Hyper-Kamiokande Oscillation Physics

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for the Hyper-Kamiokande collaboration

NuFact2024

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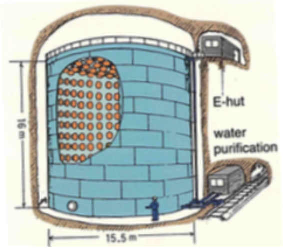
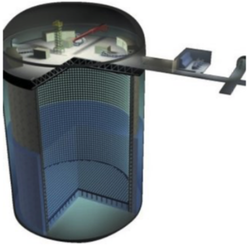
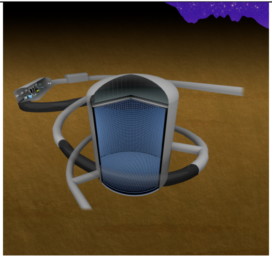
Hyper-Kamiokande

Towards Hyper-Kamiokande

	Kamiokande	Super-K	Hyper-K
Operation	1983–1995	1996–	2027–
Mass (fiducial)	4.5 (0.68) kton	50 (22.5) kton	258 (187) kton







- Hyper-K under construction, building on decades of expertise
- Fiducial mass increase $> \times 8$, relative to Super-K
- $\sim$20k improved 20" PMTs with $\sim \times 2$ photo detection efficiency, relative to Super-K PMTs
- Addition of $\sim$800 fine-grained "mPMTs", enhancing reconstruction & providing cross-calibration with 20" PMTs

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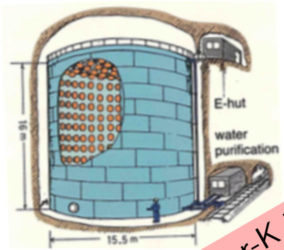
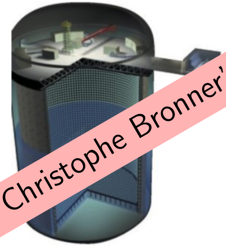
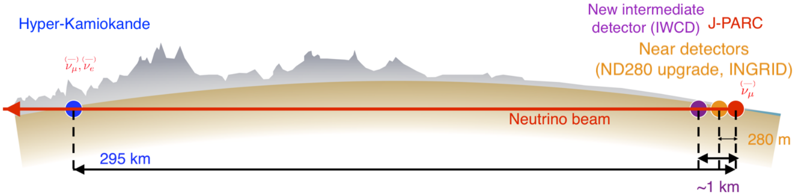




More details about Hyper-K in Christophe Bronner's talk [Friday plenary]

- Hyper-K under constructi[illegible]uilding on decades of expertise
- Fiducial mass increa[illegible]×8, relative to Super-K
- ∼20k improve[illegible] MTs with ∼ ×2 photo detection efficiency, relative to Super-K P[illegible]
- Addition of ∼800 fine-grained "mPMTs", enhancing reconstruction & providing cross-calibration with 20" PMTs

Hyper-Kamiokande ν_μ & $\overline{\nu}_\mu$ beam



Hyper-Kamiokande ν_μ & $\overline{\nu}_\mu$ beam

- 20 times more stats at far detector than T2K, in 10 HK-years
  - J-PARC beam upgraded to 1.3 MW
  - New 188 kt fiducial far detector
- On-axis near detector (INGRID)
- Upgraded off-axis near detector (ND280-upgrade)
- New Intermediate Water Cherenkov Detector (IWCD)

Hyper-Kamiokande ν_μ & $\overline{\nu}_\mu$ beam

More details about J-PARC neutrino beam in Sekiguchi-san's talk [WG3 Tuesday]

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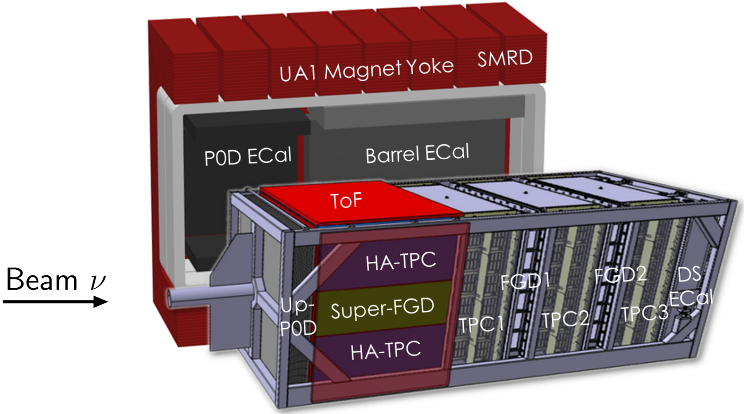
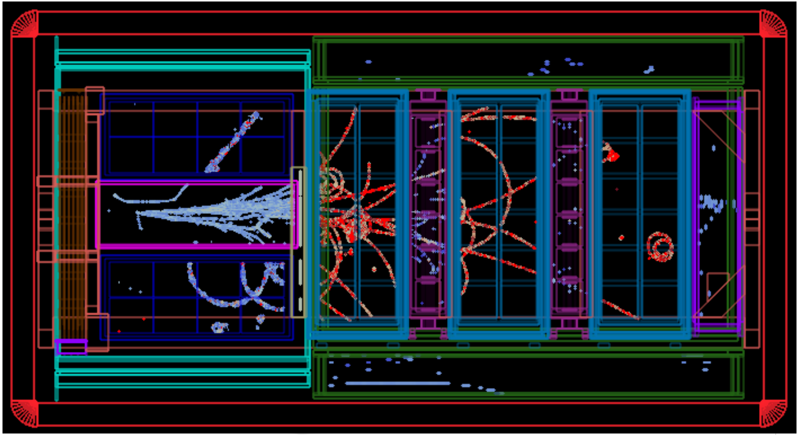
ND280-upgrade



- Upgrade to T2Ks magnetised off-axis near detector @ 280 m
- Increased efficiency for
  - Low-momentum tracks
  - High-angle tracks



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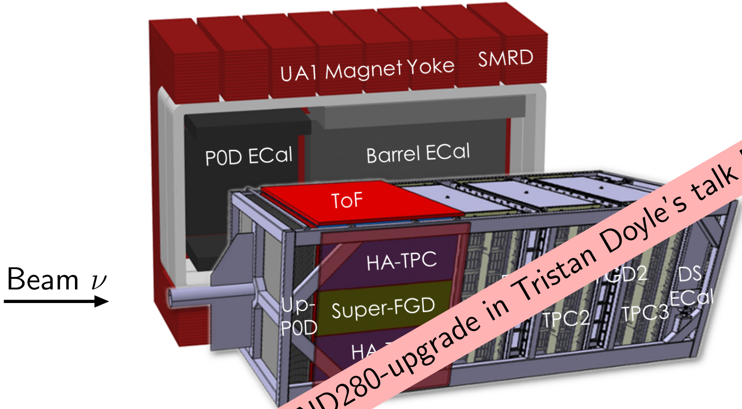
- Complete upgraded detector has been taking data this year!

