Hyper-Kamiokande

THE UNIVERSITY OF WINNIPEG

TRIUMF

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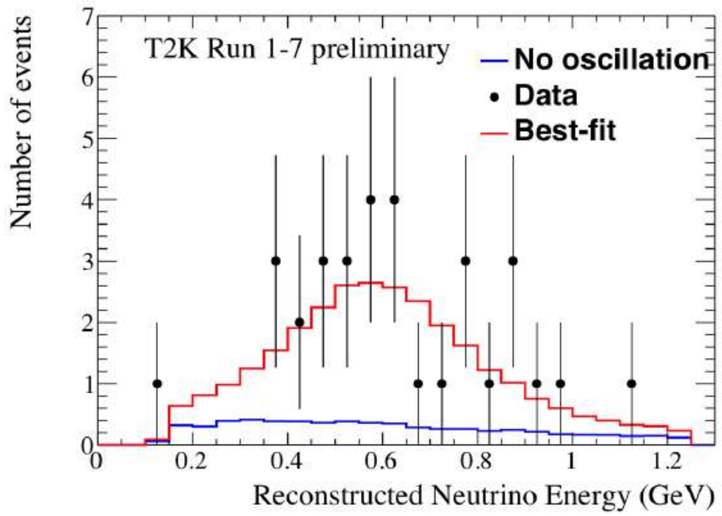
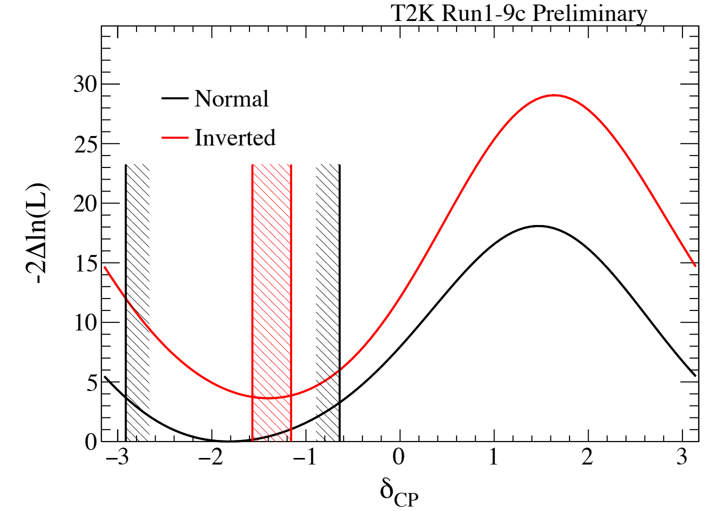
Physics potential of Hyper-Kamiokande for neutrino oscillation measurements

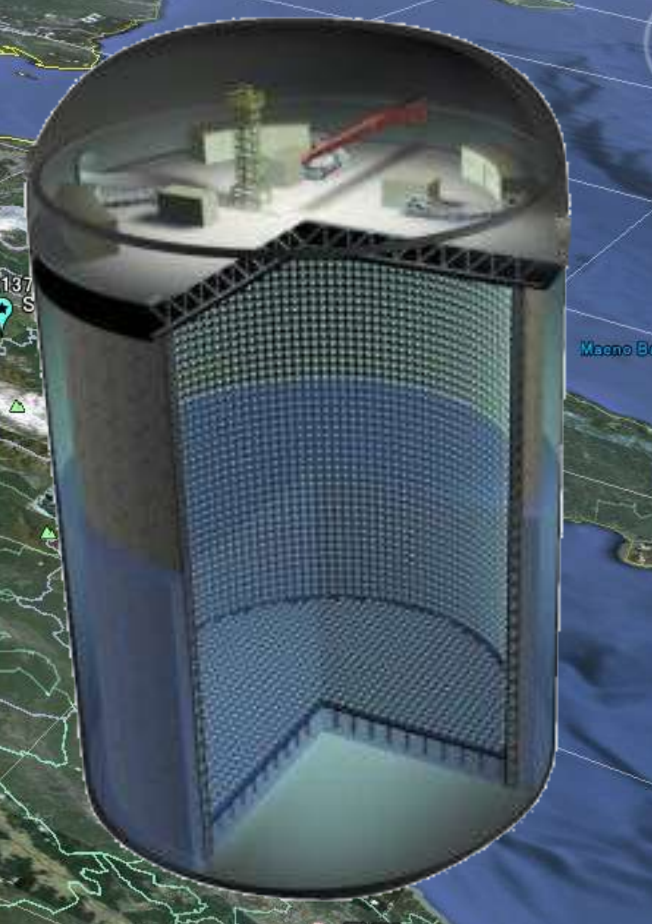
TOKAI TO KAMIOKA (T2K) EXPERIMENT

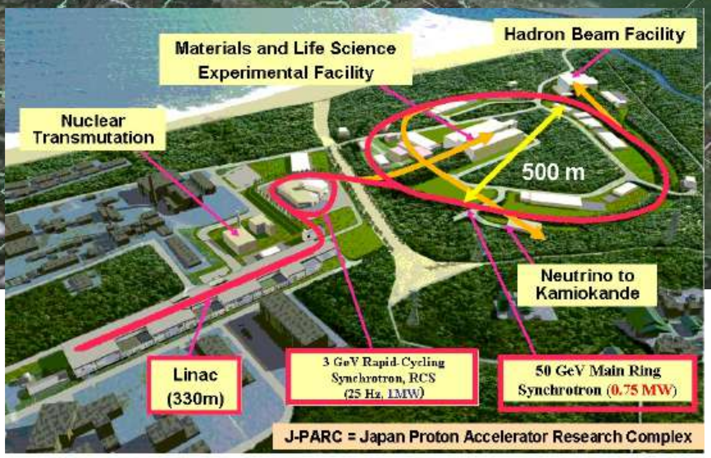
First observation of ν_e appearance



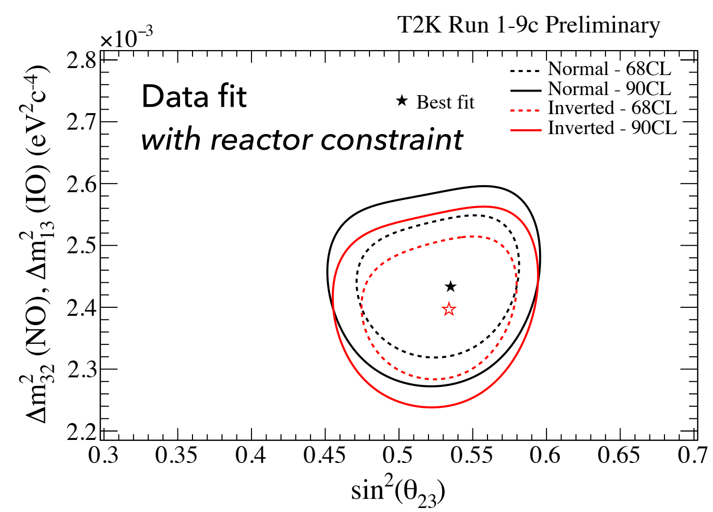
Exclusion of CP conservation in lepton sector at 2σ







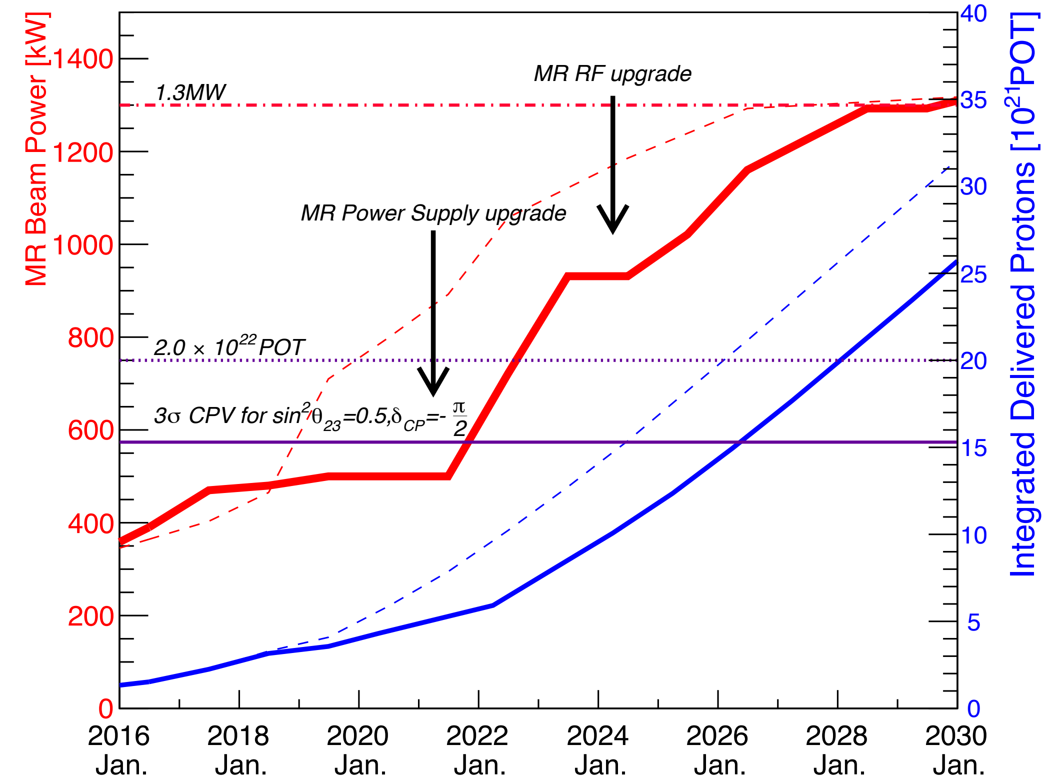
World-leading measurements of $\sin^2\theta_{23}$ and Δm^2_{23}.

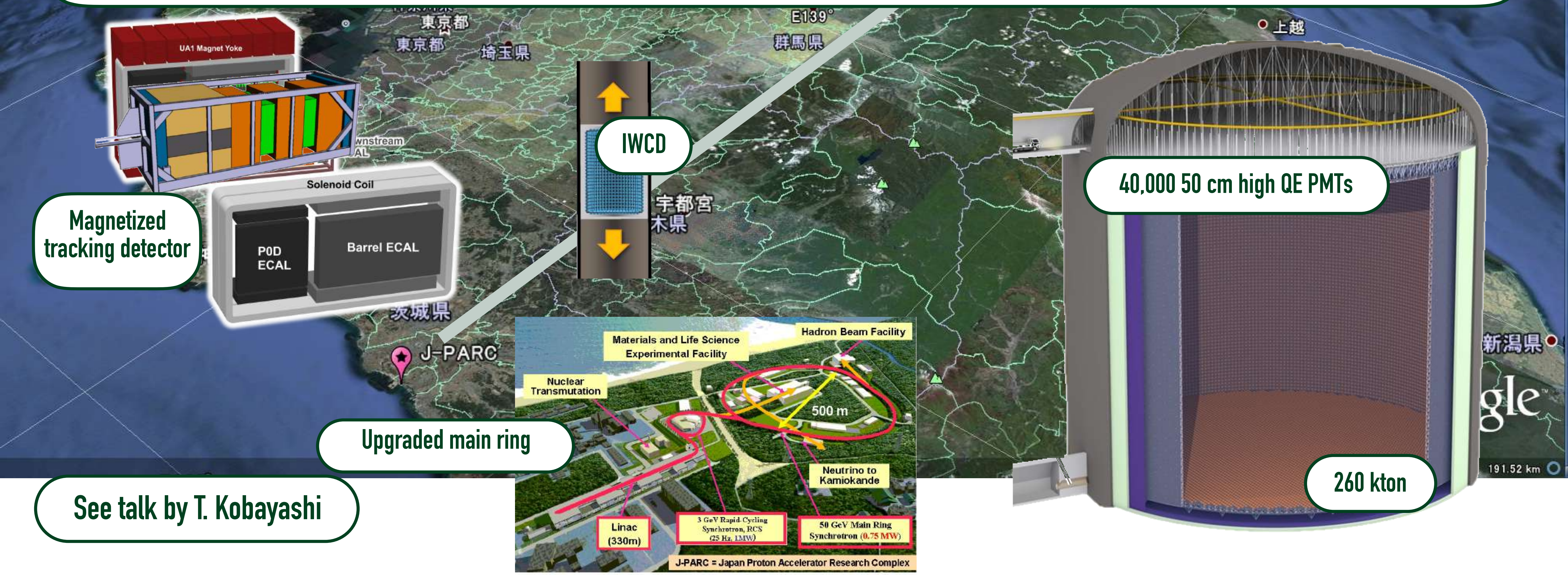


See talk by F. Bench

HYPER-KAMIOKANDE PROJECT

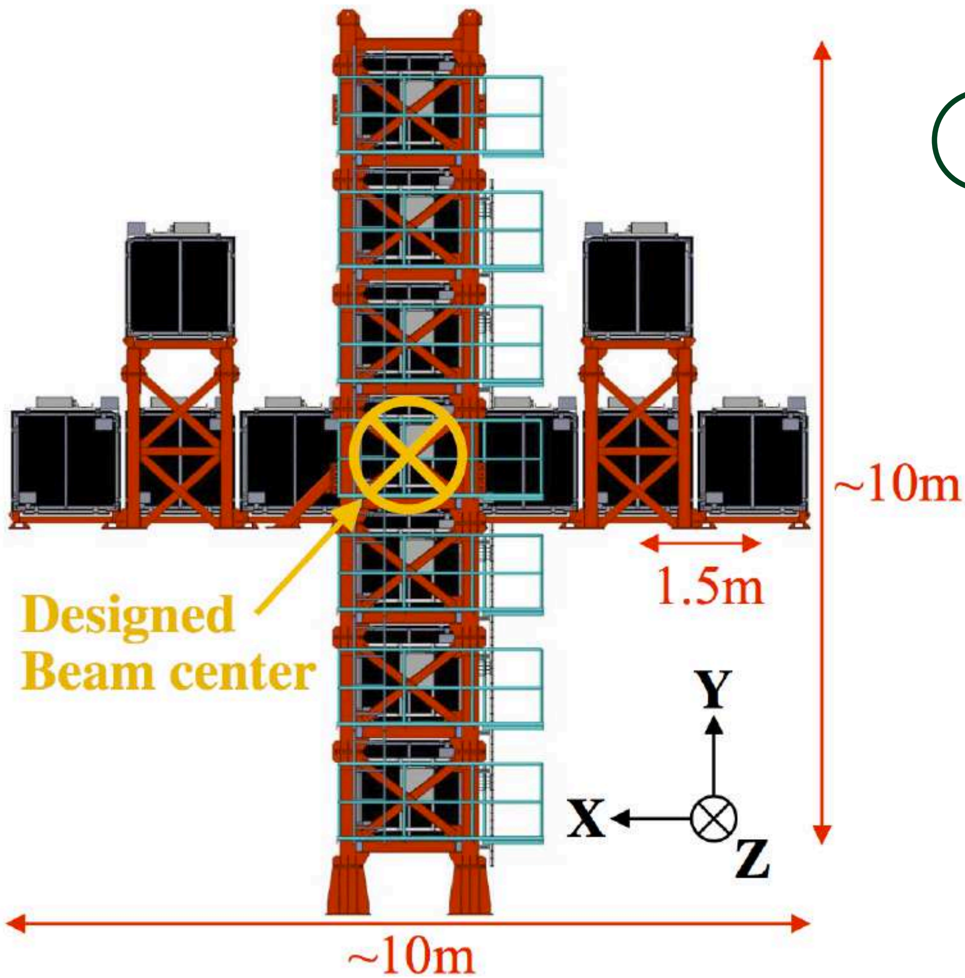
- Next generation water-Cherenkov detector with extensive physics program.
- Hyper-K 1st detector construction seed funding secured - starts in April 2020!
  - Potential for a second tank in Japan or Korea.
- Hyper-K will have an 8 times larger fiducial mass than Super-K.
- Beam will be upgraded from ~500 kW to 1.3 MW.
- Will accumulate statistics 20x faster than T2K does.
- Improvements to near detectors integral to mitigating the effect of neutrino interaction uncertainties (ND upgrade and IWCD).





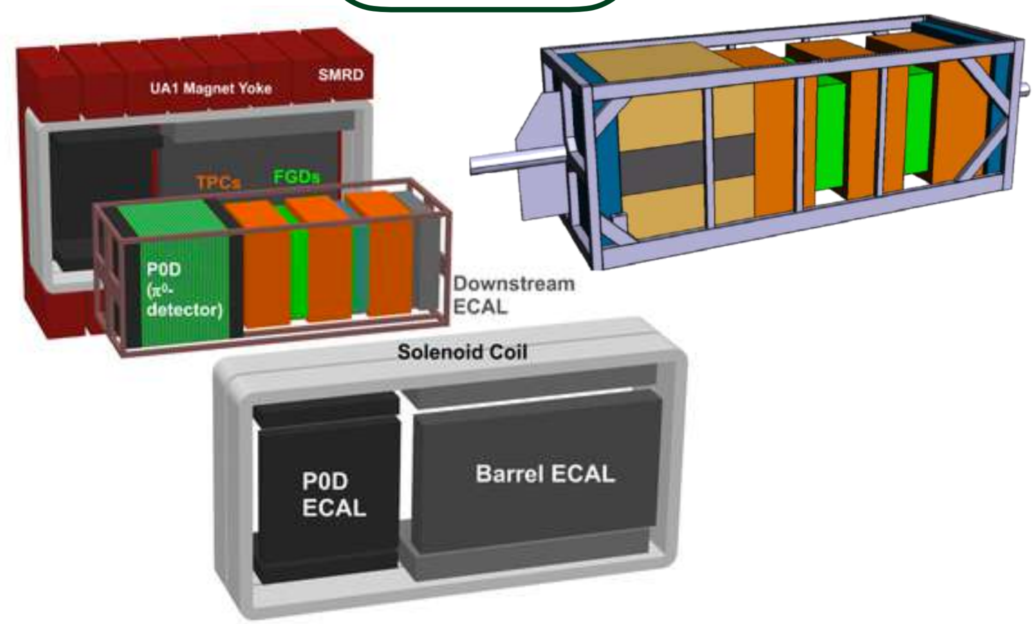
See talk by T. Kobayashi

NEAR/INTERMEDIATE DETECTOR SUITE

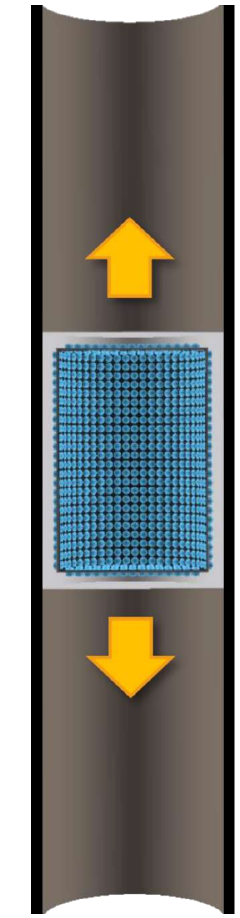


On-axis detector (INGRID)

ND280 → ND280 upgrade for T2K → ?? for HK



Off-axis magnetized tracker

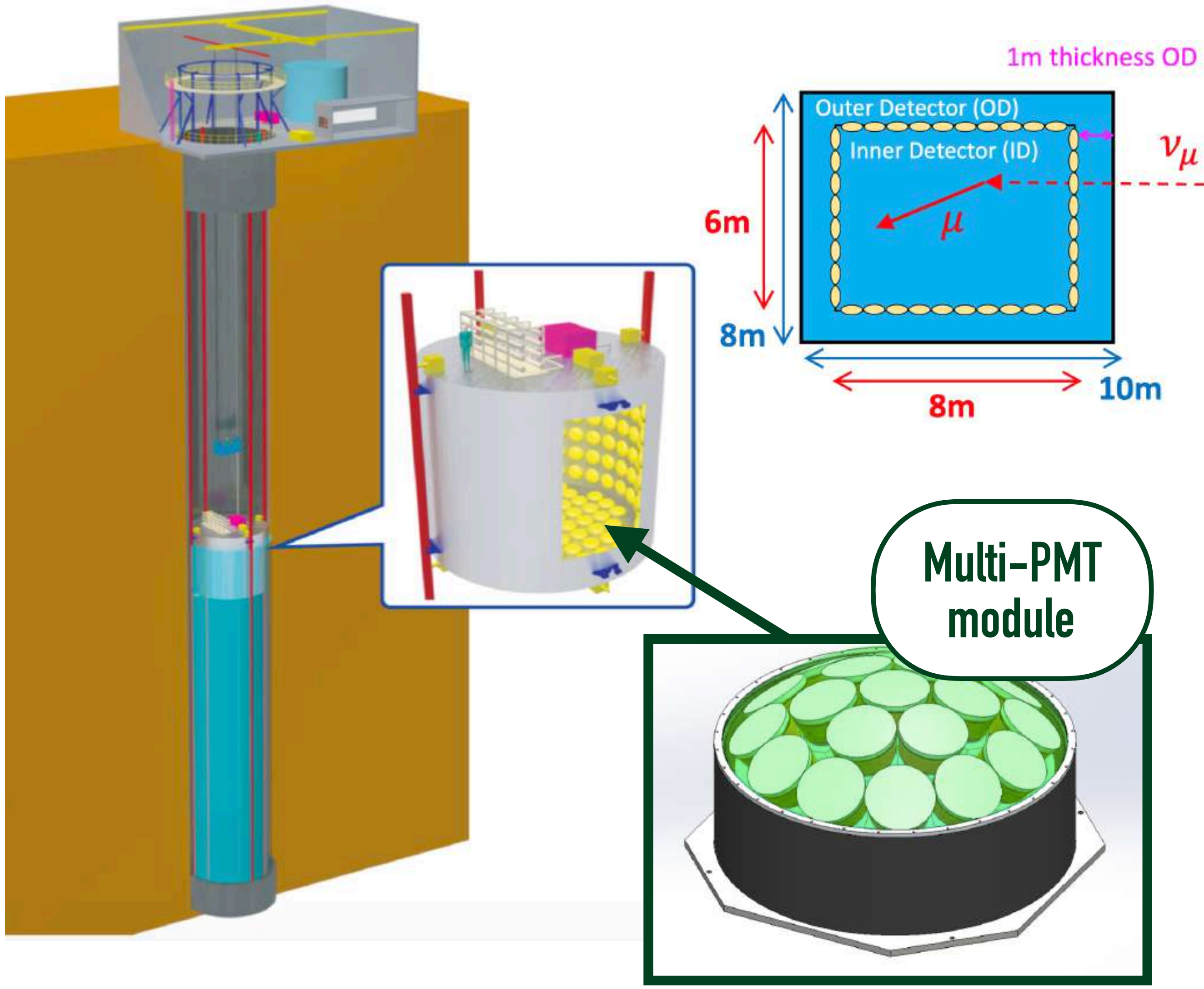


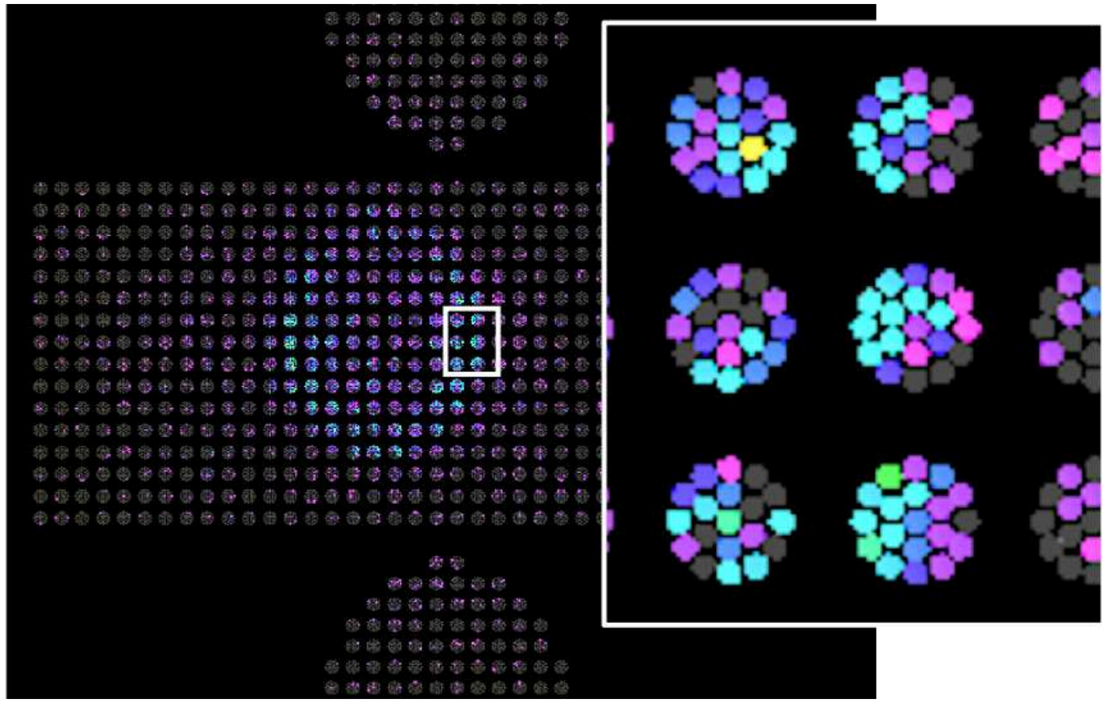
Off-axis spanning intermediate water-Cherenkov detector (IWCD)

- On-axis detector: monitors beam direction and event rate.
- Off-axis magnetized tracker: charge separation to measure wrong-sign background, flux constraint, and study of recoil system.
  - Upgrades of the detector inherited from T2K will be necessary.
- Off-axis angle spanning water-Cherenkov detector: intrinsic backgrounds, electron (anti)neutrino cross sections, neutrino energy versus observables, H_20 target, neutron multiplicity measurement.

THE IWCD

- An intermediate water-Cherenkov detector.
  - Same nuclear target as the far detector.
  - Smaller near to far extrapolation systematic.
- Instrumented portion of the detector moveable through deep cylindrical chamber.
  - Samples neutrino interactions from the J-PARC neutrino beam in the 1-4 degrees off-axis angle range.
- Has optically separated inner and outer volumes.
  - Inner detector: 8 m diameter, 6 m tall.
  - Outer detector: 10 m diameter, 8 m tall.
  - Contains up to 1 GeV muons.
- Gadolinium doping (0.1% by weight) to measure neutron production in neutrino interactions.
- Tank is populated with multi-PMT (mPMT) modules.
  - Improves resolution of Cherenkov ring.

