AN INTERMEDIATE WATER CHERENKOV DETECTOR FOR HYPER-K

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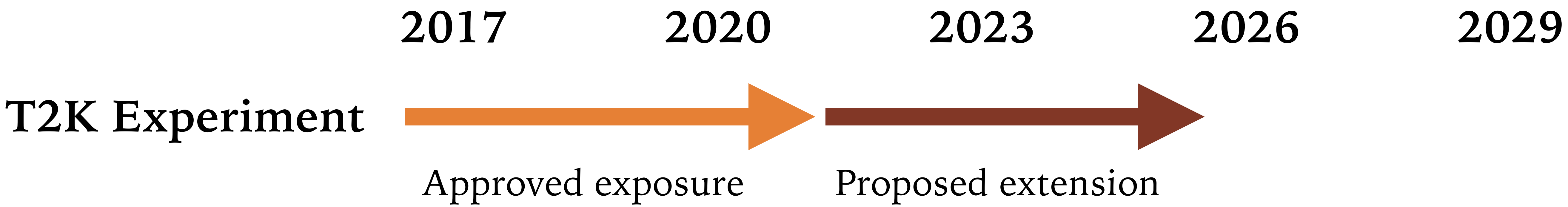
OUTLINE

- Long baseline neutrinos program in Japan
- Systematic errors in T2K and Hyper-K
- Why an intermediate water Cherenkov detector?
- The E61 experiment and Hyper-K
    - Physics measurements
    - ~~Design status~~
- A test beam experiment

LONG BASELINE NEUTRINOS IN JAPAN


2017 2020 2023 2026 2029

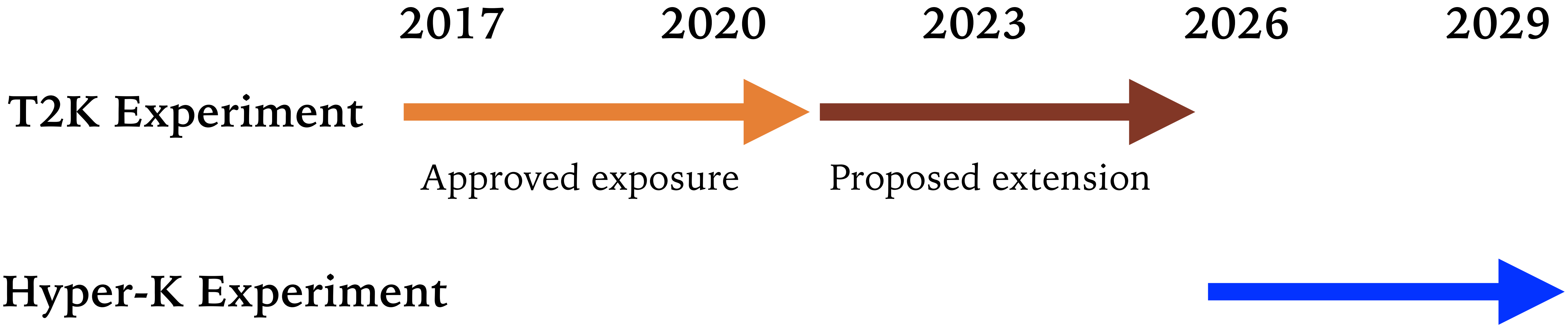
T2K Experiment

Approved exposure

Proposed extension

LONG BASELINE NEUTRINOS IN JAPAN

Hyper-Kamiokande
8x larger fiducial mass than SK



T2K Experiment

Approved exposure

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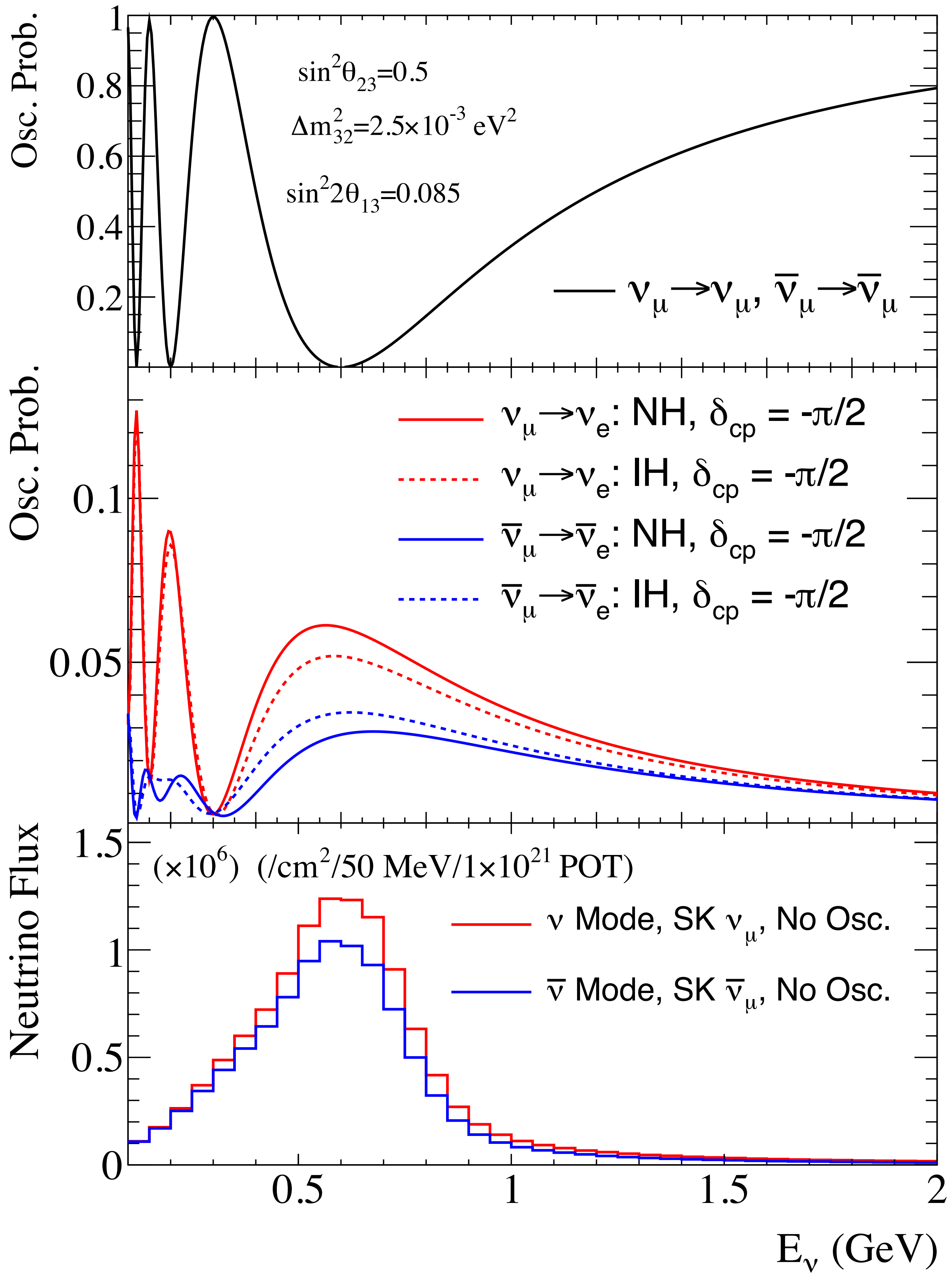
Hyper-K Experiment

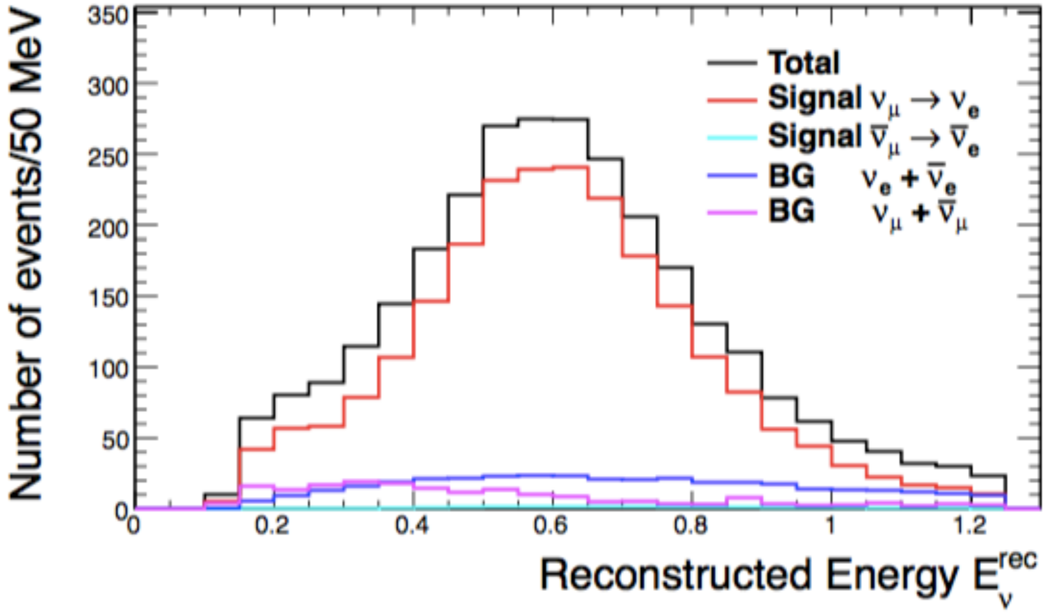
LONG BASELINE OSCILLATION PHYSICS



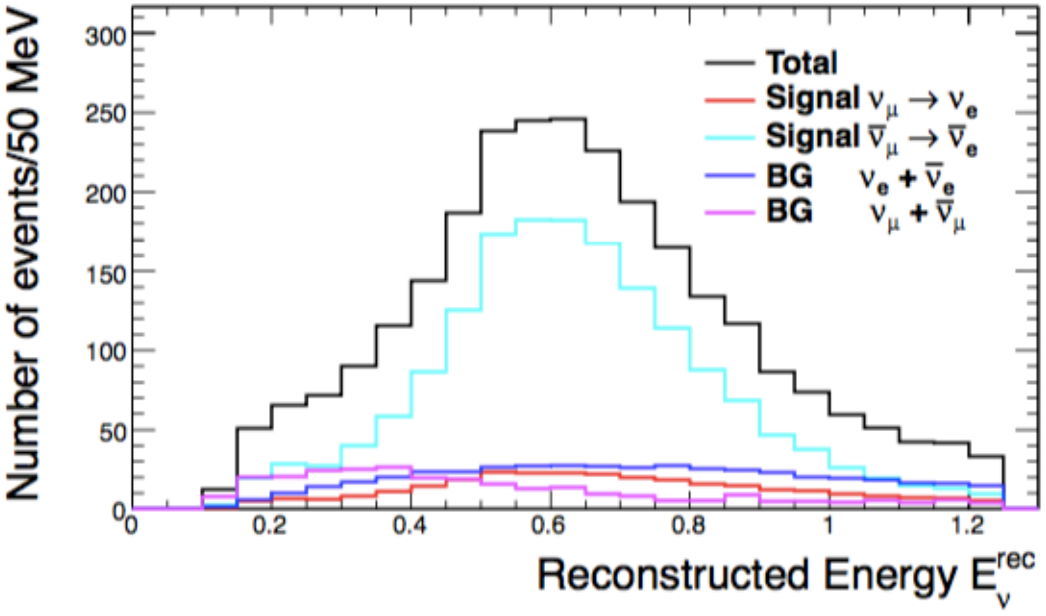
- **Muon (anti)neutrino survival** to measure **$\sin^2(2\theta_{23})$** and **Δm^2_{32}**
- **Electron (anti)neutrino appearance**
  - **$\sin^2(\theta_{23})$**, **$\sin^2(2\theta_{13})$** and **Δm^2_{32}** in leading term
  - Sub-leading dependence on **δ_{cp}**
    - CP conservation at **$\delta_{cp}=0,\pi$**
    - Maximal CP violation at **$\delta_{cp}=-\pi/2,\pi/2$**
  - Matter effect → dependence on the mass hierarchy

ELECTRON (ANTI)NEUTRINO CANDIDATES AT HYPER-K

Electron neutrino candidates



Electron antineutrino candidates



10 years, 1 Tank, $\sin^2(2\theta_{13})=0.1$, $\delta_{cp}=0$:

Horn Polarity Mode	Right-Sign Signal	Wrong-Sign	Background	Total
Neutrino Mode	1643	15	400	2057
Antineutrino Mode	1183	206	517	1906

- Statistical error on relative rate of electron neutrino and antineutrino candidates is 3.2%

ELECTRON (ANTI)NEUTRINO CANDIDATES AT HYPER-K

Error Source	% Error on neutrino/antineutrino rate
SK Detector Modeling	1.60
Pion Interaction Modeling in Nucleus and Detector	1.57
Neutral Current Background	1.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\nu_e\text{-bar})/\sigma(\nu_\mu\text{-bar})$	3.03
Extrapolation from near detector	2.50
Total	4.77