ND280-upgrade



More details about ND280-upgrade in Tristan Doyle's talk [WG6 Thursday]

- Upgrade to T2Ks magn… off-axis near detector @ 280 m
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  - Low-mo… tracks
  - High-a… tracks
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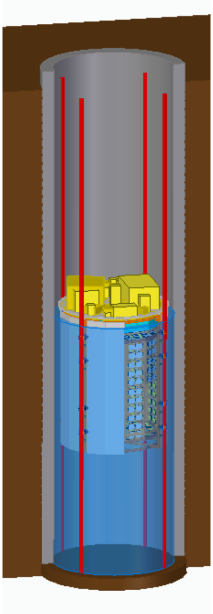
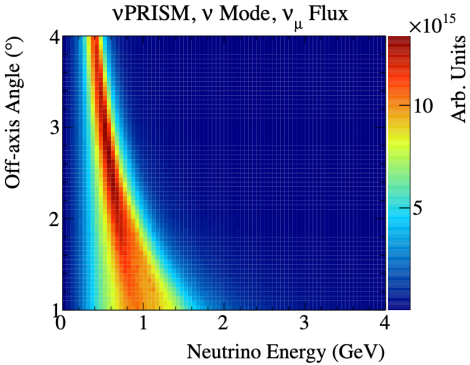
Intermediate water Cherenkov detector (IWCD)



- Water Cherenkov detector @ ∼1 km
  - Brand new detector & facility for the Hyper-K era
- Novel moving detector, providing measurements of neutrino interactions across a range of ∼1.5–4° off-axis angles, allows
  - Creation of narrow beam for cross-section analyses
  - Reconstruction of the oscillated flux



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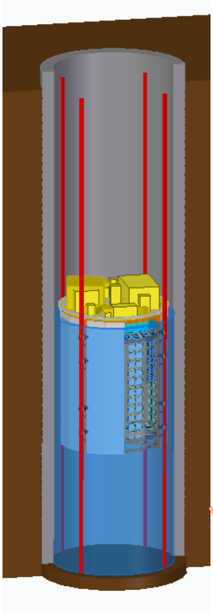

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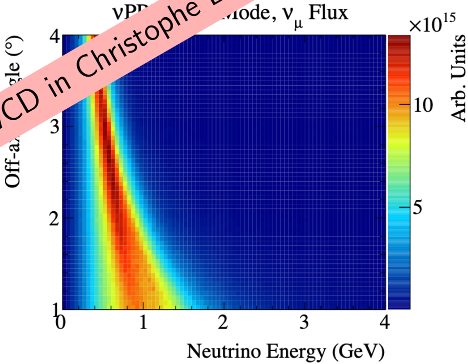
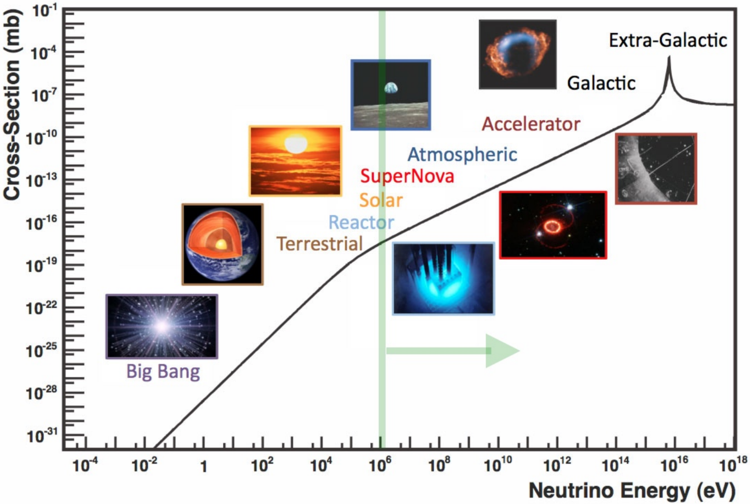
More details about IWCD in Christophe Bronner's talk [Friday plenary]



Hyper-Kamiokande physics



ν CP violation

Precision ν oscillation measurements

Solar ν

Proton decay

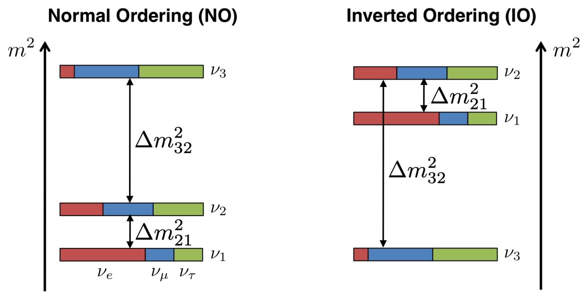
Supernova burst ν

Diffuse supernova ν background

and many more...

Neutrino oscillation open questions

Hyper-K has sensitivity to	Beam	Atmospheric	Solar
δ_{CP}	✓	✓	
θ_{13}	✓	✓	
θ_{23}	✓	✓	
$\|\Delta m^2_{32}\|$	✓	✓	
Mass ordering	✓	✓	
θ_{12}			✓
Δm^2_{21}			✓



- Is there CP violation?
  Does $\sin \delta_{CP} = 0$?
- Is θ_{23} maximal $(= 45°)$?
  If not, which octant $(< \text{or} > 45°)$?
- Which mass ordering?
  $\Delta m^2_{32} < \text{or} > 0$?

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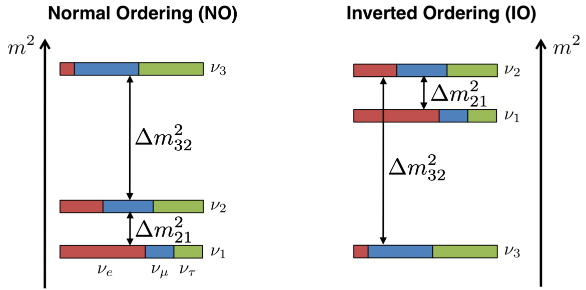

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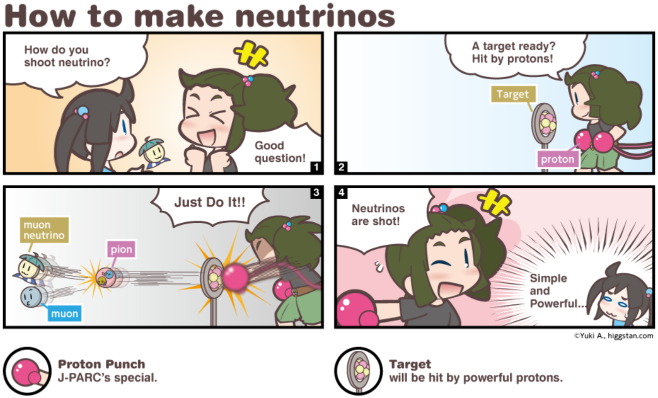
  Does $\sin \delta_{CP} = 0$?
- Is θ_{23} maximal ($= 45°$)?
  If not, which octant ($<$ or $> 45°$)?
- Which mass ordering?
  $\Delta m^2_{32} <$ or > 0?

Beam-only sensitivities



higgstan.com

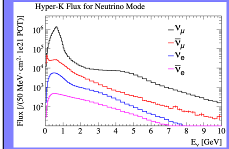
Standard Hyper-K analysis will be beam + atmospherics

For these beam-only results

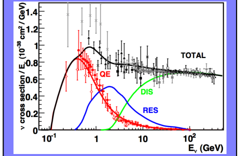
- Assuming true normal mass ordering is known
  - Approximates effect of adding atmospheric samples
- Using a constraint on $\sin^2(\theta_{13})$ from reactor experiments

