ANALYSIS TECHNIQUES AND SYSTEMATIC UNCERTAINTIES FOR HYPER-K

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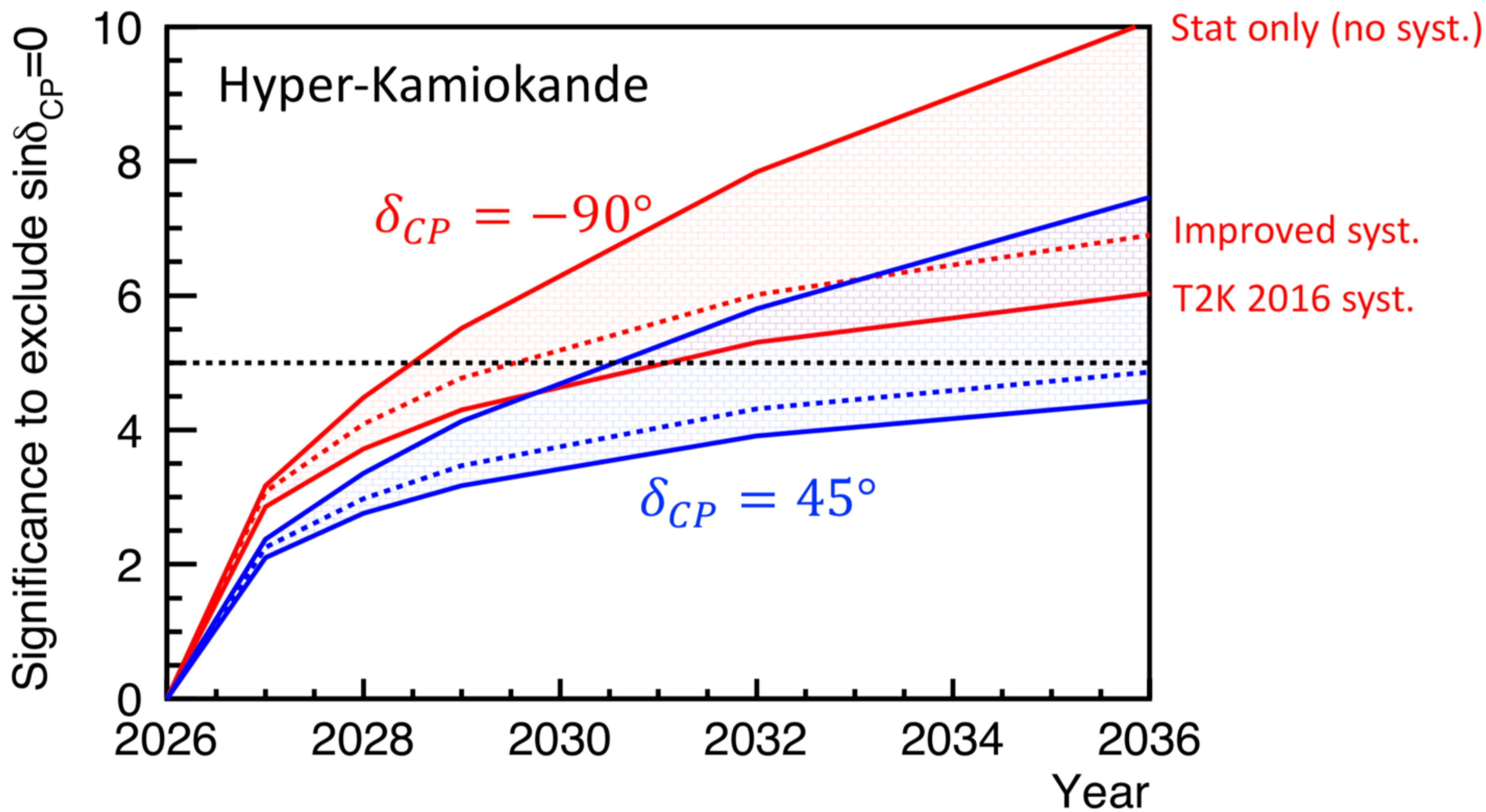
MAXIMIZING THE SENSITIVITY OF HYPER-K

- Hyper-K: unprecedented sensitivity for a range of physics measurements
- **To take full advantage of the Hyper-K detector:**
  - Control systematic errors with near/intermediate detectors, external measurements, calibration
  - Optimize analysis tools and methods to maximize signal and control backgrounds
- **In this talk I will cover:**
  - Physics topics that motivate systematic error reduction and analysis improvements
  - Controlling systematic errors with near detector measurements
  - Overview of analysis tools and areas for improvement

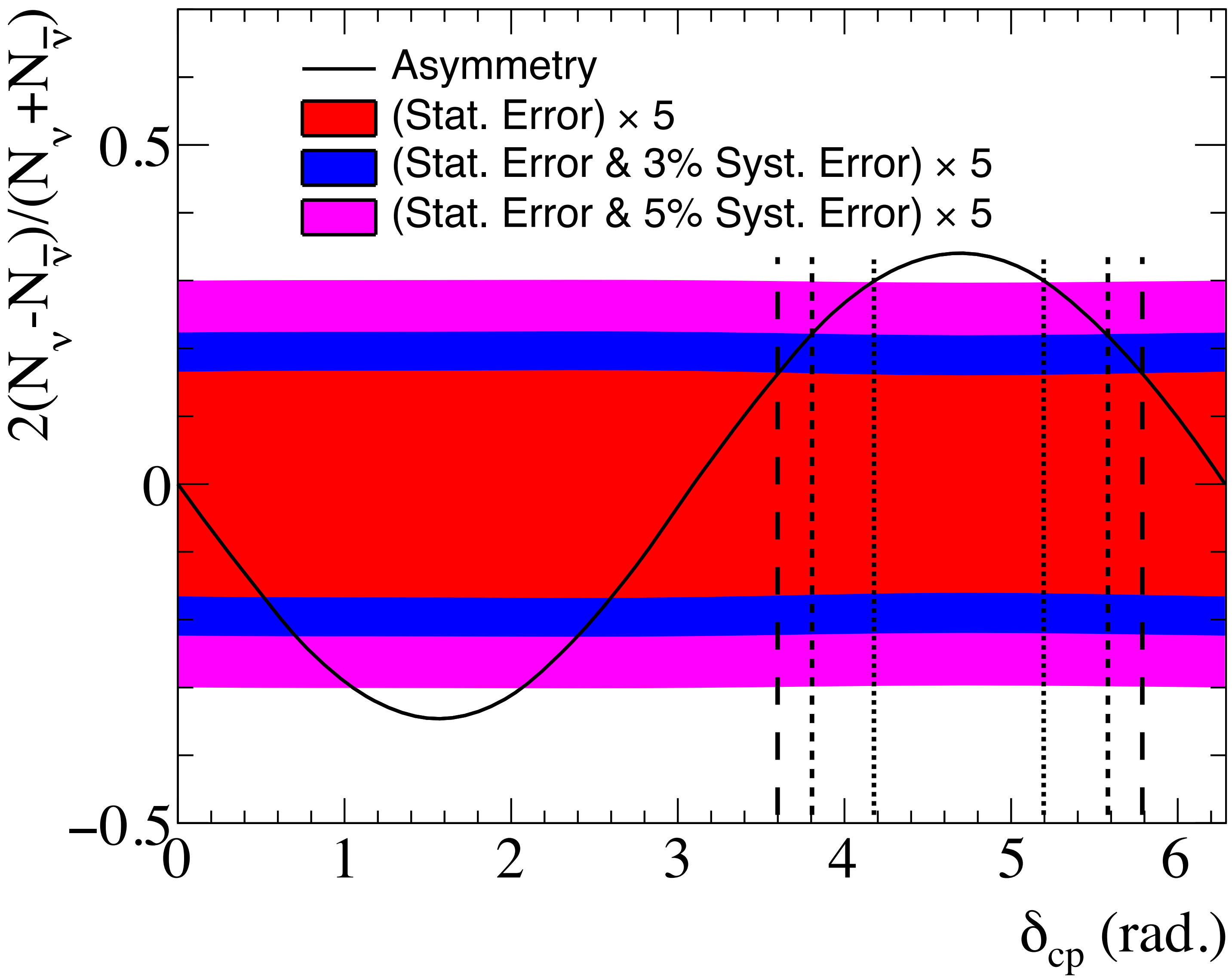
IMPACT OF SYSTEMATIC ERRORS ON CPV MEASUREMENT



- The sensitivity for the CP violation discovery strongly depends on the systematic error level that can be achieved
- T2K has controlled errors to ~6%
- **We need reduction of the systematic errors for Hyper-K**

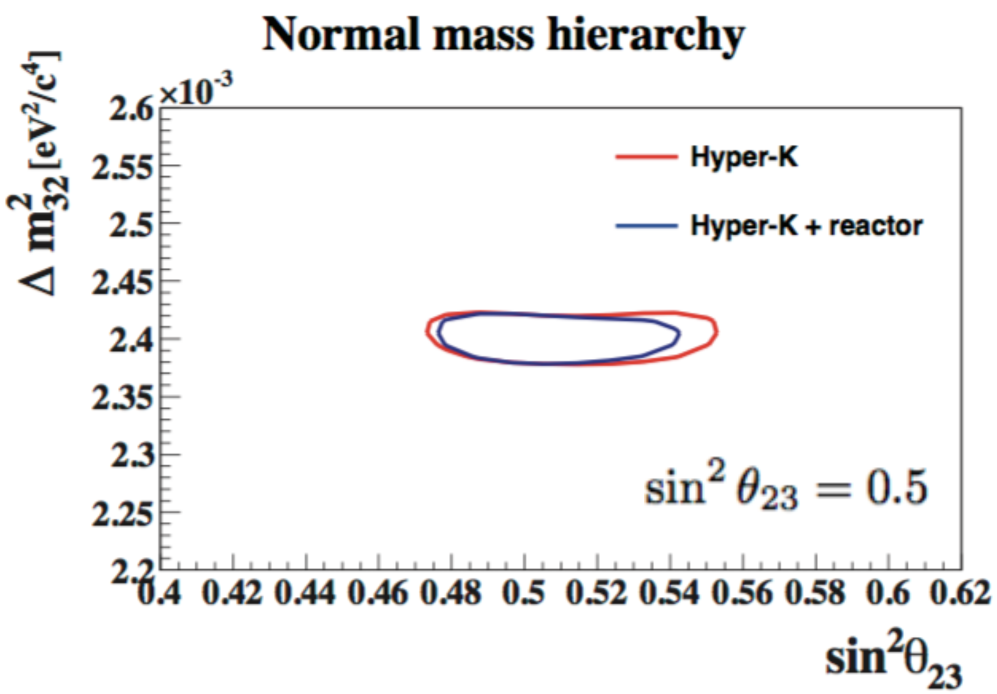
HYPER-K PHYSICS – CP VIOLATION

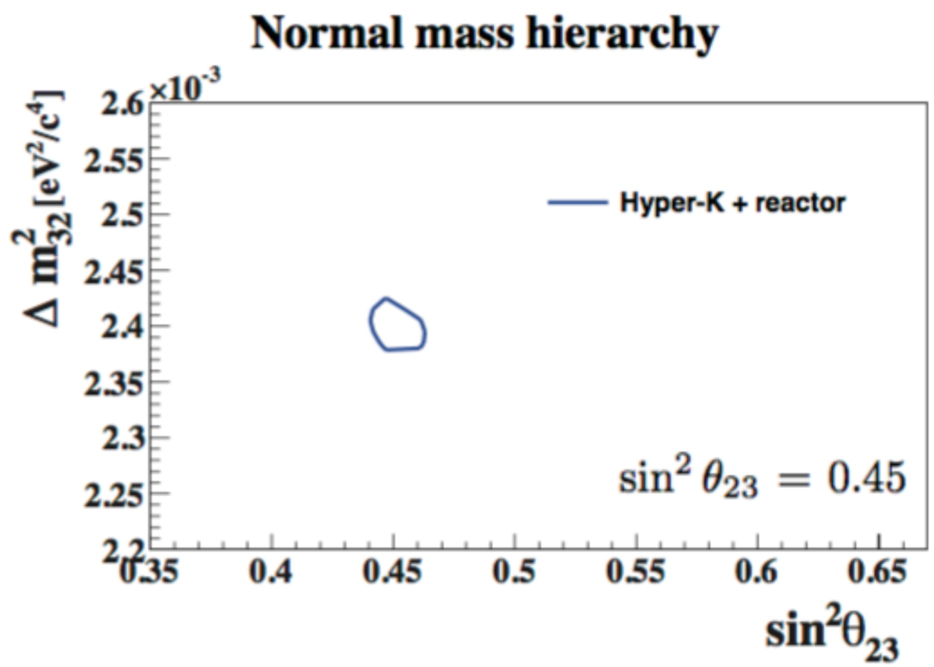
- Hyper-K collects ~2000 neutrino and antineutrino candidates
- ~3% statistical error on the relative number of neutrino and antineutrino candidates



- Controlling systematic errors to the 3% level or better is necessary or sensitivity is significantly degraded

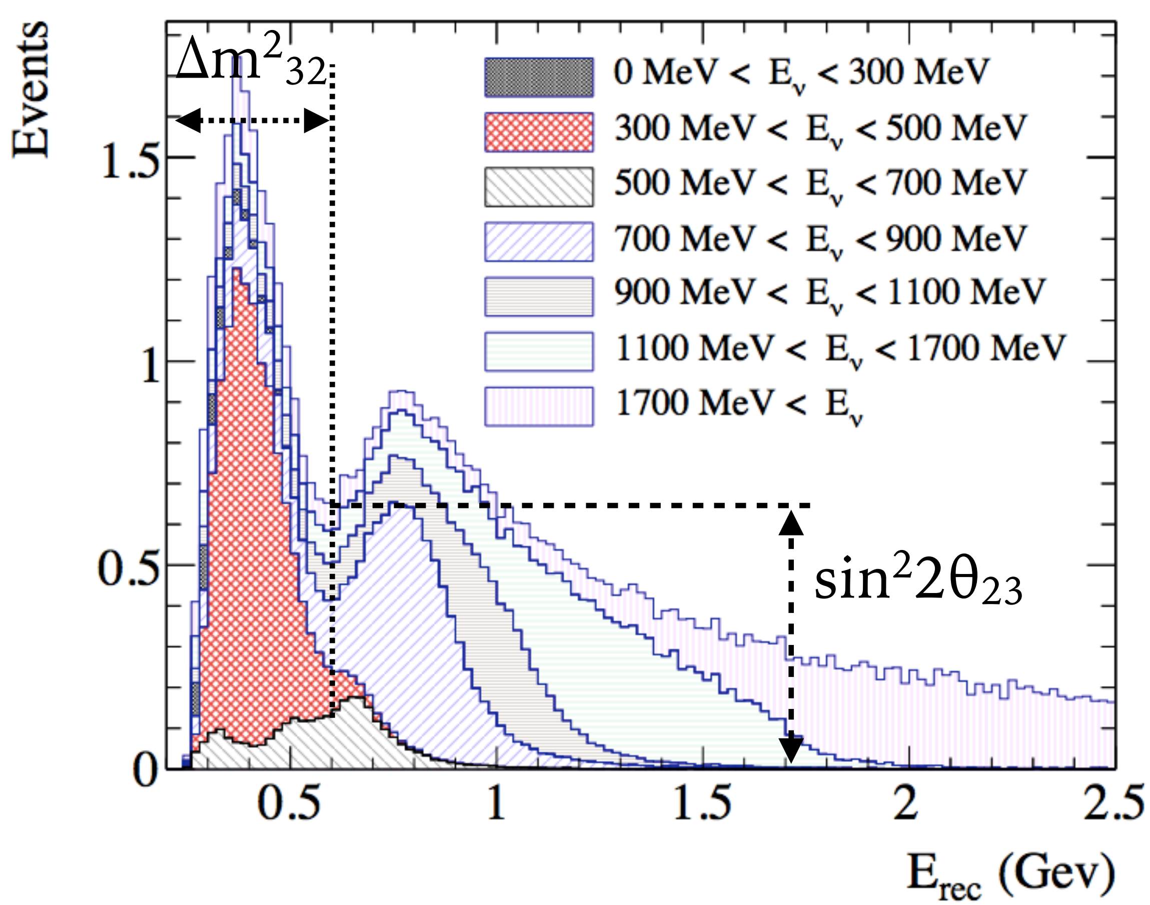
HYPER-K PHYSICS – LBL DISAPPEARANCE CHANNEL





Hyper-K Design Report: arXiv:1805.04163

- We aim for a 0.6% error on Δm^2_{32} and as low as a 1.3% error on $\sin^2\theta_{23}$ parameters



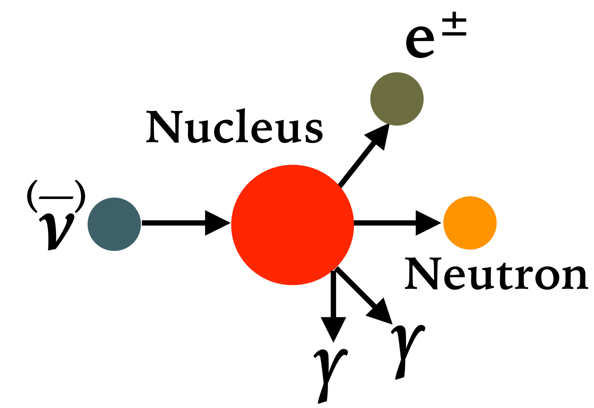
- Determine the position of the oscillation dip with 0.5% accuracy for Δm^2_{32} measurement
- Accurately predict the feed-down contributions into the dip region for $\sin^2\theta_{23}$ measurement

NEUTRON DETECTION

- Neutron detection is used in a broad range of physics in Hyper-K, including high and low energy signals

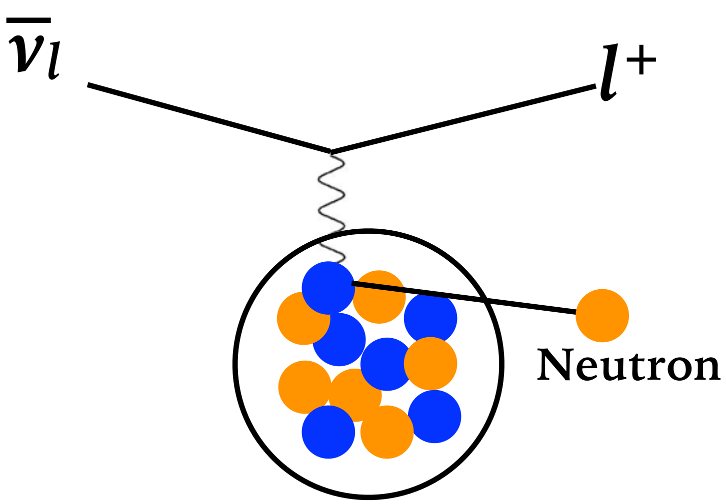
Proton decay:

- Reject atmospheric background neutrino events
- 70% tagging efficiency = 70% rejection rate in $p \rightarrow e^+ \pi^0$ channel



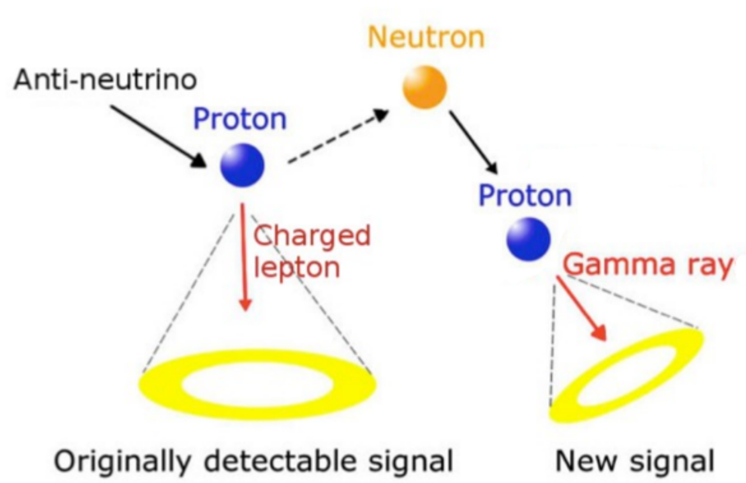
Atmospheric neutrinos:

- Statistical separation of neutrinos and antineutrinos is improved by neutron tagging of antineutrino candidates



Supernova relic neutrinos:

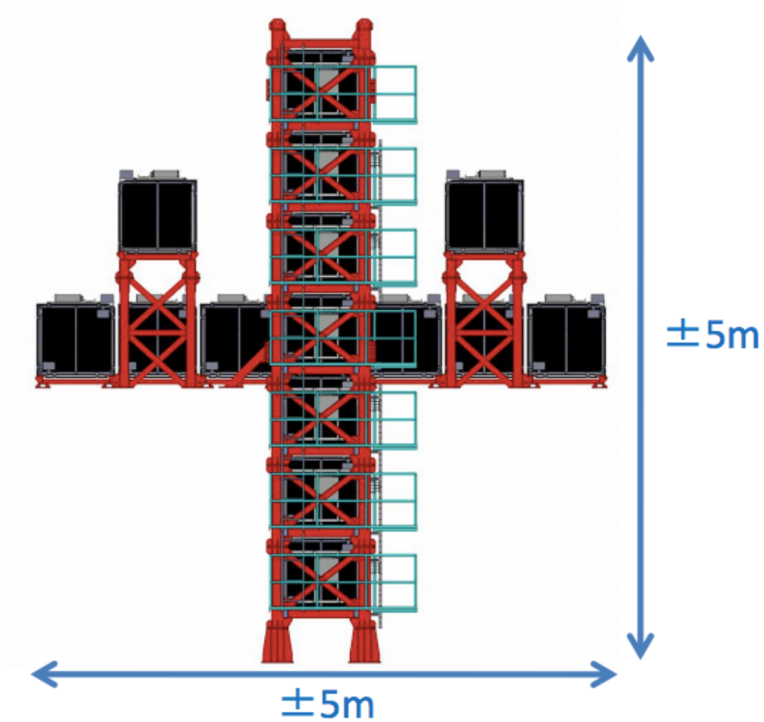
- Tag neutron to select inverse beta decay events and reject solar neutrino backgrounds



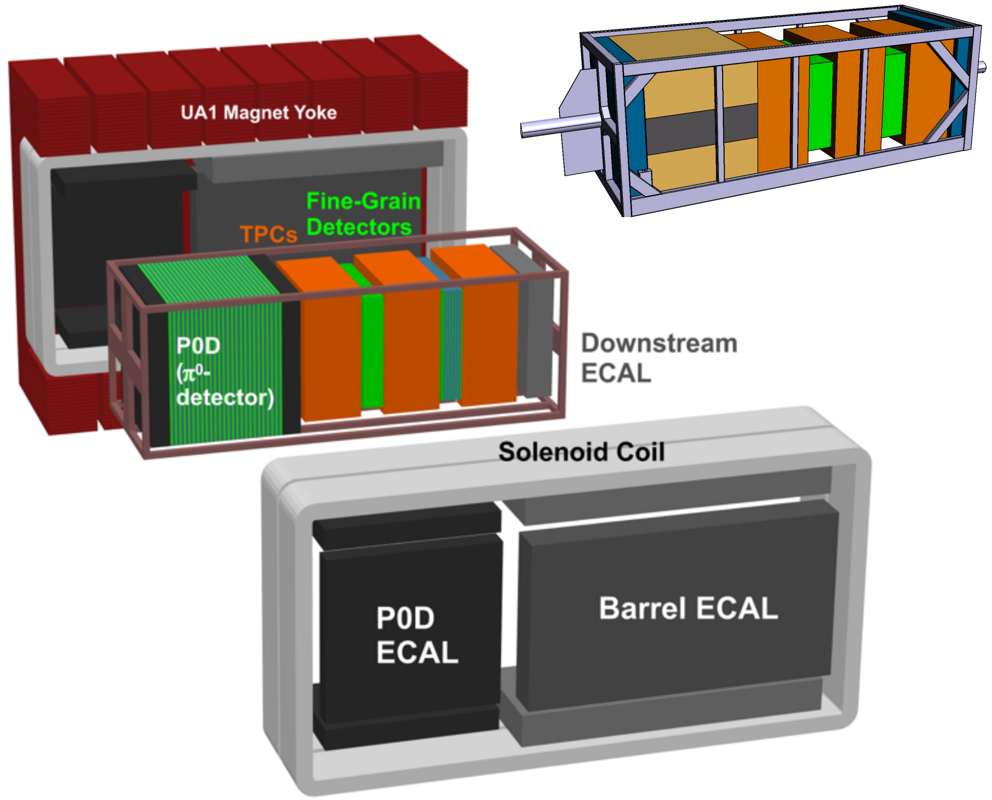
SYSTEMATIC ERRORS: NEAR AND INTERMEDIATE DETECTORS

BASELINE DESIGN FOR NEAR/INTERMEDIATE DETECTORS

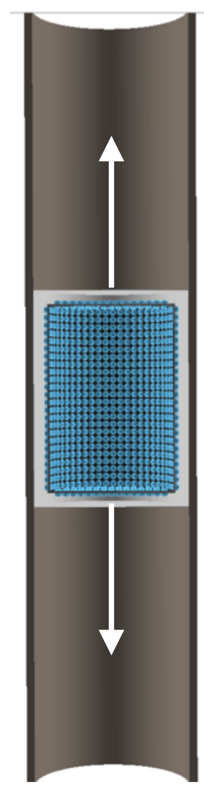
On-axis Detector (INGRID)



Off-axis Magnetized Tracker (ND280→ND280 Upgrade→??)



