J-PARC E61 experiment

Feb. 21, 2018

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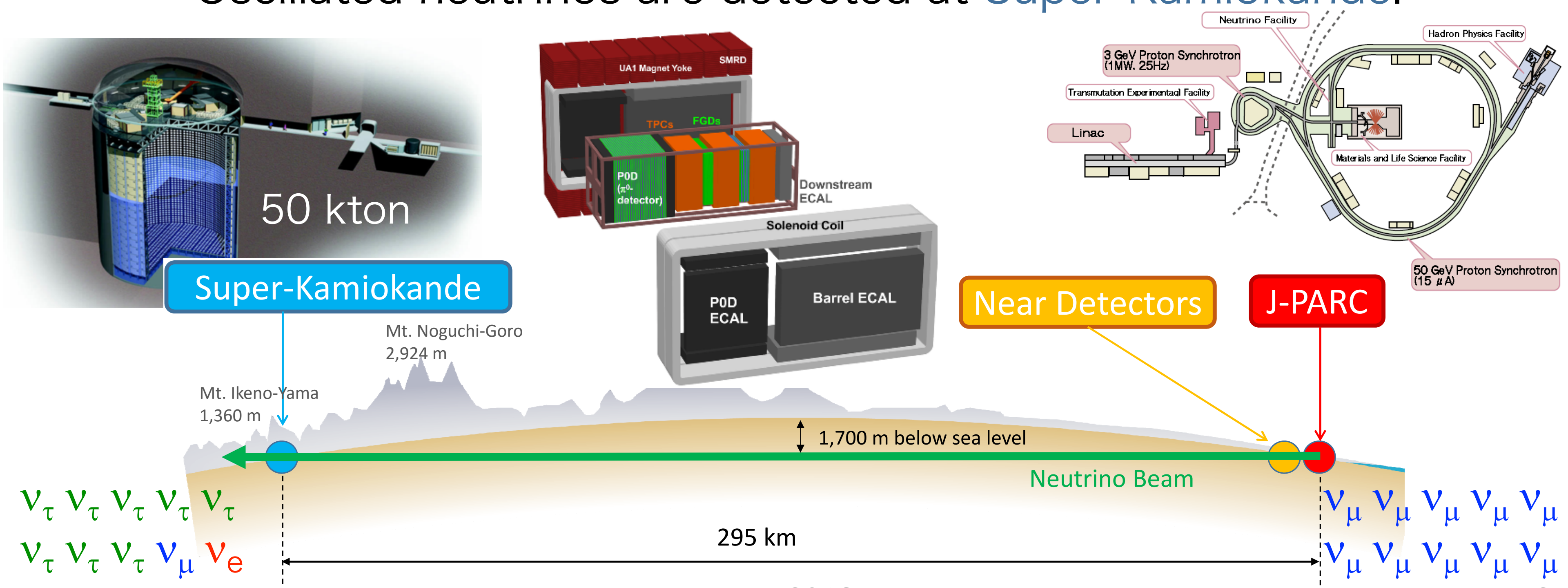
For J-PARC E61 collaboration

Lake Louise Winter Institute

T2K experiment

One of the world-leading neutrino oscillation experiments

- (Anti-) muon neutrino beam is generated at J-PARC.
- Beam property and neutrino interaction are measured at near detectors.
- Oscillated neutrinos are detected at Super-Kamiokande.

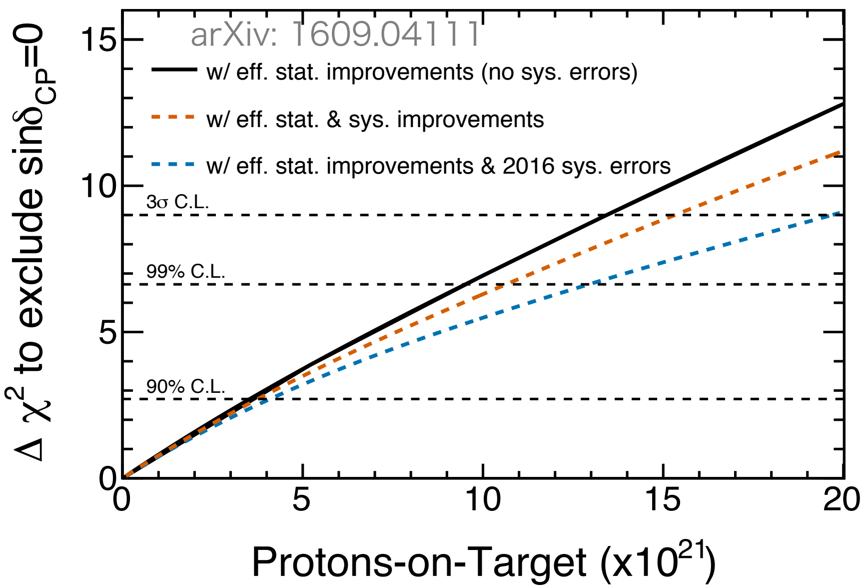


Future LBL experiments in Japan

T2K-II (–2025)

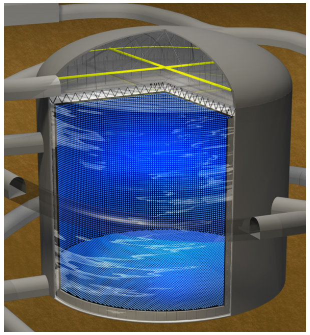
Proposed T2K extension from original 7.8×10^{21} POT to 20×10^{21} POT

Exclude CP conservation at 3σ at maximal



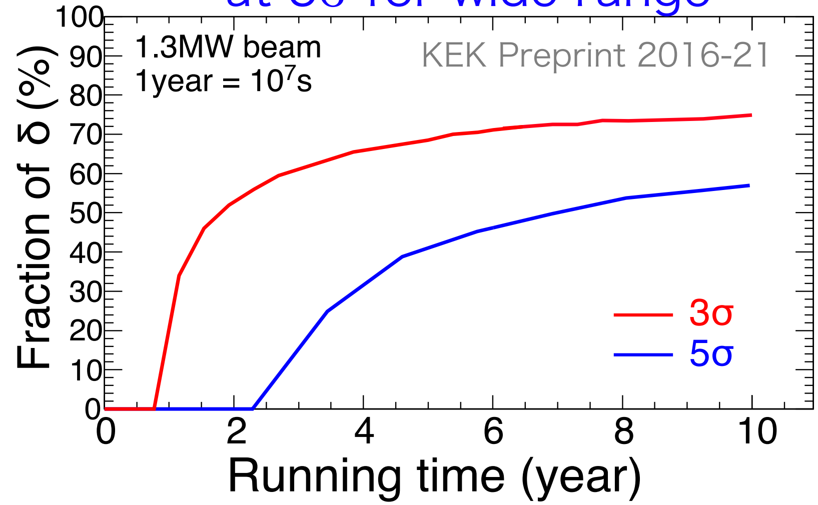
Hyper-Kamiokande (2026–)

