Plans and status of Hyper-Kamiokande

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Matter To The Deepest 2025,
Sep 16, 2025
Katowice, Poland

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- Physics goals
- Status and plans
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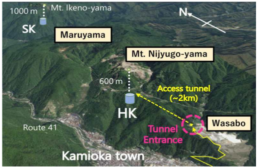
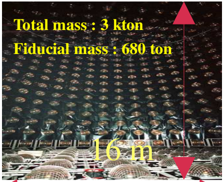
Water Cherenkov experiments in Japan



- 20% coverage
- 50 cm PMT
- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A
- 2002 Physics Nobel for Masatoshi Koshiba



16 m

Kamiokande

(1983-1996)

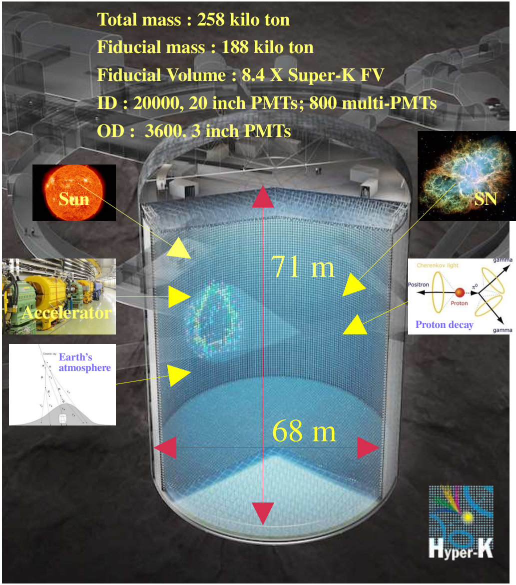
- 40% coverage; 50 cm PMT
- Solar neutrinos, constraints on proton decay, DSNB
- Far detector for T2K
- Discovery of atmospheric neutrino oscillations
- 2015 Physics Nobel for Takaki Kajita

39.3 m

Super Kamiokande

(1996 – 2020 : Pure water)

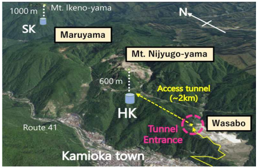
(2020 - : Gd loaded)



Hyper Kamiokande

(2028 -)

Water Cherenkov experiments in Japan



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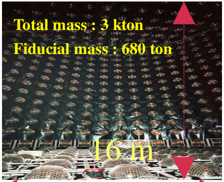

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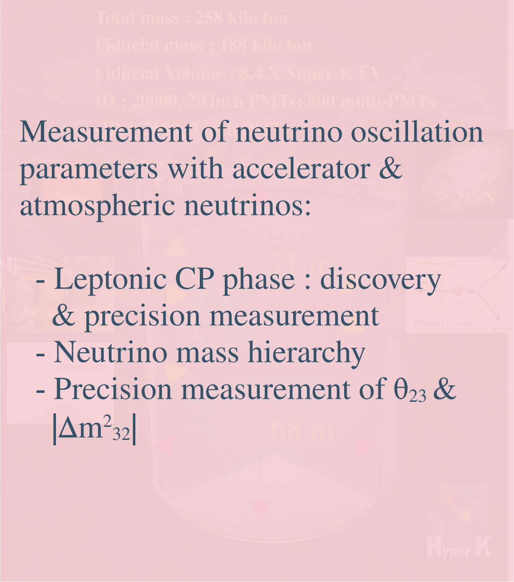


Measurement of neutrino oscillation parameters with accelerator & atmospheric neutrinos:

- Leptonic CP phase : discovery & precision measurement
- Neutrino mass hierarchy
- Precision measurement of θ_{23} & $|\Delta m^2_{32}|$

Hyper Kamiokande

(2028 -)

Studies of 3-flavour neutrino oscillation parameters at HK

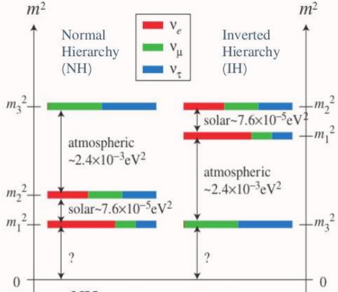
Flavour eigen states $\alpha = e, \mu, \tau$ ← $\boxed{|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle}$ → Mass eigen states $i = 1, 2, 3.$

$$U_{\alpha i} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric, accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor}}$$

Current status of neutrino oscillation parameters

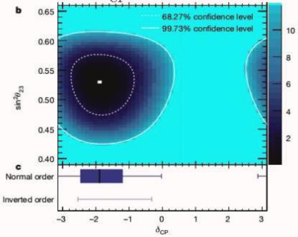
- Known : $\theta_{12} \approx 33.68^\circ$, $\theta_{13} \approx 8.6^\circ$
  $\Delta m^2_{21} \approx 7.49 \times 10^{-5}$ eV^2
- Going on : $\theta_{23} \approx 41^\circ$-$50^\circ$
  $|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}$ eV^2
- UNKNOWN! : Sign of Δm^2_{32} (mass hierarchy)
  δ_{CP}, octant of θ_{23}

Octant of θ_{23} = ?
$\theta_{23} < 45^\circ$: Lower octant
$\theta_{23} = 45^\circ$: Maximal
$\theta_{23} > 45^\circ$: Higher octant



NH : $m_1 < m_2 << m_3$
IH : $m_3 << m_1 < m_2$

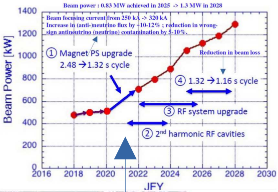
Hints of $\delta_{CP} \approx -90^\circ$ from T2K

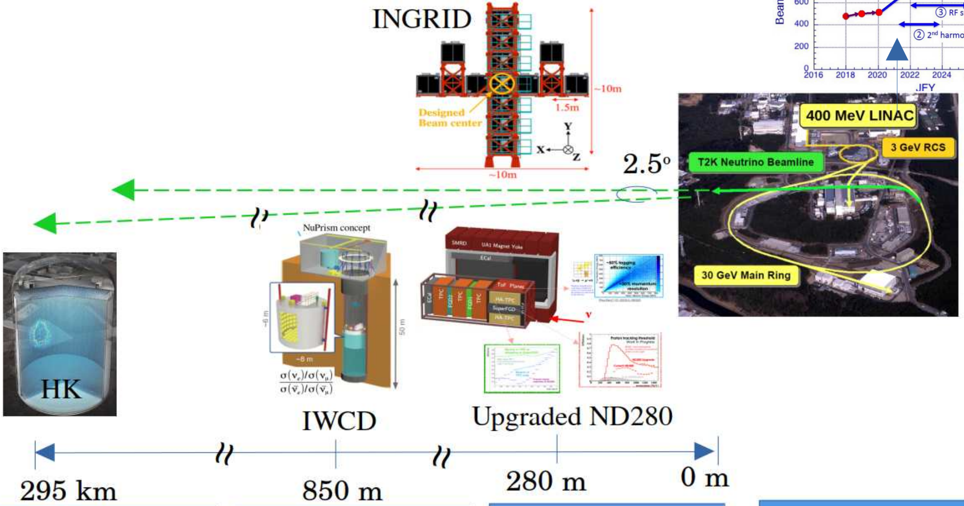


Nature volume 580, pages 339–344 (2020)

https://doi.org/10.1038/s41586-020-2177-0

Accelerator neutrinos at HK





Far Detector
Hyper-Kamiokande

$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \varepsilon_{FD} \cdot P_{osc}$

Intermediate detector
IWCD
Different off-axis angles including 2.5°

Near Detectors
On Axis – INGRID
2.5° Off Axis – ND280

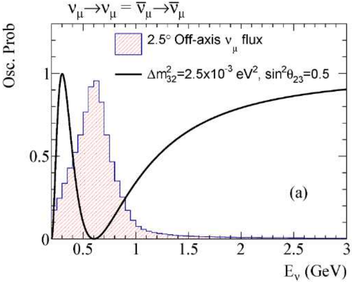
$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \varepsilon_{ND}$

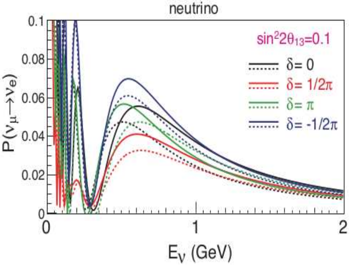
J-PARC
Accelerator complex
Neutrino beamline

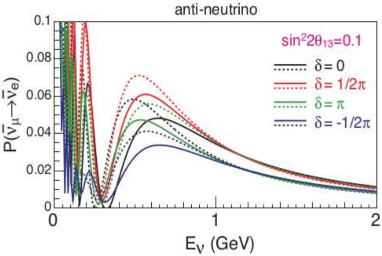
Neutrino oscillation probabilities at L = 295 km

$$P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_\mu}) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times (1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2_{32}L}{E}\right)$$

$$\begin{aligned}
P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}) \simeq\ & 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2\Delta_{31} \\
& + 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23}) \\
& \qquad \cdot \cos\Delta_{32}\cdot\sin\Delta_{31}\cdot\sin\Delta_{21} \\
& -(+) 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\cdot\sin\Delta_{32}\cdot\sin\Delta_{31}\cdot\sin\Delta_{21} \\
& + 4c_{13}^2 s_{12}^2(c_{12}^2c_{23}^2 + s_{12}^2s_{13}^2s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{CP}) \\
& \qquad \cdot \sin^2\Delta_{21}, \quad (
\end{aligned}$$







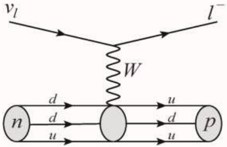
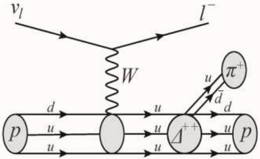
- Sensitivity to $\sin^2(2\theta_{23})$, $|\Delta m^2_{32}|$

- Sensitivity to $\sin^2(2\theta_{13})$, $\sin^2\theta_{23}$ (θ_{23} octant)
- Sensitive to CP phase δ_{CP}

L = 295 km “not very long” → δ_{CP} effect dominates compared to that of mass ordering(~<27% vs ~10%)

Exposure and samples for sensitivity studies

- 2.7×10^{21} Protons-On-Target (POT) per calendar year
- FHC : RHC ratio = 1:3

Interaction	Visible Topology	Mode
$\nu_l, \bar{\nu}_l$ CCQE, $l = \mu, e$ 	- 1 ring μ–like - 1 ring e–like	ν and $\bar{\nu}$
ν_l CC RES $1\pi^+$, $l = e$, 	- 1 ring e–like + 1 decay electron (π^+ is below the Cherenkov threshold)	ν only