Off-axis spanning intermediate water Cherenkov detector (IWCD)



- On-axis detector: measure beam direction, monitor event rate
- Off-axis magnetized tracker: charge separation (measurement of wrong-sign background), study of recoil system
  - Expect upgrades of detector inherited from T2K will be necessary
- Off-axis spanning water Cherenkov detector: intrinsic backgrounds, electron (anti)neutrino cross-sections, neutrino energy vs. observables, H_2O target, neutron multiplicity measurement

CONTROLLING BACKGROUND FOR CPV MEASUREMENT

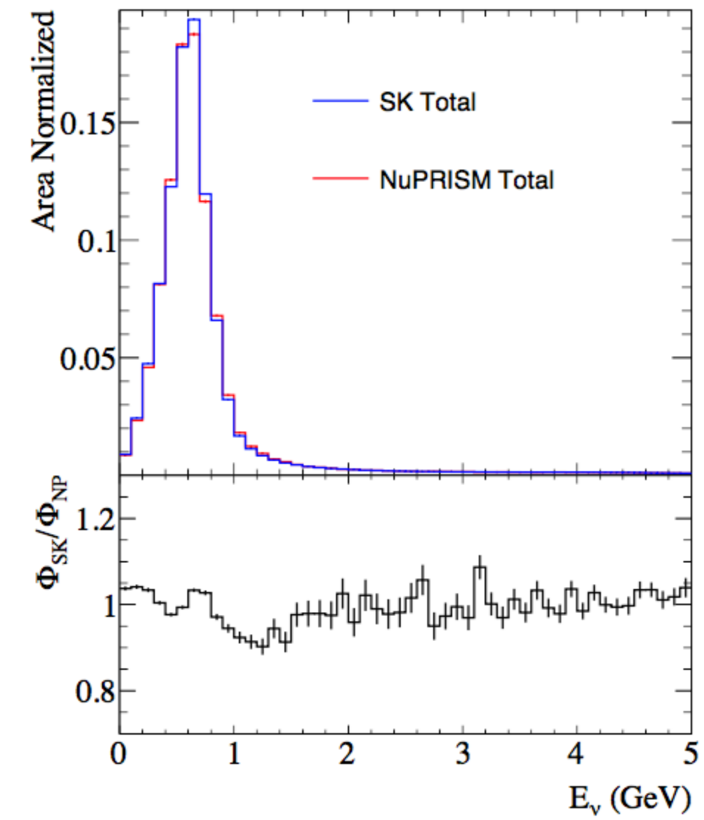
Sample Composition:

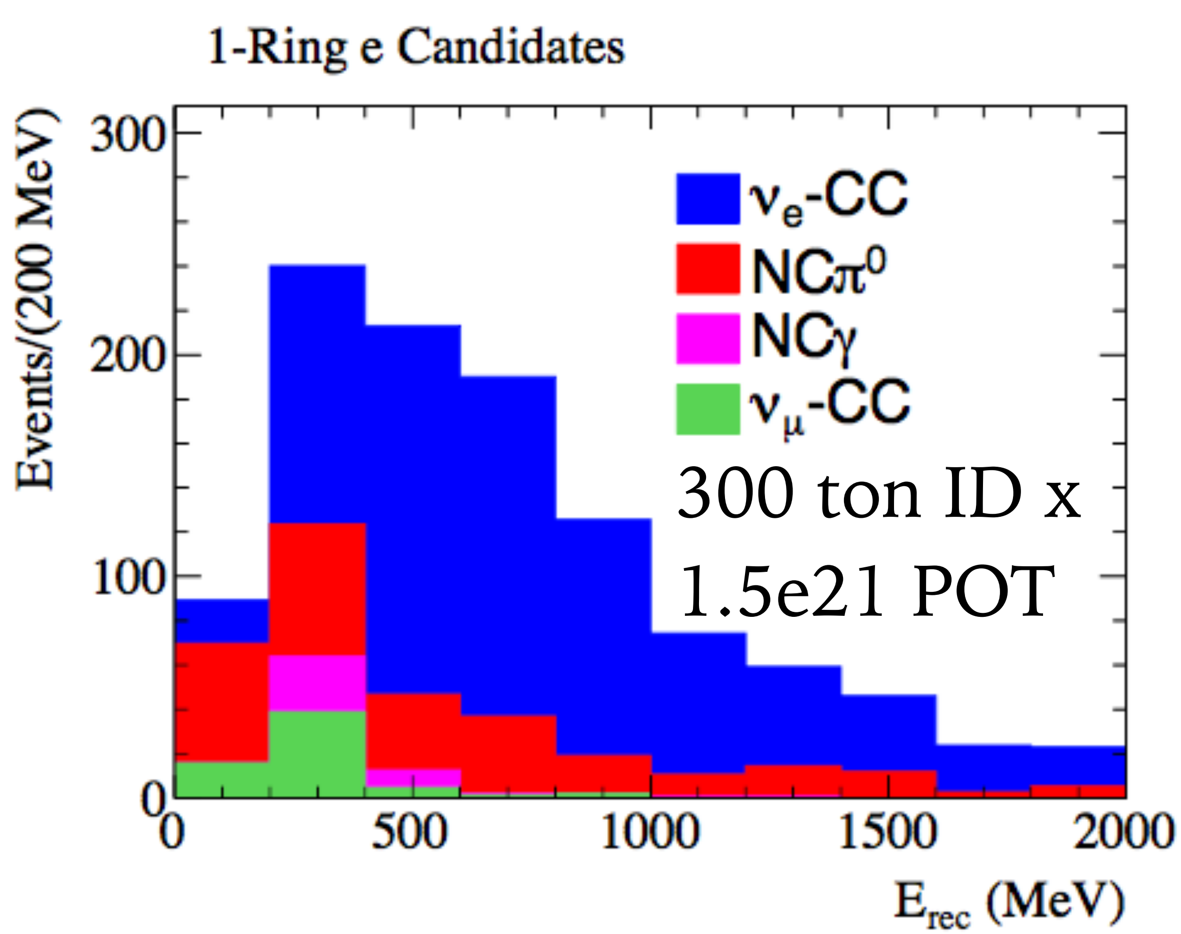
	Neutrino Candidates	Antineutrino Candidates
Signal	80%	62%
Wrong-sign Background	1%	11%
Intrinsic electron (anti)neutrino & NC	19%	27%

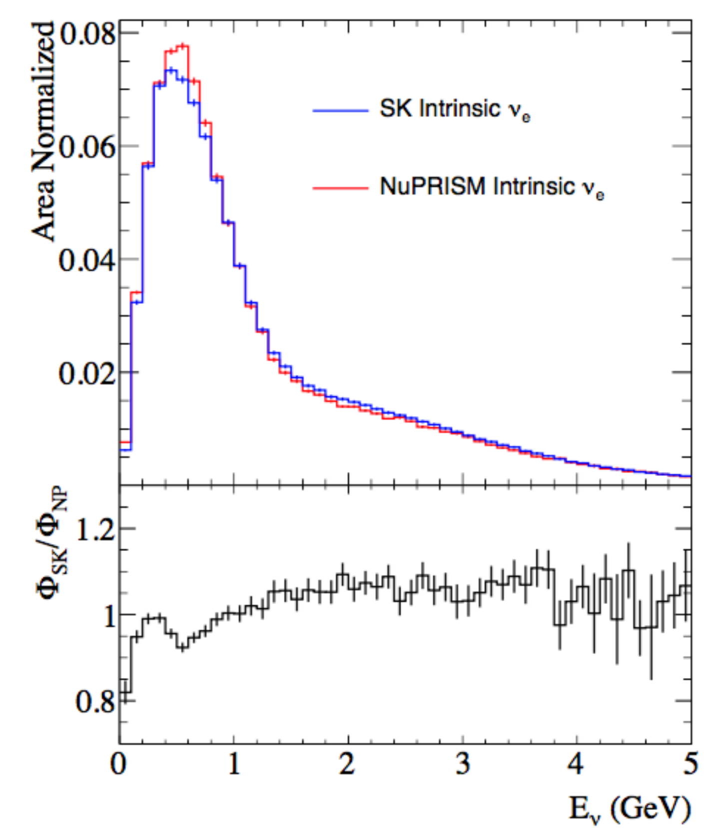
- We aim for a 1% systematic error contribution from the wrong-sign background and intrinsic electron (anti)neutrino & NC background respectively
- Wrong-sign background must be measured with 9% accuracy
  - Can be done in magnetized tracking detectors
- Intrinsic electron (anti)neutrino & NC background must be measured with 3% accuracy

NC AND INTRINSIC ELECTRON (ANTI)NEUTRINO BACKGROUND

- Total and electron (anti)neutrino fluxes are nearly identical at IWCD and far detector
- Can directly measure these backgrounds at the IWCD
- We can achieve 3% statistical precision with 6 m diameter inner detector, even better with larger diameter





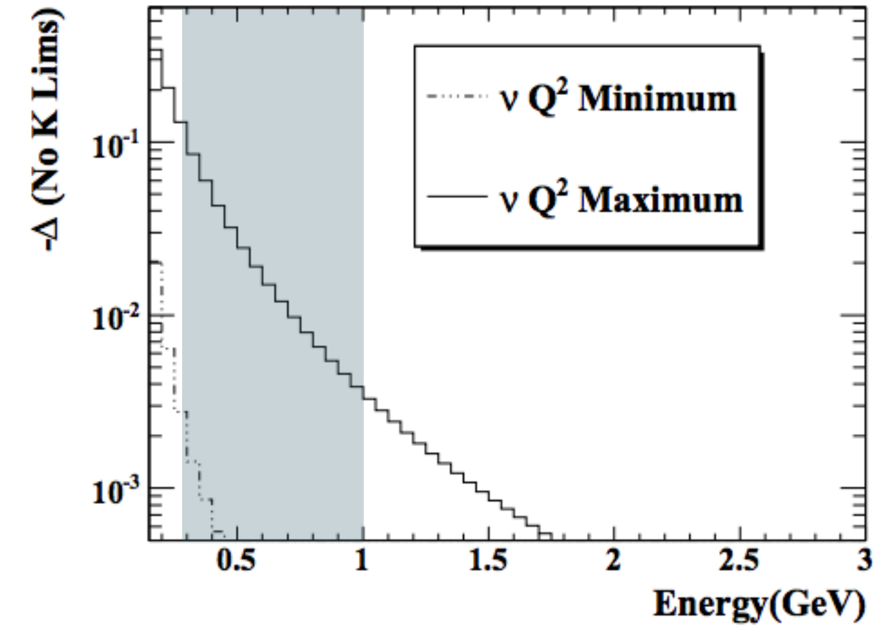


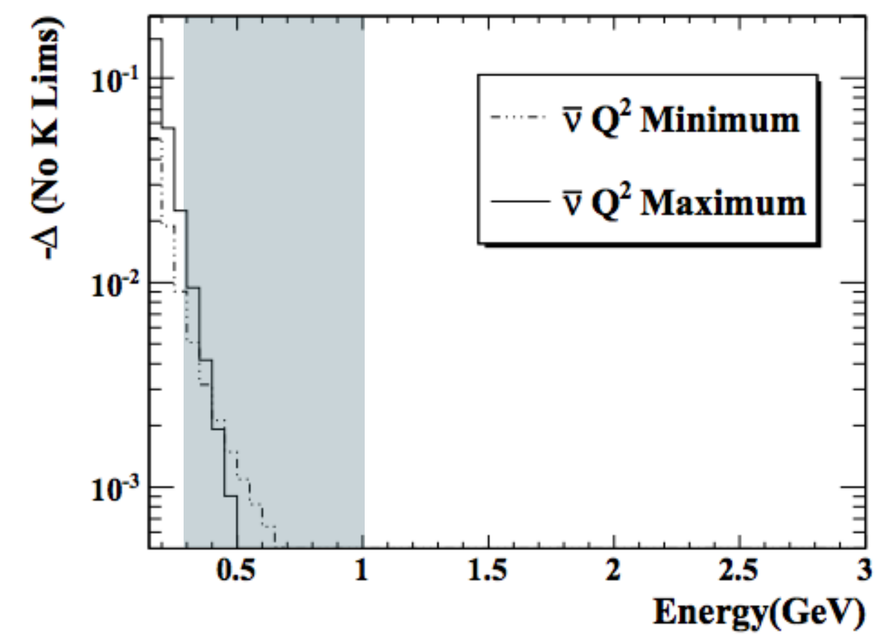
ELECTRON (ANTI)NEUTRINO CROSS SECTION

- Source of systematic error on the signal contribution from the electron (anti)neutrino cross section
- Uncertainties on the relative cross section ratios propagate directly into the analyses

$$\sigma_{\nu_e}/\sigma_{\nu_\mu}$$
$$\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$$

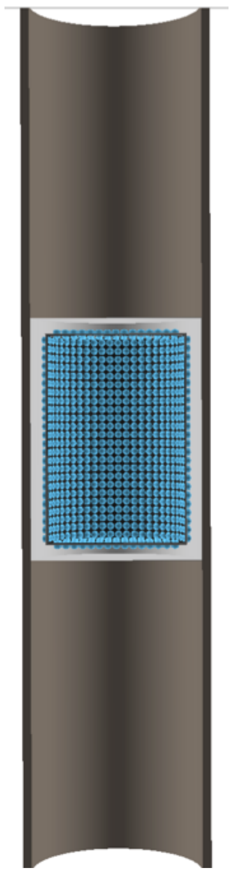
- Sources of errors are:
  - Phase space difference between interactions involving muons and electrons
  - Radiative corrections
  - Form factor uncertainties for sub-leading terms in cross section that depend on lepton mass
- We should make direct and indirect measurements to address these uncertainties



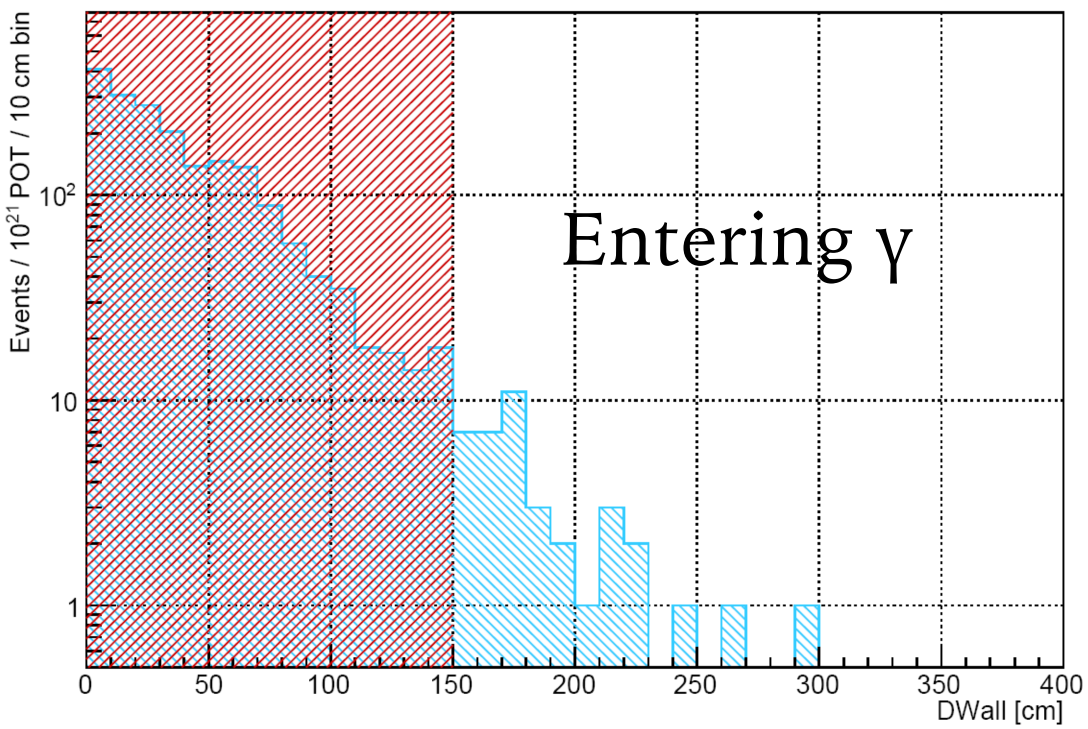


Phys.Rev. D86 (2012) 053003

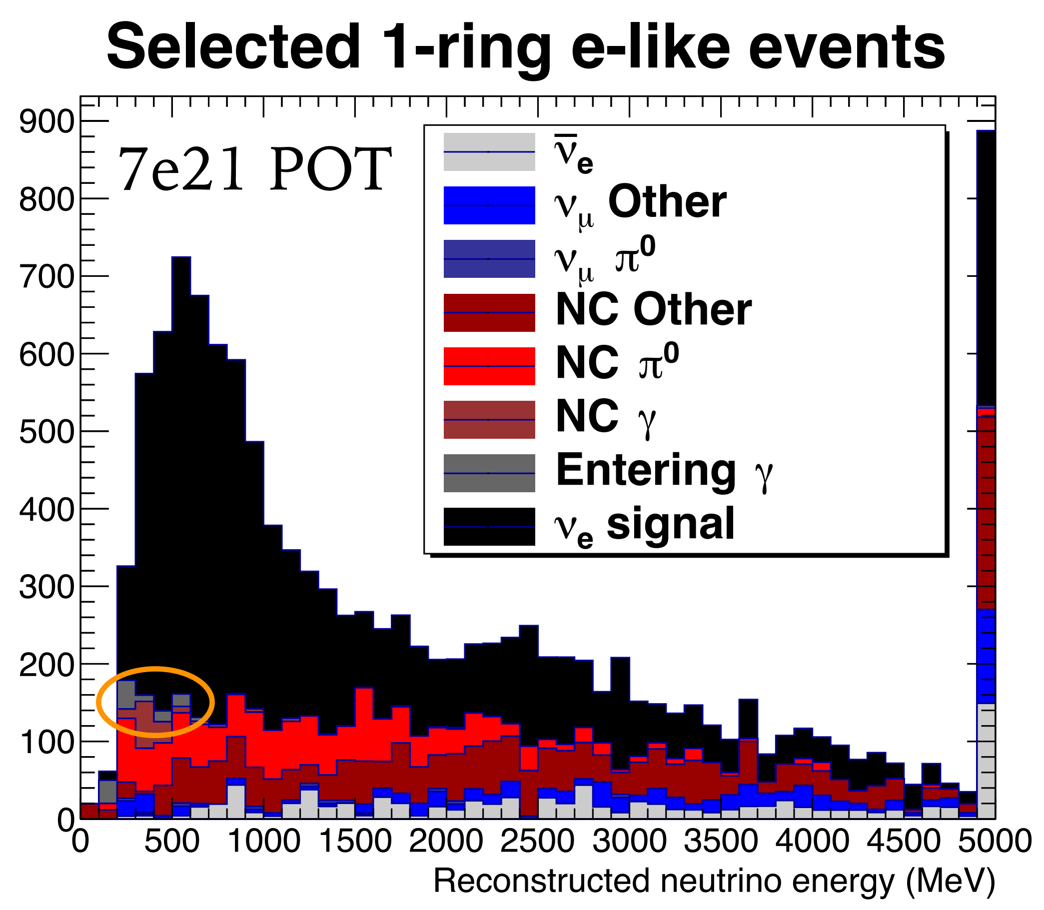
ELECTRON (ANTI)NEUTRINO CROSS SECTION MEASUREMENT



