APPROVED

Hyper-K: A new era of precision in neutrino physics

Hyper-Kamiokande

NExT Workshop

29 April 2020

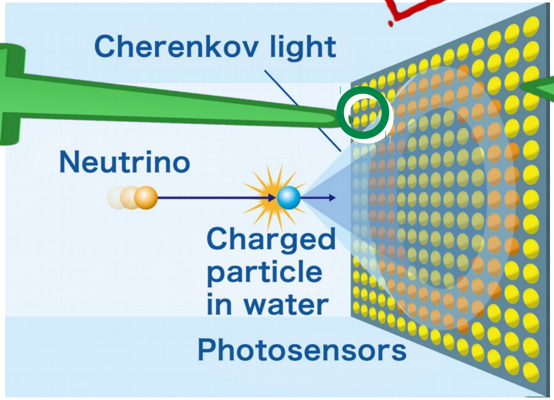
KING'S College LONDON

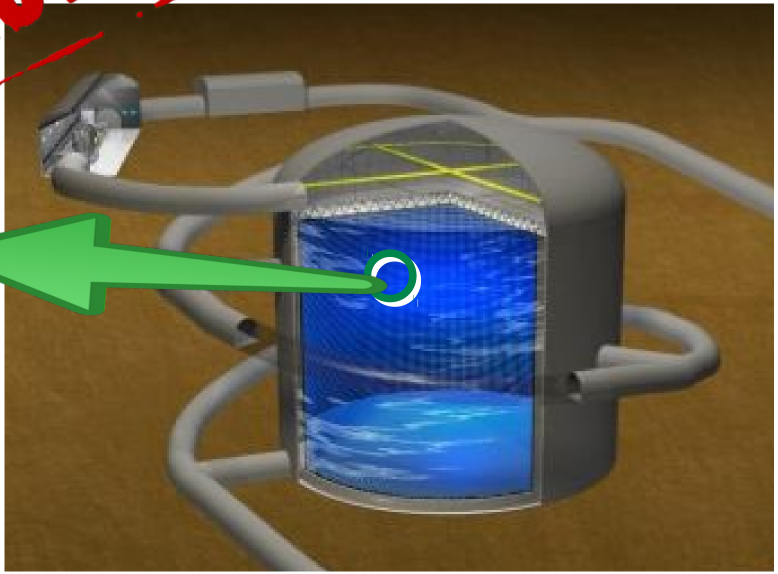
Sophie King

The Hyper-K Detector

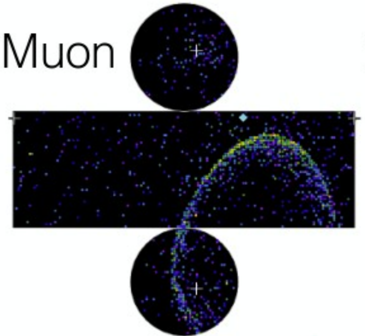
Water Cherenkov detector

Photomultiplier tube
(PMT)

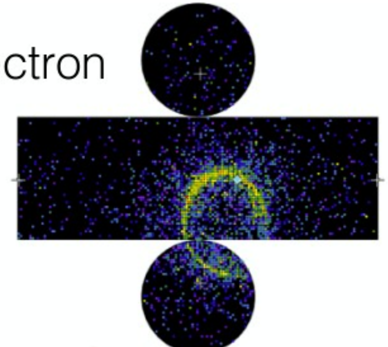




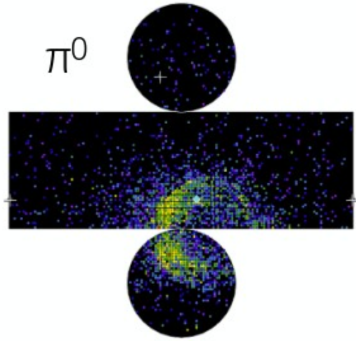
Muon



Electron



π^0



Hyper-K will begin taking data in 2027

The Hyper-K Detector

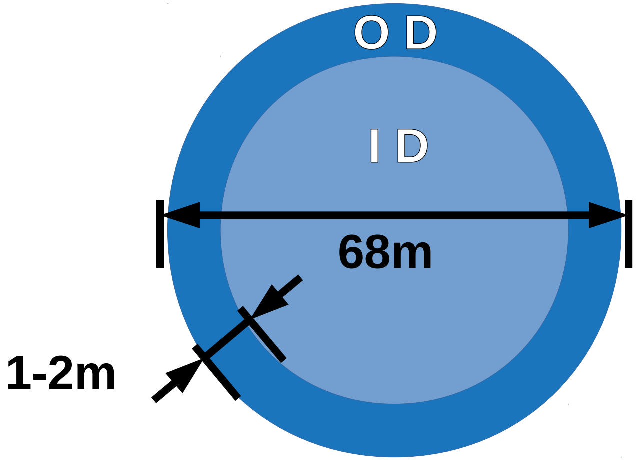
Inner detector (ID):

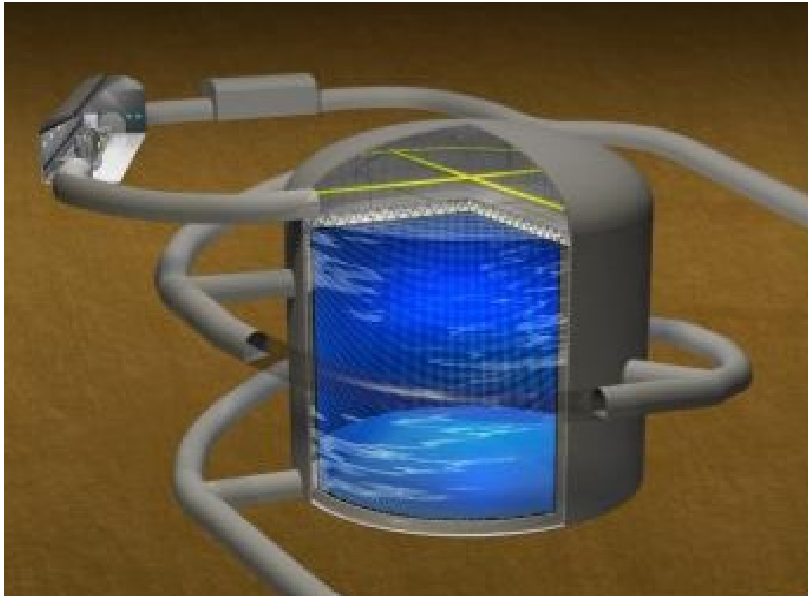
* 216 kton

Outer detector (OD):

* 1-2m thick round the edge

* veto region (incoming/outgoing particles)





Height = 71m,   Diameter = 68m

Volume: 258kton

PMT Photosensors

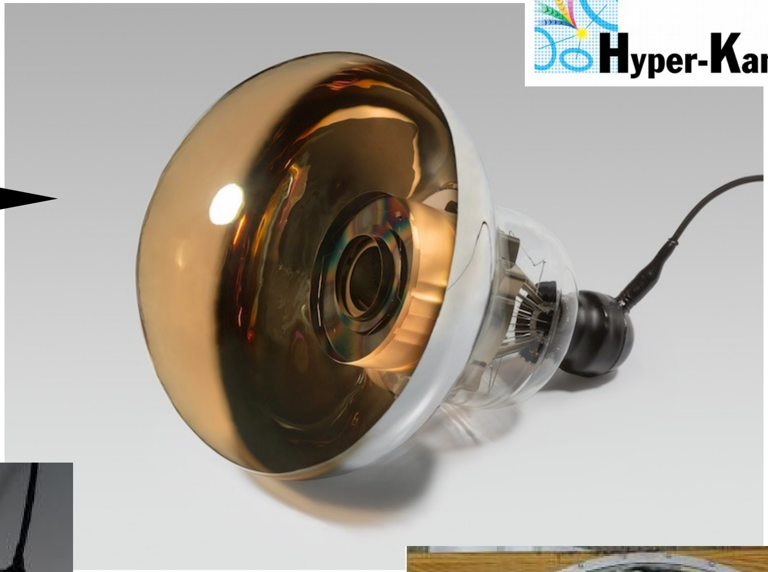
50cm PMTs

- 2.6 ns timing resolution

Inner detector (ID)

Up to 40,000 * 50cm PMTs

→ up to 40% coverage



8cm PMTs

Outer detector (OD)

13,300 * 8cm PMTs

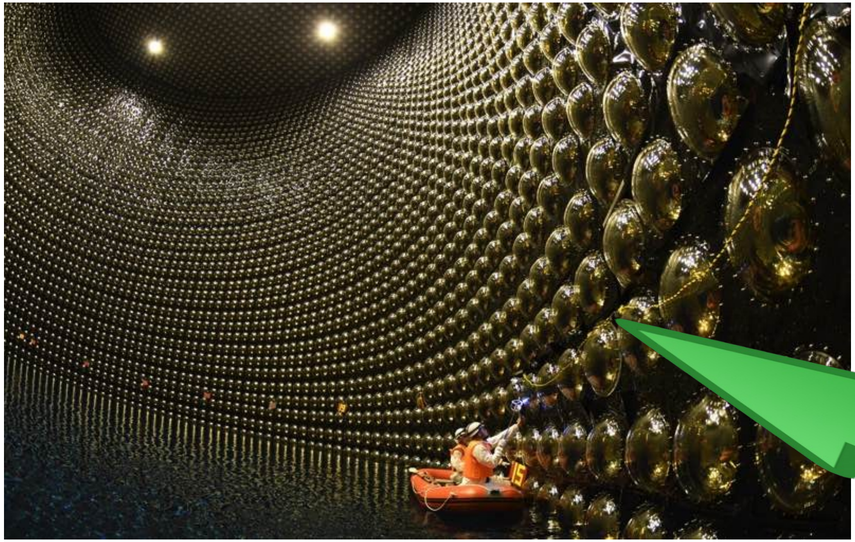
Multi-PMTs (mPMTs)

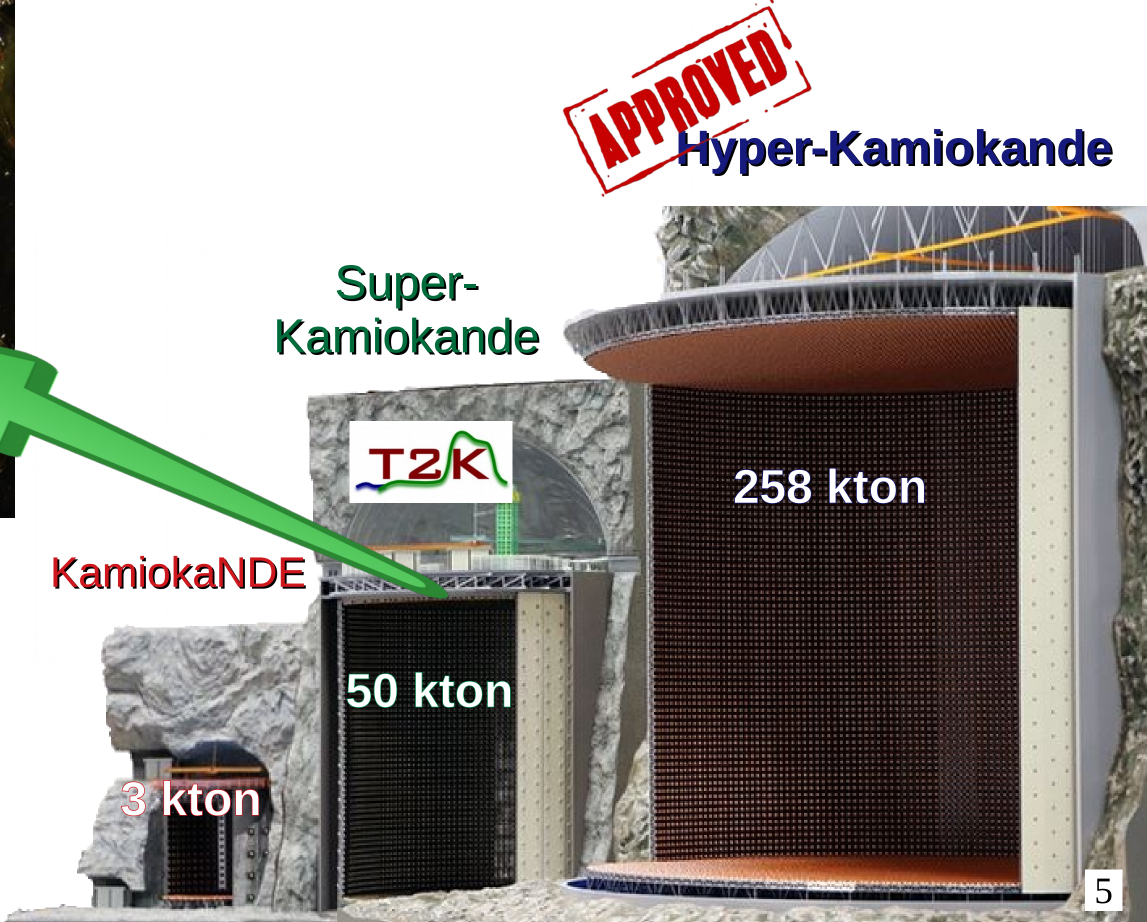
- 19 x 8cm PMTs inside single pressure vessel
- directional information and improved timing and spatial resolutions

Inner detector (ID)

Considering adding up to 10,000 mPMTs to ID

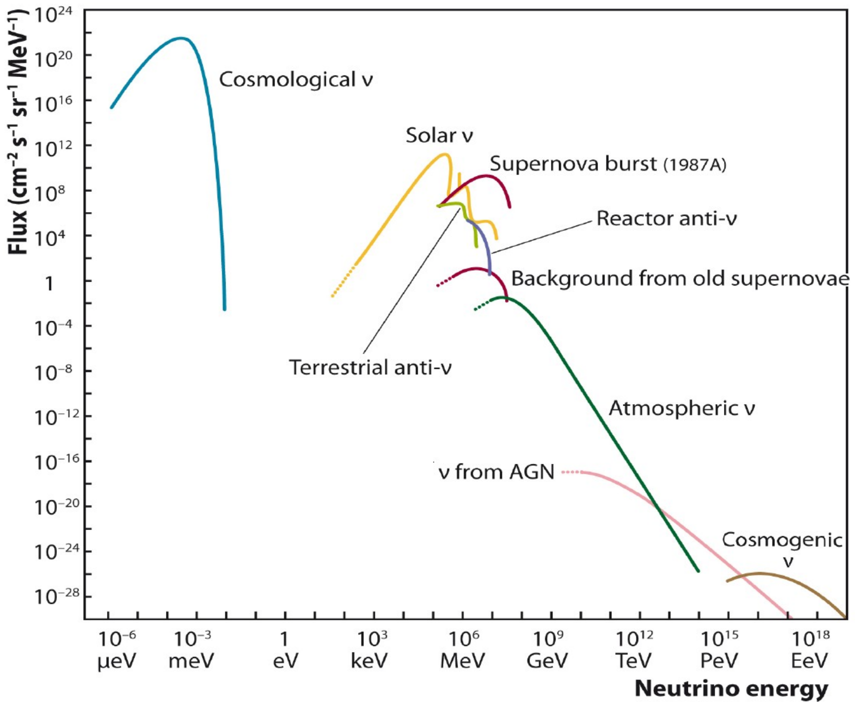
The Kamiokande Series





The Kamiokande Series

* Proton decay
* Solar, supernova and atmospheric neutrinos
* Accelerator beam neutrinos



Hyper-Kamiokande Physics

* Neutrino Oscillations
  - beam, atmospheric, solar neutrinos
  - BSM (sterile searches, non-standard interactions etc.)

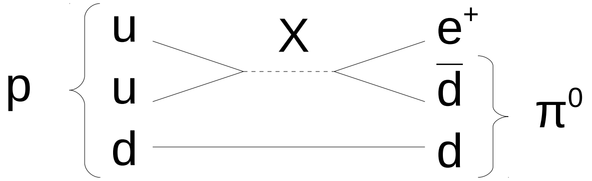
* Astrophysics
  - solar neutrinos, supernova neutrinos
  - dark matter, gravitational-wave sources
  - gamma-ray sources

* Nuclear physics
  - neutrino interactions

* Geophysics
  - matter effect on oscillations
  - electron density of Earths outer core

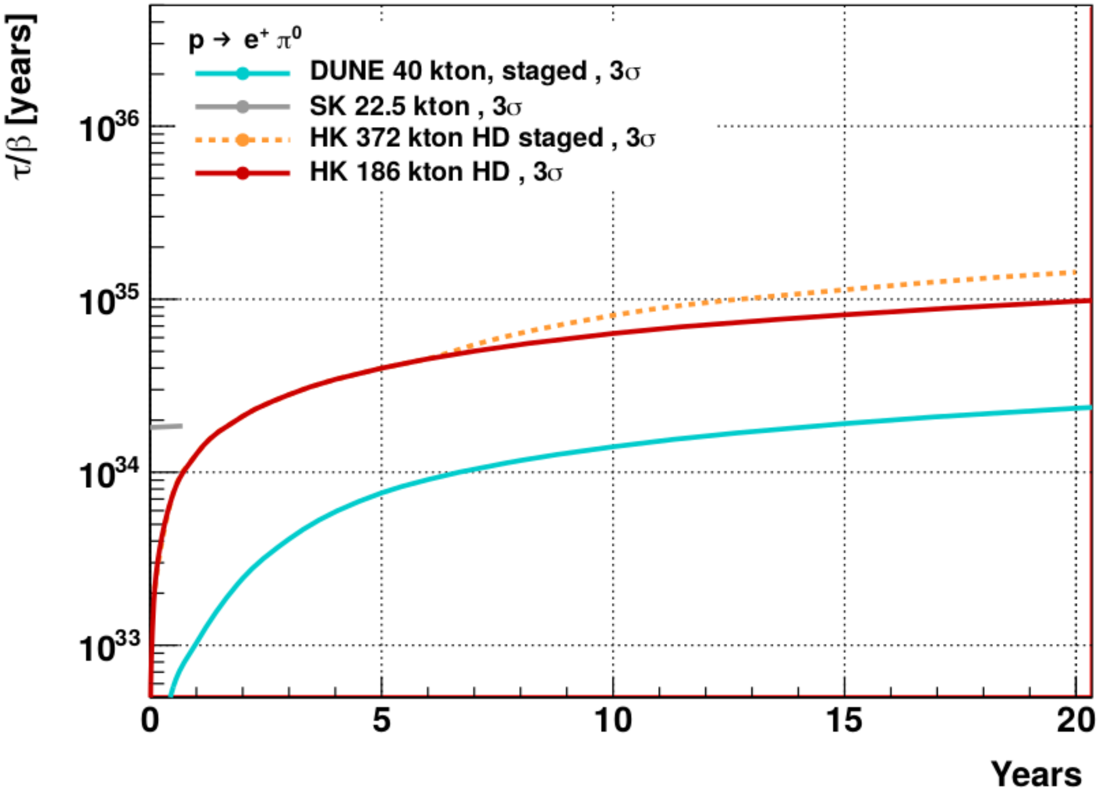
Proton Decay

Proton decay



HK can improve the SK limit on

this process from 10^{34} to 10^{35} years



Can also constrain

$p \rightarrow K^{+} \nu$

* Harder to identify

- due to atmospheric neutrino background

Neutrino Oscillations

Neutrino Oscillations

Hyper-Kamiokande

Flavour eigenstate: Interact
Mass eigenstate: Propagate

Neutrino oscillation
→ mass states do not align with flavour states
→ non-zero masses

Oscillations governed by PMNS flavour-mass mixing matrix, U

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavour states

Mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric and accelerator}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor and accelerator}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar and reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \sim$: 45°
$|\Delta m_{32}^2| \sim 2.5\mathrm{x}10^{-3}$ eV^2

Reactor and accelerator
$\theta_{13} \sim 8°$
Accelerator only $\delta_{CP} = ??$

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\mathrm{x}10^{-5}$ eV^2

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

$\Delta m^2_{ij} = m^2_i - m^2_j$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

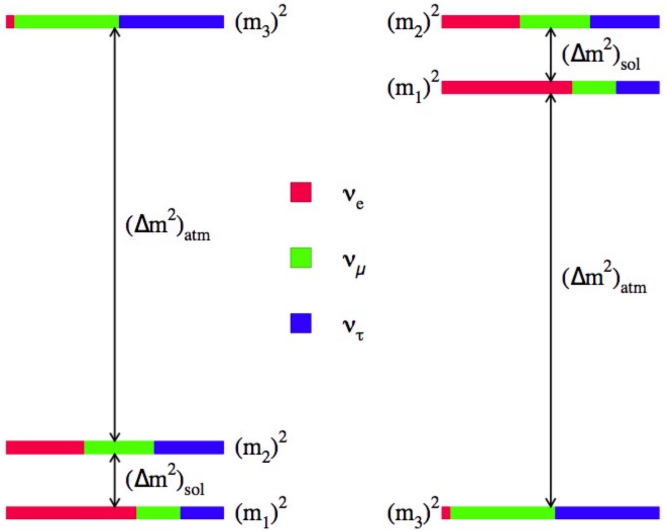
→ **Amplitude** of oscillation: **mixing angles and phase**

→ **Distance** of oscillation: **squared mass differences and Energy**

Neutrino Oscillation Questions

Hyper-Kamiokande

1) Mass Odering (NO or IO)



Normal Ordering (NH) Inverted Ordering (IH)

- Do not know the **ordering of the m_i**
- Is m_3 smaller/bigger than m_1 and m_2 ?

2) CP violation ($\delta_{cp} \neq 0, \pm\pi$)

θ_{13} precisely measured and not too small

→ opens the door for δ_{cp} measurements

$\delta_{cp} = 0, \pm\pi$ → CP conserved: $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$\delta_{cp} \neq 0, \pm\pi$ → **CP violated**: $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Compare oscillation of ν and $\bar{\nu}$ to probe δ_{cp}

3) θ_{23} octant:

$\theta_{23} > \pi/4$

or

$\theta_{23} < \pi/4$

Matter effects! (electrons)

→ difference between ν_e and $\bar{\nu}_e$ as they travel through the earth (similar effect as δ_{cp})

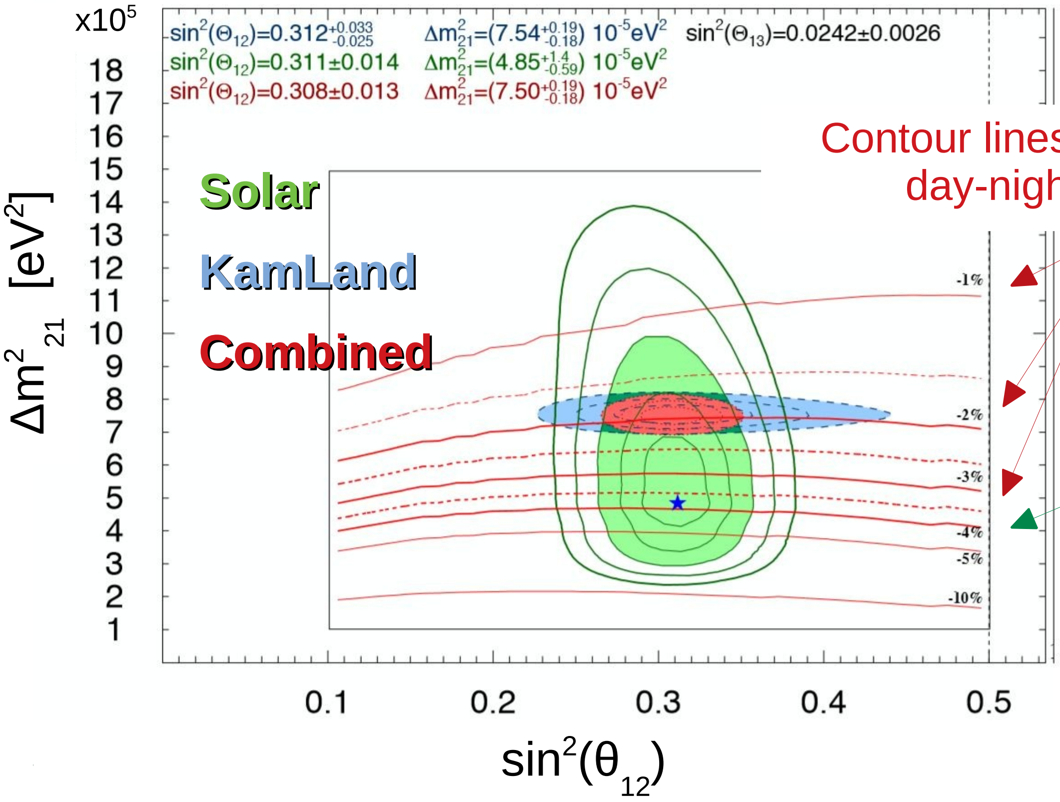
→ allows for mass hierarchy determination

Solar Neutrinos

Solar Neutrinos

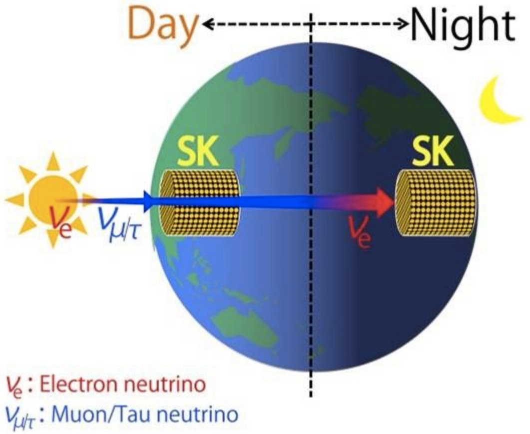
Hyper-Kamiokande

~ 2σ tension in Δm^2_{21} between solar & kamLAND (reactor)



Contour lines of constant day-night asym.