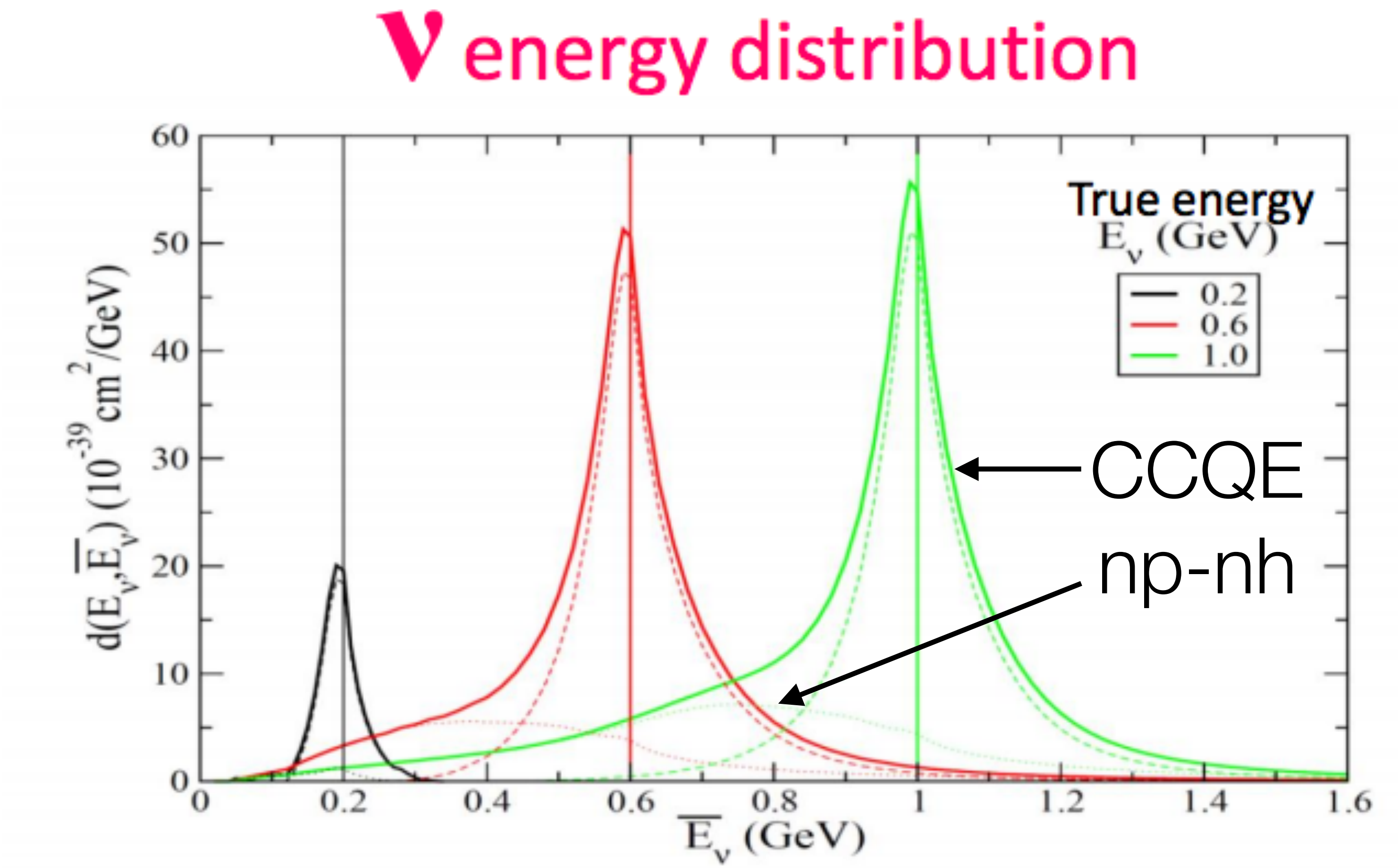
- Can benefit from near detector with same nuclear target and detection thresholds
- Beam ν_e and NC backgrounds can be directly measured in near detector with same flux/efficiency as far detector
- Need to take advantage of the intrinsic ν_e(-bar) in the beam to measure this
- Inference of neutrino energy plays and important role here

ENERGY RECONSTRUCTION IN HYPER-K

- Hyper-K signal mode consists mostly of QE scatters
- Infer neutrino energy from momentum and angle of lepton in final state (usually with QE scattering formula)

$$E_\nu^{\rm rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e\cos\theta_e)}$$

- Non-QE contributions arising from nuclear effects change the relationship between true neutrino energy and inferred energy

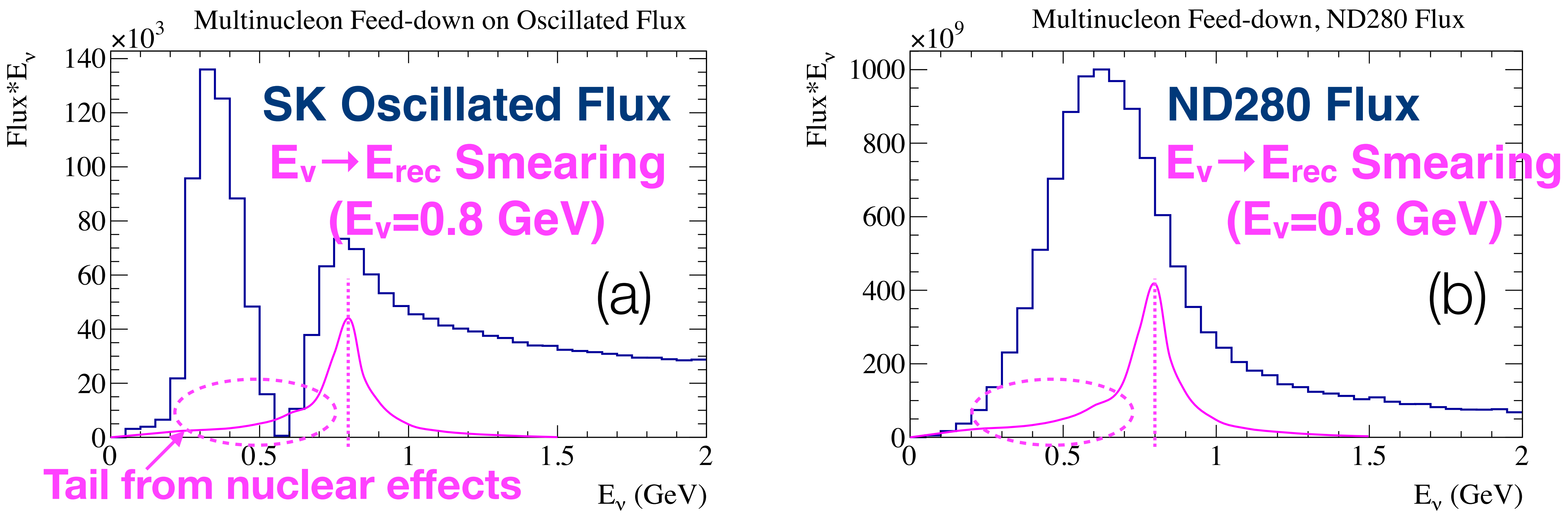


- Normalisation and kinematics of non-QE component can change significantly with different models
- Problem is under-constrained with current near detector data

M. Martini, M. Ericson, G. Chanfray, Phys. Rev. D 85 093012 (2012)

NEAR TO FAR EXTRAPOLATION

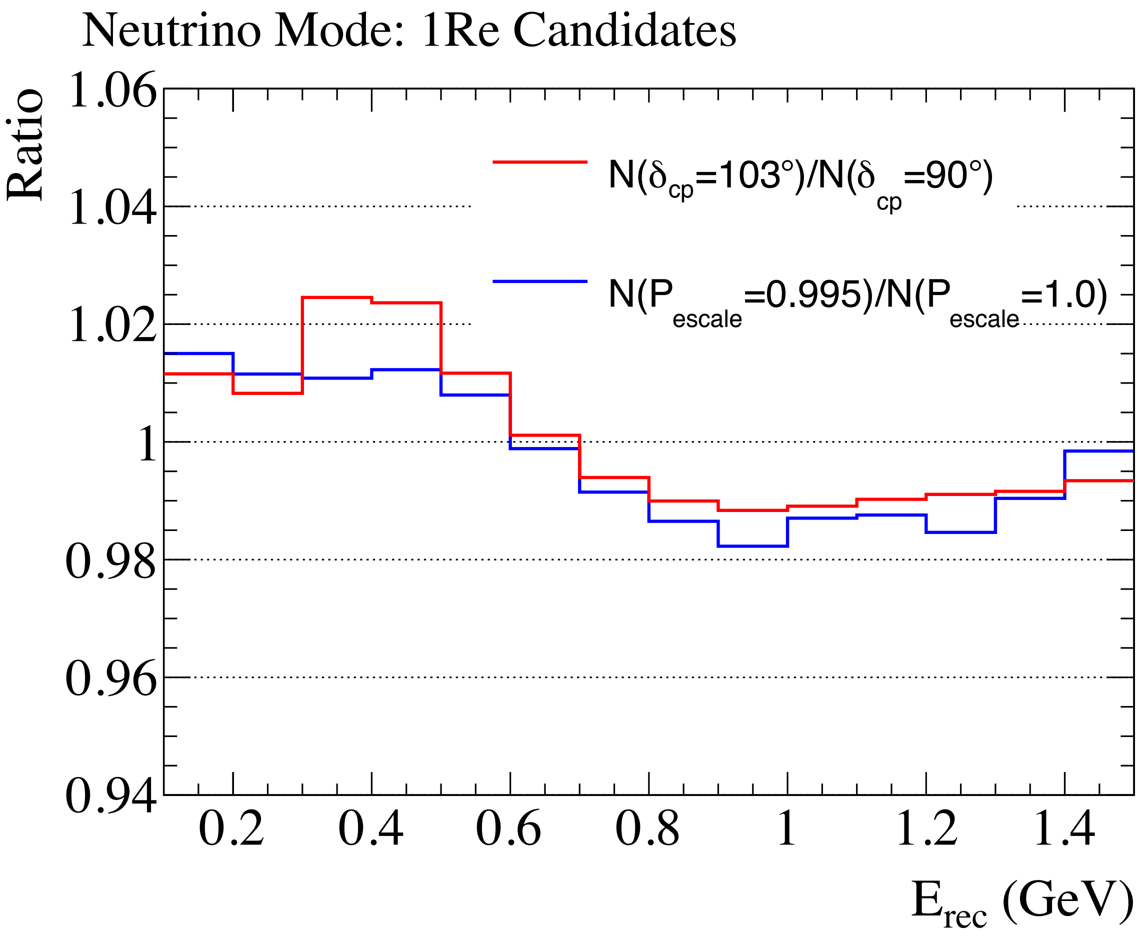
- Oscillations create a different spectrum at the far detector
- Different energy ranges can be relevant at near and far detectors



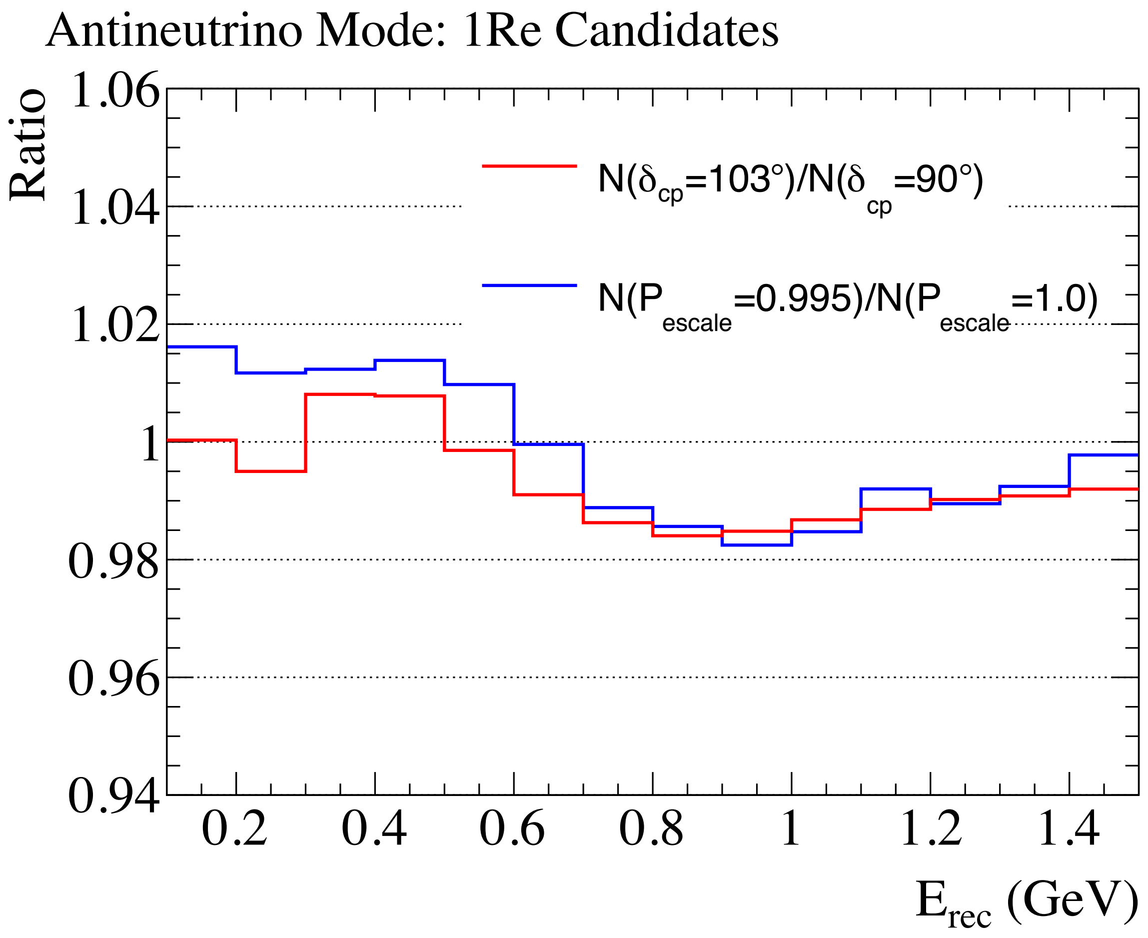
- We don't necessarily expect good cancellation of systematic effects between the near and far detector when energy inference is important

SHAPE MATTERS FOR DIRAC PHASE AS WELL

- Do we just care about normalisation for measurement of δ_{cp}?
- For values of δ_{cp} near maximal CPV, the $\cos\delta_{cp}$ term becomes dominant for constraining the phase
- Then shape effects are important:



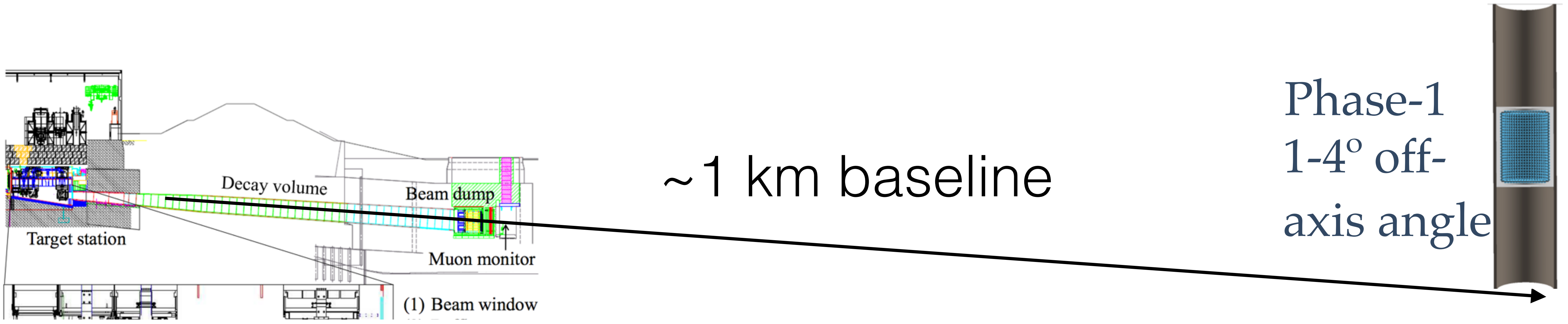
Neutrino Mode: 1Re Candidates



Antineutrino Mode: 1Re Candidates

- 13 degree shift in δ_{cp} has a similar effect on the predicted spectra as a 0.5% change in the energy scale
- Predicting the spectrum shape can be important!

