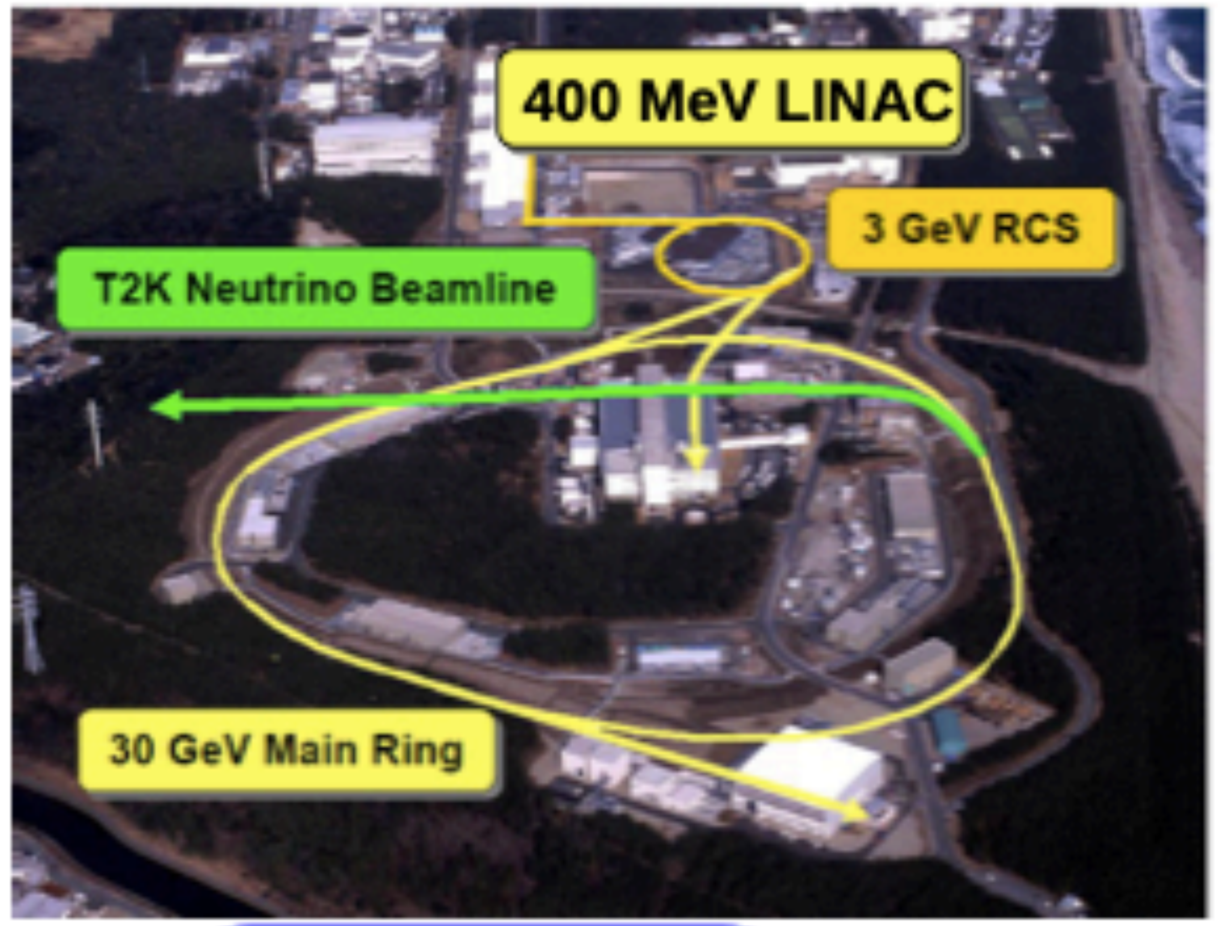
Mark Hartz

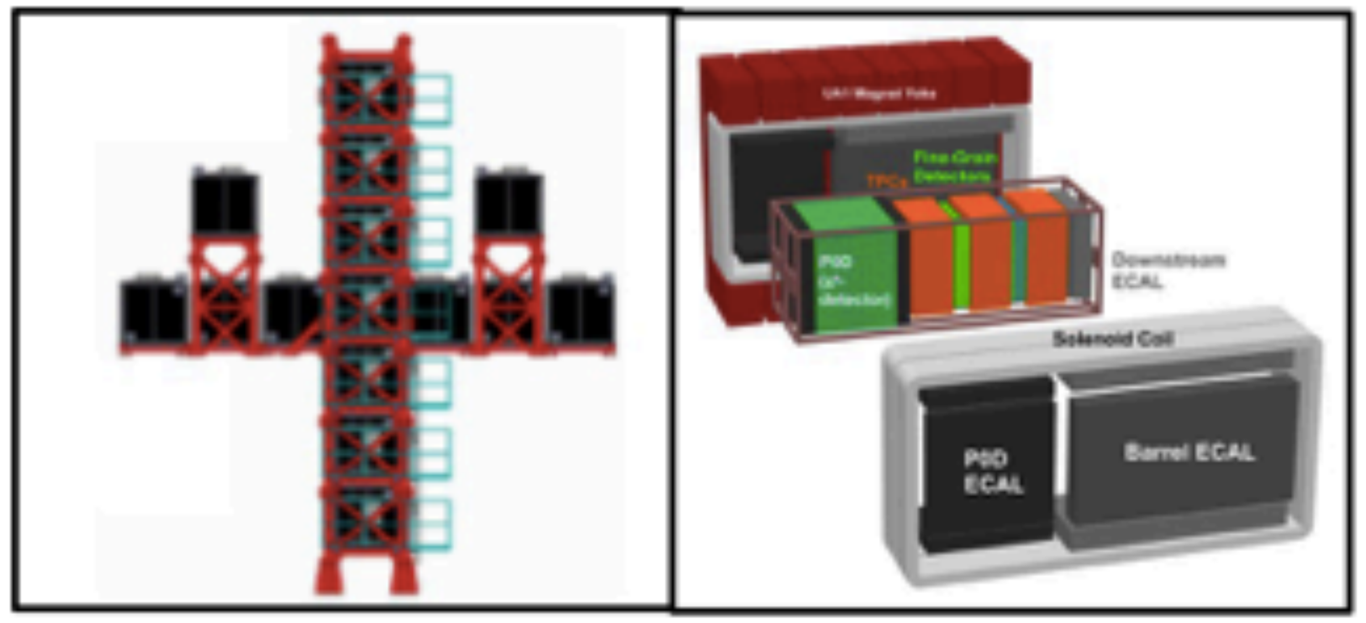
WCTE Workshop, 2020/11/23

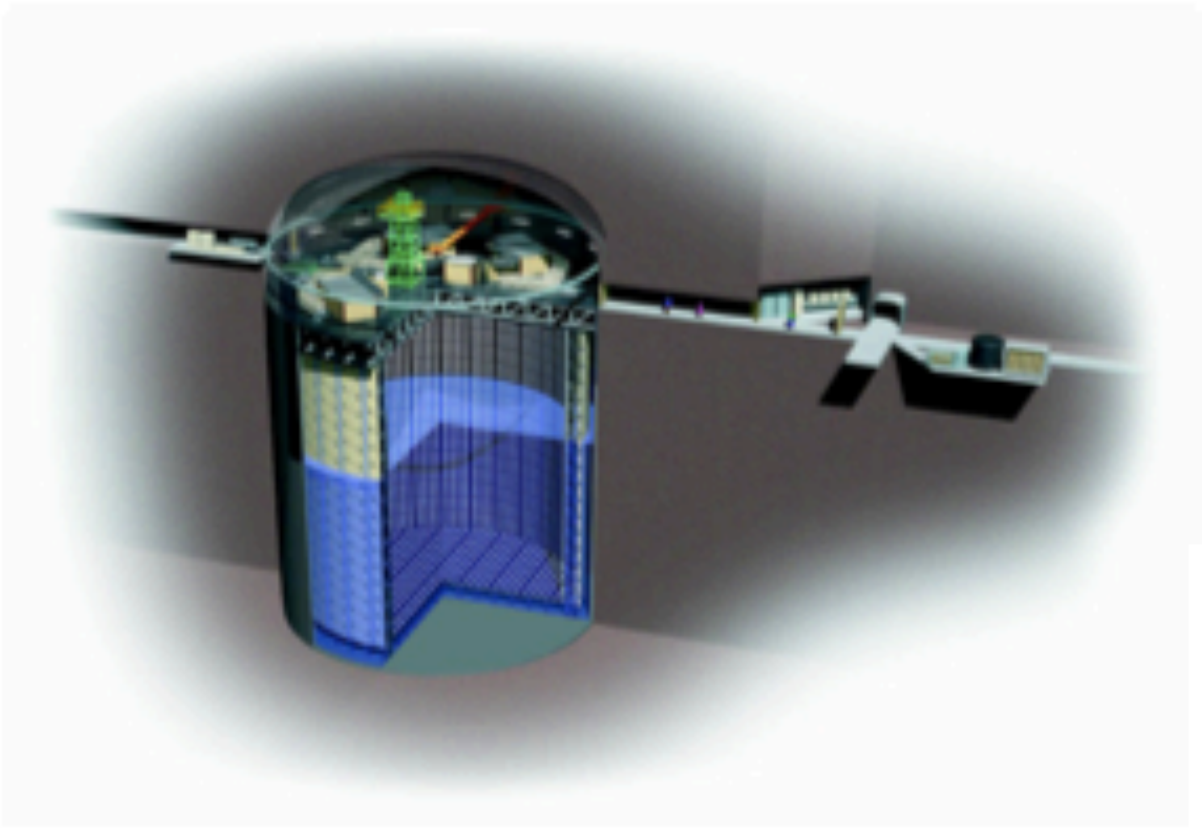
Outline

- Overview of oscillation measurements at T2K and SK
- Motivation of measurements related to secondary neutron production
- Motivation of measurements related to secondary pion interactions

