Hyper-Kamiokande Neutrino Beam Oscillation Sensitivities

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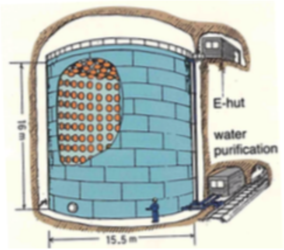
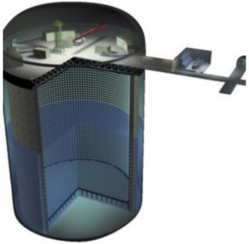
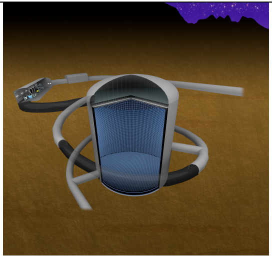
for the Hyper-Kamiokande collaboration

NuTel2021

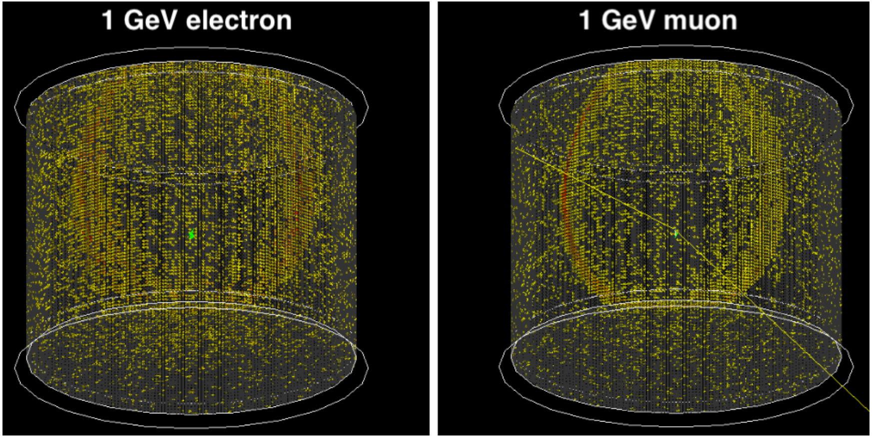
24th February, 2021

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
			

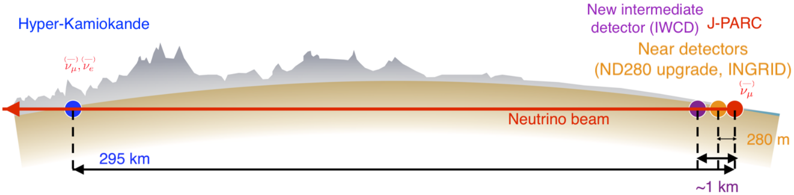
- Building on decades of expertise
- Fiducial mass increase $> \times 8$
- Improved PMTs $\sim \times 2$ photo detection efficiency

Event displays



- Electron vs muon particle identification via
  - Fuzzy vs sharp ring
  - Delayed decay (Michel) electrons

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



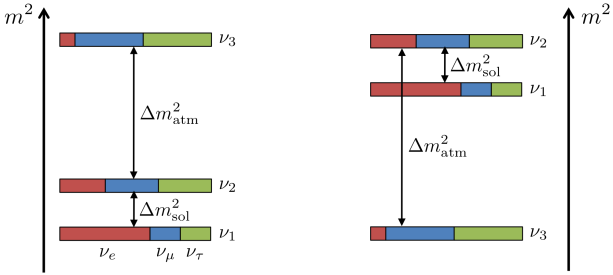
Hyper-Kamiokande ν_μ & $\overline{\nu}_\mu$ beam

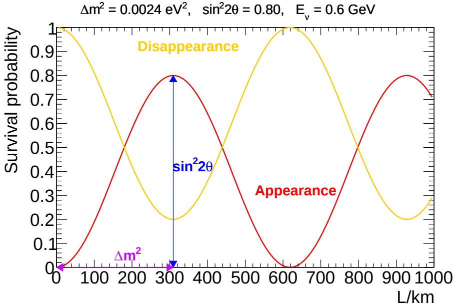
- 20 times more stats than T2K
  - J-PARC beam upgraded to 1.3 MW
  - New 188 kt fiducial far detector
- New Intermediate Water Cherenkov Detector (IWCD)
- Upgraded near detector (ND280 upgrade)

Neutrino oscillation physics

- Neutrino flavours mix while propagating
- In two flavours: $P_{\alpha\rightarrow\beta,\alpha\neq\beta} \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
- L/E for Hyper-K chosen to maximise Δm^2_{32} terms
  - Can measure δ_{CP}, Δm^2_{32}, $\sin^2(\theta_{23})$

normal hierarchy (NH) **inverted hierarchy (IH)**



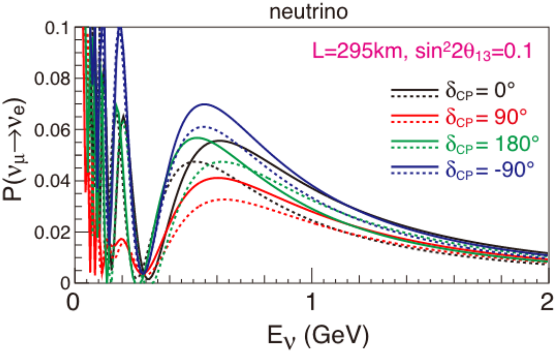


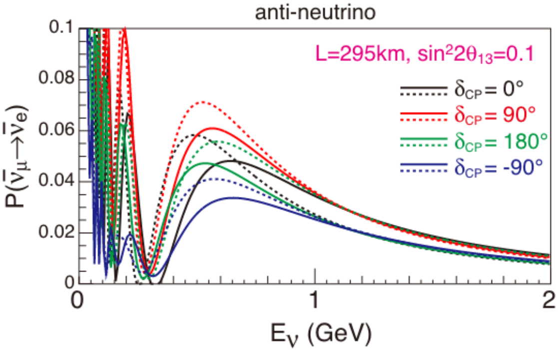
- $\theta_{23} \sim 49°$
- $\theta_{12} \sim 33°$
- $\theta_{13} \sim 9°$
- $\pm\Delta m^2_{32} \sim 2.5\times10^{-3}\,\mathrm{eV}^2$
- $+\Delta m^2_{21} \sim 7.4\times10^{-5}\,\mathrm{eV}^2$
- $\delta_{CP} \sim 200°$

JHEP 09 (2020) 178 NuFIT 5.0 (2020)