Proposed water Cherenkov detector



260 kton / tank

Exclude CP conservation at 5σ for wide range

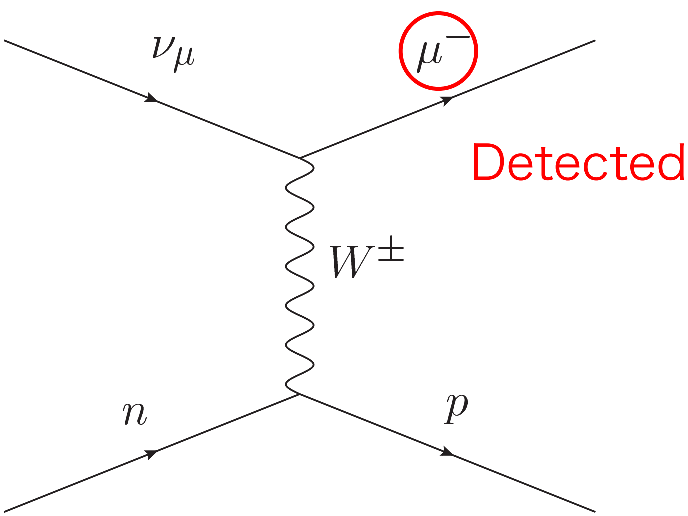


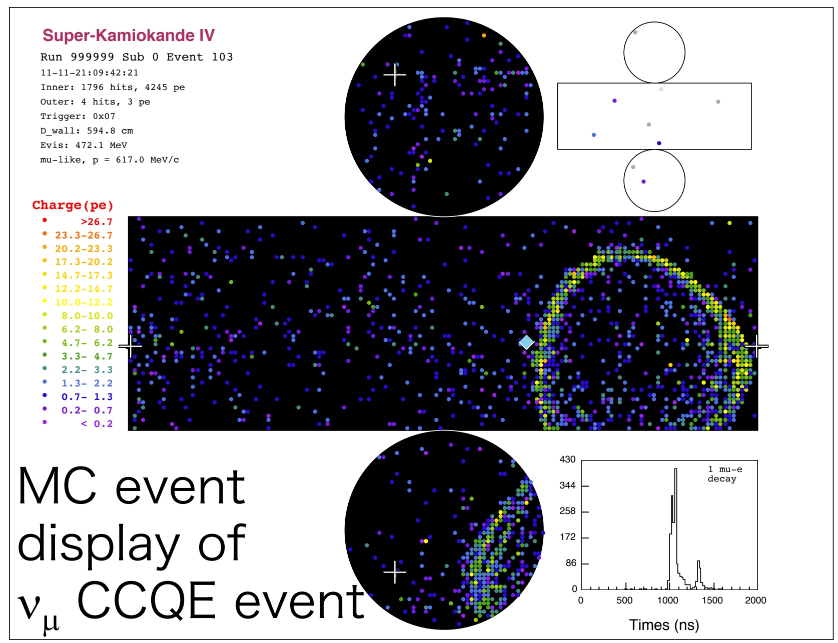
Long-baseline experiments will enter the precision era.

Neutrino energy reconstruction

Energy reconstruction is crucial since the oscillation probability depends on neutrino energy.

- Single ring events are selected at Super-K.
- Neutrino energy is reconstructed from momentum and direction of the charged lepton, assuming charged current quasi-elastic (CCQE) kinematics.



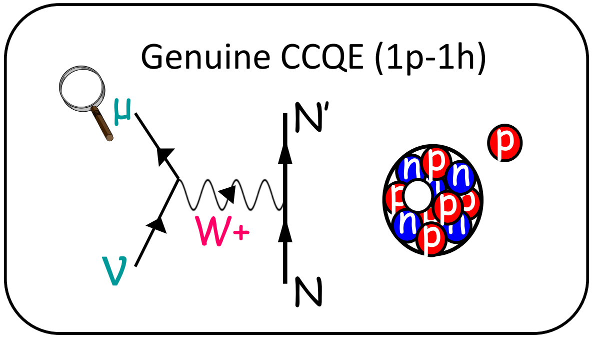


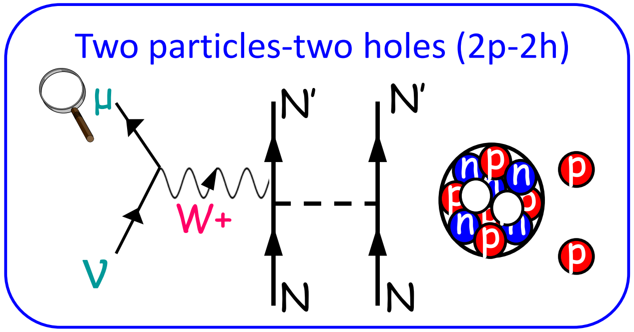
MC event display of ν_μ CCQE event

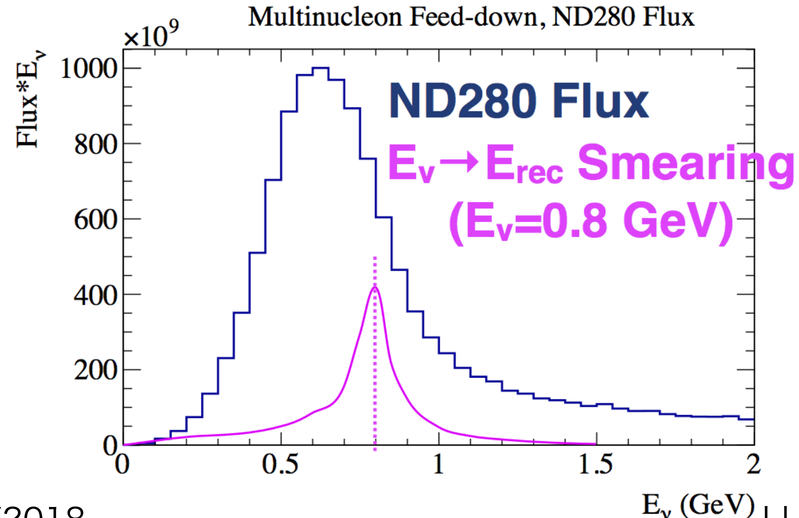
Interaction model uncertainties

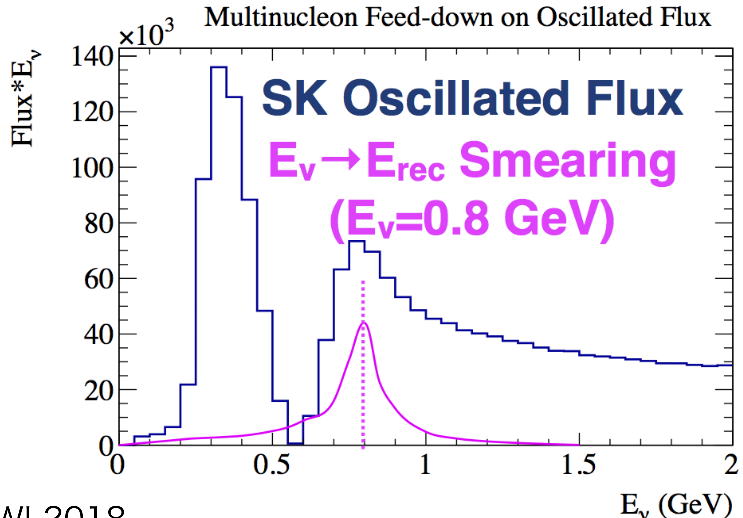
Reducing model uncertainties will be more and more important in future.

- Multi-nucleon interaction components can bias neutrino energy reconstruction.
- Although this smearing may not be seen significantly at near detectors, the bias might be crucial at far detector, as neutrino oscillate.