T2K Overview







J-PARC accelerator complex and neutrino beamline

ν_μ

2.5°

On-axis: INGRID

Off-axis: ND280

ν_μ

Super-Kamiokande

0

280m

295 km

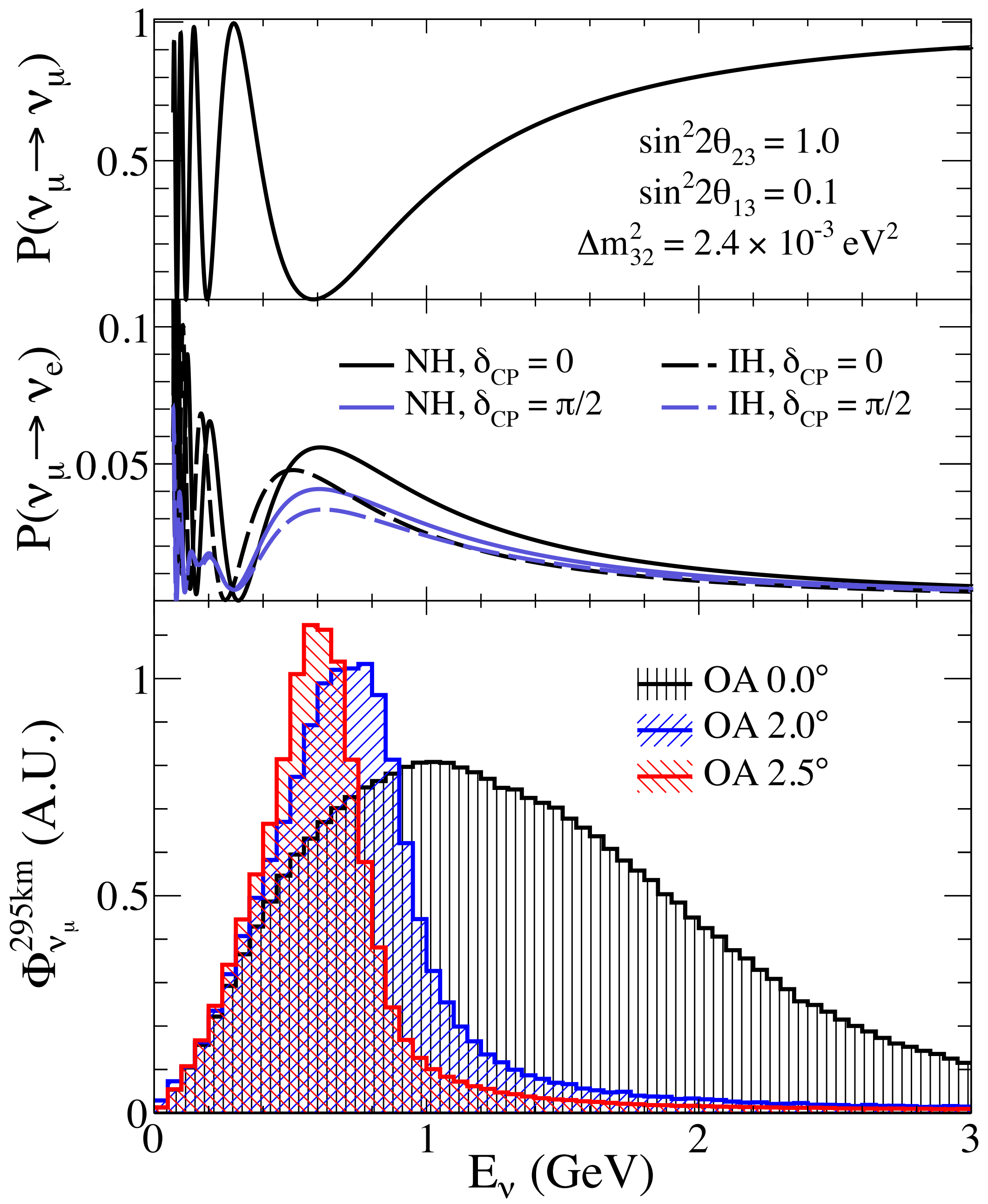
ν production

Near detectors

Far detector

- Characterise ν beam
- Constrain systematic uncertainties

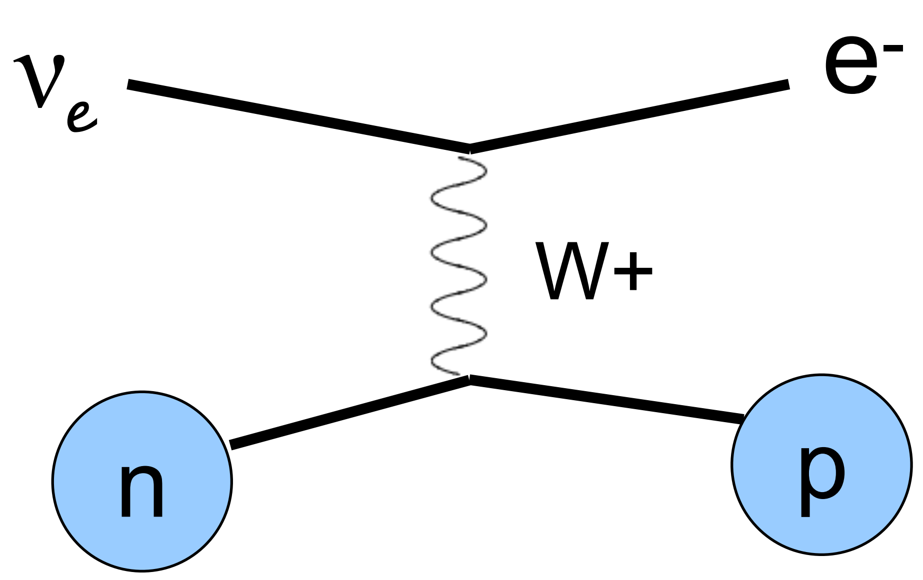
Study ν oscillations



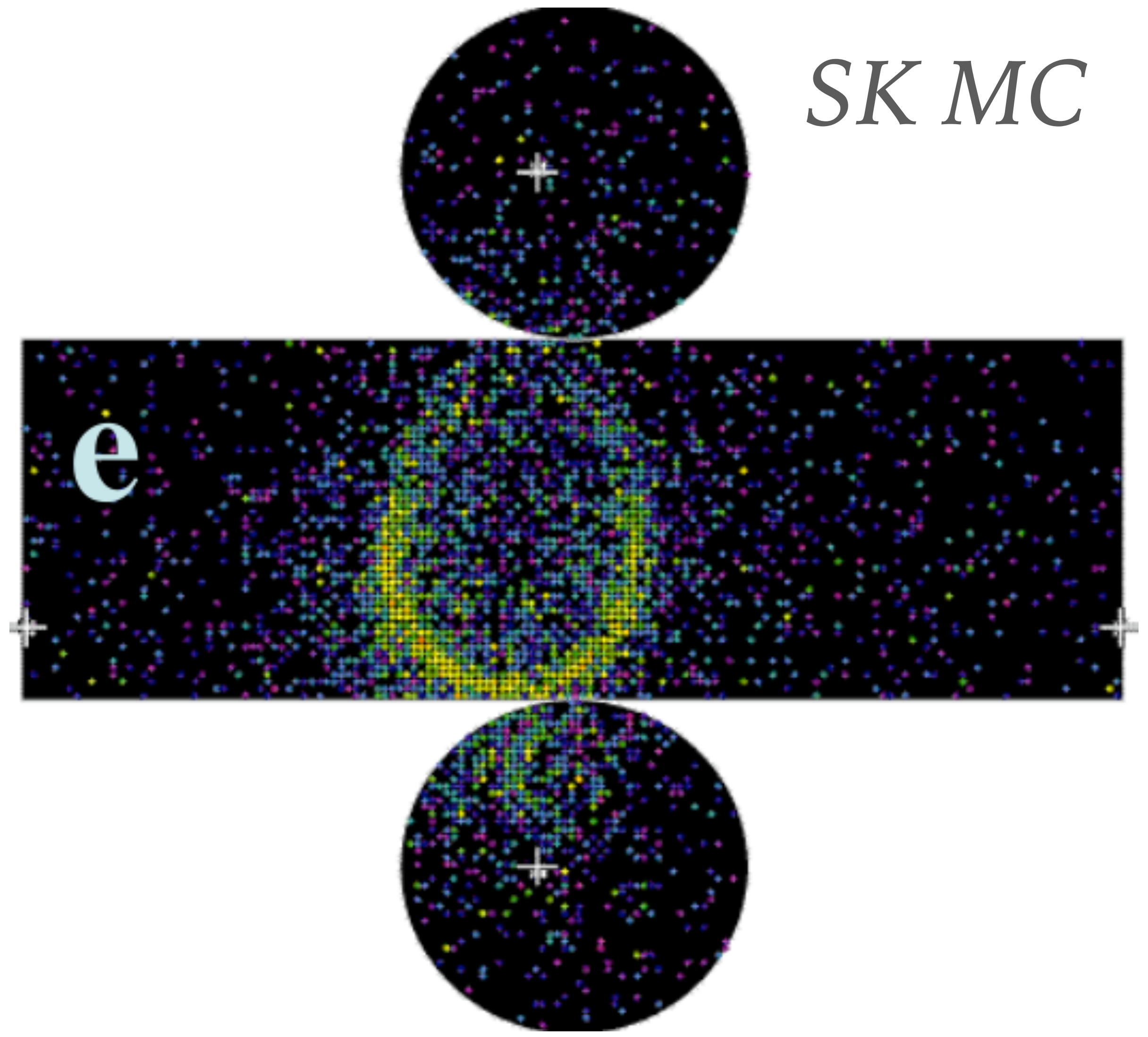
Off-axis beam

Neutrino Detection at Super-K (Single Ring)

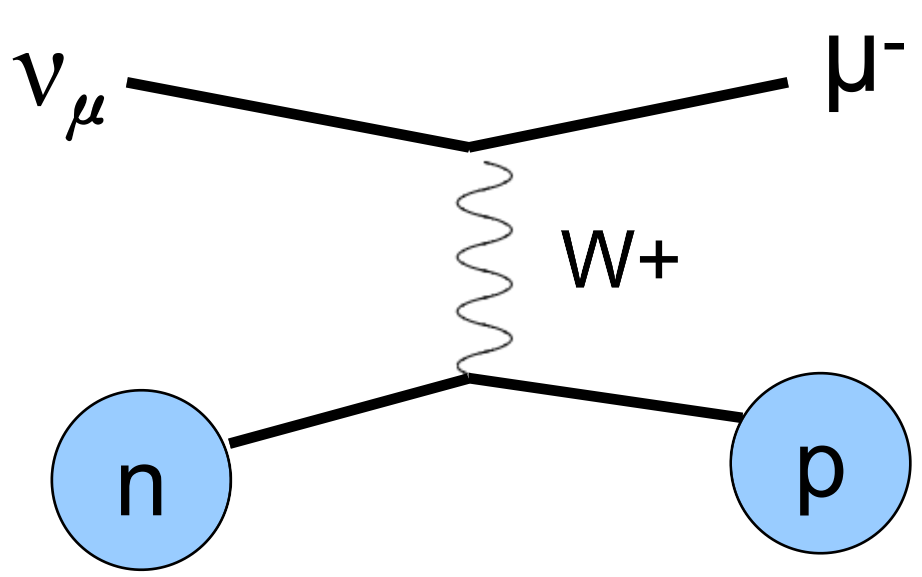
Electron neutrino appearance signal:



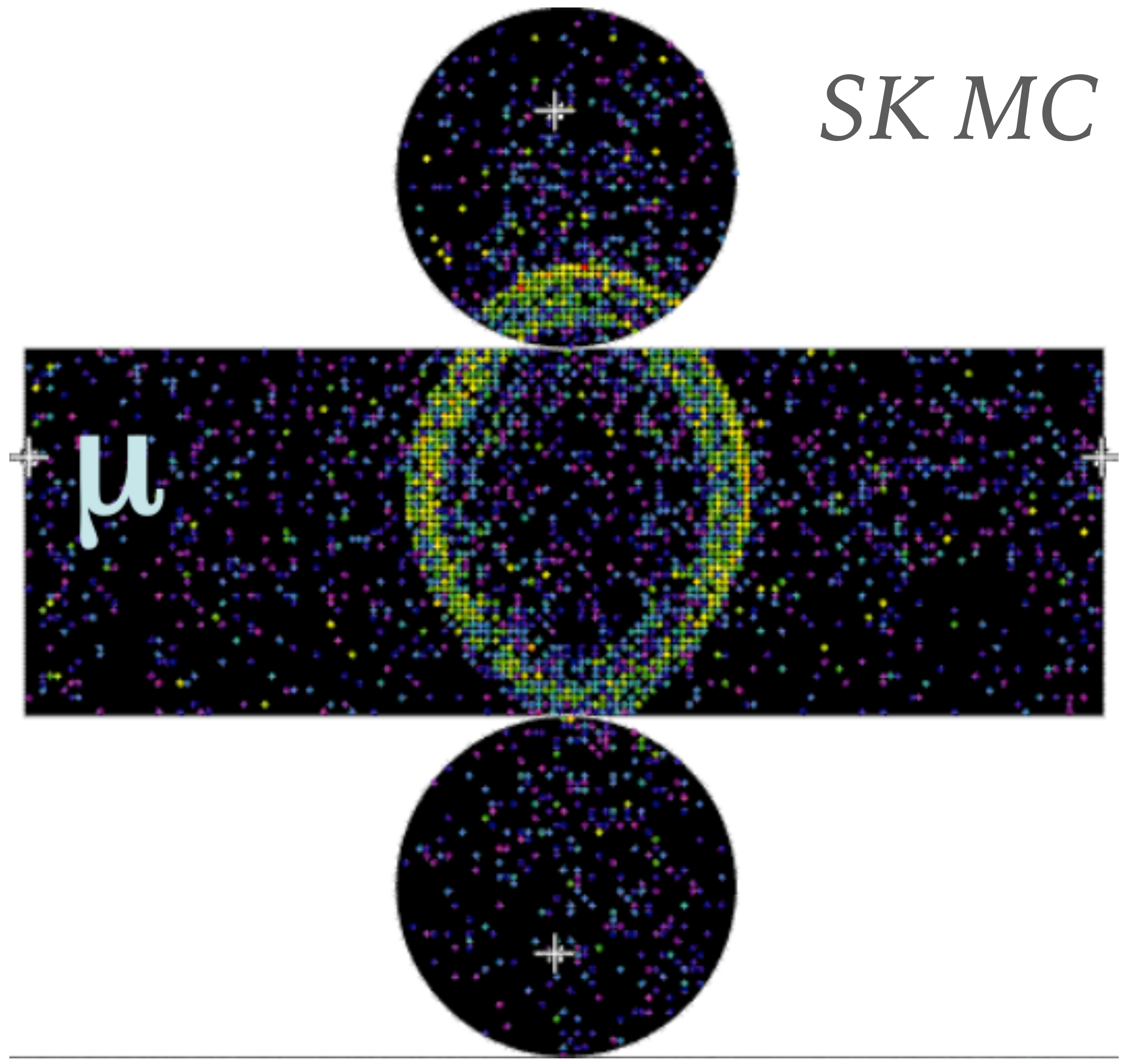
Detected electron produces a shower: "fuzzy" ring



Muon neutrino survival signal:

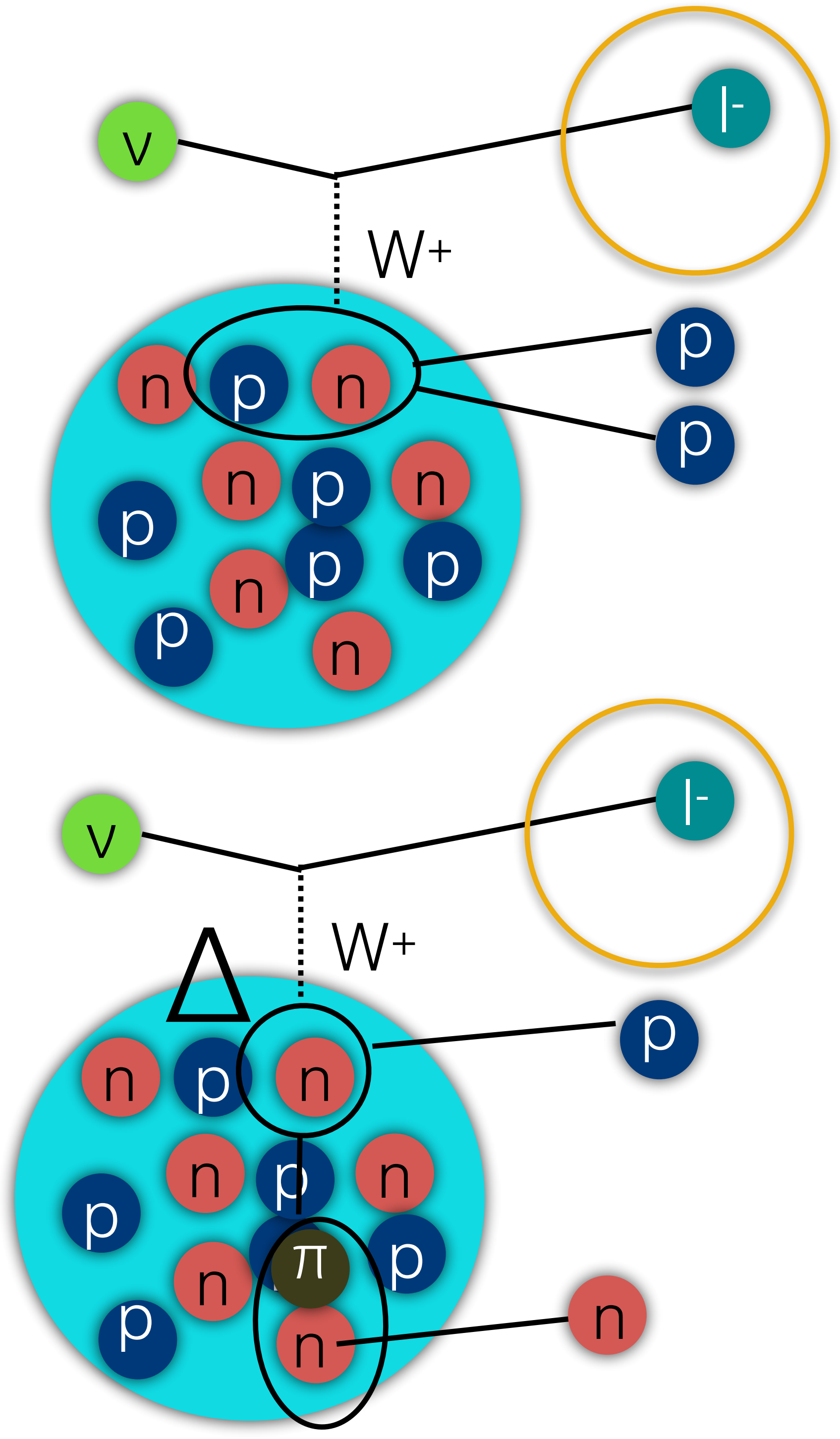


Detected muon produces a sharp ring



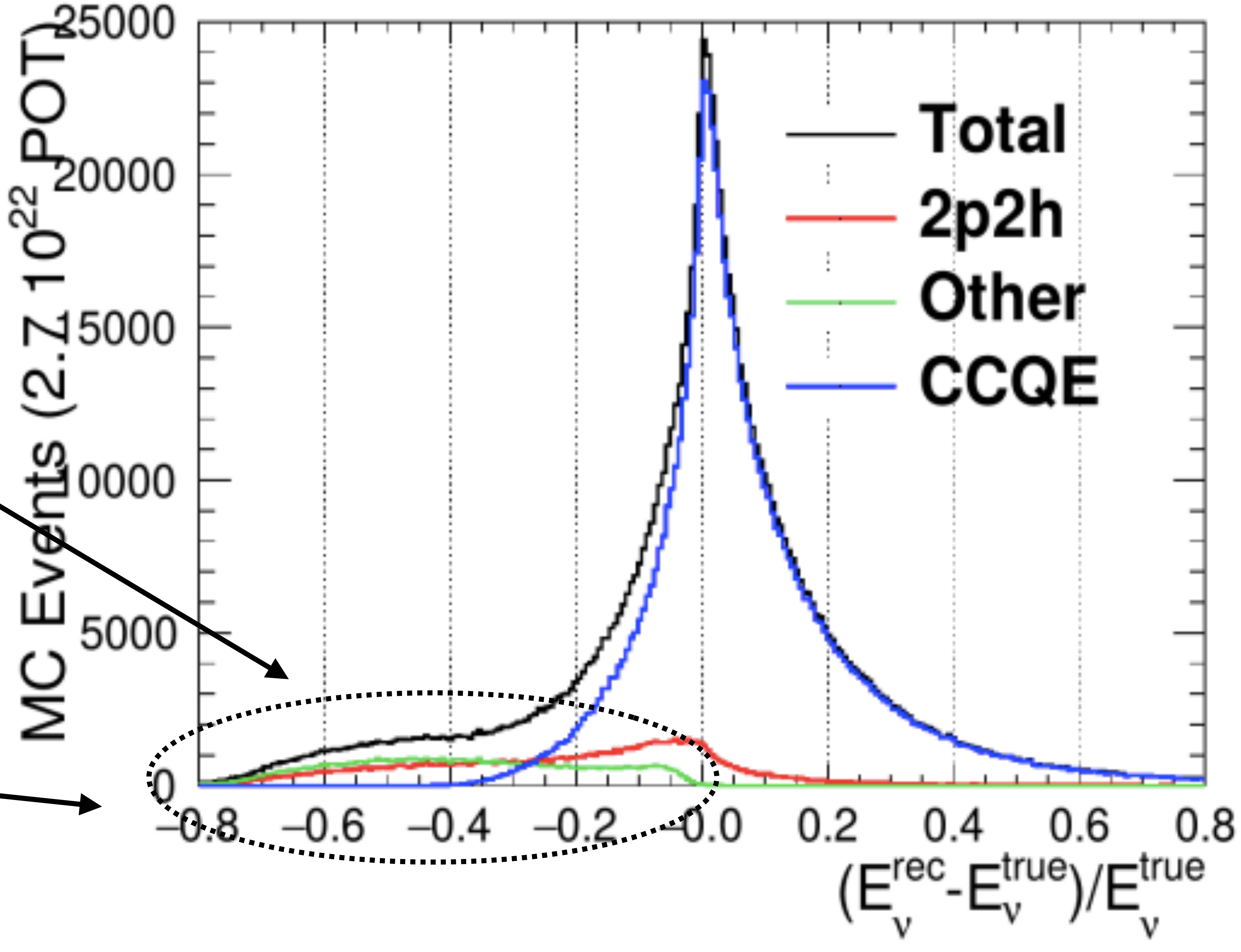
Challenge of Energy Reconstruction

- Oscillations depend on neutrino energy
- We must infer neutrino energy from particles we observe in detectors
- If we make the quasi-elastic assumption, inferred energy will be biased for other processes



Scattering on correlated pairs of nucleons "multi-nucleon or 2p-2h"

Pion production, where pion is absorbed in nucleus



Samples in T2K Analysis

Neutrino Mode (forward horn current FHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

(CCQE) 1 Electron-like Ring, 0 decay electrons

(CC1π) 1 Electron-like Ring, 1 decay electron

Antineutrino Mode (reverse horn current RHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

(CCQE) 1 Electron-like Ring, 0 decay electrons

$$\nu_\mu(\bar{\nu}_\mu) + N \to \mu^-(\mu^+) + X$$

$$\downarrow$$

$$e^-(e^+) + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

$$\nu_e(\bar{\nu}_e) + N \to e^-(e^+) + X$$

$$\nu_e + N \to e^- + \pi^+ + X$$

$$\downarrow$$

$$\mu^+ + \nu_\mu$$

$$\downarrow$$

$$e^+ + \nu_e + \bar{\nu}_\mu$$

○ = *detected particles*

Samples in T2K Analysis

Neutrino Mode (forward horn current FHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

(CCQE) 1 Electron-like Ring, 0 decay electrons

(CC1π) 1 Electron-like Ring, 1 decay electron

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X$$

$$e^-(e^+) + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

$$\nu_e(\bar{\nu}_e) + N \rightarrow e^-(e^+) + X$$

Antineut

(CCQE)

(CCQE)

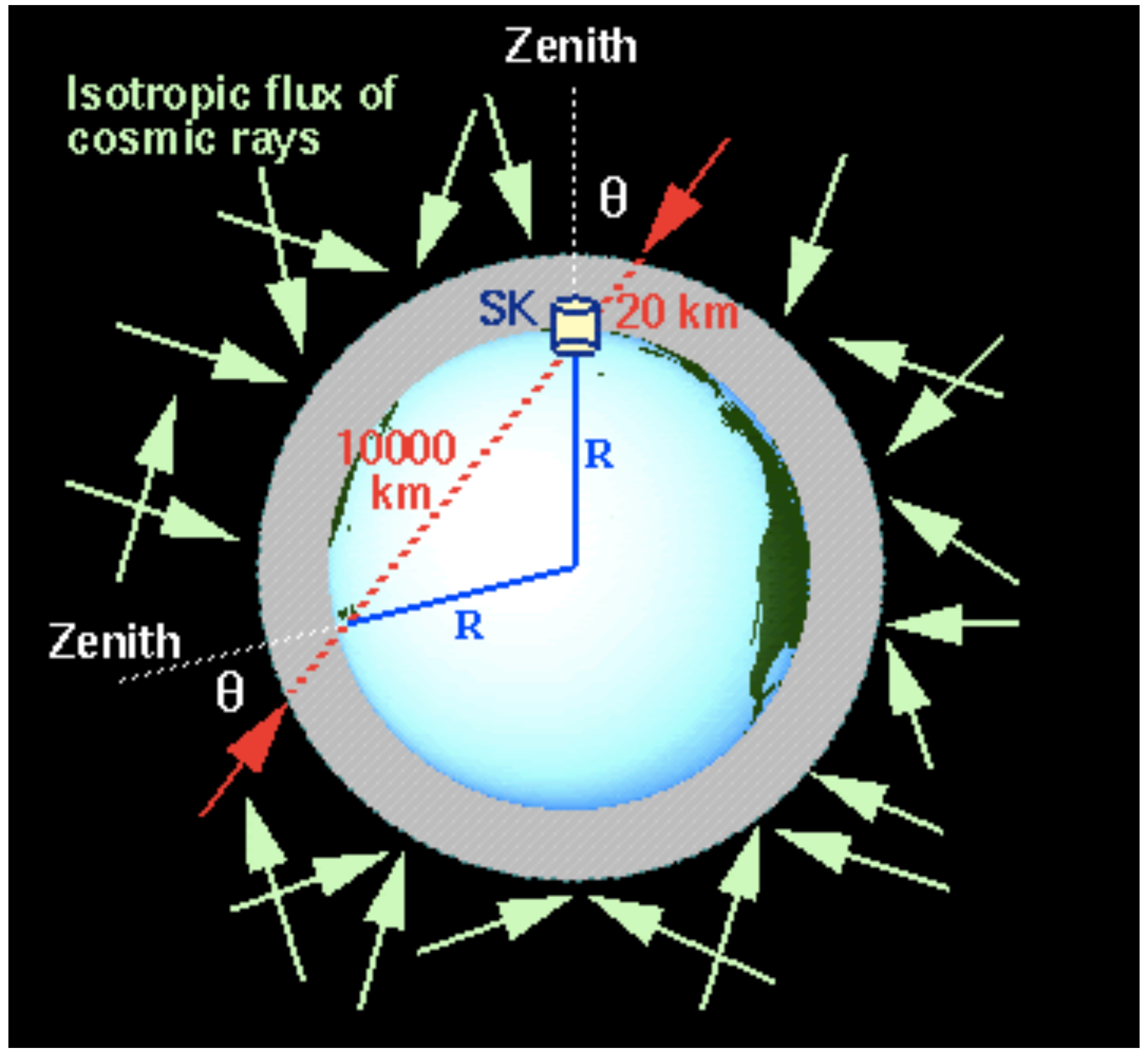
T2K, Neutrino 2020

Table 21: Uncertainty on the number of event in each SK sample broken by error source before the BANFF fit.

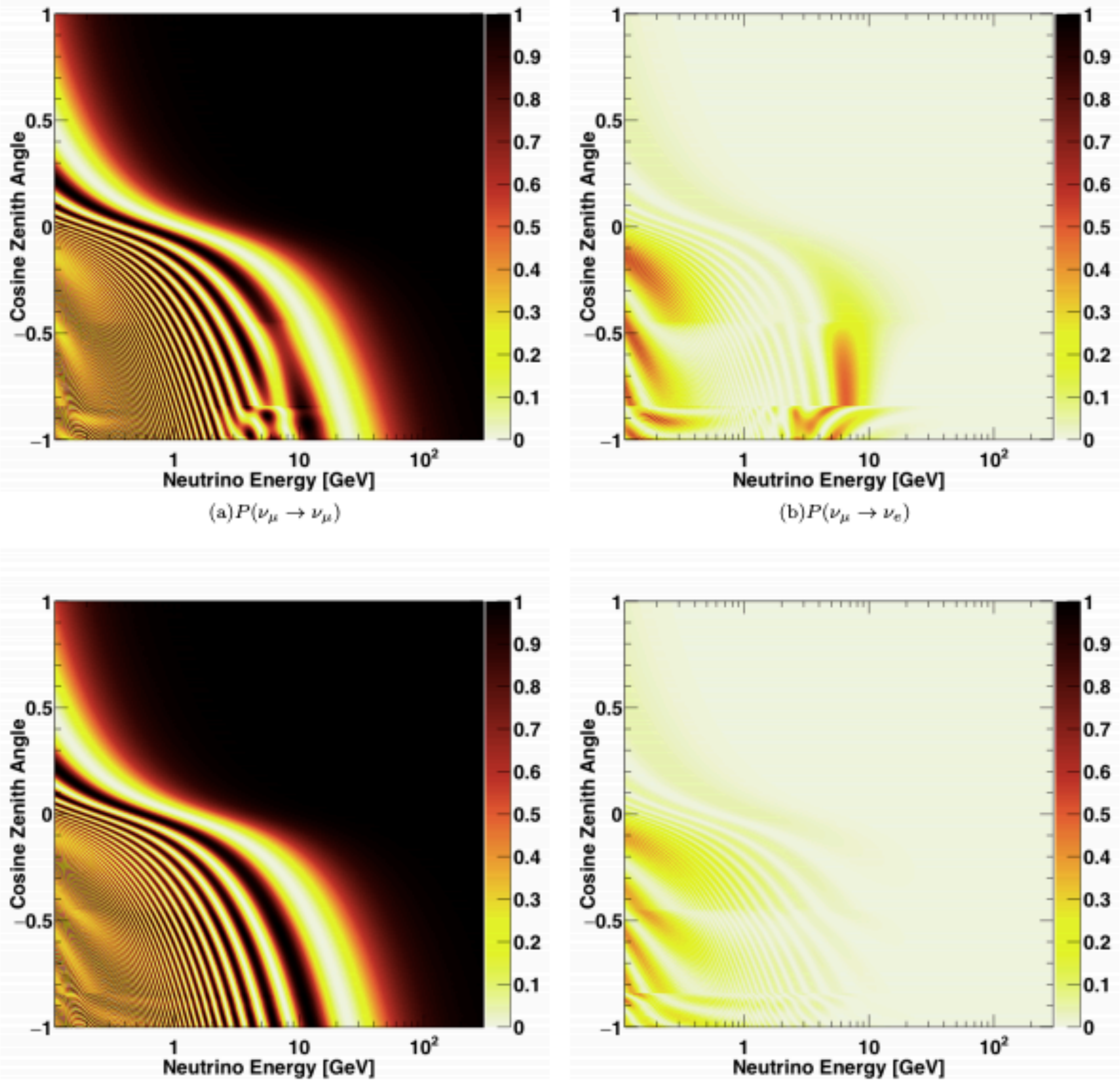
Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π+	1Re FHC/RHC
Flux	5.1%	4.7%	4.8%	4.7%	4.9%	2.7%
Cross-section (all)	10.1%	10.1%	11.9%	10.3%	12.0%	10.4%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%	1.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%	10.7%

Large detector model uncertainty on these undetected pions

Super-K Atmospheric Neutrino Measurements



Phys.Rev.D 97 (2018) 7, 072001



(a) $P(\nu_\mu \rightarrow \nu_\mu)$ (b) $P(\nu_\mu \rightarrow \nu_e)$ (c) $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ (d) $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

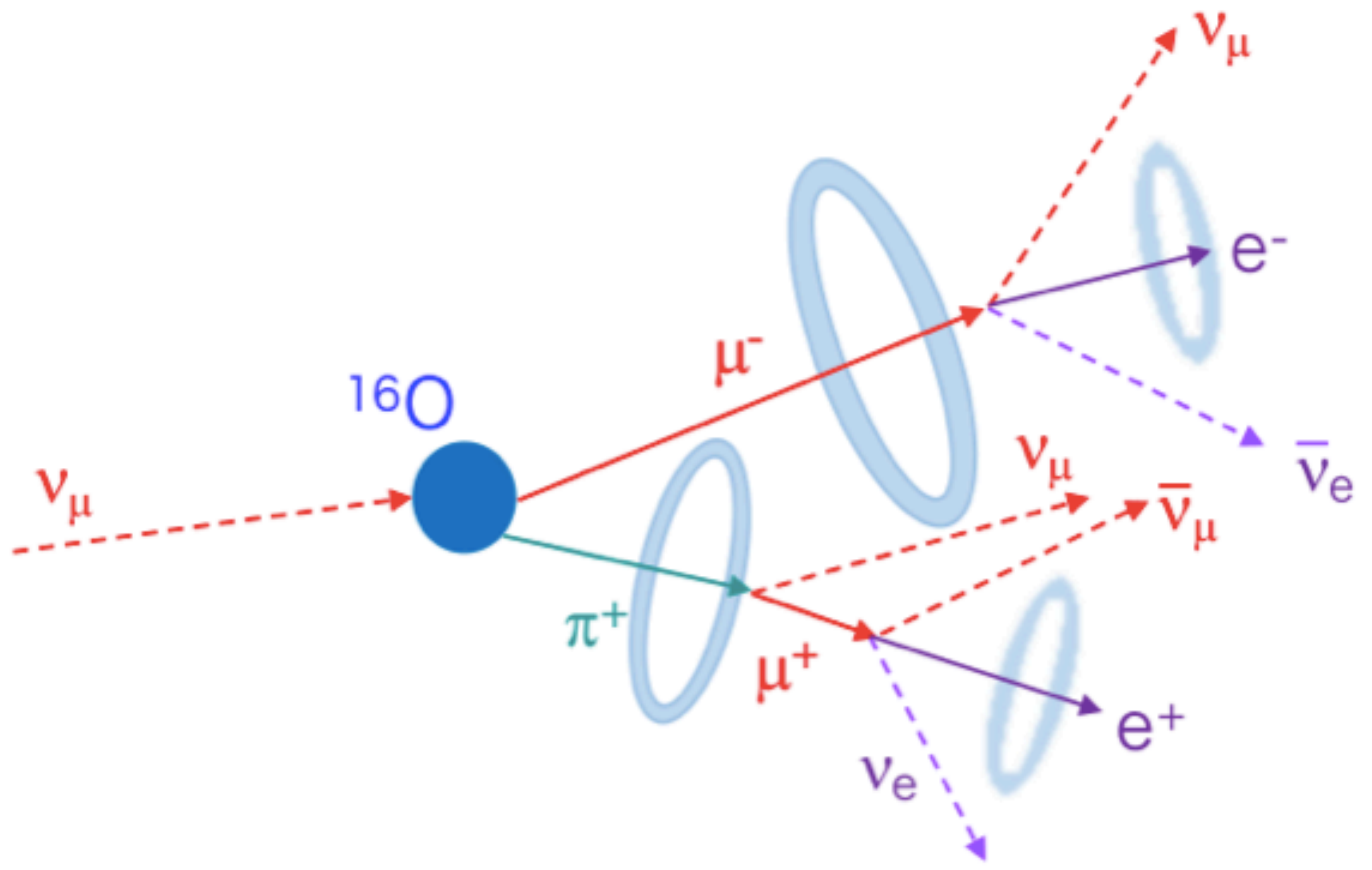
- Aim to measure oscillation patterns in zenith angle and neutrino energy
- Limited by resolution of zenith angle and neutrino energy due to undetected particles in hadronic recoils system
- Also limited by inability to clearly separate neutrinos and antineutrinos