- Measure in the intermediate water Cherenkov detector
- The fraction of electron (anti)neutrinos increases at further off-axis angles

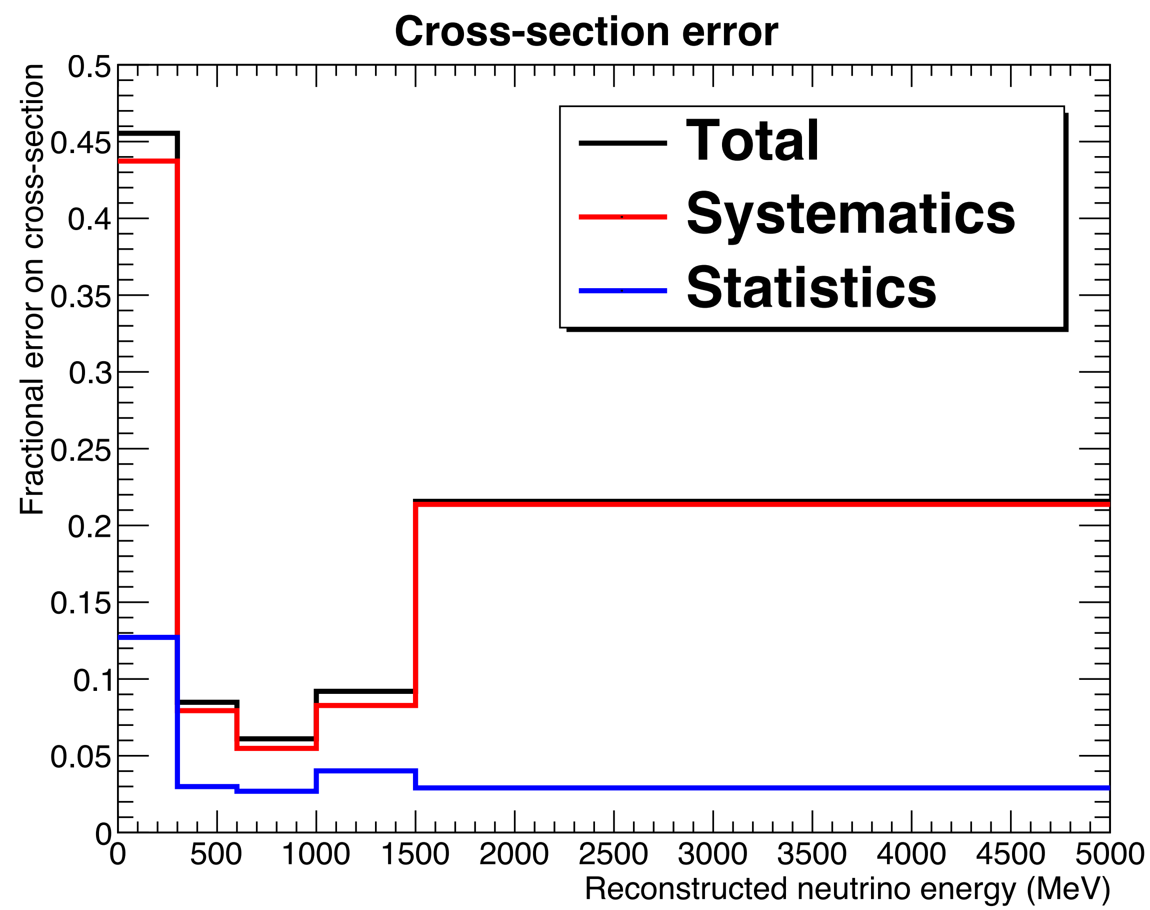


- The entering γ background is controlled by outer detector veto and fiducial cut (>1.5 m from wall)
- The cross section is measured relative to the muon neutrino candidates to produce a cross section ratio



UNCERTAINTY ON ELECTRON NEUTRINO CROSS SECTION

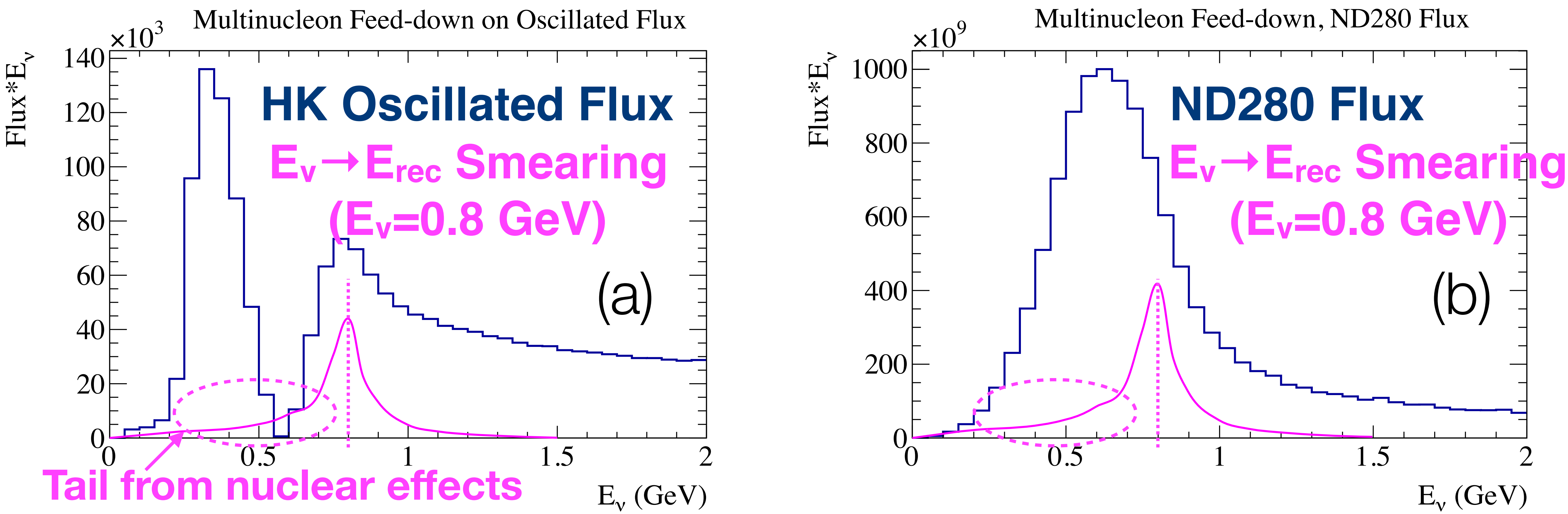
- The electron neutrino cross section relative to the muon neutrino cross section is extracted



- Statistical error of 3% can be achieved in relevant bins
- Systematic error should be reduced with update to new flux errors and better use of control samples to constrain backgrounds
  - May need additional measurements to control relative flux error
- Analysis will be extended to electron (anti)neutrinos

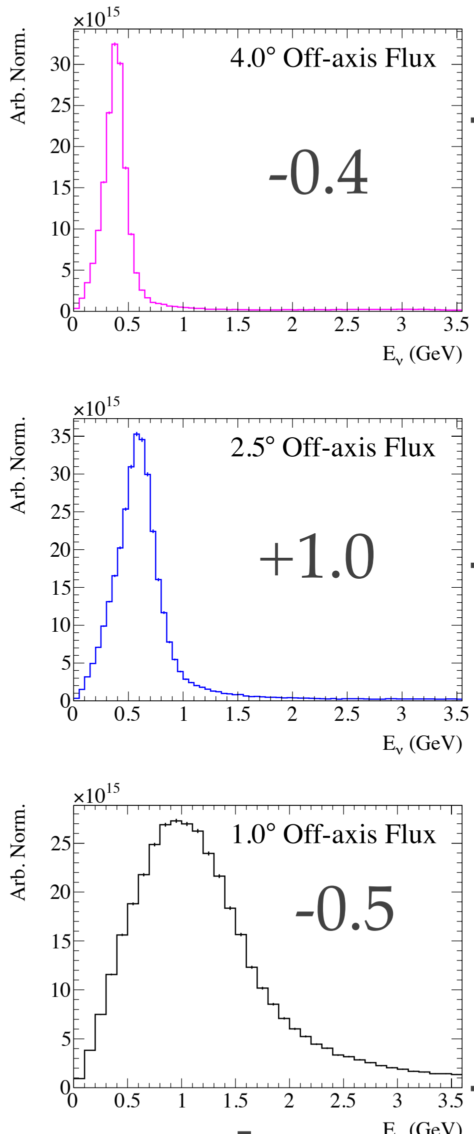
SPECTRUM UNCERTAINTIES

- Previous discussion covered normalization type errors.
- Uncertainties that impact the shape of the reconstructed spectra are also important
- Example:

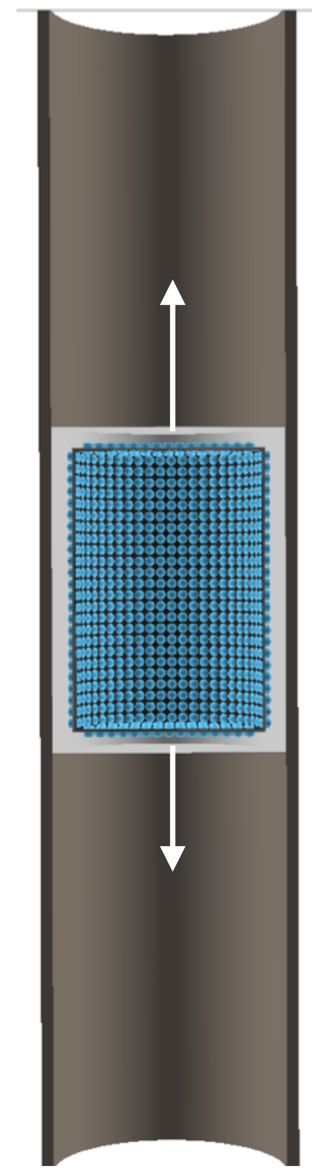


- Modeling the feed-down component is critical for disappearance measurement
- Difficult to measure in the near detector, where it resides under the flux peak

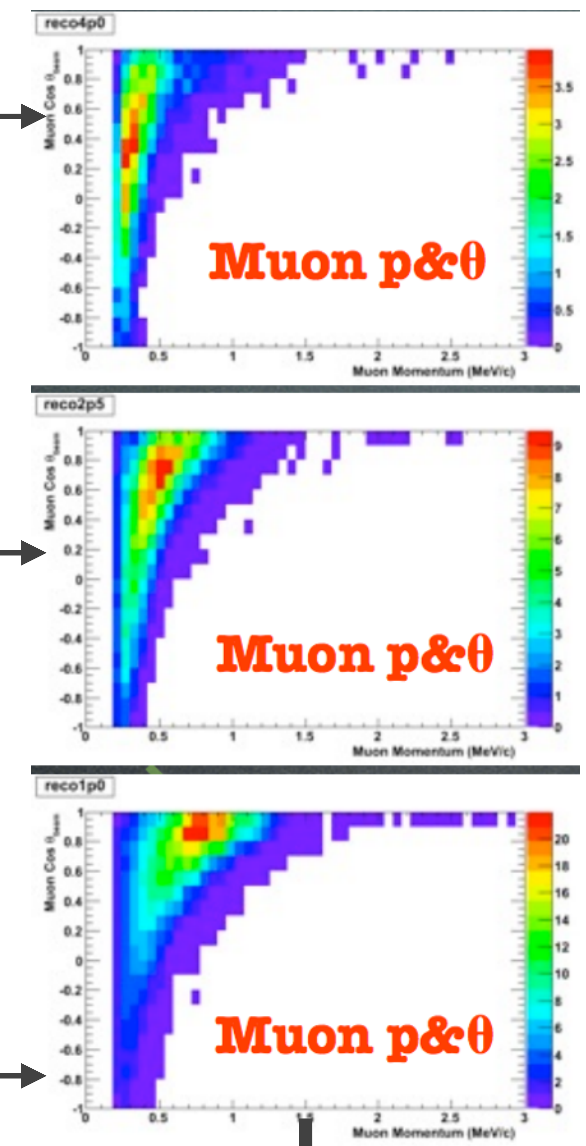
OFF-AXIS MEASUREMENTS IN IWCD

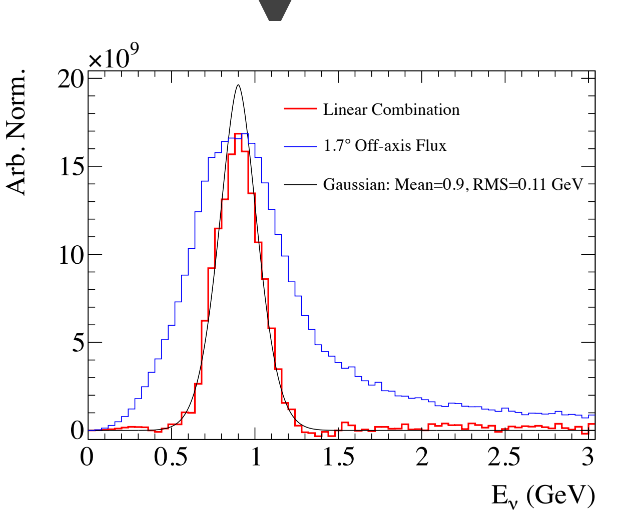


Spectra at at each off-axis bin

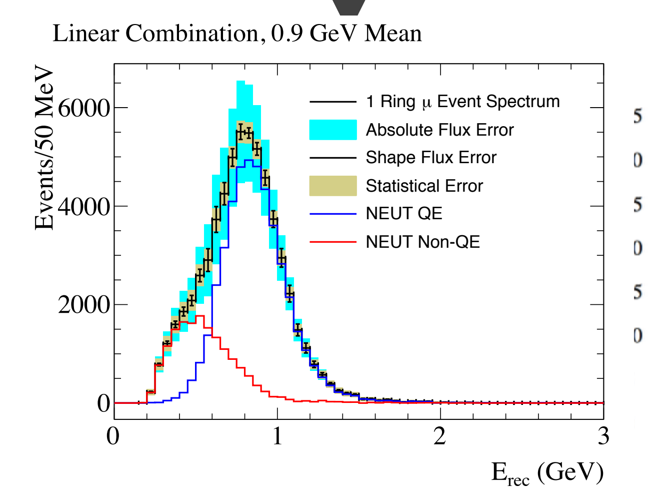


Observed muon kinematic distributions





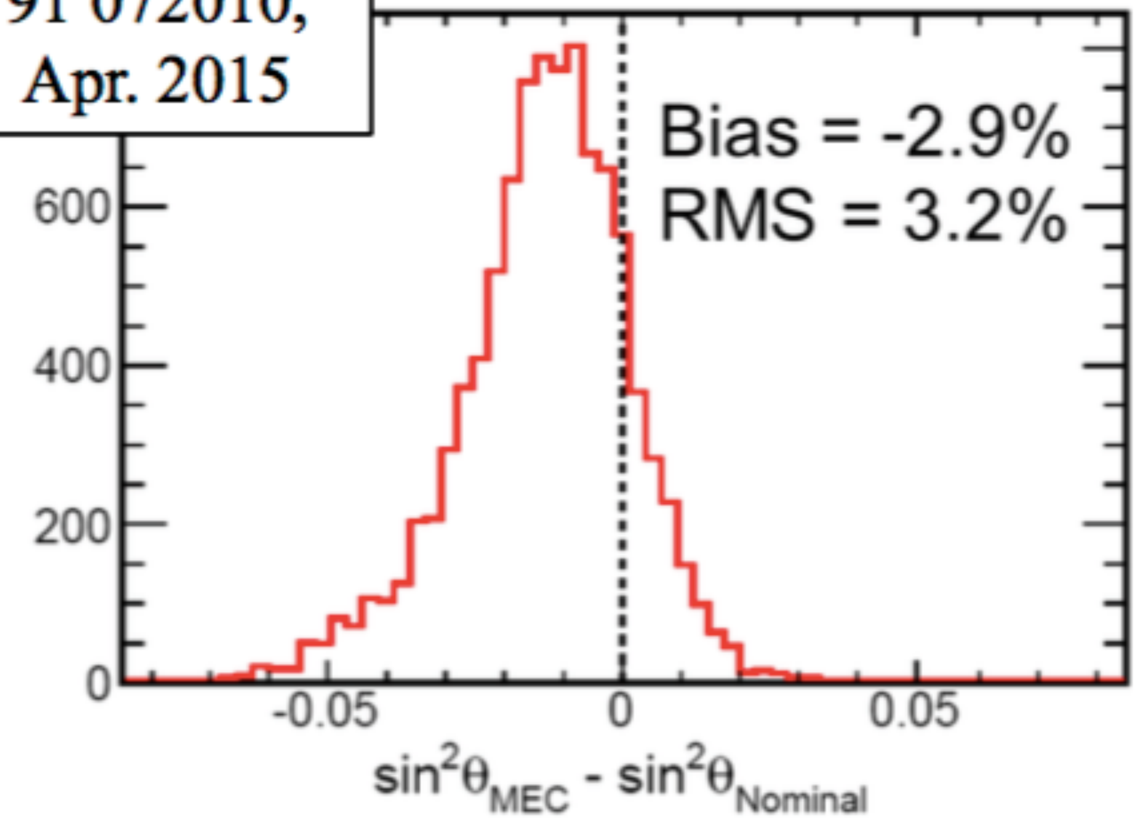
Subtract off low energy and high energy tails of flux → produce very narrow beam to measure energy response.

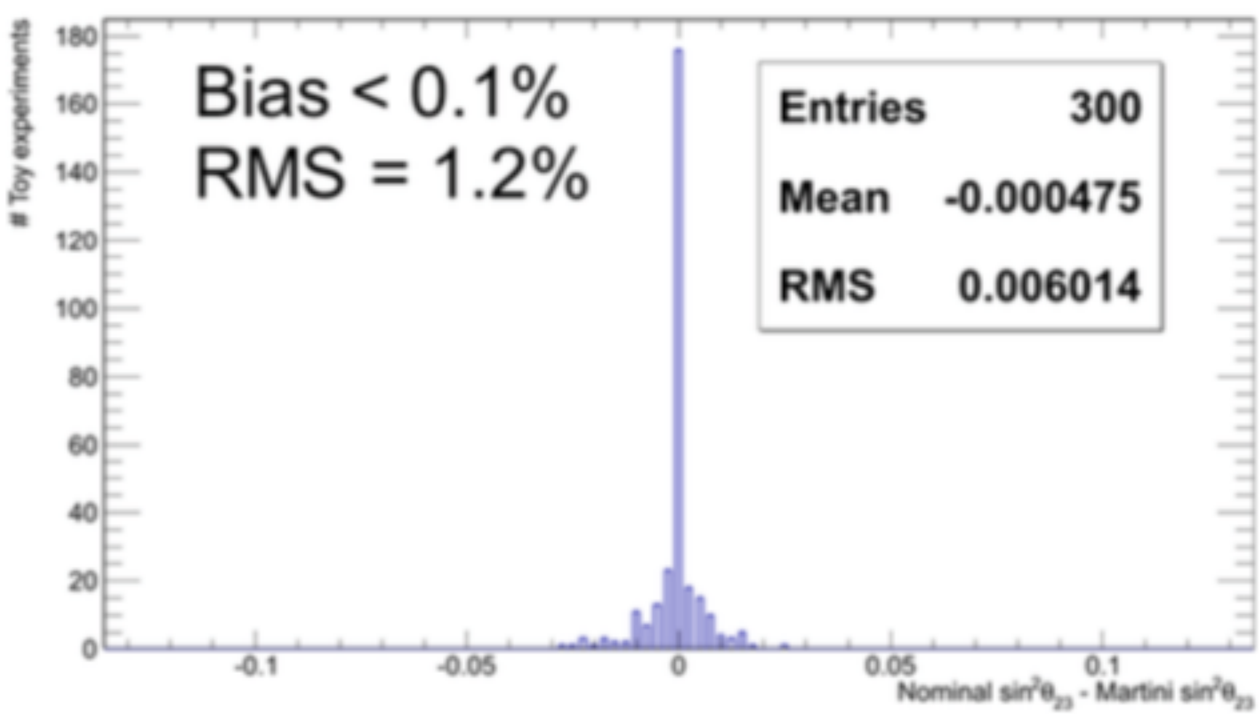


OFF-AXIS MEASUREMENTS IN IWCD

- Mock data analysis at T2K
  - Addition of multi-nucleon events to mock data
  - Analyze MC without multi-nucleon events
  - Biased values of θ_{23} measured