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

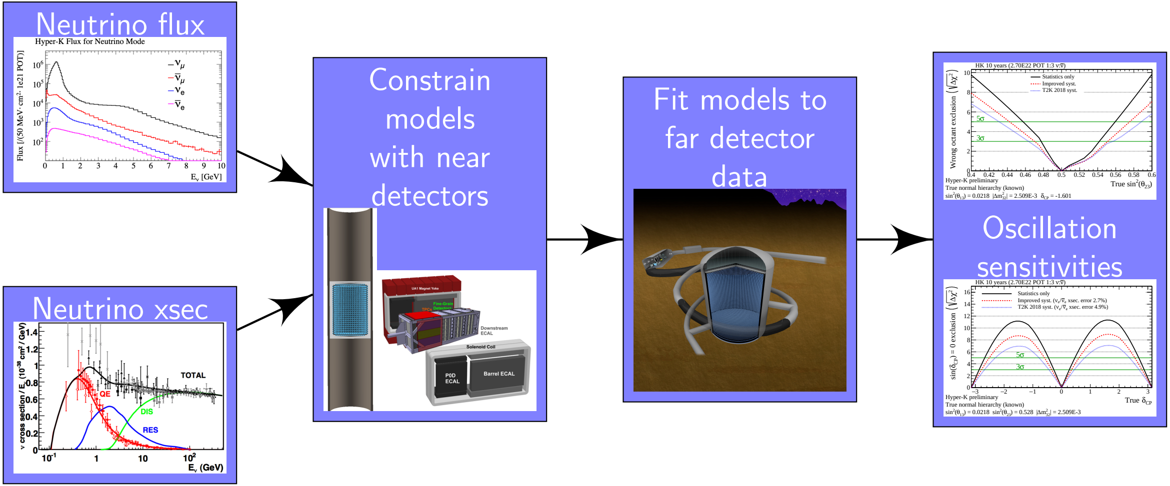
ν_e & $\overline{\nu}_e$ appearance probabilities





- Hyper-K ν & $\bar{\nu}$ beam flux peaks $\sim$0.6 GeV
- @ $\delta_{CP} = -90^\circ$ $(-\pi/2)$
  - ν_e appearance enhanced; $\overline{\nu}_e$ appearance suppressed
- Unknown mass hierarchy (solid vs dashed) complicates δ_{CP} measurement
  - Sensitivities we show today are for known normal hierarchy
  - Hyper-K can use atmospheric data to exclude incorrect mass hierarchy @ 4–6σ

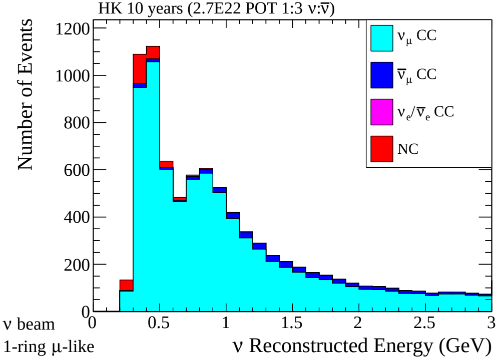
Hyper-K neutrino beam analysis method



- Using T2K analysis method
  - Super-K MC scaled to Hyper-K exposure

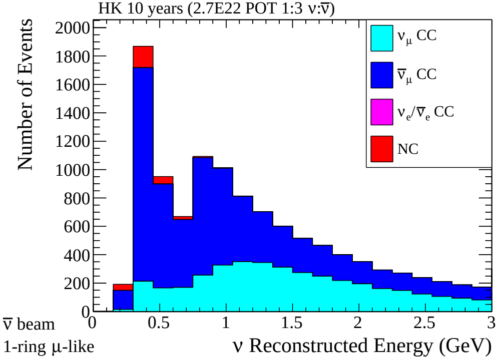
1-ring μ-like event samples

ν-mode beam



∼9300 events

$\bar{\nu}$-mode beam

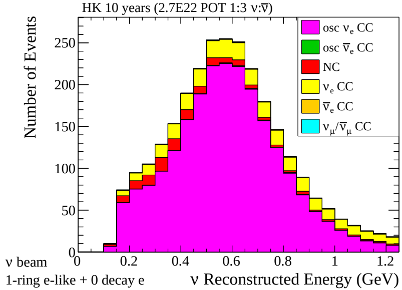


∼12300 events

@ 10 years (2.7E22 POT), ν:$\bar{\nu}$ = 1:3

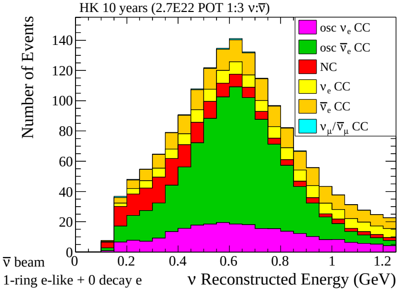
1-ring e-like event samples

ν-mode beam



$\sim$2300 events

$\bar{\nu}$-mode beam

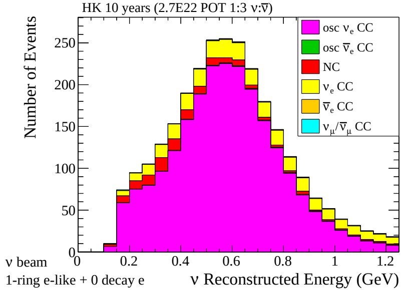


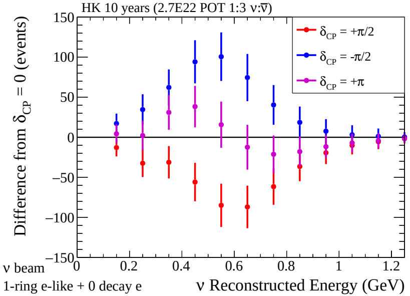
$\sim$1900 events

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

1-ring e-like event samples

ν-mode beam





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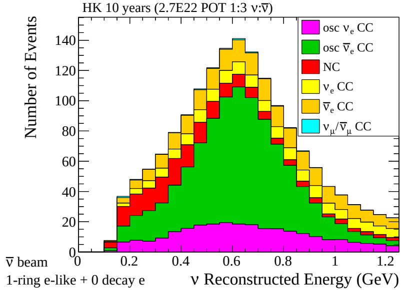

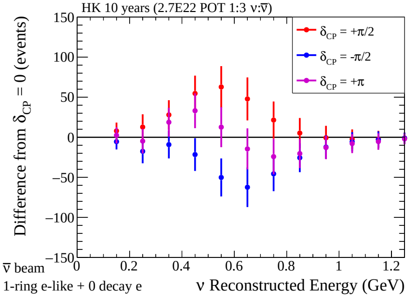

Systematics

- Hyper-K has high statistics $\rightarrow$ systematics limited
- Going to show sensitivities
  - We have a range of systematics scenarios that span the possible values

