Long-Baseline Neutrino Oscillation Sensitivities at Hyper-Kamiokande

& Impact of **I**ntermediate **W**ater **C**herenkov **D**etector

Tailin Zhu

On behalf of the Hyper-Kamiokande Collaboration

(t.zhu20@imperial.ac.uk)

September 6, 2022

NOW 2022

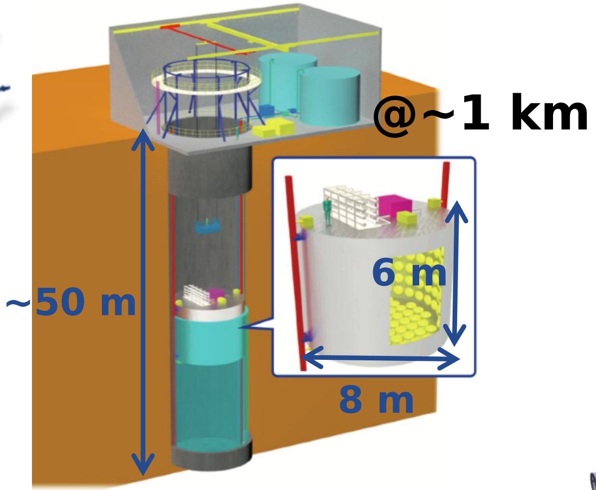
Neutrino Oscillation Workshop

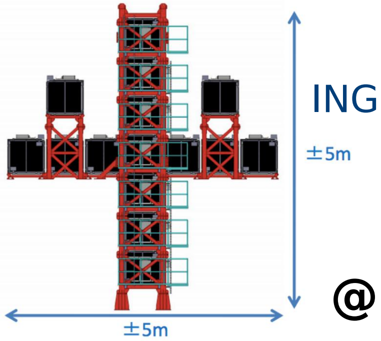
Rosa Marina (Ostuni, Italy)

Hyper-Kamiokande

Hyper-Kamiokande

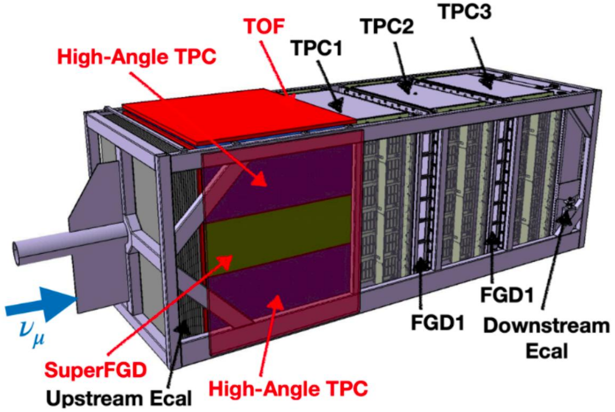
Intermediate Water Cherenkov Detector





INGRID

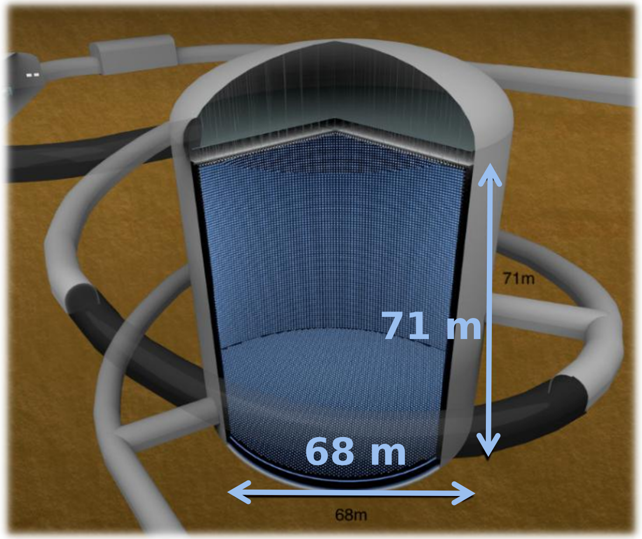
@280 m



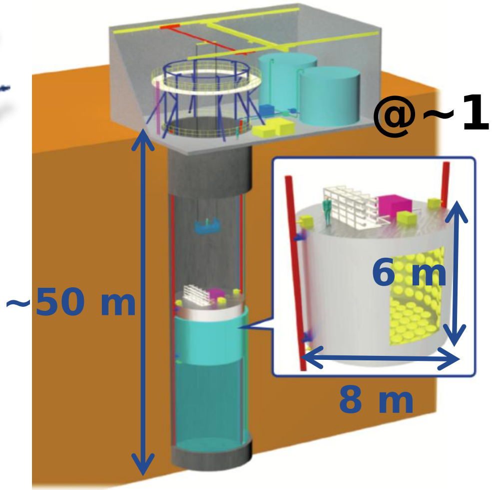
ND280 Upgrade

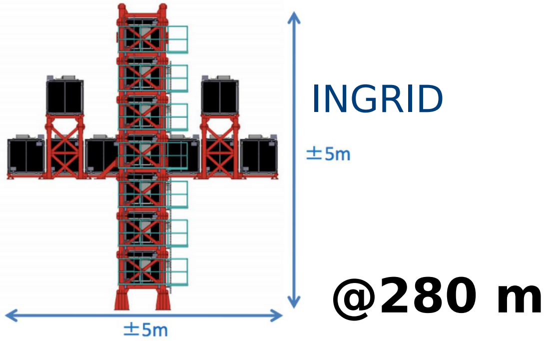
Hyper-Kamiokande

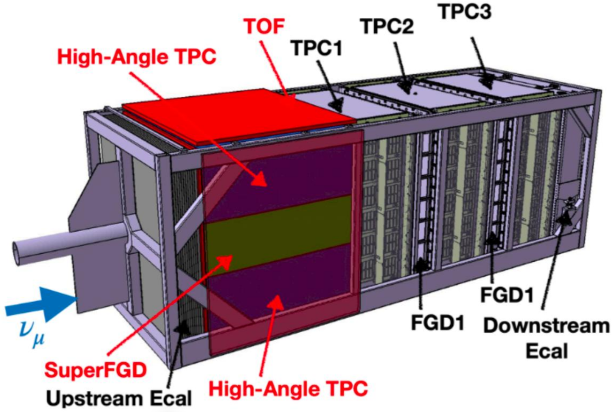
Far Detector



Intermediate
Water Cherenkov
Detector







ND280 Upgrade

See talk by
[Zhenxiong Xie]
on 10:15am, 6th Sep

Neutrino Oscillation Physics

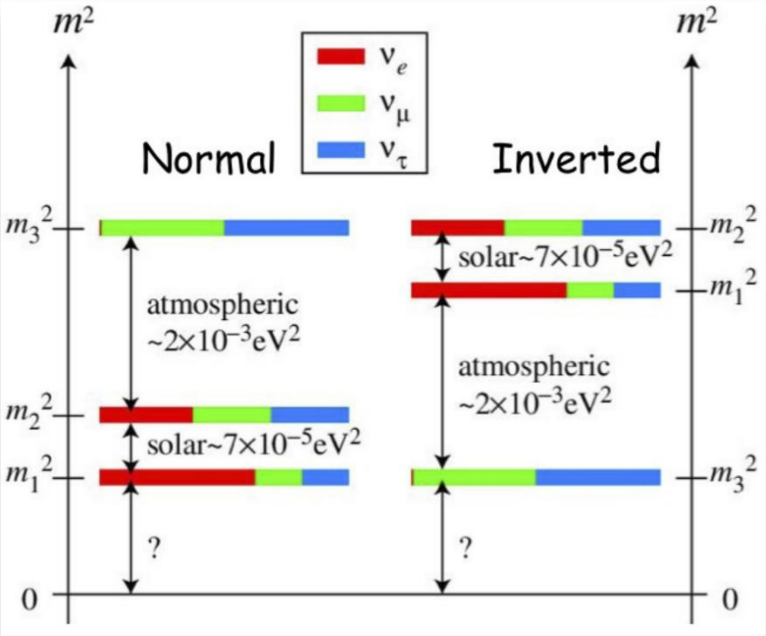
- Described by the PMNS matrix under 3 Dirac neutrino mixing hypothesis

$$U_{i\alpha} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

- θ_{12} = 33.6°± 0.8° (solar)
- θ_{13} = 8.3°± 0.2° (reactor)
- θ_{23} = 45.6° ± 2.3° (accelerator/atmospheric)
  - Is θ_{23} = 45°? If not, what is the octant of θ_{23} ?
- δ_{CP} unknown
  - Any CP violation in the lepton sector ?

PDG2022



- What is the neutrino mass ordering ?

- Need precise measurements to fully understand neutrino oscillations

HK Planned Improvements

- Upgraded ND280 detector

Jaafar Chakrani on 4:00pm, 6th Sep

- New Intermediate Water Cherenkov detector (IWCD)
  - 300t fiducial volume with excellent electron identification power will provide high statistics ν_e and $\bar{\nu}_e$ samples
  - Off-axis fluxes will provide ν_μ samples with spectra peaked at different energies having different neutrino interaction types to constrain neutrino cross section better

Reduce the impact of flux and cross-section uncertainties on neutrino oscillation measurements

- Approx. 20x event rate compared to the T2K experiment
  - Twice the J-PARC neutrino beam power (1.3 MW)
  - 8x far detector fiducial volume (188 kt)

- Improved photo sensors and calibration at the far detector

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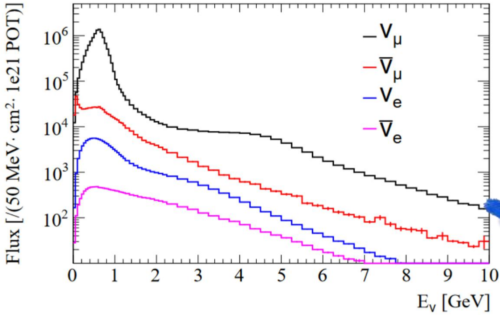
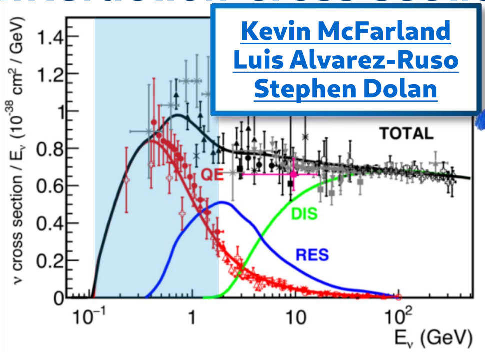
HK Oscillation Analysis and Sensitivities

HK Oscillation Analysis Methods

Neutrino Flux



Interaction Cross section



Kevin McFarland
Luis Alvarez-Ruso
Stephen Dolan

Constrain Models using Near and Intermediate Detectors

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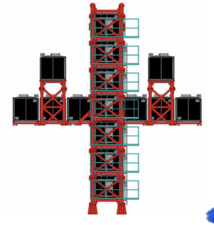
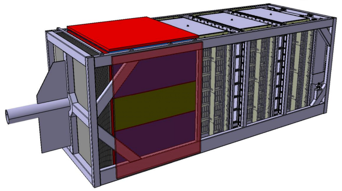
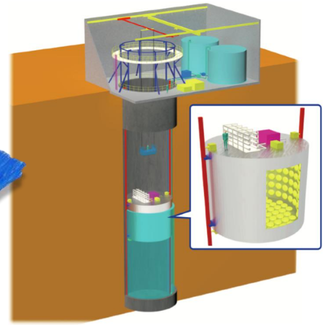


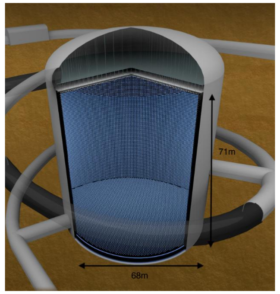


ND280 Upgrade

IWCD

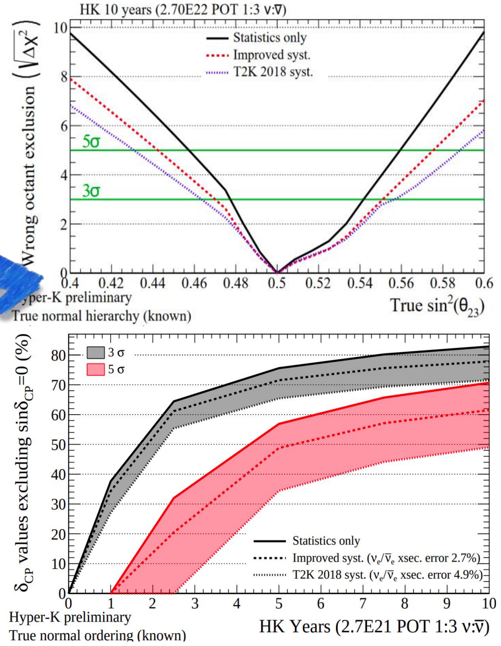


Model Fit to Far Detector Data



Super-K MC, scaled to HK statistics

Oscillation Parameter Sensitivities



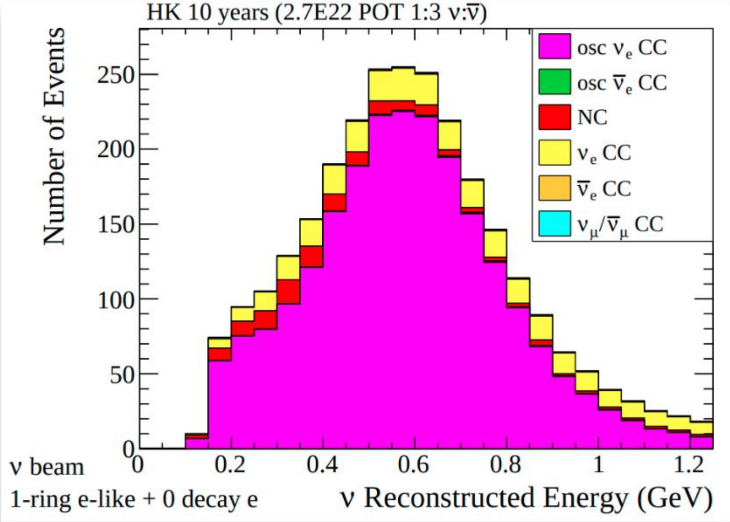
Lukas Berns on 9:15pm, 5th Sep

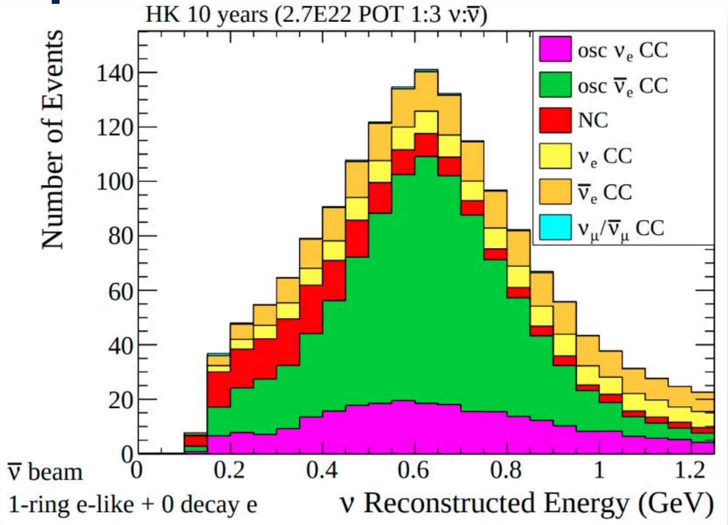
- Based on T2K oscillation analysis method
- 5 event samples: 4 CCQE-like + 1 CC1π-like; 2.7E22 POT over 10 years, $\nu:\bar{\nu}$ - mode $= 1:3$

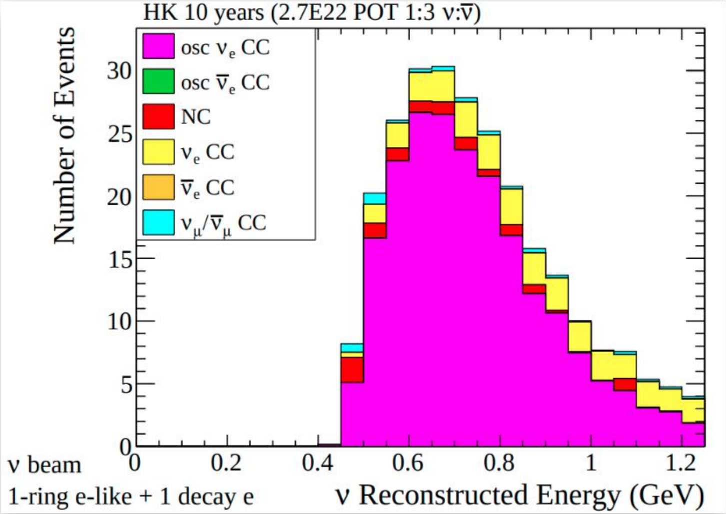
HK e-like Event Samples

- Expecting
  - $\sim 2700\ \nu_e$ events
  - $\sim 1600\ \bar{\nu}_e$ events
  - Asssuming
    - NO
    - $\sin^2\theta_{13} = 0.0218$
    - $\sin^2\theta_{23} = 0.528$
    - $\delta_{CP} = 0$
    - $\Delta m^2_{32} = 2.509\text{E-}3\ \text{eV}^2$

