Systematics in Hyper-Kamiokande experiment

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For the Hyper-Kamiokande collaboration

NNN18

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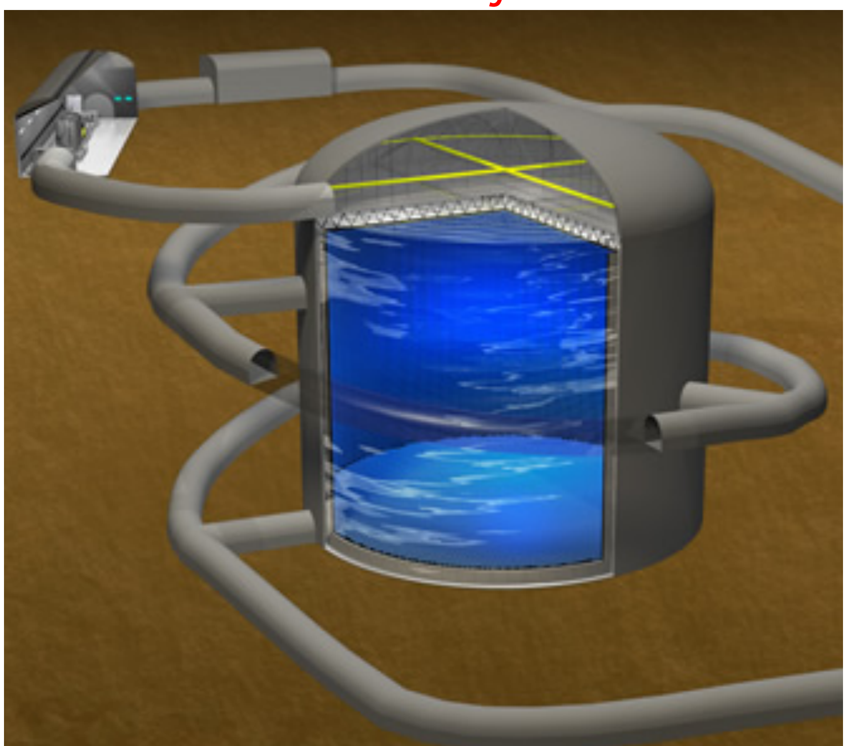
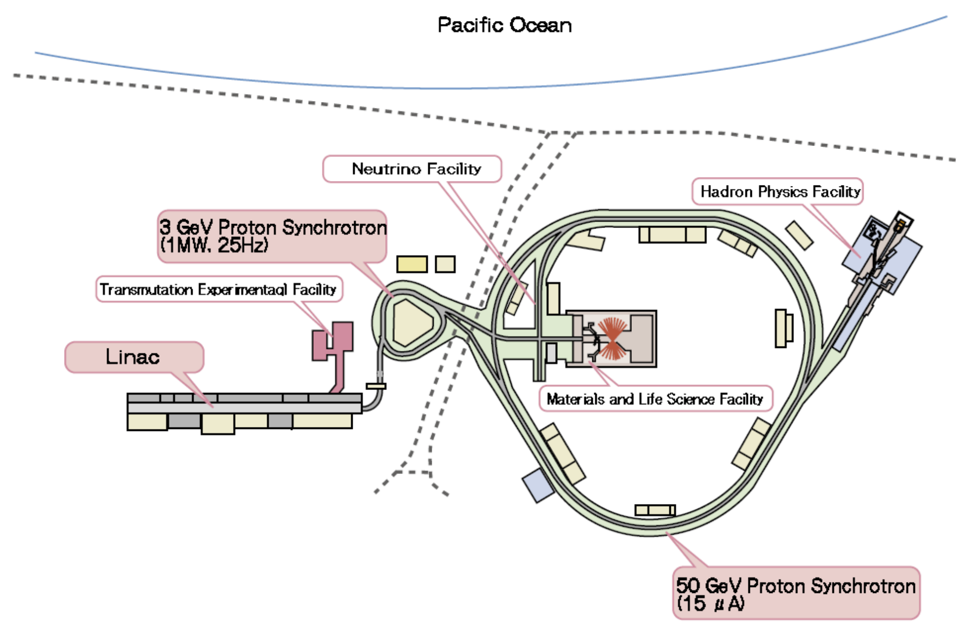
1. Introduction

Hyper-Kamiokande experiment

Next-generation water-Cherenkov detector

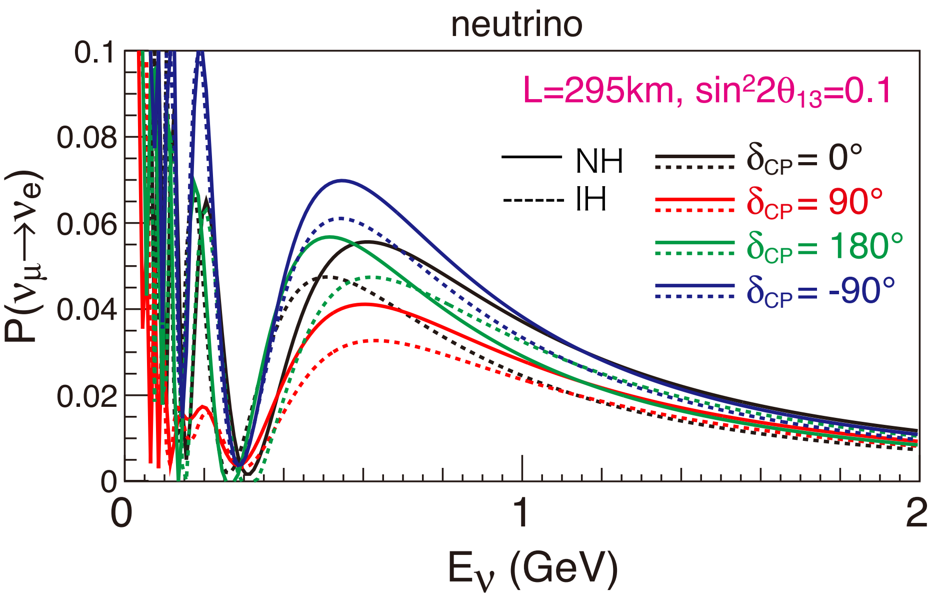
- CP phase measurement using the neutrino beam from J-PARC
- Mass hierarchy measurement with atmospheric neutrinos
- Proton decay search