1. T2K 2018 systematics
   - Where we are now
2. Improved systematics
   - Where we expect to be with ND280-upgrade & IWCD
   - Produced by scaling T2K systematics based on ND280-upgrade/IWCD sensitivity
3. No systematics
   - Ideal case

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 2018	4.63%	4.10%	5.97%	6.25%	18.49%	4.95%
Improved	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

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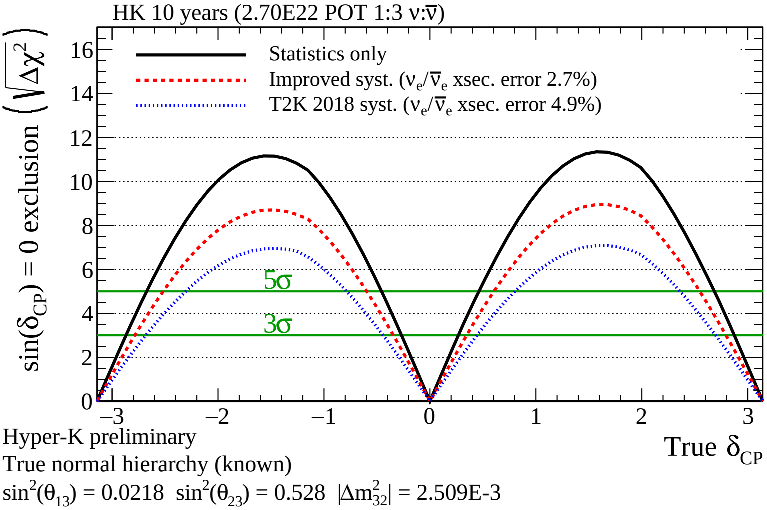
$\sin\delta_{CP} \neq 0$ sensitivity

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



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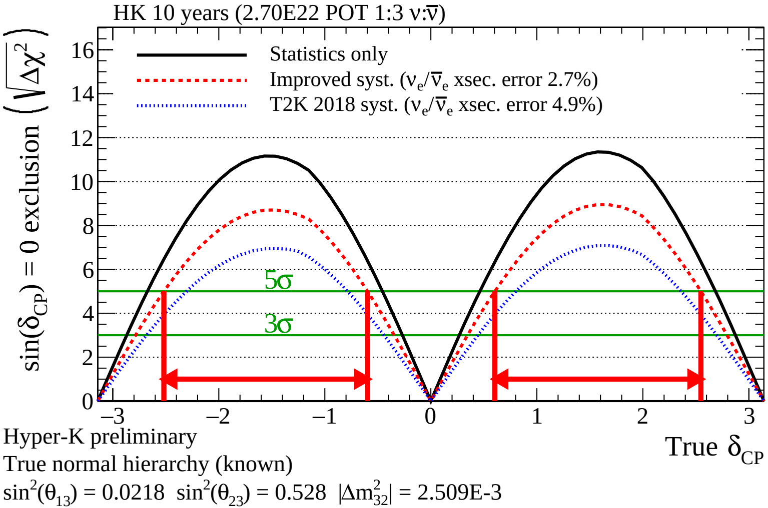
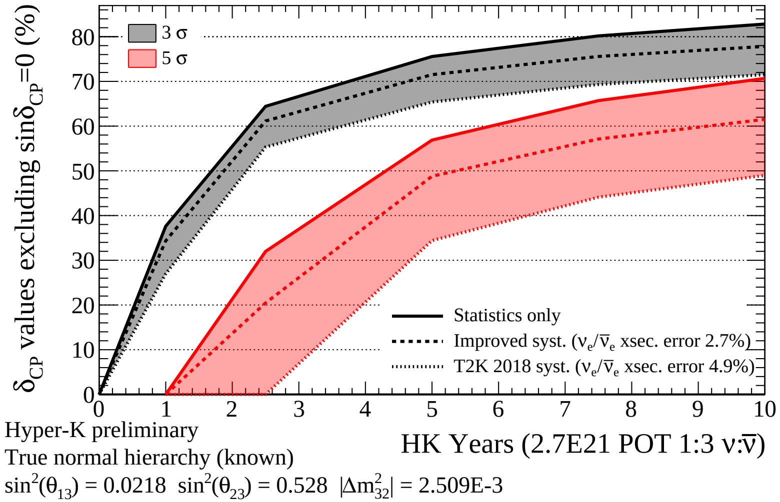


- Exclude CP conservation for 62% of true δ_{CP} values @ 5σ

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

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



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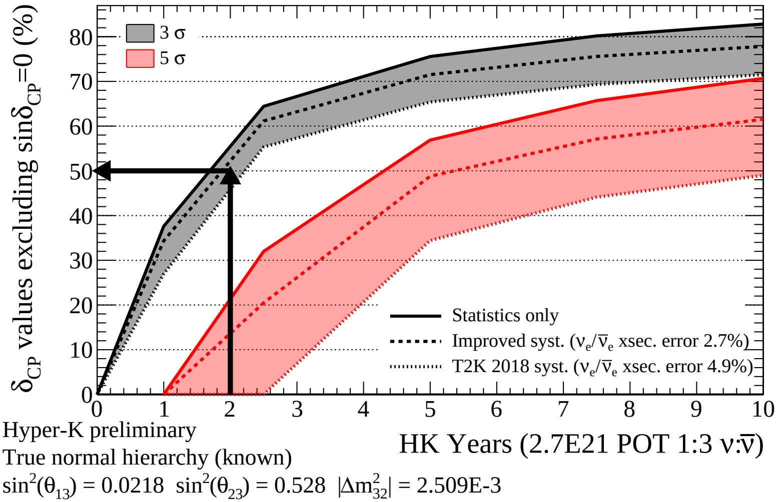

