Physics with T2HK

Megan Friend (KEK)

For the HK Collaboration

April 9, 2019

Physics with ~~T2HK~~ the Hyper-Kamiokande Long-Baseline Program

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Outline

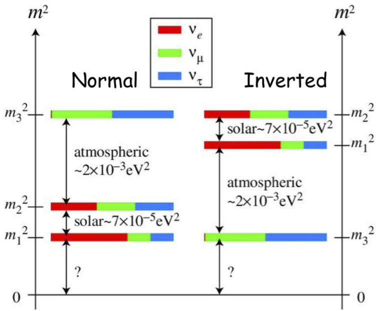
- Hyper-Kamiokande overview and status
- Hyper-Kamiokande components
- Hyper-Kamiokande long-baseline physics sensitivities
  - δ_{CP}
  - Mass Hierarchy
  - θ_{23}
  - Non-oscillation physics

Neutrino Oscillation

Neutrino oscillation can be described by the PMNS mixing matrix:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +C_{23} & +S_{23} \\ 0 & -S_{23} & +C_{23} \end{pmatrix} \begin{pmatrix} +C_{13} & 0 & +S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{CP}} & 0 & +C_{13} \end{pmatrix} \begin{pmatrix} +C_{12} & +S_{12} & 0 \\ -S_{12} & +C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$(C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij})$



- MH unknown

Precisely measure all parameters to fully understand neutrino oscillation

- $\theta_{12} = 33.6^\circ \pm 0.8^\circ$ – solar ν's
- $\theta_{23} = 45.6^\circ \pm 2.3^\circ$
  – is θ_{23} maximal?
- $\theta_{13} = 8.3^\circ \pm 0.2^\circ$ – recent reactor $\bar{\nu}_e$ disappearance measurements

δ_{CP} unknown $\rightarrow$ possibility of CP violation in the lepton sector

$\rightarrow$ May be able to help explain the dominance of matter over anti-matter in the Universe

Hyper-Kamiokande Long-Baseline Program

- MW-class neutrino beam by upgraded J-PARC MR accelerator
  - Produce primarily ν_μ or $\bar{\nu}_\mu$ beam, 2.5° off-axis
- Neutrino flux and systematic errors constrained by upgraded ND280 detector and new Intermediate Water Cherenkov Detector
- Gigantic Hyper-Kamiokande water Cherenkov detector
  - Measure $\nu_\mu \to \nu_e$ appearance and $\nu_\mu \to \nu_\mu$ disappearance oscillations

The Hyper-Kamiokande Proto-Collaboration

International proto-collaboration since 2015

Consists of ~300 members from 73 institutes in 15 countries

Hyper-Kamiokande Status

東京大学
THE UNIVERSITY OF TOKYO

The University of Tokyo

Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

September 12th, 2018

Concerning the Start of Hyper-Kamiokande

Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

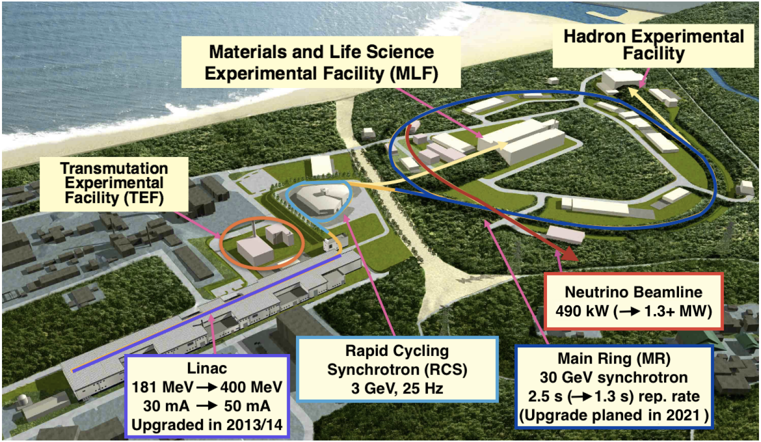
The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

Makoto Gonokami
President, The University of Tokyo

- Selected by Science Council of Japan as a top-priority large-scale project (Master Plan 2017)
- Will receive MEXT seed funding in JFY2019
- "University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020"

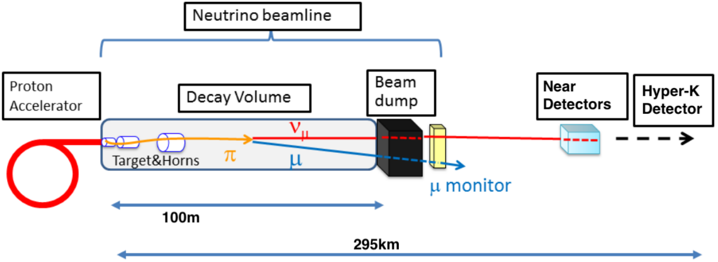
Hyper-K construction will begin in April 2020!
(The construction will take 7-8 years!)
You are most welcome to join Hyper-K!