K. Abe *et al*, *Phys. Rev. D*, 91 072010, Apr. 2015

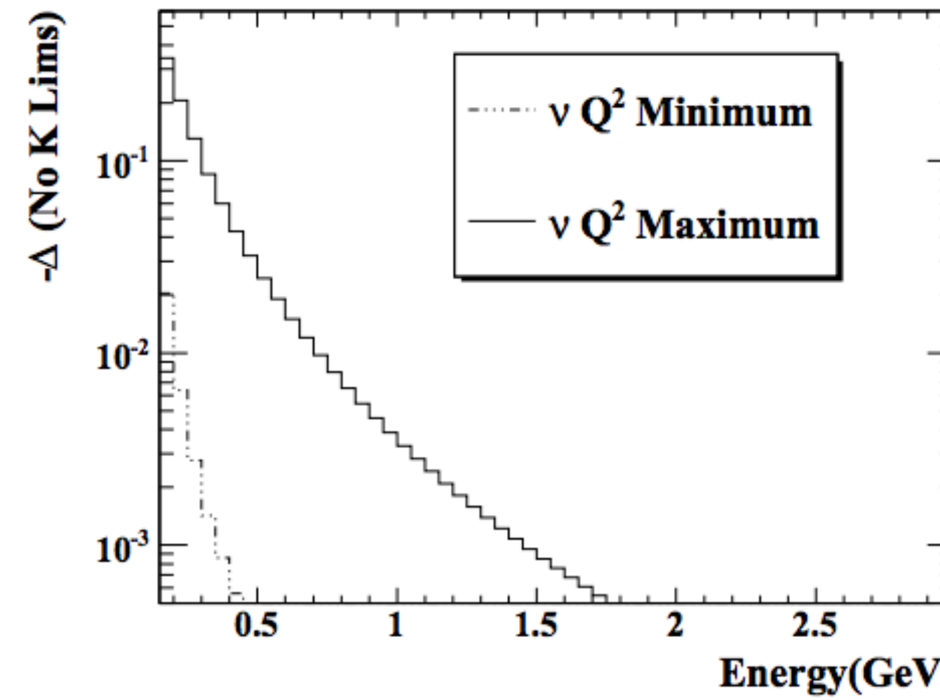


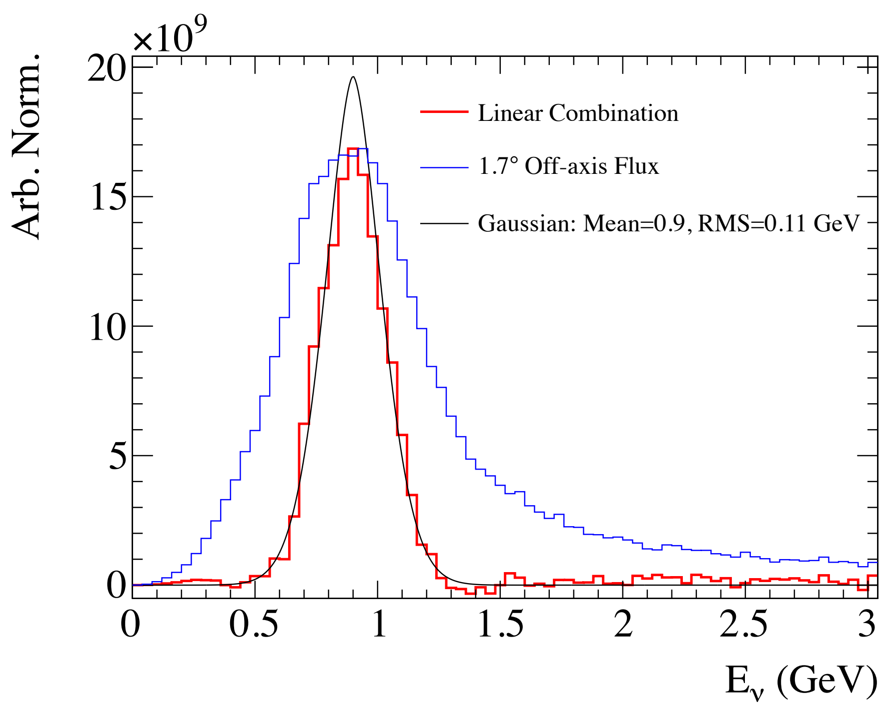


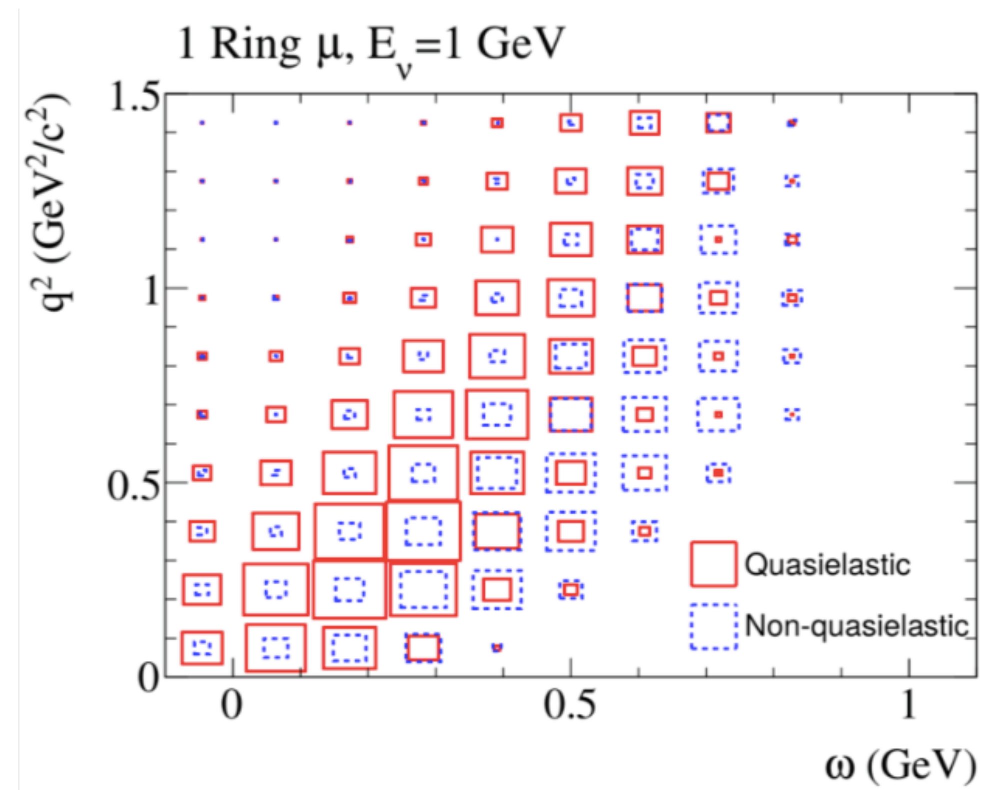
- Identical analysis with IWCD
  - Multi-nucleon events added to mock data
    - Not added to MC
  - Linear combination applied
  - Measured θ_{23} unbiased

ANOTHER USE FOR NARROW BAND BEAMS

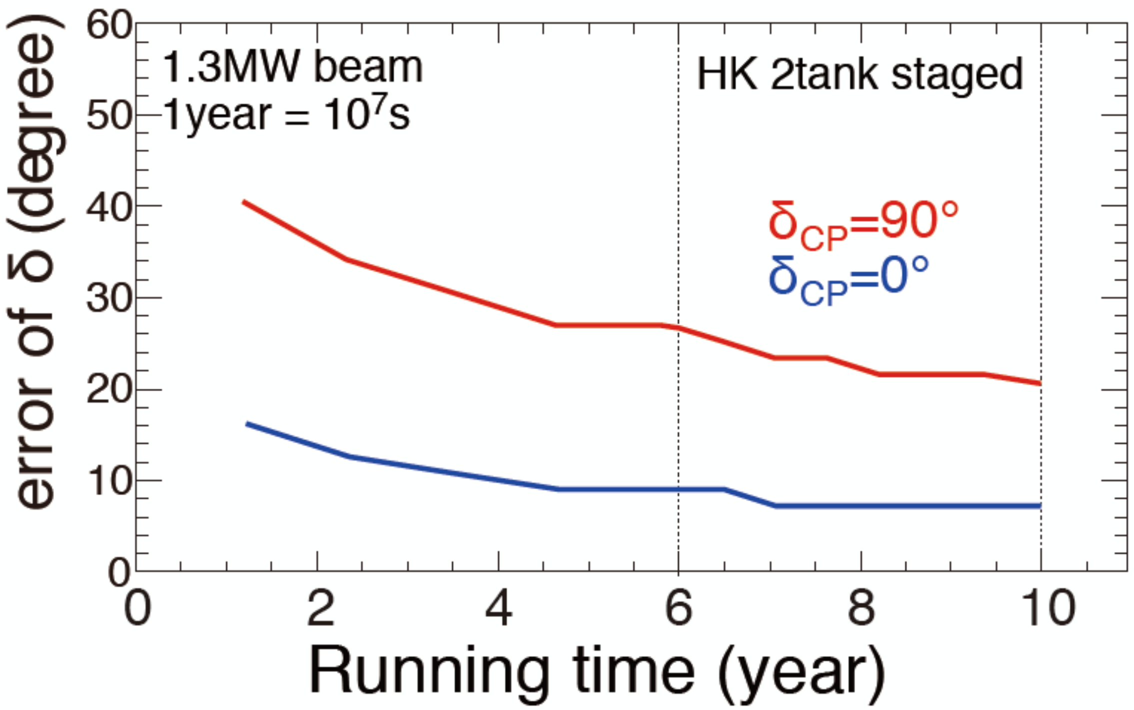
- Source of error on the relative ν_e to ν_μ cross section: phase space difference
- Use linear combination method to produce narrow band beam
- Can reconstruction the momentum and energy transfer
- Study the regions of phase space where the electron neutrino and muon neutrino differ



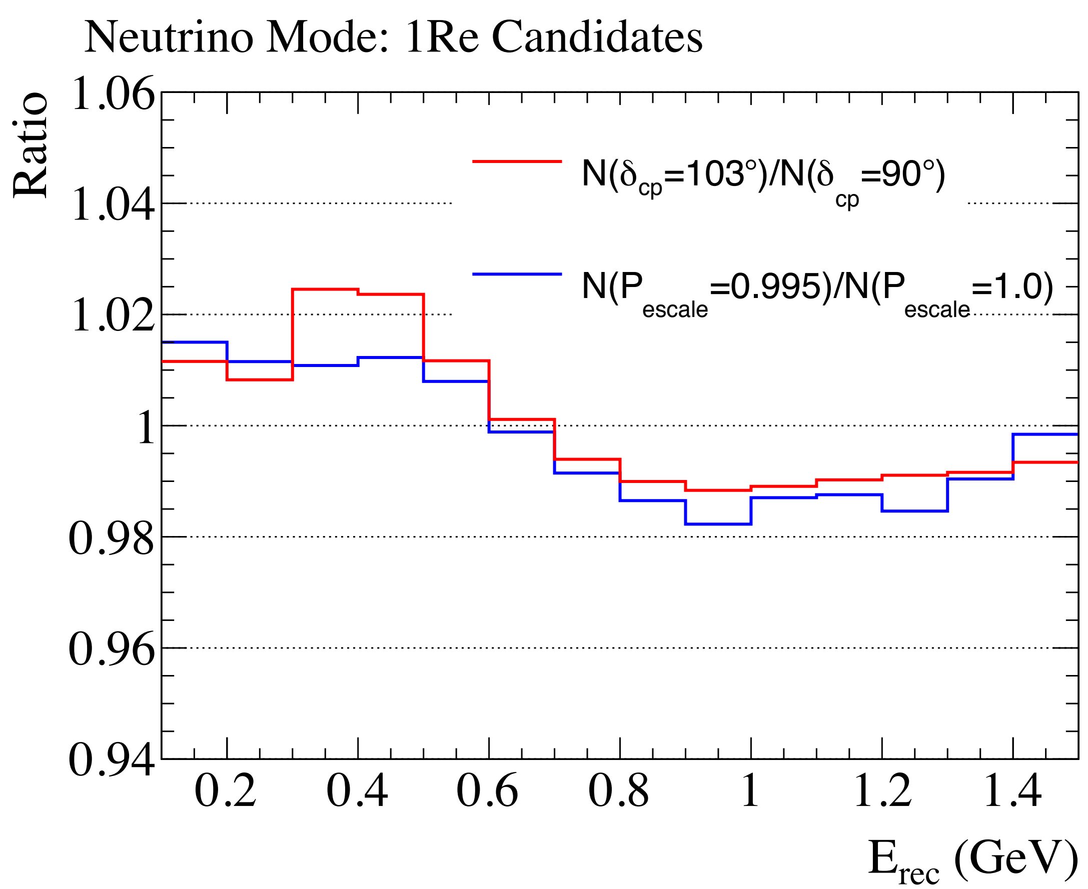




SHAPE MATTERS FOR CP PHASE TOO



- ➤ If δ_{cp} is near 90° or 270°, precision measurement becomes challenging
- ➤ Rely on spectrum variations introduced by $\cos(\delta_{cp})$ term



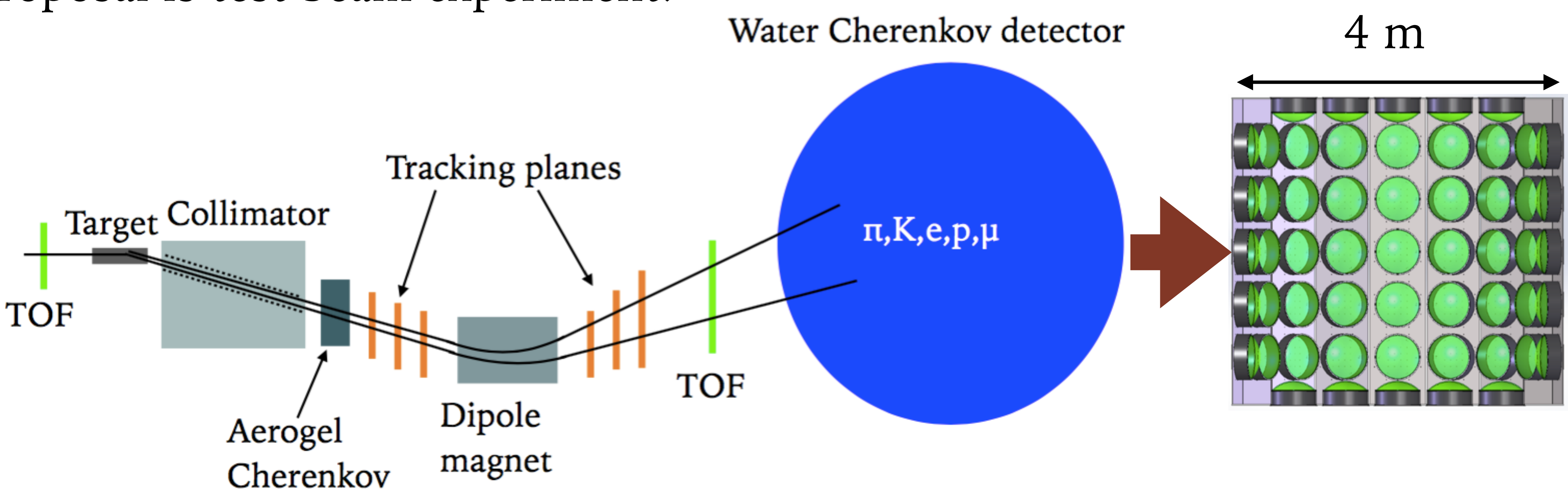
- ➤ A shift of δ_{cp} by 13° is nearly indistinguishable from a change of energy scale by 0.5%
- ➤ We also need precise calibration of the energy response in an our near/intermediate detectors and Hyper-K
- ➤ Similar precision is needed for Δm^2_{32} measurement

SOURCES OF SHAPE UNCERTAINTY

- **Uncertainty on beam direction:**
  - Should be measured precisely by INGRID detector
- **Uncertainty on feed-down contributions and removal energy from nuclear effects**
  - Measure directly in IWCD
  - Study nuclear effects with hadronic recoil system measurements in magnetized tracker
- **Uncertainty on energy scale in near/intermediate detectors and Hyper-K**
  - Need precision energy scale calibration in all detectors
  - Work needed to improve on 2% energy scale uncertainty in T2K analyses

A TEST BEAM EXPERIMENT

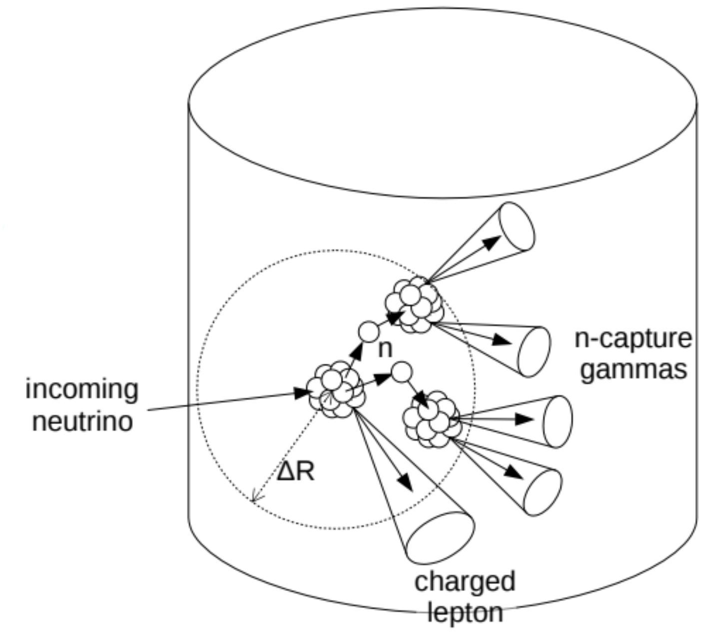
- Calibrating water Cherenkov detectors with 1% level precision is necessary for Hyper-K
- Study detector response and performance of calibration systems in a test beam with known particle type and momenta
- Proposal is test beam experiment:



- Considering test beams at Fermilab and CERN
- Looking for collaborators

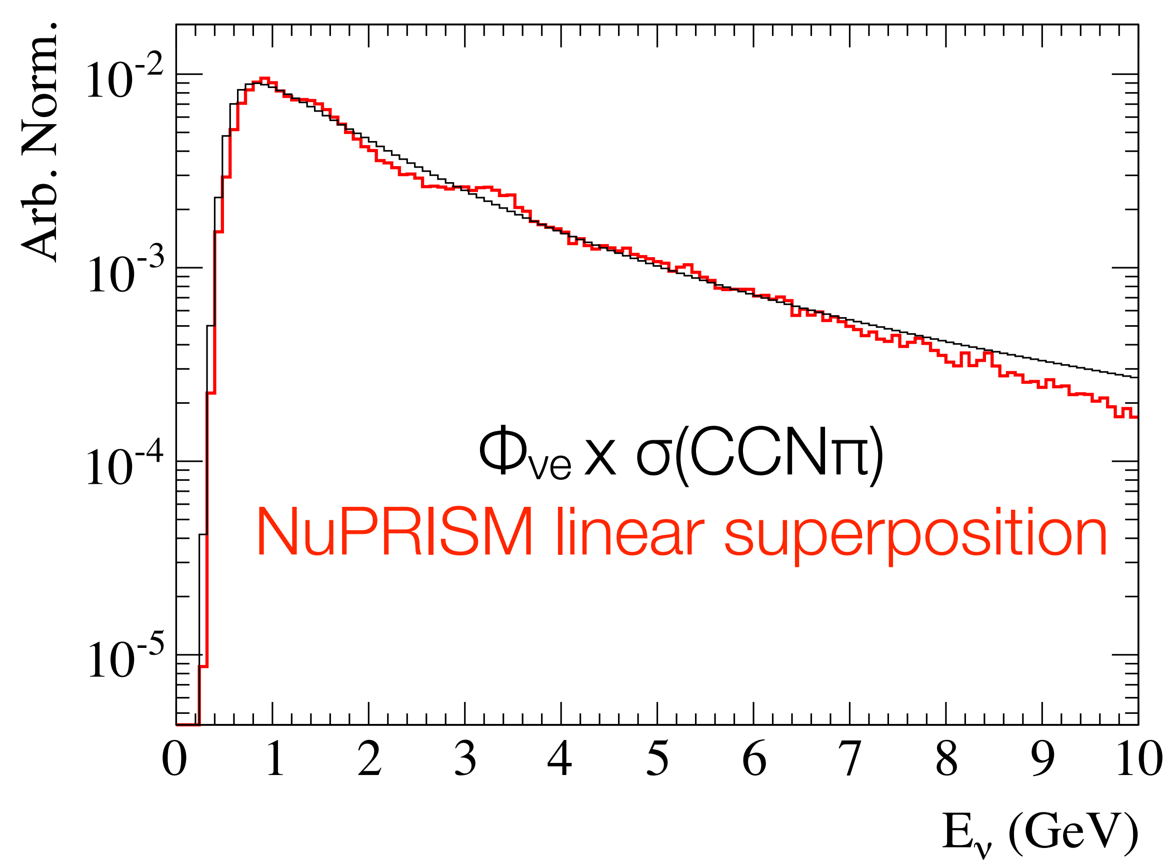
NUCLEON DECAY BACKGROUND AND NEUTRON DETECTION

- IWCD: measure the $\mu^+\pi^0$ background from neutrino interactions, related to the $p \rightarrow e^+\pi^0$ proton decay mode



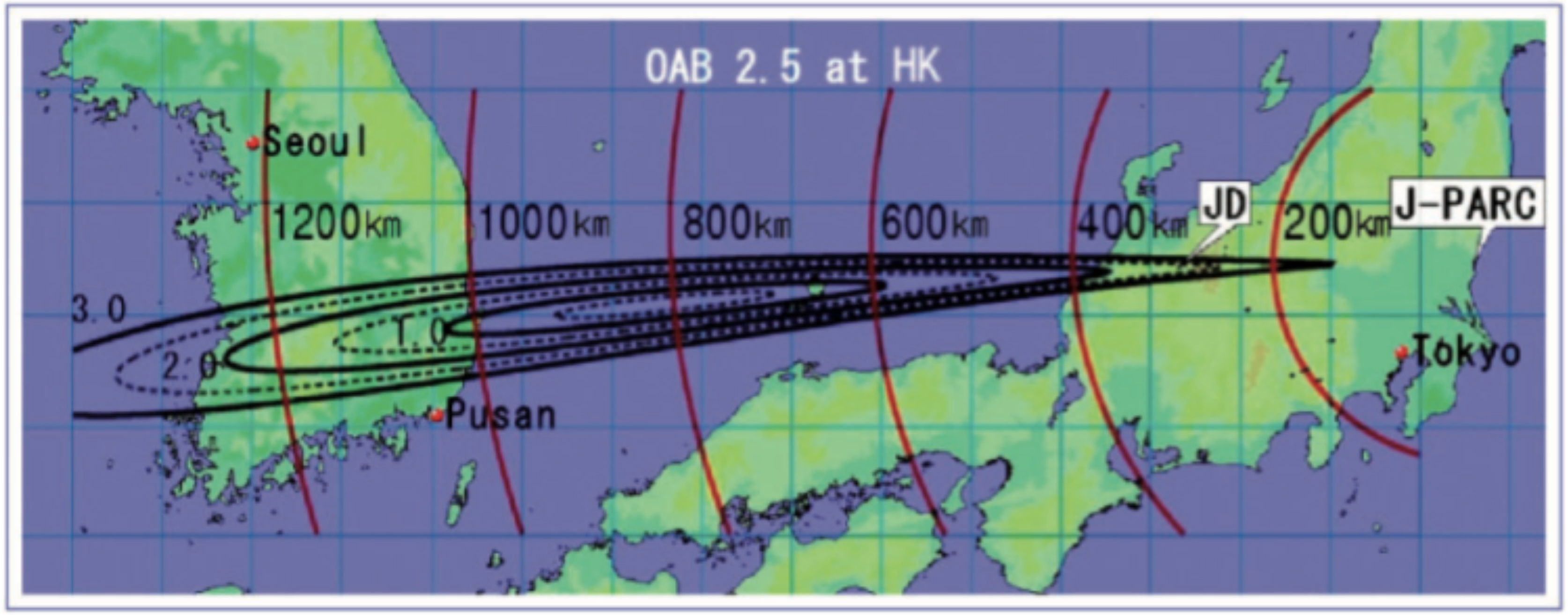
- Will load with Gd for neutron detection
  - Simulation including neutron backgrounds shows 75% tagging efficiency with 92% purity can be achieved