Samples in Super-K Atmospheric Analysis

Phys.Rev.D 97 (2018) 7, 072001

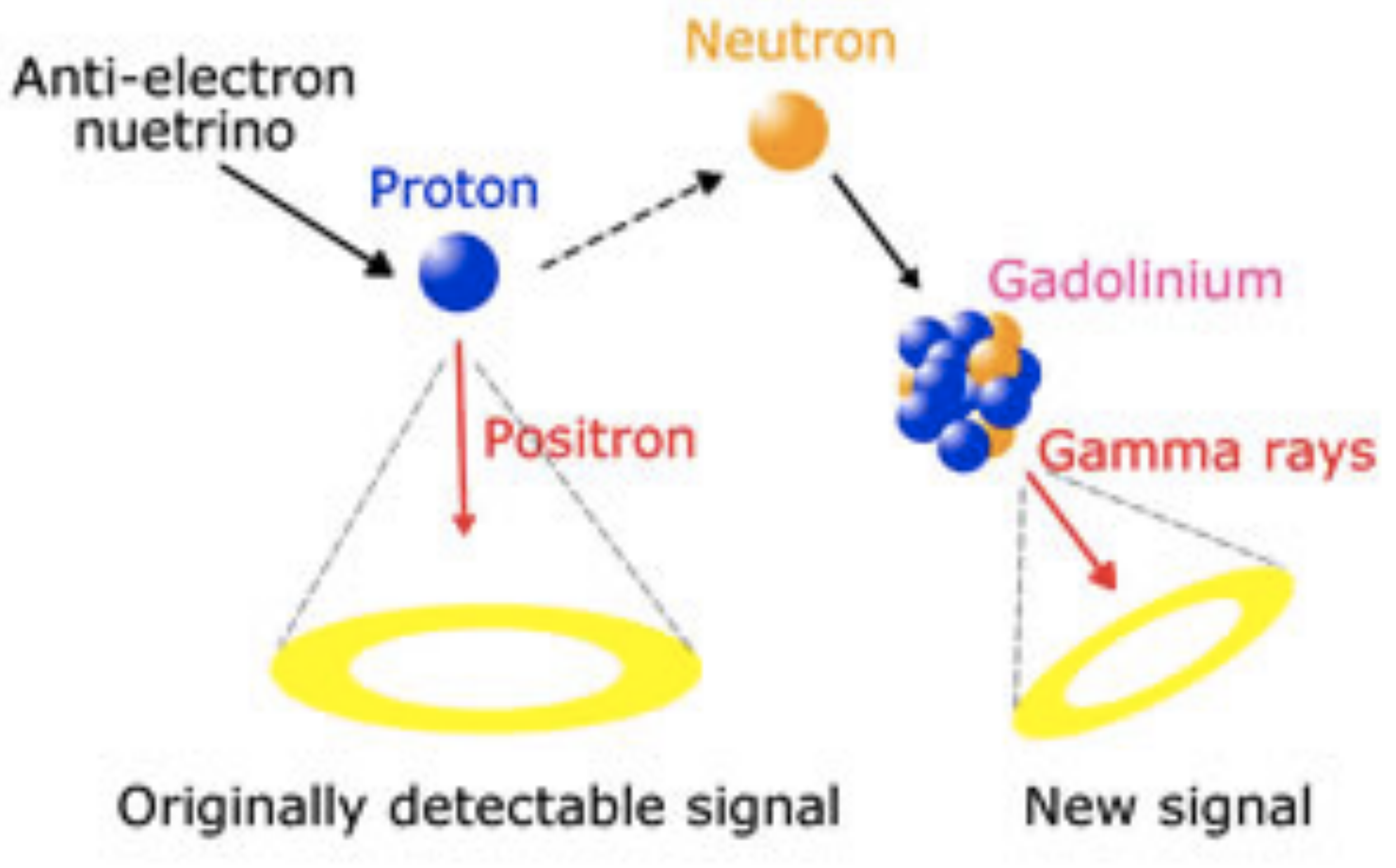
Sample	Energy bins	$\cos\theta_z$ bins	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	CC ν_τ	NC	Data	MC
Fully Contained (FC) Sub-GeV									
e-like, Single-ring									
0 decay-e	5 $e^\pm$ momentum	10 in $[-1, 1]$	0.717	0.248	0.002	0.000	0.033	10294	10266.1
1 decay-e	5 $e^\pm$ momentum	single bin	0.805	0.019	0.108	0.001	0.067	1174	1150.7
μ-like, Single-ring									
0 decay-e	5 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.041	0.013	0.759	0.001	0.186	2843	2824.3
1 decay-e	5 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.001	0.000	0.972	0.000	0.027	8011	8008.7
2 decay-e	5 $\mu^\pm$ momentum	single bin	0.000	0.000	0.979	0.001	0.020	687	687.0
π^0-like									
Single-ring	5 $e^\pm$ momentum	single bin	0.096	0.033	0.015	0.000	0.856	578	571.8
Two-ring	5 π^0 momentum	single bin	0.067	0.025	0.011	0.000	0.897	1720	1728.4
Multi-ring			0.294	0.047	0.342	0.000	0.318	(1682)	(1624.2)
Fully Contained (FC) Multi-GeV									
Single-ring									
ν_e-like	4 $e^\pm$ momentum	10 in $[-1, 1]$	0.621	0.090	0.100	0.033	0.156	705	671.3
$\bar{\nu}_e$-like	4 $e^\pm$ momentum	10 in $[-1, 1]$	0.546	0.372	0.009	0.010	0.063	2142	2193.7
μ-like	2 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.003	0.001	0.992	0.002	0.002	2565	2573.8
Multi-ring									
ν_e-like	3 visible energy	10 in $[-1, 1]$	0.557	0.102	0.117	0.040	0.184	907	915.5
$\bar{\nu}_e$-like	3 visible energy	10 in $[-1, 1]$	0.531	0.270	0.041	0.022	0.136	745	773.8
μ-like	4 visible energy	10 in $[-1, 1]$	0.027	0.004	0.913	0.005	0.051	2310	2294.0
Other	4 visible energy	10 in $[-1, 1]$	0.275	0.029	0.348	0.049	0.299	1808	1772.6
Partially Contained (PC)									
Stopping	2 visible energy	10 in $[-1, 1]$	0.084	0.032	0.829	0.010	0.045	566	570.0
Through-going	4 visible energy	10 in $[-1, 1]$	0.006	0.003	0.978	0.007	0.006	2801	2889.9
Upward-going Muons (Up-μ)									
Stopping	3 visible energy	10 in $[-1, 0]$	0.008	0.003	0.986	0.000	0.003	1456.4	1448.9
Through-going									
Non-showering	single bin	10 in $[-1, 0]$	0.002	0.001	0.996	0.000	0.001	5035.3	4900.4
Showering	single bin	10 in $[-1, 0]$	0.001	0.000	0.998	0.000	0.001	1231.0	1305.0

Multi-ring samples include pion production:



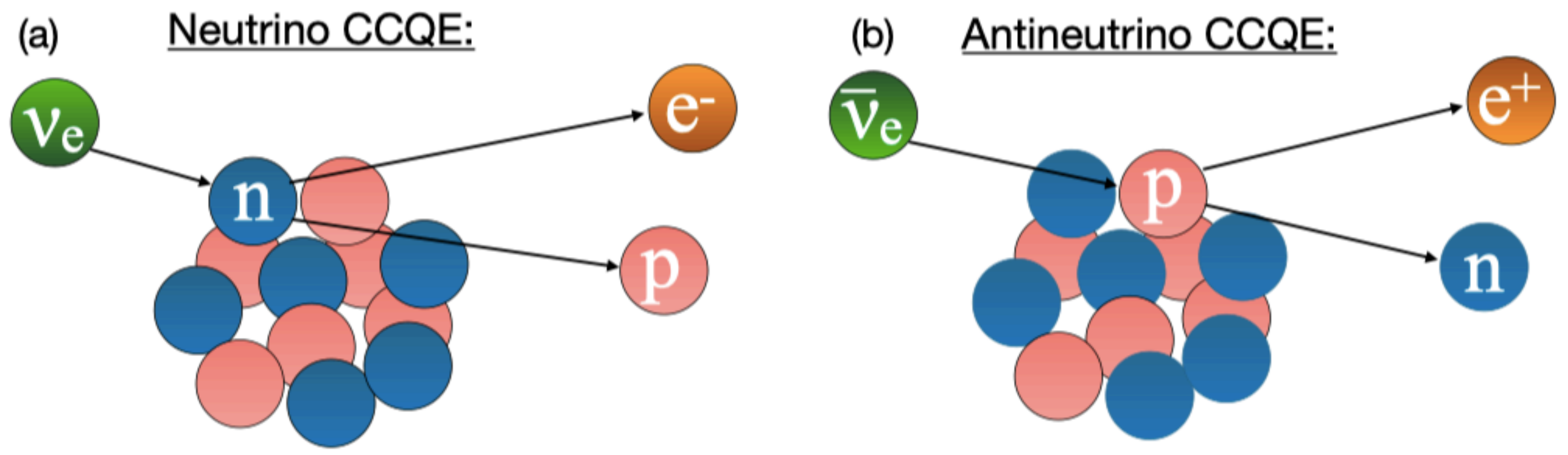
Neutron Tagging and Gd

- As reported at Neutrino 2020, Super-K is starting the process to add $Gd_2(SO_4)_3$
- This will increase the efficiency to detect neutrons in the final state of neutrino/antineutrino interactions
- Potential to improve:
  - Separation of neutrino and antineutrino interactions
  - Separation of quasi-elastic and non-quasi-elastic neutrino interactions

