Measurement of the Charged Current ν_e Interaction Rate on Water with the T2K π^0 Detector

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on behalf of T2K Collaboration

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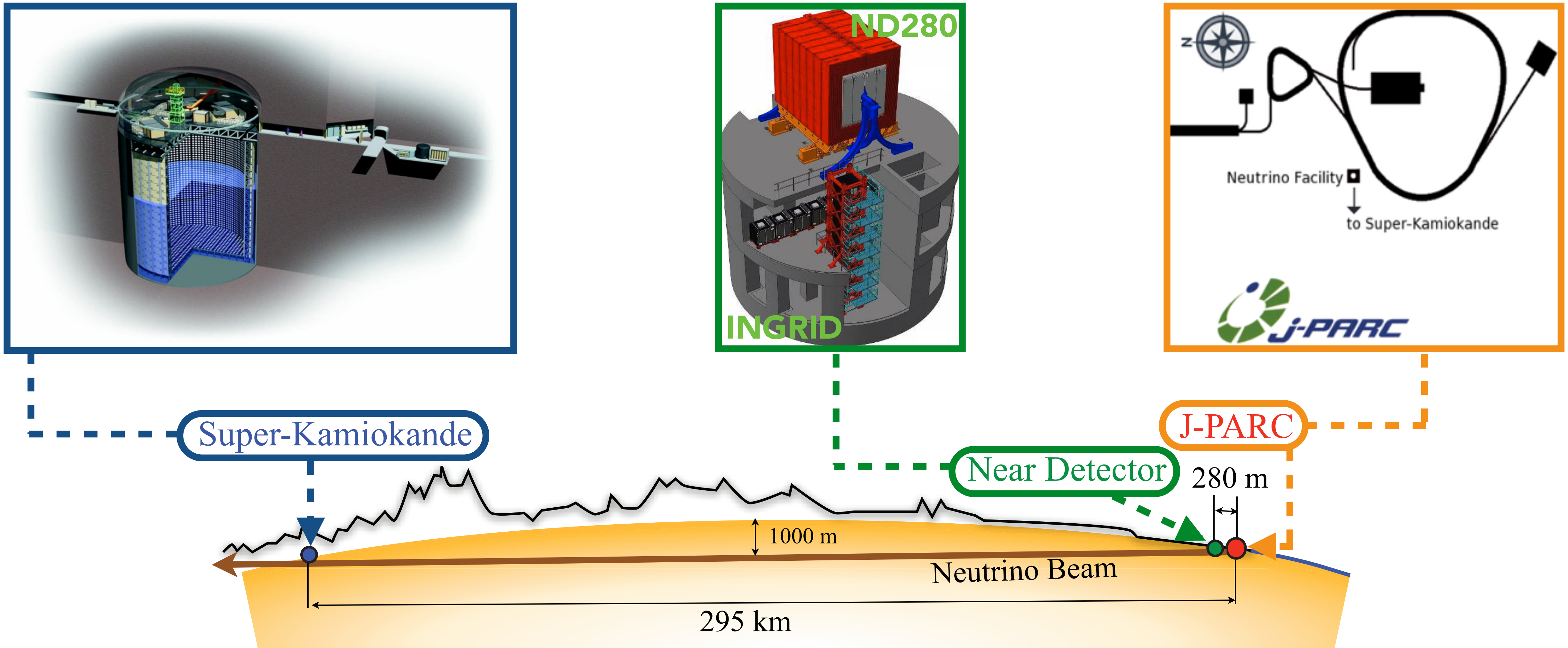
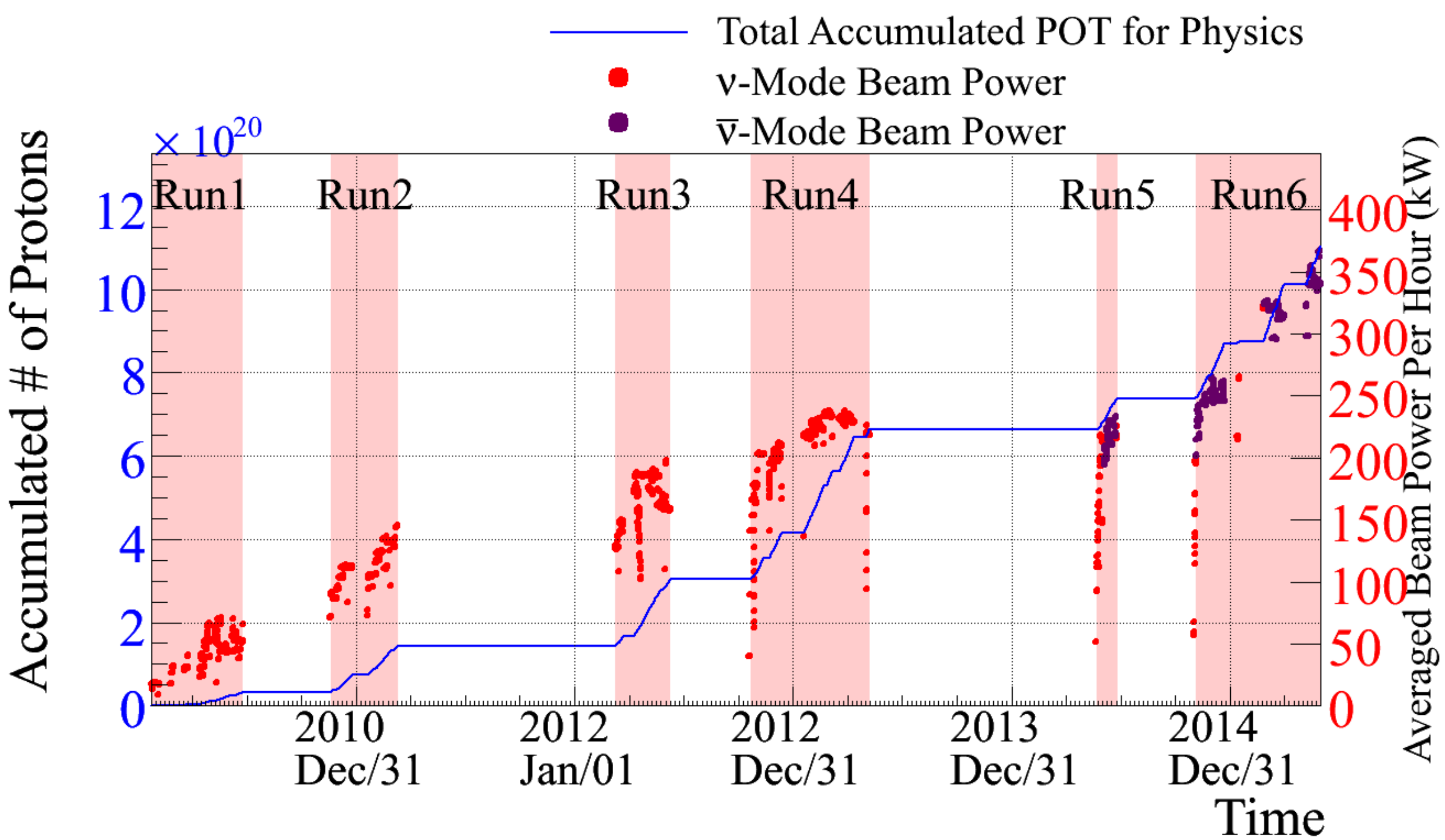
Stony Brook University

T2K Experiment: Overview



- Long baseline neutrino oscillation experiment
- Muon/anti-muon neutrinos produced from a 30 GeV proton beam at J-PARC
- Super-Kamiokande, 50 kton water Cherenkov detector, is used as the far detector
- Main goals:
  - ν_μ ($\overline{\nu}_\mu$) disappearance $P(\nu_\mu \to \nu_\mu)$, $P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$: explore Δm^2_{32} and θ_{23}
  - ν_e ($\overline{\nu}_e$) appearance $P(\nu_\mu \to \nu_e)$, $P(\overline{\nu}_\mu \to \overline{\nu}_e)$: explore θ_{13} and constrain δ_{CP}

T2K Experiment: Data Taking

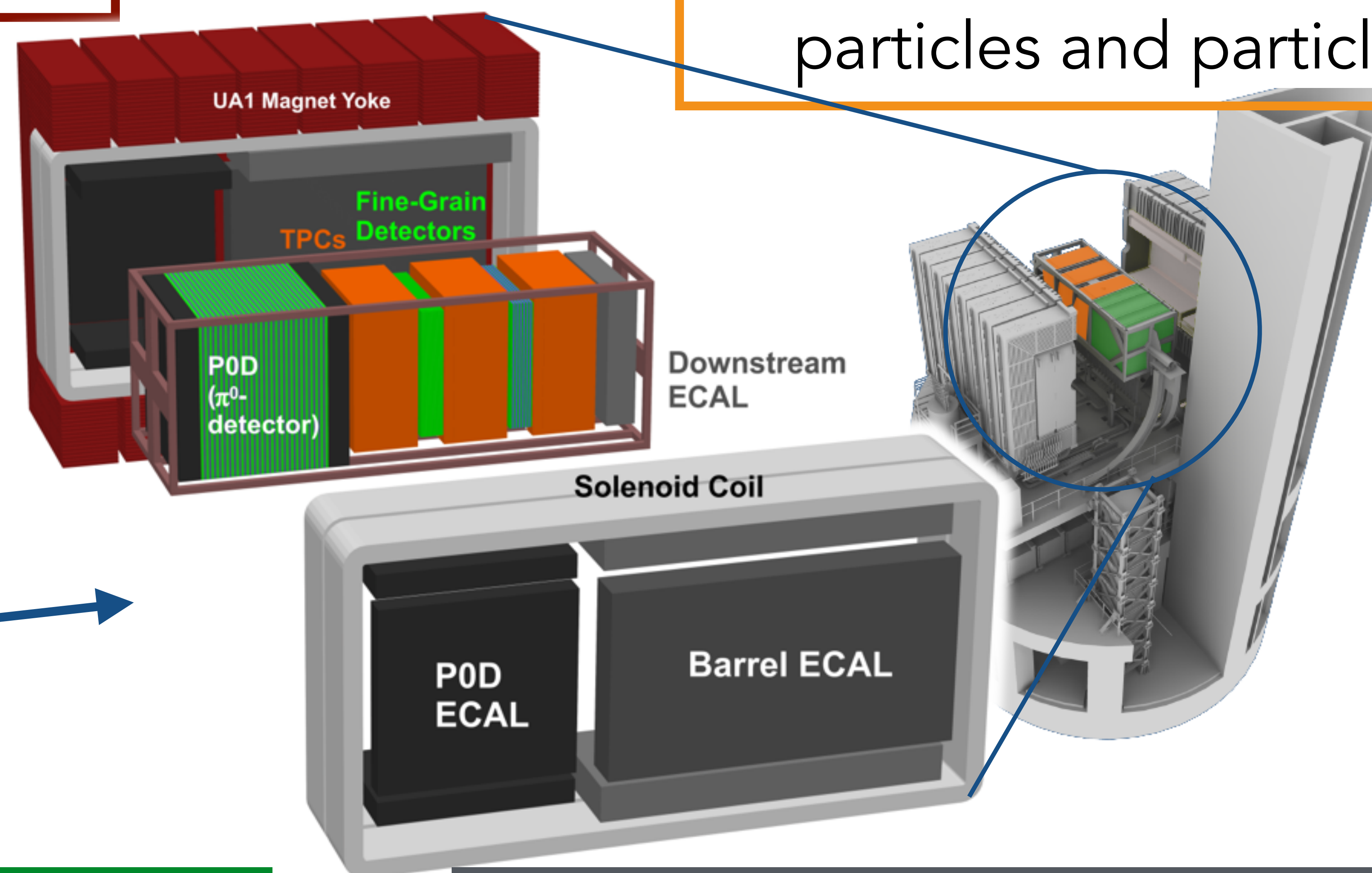


- Maximum stable beam power recorded ~370 kW recently
- Beam delivery
  - 11.04×10^{20} protons on target until June 2015 (~14% of approved P.O.T)
    - 7.0×10^{20} protons on target in ν-mode
    - 4.04×10^{20} protons on target in $\bar{\nu}$-mode

Off-Axis Near Detector: ND280

UA1 magnet
0.2T magnetic field

Tracker: FGDs + TPCs
Measure momenta of charged particles and particle ID



ν beam

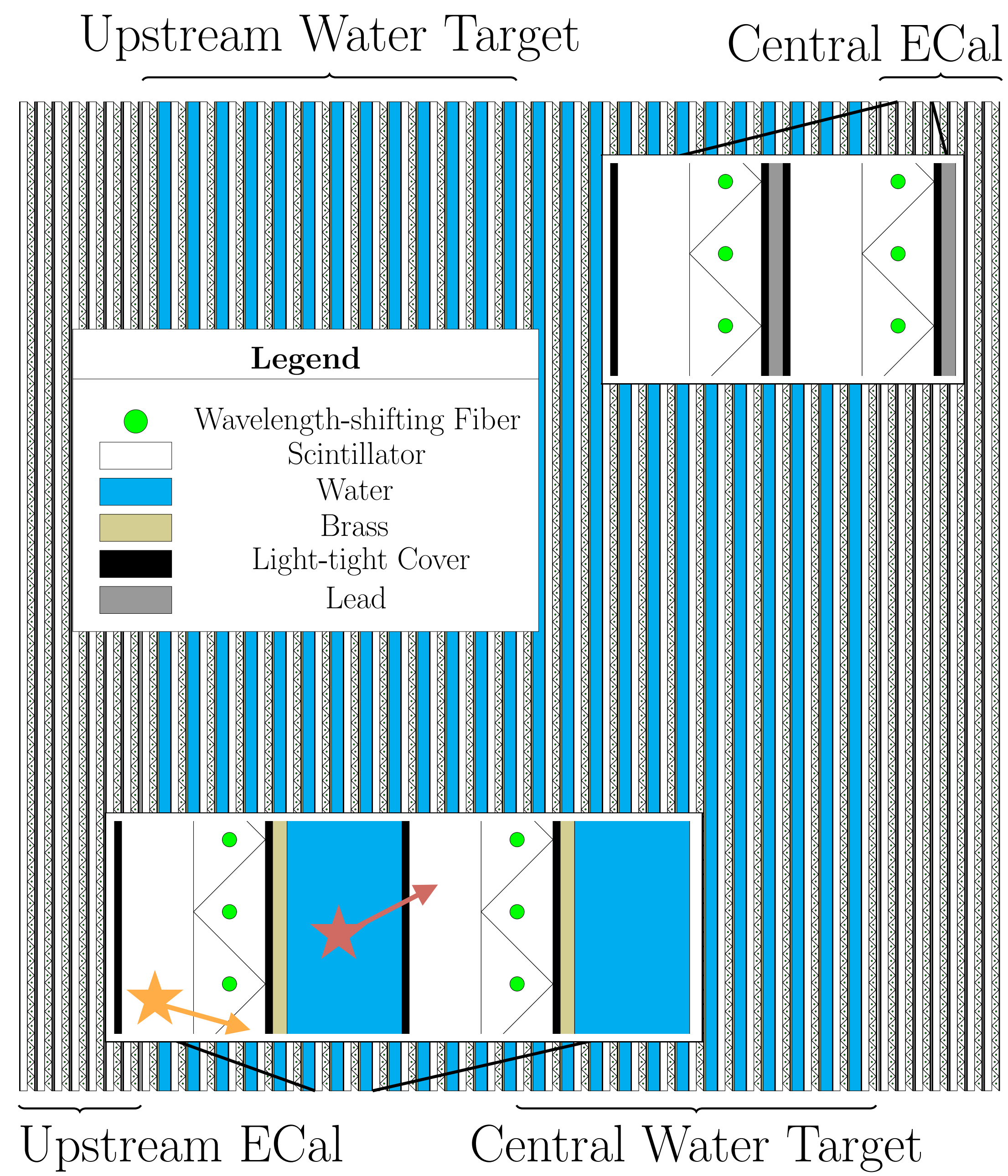
π^0 Detector (P0D)
Scintillator interleaved with carbon and water targets

Electromagnetic Calorimeter (ECAL)
Plastic scintillator and lead,
Aids in PID

Off-Axis Near Detector: π^0 Detector

- π^0 Detector (P0D) is designed to measure NC process (ν_x +N → ν_x +N+π^0+X) on a water target
- One of the primary objectives of the P0D is to measure ν_e rate in the T2K beam
- With water-in and water-out configurations, P0D is capable of on-water measurement
- Definition
  - On-Water: Events interact with water target
  - Not-Water: Events interact with non-water materials (scintillator, brass, lead, etc.)

Assylbekov et.al. Nucl. Instrum. Meth. A686, 48 (2012)



Motivation: ν_e Analyses in ND280

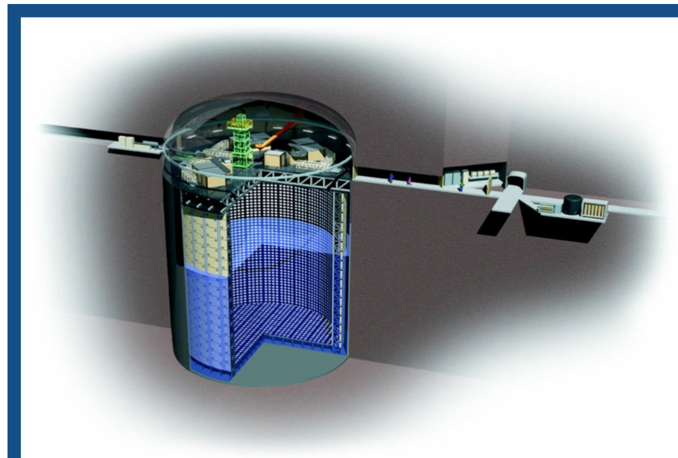
- ND280 measurements constrain the flux and cross section uncertainty very well in the T2K oscillation analysis
  - ND280 ν_μ measurements on C target is used in the oscillation analysis
  - T2K detectors have both C and H_2O targets
  - ND280 ν_e measurement on C target has been used as a cross-check (ND280 Tracker), but ν_e measurement on H_2O target never been used
- The largest background to the ν_e appearance at the far detector is the intrinsic ν_e beam contamination
  - Predicted 3.2 intrinsic ν_e beam events in total background expectation of 4.92 +/- 0.55 events (θ_{13} = 0)

<The uncertainty on the predicted number of ν_μ/ν_e events>

Error source [%]	ν_μ sample	ν_e sample
Beam flux and near detector	2.74	3.15
(w/o ND280 constraint)	(21.75)	(26.04)
Uncorrelated ν interaction	5.00	4.69
Far detector	4.03	2.72
FSI+SI+PN	2.98	2.44
Total	7.65	6.75

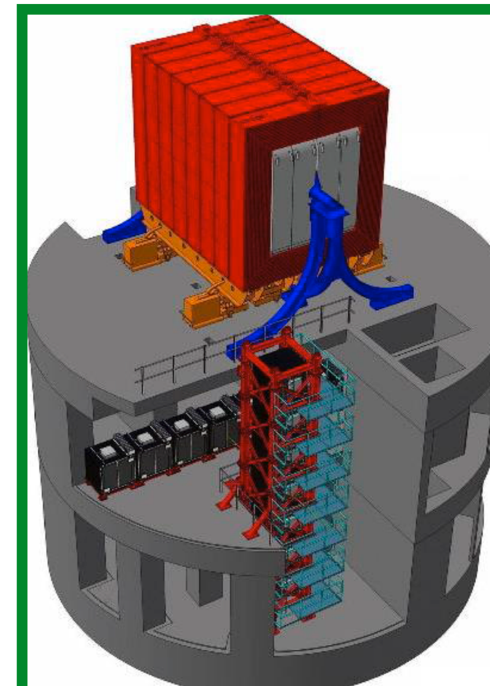
Phys. Rev. Lett. **112**, 061802 (2014)

Super-Kamiokande



H_2O Target

Near Detector



C, H_2O Target

Motivation: High Energy CC ν_e Analysis

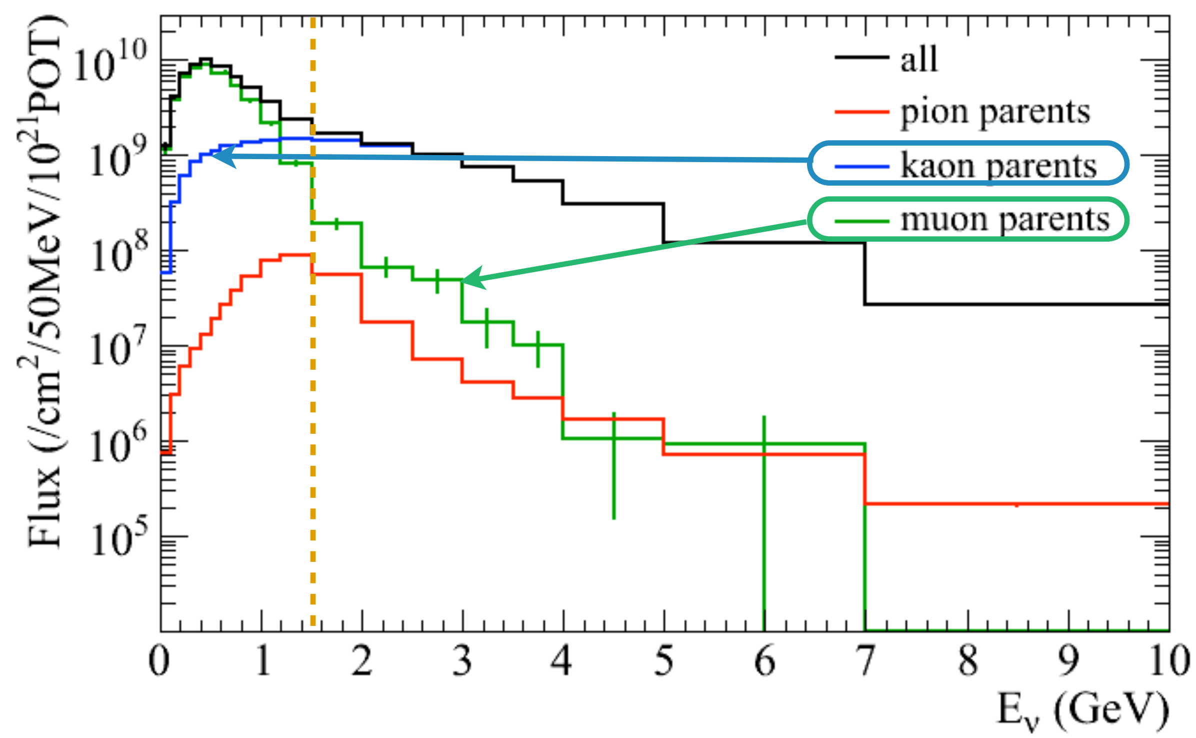
- In T2K the 30 GeV proton beam produces $\pi^{\pm}$ and $K^{\pm}$, which are focused by three horns, selecting π^{+} and K^{+}