SK best fit 4%



ν_e flux differs between night and day

→ matter effects

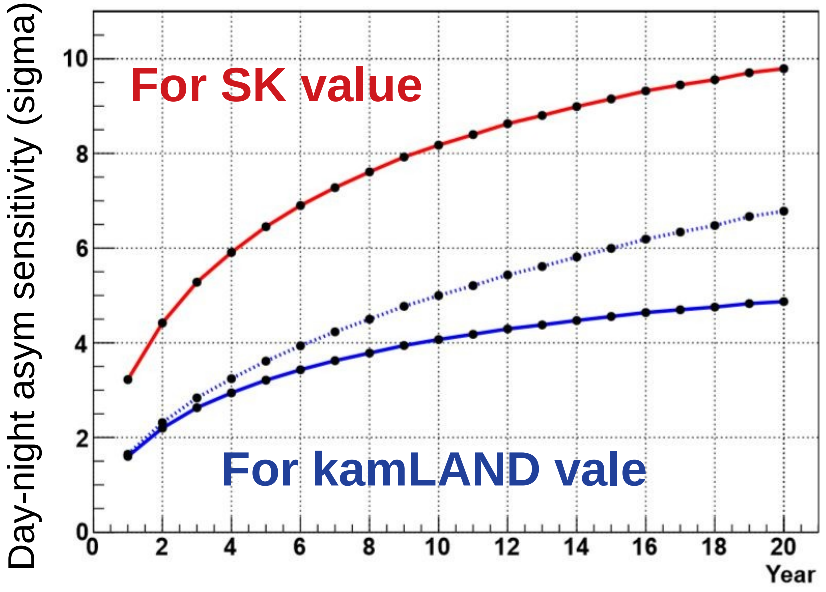
→ *day-night asymmetry*

Day-night asymmetry higher than expected from reactor constraint

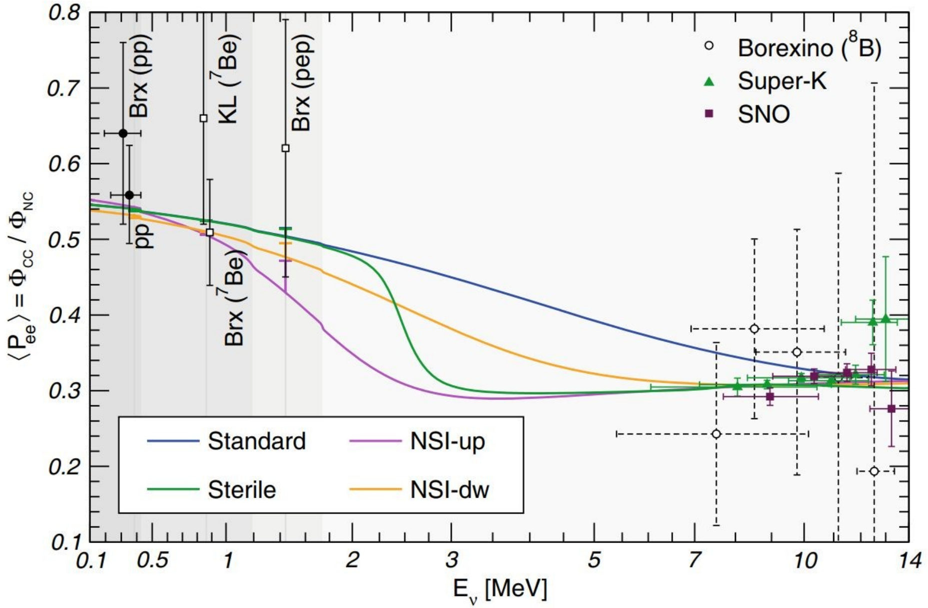
→ contributes to the Δm^2_{21} tension

Solar Neutrinos

Hyper-K can constrain the **Day-Night Asymmetry** (and resolve **Δm^2_{21} tension**)



Hyper-K can constrain the **'upturn'** in the low energy solar neutrino **survival probability**



–> Potential areas for new physics

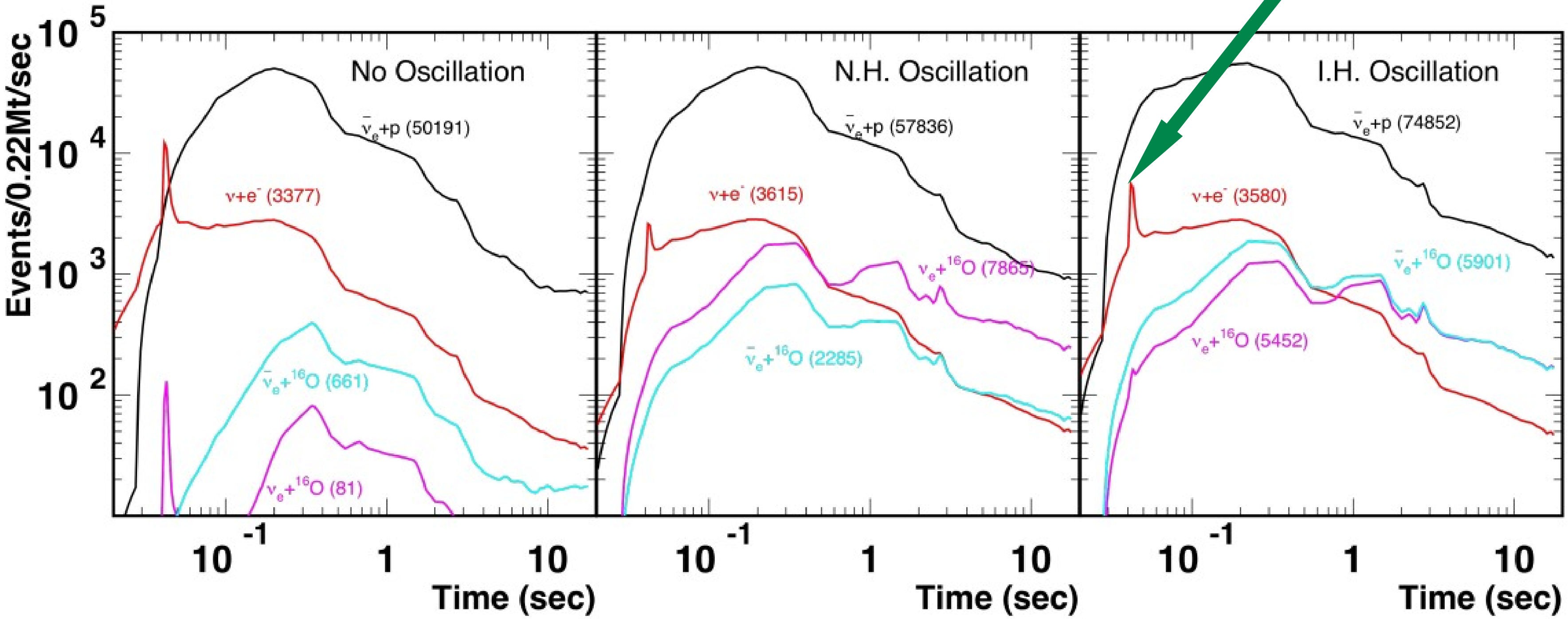
Supernova Neutrinos

Supernova Neutrinos

Expected time profile of a supernova at 10kpc
- numbers in brakcets total interactions integrated over the 10s burst
- peak event rate of inverse beta decay events (black) reaches ~50 kHz

Neutronization peak

Predicted event numbers in HK far detector



Fluxes and energy spectra are from the Livermore simulation

Supernova Neutrinos

Inverse beta decay dominates

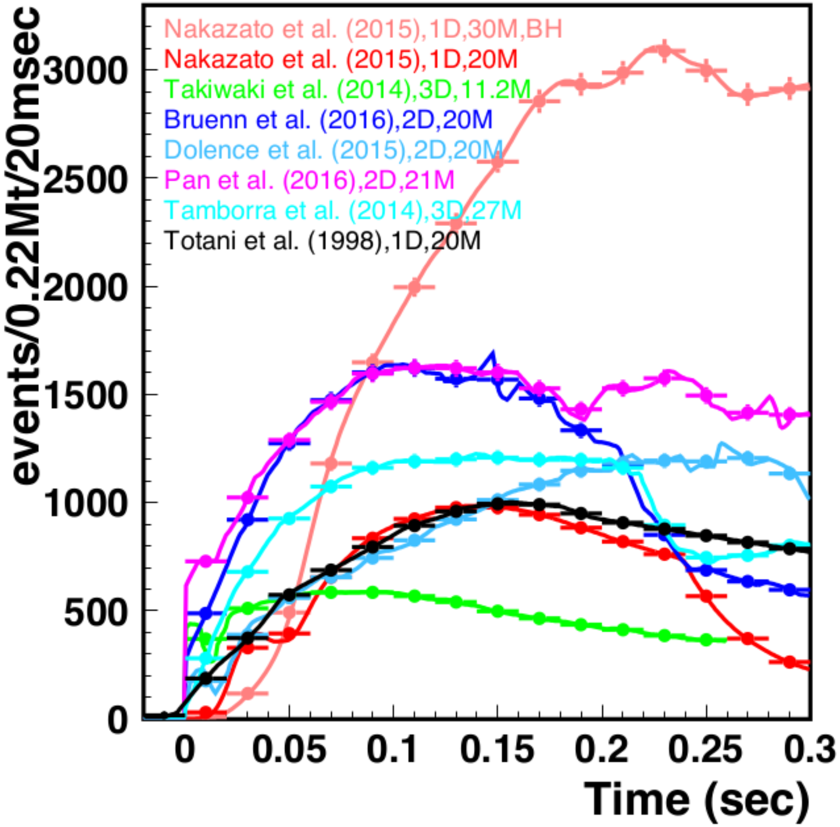
$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

Different models predict different electron antineutrino rates

→ Hyper-K can constrain different models

→ Stat error is much smaller than the difference between models

Predicted inverse beta decay rates



Beam neutrinos
Long-base neutrino oscillations

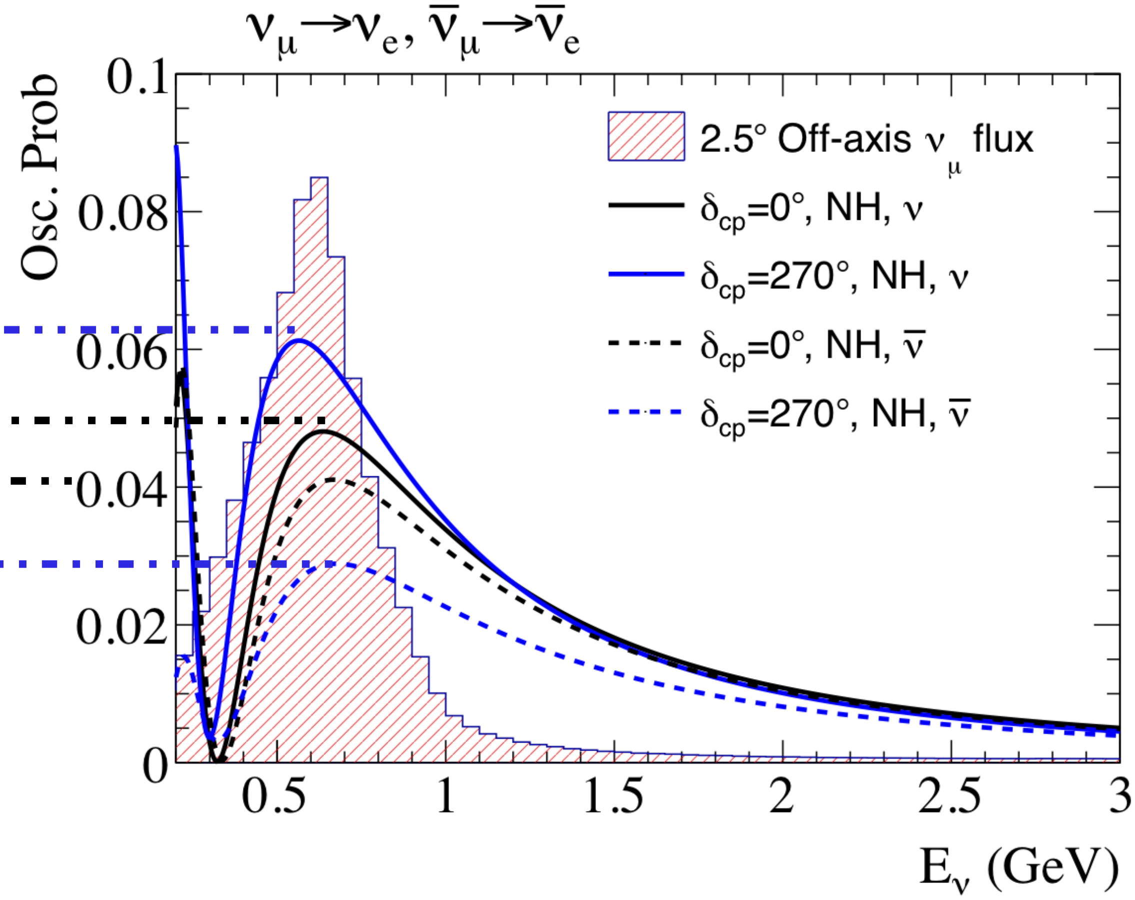
ν_e ($\bar{\nu}_e$) appearance

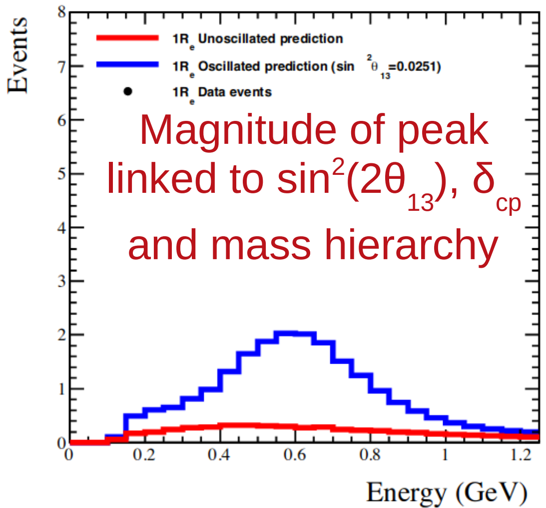
Oscillation peak causes peak in
ν_e ($\bar{\nu}_e$) observed at SK

sensitive to $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$

Maximum possible δ_{cp} effect ~30%

Matter effect





Magnitude of peak linked to $\sin^2(2\theta_{13})$, δ_{cp} and mass hierarchy

Test CP symmetry

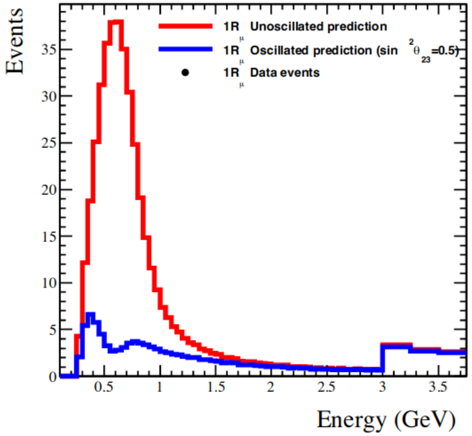
ν_μ ($\bar{\nu}_\mu$) disappearance

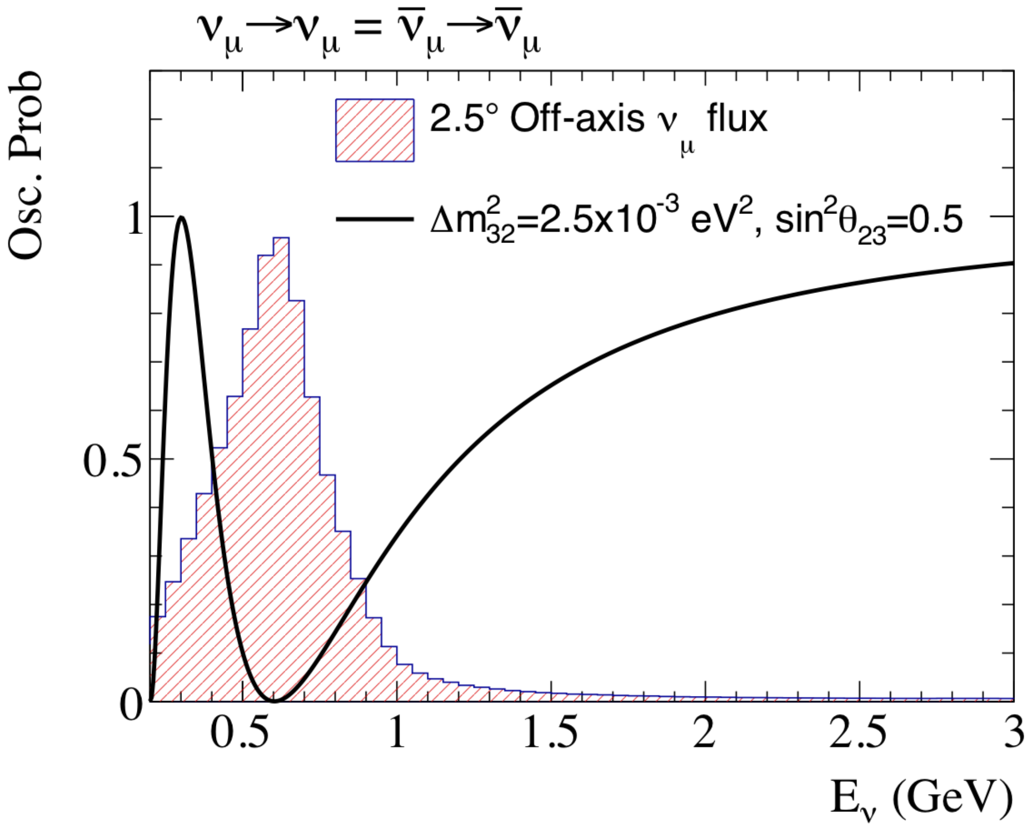
Probability minimum causes a dip in the number of ν_μ observed at SK

Depth of dip – $\sin^2(\theta_{23})$

Energy of dip – $|\Delta m^2_{32}|$ ($|\Delta m^2_{13}|$)

Hard to distinguish mass ordering





Test CPT symmetry

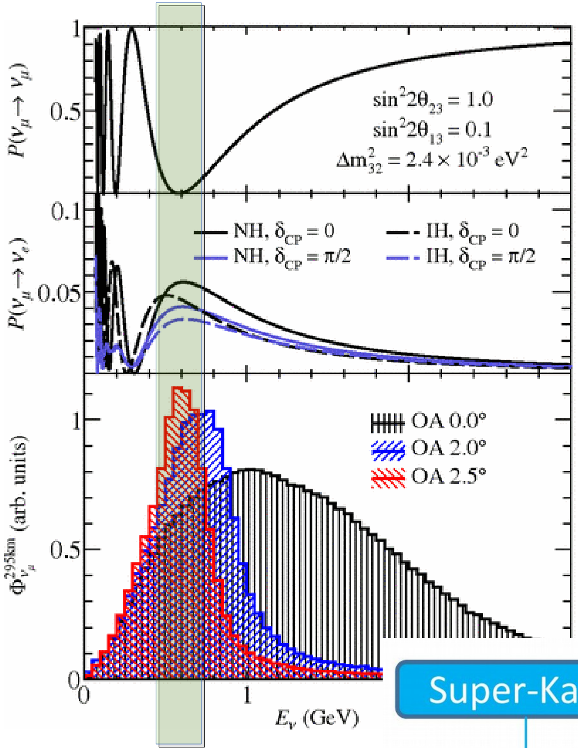
The T2K Experiment

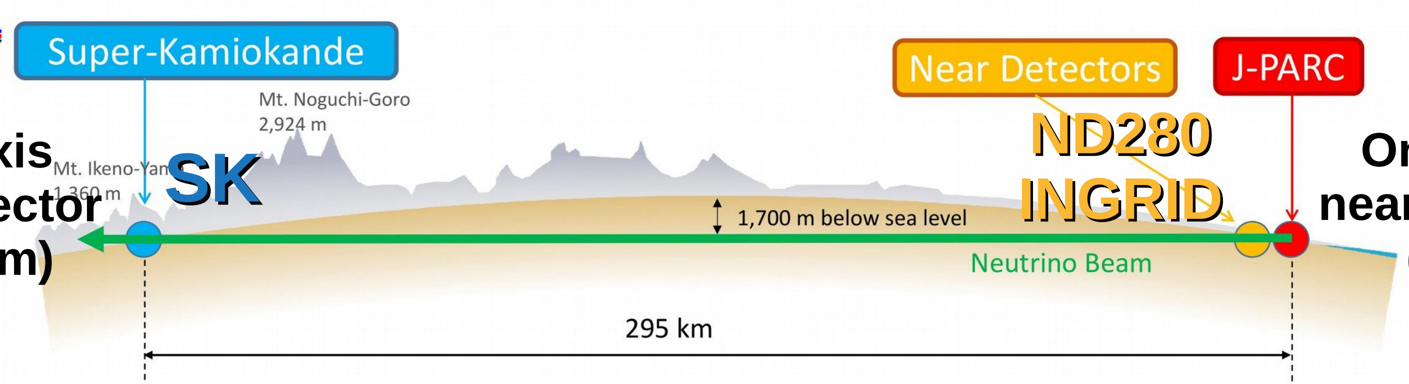
* Long-baseline neutrino oscillation experiment

* High intensity neutrino beam, predominantly ν_μ ($\bar{\nu}_\mu$)