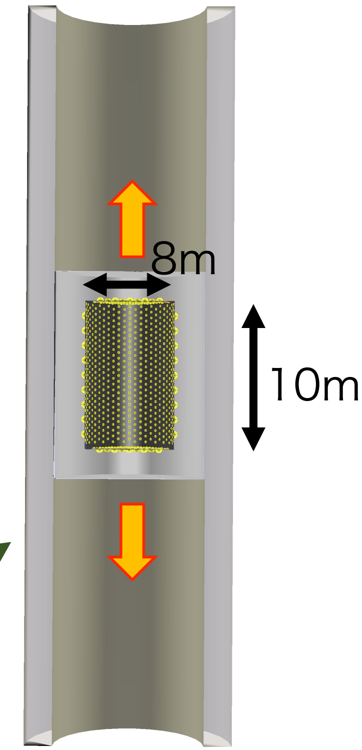


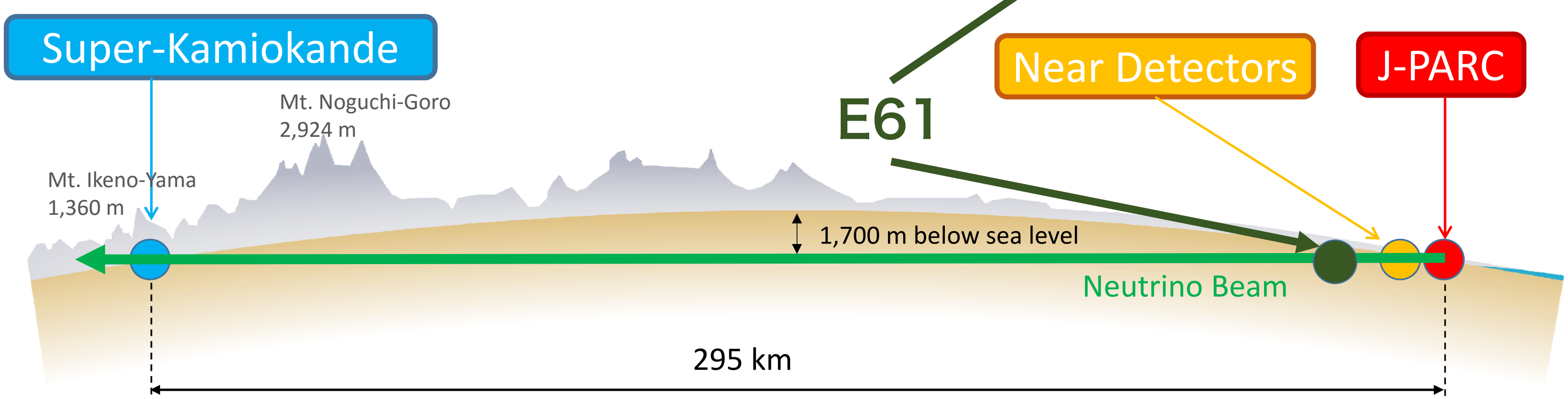
arXiv: 1611.07770

J-PARC E61 detector proposal

An intermediate water Cherenkov detector at 1 – 2 km downstream of J-PARC neutrino beam

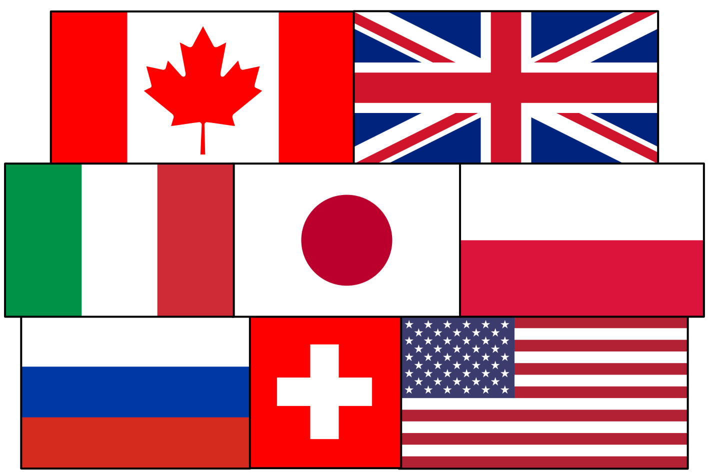
- An instrumented volume moves vertically within a 50 m tall water pit
- Optically separated inner and outer detectors





J-PARC E61 collaboration

- 2 collaborations, NuPRISM and TITUS merged.
- 110 collaborators from 35 institutes in 8 countries as of Jan. 2018



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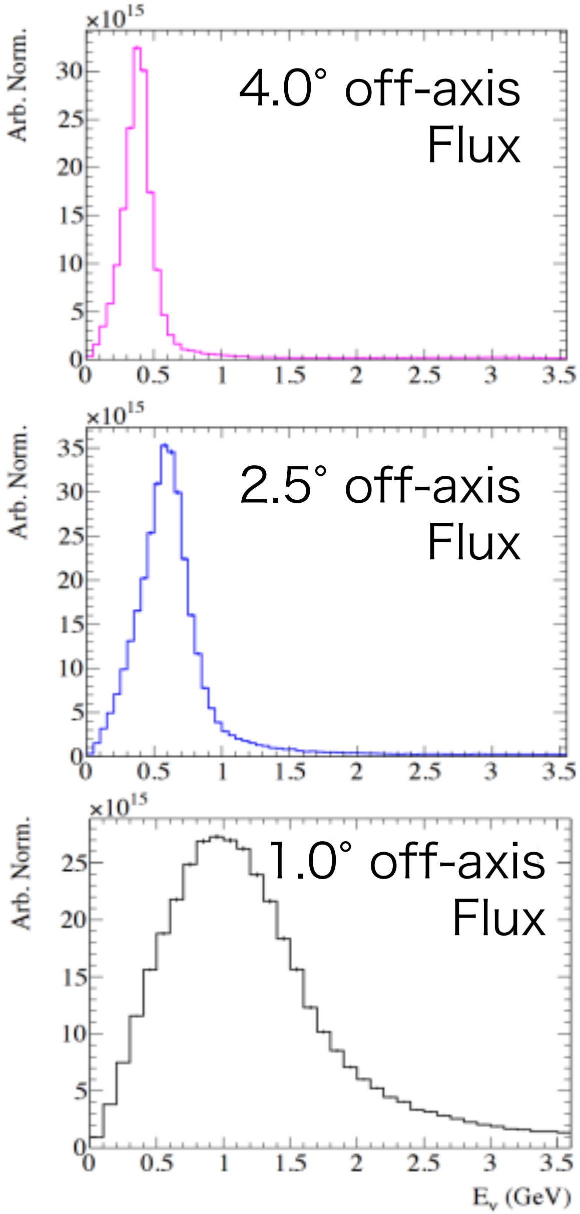
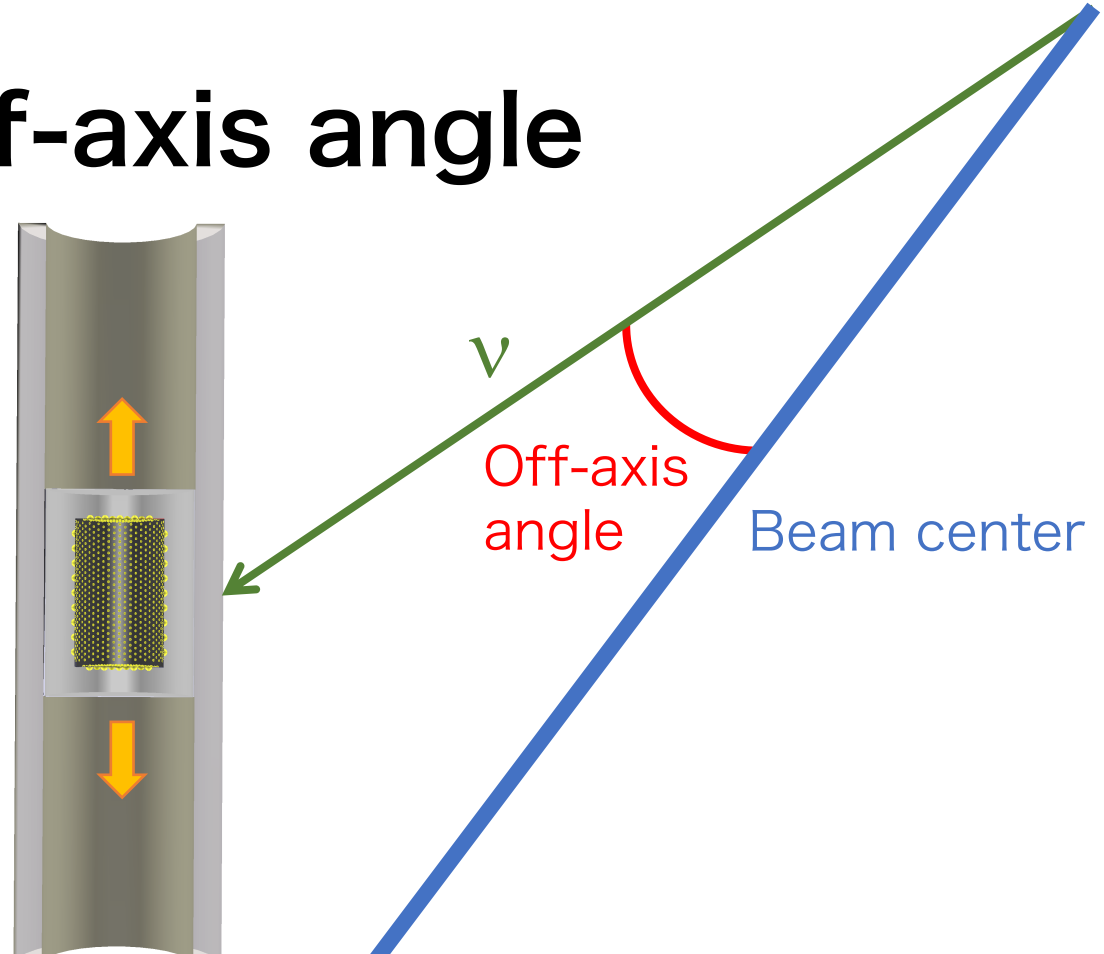
Spanning off-axis angle