- This leads to two sources of ν_e contamination in the T2K ν_μ beam

  - E_ν > 1.5 GeV is the region where the ν_e contamination is predominantly from K decay

  - Kaon flux is less well constrained than muon flux

Phys. Rev. D **87**, 012001 (2013)



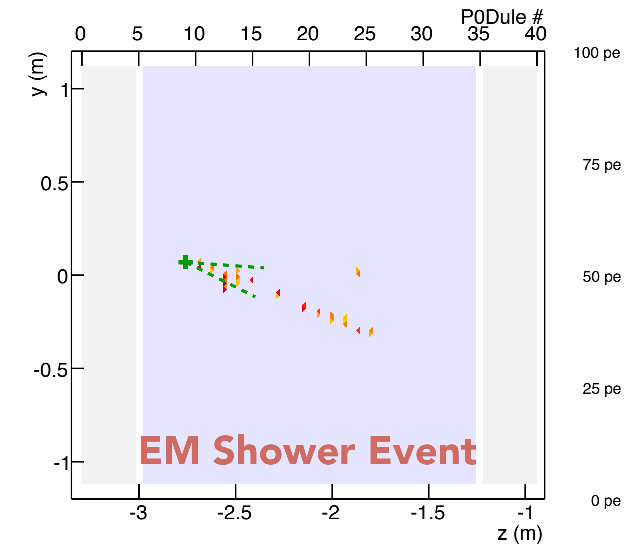
Total ν_e Flux at ND280 by Parent Type

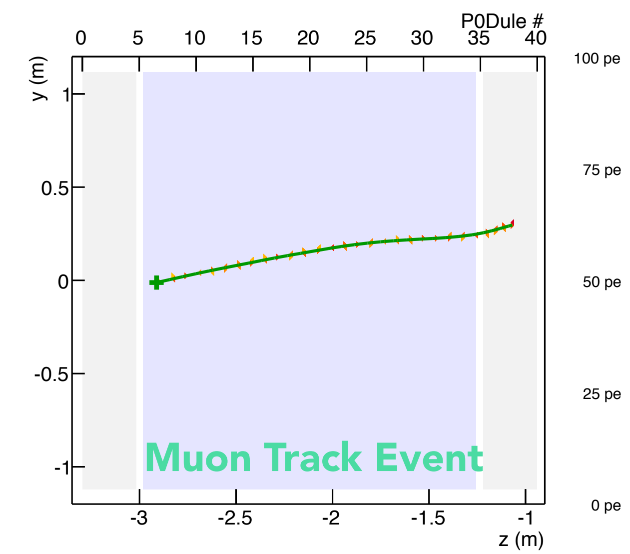
$$\pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

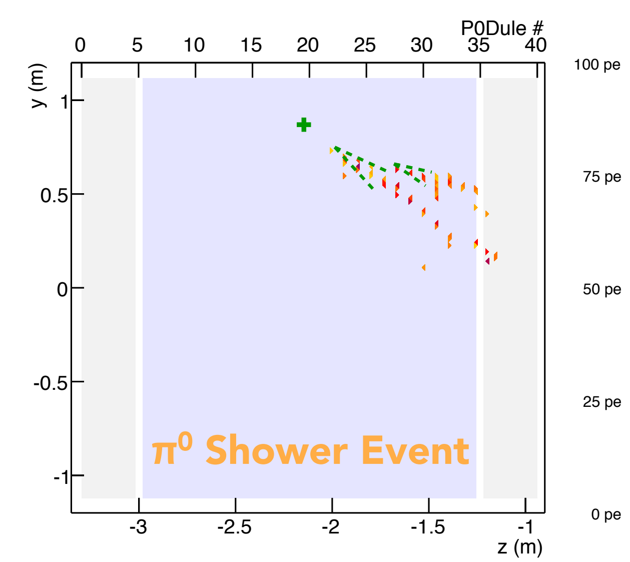
$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

Analysis: Event Selection

- The selection is to identify a sample of **charged current inclusive ν_e events** in the P0D
  - **Basic event selection**
    - Data/Beam quality checks
    - Basic reconstruction quality checks
    - Fiducial volume
  - **Particle angle w.r.t beam axis < 45°** : Prevent reconstruction efficiency decrease
  - **Reconstructed neutrino energy > 1.5 GeV**
  - **Track Median Width**: Width based PID to remove **muon** backgrounds
  - **Shower Median Width**: Width based PID to remove **pion** backgrounds
  - **Shower Charge Fraction**: All charge in a single electron shower



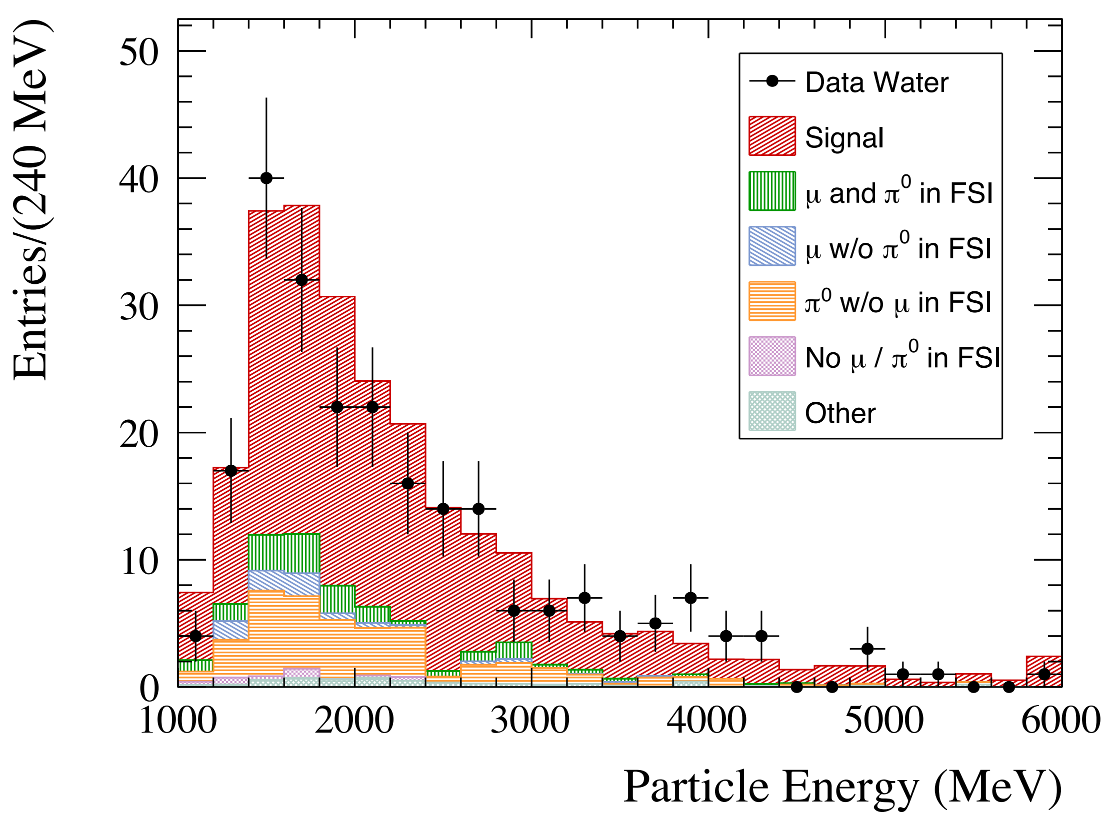




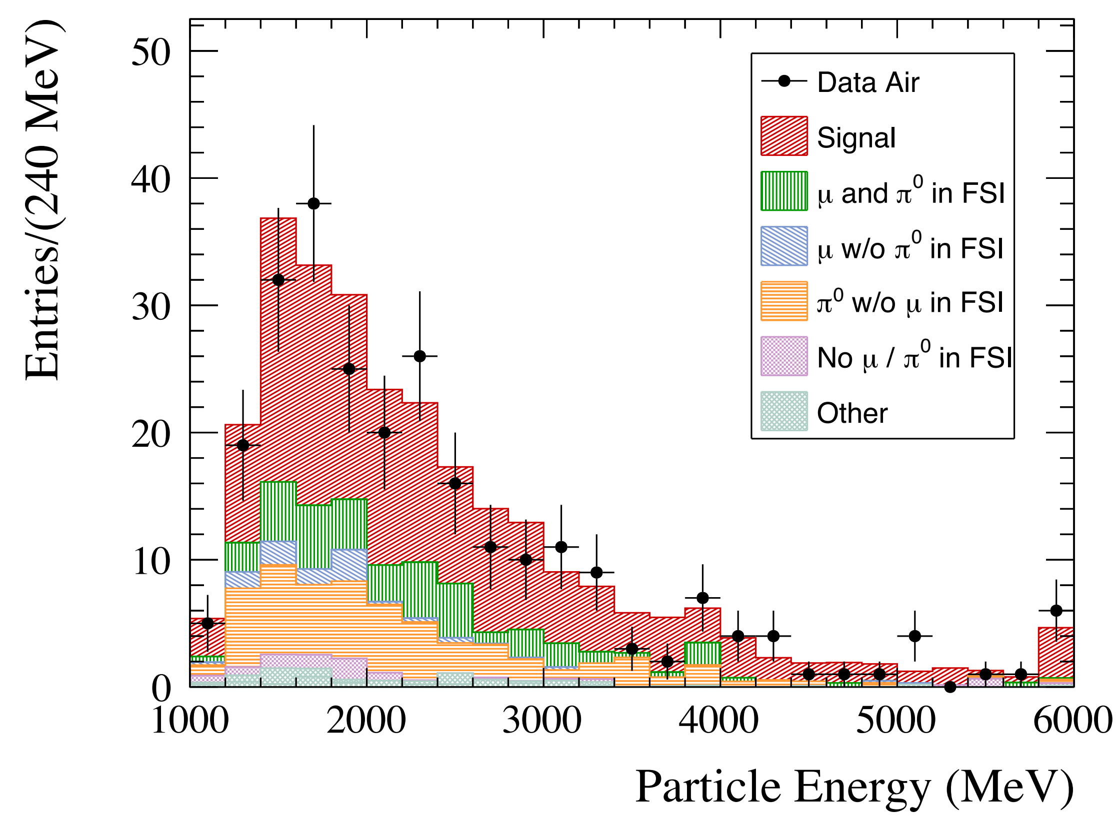
Analysis: Selected Event Sample

	MC Signal S	MC Background B	MC Total $S+B$	Data D
Water (Water filled)	196.1 ± 4.8	56.7 ± 2.7	252.8 ± 5.5	230
On-Water	60.2 ± 2.6	14.5 ± 1.3	74.7 ± 2.9	
Not-Water	135.9 ± 4.0	42.2 ± 2.3	178.2 ± 4.6	
Air (Water drained)	173.6 ± 4.6	97.4 ± 3.6	271.0 ± 5.8	257

(Errors are due to statistical error from limited MC statistics)



Selected Signal Events for Water Configuration

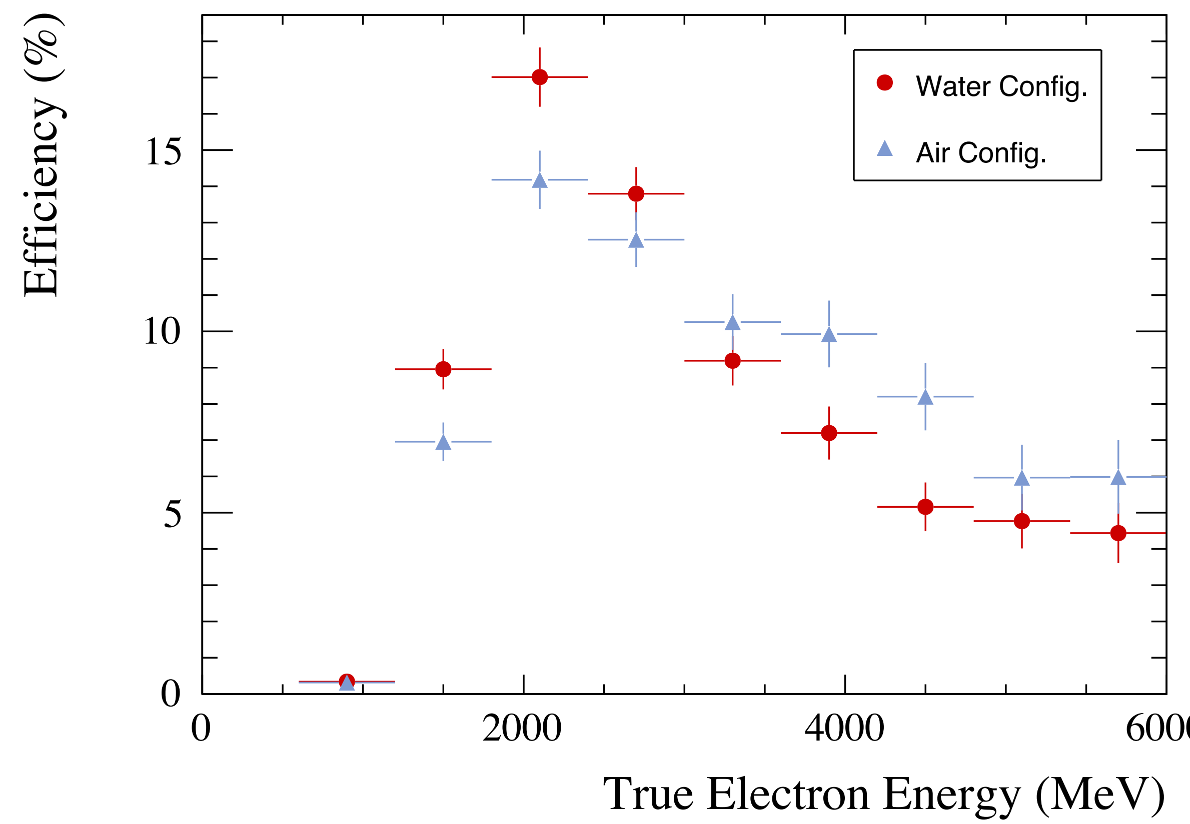


Selected Signal Events for Air Configuration

Selection Efficiency

- Selection efficiency is rather heavily dependent on electron energy
  - Low energy signal selection is suppressed by the neutrino energy cut
  - High energy signal selection is suppressed by the shower median width cut and shower charge fraction cut
- On-Water: Events interact with water target

  Not-Water: Events interact with non-water materials (scintillator, brass, lead, etc.)



	Efficiency ϵ	Purity p
Water	$(10.9 \pm 0.3)\%$	$(77.6 \pm 2.5)\%$
On-Water	$(9.8 \pm 0.4)\%$	$(80.6 \pm 4.7)\%$
Not-Water	$(11.5 \pm 0.4)\%$	$(76.3 \pm 3.0)\%$
Air	$(11.0 \pm 0.3)\%$	$(64.1 \pm 2.2)\%$

Analysis: Water Subtraction

- Perform a background subtraction to measure *signal* from data (*N*: Number of events, *D*: Data, *B*: MC Background)

$$N^{Data}_{\mathrm{CC}\nu_e,\mathrm{water}} = D_{\mathrm{water}} - g_{\mathrm{water}} \cdot B_{\mathrm{water}}$$
$$N^{Data}_{\mathrm{CC}\nu_e,\mathrm{air}} = D_{\mathrm{air}} - g_{\mathrm{air}} \cdot B_{\mathrm{air}}$$

- *Background* can be weighted by factor *g* (*g* = 1 for simple background subtraction)

- The number of *on-water signal* events is extracted by the following:

$$N^{Data}_{\mathrm{CC}\nu_e,\mathrm{on\text{-}water}} = N^{Data}_{\mathrm{CC}\nu_e,\mathrm{water}} - \frac{\epsilon_{\mathrm{not\text{-}water}} \cdot \mathrm{POT}_{\mathrm{water}}}{\epsilon_{\mathrm{air}} \cdot \mathrm{POT}_{\mathrm{air}}} \cdot N^{Data}_{\mathrm{CC}\nu_e,\mathrm{air}}$$

  - ε are the efficiencies
  - The number of *on-water signal* events is then:

$$N^{Data}_{\mathrm{CC}\nu_e,\mathrm{on\text{-}water}} = N^{Data}_{\mathrm{on\text{-}water}} - g_{\mathrm{water}} \cdot B_{\mathrm{on\text{-}water}}$$

Analysis: Systematic Uncertainties Summary

Systematic Uncertainty for CCν_e Data/MC Ratio	R_{water}	R_{air}	$R_{\text{on-water}}$
MC Statistics	0.03	0.04	0.12
Bias Analysis Method	0.00	0.00	0.02
PØD Mass	0.01	0.01	0.01
PØD Fiducial Volume	< 0.01	< 0.01	< 0.01
PØD Alignment	< 0.01	< 0.01	< 0.01
Energy Scale	0.05	0.05	0.10
Hit Matching	< 0.01	< 0.01	< 0.01
Track PID	0.05	0.05	0.09
Energy Resolution	< 0.01	< 0.01	0.01
Angular Resolution	< 0.01	< 0.01	0.01
Track Median Width	< 0.01	< 0.01	< 0.01
Shower Median Width	0.04	0.04	0.08
Shower Charge Fraction	0.01	0.04	0.04
Flux and Cross Sections Pre-Fit (Before ND280 Constraints)	0.22	0.26	0.17
Flux and Cross Sections Post-Fit (After ND280 Constraints)	0.07	0.09	0.06
Total with Pre-Fit (Before ND280 Constraints)	0.24	0.28	0.27
Total with Post-Fit (After ND280 Constraints)	0.11	0.13	0.21

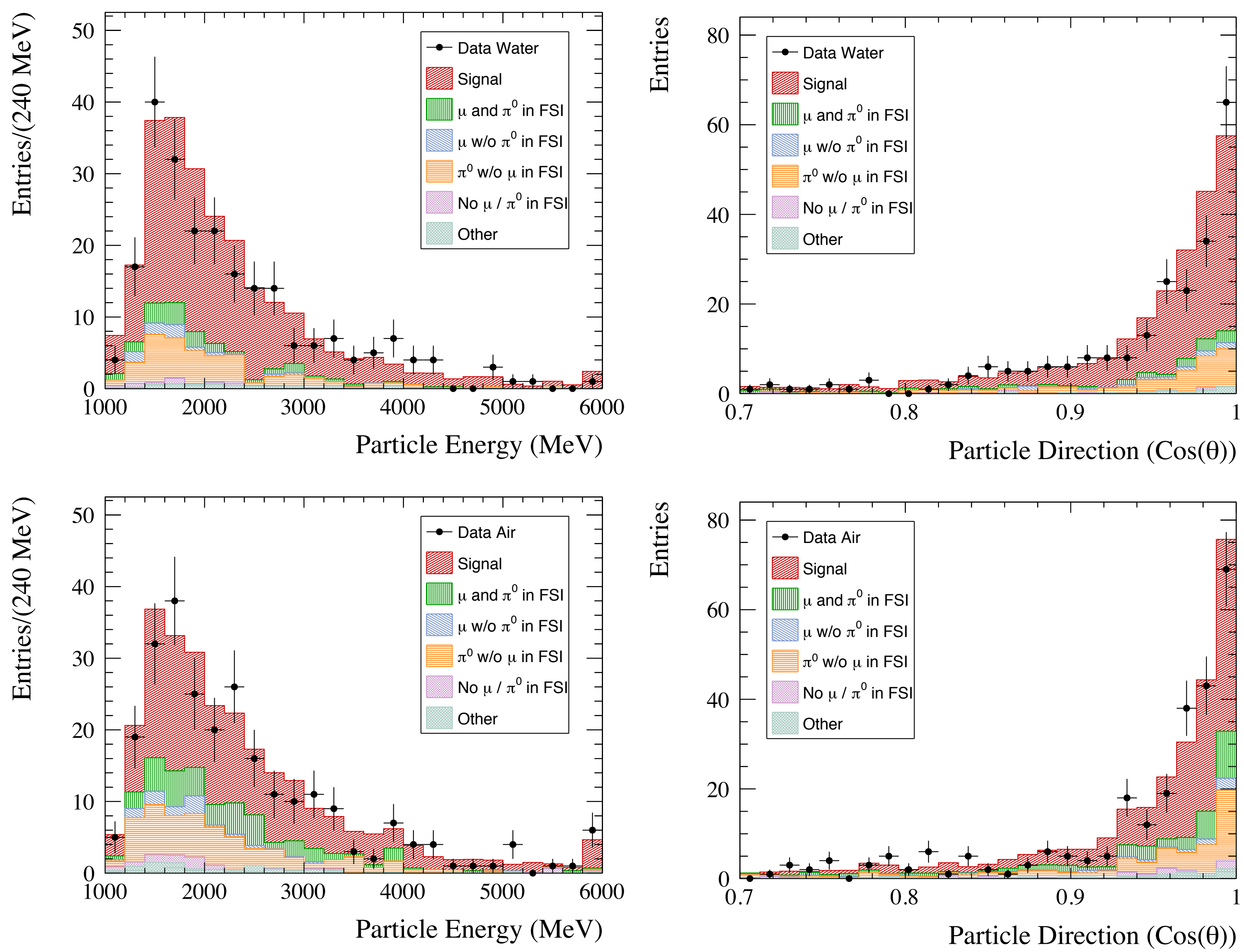
Analysis: Results

- $CC\nu_e$ background subtracted data/MC ratios is:

$$
\begin{aligned}
R_{\text{water}} &= 0.89 \pm 0.08\ (\text{stat.}) \pm 0.11\ (\text{sys.})\\
R_{\text{air}} &= 0.90 \pm 0.09\ (\text{stat.}) \pm 0.13\ (\text{sys.})\\
R_{\text{on-water}} &= 0.87 \pm 0.33\ (\text{stat.}) \pm 0.21\ (\text{sys.})
\end{aligned}
$$

- Fit results from ND280 data are applied
- The result indicates that the beam ν_e component in high energy region measured in the data is consistent with expectations

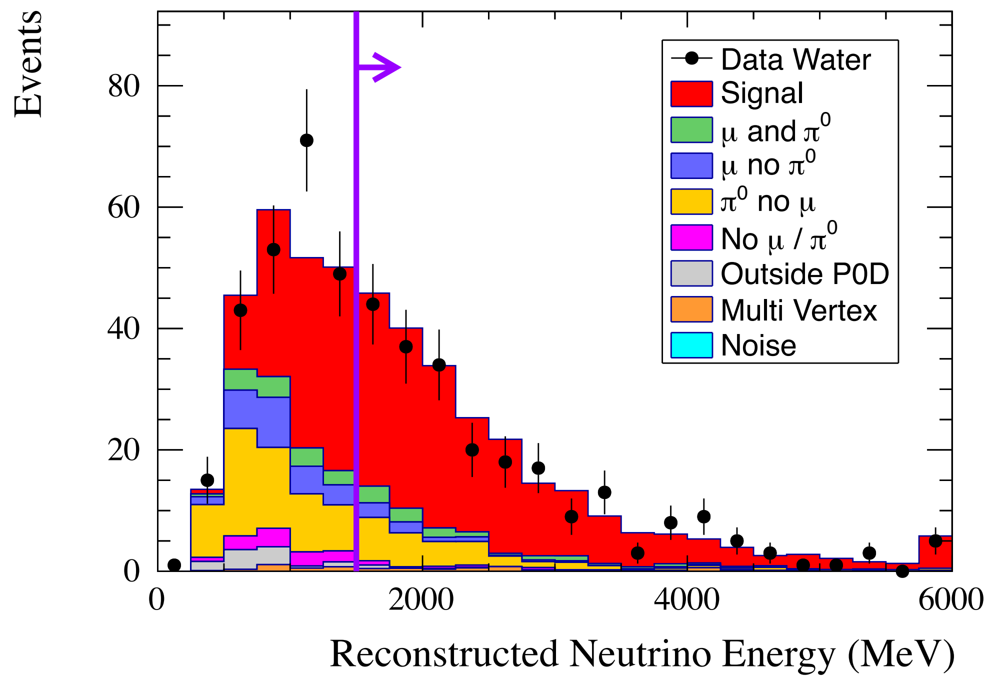
Water config.