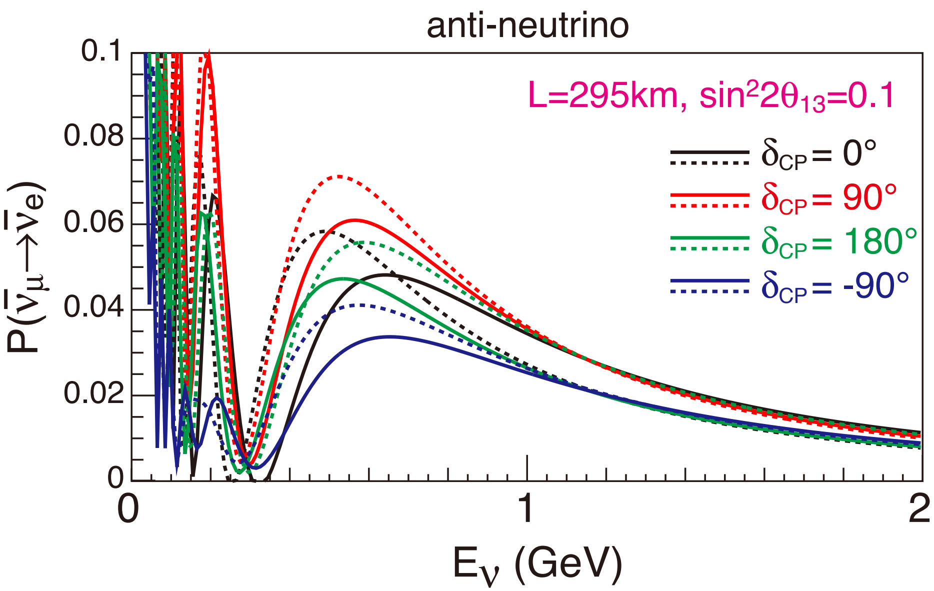




δ_{CP} measurement at Hyper-K

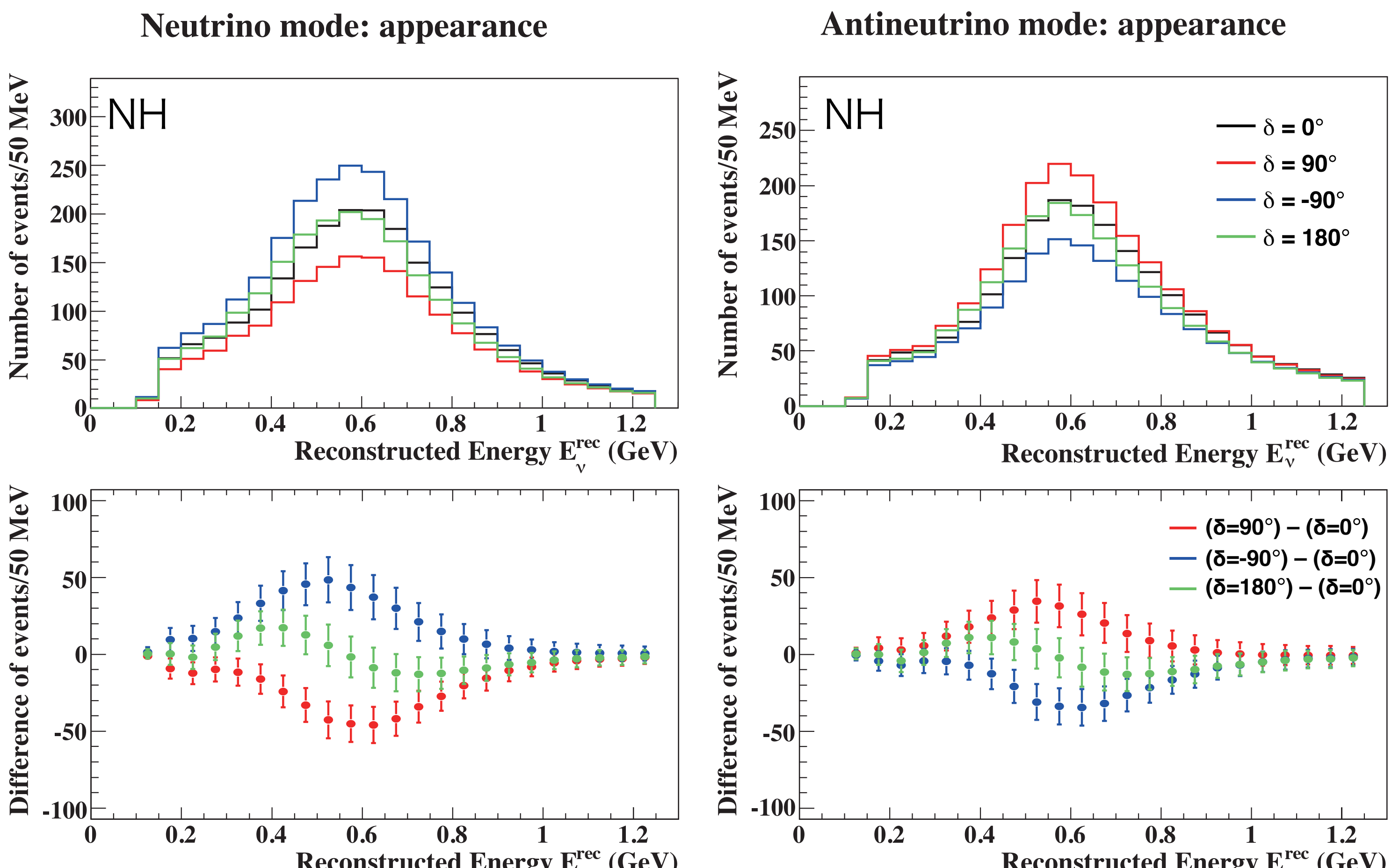
- This talk will focus on δ_{CP} measurement.
- CP phase is measured as the difference between neutrino and anti-neutrino appearance probabilities.





Expected event rates

Statistical uncertainties decreases to a few % by 10-years operation with 1.3 MW beam



2. Systematics for CP phase measurement at Hyper-K

Current T2K systematics

- Total systematics of 4–9% for ~10% statistical uncertainty
- Systematics of ν_e events are dominated by ND-independent neutrino interaction uncertainty.
- For more details, see T2K talks by L. Kormos and K. McFarland

Systematics uncertainties on number of events at SK

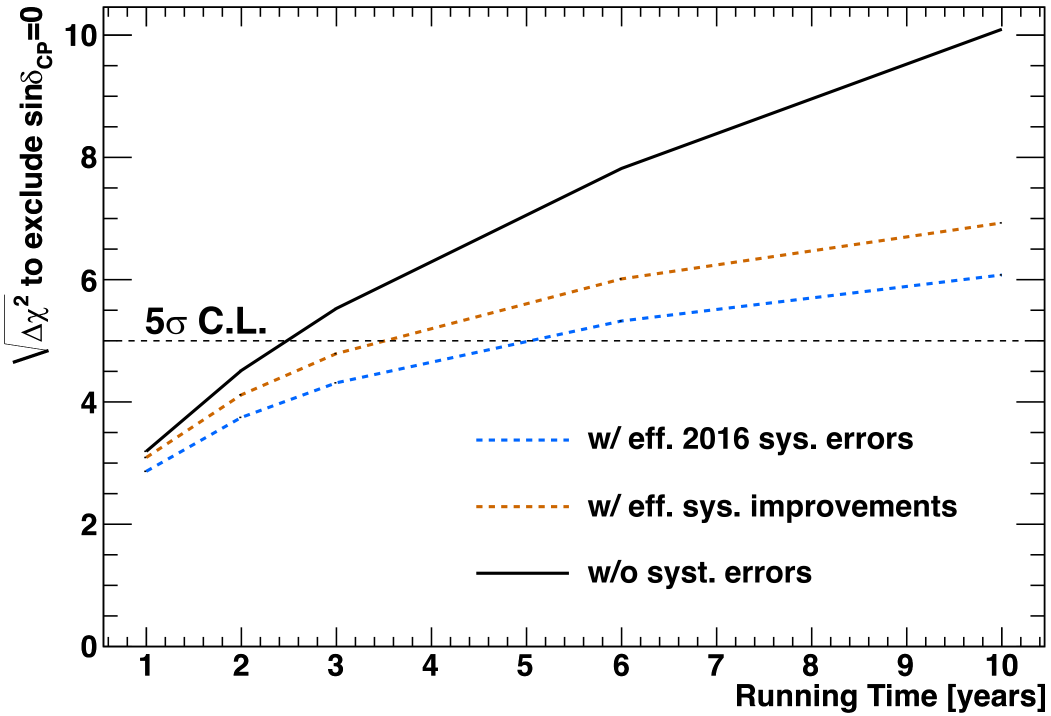
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Hadronic re-interaction	Total
ν-mode	Appearance	3.2%	7.8%	2.9%	3.0%	8.8%
	Disappearance	3.3%	2.4%	2.4%	2.2%	5.1%
$\bar{\nu}$-mode	Appearance	2.9%	4.8%	3.8%	2.3%	7.1%
	Disappearance	2.7%	1.7%	2.0%	2.0%	4.3%

arXiv:1807.07891

Impact of systematic in Hyper-K

Reduction of systematic uncertainties will significantly enhance physics capability of Hyper-K, maximizing strength of unprecedented high statistics neutrino data.