- Using the linear combination method, produce atmospheric spectrum for CCNπ production
  - Can measure the neutron production with the correct input spectrum



SYSTEMATIC ERRORS: NEAR AND INTERMEDIATE DETECTORS

ADDITION OF THE KOREAN DETECTOR

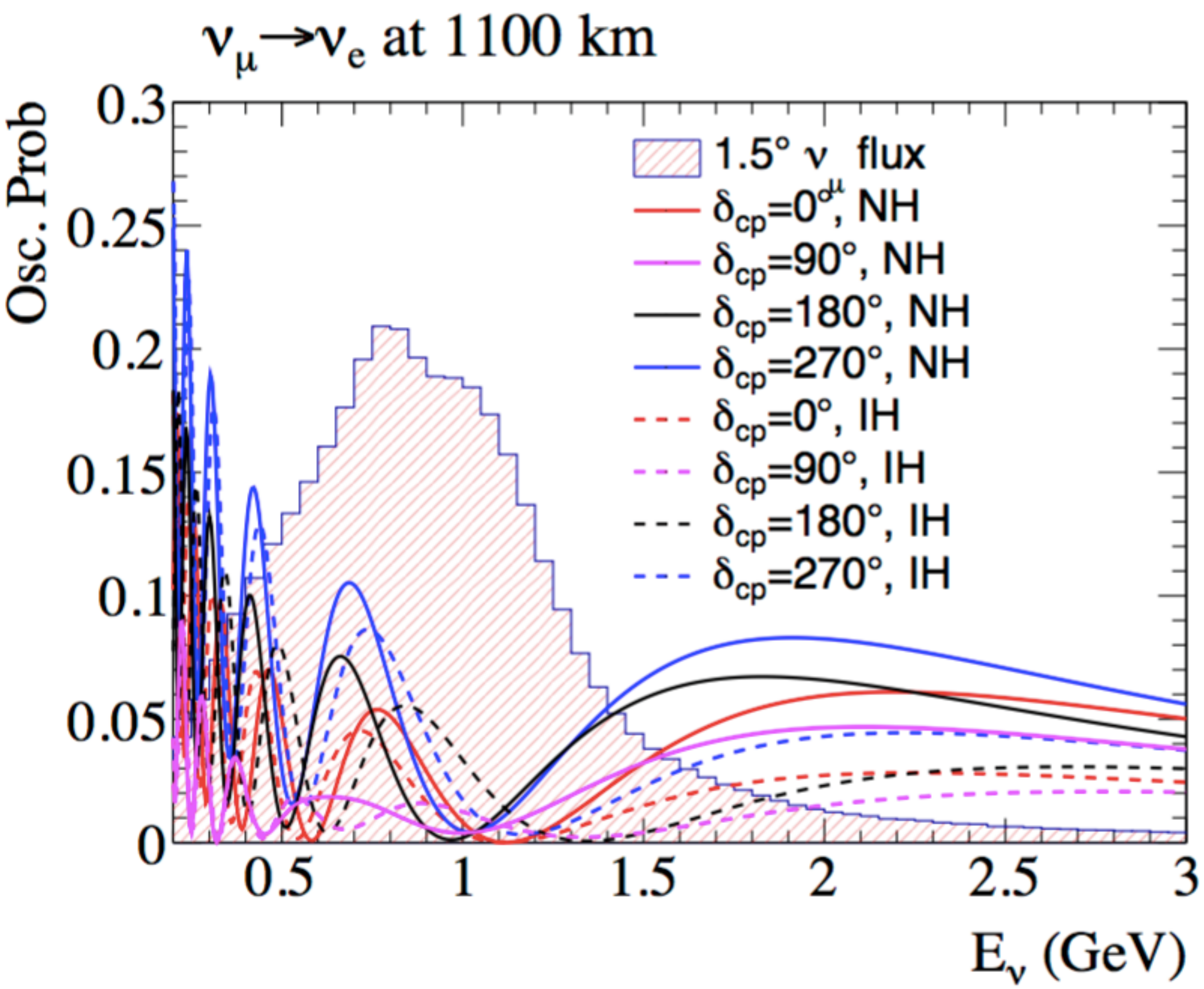


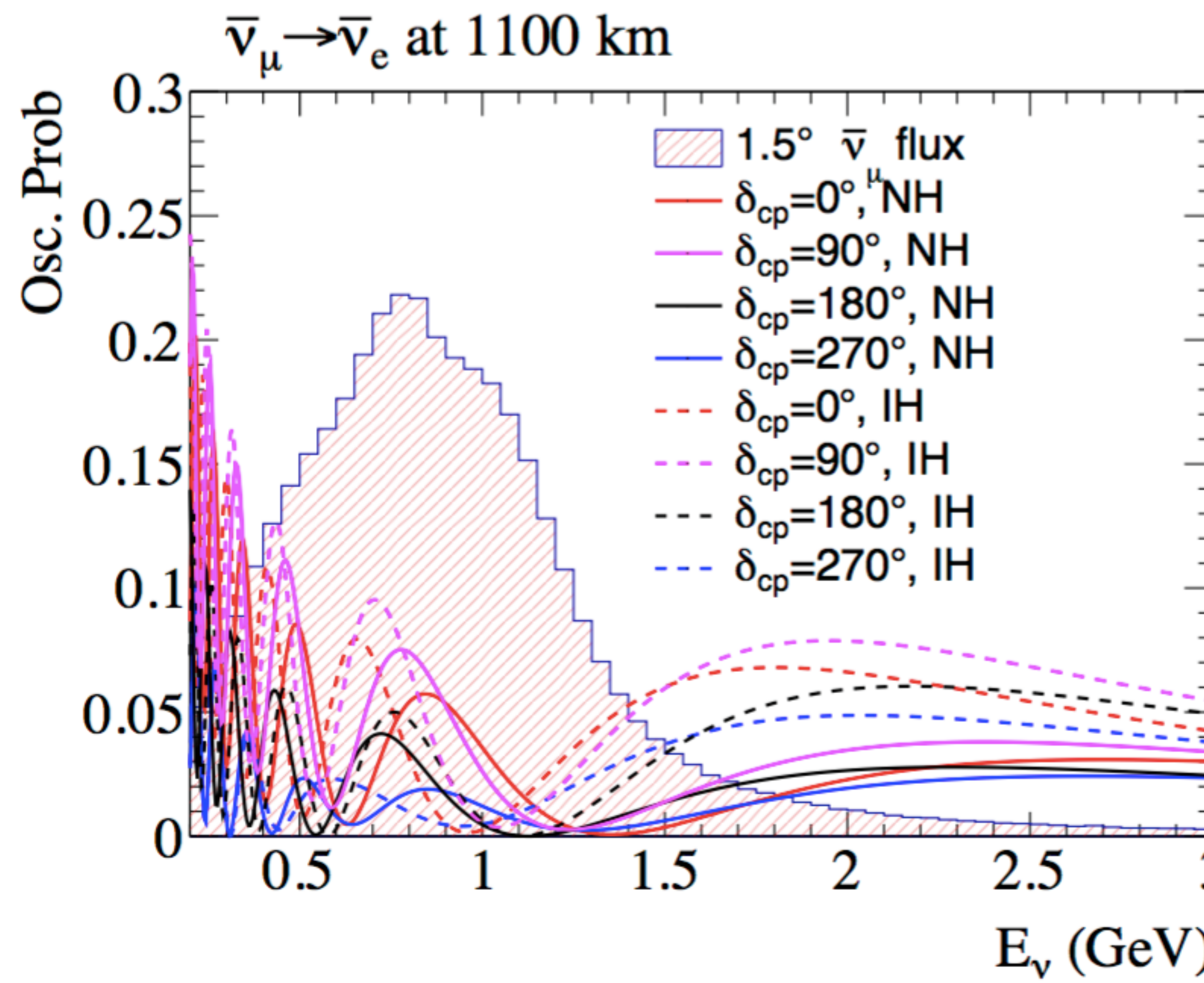
- Plans for a second detector in Korea are being developed
  - Physics studies of possible baselines/off-axis angles
  - Selection of two candidate sites:
    - Mt. Bisul: 1.3° off-axis, 1088 km baseline, 1084 m overburden
    - Mt. Bohyun: 2.3° off-axis, 1043 km baseline, 1124 m overburden
  - Preliminary geological survey and cost estimation have been carried out for candidate sites

Prog. Theor. Exp. Phys. 2018, 063C01

LONG BASELINE PHYSICS AT THE KOREAN DETECTOR

- Consider Mt. Bisul site at 1.3° as primary option





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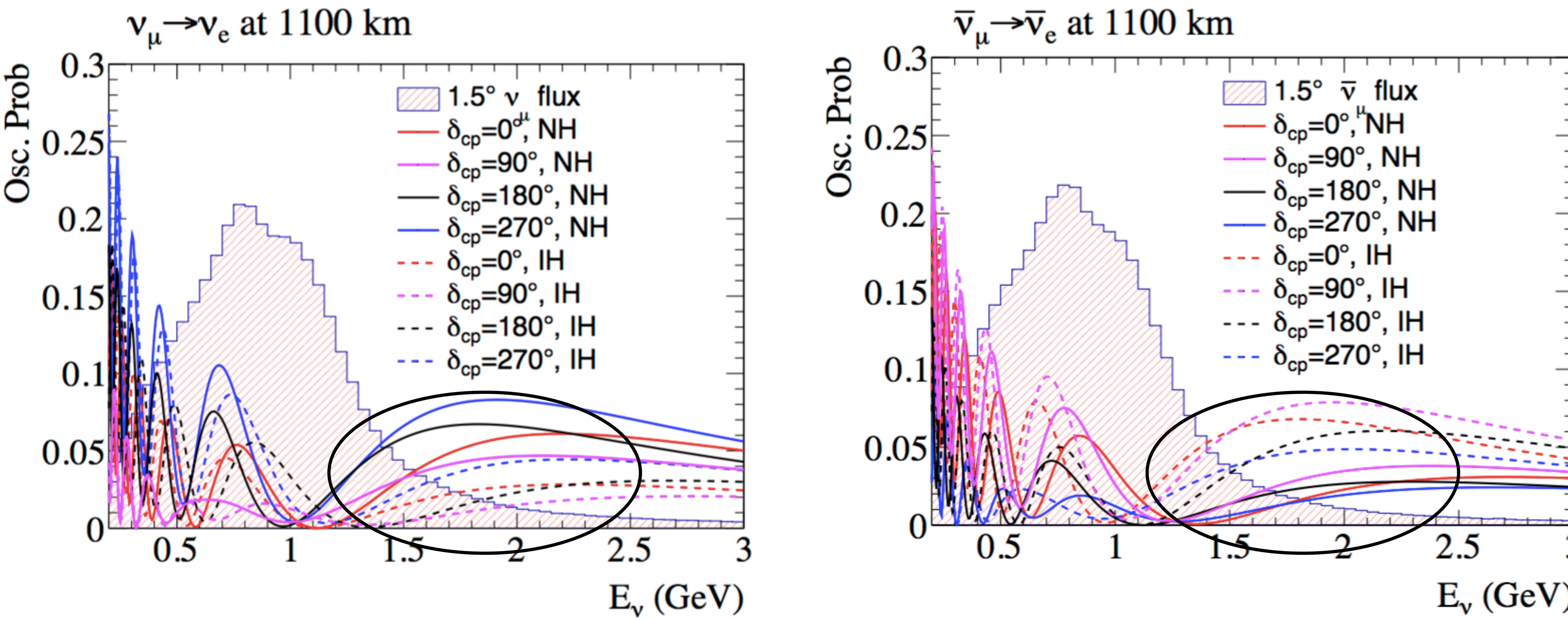

- Low energy part of first oscillation maximum: sensitivity to mass hierarchy

LONG BASELINE PHYSICS AT THE KOREAN DETECTOR

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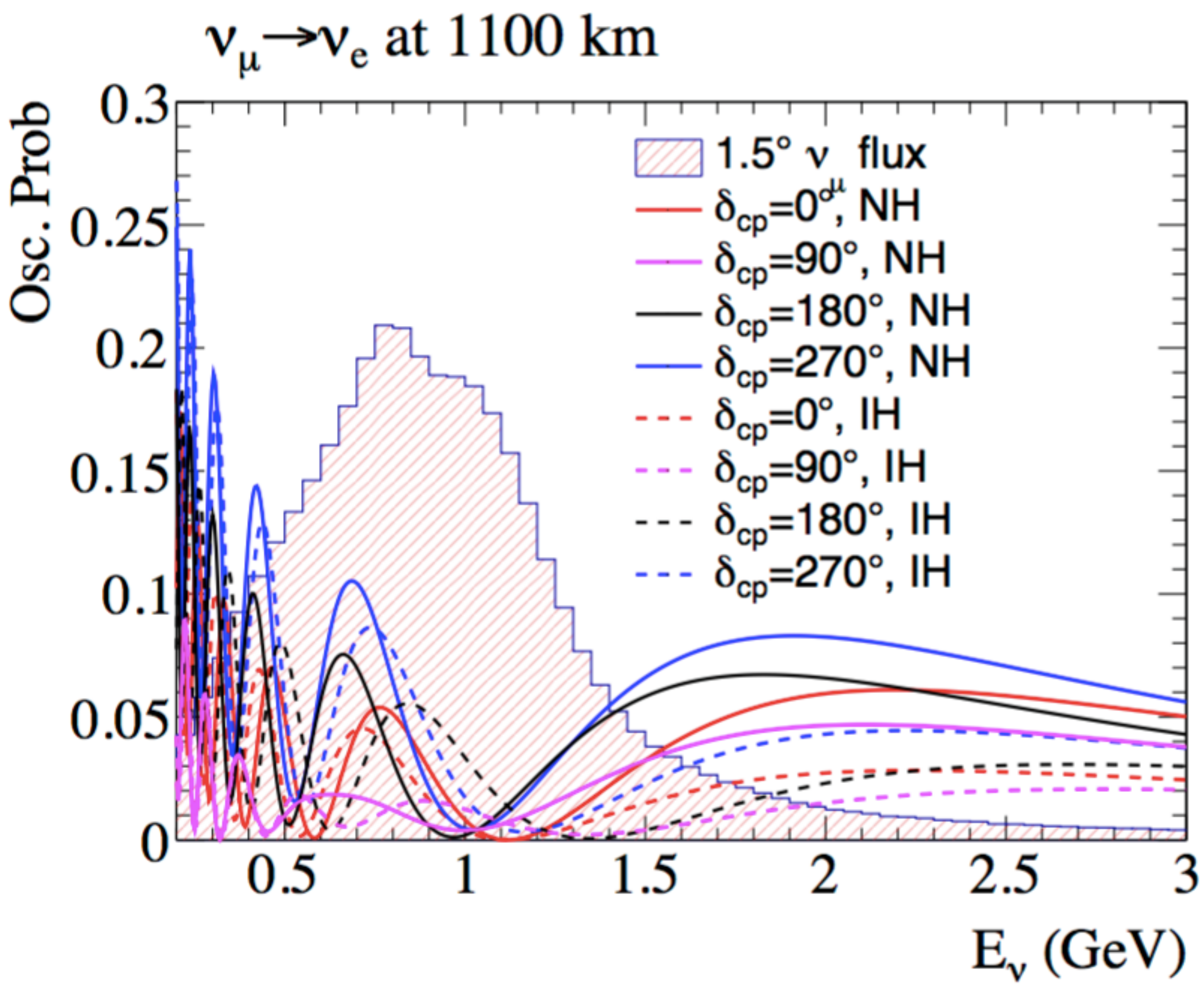

