FPCP 2024

22nd Conference on Flavor Physics and CP Violation

Future neutrino physics with Hyper-Kamiokande

28th May 2024

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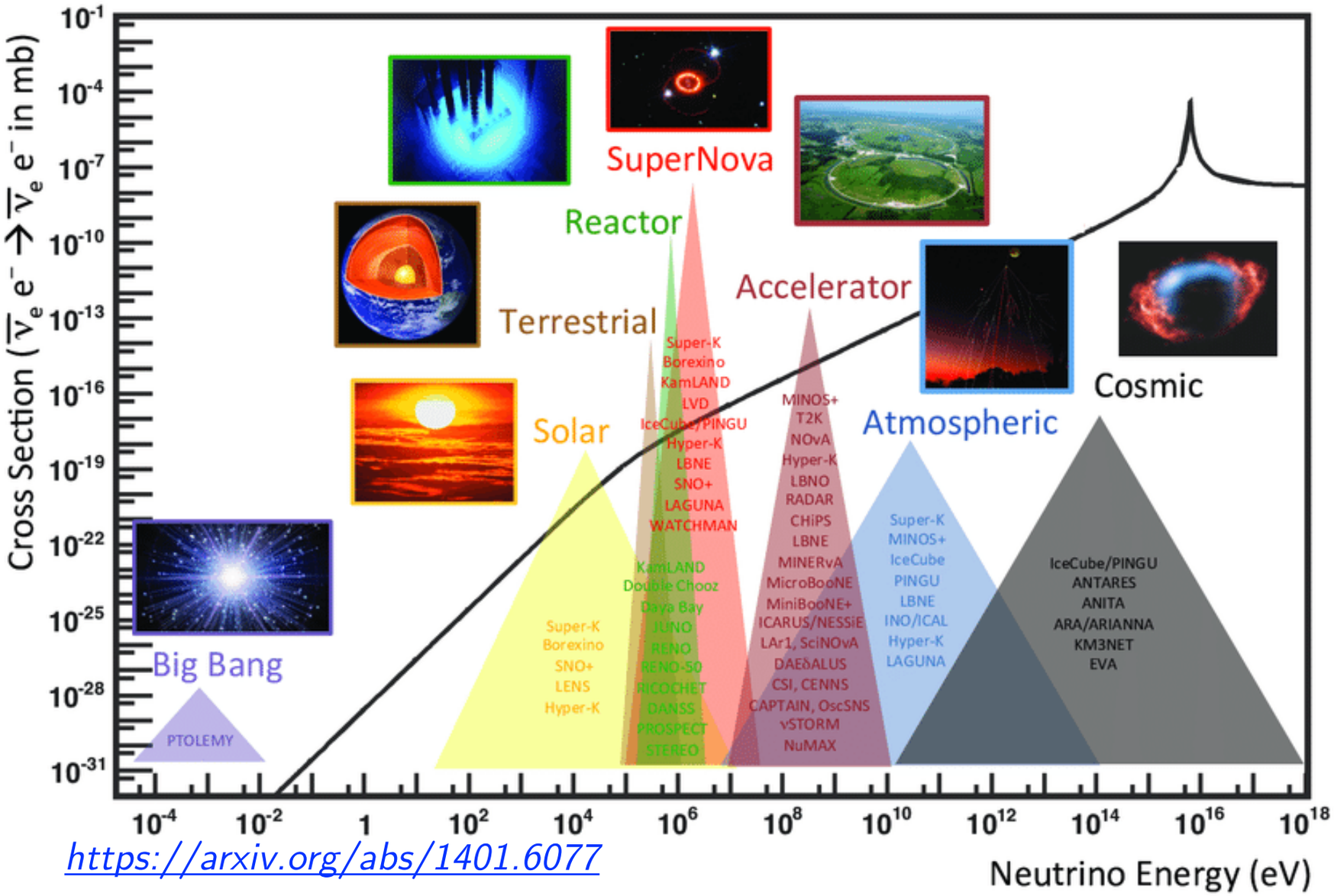
On behalf of the Hyper-Kamiokande collaboration

Hyper-Kamiokande

The Landscape of Neutrino Physics

Hyper-Kamiokande

- Most abundant known massive particles. Span a HUGE energy range.
- Crucial in nuclear physics, astrophysics and cosmology.
- Tiny cross section → poorly known compared to other SM fermions.