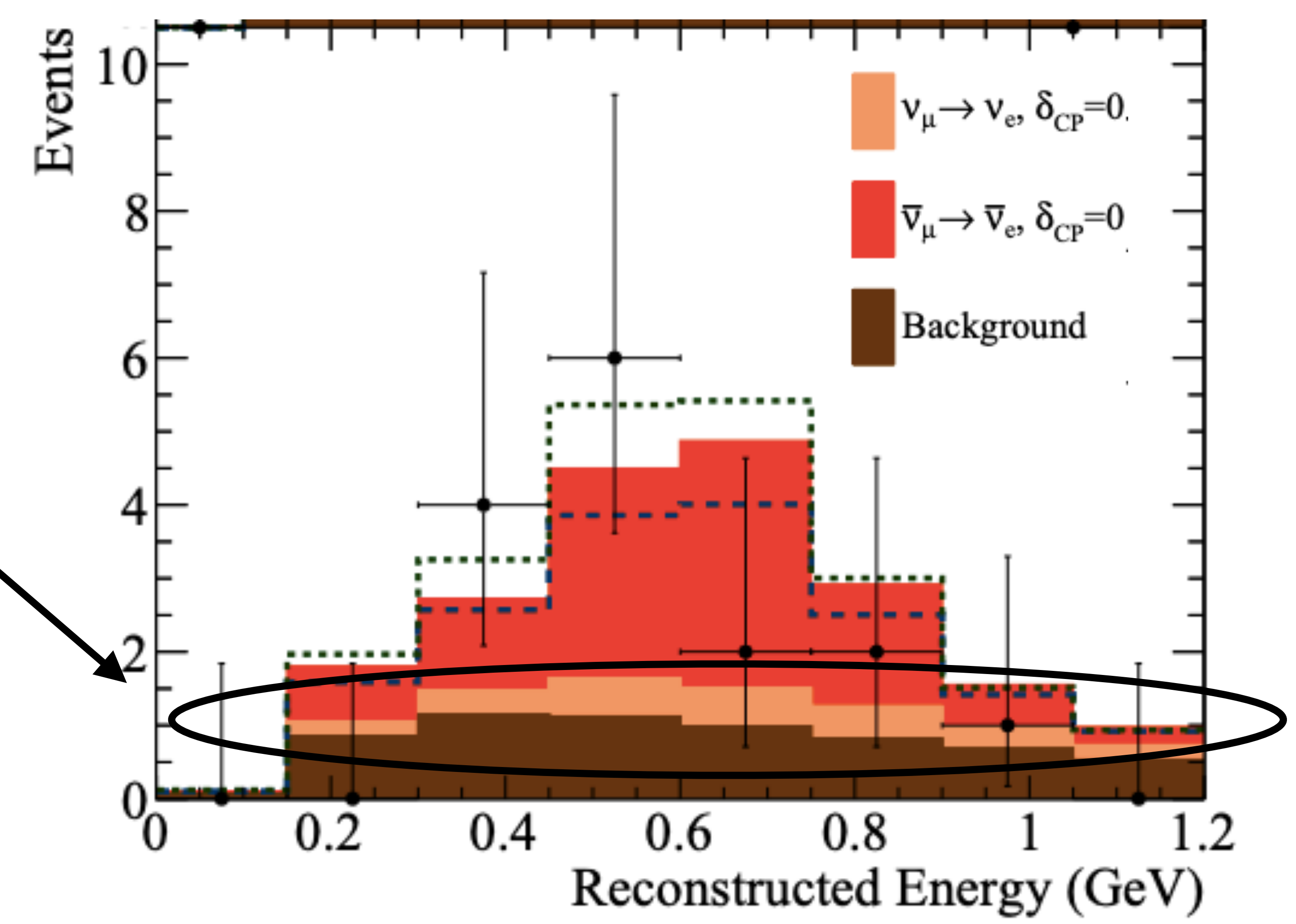


Motivation for Secondary Neutron Measurements

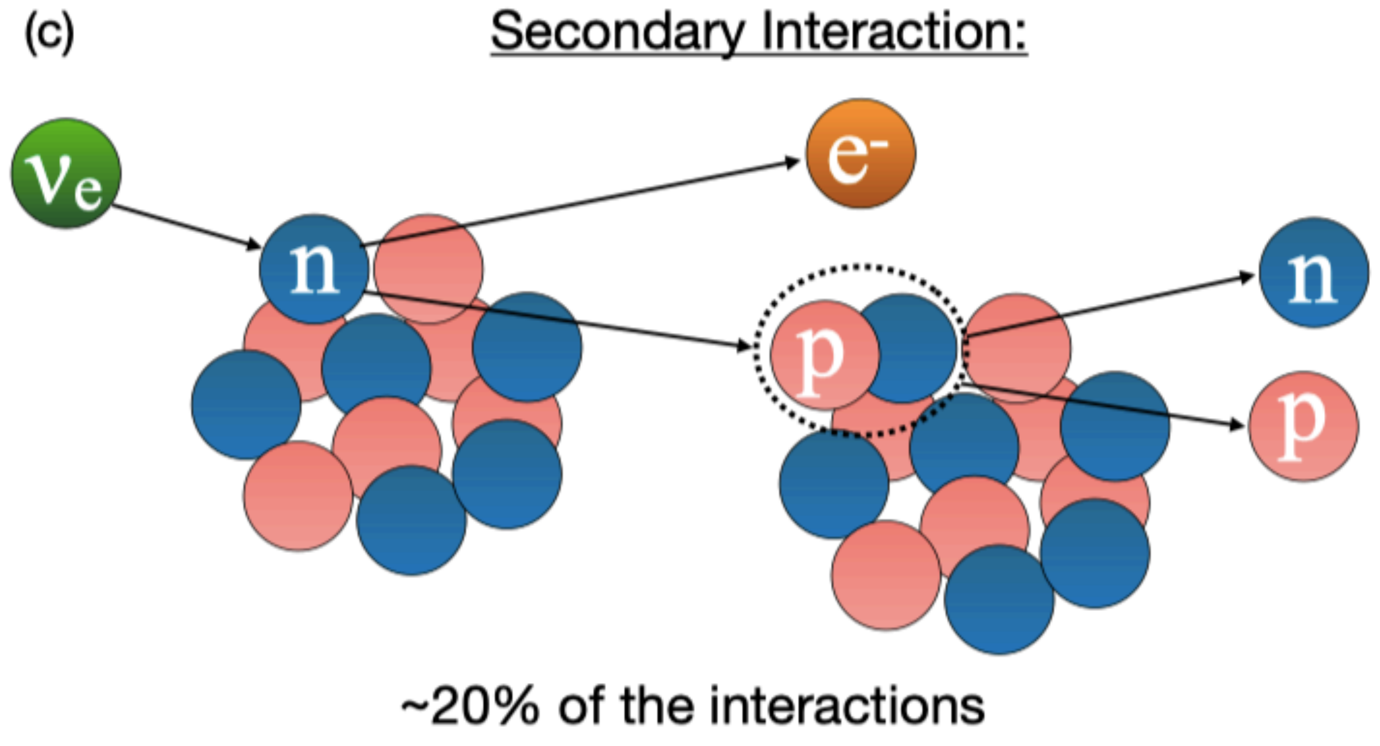
Applications of Neutron Detection in T2K



- For CCQE scattering, we expect neutrons only for antineutrino interactions in absence of FSI and SI
- Presence of neutron may be used to produce antineutrino enhanced sample (reduce wrong-sign fraction)
- Effectiveness is reduced by neutron production through FSI and SI of protons

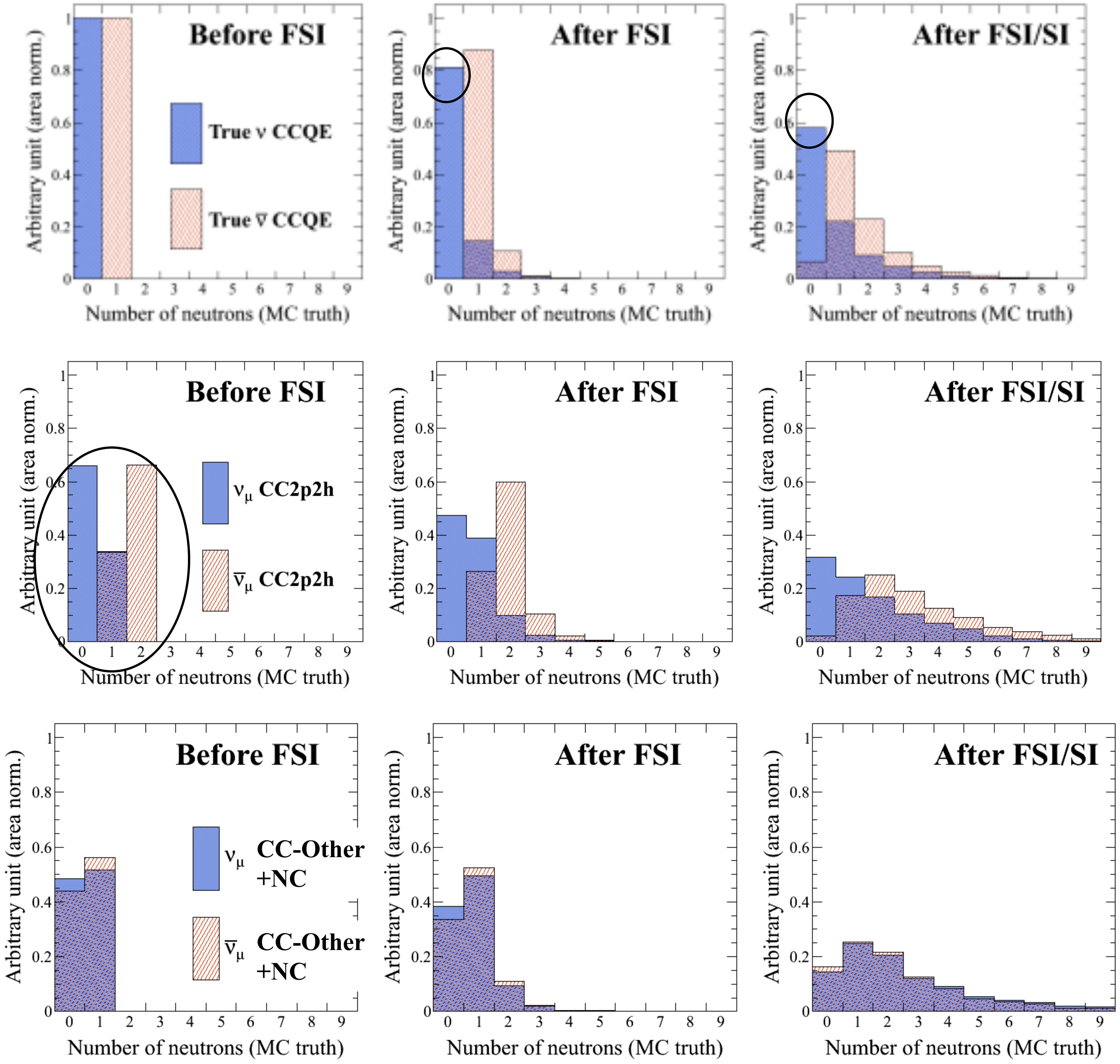


Nature 580 (2020) 7803, 339-344



Neutron Multiplicities (Single Ring Samples)

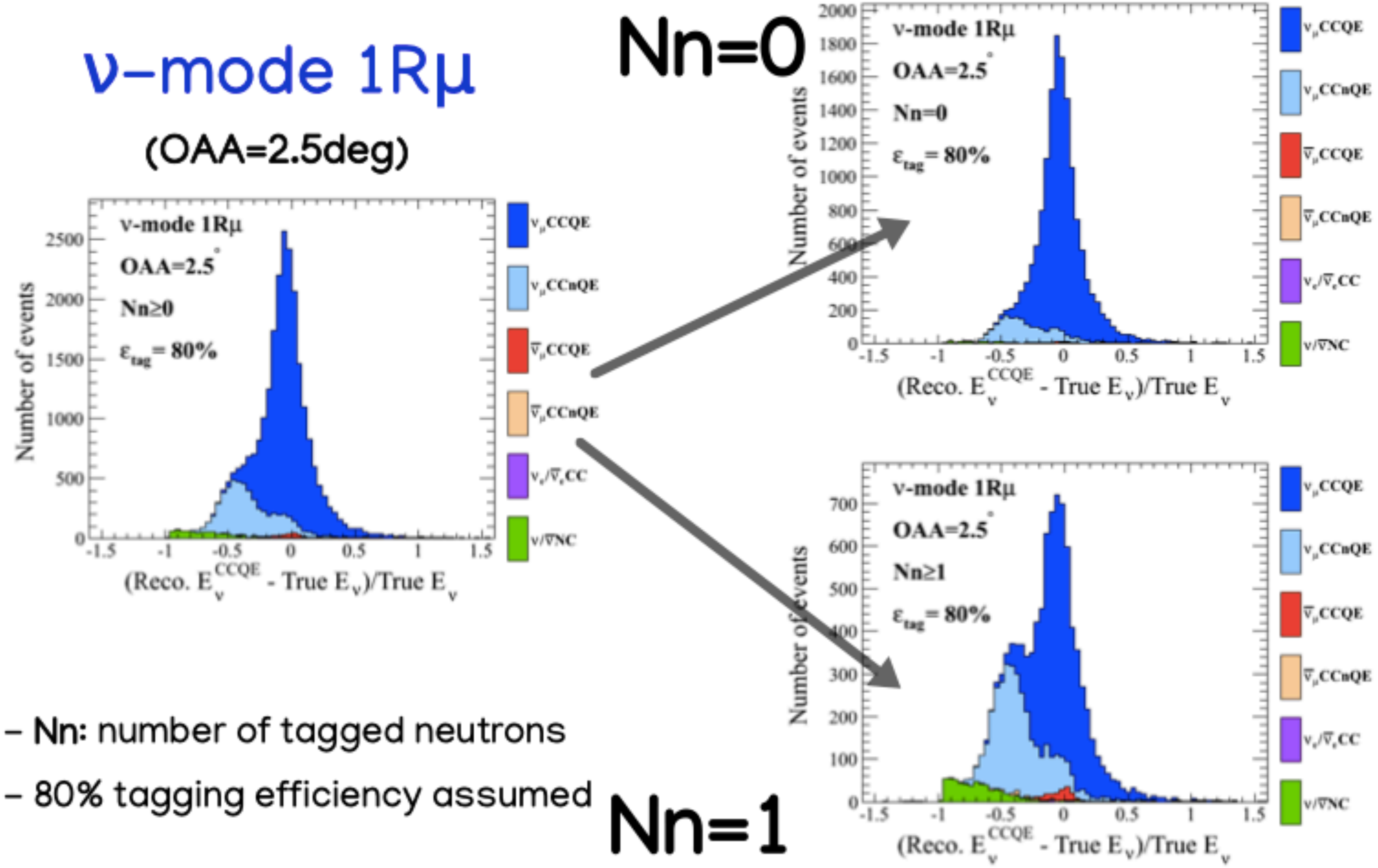
R. Akutsu



- About 20% of neutrino CCQE events pick up neutrons through FSI
- Another ~25% through SI
- Number of neutrons in 2p-2h interactions depends on fraction of initial np pairs vs. pp or nn pairs
- Other interactions start with about equal probability of 0 or 1 neutrons

Interaction Mode Separation?

IWCD Studies (preliminary)