- 50% in 2 years @ 3σ

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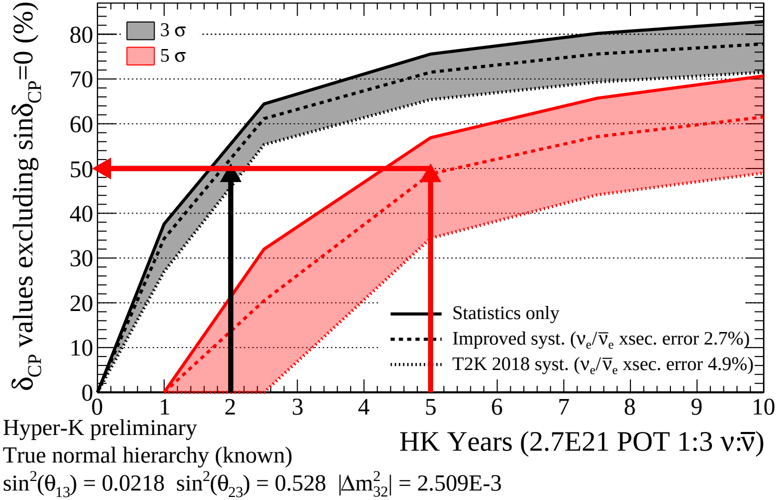
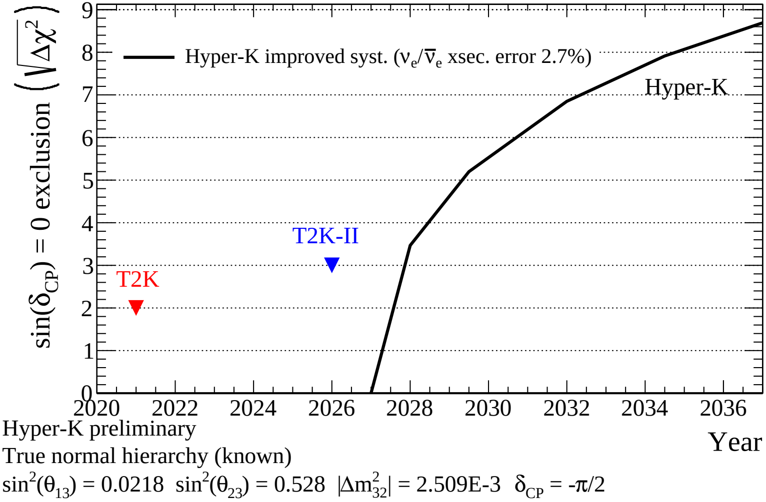


- 50% in 2 years @ 3σ
- 50% in 5 years @ 5σ

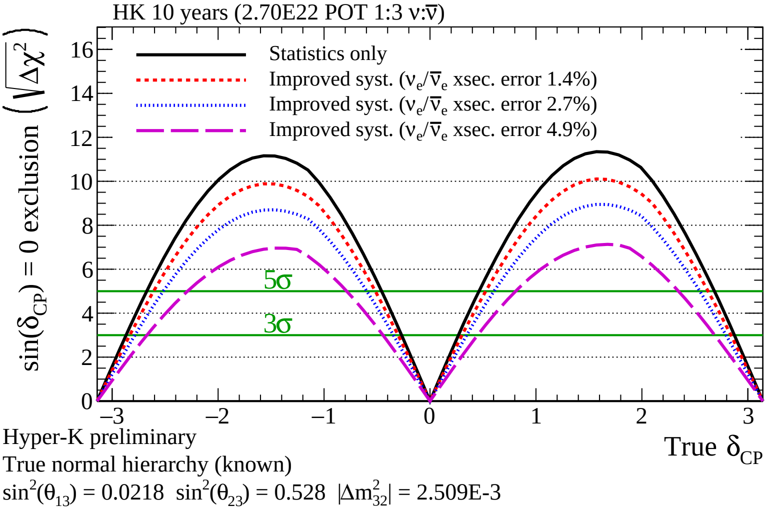
$\sin\delta_{CP} \neq 0$ sensitivity vs time

- What is the significance to exclude CP conservation for true $\delta_{CP} = -\pi/2$, as a function of time?



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

- $\nu_e/\overline{\nu}_e$ cross-section uncertainty dominates this measurement
  - Coloured/dashed lines use same "Improved syst." baseline model, just changing 2 parameters driving this ratio



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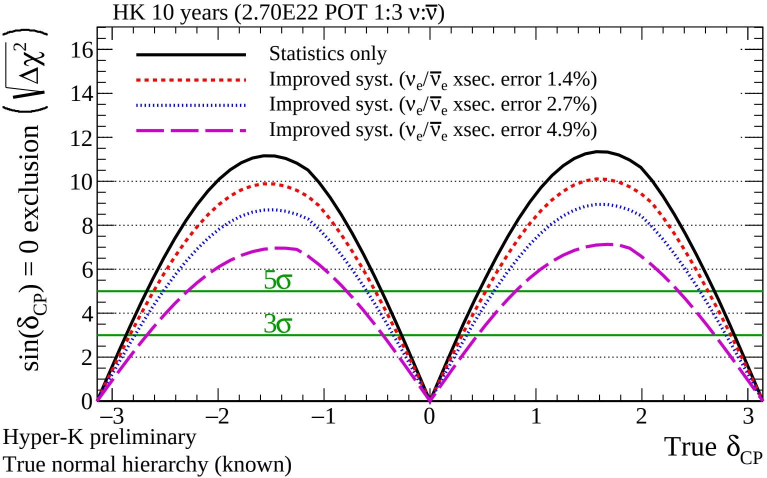
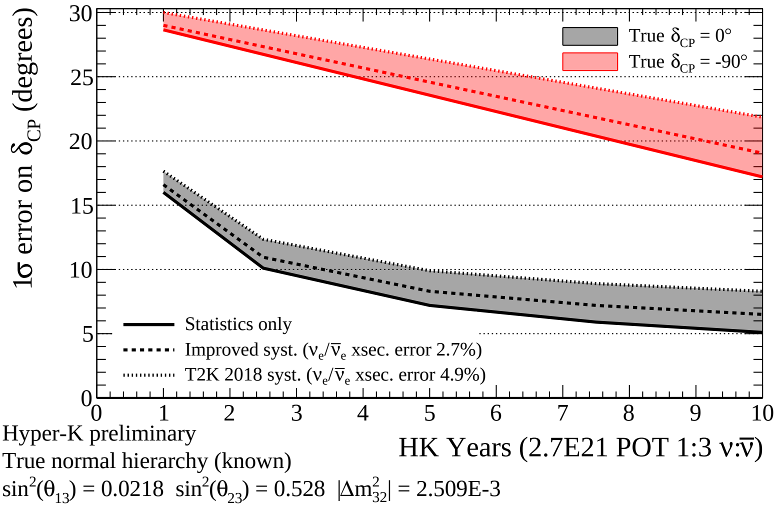


Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$

- Need to measure this ratio with low uncertainty!

δ_{CP} resolution sensitivity

- How accurately can we measure the value of δ_{CP}?