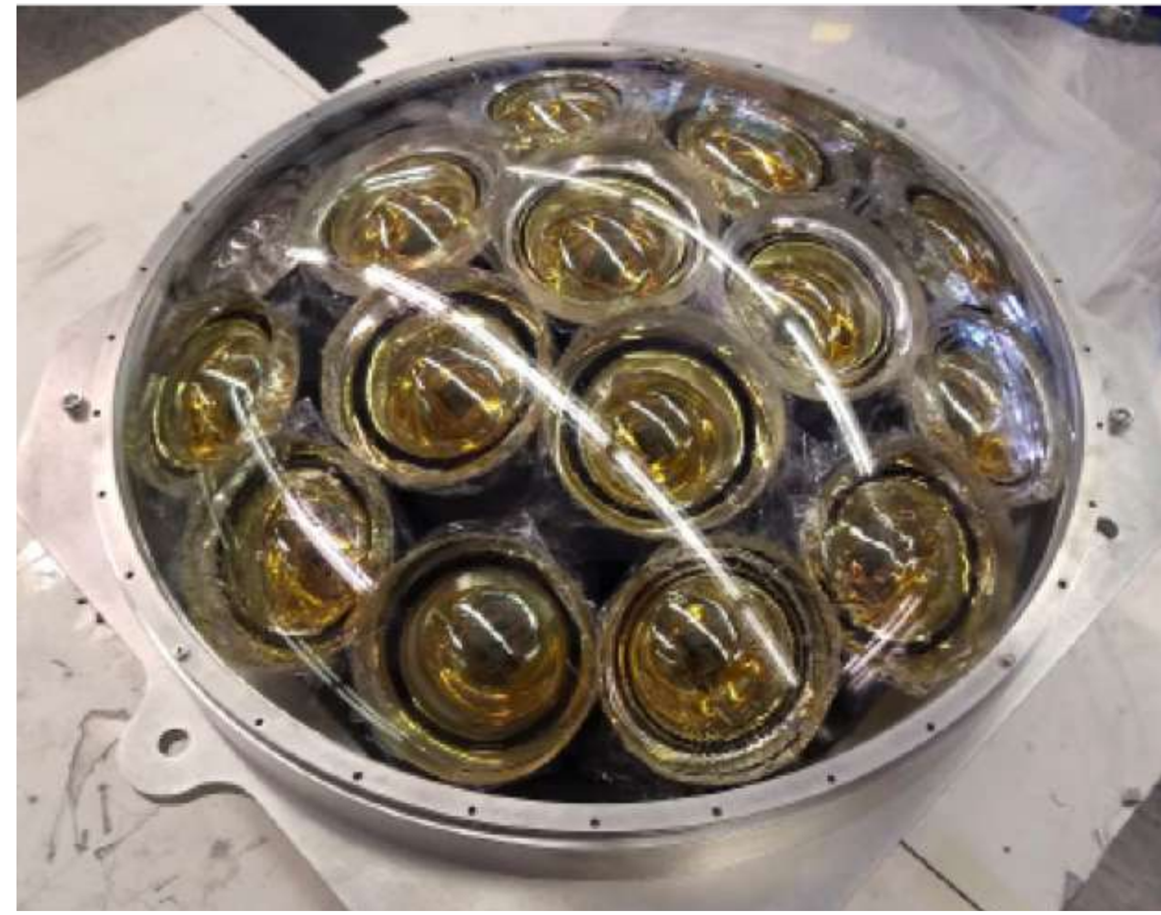


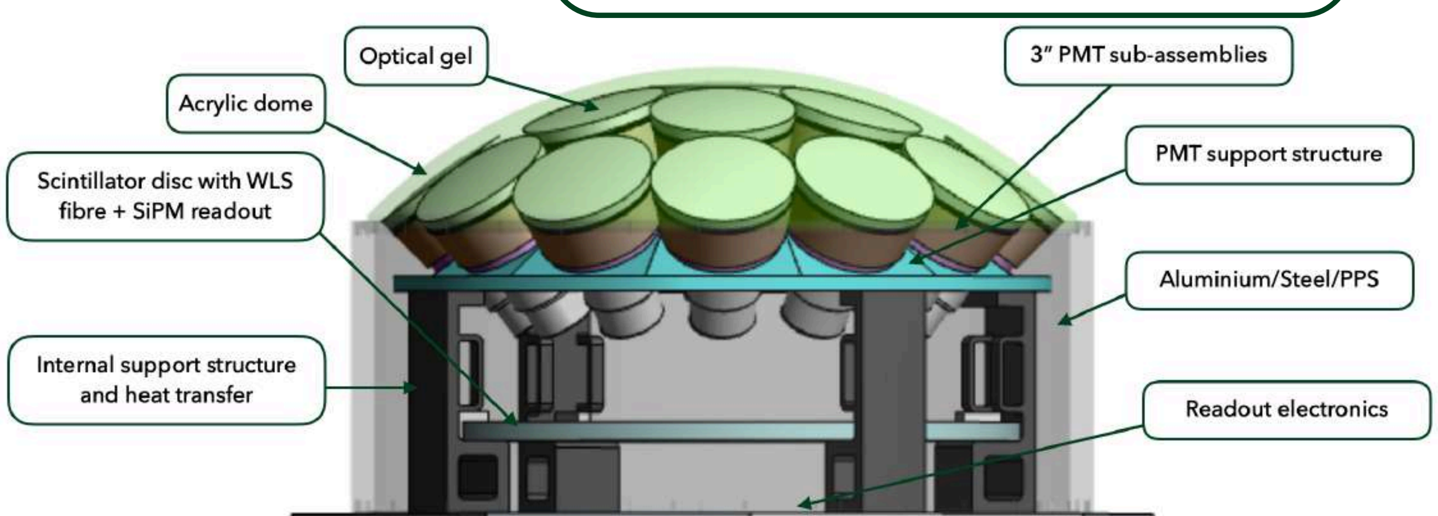


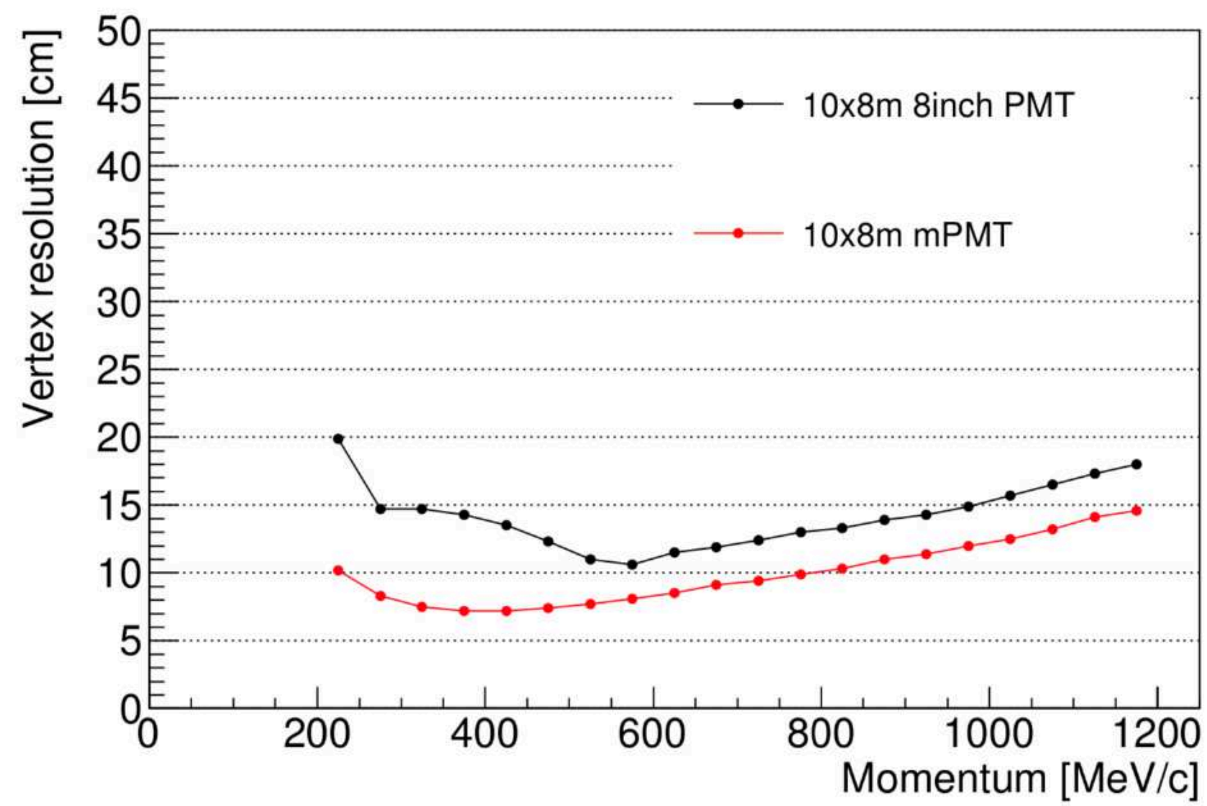
MULTI-PMT (MPMT) R&D

- IWCD requires small and fast photosensors.
- Modular approach to PMT instrumentation.
  - Array of small (~3'') PMTs.
    - Finer granularity of Cherenkov image and better timing response.
  - Directional information as each PMT images a different part of the tank - improved vertex resolution.
  - Waterproofing, pressure protection.
  - Readout electronics, monitoring, calibration devices located in vessel.
- Leveraging lessons learned from KM3NeT.
- Also plan to install ~5000 in Hyper-K.

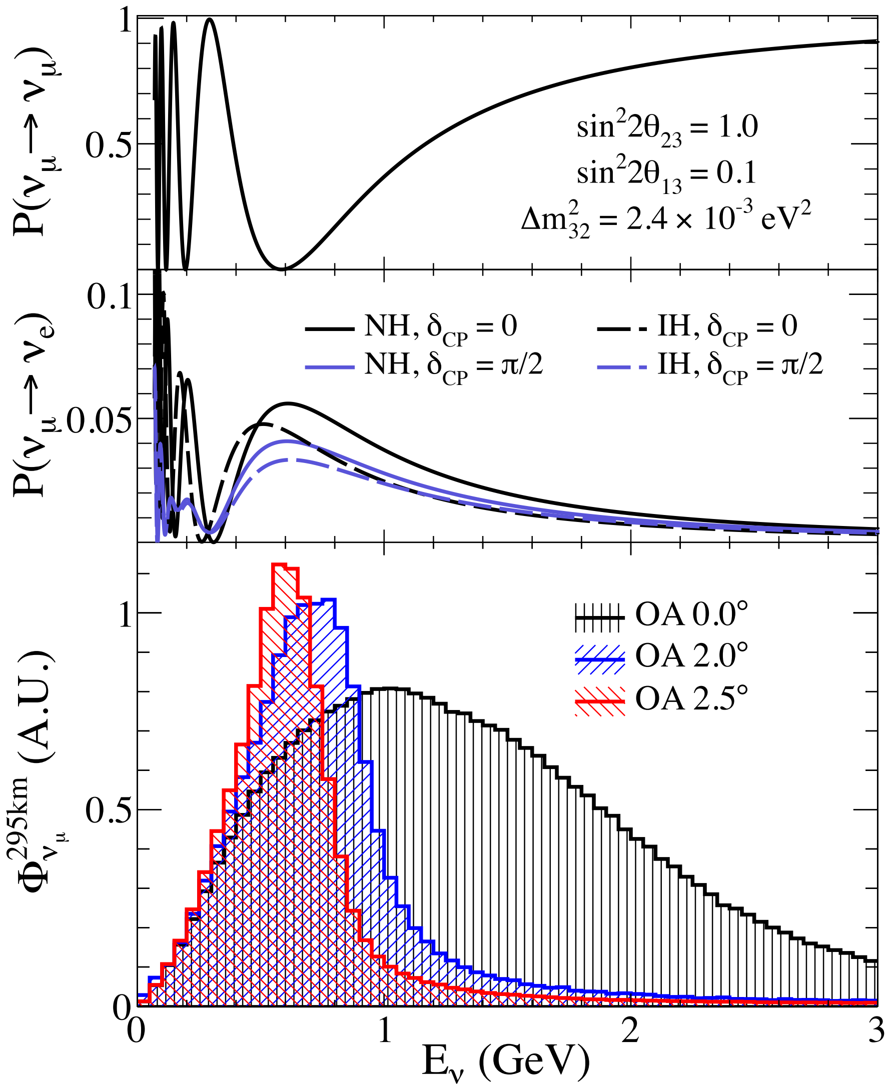
KM3NET LOI: https://arxiv.org/abs/1601.07459



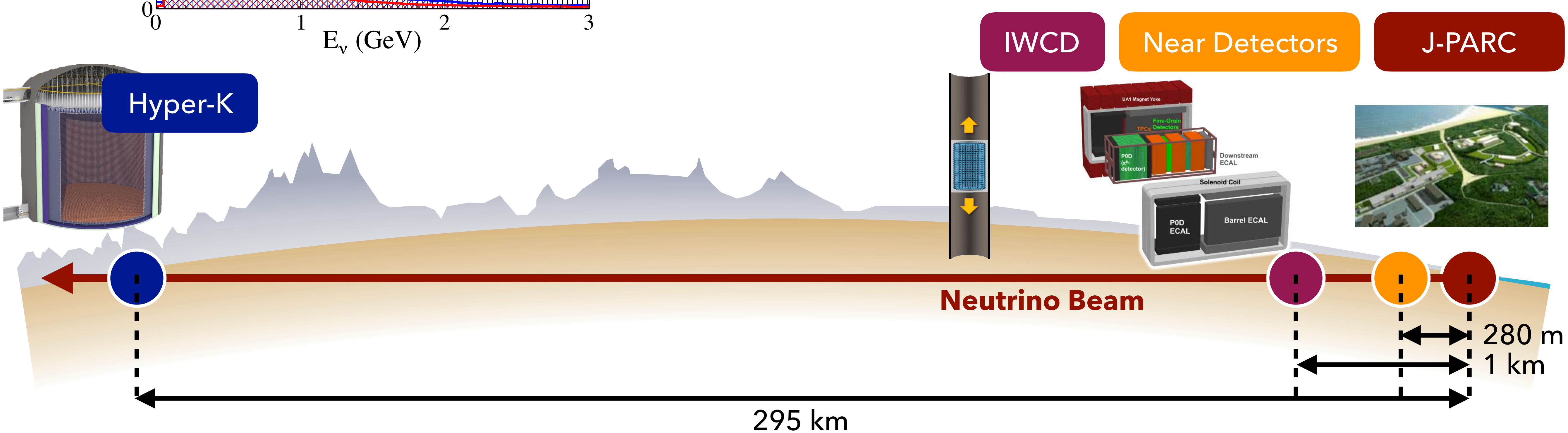




ACCELERATOR-BASED PHYSICS

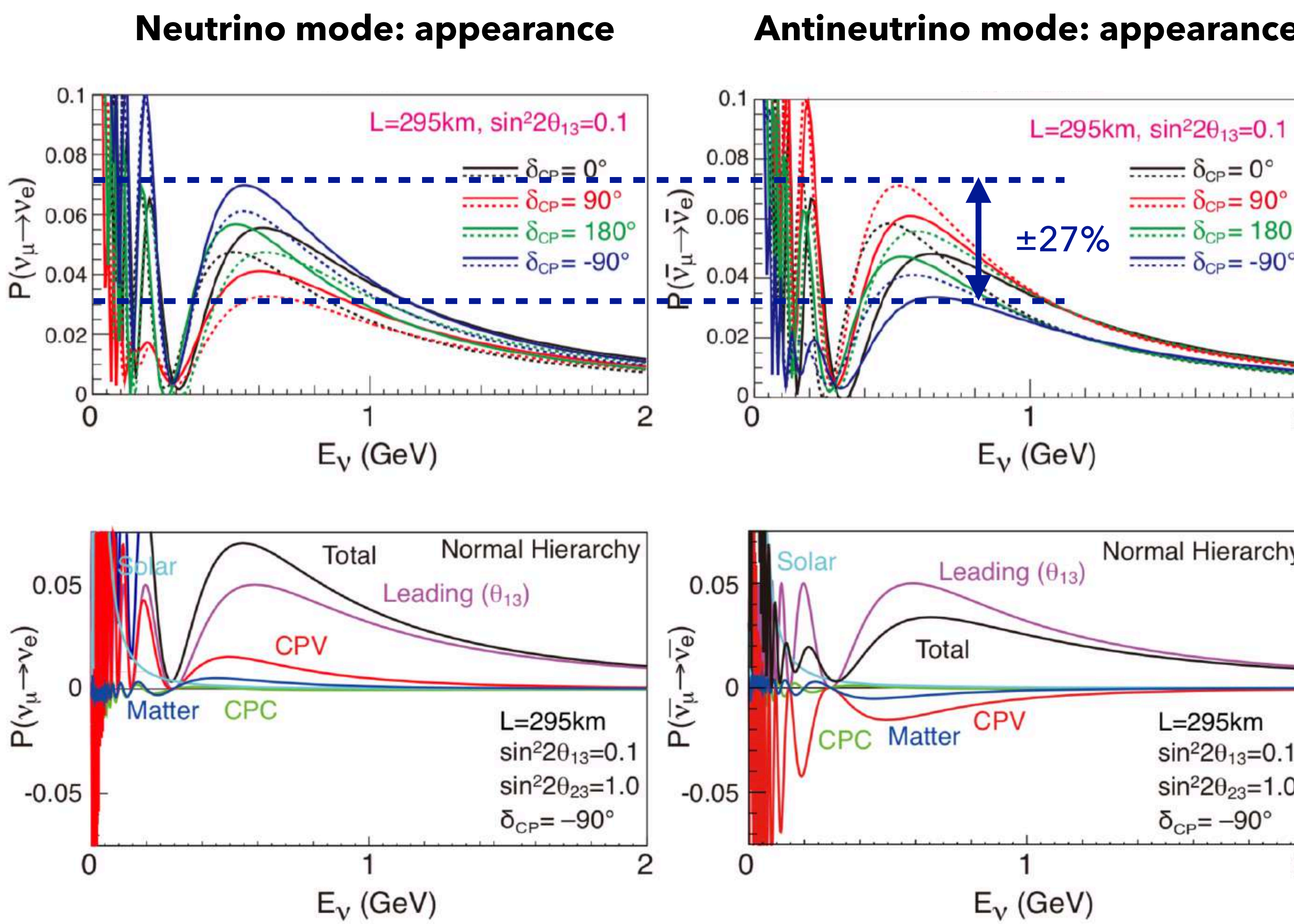


- Muon (anti)neutrino beam at 2.5° off-axis angle.
  - Narrow band energy peak at ~600 MeV.
- **Muon (anti)neutrino survival**.
  - Sensitive to $\sin^2 2\theta_{23}$ and Δm^2_{32}.
- **Electron (anti)neutrino appearance**.
  - Sensitive to $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, and Δm^2_{32} in leading term.
  - δ_{CP} in sub-leading terms.
  - Mass ordering through the matter effect.



CP EFFECT ON OSCILLATION PROBABILITY

- ν_e appearance probability changes as a function of E_ν depending on the value of δ_{CP}.
- Sensitive to CP violation by observing the difference in appearance probability for neutrinos and antineutrinos.
- The maximum difference in appearance probability is ±27% for δ_{CP} = -90°.
- The matter effect is small (~10% contribution) compared to the CP effect for a baseline of 295 km.



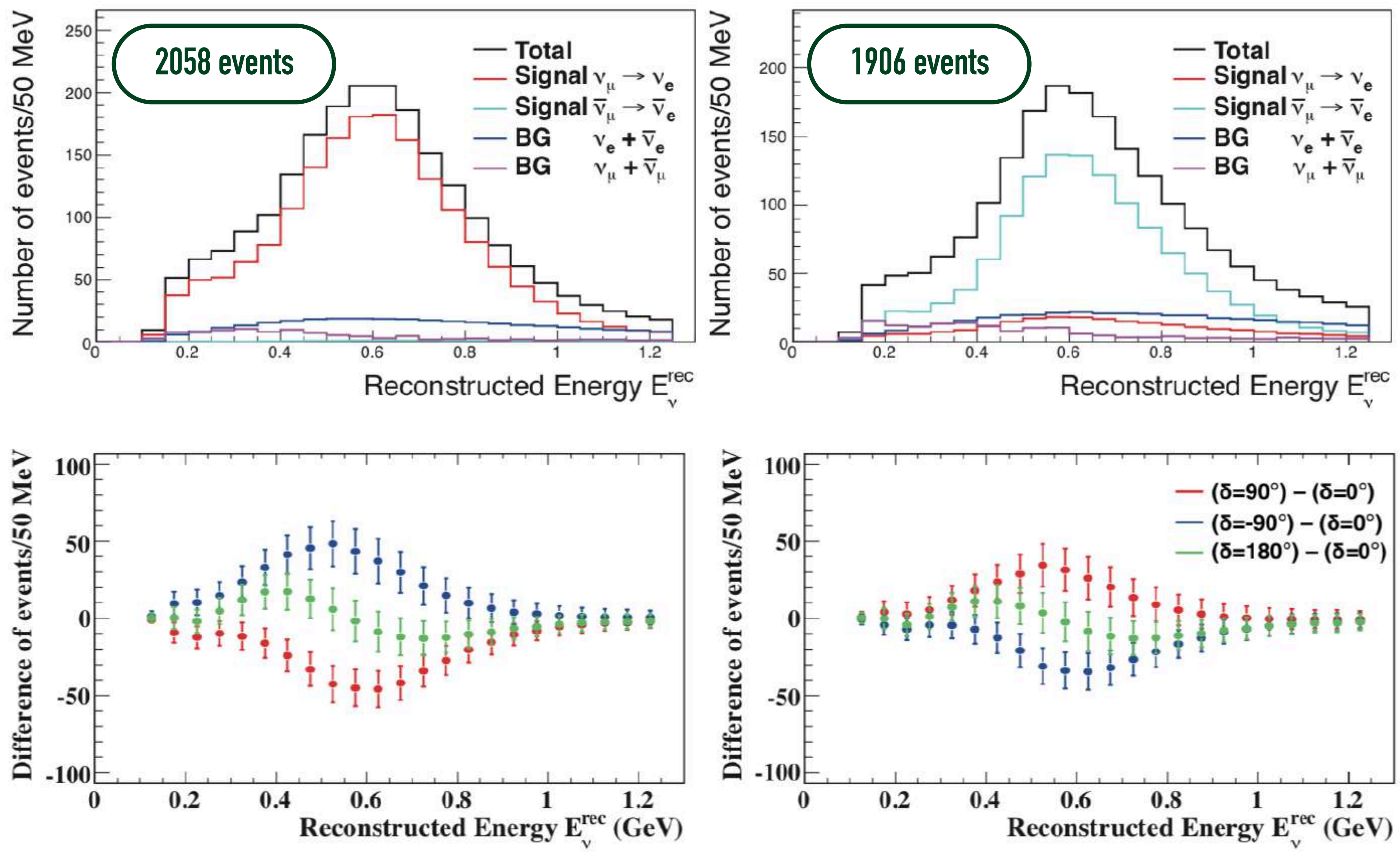
EXPECTED EVENTS FOR CPV

- T2K and NOvA are observing 10s of candidate events.
- Hyper-K will observe ~2000 electron neutrino and antineutrino candidate events each.
- Achieves a 3.2% statistical error on the CP violation measurement.

$\delta = \pm 90°$ shows maximum differences between ν and anti ν.

$\delta = 0$ and 180° can be distinguished by shape.

Neutrino mode: appearance | **Antineutrino mode: appearance**

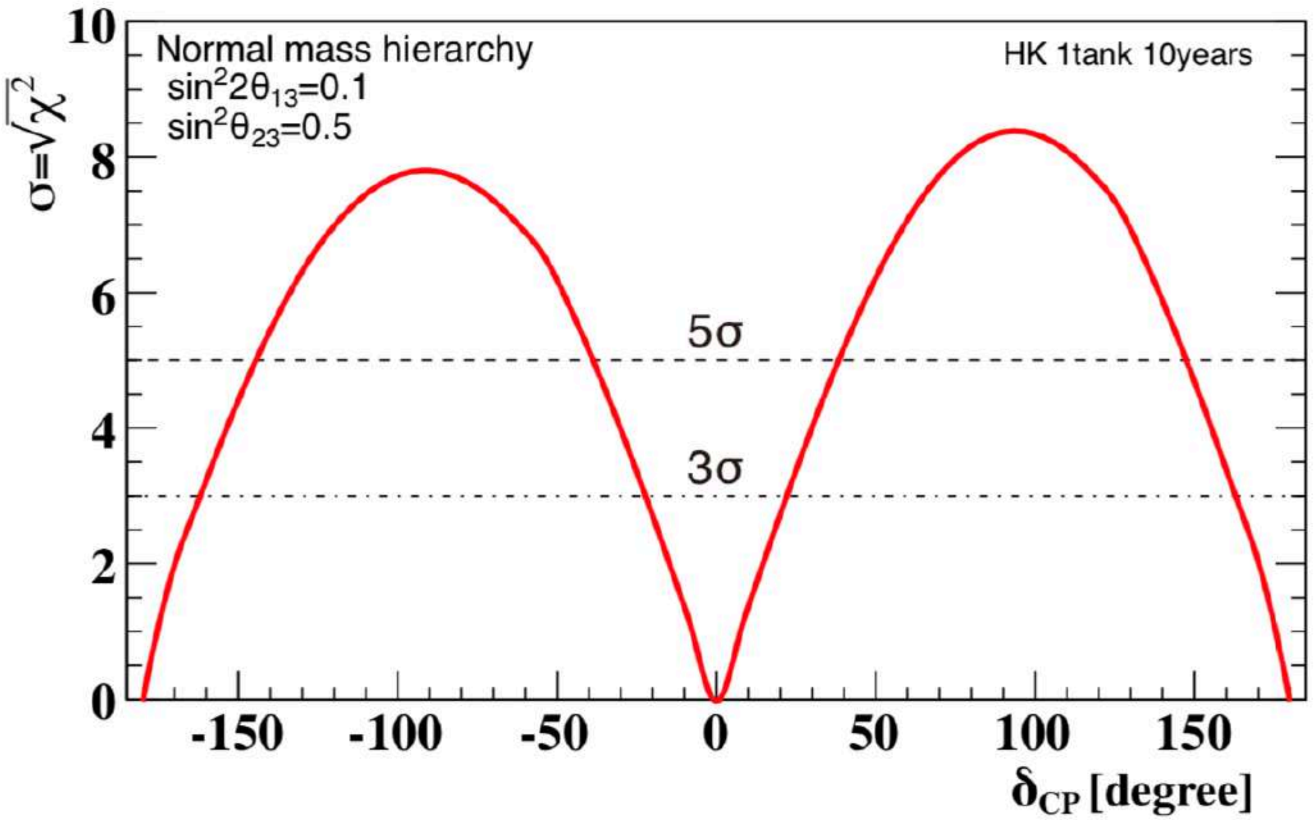


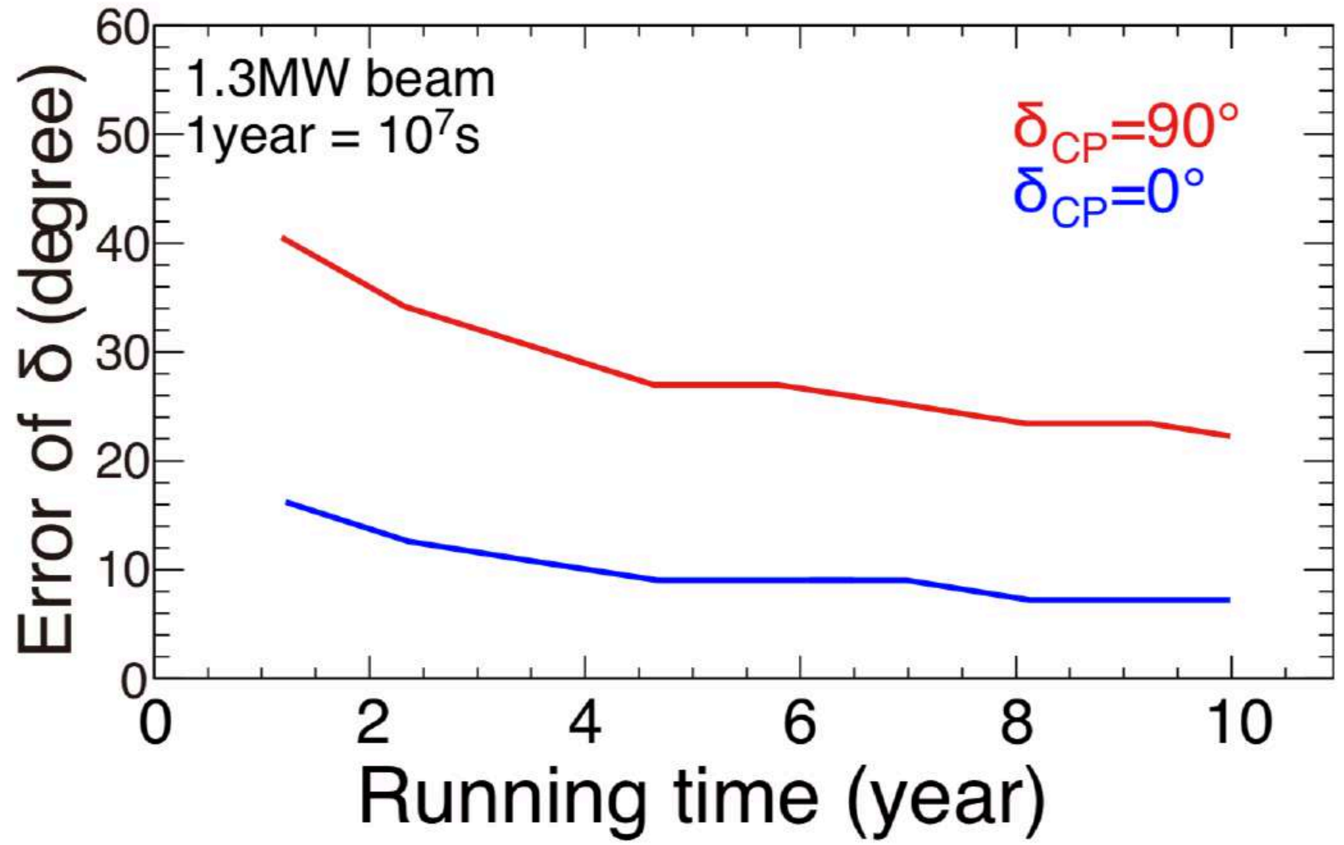
Assumptions:
- 1.3 MW x 10 years
- ν : anti-ν = 1 : 3
- $\sin^2 2\theta_{13} = 0.1$
- Normal hierarchy

For δ_{CP}=0	Signal νμ→νe CC	Wrong sign appearance	νμ/anti-νμ CC	Beam νe/anti-νe contamination	NC
ν beam	1643	15	7	259	134
anti-ν beam	1183	206	4	317	196

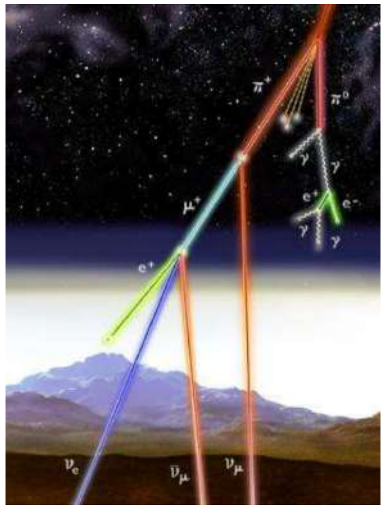
CP VIOLATION SENSITIVITY

- After 10 years of operation, Hyper-K has the sensitivity to exclude CP conservation with:
  - 76% coverage of parameter space at 3σ level.
  - 57% coverage of parameter space at 5σ level.
- Hyper-K can measure δ_{CP} with a precision of:
  - 22° for $\delta_{CP} = \pm 90°$.
  - 7° for δ_{CP} = 0° or 180°.
- Larger uncertainty at $\delta_{CP} = \pm 90°$ because derivative of CP violating term which depends on $\sin(\delta_{CP})$ goes to 0.
  - Rely on interference term which depends on $\cos(\delta_{CP})$.
- Sensitivity enhanced by combining atmospheric ν data.