* Near detectors constrain uncertainty on flux and neutrino interaction models

→ reduces the error on SK results

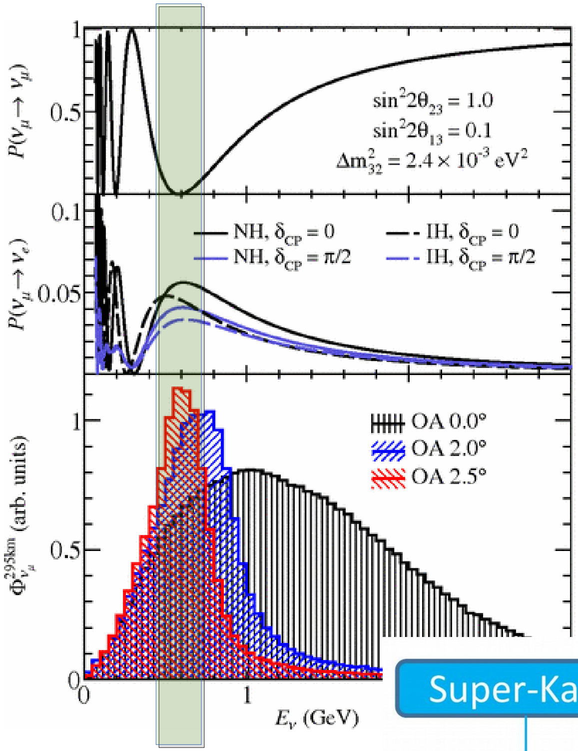


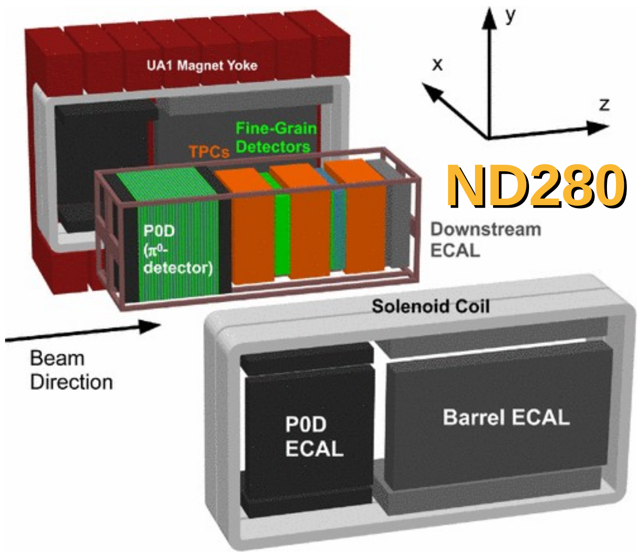


Off-axis
far detector
(295 km)

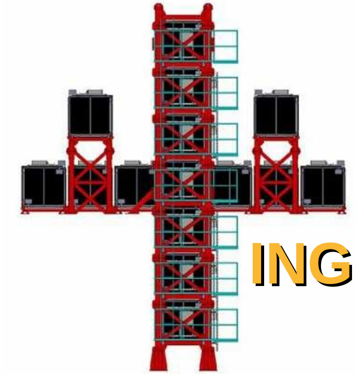
On/Off-axis
near detectors
(280m)

The T2K Experiment

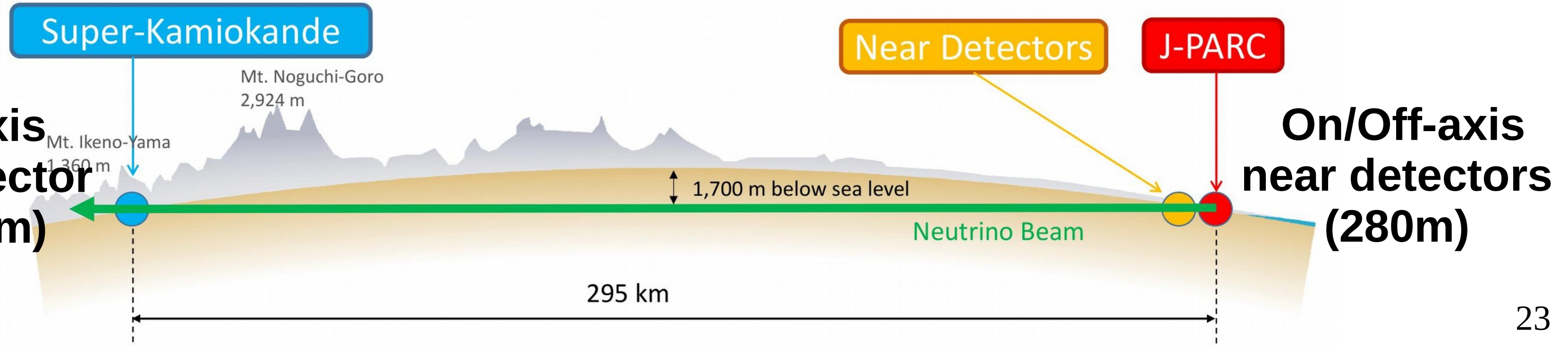




ND280



INGRID



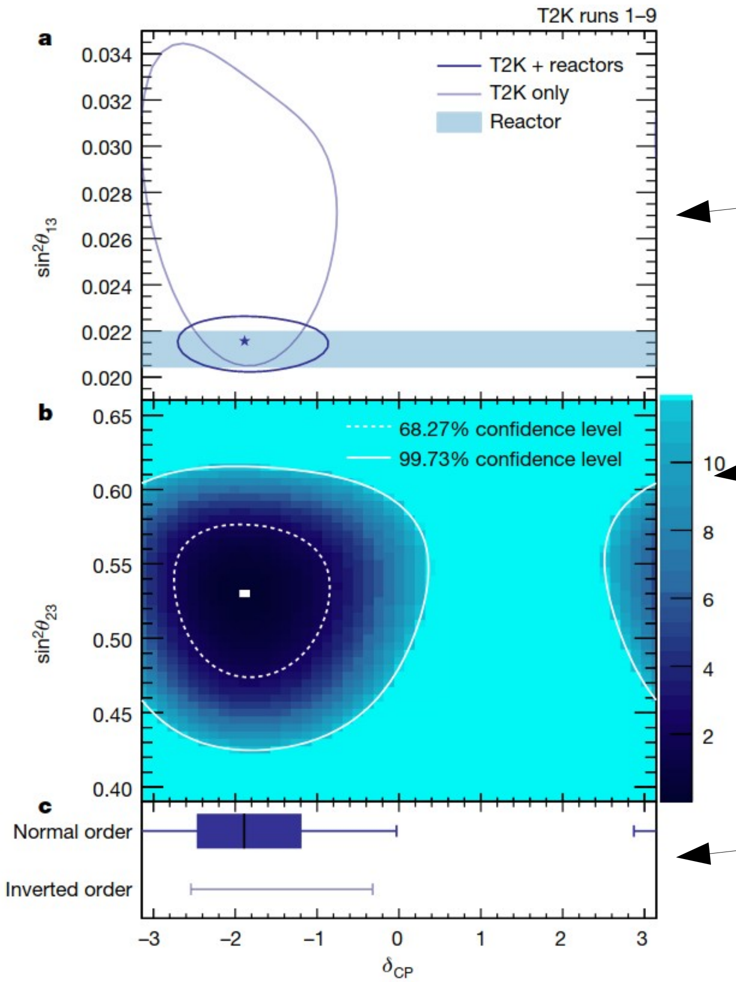
Off-axis far detector (295 km)

On/Off-axis near detectors (280m)

Recent T2K results

T2K 2020 Nature paper:

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



1 sigma
confidence intervals
for NO case

1 and 3 sigma
confidence intervals
for NO case
Includes reactor constraint

1 and 3 sigma
confidence intervals

* Joint fit between
ν-beam and $\bar{\nu}$-beam data

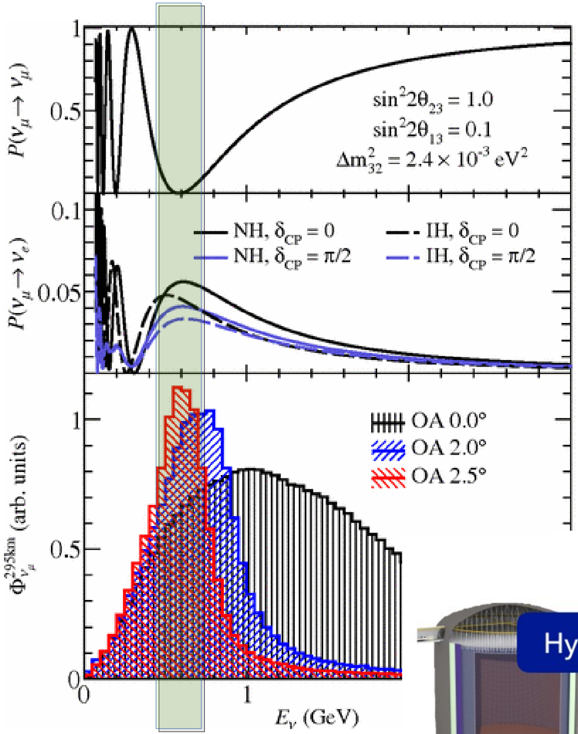
* Near detector constraints
are applied

Normal Ordering preferred

Best fit value of δ_{cp} close to maximal (-π/2)

CP conserving values of δ_{cp} ruled out at 95% confidence level

Hyper-Kamiokande long-baseline

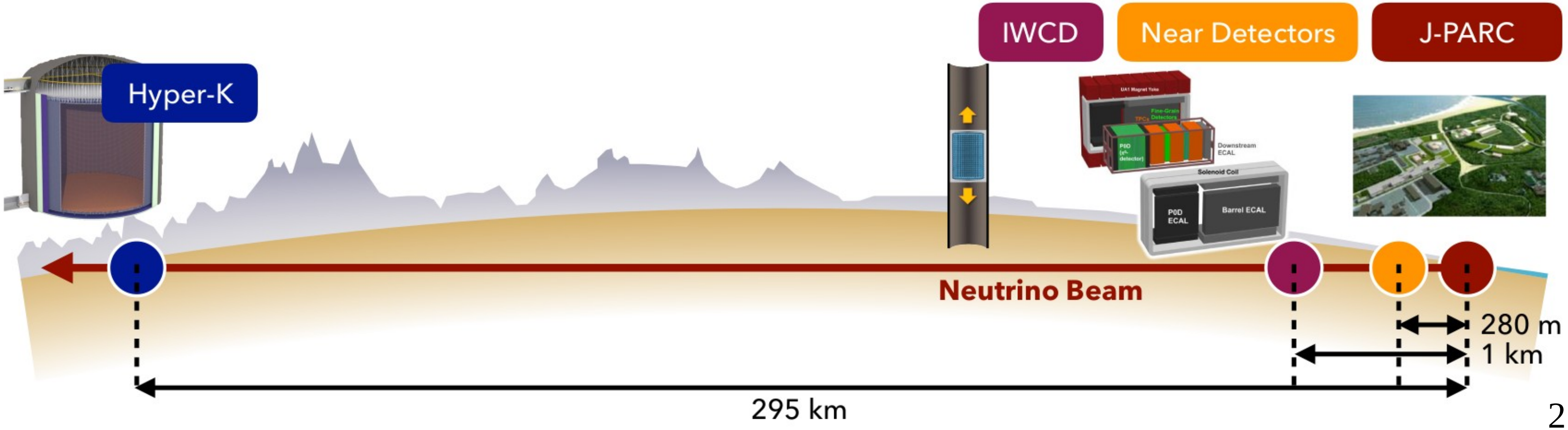


* Upgrade T2K beam

* Upgrade ND280

*** New intermediate water Cherenkov detector**

* Hyper-K far detector



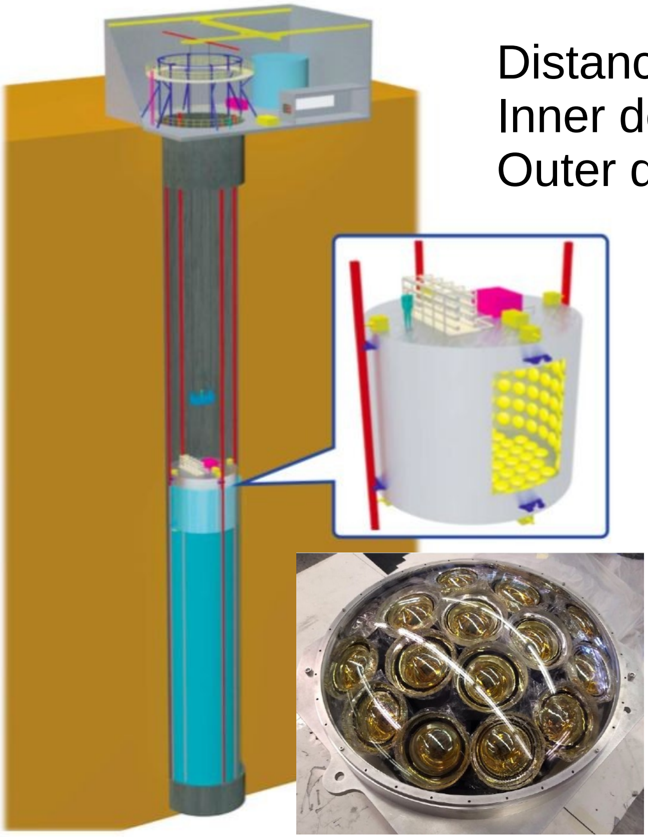
HK at same dist and off-axis angle as SK

Intermediate water Cherenkov detector (IWCD)

*** Constrain flux and neutrino interactions**
*** Same target as far detector**

Distance: 0.75 – 2 km
Inner detector: Diameter = 8m, height = 6m
Outer detector: 1m wide all around

Gadolinium doping:
0.1% Gd
→ Neutron tagging

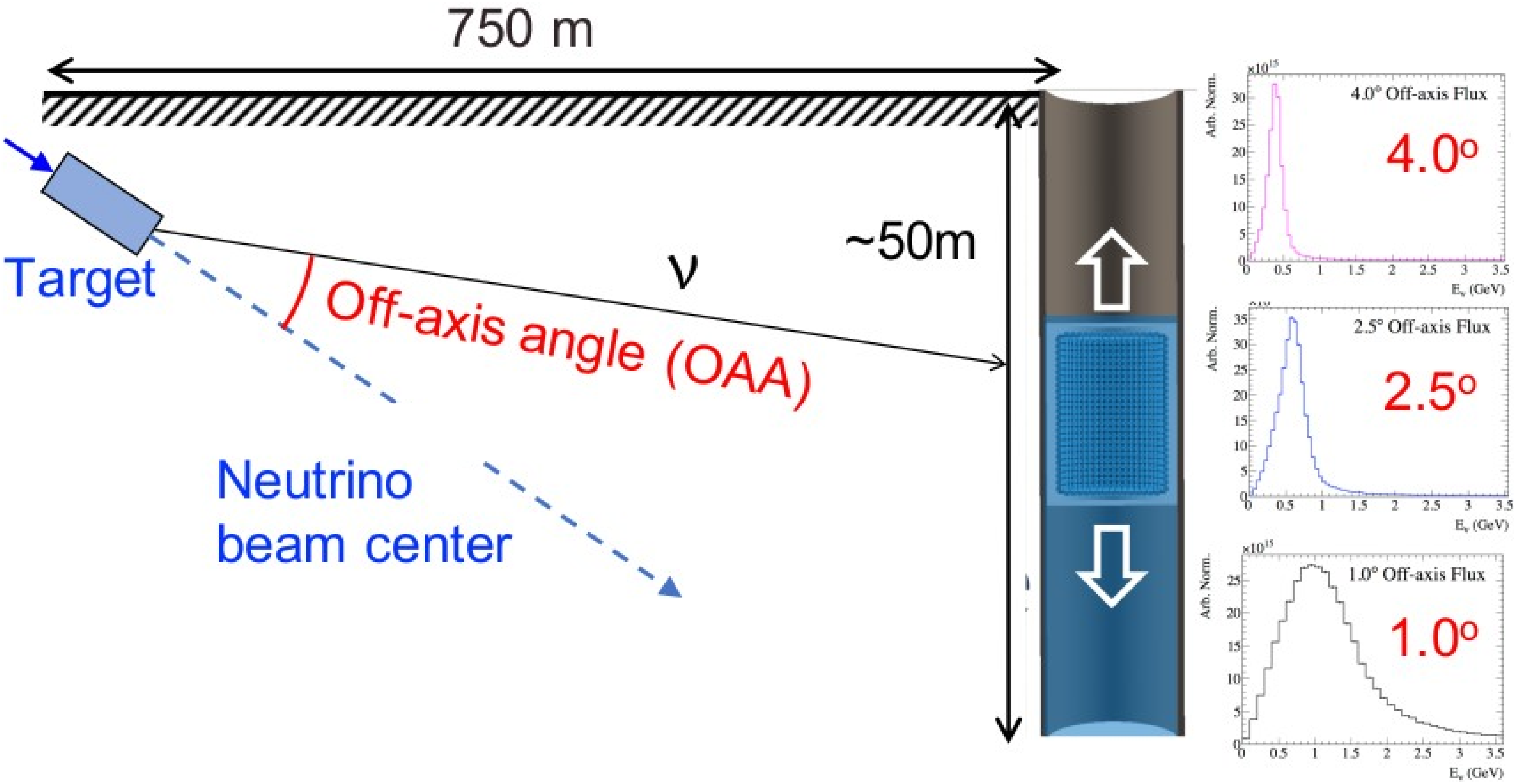


Size optimised to contain 1GeV muons,
while minimizing beam pile up events

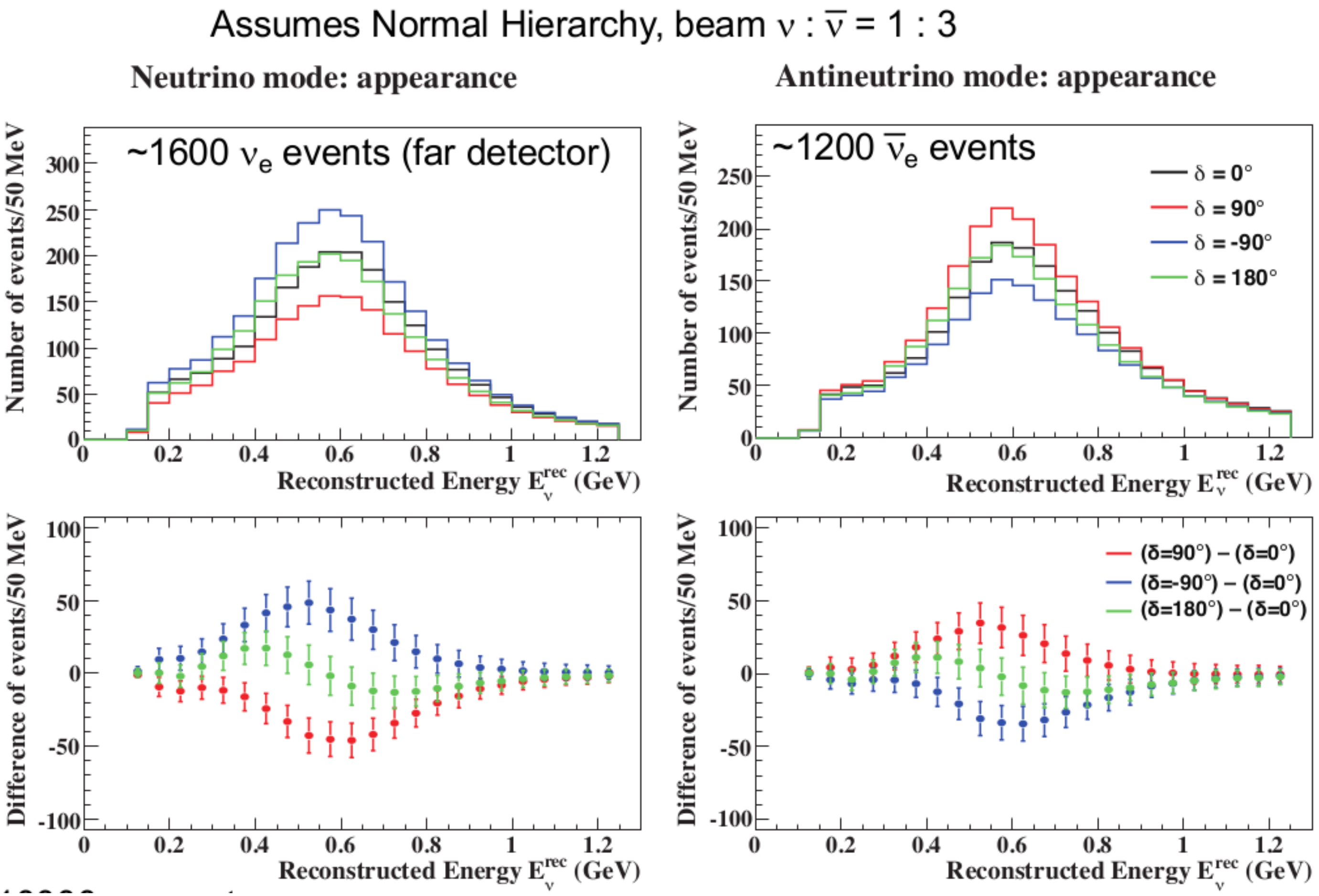
Vertical pit: ~ 50 – 100 m, detector moves up and down
→ samples flux at different angles
→ sample flux with different energy peaks/profiles

Multi-PMTs
* better timing and spatial resolution
→ good reconstruction despite small detector

Intermediate water Cherenkov detector



Hyper-Kamiokande long-baseline



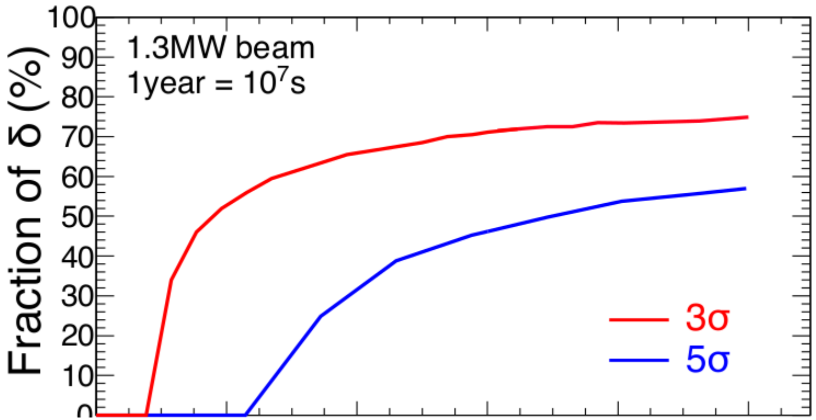
Predicted HK far detector event yields for 10 years of operation

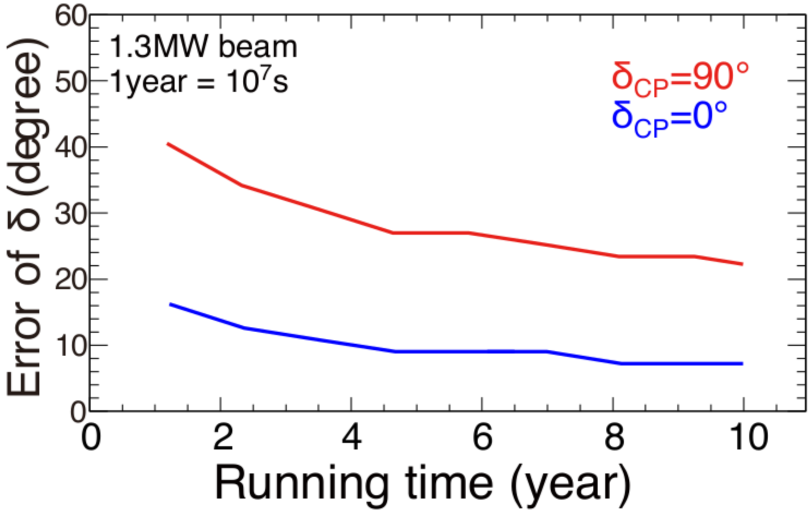
For different values of deltaCP

$\nu : \bar{\nu} = 1 : 3$

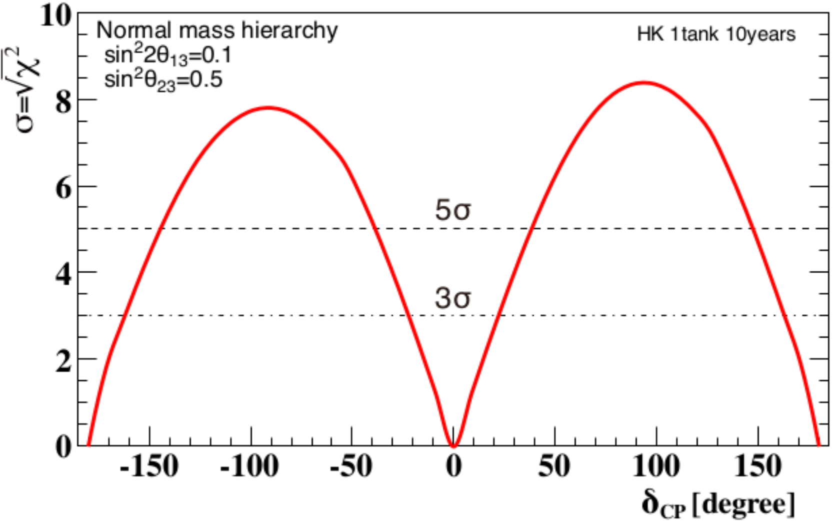
Run mode chosen to optimise deltaCP sensitivity