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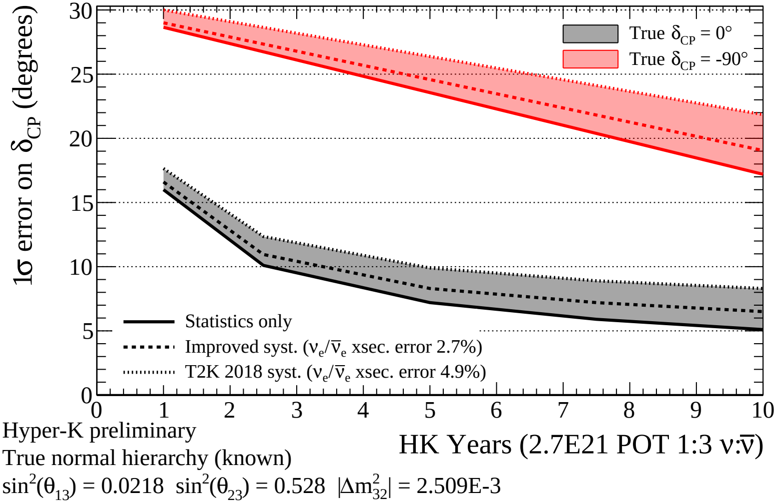
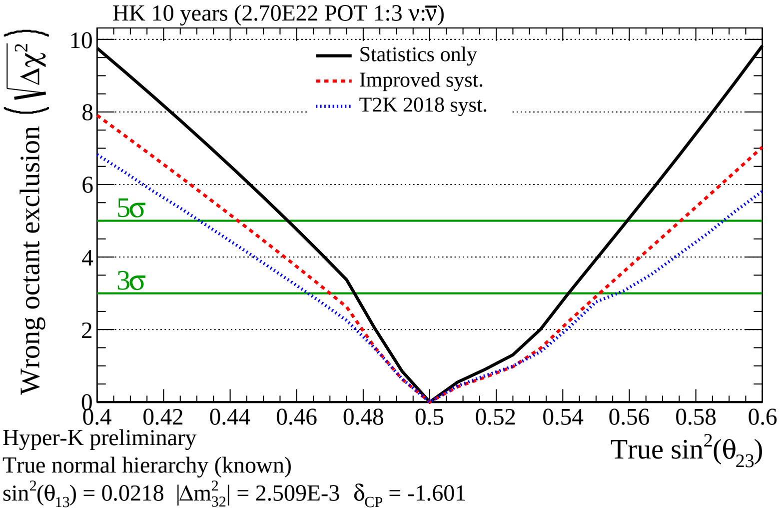


- $\sim 19^\circ$ for true $\delta_{CP} = -\pi/2 = -90^\circ$
- $\sim 7^\circ$ for true $\delta_{CP} = 0$

$\sin^2(\theta_{23})$ octant sensitivity

- For a true value of $\sin^2(\theta_{23})$, how much can we exclude the wrong octant? ($\sin^2(\theta_{23}) < $ or > 0.5)



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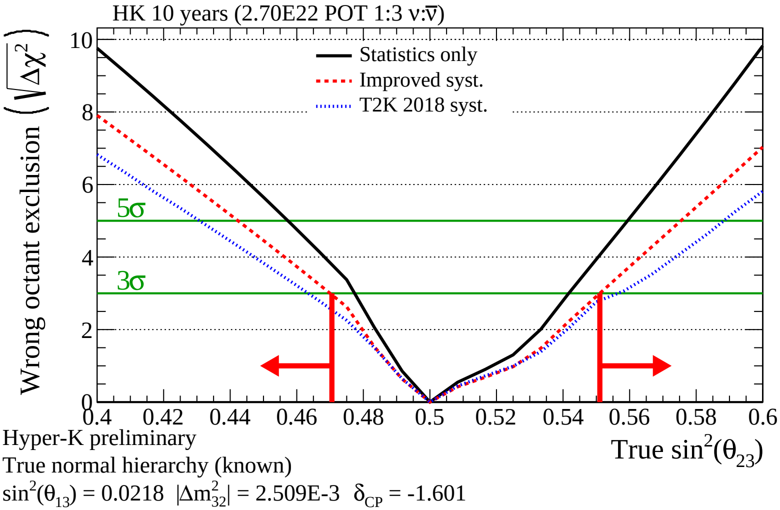


- 3σ exclusion @ $\sin^2(\theta_{23}) < 0.47$ & $\sin^2(\theta_{23}) > 0.55$

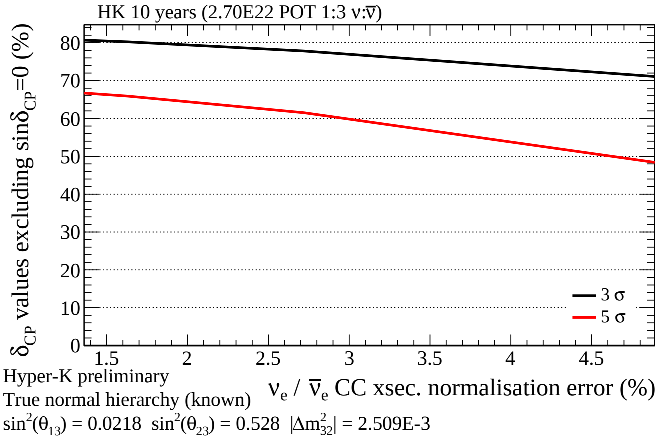
Summary

- Updated Hyper-K long-baseline oscillation-parameter sensitivities
- After 10 years & improving on T2K-2018 error model based on sensitivity of ND280-upgrade & IWCD, we see
  - CP conservation exclusion for 62% of true δ_{CP} @ 5σ
  - δ_{CP} precision $\sim 19^\circ$ ($\delta_{CP} = -\pi/2$), $\sim 7^\circ$ ($\delta_{CP} = 0$)
  - Octant determination & maximal mixing exclusion for $\sin^2(\theta_{23}) < 0.47$ & $\sin^2(\theta_{23}) > 0.55$ @ 3σ
- Other Hyper-K talks at the conference
  - Supernova model discrimination with Hyper-K **J. Migenda** Friday 19th 10:20
  - Multi-PMT optical module for Hyper-K **A. Ruggeri** Thursday 25th 12:20
  - Hyper-Kamiokande **F. Di Lodovico** Thursday 25th 16:45

Backup

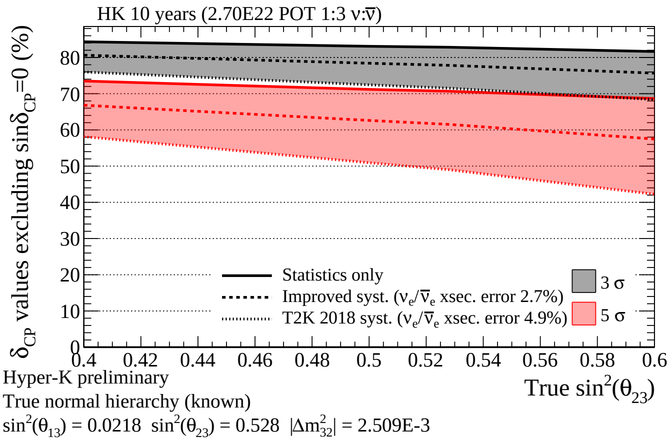
5. Other sensitivities
   - δ_{CP}
   - $\sin^2(\theta_{23})$ sensitivities
6. Neutrino oscillations
7. Atmospheric neutrino oscillations
8. Near/intermediate detectors
   - ND280 upgrade
   - IWCD
9. Systematics

$\sin \delta_{CP} \neq 0$ sensitivity dependence on systematics



- $\nu_e/\overline{\nu}_e$ cross-section uncertainty dominates the δ_{CP} measurement
- Need to measure this ratio with low uncertainty!