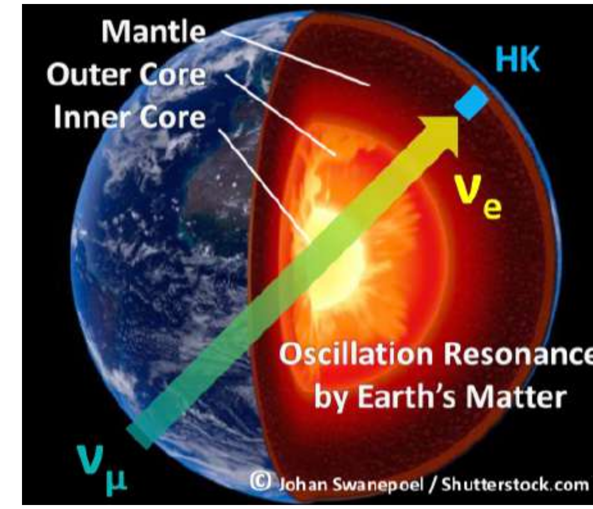




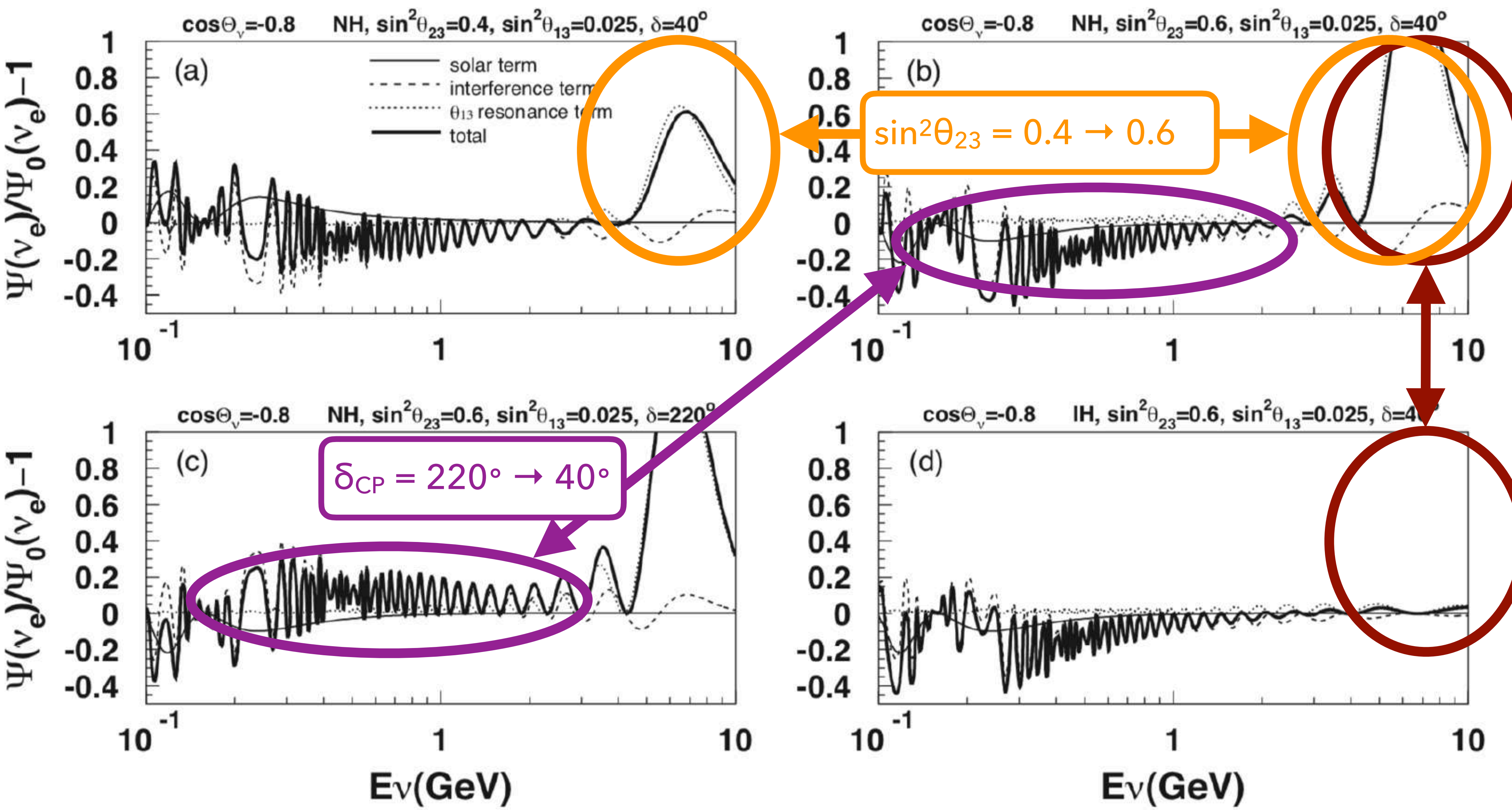
ATMOSPHERIC NEUTRINOS



- Primary cosmic ray interactions produce flux of atmospheric neutrinos.
- Mixture of ν_μ and ν_e, and their antineutrinos.
- Wide energy range and wide range of flight lengths.
- Earth Matter Effect modifies energy spectrum of atmospheric neutrino oscillations as they pass through core.



ν_e flux (relative to no oscillations) at $\cos\theta_{zenith}$ = 0.8



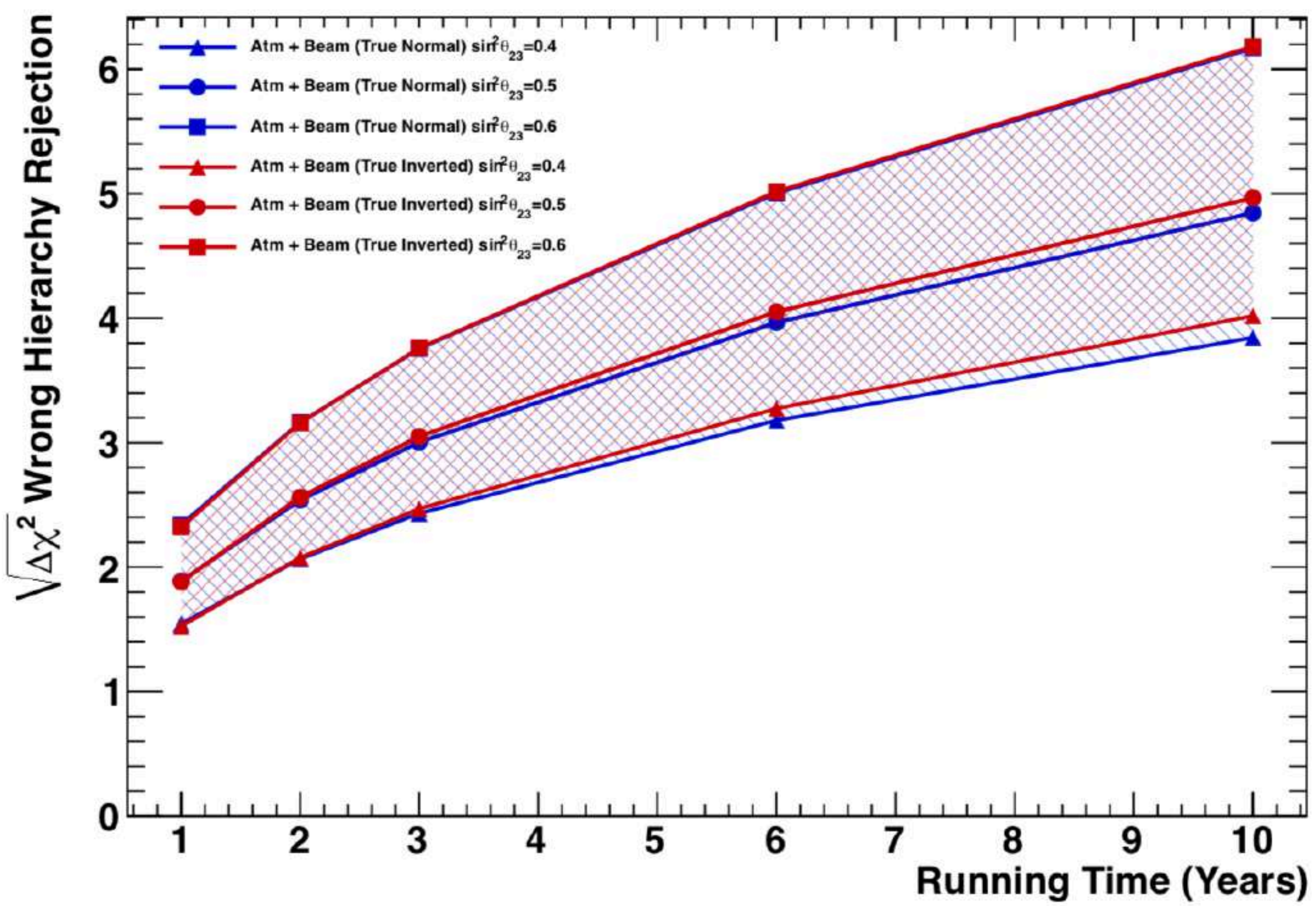
NH→IH
No resonance in ν
Present in anti-ν

- Mass hierarchy creates resonance in ν_e or anti-ν_e multi-GeV events.
- θ_{23} octant sets magnitude of the resonance.
- δ_{CP} sets scale/ direction of ~1 GeV interference.

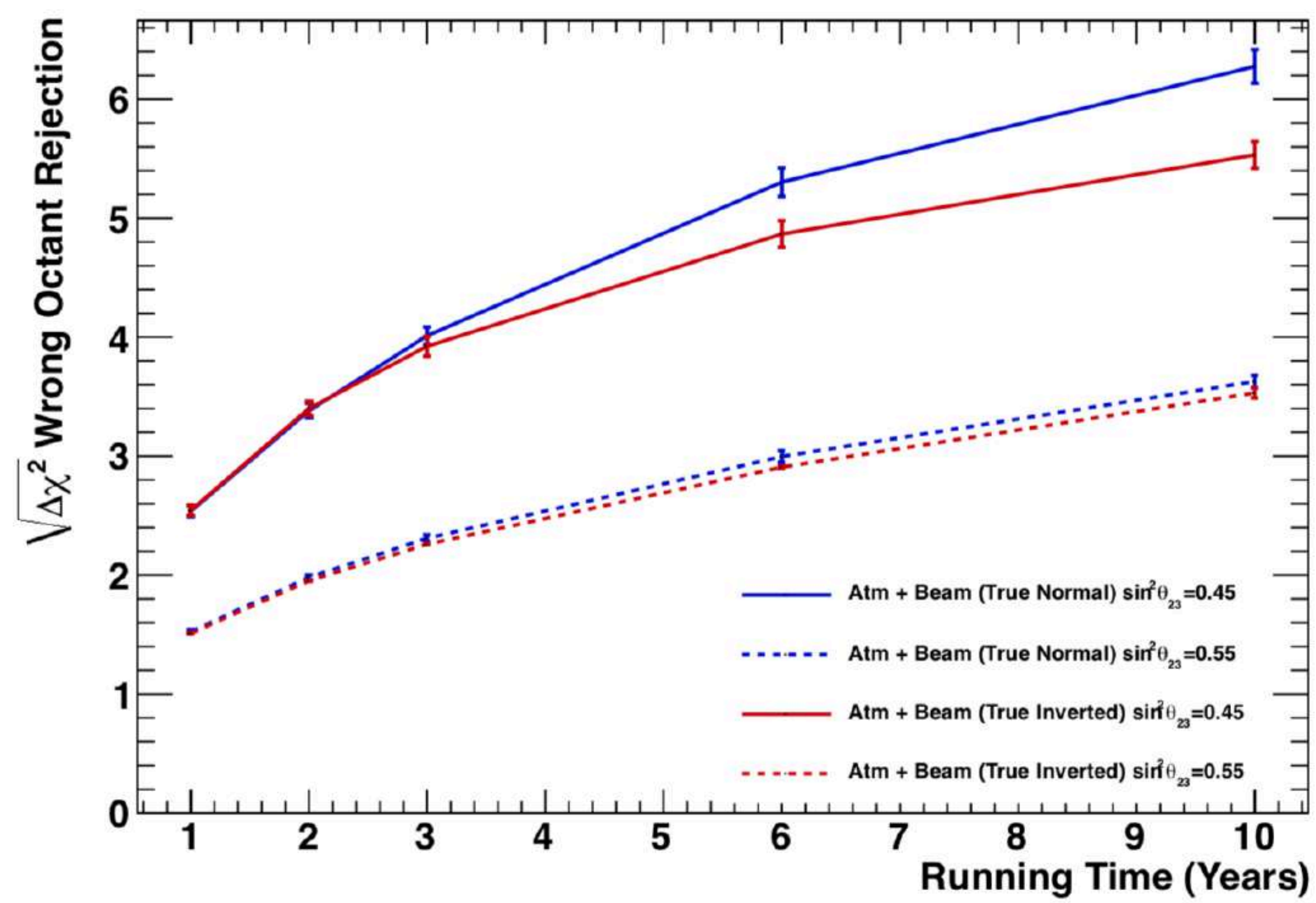
HIERARCHY AND OCTANT SENSITIVITIES

- Combining atmospheric and beam neutrinos in joint fit analysis.

Wrong Hierarchy Rejection



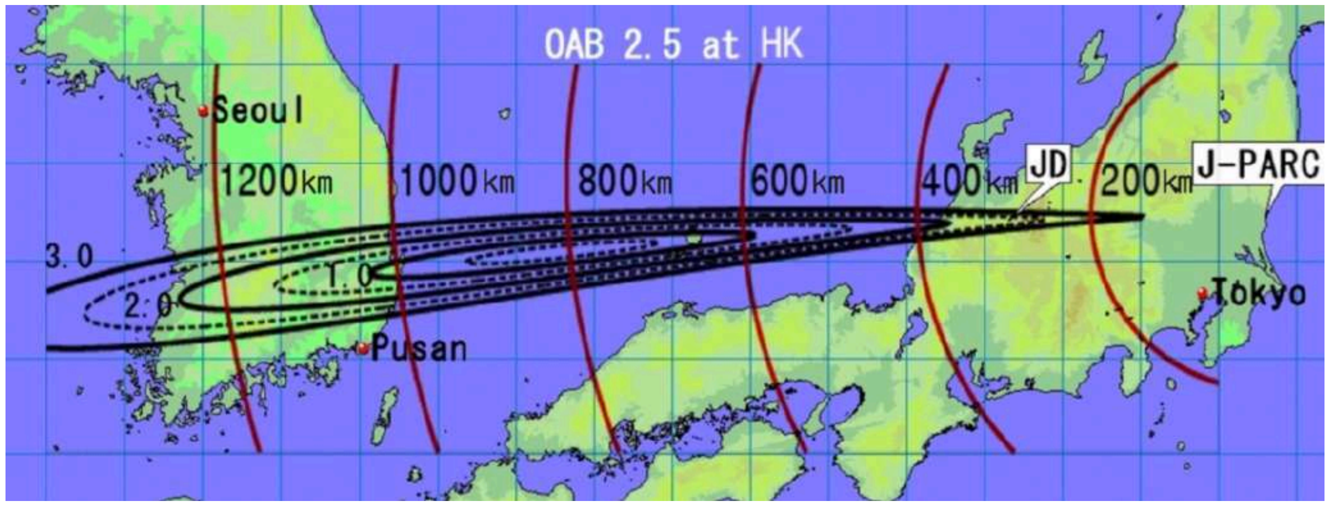
Wrong Octant Rejection



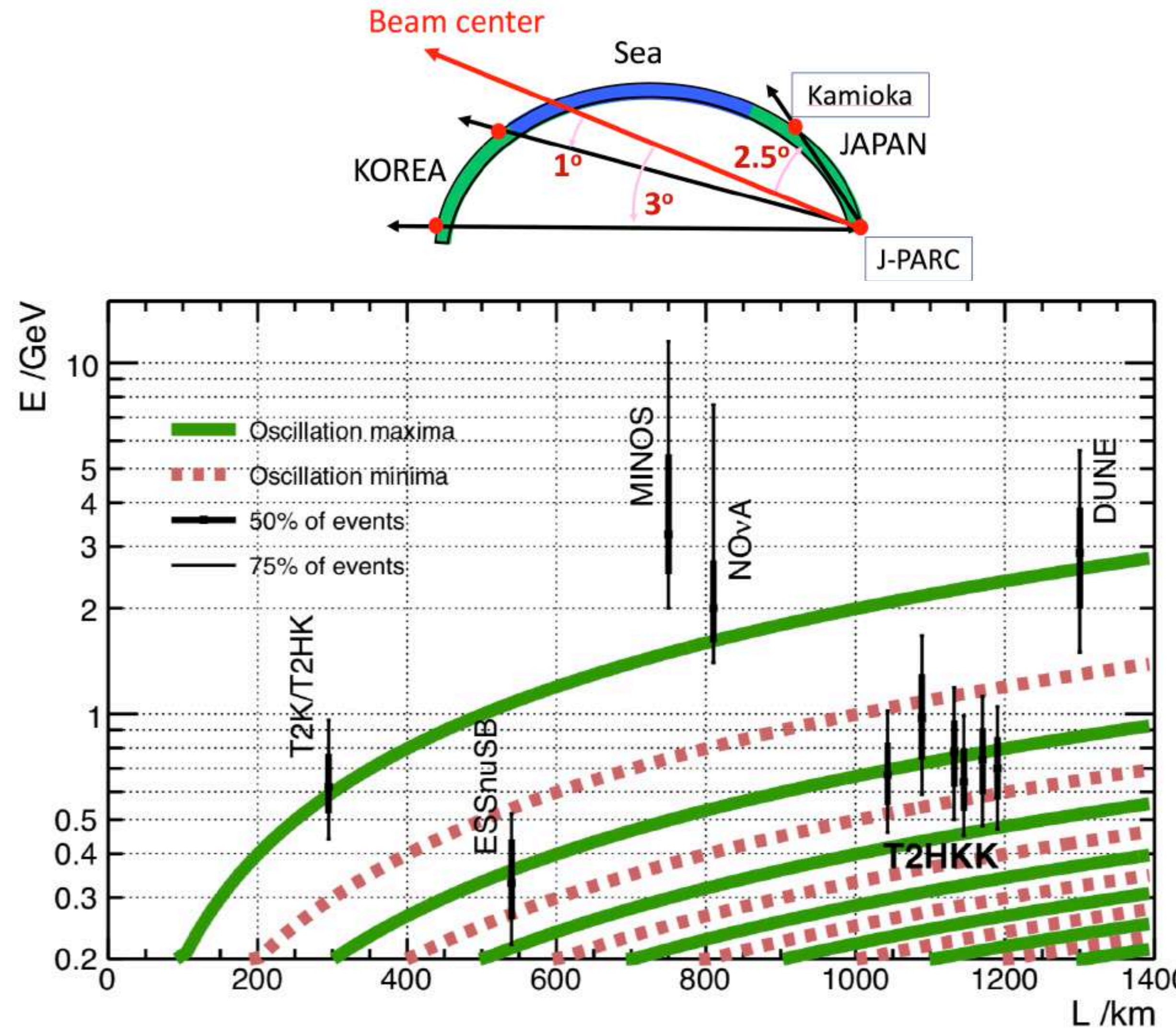
Wrong mass hierarchy rejection at 3σ for all possible values of θ_{23}.

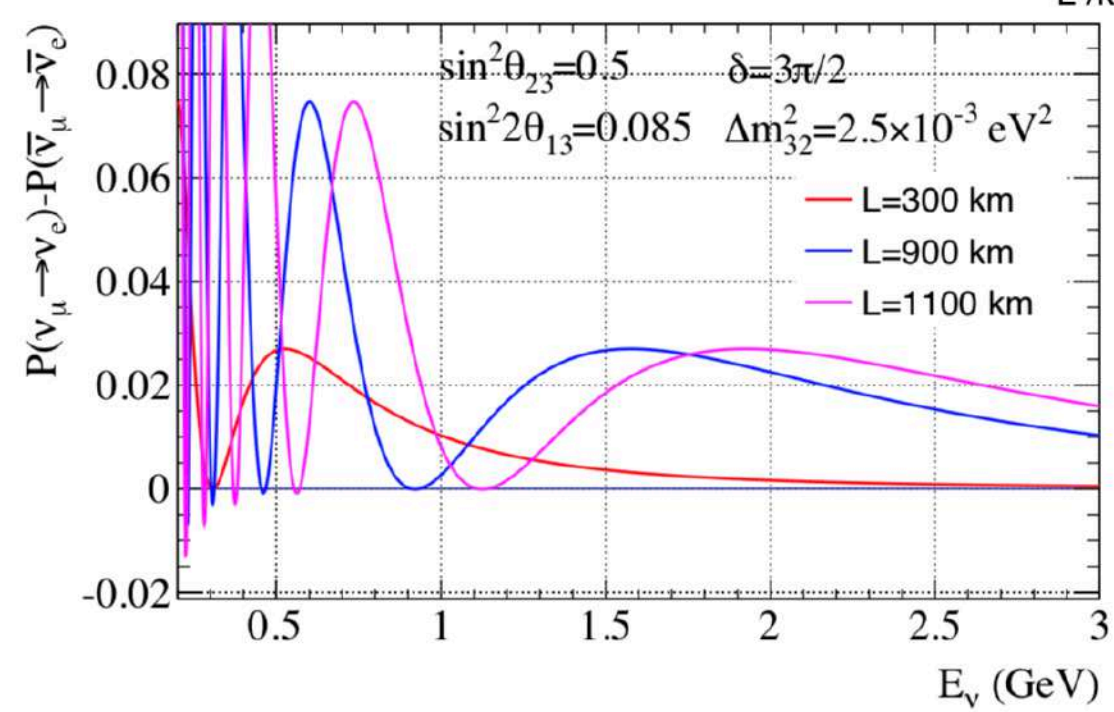
Wrong octant rejection at 3σ for $|\theta_{23} - 45^\circ| \geq 2.3^\circ$.

SECOND TANK IN KOREA



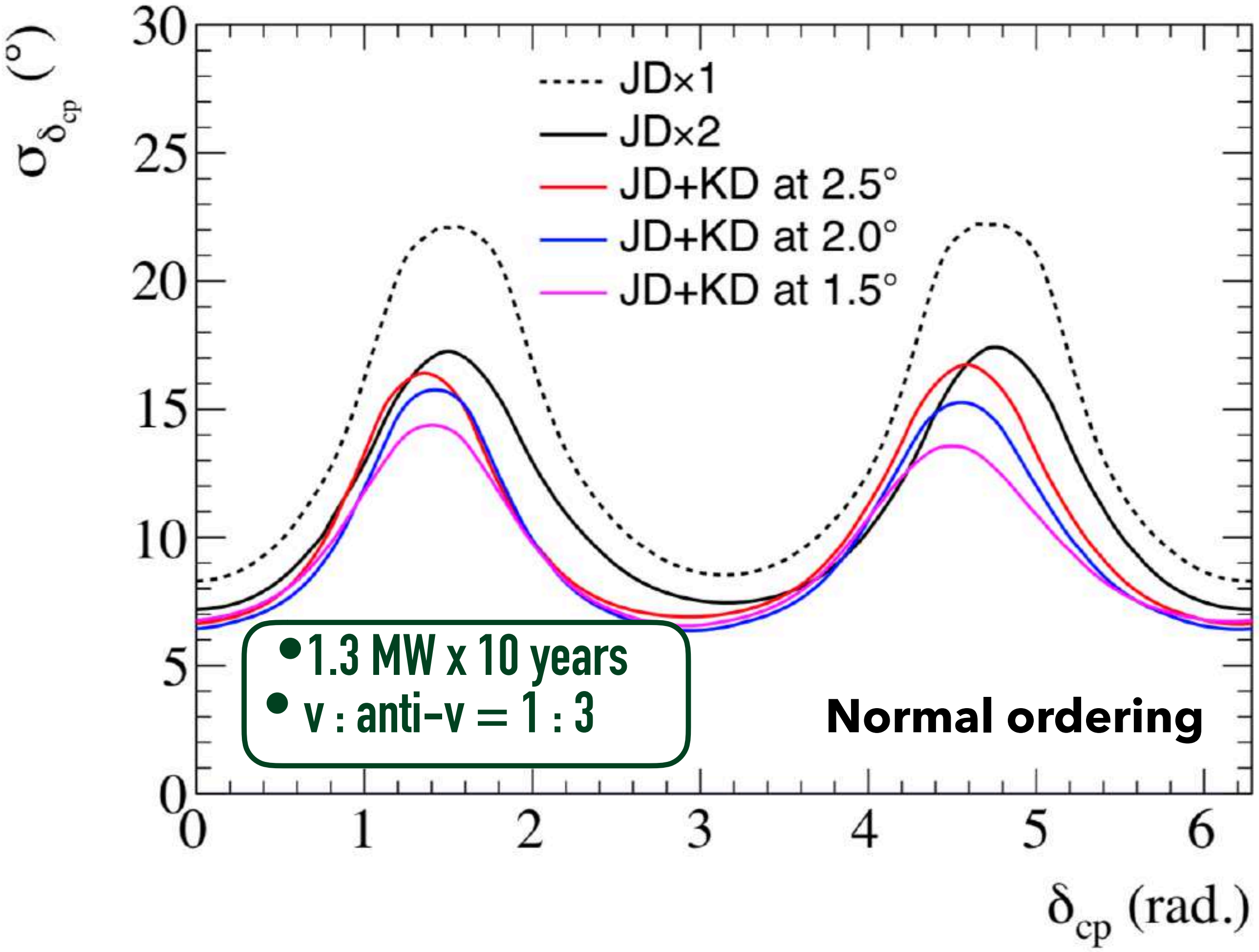
- A second tank in Korea is being considered.
- Mt. Bisul site at L = 1088 km, OA = 1.3°.
- Access to the second oscillation maxima.
    - δ_{CP} effect enhanced.
- Higher mass hierarchy sensitivity.
    - Longer baseline.
    - Higher neutrino energies.
- Increased overburden so lower backgrounds for solar physics.
- More mass for proton decay.