Central values of oscillation parameters

$\sin^2\theta_{12}$	Δm^2_{21} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{13}$	δ_{CP}	Mass ordering
0.307	7.53×10^{-5}	0.528	2.509×10^{-3}	0.0218	-1.601 rad	Normal

Models and different uncertainties

1) Statistical uncertainty only
2) T2K models & parametrisation of uncertainties on :
   - neutrino flux
   - neutrino-nucleus interaction cross-section
   - detector response

→ Same as in Eur. Phys. J. C (2023) 83: 782

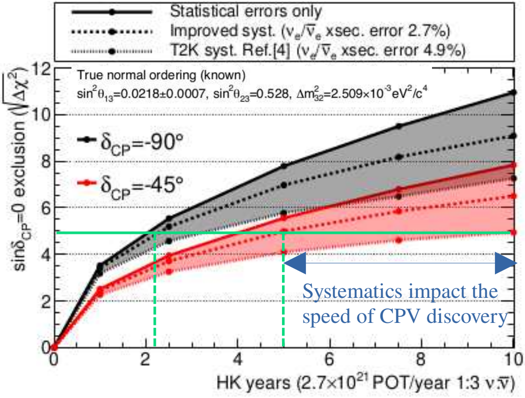
3) Improved systematic uncertainties :
   (a) Errors constrained by ND280 & far detector systematics -> scaled by $1/\sqrt{N}$, where N = 7.5
   (b) From upgraded ND280 + IWCD

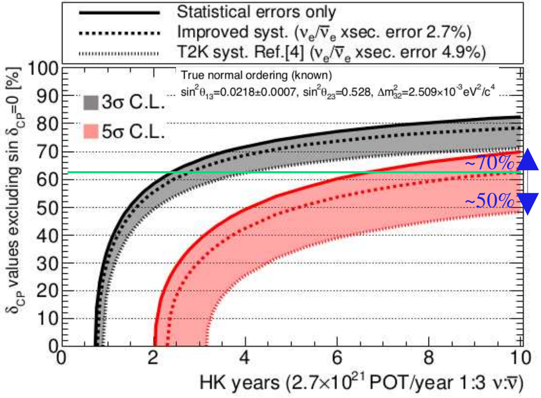
→
- $\sigma^{syst}_{ND} < \sigma^{stat}_{ND}$
- Near to far detector data-taking ratio similar between T2K and HK

- 10 years of statistics with 27×10^{21} POT (6.75×10^{21} POT in FHC & 20.25×10^{21} POT in RHC)

https://doi.org/10.48550/arXiv.2505.15019

Sensitivity to CP Violation with true mass ordering known as normal

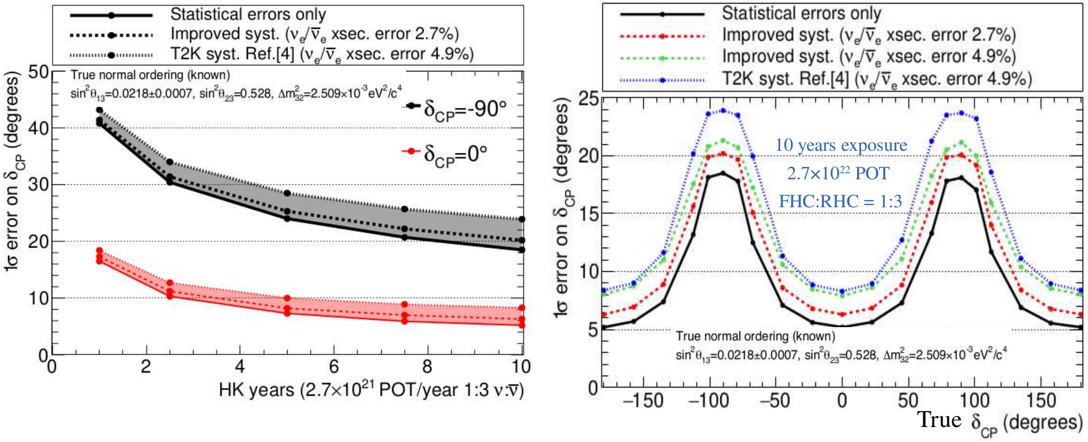




- True $\delta_{CP} = -\pi/2$: 5σ discovery of CPV in ≤ 3 years
- True $\delta_{CP} = -\pi/4$: 5σ discovery of CPV in < 6 years with improved systematics

- CPV discovery at 5σ for 60% of true δ_{CP} values with 10 years exposure -> With improved systematics
- CPV sensitivity most degraded by uncertainty on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ cross-section ratio.

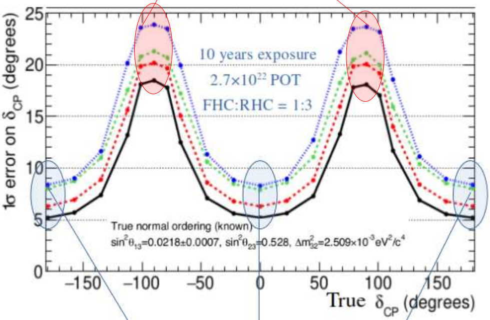
Precision on δ_{CP} with true mass ordering known as normal



- Precision on δ_{CP} depends on
  - the true value of δ_{CP} : better precision for CP conserving values
  - systematic uncertainties

Impact of systematics on the resolution of δ_{CP} with true mass ordering known as normal

- $\delta_{CP} = \pm\pi/2$: $\cos\delta_{CP} = 0$ -> derivative $-\sin\delta_{CP}$ is maximal
- Precision of δ_{CP} : dominated by $\cos\delta_{CP}$ induced shape effects on energy spectra
- Systematic effects related to the neutrino reconstructed energy

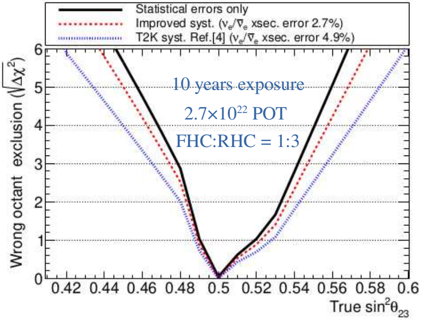


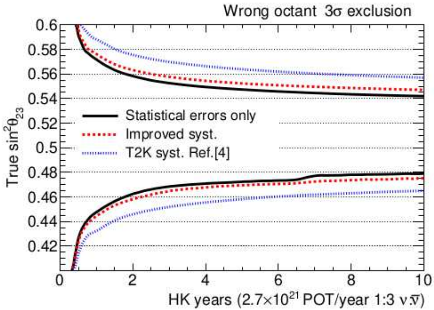
Experimentally constrain the relevant uncertainties with ND280++ & IWCD.

- $\delta_{CP} = 0, \pm\pi$: $\sin\delta_{CP} = 0$ -> derivative $\cos\delta_{CP}$ is maximal
- Precision of δ_{CP} around CP-conserving values : difference between ν_e & $\bar{\nu}_e$ events
- $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ ratio -> significant impact on the resolution

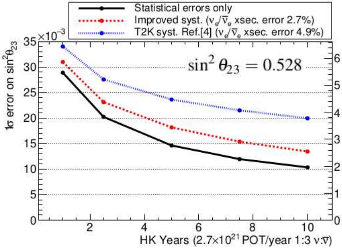
Constraints on 2–3 oscillation parameters

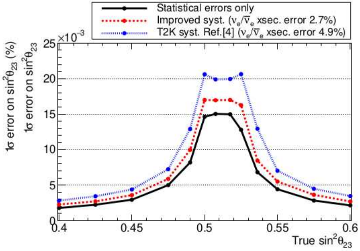
Ability to exclude wrong octant of θ_{23}

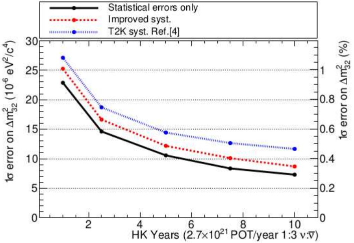




Precision on θ_{23} & Δm^2_{32}

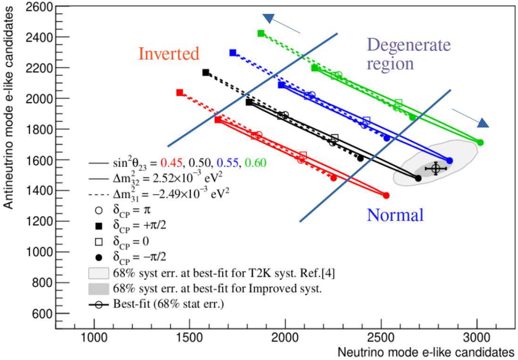




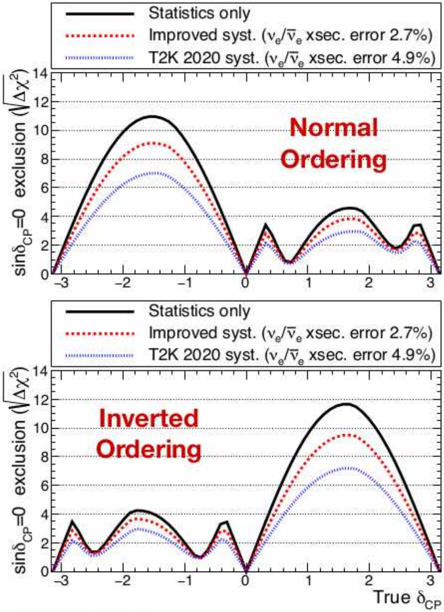


Degeneracy of δ_{CP} with mass ordering

- Sensitivity to CPV is degraded in degenerate regions if mass ordering is unknown.



- Mass ordering can be determined independently by atmospheric neutrino samples. -> Help to lift the degeneracy.