J-PARC Accelerator



- World-class proton accelerator and neutrino beamline facility located in Tokai village, Ibaraki prefecture
- Currently producing the neutrino beam for the T2K experiment
- J-PARC accelerator undergoing upgrades to increase the proton beam power from $\sim$500kW$\rightarrow$1.3MW

J-PARC Neutrino Beam



- Slam high-intensity 30GeV proton beam into 90-cm carbon target
- Focus outgoing hadrons (pions, kaons, etc.) in 3 electro-magnetic focusing horns
  - Switch between ν- or $\bar{\nu}$-mode by changing the horn polarity
- Pions decay to muons and ν_μ's in 100-m-long decay volume
- Stop interacting particles in beam dump; neutrinos continue on to near and far detectors
  - Monitor >5GeV muon beam by Muon Monitor in beam dump
- Constrain proton interactions by external hadon production measurements (NA61, EMPHATIC) to precisely simulate the flux

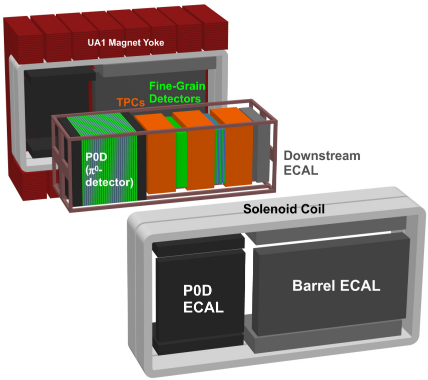
J-PARC Beam Upgrades

Beam Power	485kW (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.4×10^{14}	2.0×10^{14} [3.3×10^{14}]	2.6×10^{14}	3.2×10^{14}
Operation cycle	2.48 s	1.3 s [2.1 s]	1shot	1.16 s

+25% +18%

- Currently : 485 kW with 2.48 s repetition rate
    - 500+ kW achieved during beam tests
- Plan to upgrade MR power supplies in 2020/2021 to reach 1.3 s repetition rate
    - RF improvements can allow for further decrease to 1.16 s
- Plan to improve beam stability, reduce MR beam losses to increase number of protons per pulse
- Upgrades to the neutrino extraction beamline necessary to accommodate the 1.3MW proton beam
    - Radioactive water handling, component cooling, radioactive component handling, readout electronics+interlock, beam profile monitoring, etc...
    - Necessary extraction beamline upgrades to be completed by 2021

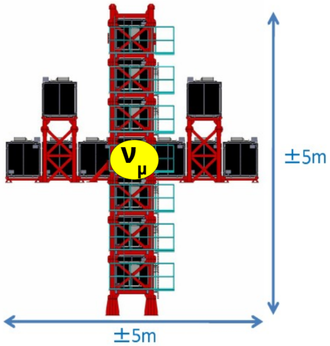
ND280 Near Detector Complex



Near Detector upgrades underway

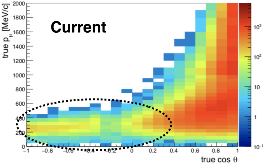
Magnetized off-axis ND280 detector to constrain the neutrino flux and precisely measure neutrino cross sections

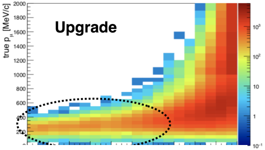
On-axis INGRID detector to measure the neutrino beam stability and direction, as well as neutrino interactions