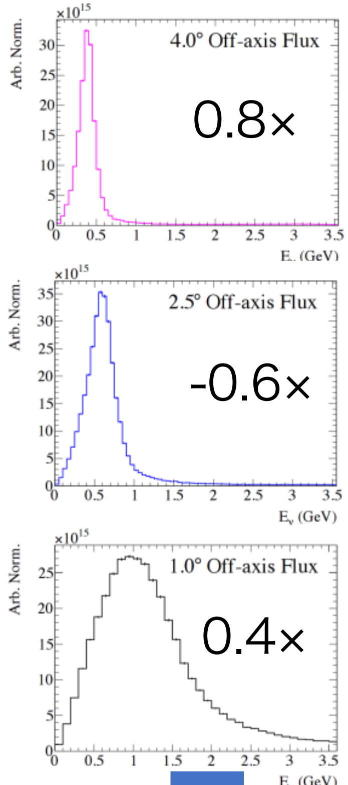


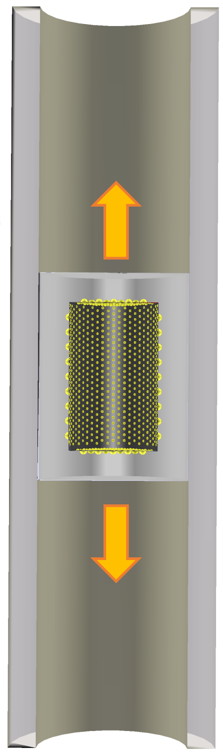
Neutrinos with different energy spectra are measured by spanning off-axis angle

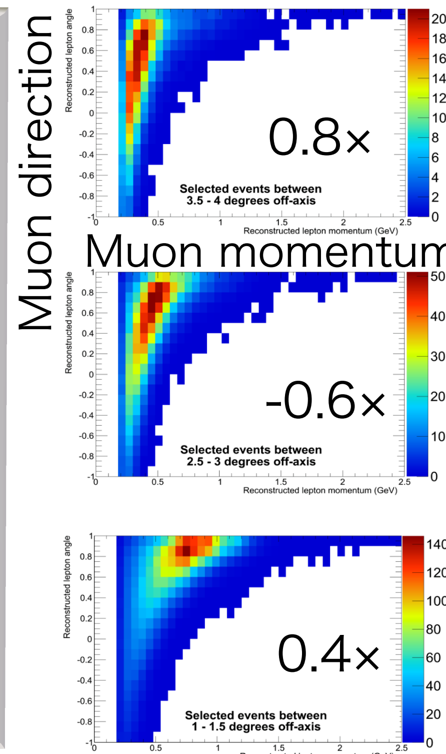
$$E_{\nu} = \frac{m_{\pi}^{2} - m_{\mu}^{2}}{2E_{\pi}(1 - \beta_{\pi}\cos\theta)}$$

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.