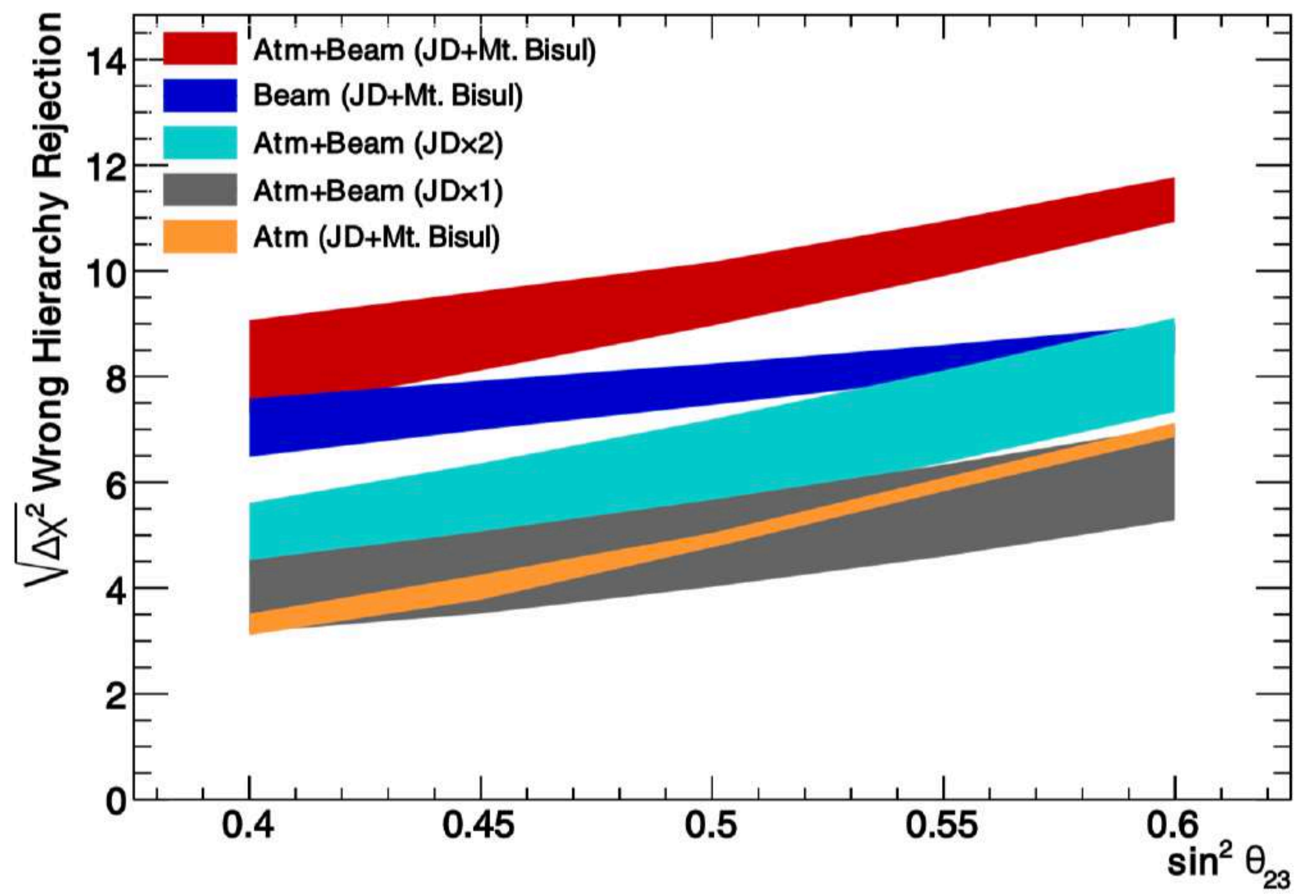


PHYSICS SENSITIVITY WITH KOREAN DETECTOR

δCP 1σ precision



Mass hierarchy rejection



- Locating second detector in Korea gives improved sensitivity compared to single and two Japanese detectors.
- Better δ_{CP} measurement precision:
  - 22° (1 tank) → 14° at δ_{CP} = -90°.
- Higher mass hierarchy sensitivity:
  - 4.5σ (1 tank) → 9σ at $\sin^2\theta_{23}$ = 0.5.

SYSTEMATIC ERRORS

- Systematics assumed for the Hyper-K ν_e and anti-ν_e appearance signal events.

	Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
Neutrino mode	3.0%	0.5%	0.7%	3.2%
Antineutrino mode	3.2%	1.5%	1.5%	3.9%

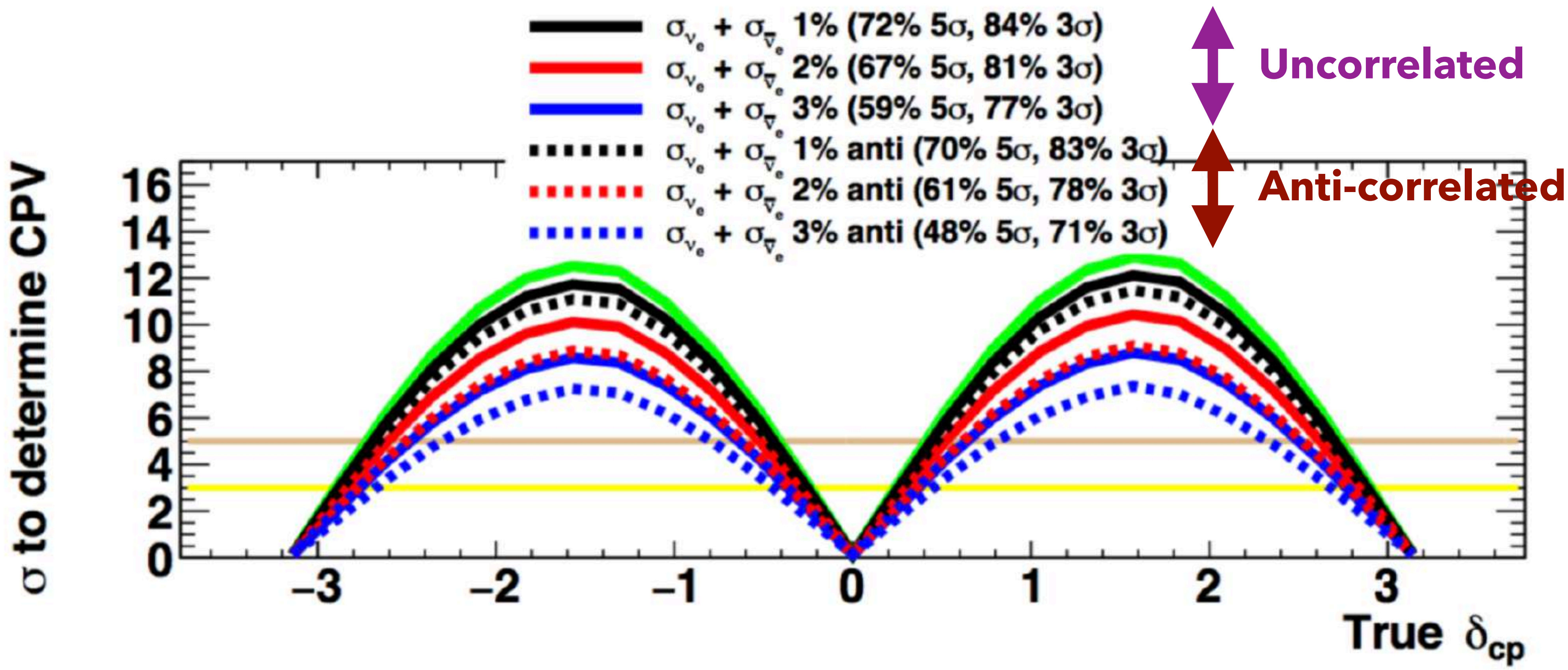
- These are optimistic assumptions!
- These are the current errors on the T2K predicted event rates:

	Source of uncertainty	1-Ring μ		1-Ring e			
		FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
Detector	Super-K Detector	2.40	2.01	2.83	3.79	13.16	1.47
Detector	Super-K FSI + SI + PN	2.20	1.98	3.02	2.31	11.44	1.58
	Flux and cross-section (w/ ND280 constraint)	2.88	2.68	3.02	2.86	3.82	2.31
Cross section	Nucleon removal energy	2.43	1.73	7.62	3.66	3.01	3.74
Cross section	$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
Cross section	NC 1-γ	0.00	0.00	1.07	2.58	0.33	1.49
Cross section	NC Other	0.25	0.25	0.14	0.33	0.99	0.18
	Total	4.91	4.28	8.79	7.00	18.26	5.88

- Systematics need to be reduced to below the 3.2% statistical error.

CONTROLLING SYSTEMATICS FOR CP VIOLATION

σ(δCP) for different uncertainties on electron (anti)neutrino cross sections



- A 2% anti-correlated systematic effect is the same as a 3% uncorrelated systematic effect.
- To achieve 5σ for ~60% of δ_{CP} need need 4% error on relative predicted rates of electron neutrinos and antineutrinos.
- Uncertainty on ν_e/ν_μ and anti-ν_e/anti-ν_μ cross section ratios likely to dominate budget.
  - Current uncertainty of 3% is theory motivated.
  - We should measure this!

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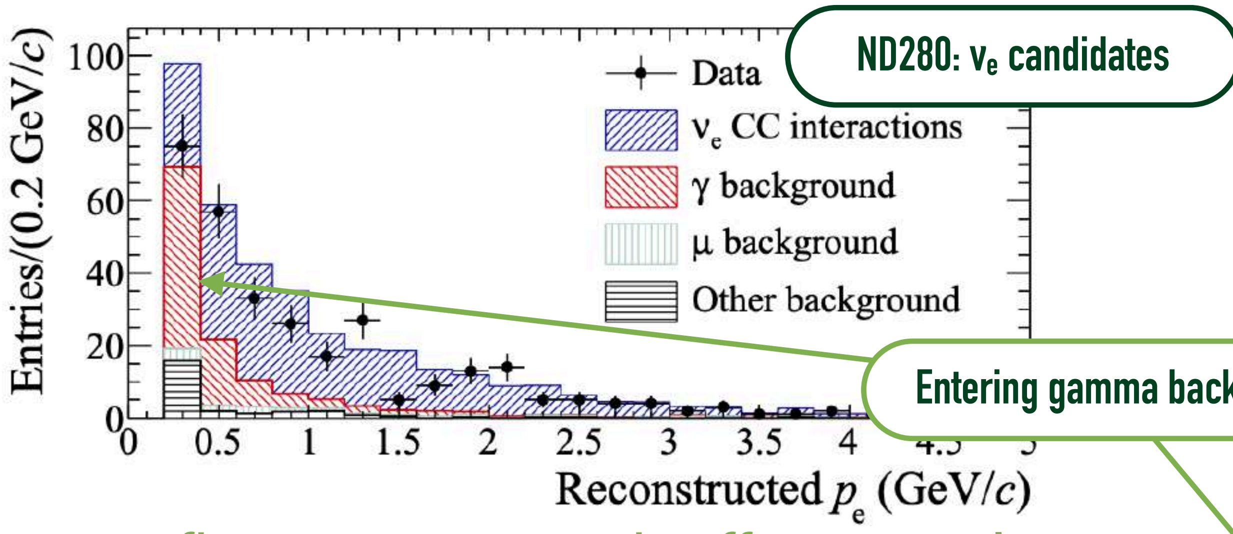
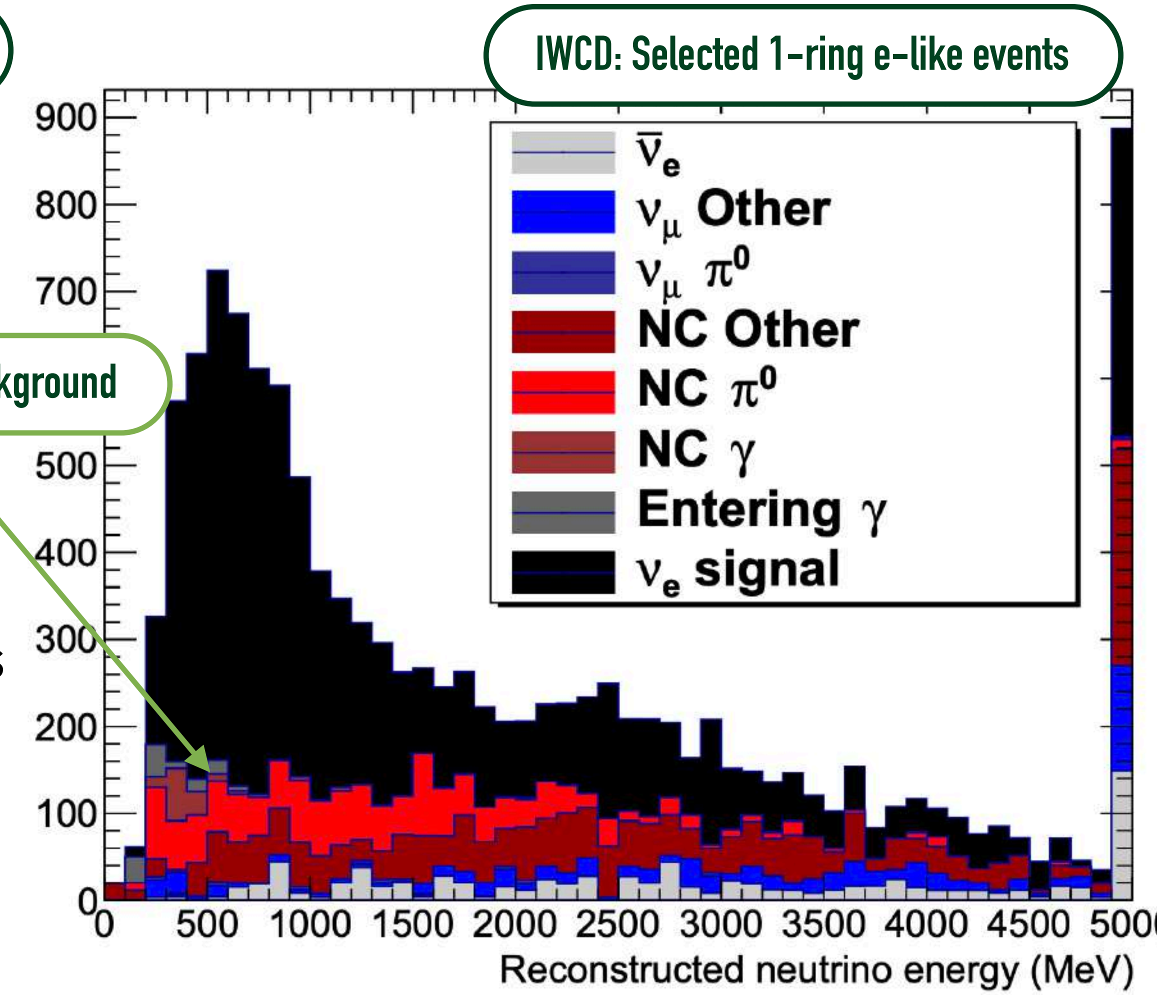
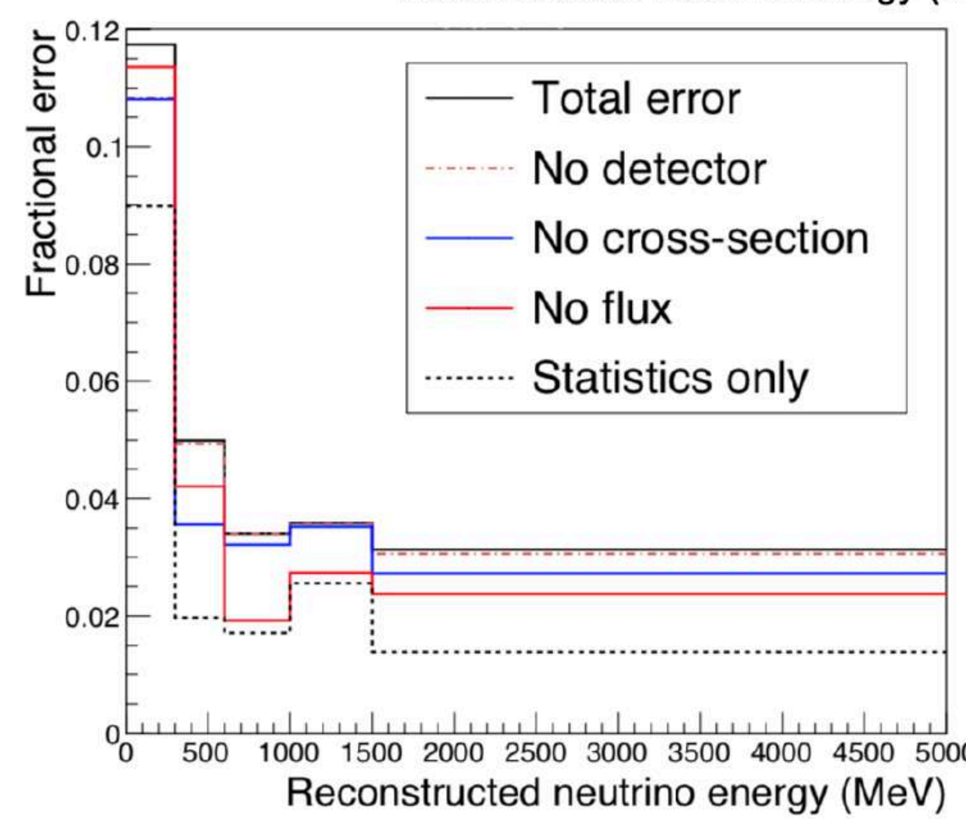
ν_e CROSS-SECTION MEASUREMENT







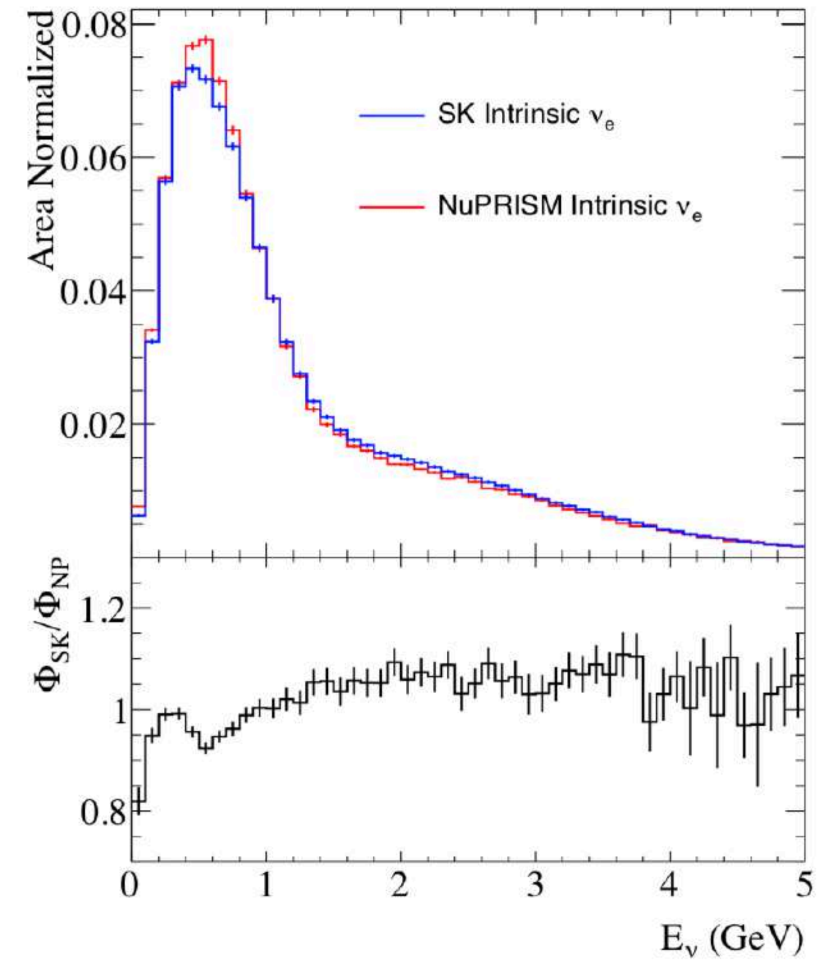
- Relative ν_e flux increases with off-axis angle.
  - Can make a direct measurement of the ν_e cross section on water with IWCD.
- Active shielding reduces gamma background.
- In momenta of interest for HK expect a 2% statistical uncertainty, with total uncertainty of <4%.
- Systematic uncertainties dominated by flux and cross section.
  - Expect reduction in uncertainty from improved external flux measurements (EMPHATIC) and cross-section modelling from IWCD mono-energetic beam technique.
- Other uncertainties that introduce asymmetry should be kept to the 1% level if possible.

WRONG-SIGN AND INTRINSIC BACKGROUNDS

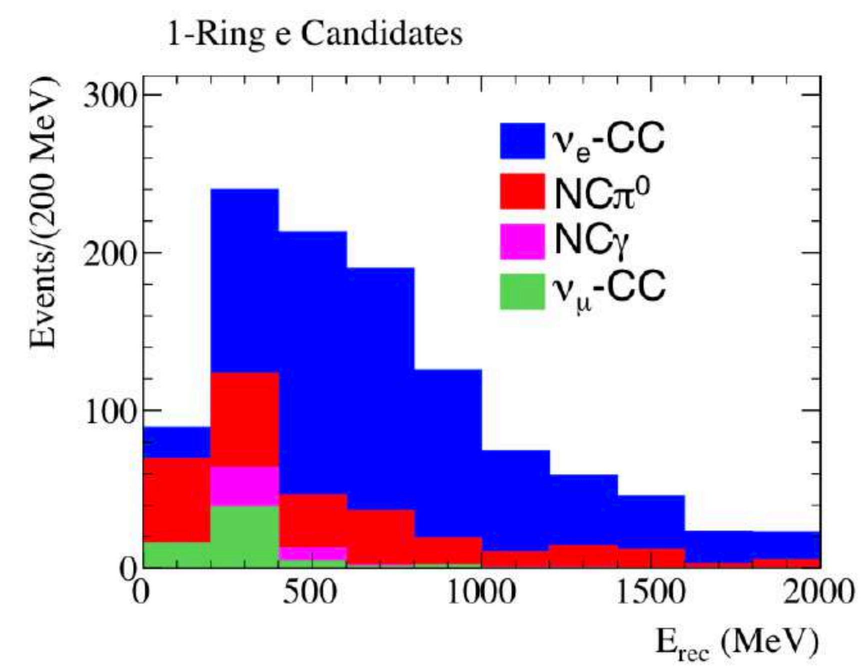
- Electron (anti)neutrino sample composition:

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

- Aiming for a 1% systematic error contribution from the wrong-sign and intrinsic electron (anti)neutrino and NC background.
- Wrong-sign background must be measured with 9% accuracy.
  - Can be achieved with a magnetized tracking detector.
- Intrinsic electron (anti)neutrino and NC background must be measured with 3% accuracy.
  - Achieved by intermediate water-Cherenkov detector.

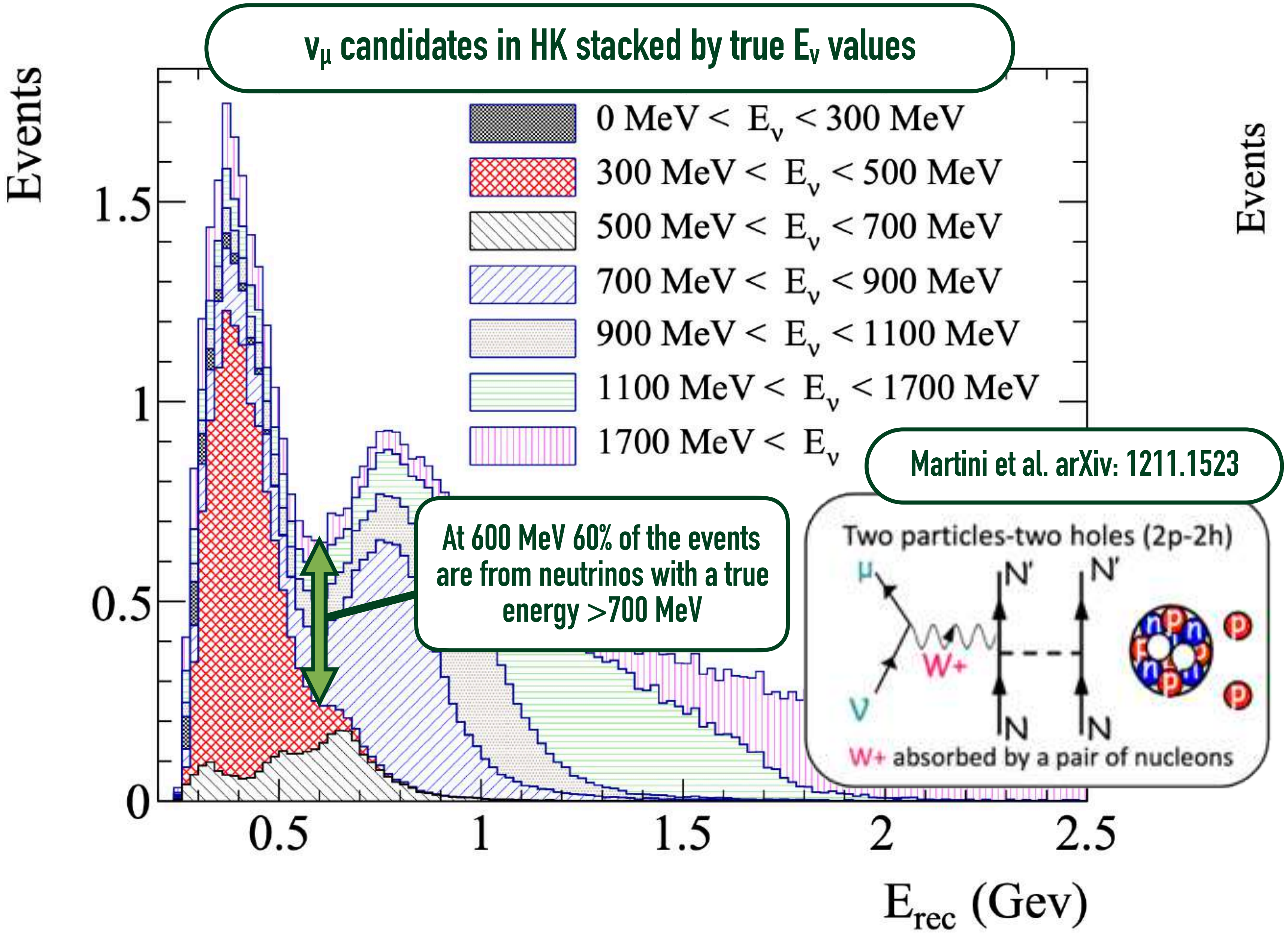


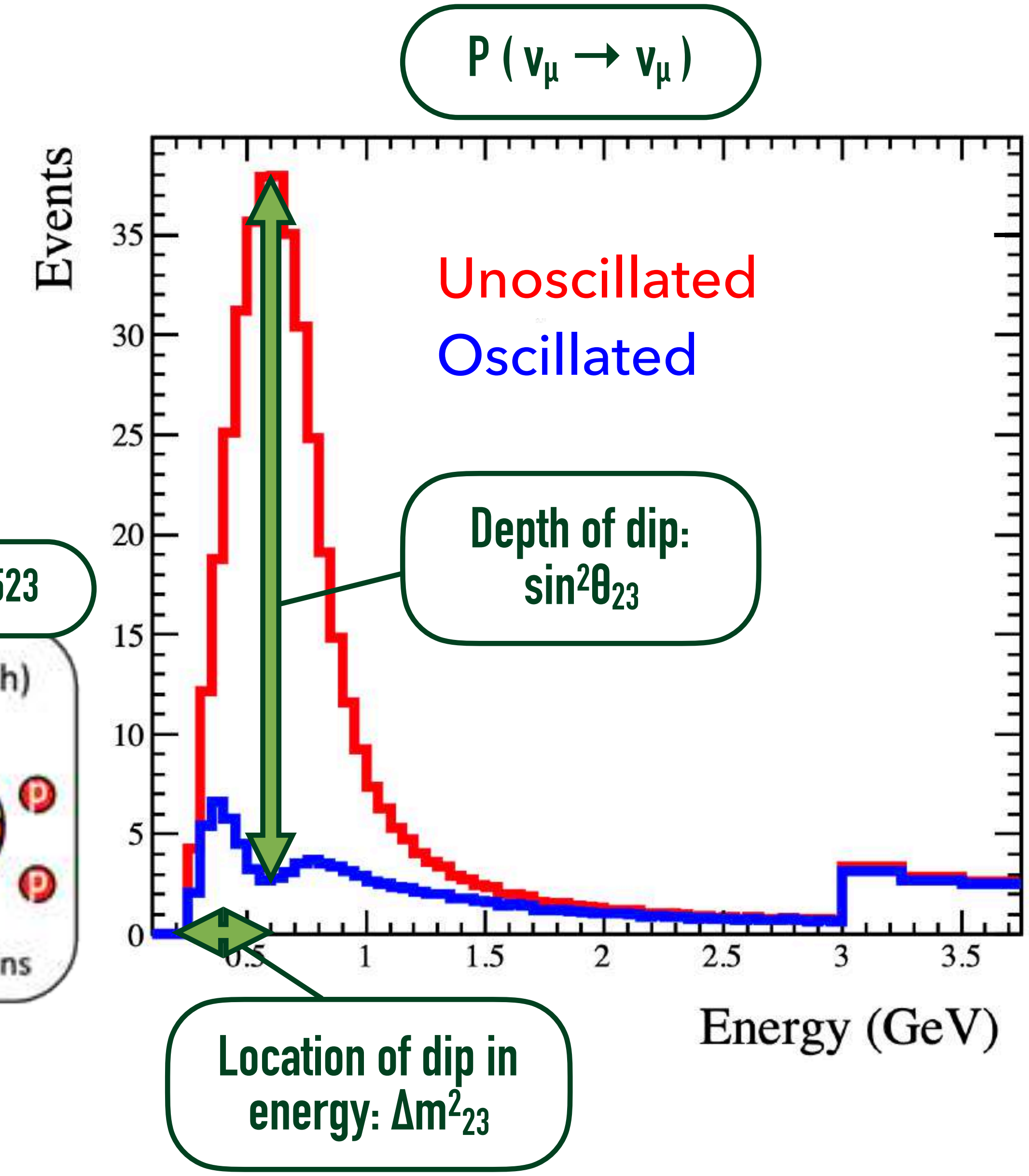
Spectra for intrinsic background at IWCD and Hyper-K