Hyper-K neutrino beam analysis method

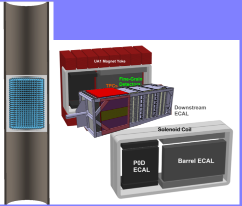
Neutrino flux



Neutrino xsec

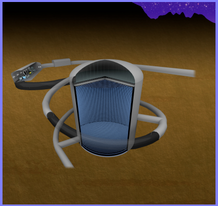


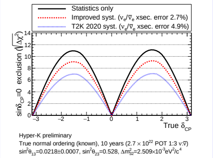
Constrain models with near detectors



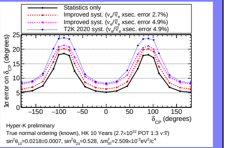
ND280-upgrade & IWCD

Fit constrained models to far detector data



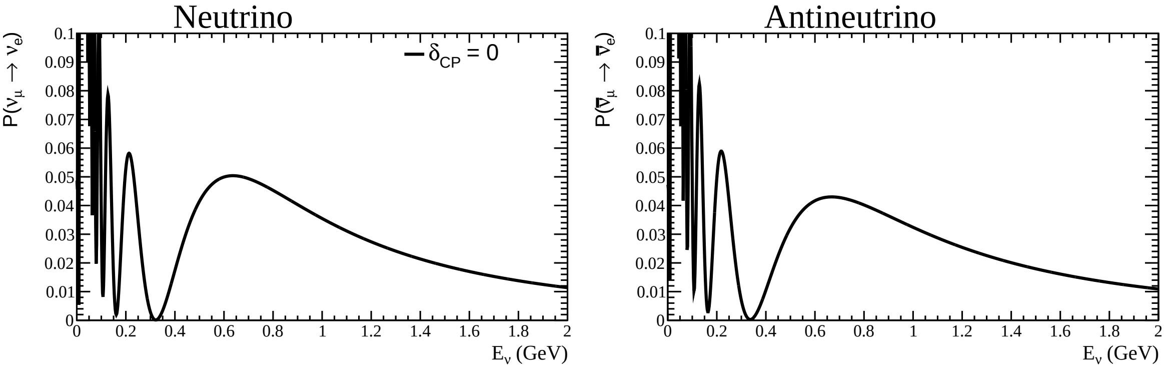


Oscillation sensitivities



- Using T2K analysis method

ν_e & $\overline{\nu}_e$ appearance probabilities @ 295 km



- Hyper-K ν & $\bar{\nu}$ beam flux peaks $\sim$0.6 GeV

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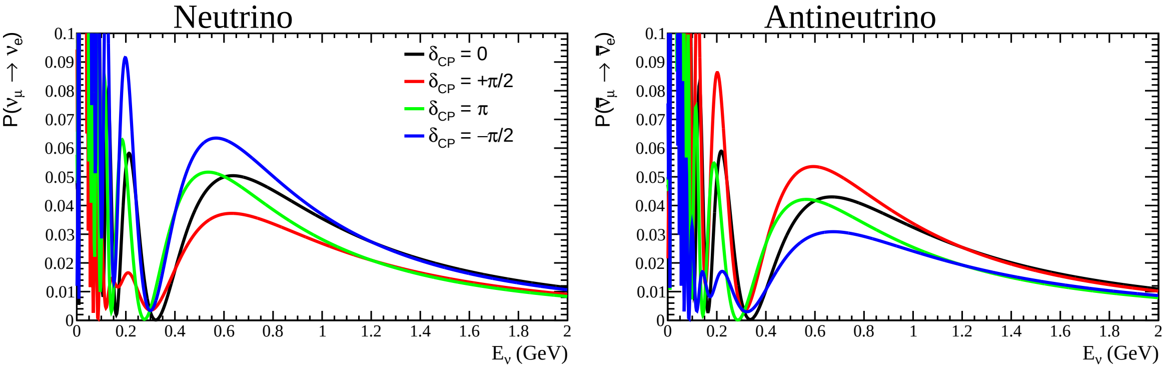
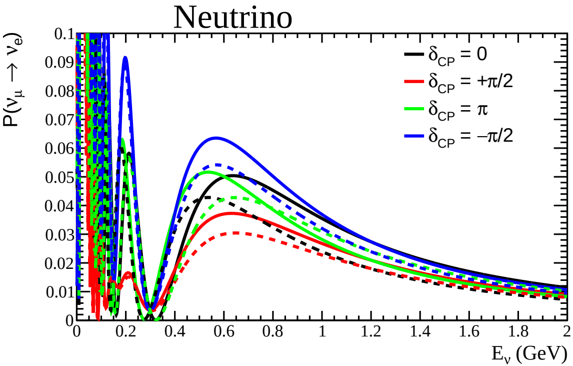
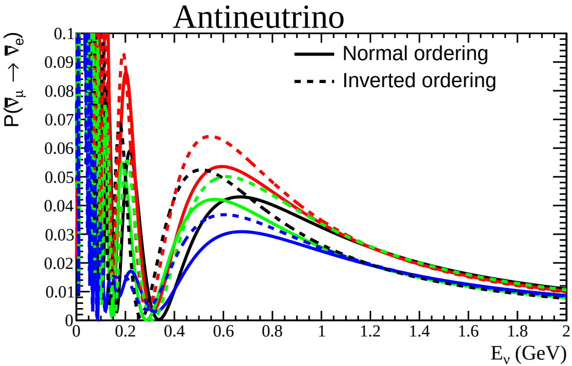


- Hyper-K ν & $\bar{\nu}$ beam flux peaks ~0.6 GeV
- @ $\delta_{CP} = -\pi/2$
  - ν_e appearance enhanced; $\overline{\nu}_e$ appearance suppressed

ν_e & $\overline{\nu}_e$ appearance probabilities @ 295 km

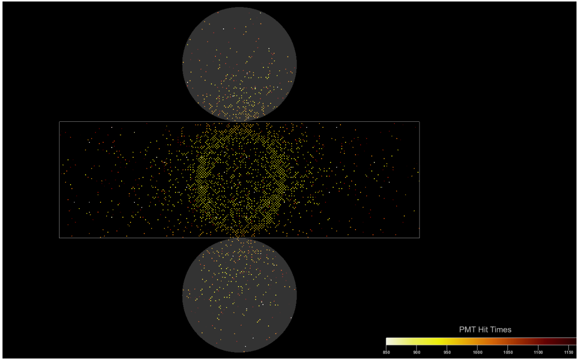




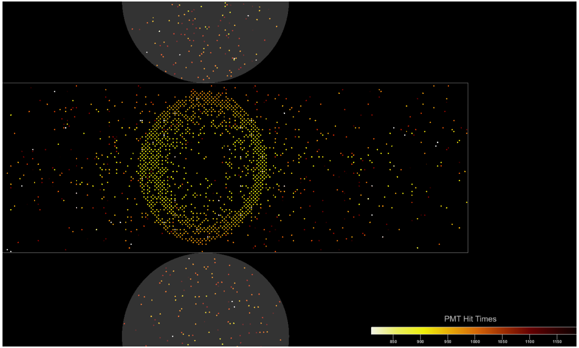
- Hyper-K ν & $\bar{\nu}$ beam flux peaks ∼0.6 GeV
- @ $\delta_{CP} = -\pi/2$
  - ν_e appearance enhanced; $\overline{\nu}_e$ appearance suppressed
- Unknown mass ordering (solid vs dashed) complicates δ_{CP} measurement
  - Hyper-K can use atmospheric data to exclude incorrect MO

Event samples

Electron event



Muon event

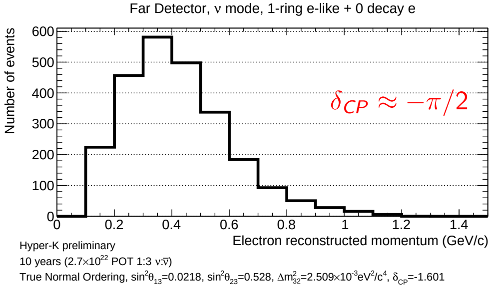


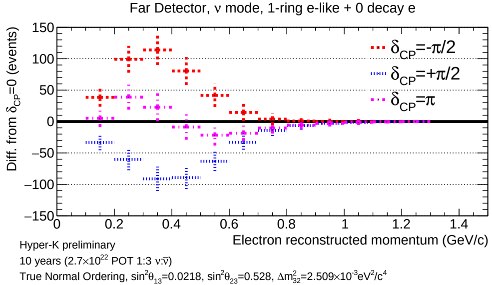
Expected event rate @ 10 years (2.7E22 POT),
ν:$\bar{\nu}$ = 1:3, @ $\delta_{CP} = 0$

ν-mode beam, 1-ring μ-like	$\sim$8800
$\bar{\nu}$-mode beam, 1-ring μ-like	$\sim$12000
ν-mode beam, 1-ring e-like + 0 decay e	$\sim$2100
$\bar{\nu}$-mode beam, 1-ring e-like + 0 decay e	$\sim$1800
ν-mode beam, 1-ring e-like + 1 decay e	$\sim$300