- Sensitive to δ_{CP} from $\nu_\mu \to \nu_e$ appearance spectra comparing number of events in ν and $\bar{\nu}$ mode







ν-Mode Beam

$\bar{\nu}$-Mode Beam

Effect of δ_{CP}

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  - $\sim$ 1600 $\bar{\nu}_e$ events
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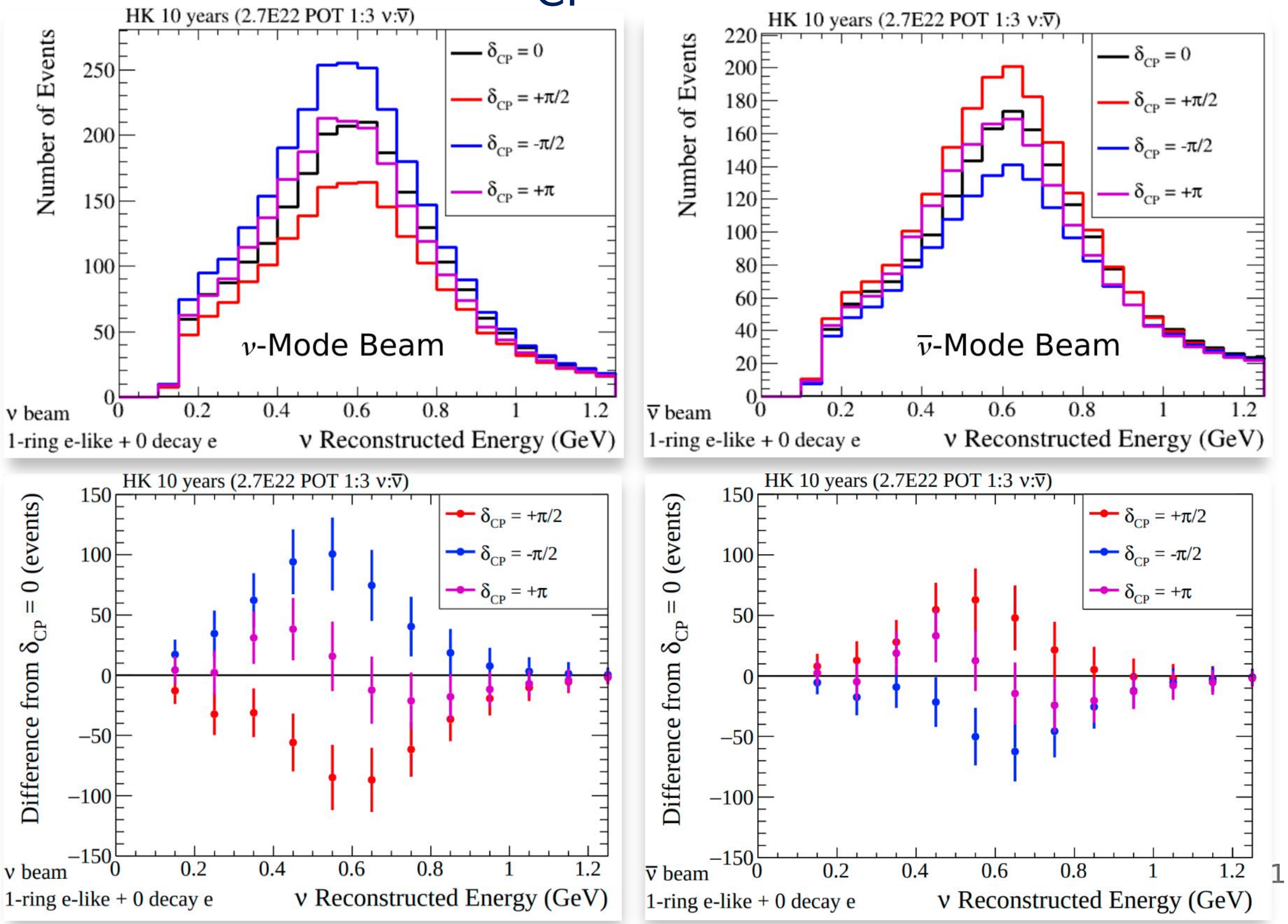

Effect of $\sin^2\theta_{23}$

- Expecting
  - ~ 2700 ν_e events
  - ~ 1600 $\bar{\nu}_e$ events
  - Asssuming
    - NO
    - $\sin^2\theta_{13} = 0.0218$
    - $\sin^2\theta_{23} = 0.528$
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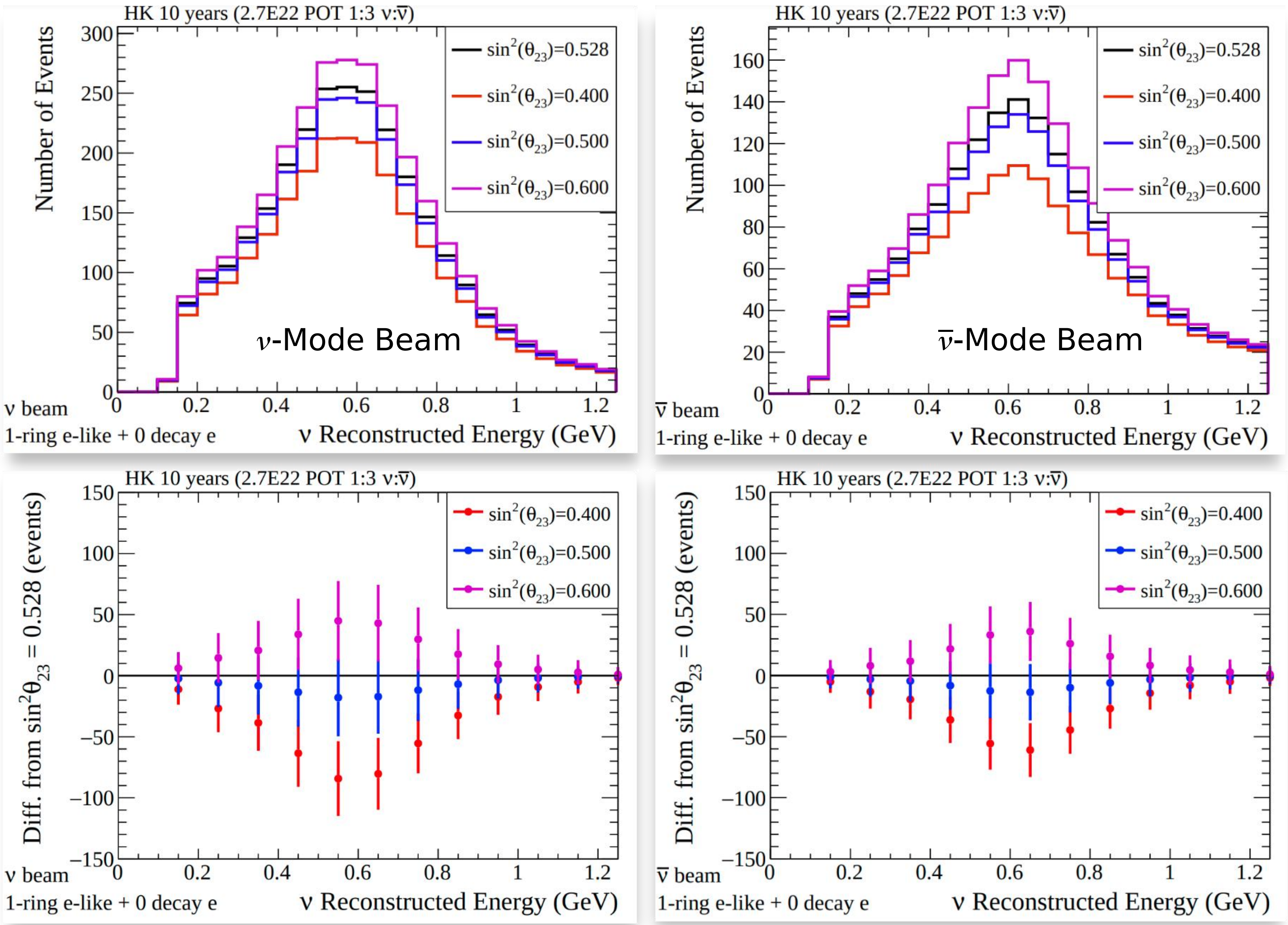
- Sensitive to $\sin^2\theta_{23}$ and Δm^2_{32} from ν_μ disappearance and $\boldsymbol{\nu_e}$ **appearance** spectra shape in ν and $\bar{\nu}$ mode



HK μ-like Event Samples

- Expecting
  - $\sim$ 9300 ν_μ events
  - $\sim$ 12300 $\bar{\nu}_\mu$ events
  - Asssuming
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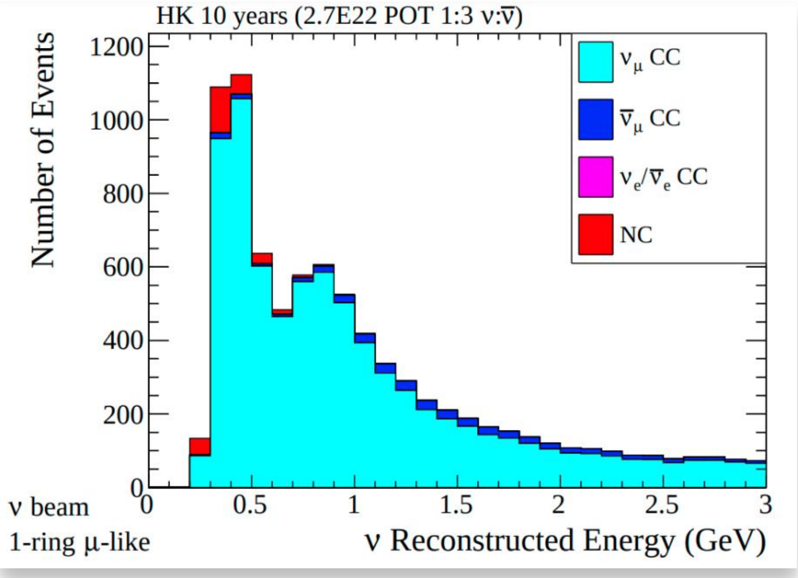
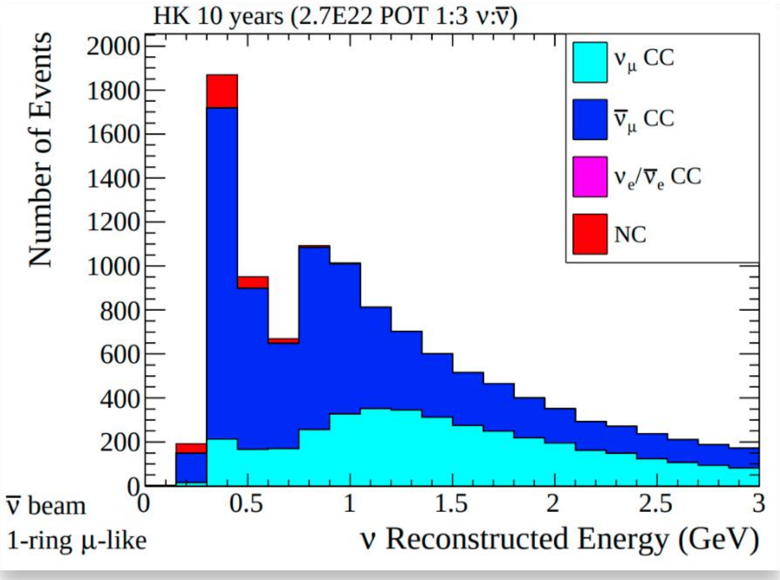


ν-Mode Beam



$\bar{\nu}$-Mode Beam

Effect of $\sin^2\theta_{23}$

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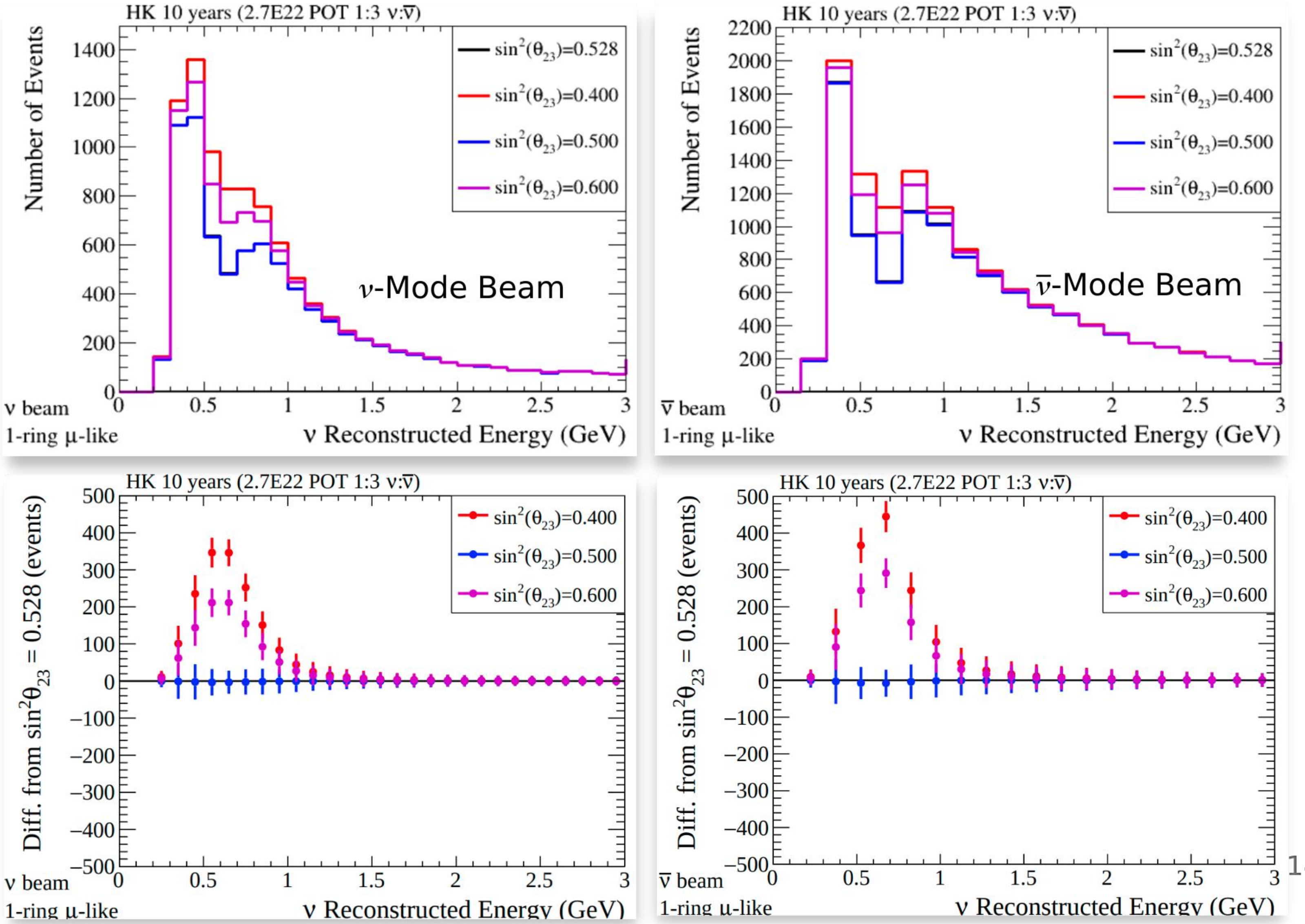
- Sensitive to $\sin^2\theta_{23}$ and Δm^2_{32} from ν_μ **disappearance** and ν_e appearance spectra shape in ν and $\bar{\nu}$ mode



HK Systematic Uncertainty Models

- T2K 2018 model
  - Flux error from hadron-production + J-PARC beamline
  - Cross-section error from neutrino interaction models
  - Detector + FSI + SI describes the detector response systematics
  - Near detector constraints applied to the flux + cross section uncertainties

- Improved systematics for HK
  - Scaling the T2K 2018 model with the increase of statistics and sensitivities from ND280 upgrade and IWCD
    - No parameter was allowed to have an uncertainty of less than 1%
  - Adding new systematic parameters

- Systematic uncertainties are parameterized based on the ν flavor, ν beam mode, ν interaction properties, event type, energy scale, etc, against the true (near detector constraints) and reconstructed (far detector constraints) ν energies.
  - Details see backup slides

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HK Systematic Uncertainties

- Error on event rate due to systematic uncertainties
- Flux and cross sections is the main contribution to the $\nu_e/\bar{\nu}_e$ uncertainty
  - Also a small fraction from the far detector systematics
  - Aims to reduce total systematics by approx. 50%
- $\nu_\mu(\bar{\nu}_\mu)$ uncertainty is also expected to be reduced by 75%