Hyper-Kamiokande long-baseline





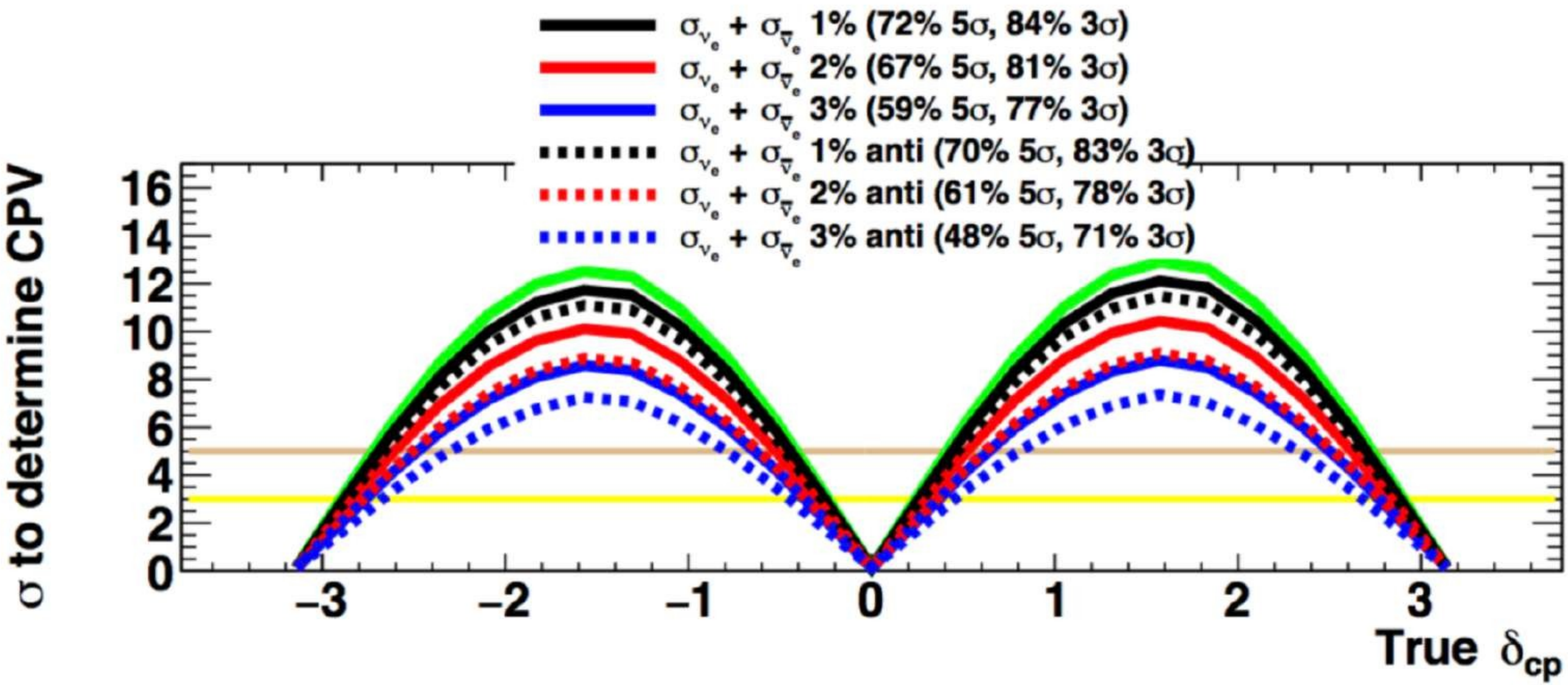
Fraction of δ_{cp} for which $\delta_{cp} = 0$ can be excluded



Significance to exclude dCP = 0
(i.e. exclude CP conservation)

Note: These plots assume that the mass ordering is NO and known

Hyper-Kamiokande long-baseline

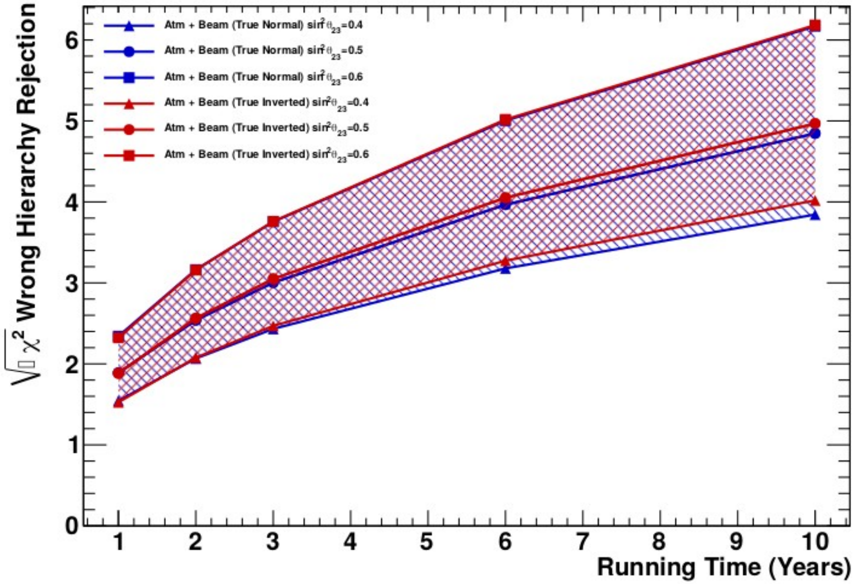


Minimizing **systematics errors** is very important!

→ Near/intermediate detectors play a vital role in constraining the errors

Atmospheric neutrinos (+ beam)

Sensitivity to mass ordering



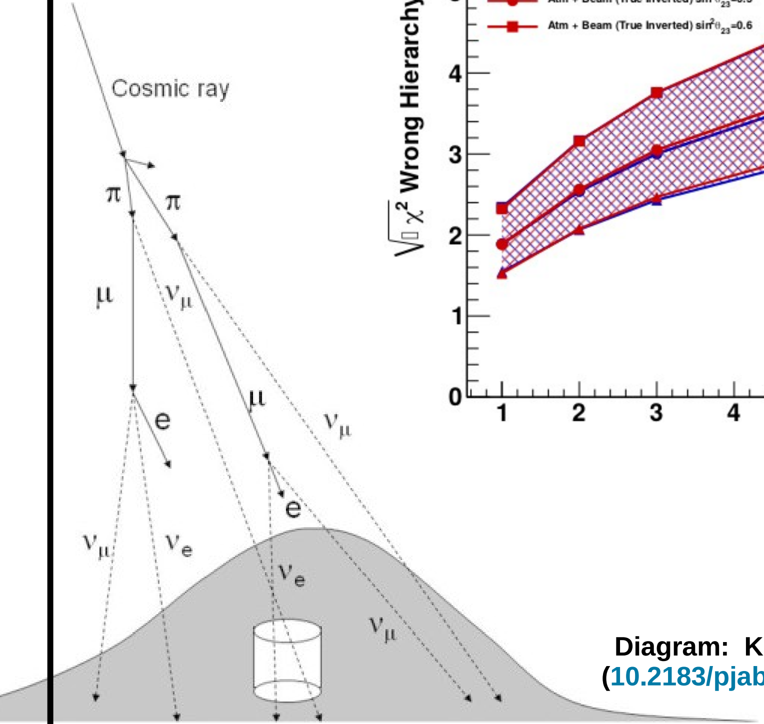


Diagram: Kajita T.
(10.2183/pjab.86.303)

Atmospheric neutrinos sensitive to matter effects as they travel through the Earth

→ Sensitive to mass ordering

Combined fit of
atmospheric data + beam data
Gives the best sensitivity to mass ordering

Note: atmospheric is also sensitive to theta23 octant

(and limited sensitivity to deltaCP)

Summary

Summary

The Hyper-Kamiokande is a next-generation neutrino experiment

* Builds on the expertise and knowledge gained from Super-K
* Bigger and better than SK
  - Fiducial volume 8 times larger than SK
  - Improved photosensors
  - beam upgrade to 1.3 MV
  - New intermediate water Cherenkov detector and upgraded near detectors

Wide range of physics

* CP violation in the lepton sector
* Nucleon decays
* Astrophysics
* Potential to discover new physics in many areas

Construction, 2020
Data taking, 2027

BACKUP

Backup – Hyper-K

Proton decay

$p \rightarrow K^{+}\nu$

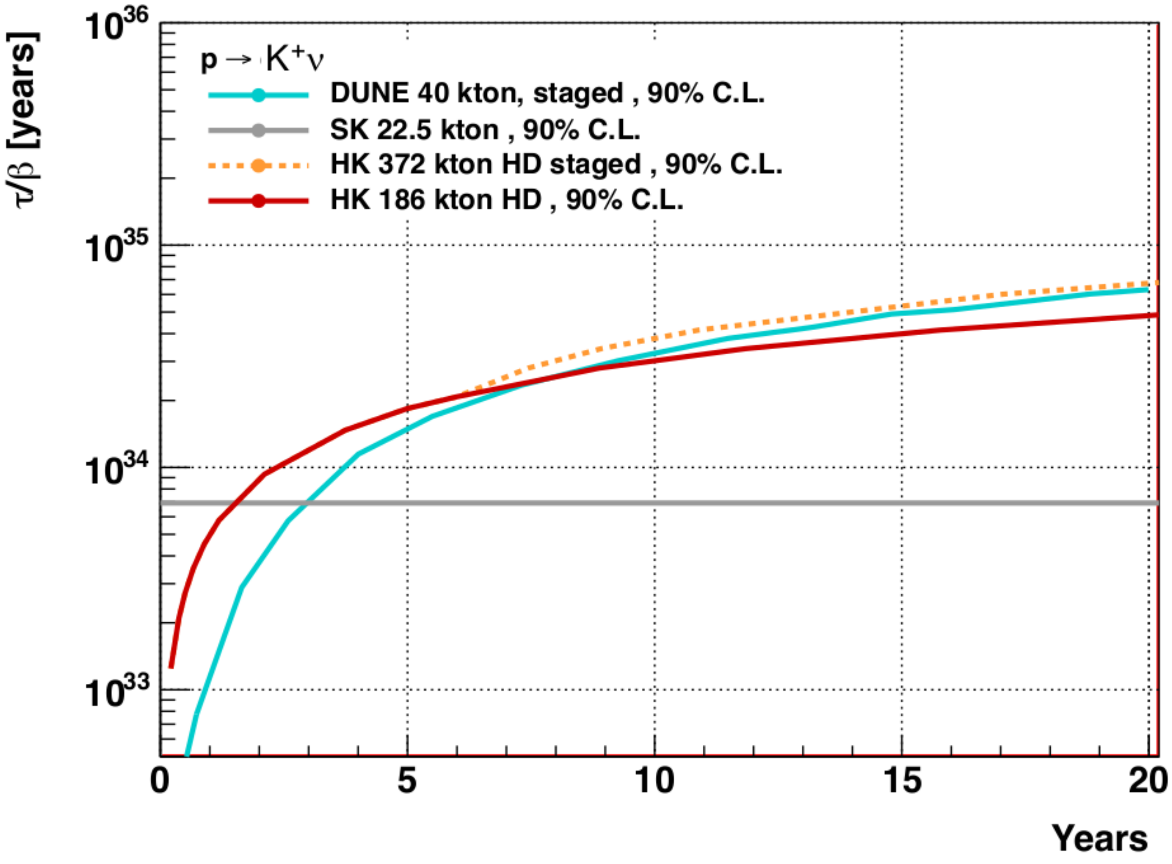
Harder to identify

* atmospheric neutrino background

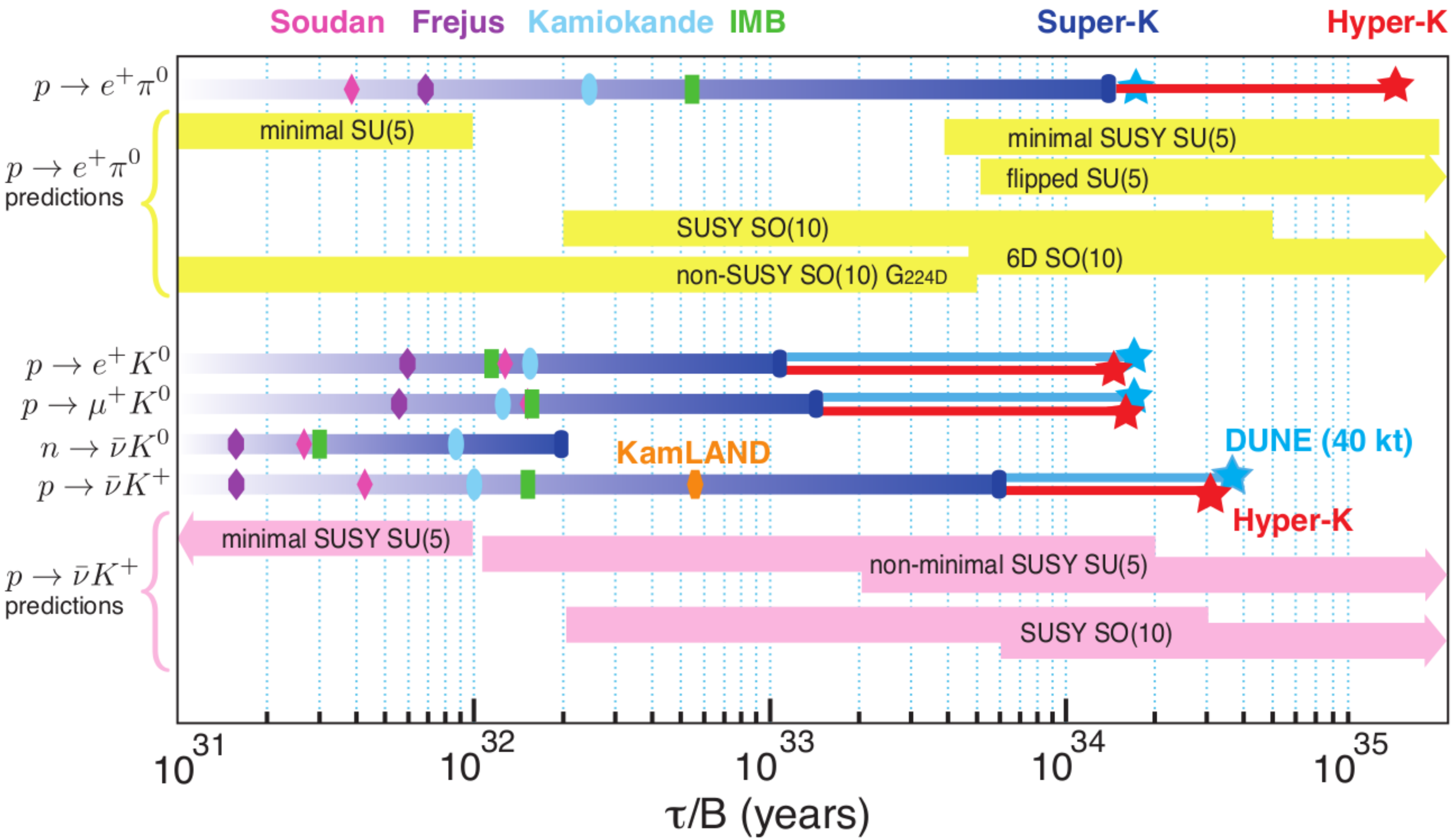
* K+ is below the Cherenkov threshold in water

→ detect mu when it decays

→ detect gamma from transition
16 O → 15 N*



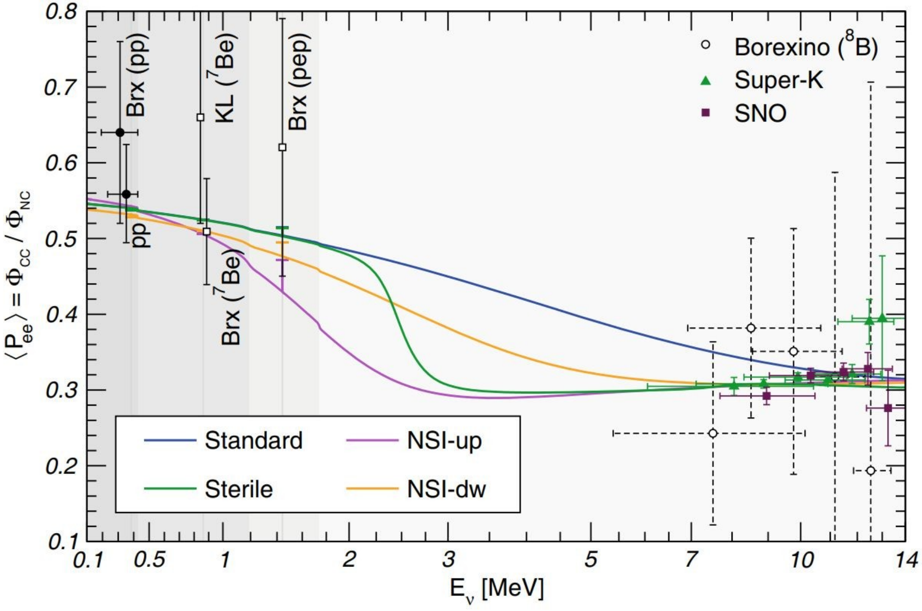
Proton decay



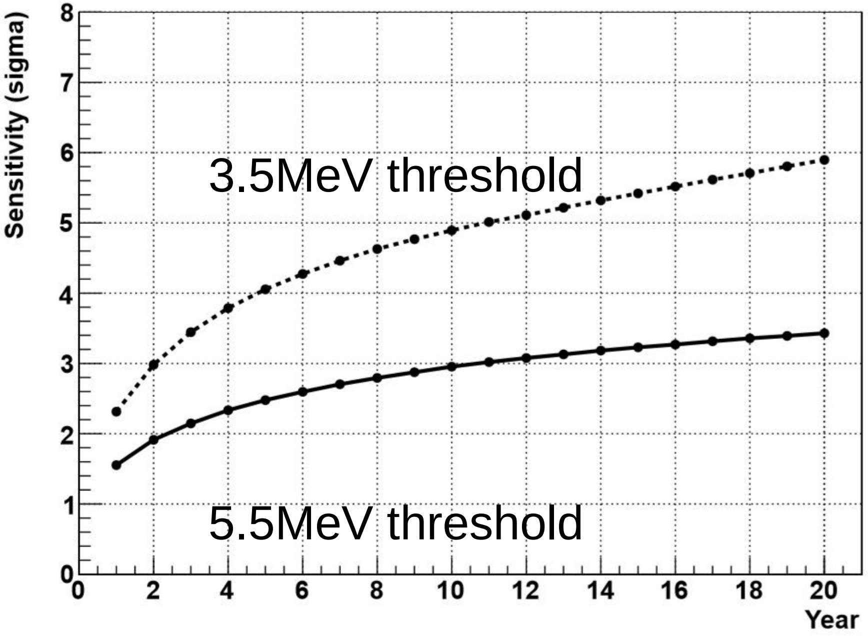
Solar Neutrinos

Hyper-Kamiokande

‘Upturn’: increase in the solar neutrino survival probability at low energy
→ matter effect dominate



M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

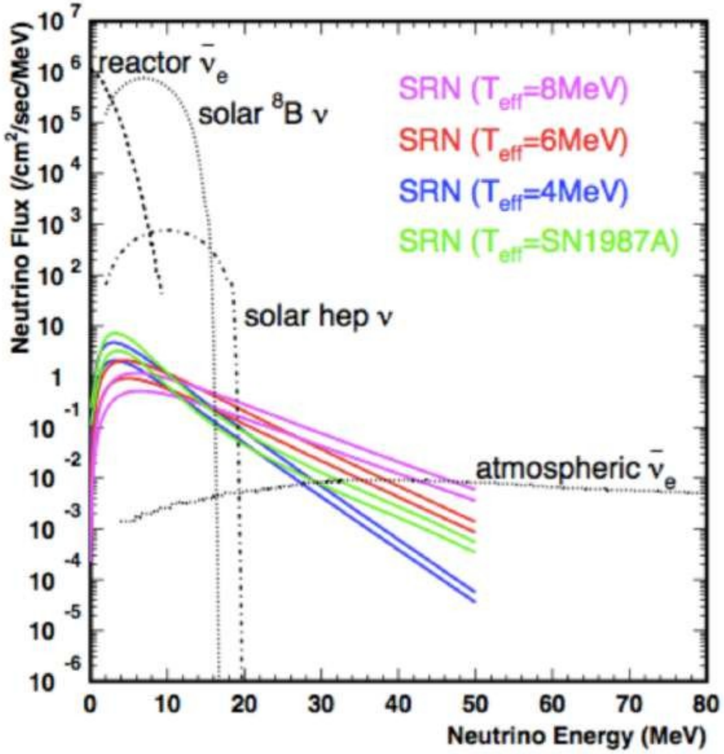


Significance of upturn detection at HK

Supernova Relic Neutrinos

Hyper-Kamiokande

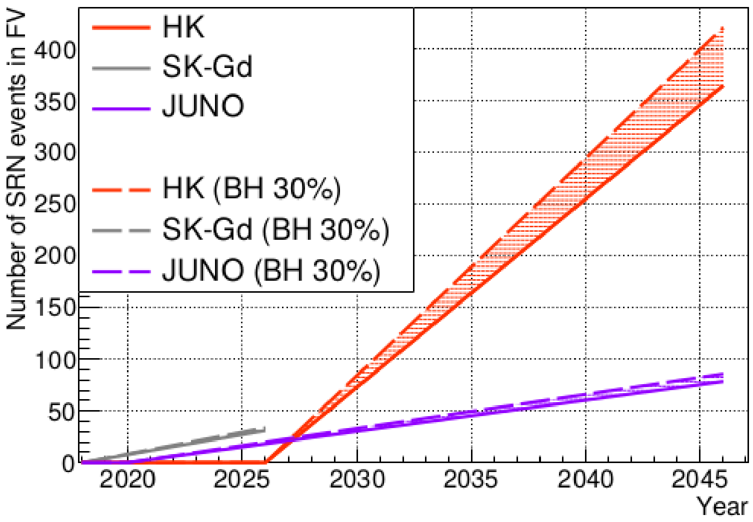
Predicted flux for different models



* Small flux
* Large backgrounds

→ No evidence of supernova relic neutrinos at SK yet

Predicted event numbers

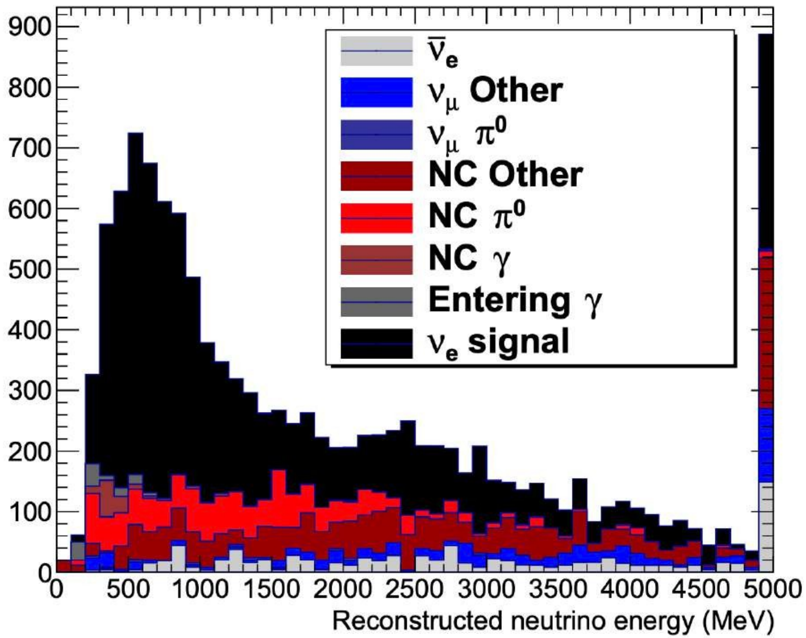


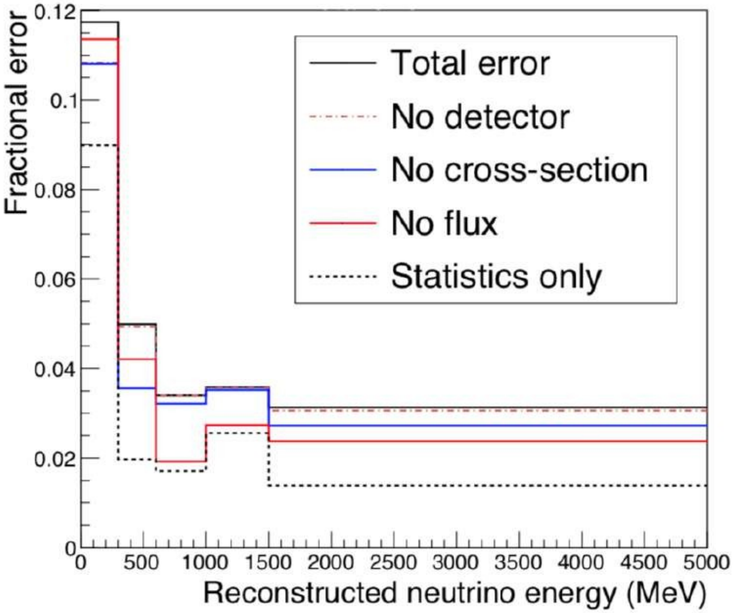
Dashed line for case where 30% form black hole and emit higher energy neutrinos