Intrinsic one-ring electron background

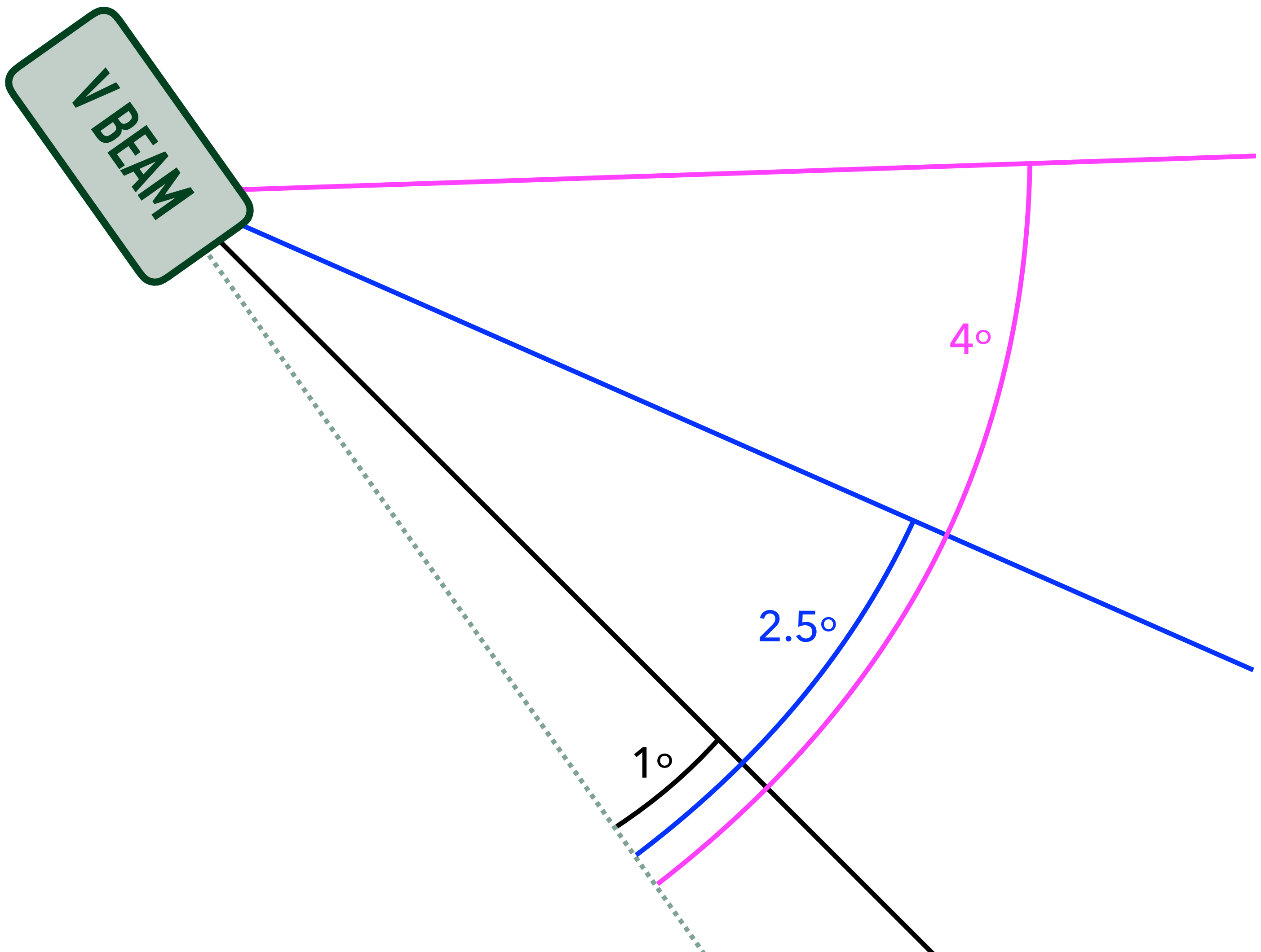
CONTROLLING SYSTEMATICS FOR ATMOSPHERIC PARAMETERS

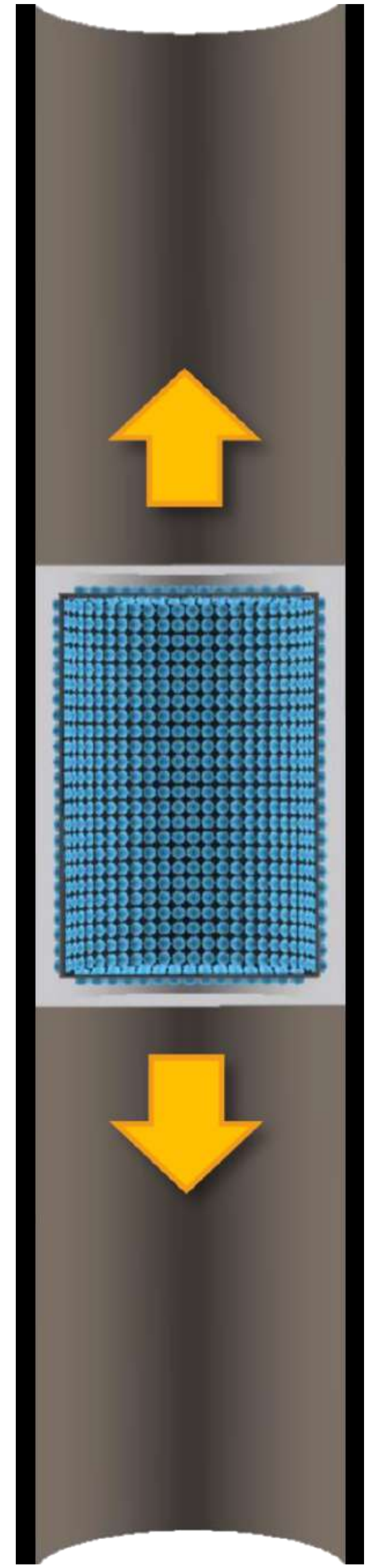


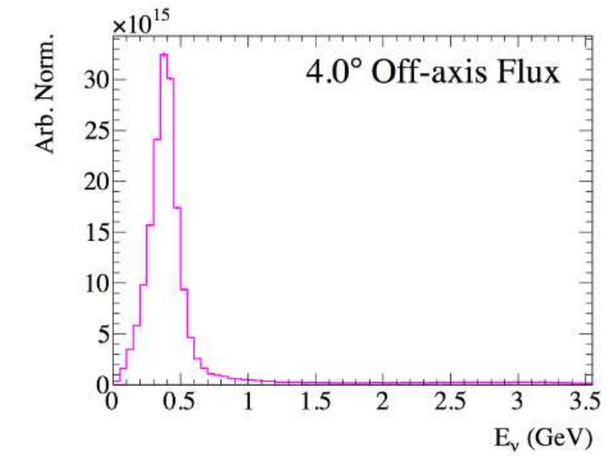


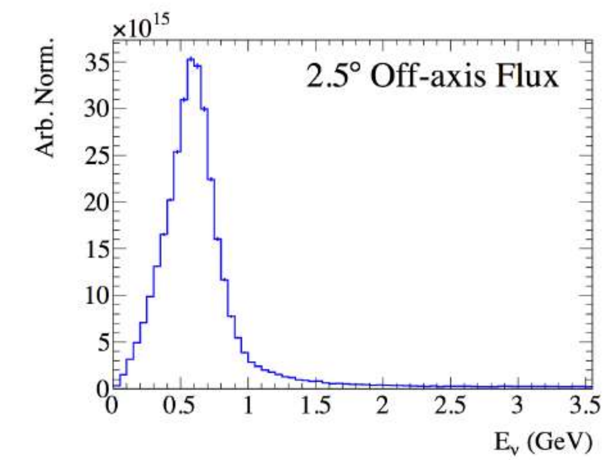
- We rely on a neutrino interaction model to reconstruct the neutrino energy from the final state lepton kinematics.
- Non-CCQE processes tend to feed-down to lower neutrino energies.
  - In the muon neutrino and antineutrino analyses this feed-down fills the region of the oscillation maximum and can bias the measurement if not properly modelled.
- Need 5% precision on measurement of feed-down to achieve 3.5% error on $\sin^2\theta_{23}$.

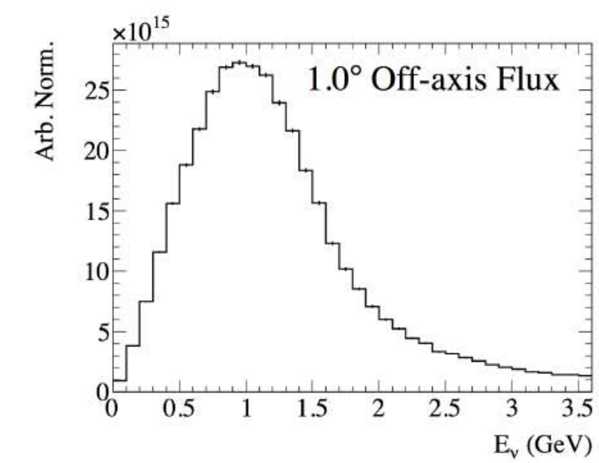
IWCD CONCEPT









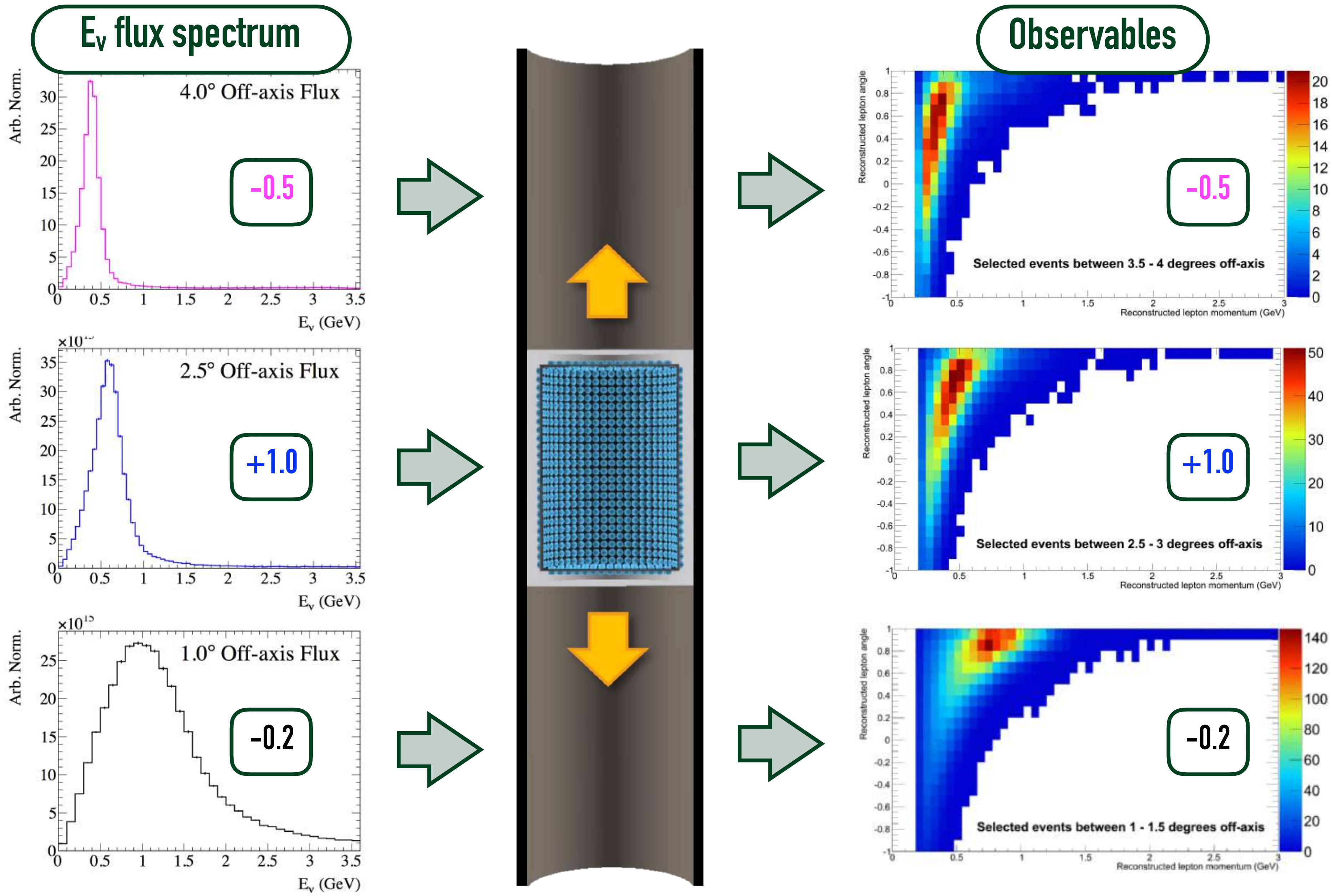


- Neutrinos produced by pion decays.
  - Higher energy spectrum for more forward going neutrinos.
- Reduction in flux uncertainty from EMPHATIC experiment.
- Can make energy dependent measurements.

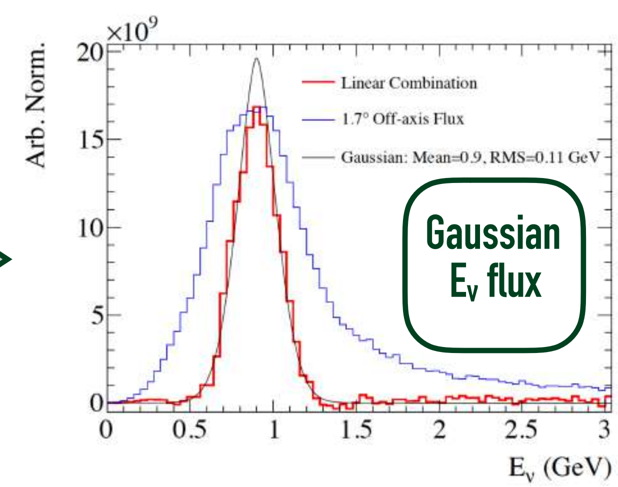
LINEAR COMBINATION ANALYSIS

Use off-axis angle dependence of ν flux:

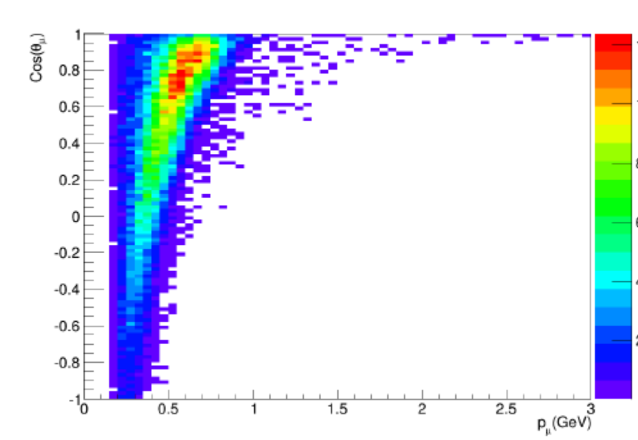
1. Bin E_ν flux spectrum into 60 different off-axis angle slices.
2. Take linear combinations of off-axis angle slices to create a neutrino flux of interest e.g. Gaussian.
3. Collect distribution of observables for same off-axis angle slices.



Find linear combinations for desired neutrino flux distribution.

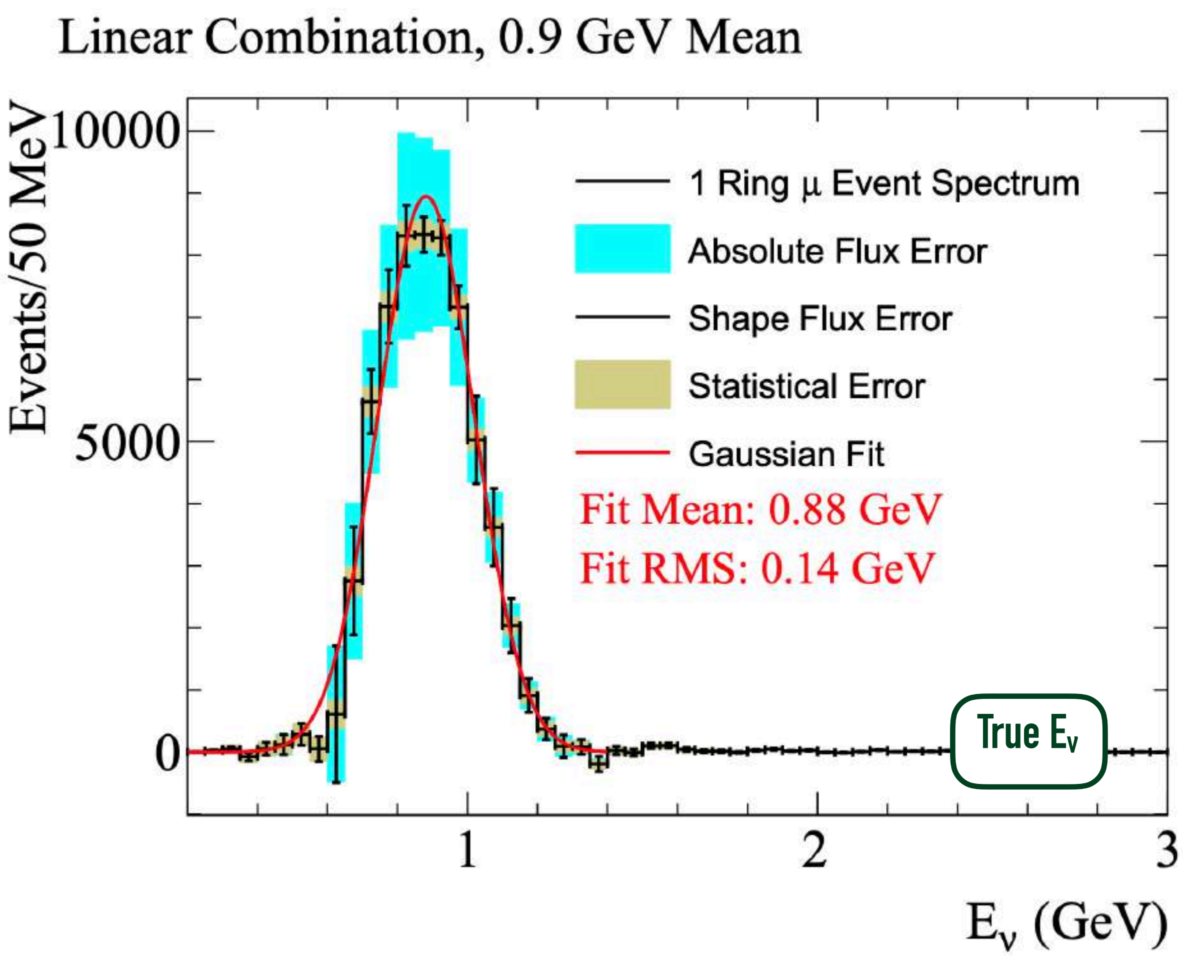


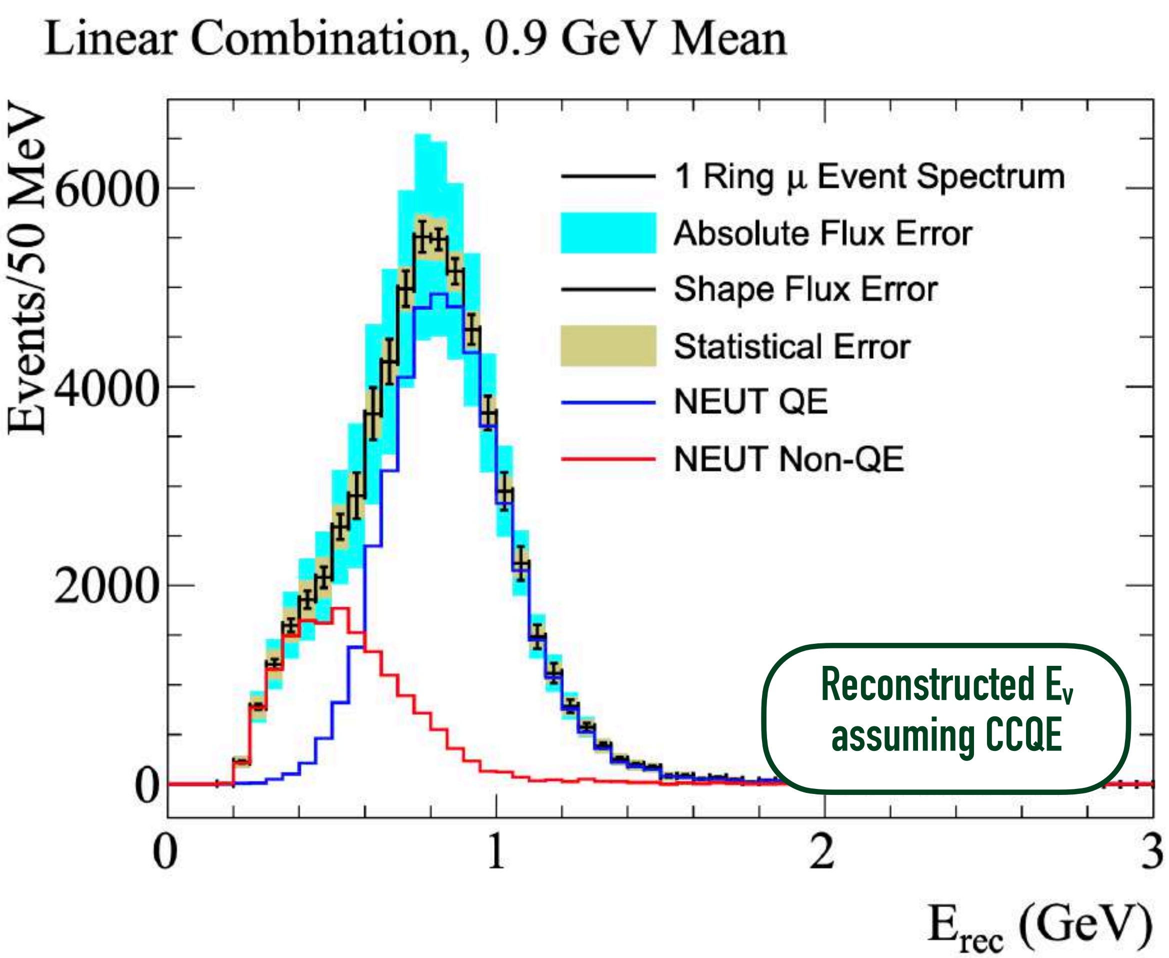
Apply coefficients to distribution of observables.



PSEUDO-MONOCHROMATIC BEAMS

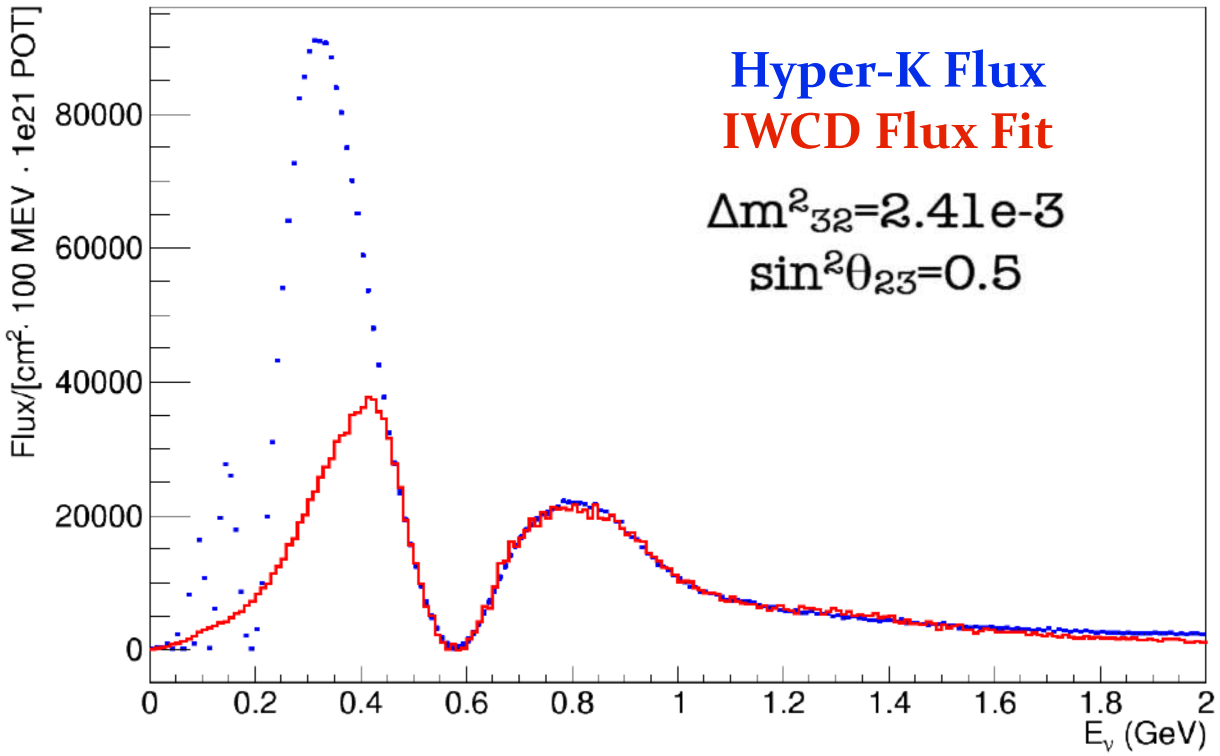
- Energy distribution for single muon candidate events after applying linear coefficients for a monochromatic beam centred at 0.9 GeV.

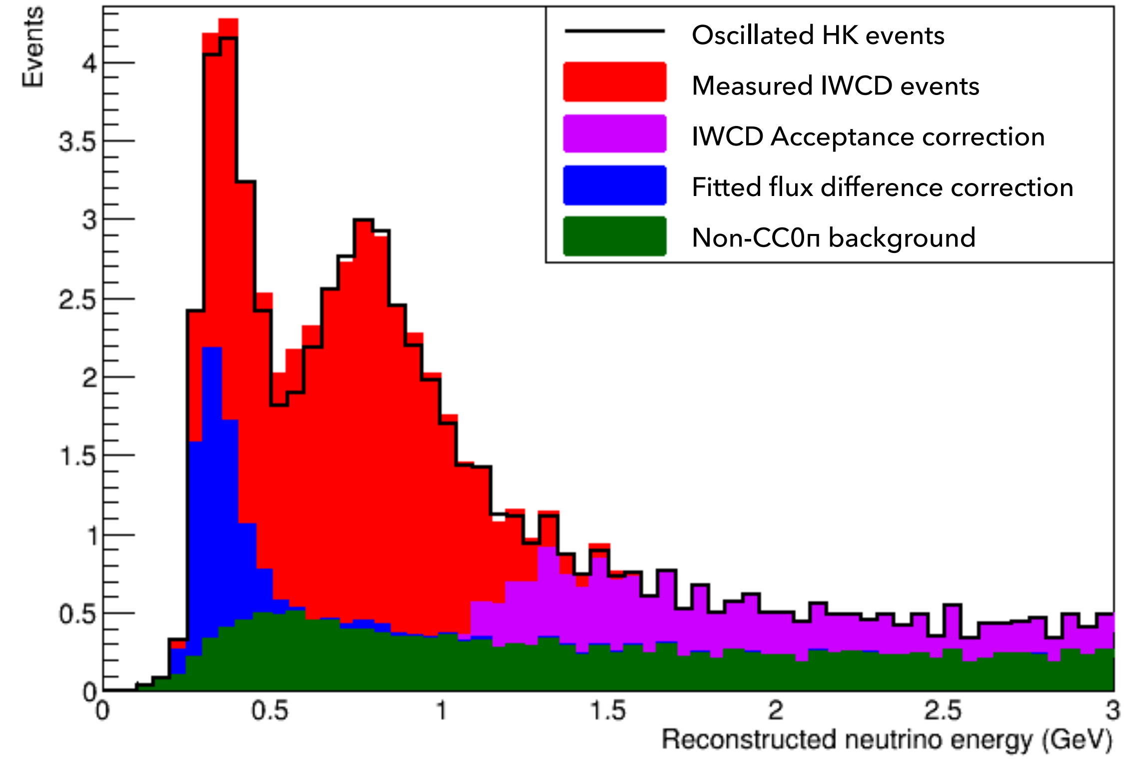




- Can observe the separation of CCQE and non-CCQE (including multi-nucleon) scatters.
  - Directly predict the effect of non-CCQE scatters in oscillation measurements and provide a unique constraint on nuclear models.
- Measure cross sections as function of true neutrino energy.
- Measure cross sections vs true observables Q^2 and ω - variables controlling interaction mode.