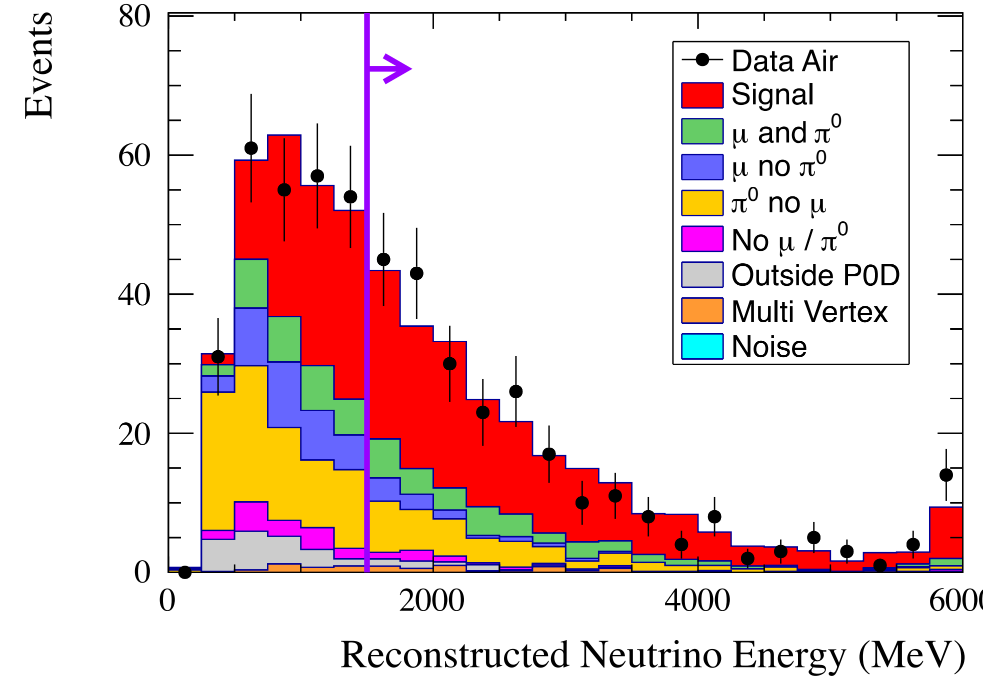
Air config.

Phys. Rev. D **91**, 112010 (2015)

Prospect: ν_e Analysis without Energy Threshold



(a) Water Configuration



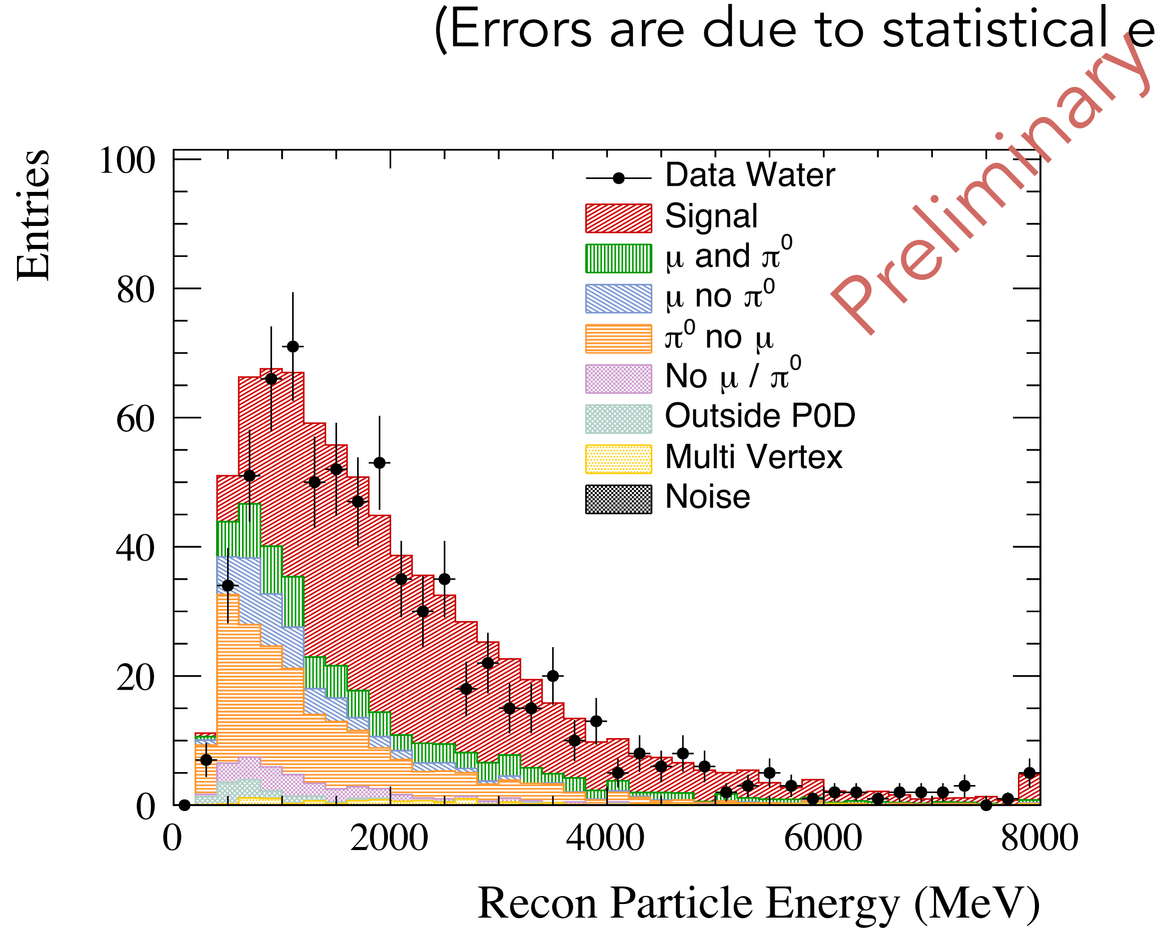
(b) Air Configuration

- The limitation of the previous analysis (high energy analysis) is the existence of the neutrino energy threshold
- To provide valuable information outside the T2K as well as to measure ν_e cross section on water in future, we need to remove the threshold
- New reconstruction algorithm and event selections applied

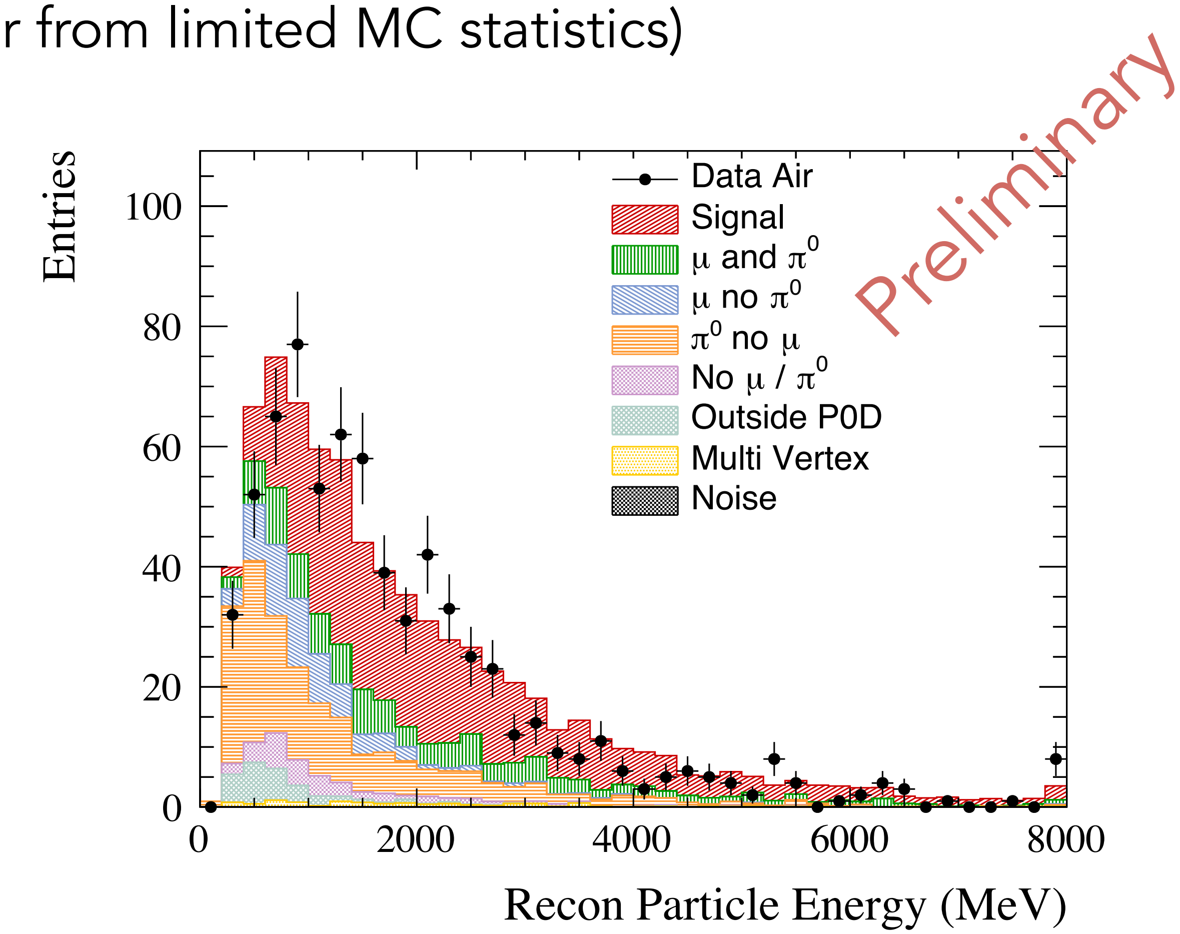
Prospect: ν_e Analysis without Energy Threshold

	MC Signal S	MC Background B	MC Total $S+B$	Data D
Water (Water filled)	447.6 ± 7.1	343.2 ± 6.4	790.8 ± 9.6	711
On-Water	152.7 ± 4.1	100.7 ± 3.4	253.4 ± 5.3	
Not-Water	294.9 ± 5.8	242.5 ± 5.4	537.4 ± 7.9	
Air (Water Drained)	355.6 ± 6.3	399.7 ± 6.9	755.3 ± 9.4	709

(Errors are due to statistical error from limited MC statistics)

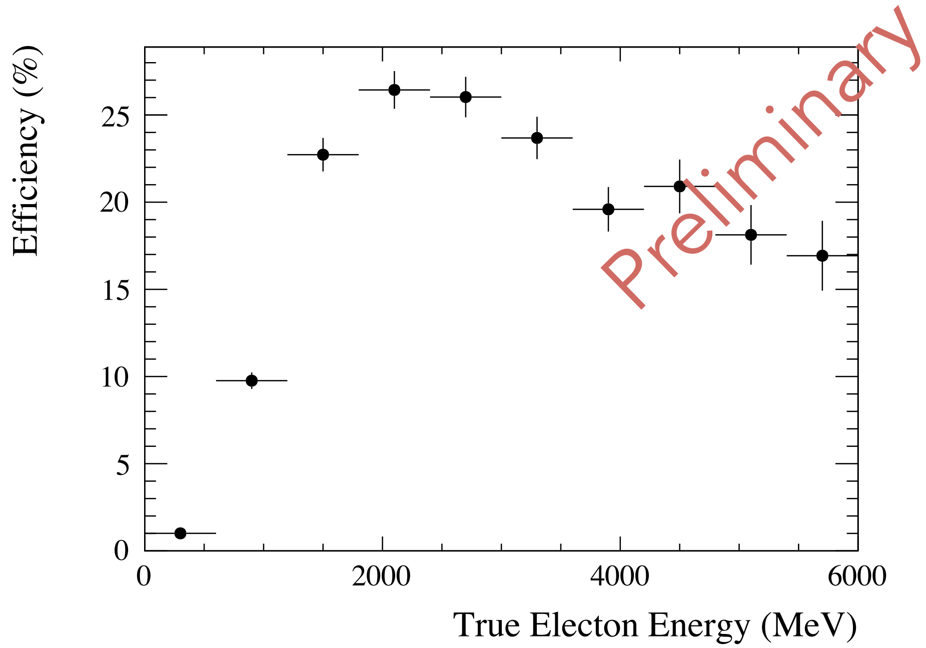


Selected Signal Events for Water Configuration

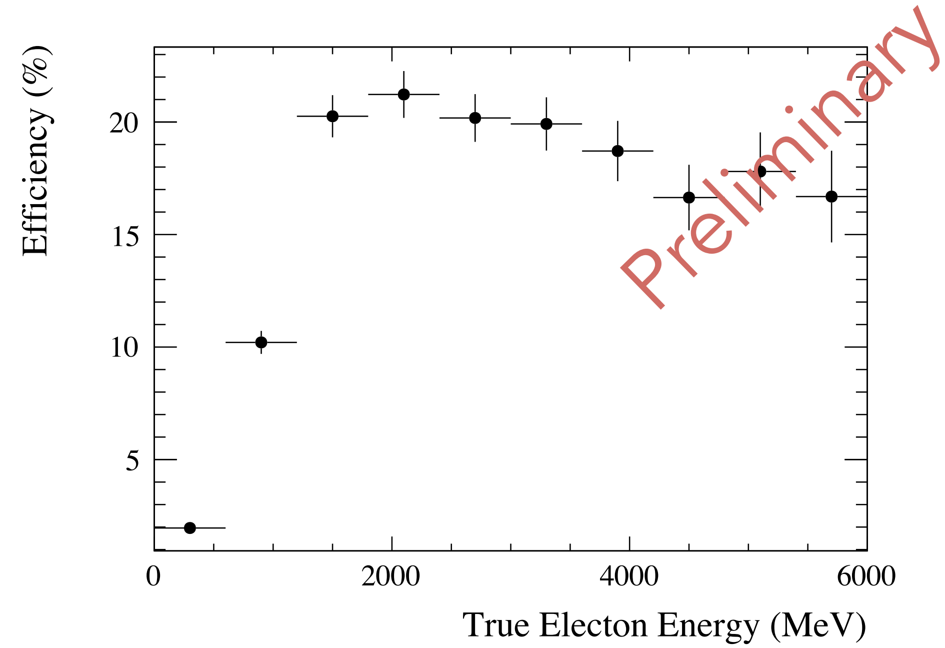


Selected Signal Events for Air Configuration

Prospect: ν_e Analysis without Energy Threshold



(a) Water Configuration



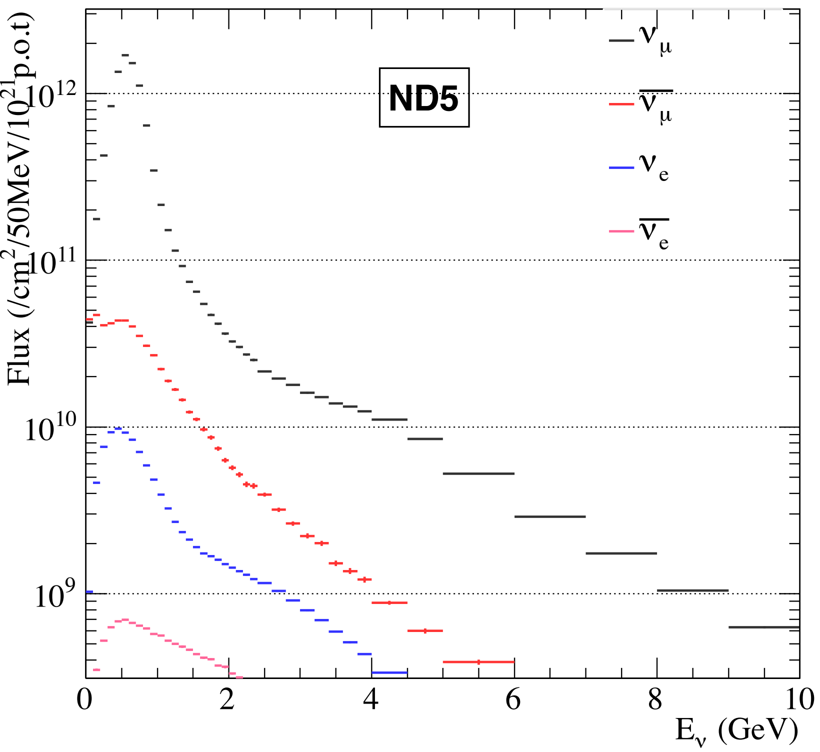
(b) Air Configuration

	Truth T	Efficiency ϵ	Purity p
Water	2459.0 ± 16.7	$(18.2 \pm 0.5)\,\%$	$(56.6 \pm 3.1)\,\%$
On-Water	819.3 ± 9.5	$(18.6 \pm 0.6)\,\%$	$(60.3 \pm 5.3)\,\%$
Not-Water	1639.6 ± 13.7	$(18.0 \pm 0.5)\,\%$	$(54.9 \pm 3.9)\,\%$
Air	2200.2 ± 15.8	$(16.2 \pm 0.5)\,\%$	$(47.1 \pm 3.4)\,\%$

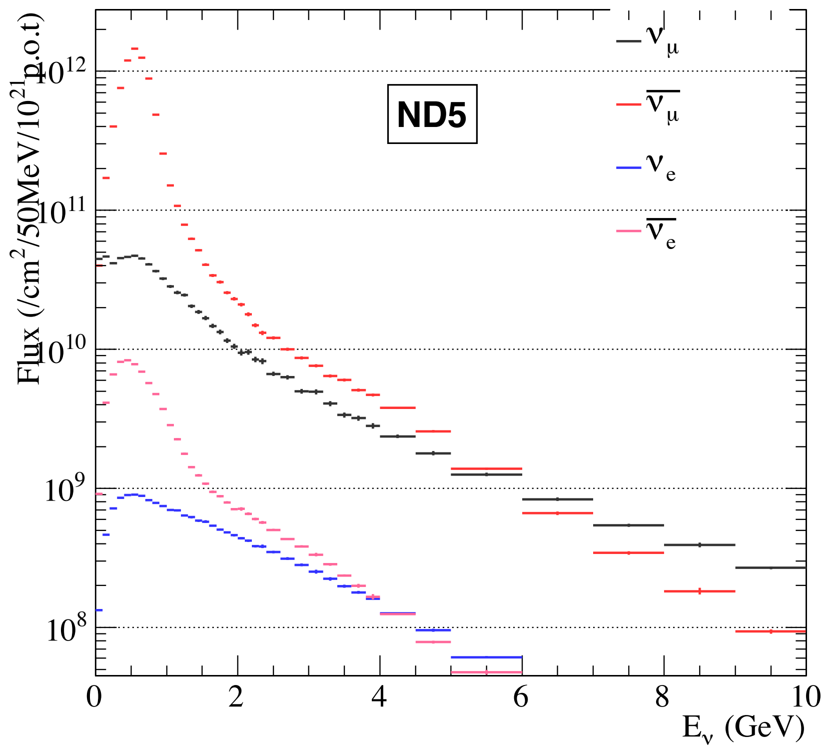
- Compared to the high energy analysis, high energy selection is not as suppressed
  - Shower charge fraction cut has been relaxed (tuned) from 1.0 to 0.9
- Lower purity but with higher efficiency