IWCD: nue cross-section measurement

ν_e selection in the IWCD

IWCD OD helps to reduce the photon background



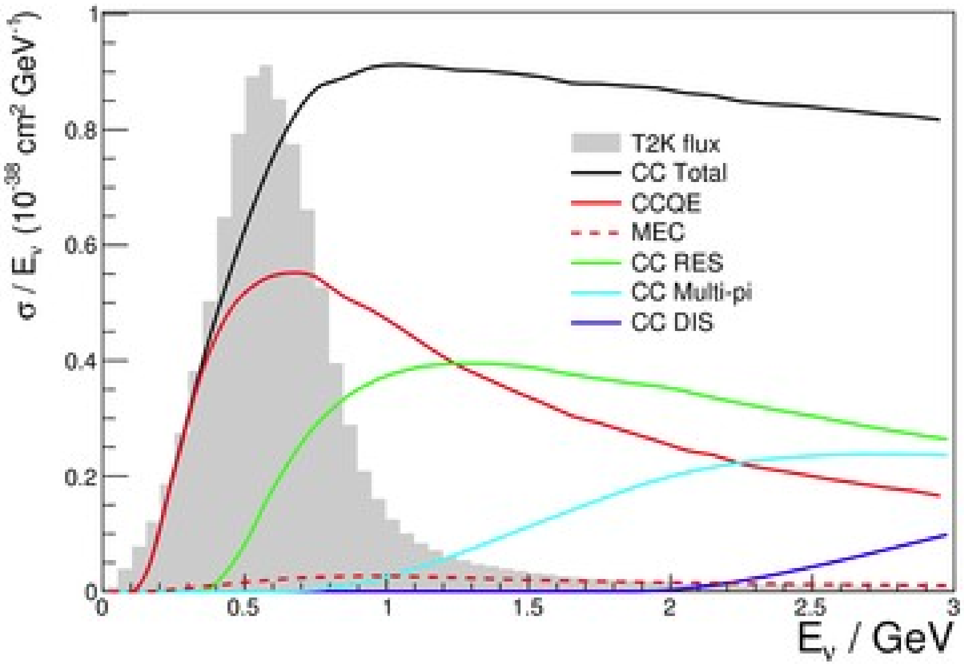


Total error <4% at the relevant momenta for HK

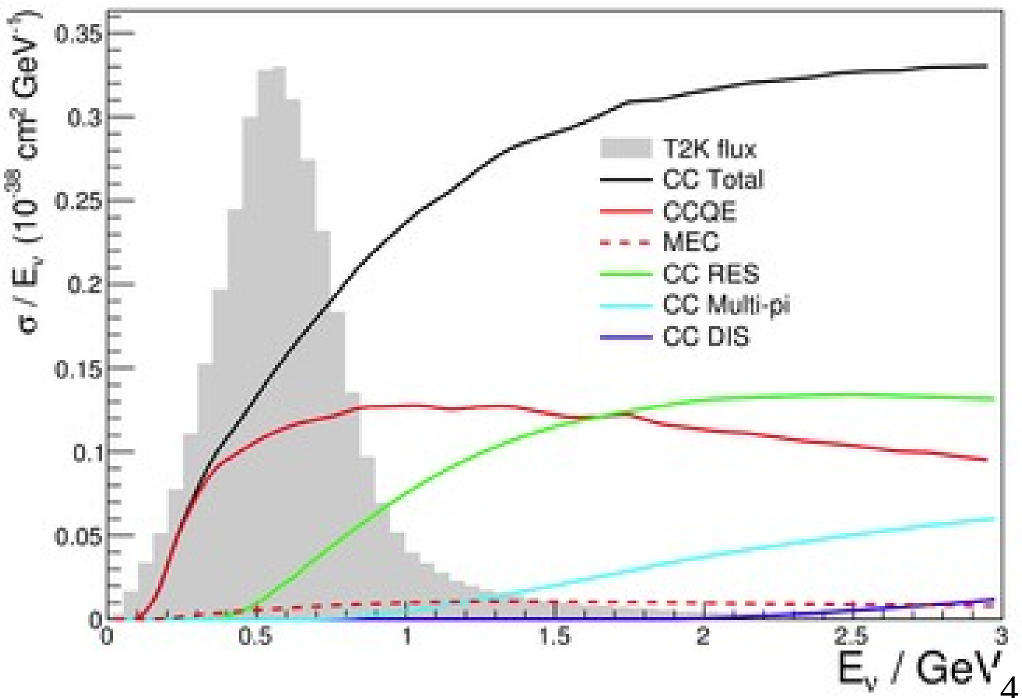
→ expect further improvements due to reductions in flux and xs errors

Neutrino interaction cross sections and T2K/HK flux

ν



$\bar{\nu}$



Supernova Neutrinos

Hyper-Kamiokande

M31 (Andromeda 6898 Galaxy)
~ 10 to 16 events expected at Hyper-K.

Large Magellanic Cloud (where SN1987A was located)
~ 2,200 to 3,600 events expected at Hyper-K

Betelgeuse (200pc)
~ 117.5 million – 180 million

Supernova Neutrinos

Hyper-Kamiokande

* Blackhole formation can be observed as a sharp drop in neutrino flux

* Hyper-K can confirm/refute models relating to the dynamics of the explosion
(Standing Accretion Shock Instability)

* Supernova flux is sensitive to mass ordering without too much model dependence
→ neutronization burst

Supernova Neutrinos

Hyper-Kamiokande

These supernova events will be detected via the following interactions in Super-K, where the numbers in parentheses show the fractions of the total number of events with/without neutrino oscillations:

$$\overline{\nu}_e + p \rightarrow n + e^+ \quad (88\%/89\%), \qquad (1)$$

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad (1.5\%/1.5\%), \qquad (2)$$

$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^- \quad (<1\%/<1\%), \qquad (3)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (1\%/1\%), \qquad (4)$$

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F} \quad (2.5\%/<1\%), \qquad (5)$$

$$\overline{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N} \quad (1.5\%/1\%), \qquad (6)$$

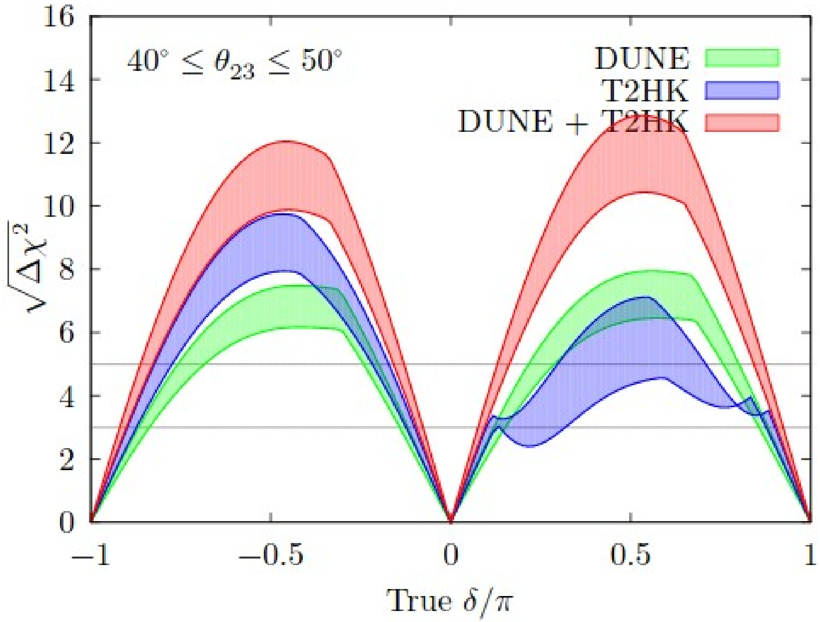
$$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + \mathrm{O}^*/\mathrm{N}^* + \gamma \quad (5\%/6\%), \qquad (7)$$

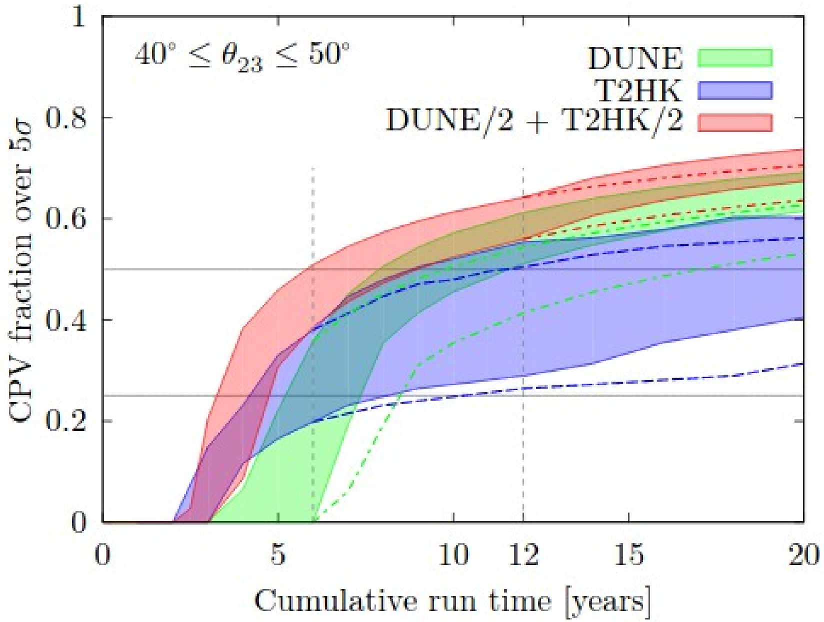
Astrophys.J.669:519-524,2007

CP sensitivity

Assuming the mass hierarchy is NOT known

https://arxiv.org/pdf/1612.07275.pdf





Note: HK sensitivity will improve if combined with HK atmospheric data!

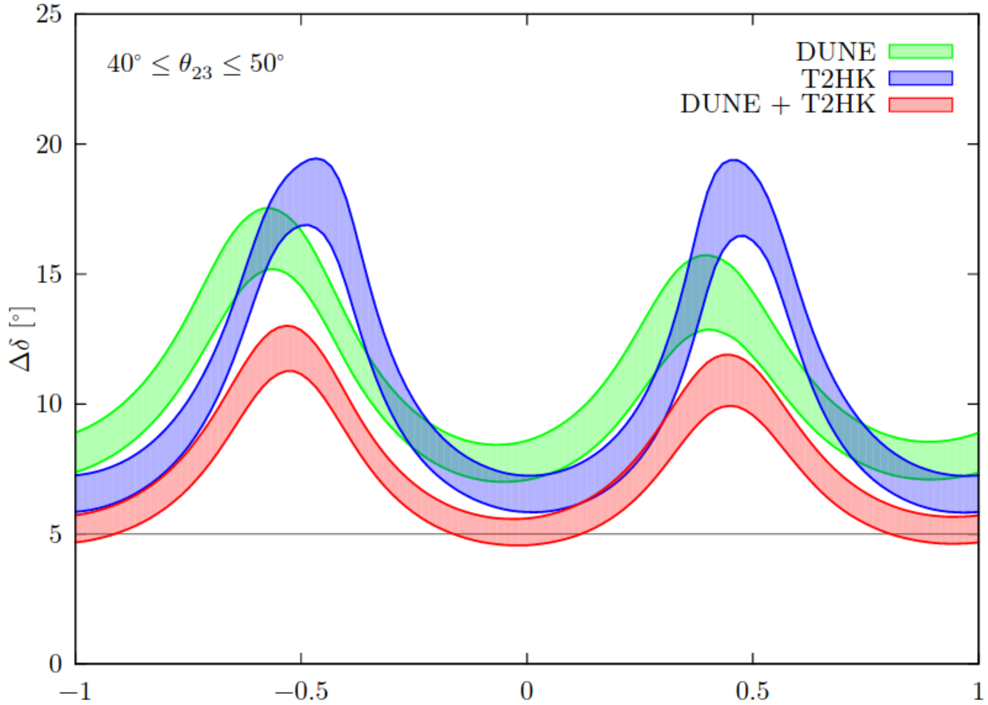
Note: **higher** values are better (better sensitivity)

CP sensitivity

Hyper-Kamiokande

	Label	$\nu : \overline{\nu}$ at DUNE	$\nu : \overline{\nu}$ at T2HK
Fixed run time	DUNE	5 : 5	0 : 0
	T2HK	0 : 0	2.5 : 7.5
	DUNE + T2HK	5 : 5	2.5 : 7.5

https://arxiv.org/pdf/1612.07275.pdf



Assuming ordering is known and NO

T2K has better sensitivity in most re

Note: **lower** values are better
(smaller error)

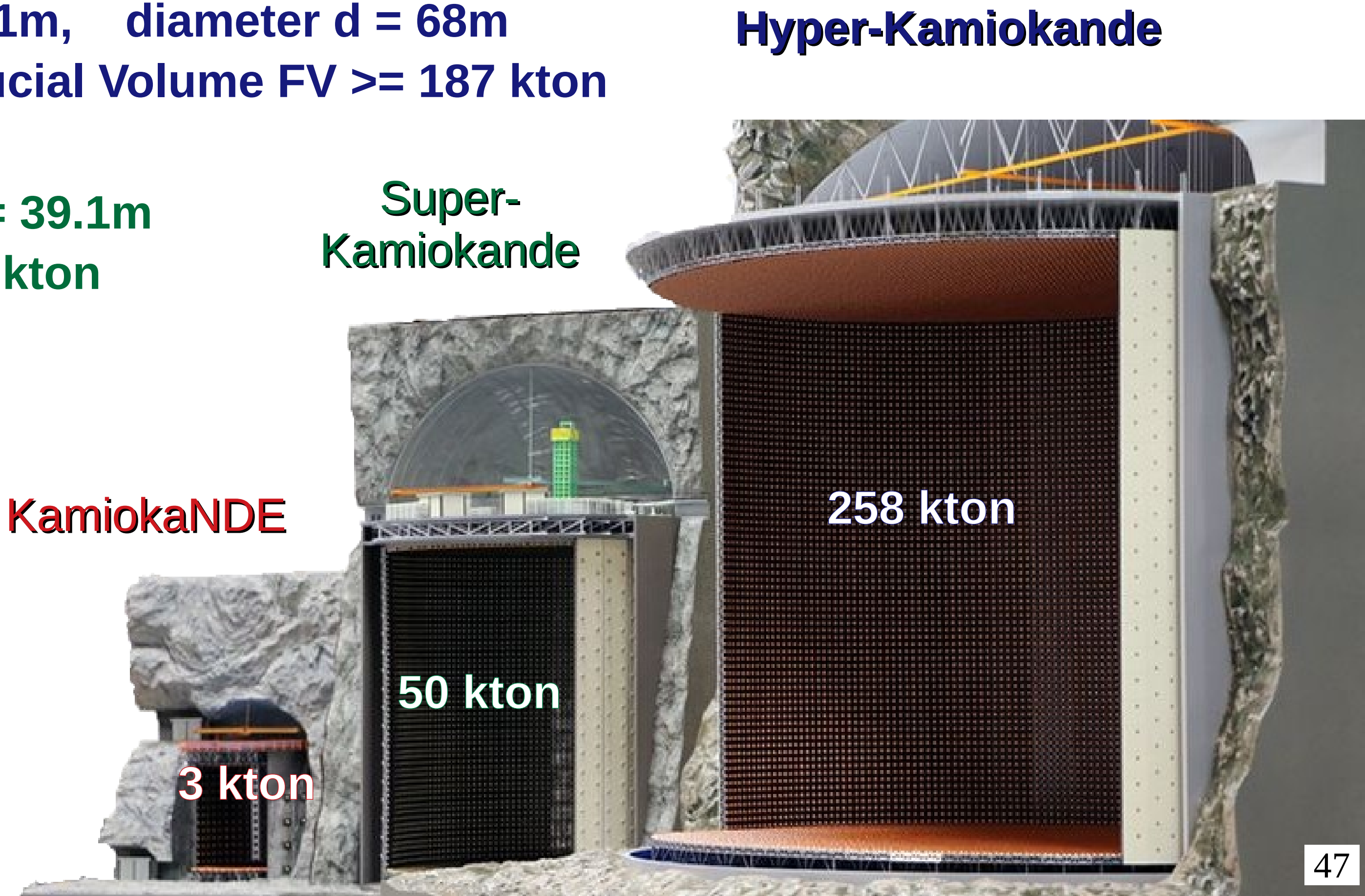
The Kamiokande Series

Hyper-K: Height h = 71m, diameter d = 68m
Volume V = 258 kton, Fiducial Volume FV >= 187 kton

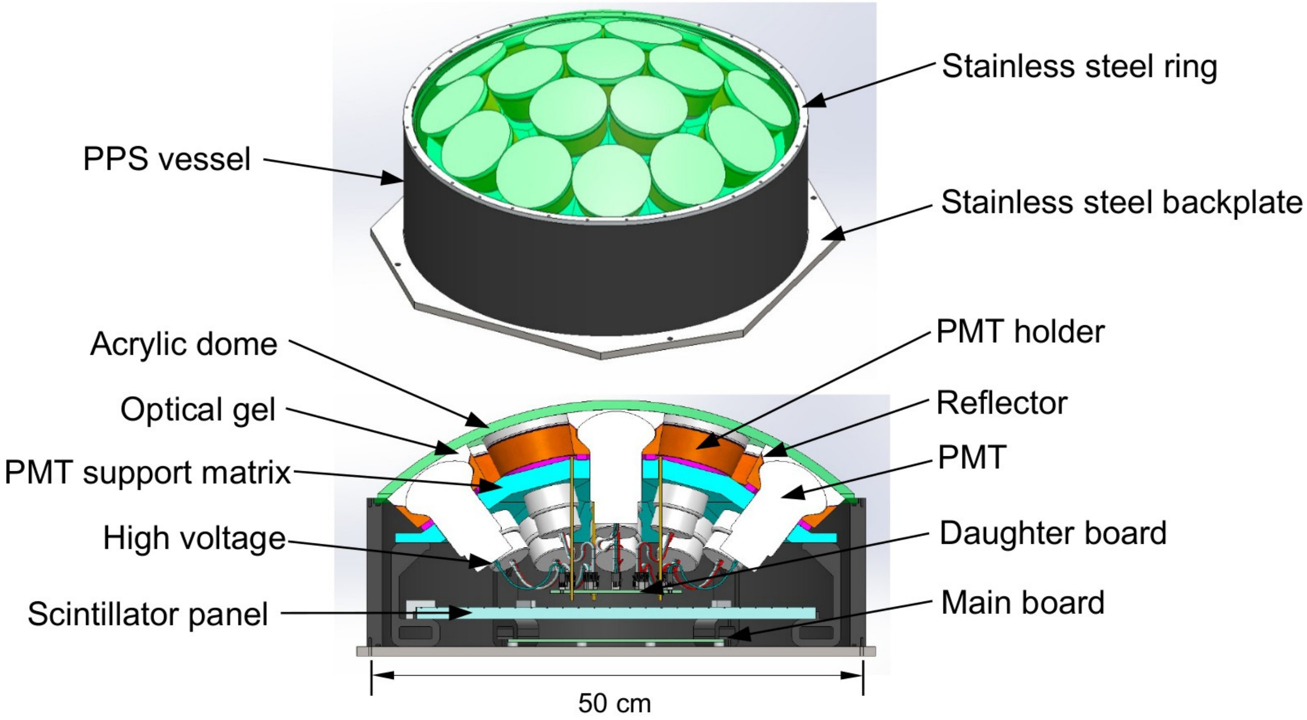
Super-K: h = 41.4m, d = 39.1m
V = 50kton, FV: 22.5 kton

Kamiokande

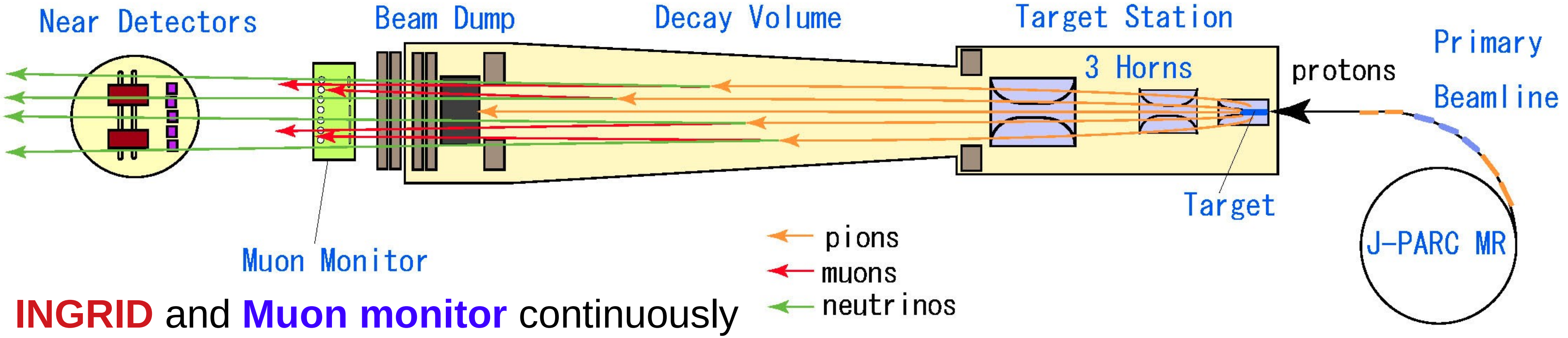
h = 16 m
d = 15.6 m
V = 3 kton
FV = 0.68 kton



Multi-PMT (mPMT)



Neutrino beam



INGRID and **Muon monitor** continuously measure beam rate and direction

* **30GeV protons** → **graphite** target → charged **hadrons**
* **charge selection** and focusing of hadrons with **3 electromagnetic horns**
* **hadrons decay to ν or $\bar{\nu}$** (depending on charge of hadron)

Dominant systematic error due to hadron interaction modelling
→ Constrained using NA61/SHINE replica target measurements
→ In future flux uncertainty will be reduced by the EMPHATIC experiment