OFF-AXIS SPANNING INTERMEDIATE WC DETCTOR

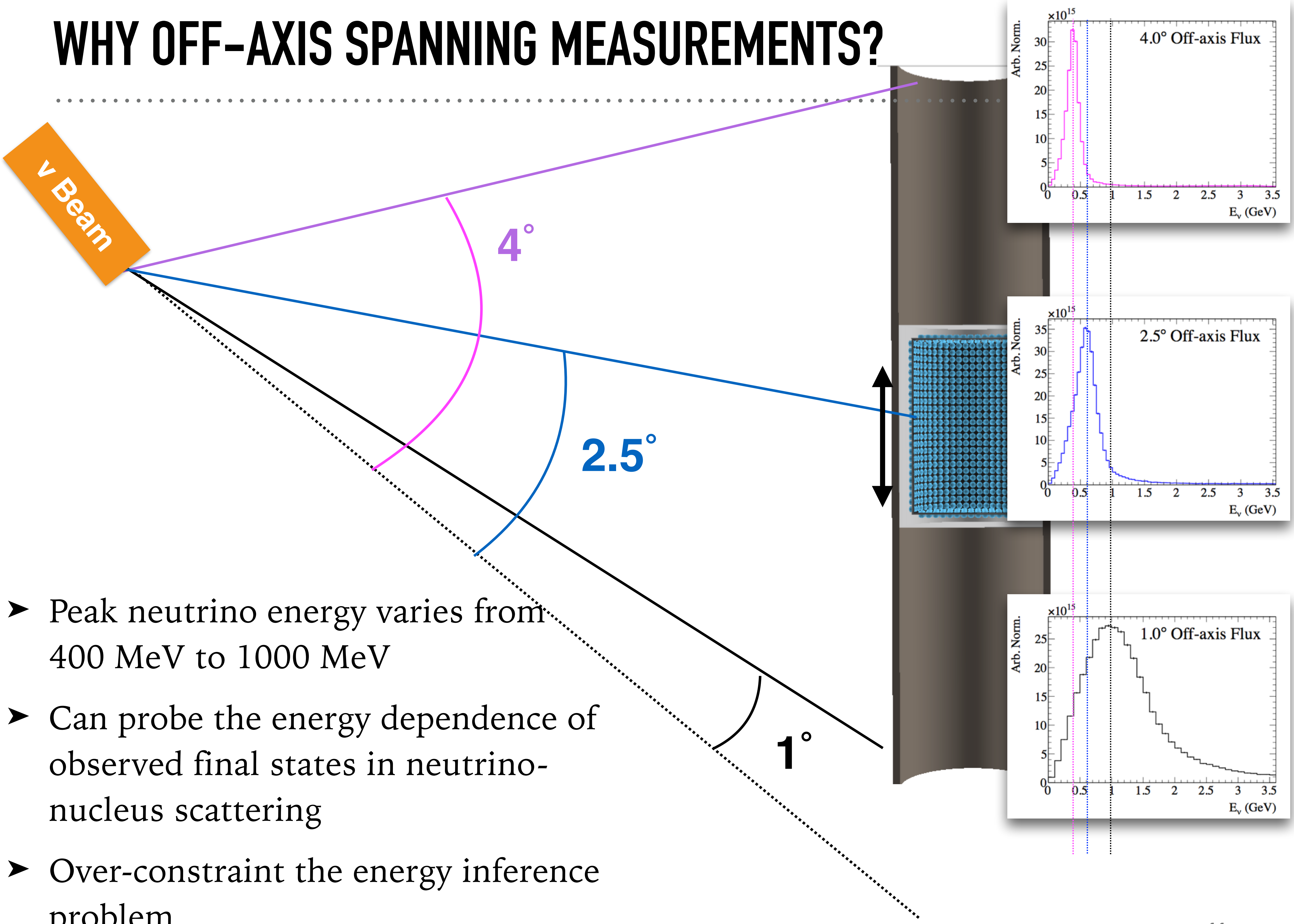


~1 km baseline

Phase-1
1-4° off-
axis angle

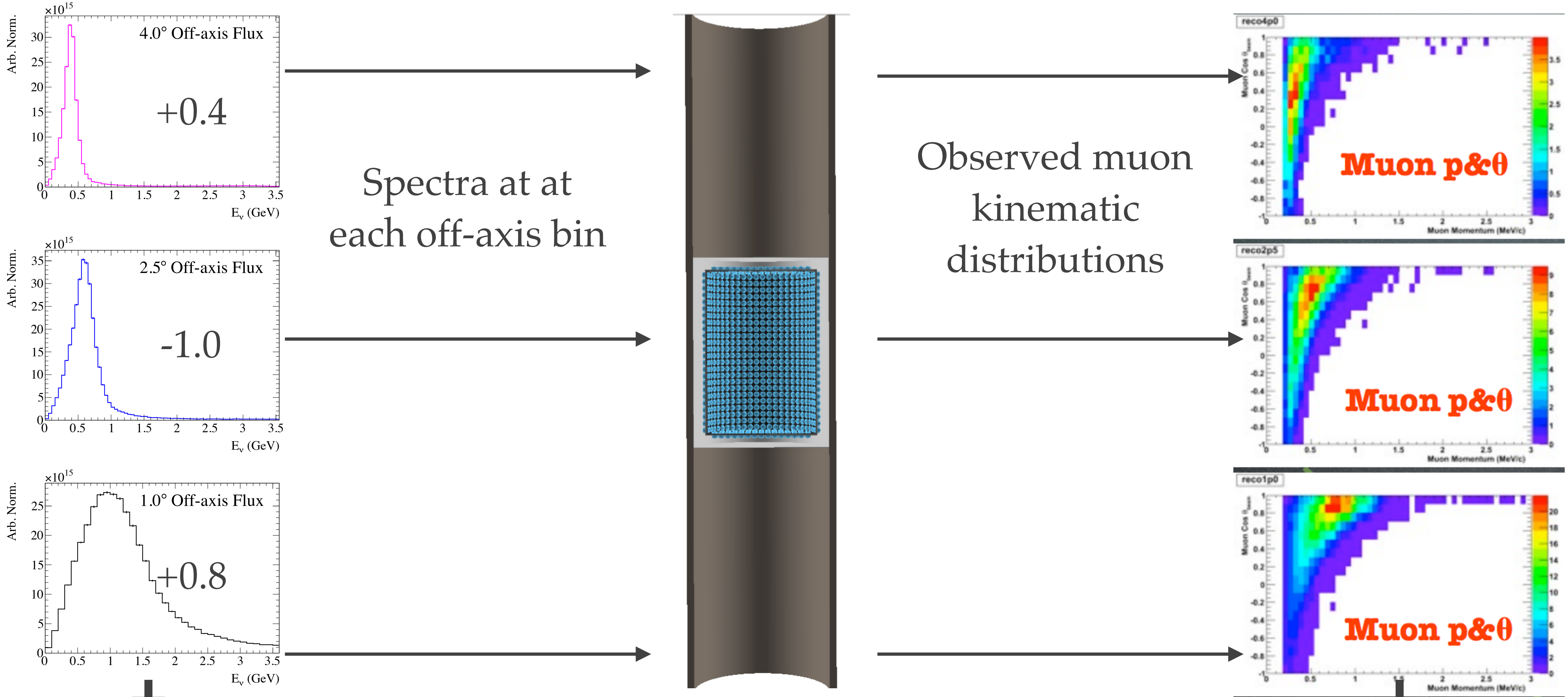
- E61 is proposed as an intermediate detector for Hyper-K and the later part T2K experiment
- 1 kilo-ton scale water Cherenkov detector located ~1 km from the neutrino source
- Position of instrumented part of the detector can be moved in ~50 shaft to make measurements at different off-axis angles
- **Measurements to address uncertainties on neutrino-nucleus scattering modelling for Hyper-K**
- E61 collaboration formed from the merger of two intermediate water Cherenkov detector groups (NuPRISM and TITUS)

WHY OFF-AXIS SPANNING MEASUREMENTS?



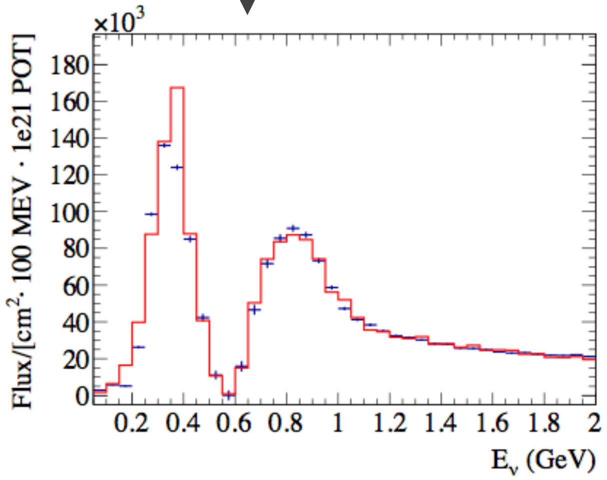
- Peak neutrino energy varies from 400 MeV to 1000 MeV
- Can probe the energy dependence of observed final states in neutrino-nucleus scattering
- Over-constraint the energy inference problem

ENERGY RESPONSE MEASUREMENT

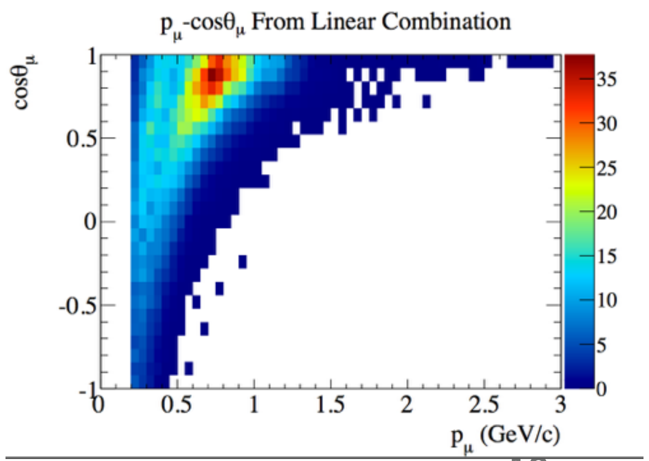


Spectra at at each off-axis bin

Observed muon kinematic distributions



Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



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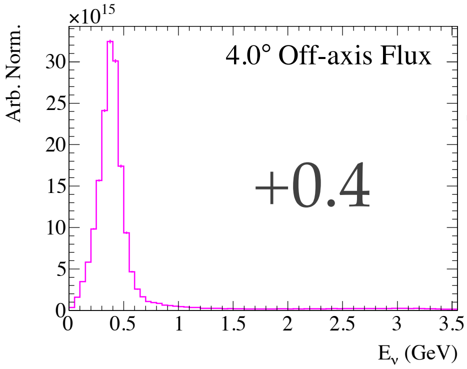

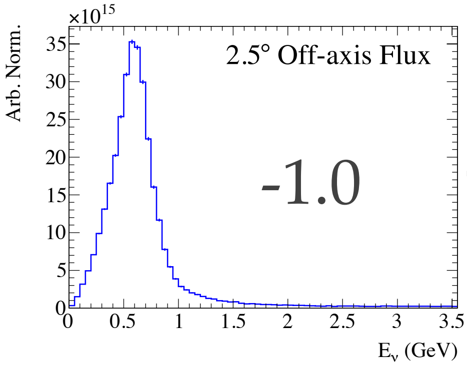

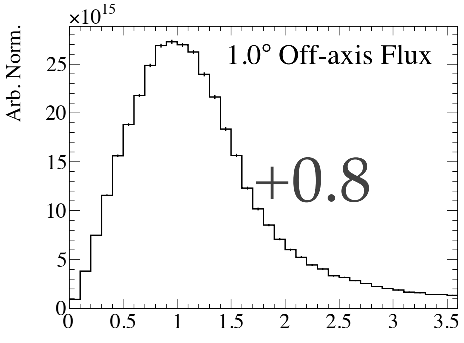

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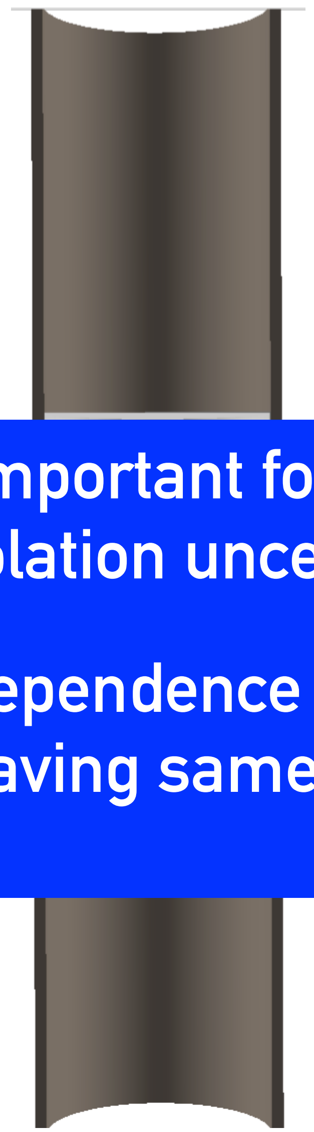