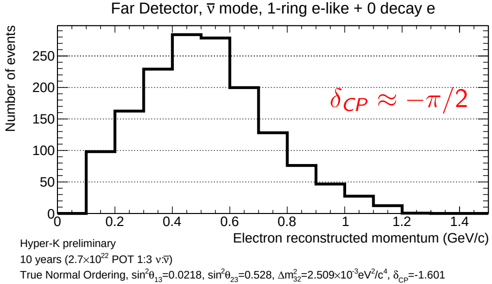
1-ring e-like + 0 decay e event samples

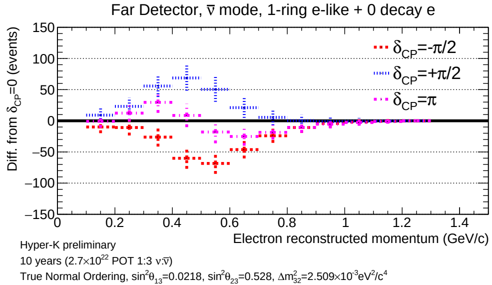
ν-mode beam





$\bar{\nu}$-mode beam





Systematics

- Hyper-K has high statistics
  1. Must work to reduce systematics as much as possible
     - ⋆ Improved xsec/flux model constraints from new IWCD / ND280-upgrade
     - ⋆ Comprehensive calibration scheme leveraging 20" PMT / mPMT cross-calibration
     - ⋆ Higher statistics available in control samples
  2. Must work to produce a more sophisticated error model
     - ⋆ An error model with more degrees of freedom is required

Systematics

- Hyper-K has high statistics
  1. Must work to reduce systematics as much as possible
  2. Must work to produce a more sophisticated error model (Future work)
- Going to show sensitivities with a range of systematics scenarios

A. T2K 2020 systematics
   - Where we are now

B. Improved systematics
   - Where we want to be with ND280-upgrade, IWCD, & increased statistics
   - Produced by scaling T2K systematics based on ND280-upgrade/IWCD sensitivity

C. Statistics only
   - Ideal case of no systematics

Total percentage error on sample event rates:

Error model	μ-like		e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode 0 d.e.	$\bar{\nu}$-mode 0 d.e.	ν-mode 1 d.e.	$\nu/\bar{\nu}$ modes 0 d.e.
T2K 2020	3.0%	4.0%	4.7%	5.9%	14.1%	4.6%
Improved	1.2%	1.1%	2.1%	2.2%	5.2%	2.0%

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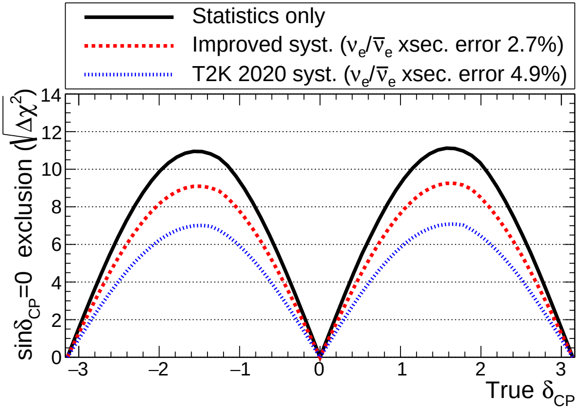
$\sin \delta_{CP} \neq 0$ sensitivity

Beam only

- For a true value of δ_{CP}, how much can we exclude CP conservation? ($\delta_{CP} = 0, \pm\pi$)



Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4

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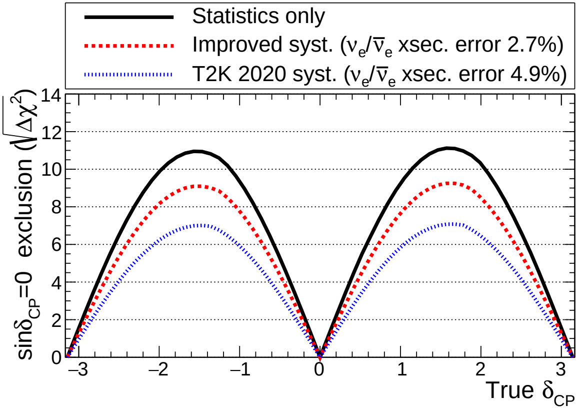

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$\nu_e/\overline{\nu}_e$ cross-section error drives this measurement

- 4.9% for T2K based on theoretical considerations
- 2.7% for Improved based on ND280-upgrade & IWCD sensitivity

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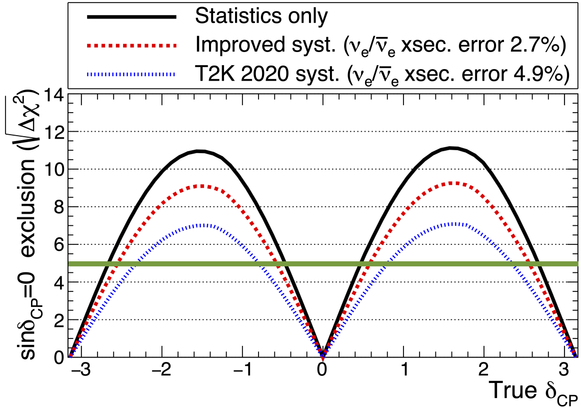

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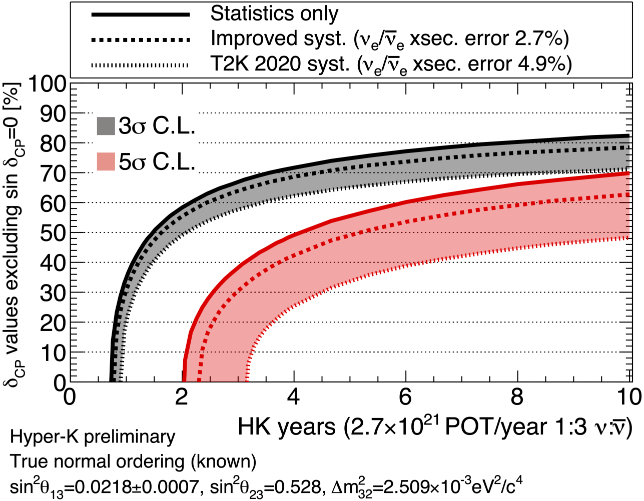
With Improved systematics

- Exclude CP conservation for 62% of true δ_{CP} values @ 5σ

$\sin\delta_{CP} \neq 0$ sensitivity vs time

Beam only

- What % of true values of δ_{CP} where we can exclude CP conservation, as a function of time?



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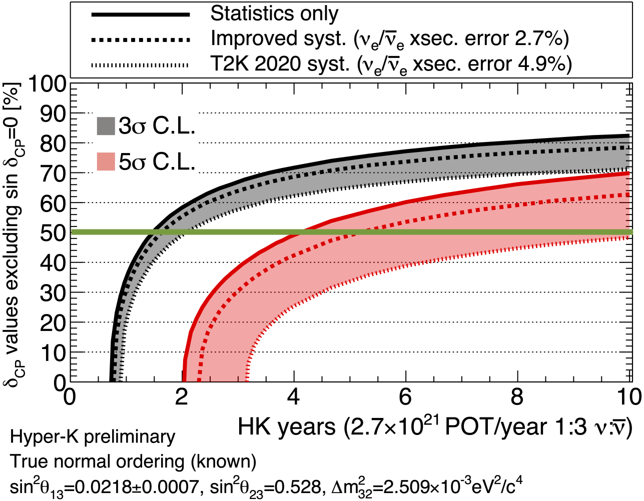

With Improved systematics

- 50% in <2 years @ 3σ

$\sin\delta_{CP} \neq 0$ sensitivity vs time

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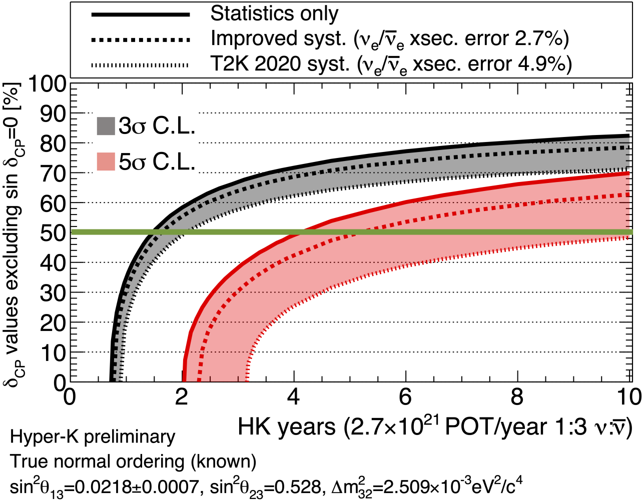