Prospect: Anti-nue Analysis

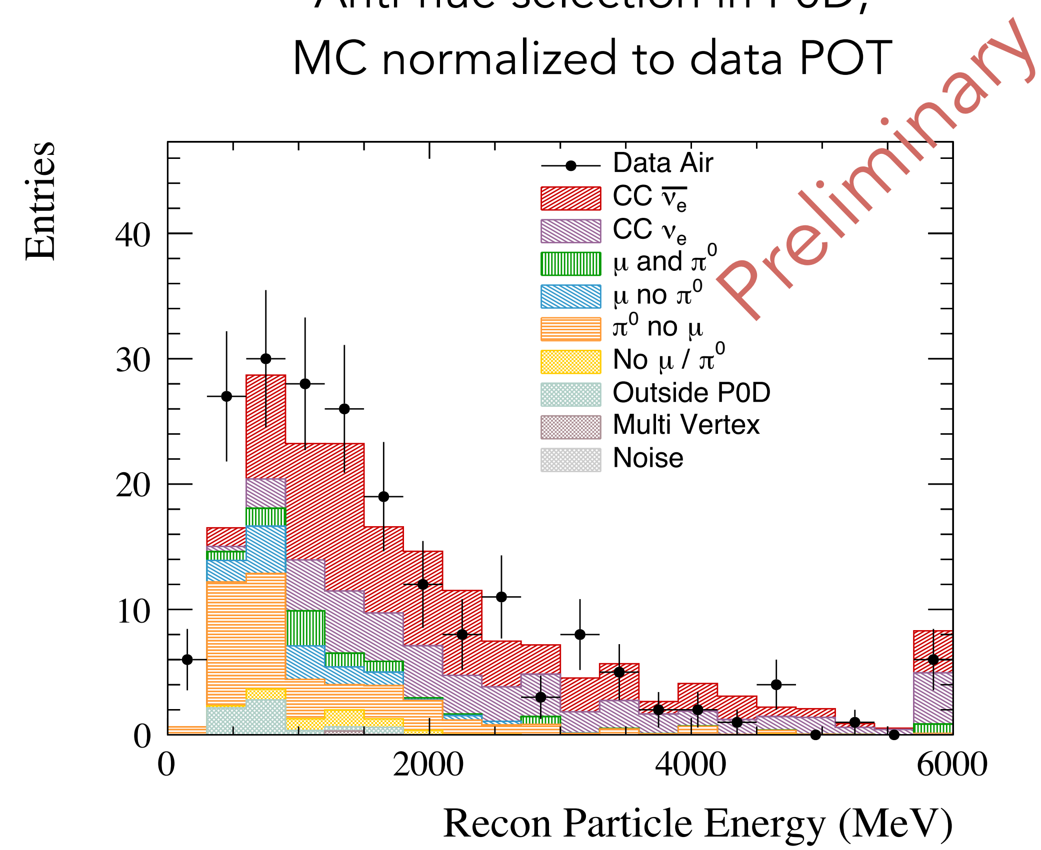
Neutrino flux prediction at ND280 in neutrino mode

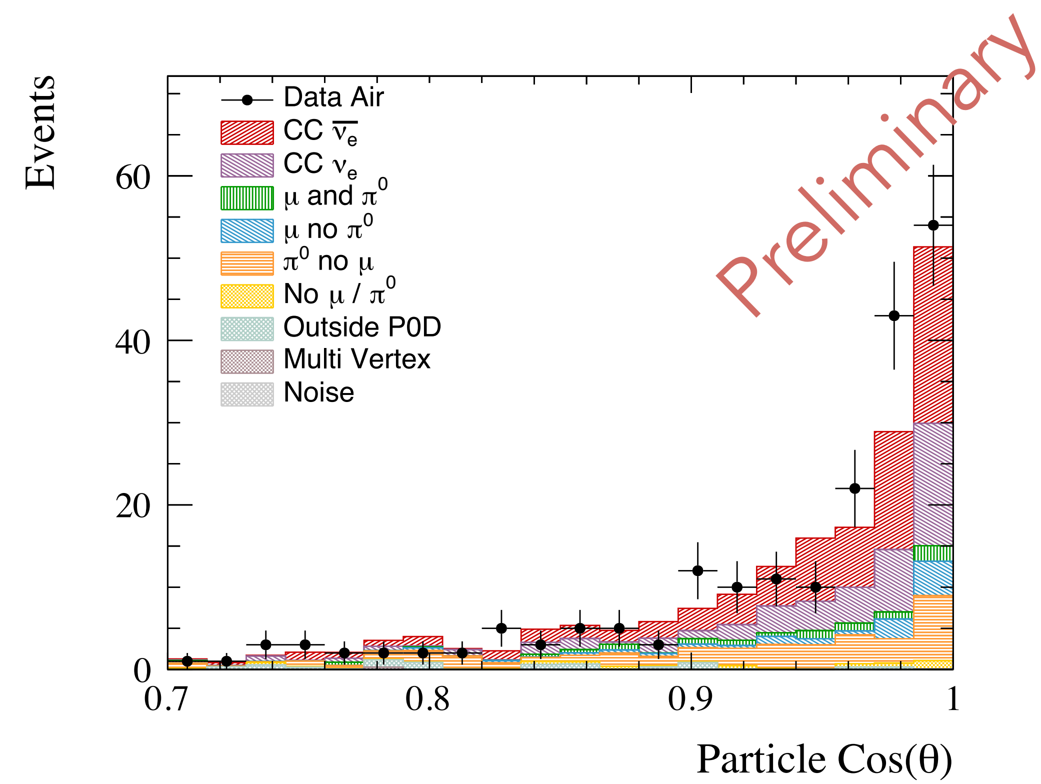


Neutrino flux prediction at ND280 in anti-neutrino mode



Anti-nue selection in P0D, MC normalized to data POT





- Using recent anti-neutrino mode data
  - Air configuration: 2.83 x 10^{19} POT
- Same event selection as ν_e analysis applied, optimized for $\nu_e + \bar{\nu}_e$ events
  - ν_e background is non-negligible when selecting $\bar{\nu}_e$ events!
  - For $\nu_e + \bar{\nu}_e$, ~64% purity is gained with 199 total data events
- Will soon look at systematic uncertainties

Conclusion and Future Outlook

- T2K is a long baseline neutrino oscillation experiment with world leading results
- Detailed understanding of the neutrino interactions is required for the future ν_e appearance precision measurements
- Successfully finished the intrinsic ν_e measurement on water:

$$\begin{aligned} R_{\text{water}} &= 0.89 \pm 0.08\ (\text{stat.}) \pm 0.11\ (\text{sys.}) \\ R_{\text{air}} &= 0.90 \pm 0.09\ (\text{stat.}) \pm 0.13\ (\text{sys.}) \\ R_{\text{on-water}} &= 0.87 \pm 0.33\ (\text{stat.}) \pm 0.21\ (\text{sys.}) \end{aligned}$$

  - Result recently published (Phys. Rev. D **91**, 112010 (2015))
  - The first measurement of ν_e interaction rate on water in the few GeV energy region
- New analysis to improve this measurement is on-going
  - Removed 1.5 GeV neutrino energy threshold and new software/selection criteria is applied
  - The study will be extended to measure ν_e absolute cross-section on water
- T2K has been collecting data with anti-neutrino mode
  - $\bar{\nu}_e$ analysis result coming soon!

Backup

Introduction: Neutrino Oscillations

PMNS mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix}} \boxed{\begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix}} \boxed{\begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates | Atmospheric | Reactor/Accelerator | Solar | mass eigenstates

$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$

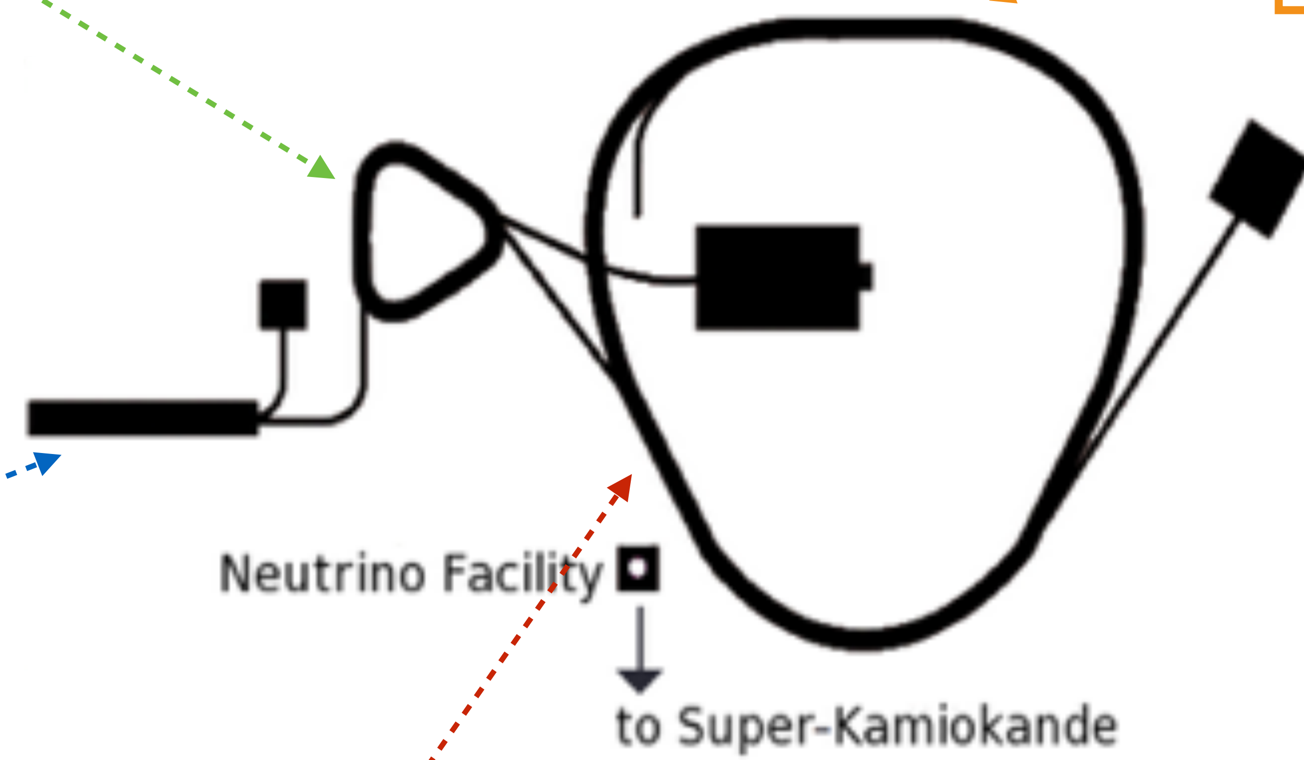
- Neutrino oscillation described by the PMNS matrix
  - 3 mixing angles, 2 mass splittings, 1 complex CP phase
- Mixing angles and mass splittings have been measured
  - $\boldsymbol{\theta_{12}}$~34°, $\boldsymbol{\theta_{23}}$~45°, $\boldsymbol{\theta_{13}}$~9°, $\boldsymbol{\Delta m^2_{12}}$~7.6x$10^{-5}$ eV^2, $\boldsymbol{|\Delta m^2_{23}|}$~2.4x$10^{-3}$ eV^2
- We still do <u>not</u> know: CP phase, neutrino mass hierarchy, existence of sterile neutrinos, …

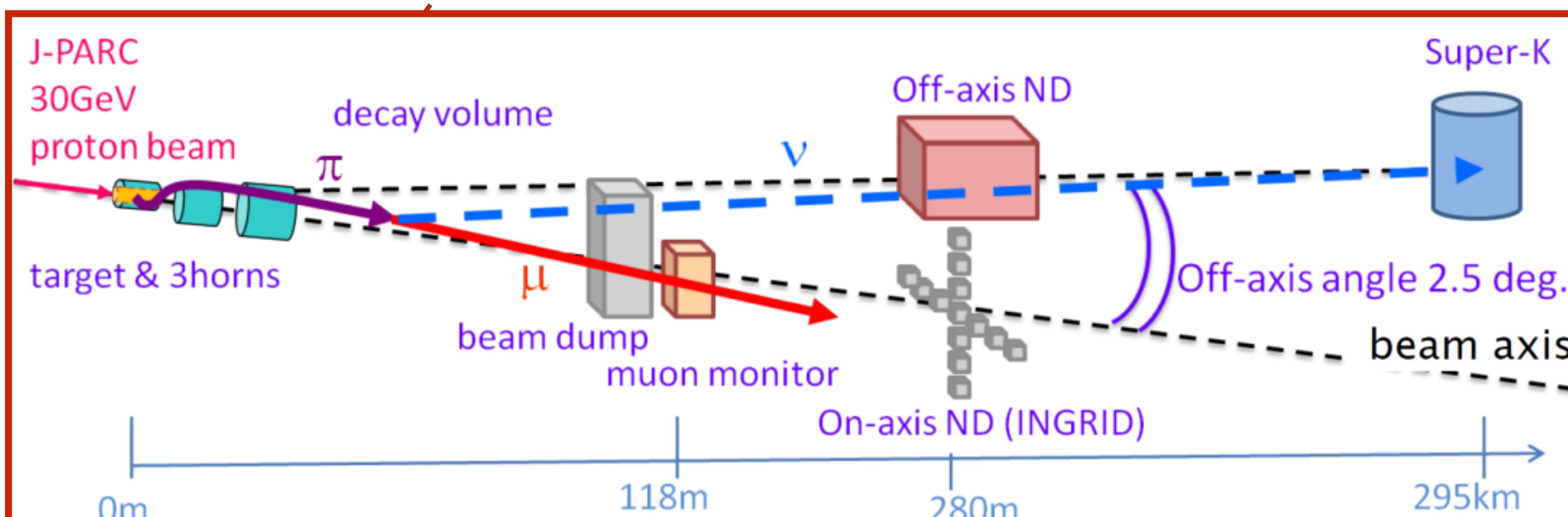
T2K Beamline @ J-PARC

3 GeV
Rapid Cycling Synchrotron

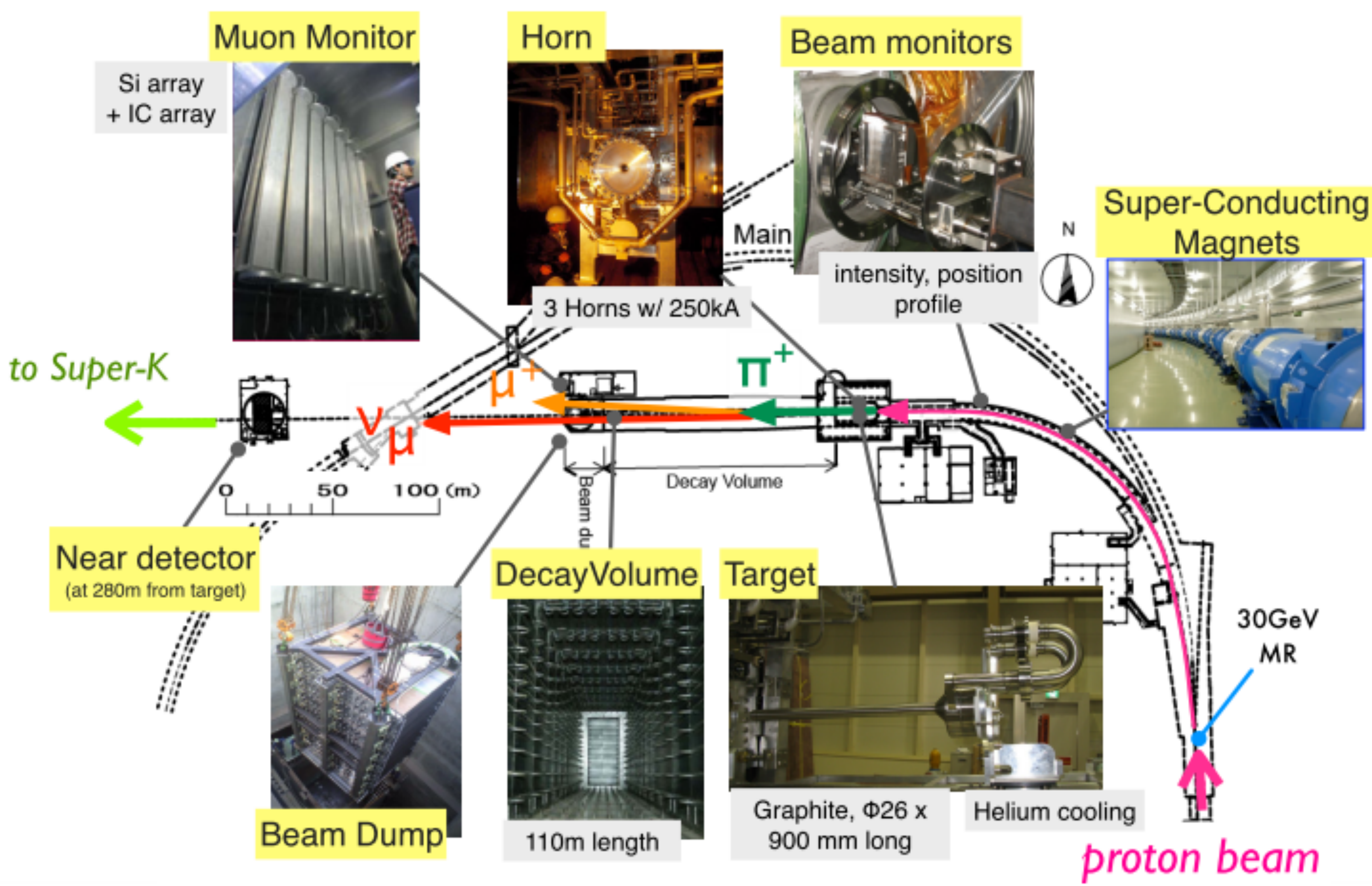
30 GeV
Main Ring Synchrotron

400 MeV
LINAC



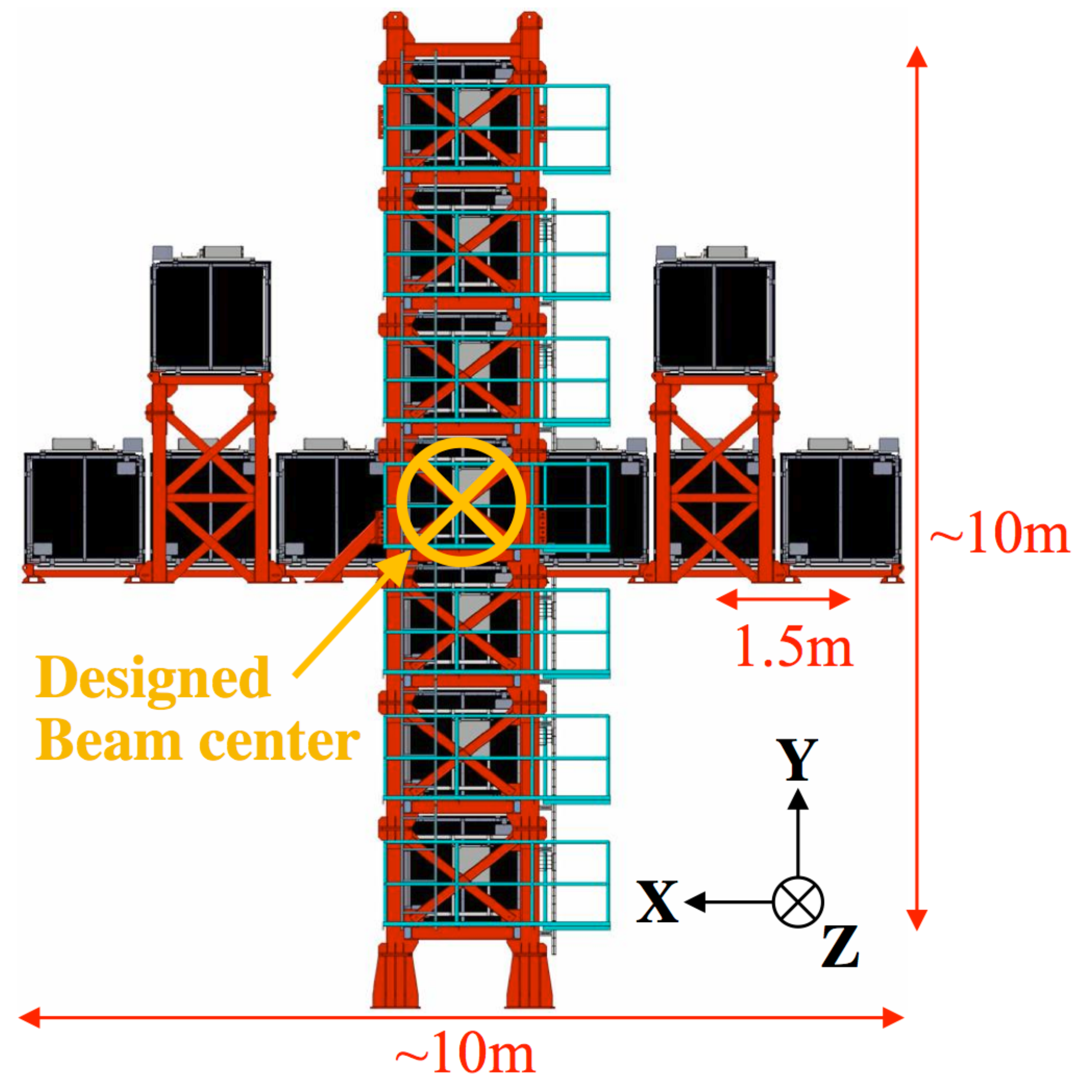


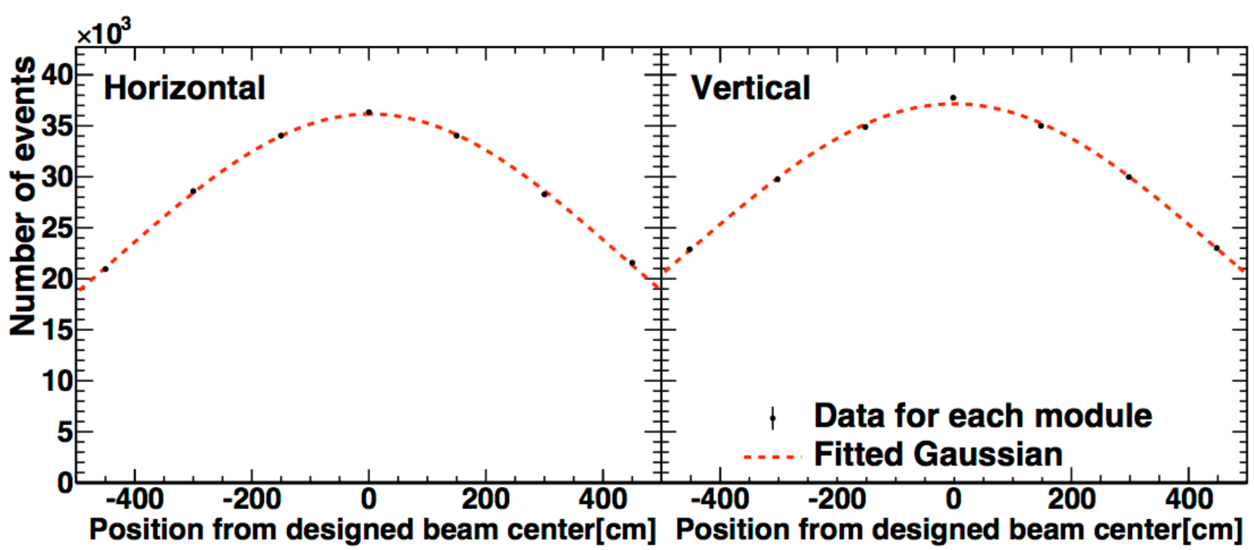
J-PARC Neutrino Beam Facility



On-Axis Near Detector: INGRID

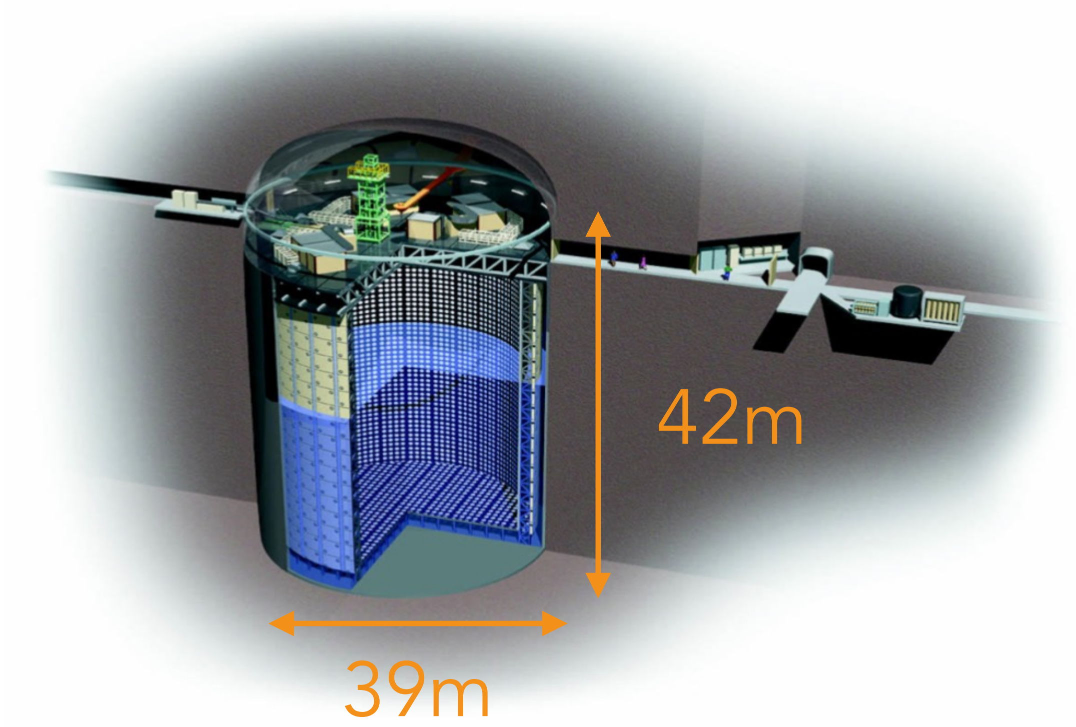
- Interactive Neutrino GRID
  - 280m from target on beam axis
  - 16 iron/scintillator module
  - 1 scintillator tracking module
  - Monitors beam center, profile and neutrino flux