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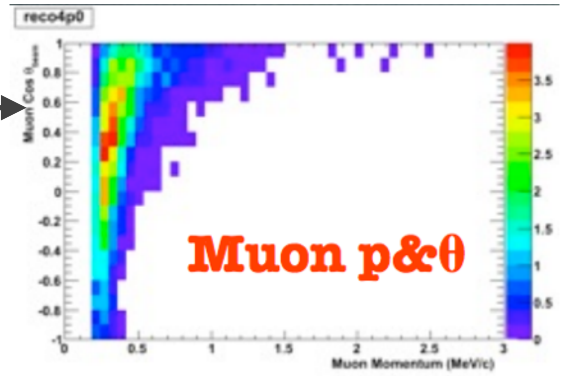
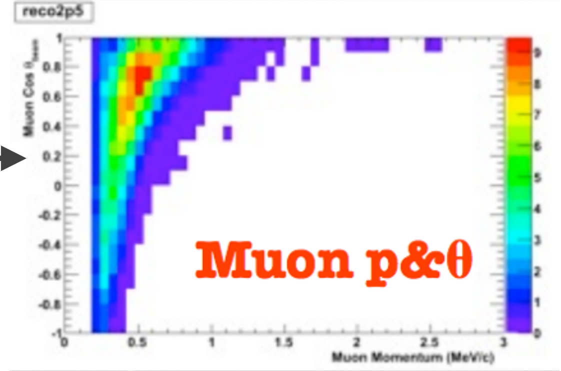
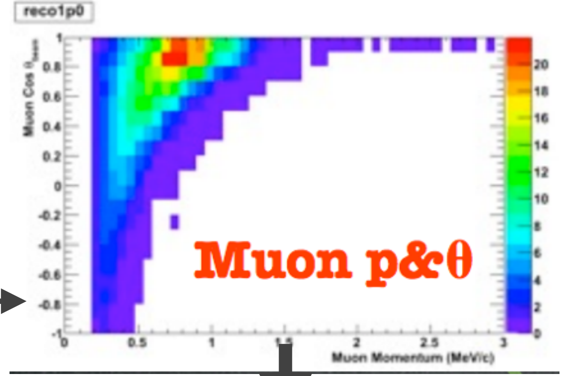
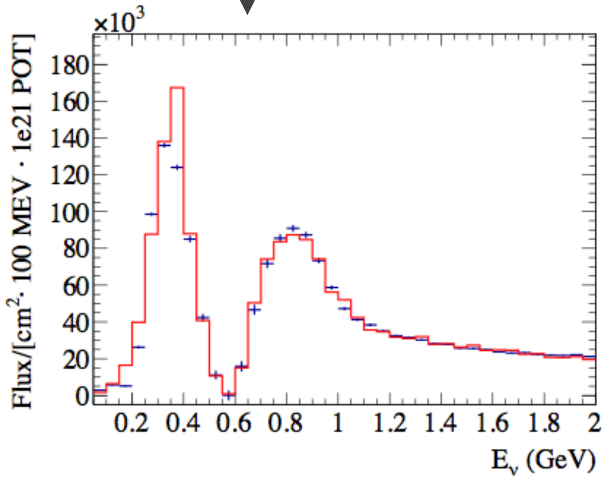






This approach is important for reducing the near to far extrapolation uncertainty.

Minimize model dependence in the extrapolation by having same spectrum in near and far detector.



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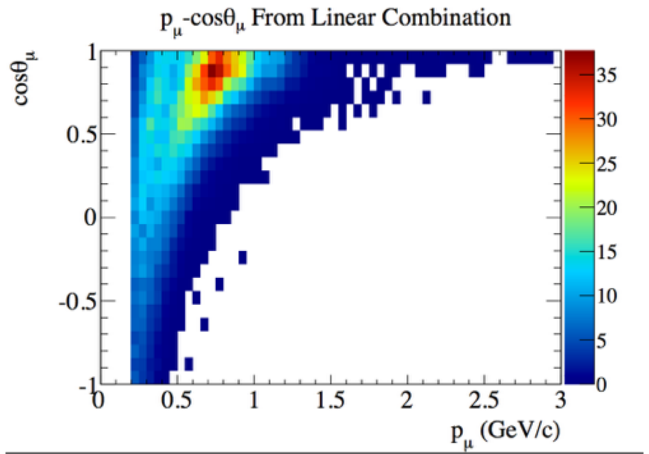
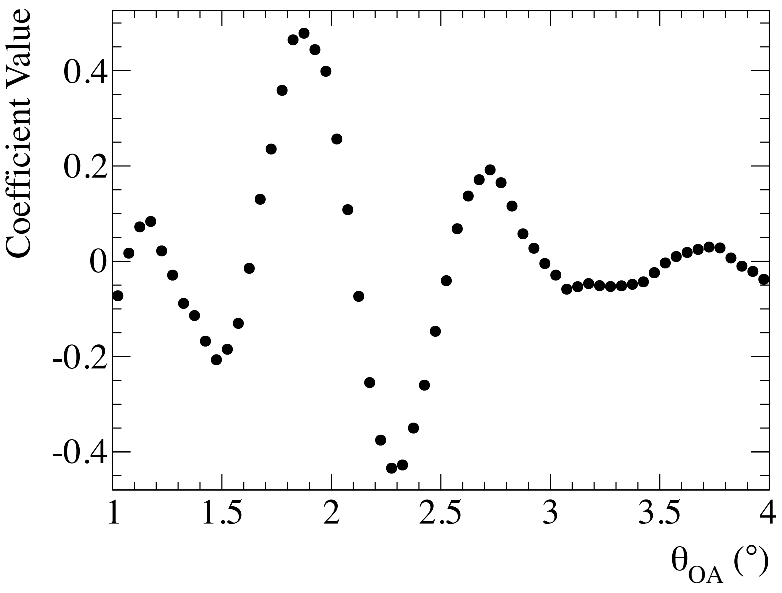
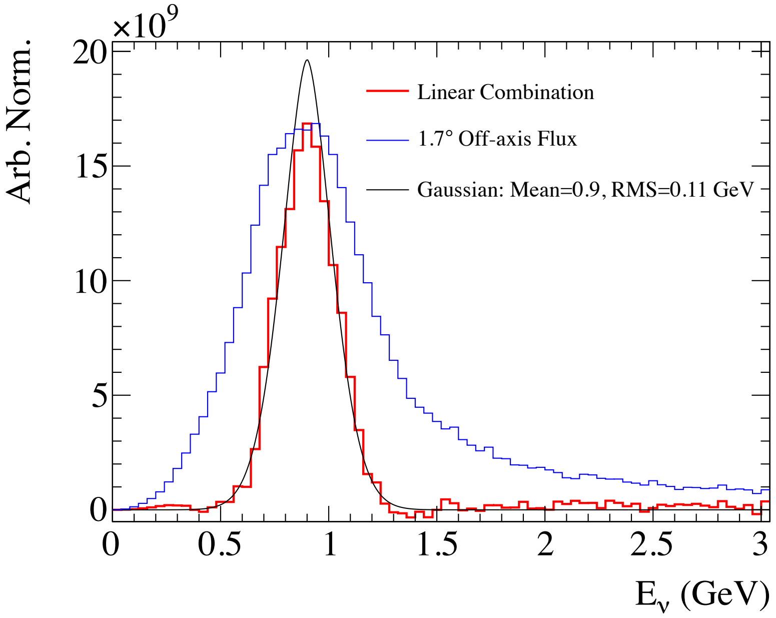


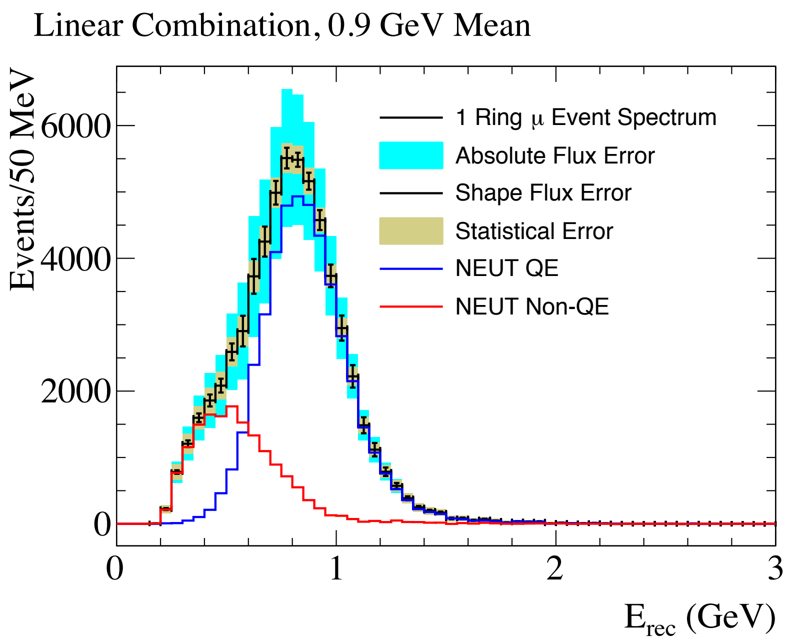
MEASURING RECONSTRUCTED ENERGY



Off-axis coefficients chosen to subtract off low and high energy tails of the neutrino spectrum



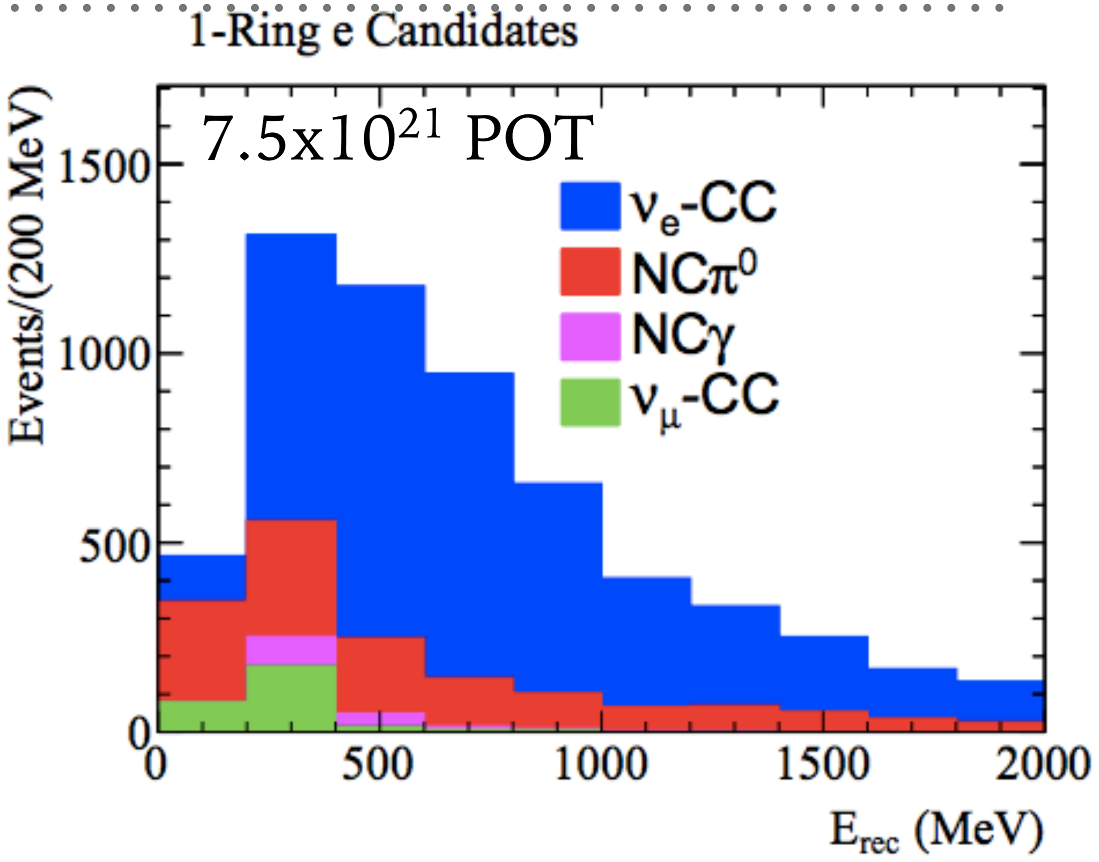
Can produce a spectrum derived from the linear combination of off-axis fluxes with RMS of ~110 MeV (small enough to see nuclear effects)