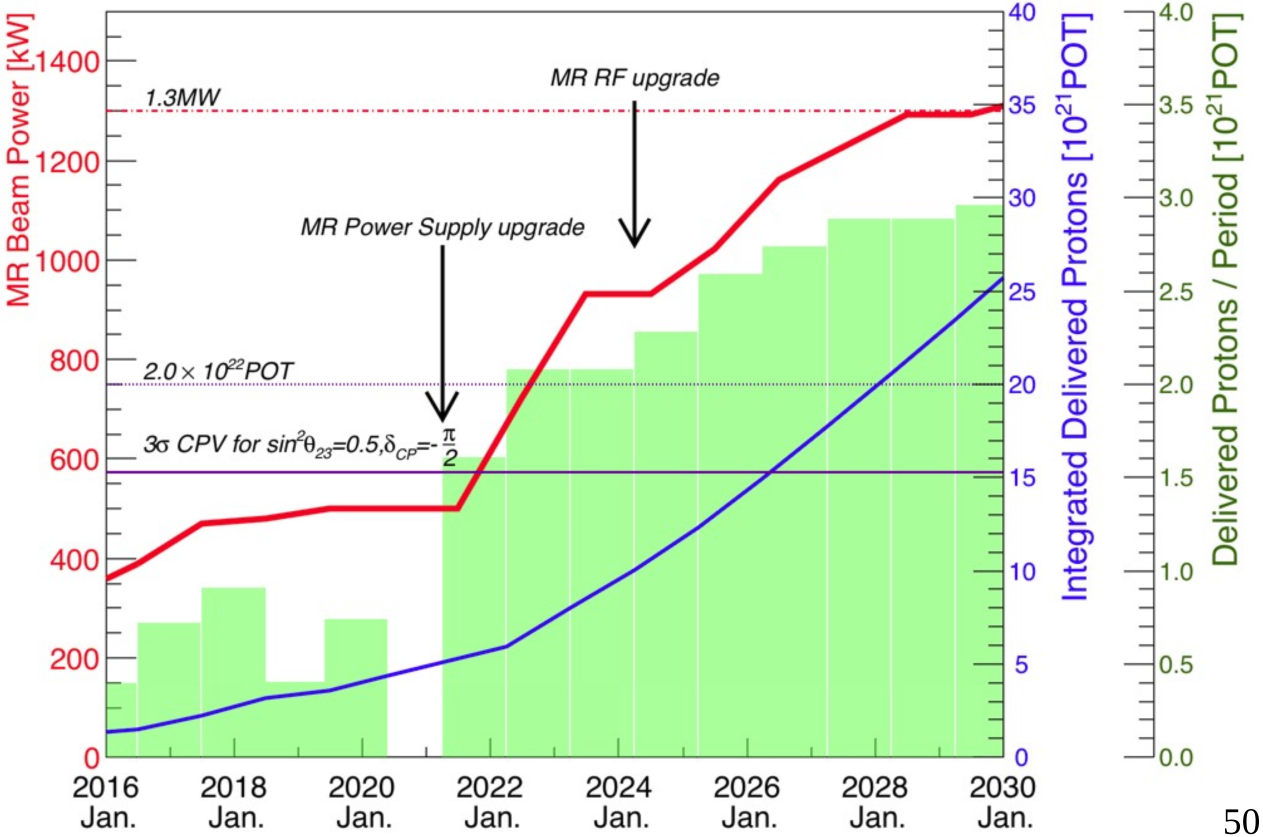
T2K/HK Beam upgrade

Hyper-Kamiokande

* Beam currently capable of 450-500kW stable running

* Beam line upgrade in 2021
  - Nd280 upgrade will happen at the same time

* target power: 1.3MW



T2HK: Tokai to Hyper-K

Beam power: 1.3 MV $\times 10^8$ s

Beam mode: $\nu:\bar{\nu} = 1:3$

First 10 years of operation
Expected protons on target: 2.7×20^{22} POT

The Hyper-K Experiment

Hyper-Kamiokande

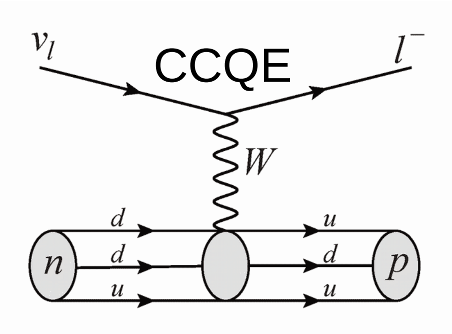
Politics:

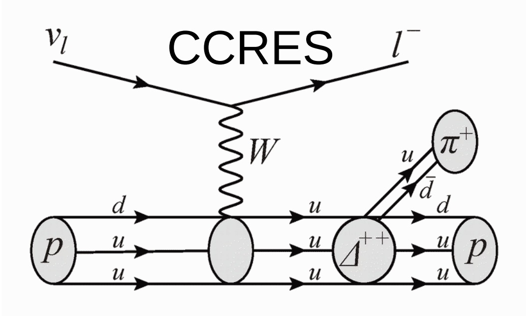
The supplementary budget for FY2019 which includes the first-year construction budget of 3.5 billion yen for the Hyper-Kamiokande project was approved by the Japanese Diet.

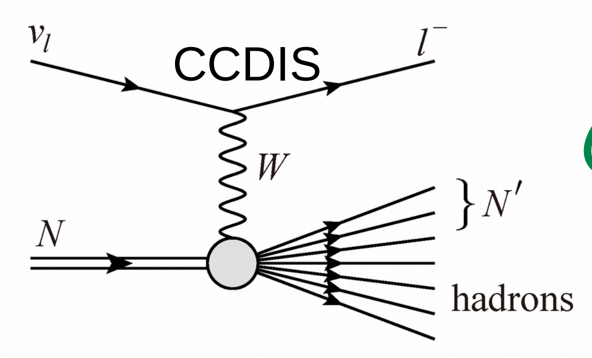
The Hyper-K project has officially started.

The operations will begin in 2027.

Neutrino interactions



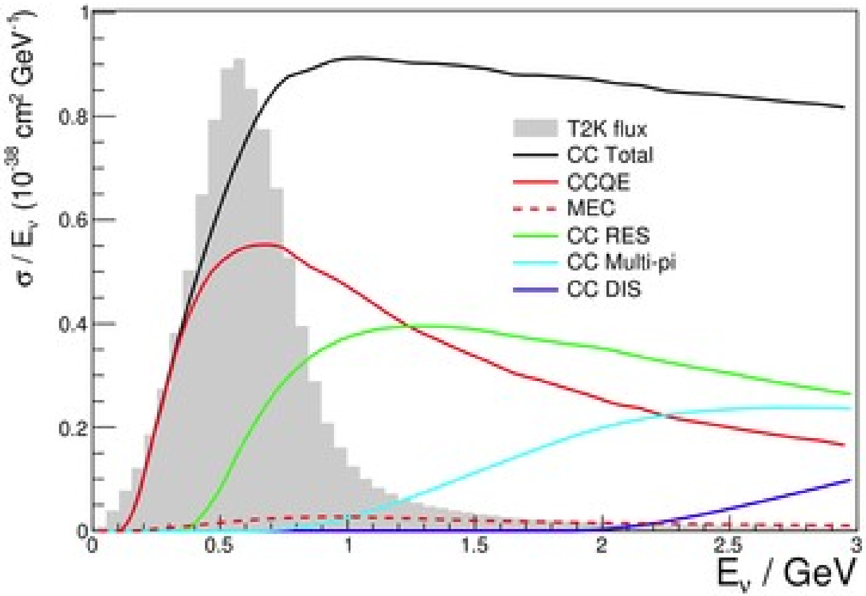




NC interactions also important

e.g. NCπ^0, NC1γ

→ background



Interactions occur with nucleons bound inside a nucleus

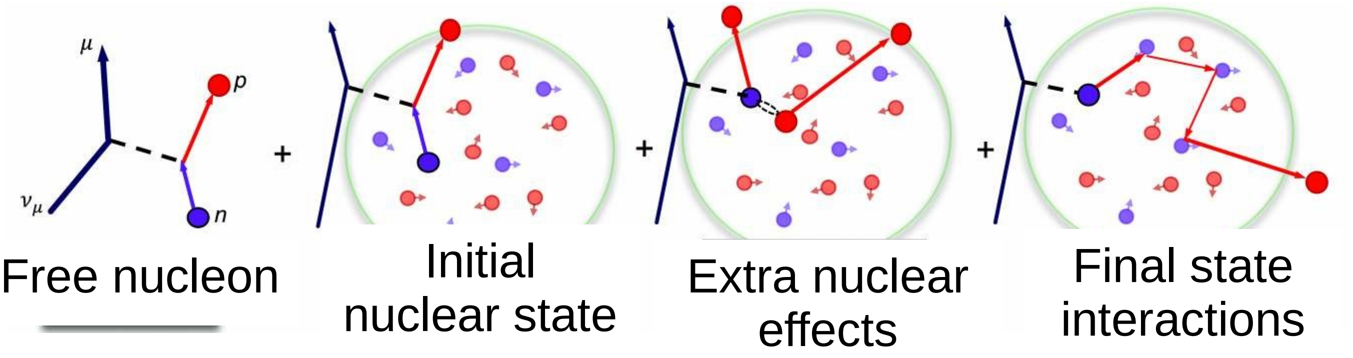
→ **Nuclear effects!!**

We only measure particles that exit the nucleus

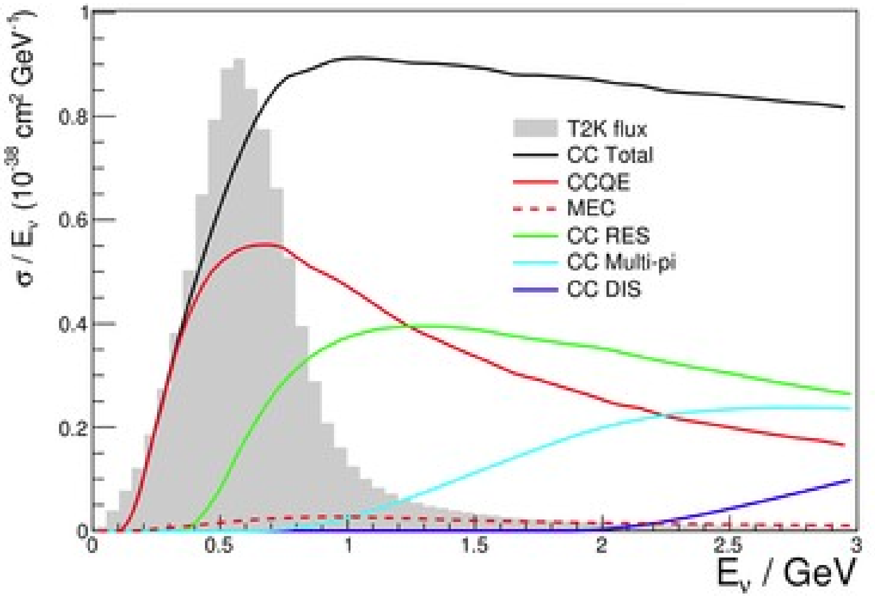
→ lose information about the initial interaction

→ can create a bias in energy reconstruction

Neutrino interactions



Interaction modes and Nuclear models tuned to external data



Interactions occur with nucleons bound inside a nucleus

→ **Nuclear effects!!**

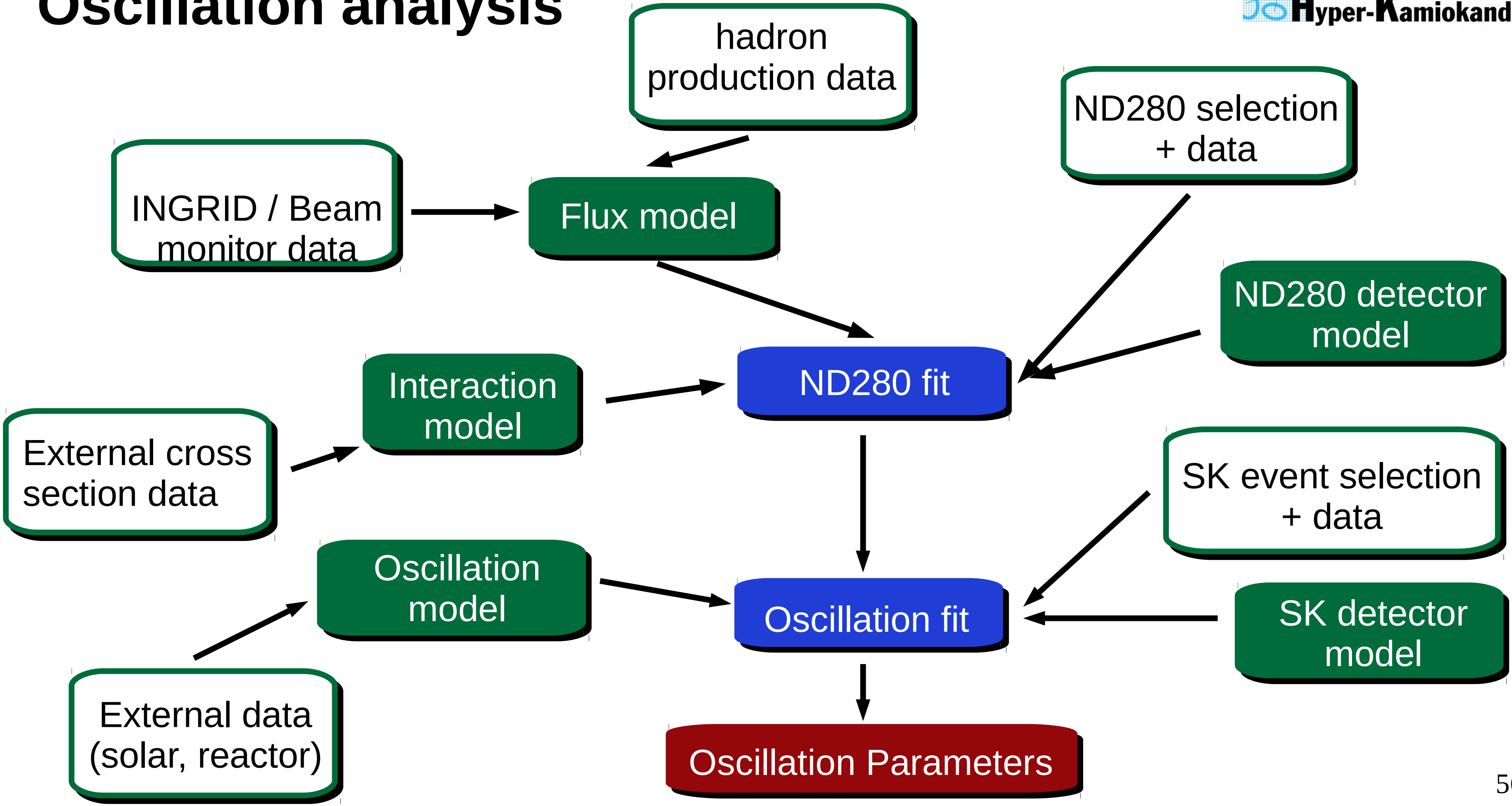
We only measure particles that exit the nucleus

→ lose information about the initial interaction

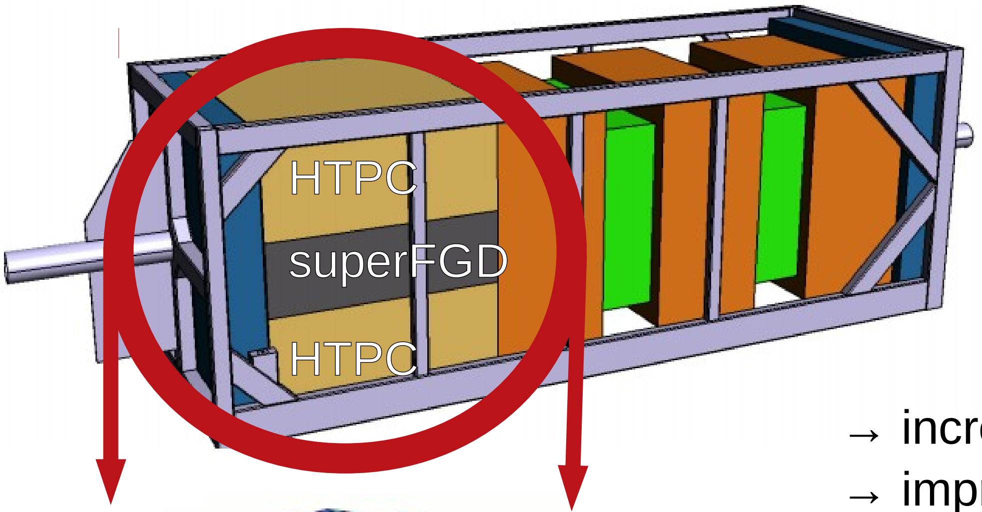
→ can create a bias in energy reconstruction

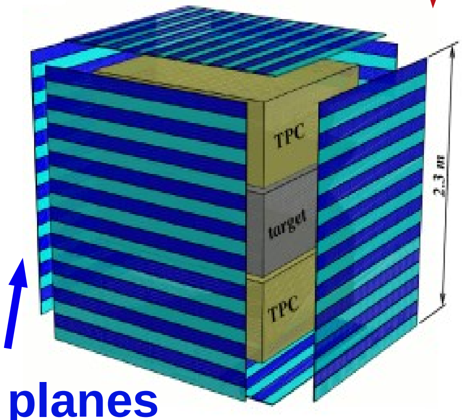
Backup – T2K

Oscillation analysis



ND280 upgrade (2021)





6 ToF planes

Pi0 detector is being replaced by

*** SuperFGD**

- higher granularity, 3D readout

*** Horizontal TPCs (HTPCs)**

*** Time of Flight (ToF) planes**

→ increases active target **mass** for oscillation analysis

→ improved **angular acceptance**

→ able to reconstruct **low energy short tracks**

→ improved hadronic information

→ better $\gamma \rightarrow e^+ e^-$ identification

Reduce systematic uncertainty to 4%

→ 3σ exclusion of CP conservation for 36% of the δ_{cp} phase space (if mass hierarchy is known)

ND280 upgrade

Constraints provided to SK

Current ND280 constraint compared to predicted ND280 upgrade constraint

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation	3.1	2.4
$(0.6 < E_\nu < 0.7\ \mathrm{GeV})$		
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

Note: preliminary estimation

Near Detectors

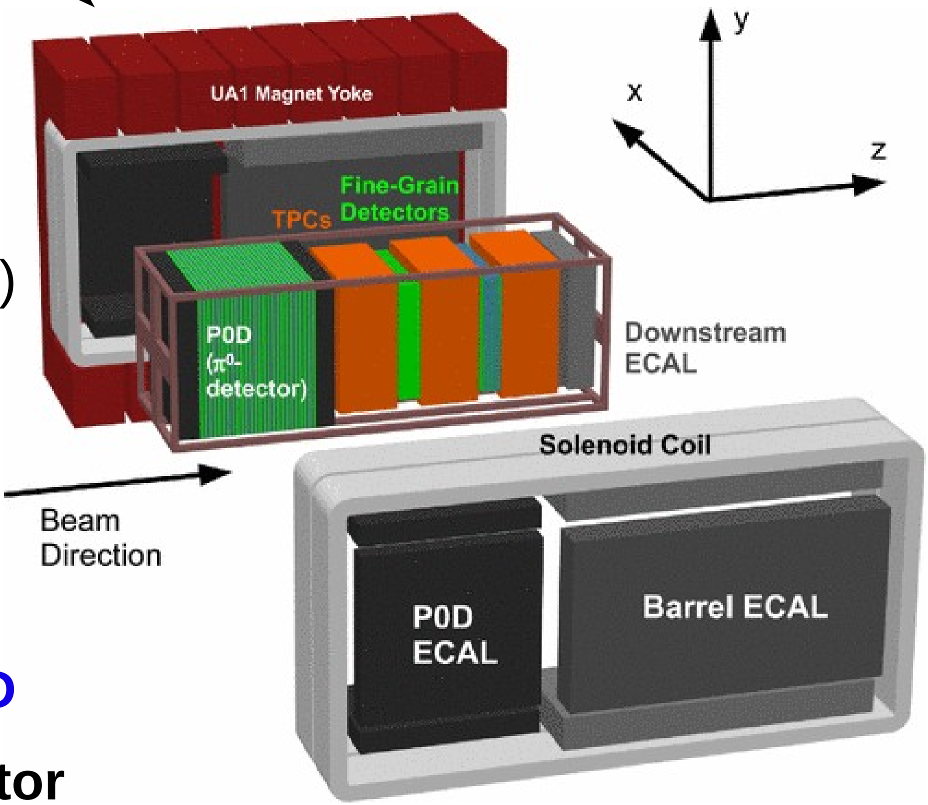
280m from the ν ($\bar{\nu}$) source

ND280

Same off-axis angle as SK

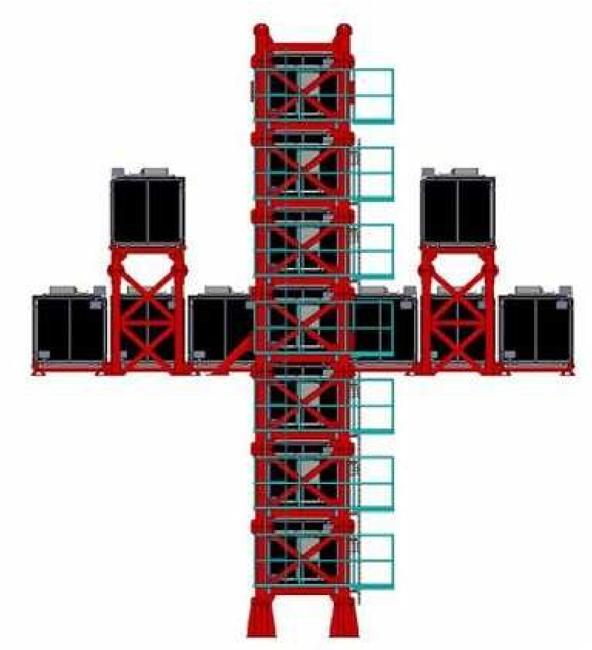
- Active target mass → 2 x scintilltors (**FGDs**)
  → vertex reconstruction
- 3 Time projection chambers (**TPC**)
  → **momentum** reconstruction
  → **charge** identification
  → Particle identification (**PID**)
- Electromagnetic calorimeters (**Ecal**) → **PID**
- **π^0 detector** and **side muon range detector**

Magnetised



Near Detectors

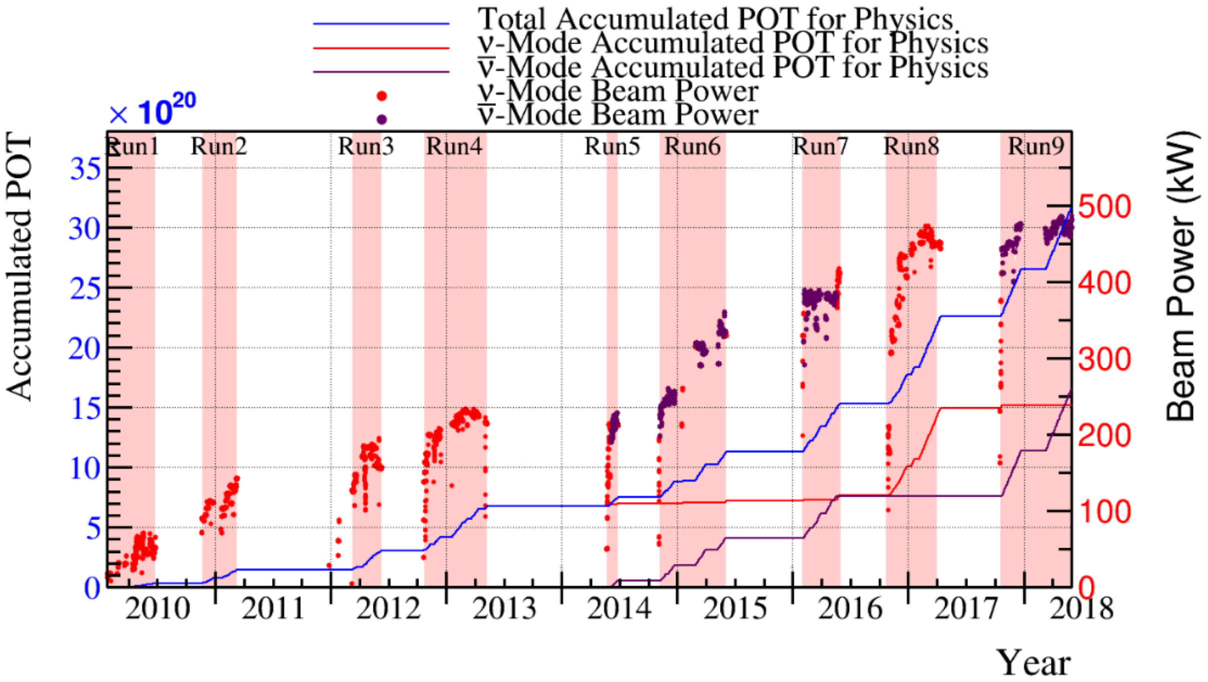
280m from the ν ($\bar{\nu}$) source



INGRID

- On-axis, scintillator and iron
- monitors beam direction, intensity and stability