Hyper-K preliminary
True inverted ordering (Unknown), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$eV^2/c^4

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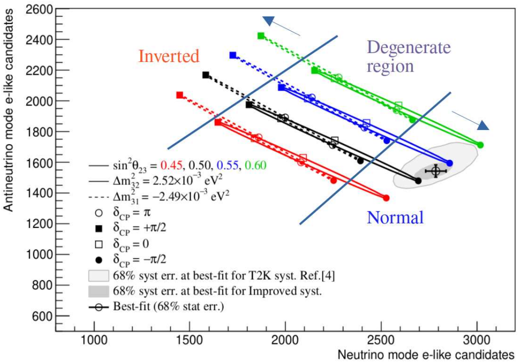
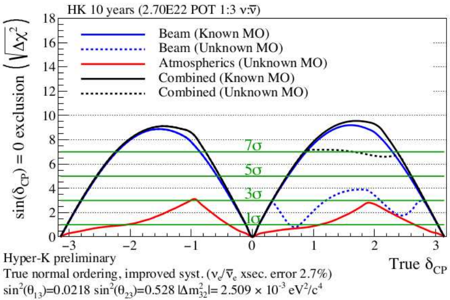


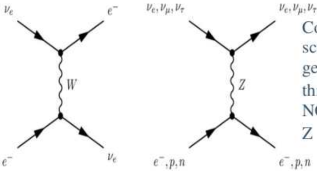
From a previous analysis



- Joint fit of 10 years of beam and atmospheric neutrinos can give 5σ discovery potential in both regions.
- New HK beam + atmospheric joint fit going on -> Based on SK + T2K joint fit Phys. Rev. Lett. 134, 011801
- Mass ordering can be determined independently by atmospheric neutrino samples. -> Help to lift the degeneracy.

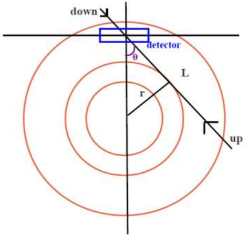
Atmospheric neutrinos in HK

Earth matter effects on neutrino propagation



Coherent forward elastic scattering processes generate CC potential V_{CC} through W exchange and NC potential V_{NC} through Z exchange.

G_F = Fermi constant
n_e = electron number density in matter
ρ = the matter density



Span a wide range of L/E.

$A_{CC} = 2EV_{CC} = 2\sqrt{2}G_F n_e E = 7.63 \times 10^{-5} \rho(\text{gm/cc})\, E(\text{GeV})\ \text{eV}^2,$

Resonance in Earth matter

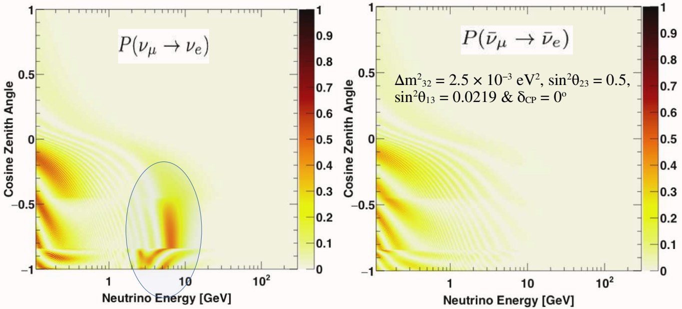
Non-zero θ_{13} is crucial

$$\sin 2\theta_{13}^m = \frac{\sin 2\theta_{13}}{\left[\left(\cos 2\theta_{13} - (A_{CC}/\Delta m^2_{32})\right)^2 + \sin^2 2\theta_{13}\right]^{1/2}}$$

Resonance condition: $\cos 2\theta_{13} = A_{cc}/\Delta m^2_{32}$

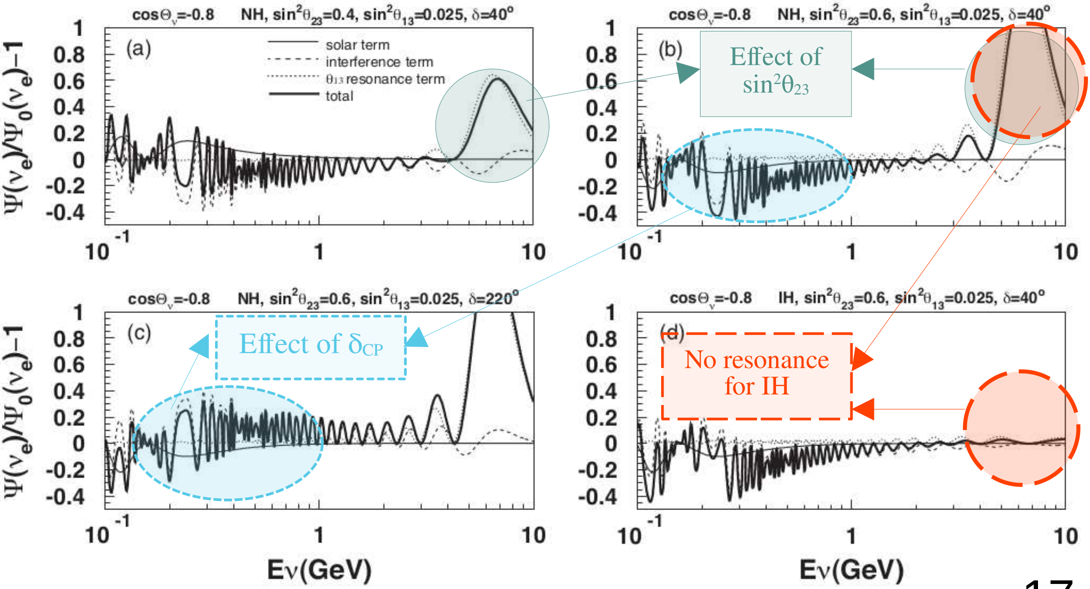
Occurs in $\nu(\bar{\nu})$ if the true hierarchy is normal (inverted).

~80 atmospheric neutrino events/day

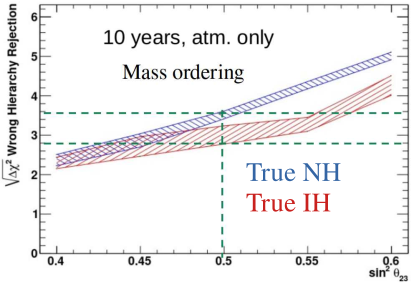


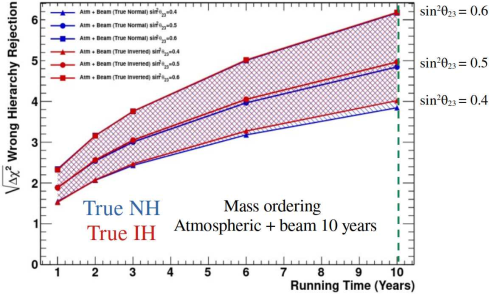
True normal hierarchy

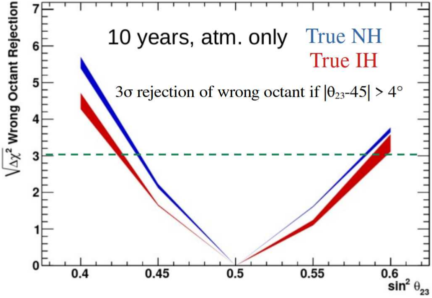
Oscillated ν_e flux relative to the unoscillated flux vs E_ν (GeV); $\cos\Theta_\nu = -0.8$

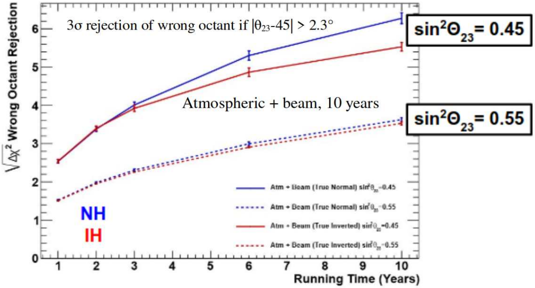


Sensitivities with atmospheric neutrino events

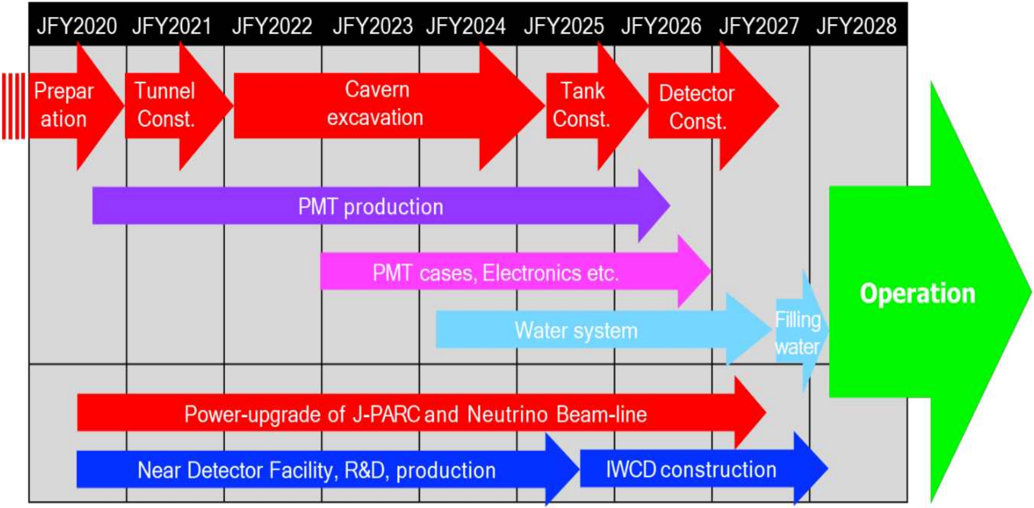








Status of the experiment - Schedule



Far detector

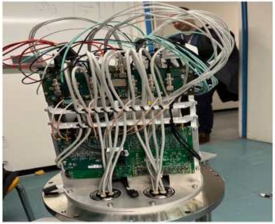
- Detector cavern : completed on July 31, 2025.

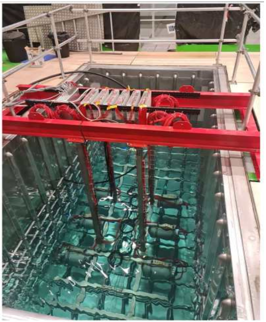
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/1006

- Photodetectors

- Mass production of 20" (ID) PMTs :
  ~15000 PMTs delivered & tested : QA, signal check, visual check
  - QA shift by collaborators
- 2 dark rooms in Kamioka, each for 100 PMTs

- Tests of underwater electronics in Kamioka & CERN





Summary and conclusions

- Hyper-K is a next generation neutrino detector that can detect neutrinos from particle accelerators, Earth's atmosphere, the Sun and supernovae and probe proton decay.

- With 10 years of exposure :

  - Beam neutrinos : 2.7×10^{21} POT/year, FHC:RHC = 1:3 – 5σ discovery of CPV within a few years with improved systematics
  - joint analysis with atmospheric neutrinos to lift the δ_{CP} - mass ordering degeneracy.