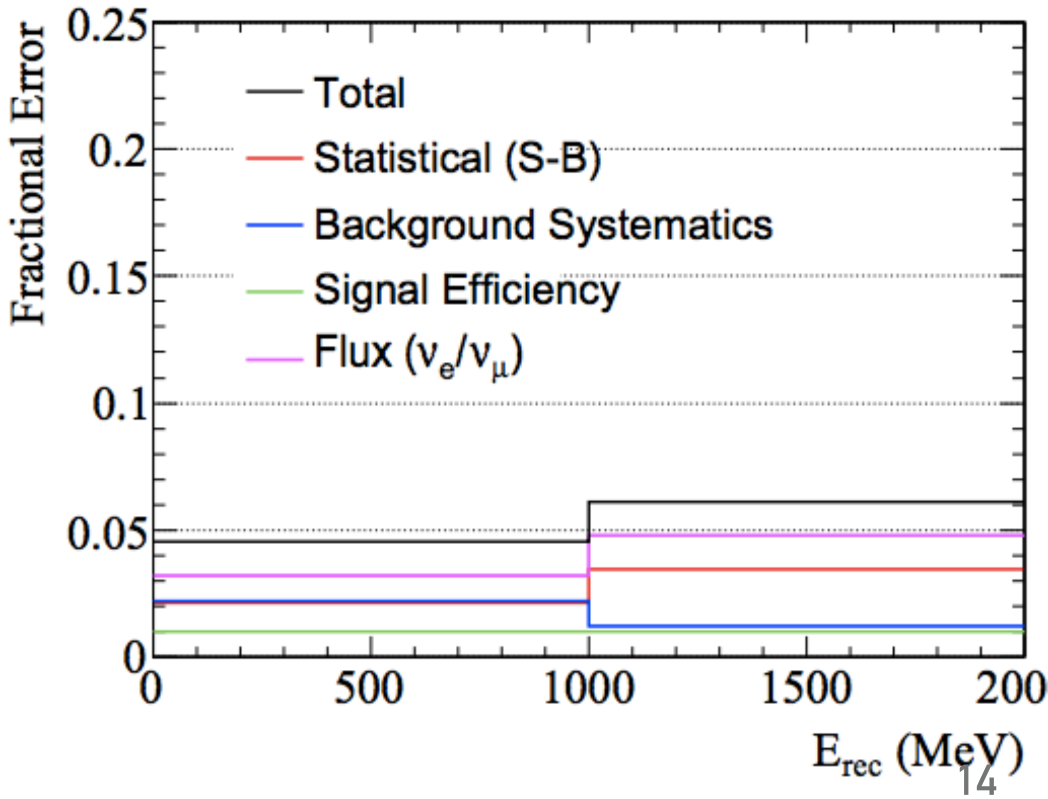
When the reconstructed events are binned with the derived coefficients the “mis-reconstructed” energy tail can be measured

ELECTRON NEUTRINO CROSS SECTION MEASUREMENT

- Beam contains 1% electron (anti)neutrinos from muon and kaon decays
    - Fraction increases further off-axis (3-body vs 2-body decays)
- Use these to measure the electron neutrino cross section
- So far, a measurement with <5% uncertainty can be achieved
- Potential improvements:
    - Expand fiducial volume
    - Improved reconstruction with better photosensors
    - External measurements to reduce flux uncertainties
- Working on updated analysis that include antineutrinos

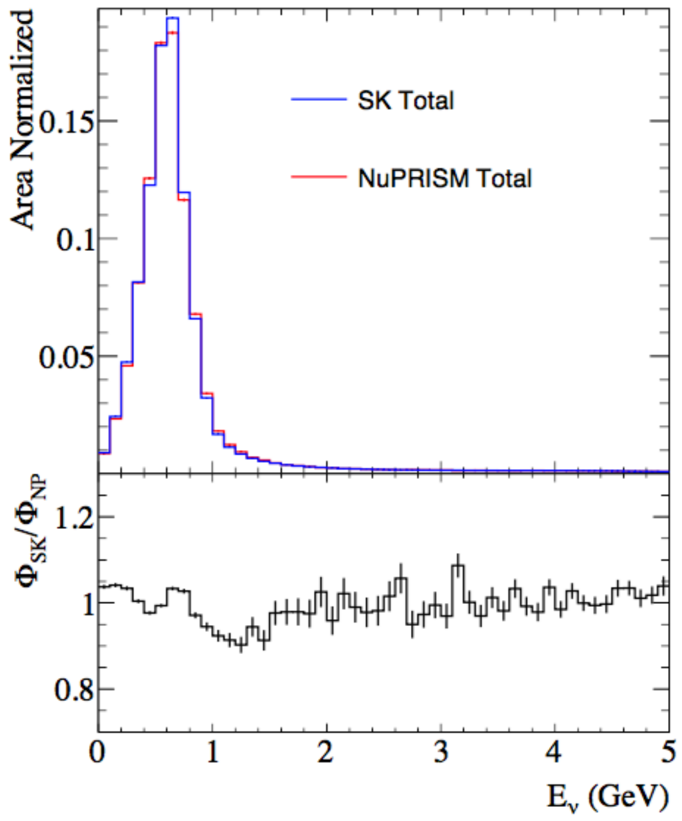


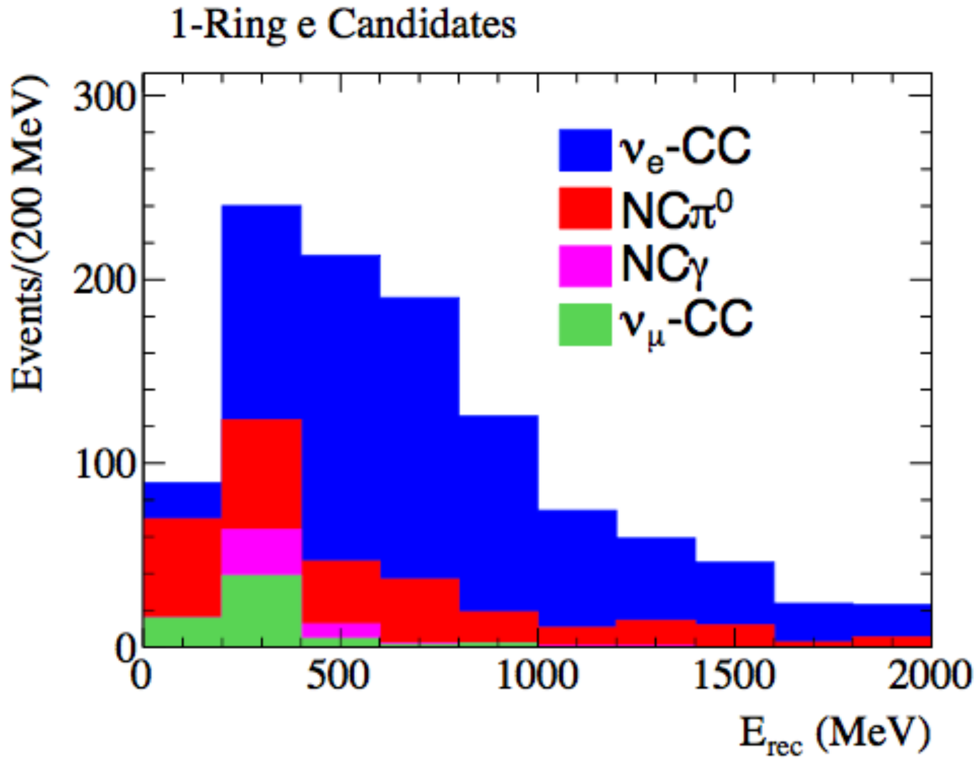
Uncertainty on Measurement



INTRINSIC NC AND ELECTRON NEUTRINO BACKGROUND

- Total neutrino and intrinsic ν_e and fluxes are nearly identical in the intermediate and far detectors
- Can measure the intrinsic+NC background directly in the intermediate detector

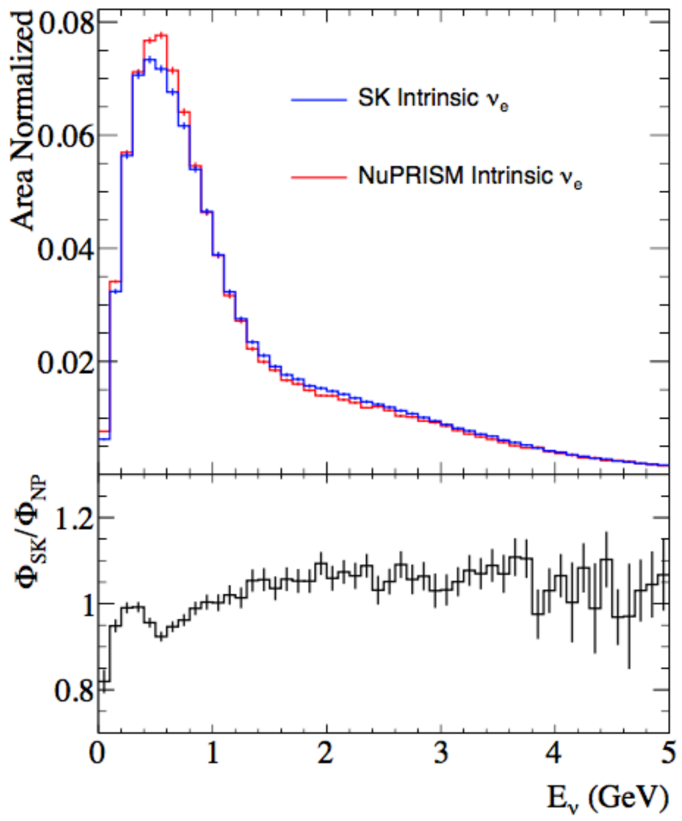




300 ton ID x 1.5e21 POT

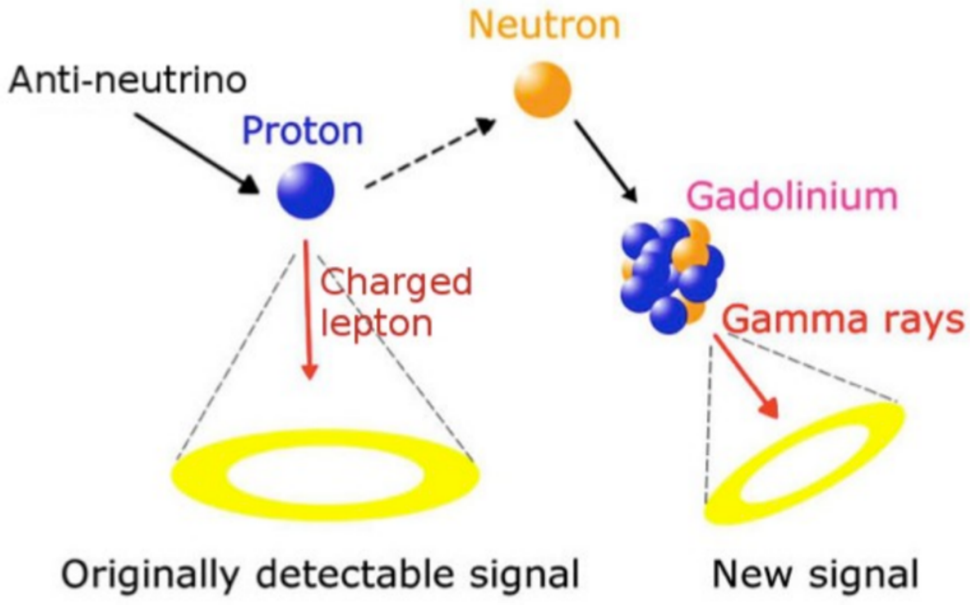
3% statistical precision can be achieved

Study of systematic errors is planned



GD LOADING & NEUTRON DETECTION

- In Hyper-K neutron tagging is used for:
  - Reduction of atmospheric neutrino background for nucleon decay searches
  - Statistical separation of atmospheric neutrinos and antineutrinos



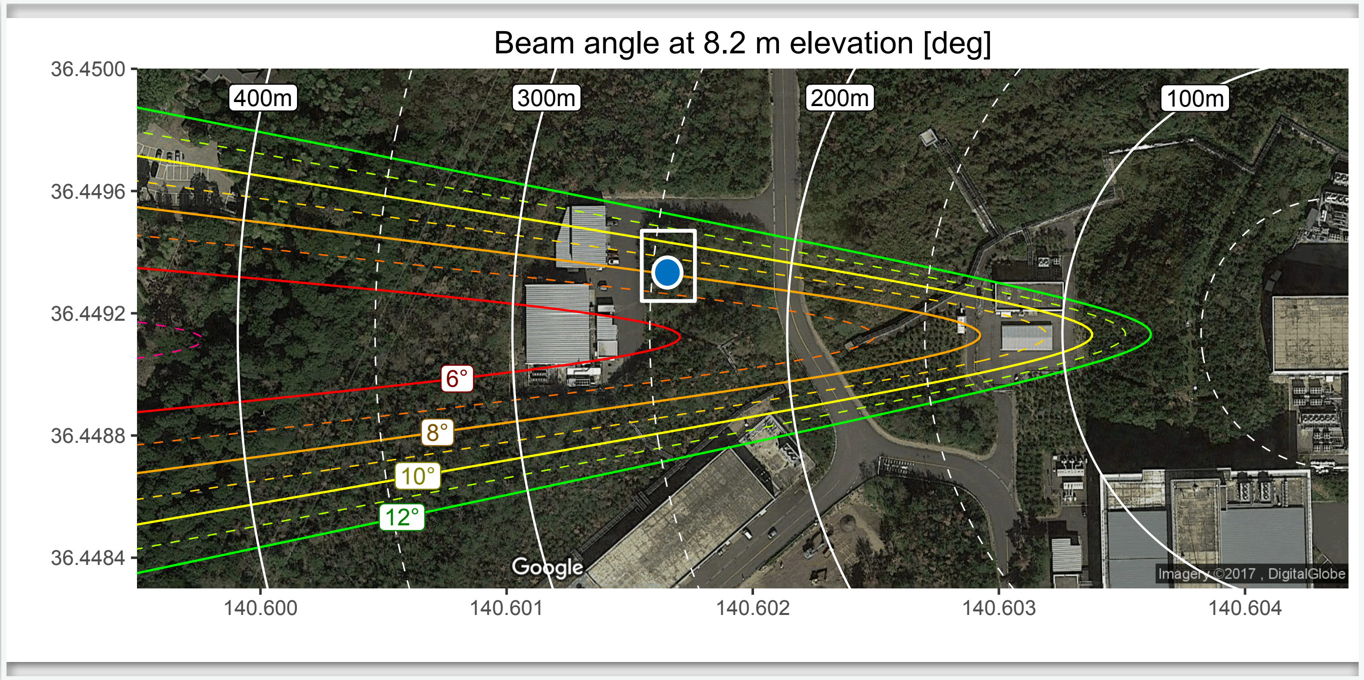
- Large uncertainties on the modeling of neutrino production in neutrino-nucleus scattering
- Load E61 with $Gd_2(SO4)_3$ to enhance neutron detection
- Measure the neutron production in ~1 GeV neutrino-nucleus scattering in E61