T2K Protons on target (POT)



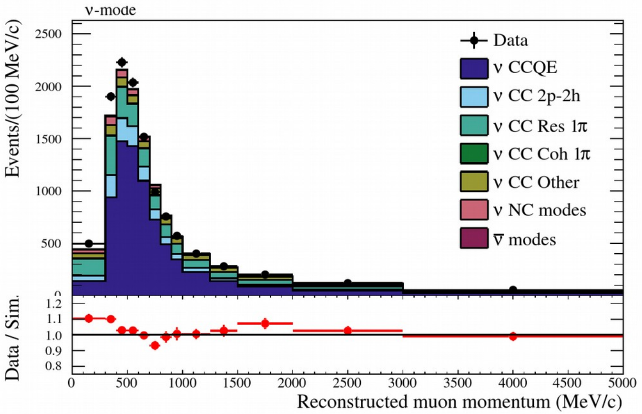
23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

ν-mode 1.51×10^{21} (47.83%)

$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

ND280 Fit

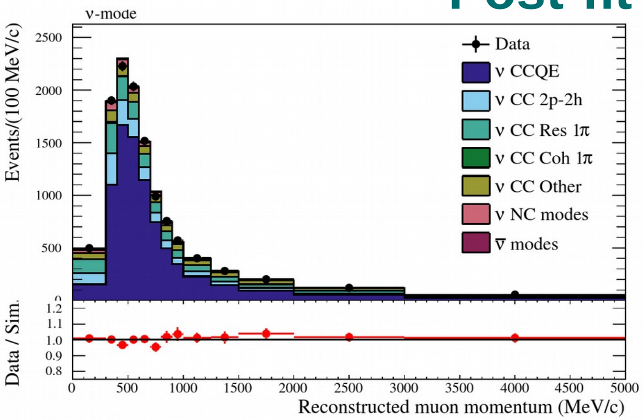


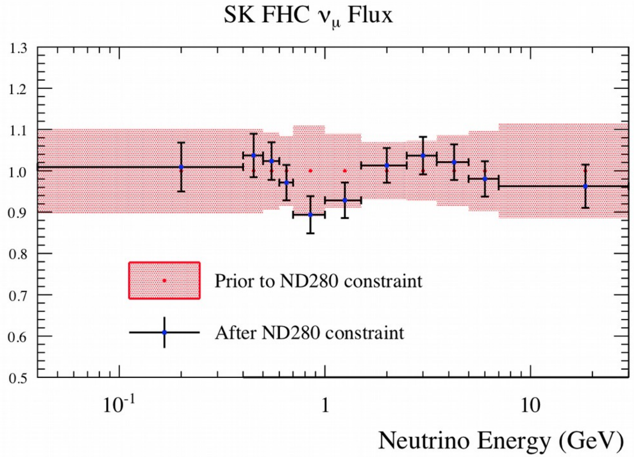
PRELIMINARY

Pre-fit

FGD1 CC0π sample

Post-fit





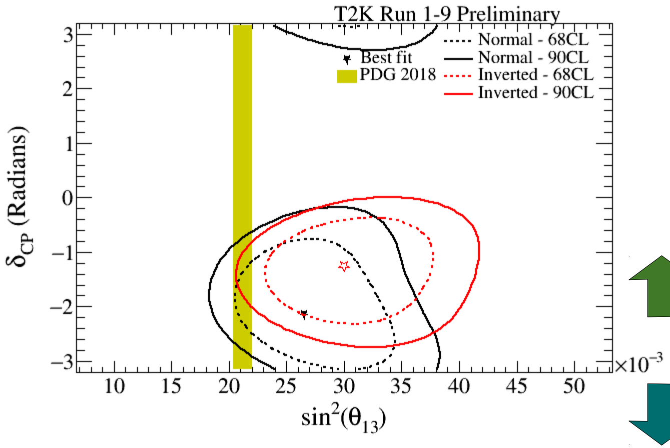
SK event selection errors (%)

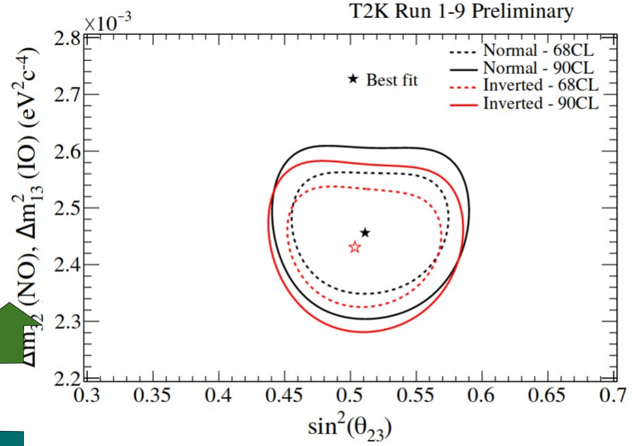
	Pre-fit	Post-fit
ν-beam 1-Ring-μ	15	5
$\bar{\nu}$-beam 1-Ring-μ	13	4
ν-beam 1-Ring-e	17	9
$\bar{\nu}$-beam 1-Ring-e	14	7
ν-beam 1-Ring-e + 1π^+	22	18

Oscillation parameter fits

Joint fit between ν-beam and $\bar{\nu}$-beam data across 5 event samples at SK

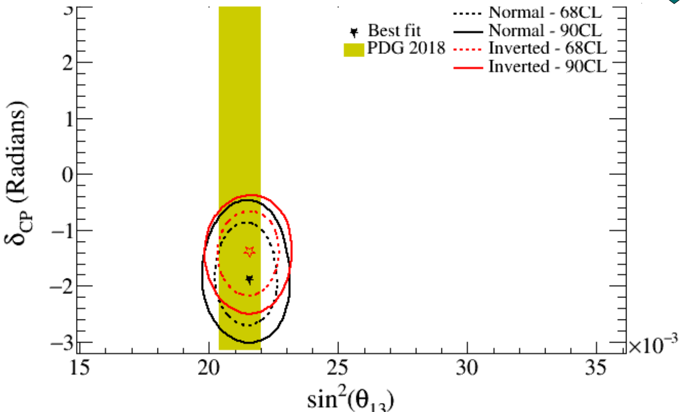
Near detector constraints are applied

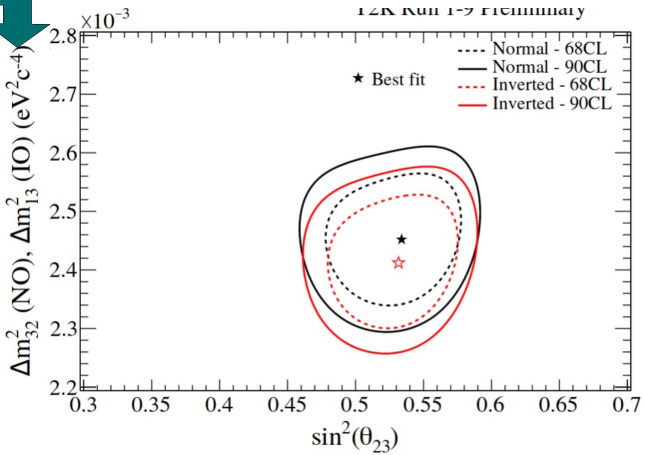




w/o reactor constraint

w/ reactor constrain





Consistent with maximal mixing

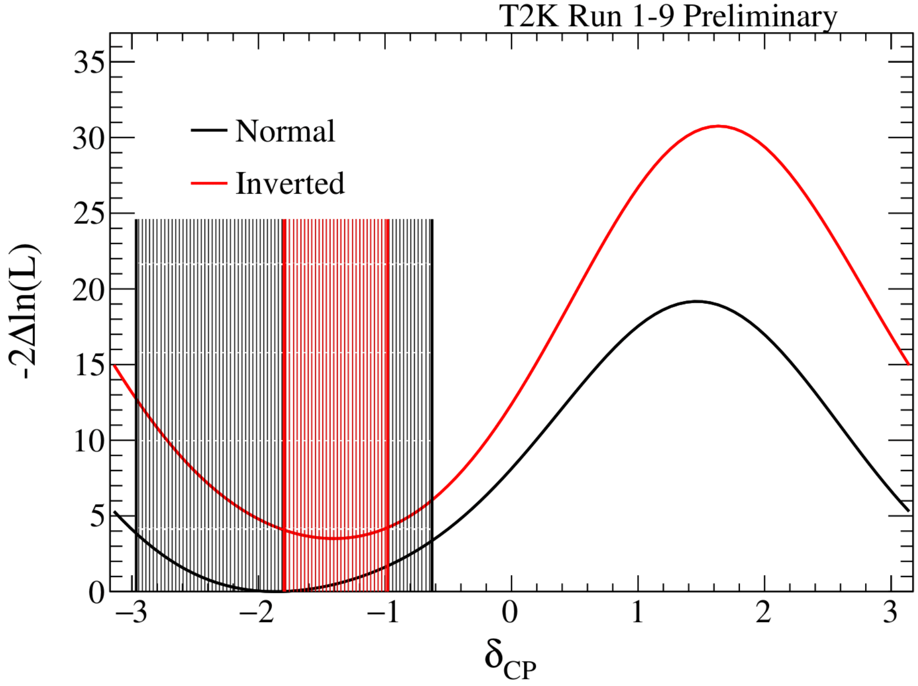
θ_{23} >45 preferred

δ_{cp} sensitivity

Joint fit between ν-beam and $\bar{\nu}$-beam data across 5 event samples at SK

Near detector constraints are applied

2 sigma C.L. exclusion region



Best fit values:

NH: -1.89

IH: -1.38

CP conservation excluded at 2σ level for both mass hierarchy

Normal hierarchy preferred for all parameter fits to data

The Beam

Major neutrino-producing decay modes in the decay volume:

For a neutrino beam

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$K^+ \rightarrow \mu^+ + \nu_\mu$

$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$

$K^0 \rightarrow \pi^- + \mu^+ + \nu_\mu$

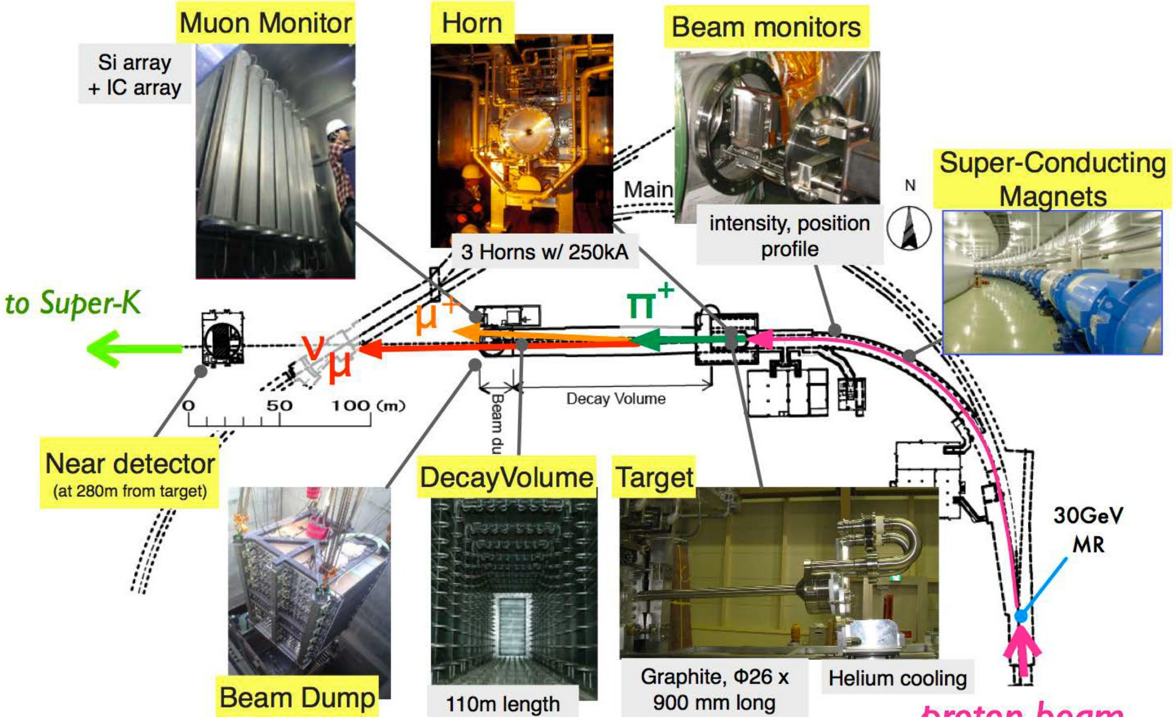
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$K^+ \rightarrow \pi^0 + e^+ + \nu_e$

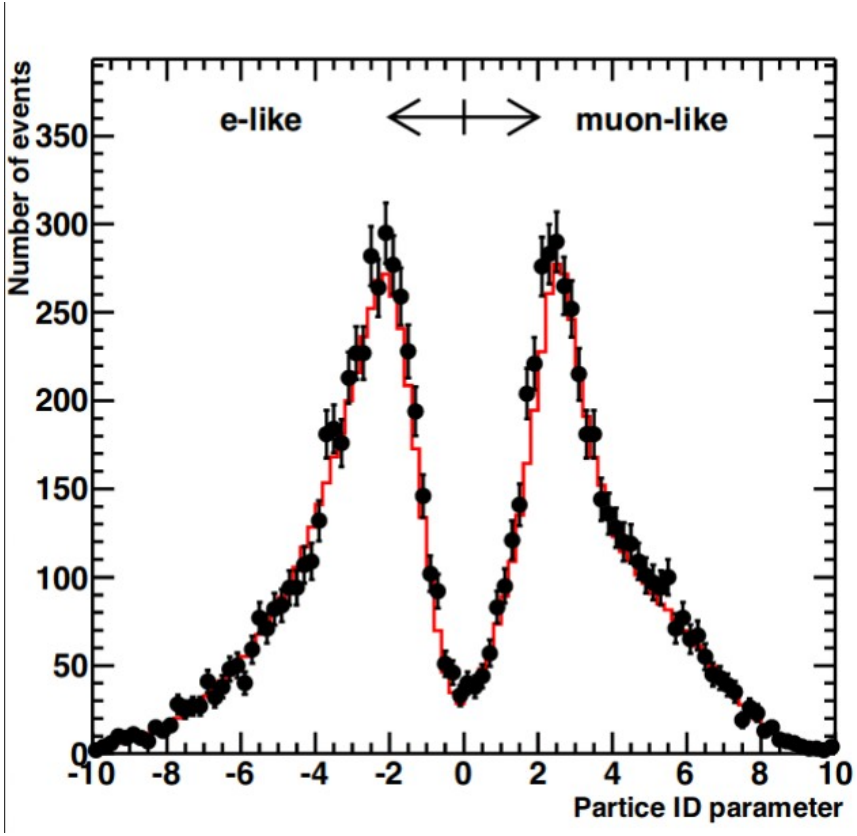
$\pi^+ \rightarrow e^+ + \nu_e$

$K^0 \rightarrow \pi^- + \mu^+ + \nu_\mu$

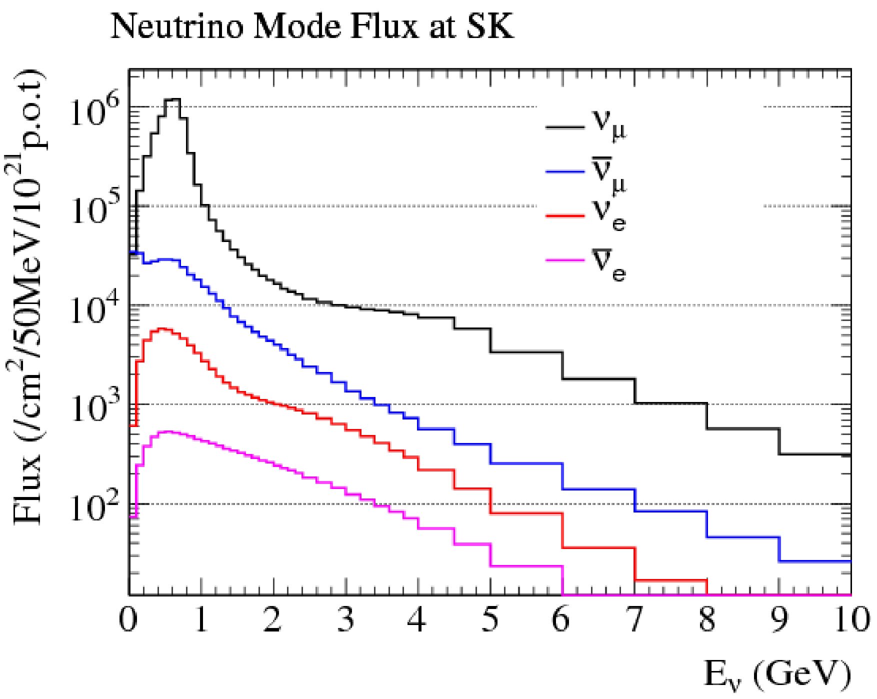
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

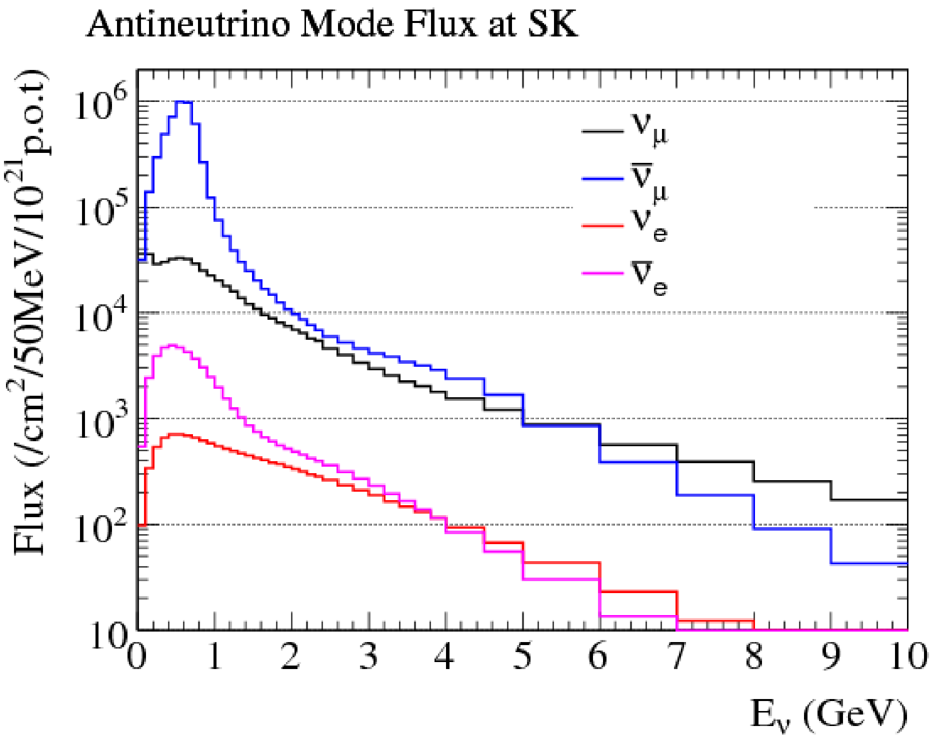


SK particle identification



Beam Flux


Neutrino Mode Flux at SK
Flux (/cm^2/50MeV/10^{21}p.o.t)
10^2
10^3
10^4
10^5
10^6
0 1 2 3 4 5 6 7 8 9 10
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$


Antineutrino Mode Flux at SK
Flux (/cm^2/50MeV/10^{21}p.o.t)
10
10^2
10^3
10^4
10^5
10^6
0 1 2 3 4 5 6 7 8 9 10
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

T2K Oscillation fit priors
(VALOR framework)

$\sin^2(2\theta_{13})$

Two options for prior

- reactor constraint
- uniform prior

Taken from

* T2K 2015 best fit results (most probable, Bayesian fit including reactor)

T2K 2015: Phys. Rev. D 91, 072010 (2015)

* 2016 PDG

C. Patrignani et al (Particle Data Group). Chin. Phys. C, 2016, 40(10): 100001

Parameter(s)	Prior	Range	
$\sin^2\theta_{23}$	uniform	$[0.3; 0.7]$	→ T2K 2015
$\sin^2 2\theta_{13}$ reactors	gaussian	0.0830 ± 0.0031	→ PDG
$\sin^2 2\theta_{13}$ T2K only	uniform	$[0.03; 0.2]$	→ T2K 2015
$\sin^2 2\theta_{12}$	gaussian	0.851 ± 0.020	→ PDG
$\lvert\Delta m^2_{32}\rvert$ (NH) / $\lvert\Delta m^2_{13}\rvert$ (IH)	uniform	$[2.3; 2.7] \times 10^{-3}$ eV^2/c^4	→ T2K 2015
Δm^2_{21}	gaussian	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2/c^4	→ PDG
δ_{CP}	uniform	$[-\pi; +\pi]$	
Mass Hierarchy	fixed	NH or IH	

Systematic errors

Systematic errors on the event rate for each sample at SK

Final column is error on the ratio of FHC/RHC of 1-ring e sample (important for δ_{cp})

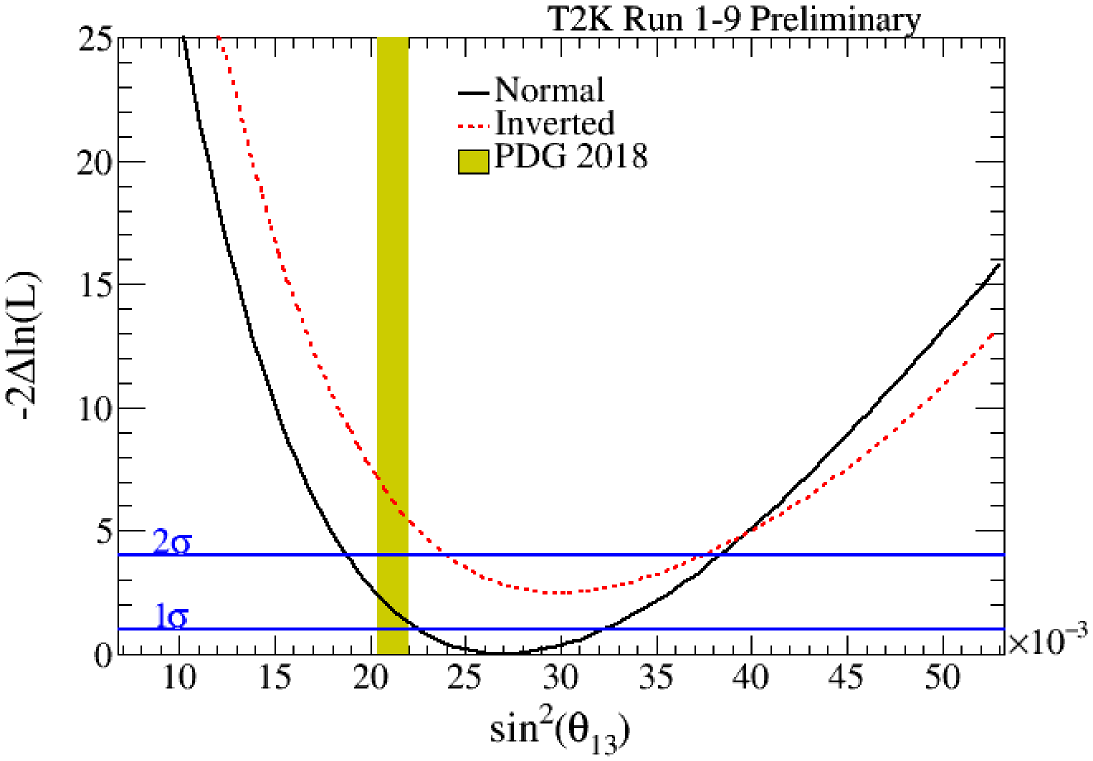
Systematics grouped by type/source

Error (%)

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03

Table 5: Percentage error on event rate by error source and sample. Final column is the percentage error on the ratio of FHC/RHC events in the one-ring e sample.