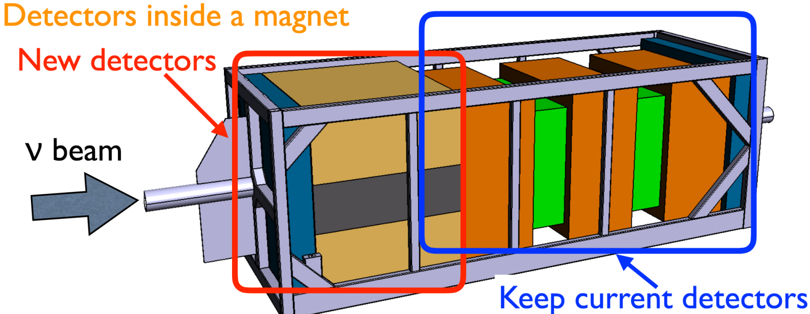


ND280 Upgrades

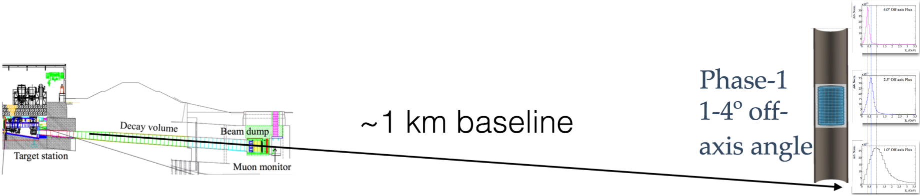
- Improve acceptance for high-angle and backwards tracks to improve systematic error constraint by Near Detector
- Replace P0D with : superFGD + 2 High-Angle TPCs + TOF
- Upgrade TDR under review now
- Plan to install in late 2021





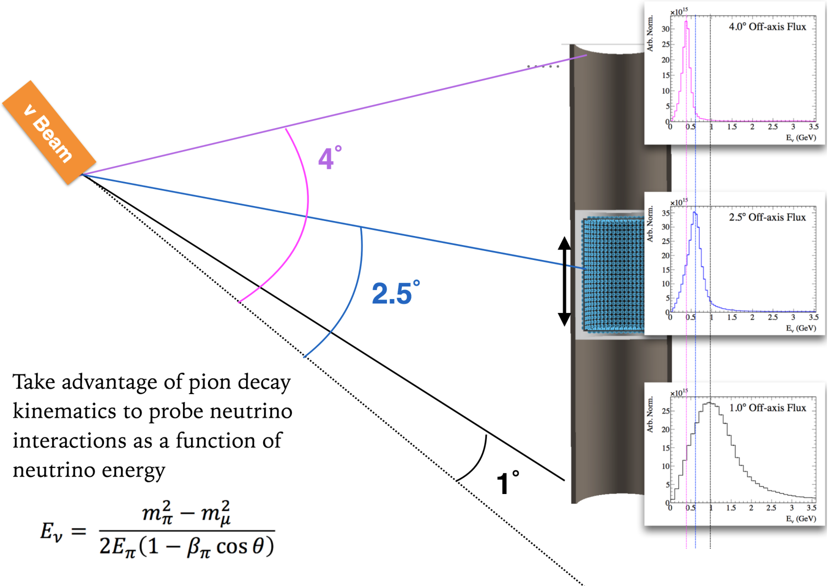


Intermediate Water Cherenkov Detector



- 1 kilo-ton scale water Cherenkov detector located $\sim$1 km from the neutrino source
- Position of instrumented part of the detector can be moved in $\sim$50 m shaft to make measurements at different off-axis angles
  - Take advantage of pion decay kinematics to probe neutrino interactions as a function of neutrino energy
- Measurements to address uncertainties on neutrino-nucleus scattering modeling for Hyper-K
  - Measure relationship between neutrino energy and final state particles
  - Precisely measure the $\nu_e/\bar{\nu}_e$ cross section
  - Measure neutron production in neutrino-nucleus scattering
- Now optimizing the detector design

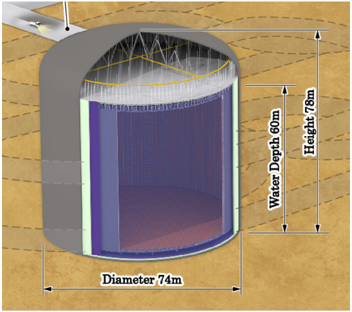
Intermediate Water Cherenkov Detector Off-Axis Angle Range



Take advantage of pion decay kinematics to probe neutrino interactions as a function of neutrino energy

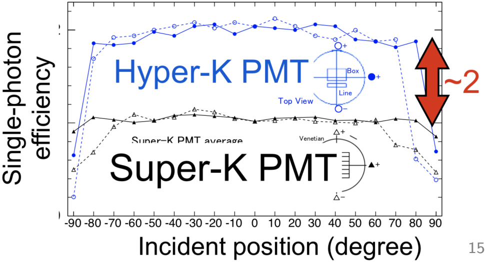
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2E_\pi(1 - \beta_\pi \cos\theta)}$$