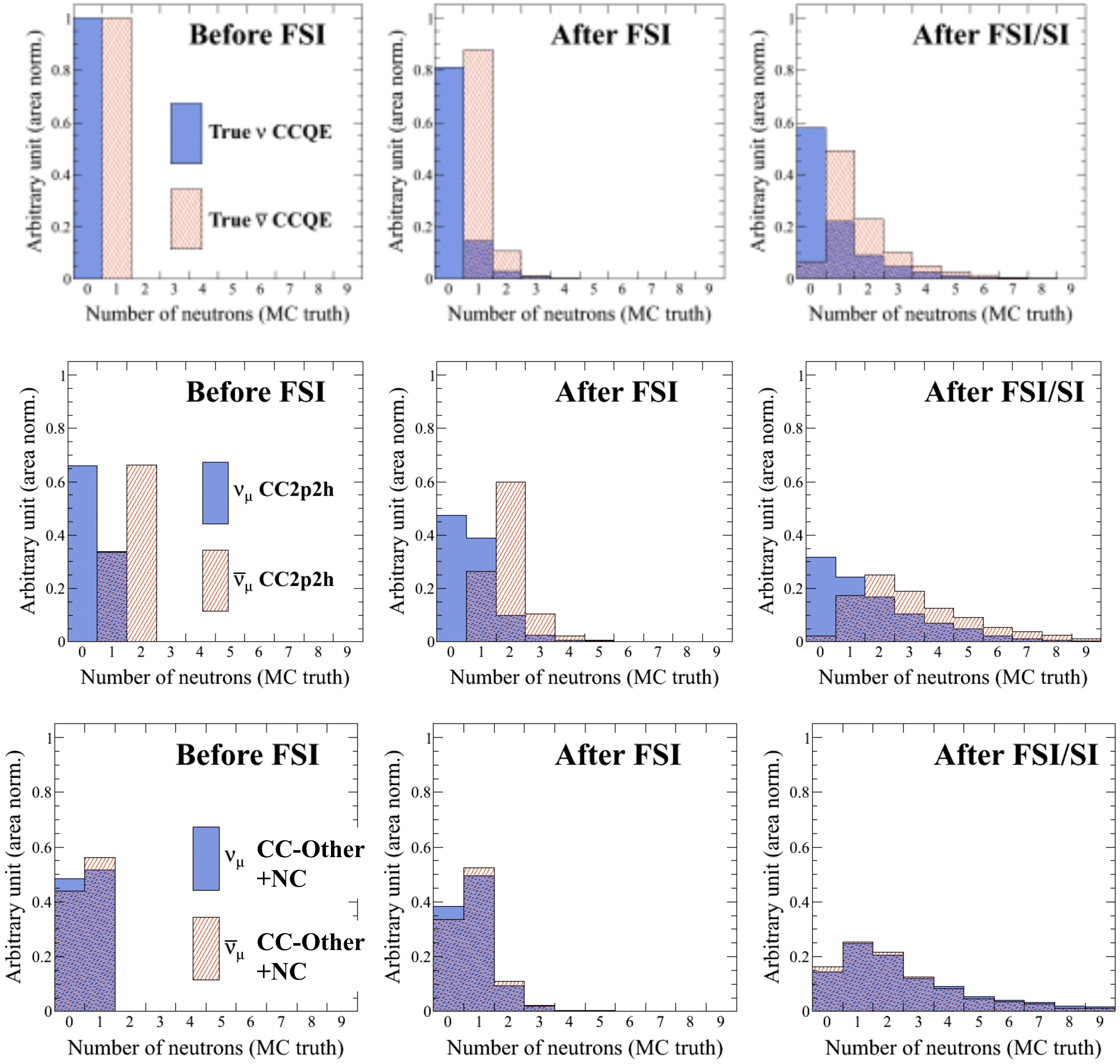


– Nn: number of tagged neutrons

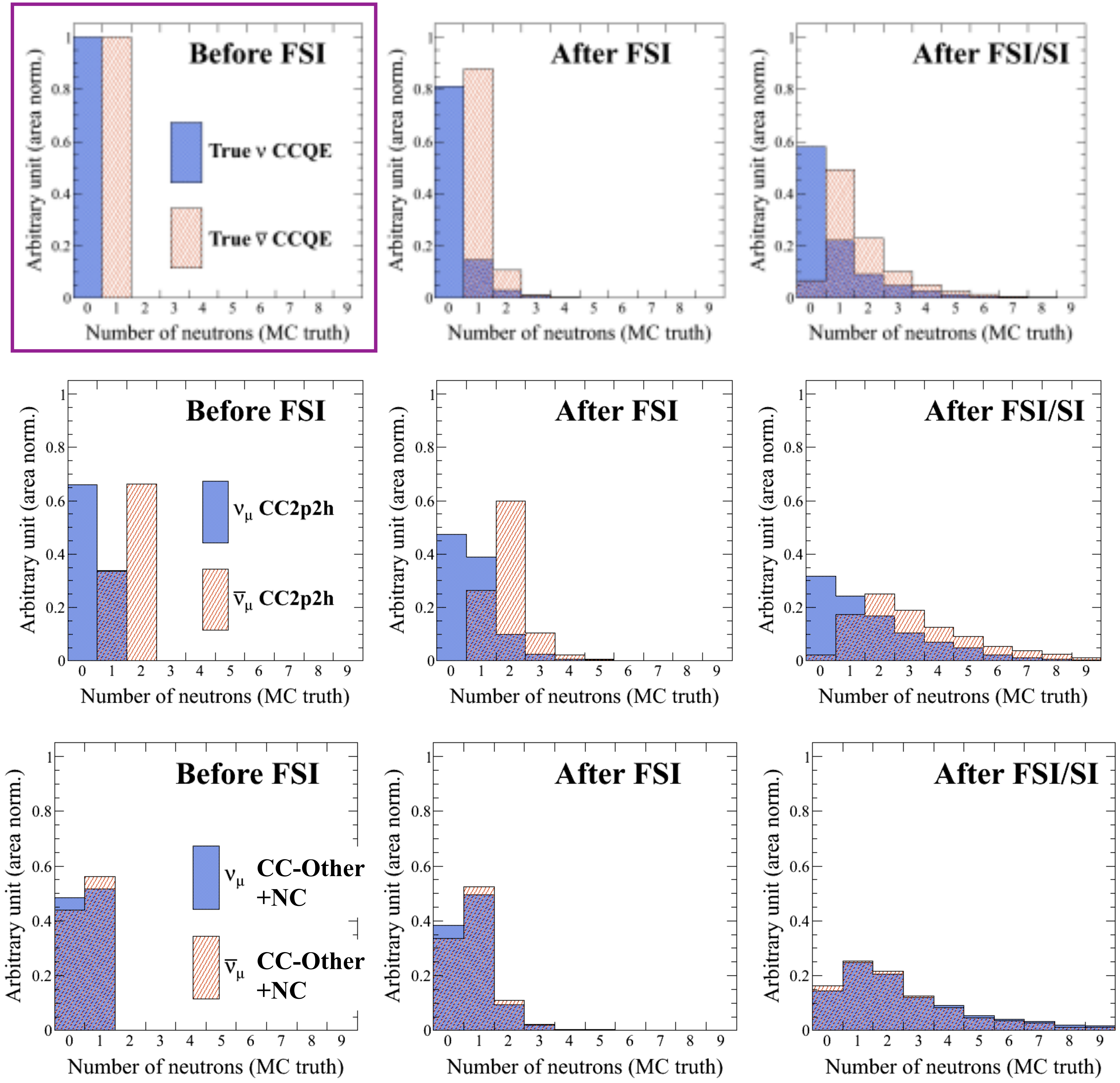
– 80% tagging efficiency assumed

- Requiring no neutron may produce a sample that is much more enhanced in CCQE (for neutrinos)
- This sample would have better energy resolution under QE assumption
- Control sample with a neutron will have more non-QE interactions
- **But using this depends on good neutron production modeling!**

Neutron Multiplicities Constraints

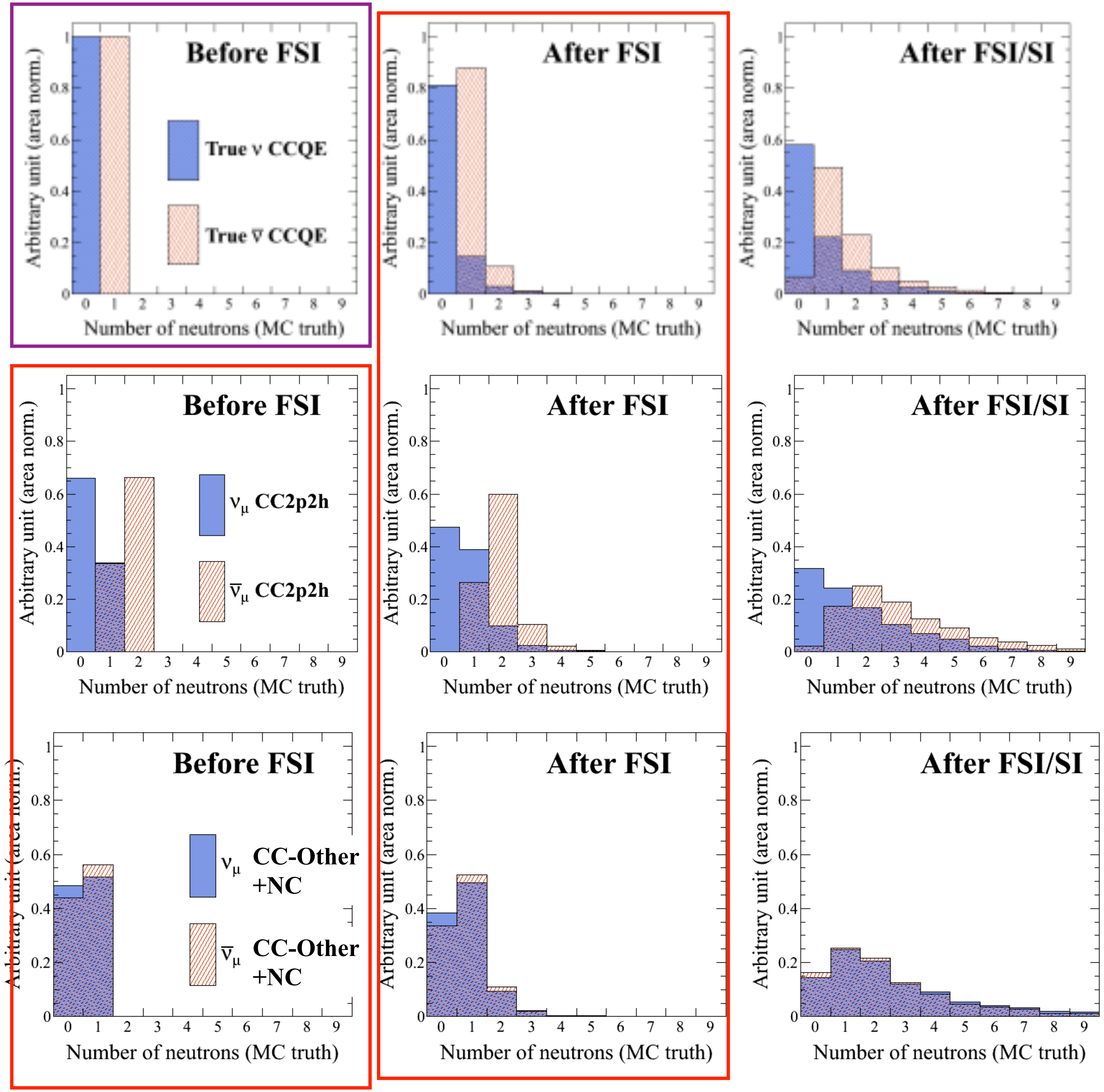


Neutron Multiplicities Constraints



Derived from model

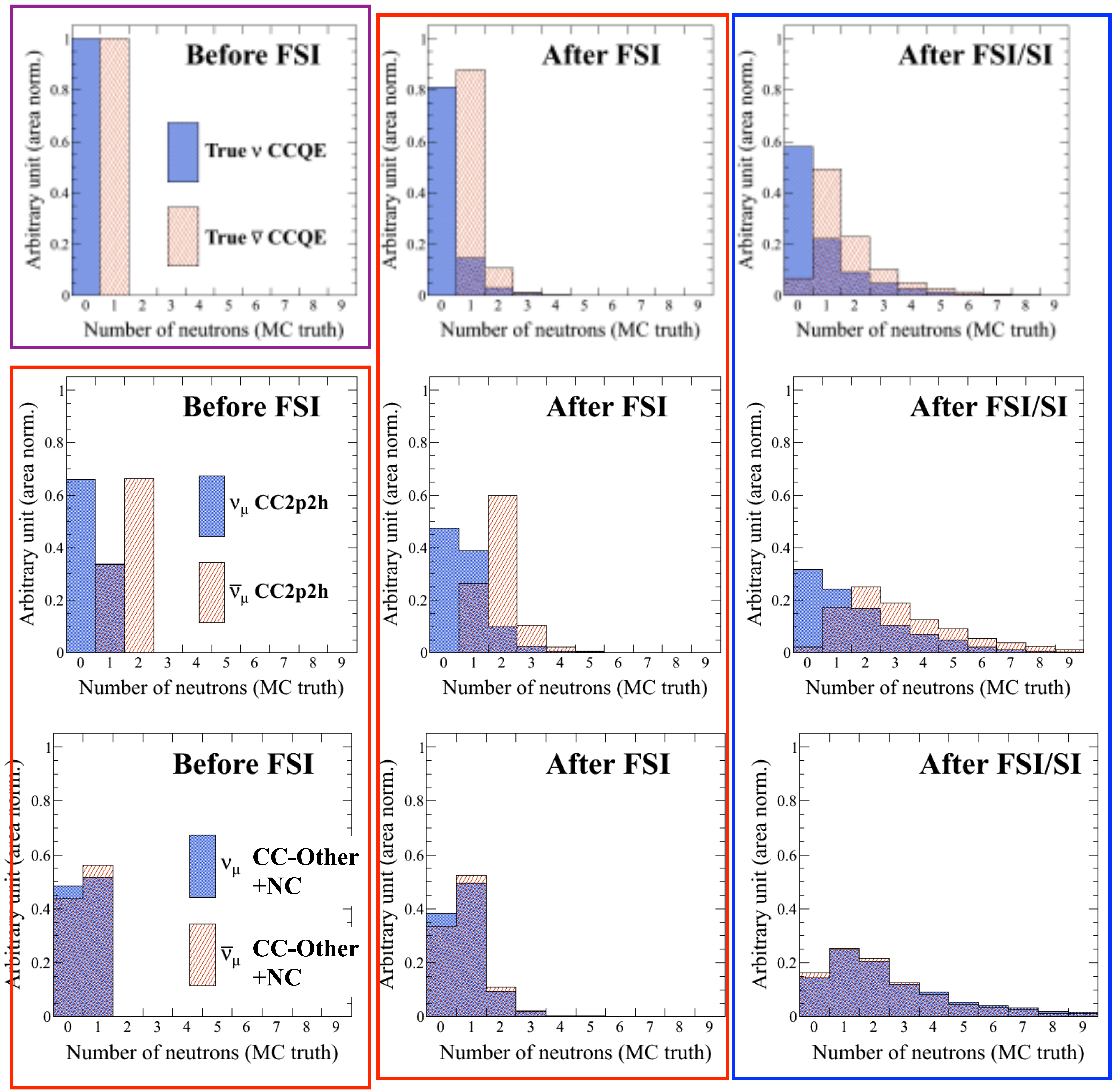
Neutron Multiplicities Constraints



Derived from model

Constrained by ND280 (upgrade) measurements

Neutron Multiplicities Constraints



Derived from model

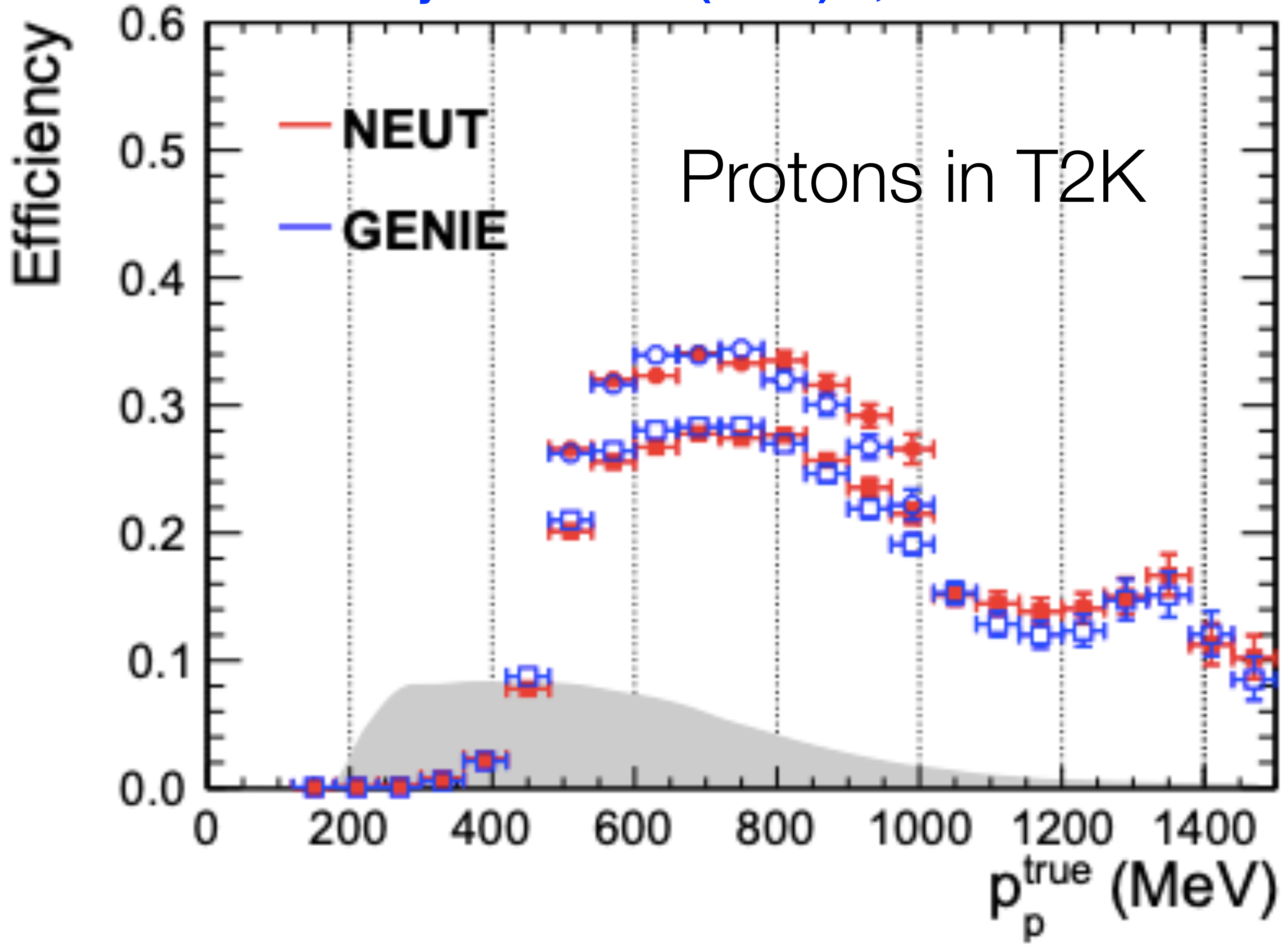
Constrained by ND280 (upgrade) measurements