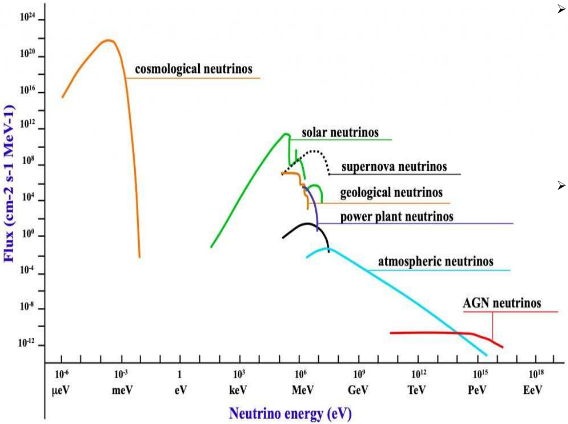
- Currently the preparations are going on (construction of the facility, testing of detector components etc)
  - JPARC beam and near detectors have been upgraded
  - New Intermediate Water Cherenkov detector to further constrain systematic uncertainties

- Will start data taking in 2028.

Thank you

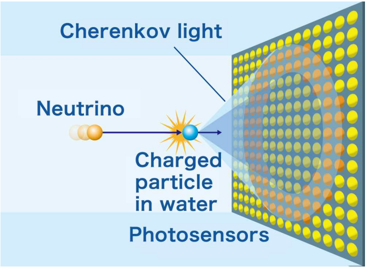
Backup slides

Different sources of neutrinos

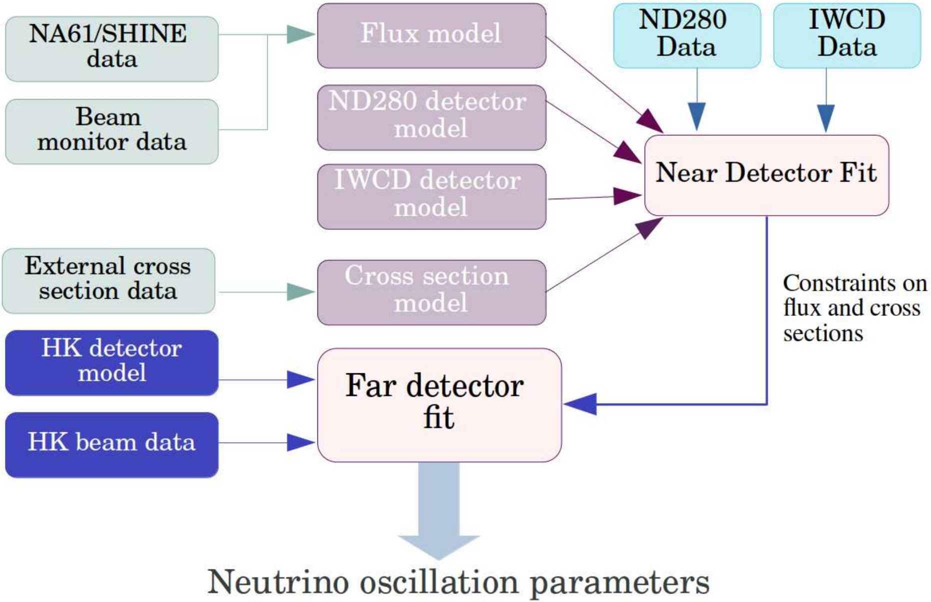


- Currently being detected and studied by different types of neutrino detectors across the World.

- One main category of neutrino detectors : Water Cherenkov Experiments

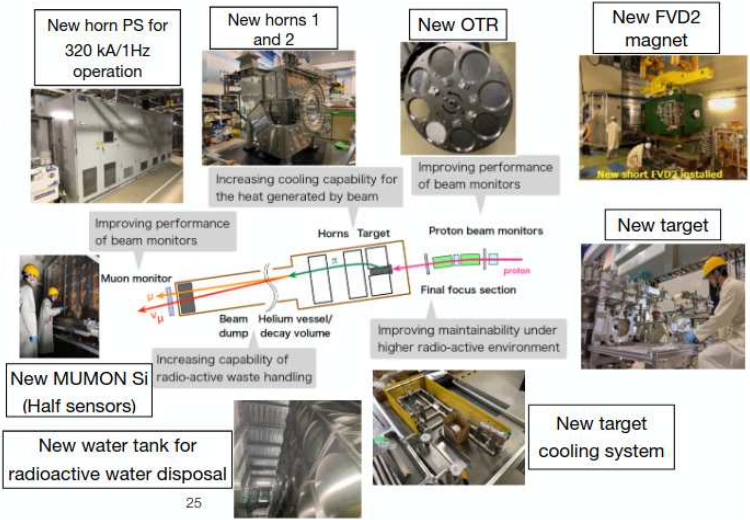


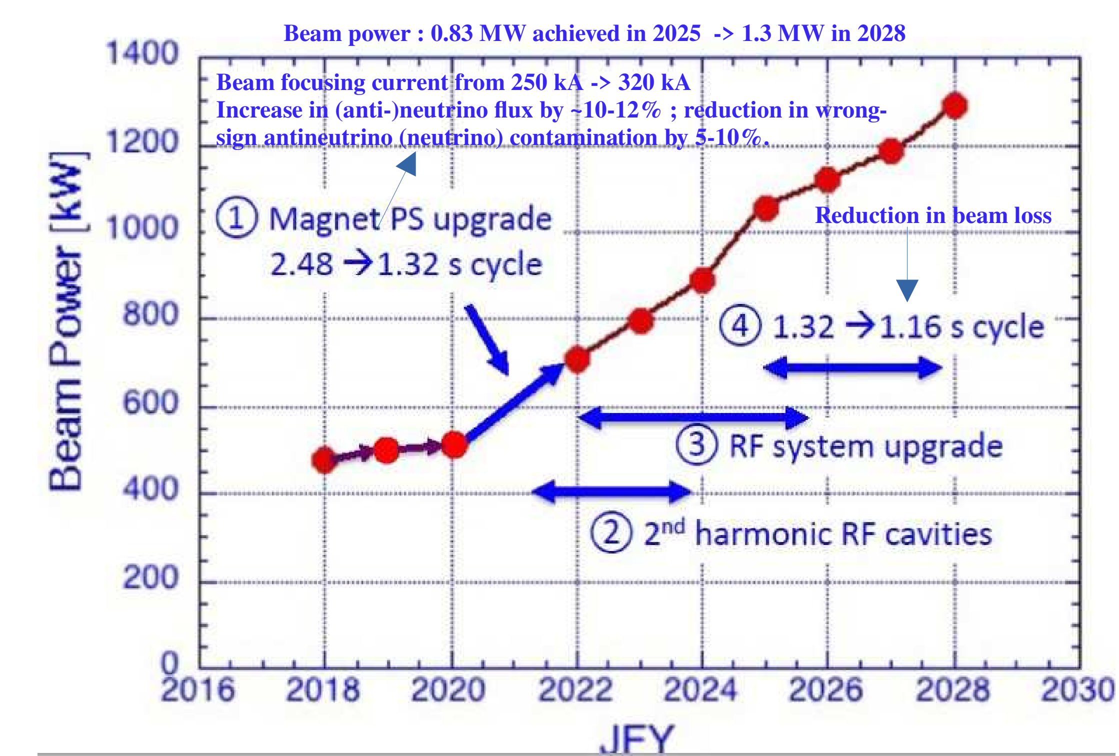
Consecutive ND+FD fit



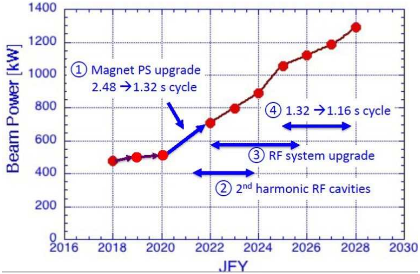
Neutrino beamline upgrades

- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48s to 1.36s
- Several upgrades done on the neutrino beamline to cope with higher beam power
- Horn being operated at 320 kA instead of 250 kA → ~10% increase in the ν flux



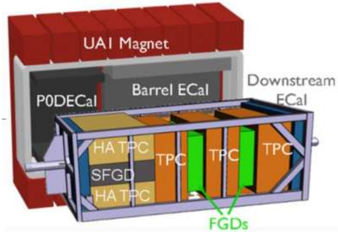

Beam power : 0.83 MW achieved in 2025 -> 1.3 MW in 2028
Beam focusing current from 250 kA -> 320 kA
Increase in (anti-)neutrino flux by ~10-12% ; reduction in wrong-sign antineutrino (neutrino) contamination by 5-10%.
1 Magnet PS upgrade
2.48 → 1.32 s cycle
Reduction in beam loss
4 1.32 → 1.16 s cycle
3 RF system upgrade
2 2nd harmonic RF cavities
Beam Power [kW]
JFY
1400
1200
1000
800
600
400
200
0
2016
2018
2020
2022
2024
2026
2028
2030

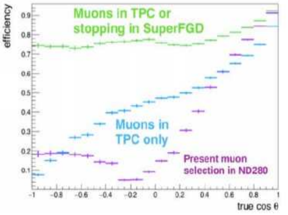
Upgrade of JPARC beam facility



- Beam power : 0.83 MW achieved in 2025 -> 1.3 MW in 2028
- Cycle time 1.36 s (in 2025) -> 1.16 s -> Reduction in beam loss
- Magnetic horns power supply replacement : beam focusing current from 250 kA -> 320 kA.
- Increase in (anti-)neutrino flux by ~10-12% ; reduction in wrong-sign antineutrino (neutrino) contamination by 5-10%.