Hyper-K sensitivity to CP violation assuming true $\delta_{CP} = \pi/2$



Hyper-K systematics goal

- Current target is total systematics of 3–4% for ~3% statistical uncertainty
- To achieve that goal, all the sources of uncertainties need to be further understood.
    - Beam flux, neutrino interaction, hadronic re-interaction, far detector response

Systematic uncertainties on number of events at HK

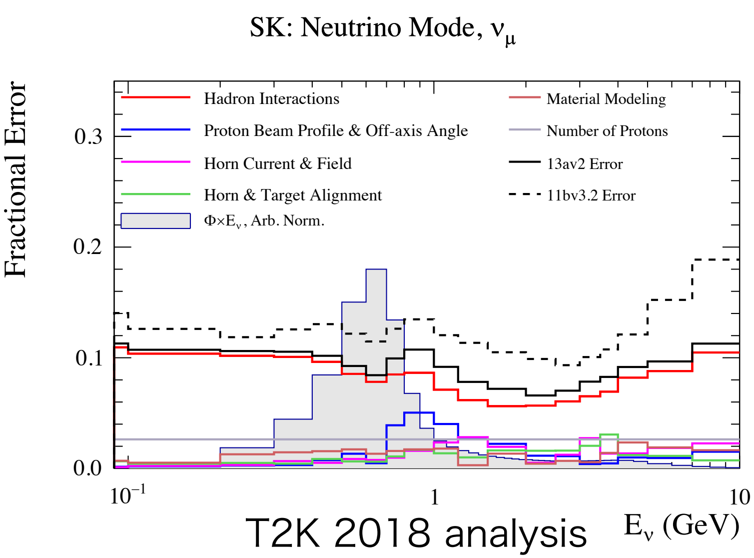
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0%	0.5%	0.7%	3.2%
	Disappearance	3.3%	0.9%	1.0%	3.6%
$\bar{\nu}$ mode	Appearance	3.2%	1.5%	1.5%	3.9%
	Disappearance	3.3%	0.9%	1.1%	3.6%

arXiv: 1805.04163

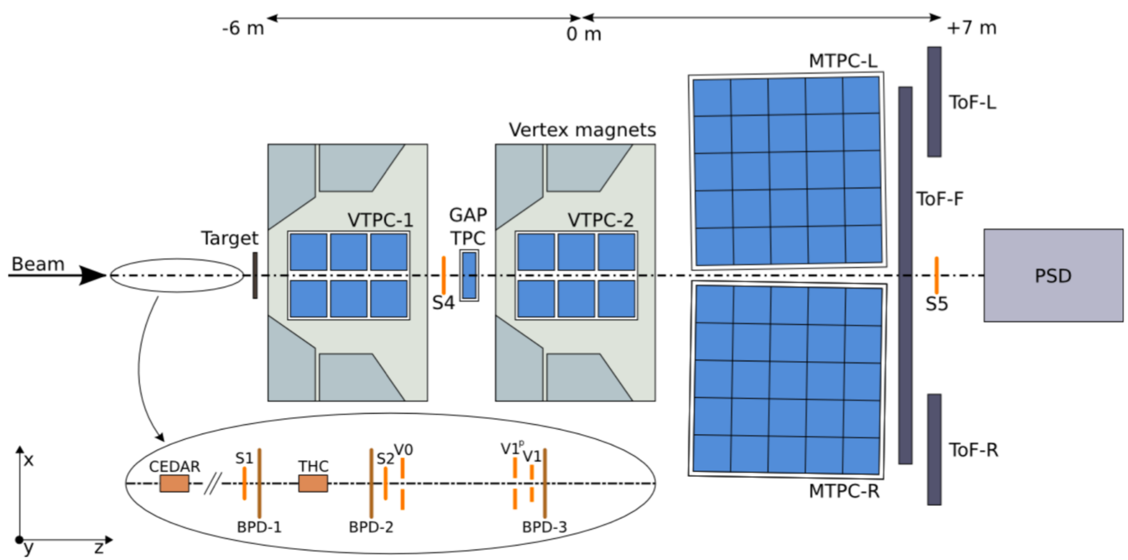
3. Improvements of flux uncertainties

Neutrino flux prediction

- The major source of flux uncertainties originates from hadron production process in the graphite target.
- T2K has been using NA61 2cm thin target results to tune the hadron production simulation.
- Efforts are ongoing to use newly provided 90cm replica target data to reduce flux uncertainty from ~10% to ~5%.



T2K 2018 analysis

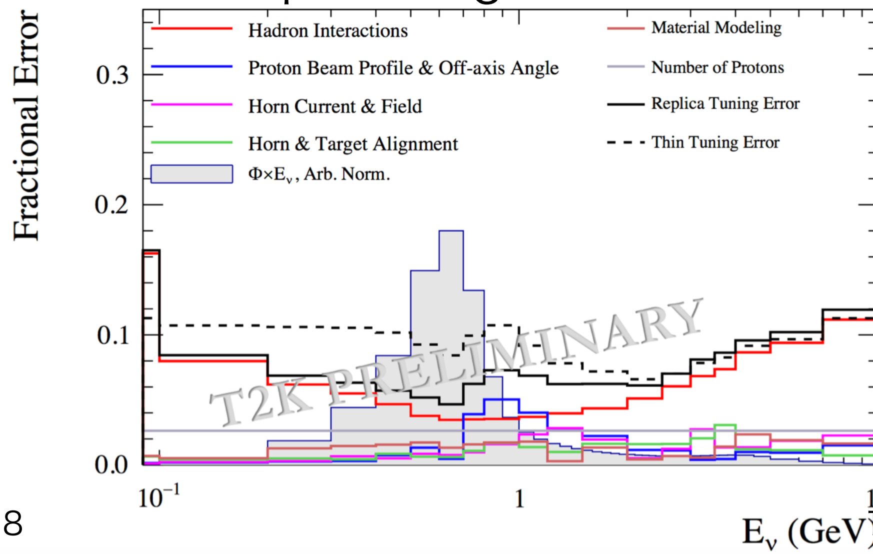


NA61 experimental setup

Flux prediction in near future

- When the hadron production uncertainties are reduced by replica target measurements, proton beam profile and off-axis angle would be the next most dominant.
- The error is estimated conservatively by proton beam profile measured just upstream of the target and neutrino beam direction obtained by on-axis near detector.
- Now the study of new analysis technique has started in T2K to take account of correlations of the two measurements more strictly.

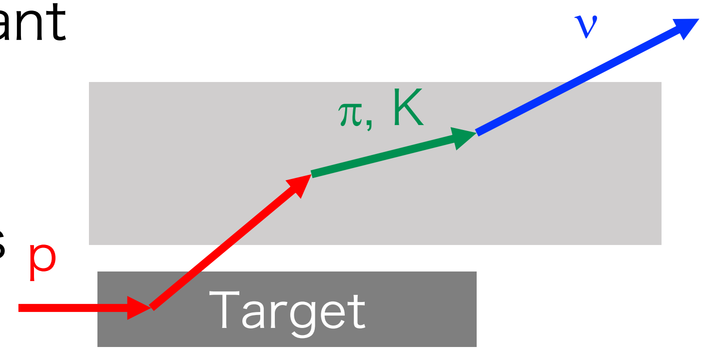
T2K flux uncertainties after replica target constrain



NA61 beyond 2020

- Out-of-target interaction is a significant source of wrong-sign component.

  In anti-neutrino mode, almost half of neutrinos originate from mesons interacting in the horn etc.



- Measurements with various target materials (Al, Fe, etc.) at lower energy would help understanding those interactions.

- Recently an idea to design a hybrid target came up in T2K.
  - Also motivate NA61 measurements with other target (Si, Al)

Graphite to allow π to exit the target

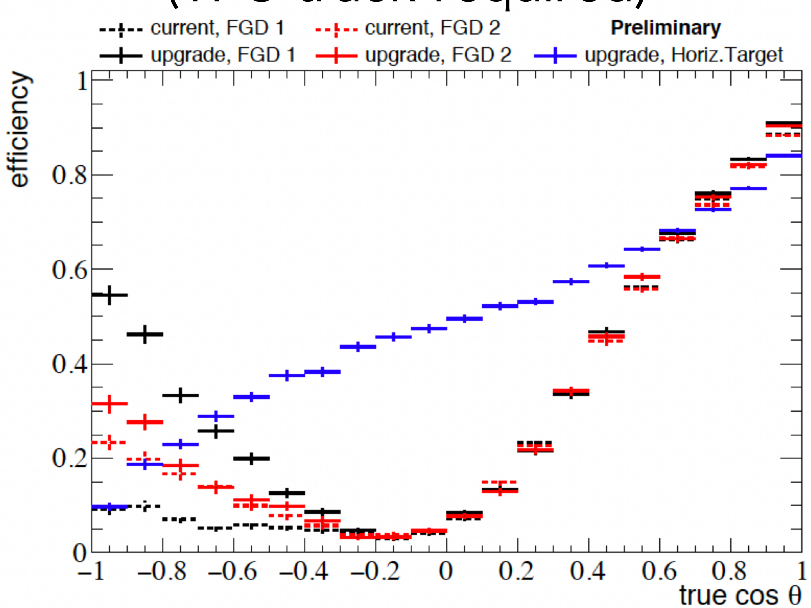
Core with heavier material (super-sialon) to increase π production