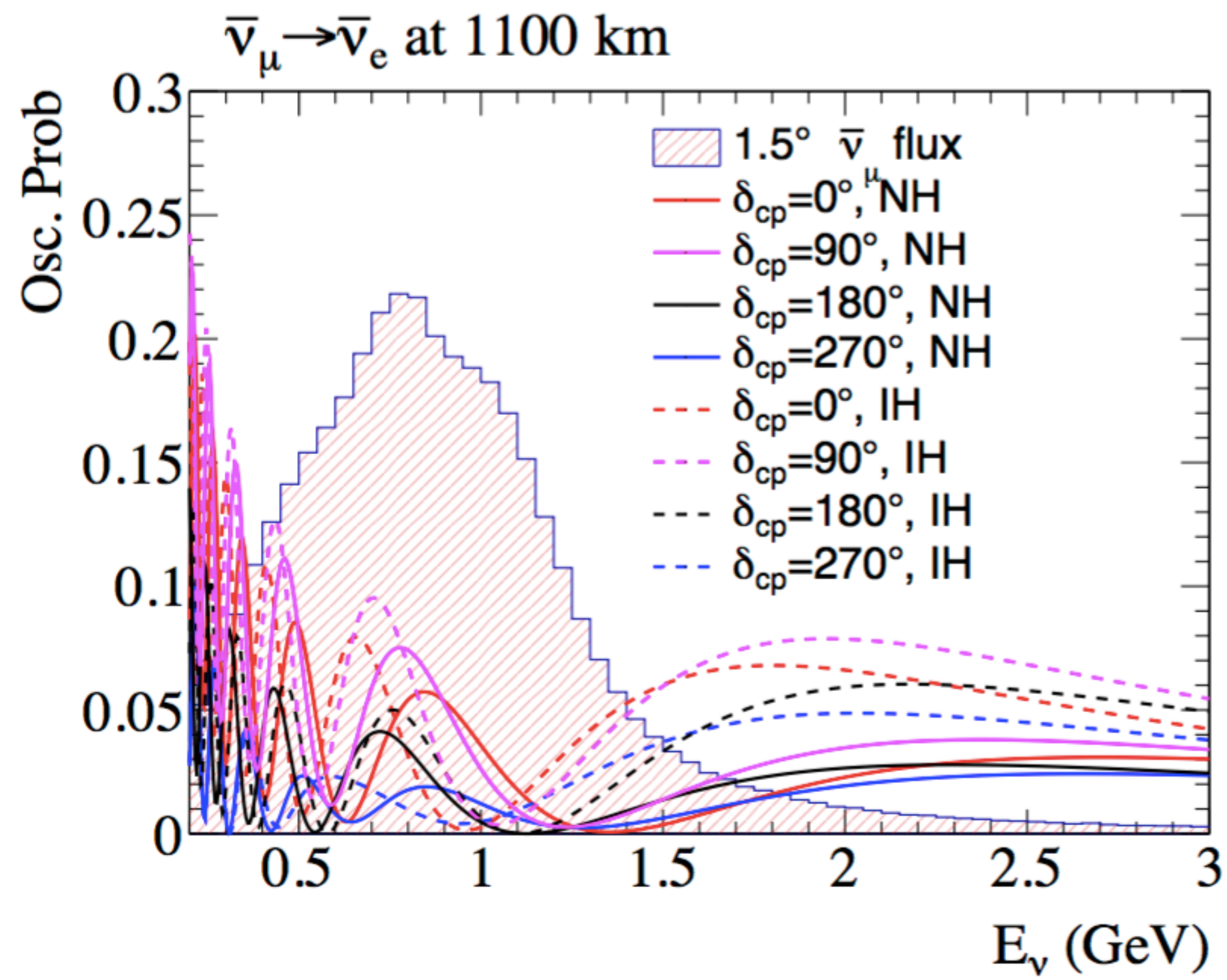

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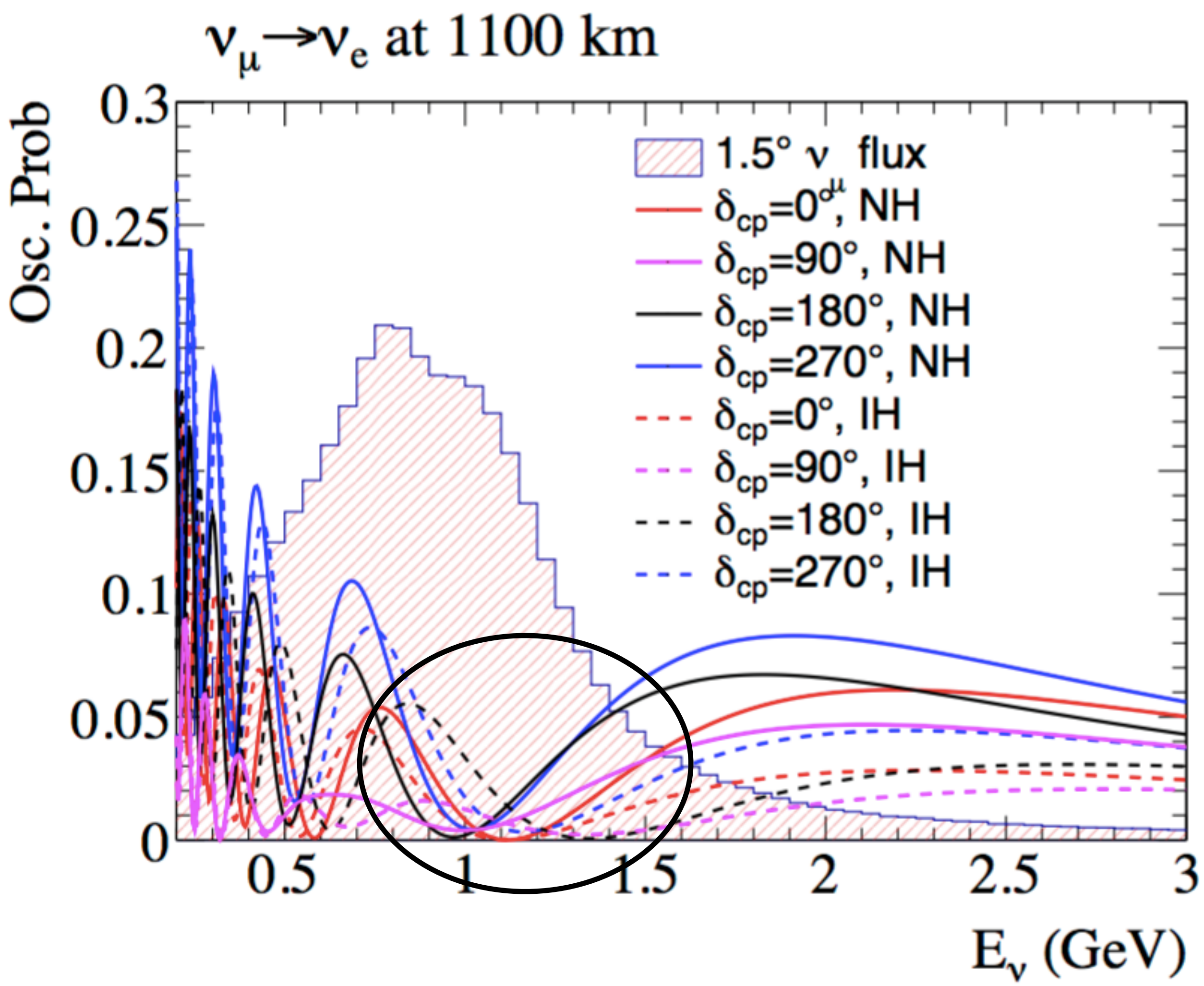
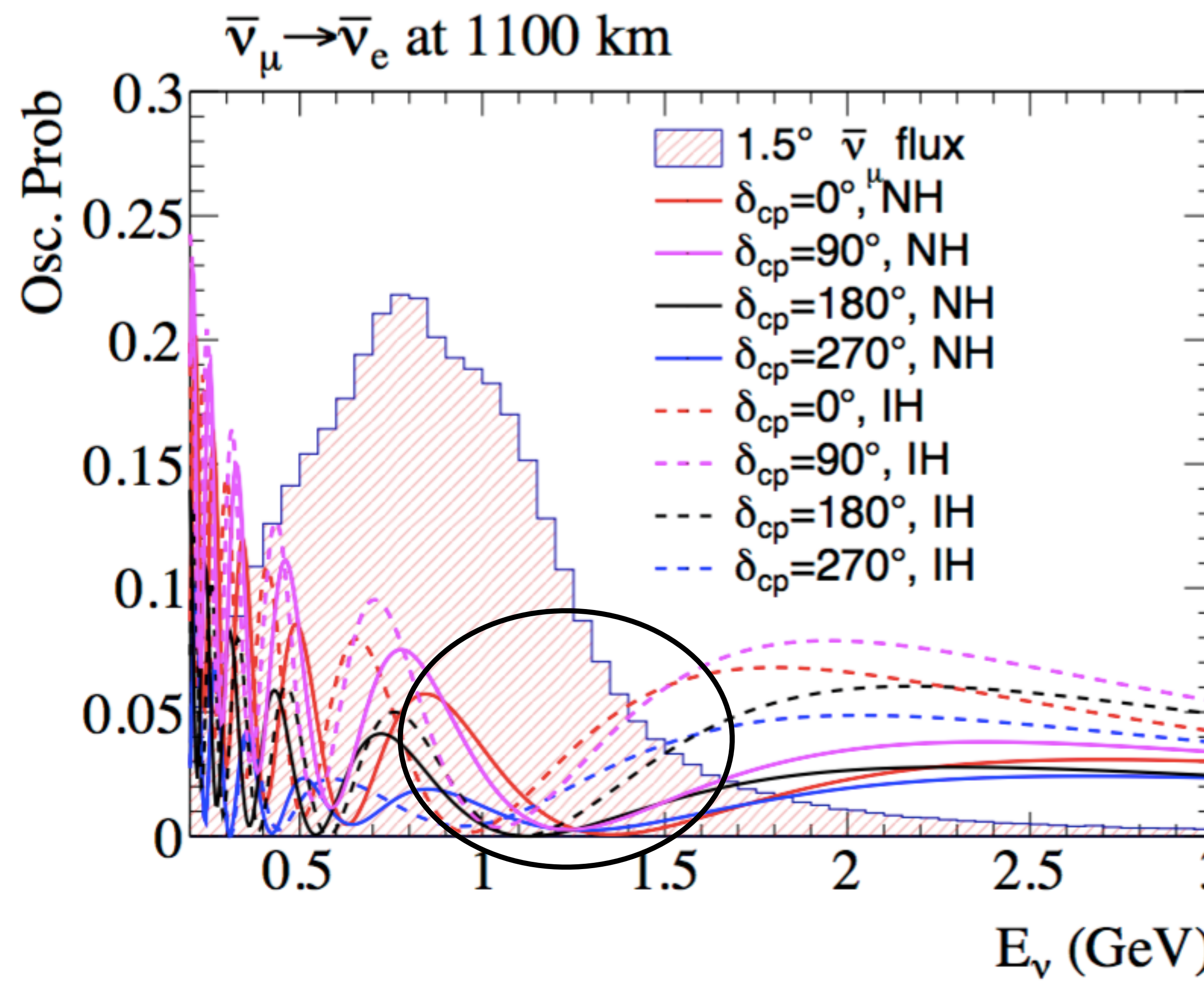
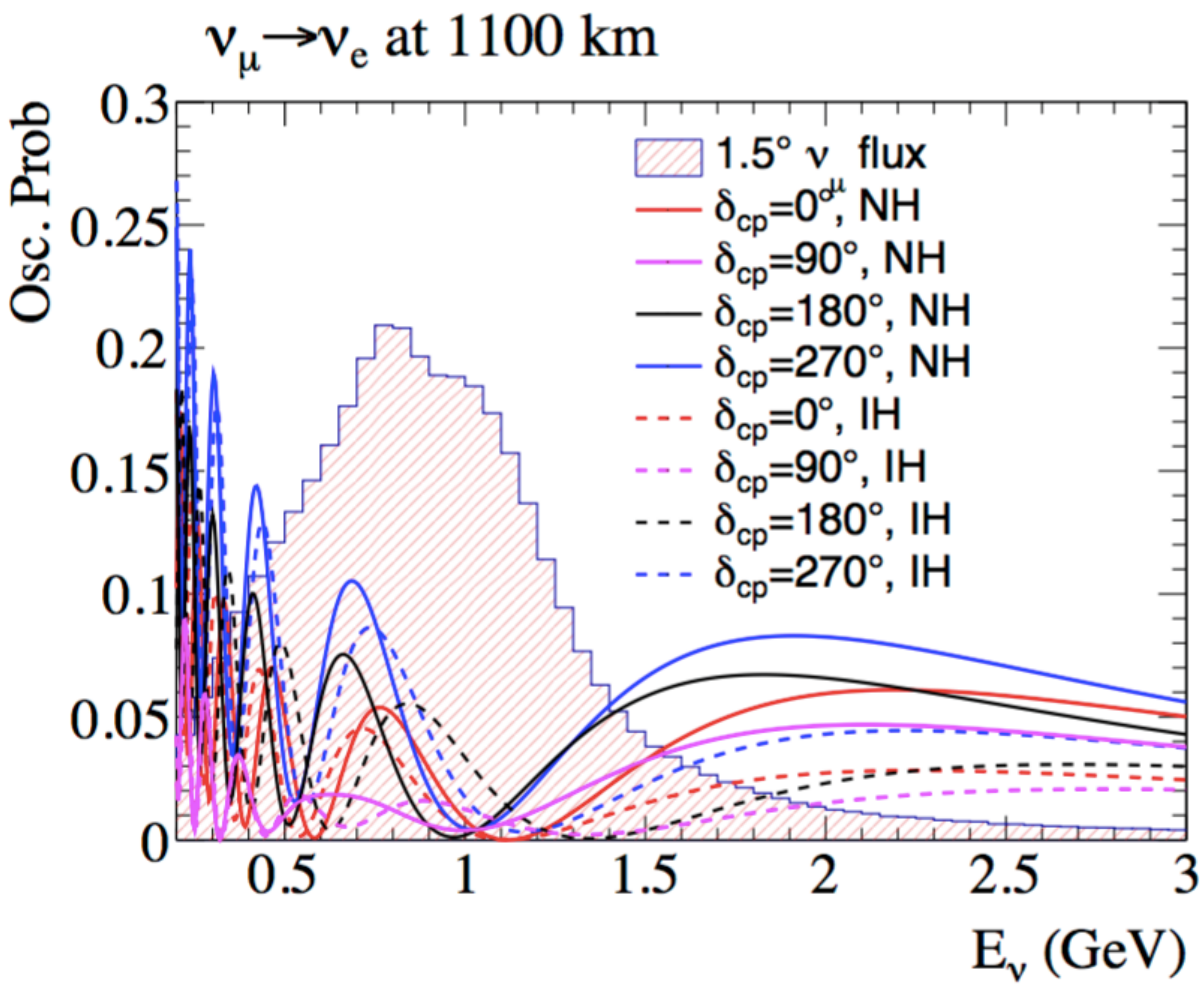


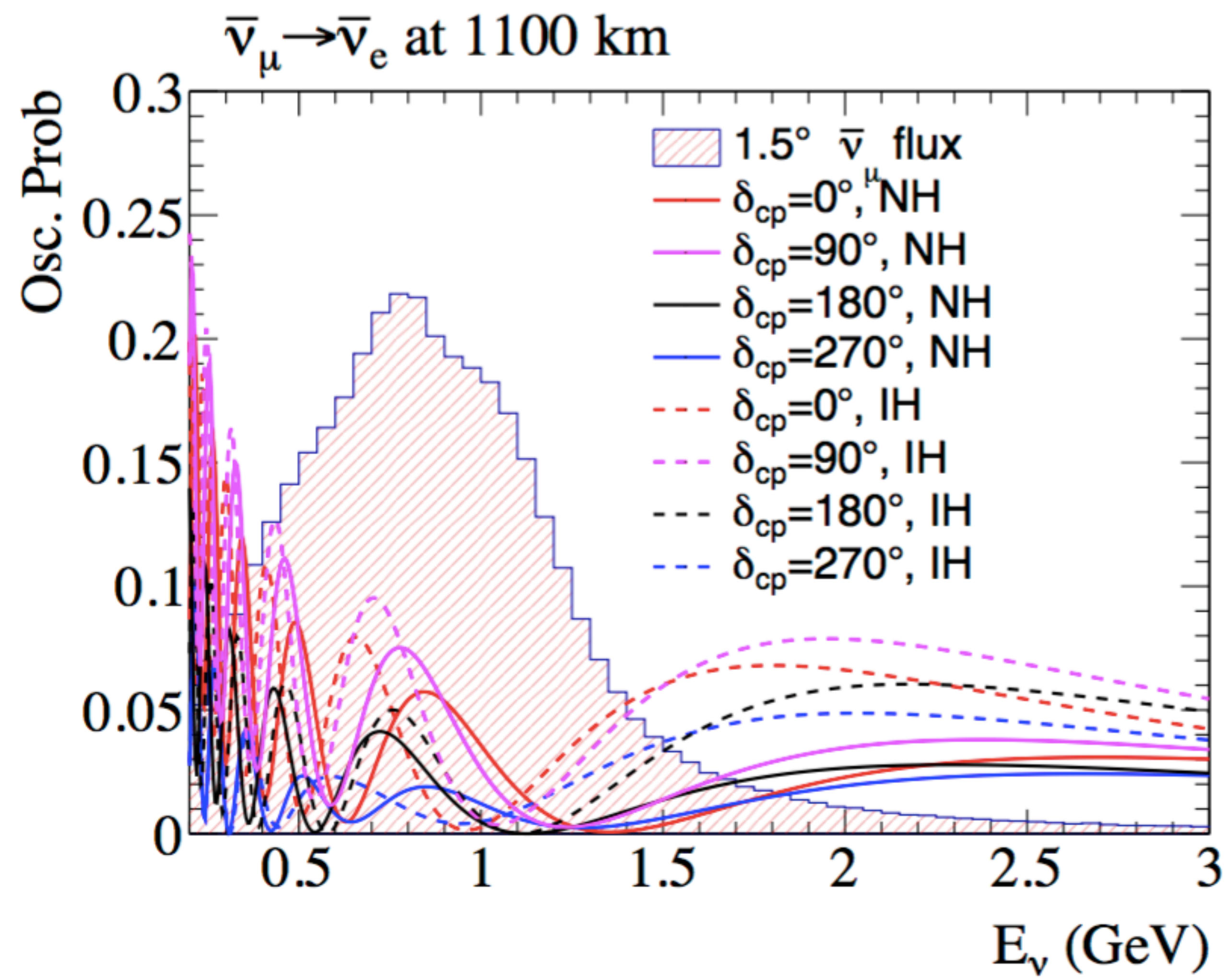


- Region between first and second oscillation maximum: sensitive to cosδ term

LONG BASELINE PHYSICS AT THE KOREAN DETECTOR

- Consider Mt. Bisul site at 1.3° as primary option





LONG BASELINE PHYSICS AT THE KOREAN DETECTOR

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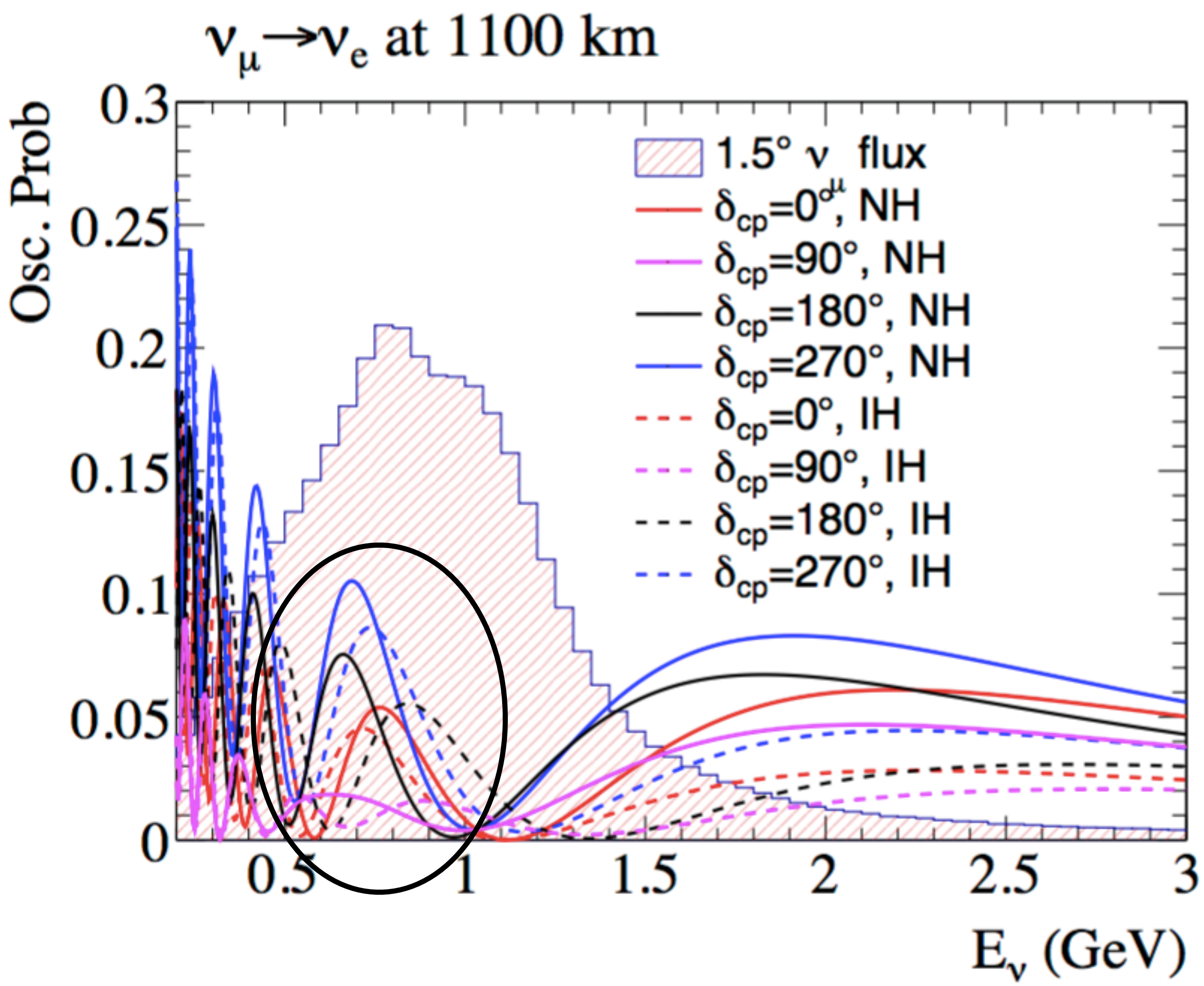
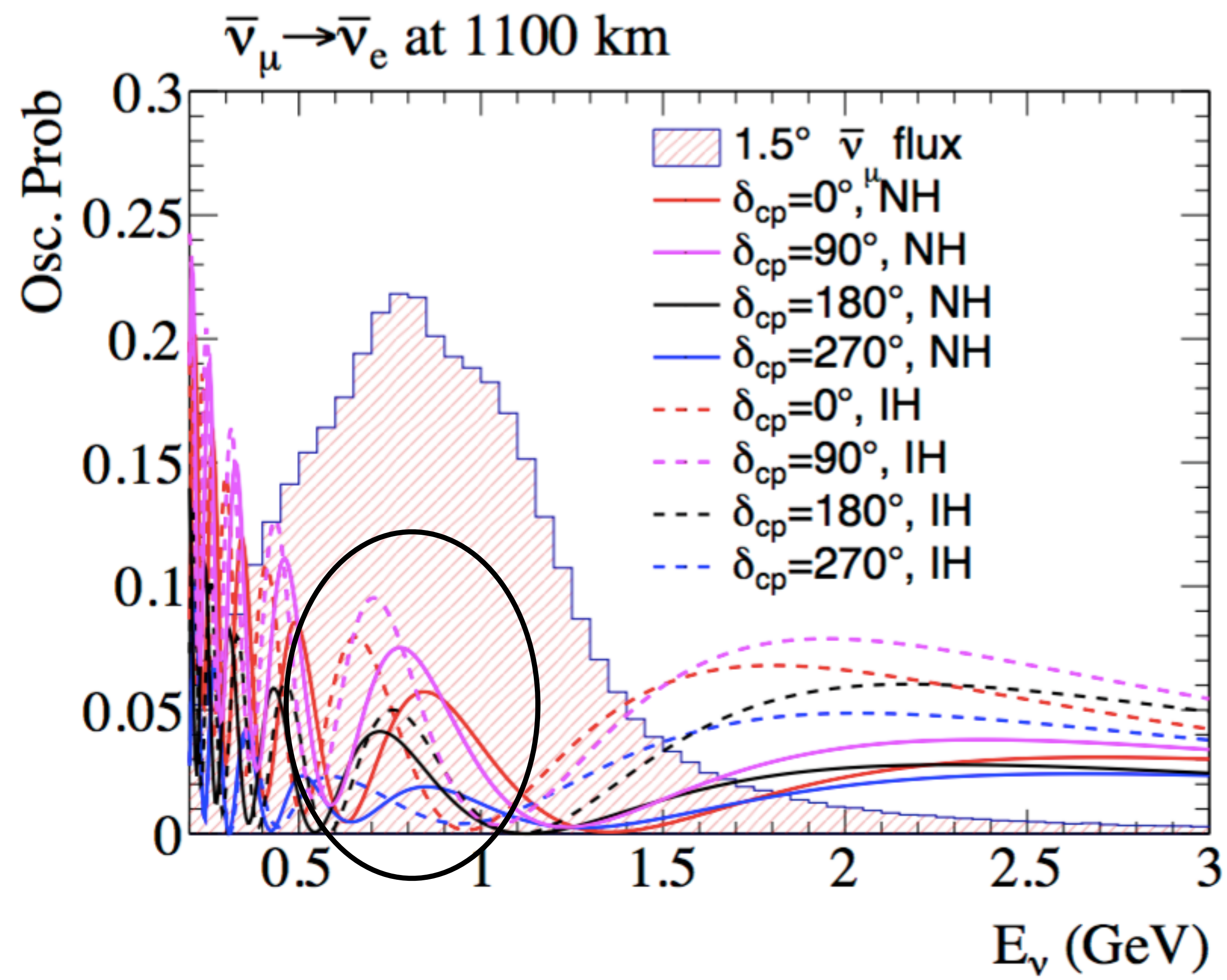
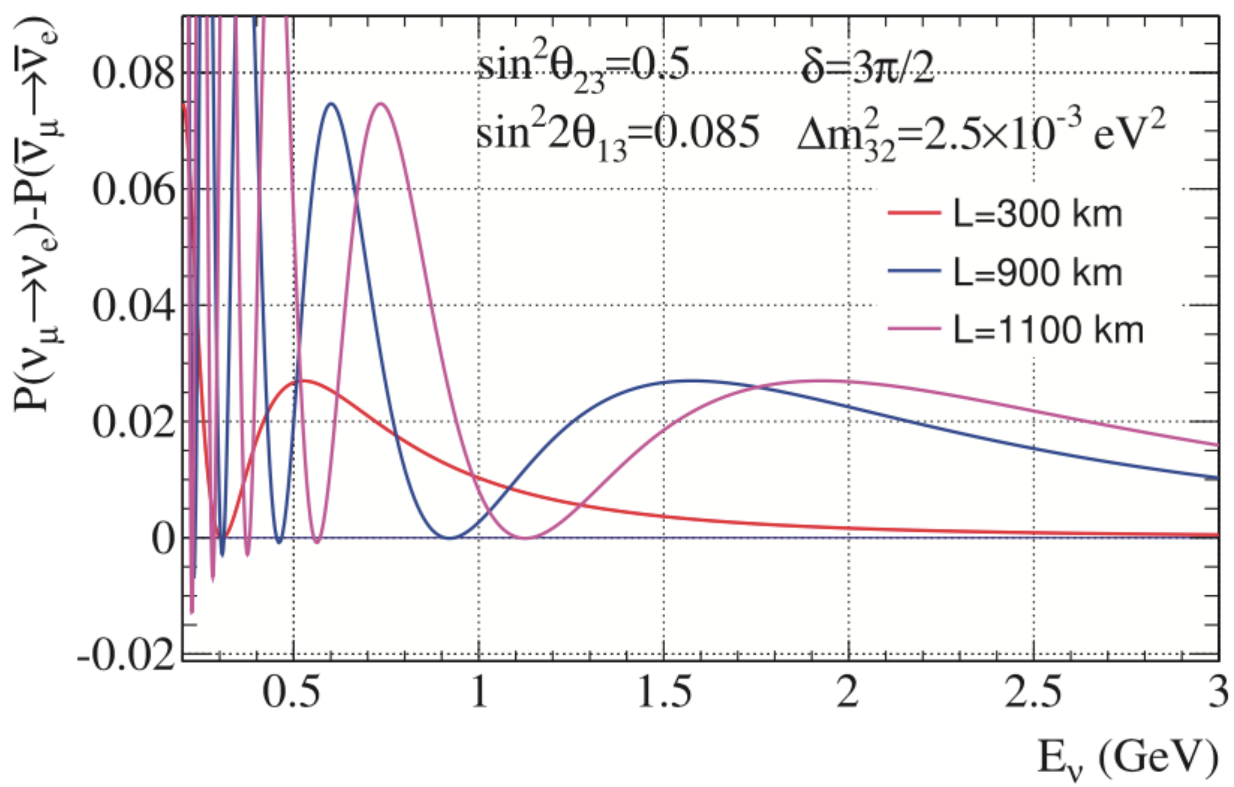