PHASED APPROACH

INITIAL PHASES OF E61 EXPERIMENT

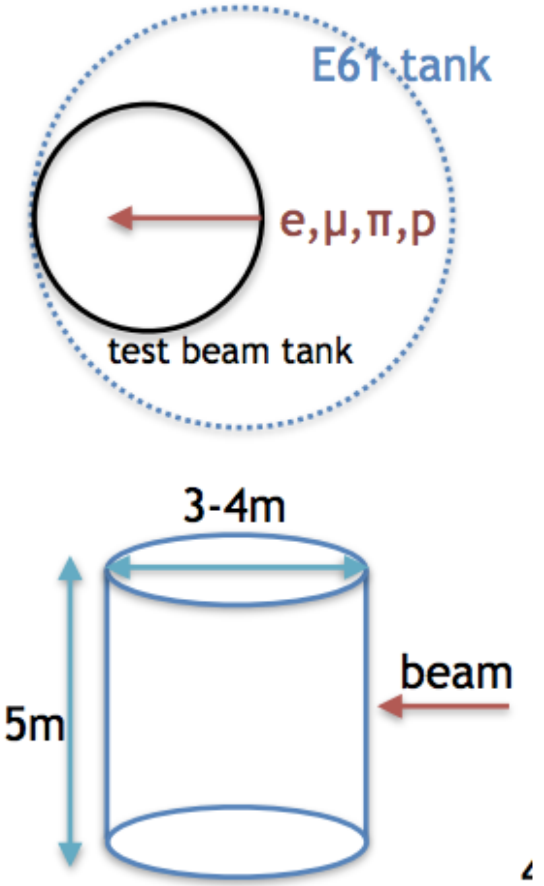
- E61 is pursuing a phased approach of the experiment:
  - Initial phase: reduced cost experiment to gain experience with 1% level calibration
  - Two options being considered:

Surface detector at J-PARC



Neutrino interactions at 8 degrees off-axis to study the electron neutrino cross section

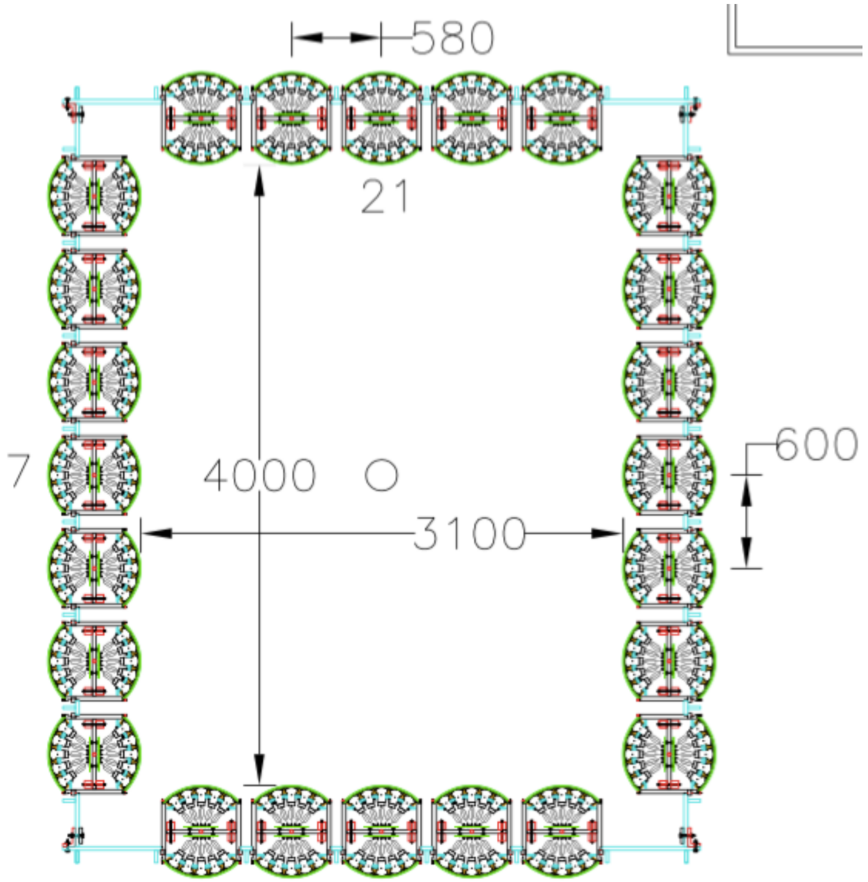
Charged particle beam test



Calibrate and study detector response with known particle type, momentum.

TEST BEAM EXPERIMENT

- Primary alternative being considered is a charged particle test beam experiment
- 3-4 m sized detector with ~168 mPMT modules deployed
- Goals:
  - Demonstrate performance and calibration technique with know particle fluxes
  - A large scale experiment for integrating and testing all detector components
  - Study interesting physics for WC detectors
    - Detailed measurements of Cherenkov rings for μ, e, π, p, etc.
    - Measurements of pion scattering
- Availability of test beams being investigated
- Start of construction in 2019, start of operation in 2021



TEST BEAM REQUIREMENTS

- Availability of e, μ, π, p
- Ideally particle momenta down to the muon Cherenkov threshold (0.12 GeV/c)
- Momenta up to ~1.2 GeV/c
- Particles rates of ~100 Hz
- Momentum spread of <2%
- No beam line investigated so far meets all the requirements
    - Fermilab MCenter meets most but only goes down to 0.2 GeV/c

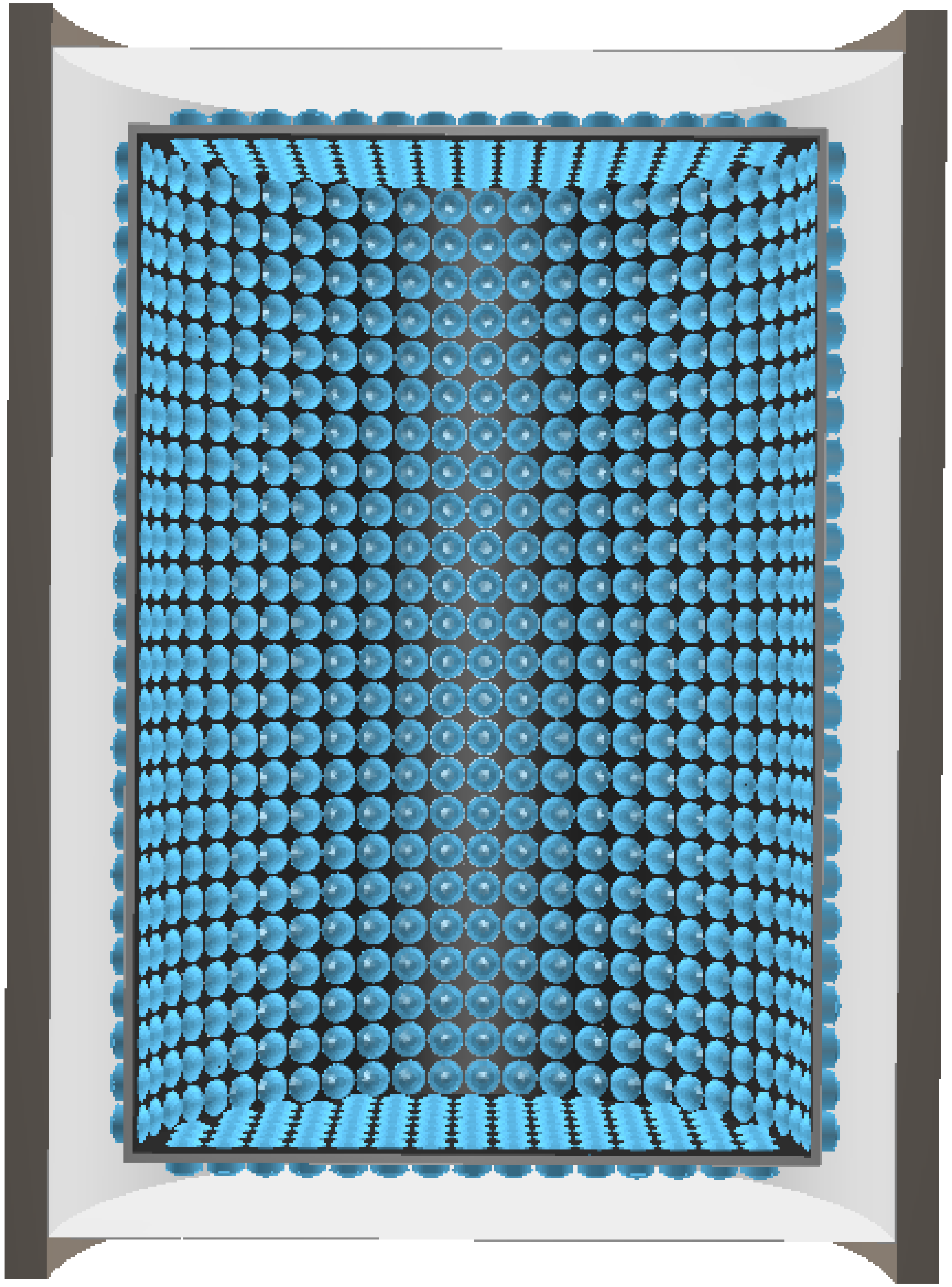
CONCLUSION

- Reduction of systematic errors for HK is critical
- An intermediate WC can play a critical role in the systematic error reduction
  - Off-axis spanning measurements probe the inference of neutrino energy problem
- The E61 experiment is proposed as an intermediate detector for Hyper-K
- Considering an initial phase of the experiment that can be done in a charged particle test beam to prove 1% detector calibration can be achieved

DETECTOR TECHNOLOGIES

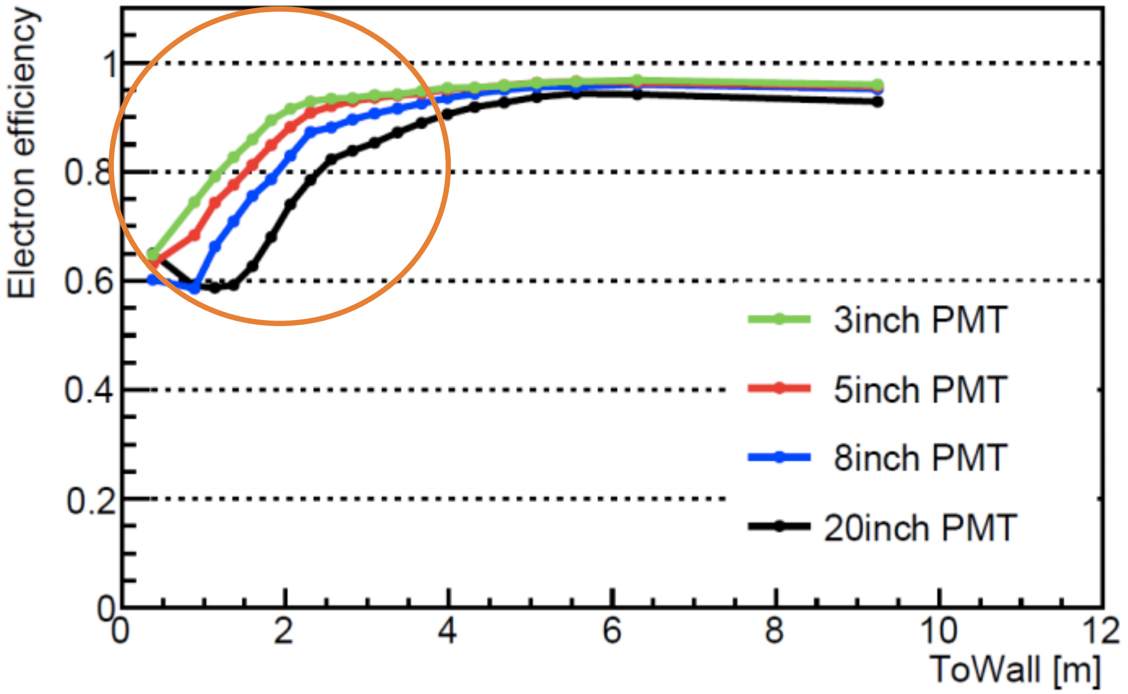
THE E61 DETECTOR

- 10 m diameter detector
- Height is being optimized 8-12 m
- 1 m thick optically separated outer detector
- Photo-sensor modules can view both the inner and outer detectors

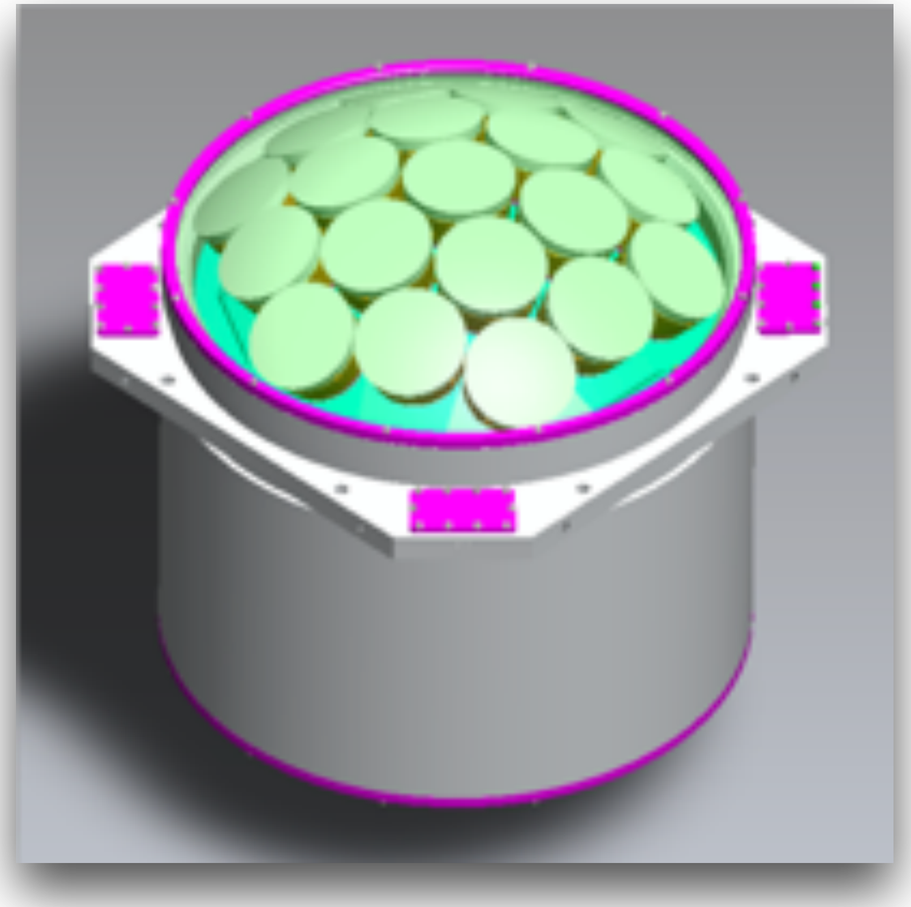


MULTI-PMTS IN E61

- Simulation studies show that the detector performance is improved with smaller photo-multiplier tubes with better timing resolution