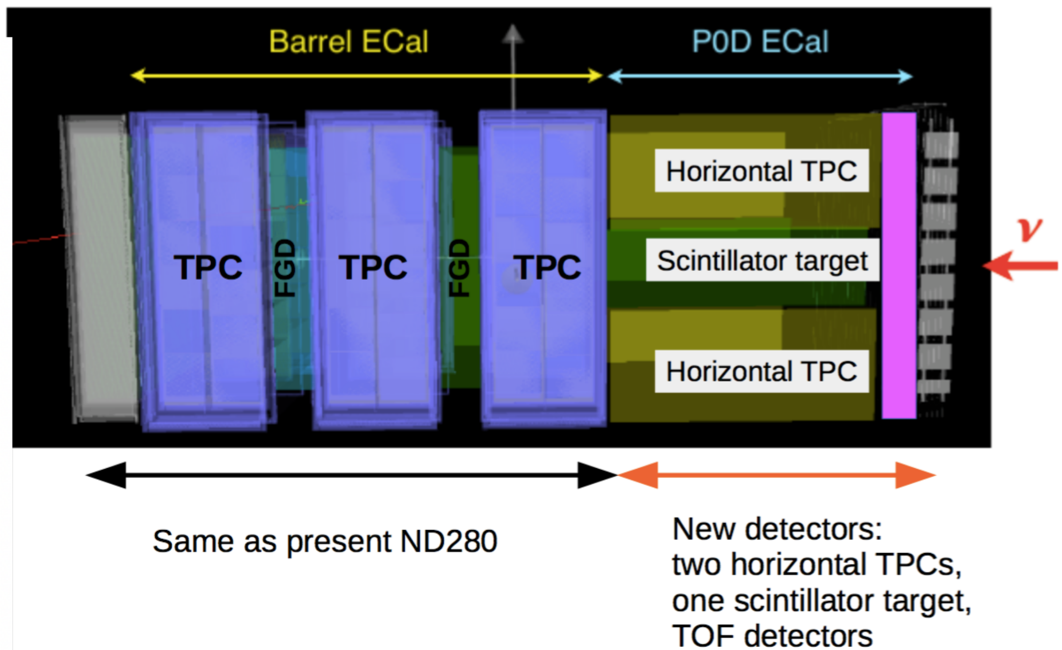
4. ND280 upgrades

ND280 upgrades

- Acceptance of high-angle muons will be increased by horizontal TPCs.
- Neutrino interaction uncertainty at high-Q^2 region would be reduced.

ν_μ CC selection efficiency (TPC track required)

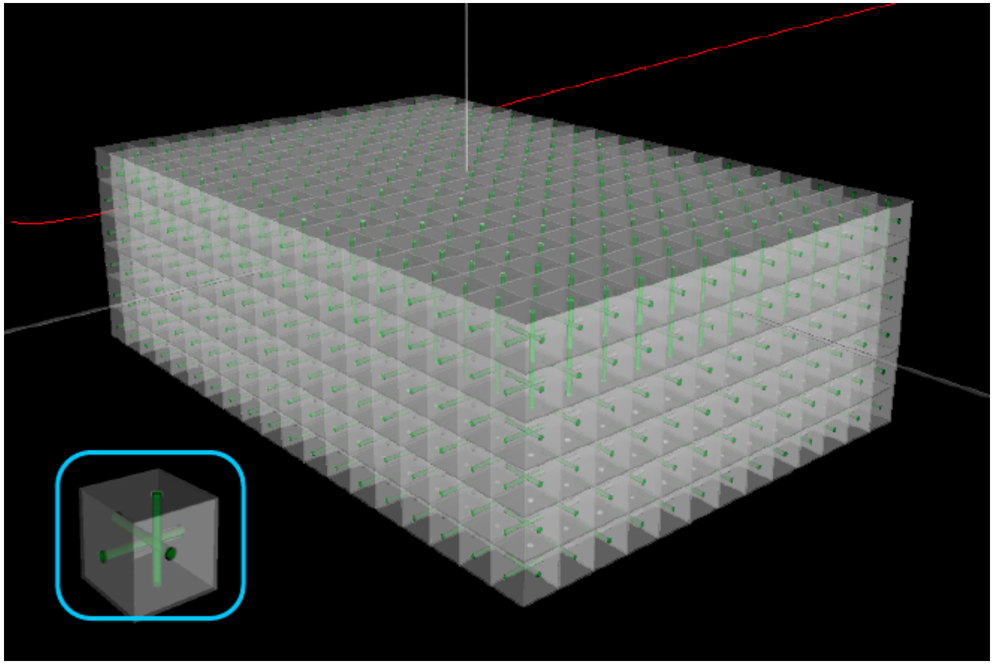




Fine-grained neutrino target

Fully active tracker with 2 tons consists of 1 cm^3 scintillator cubes.

- Statistics will be increased by a factor of 2.
- Lower tracking threshold compared to current tracker made of scintillator bars.
- e/γ separation using dE/dx
- Full 4π acceptance



For more details of the detector, see talk by E. Noah in detector session.

Estimated performance

Sensitivity studies were performed using parametrized detector performance based on Geant4 simulation of new sub-detectors and known performance of current TPCs.

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation	3.1	2.4
($0.6 < E_\nu < 0.7$ GeV)		
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

Assuming T2K interaction model and parametrization, total uncertainty will be reduced by 15–20%.

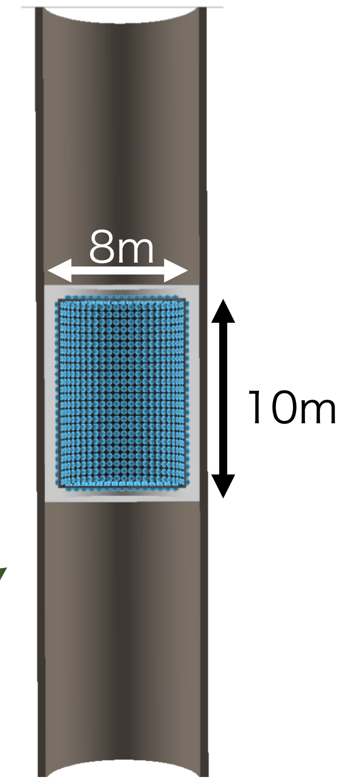
Source of uncertainty		ν_e CCQE-like $\delta N/N$ (%)	ν_μ $\delta N/N$ (%)	ν_e $CC1\pi^+$ $\delta N/N$ (%)
Flux + cross-section (constrained by ND280)	Current ND280	2.22	2.27	2.08
	Upgrade ND280	1.77	1.94	1.35