Hyper-Kamiokande Detector

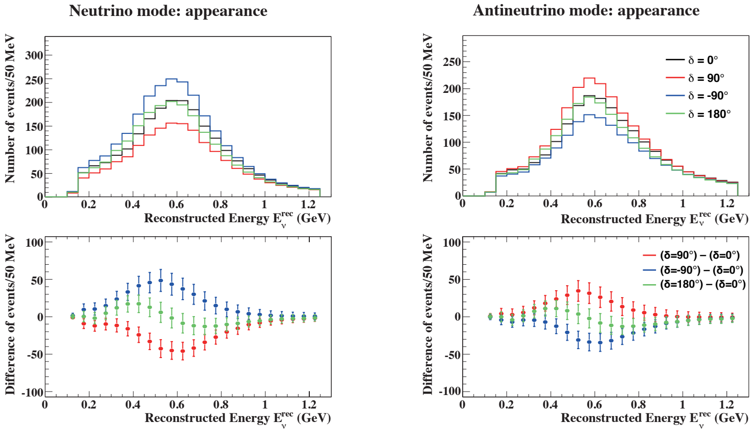


- 190kton fiducial mass water Cherenkov detector (~8x larger than SK)
- Sub-GeV ring-imaging capability
- Excellent ν_e/ν_μ particle ID capability
- Detector site identified
- Photosensor R&D underway
  - Optimization of photo coverage
  - Add multi-PMTs ?
- Precision calibration systems, etc..

50cm Hyper-K PMT

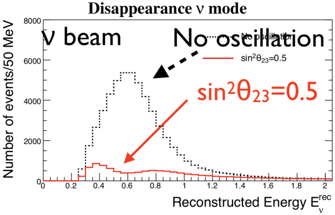


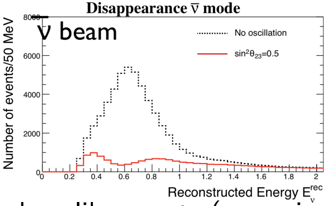
HK Expected Number of ν_e-Like Events



- Number of expected ν_e-like events (assuming 10 years at 1.3MW$\times 10^7$seconds, 1:3 ν:$\bar{\nu}$, NH, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$) :
  - ν-mode – $\sim$1600 signal + $\sim$400 background events
  - $\bar{\nu}$-mode – $\sim$1200 signal + $\sim$500 background events
- Analysis improvements now underway to increase signal without degrading purity (improved fiducial volume, new event samples, etc)

HK Expected Number of ν_μ-Like Events





- Number of expected ν_μ-like events (assuming 10 years at 1.3MW$\times 10^7$seconds, 1:3 ν:$\bar{\nu}$, NH, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$) :
  - ν-mode – $\sim$9000 ν_μ signal + $\sim$500 $\bar{\nu}_\mu$ + $\sim$500 background events
  - $\bar{\nu}$-mode – $\sim$8000 $\bar{\nu}_\mu$ signal + $\sim$5000 ν_μ + $\sim$600 background events
- Analysis improvements now underway to increase signal without degrading purity (improved fiducial volume, new event samples, etc)

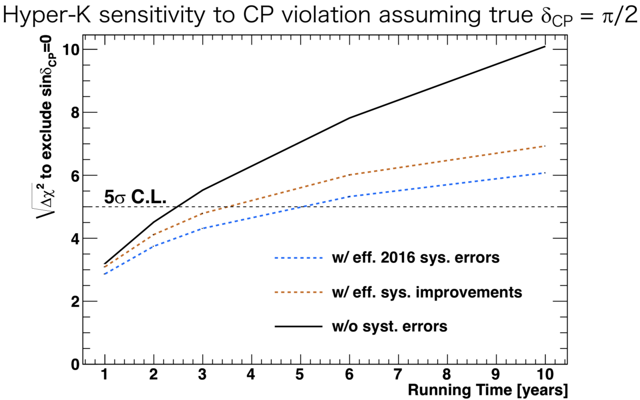
HK Long-Baseline Systematic Errors

- At first pass, base HK long-baseline systematics on T2K errors
- For HK, plan to reduce errors from T2K error $\rightarrow \sim$4%
- Now updating error budget based on planned Near Detector design