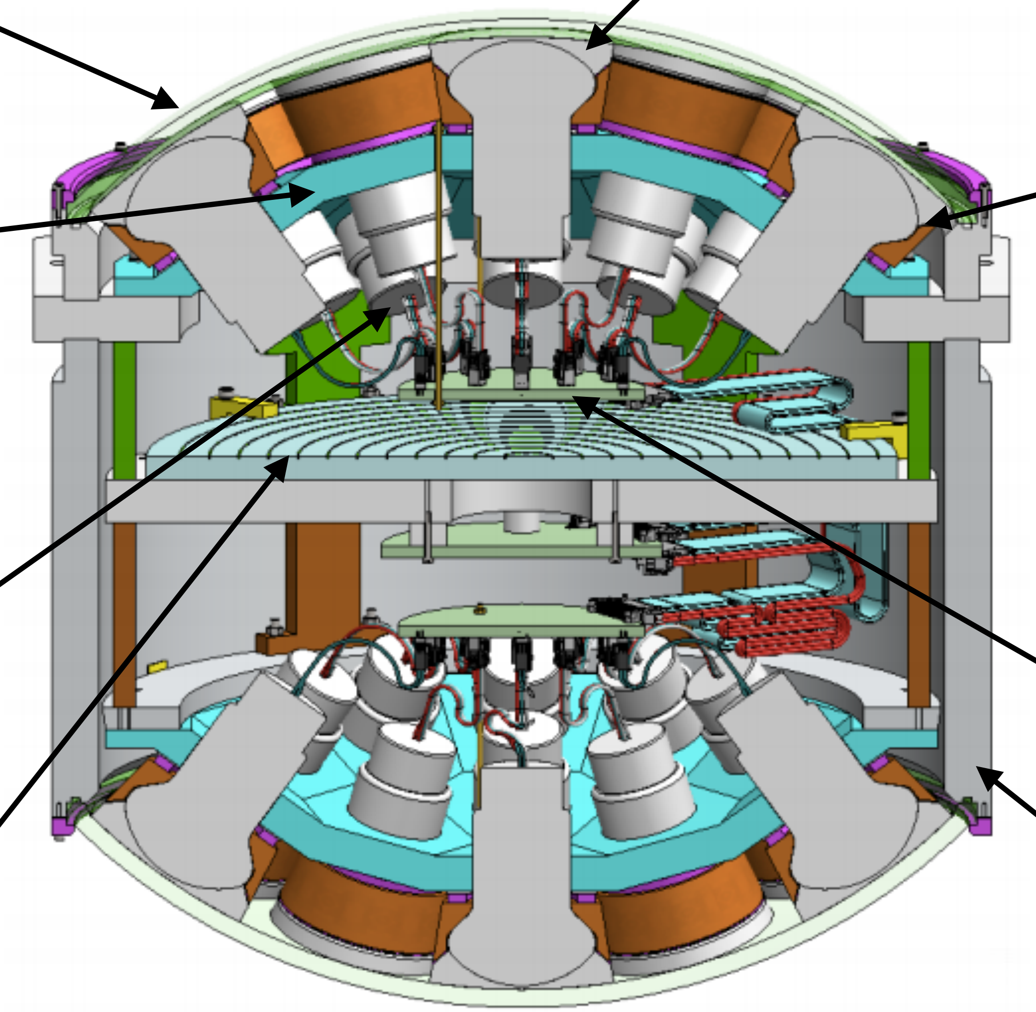


- Building on the KM3NeT approach, we will deploy multi-PMT modules with 3 inch PMTs
- 19 PMTs view the inner detector
- 7 or fewer PMTs view the outer detector
- Modules contain high voltage generation and readout electronics



MULTI-PMT MODULE DESIGN

One mPMT module design being considered:



UV transparent acrylic

Optical gel coupling between PMT and acrylic

Reflectors to improve light collection

3D printed PMT support structure

HV generation at PMT base

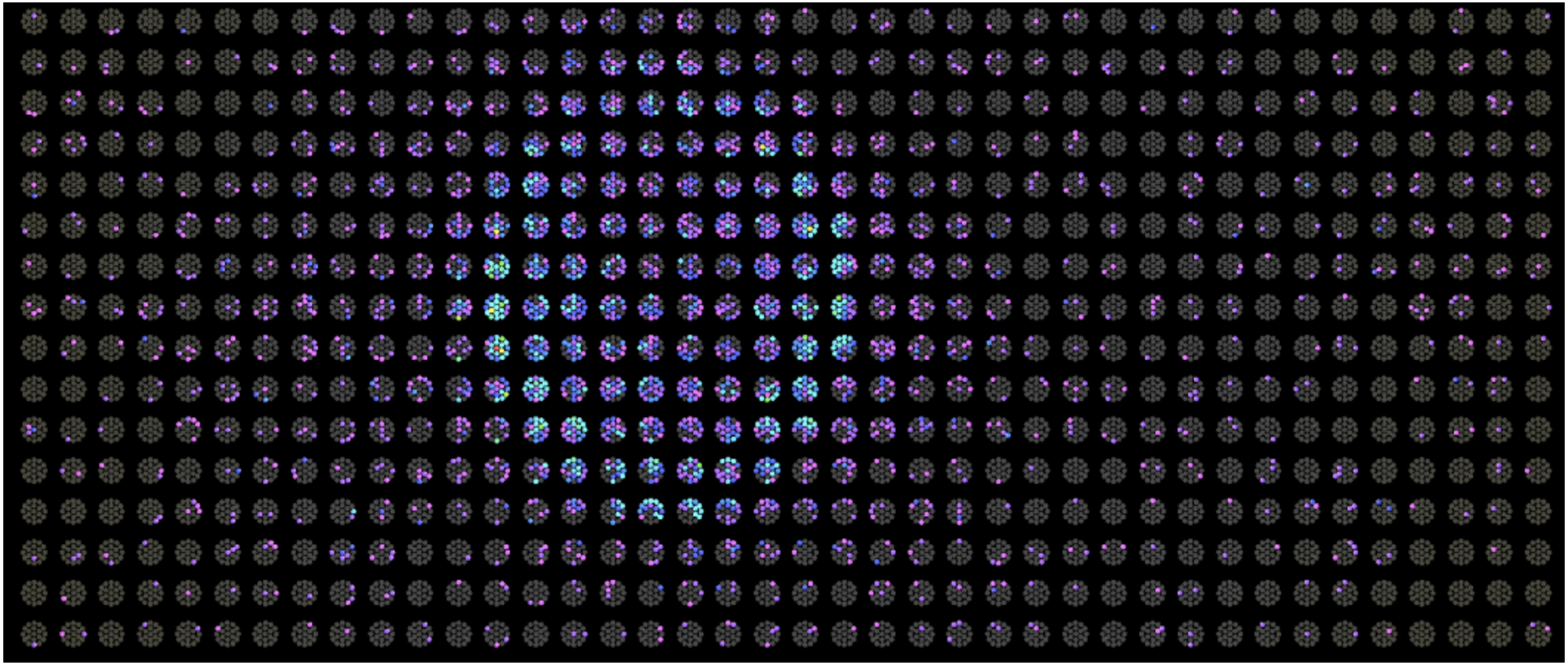
Readout electronics board

Scintillator panel

Stainless steel or aluminum cylinder

JAPANESE CONTRIBUTIONS – MPMT SIMULATION

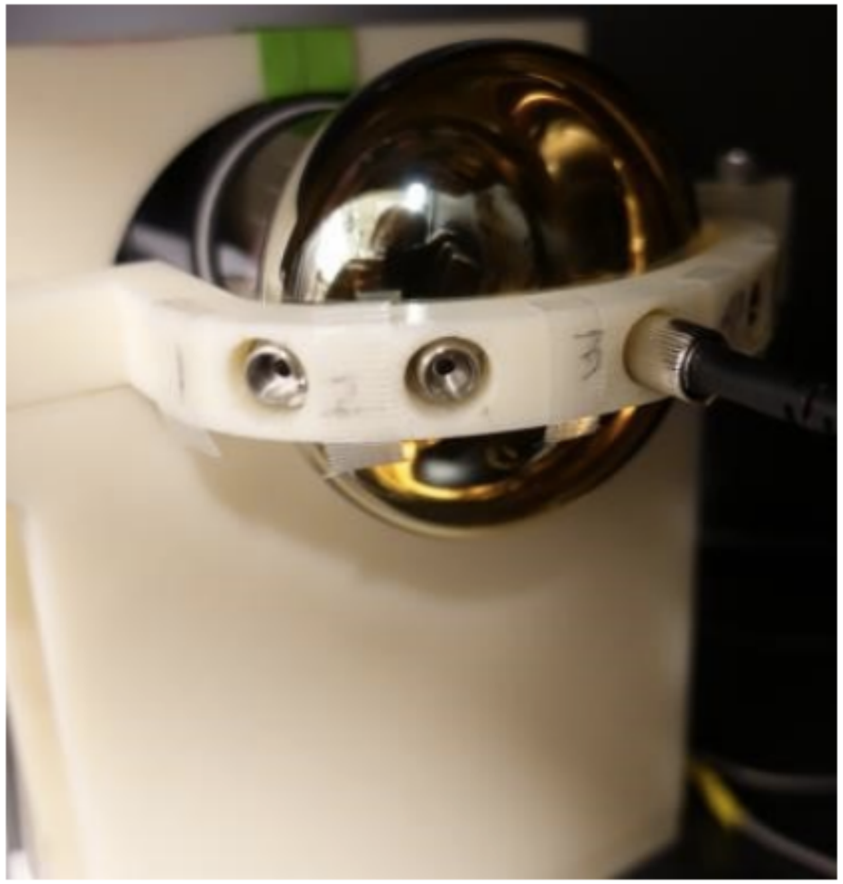
- Simulation studies of 3 inch PMTs and development of simulation and reconstruction with multi-PMTs (Tokyo Tech, Tokyo Univ. of Science)
- Example event display from the mPMT simulation:



JAPANESE CONTRIBUTIONS – PMT CHARACTERIZATION

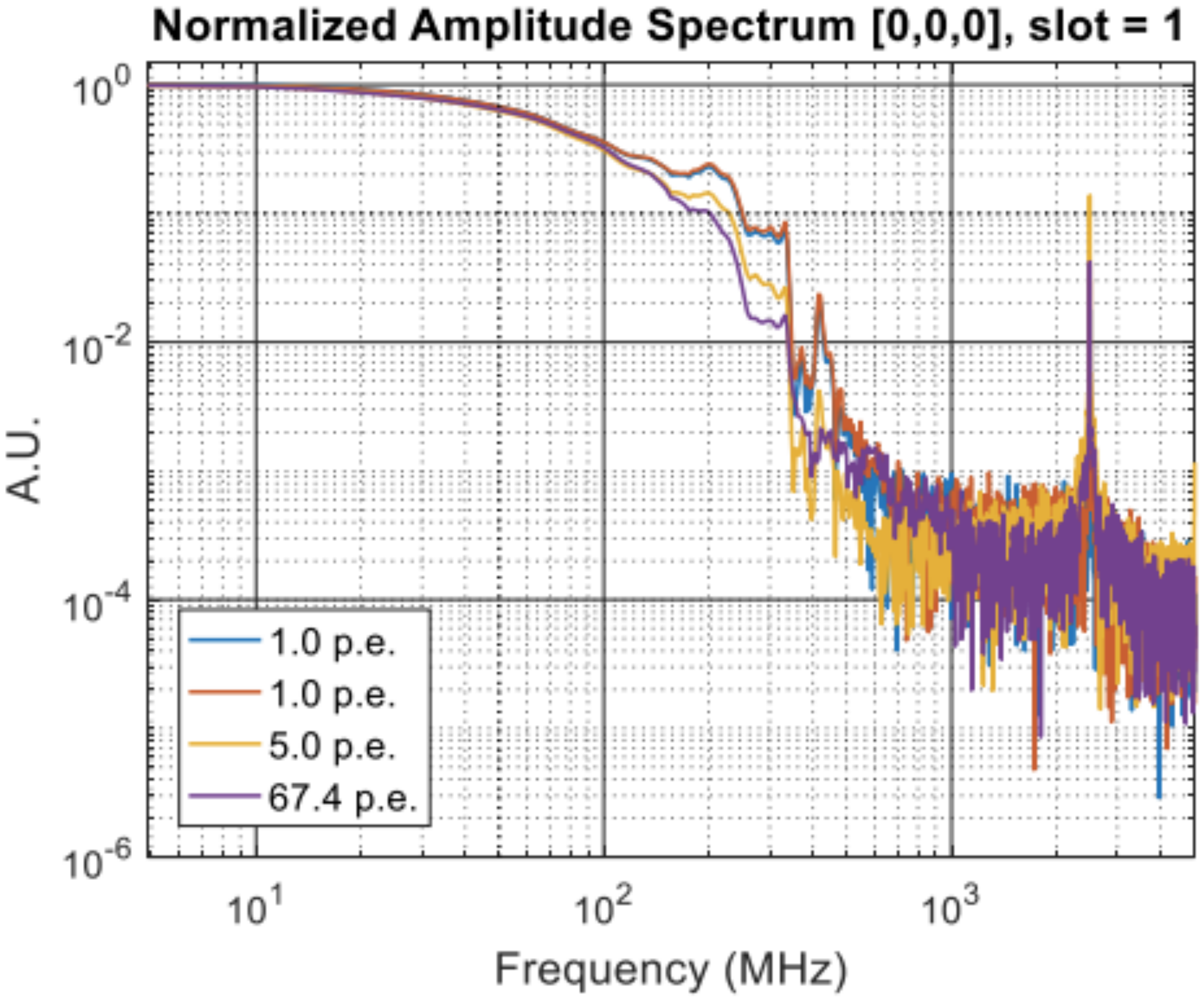
- Evaluation of new 3 inch PMTs from Hamamatsu (R14374) with improved timing resolution (ICRR, Kavli IPMU, Tokyo Univ. of Science, Tokyo Tech)

PMT operation with pico-second pulsed laser at Kavli IPMU



Fiber slots

Analysis of PMT waveform bandwidth by WUT. Input to readout electronics design.