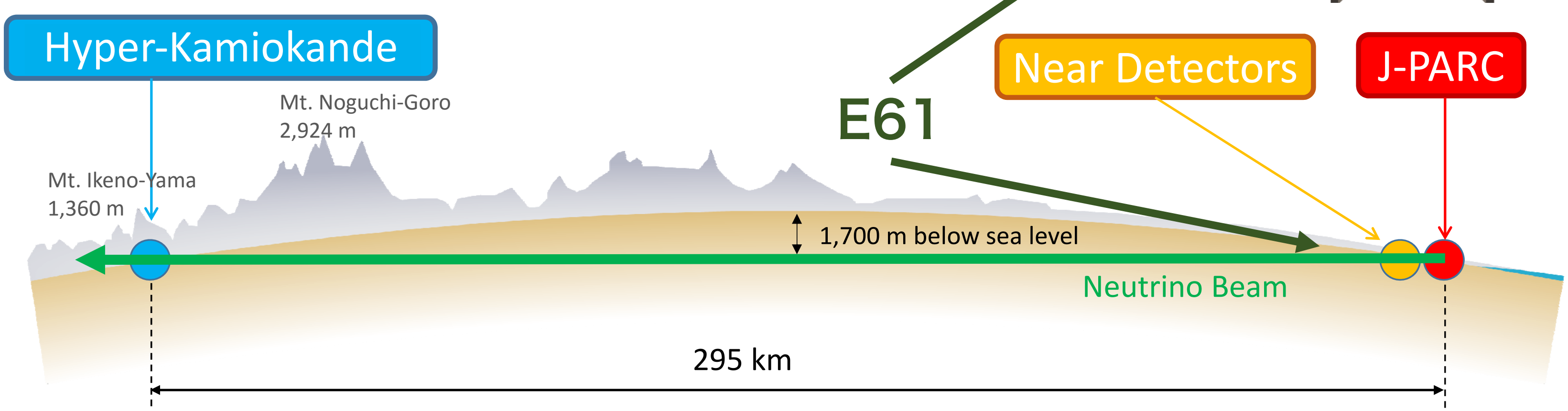
CERN-SPSC-2018-001.
SPSC-P-357

5. Intermediate water Cherenkov detector (J-PARC E61)

Intermediate Water Cherenkov

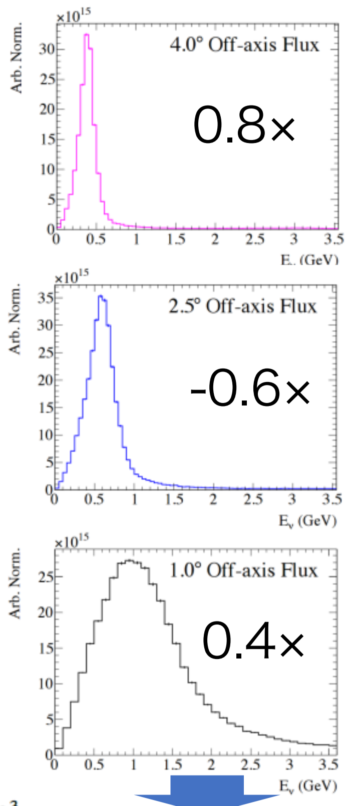
- A new intermediate water Cherenkov detector will be located at 1–2 km downstream of the neutrino production target.
- An instrumented volume moves vertically within a 50 m tall water pit
- Cherenkov photons are detected by 3inch PMTs enveloped in mPMT modules (19 PMTs for inner detector side).

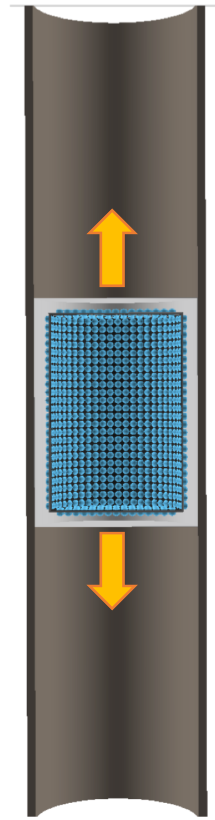


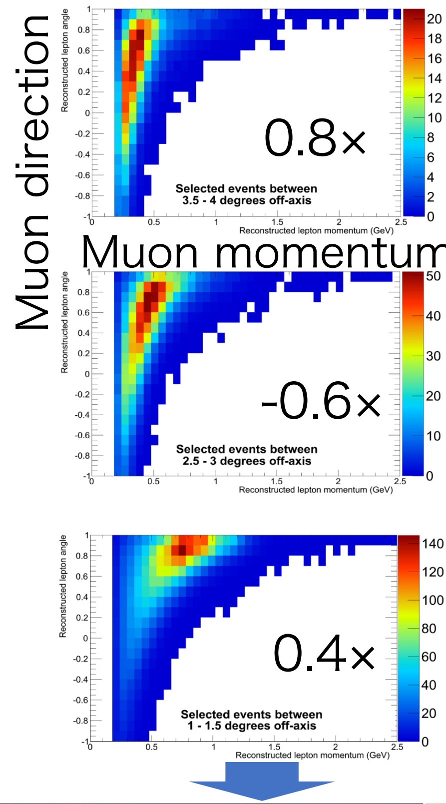


Linear combination of off-axis bins

1. Separate detector volume to 30 off-axis slices.
2. Take a linear combination of off-axis slices to reproduce desired spectrum.

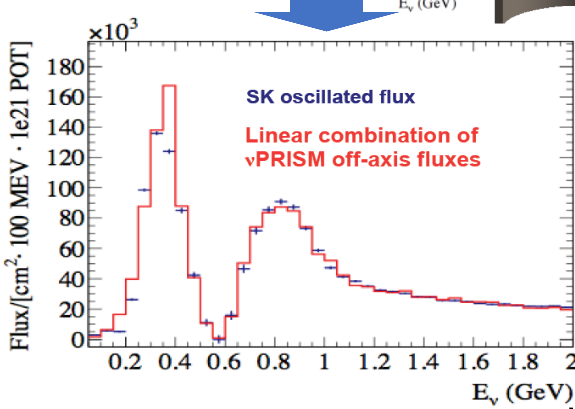


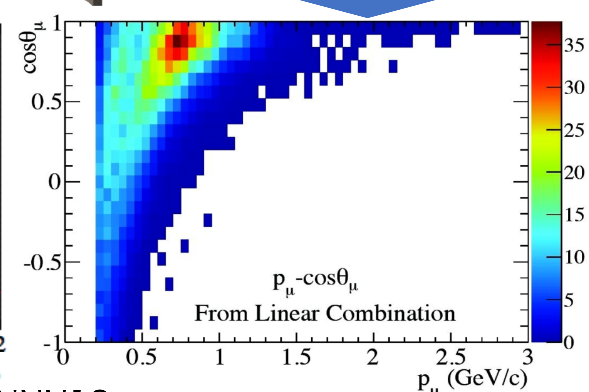




3. Take the same linear combination of observed variables to predict the distribution corresponding to that spectrum.

Example: Oscillated far detector spectrum



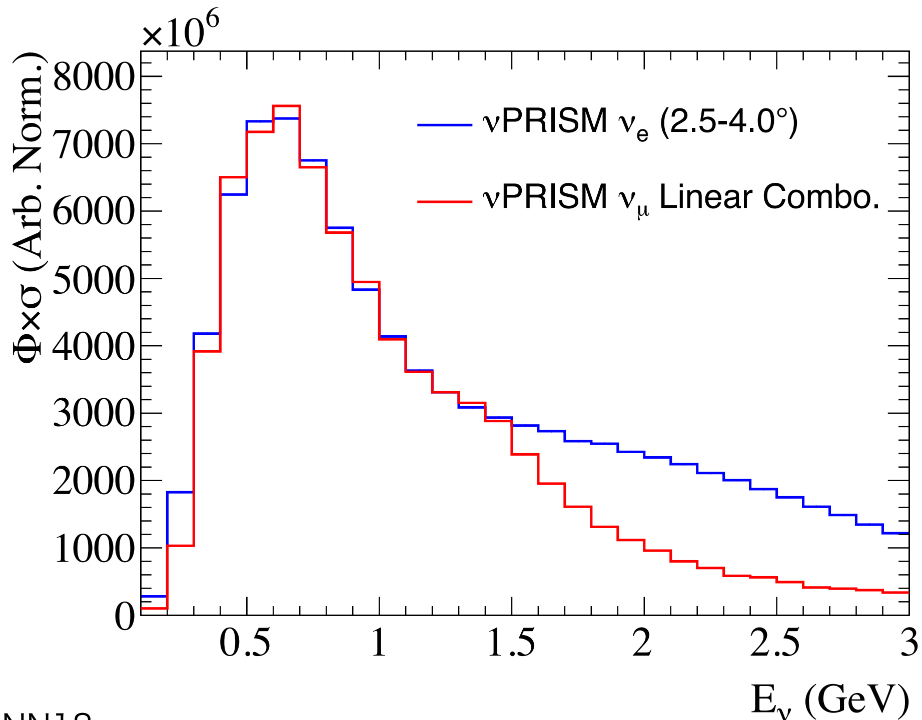


Enables data driven fit less-dependent on interaction models. Some ND-independent systematics can be canceled.

ν_e interaction measurement

E61 provides a data-driven constraint on $\sigma(\nu_e)/\sigma(\nu_\mu)$ to 2–3%

- Base on full detector MC, 1-ring ν_e candidates are selected with a purity of ~60% out of 1% beam ν_e contamination.
- By taking linear combination of ν_μ spectra to match ν_e spectrum, $\sigma(\nu_e)/\sigma(\nu_\mu)$ will be measured as a function of kinematics.