- Second oscillation maximum: sensitive to sinδ term

ADVANTAGE 1: LARGER CP EFFECT

- For a fixed energy, the CP effect is three times larger at the second oscillation maximum (in vacuum)



- Accounting for actual baseline, spectrum and matter effects:
  - Maximum CP asymmetry at Japanese detector: 20%
  - Maximum CP asymmetry at Korean detector: 37%-44%
- Since the CP effect is twice as large, can survive with twice larger systematic normalization errors in the Korean detector
- Rate of accumulating statistics is lower due to the longer baseline

KOREAN DETECTOR SENSITIVITIES – CP VIOLATION

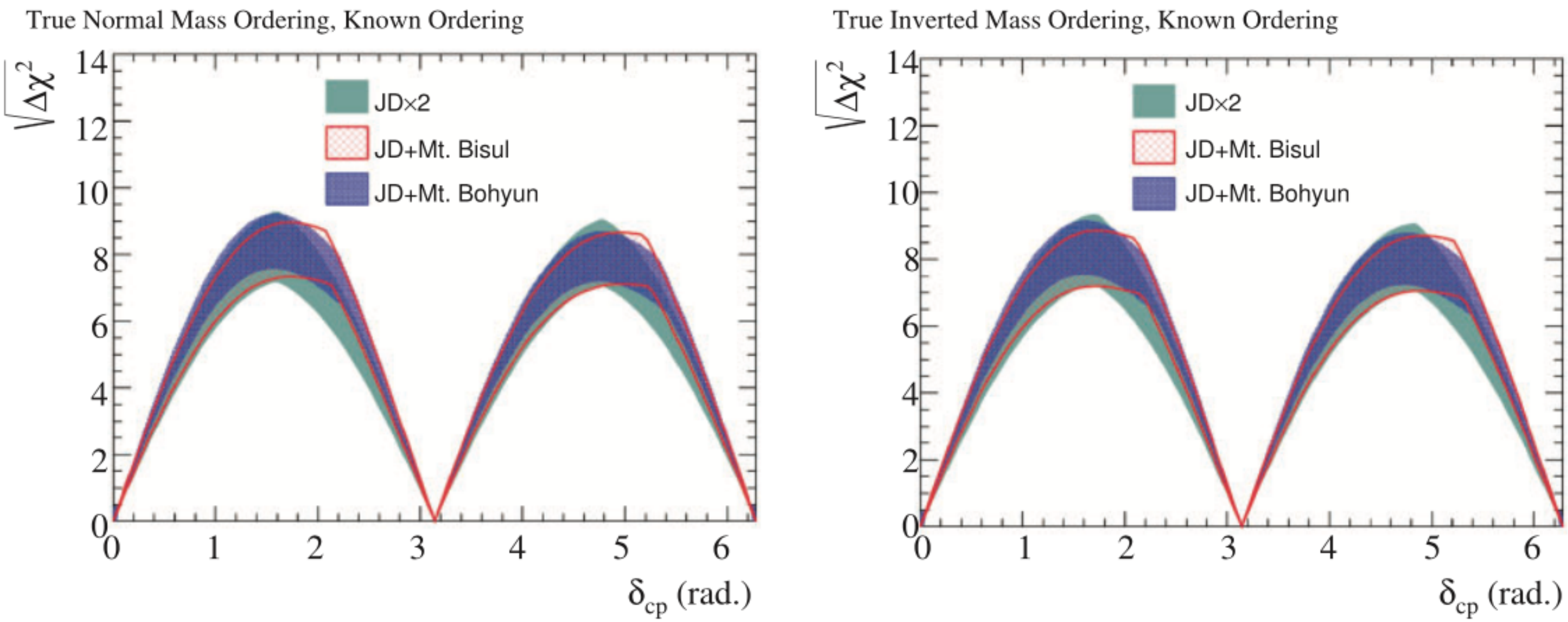
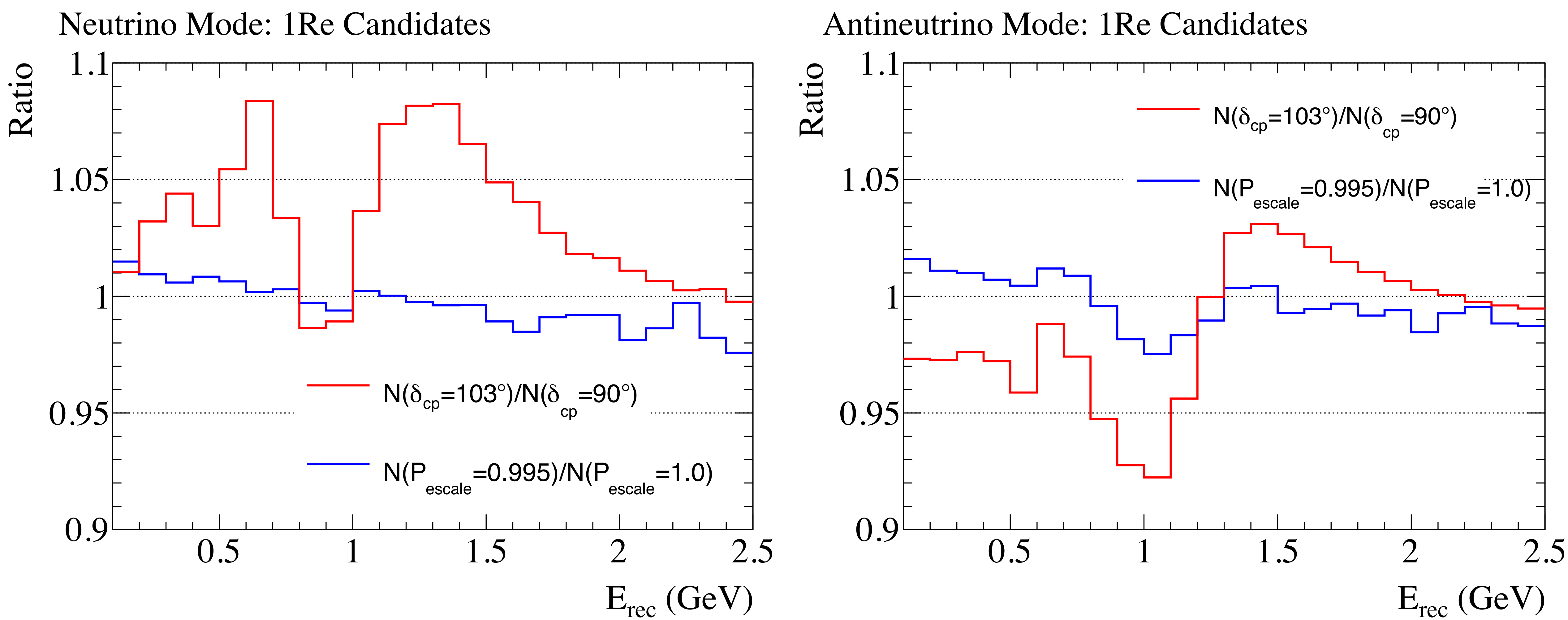


Table 7. The fraction of true δ_{CP} values for which CP violation can be discovered at 3σ or 5σ.

	True NH, known		True IH, known		True NH, unknown		True IH, unknown	
	3σ	5σ	3σ	5σ	3σ	5σ	3σ	5σ
JD×1	0.70	0.47	0.71	0.48	0.43	0.23	0.41	0.24
JD×2	0.74	0.55	0.74	0.55	0.52	0.27	0.50	0.28
JD+KD at 2.5°	0.76	0.58	0.76	0.59	0.76	0.48	0.72	0.30
JD+KD at 2.0°	0.78	0.61	0.78	0.61	0.77	0.55	0.79	0.51
JD+KD at 1.5°	0.77	0.59	0.77	0.59	0.77	0.59	0.77	0.59

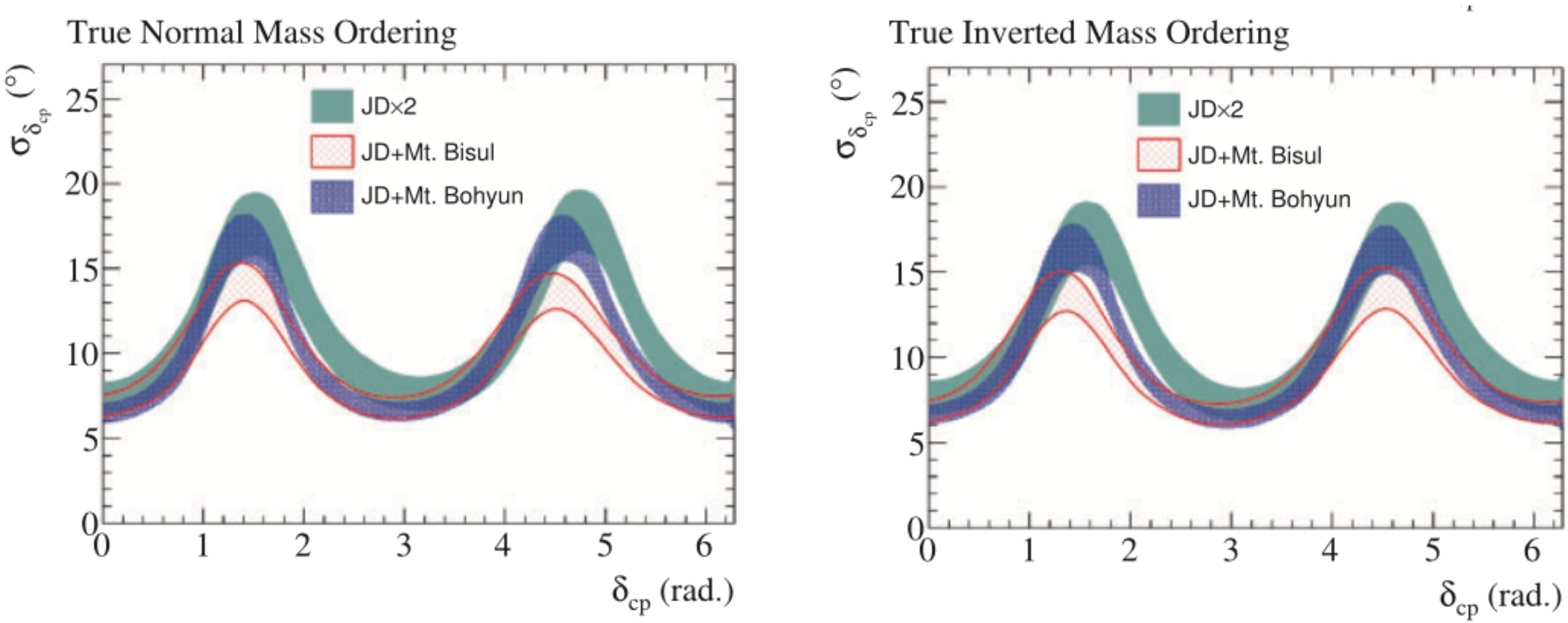
- The Korean detector improves the CP violation discovery sensitivity relative to 1 or 2 detectors in Japan

ADVANTAGE 2: cosδ SENSITIVE REGION



- By probing the region between the first and second oscillation maximum, the degeneracy between energy scale and the δ_{cp} variation is removed
- Effect of $\cos\delta_{cp}$ interference term is largest between oscillation maxima

KOREAN DETECTOR SENSITIVITIES – CP PRECISION



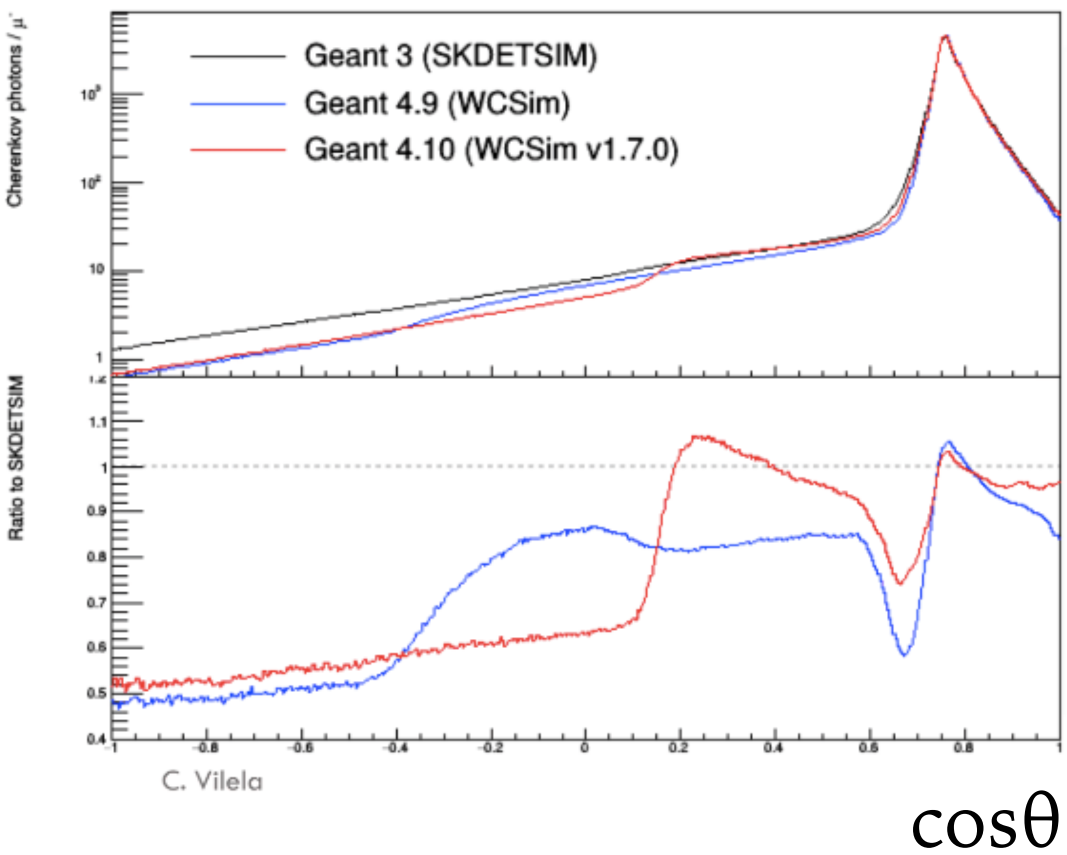
- With the Mt. Bisul location, the phase precision near maximal CP violation values is improved to better than 15 degrees
- Longer running time or increased beam power can lead to further improvement of the precision

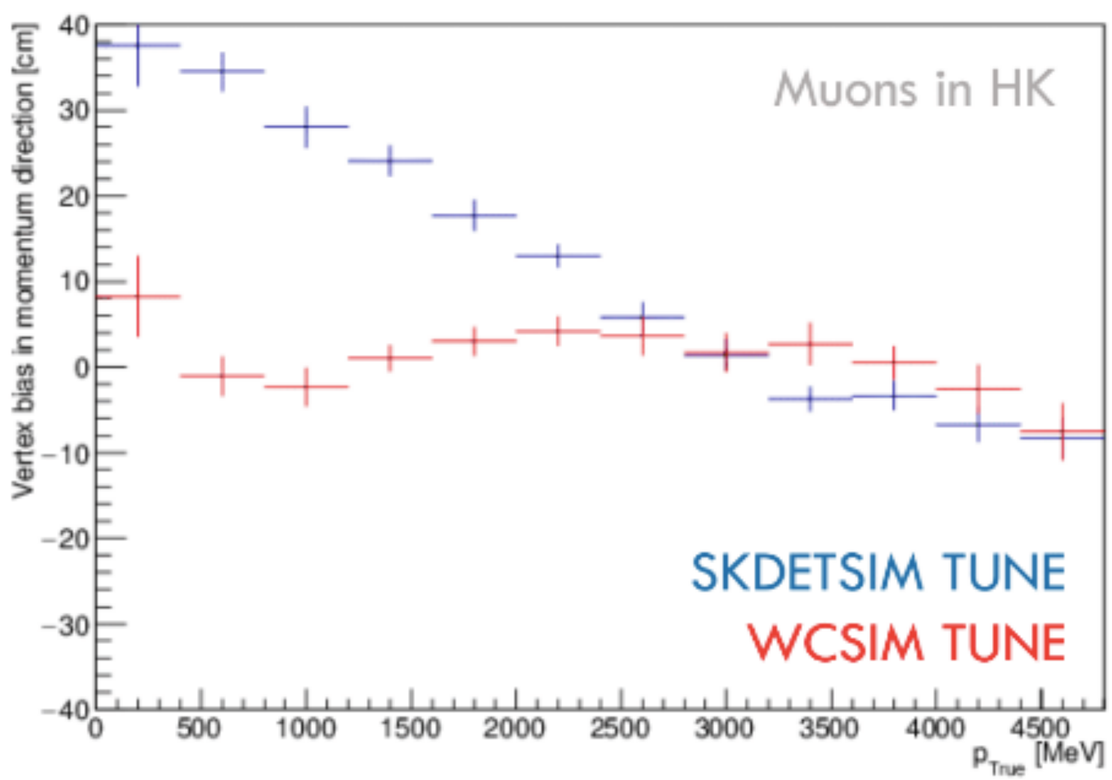
ANALYSIS SOFTWARE

ANALYSIS SOFTWARE

- Analysis software tools used in Hyper-K:
  - **JNUBEAM:** simulates neutrino production. Should be migrated from GEANT3 to GEANT4
  - **NEUT:** generates neutrino interactions in the detectors
  - **WCSim:** simulate the detector response for water Cherenkov detectors
  - **fiTQun:** likelihood based event reconstruction for high energy events
  - **BONSAI:** time residual vertex likelihood fit for low energy events

WCSIM PHYSICS





- We can benefit from work on the physics models in WCSim
- Even Cherenkov photons from muons show differences in different simulation code
  - Impact on reconstructed quantities (vertex) can be significant
- May be resolved with literature review, or may need new measurements
  - Possible measurement in water Cherenkov test experiment

FITQUN RECONSTRUCTION

FiTQun is originally developed for T2K experiment, and is based on maximum likelihood method.

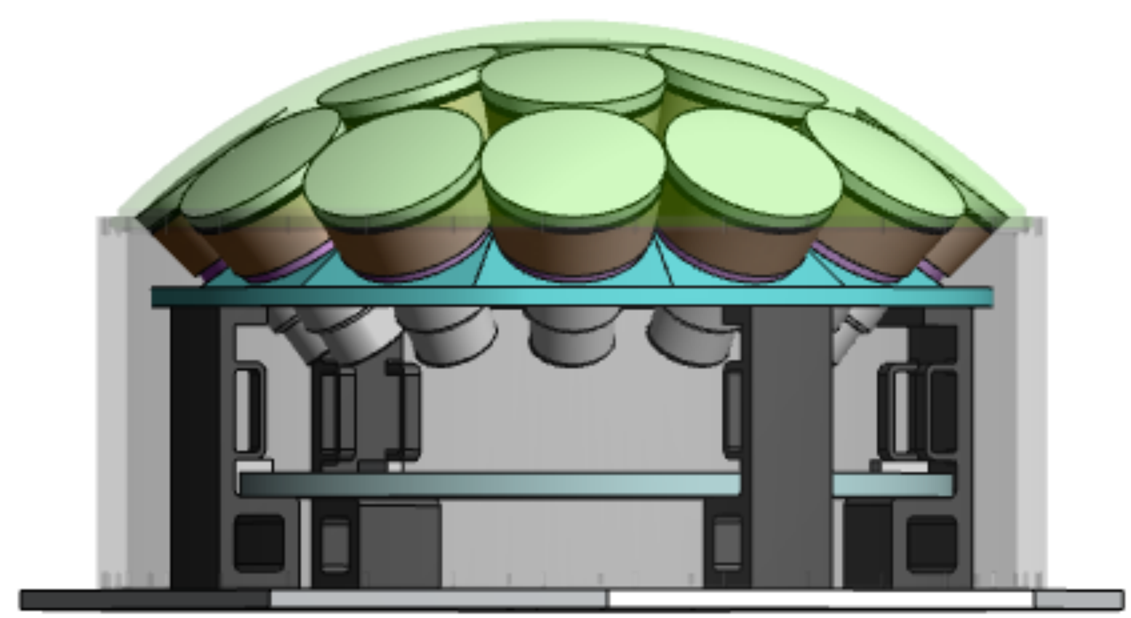
PMT unhit probability — PMT hit probability — PMT charge pdf — PMT timing pdf

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

$\mathbf{x} = (\boldsymbol{x}, t, p, \theta, \phi)$: Particle hypothesis

$\mu = \mu^{\text{dir}} + \mu^{\text{sct}}$: Poisson mean of predicted charge detected by each PMT, which is also a function of $\mathbf{x}$

- Current optimization of fiTQun to handle multi-PMTs is ongoing
  - Code modification to account for the angular response and orientation of each 3-inch PMT in the module



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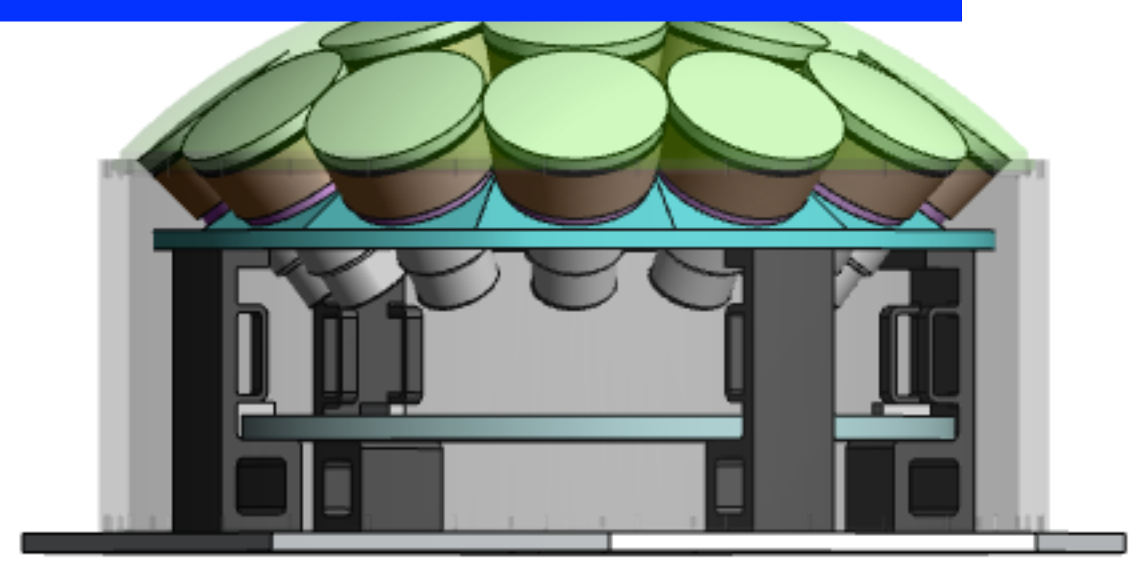
Further improvements to the high energy reconstruction?