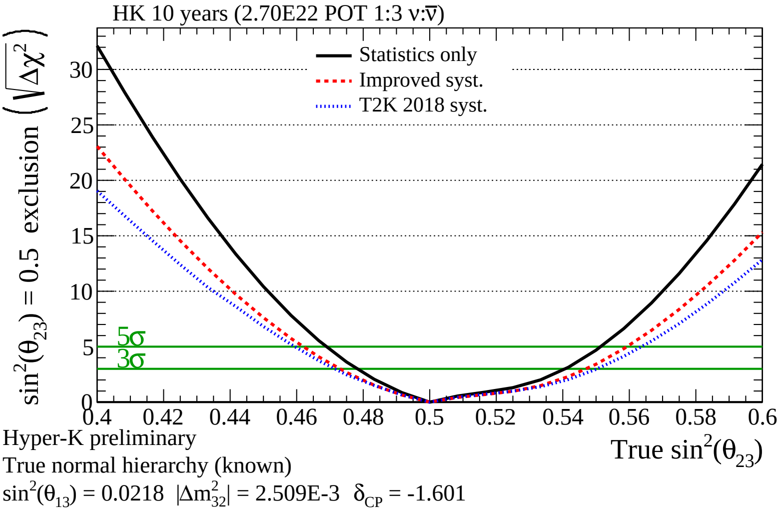
$\sin\delta_{CP} \neq 0$ sensitivity dependence on $\sin^2(\theta_{23})$



- Effect driven by event rate
  - $P(\nu_\mu \to \nu_e) \simeq 4\cos^2\theta_{13} \cdot \sin^2\theta_{13} \cdot \sin^2\theta_{23} \cdot \sin^2\left(\Delta m^2_{31} L/4E\right)$

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

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



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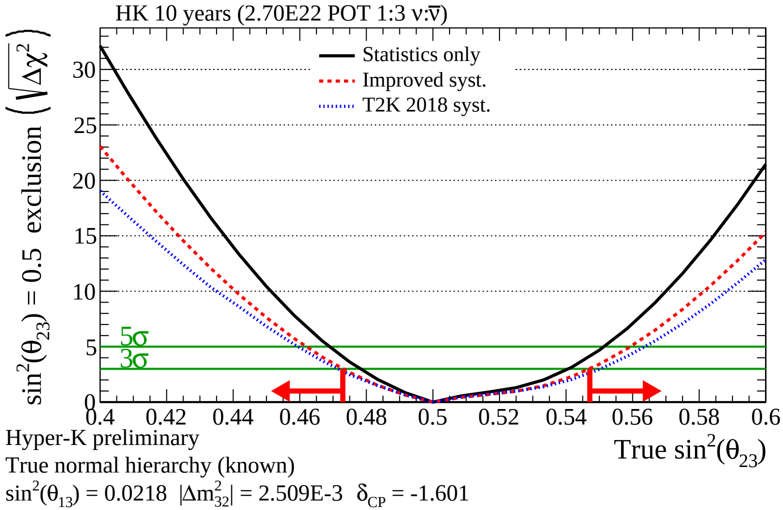
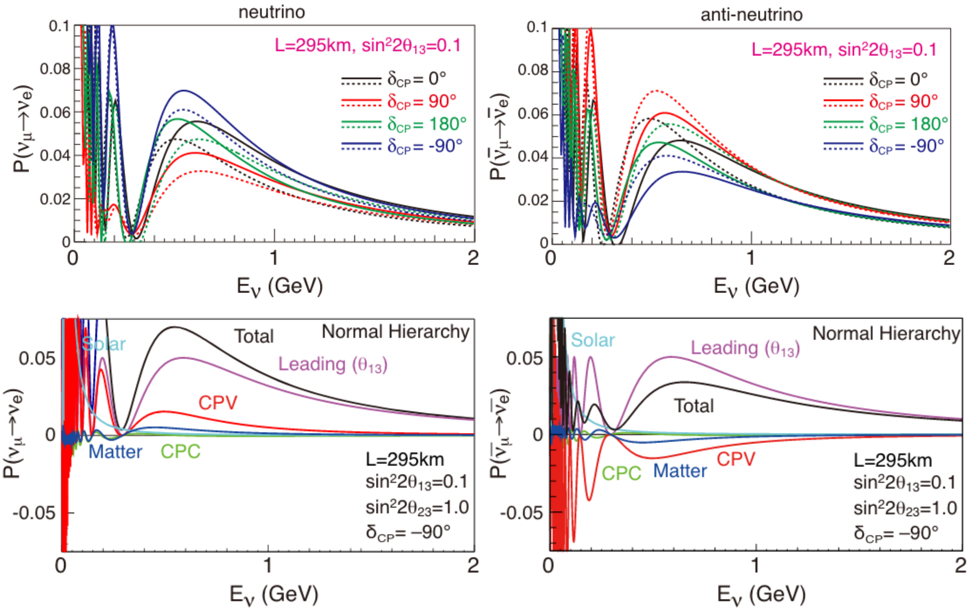