Common cross-section uncertainties are canceled, and only the difference is extracted.

$$\frac{N_{\nu_e}}{N_{\nu_\mu}} = \frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} \frac{\sigma_{\nu_e}}{\sigma_{\nu_\mu}} \frac{\epsilon_{\nu_e}}{\epsilon_{\nu_\mu}}$$

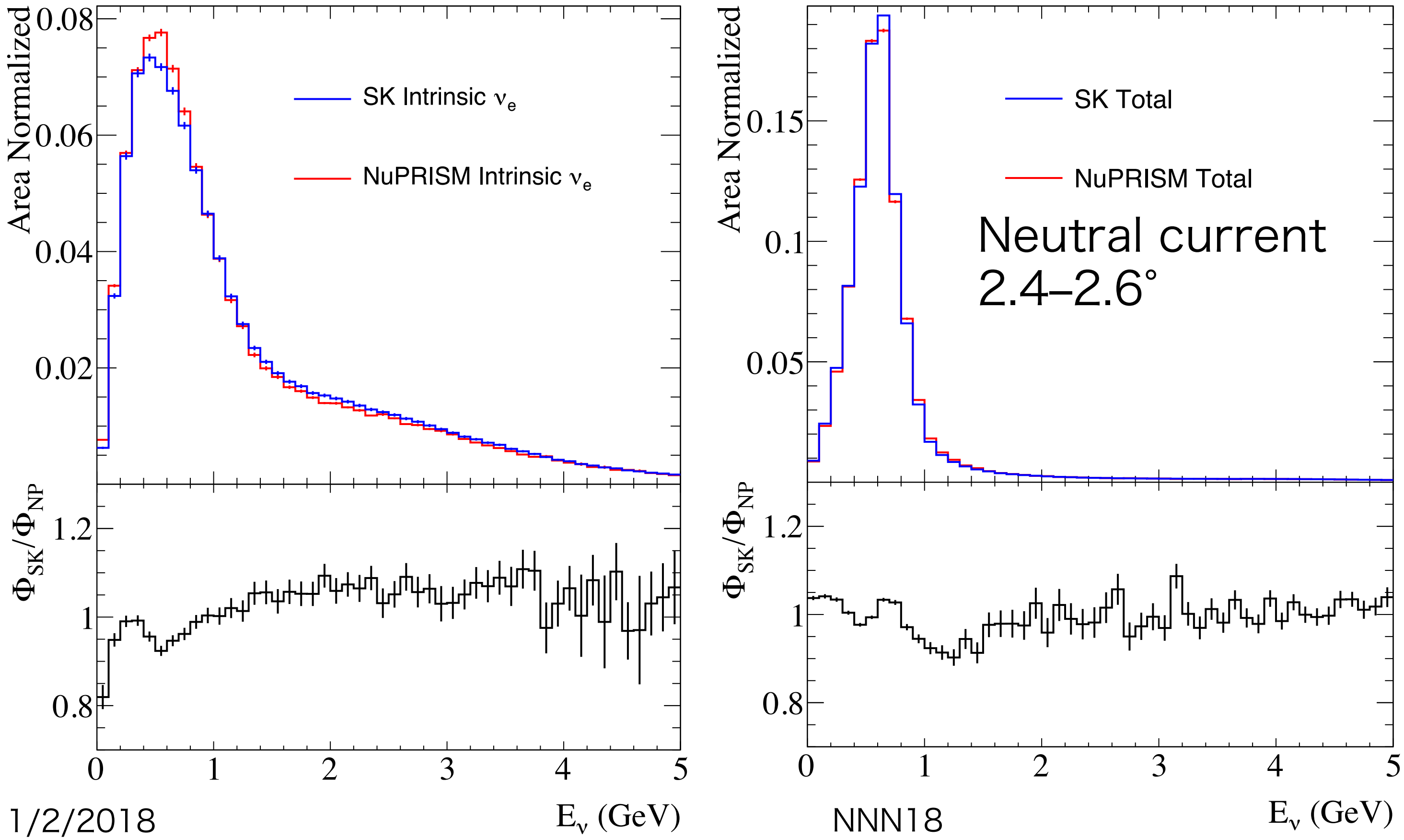
Measured

Common flux uncertainties are canceled.

By matching the spectra, difference of efficiencies is reduced.

ν_e background measurements

Intrinsic ν_e and neutral current background at the far detector will be constrained with a statistical precision of 3% by measurement at 2.5° off axis, the same angle as Hyper-K.



See Hyper-K near detector talk by J. Walker for more detail of E61

5. Beam and atmospheric combined analysis

Beam and atmospheric combined analysis

As the T2K and Super-K are different collaborations, their analyses were developed separately.

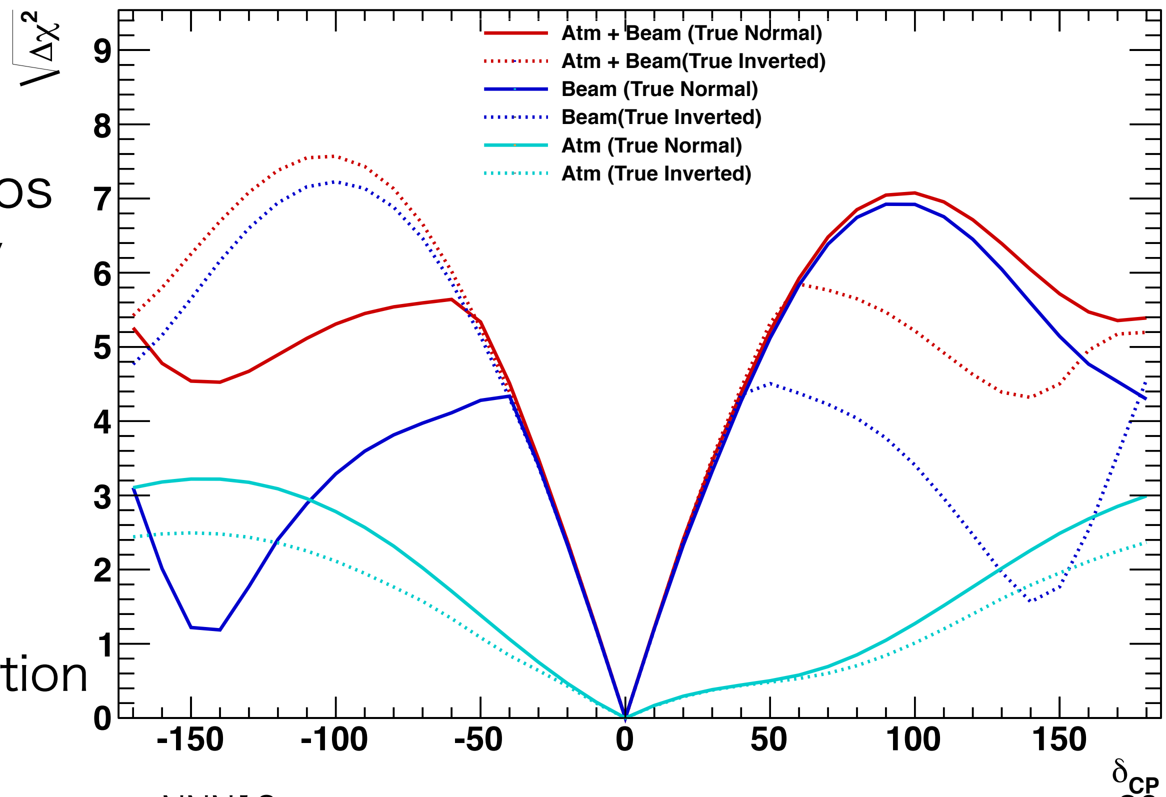
- Some of current Super-K detector systematics in the T2K analysis are estimated using atmospheric neutrinos.
  - Part of atmospheric flux and cross section uncertainties propagate to T2K oscillation analysis.
- Super-K produces "atmospheric only" results and "atmospheric + beam" results using only published T2K constraints.
  - Part of atmospheric flux and cross section uncertainties and Super-K detector systematics are double-counted.

Hyper-K proto-collaboration includes beam, near and far detectors. Beam and atmospheric combined analysis will be straightforward in such organization with single collaboration.

Another merit of combined analysis

Beam and atmospheric events have complementary sensitivities.

- Precision measurement of oscillation parameters with beam neutrino improves sensitivity to mass hierarchy and θ_{23} octant of atmospheric neutrinos.
- Determining mass hierarchy by atmospheric neutrinos resolves degeneracy in δ_{CP} and hierarchy.