T2K 2018 Errors

	1-Ring ν_μ-like		1-Ring ν_e-like			
Error source	ν-Mode	$\bar{\nu}$-Mode	ν-Mode CCQE-like	$\bar{\nu}$-Mode CCQE-like	ν-Mode CC1π-like	ν-Mode/$\bar{\nu}$-Mode CCQE-like
Flux + Cross section	3.27%	2.95%	4.33%	4.37%	4.99%	4.52%
Detector + FSI + SI	3.22%	2.76%	4.14%	4.39%	17.77%	2.06%
All systematics	4.63%	4.10%	5.97%	6.25%	18.49%	4.95%

Improved HK Errors

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Flux + Cross section	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector + FSI + SI	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All systematics	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

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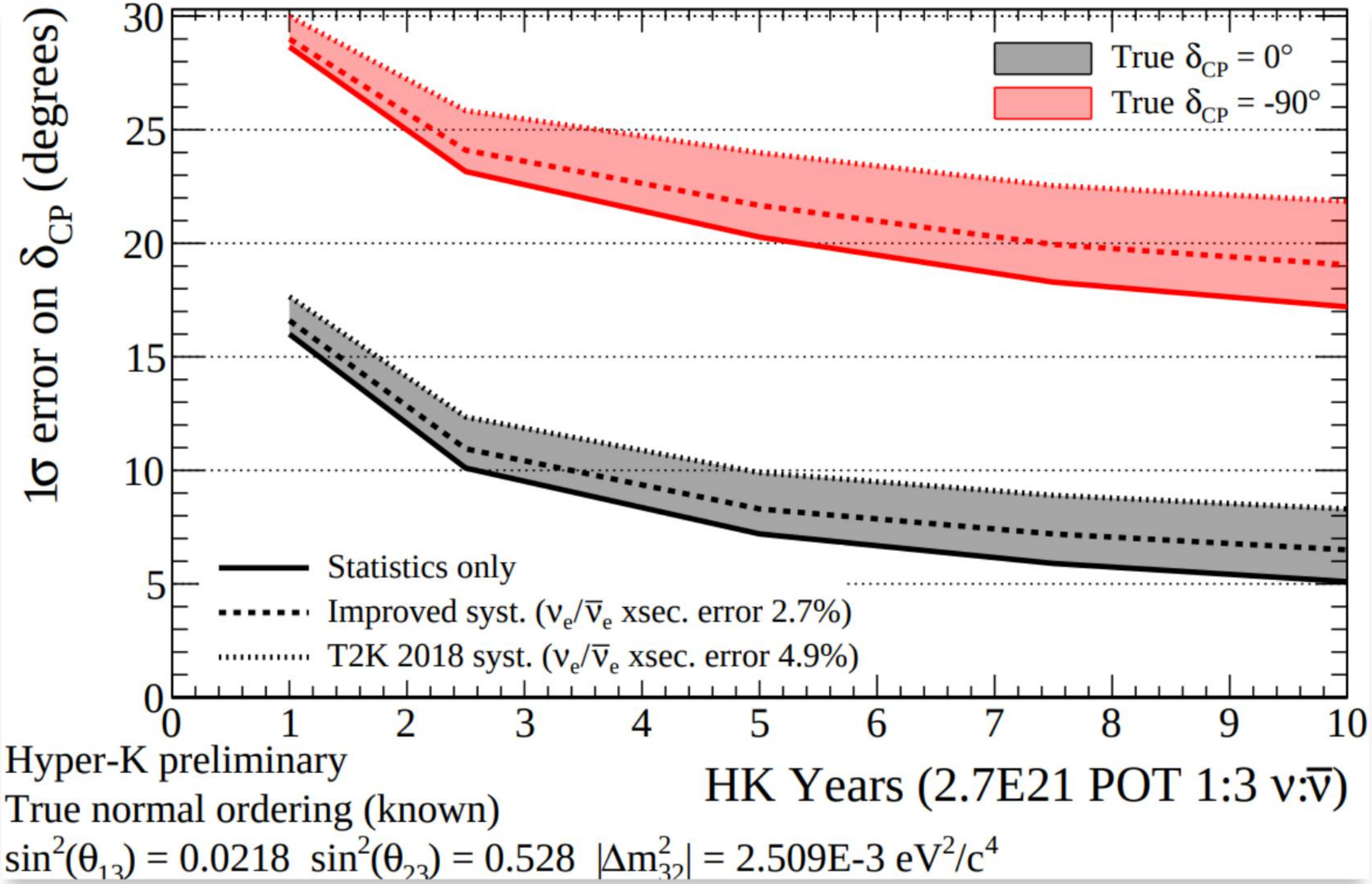
Error on event rate due to systematic uncertainties

δ_{CP} Precision

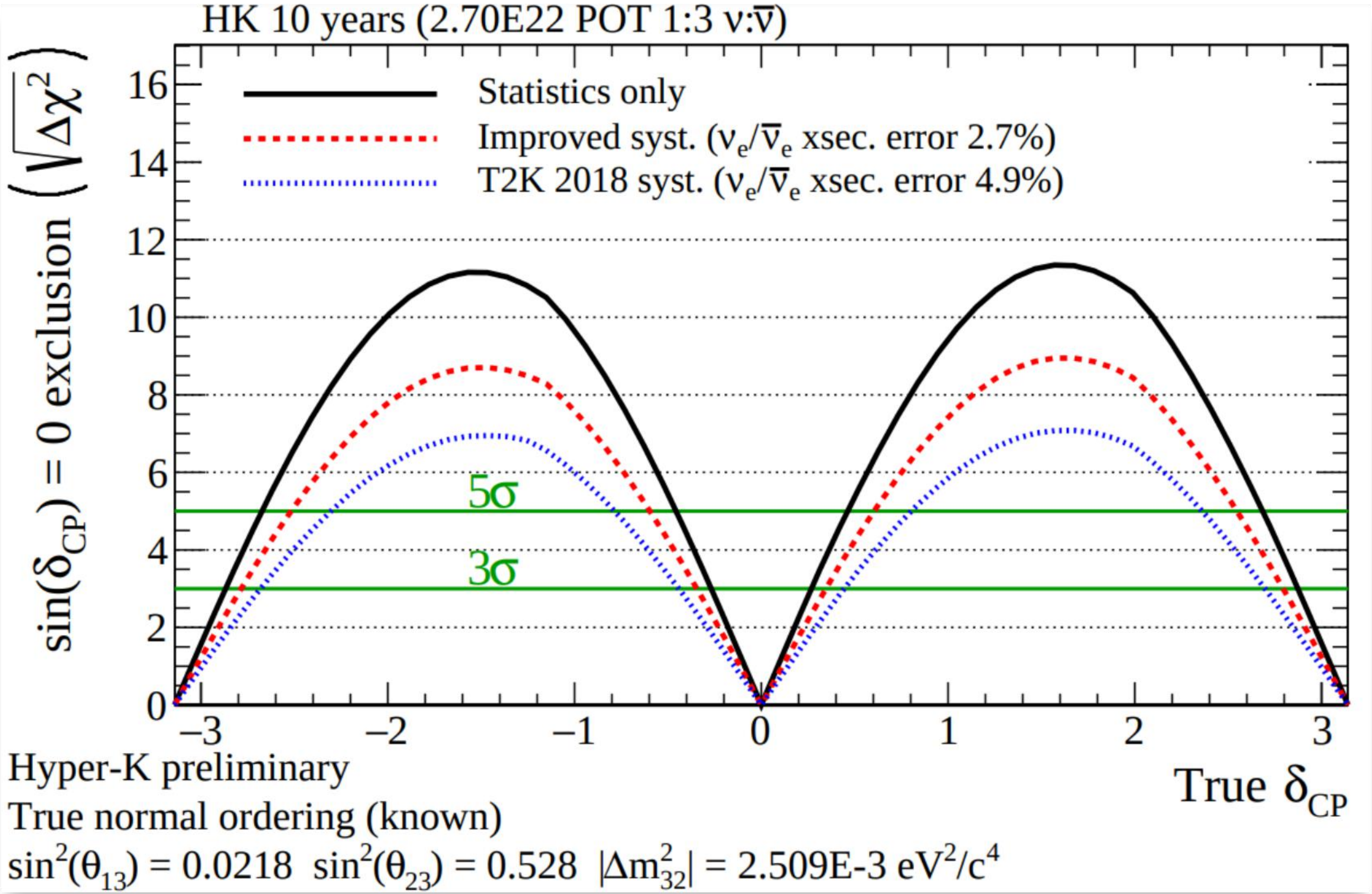
- Uncertainty on δ_{CP} plotted as a function of beam running years
- Precise measurement of δ_{CP} is available
- With 10 years of operation, can achieve 1σ error for δ_{CP} of $19°$ ($6.5°$) in the case of true $\delta_{CP} = -90°$ ($0°$)



CP Violation Sensitivity

- With 10 years of operation, CPV is expected to be established at 5(3)σ for 61%(77%) of true δ_{CP} values in the case of the improved systematics

- Sensitive to the 1-ring e-like $\nu/\bar{\nu}$ uncertainty, which are reduced from 4.9% to 2.7% assuming improved systematics



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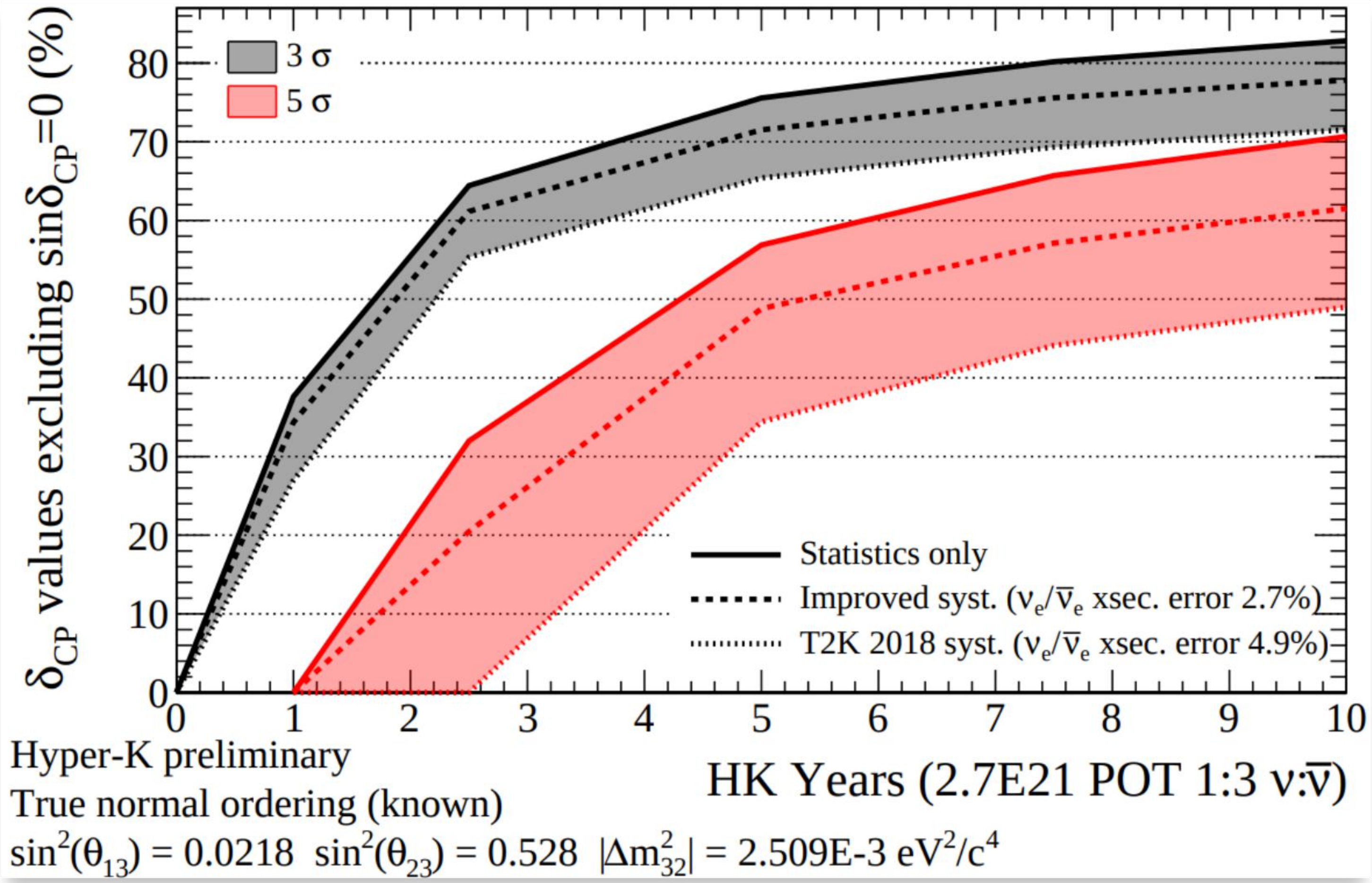
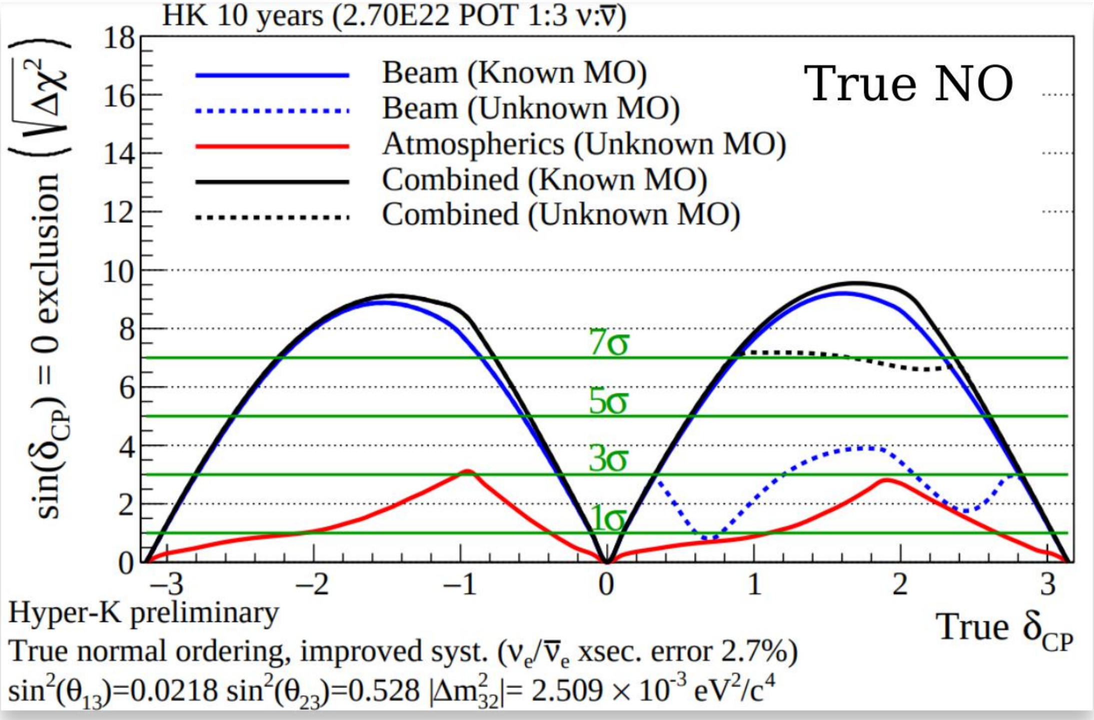
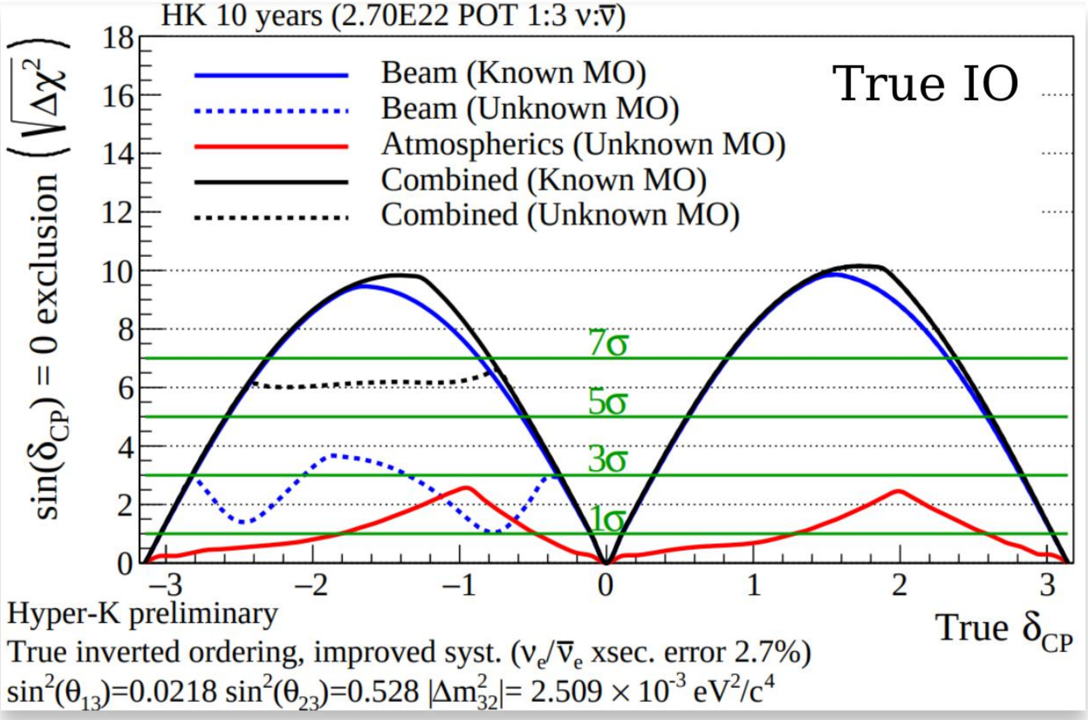