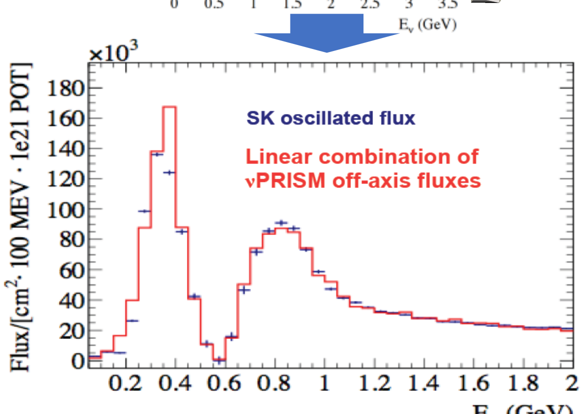


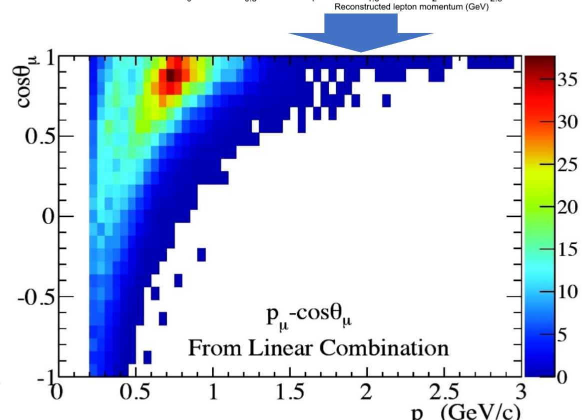




3. Take the same linear combination of observed variables to expect their distributions corresponding to that spectrum.

Example1: Oscillated far detector spectrum

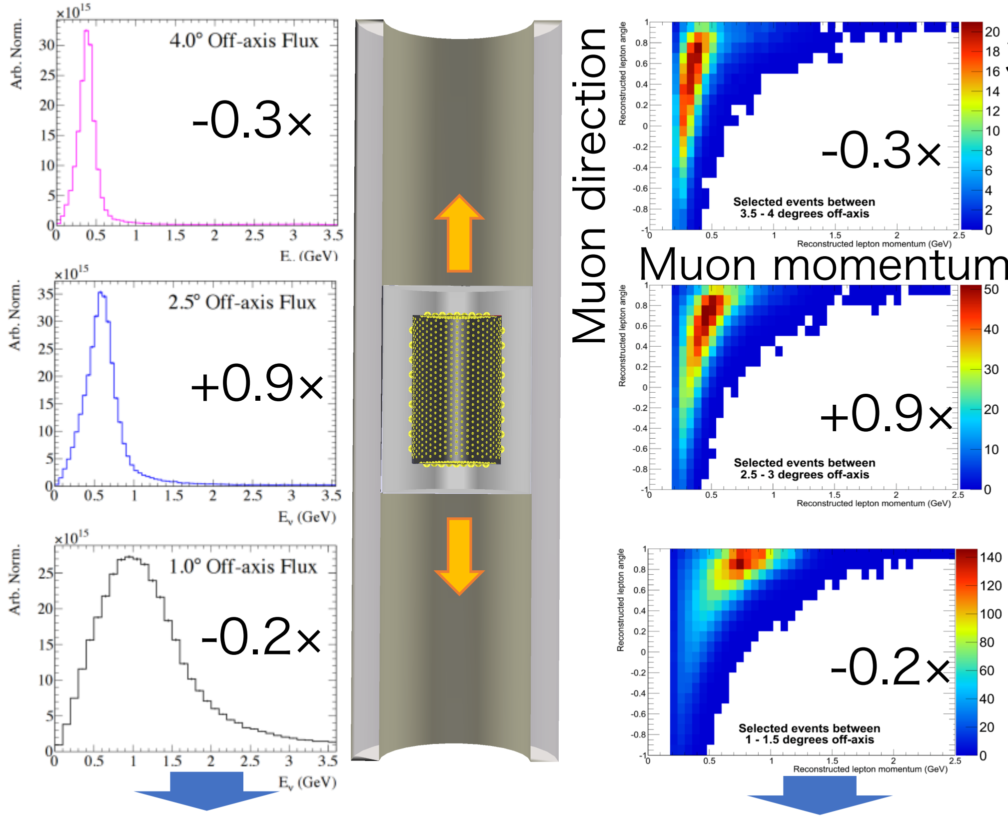




Enables data-to-data fit to extract oscillation parameters, independent of interaction models

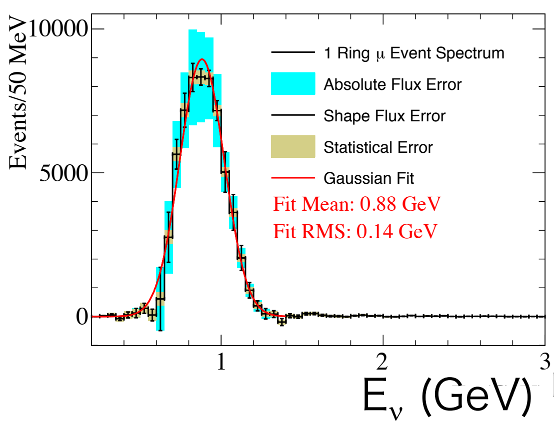
Linear combination of off-axis bins

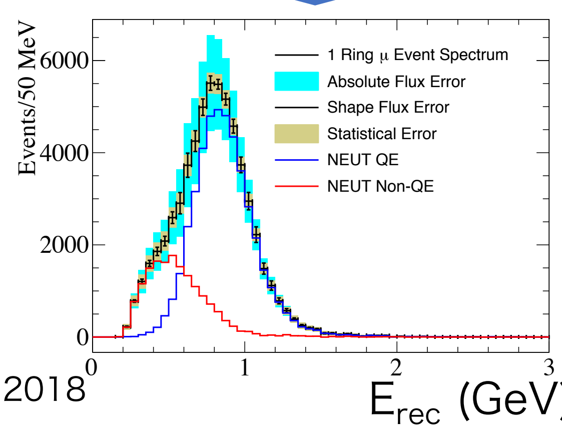
1. Separate detector volume to 30 off-axis slices.
2. Take a linear combination of off-axis slices to reproduce desired spectrum.



3. Take the same linear combination of observed variables to expect their distributions corresponding to that spectrum.

Example2: Gaussian



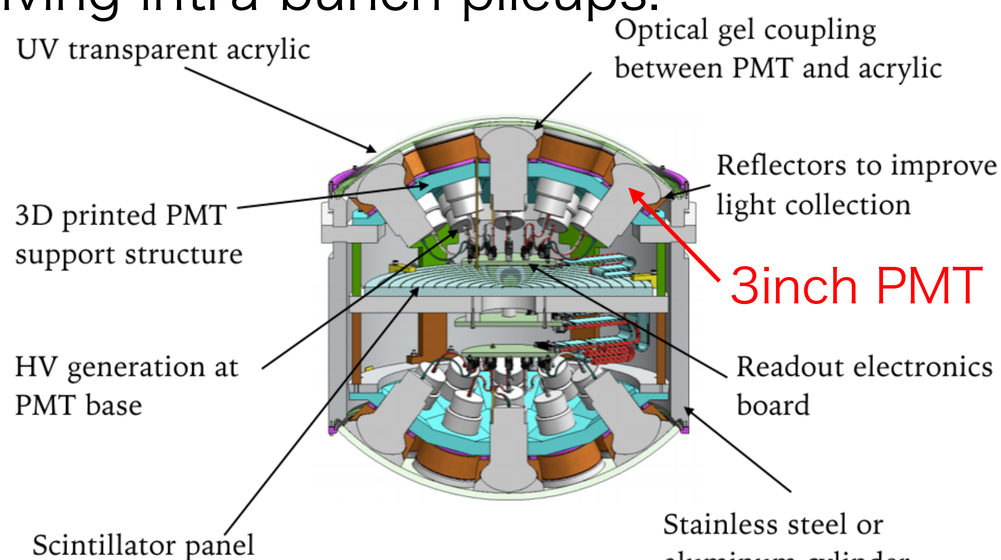


Can study neutrino interaction using pseudo-monochromatic beam

Multi-PMT developments

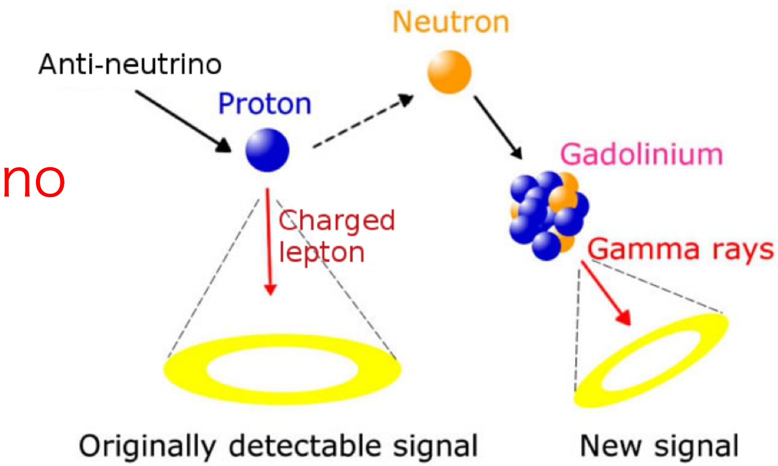
The E61 baseline design is equipped with multi-PMT modules with 27% of photo-cathode coverage.

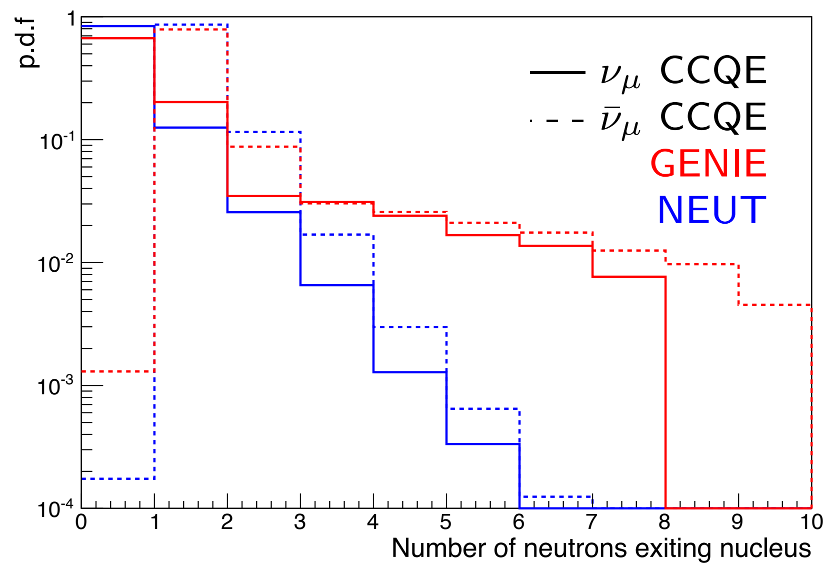
- Fine granularity of Cherenkov ring images improves event reconstruction.
- Timing resolution is improved by using smaller PMTs, which is important for resolving intra-bunch pileups.
- R&D is ongoing.
    - PMT, acrylic, gel, …
    - Electronics
    - Prototype production
- Geant4-based full detector simulation is developed.
- Event reconstruction development is underway.