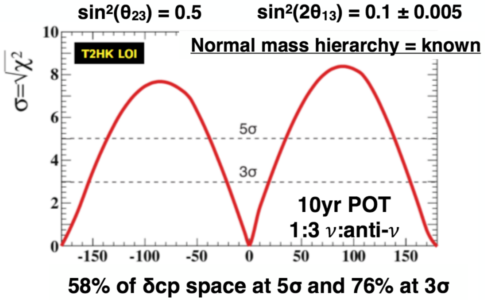
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	ν_e	3.0%	0.5%	0.7%	3.2%
	ν_μ	3.3%	0.9%	1.0%	3.6%
$\overline{\nu}$ mode	ν_e	3.2%	1.5%	1.5%	3.9%
	ν_μ	3.3%	0.9%	1.1%	3.6%

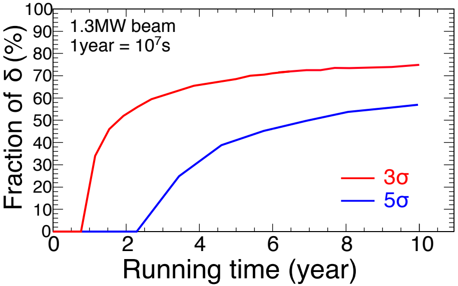
HK Long-Baseline Systematic Errors

- At first pass, base HK long-baseline systematics on T2K errors
- For HK, plan to reduce errors from T2K error $\rightarrow \sim 4\%$
- Sensitivity to exclude $\sin\delta_{CP} \neq 0$ as a function of year for different systematics assumptions :



HK Sensitivity to the $\sin\delta_{CP} \neq 0$

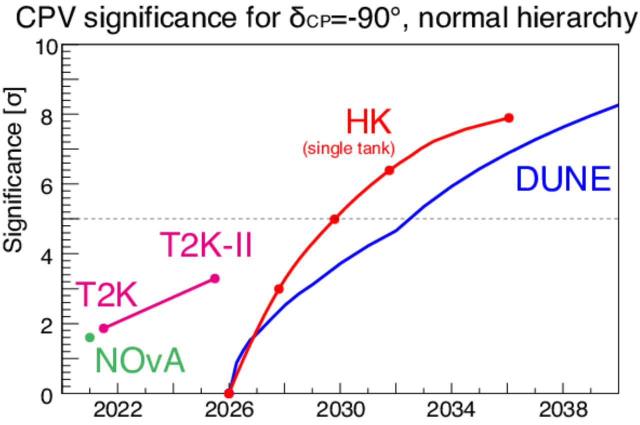




Sensitivity to exclude $\sin\delta_{CP} \neq 0$ for different true values of δ_{CP}

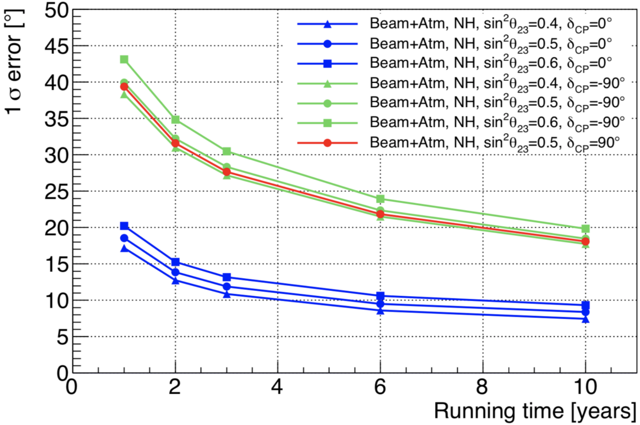
Can measure non-zero δ_{CP} for 58% of possible true values of δ_{CP} at 5σ and 76% at 3σ if MH is known

HK Sensitivity to the $\sin \delta_{CP} \neq 0$



- Sensitivity to exclude $\sin \delta_{CP} \neq 0$ for different true values of δ_{CP} vs year compared to other experiments
- Assuming known MH

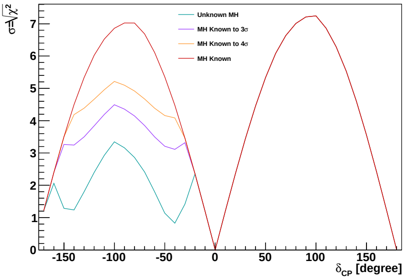
HK Sensitivity δ_{CP}



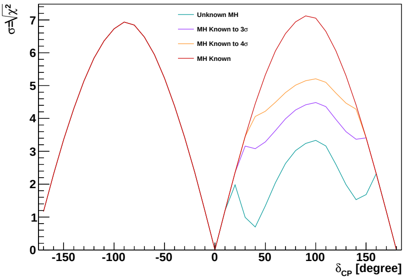
- 1σ error on the value of δ_{CP} vs running time for different true values of δ_{CP}
- $\sim 18^\circ$ error for $\delta_{CP} = +/-90^\circ$, $\sim 8^\circ$ error for $\delta_{CP} = 0$ at full HK statistics