Effect of Atmospheric Neutrinos

- Joint-fit of HK long-baseline and atmospheric neutrinos
- Adding atmospheric neutrinos can drive the sensitivity to δ_{CP} in excluding the CP conservation





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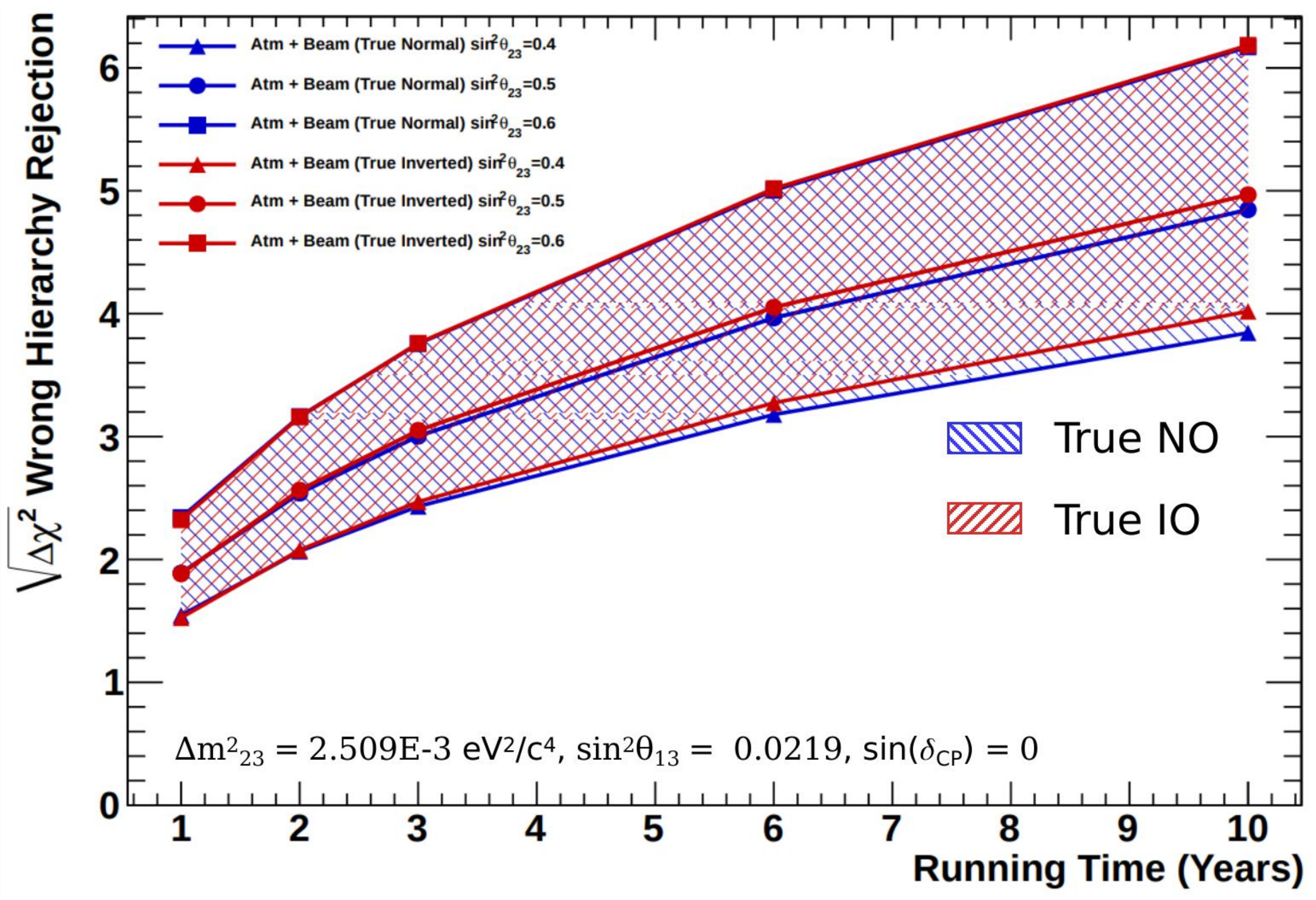
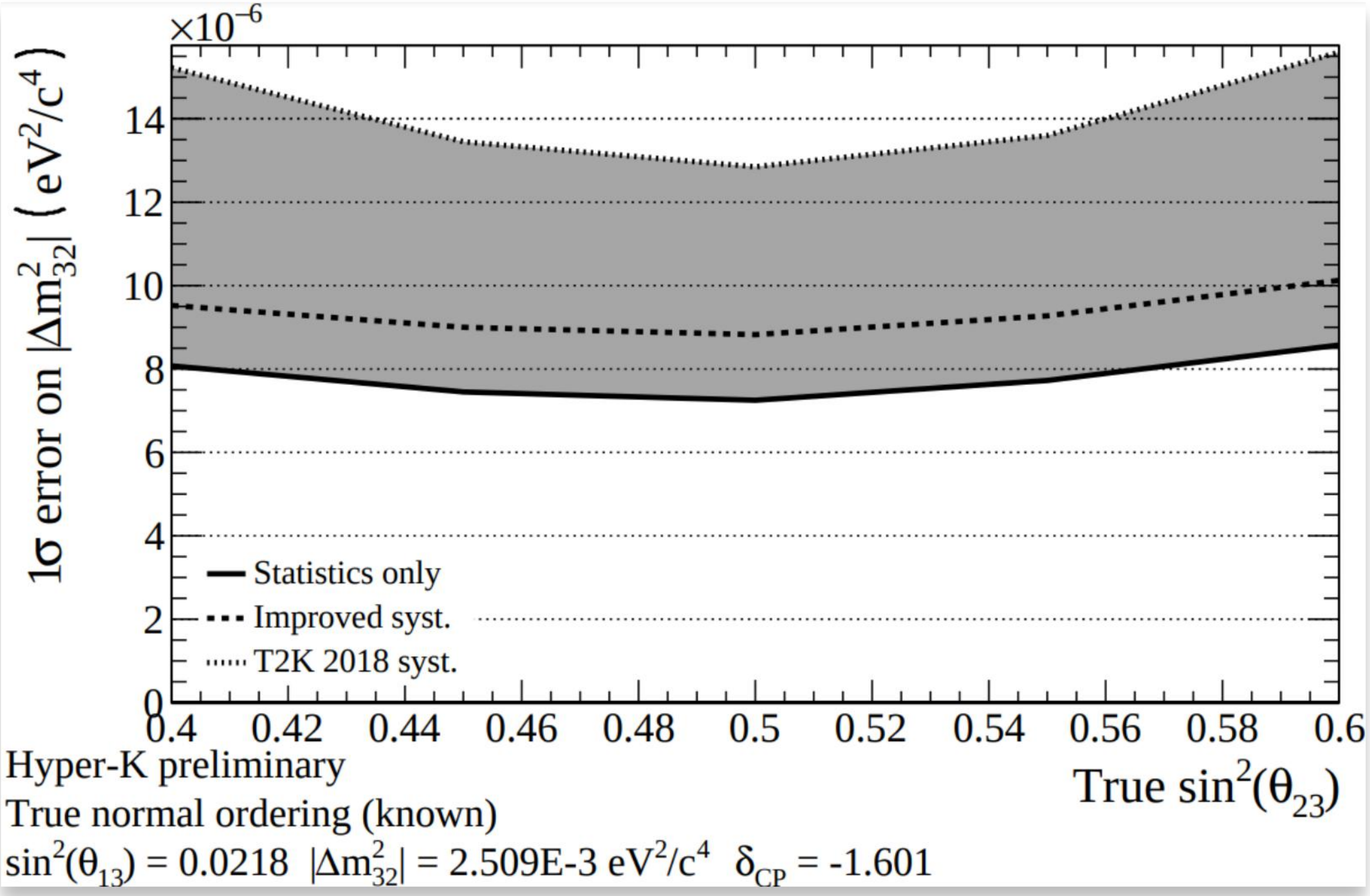


- Adding significance to reject the wrong mass ordering
- Sensitive to mass ordering at 3.8 ~ 6.2σ after 10 years

Δm^2_{32} Uncertainty

- Δm^2_{32} uncertainty for different values of true $\sin^2\theta_{23}$, atmospheric neutrinos sample not included
- Sensitive to μ-like + e-like uncertainties, and are reduced by improved systematics
- With 10 years of operation, 1σ error can achieve 0.35% with the improved systematics, reduced by a factor of 3.6 comparing to current error (PDG)



θ_{23} Octant Sensitivity

- Wrong θ_{23} octant exclusion over true $\sin^2\theta_{23}$, atmospheric neutrinos sample not included
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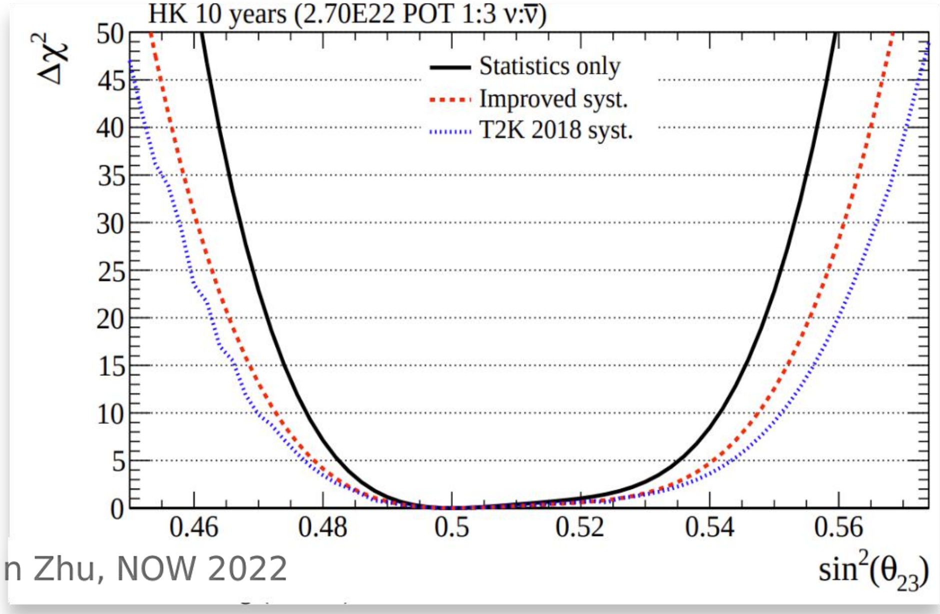
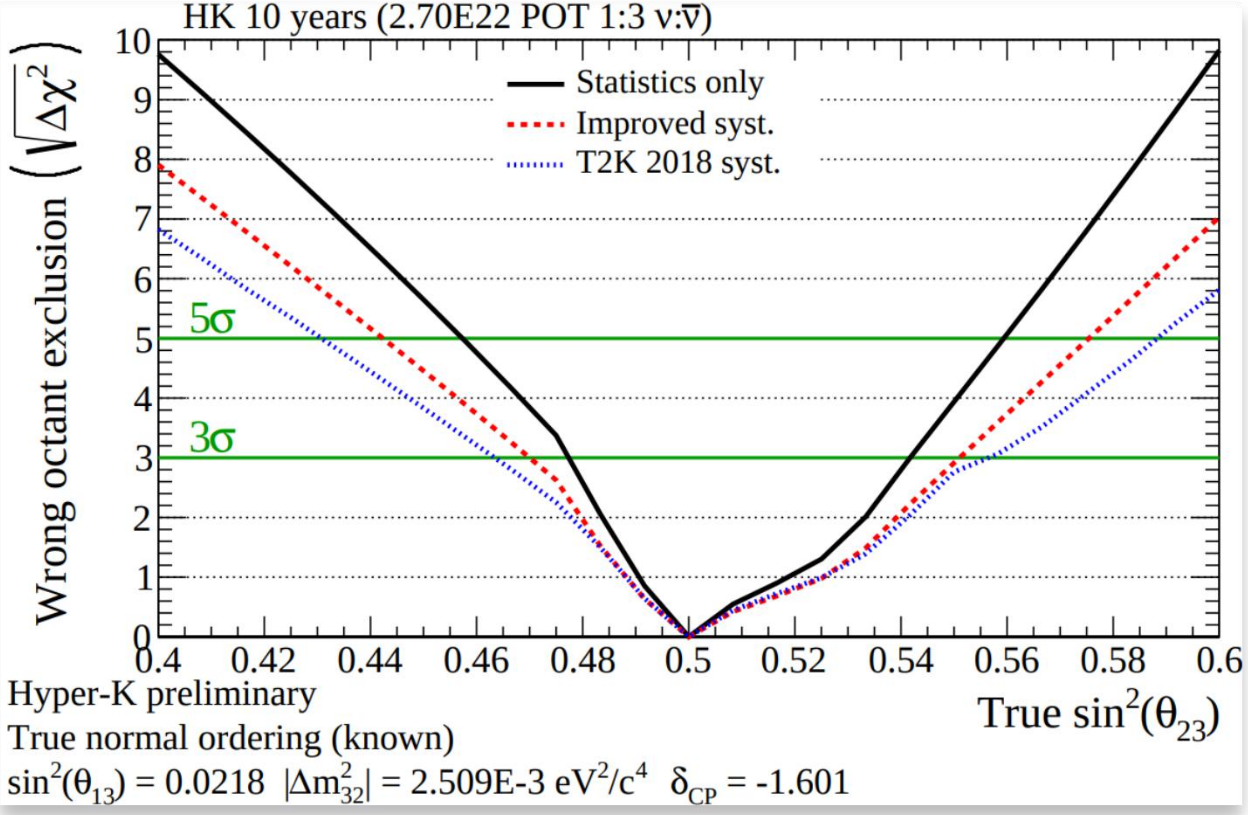




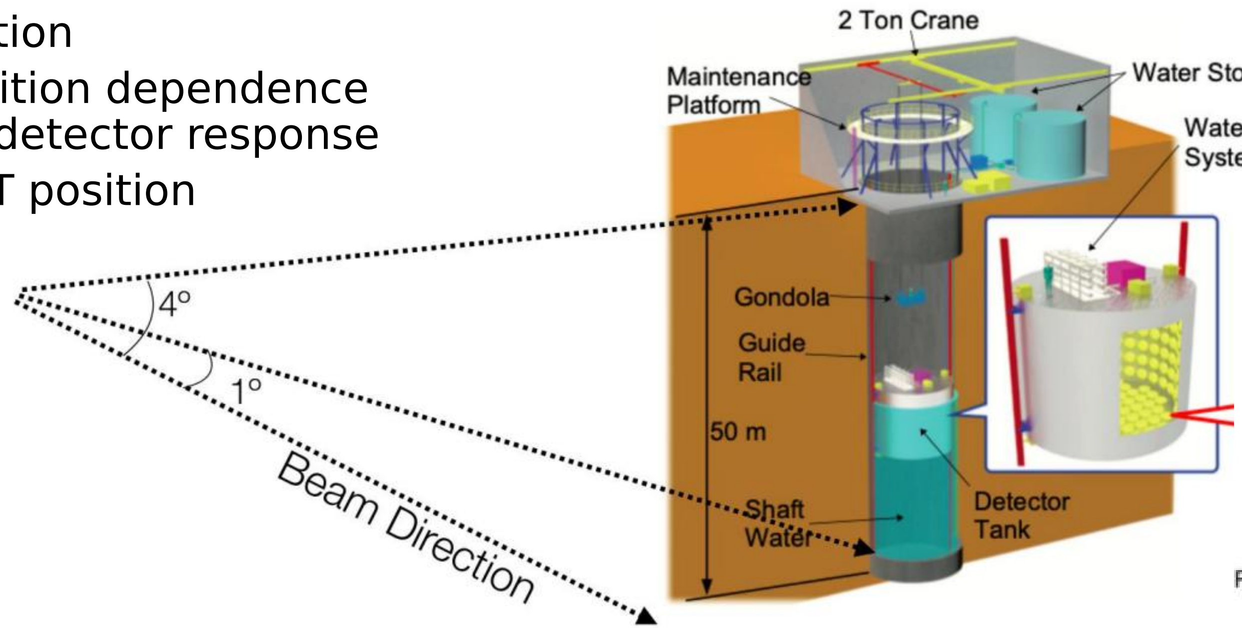
Impact of IWCD on HK Sensitivities

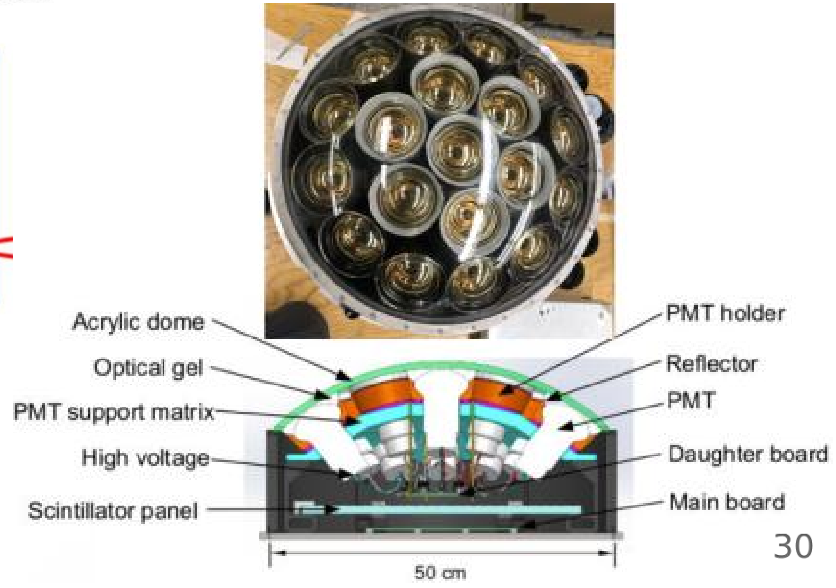
The Intermediate Water Cherenkov Detector