MUON NEUTRINO DISAPPEARANCE

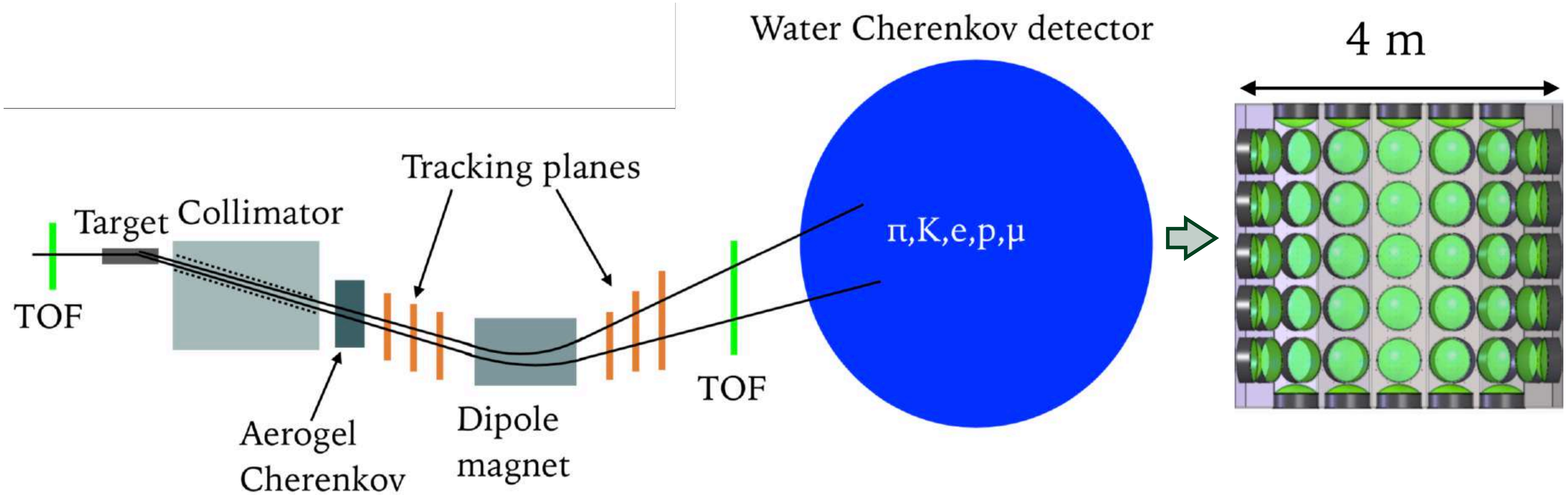




- Use linear combinations to produce the oscillated far detector neutrino flux between 400 MeV and 1 GeV.
- For each oscillation hypothesis to test, we can find a linear combination of the IWCD off-axis fluxes to give the oscillated spectrum.
- Directly compare IWCD muon p-theta prediction to observed HK events to obtain oscillation parameters.
- IWCD and HK have the same interaction material - same interaction cross-section.
  - Reduced dependence on the cross-section model and sensitivity to wrong model choice.
- Background, flux, and acceptance corrections are necessary for HK prediction.
  - Significant uncertainty cancellation in background subtraction.

IWCD TEST BEAM EXPERIMENT

- Planning for an initial stage prototype experiment in a charged particle test beam.
  - Known particle type, momentum, track start point.
    - Want measurements with p, e, $\pi^{\pm}$, $\mu^{\pm}$.
  - Beam momenta range from 140-1200 MeV/c are the goal.
  - In discussions with CERN.
- Goals:
  - Test critical components for full IWCD.
  - Prove bottom-up calibration of WC detector to 1% level.
  - Measure physics processes, such as Cherenkov light profile and pion scattering.
- Aim for data taking in 2021.



SUMMARY

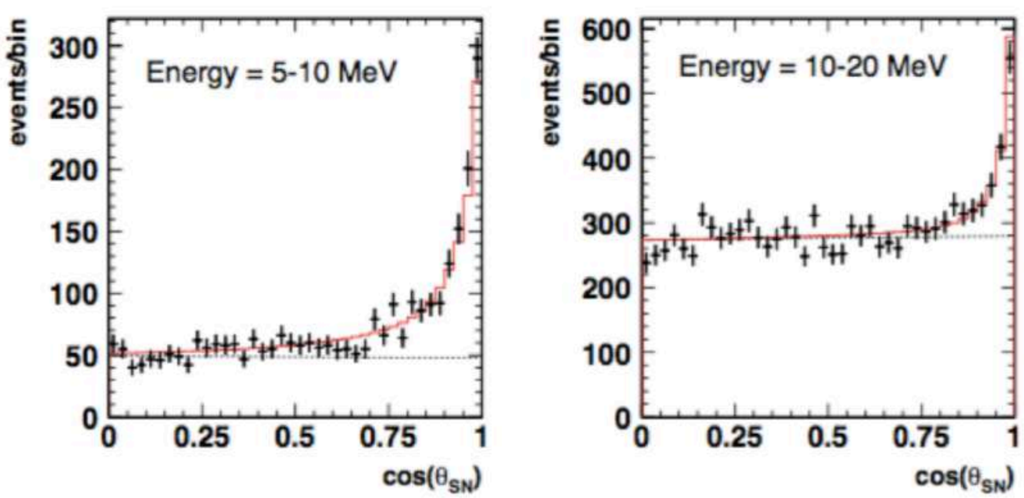
- Hyper-K a next generation water Cherenkov detector.
- Can study neutrino oscillations via beam, atmospheric and solar neutrinos.
- Plan to add a second tank in South Korea.
  - Improves sensitivities for all Hyper-K physics studies.
- Future long-baseline oscillation experiments, such as Hyper-K, will be dominated by systematic rather than statistical uncertainty.
- IWCD a novel near detector capable of controlling many of the systematics.

BACKUP SLIDES

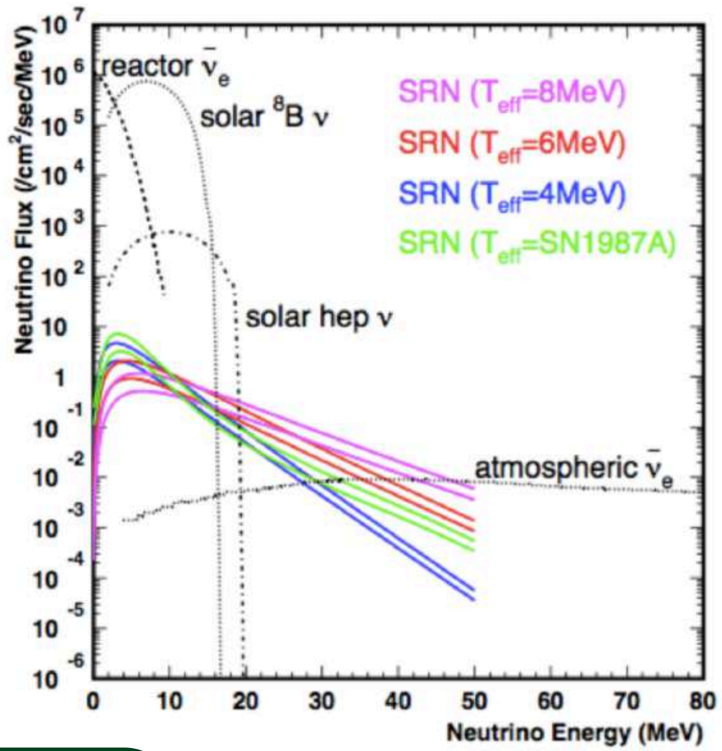
HYPER-K'S BROAD PHYSICS PROGRAM

- Hyper-K has a broad physics program beyond neutrino oscillation physics.

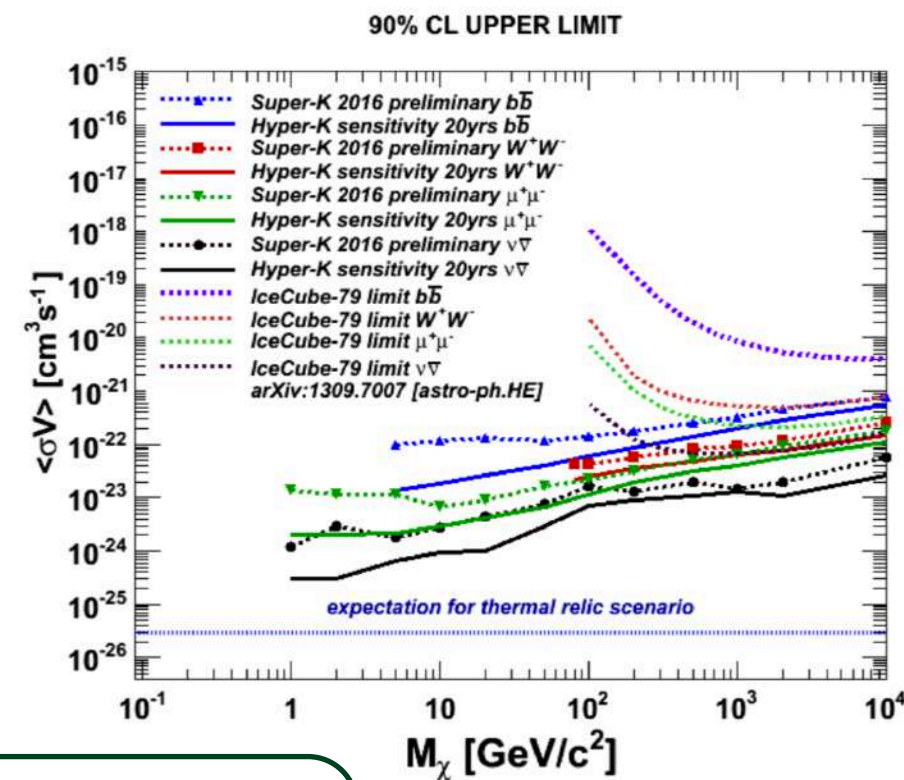
Supernova burst



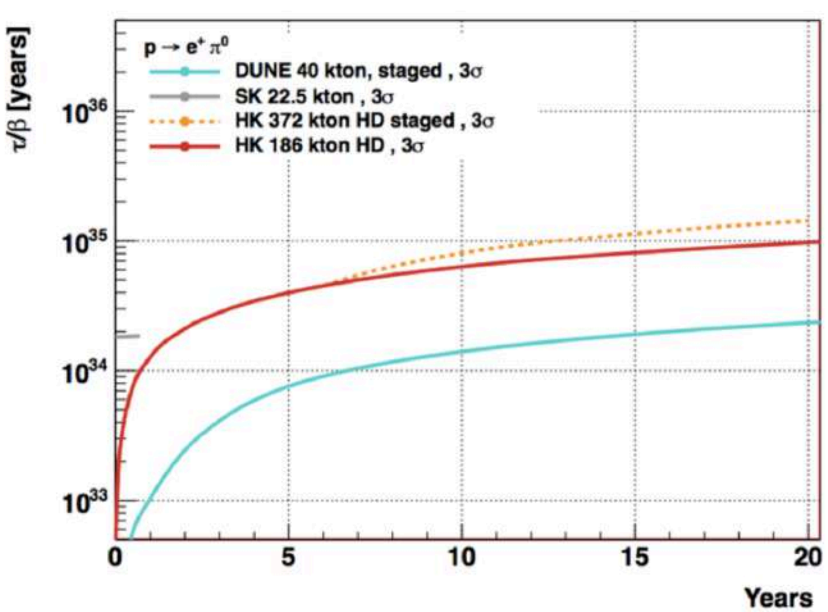
Supernova relic neutrinos



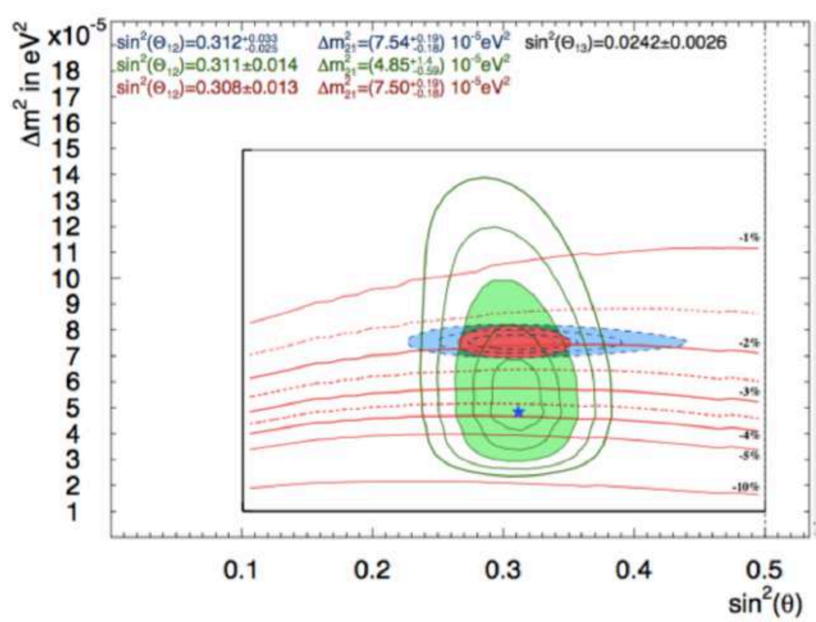
Dark matter



Nucleon decay

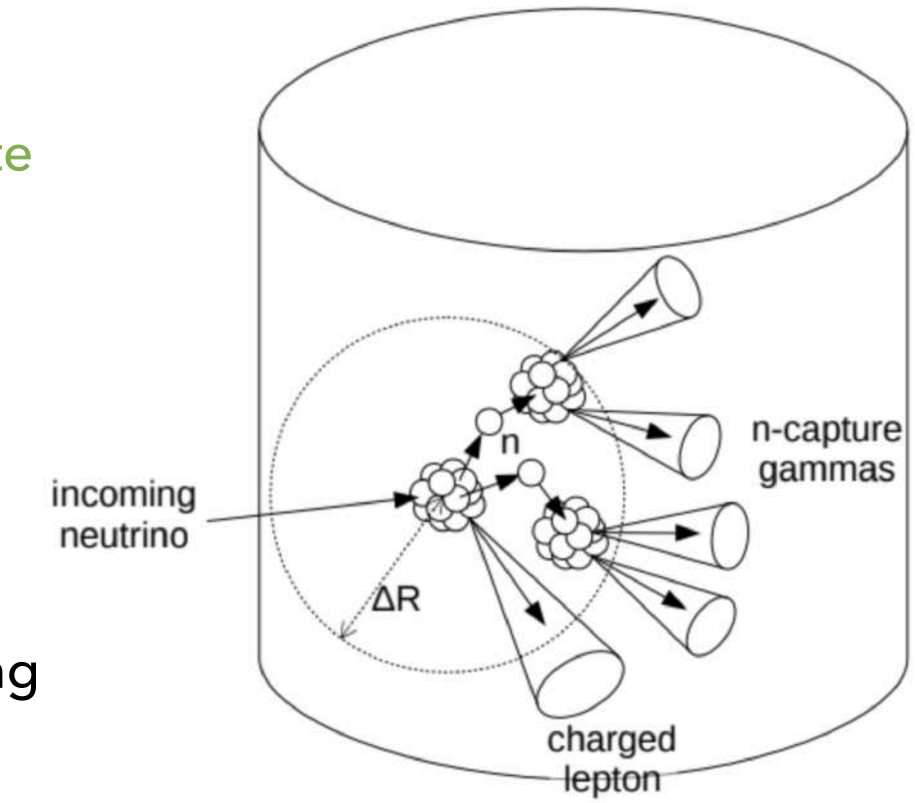


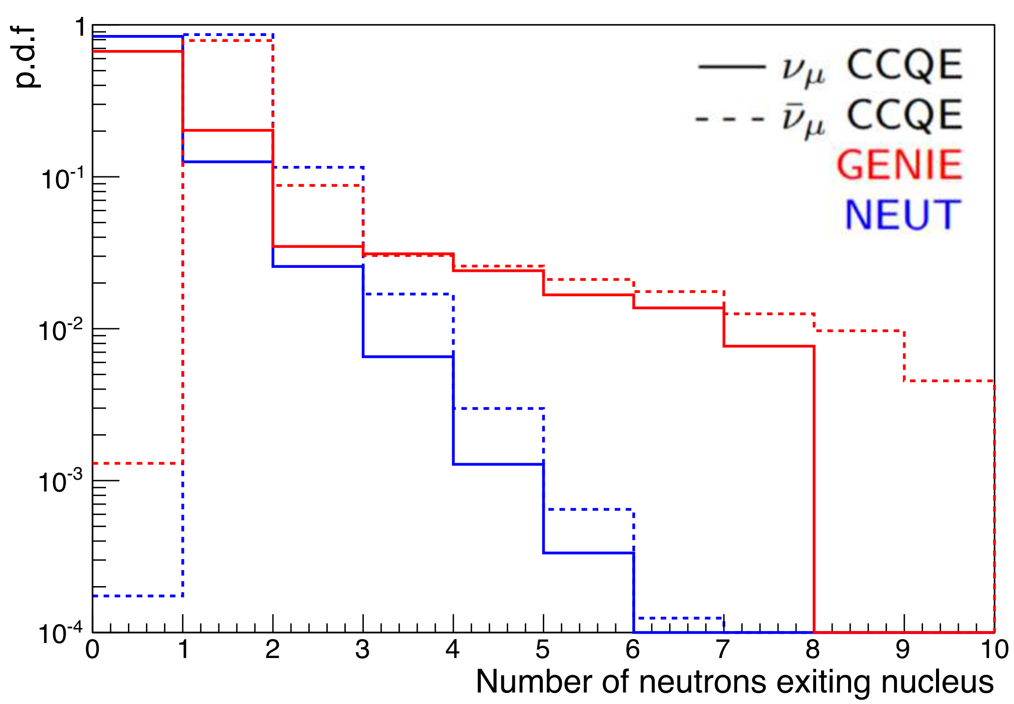
Solar neutrinos



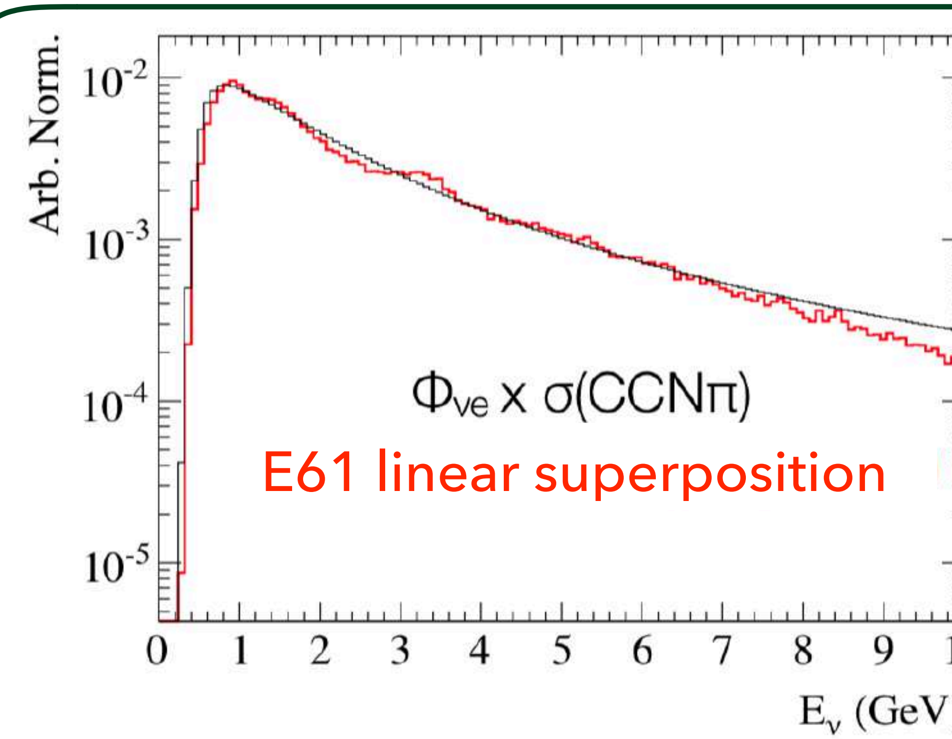
GADOLINIUM LOADING

- Gadolinium has a high neutron capture cross section.
  - Captures produce ~8 MeV photon cascade.
- Measurement of neutron multiplicity in order to statistical separate ν/anti-ν interactions.
  - Separate atmospheric neutrino samples.
  - Reduce wrong-sign background for beam samples.
- Can measure the $\mu^+\pi^0$ background from neutrino interactions to improve the $p \rightarrow e^+\pi^0$ proton decay search.
  - Simulation including neutron backgrounds shows 75% tagging efficiency with 92% purity can be achieved.





Significant differences between GENIE and NEUT neutron models

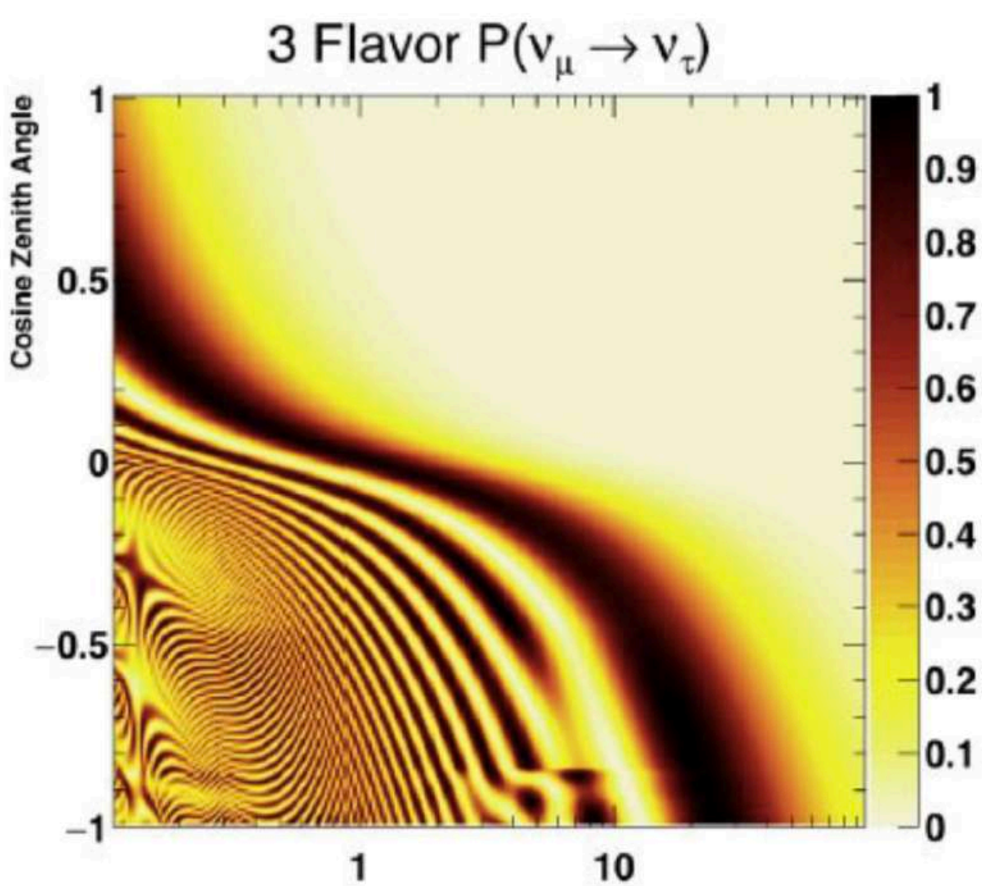


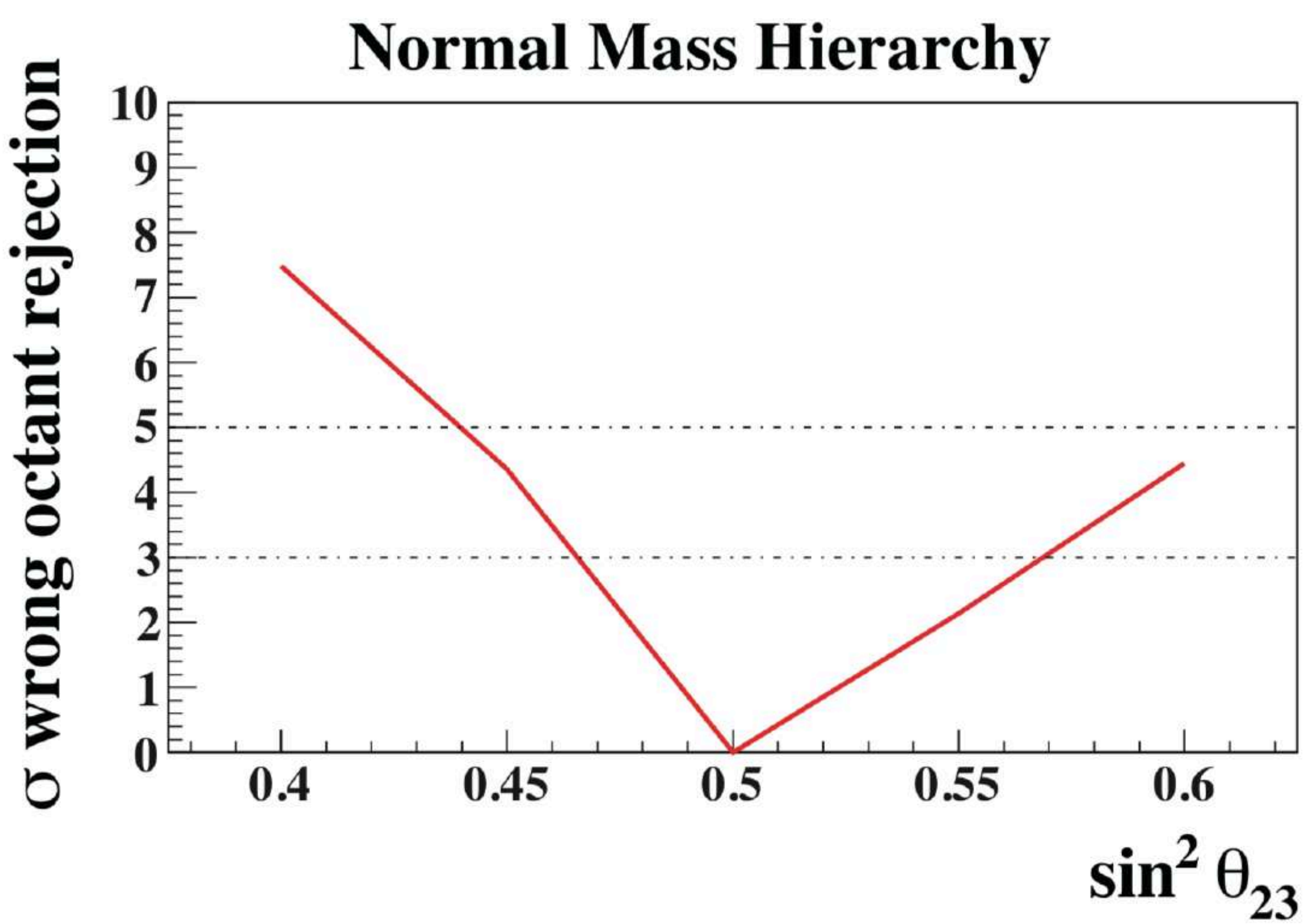
Directly measure $\mu^+\pi^0$ background with E61

ATMOSPHERIC PARAMETERS

- Target sensitivity of 1.6%-3.4% on $\sin^2\theta_{23}$ and 0.6% on Δm^2_{32}.
- Aim to identify the θ_{23} octant for values that deviate significantly from $\sin^2\theta_{23} = 0.5$.
- Answer the question: Is θ_{23} consistent with 45°, indicating underlying symmetry?