Gd loading option

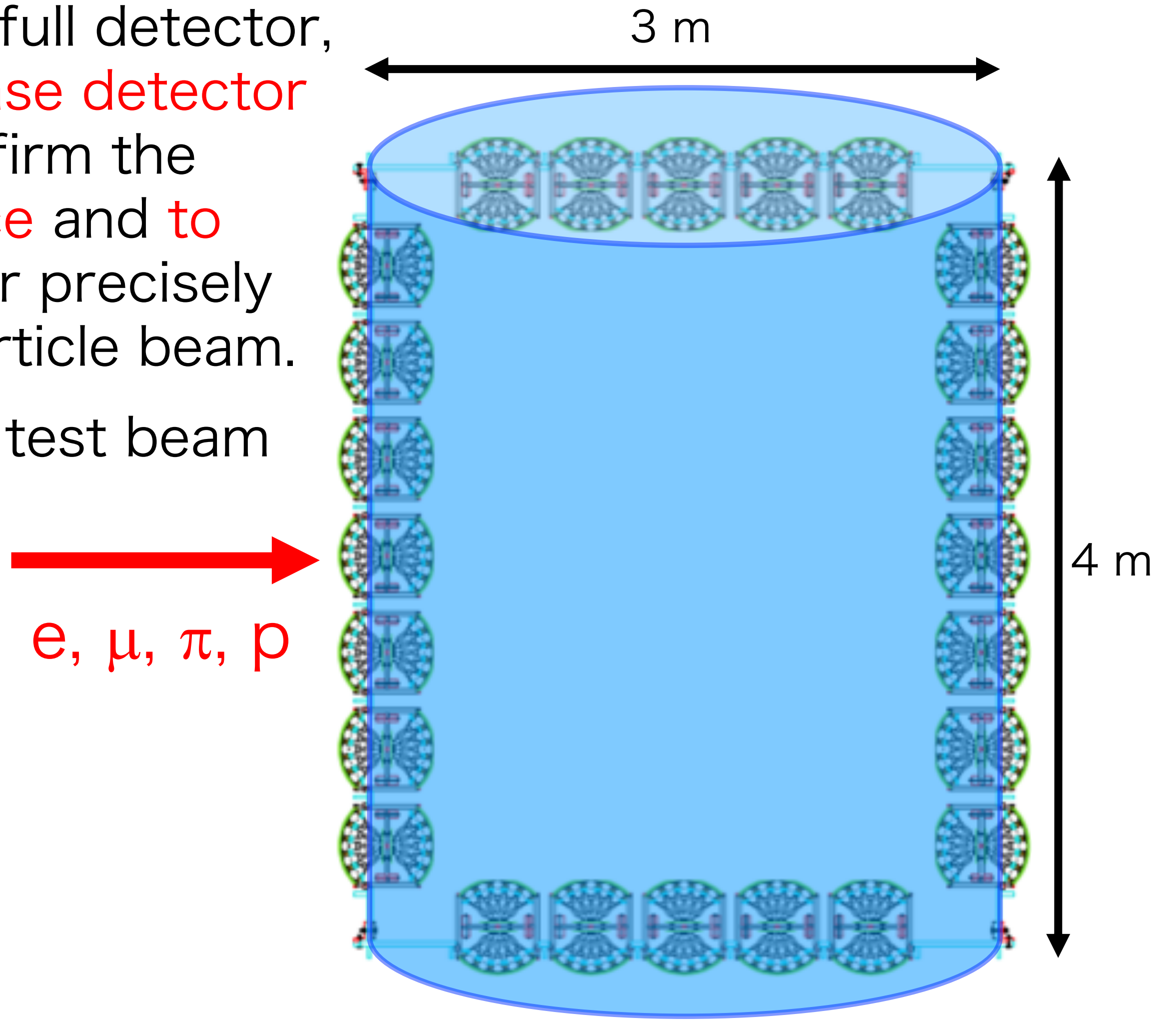
- Super-Kamiokande plans to load Gd in the water.
  - Statistical neutrino/anti-neutrino separation would be possible.
- However, there is no measurement of neutrino-induced neutron capture by Gd in water Cherenkov detector.
- Gd loading to E61 detector would help constraining neutron emission rates and tagging efficiency.





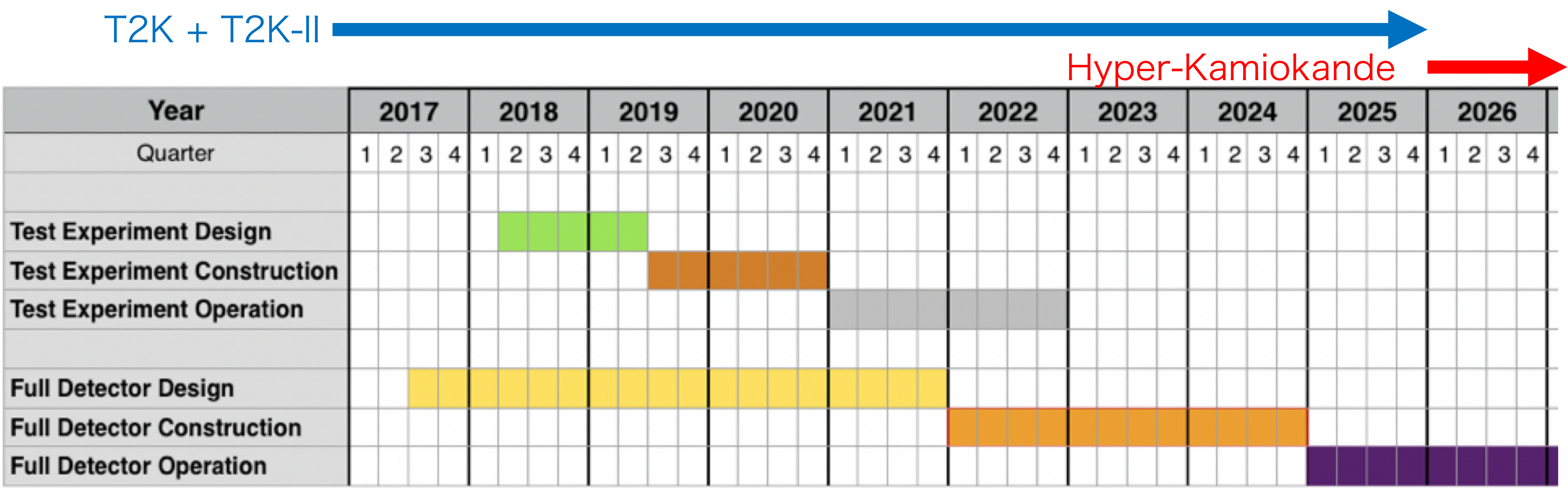
Staged approach — Beam test

- Before constructing full detector, small-scale initial-phase detector is considered to confirm the detector performance and to calibrate the detector precisely by using charged particle beam.
- We are investigating test beam facility at Fermilab.