Rejection of $\delta_{CP} = 0$
assuming 10 years of operation

Summary

- Statistical uncertainty of neutrino data will be suppressed to a few percent with Hyper-Kamiokande far detector and upgraded J-PARC neutrino beam. The goal of the systematic uncertainty is therefore 3% level.
- Many efforts are on-going to realize that precision across multiple collaborations.
  - Understand hadron production with external data
  - Constrain beam properties and neutrino interaction model with upgraded near detectors
  - Develop less model-dependent analysis with intermediate water Cherenkov detector
  - Use both beam and atmospheric data in the most efficient way

Supplemental slides

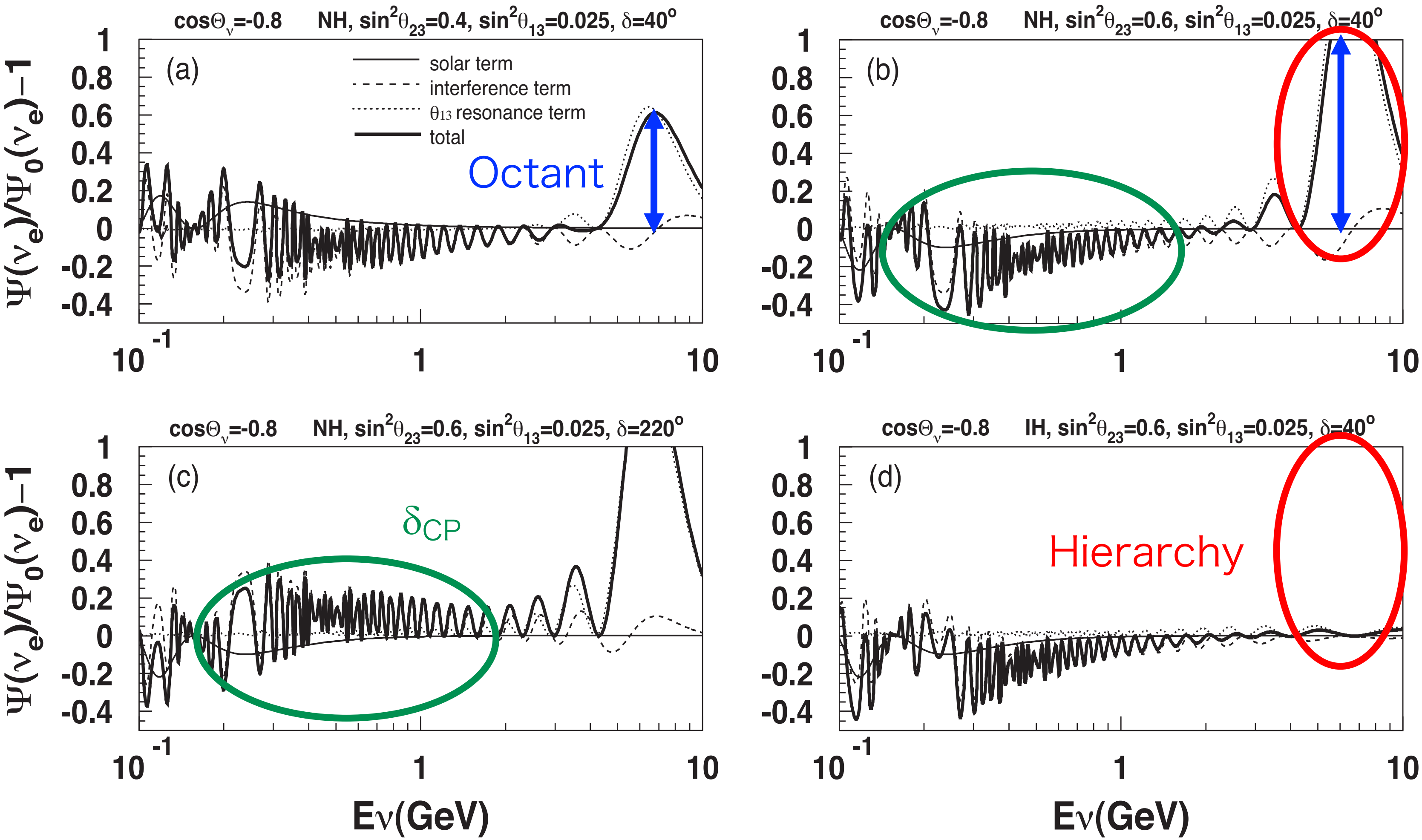
Event rates and efficiencies

- NH assumed

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

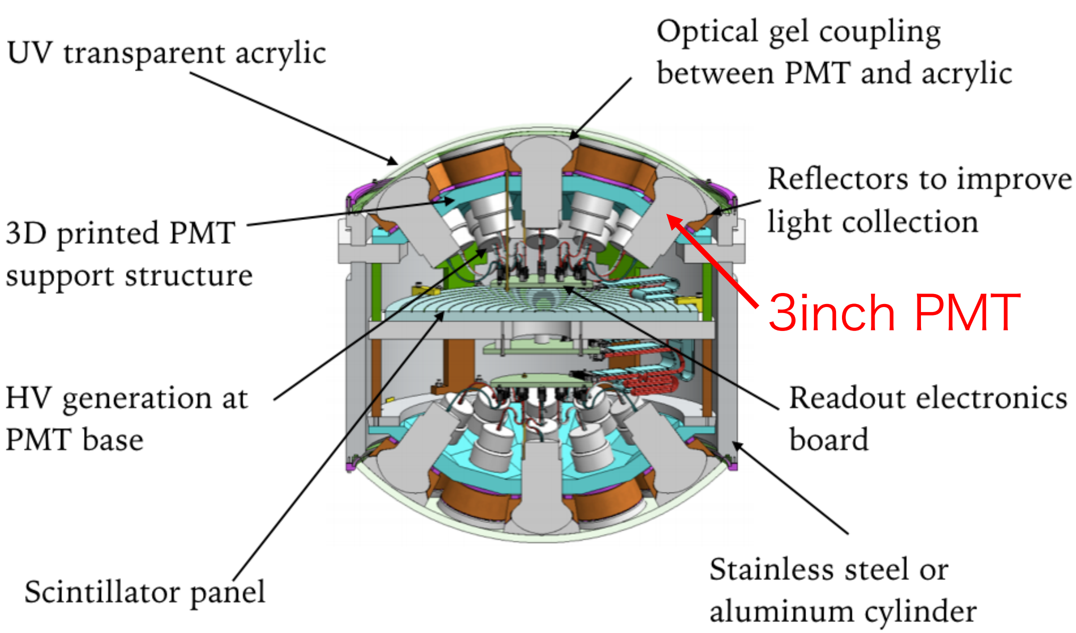
Atmospheric sensitivities

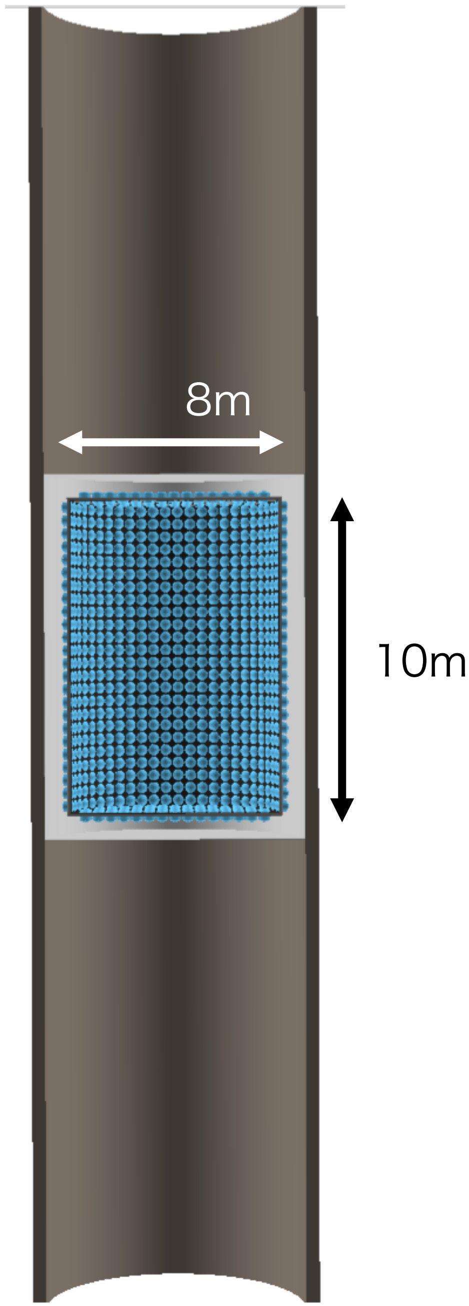
Atmospheric ν_e appearance probabilities



E61 detector

- The detector has optically separated inner and outer detectors.
- Cherenkov photons are detected by 3inch PMTs enveloped in mPMT modules (19 PMTs for ID side).