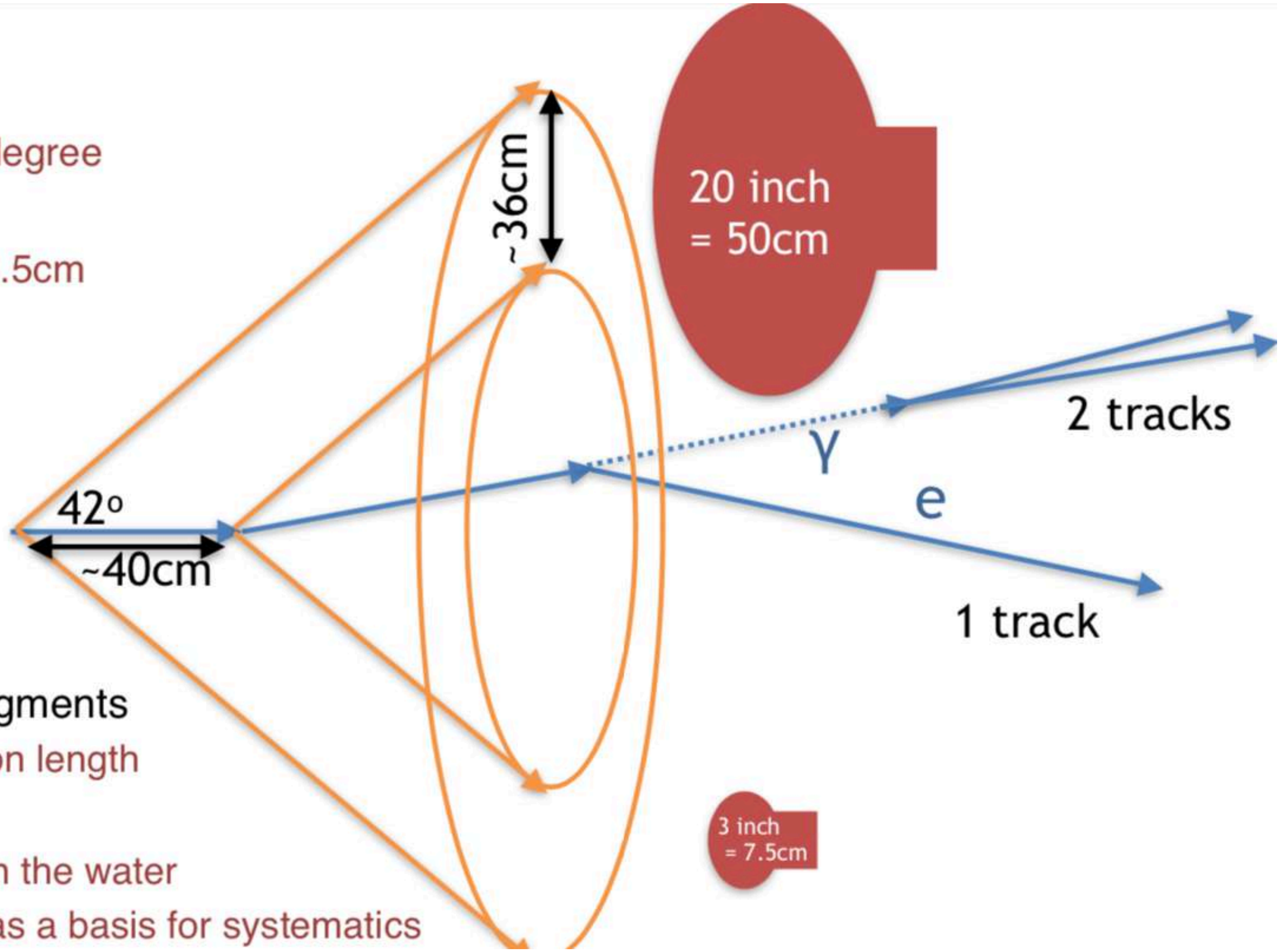
True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$
NH	1.4×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009
IH	1.5×10^{-5}	0.006	1.4×10^{-5}	0.017	1.5×10^{-5}	0.009





IMPROVED EVENT RECONSTRUCTION

- Water
  - index: n=1.33, θ(β=1) ~ 42degree
  - radiation length ~ 36cm
  - nuclear collision length ~ 58.5cm



- Optical TPC:
  mPMT to catch each track segments
  - Finer granularity than radiation length
  - e/γ separation
  - identification of π scattering in the water
  - track elements can be used as a basis for systematics

HYPER-K SYSTEMATIC REQUIREMENTS

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
$\sigma(\nu_e)/\sigma(\nu_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	**IWCD**	3.5-5%
$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	**IWCD**	4-7%
Wrong-sign background normalization	9%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	ND280	TBD (expect <9%)
Intrinsic ν_e,$\bar{\nu}_e$ and NC backgrounds	3-4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	**IWCD**	2.3% (neutrino)
Normalization of non-QE with E_ν>0.7 GeV	5%	θ_{23} precision at $\sin(\theta_{23})\neq0.5$	**IWCD**	5% (neutrino)
Normalization of non-QE with all energies	5%	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	**IWCD**, ND280*	5% (IWCD neutrino) <4% (N280 neutrino) <7% (ND280 antineutrino)

- Complementary approaches in IWCD and ND280. IWCD relies on flux model in linear combination method, but minimises cross section model dependence. ND280 fits transverse variables to constrain cross section model.

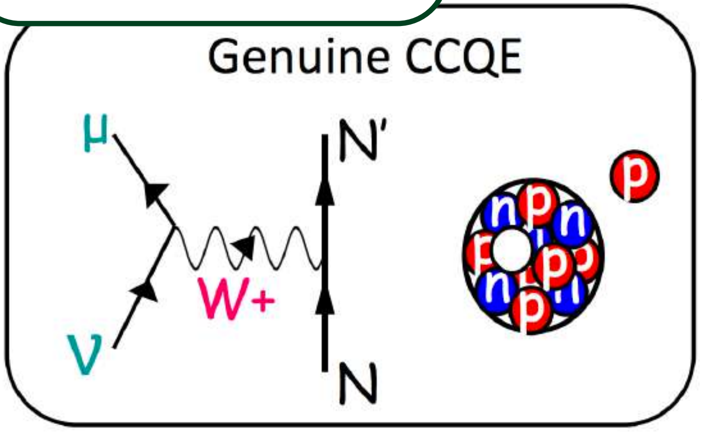
HYPER-K SYSTEMATIC REQUIREMENTS

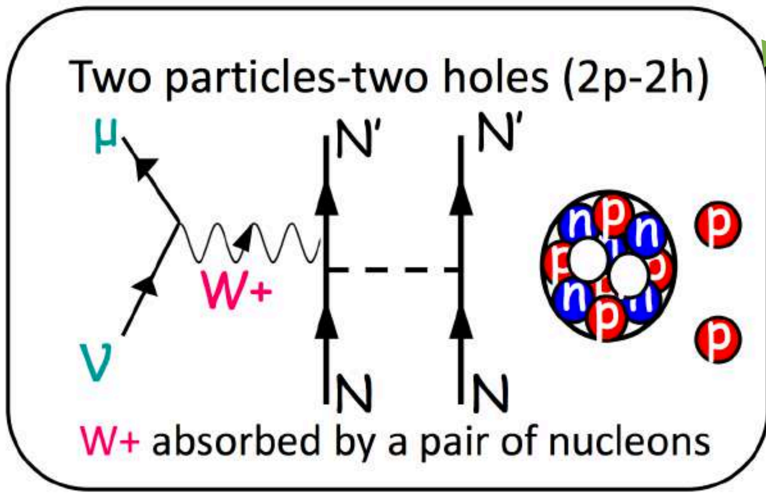
Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
Beam Direction	0.6 mrad (4 MeV shift)	δ_{cp} precision at $\sin(\delta_{cp}) \sim 0$ Δm^2_{32} precision	INGRID	<0.3 mrad (<2 MeV)
Removal (binding) energy	4 MeV*	δ_{cp} precision at $\sin(\delta_{cp}) \sim 0$ Δm^2_{32} precision	**IWCD**, ND280	2.6 MeV (IWCD on O) ~1 MeV (ND280 on C)**
High angle measurement ($\cos\theta<0.2$)	4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp}) \sim 0$	**IWCD**, ND280	<4% statistical precision in both detectors
Beam rate monitoring	~1% per day	General monitoring of beam quality	INGRID	<0.5% per day for neutrinos and antineutrinos
Neutron Multiplicity	TBD	Atmospheric neutrino Nucleon decay	**IWCD**, ND280	<5% IWCD <4% ND280
$\mu\pi^0$ cross section & neutron multiplicity	TBD	$e\pi^0$ proton decay	**IWCD**	TBD

- Energy scale in detectors must be calibrated to 0.5% to achieve this level.
- The IWCD is critical for controlling many of the important systematic errors for Hyper-K.

MEASURING NEUTRINO ENERGY

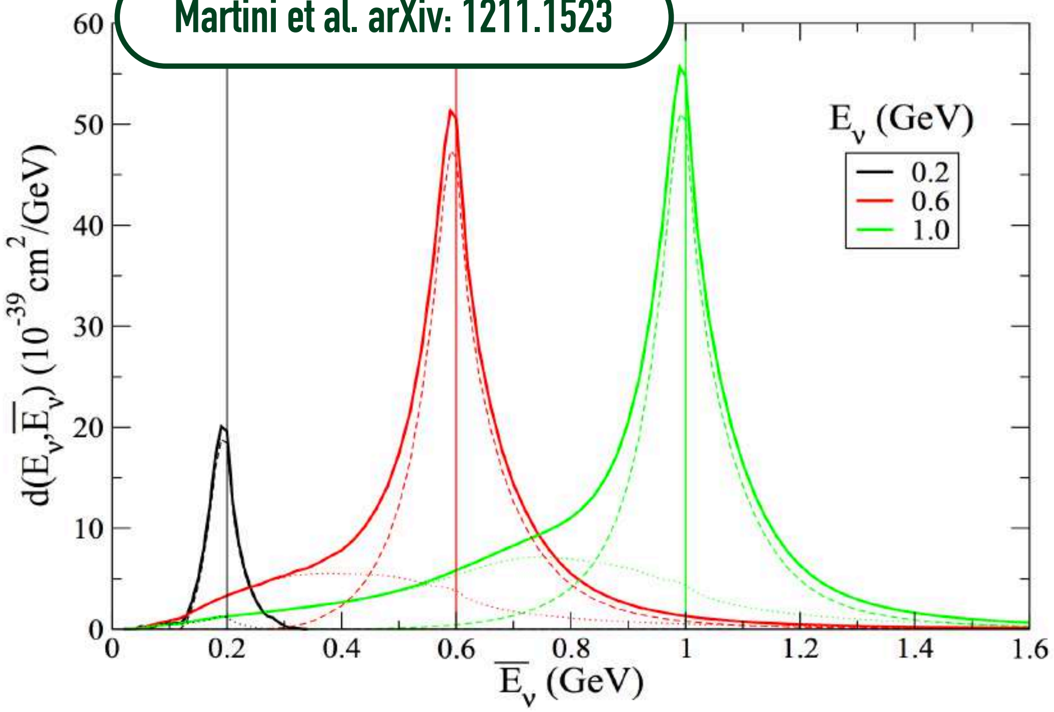
M. Martini NuFACT 2015

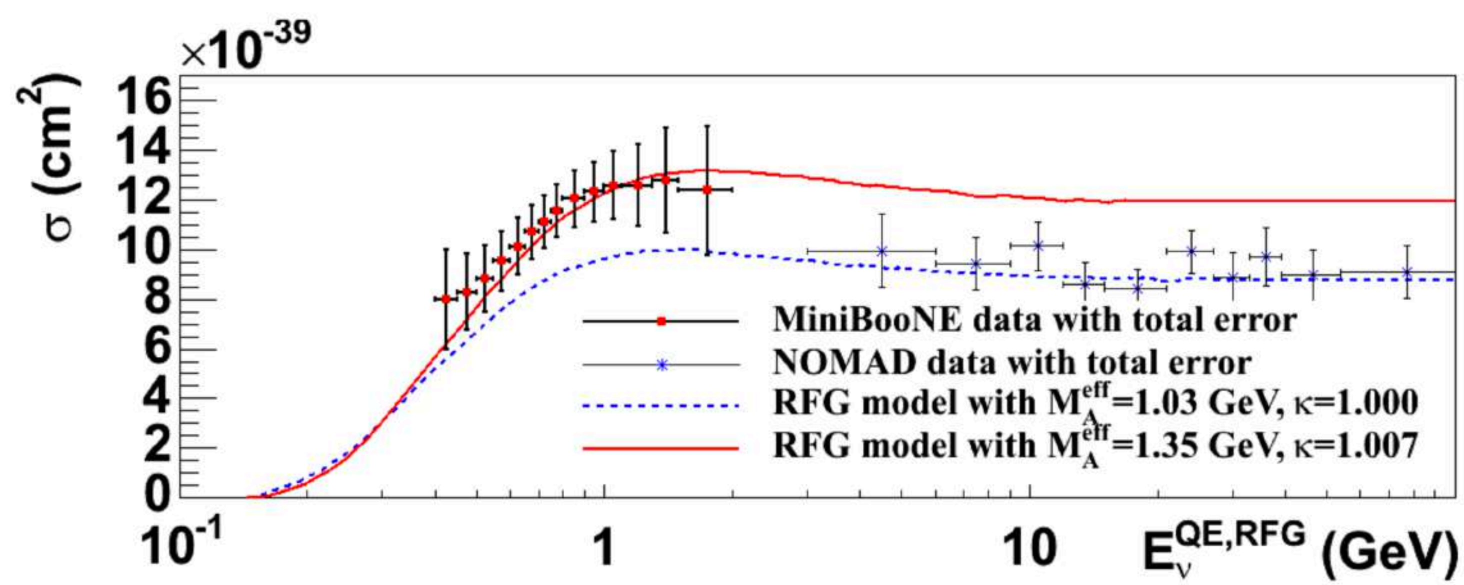




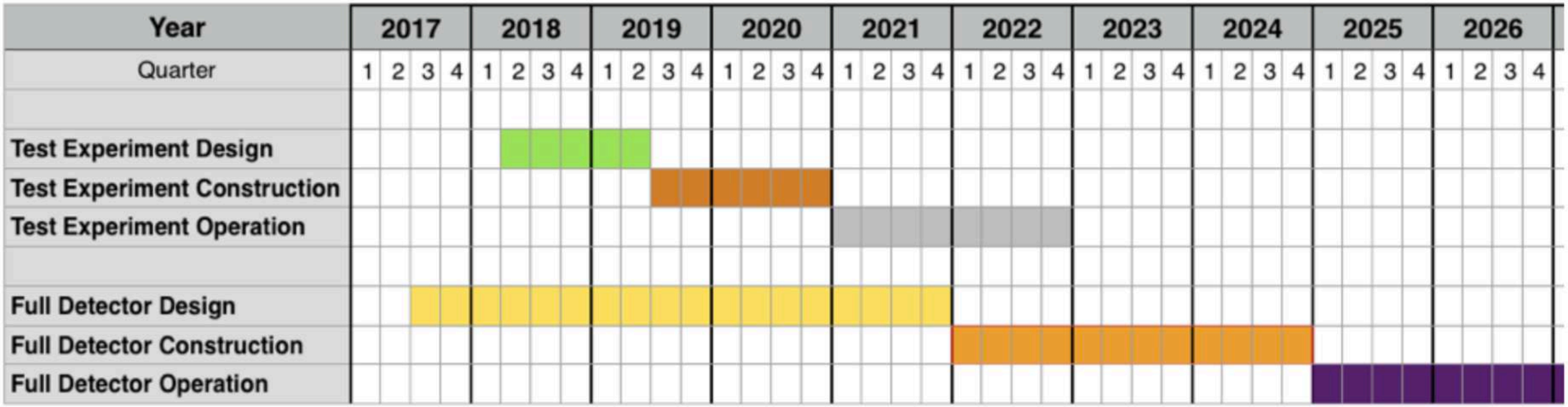
- Model assumptions play an important role in inferring neutrino energy from detected neutrino-nucleus interaction products.
- In Hyper-K charged lepton kinematics will be measured and CCQE dynamics assumed.
- Large uncertainties from final state and secondary interaction models.
  - Multi-nucleon interactions have two protons exiting a pair of nucleons.
  - Explains larger axial mass preferred by MiniBooNE over NOMAD.
  - Further missing energy from unseen pions.
- Calorimetric measurements suffer from similar model dependence.
  - For example, through uncertainties in the multiplicity of undetected neutrons.

Martini et al. arXiv: 1211.1523





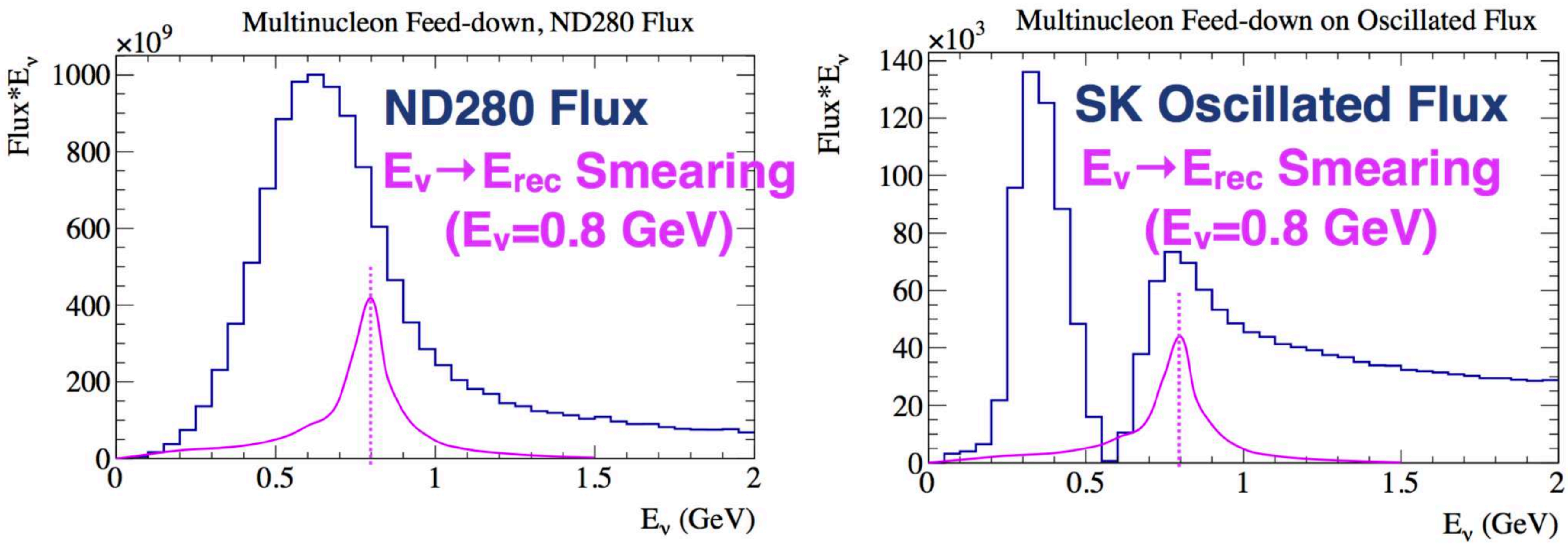
PROJECT STATUS



- Construction schedule is driven by multi-PMT module production.
- Aim to run the test beam experiment for two years starting 2021.
- Full-scale detector construction concurrent with test experiment operation.
- Aim for full-scale experiment to be taking neutrino data in 2025, one year before the start of Hyper-K.

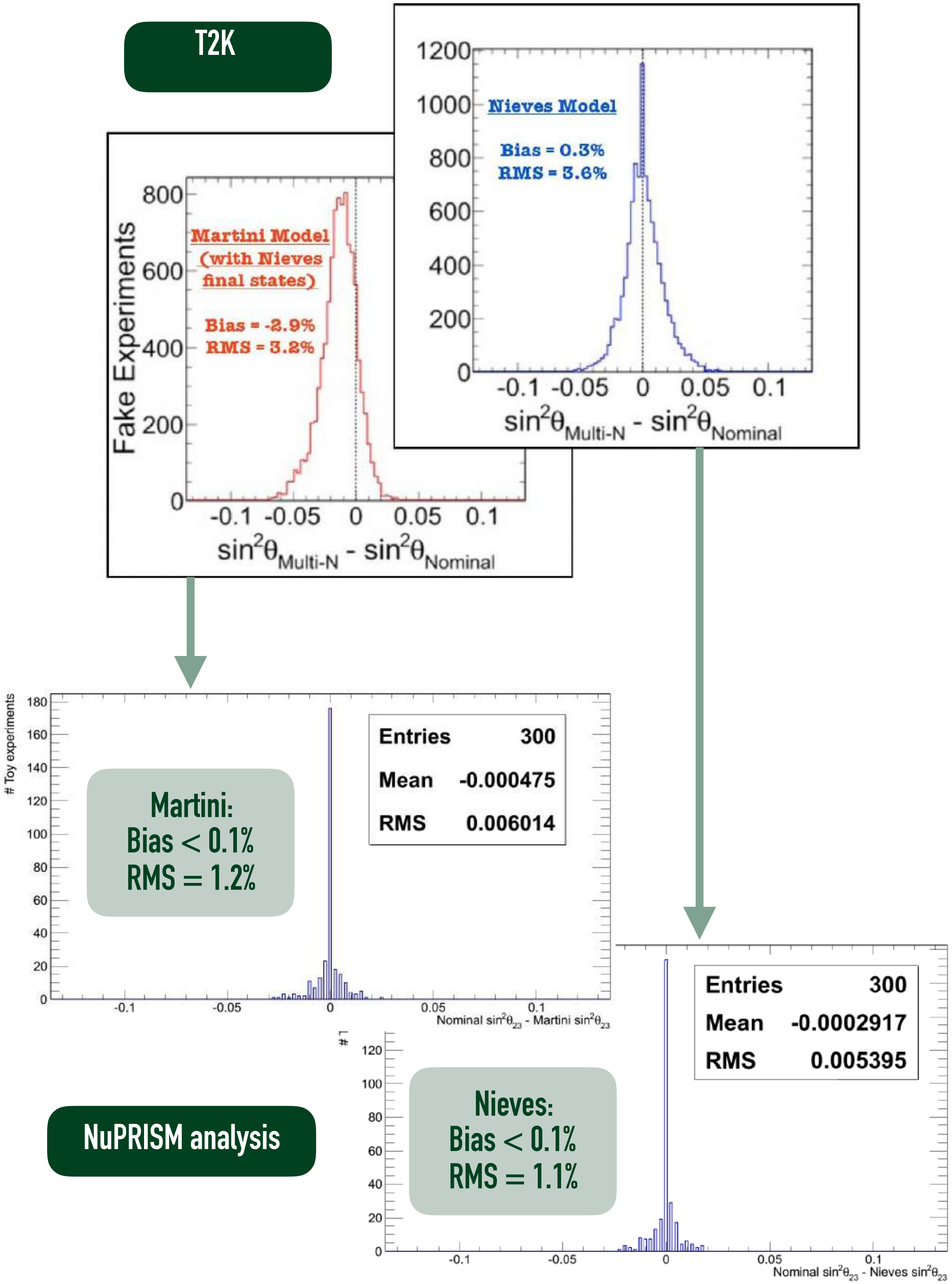
NEAR DETECTOR CONSTRAINT

- Oscillations result in different fluxes at the near and far detectors.
  - Presents an additional complication in constraining interaction model that predicts far detector event rates.



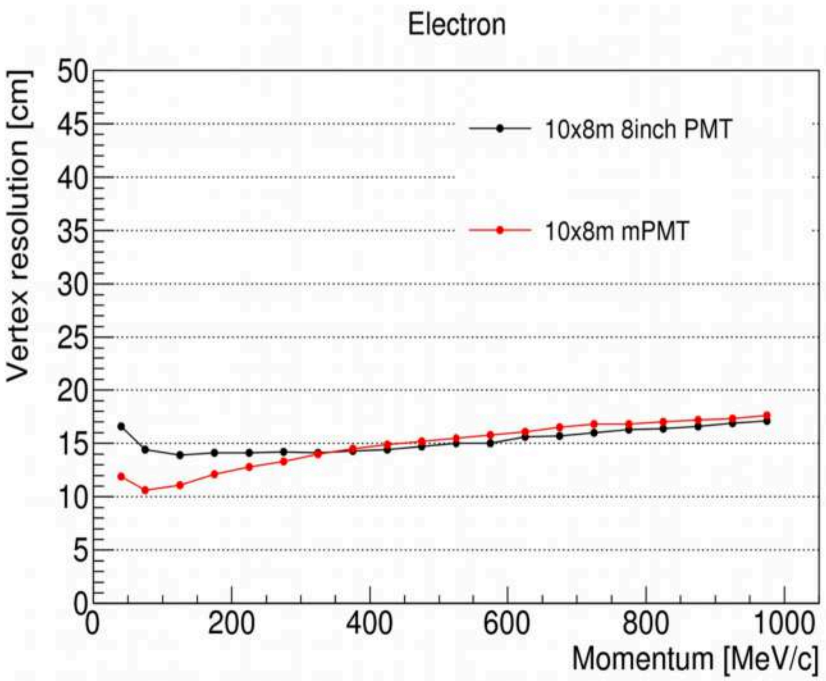
- We can only measure a convolution of the neutrino flux and cross section.
  - Hard to constrain uncertainties with a traditional near detector.
- Multi-nucleon effects and other missing interaction products can smear the reconstructed neutrino energy into the oscillation dip at the far detector.
  - Results in a bias in the measurement.
  - The bias is obscured by the flux peak at the near detector.

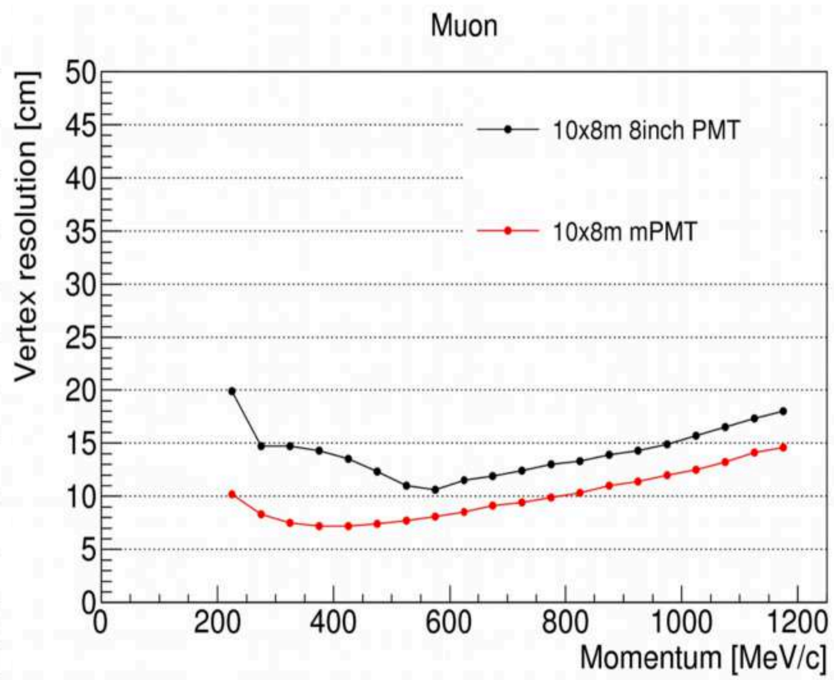
EFFECT OF MULTI-NUCLEON CROSS-SECTION MODELLING

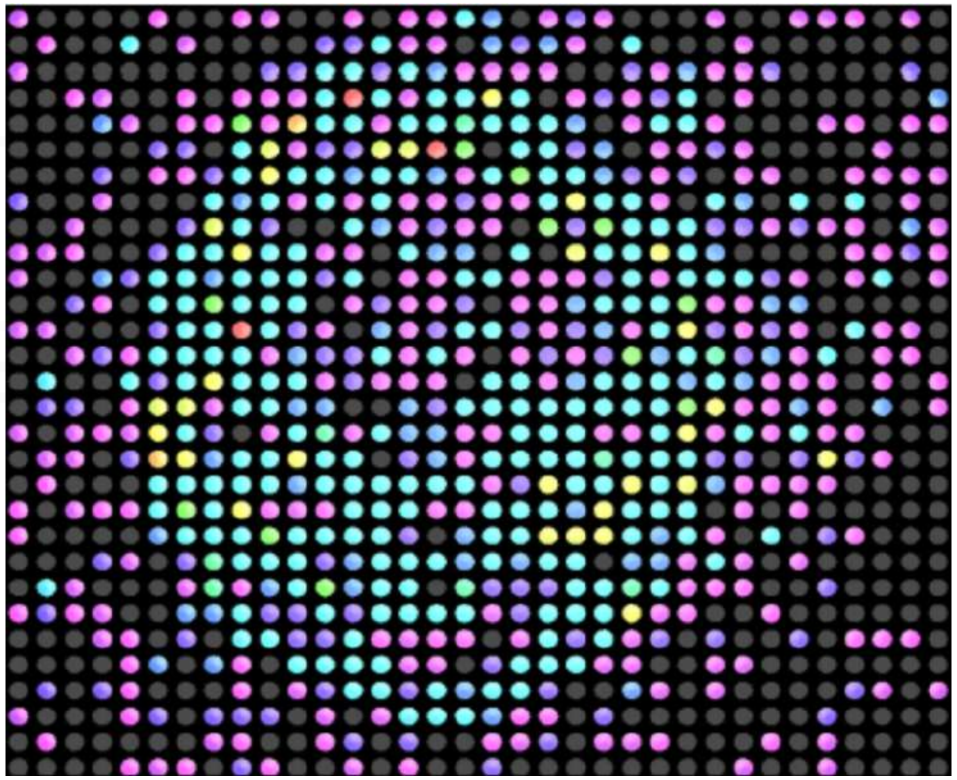


- T2K study of $\sin^2\theta_{23}$ uncertainty from mis-modelling the 2p-2h part of the cross-section found a significant bias and uncertainty.
- Same study is carried out using NuPRISM near detector fit.
- SK event rate is accurately predicted even with additional 2p-2h interactions added to the toy data.
- The $\sin^2\theta_{23}$ bias and uncertainty are reduced to ~1% with the NuPRISM measurement.
- NuPRISM analysis largely independent of cross-section model.