Prospects

- We aim to take neutrino beam data before Hyper-Kamiokande operation starts.
- E61 received J-PARC Stage-1 status in 2016.
  - Scientific merit is recognized.
  - Developing concrete design is required for construction.



Summary

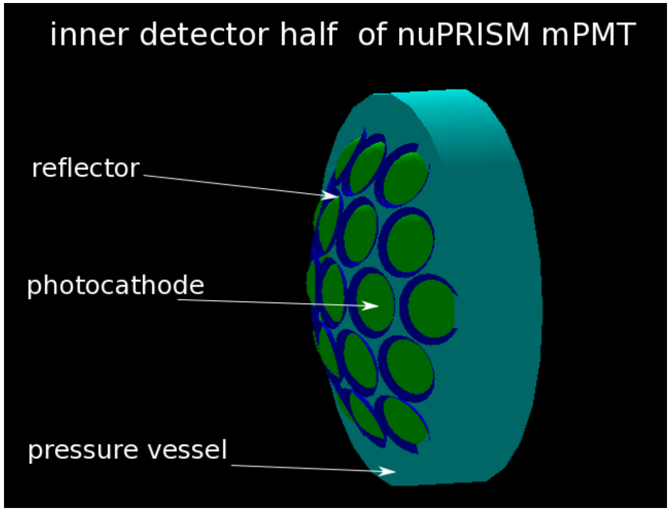
- Reducing neutrino interaction model uncertainties will be more and more important in future oscillation experiments.
- J-PARC E61 experiment aims to give a data-driven method to convert observable final state kinematics to neutrino energy.
- R&D of multi-PMT module is ongoing, with initial prototypes in production.
- Analysis scheme based on multi-PMT is being developed using full detector simulation and event reconstruction algorithm.
- The construction of an initial phase of the detector has been proposed to ensure detector performance.

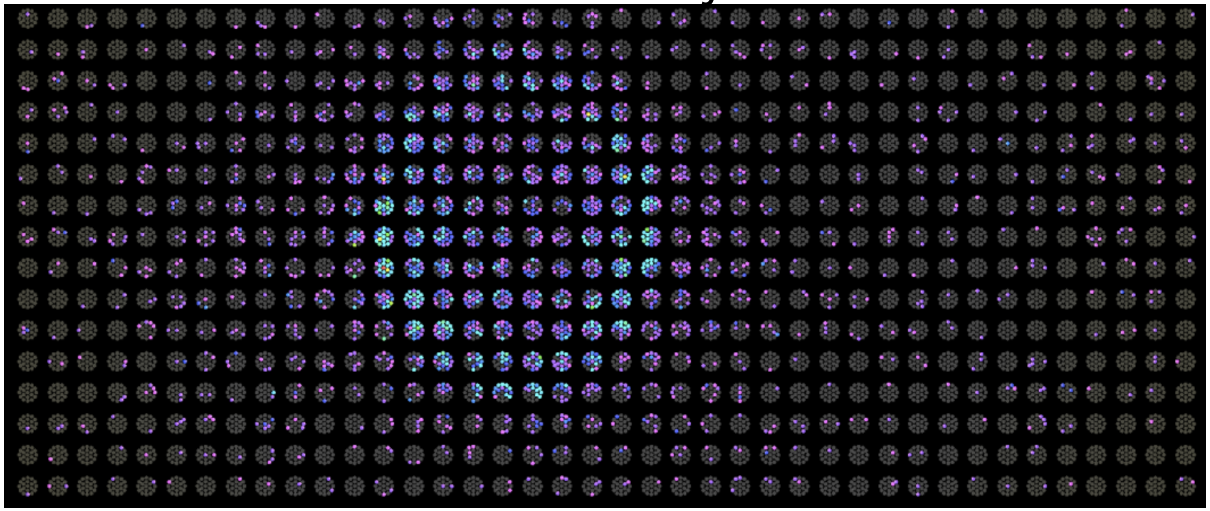
Back up

Software development

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

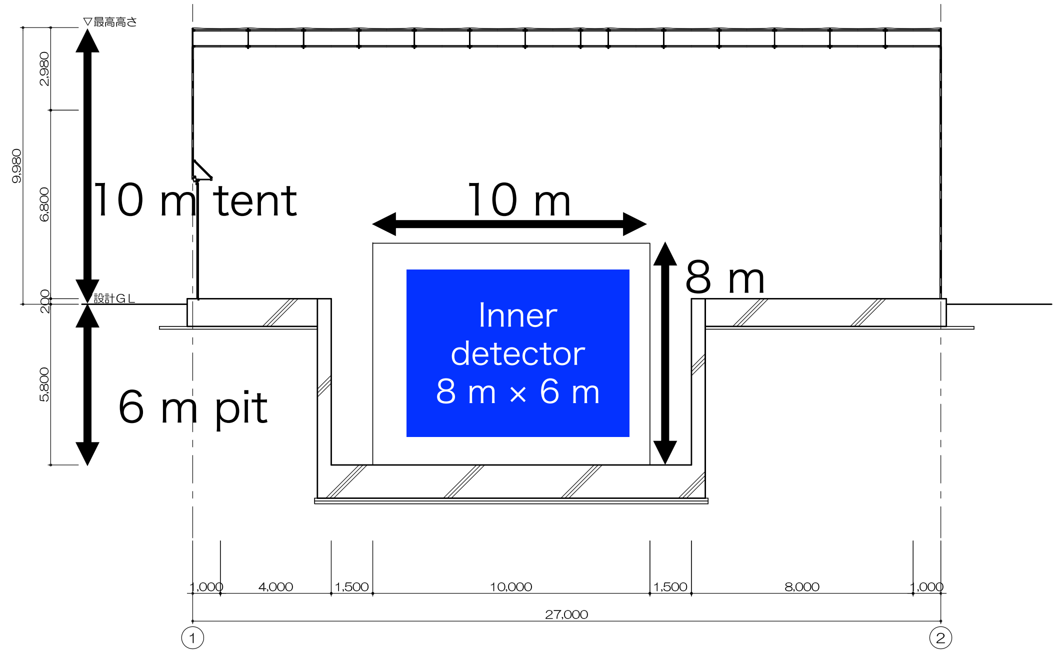
- Development of Geant4-based detector simulation is in cooperation with Hyper-Kamiokande collaboration. Multi-PMT is implemented.
- Event reconstruction is based on the algorithm used in T2K. Implementation of multi-PMT is underway.

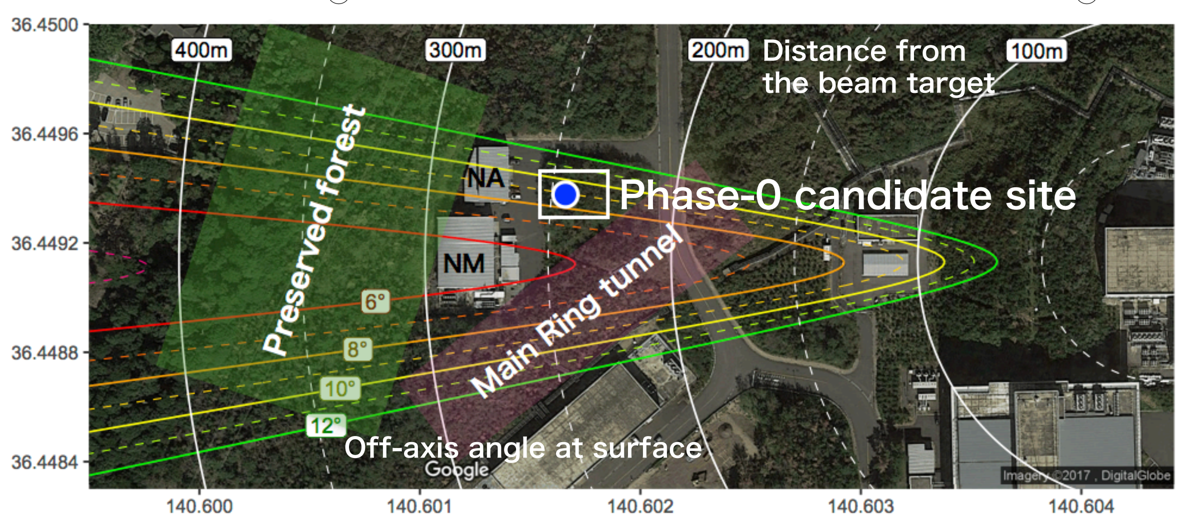




Staged approaches — Phase-0

- To demonstrate detector performance and calibration methods by a surface detector
- ν_e cross section and neutron multiplicity measurements are expected.
- Most detector components will be reused in Phase-1 operation inside the 50m-deep pit.