Upgrade of ND280





Part of T2K operational from 2024

New Detectors

- SFGD
- HA TPCs
- Time Of Flight

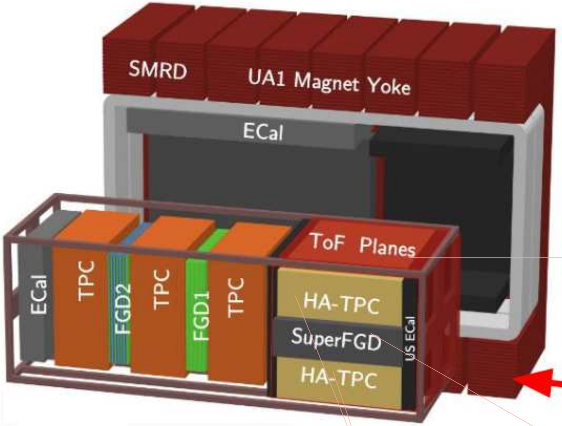
Constrain predictions for far detector

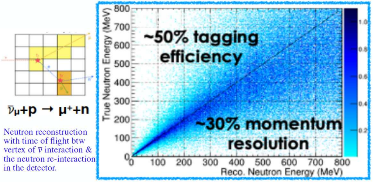
- Measure flux x cross section

Magnetised : to measure wrong sign backgrounds

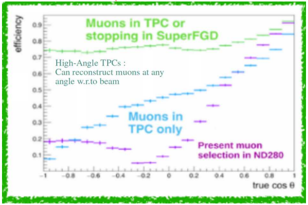
Contraints and development of cross section models via detailed kinematic measurements

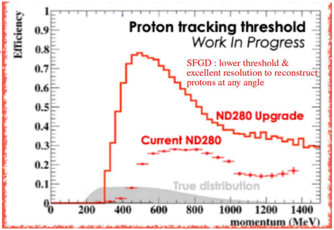
ND280





Phys.Rev.D 101 (2020) 9, 092003





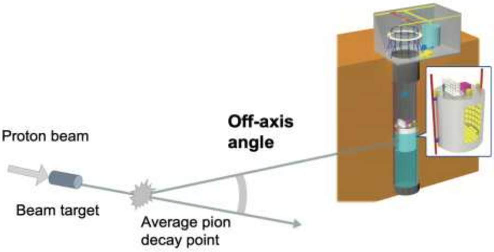
Intermediate Water Cherenkov detector (IWCD)

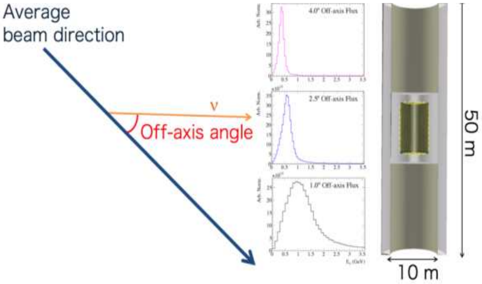
- Work on the vertically movable water Cherenkov
  detector facility at 850 m from the target has begun.

- Will measure :
  - electron (anti)neutrino cross section
  - intrinsic electron-like background events at 2.5°
  - feed-down of muon neutrino events from higher energy to lower reconstructed energy.

- Same target material and detector technology as the far detector .

- Off-axis angle can be varied via vertical movement :
  - access to different neutrino energy ranges & fluxes
  - increase in statistics at higher neutrino energies (constrain non-QE interactions)

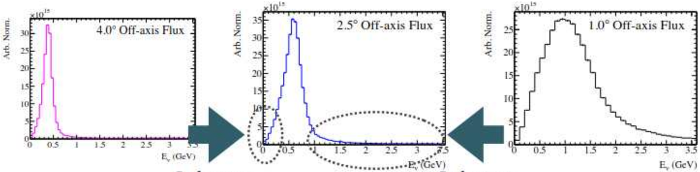




Credit: Evangelia Drakopoulou, POS 2017

NuPRISM Concept

Hyper-Kamiokande

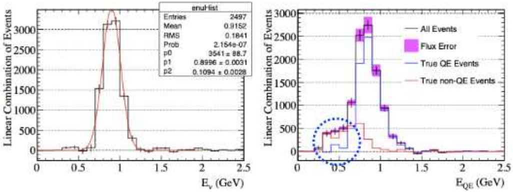


Subtract Subtract

Due to pion decay properties, neutrino spectrum varies with off-axis angle

Measurements at different off-axis angle can subtract high and low energy tails

Obtain very narrow spectrum



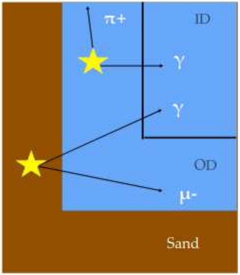
Measure reconstructed energy of events

5% measurement precision on events with large mis-reconstruction

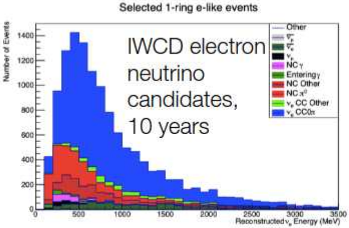
https://indico.cern.ch/event/981823/contributions/4295370/attachments/2250599/3817673/iwcd_tipp2021_mhartz.pdf

Electron (anti)Neutrinos

- Using 1% contamination in beam, we measure: $\dfrac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$
- More off-axis position has larger fraction of electron (anti)neutrinos
- Water Cherenkov detector has large active shielding agains gamma background - almost completely removed



- 2.8% error on relative event rates for CP violation search
  - Compared to 3.0% error from T2K
  - Aim to improve with application of machine learning



https://indico.cern.ch/event/981823/contributions/4295370/attachments/2250599/3817673/iwcd_tipp2021_mhartz.pdf

Central values of oscillation parameters and nominal number of events

$\sin^2\theta_{12}$	Δm^2_{21} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{13}$	δ_{CP}	Mass ordering
0.307	7.53×10^{-5}	0.528	2.509×10^{-3}	0.0218	-1.601 rad	Normal

	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 e-like + 0 decay e	143.9	294.3	5.3	12.0	2007.5	11.7	2474.7
$\bar{\nu}$-mode, 1-ring e-like + 0 decay e	59.1	130.1	96.3	234.8	229.2	793.2	1542.7
ν-mode, 1-ring e-like + 1 decay e	14.0	40.2	0.6	0.3	255.3	0.2	310.6
ν-mode, 1-ring μ-like	8355.4	8.4	478.0	0.7	2.6	0.01	8845.1
$\bar{\nu}$-mode, 1-ring μ-like	4255.9	6.0	7759.9	4.7	0.2	0.4	12027.2

- Expected number of events at HK after 10 years of statistics with 27×10^{21} POT (6.75×10^{21} POT in FHC & 20.25×10^{21} POT in RHC)

Sensitivity to proton decay in HK

- Matter is very stable (age of the Universe ~ 10^{10} years)
- Electrons must be stable due to the conservation of electric charge
- Neutrons decay if left outside of the nucleus

- What about protons?

- Conservation of Baryon number introduced to explain matter stability [Weyl, 1929; Wigner, 1949]
  Accidental global symmetry in the Standard Model, might be violated.

Proton decay is a valuable tool to probe physics Beyond the Standard Model (BSM)

https://agenda.infn.it/event/45476/contributions/261687/attachments/133726/199931/Calabria_PISA_2025.pdf

Grand Unified Theories (GUTs)

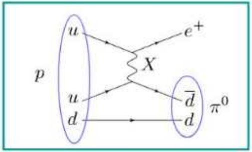
- **Unify SM gauge groups [Georgi, Glashow, 1974; Fritzch, Minkowski, 1975]**
- **GUTs scale: $10^{14\text{-}16}$ GeV, well beyond collider energies.**
- **Lepton and baryon numbers are not conserved: protons can decay.**

https://agenda.infn.it/event/45476/contributions/261687/attachments/133726/199931/Calabria_PISA_2025.pdf

SUSY

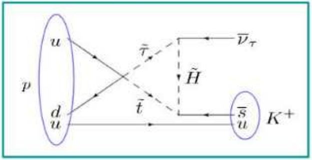
typically dominant: $p \to e^+\pi^0$ $SU(5)$

$\tau = \frac{1}{\Gamma} \propto \left[\frac{M_X^2}{\alpha^2}\right]^2$



$\to$ prediction $\tau \sim 10^{29-36}$ yrs
$\to$ minimal model ruled out (IMB-3, Kamiokande, Super-K)

$p \to \bar{\nu} K^+$ $SU(5)$



$\tau = \frac{1}{\Gamma} \propto \left[\frac{M_s M_T}{\alpha^2}\right]^2$

$\to$ prediction $\tau \sim 10^{29-36}$ yrs
$\to$ minimal (TeV-)SUSY model ruled out by Super-K [Kobayashi+ (SK), 2005]

https://indico.kit.edu/event/4294/contributions/17219/attachments/8084/13058/BLV2024_HK_Takhistov.pdf

Experimental search for proton decay

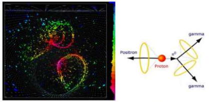
- Predicted proton lifetimes > 10^{30} years
  Age of the Universe: ~10^{10} years

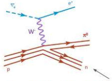
- Impossible to observe a single proton for a long time.
  Observe $\geq 10^{30}$ protons for relatively shorter time
  Lifetime τ: $N(t)=N(t=0)\exp(-t/\tau)$

- Large scale water Cherenkov detectors :
  H_2O -> cheap & abundant
  10 protons per molecule; 2 are free (no nuclear momentum)
  Easily scalable detectors

$p \to e^+\pi^0$ in Super-K

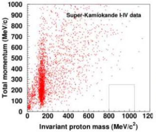
- Final state (positron + 2 gammas) is fully visible, easy to identify
  → can reconstruct proton mass/momentum, clean channel nearly background-free





typical atm. ν background

neutron hard to see, benefits from improved n-tag efficiency (SK pure water ~ 20%)



- *Exposure:* 450 kton*yr
- *Signal efficiency:* 38.6% (SK I-IV)
- *Expected background:* 0.05 ev. $P_{tot} < 100$ MeV; 0.58 ev. in region $100 \le P_{tot} < 250$ MeV

No candidates, set most stringent lower limit:

$> 2.4 \times 10^{34}$ yrs.

[Abe+ (SK), 2020]

p -> ν K⁺ in Super-Kamiokande

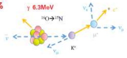
K⁺ Cherenkov threshold in water is 560 MeV/c
most of K⁺ can't emit a ring

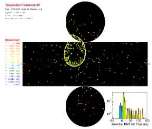
Most of K⁺ produced stop in water (~89%)

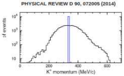
Look for K⁺ decays:

- K⁺ -> νμ⁺ : 64%
  (P = 236 MeV/c if decay at rest)

γ emission prob. 40%



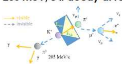


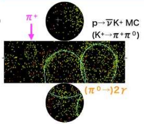


2 possible methods for K⁺ -> νμ⁺ search:
1. Prompt γ
2. Spectrum fit

Dominant background:
νp -> νΛK⁺, Λ -> pπ⁻

- K⁺ -> π⁺π⁰ : 21%
  (P = 205 MeV/c if decay at rest)





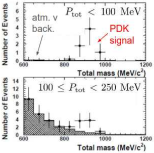
Dominant background:
$\nu_\mu CC1\pi$

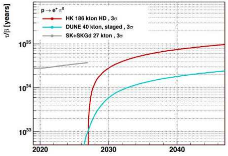
Three methods combined over 260 kton*year exposure:
τ > 5.9 x 10³³ years

$p \to e^+\pi^0$ in Hyper-K

Assuming life. around SK limit $\sim$ few $\times 10^{34}$ yrs

HK (10 years)





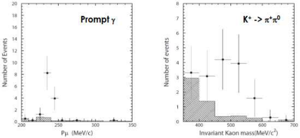
$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