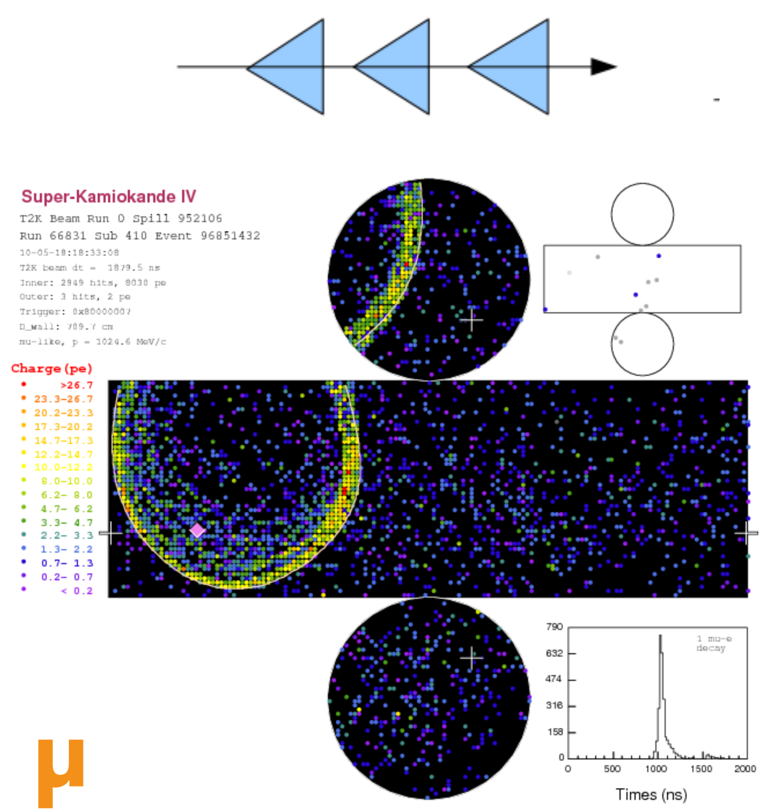


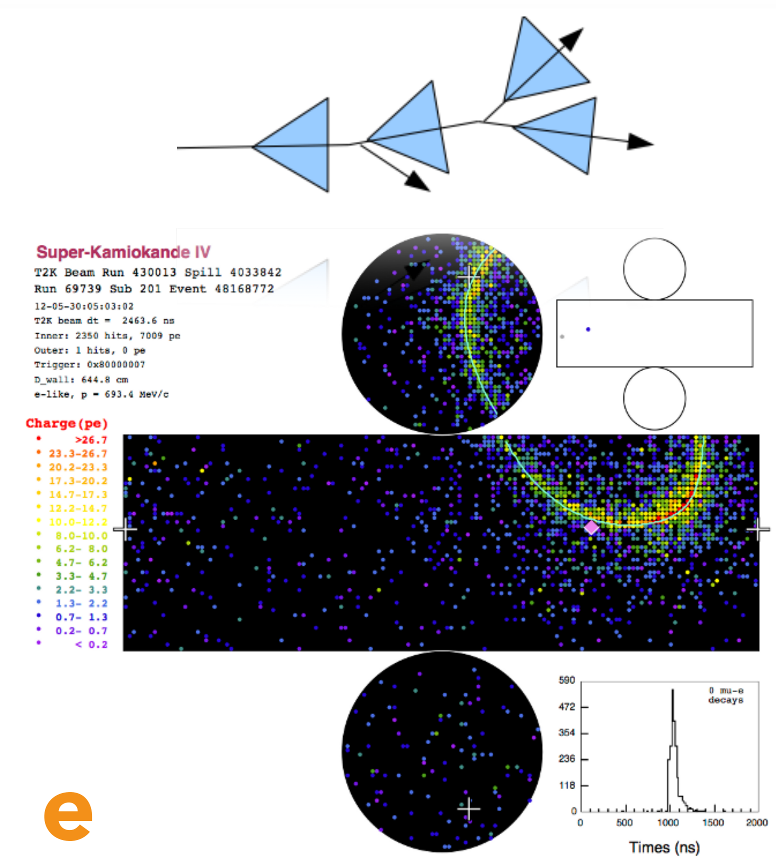


Far Detector: Super-Kamiokande

- 50 kton water Cherenkov detector (22.5 kton fiducial volume)
- Inner detector: ~11,000 20inch PMTs
- Outer detector: ~2,000 8inch PMTs

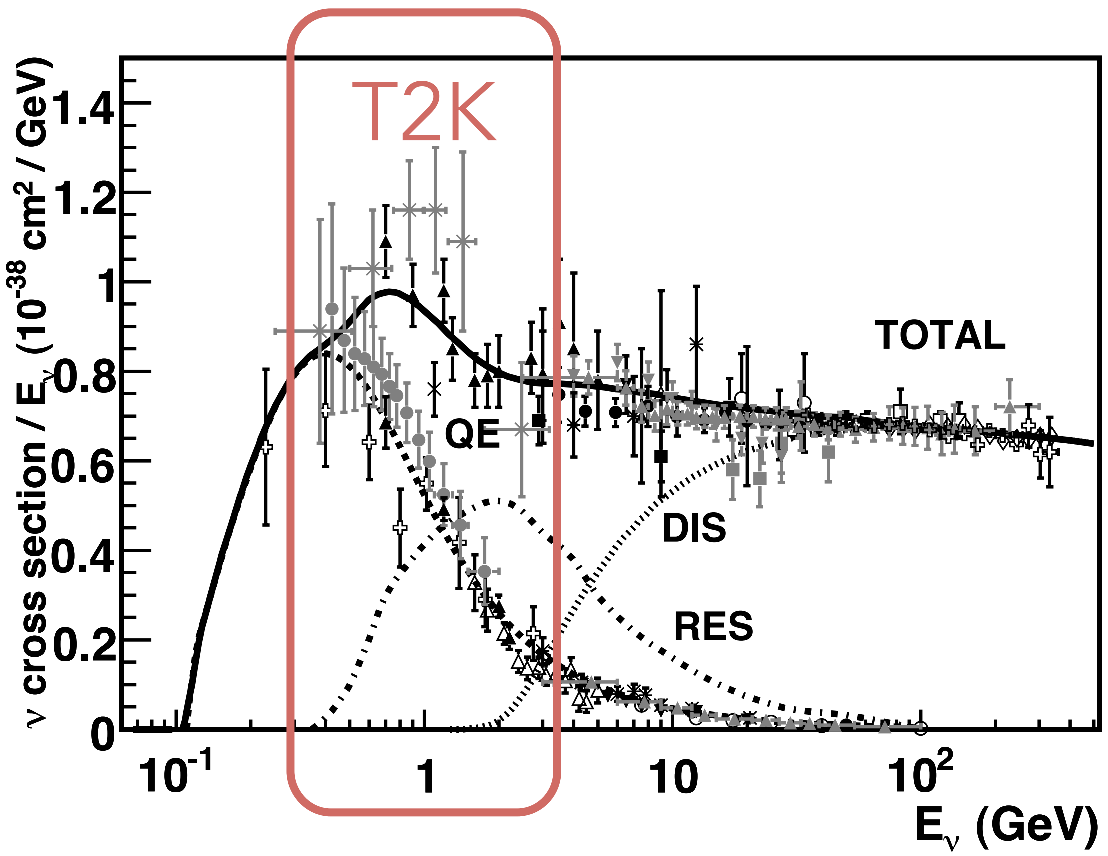


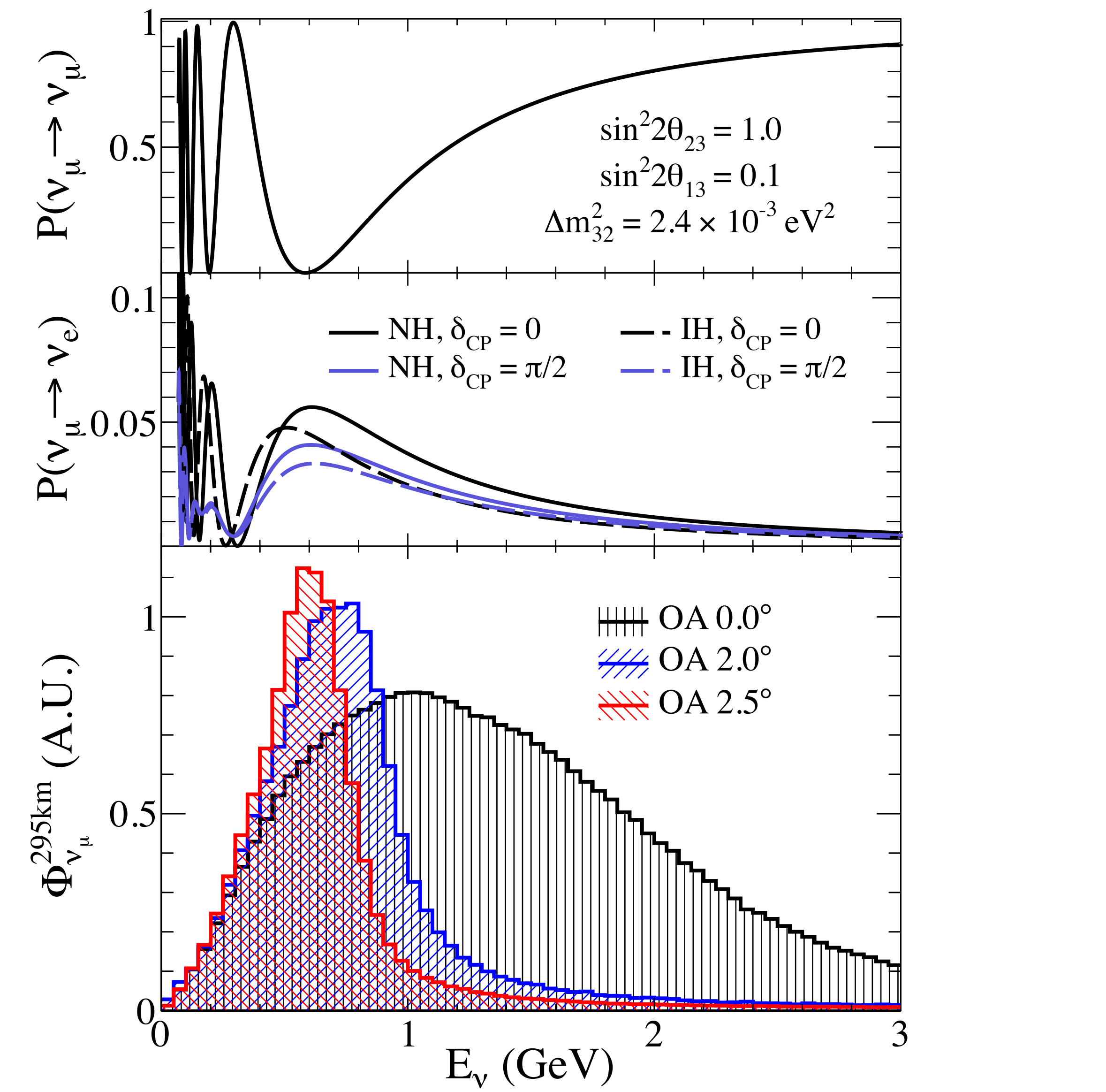




T2K Experiment: Off-Axis Technique

Formaggio et al. Rev. Mod. Phys. 84 (2012)





- ND280 located at 2.5 degrees off-axis
- Off-axis gives 'narrow band' beam peak at the oscillation maximum, E~600MeV
  - Higher statistics of oscillated neutrinos
  - Reduced contamination from non-oscillated high energy neutrinos

T2K Experiment: Oscillation Analysis Strategy

Neutrino flux prediction

- Simulation of hadronic interactions in target and propagation of secondary particles
- Hadron production data from NA61/SHINE

ND280

ν_μ MC sample enhanced in CC events

ν_μ Data sample enhanced in CC events

Fit to ND280 data constrains flux and cross section parameters

SK

Expected ν_e (ν_μ) events in MC

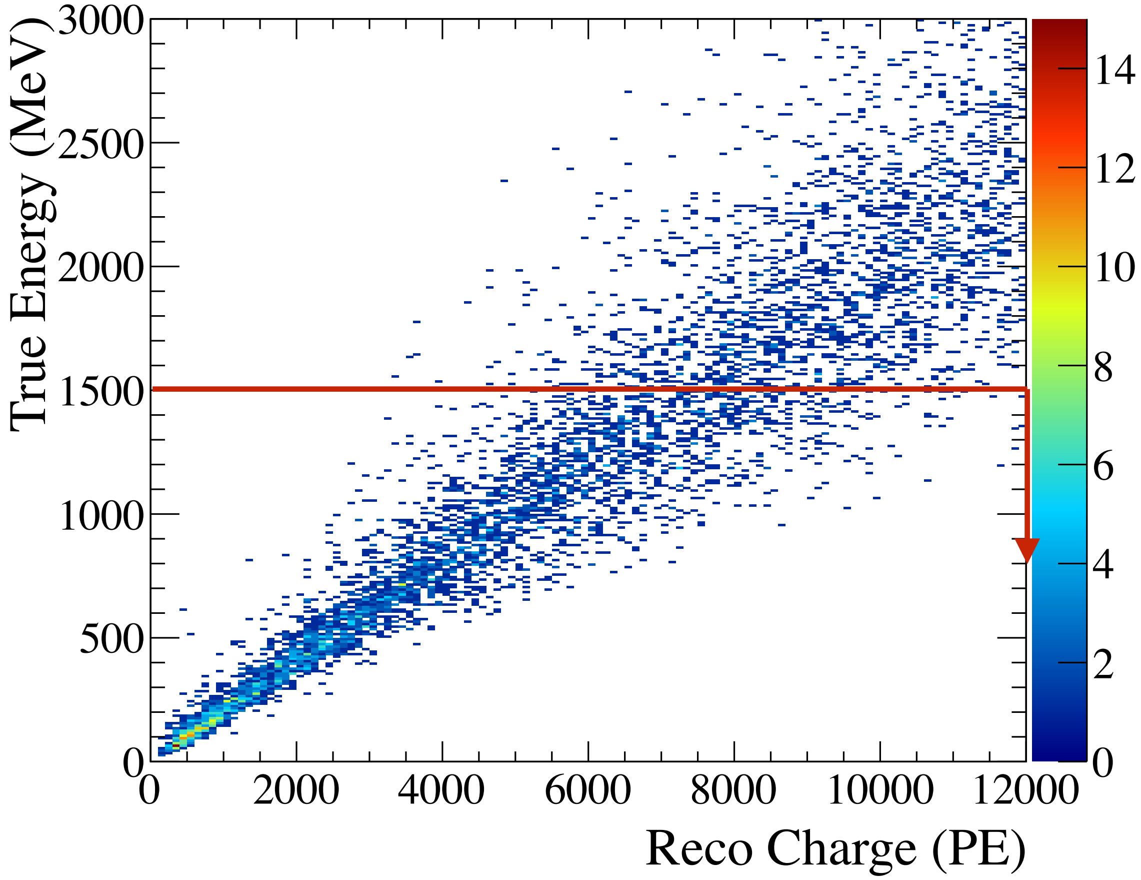
ν_e (ν_μ) events selection in Data

Cross section models

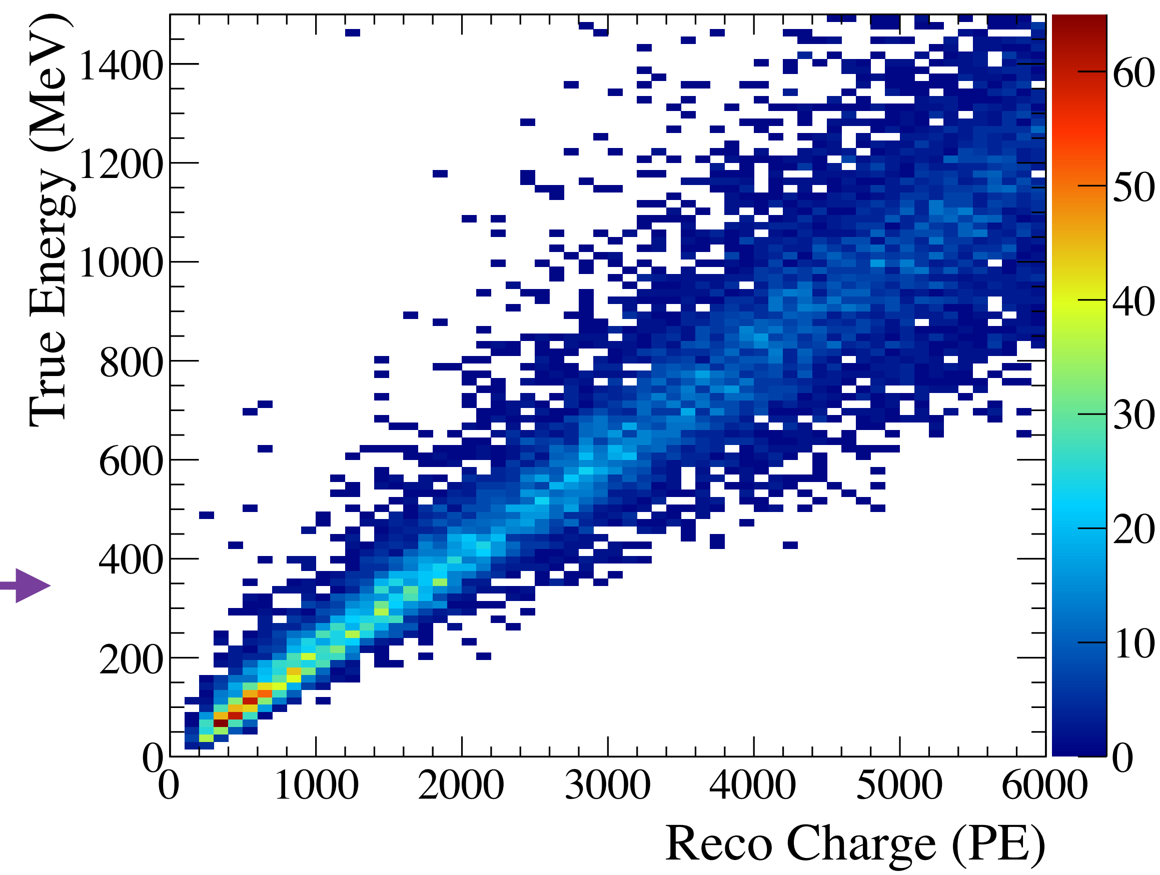
- Interaction generator (NEUT)
- External cross-section data (MiniBooNE)