T2K systematics

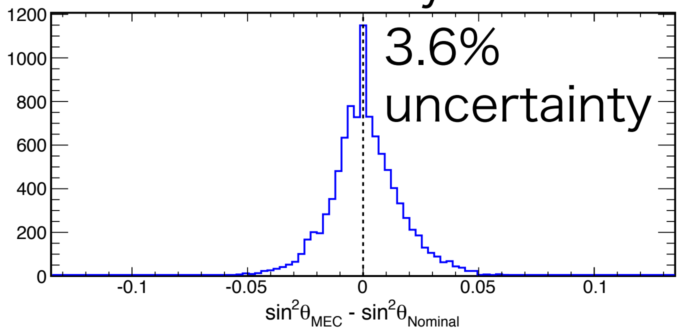
Current T2K systematic errors taken from PRD 96, 092006 (2017)

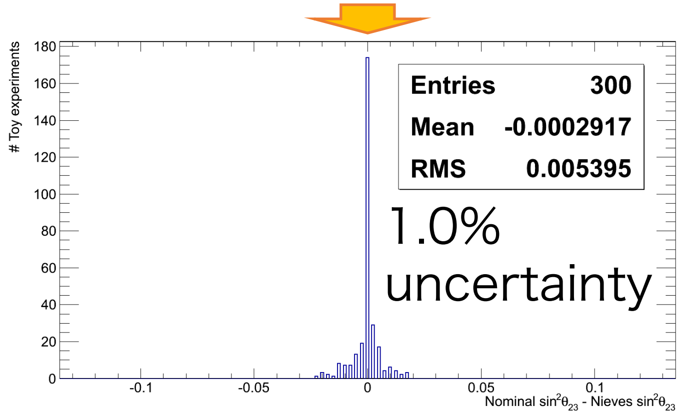
	$\delta N_{SK}/N_{SK}$ [%]			
	1-ring μ		1-ring e	
	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode
Flux + Cross section	2.9	3.5	4.2	4.7
Final state interaction + secondary interaction + photonuclear effect at SK	1.5	2.1	2.5	3.0
SK detector	3.9	3.4	2.4	2.5
Total	5.1	5.3	5.5	6.5

E61 contributions to ν_μ disappearance analysis

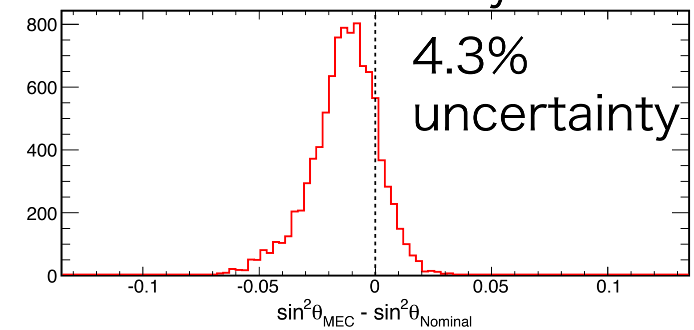
- E61 analysis is less sensitive to neutrino interaction models

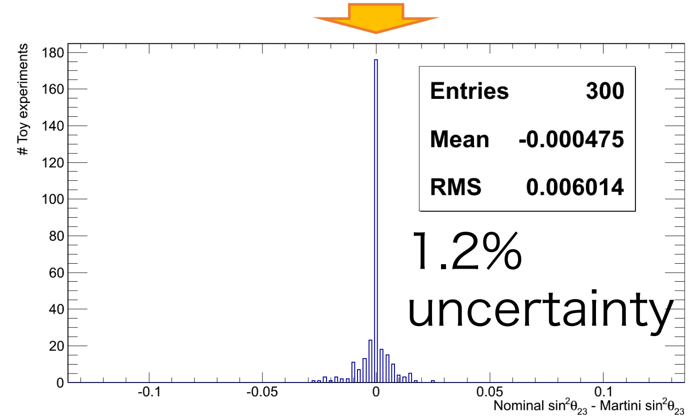
Nieves model fitted by nominal model





Martini model fitted by nominal mode





- Most of flux uncertainties cancel between E61 and SK

E61 contributions to ν_e appearance analysis

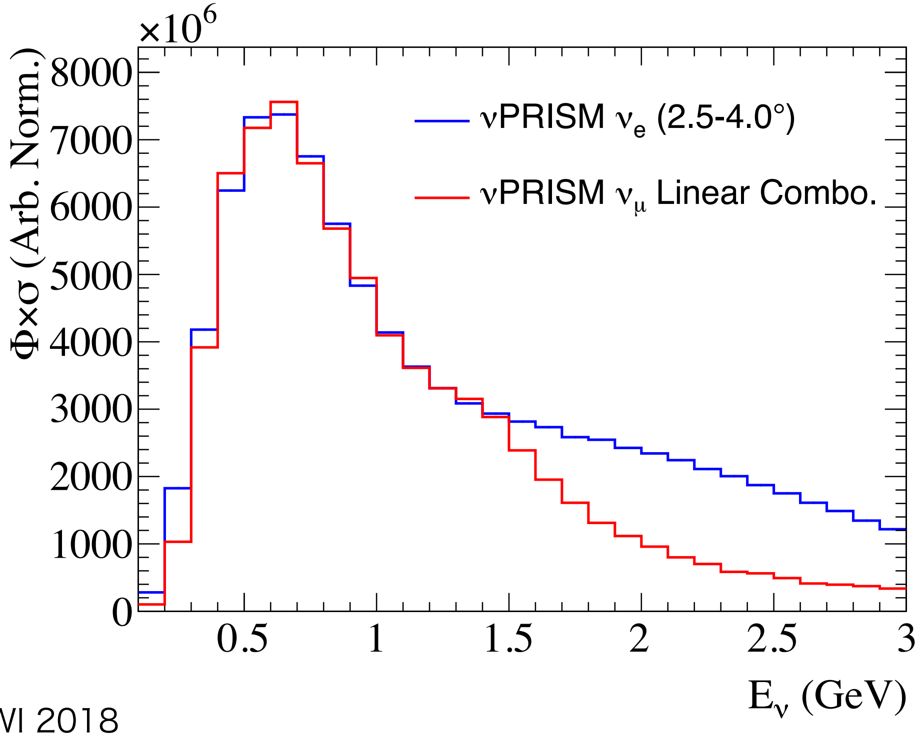
E61 provides a data-driven constraint on $\sigma(\nu_e)/\sigma(\nu_\mu)$ to 2–3%

- 1-ring ν_e candidates are selected with the 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.

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

Measured

Common flux uncertainties are canceled



E61 contributions to ν_e appearance analysis

Intrinsic ν_e and neutral current background at the far detector are constrained by measurement at 2.5° off axis