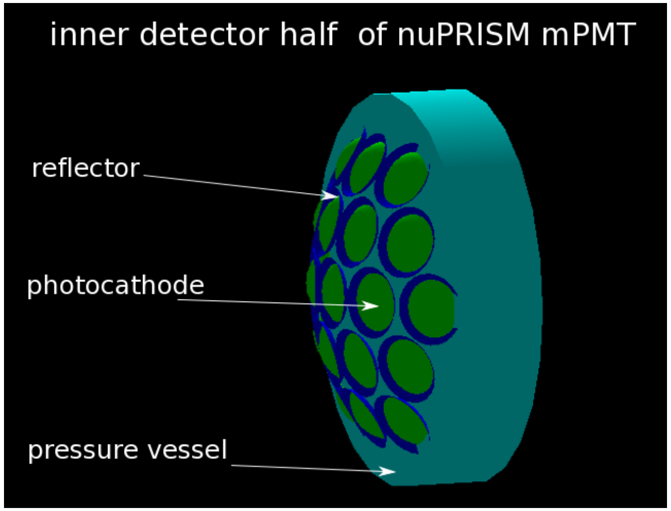


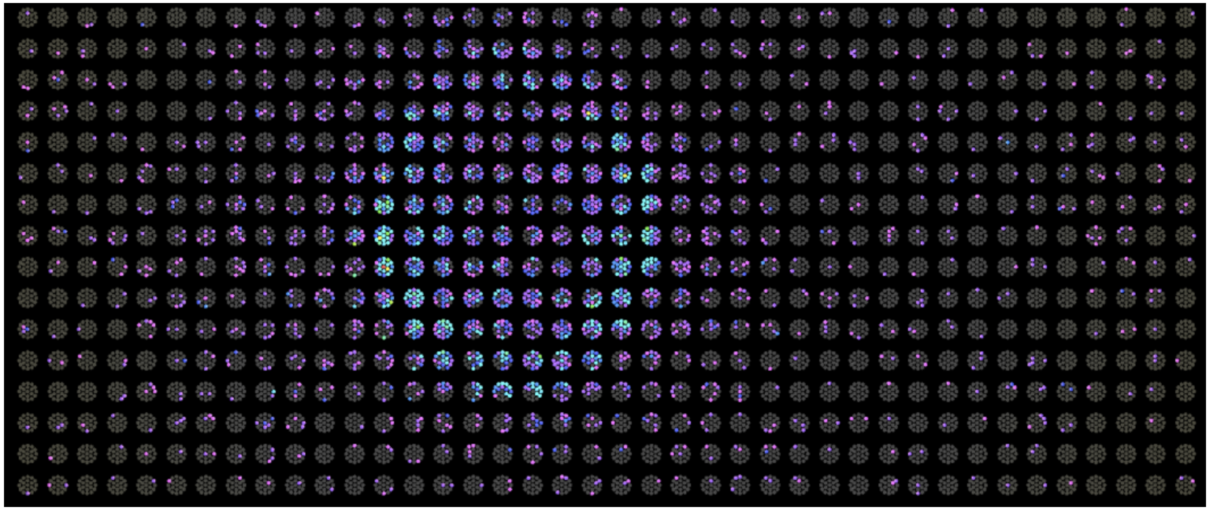


Software development

Full detector simulation and event reconstruction algorithm are developed to study detector optimization and physics sensitivities.

- Detector simulation **WCSim**
- Event reconstruction algorithm **fiTQun**

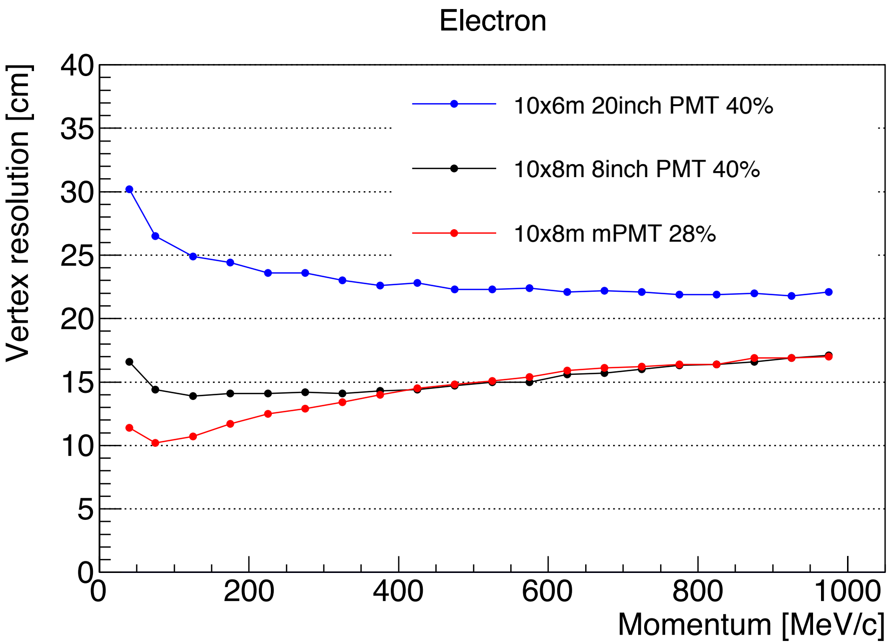


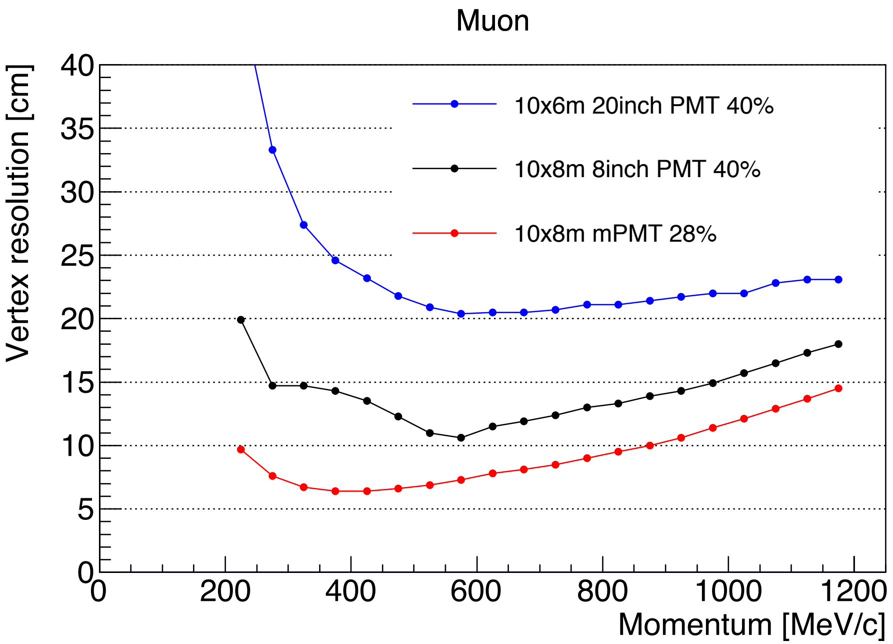


Vertex resolution

Vertex resolution is improved by using smaller PMTs.

- Timing resolution of PMTs is improved
- Location of each photon is decided more precisely





Toward the combined analysis

Recently, studies have been started to fit beam and atmospheric events simultaneously in T2K and Super-K .

- As a first step, atmospheric 1-ring sub-GeV (<1.33 GeV) events were simultaneously fitted with T2K beam events with the T2K parameterization of interaction systematics.
- This demonstrated that the T2K interaction model also describes atmospheric sub-GeV events well enough and that detector systematics are significantly reduced for beam events.
- Further study is necessary to include atmospheric events with higher energy since the T2K interaction model is focused on interactions below a few GeV.