- 3σ exclusion @ $\sin^2(\theta_{23}) < 0.47$ & $\sin^2(\theta_{23}) > 0.55$

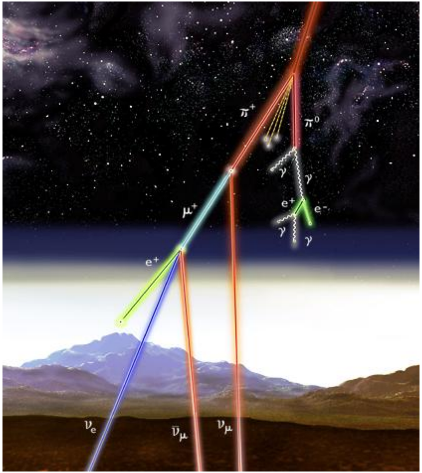
Backup

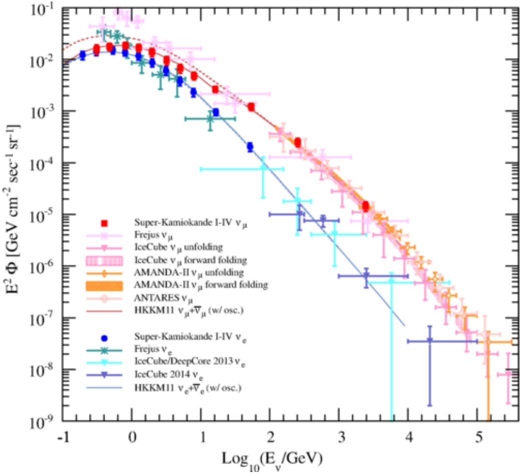
Oscillation probabilities



Backup

Atmospheric neutrino generation

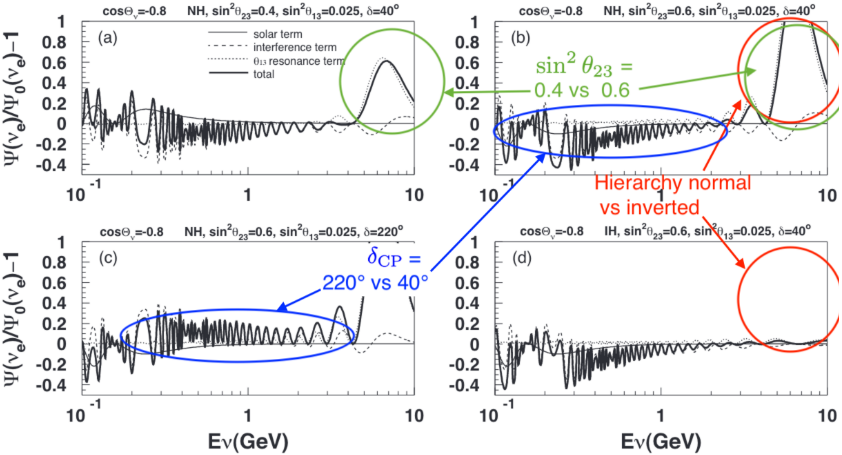




- Cosmic rays strike nuclei creating ν_μ & ν_e with ratio:
  - 2:1 $<$ 1 GeV, rising to 3:1 @ 10 GeV

Atmospheric neutrino oscillations

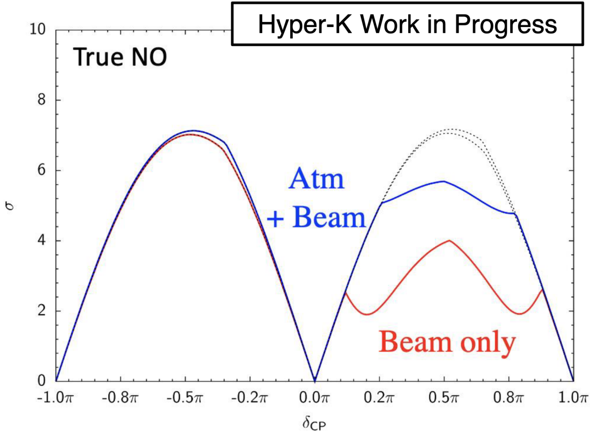
ν_e flux (relative no oscillations) at $\cos\theta_{\text{zenith}} = 0.8$



- Mass hierarchy creates resonance in ν_e or $\overline{\nu}_e$ multi-GeV events
- 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 hierarchy

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



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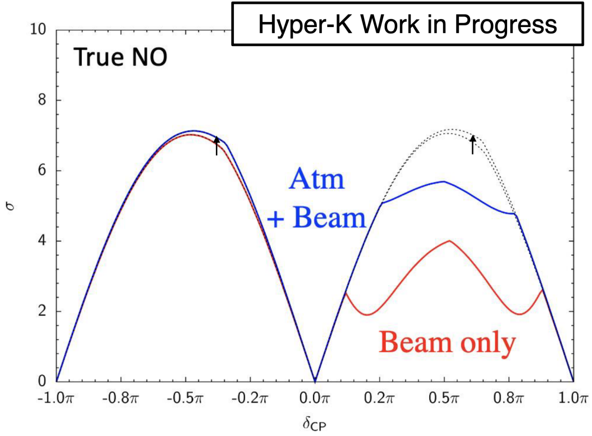

- Dashed lines show case where mass hierarchy is known
  - Addition of atmospherics enhances sensitivity slightly

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

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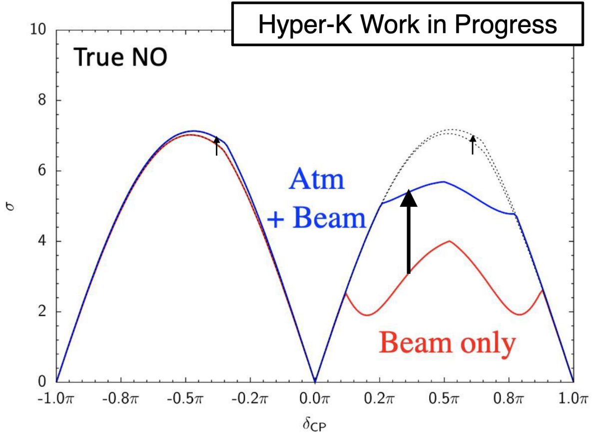
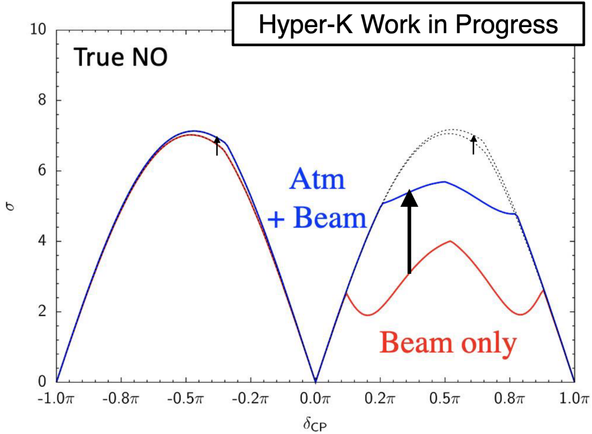


- Solid lines show case where mass hierarchy is unknown
  - Addition of atmospherics gives massive improvement