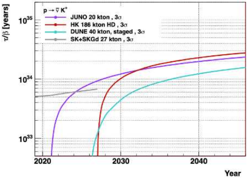
Probe at 3σ lifetime $\tau \sim 10^{35}$ yrs

HK background ½ of SK
(improved n-tag with upgraded PMTs…)

p -> ν K⁺ in Hyper-K

10 years HK exposure assuming τ = 6.6 x 10³³ years





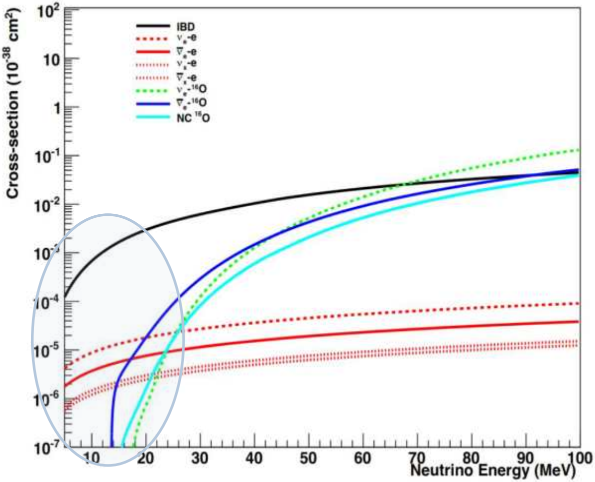
Prompt γ		$\pi^+\pi^0$		p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

https://indico.kit.edu/event/4294/contributions/17219/attachments/8084/13058/BLV2024_HK_Takhistov.pdf

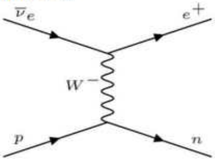
https://agenda.infn.it/event/45476/contributions/261687/attachments/133726/199931/Calabria_PISA_2025.pdf

Neutrino astrophysics

Supernova interactions in HK



Dominant cross-section is inverse beta decay (IBD)



$\overline{\nu}_e + p \rightarrow e^+ + n$

~90% of the expected interactions

Positron emission is (roughly) nondirectional

Sub-dominant interaction

Elastic scattering $\nu + e \rightarrow \nu + e$

~5% of the expected interactions

Preserves direction information

Other modes

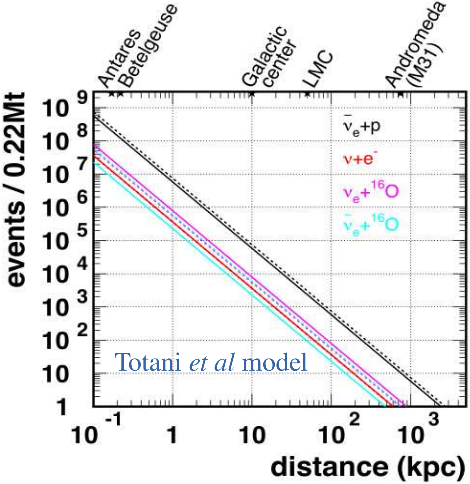
Highly model dependent, due to threshold effects

e.g. $\nu_e + {}^{16}O \rightarrow e + {}^{16}F$ (E_{thresh} = 15 MeV)

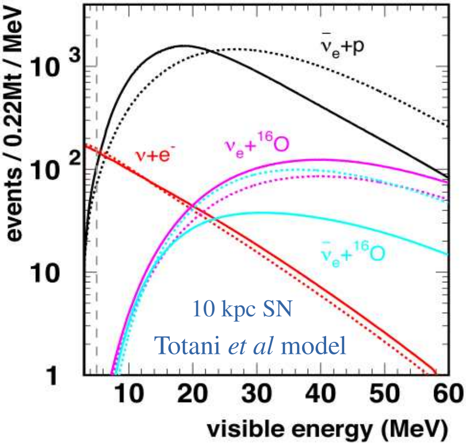
~5% of the expected interactions

https://agenda.infn.it/event/27159/contributions/191103/attachments/105943/149045/SNvD_HK_GDR.pdf

Expected no:of events vs SN distance



True energy spectra of prompt events in the full inner detector



Solid (dashed) lines : Normal (inverted) mass ordering

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Supernova burst neutrinos

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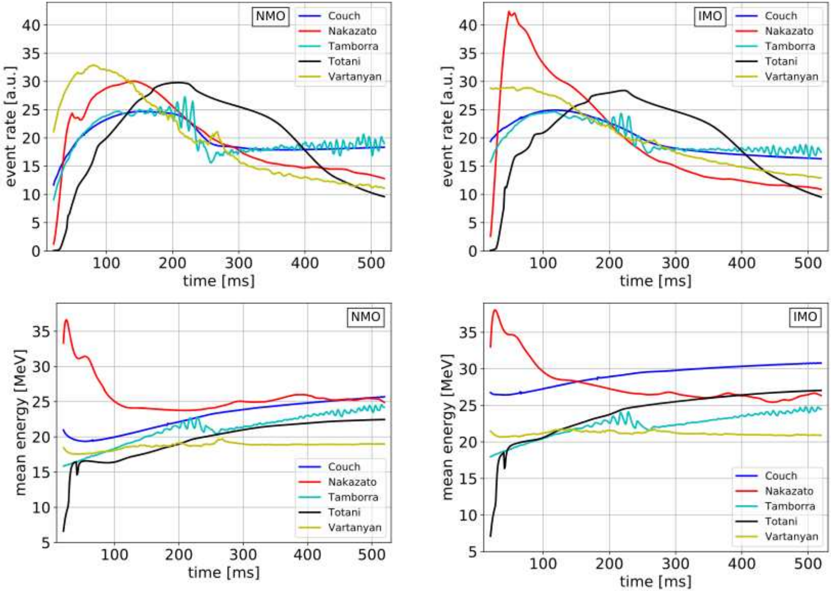

Figure 3. Event rate (top) and mean energy (bottom) of observed events in Hyper-Kamiokande, as predicted by the five supernova models used in this paper for normal (left) or inverted (right) mass ordering. All plots show the time interval from 20 ms to 520 ms after core bounce. The event rate is normalized to produce the same total number of events for each model, reflecting the assumption made in this paper that the distance of the supernova is unknown.

Number of Events Expected in Hyper-Kamiokande

Model	Normal Mass Ordering			Inverted Mass Ordering		
	$N_{10\ \mathrm{kpc}}$	d_{100}	d_{300}	$N_{10\ \mathrm{kpc}}$	d_{100}	d_{300}
Totani	20021	141 kpc	82 kpc	22717	151 kpc	87 kpc
Nakazato	17978	134 kpc	77 kpc	16005	127 kpc	73 kpc
Couch	27539	166 kpc	96 kpc	24983	158 kpc	91 kpc
Vartanyan	10372	102 kpc	59 kpc	9400	97 kpc	56 kpc
Tamborra	25025	158 kpc	91 kpc	20274	142 kpc	82 kpc

Note. Number of events expected during the time interval of 20 ms to 520 ms for a supernova at the fiducial distance of 10 kpc ($N_{10\ \mathrm{kpc}}$) and the distances at which 100 or 300 events are expected in the inner detector of Hyper-Kamiokande (d_{100} and d_{300}, respectively) for the five supernova models considered in this work and for both normal and inverted mass ordering.

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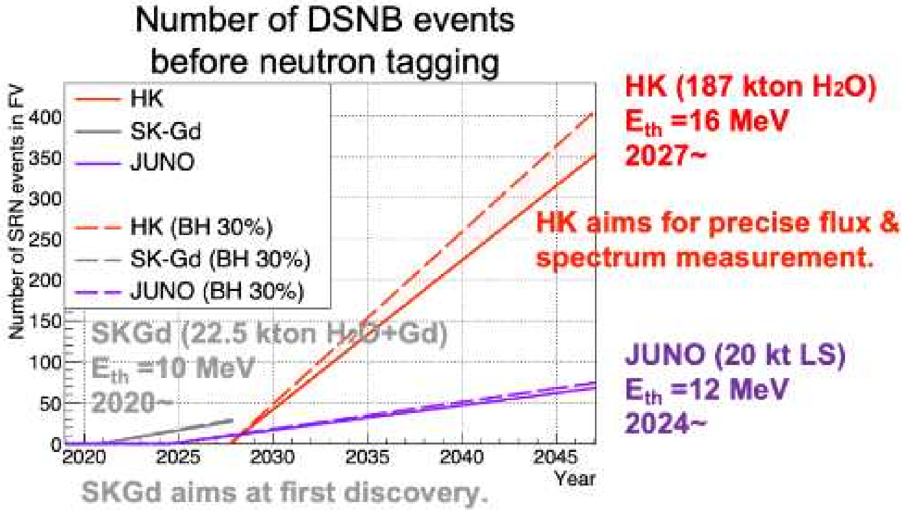
Diffuse Supernova Background (DSNB)

- Extra-galactic neutrinos from past supernovae -> undiscovered yet
- Carry convoluted information of :
  - Supernova burst neutrino spectrum (SN temperature, extraordinary SN)
  - History of star formation rate = evolution of the universe
- Super-K (Gd) : 2.3σ excess for DSNB with (5823 days SK + 956 days of SK-Gd)

  [https://indico.cern.ch/event/1258933/contributions/6485831/attachments/3105018/5503253/20250716_Harada_v3.pdf]

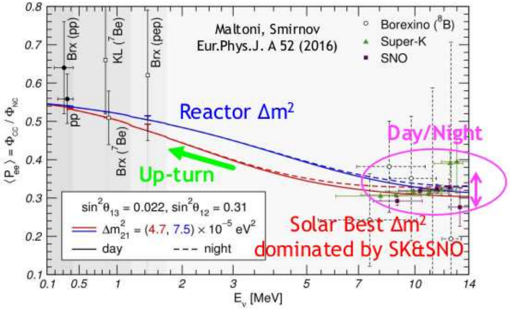
- DSNB search is limited by background:
  - from spallation in low energies
  - from atmospheric neutrinos in high energies

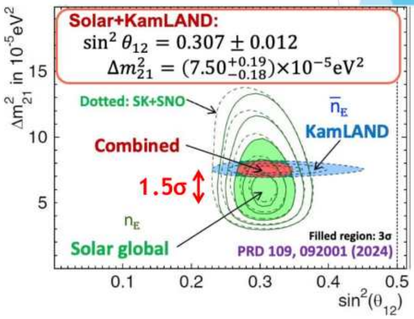


Number of DSNB events
before neutron tagging
Number of SRN events in FV
HK
SK-Gd
JUNO
HK (BH 30%)
SK-Gd (BH 30%)
JUNO (BH 30%)
SKGd (22.5 kton H2O+Gd)
Eth =10 MeV
2020~
Year
HK (187 kton H2O)
Eth =16 MeV
2027~
HK aims for precise flux &
spectrum measurement.
JUNO (20 kt LS)
Eth =12 MeV
2024~
SKGd aims at first discovery.