- Vertically movable Water Cherenkov detector

- Approx. 500 mPMTs to improve vertex resolution
  - High voltage and readout electronics
  - Good optical contact between acrylic dome and PMTs with optical gel

- Calibration
  - Position dependence on detector response
  - PMT position

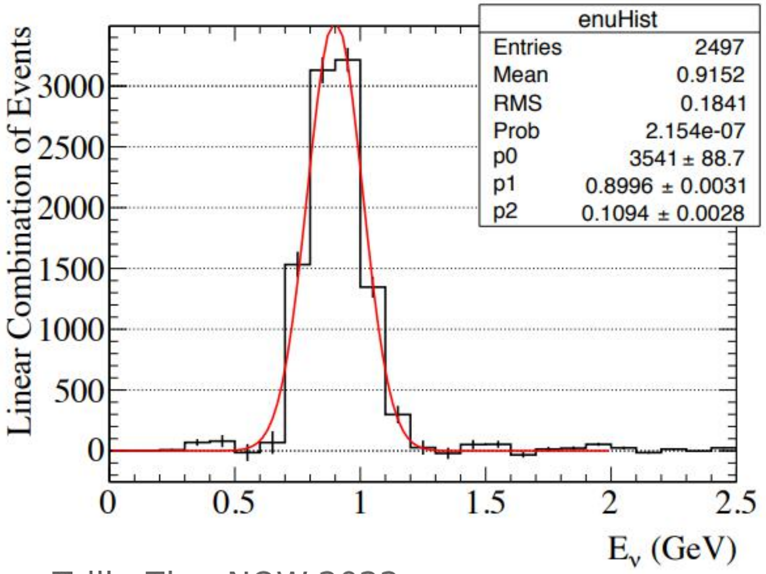


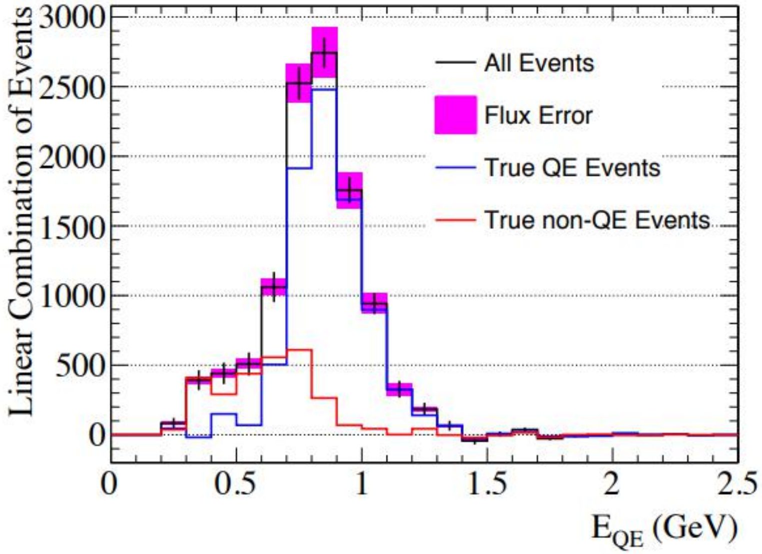


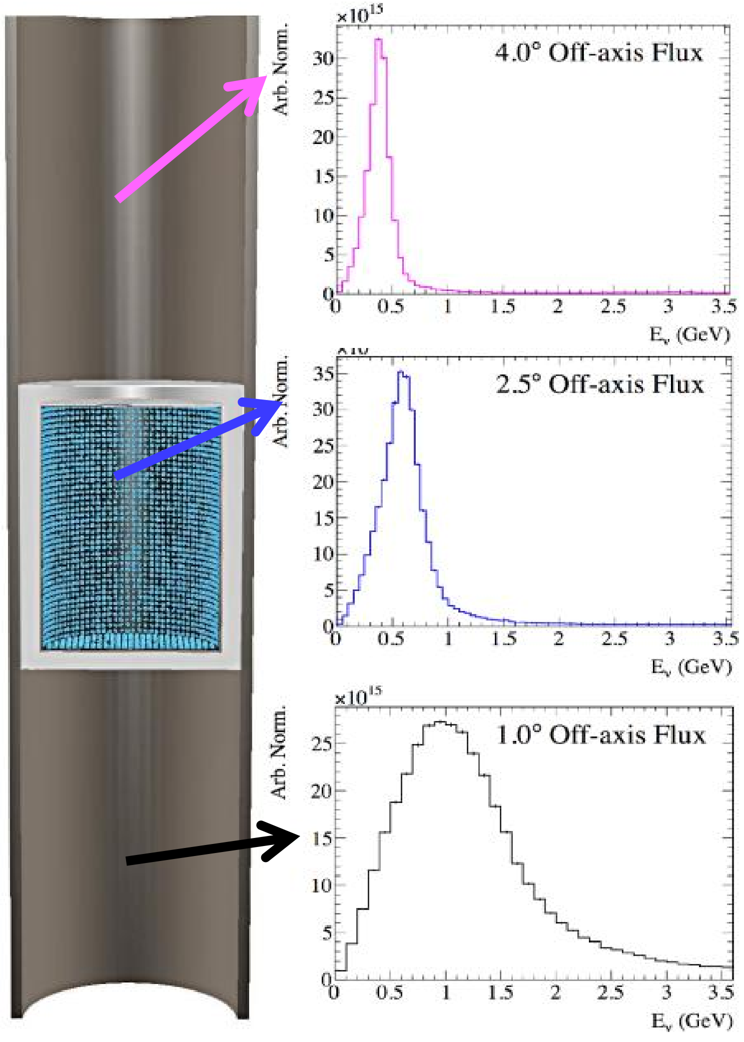
NuPRISM Concept for IWCD

- Vertically movable Water Cherenkov detector
  - Sample different flux positions
  - Scan mean ν energies from 0.4 GeV (4°) to 1 GeV (1°)
  - Linear combination techniques
    - Information on neutrino interactions can be extracted by fitting weighted true spectrum to reconstructed spectrum

- Measure non-quasi-elastic component with 5% uncertainty







Cross-section Measurements with IWCD

- $\nu_e/\bar{\nu}_e$ cross-section uncertainty limits the HK sensitivity on δ_{CP} and $\sin^2\theta_{23}$
    - This is the cross section(σ) described by $[\sigma(\nu_e) / \sigma(\nu_\mu)] / [\sigma(\bar{\nu}_e) / \sigma(\bar{\nu}_\mu)]$

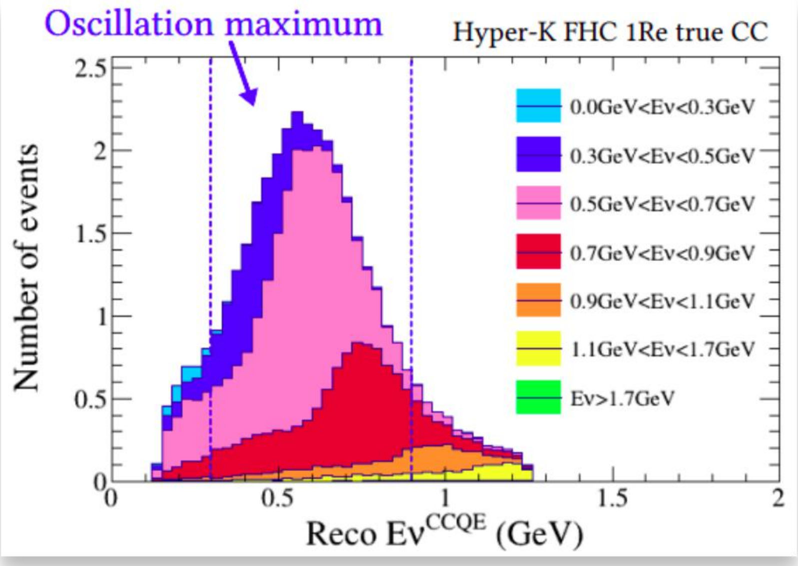
- IWCD measures the $\nu_e/\bar{\nu}_e$ cross section in water by using the 1% intrinsic $\nu_e(\bar{\nu}_e)$ contamination in the neutrino beam

- T2K theory-driven $\nu_e/\bar{\nu}_e$ cross-section error can be improved by measurements from IWCD in a less model-dependent way

- Implementing the systematics from the IWCD analysis to the HK oscillation analysis framework

Cross-section Measurements with IWCD

- IWCD aims to measure $\nu_e/\bar{\nu}_e$ cross section especially in a region of 0.3 GeV <E_ν < 0.9 GeV, where E_ν = true ν energy



- CC non-QE events with higher E_ν than CCQE events are reconstructed as low energy events at IWCD.
  - These CC non-QE events (a.k.a feed-down events) can affect the cross-section measurement
  - Feed-down component needs to be constrained by ν_μ events
  - Require ν_μ events with E_ν > 0.9 GeV to be produced
  - Fixed 2.5° off-axis angle has only contains a tiny fraction of those events
  - Larger off-axis angle can increase the fraction, and thus constrain the feed-down events better

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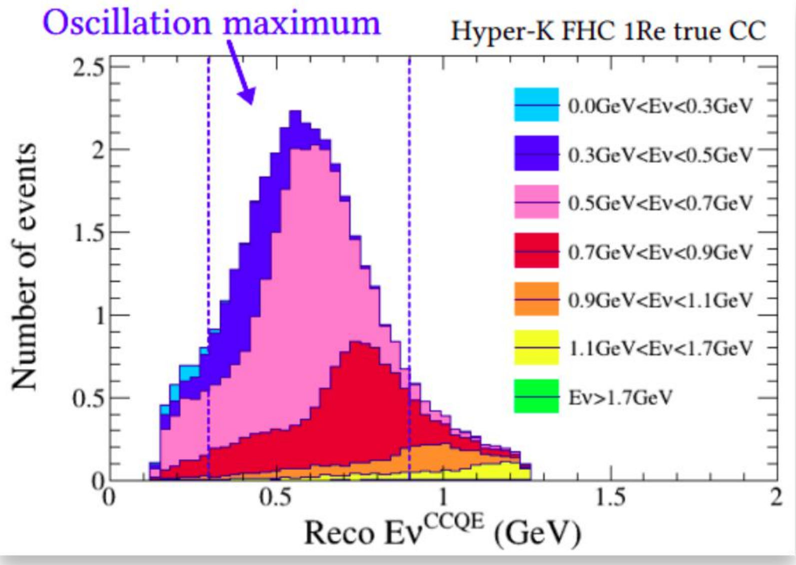
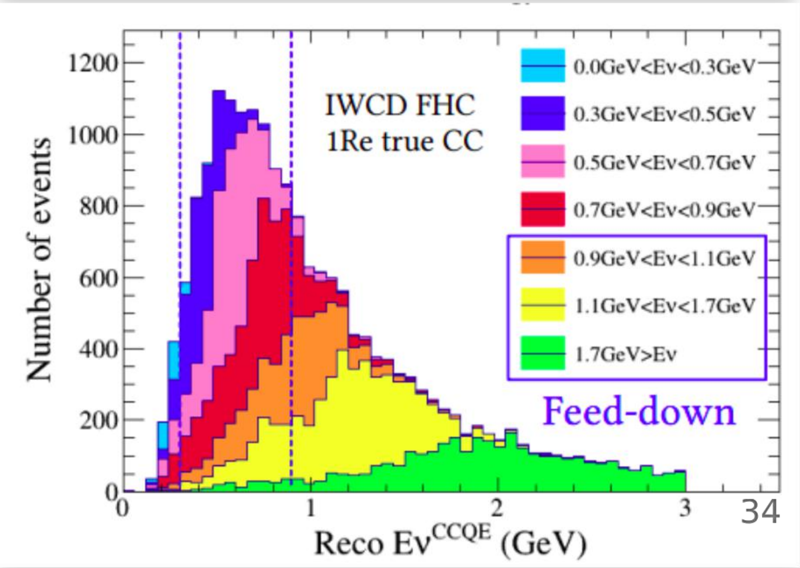
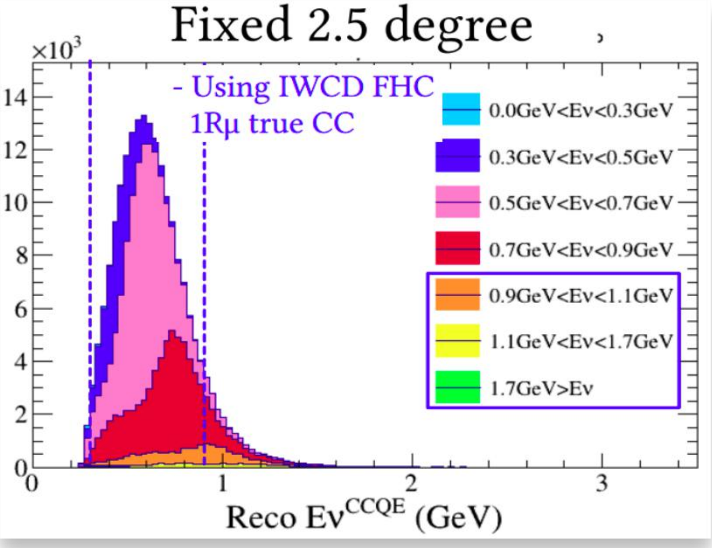




Cross-section Measurements with IWCD



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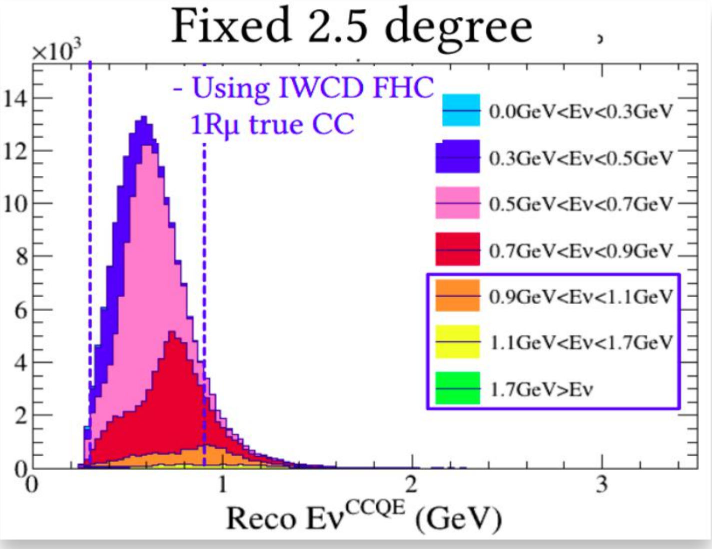

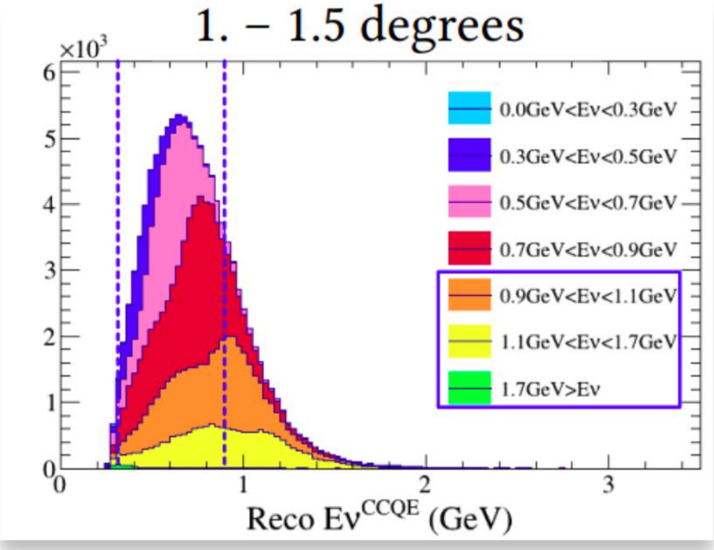

IWCD - Analysis Samples

- 6 Samples: 1Rμ, 1Re, 2Rπ^0 states in both ν- and $\bar{\nu}$-modes
  - 1Rμ sample constrains the total ν cross sections
  - 1Re sample constrains additional parameter describing the difference in the ν_μ and ν_e cross sections
  - 2Rπ^0 constrains the NCπ^0 background in the 1Re samples