Extraction of the oscillation parameters

MC Energy Calibration



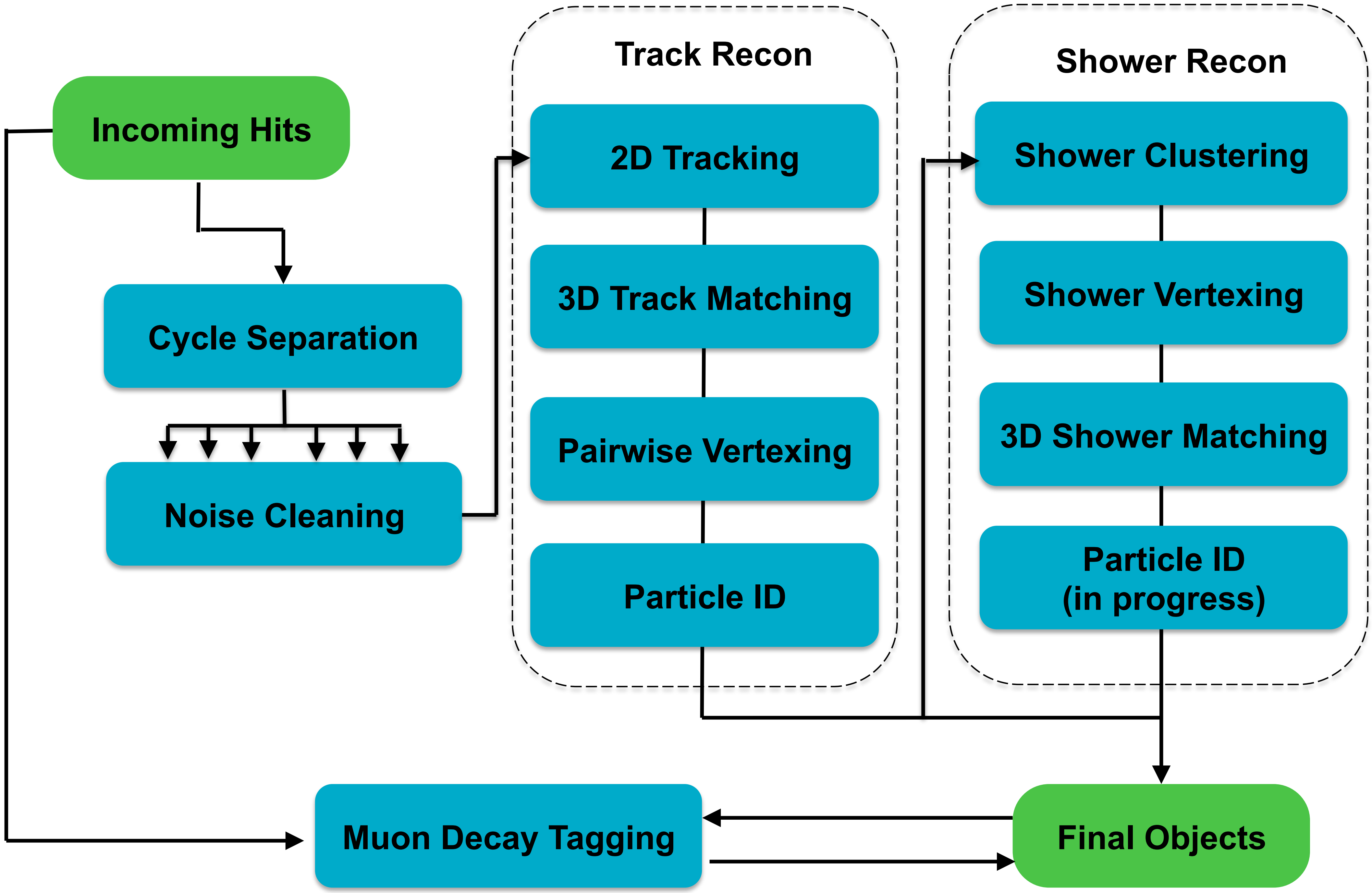
(True Electron Energy 0~3 GeV)



(True Electron Energy 0~1.5 GeV)

- Compare reconstructed charge of tracks/showers of MC events with the corresponding true particle energy
- MC electron particle gun is used

P0D Reconstruction



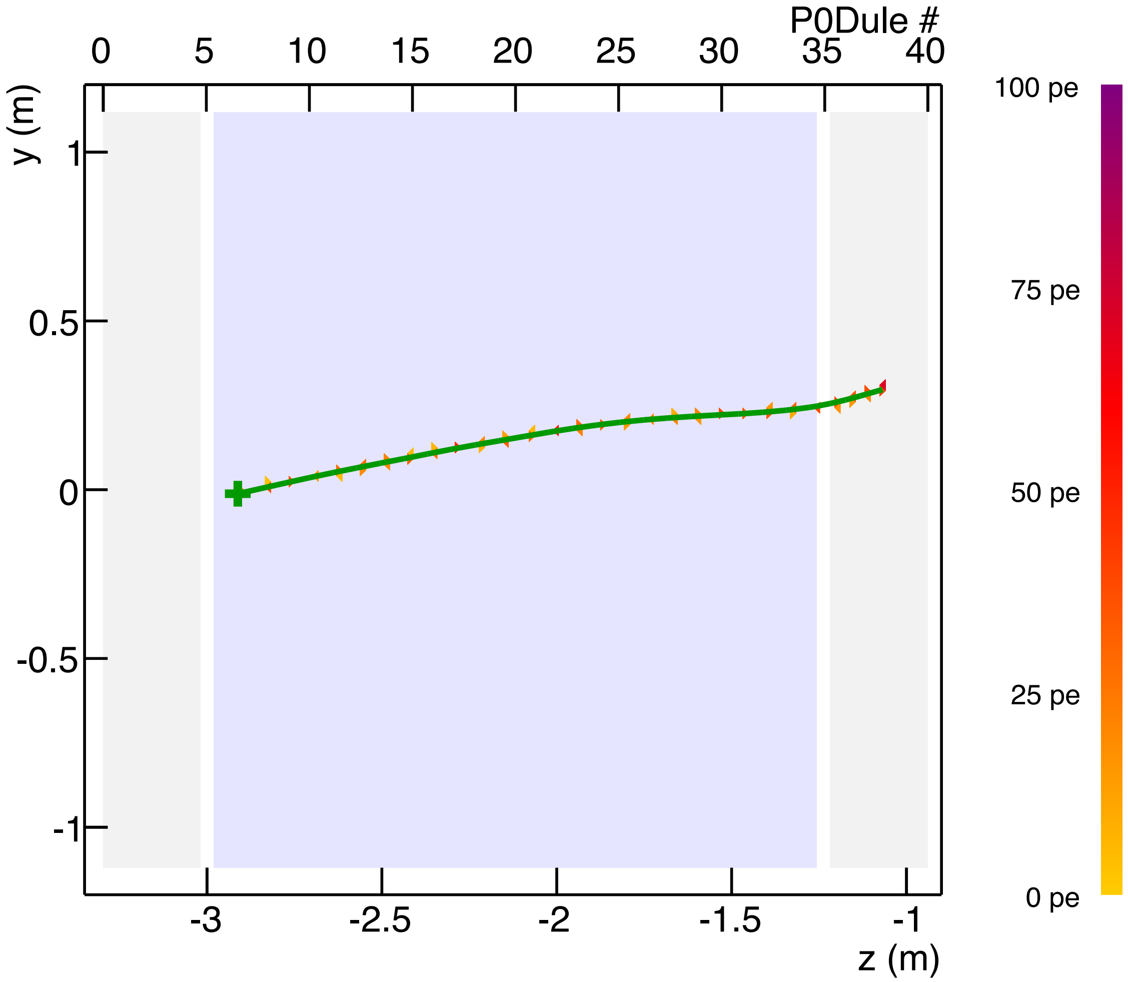
Analysis: Data and Monte Carlo Samples

TABLE I. Summary of T2K runs and the number of protons on target (POT) used in the analysis.

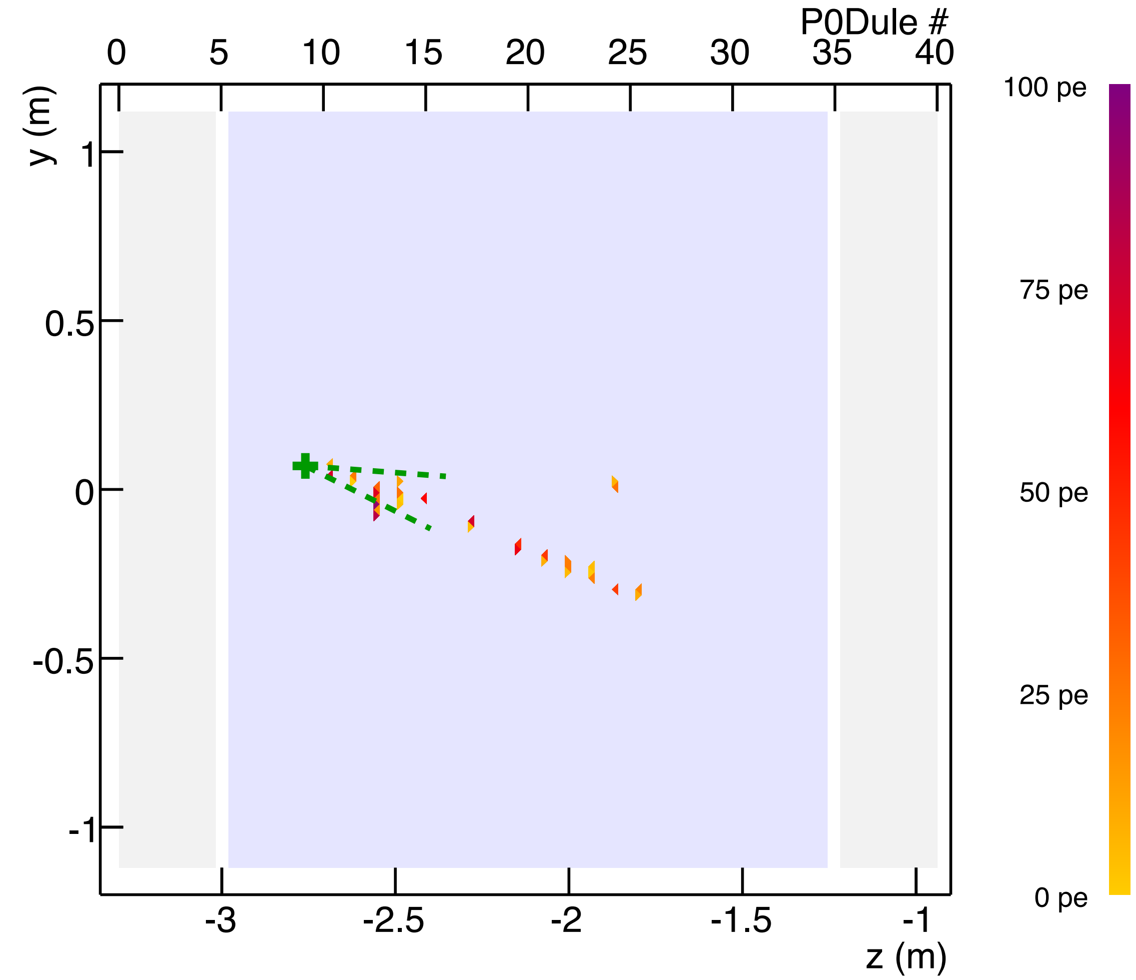
T2K run	PØD Config.	Beam Power (kW)	POT ($\times 10^{19}$)
Run I	Water	50	2.96
Run II	Water	120	6.96
Run II	Air	120	3.59
Run III	Air	178	13.5
Run IV	Water	178	16.5
Run IV	Air	178	17.8
Total	Water		26.4
	Air		34.9

- Full T2K neutrino-mode data sets used in this analysis: Run1 ~ Run4
- Total POT:
  - Water configuration: 2.64×10^{20}
  - Air configuration: 3.49×10^{20}
- 10 times data POT for Monte Carlo

Event Selection: Track Median Width

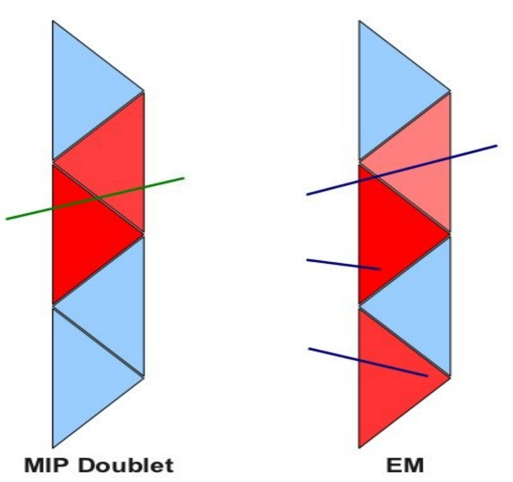


Muon Track Event (Background)

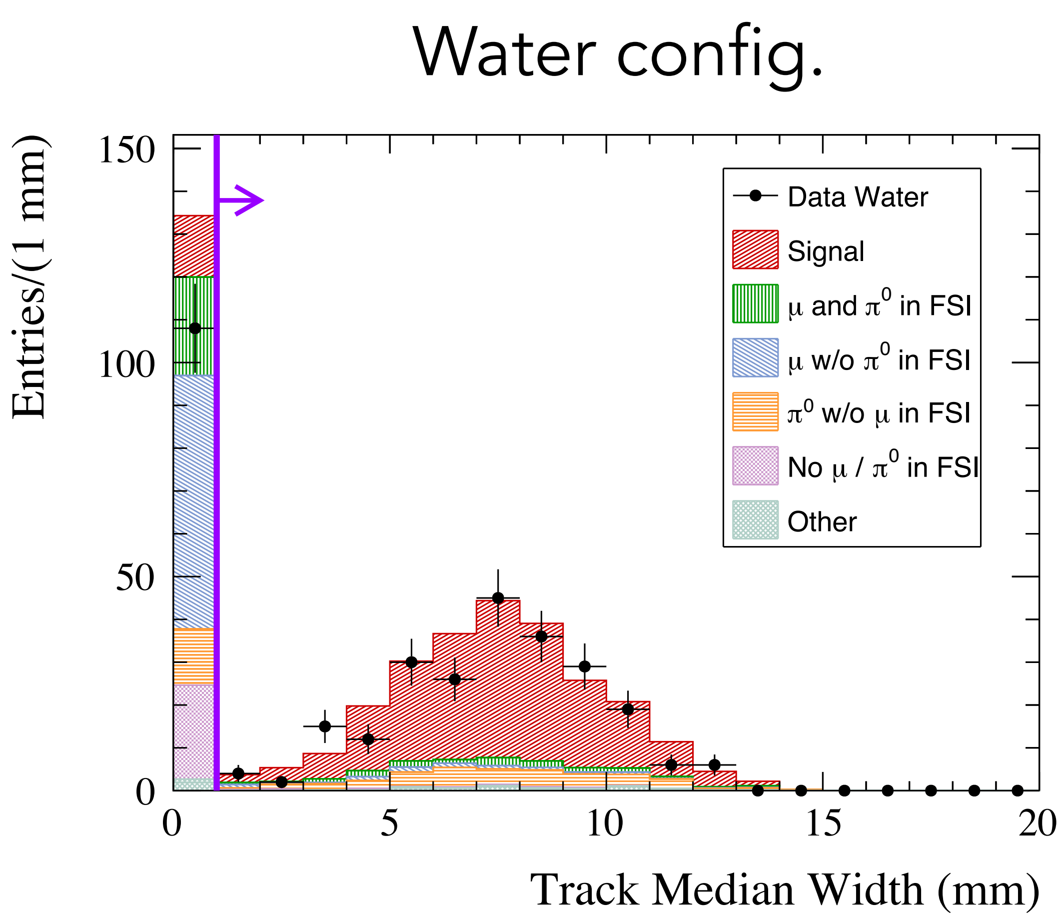


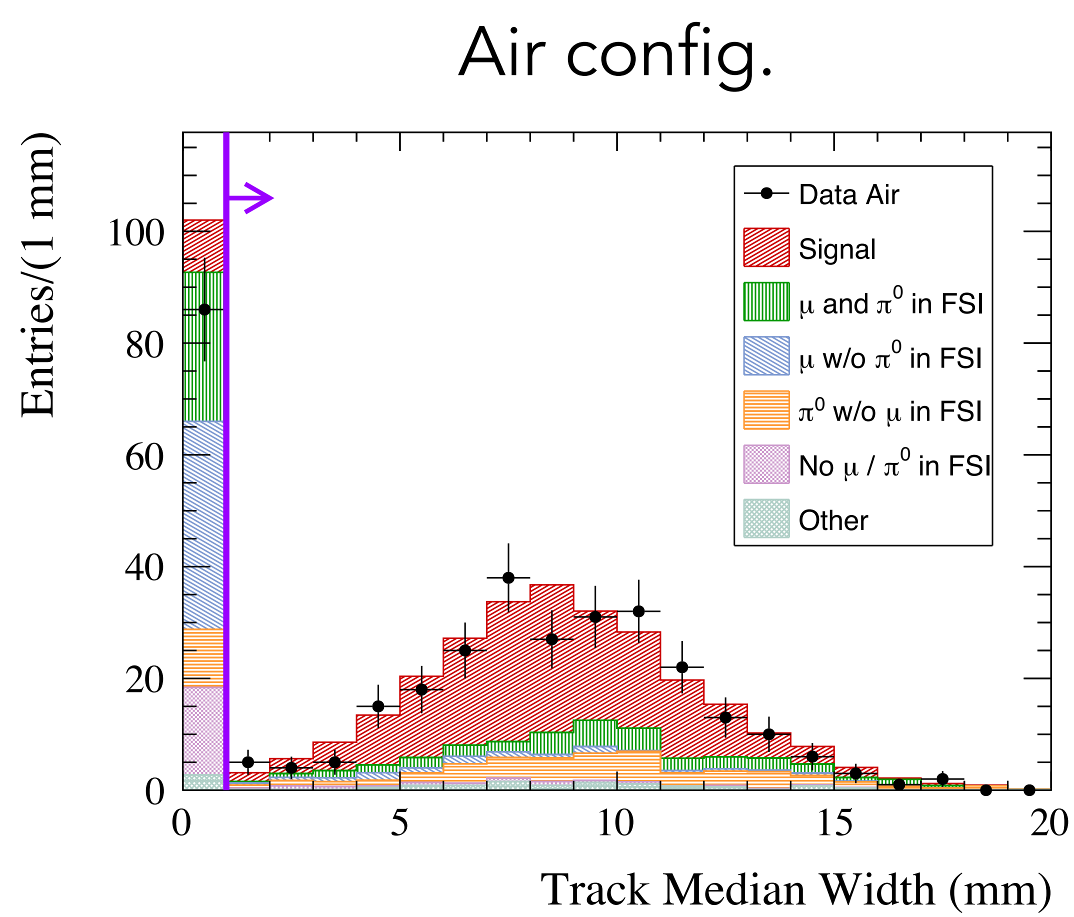
EM Shower Event (Signal)

- Event displays (side view) of typical muon background and electron signal event
- Reconstructed track of an electron is typically wider than the track of a muon
  - Muon events involve 1 or 2 adjacent triangular bar hits
  - Signal events involve 2 or more (not necessarily adjacent) triangular bar hits



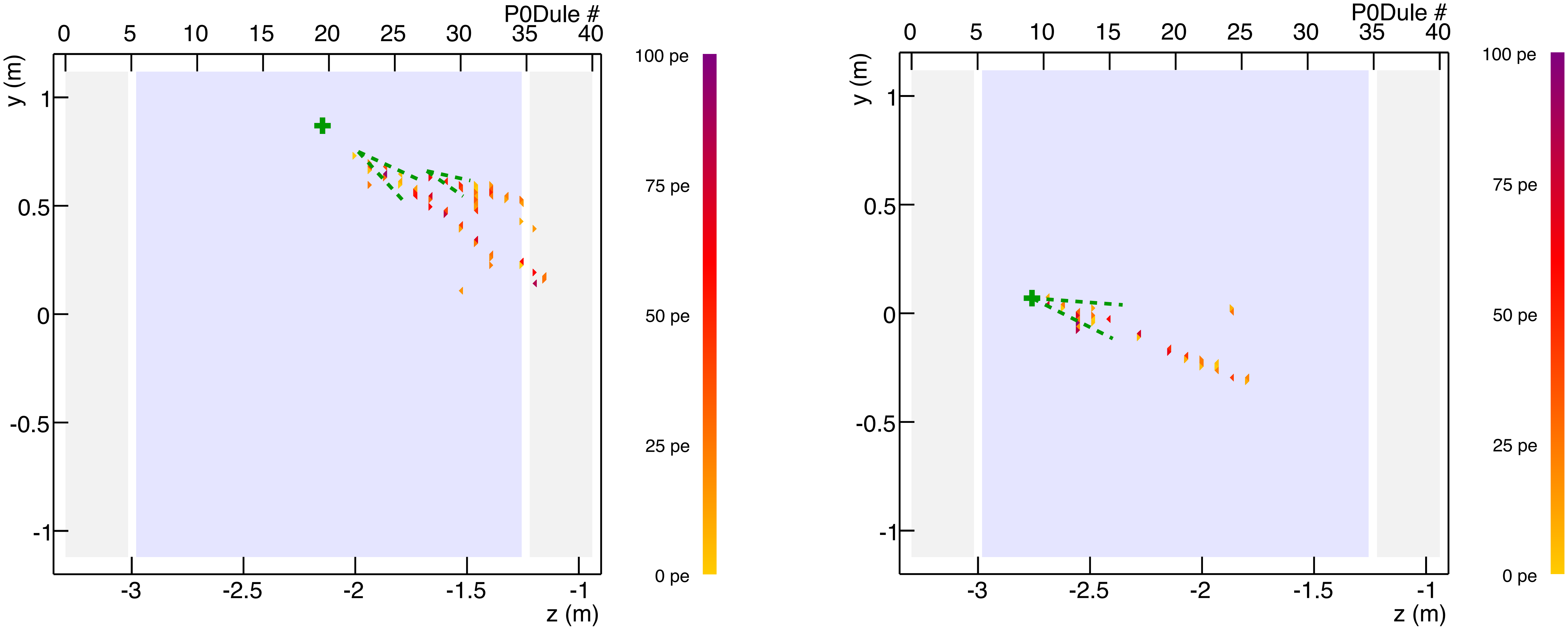
Event Selection: Track Median Width





- All cuts except Track width cut applied (Track median width N-1)
- First bin includes events with too short track to be width-calculated
- Works very well in removing muon backgrounds!