Build correlations between PMTs into the charge PDF

Machine learning approaches to improved event selection and particle identification

- Current optimization of fiTQun to handle multi-PMTs is ongoing
  - Code modification to account for the angular response and orientation of each 3-inch PMT in the module

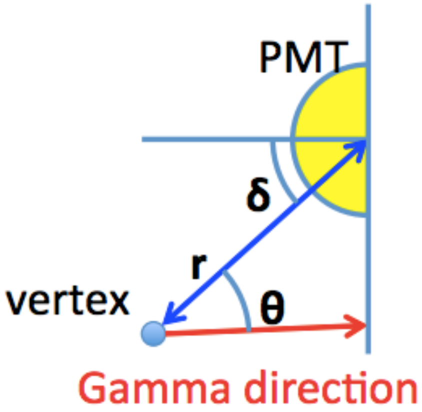


LOW ENERGY RECONSTRUCTION IMPROVEMENTS

- Significant work is ongoing to develop low energy tagging of 2.2 MeV from neutron captures

- Likelihoods that include the angular acceptance of the PMT are being used

$$L_{\text{signal}} = \sum_i^{\text{all hits}} \log\left(\frac{\frac{\epsilon(\cos\delta_i)}{r_i^2} e^{-\frac{r_i}{\lambda}}}{\sum_j^{\text{all PMT}} \left(\frac{\epsilon(\cos\delta_j)}{r_j^2} e^{-\frac{r_j}{\lambda}}\right)}\right), \quad L_{\text{dark}} = \sum_i^{\text{all hits}} \log\left(\frac{1}{N_{\text{PMT}}}\right)$$



- PMT angular acceptance likelihood, opening angle, neutron capture time, number of hits in 10 ns window and goodness of vertex fit combined in TMVA

- Tagging efficiency for 8.4 kHz dark noise is improved from 42.5% to 52.9%

- Addition of multi-PMTs for neutron tagging is open topic

SUMMARY

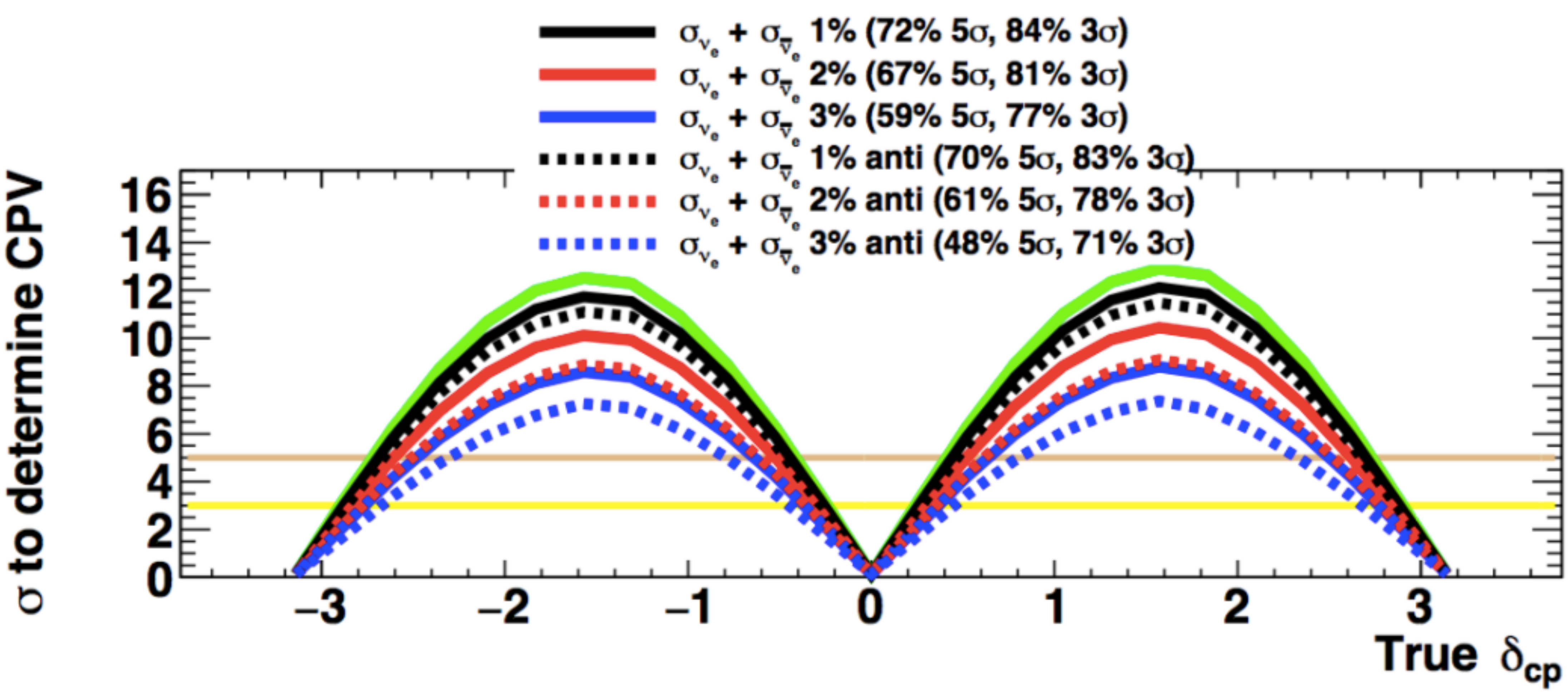
- There are many areas to contribute to Hyper-K to improve physics results including:
  - Development of near and intermediate detectors to control systematic errors
    - Intermediate water Cherenkov detector
    - Off-axis magnetized detector
  - Development of calibration systems at near and far detectors
    - Chance to test calibration systems in test beam experiment
  - Development of new analysis software tools
    - Improvement of simulation physics models and upgrades to modern tools
    - Improving reconstruction by adding new PMT information (angular acceptance) and developing new techniques (multi-variate analysis and machine learning)

THANK YOU

FURTHER IMPROVEMENTS TO HIGH ENERGY RECONSTRUCTION?

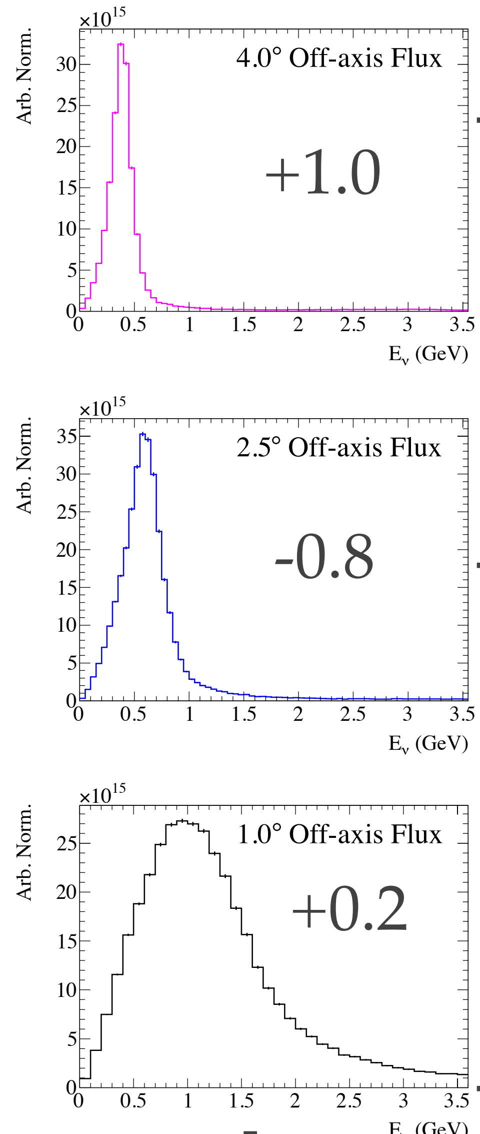
- The charge PDF used in fiTQun is an average over many events
  - Only see the average effects of lepton and photon scattering processes?
  - Does this limit ability to separate electron and photons or other aspect of particle ID performance?
- To account for structure within the ring due to stochastic scattering processes two approaches may be considered
  - Calculate correlations between PMTs when calculating the charge PDF
  - Apply machine learning methods that train on collections of single electron, muon, photon, pion, etc. events

NORMALIZATION ERROR FOR THE CPV MEASUREMENT

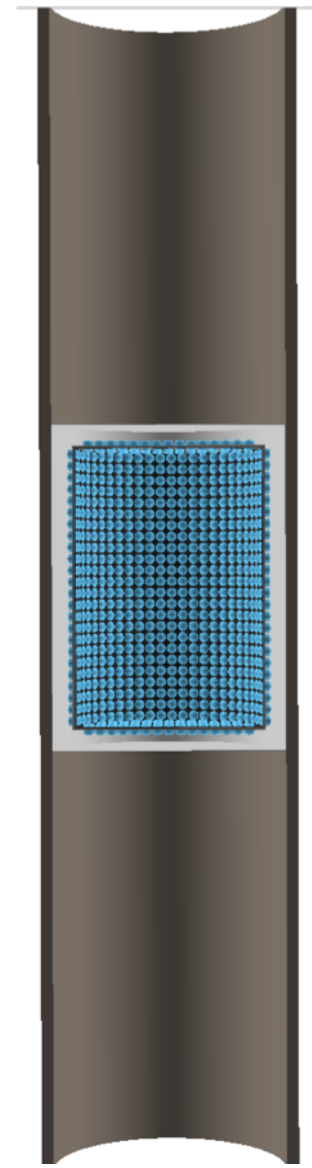


- Aiming to achieve 3% error or better on the relative rate of electron neutrino and electron (anti)neutrino rates
- Total systematic error is the quadrature sum of all systematic errors
  - Should aim to keep each individual error source below 1% if possible
- Three examples on the following slides

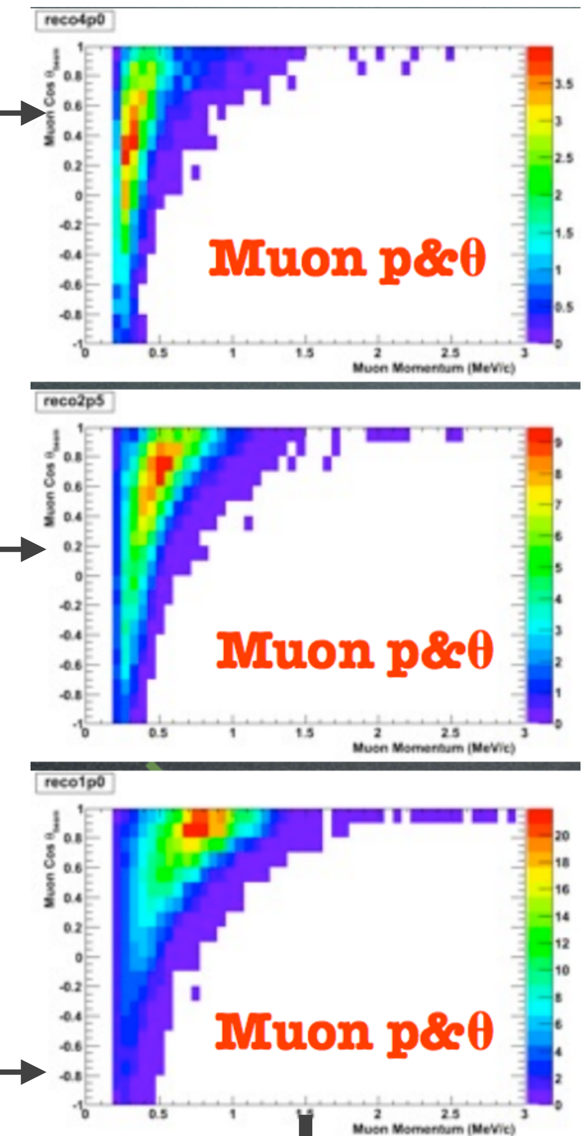
OFF-AXIS MEASUREMENTS IN IWCD

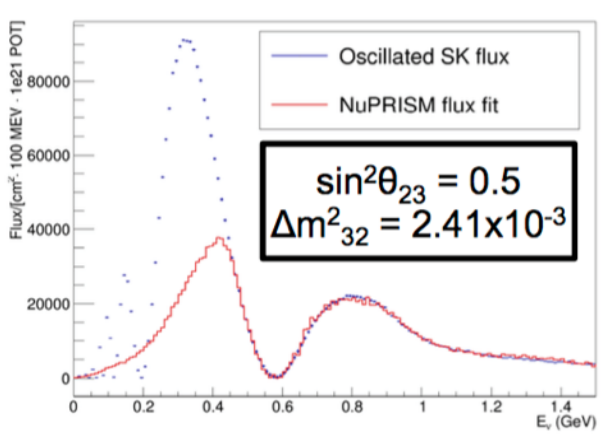


Spectra at at each off-axis bin

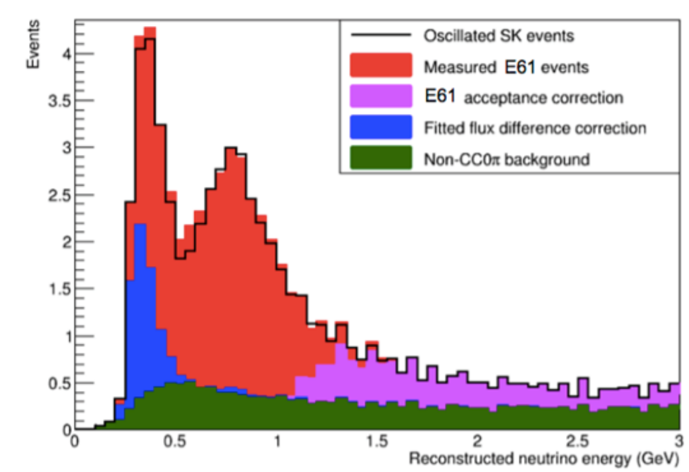


Observed muon kinematic distributions





Subtract off flux peak region to get oscillated spectrum



FURTHER COMMENTS ON SYSTEMATIC ERRORS

- In addition to near/intermediate detector measurements, calibration of the far detector is critical
- More precise and extensive measurements of hadron production will help extract the critical neutrino interaction information from the data observed in near and intermediate detectors
- Modeling of the atmospheric neutrino backgrounds are important for nucleon decay measurements
  - These should be measured in the near and intermediate detectors where possible
- Neutrino interaction measurements in the near and intermediate detectors an also constrain systematic errors relevant for the atmospheric neutrino measurements

NEUTRON DETECTION – NUCLEON DECAY

- Neutron detection plays a key role in a number of Hyper-K physics analyses
- In the baseline design, the neutrons are detected by the captures on H that produce a 2.2 MeV gamma
  - Gd loading in Hyper-K can increase the neutron detection efficiency

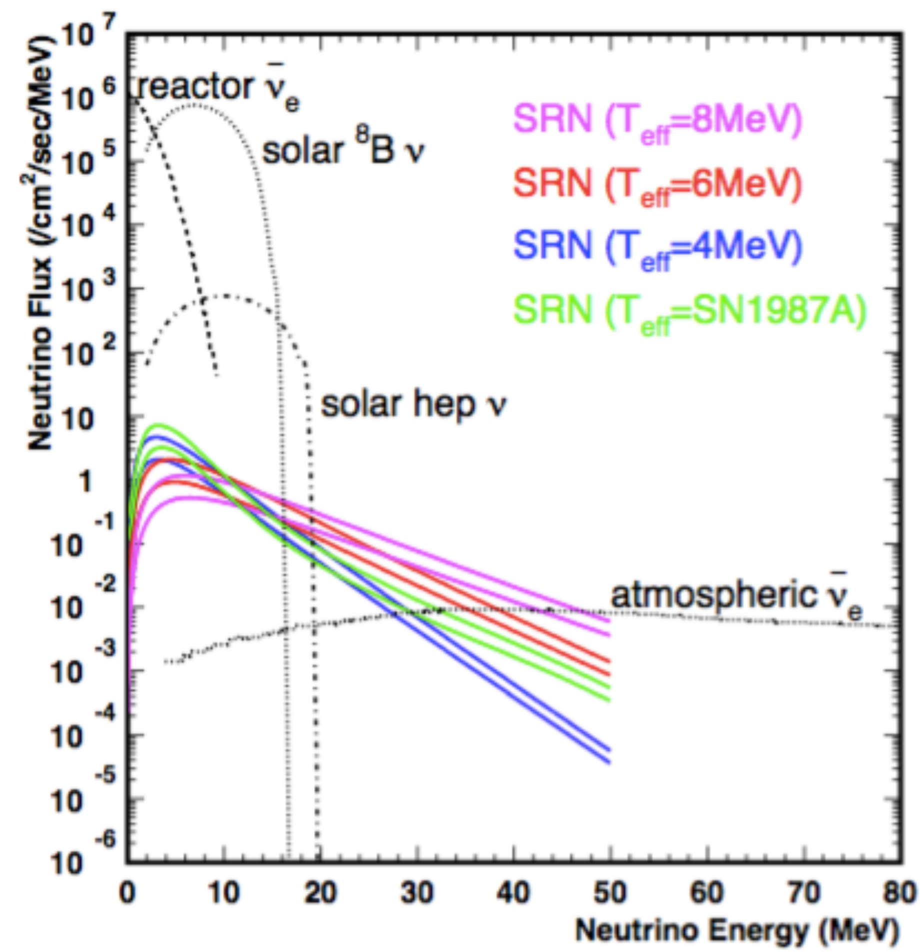
Proton decay:

- In the $p \rightarrow e^+ \pi^0$ channel, about 3 atmospheric neutrino background events after 10 years
- According to simulation, 80% of atmospheric background interactions eject at least one neutron
- 70% neutron tagging efficiency leads to 70% reduction of atmospheric background
- Measurements of the (anti)neutrino background and neutron production are critical for estimating the background
- Analysis improvements that improve the neutron tagging efficiency can have a large impact

NEUTRON DETECTION – SUPERNOVA NEUTRINOS

Supernova relic neutrino detection

- Detection of the relic supernova neutrino background
- Detection of the anti-electron neutrino through the IBD channel
- IBD channel can tagged with detection of neutron, removing solar background and lowering threshold



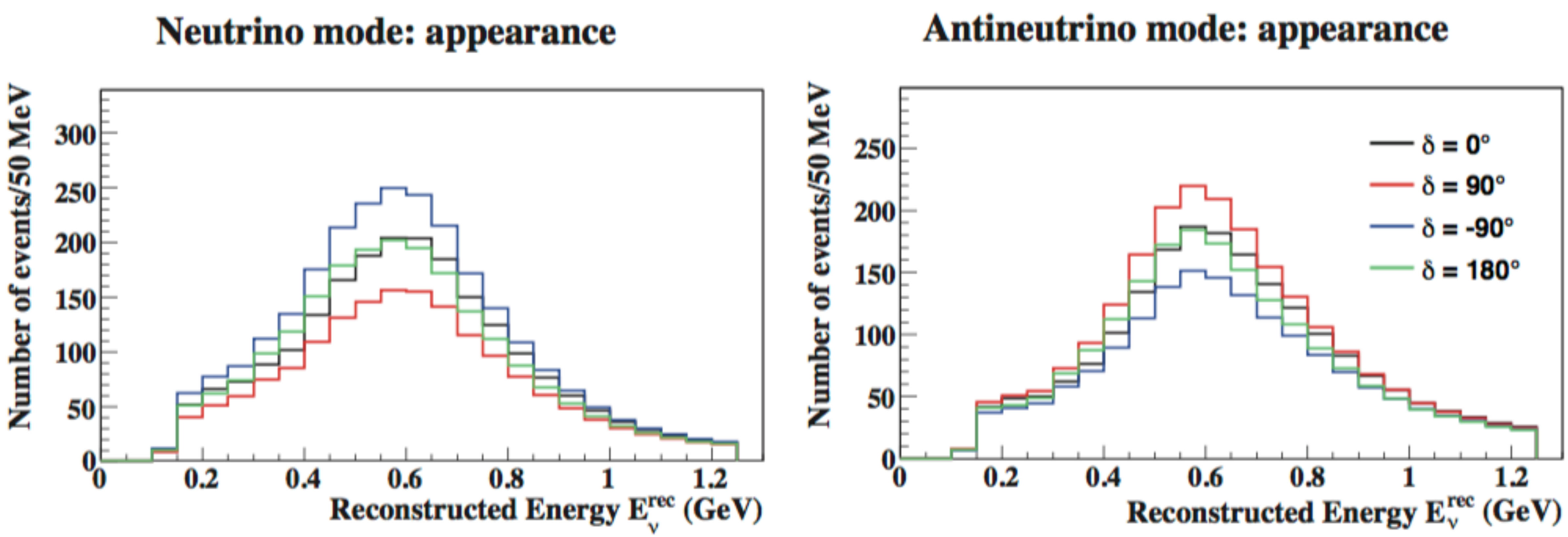
Supernova burst neutrino detection

- Pointing accuracy of supernova neutrino detection is important to direct multi-messenger observation of the supernova
- Directional information comes from neutrino-electron scattering events
  - They sit on a large background of IBD events
- If IBD events are removed with neutron tagging, direction accuracy can be improved

HYPER-K PHYSICS - CP VIOLATION

- Search for an asymmetry in the muon (anti)neutrino to electron (anti)neutrino oscillation probabilities

$$P_{\mu\to e}=\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\mp\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\sin\delta_{CP}+\ldots$$



- With about 2000 candidates in each channel, the statistical error on the relative neutrino/antineutrino rate is about 3% - systematic errors should be smaller