- Binned in reconstructed kinematic variables and off-axis angle spans

- Improving constraint by utilizing both μ-like + e-like samples
  - Various parameterizations for the ν ($\bar{\nu}$) cross-section errors

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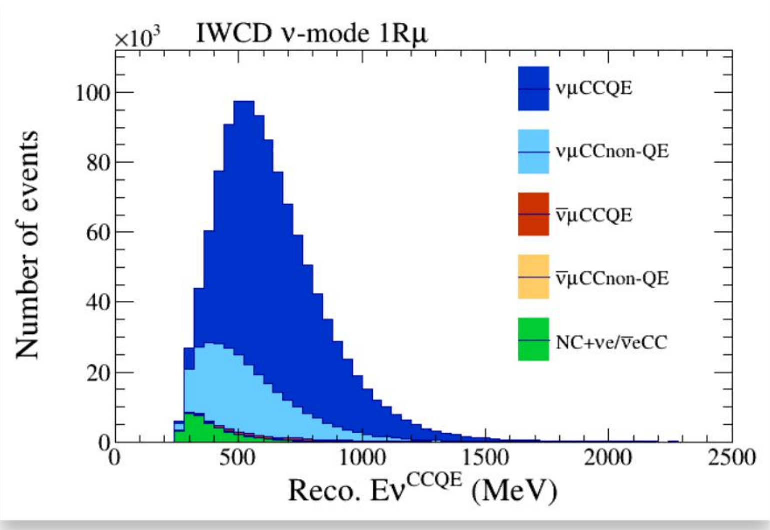

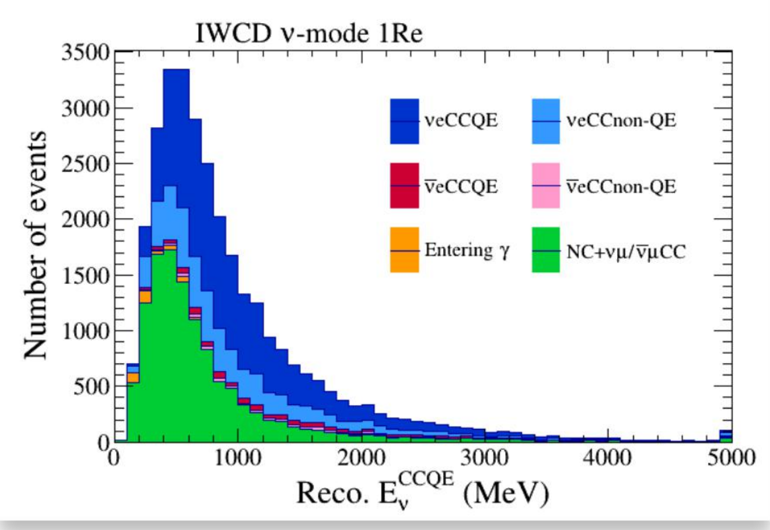

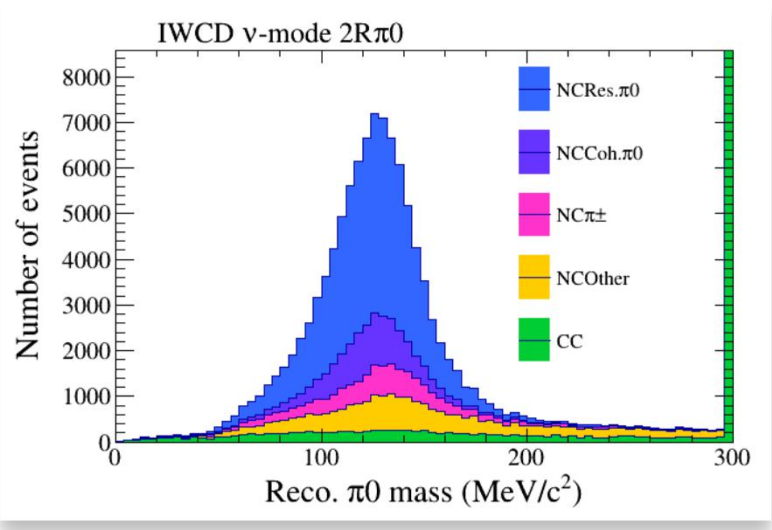

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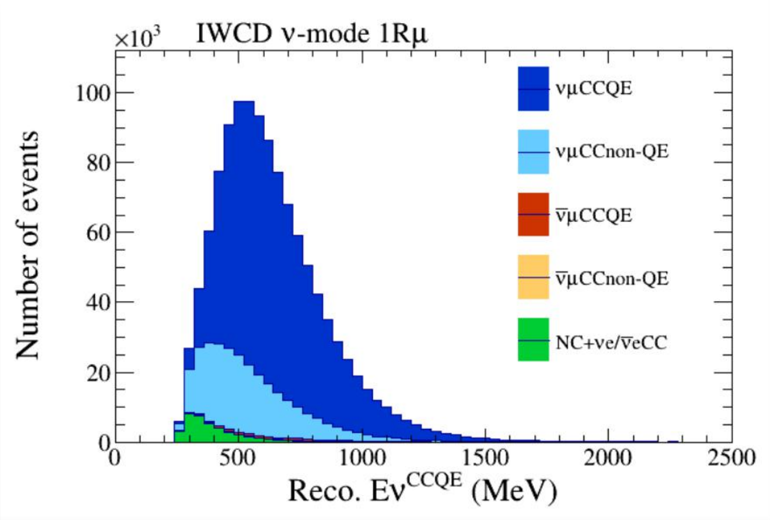
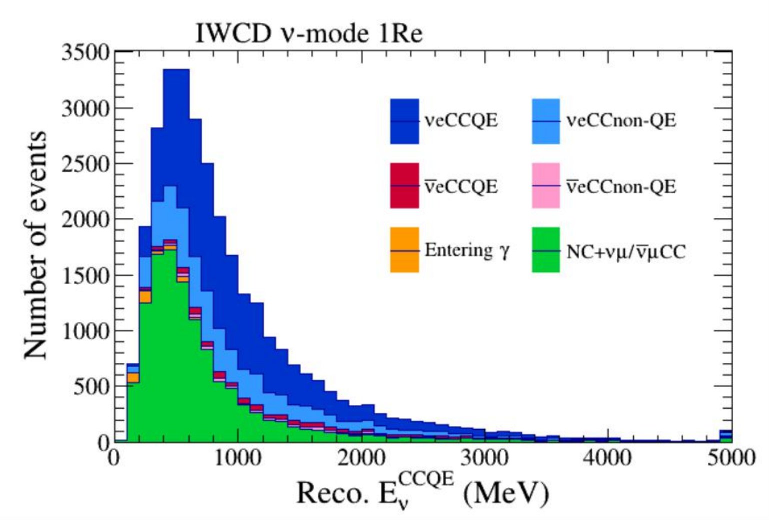
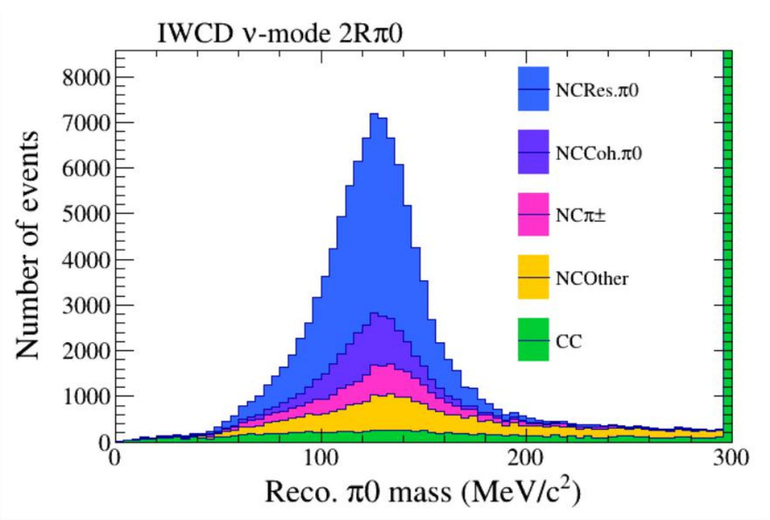






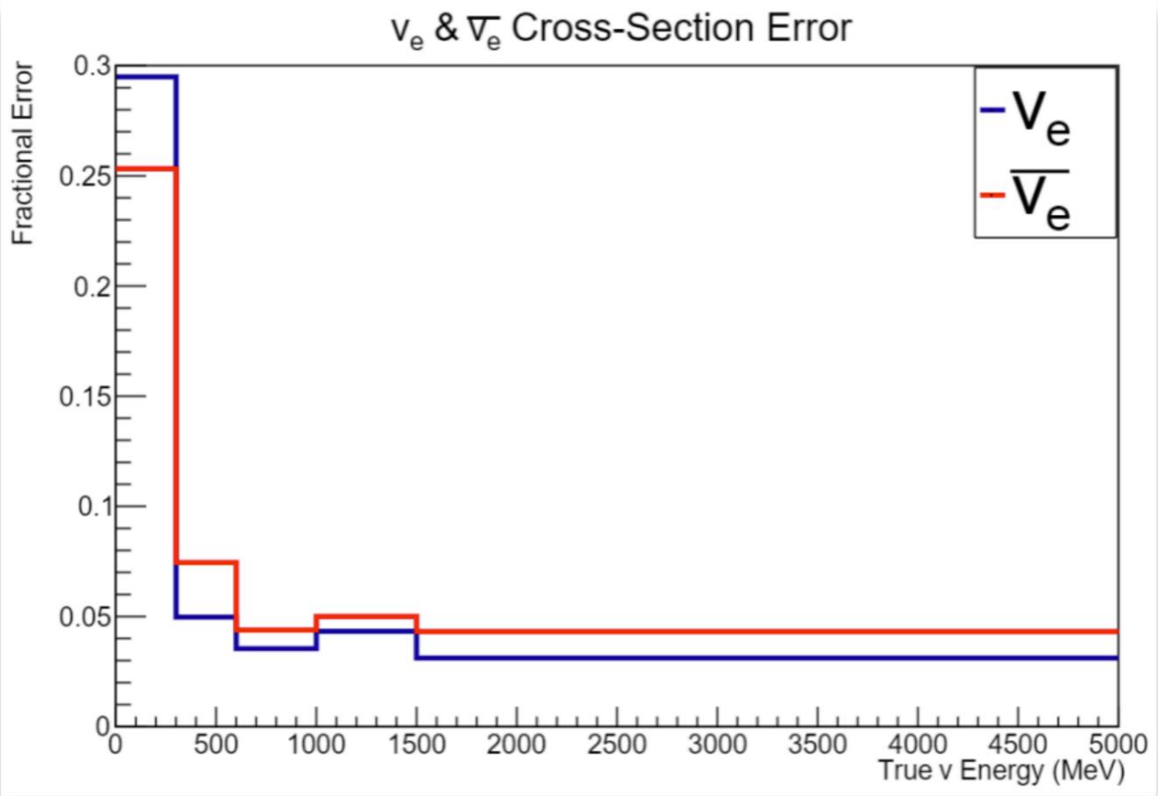
- Improving constraint by utilizing both μ-like + e-like samples
  - Various parameterizations for the ν ($\bar{\nu}$) cross-section errors

IWCD - Cross-section Parameterization

- Systematic uncertainty parameters from the Improved syst. model

- Additional parameterizations based on the improved syst. model
  - Describing the CC ν_e + CC $\bar{\nu}_e$ cross-section uncertainties
  - 1D parameterization in the true ν energy space (E_ν)

- Constraints on these parameters are produced as a covariance matrix



IWCD - Event Rate Uncertainties

- Error on event rate due to systematic uncertainties:

	1-Ring ν_μ-like		1-Ring ν_e-like			
Error source	ν-Mode	$\bar{\nu}$-Mode	ν-Mode CCQE-like	$\bar{\nu}$-Mode CCQE-like	ν-Mode CC1π-like	ν-Mode/$\bar{\nu}$-Mode CCQE-like
T2K 2018 systematics	4.63%	4.10%	5.97%	6.25%	18.49%	4.95%
Improved systematics	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%
IWCD 1D Analysis	1.35%	1.25%	2.68%	3.26%	5.37%	2.65%

- Improved by approx. 50% in the $\nu_e/\bar{\nu}_e$ error compared to T2K 2018 model

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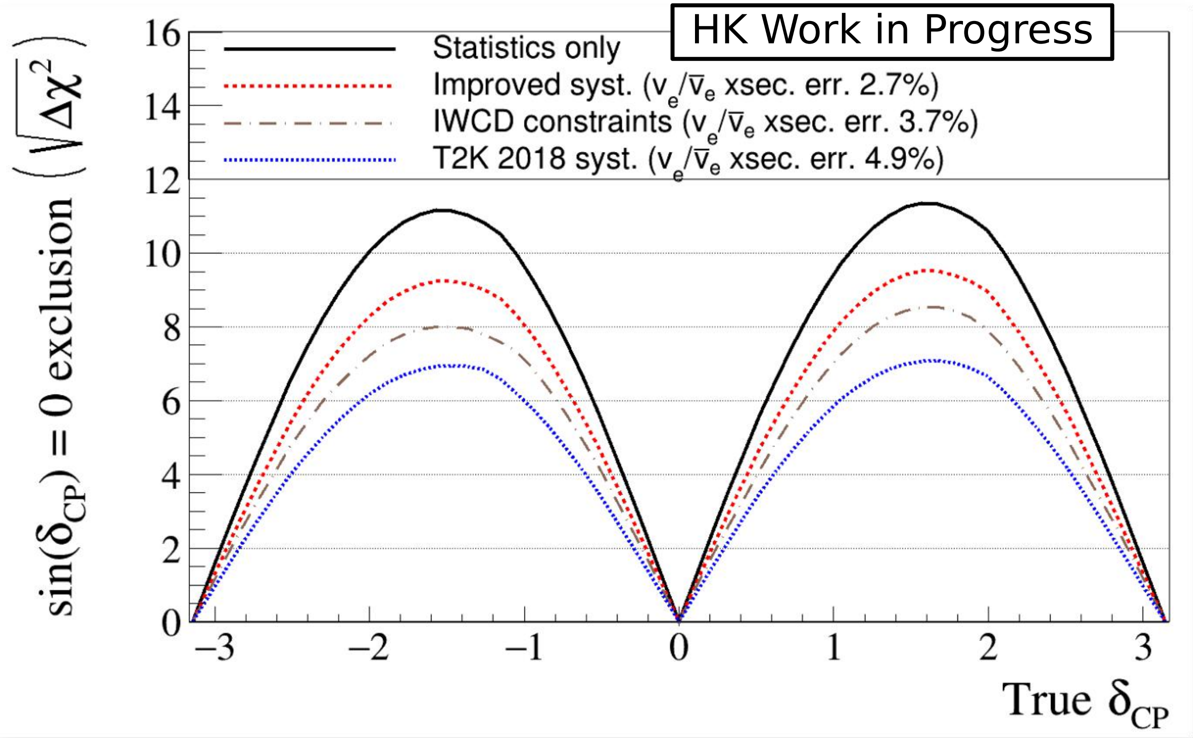
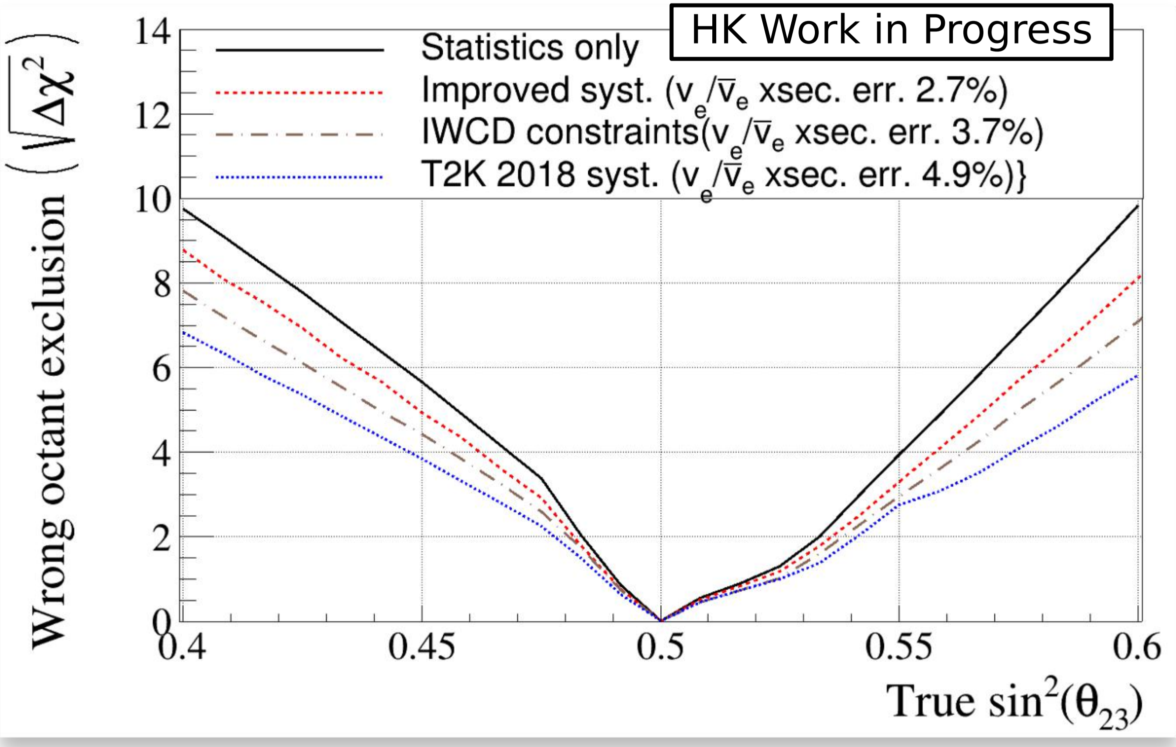
IWCD - Sensitivities