Event Selection: Shower Median Width

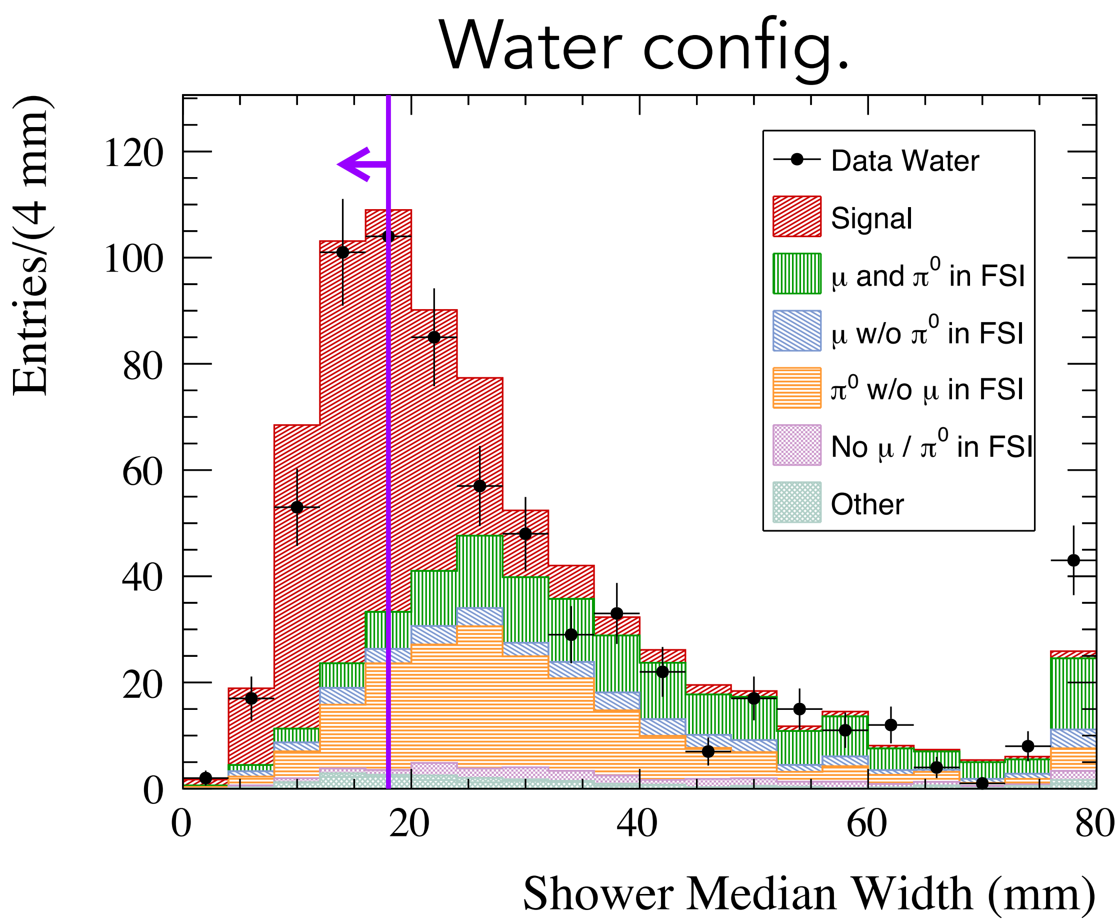


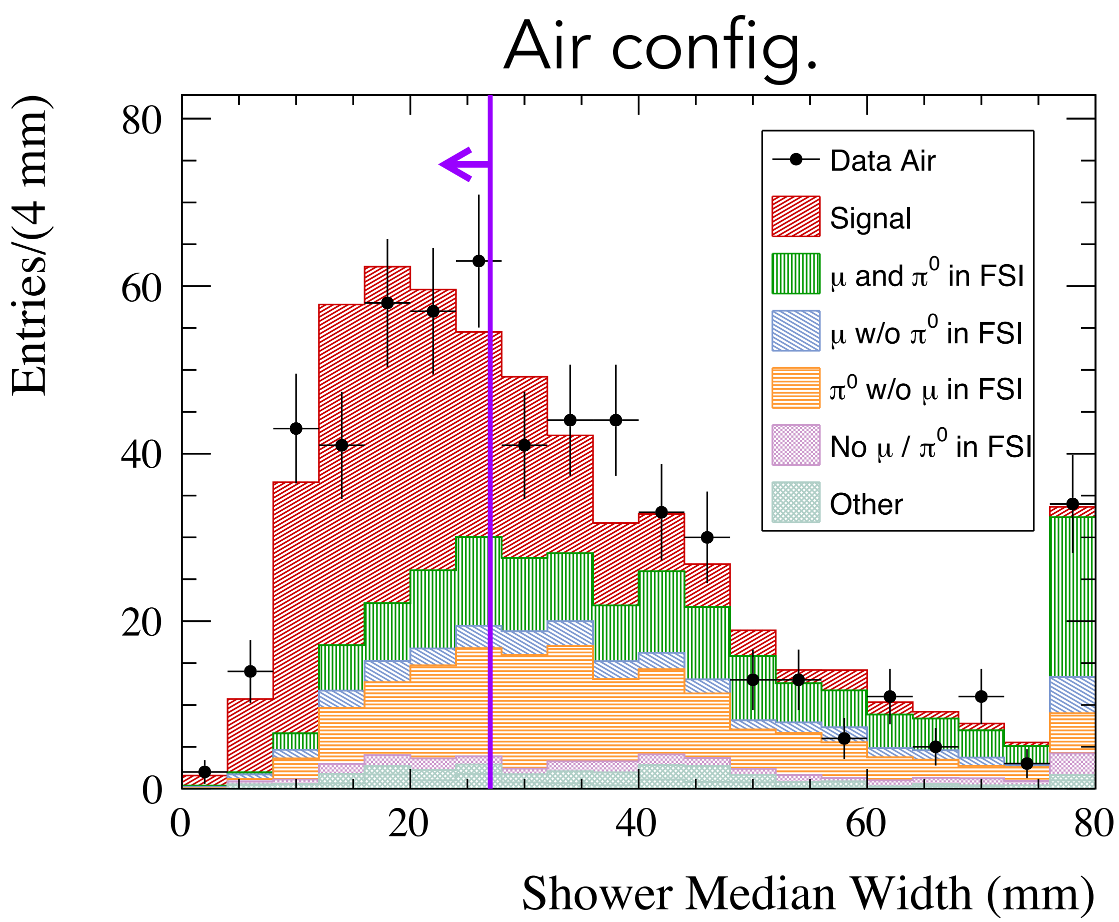
π^0 Shower Event (Background)

EM Shower Event (Signal)

- Event displays (side view) of typical neutral pion background and electron signal event
- Reconstructed shower of an electron is typically narrower than the shower of a neutral pion
  - When neutral pion event has 2 overlapping showers, it will be reconstructed as a wide shower

Event Selection: Shower Median Width





- All cuts except Shower width cut applied (Shower median width N-1)
- Pion background events tend to have larger shower width
- Works well in removing pion backgrounds!

Systematic Uncertainties

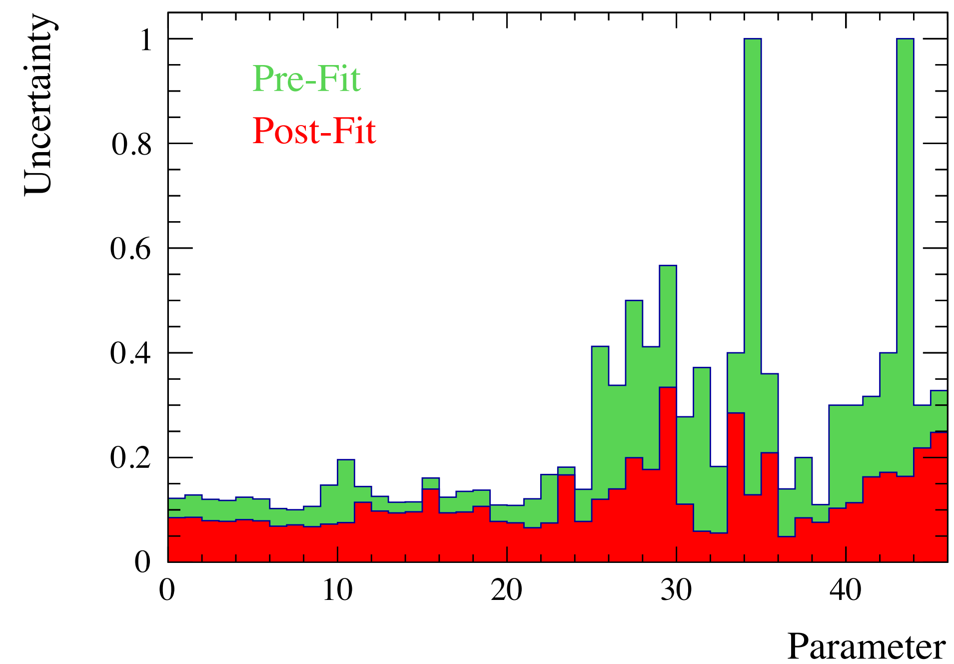
- The systematic uncertainties can be broadly grouped into three categories:
  - Detector systematics
  - Reconstruction systematics
  - Flux and cross section uncertainties
- The systematics are determined based on the background-subtracted data/MC ratio uncertainties
- The largest uncertainties come from the energy scale and the flux/cross section

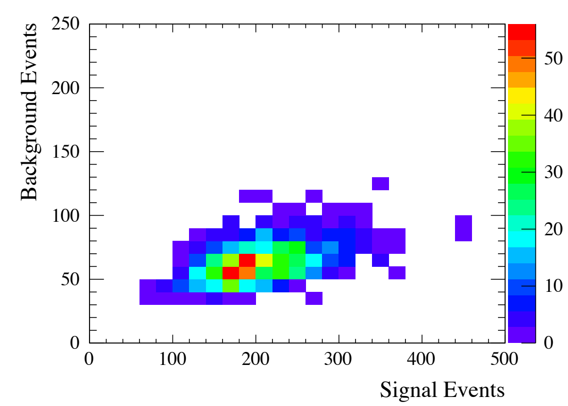
Systematics: Energy Scale

- Possible systematic effect exist when reconstructing electron energy
- As P0D detector does not have test beam for controlled data sample, we can only estimate the upper bound of the systematics by looking at various possible factors
- Possible factors:
  - P0D material density uncertainty
  - Variation in P0D response with time
  - GEANT4 uncertainty
- Shifted data/MC ratio after nue selection, will be an uncertainty: 0.05 for both water and air, and 0.10 for on-water

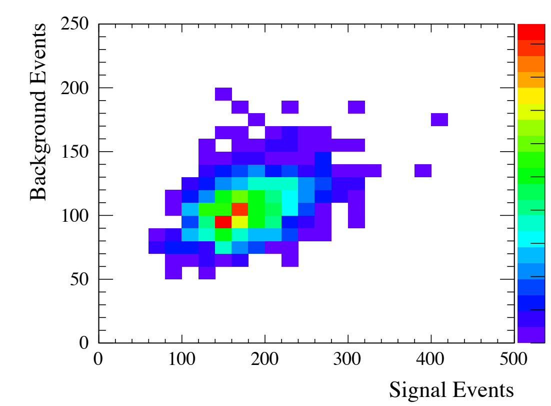
Systematics: Flux and Cross Section

- The largest systematic comes from the flux and cross section uncertainty
- T2KReWeight package is used to estimate this systematic
  - Each MC event is re-weighted according to the uncertainties of the flux and cross section parameters
  - 46 parameters are included in the analysis
- BANFF fit: Use ND280 ν_{μ} data to constrain flux and cross-section model parameters