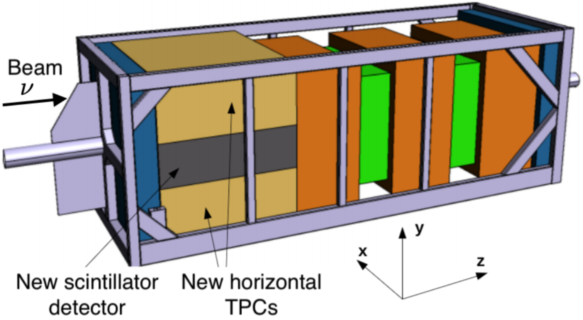
$\sin\delta_{CP} \neq 0$ sensitivity with unknown mass hierarchy



- Atmospheric neutrinos have longer baseline & higher energies
  - → Enhances matter effect ($\propto E_\nu n_e$)
  - → Sensitivity to mass hierarchy
  - → Exclude incorrect mass hierarchy at 4–6σ (depending on true $\sin^2(\theta_{23})$)

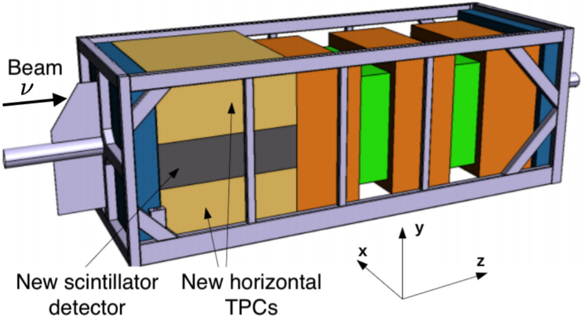
Backup

ND280 upgrade

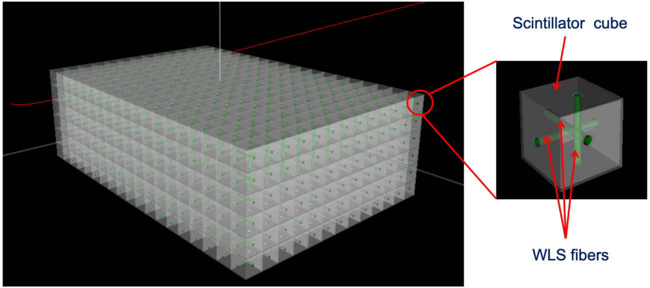


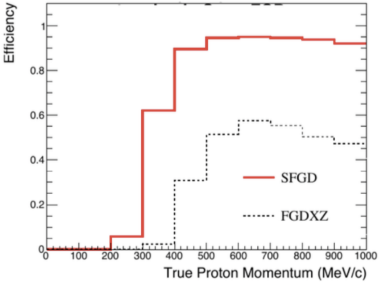
- Upgrade to T2K off-axis near detector @ 280 m
- Increased efficiency for
  - Low-momentum tracks
  - High-angle tracks
- Being developed for T2K
  - Hyper-K will inherit it

ND280 upgrade

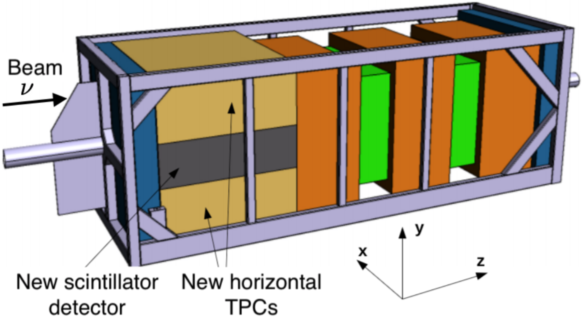


- Upgrade to T2K off-axis near detector @ 280 m
- Increased efficiency for
  - Low-momentum tracks
  - High-angle tracks
- Being developed for T2K
  - Hyper-K will inherit it





ND280 upgrade



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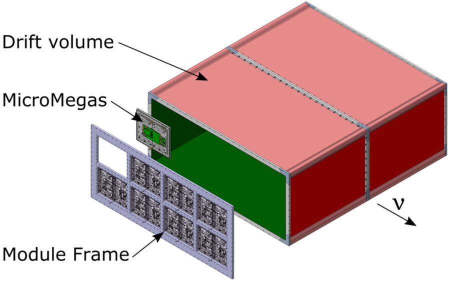
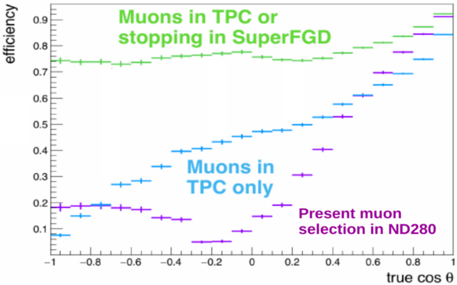
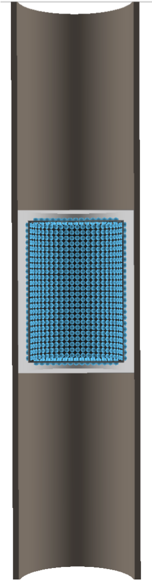




Intermediate water Cherenkov detector (IWCD)



- Water Cherenkov detector @ $\sim$1 km
- Novel off-axis angle spanning method allows
  - Creation of narrow beam for cross-section analyses
  - Reconstruction of the oscillated flux

Backup

T2K 2018 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 5.3.2

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

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Scaling systematics for Hyper-K

- Statistical error on Hyper-K atmospheric samples will reduce
  - Hyper-K fiducial volume = 8.4 × Super-K
- Statistical error at ND280 will reduce
  - ND280-upgrade increases fiducial mass by ∼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 %

Systematics

T2K 2018 model						
	μ-like		e-like			
Error source	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.
Flux + xsec	3.27%	2.95%	4.33%	4.37%	4.99%	4.52%
Detector + FSI	3.22%	2.76%	4.14%	4.39%	17.77%	2.06%
All syst	4.63%	4.10%	5.97%	6.25%	18.49%	4.95%

Improved model						
	μ-like		e-like			
Error source	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.
Flux + xsec	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector + FSI	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All syst	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

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Assumptions reduce μ-like error $\sim$4% $\rightarrow$ $\sim$2%

Systematics

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Assumptions reduce 1-ring e-like + 0 decay e error $\sim$6% $\rightarrow$ $\sim$2.5%

Systematics

T2K 2018 model						
	μ-like		e-like			
Error source	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.
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	μ-like		e-like			
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All syst	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

Assumptions reduce total 1-ring e-like + 0 decay e ν-mode/$\bar{\nu}$-mode error $\sim$5% $\rightarrow$ $\sim$2.5%