Solar neutrinos

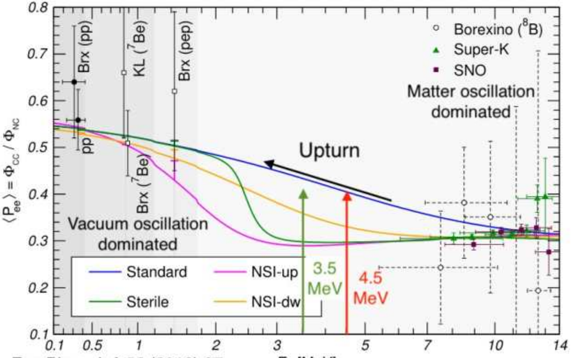
- Solar ^8B neutrino observation, oscillation measurement.
  - Realtime solar core activity monitoring with large statistics, 130 ev./day.
  - ~5σ sensitivity to Day/Night asymmetry (terrestrial matter effect) in 10 yrs.
    - ~2σ sensitivity in 10 yrs, to prove the difference of reactor and solar Δm^2 (CPT violation)
  - ~3σ sensitivity to observe the spectrum up-turn.
    - Connecting MSW dominant and vacuum-oscillation dominant energy (BSM).



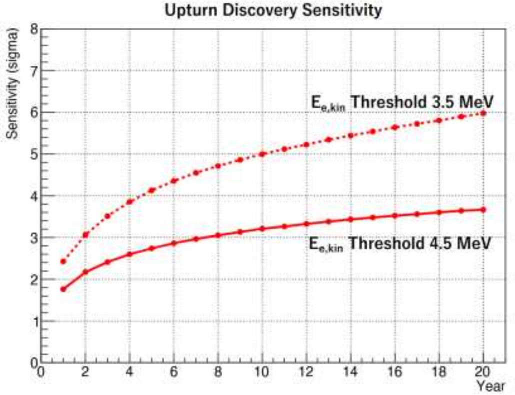


https://indico.cern.ch/event/1258933/contributions/6485844/

Solar neutrinos



Eur. Phys. J. A 52 (2016) 87



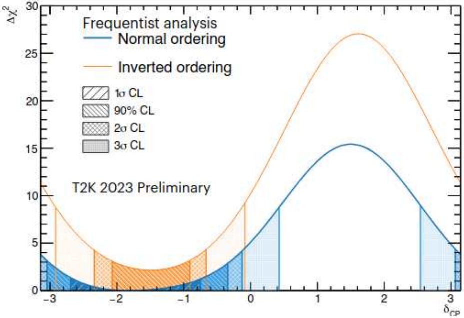
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ →	3.8 σ
	0.60	4.9 σ →	6.2 σ
θ_{23} octant	0.45	2.2 σ →	6.2 σ
	0.55	1.6 σ →	3.6 σ

10 years with 1.3MW, normal mass ordering is assumed

Hyper-K sensitivities at a glance

Physics	Parameter	Sensitivity
J-PARC beam neutrinos (1.3 MW; 10 years)	δ_{CP}	7° - 20°
	CPV coverage: 3σ (5σ)	76% (58%)
	$sin^2\theta_{23}$ (uncertainty for 0.5)	± 0.017
J-PARC beam neutrinos + atmospheric (10 years)	Mass ordering	>3.8σ
	Octant determination, 3σ	$\|\theta_{23} - 45°\| > 2°$
Solar neutrinos (10 years)	Day/Night: from 0 (from KL)	8σ (4σ)
	Upturn	$> 3\sigma$
Supernova neutrinos	10 kpc burst	54k – 90k events
	Relic neutrinos	~70 in 10 years
Proton decay (20 years)	Lifetime (3σ): $e^+\pi^0$	1×10^{35} $years$
	Lifetime (3σ): νK^+	3×10^{34} $years$

Recent results from T2K



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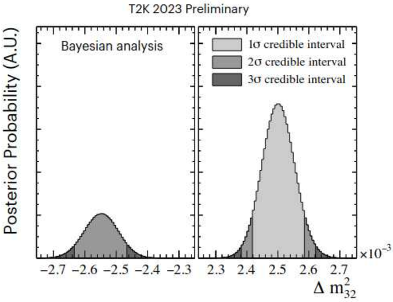

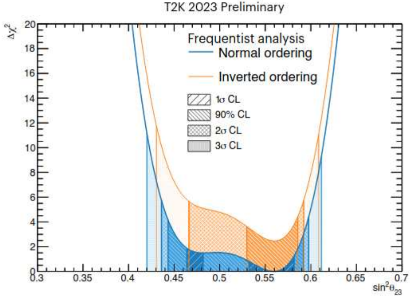

Recent results from SK+T2K

- Exclusion of CP conserving value of Jarlskog invariant with a significance between 1.9σ - 2σ (after fake data studies)
- A limited preference of normal ordering with a 1.2σ exclusion of inverted ordering.
- The joint analysis shows no strong preference for the octant of θ_{23}.
- Results of the first joint analysis now published: PRL 134, 011801 (2025)

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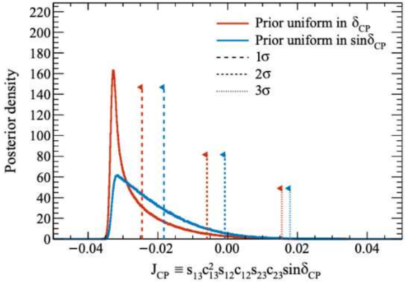
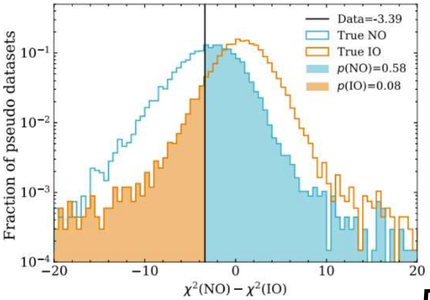
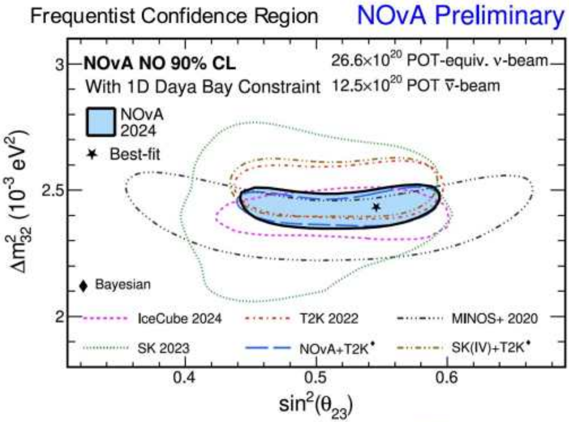




Recent results from NOνA



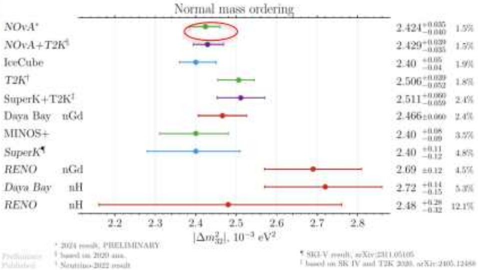
(Frequentist) best fit:

$$\Delta m^2_{32} = \left(+2.433^{+0.035}_{-0.036}\right) \times 10^{-3}\,\mathrm{eV}^2$$

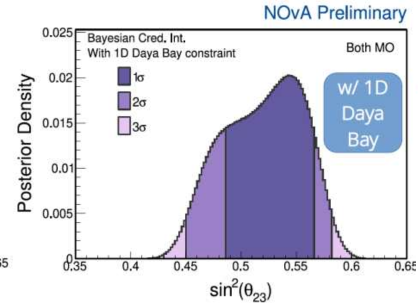
$$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$$

Mild Upper Octant preference

(69% prob; Bayes factor = 2.2)

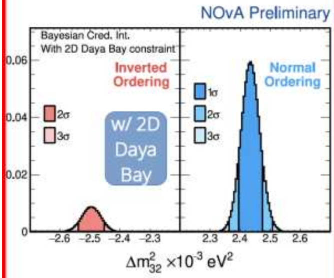


- NOνA's measurements consistent with the rest of the accelerator and atmospheric experiments
- Δm^2_{32} best-fit lies in the normal mass ordering (NO)
- $\sin^2(\theta_{23})$ best-fit value lies in the upper octant



Mild Upper Octant preference
(69% prob; Bayes factor = 2.2)
emerges from applying reactor constraint
(due to correlation between θ_{13} and θ_{23}, see overflow)

Maximal mixing is allowed at <1σ



Daya Bay ($\sin^2 2\theta_{13}$, Δm_{32}^2)
N.O. preference:
87% (Bayes factor: 6.8)
Frequentist significance*: 1.6σ

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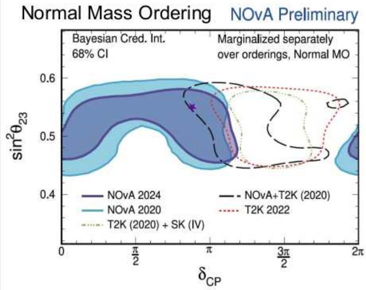
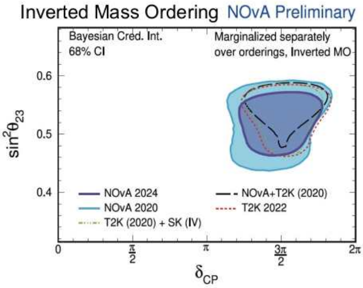


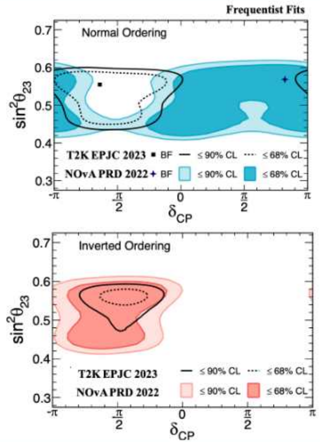


NOvA vs. other data favor different regions in NO, same region in IO

Joint analysis of T2K + NOνA

- Complementary in every aspect.
- NOvA has better MO sensitivity while T2K has it for δ_{CP}.
- The joint analysis probes both spaces lifting degeneracies of individual experiments