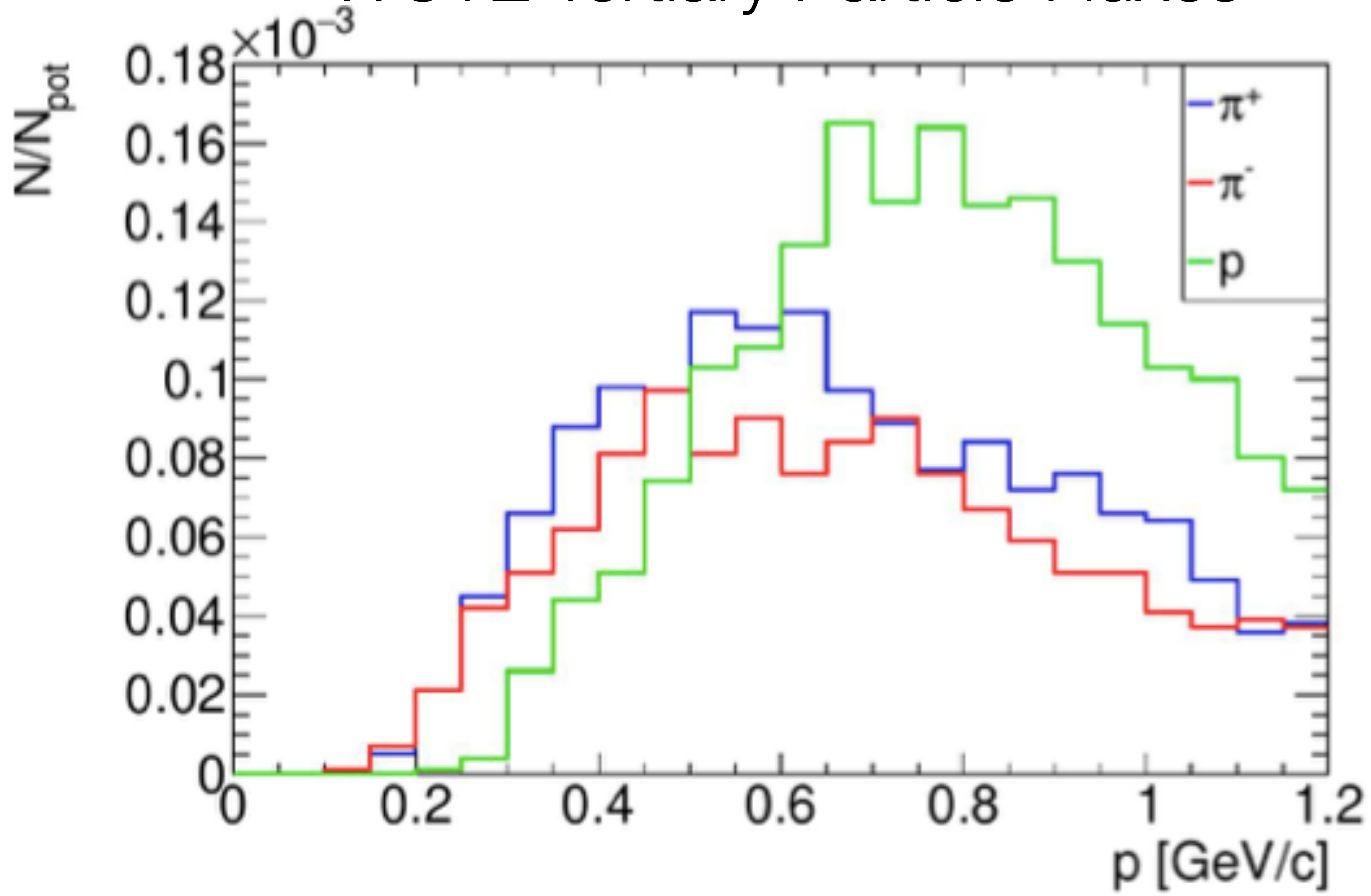
Constrained by WCTE measurements

Measurements in WCTE

- WCTE will have a phase loaded with Gd - neutron detection will be possible
- WCTE proton fluxes in tertiary beam have good overlap with T2K proton spectrum
- For particles entering at beam window, ~80% of produced neutrons capture in tank

Phys.Rev.D 98 (2018) 3, 032003

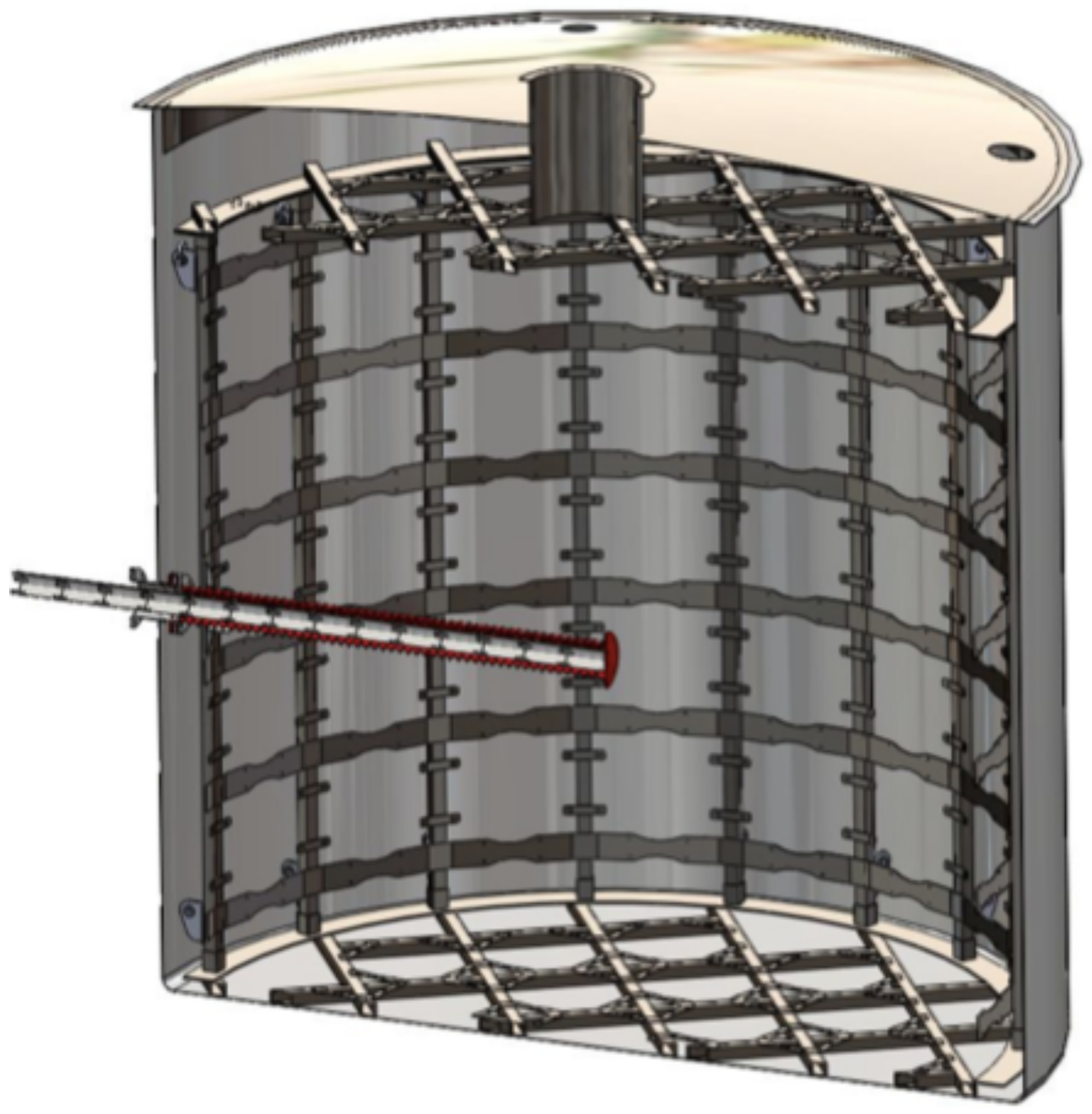


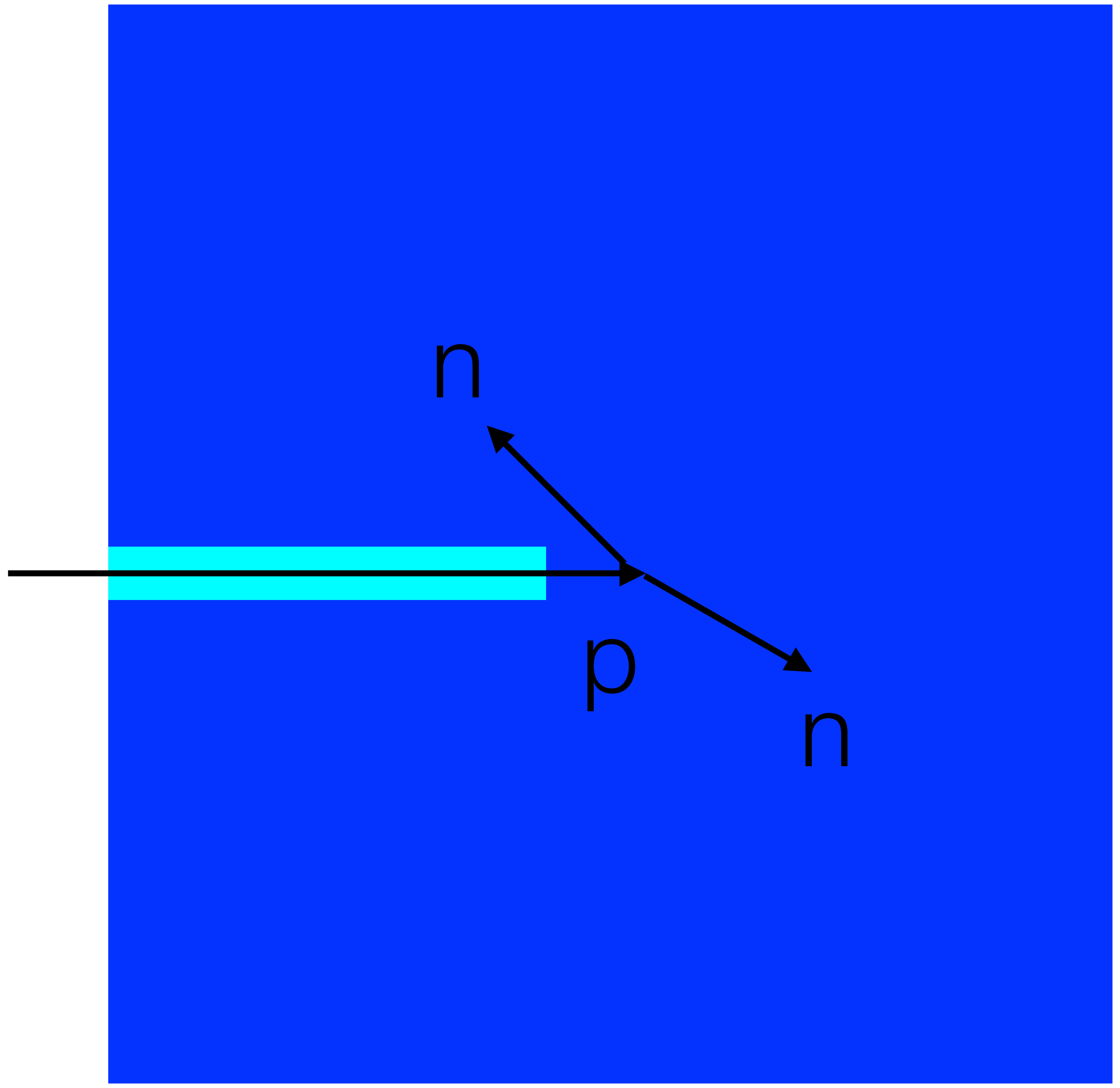


- We are also considering if we can get sufficient proton flux in the secondary beam configuration

Protons in Secondary Configuration

- We are considering proton fluxes in the secondary beam configuration
- Detector is far from secondary production target, so we expect neutron background to be negligible
- By using the beam pipe in the secondary beam configuration, we can inject protons to center of detector to contain backward produced neutrons as well