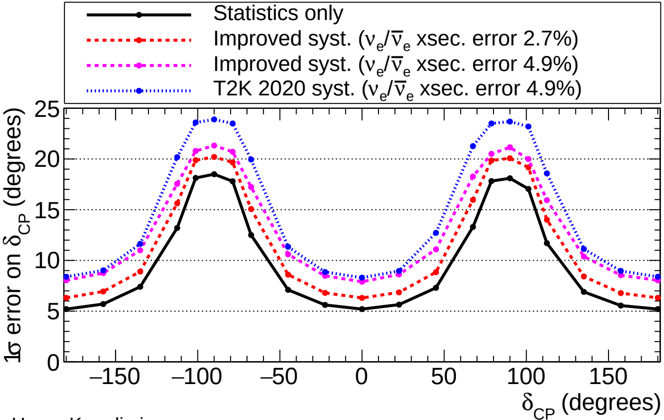
With Improved systematics

- 50% in <2 years @ 3σ
- 50% in ~5 years @ 5σ

δ_{CP} resolution sensitivity

Beam only

- How accurately can we measure the value of δ_{CP}, as a function of true δ_{CP}?



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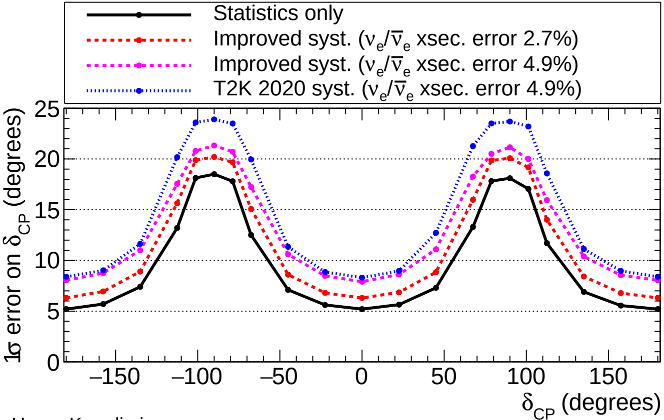
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\,\mathrm{eV}^2/c^4$

δ_{CP} resolution sensitivity

- How accurately can we measure the value of δ_{CP}, as a function of true δ_{CP}?



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

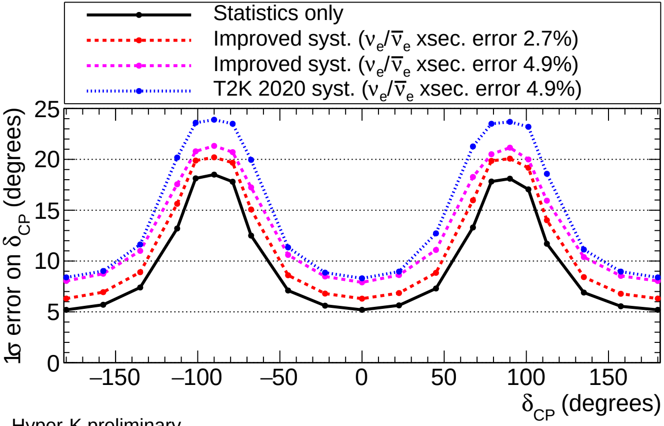
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

With Improved systematics ($\nu_e/\overline{\nu}_e$ xsec. error 2.7%)

- 20.2° for true $\delta_{CP} = -\pi/2 = -90^\circ$
- 6.3° for true $\delta_{CP} = 0$

δ_{CP} resolution sensitivity

- How accurately can we measure the value of δ_{CP}, as a function of true δ_{CP}?



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

Hyper-K is predominately sensitive to difference between ν_e & $\overline{\nu}_e$ measurements

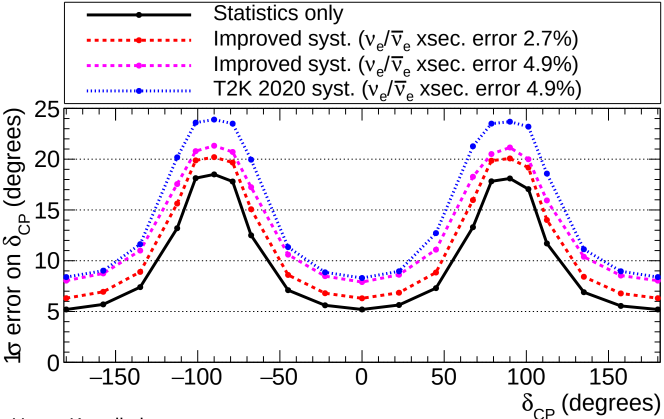
- CP-odd ($\sin\delta_{CP}$) term of oscillation probability
- $\sin\delta_{CP}$ varies more quickly at CP conserving values

$\rightarrow$ Smaller uncertainty at $\sin\delta_{CP}=0$

Beam only

δ_{CP} resolution sensitivity

- How accurately can we measure the value of δ_{CP}, as a function of true δ_{CP}?



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

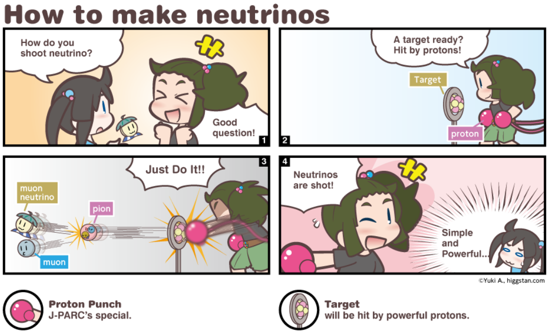
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

$\nu_e/\overline{\nu}_e$ xsec. error has large effect on difference between ν_e & $\overline{\nu}_e$ measurements

- CP-odd ($\sin\delta_{CP}$) term of oscillation probability, $P(\nu_\mu \to \nu_e)$
- Uncertainty on this term $\partial P(\nu_\mu \to \nu_e)/\partial\delta_{CP} \propto \cos(\delta_{CP})$
- At $\sin\delta_{CP} = 0$, that uncertainty is maximal

$\rightarrow$ At $\sin\delta_{CP} = 0$, uncertainty dominated by $\nu_e/\overline{\nu}_e$ xsec. error

Beam + atmospheric sensitivities



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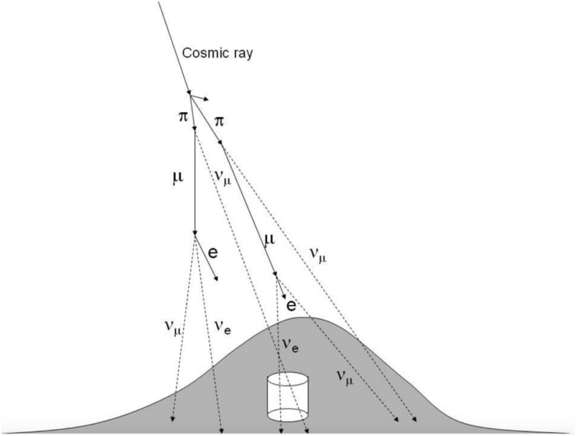
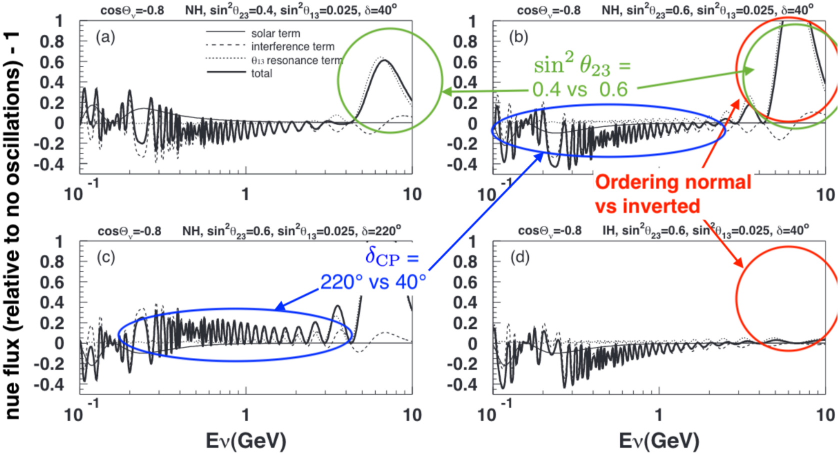