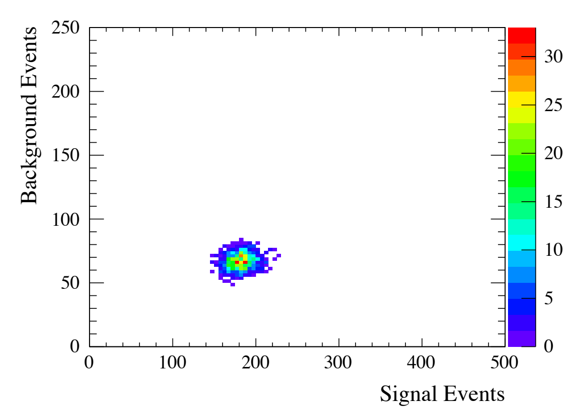




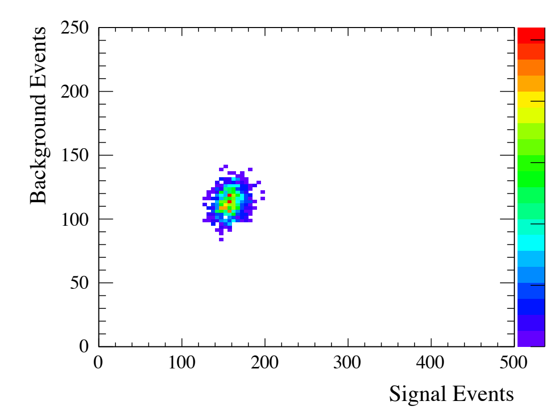
(a) BANFF Pre-Fit Water Configuration



(b) BANFF Pre-Fit Air Configuration

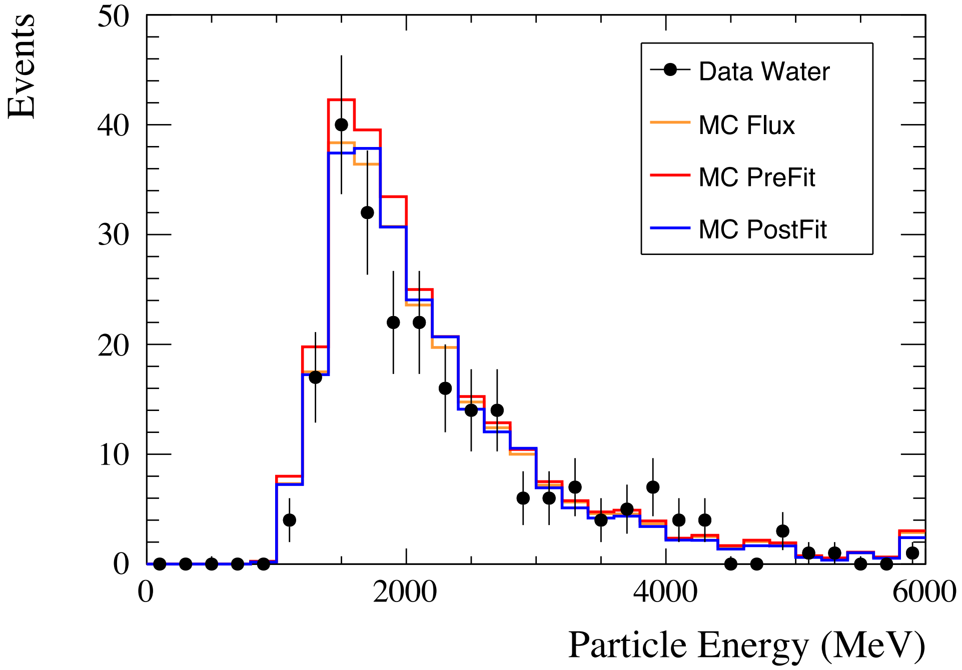


(c) BANFF Post-Fit Water Configuration

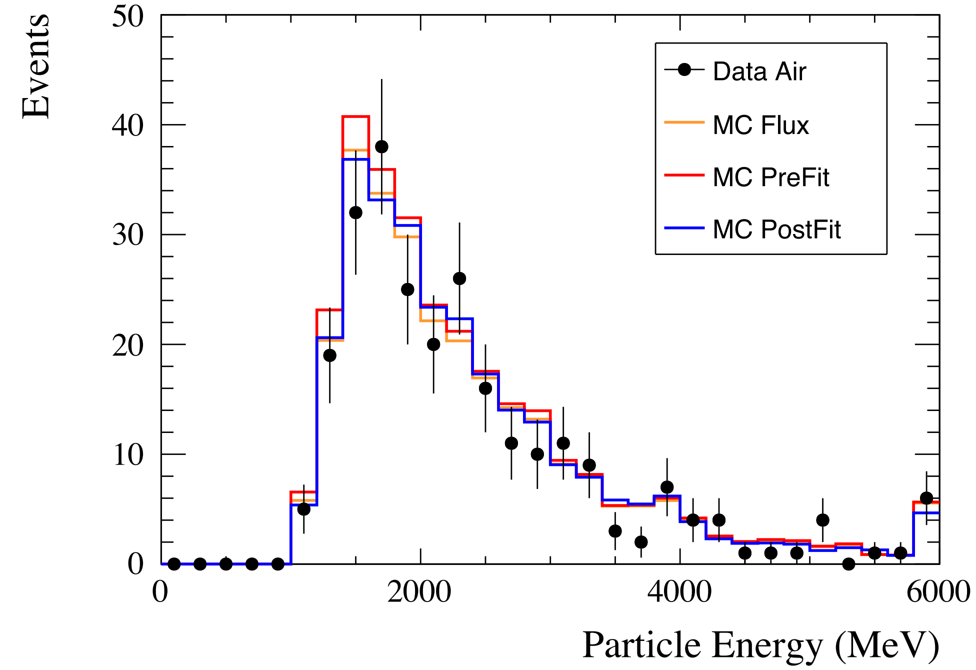


(d) BANFF Post-Fit Air Configuration

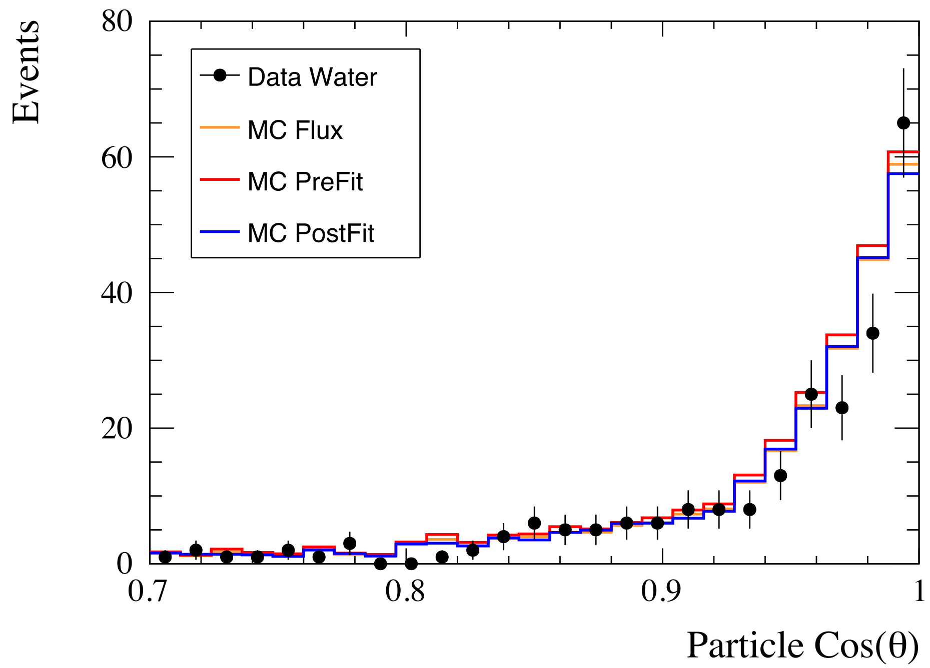
Systematics: Flux and Cross Section



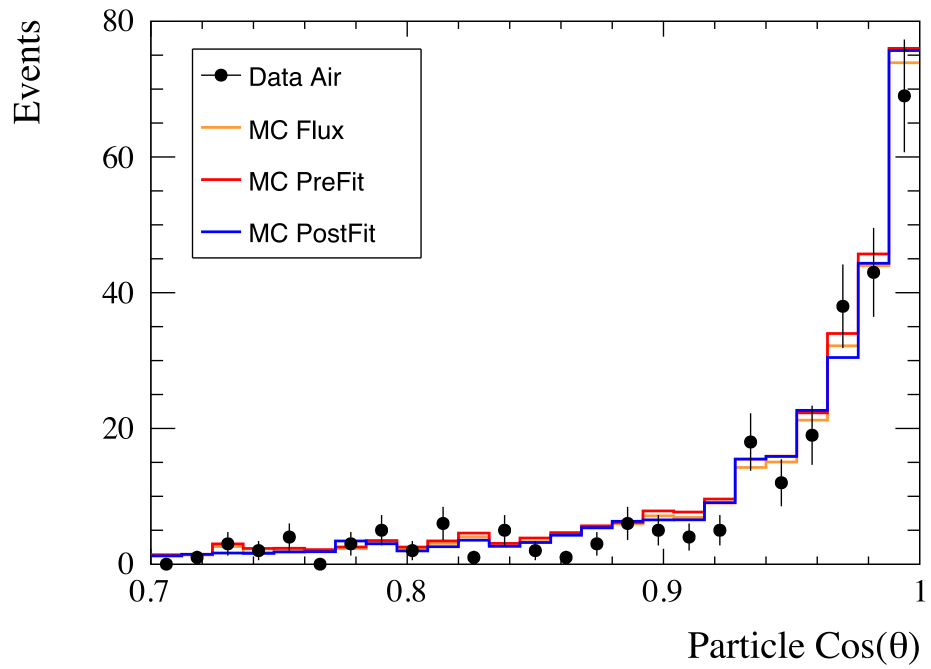
(a) Water Configuration



(b) Air Configuration



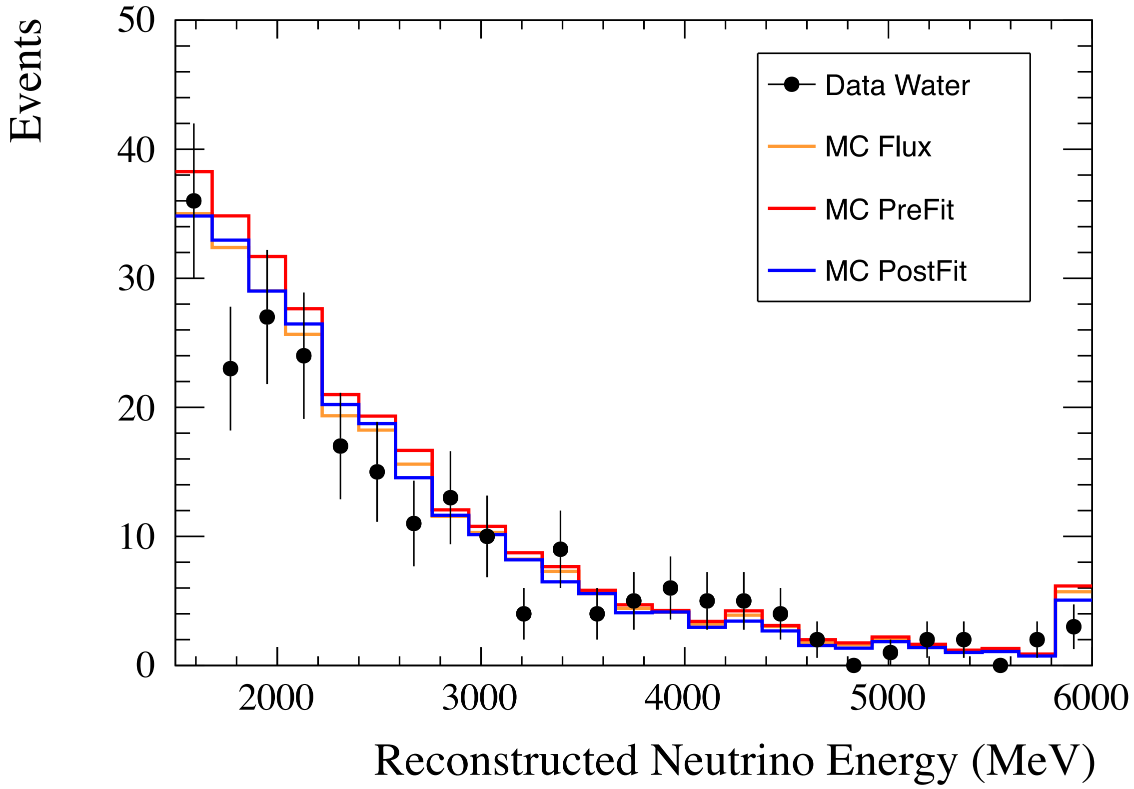
(a) Water Configuration



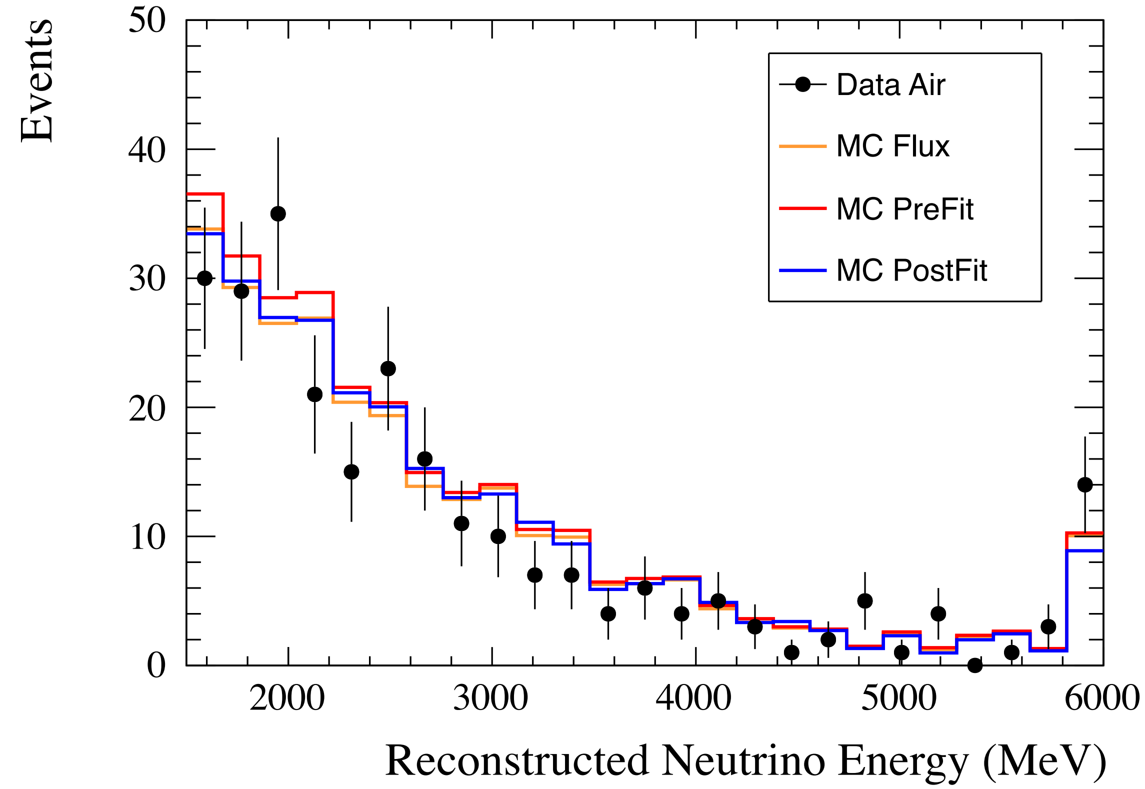
(b) Air Configuration

-MC Flux:
Flux-weighted only
-MC PreFit:
ND280 constraint not applied
-MC PostFit:
ND280 constraint applied

Systematics: Flux and Cross Section

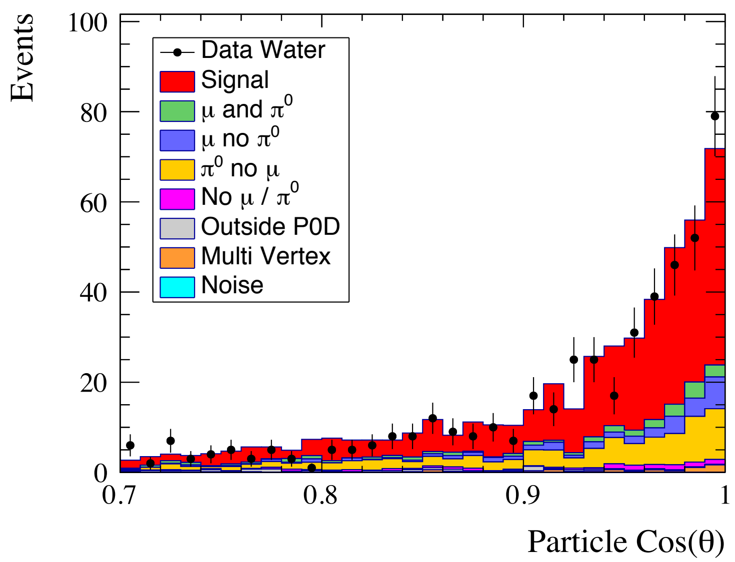


(a) Water Configuration

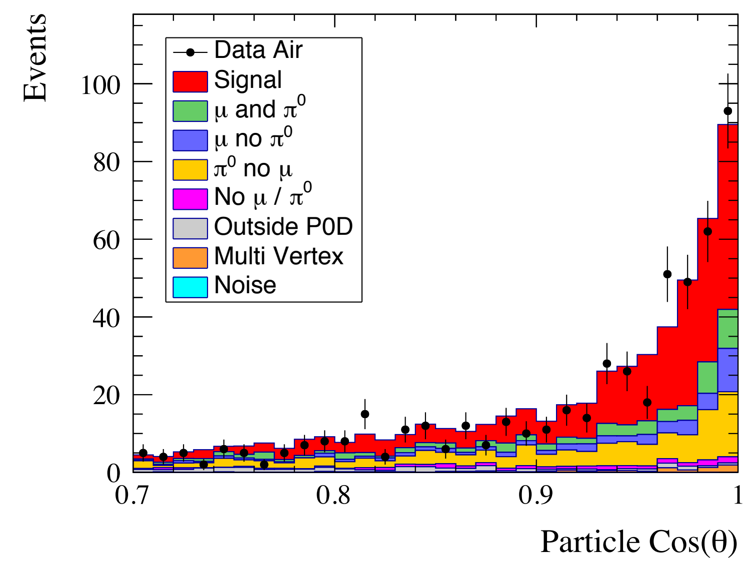


(b) Air Configuration

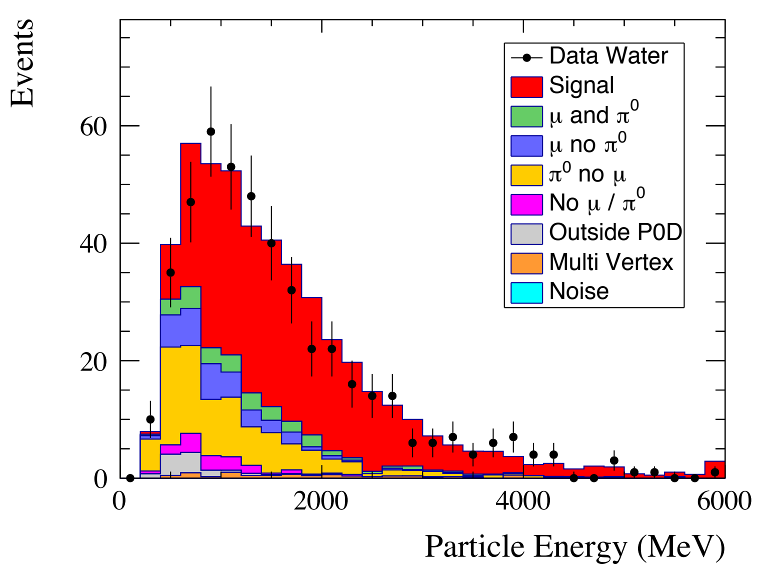
Without Neutrino Energy Threshold



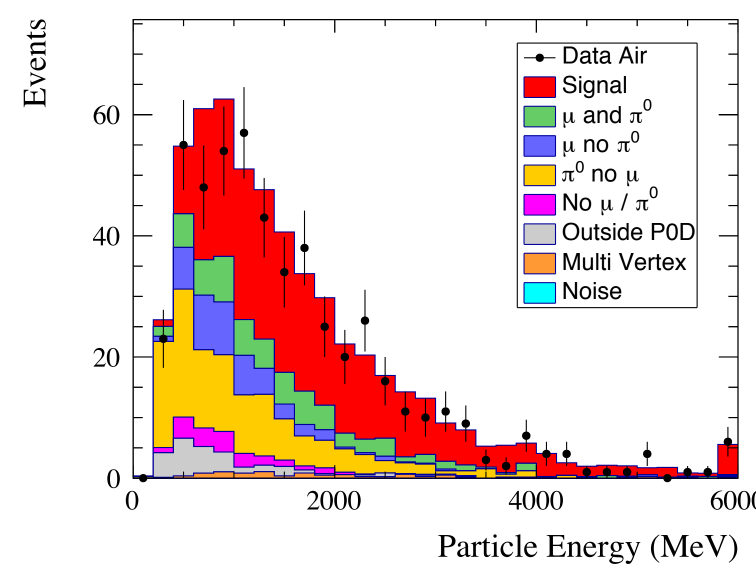
(a) Water Configuration Particle Direction



(b) Air Configuration Particle Direction



(c) Water Configuration Particle Energy



(d) Air Configuration Particle Energy

Figure 29: Events passing the event selection except Neutrino Energy cut, as a function of the particle direction and energy for water and air configuration. The MC events are normalized to data POT.

nue Analysis: Systematic Uncertainties Summary

Systematic Uncertainty for CCν_e Data/MC Ratio	R_{water}	R_{air}	$R_{\text{on-water}}$
MC Statistics	0.03	0.03	0.10
PØD Mass	0.01	0.02	0.01
PØD Fiducial Volume	< 0.01	< 0.01	< 0.01
PØD Alignment	< 0.01	< 0.01	< 0.01
Hit Matching	< 0.01	< 0.01	< 0.01
Track PID	0.03	0.05	0.10
Angular Resolution	< 0.01	< 0.01	0.01
Track Median Width	< 0.01	< 0.01	< 0.01
Shower Median Width	0.06	0.05	0.14
Shower Charge Fraction	0.03	0.05	0.09
Flux and Cross Sections Post-Fit (After ND280 Constraints)	0.11	0.13	0.10
Total with Post-Fit	0.14	0.16	0.24

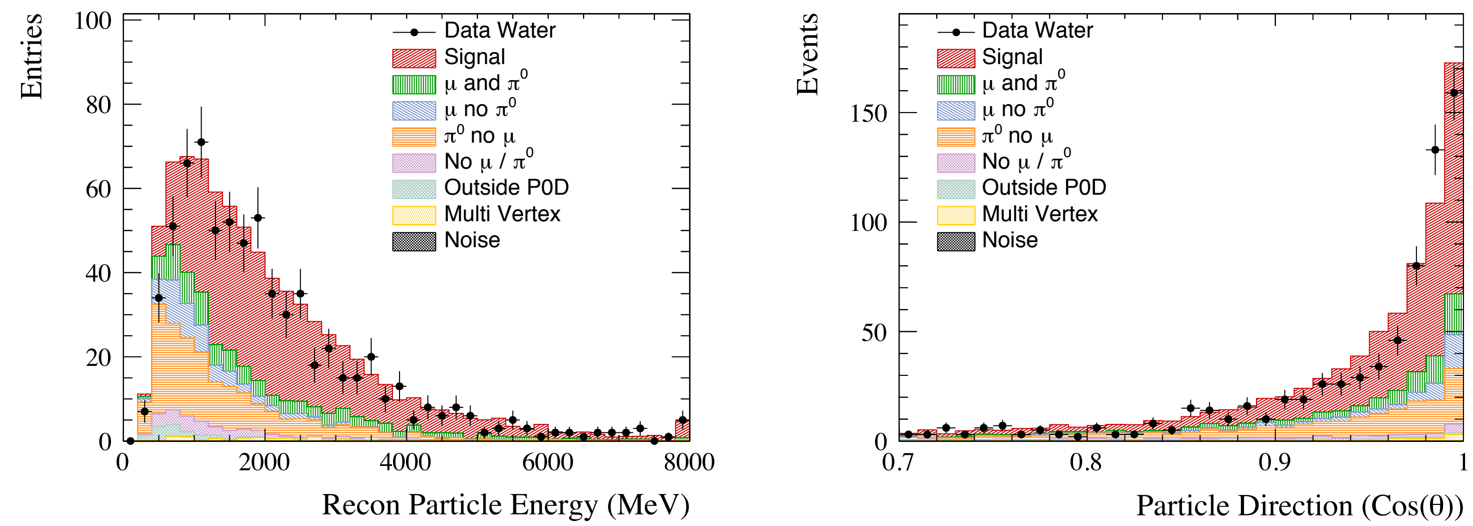
nue Analysis: Results

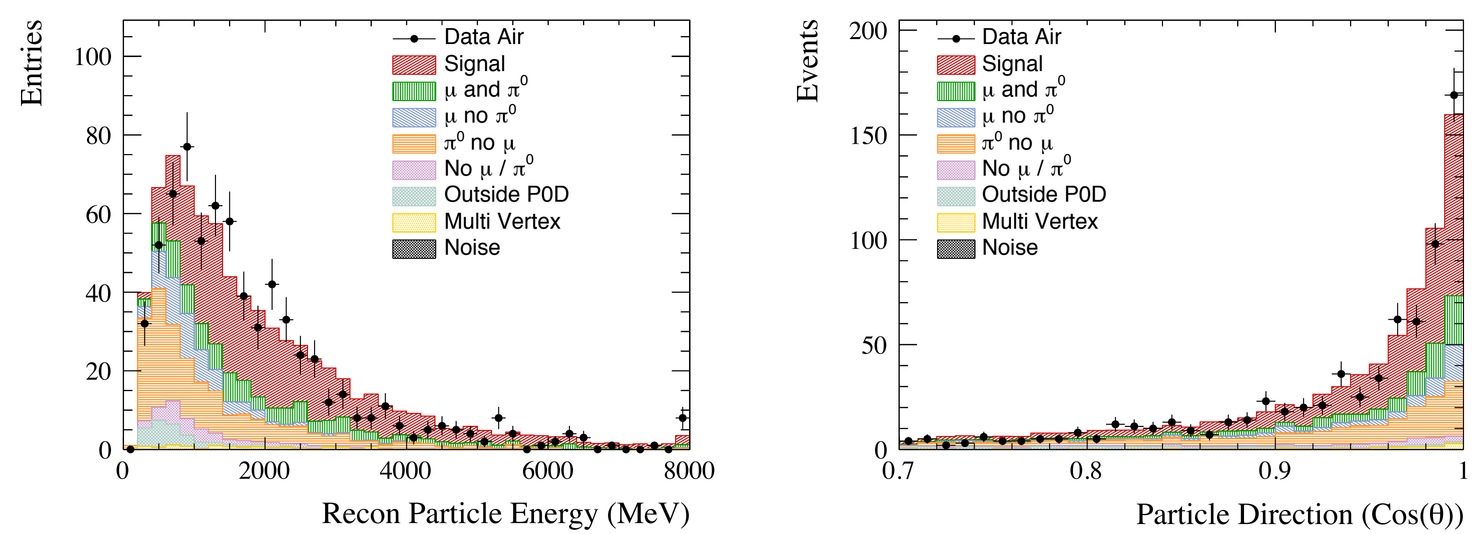
- $CC\nu_e$ background subtracted data/MC ratios is:

$$R_{\mathrm{water}} = 0.83 \pm 0.05\ (\mathrm{stat.}) \pm 0.14\ (\mathrm{sys.})$$
$$R_{\mathrm{air}} = 0.86 \pm 0.06\ (\mathrm{stat.}) \pm 0.16\ (\mathrm{sys.})$$
$$R_{\mathrm{on\text{-}water}} = 0.76 \pm 0.23\ (\mathrm{stat.}) \pm 0.24\ (\mathrm{sys.})$$

- Fit results from ND280 data are applied
- Compared to the high energy analysis, statistical error is reduced while systematic error increased
- The result indicates that the beam ν_e component measured in the data is consistent with expectations
- This is one step closer to the nue cross section measurement on water

Water config.

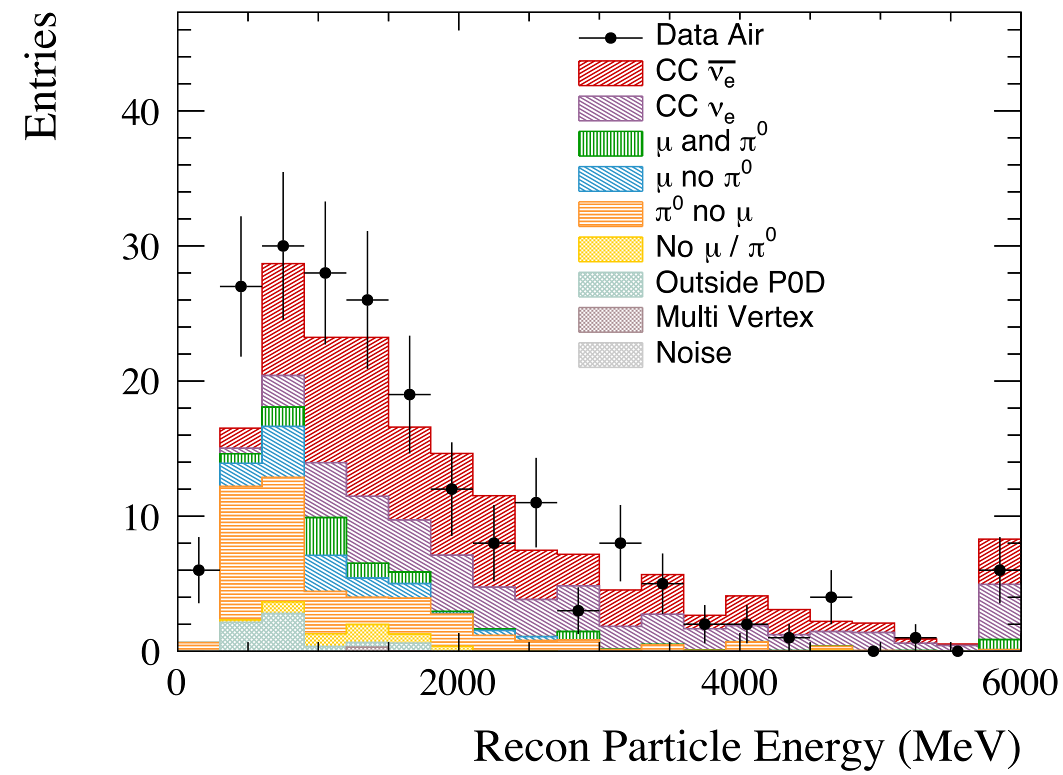




Air config.

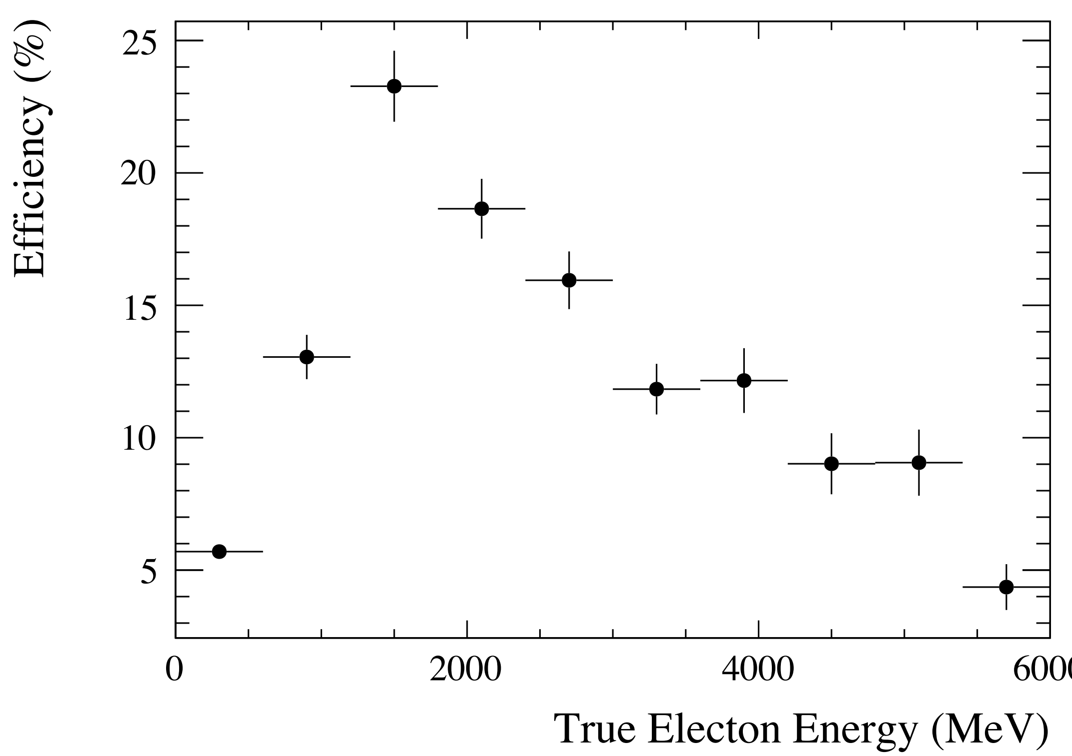
Anti-nue Analysis: Selected Event Samples/Efficiency and Purity

	MC Signal S	MC Background B	MC Total $S+B$	Data D
Air	118.2 ± 2.78	65.6 ± 2.3	183.8 ± 3.6	199



-Non-negligible nue events take up ~24% (anti-nue 40%)

	Truth T	Efficiency ϵ	Purity p
Air	858.7 ± 8.1	$(13.8 \pm 0.2)\,\%$	$(64.3 \pm 1.3)\,\%$



-Suppressed efficiency at high energy due to shower charge fraction and shower median width cut