E61 RECONSTRUCTION PERFORMANCE

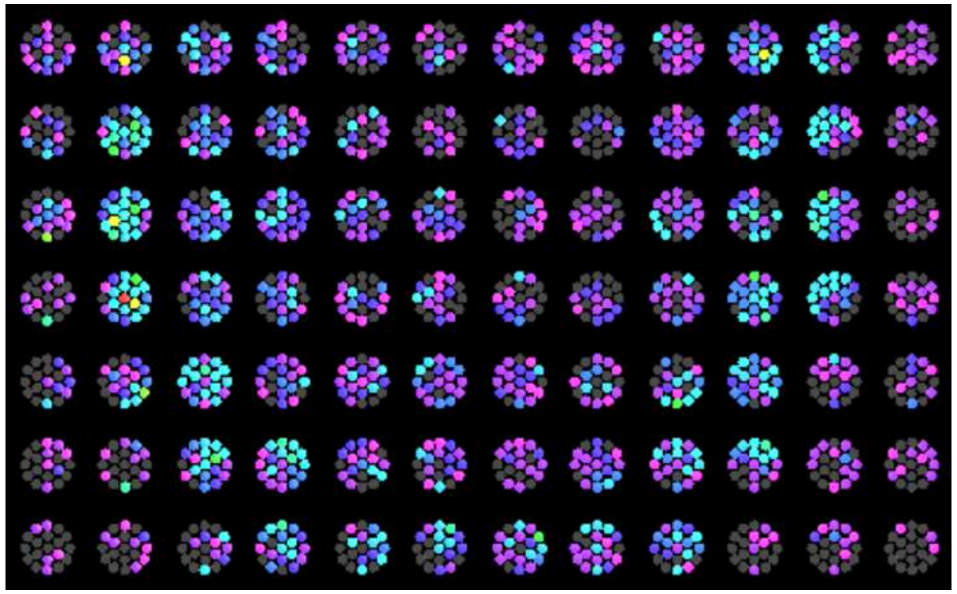






- Full detector simulation (Geant4-based WCSim) and reconstruction (fiTQun) developed for E61.
- Studies show good particle identification despite small size of inner detector.
- Quantifying reconstruction/PID improvements for mPMTs vs 8" PMTs.
- Ongoing reconstruction improvements:
  - Improve PMT angular response function.
  - Include PMT direction information to scattered and reflected light prediction.

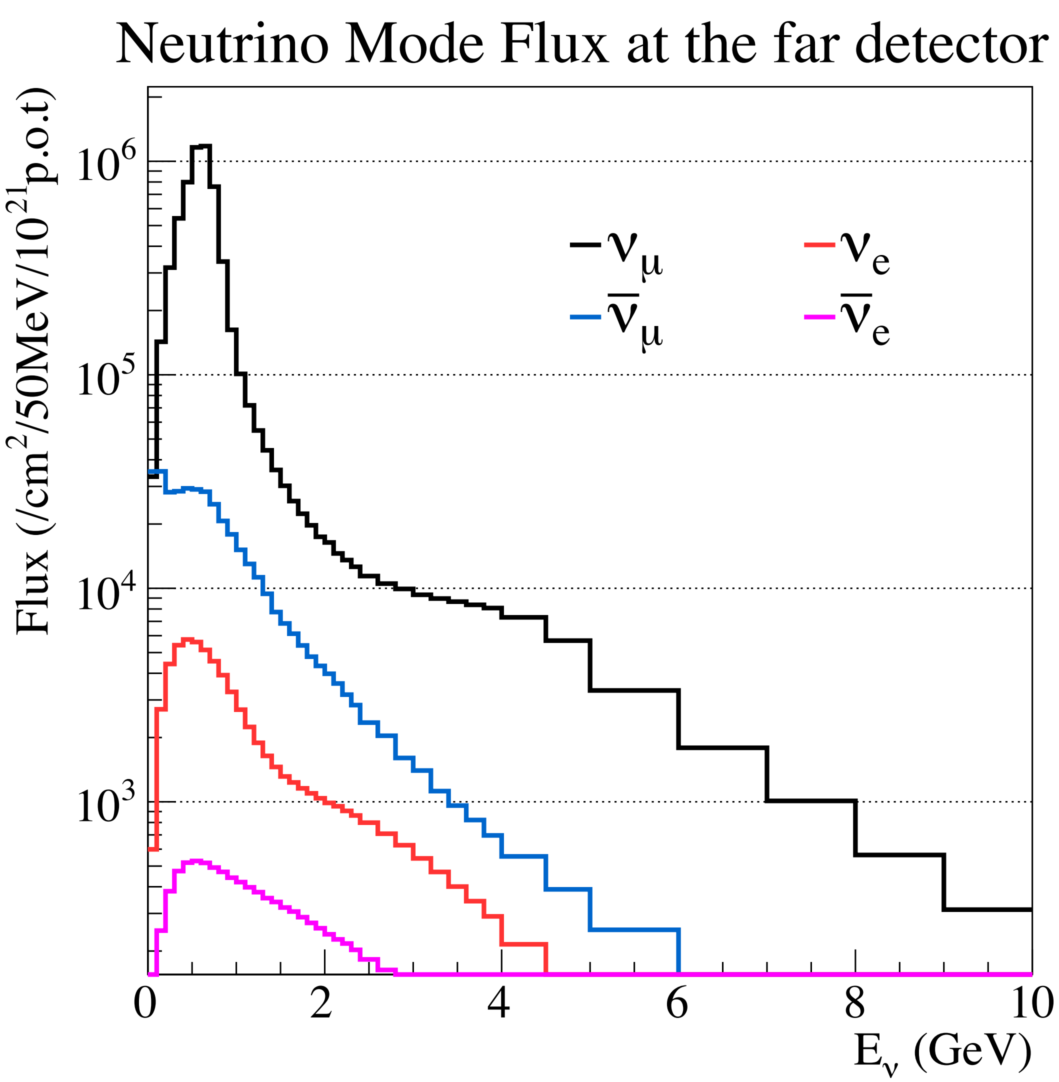
Better granularity
Same event, simulated with 8" PMTs (above) and mPMTs (below)

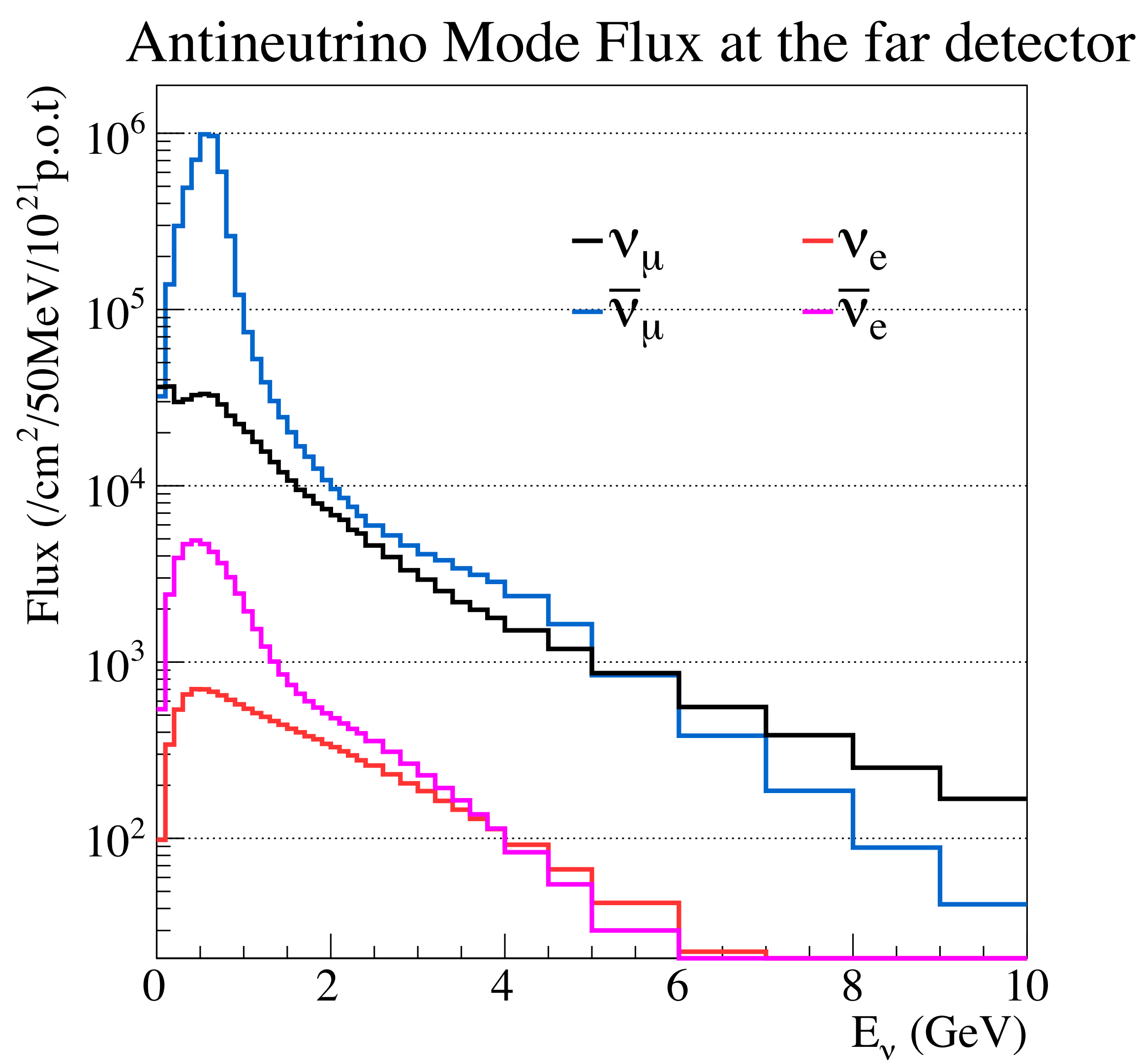


E61 DETECTOR OPTIMISATION STUDIES

ν_μ EVENT SELECTION

T2K NEUTRINO FLUX

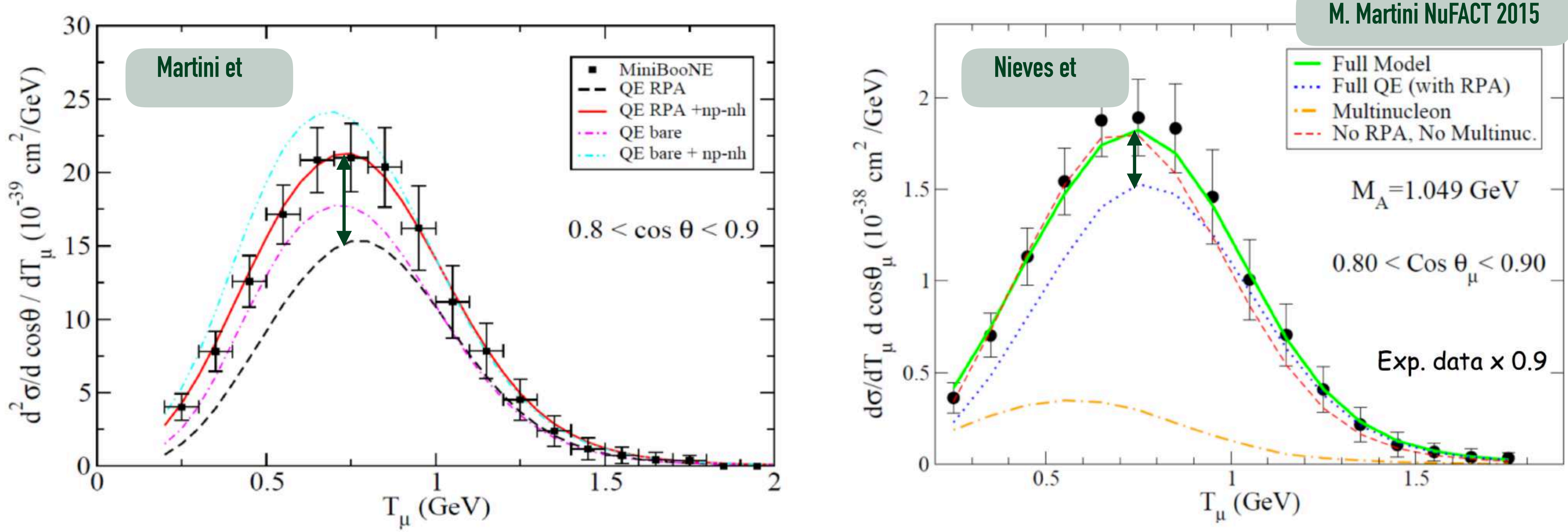




- Very low ν_e $(\overline{\nu}_e)$ contamination.
  - Less than 1% at oscillation maximum.
  - An irreducible background to ν_e $(\overline{\nu}_e)$ appearance.
- Wrong sign contamination more significant in antineutrino mode.
- Near and far flux shapes are not identical, but highly correlated.

MULTI-NUCLEON MODELS

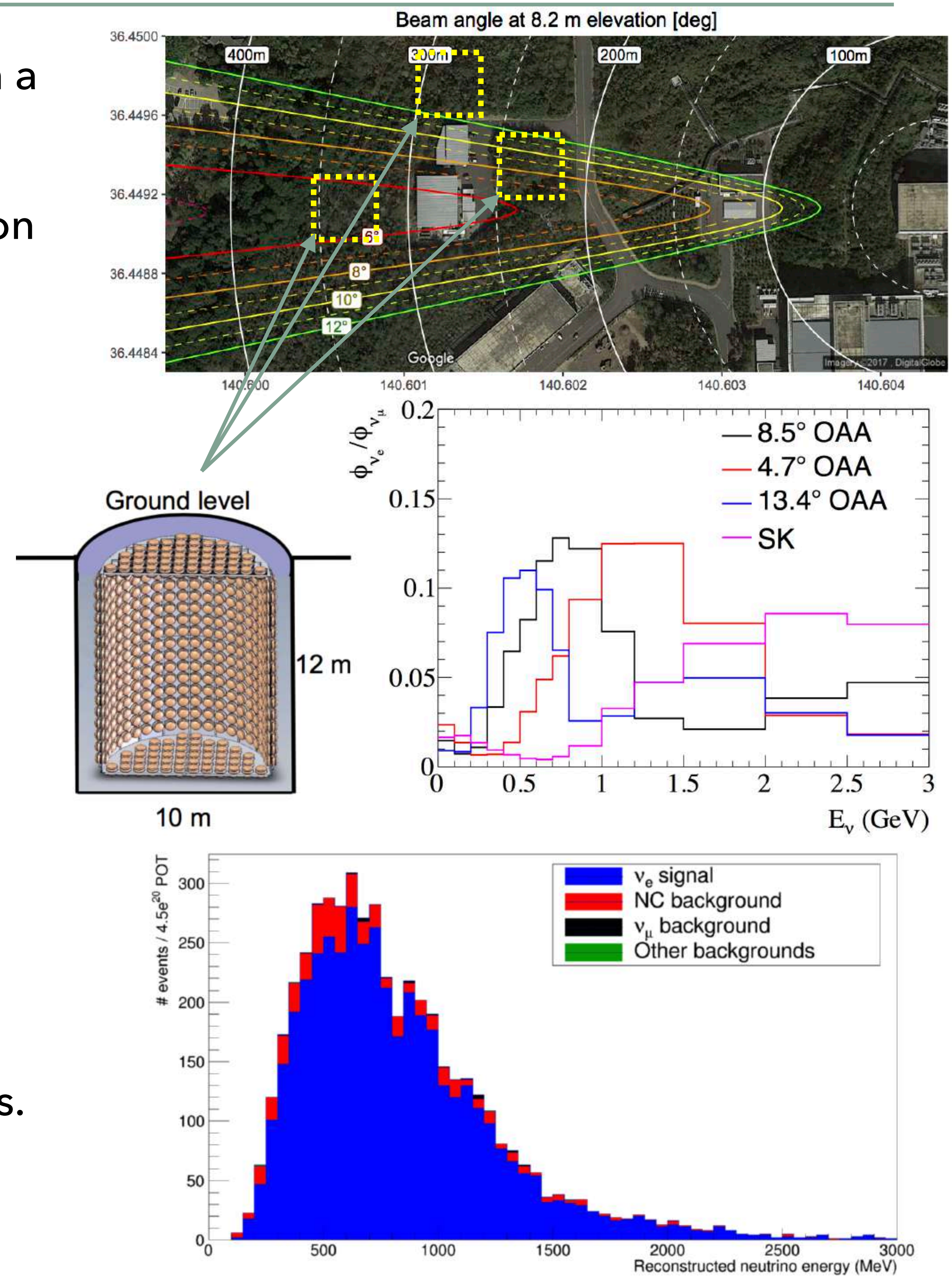
M. Martini NuFACT 2015



- Many different theoretical models.
- Martini et al. and Nieves et al. calculations are both consistent with MiniBooNE data within the MiniBooNE flux uncertainties.
- The np-nh contributions can differ by a factor of 2 in the region of interest.
- Predict different rates for neutrinos vs anti-neutrinos.
- Hard to separate models experimentally.

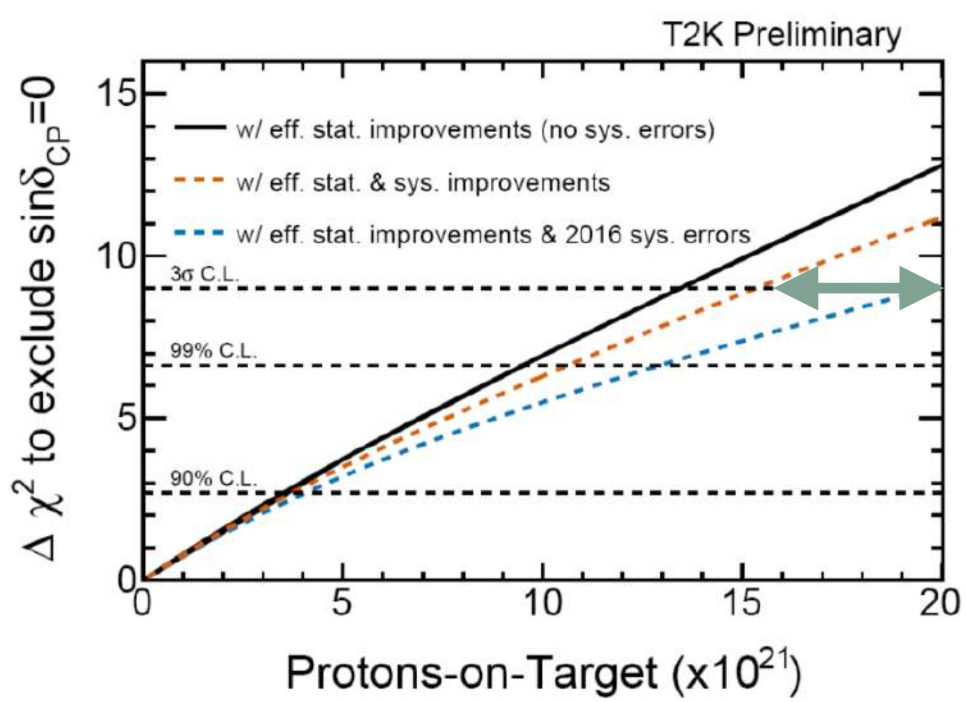
PHASE 0

- Instrumented portion of phase 1 is placed in a water tank near ND280.
- Allows us to demonstrate detector/calibration precision.
- Provides a test detector for Hyper-K R&D.
- Physics goals:
  - Measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ to ~3% precision.
  - Expect ~5500 ν_e events below 1 GeV in 1x10^{21} POT with 76% purity.
  - Gd loading to measure neutron multiplicities in neutrino-nucleus interactions.
- A range of locations being studied.
  - Optimise flux uncertainties and flux ratios.
  - Investigating feasibility of construction.

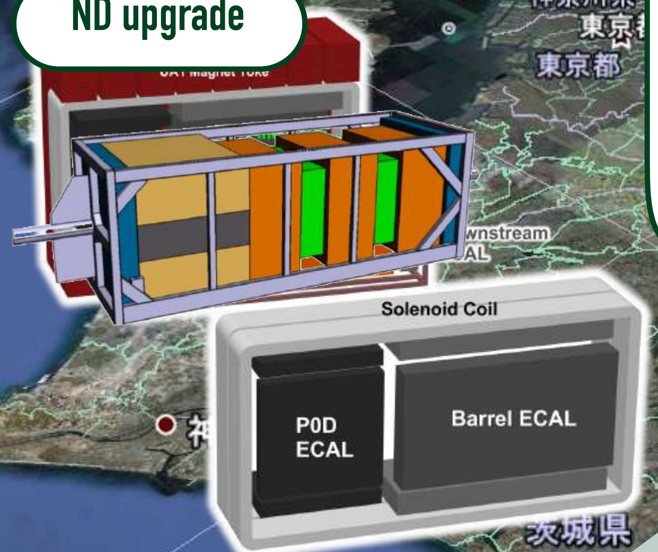


PROPOSED EXTENDED RUN OF T2K (T2K-II)

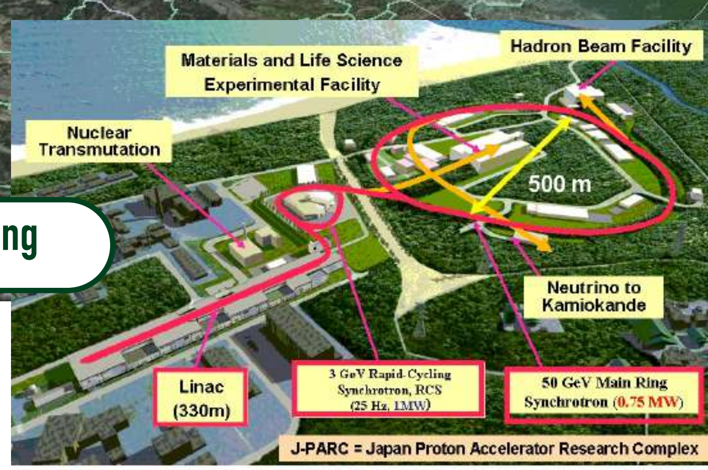
- Proposal to collect 20×10^{21} POT by ~2026.
  - 3σ sensitivity to maximal CP violation.
- Accelerator to be upgraded to 800 kW (and then 1.3 MW).
- Near detector to be upgraded.
- Addition of an intermediate water-Cherenkov detector (E61).



ND upgrade



Upgraded main ring



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CURRENT T2K SYSTEMATIC ERRORS

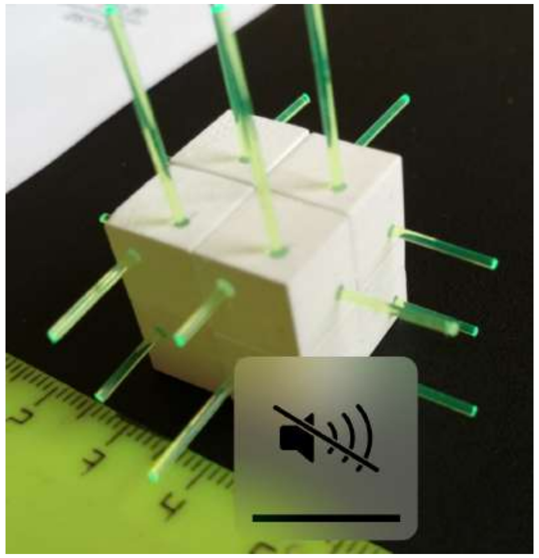
- Systematic uncertainty at the 6% level. Need reduction to ~3% level for Hyper-K.

Source of uncertainty	μ-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$	e-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$
SKDet	0.07%	1.6%
FSI+SI	2.6%	3.6%
Flux	1.8%	1.8%
Flux+XSec (ND280 constrained)	1.9%	2.2%
XSec NC other (uncorr)	0.0%	0.2%
XSec NC 1γ (uncorr)	0.0%	1.5%
XSec ν_e / ν_μ (uncorr)	0.0%	3.1%
Flux+XSec	1.9%	4.1%
All	3.2%	5.8%

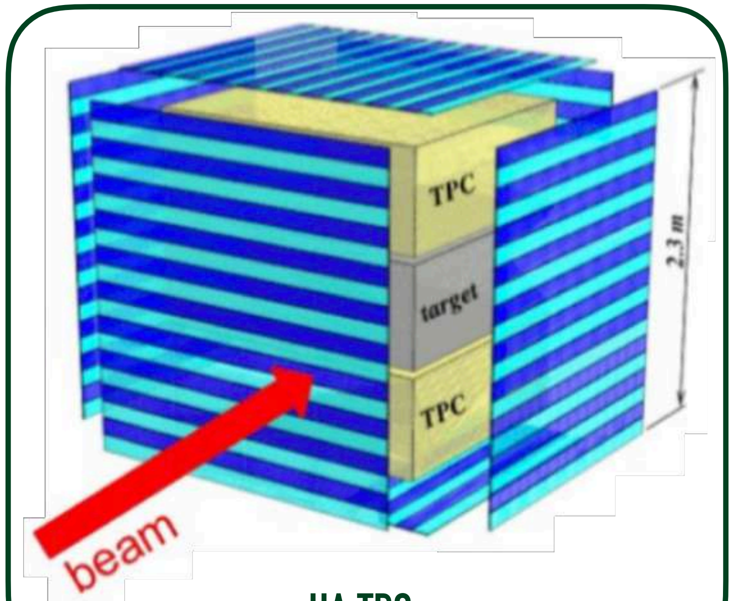
- CP violation measurement depends on uncertainty of $\nu_e/\overline{\nu}_e$ ratio.
- Dominant uncertainties:
  - Final state interactions (FSI) and secondary interactions (SI) - nuclear model extrapolated from pion-nucleus scattering experiments.
  - Electron/muon neutrino cross-section ratio - need data in energy range of interest, low statistics and large background for electron samples.
  - ND280 flux + cross-section constraint - affected by nuclear model uncertainties.

TRACKING DETECTOR UPGRADES

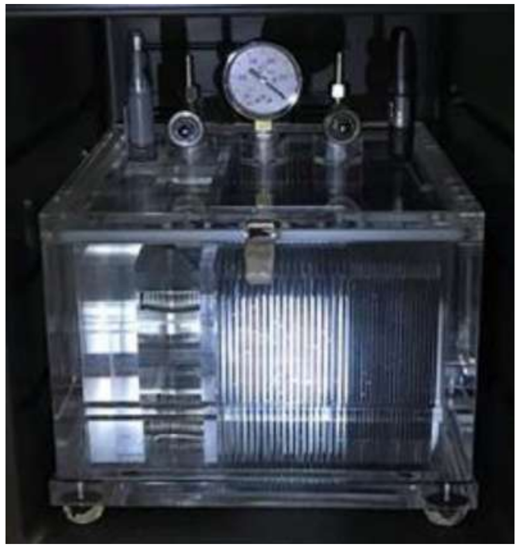
- ND280 upgrade:
  - Horizontal High Angle TPCs (HA TPCs) to improve high angle tracking.
  - SuperFGD: fine-granularity scintillator detector as an active neutrino target.
  - Time of flight detector
    - Precise timing of tracks detected in the TPC determines particle direction.
- NINJA
  - Nuclear emulsion detector measuring neutrino-nucleus interactions.
  - Water target may be installed as a hybrid detector with ND280.
  - Measure ν_e interactions and anti-ν_e interactions separately.
- High Pressure TPC (HP TPC)
  - Improved reconstruction of low energy hadrons in the final state recoil system and better reconstruction of photon conversions.



SuperFGD



HA TPCs



NINJA