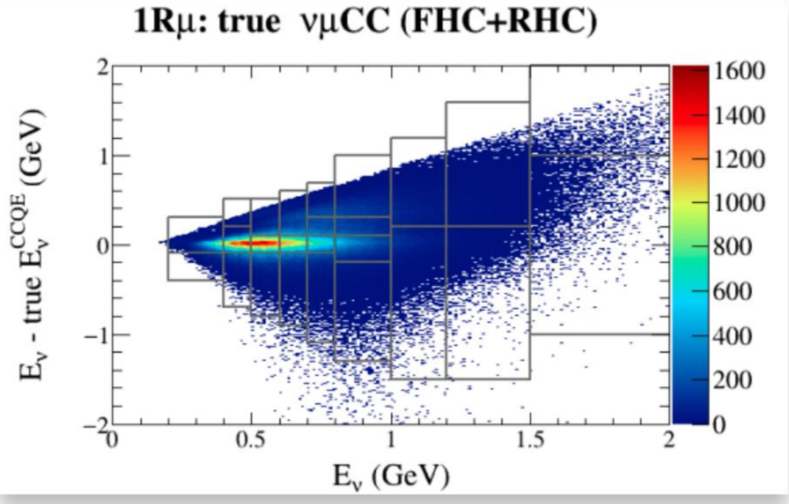
- Adding 1D parameters has increased the sensitivity to CP violation effects and θ_{23} octant
- This is a constraint so far based on theory for T2K, but aim to make a direct model-independent measurement with IWCD

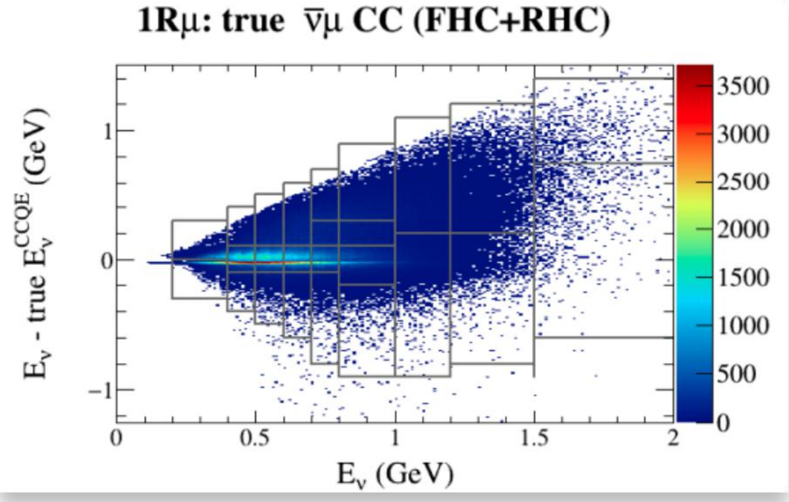
IWCD - Analysis Improvements

- ν oscillation depends on true ν energy (E_{ν}) - unknown
- Oscillation measurements reconstructed energy assuming we observe a CCQE interaction, E_{reco}^{CCQE}, which is not equal to E_{ν}
- But can calculate the energy (E_{ν}^{CCQE}): from the Monte-Carlo truth charged lepton momentum and scattering angle, assuming quasi-elastic interaction
- Can then measure the relationship between E_{ν} and E_{ν}^{CCQE}, this will give the relationship between E_{reco}^{CCQE} and E_{ν}
    - Add parameters to allow extra freedom in relationship between E_{ν} and E_{ν}^{CCQE}
    - 1D ν_e cross-section fits don't consider this freedom

IWCD - Analysis Improvements

- Additional 2D parameterizations on CC $\nu_e + \nu_\mu$ and CC $\bar{\nu}_e + \bar{\nu}_\mu$ cross-section error
  - Together with the 1D ν_e parameterization, relationship between E_ν and E_ν^{CCQE} can be constrained
  - Samples are being fit to the E_ν *vs* $E_\nu - E_\nu^{CCQE}$ space
- Study the performance of IWCD constraints itself on flux and cross-section (no ND280 constraints)
- Results on cross-section uncertainty and neutrino oscillation sensitivity are coming soon…





Conclusions

Conclusions

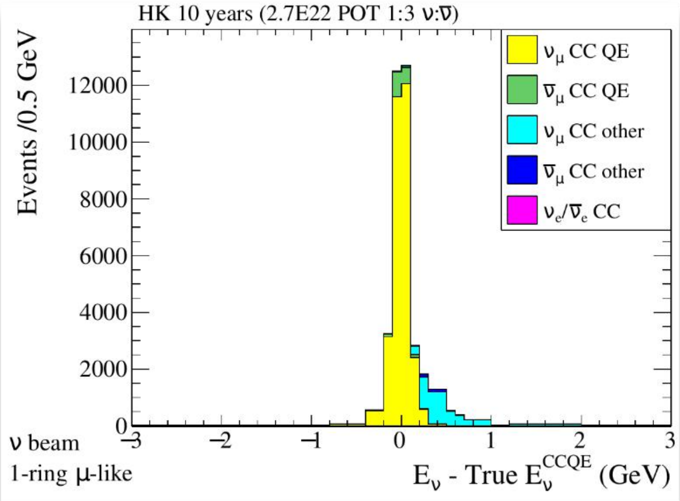
- Overview the neutrino oscillation studies at HK with the impact from IWCD

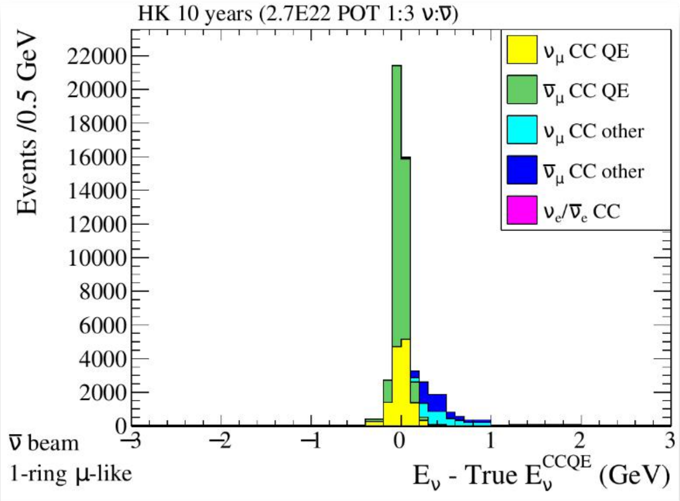
- After 10 years of running time, with the improved systematics HK will reach sensitivities to
  - Measure δ_{CP} with a precision of ≤ 19°
  - Measure Δm^2_{32} with a precision of 0.35% fractional error
  - Exclude CP conservation at 5σ for 61% of true δ_{CP} values
  - Mass ordering sensitive to $\gtrsim 5\sigma$, assuming $\sin^2\theta_{23} > 0.5$
  - Exclude wrong octant values for true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$ at 3σ

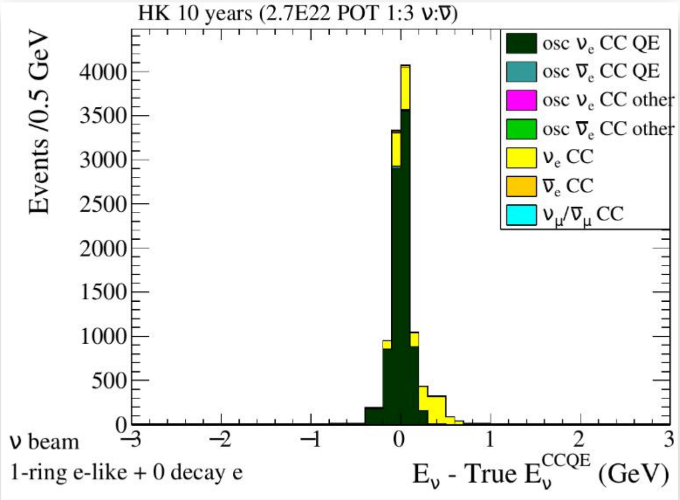
- IWCD shows 3.7% $\nu_e/\bar{\nu}_e$ cross-section experimental error, improved on the 4.9% T2K theory error
  - Lifting up the sensitivity to exclude CP conservation
  - Expecting more fit outcomes
    - Sensitivities on other oscillation parameters, different off-axis spans, …
  - Expecting analysis improvements
    - e.g. 2D parameterization, MC toy studies on cross-section errors, …

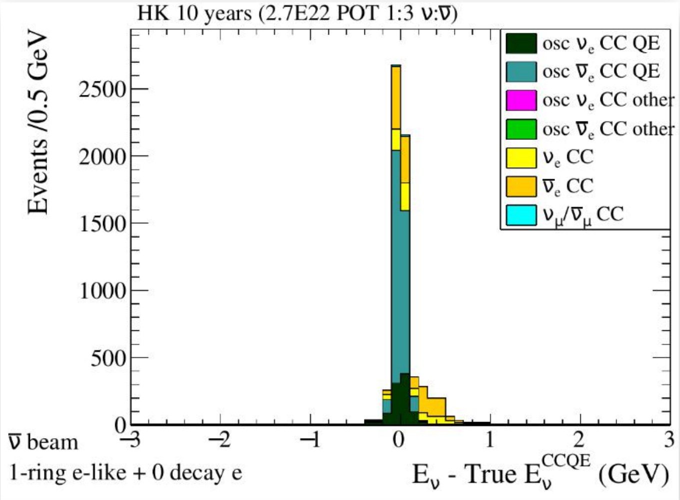
Backup Slides

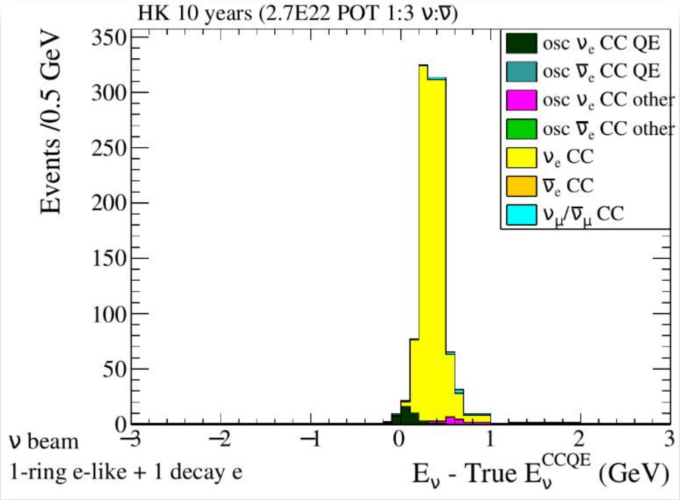
HK E_ν - E_ν^{CCQE} ν Spectra









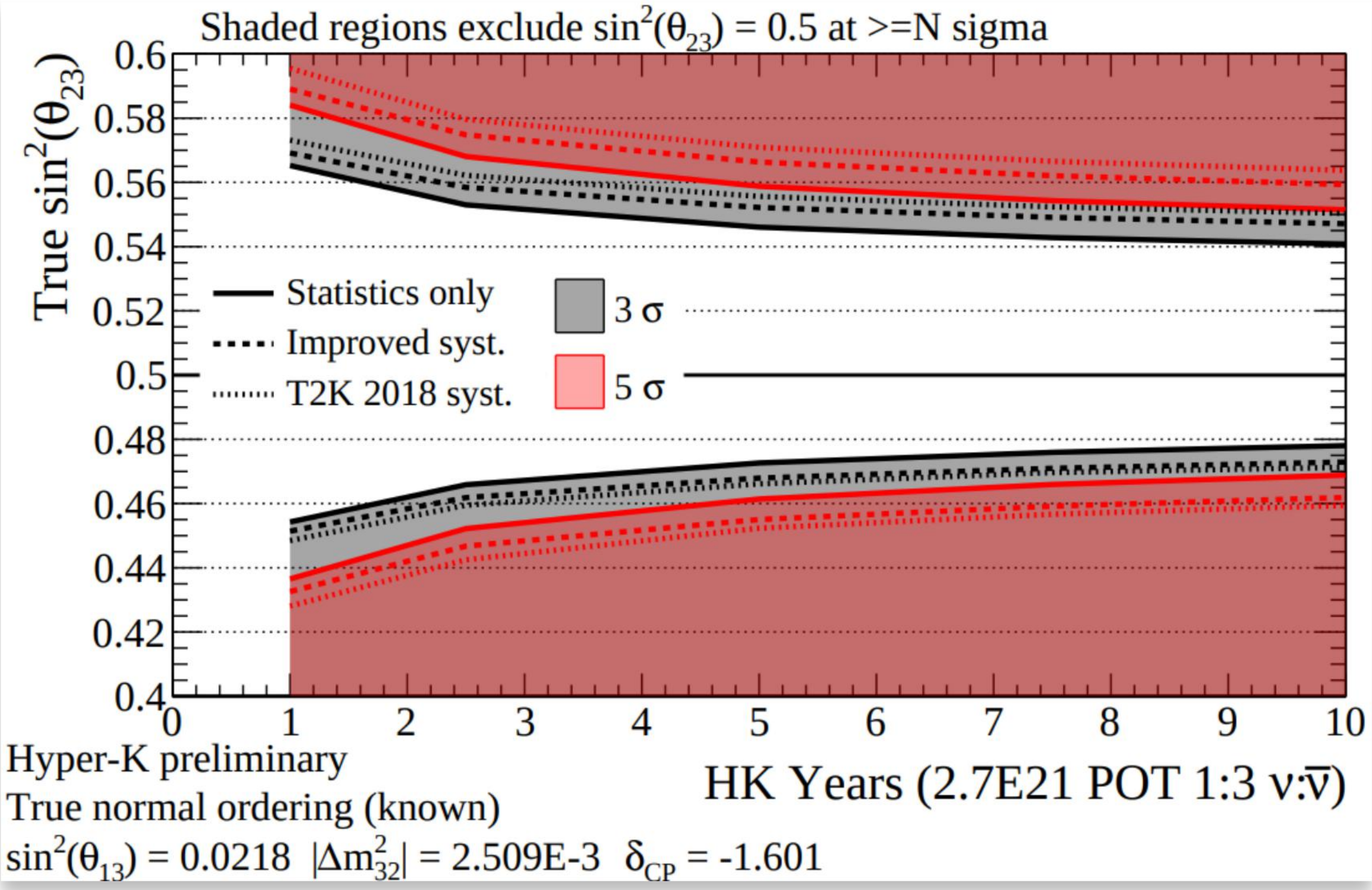


HK Systematic Uncertainty Models

- Improved systematics
  - Scaling uncertainty on flux, cross-section and SK detector systematics by $1/\sqrt{N}$, where N = 8.7 is the relative increase in neutrino beam exposure from T2K to Hyper-K
  - Studies from ND280 Upgrade and Intermediate Water Cherenkov Detector add further constraints to cross-section uncertainties
    - A factor of 3 reduction on all non-quasi-elastic uncertainties
    - A factor of 2.5 reduction on all quasi-elastic uncertainties
    - A factor 2 reduction on all anti-neutrino uncertainties
    - A reduction in neutral current uncertainties to the ~10% level
  - The ν_e / $\bar{\nu}_e$ cross-section ratio error was varied from ~3.6% to 1% to assess its impact