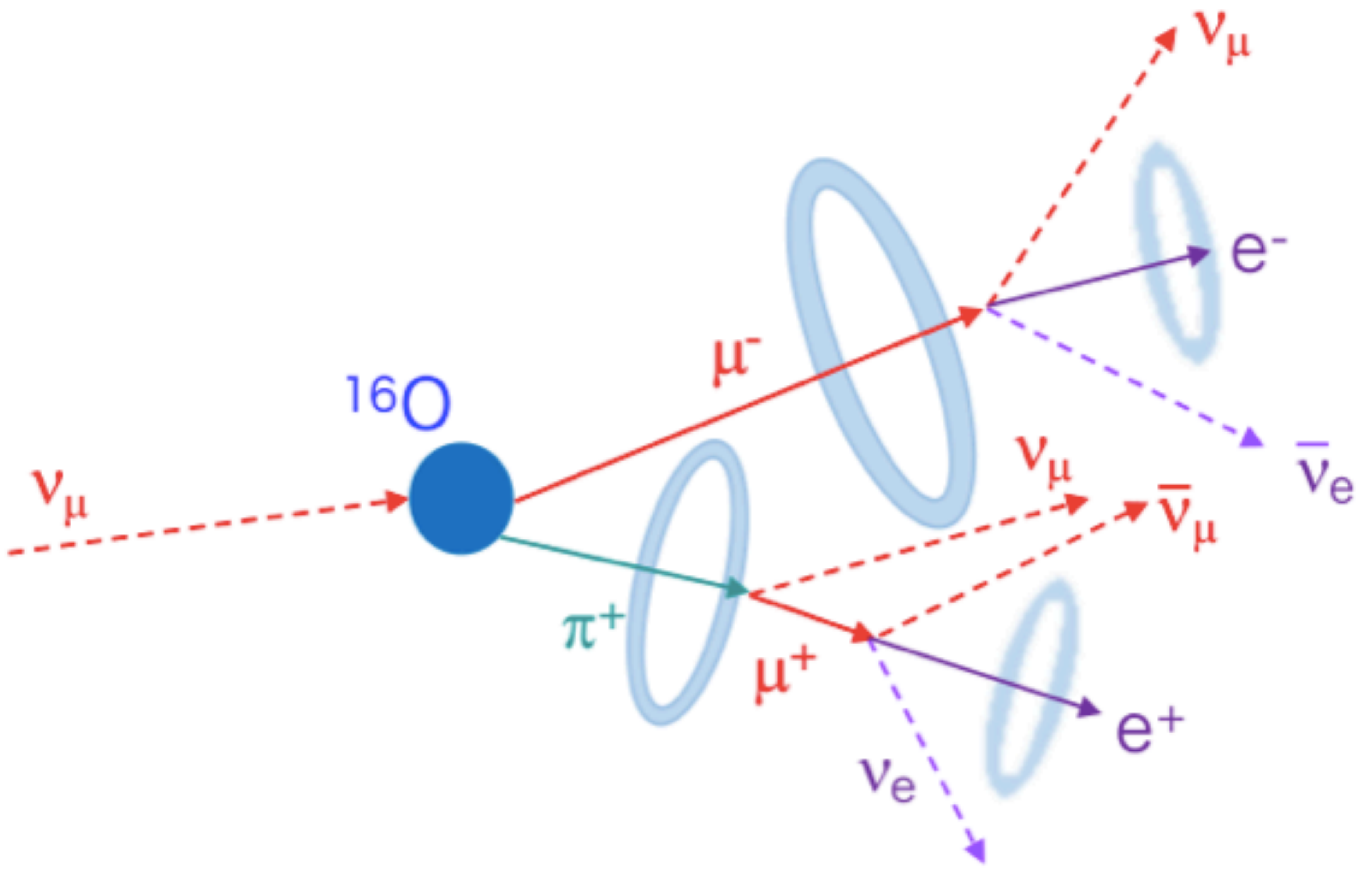


Backward neutron can be contained

Motivation for Secondary Pion Scattering

Multi-Ring Samples

- As mentioned previously, Super-K atmospheric analysis already uses multi-ring samples
- T2K aims to incorporate these as well
- Super-K uses the visible energy in multi-ring samples
- T2K may use energy reconstruction with muon kinematics and assuming recoil Δ:



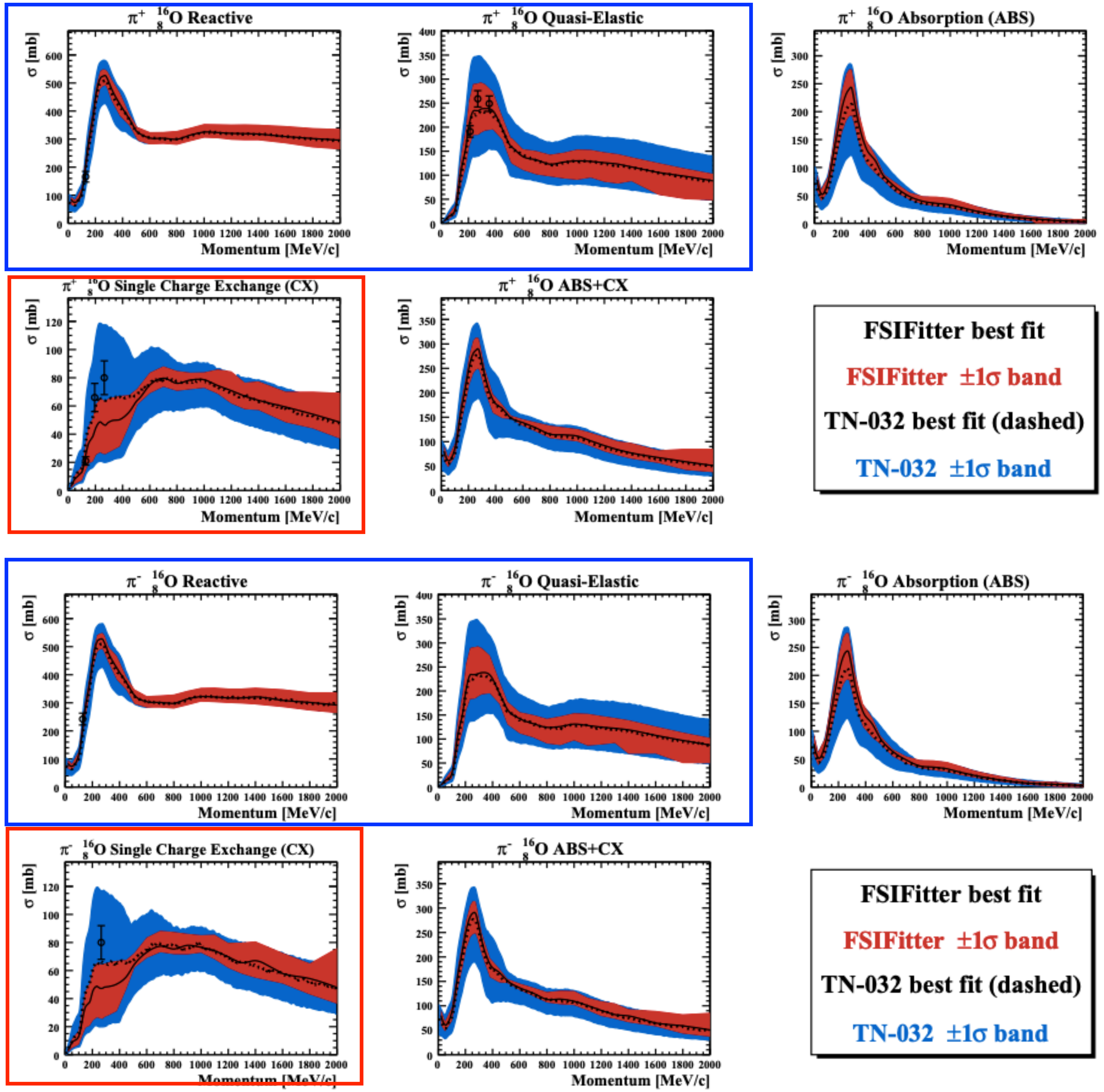
$$E_{\text{rec}}^{\nu_\mu CC\Delta^{++}} = \frac{2m_p E_\mu + m_{\Delta^{++}}^2 - m_p^2 - m_\mu^2}{2\left(m_p - E_\mu + |\boldsymbol{p}_\mu| \cos\theta_\mu\right)},$$

- Not using reconstructed pion kinematics reduces impact of uncertainties on final state and secondary interactions of pions
- Can do better if these uncertainties are reduced and reconstructed pion kinematics are included?

Pion Scattering Data

T2K Thesis, E. Pinzon

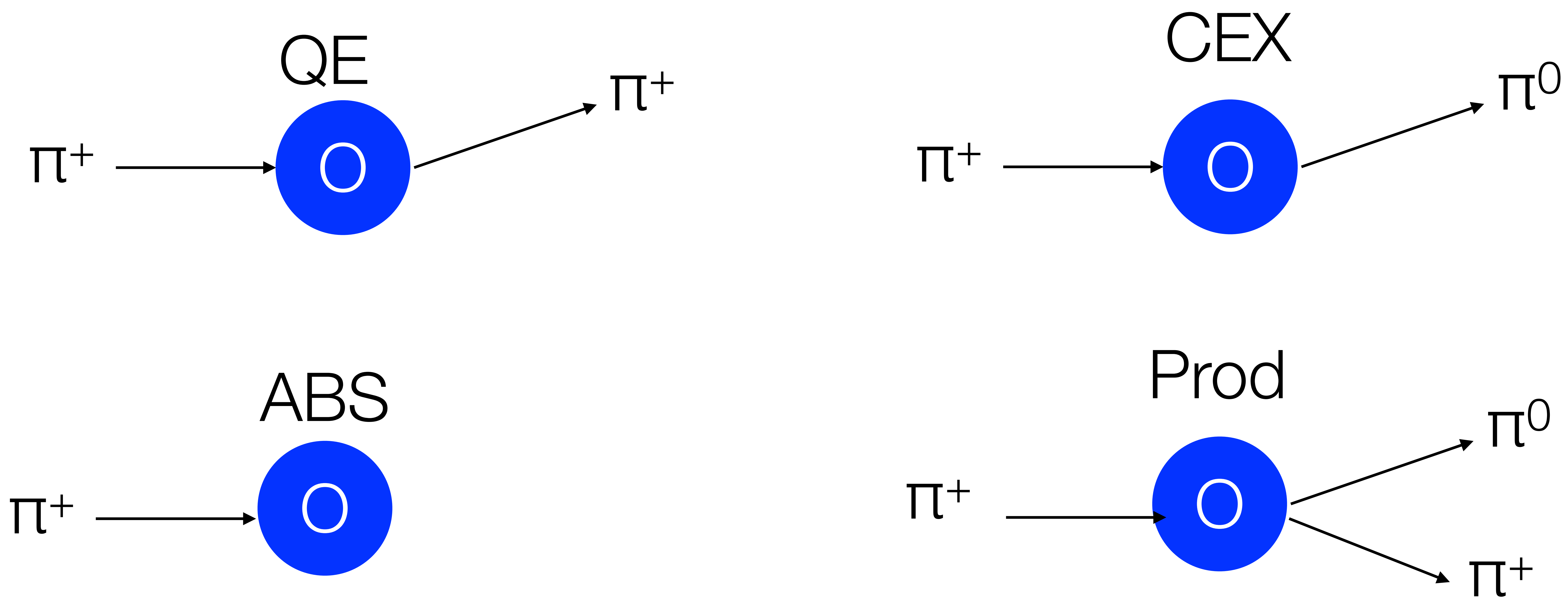
Reference	Polarity	Targets	p_π [MeV/c]	Channel(s)
B. W. Allardyce et al. [11]	$\pi^\pm$	C, Al, Pb	710-2000	REAC
A. Saunders et al. [12]	$\pi^\pm$	C, Al	116-149	REAC
C. J. Gelderloos et al. [13]	π^-	C, Al, Cu, Pb	531-615	REAC
F. Binon et al. [14]	π^-	C	219-395	REAC
O. Meirav et al. [15]	π^+	C, O	128-169	REAC
C. H. Q. Ingram [16]	π^+	O	211-353	QE
S. M. Levenson et al. [17]	π^+	C	194-416	QE
M. K. Jones et al. [18]	π^+	C, Pb	363-624	QE, CX
D. Ashery et al. [19]	π^+	C, Al, Fe	175-432	QE, ABS+CX
H. Hilscher et al. [20]	π^-	C	156	CX
T. J. Bowles [21]	$\pi^\pm$	O	128-194	CX
D. Ashery et al. [22]	$\pi^\pm$	C, O, Pb	265	CX
K. Nakai et al. [23]	$\pi^\pm$	Al, Cu	83-395	ABS
E. Bellotti et al. [24]	π^+	C	230	ABS
E. Bellotti et al. [25]	π^+	C	230	ABS
I. Navon et al. [26]	π^+	C, Fe	128	ABS+CX
R. H. Miller et al. [27]	π^-	C, Pb	254	ABS+CX
E. S. Pinzon Guerra et al. [28]	π^+	C	206-295	ABS, CX



- $\pi^\pm$+O scattering data is rather limited
- Rely on constraint of microscopic parameters within cascade model constrained by C, Al, etc. data

How to Use WCTE

- We can use the WCTE to constrain the effect of pion secondary interactions
- Tertiary beam configuration -> collect data for charged pion fluxes with known momentum and trajectory when entering the detector
- Through exclusive final state reconstruction, we may attempt to make measurements of quasi-elastic, charge exchange, absorption or production cross sections



However:

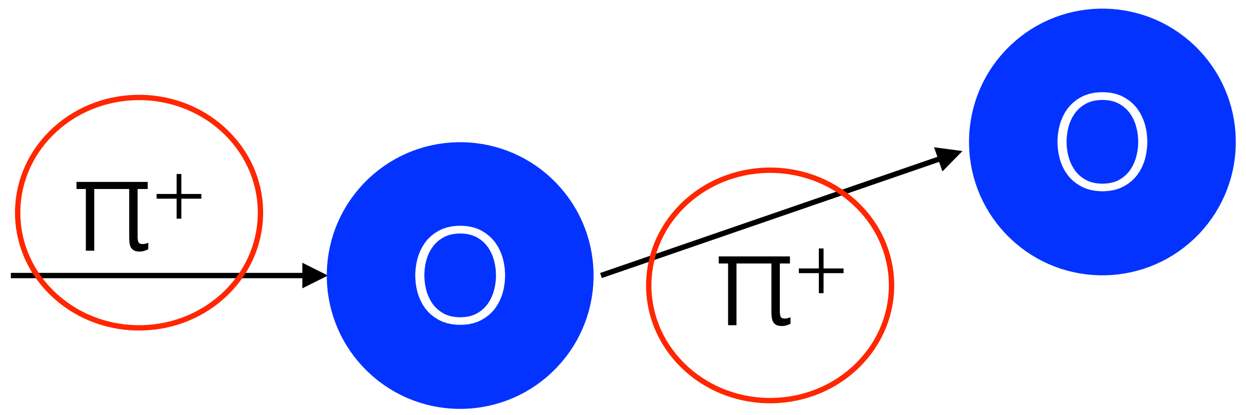
Not a thin-target experiment

Need to account for energy loss

Mapping to Observables

- Alternatively, we may directly measure a mapping between observables and initial pion momentum and direction

- Example event with two partially filled in rings:



- Multiple measurements at same incident pion momentum (p_i) can produce a mapping that is a function of the observables:

$$M(N_{rings}, E_1, \theta_1, E_2, \theta_2, \dots \mid p_i)$$

- May be used to tune the MC in an inclusive manner that is similar to replica target tuning for the flux calculation

- As with the neutron production case, ND280 measurements necessary to constrain pions exiting the target nucleus

SK+SI Error for 1Ring Samples

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

- WCTE measurements may also impact systematic errors for 1 Ring samples
- Measurement of secondary pion interactions can constrain CC1pi topology contamination
- Samples of electrons and muons can be used to validate and/or constrain our detector models

Conclusion

- WCTE will be platform to test water Cherenkov technologies and make interesting measurements with hadron and lepton fluxes
- Applications to T2K and Super-K may include:
    - Secondary neutron production measurements
    - Charged pion propagation/scattering in water measurements
- Collaborators are welcome to work on these interesting applications of the WCTE