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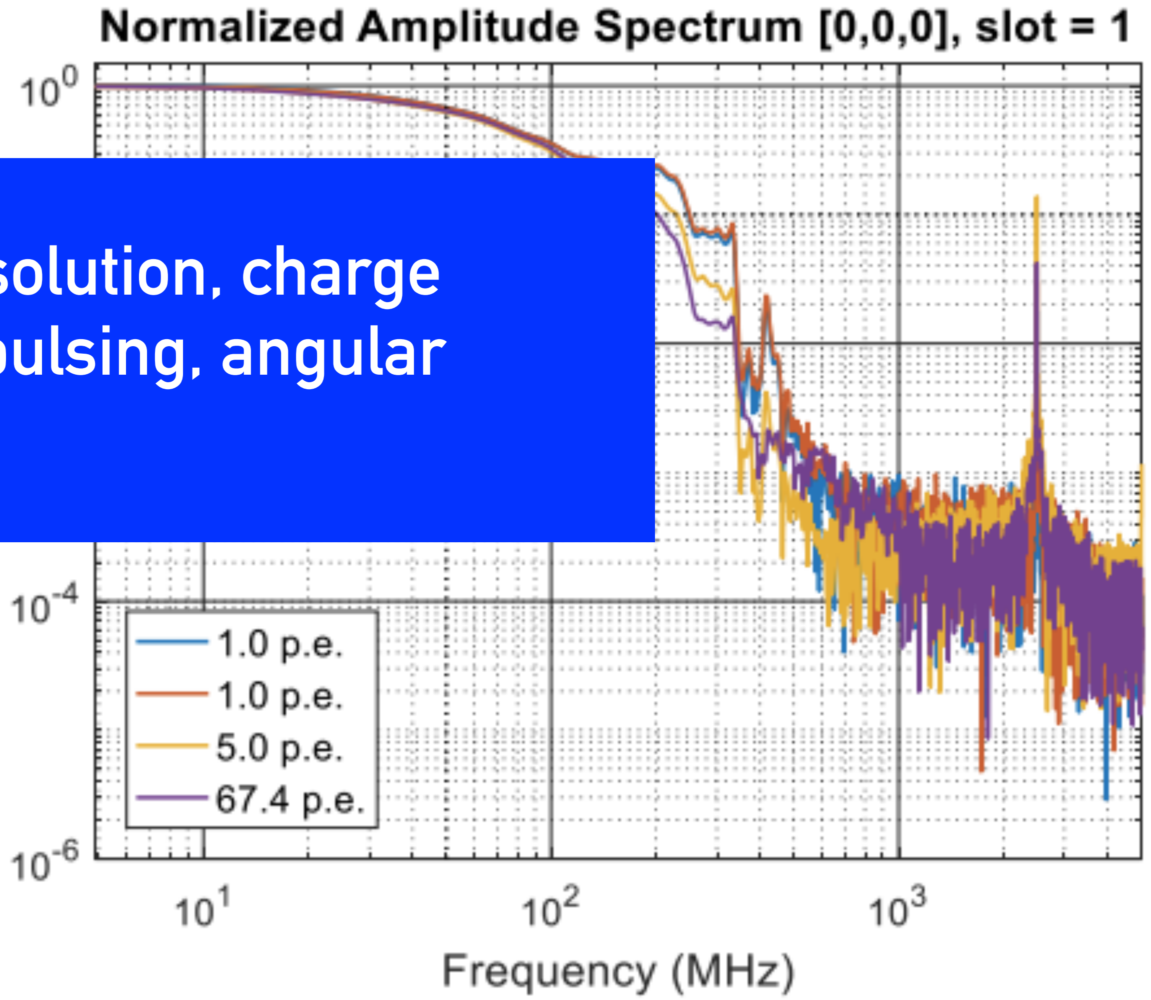

Measurements of timing resolution, charge resolution, dark rate, after-pulsing, angular response are planned

PHASED APPROACH

INITIAL PHASES OF E61 EXPERIMENT

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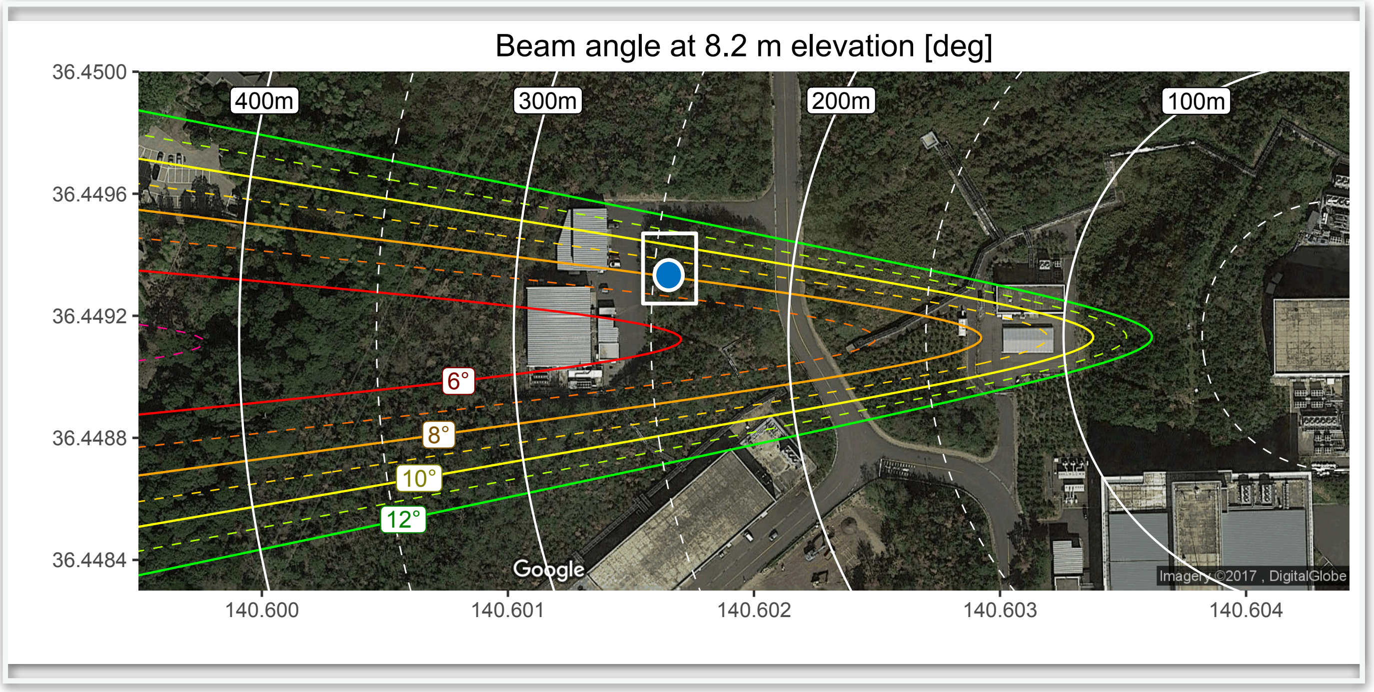

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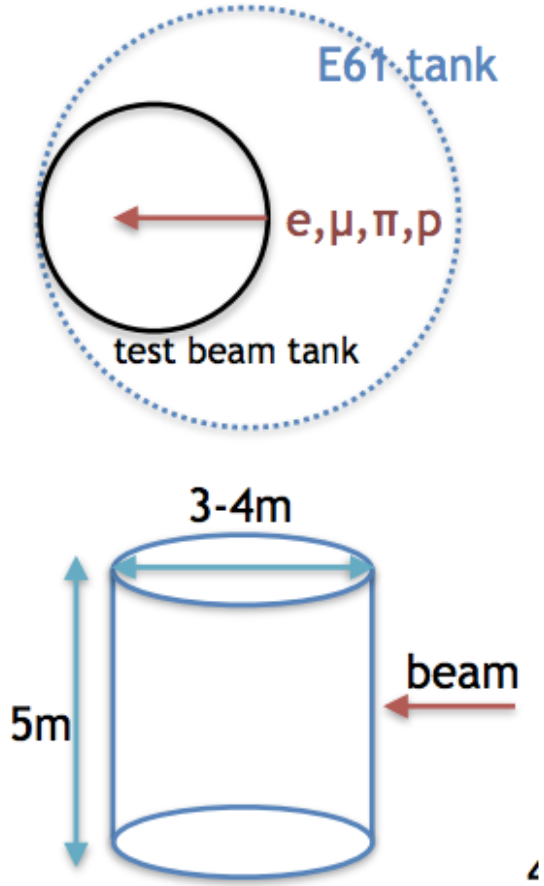
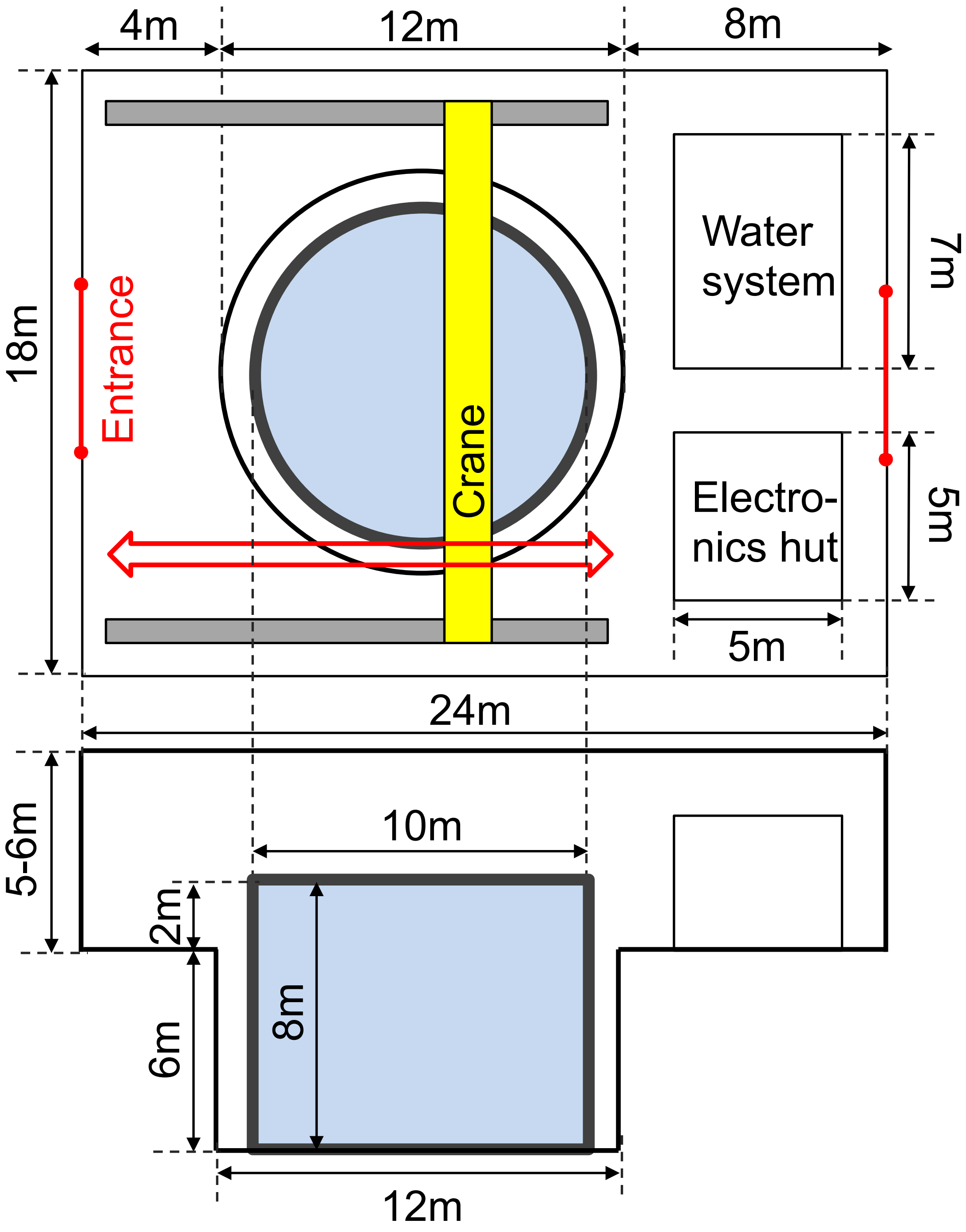


Calibrate and study detector response with known particle type, momentum.

INITIAL PHASE DESIGN (AT J-PARC)

- Design initial phase at J-PARC is now being carried out
- Partially excavation of detector depth:
  - Reduce height of building
  - Stay above the water table
- Plan to use a tent-style building



TIMELINE AND SUMMARY

- Systematic error reduction is needed for the Hyper-K long baseline neutrino physics program
- The E61 intermediate detector will address important systematic errors in neutrino-nucleus interaction modeling
- Design of the detector and components is underway
- Timeline:
  - 2017-2019: Initial phase design
  - 2020-2021: Initial phase construction
  - 2022-2023: Initial phase operation
  - 2017-2021: Full detector design
  - 2022-2025: Full detector construction
  - 2025: Start operation of full detector

THANK YOU