Proc.Japan Acad.B 86 (2010) 303-321

Atmospheric neutrino oscillations

ν_e flux (relative difference to no oscillations) versus true neutrino energy @ $\cos\theta_{\mathrm{zenith}} = 0.8$

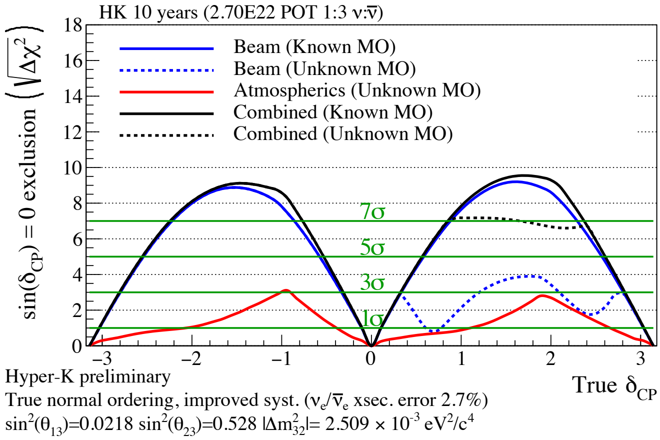


- Resonance in ν_e or $\overline{\nu}_e$ multi-GeV events, depending on the mass ordering
- θ_{23} octant sets magnitude of the resonance
- δ_{CP} sets scale/direction of $\sim$1 GeV interference

$\sin\delta_{CP} \neq 0$ sensitivity with unknown mass ordering

Beam + atmos

- For a true value of δ_{CP}, how much can we exclude CP conservation? ($\delta_{CP} = 0, \pm\pi$)



Based on 2018 T2K & 2019 SK analyses, including reactor constraint

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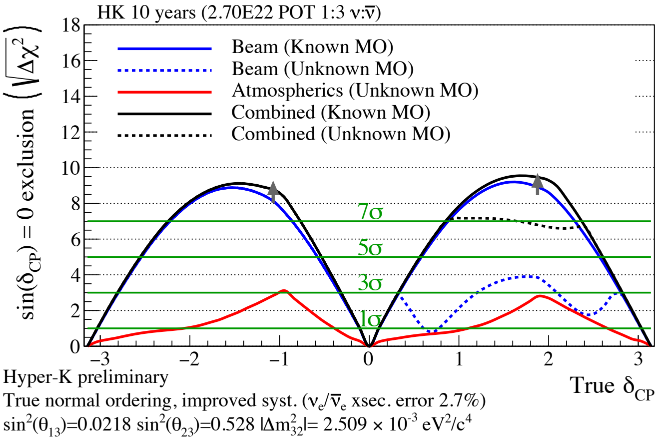


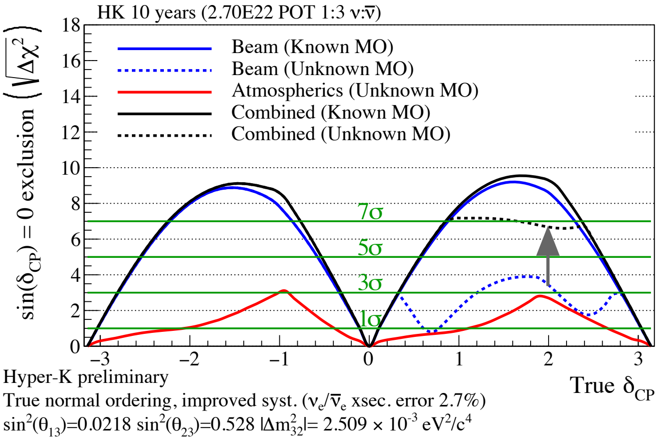
- Solid blue/black lines show case where mass ordering is known
  - Addition of atmospherics enhances sensitivity slightly

Based on 2018 T2K & 2019 SK analyses, including reactor constraint

$\sin\delta_{CP} \neq 0$ sensitivity with unknown mass ordering

Beam + atmos

- For a true value of δ_{CP}, how much can we exclude CP conservation? ($\delta_{CP} = 0, \pm\pi$)



- Dashed blue/black lines show case where mass ordering is unknown
  - Addition of atmospherics gives large improvement

Based on 2018 T2K & 2019 SK analyses, including reactor constraint

Summary

- Presented δ_{CP} sensitivities based on 10 years of beam data & improving on T2K-2020 error model based on sensitivity of ND280-upgrade & IWCD
  - Please ask about sensitivities to $\sin^2(\theta_{23})$, Δm^2_{32}, $\sin^2(\theta_{13})$ (in backup)
  - Paper coming soon!
  - Adding atmospheric neutrino data, we see enhancement of $\sin \delta_{CP} \neq 0$ sensitivity
    - Whether the mass ordering is known or unknown
- Hyper-K has high statistics
  - Must work to reduce systematics as much as possible
  - Must work to produce a more sophisticated error model
- Ultimately, we will use solar data & measure solar parameters
  - Unitarity test of the PMNS matrix in a single experiment
- Hyper-K will start data taking in 2027

Backup

8. Bonus sensitivities
   - Resolution sensitivity of other parameters (beam only)
   - $\sin^2(\theta_{23}) = 0.5$ exclusion sensitivity (beam only)
   - Wrong $\sin^2(\theta_{23})$ octant exclusion (beam only)
   - $\sin^2(\theta_{23})$ mirror point exclusion (beam only)
   - Mass ordering sensitivity (atmospherics + beam)
   - $\sin \delta_{CP} \neq 0$ sensitivity with unknown mass ordering (atmospherics + beam)
9. Far detector samples
10. Systematic errors

Backup

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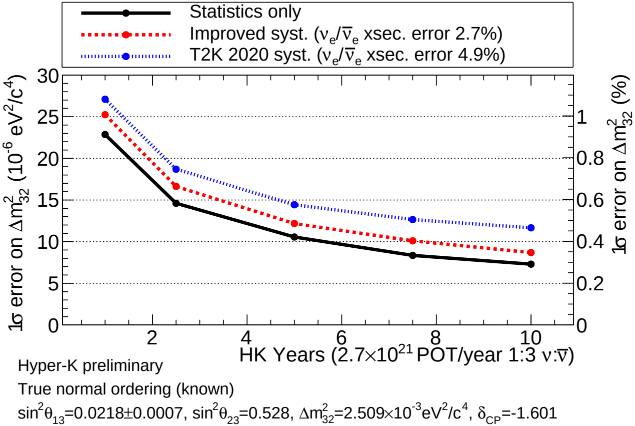
Resolution sensitivity of other parameters

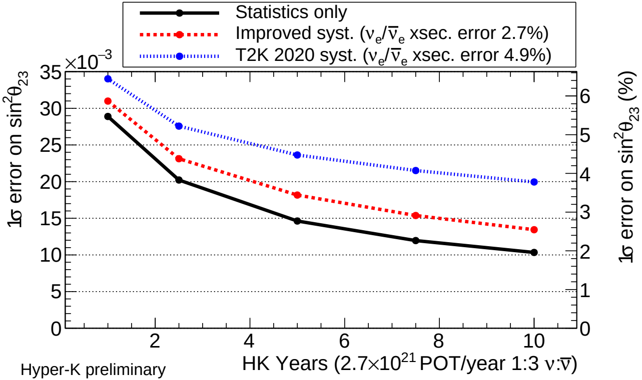
Beam only



	NuFIT 5.2 (2022)	Hyper-K uncertainty (Improved systematics)
Δm^2_{32}	$2.511^{+0.028}_{-0.027} \times 10^{-3}\,\text{eV}^2/\text{c}^4$	$\pm 0.009 \times 10^{-3}\,\text{eV}^2/\text{c}^4$
$\sin^2(\theta_{23})$	$0.572^{+0.018}_{-0.023}$	± 0.013
$\sin^2(\theta_{13})$	$0.02203^{+0.00056}_{-0.00059}$	± 0.00054