Experimental Property	T2K	NOvA
Proton beam	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection tech	FGD and Water Cherenkov	Segmented Liq scin. bars
CP effect	32%	22%
Matter effect	9%	29%



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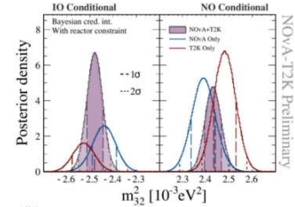
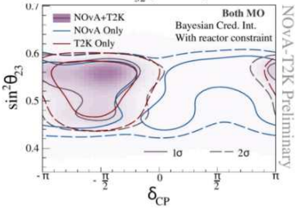
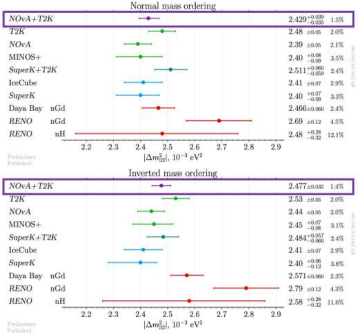
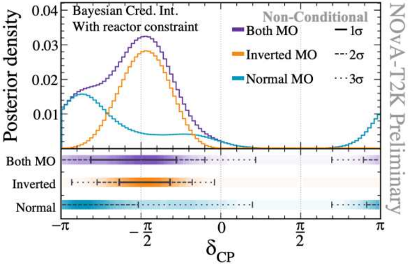




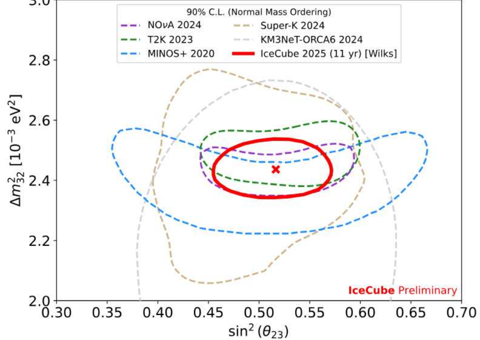




Joint analysis of T2K + NOνA

T2K plenary talk NUFACT 2025

- Small preference for inverted ordering, while individual experiments prefer normal ordering.
- In the case of inverted ordering, we get 3σ exclusion of CP conserving points, while its inconclusive in the case of normal ordering.
- Most precise measurement of $|\Delta m^2_{32}|$ so far.



IceCube

IceCube plenary talk NUFACT 2025

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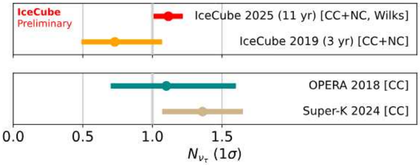
ν_τ Appearance

- Statistical measure of appearance of ν_τ from $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - No individual event-by-event ν_τ identification
- PMNS mixing unitarity and Standard Model physics would result in $N_{\nu_\tau} = 1$



Atmospheric neutrino results from SK I-V with increased fiducial volume

PHYS. REV. D 109, 072014 (2024)

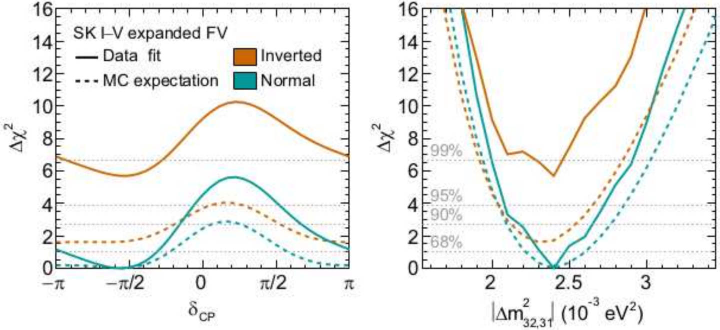


FIG. 16. 1D $\Delta\chi^2$ profiles of oscillation parameters in the analysis with $\sin^2\theta_{13}$ constrained. Solid lines correspond to the data fit result, while dashed lines correspond to the MC expectation at the data best-fit oscillation parameters, cf. Table IV. Dotted lines show critical values of the χ^2 distribution for 1 degree of freedom corresponding to 68%, 90%, 95%, and 99% probabilities.

Atmospheric neutrino results from SK I-V with increased fiducial volume

PHYS. REV. D 109, 072014 (2024)

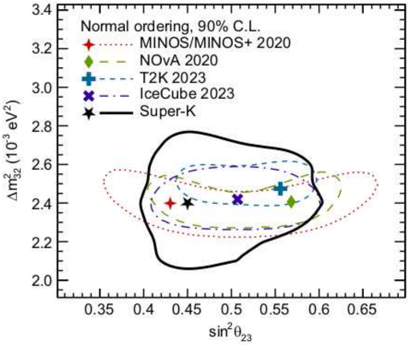


FIG. 17. 2D constant $\Delta\chi^2$ contours of neutrino oscillation parameters Δm^2_{32} and $\sin^2\theta_{23}$ for the normal mass ordering. Contours are drawn for a 90% critical χ^2 value assuming 2 degrees of freedom, with the $\Delta\chi^2$ computed for each experiment with respect to the best-fit point in the normal mass ordering. The Super-K contour shows the result of this analysis, and other contours are adapted from publications by MINOS+ [53], NOvA [4], T2K [3], and IceCube [54]. Best-fit points are indicated with markers for each experiment.

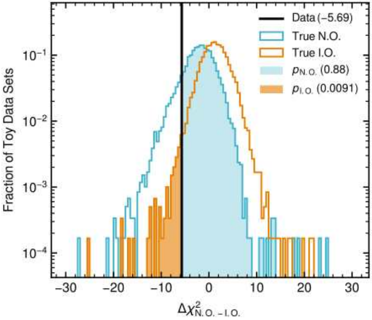


FIG. 18. Distribution of the mass-ordering preference statistic, $\Delta\chi^2_{\mathrm{I.O.-N.O.}}$, for ensembles of simulated datasets, assuming either the normal or inverted mass orderings. The data result from the atmospheric analysis with $\sin^2\theta_{13}$ constrained is shown as the vertical black line. The blue and orange histograms indicate the distribution of this statistic for toy datasets assuming the normal and inverted ordering, respectively. The filled areas to the left of the data result for inverted toy datasets and to the right of the data result for normal toy datasets indicate the p-values.

Analysis with constraints on $\sin^2\theta_{13}$ favors normal mass ordering 92.3% level.

Sensitivities from future experiments - JUNO

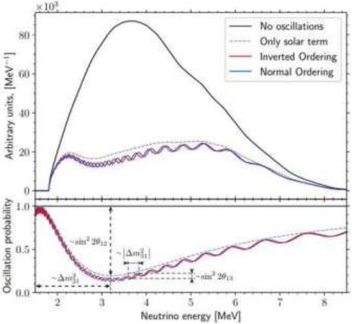


Figure 1: The expected antineutrino spectra at the JUNO detector under the assumption of perfect energy resolution (top) after 6 years of data taking with and without oscillations. The blue and red lines illustrate the normal and inverted ordering, respectively. The dotted line is scaled down by a factor 7 for better visibility. The survival probability is shown for the baseline of 52.5 km (bottom). The solar term refers to the case where only oscillations due to Δm^2_{21} and $\sin^2\theta_{12}$ take place, i.e., $\sin^2\theta_{13} = 0$. For this case, the value $\sin^2\theta_{12} = 0.282$ is used to avoid the overlap with red and blue curves, and other oscillation parameters are taken from PDG 2020 [13].

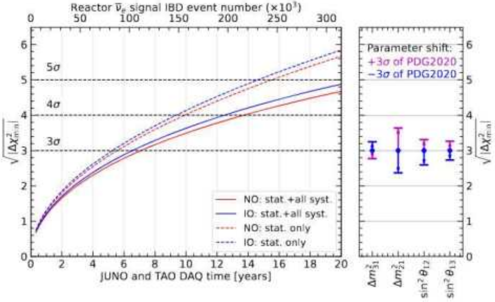
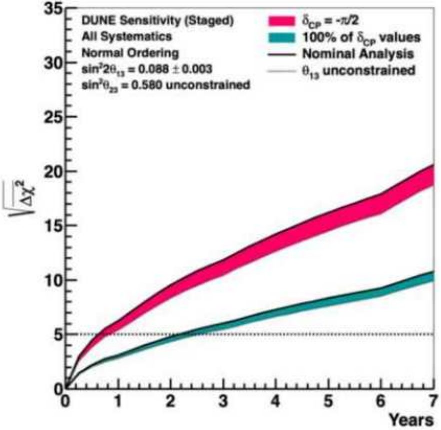


Figure 7: The NMO discriminator $\Delta\chi^2_{\rm min}$ as a function of JUNO and TAO data taking time for both the IO (red) and IO (blue). The horizontal black dashed lines represent 3σ, 4σ, and 5σ significances. The solid lines are for the cases of full systematic uncertainties, and the dashed lines are for the statistical-only case. The 11/12 reactor duty cycle is considered in the conversion of exposure to the data taking time. It can be seen that after 7.1 years of data taking, JUNO can determine the neutrino mass ordering with 3σ significance when NO is true. If IO is true, it is 3.1σ under the same exposure. It is assumed that JUNO and TAO start data-taking at the same time. The right panel shows the sensitivity dependence on the true values of the oscillation parameters, evaluated by shifting the values 3σ (of PDG2020 [13]) from the nominal values. The results are presented for the normal ordering for the exposure needed by JUNO to reach 3σ sensitivity.

arXiv:2405.18008v1

Sensitivities from future experiments - DUNE

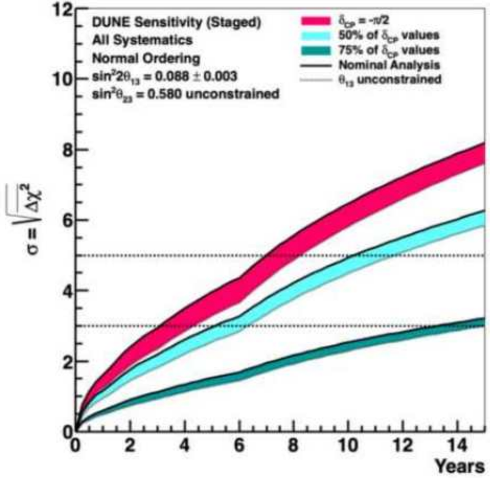
Mass Ordering Sensitivity



- 5σ sensitivty after 2 years of running

020 JINST 15 T08008

CP violation Sensitivity



- 5 σ sensitivity after 10 years of running for 50% of δ_{CP} values