T2K θ_{13} sensitivty

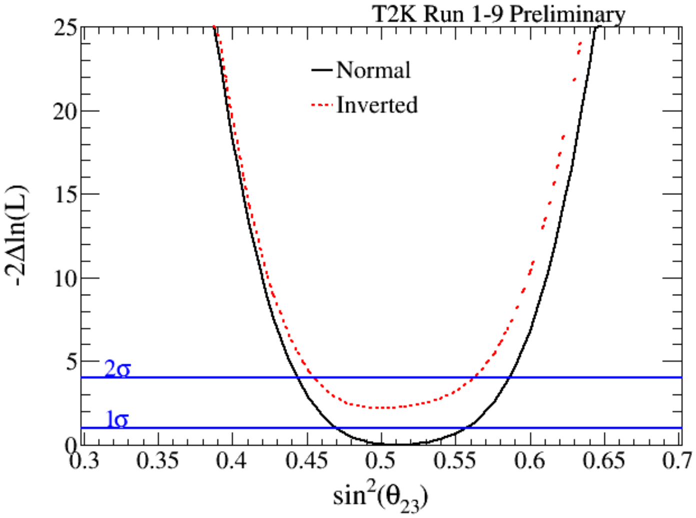


1D contours

- mass hierarchy is minimized
- normal and inverted hierarchy $\Delta\chi 2$ distributions shifted to the same global best-fit $\chi 2$ value
- global best fit value taken to be the minimum between normal and inverted hierarchy.

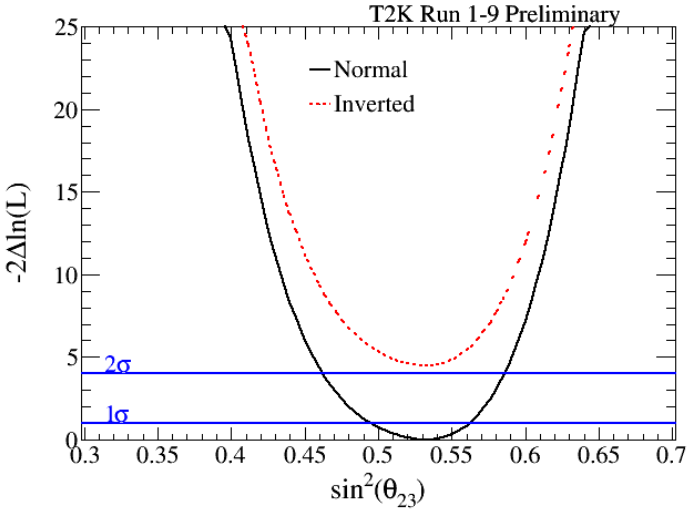
PDG / reactor constraint shown in green/yellow

T2K θ_{23} sensitivty



w/o reactor constraint

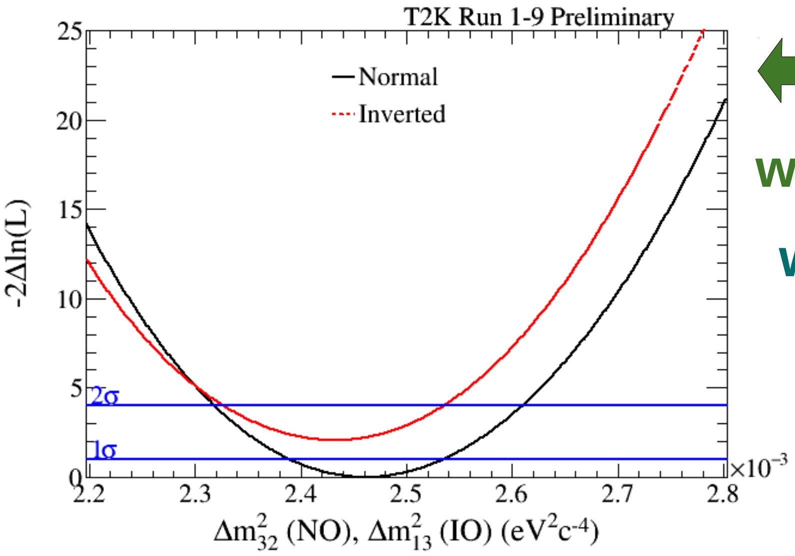
w/ reactor constrain



1D contours

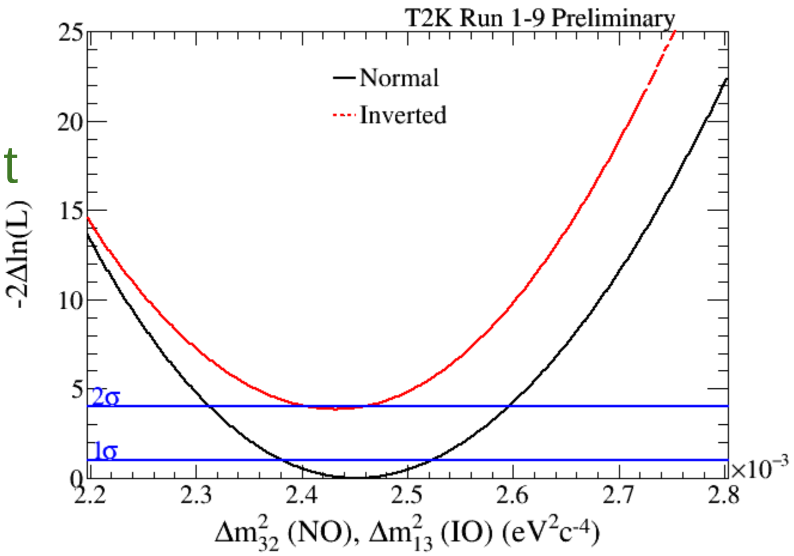
- mass hierarchy is minimized
- normal and inverted hierarchy $\Delta\chi2$ distributions shifted to the same global best-fit $\chi2$ value
- global best fit value taken to be the minimum between normal and inverted hierarchy.

T2K Δm^2 **sensitivty**



w/o reactor constraint

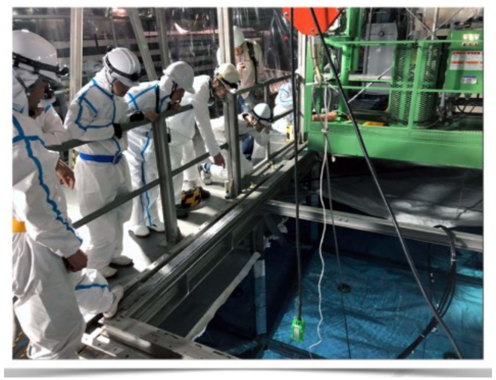
w/ reactor constrain



1D contours
- mass hierarchy is minimized
- normal and inverted hierarchy Δχ2 distributions shifted to the same global best-fit χ2 value
- global best fit value taken to be the minimum between normal and inverted hierarchy.

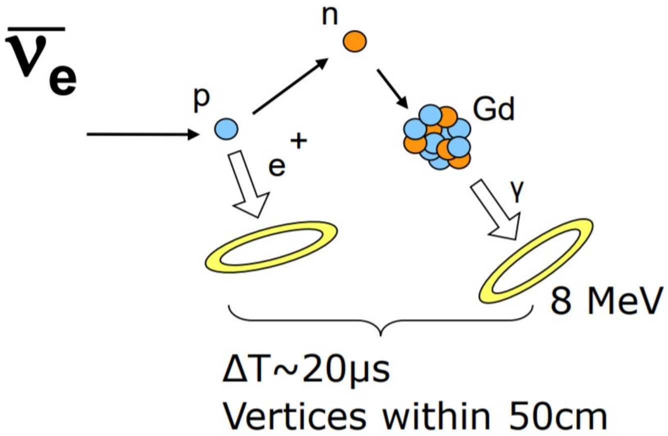
T2K II: SK upgrade

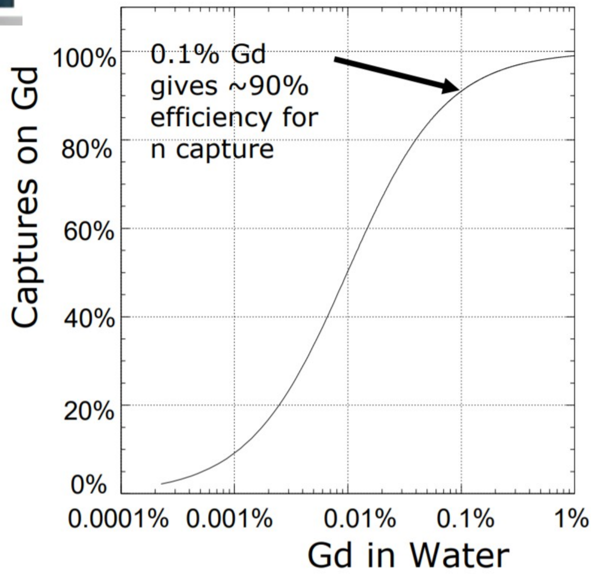
* SK repairs performed in 2018
  - detector drained and cleaned
  - reinforcement of water sealing
  - improved tank piping
  - PMTs replaced



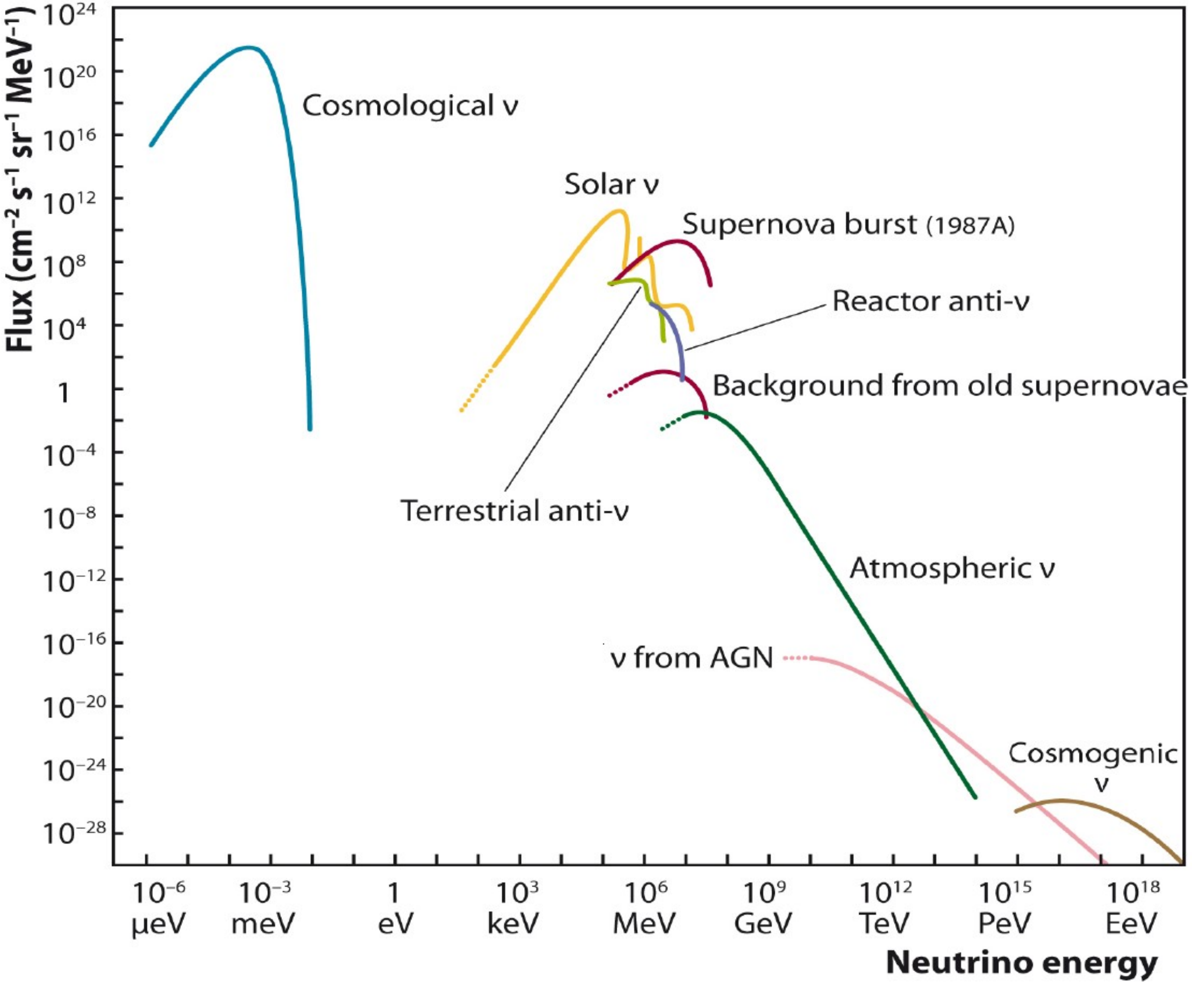
* Plan to add **Gadolinium** to the water
  - 0.01% next year
  - increase to 0.1% eventually

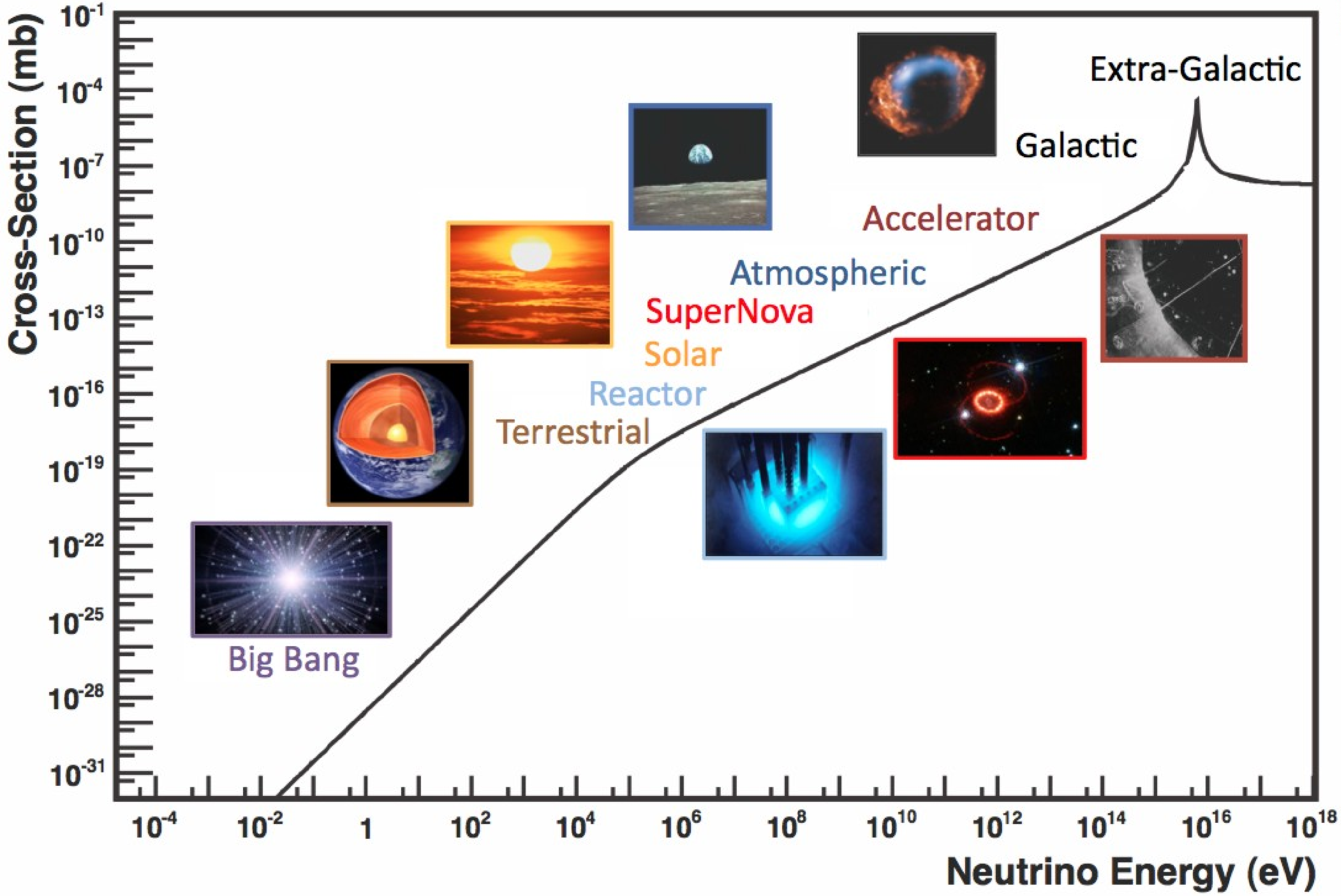
→ **Better ν / $\bar{\nu}$ separation**



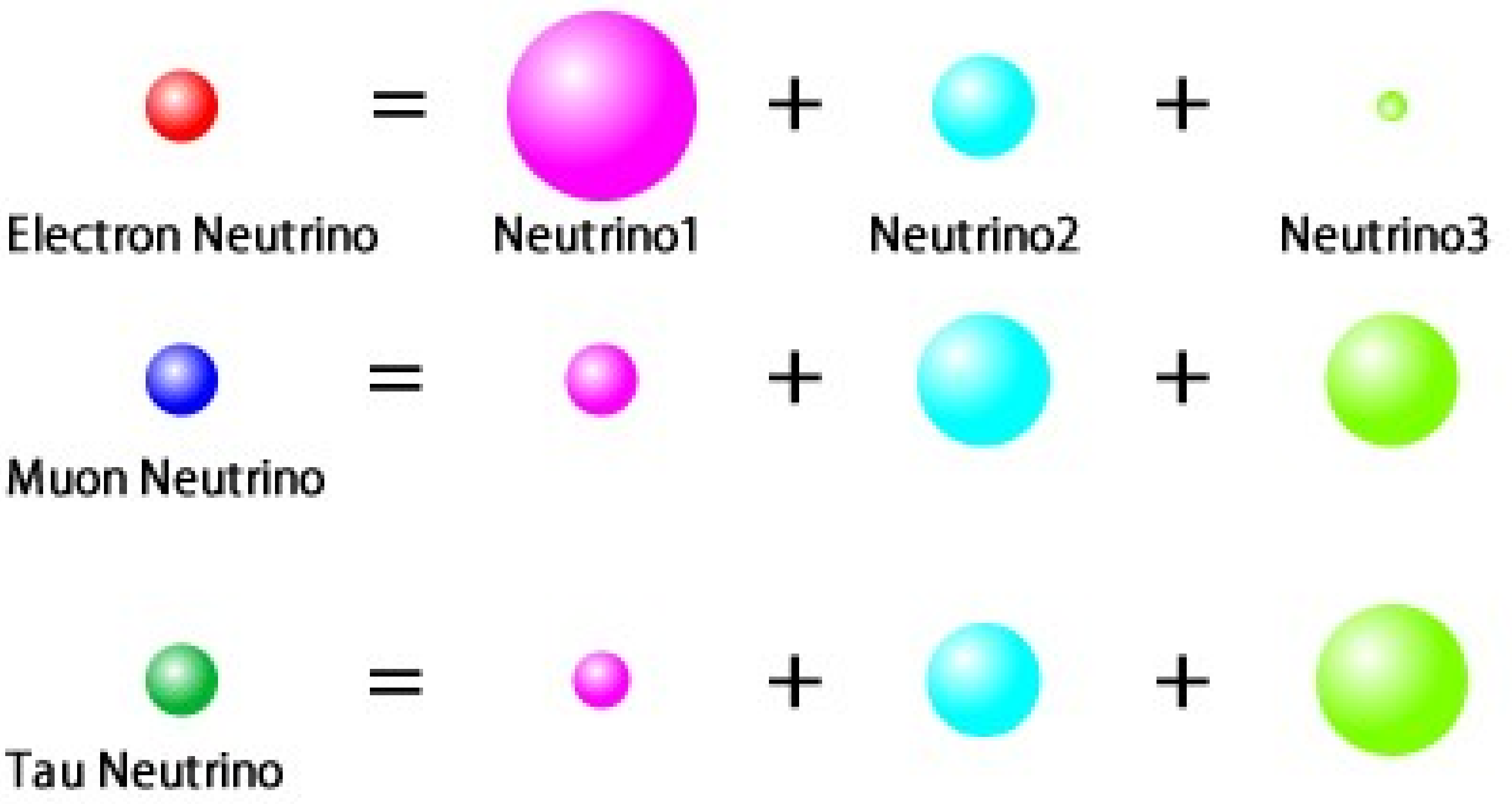


Backup – Neutrinos

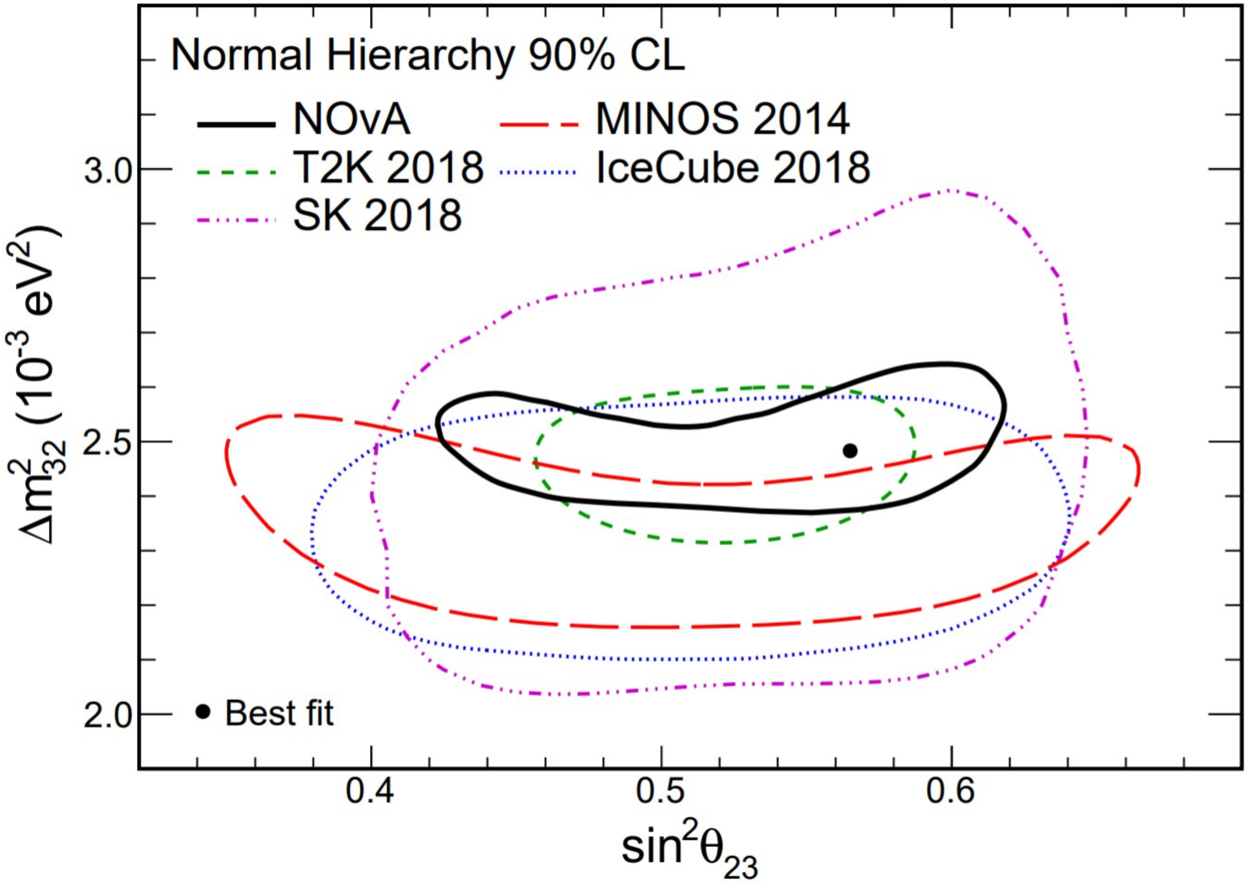

Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy



Hyper-Kamiokande


Electron Neutrino
Neutrino1
Neutrino2
Neutrino3
Muon Neutrino
Tau Neutrino

Neutrino Oscillations Parameters



arXiv:1906.04907

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