Resolution sensitivity of other parameters

Beam only



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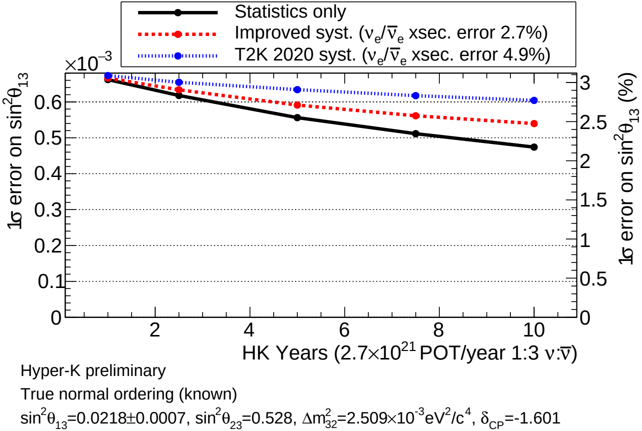
Beam only

Resolution sensitivity of other parameters



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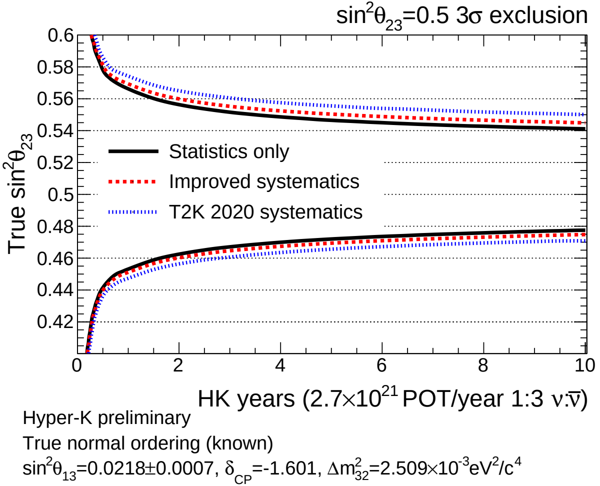
$\sin^2(\theta_{23}) = 0.5$ exclusion sensitivity

Beam only

- For a true value of $\sin^2(\theta_{23})$, how much can we exclude $\sin^2(\theta_{23}) = 0.5$?



$\sin^2(\theta_{23}) = 0.5$ exclusion sensitivity

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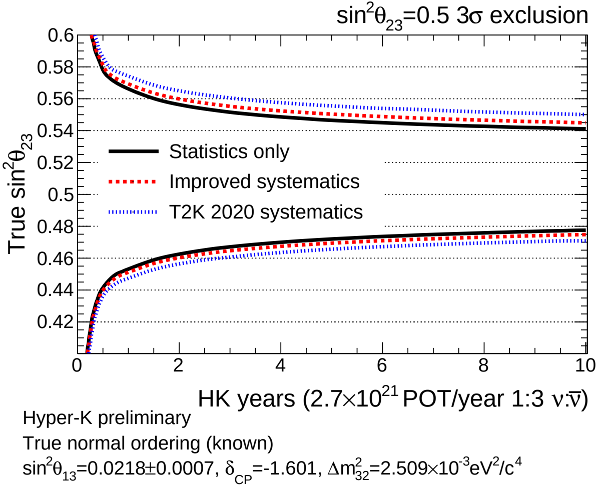


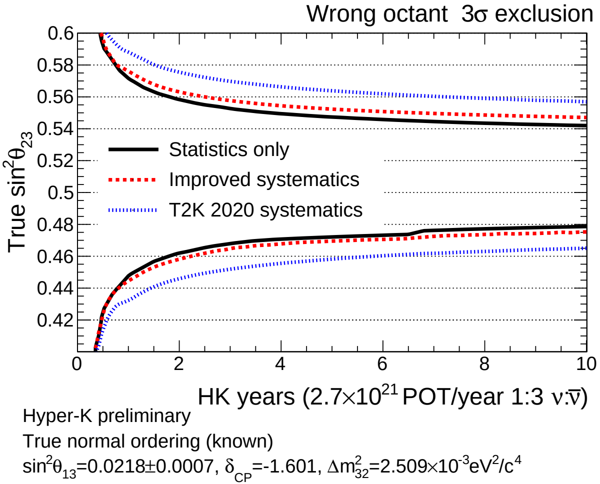
With "Improved systematics"

- 3σ exclusion outside the range of true $\sin^2(\theta_{23})$ $[0.475, 0.545]$

Wrong octant exclusion sensitivity

Beam only

- For a true value of $\sin^2(\theta_{23})$, how much can we exclude all values of $\sin^2(\theta_{23})$ in the other (wrong) octant?

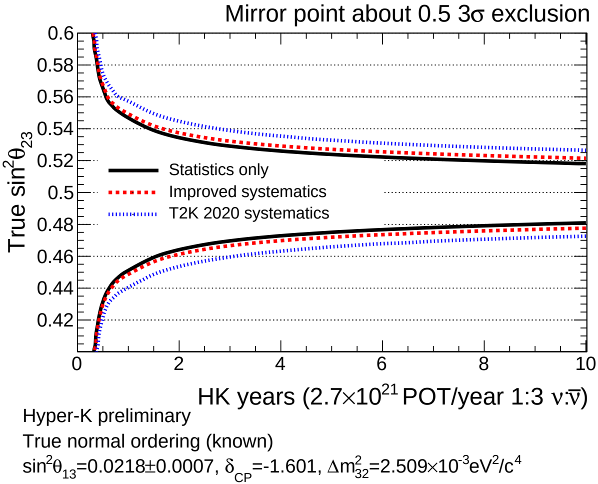


With "Improved systematics"

- 3σ exclusion outside the range of true $\sin^2(\theta_{23})$ $[0.474, 0.547]$

$\sin^2(\theta_{23})$ mirror point exclusion sensitivity

- For a true value of $\sin^2(\theta_{23})$, how much can we exclude its mirror point (flipped about $\sin^2(\theta_{23}) = 0.5$)?

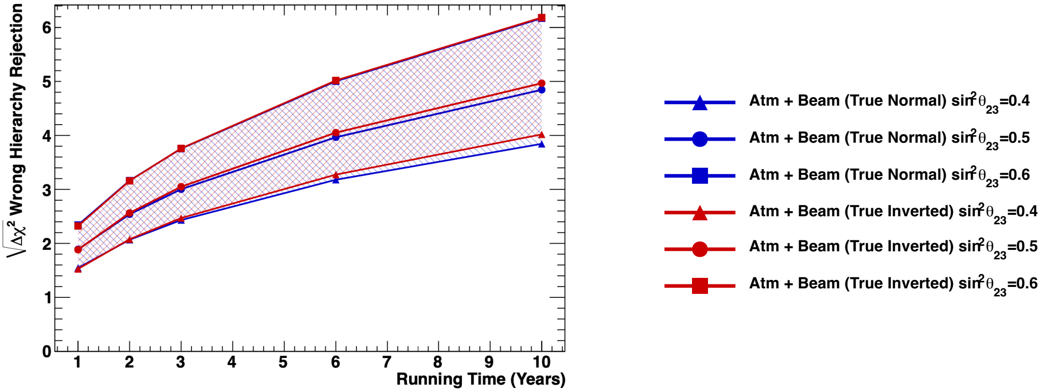


With "Improved systematics"