Importance of MH Measurement

True NH



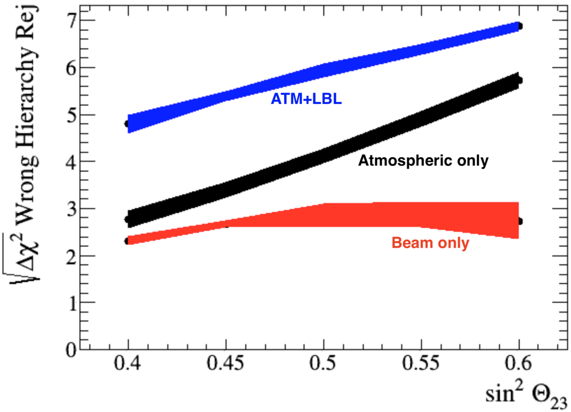
True IH



- Toy example – sensitivity to exclude $\sin\delta_{CP} \neq 0$ for different true values of δ_{CP}
  $\rightarrow$ A precise measurement of the mass hierarchy is necessary to cover the full range of possible true δ_{CP} values

HK Sensitivity to the MH

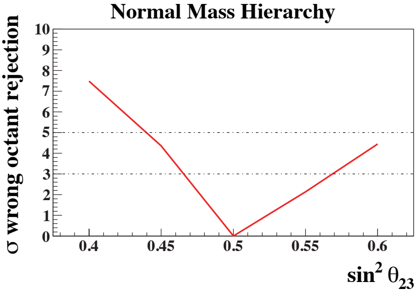
True NH, reject IH



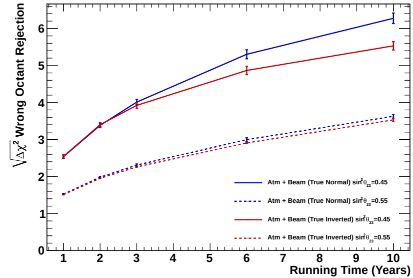
- HK MH sensitivity at 10 years
- Width of bands correspond to uncertainty on δ_{CP}
- Maximize sensitivity by combined fit of beam + atmospheric data

HK Sensitivity to θ_{23}

Beam Only



Beam + Atmospheric



- Left : sensitivity to resolve the θ_{23} octant as a function of true $\sin^2\theta_{23}$ for beam data only
- Right : sensitivity to resolve the θ_{23} octant as a function of time for a combined fit to beam + atmospheric data
- Maximize sensitivity by combined fit of beam + atmospheric data
  - Reach $\sim 6\sigma$ octant rejection sensitivity at full HK statistics at true $\sin^2\theta_{23} = 0.45$ ($\theta_{23} = 42^\circ$), $\sim 3\sigma$ at true $\sin^2\theta_{23} = 0.55$ ($\theta_{23} = 48^\circ$)

Hyper-Kamiokande Beam Non-Oscillation Physics Sensitivity

- Upgraded, intense neutrino beam + high performance detectors allow for additional precision measurements
- Precision measurements of various important neutrino cross sections at the HK near detectors
  - Intermediate Water Cherenkov Detector allows for precision interaction measurements at different off-axis angles $\rightarrow$ different beam energies
- Also aim for a search of non-standard/new physics in the HK near detectors :
  - Sterile neutrinos, heavy neutrinos (heavy neutral leptons), Lorentz violation, etc...

Conclusion

- Hyper-Kamoikande project received seed funding this Japanese Fiscal Year
  - Now finalizing optimization of near detector and far detector design
  - First beamline upgrades toward 1.3MW to take place in 2020/2021
  - Will start HK tank construction in 2020
- Exciting physics prospects :
  - Resolve $\sin\delta_{CP} \neq 0$ for $\sim$75% of δ_{CP} space at $>3\sigma$
  - Measure δ_{CP} with precision of $<20^{\circ}$
  - Determine Mass Hierarchy $>3\sigma$
  - Precision neutrino cross section measurements
  - Search for new physics
- New collaborators welcome !