θ_{23} Octant Sensitivity

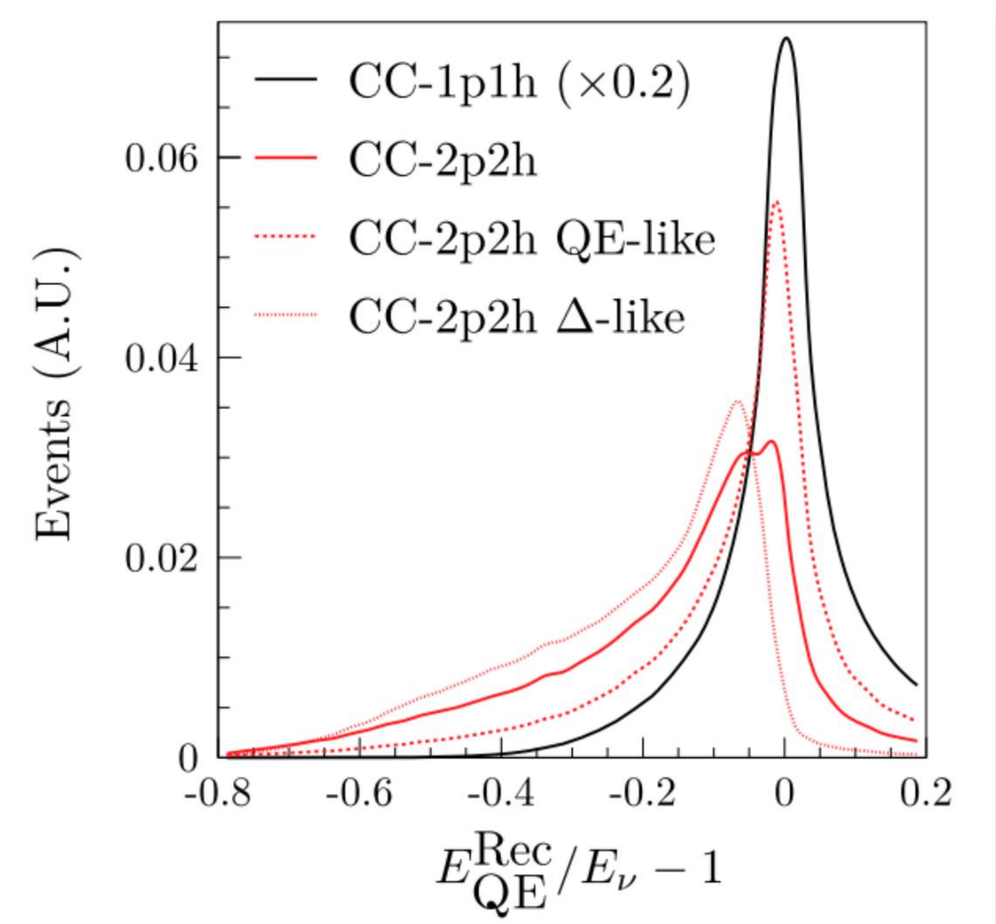
- Wrong θ_{23} octant exclusion over true $\sin^2\theta_{23}$, atmospheric neutrinos sample not included
- Sensitive to μ-like + e-like uncertainties, and are reduced by improved systematics
- After 10 years, values of true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$ can be excluded at 3σ



Reconstructed Energy Bias

- Bias for 1p1h and 2p2h events with an oscillated muon neutrino flux

- Showing the difference in the reconstructed energy smearing for 2p2h events with QE-like and Delta-like interaction kinematics



Parameterization (T2K 2018 syst.)

- Flux:
  - ν-mode ν_μ (11), ν-mode $\bar{\nu}_\mu$ (5), ν-mode ν_e (7), ν-mode $\bar{\nu}_e$ (2)
  - $\bar{\nu}$-mode $\bar{\nu}_\mu$ (11), $\bar{\nu}$-mode ν_μ (5), $\bar{\nu}$-mode $\bar{\nu}_e$ (7), $\bar{\nu}$-mode ν_e (2)
- Cross-section:
  - CCQE axial-mass scaling factor
  - Fermi momentum for ^{16}O
  - C_5^A nucleon to Δ transition axial form factor
  - Resonance-production axial-mass scaling factor
  - Scale of isospin 1/2 non-resonant background
  - CC other shape
  - ν 2p2h shape for ^{16}O
  - CC ν_e normalisation
  - CC $\bar{\nu}_e$ normalisation
  - BeRPA coefficient A, B, D, E, U
  - ν 2p2h normalisation for ^{16}O
  - CC coherent for ^{16}O normalisation
  - NC coherent normalisation
  - NC 1γ normalisation
  - NC other normalisation
  - $\bar{\nu}$ 2p2h normalisation for ^{16}O
  - 2p2h ^{12}C to ^{16}O normalisation
- Far detector + FSI + SI
  - ν-mode 1-ring μ like (6), ν-mode 1-ring e like (12), ν-mode 1-ring e like +1 decay e (8)
  - $\bar{\nu}$-mode 1-ring μ like (6), $\bar{\nu}$-mode 1-ring e like (12)
  - SK energy scale for e-like + μ-like events (1)

Parameterization (IWCD Improved syst.)

- Same flux and far detector parameterization as T2K 2018 model
- Cross-section (slightly modified based on T2K 2018 model):
  - CCQE axial-mass scaling factor
  - Fermi momentum for ^{16}O
  - C_5^A nucleon to Δ transition axial form factor
  - Resonance-production axial-mass scaling factor
  - Scale of isospin 1/2 non-resonant background
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  - 2p2h ^{12}C to ^{16}O normalisation
  - *** Binding energy on oxygen**

*** New added parameters**

Parameterization (IWCD 1D Analysis)

- Same flux and far detector parameterization as T2K 2018 model
- Cross-section (slightly modified based on T2K 2018 model):
  - CCQE axial-mass scaling factor
  - Fermi momentum for ^{16}O
  - C_5^A nucleon to Δ transition axial form factor
  - Resonance-production axial-mass scaling factor
  - Scale of isospin 1/2 non-resonant background
  - CC other shape
  - ν 2p2h shape for ^{16}O
  - *** CC ν_e normalisation (1→5)**
  - *** CC $\bar{\nu}_e$ normalisation (1→5)**
  - BeRPA coefficient A, B, D, E, U
  - ν 2p2h normalisation for ^{16}O
  - CC coherent for ^{16}O normalisation
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  - NC other normalisation
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  - 2p2h ^{12}C to ^{16}O normalisation
  - *** Binding energy on oxygen**

*** New added parameters**

Parameterization (IWCD 2D Analysis)

- Same flux and far detector parameterization as T2K 2018 model
- Cross-section (slightly modified based on T2K 2018 model):
  - CCQE axial-mass scaling factor
  - Fermi momentum for ^{16}O
  - C_5^A nucleon to Δ transition axial form factor
  - Resonance-production axial-mass scaling factor
  - Scale of isospin 1/2 non-resonant background
  - CC other shape
  - ν 2p2h shape for ^{16}O
  - *** CC ν_e normalisation (1→5)**
  - *** CC $\nu_e + \nu_\mu$ 2D normalisation (29)**
  - *** CC $\bar{\nu}_e + \bar{\nu}_\mu$ 2D normalisation (29)**
  - *** CC $\bar{\nu}_e$ normalisation (1→5)**
  - BeRPA coefficient A, B, D, E, ~~U~~
  - ν 2p2h normalisation for ^{16}O
  - CC coherent for ^{16}O normalisation
  - NC coherent normalisation
  - NC 1γ normalisation
  - NC other normalisation
  - $\bar{\nu}$ 2p2h normalisation for ^{16}O
  - ~~2p2h ^{12}C to ^{16}O normalisation~~

*** New added parameters**

IWCD - MC Properties

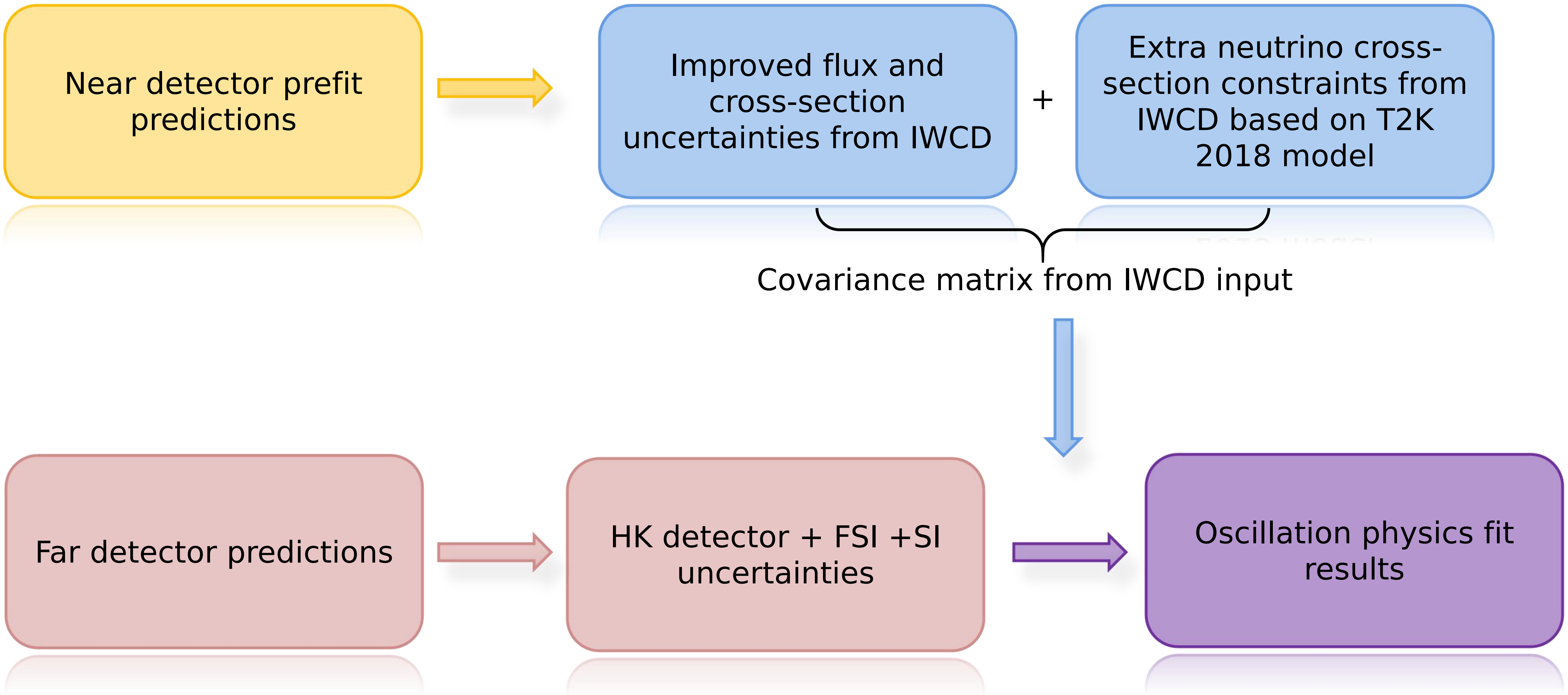
- Generated with 1 km flux and long tank geometry

- 1°-4° off-axis angle (OAA) span
  - Event generations at 7 different vertical detector positions

- Exposure
  - Same exposure between OAAs
  - 7E21 (21E21) POT for FHC (RHC)

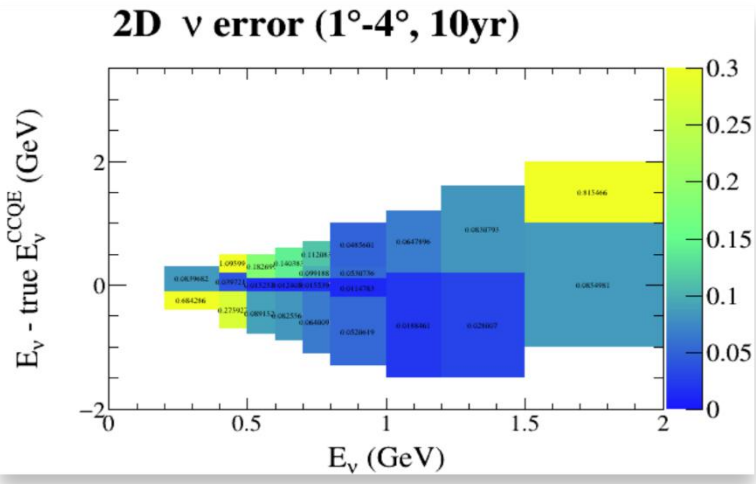
- Event pile-up efficiency based on the nominal configuration
  - Probability to observe ID interactions that are not coincident with other ID interactions or OD light
  - About 7 - 35% fraction

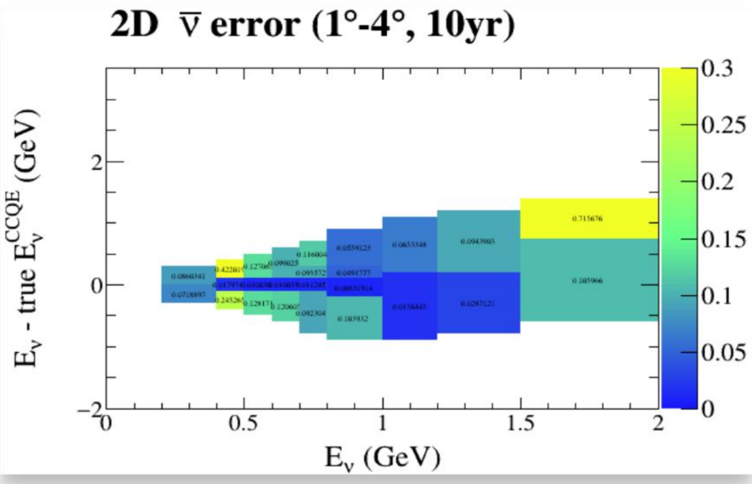
IWCD 2D Analysis Framework

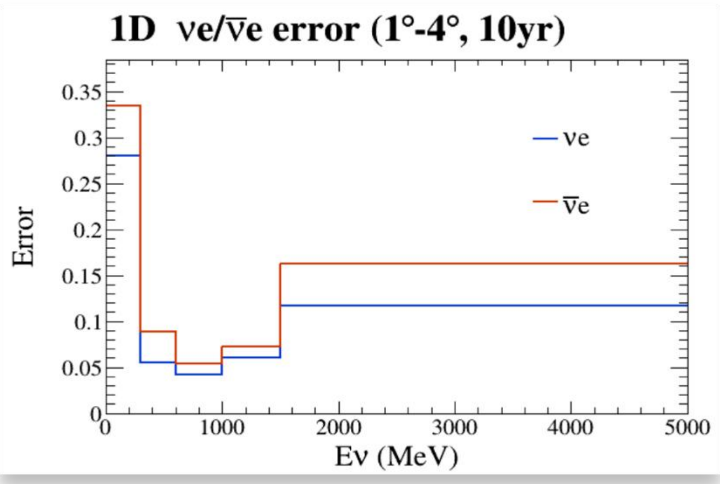


Parameterization (IWCD 2D Analysis)

- Additional IWCD cross-section constraints:







Parameter	Interaction types	Binning	# parameters
IWCD 2D $\nu + \bar{\nu}$ norm. xsec.	ν_μ ($\bar{\nu}_\mu$) CC + ν_e ($\bar{\nu}_e$) CC	E_ν vs E_ν - true E_ν^{CCQE}	29+29
IWCD 1D $\nu_e + \bar{\nu}_e$ norm. xsec.	ν_e ($\bar{\nu}_e$) CC	E_ν	5+5
Flux (T2K 2018 model)	All types (ν mode+$\bar{\nu}$ mode)	E_ν	25+25
Cross-section (modified T2K 2018 model)	CC / NC	E_ν	17
2p2h ^{12}C to ^{16}O normalisation (fixed)	CC 2p2h	-	1
SK detector efficiencies + FSI +SI (T2K 2018 model)	CC / NC	reco. E_ν^{CCQE}	44
SK energy scale	CC / NC	reco. E_ν^{CCQE}	1

IWCD - Sensitivities

- Systematic uncertainties with 1D parameterization

	1-Ring ν_μ-like		1-Ring ν_e-like			
Error source	ν-Mode	$\bar{\nu}$-Mode	ν-Mode CCQE-like	$\bar{\nu}$-Mode CCQE-like	ν-Mode CC1π-like	ν-Mode/$\bar{\nu}$-Mode CCQE-like
Flux + Cross section	0.54%	0.53%	2.31%	2.83%	2.32%	2.60%
Detector + FSI + SI	1.23%	1.13%	1.4%	1.61%	4.87%	0.54%
All systematics	1.35%	1.25%	2.68%	3.26%	5.37%	2.65%

- Improved systematics

	1-Ring ν_μ-like		1-Ring ν_e-like			
Error source	ν-Mode	$\bar{\nu}$-Mode	ν-Mode CCQE-like	$\bar{\nu}$-Mode CCQE-like	ν-Mode CC1π-like	ν-Mode/$\bar{\nu}$-Mode CCQE-like
Flux + Cross section	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector + FSI + SI	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All systematics	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%