- 3σ exclusion outside the range of true $\sin^2(\theta_{23})$ $[0.478, 0.521]$

Mass ordering sensitivity

Beam + atmos

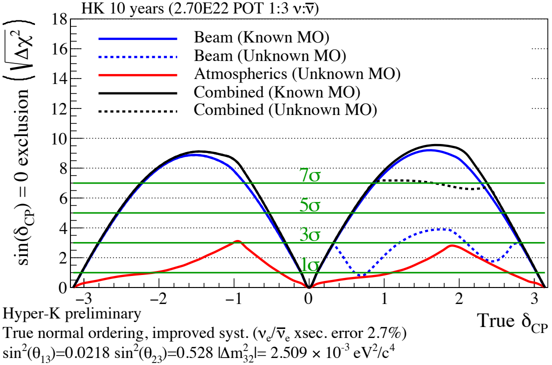


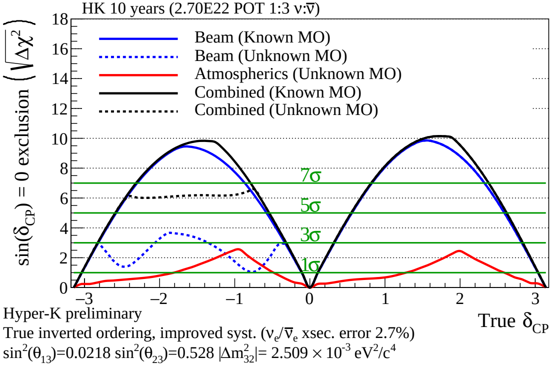
- Atmospheric neutrinos have longer baseline & higher energies than beam neutrinos (in general)
  - → Enhances matter effect ($\propto E_\nu n_e$)
  - → Increased sensitivity to mass ordering
  - → Exclude incorrect mass ordering at ∼4–6σ in 10 years
    - ★ Depending on true value of $\sin^2(\theta_{23})$

Based on older HK analysis

$\sin\delta_{CP} \neq 0$ sensitivity with unknown mass ordering

- For a true value of δ_{CP}, how much can we exclude CP conservation? ($\delta_{CP} = 0, \pm\pi$)





- Changing from true normal to true inverted MO flips the half of true-δ_{CP}-space where unknown MO has greatest effect

Based on 2018 T2K & 2019 SK analyses, including reactor constraint

Backup

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   - Resolution sensitivity of other parameters (beam only)
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   - Wrong $\sin^2(\theta_{23})$ octant exclusion (beam only)
   - $\sin^2(\theta_{23})$ mirror point exclusion (beam only)
   - Mass ordering sensitivity (atmospherics + beam)
   - $\sin\delta_{CP} \neq 0$ sensitivity with unknown mass ordering (atmospherics + beam)

9. Far detector samples

10. Systematic errors

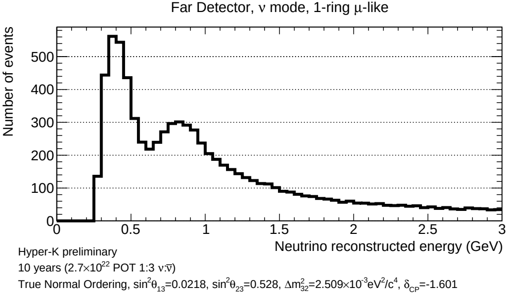
Event rates

	beam ν_μ	beam ν_e	beam $\bar{\nu}_\mu$	beam $\bar{\nu}_e$	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	Total
ν-mode, 1-ring μ-like	8355.42	8.36	478.01	0.68	2.61	0.01	8845.08
$\bar{\nu}$-mode, 1-ring μ-like	4255.94	6.02	7759.91	4.74	0.18	0.39	12027.20
ν-mode, 1-ring e-like + 0 decay e	143.91	294.27	5.29	11.97	2007.51	11.74	2474.69
$\bar{\nu}$-mode, 1-ring e-like + 0 decay e	59.10	130.13	96.28	234.83	229.21	793.17	1542.72
ν-mode, 1-ring e-like + 1 decay e	13.96	40.19	0.64	0.32	255.29	0.23	310.64

@ δ_{CP} = -1.601

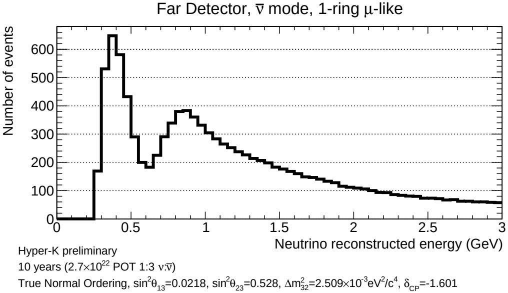
1-ring μ-like event samples

ν-mode beam



$\sim$8800 events

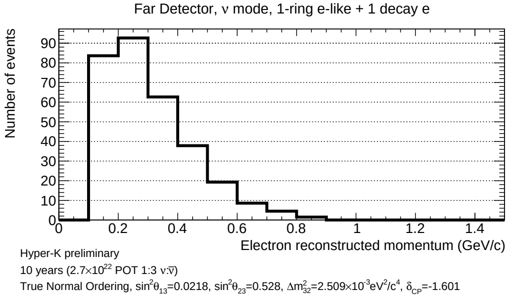
$\bar{\nu}$-mode beam



$\sim$12000 events

1-ring e-like + 1 decay e event sample

ν-mode beam



∼300 events

Backup

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   - $\sin^2(\theta_{23})$ mirror point exclusion (beam only)
   - Mass ordering sensitivity (atmospherics + beam)
   - $\sin\delta_{CP} \neq 0$ sensitivity with unknown mass ordering (atmospherics + beam)

9. Far detector samples

10. Systematic errors

T2K 2020 systematics

Flux Uses external data to tune model

- e.g. NA61/SHINE thin-target hadron-production data

Cross section Uses external data to tune model

- e.g. MINERνA, MiniBooNE, ..., ν-nucleus scattering data
- Uses NEUT 5.4.0

Final state interactions & secondary interactions Uses external data to tune model

- e.g. π-nucleus scattering data

SK detector Uses Super-K atmospheric neutrino data

- Flux & Cross-section uncertainties reduced by fit to near-detector data

Eur. Phys. J. C 83, 782 (2023)

Scaling systematics for Hyper-K

- Statistical error on Hyper-K atmospheric samples will reduce
  - Hyper-K fiducial volume $= 8.4 \times$ Super-K
- Statistical error at ND280 will reduce
  - ND280-upgrade increases fiducial mass by $\sim$30%
  - More running with a higher power beam
- New detectors will produce better results
  - SFGD has increased nucleon tracking efficiency
    - ⋆ Get a handle on final state interactions
    - ⋆ Select $\bar{\nu} + H$ events
  - IWCD has excellent ν_e/ν_μ separation
    - ⋆ Measure ν_e & $\overline{\nu}_e$ cross sections to a few %

Systematic uncertainties

	μ-like		e-like			
T2K 2020 syst.	ν-mode	$\bar{\nu}$-mode	ν-mode 0 d.e.	$\bar{\nu}$-mode 0 d.e.	ν-mode 1 d.e.	$\nu/\bar{\nu}$ 0 d.e.
ND constrained						
Flux+cross section	2.1%	3.4%	3.6%	4.3%	4.9%	4.4%
Not ND constrained						
Cross section	0.5%	2.6%	3.0%	3.7%	2.7%	4.1%
Detector	2.1%	1.9%	3.1%	3.9%	13.2%	1.1%
All	3.0%	4.0%	4.7%	5.9%	14.1%	4.6%
Improved syst.						
ND constrained						
Flux+cross section	0.9%	0.9%	1.8%	1.6%	1.8%	1.9%
Not ND constrained						
Cross section	0.4%	0.4%	1.6%	1.4%	1.6%	1.9%
Detector	0.8%	0.7%	1.1%	1.5%	4.9%	0.4%
All	1.2%	1.1%	2.1%	2.2%	5.2%	2.0%

Total percentage error on sample event rates