https://arxiv.org/abs/1401.6077

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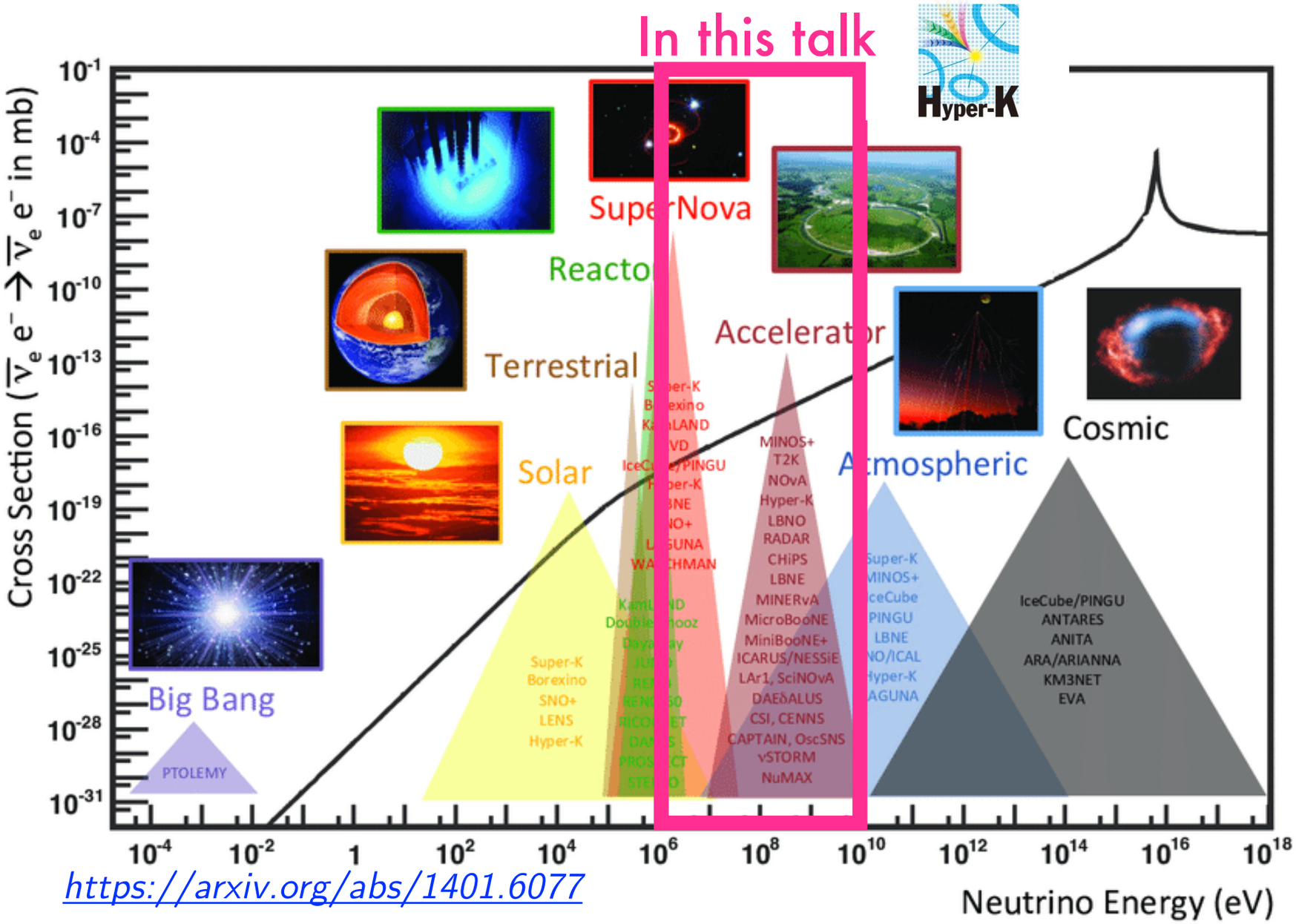

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Neutrino Oscillations in a Nutshell

Hyper-Kamiokande

Neutrinos interact as weak states $(\nu_e, \nu_\mu, \nu_\tau)$, but propagate as mass states (ν_1, ν_2, ν_3).

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

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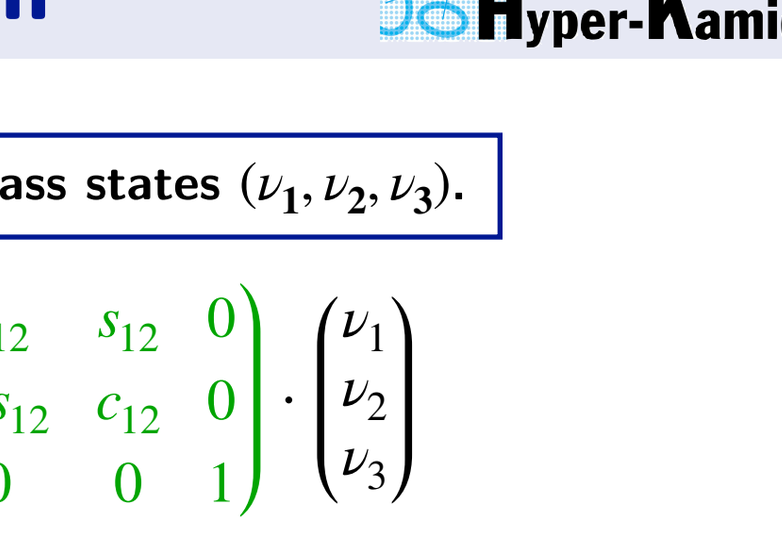
Flavor eigenstates evolve in time cyclically, with a frequency that depends on E/L.

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - \underbrace{4\sum \mathscr{A}_{ij} \sin^2 \frac{\Delta m^2_{ij} L}{4E_\nu}}_{\text{CP conserving}} \pm \underbrace{2\sum \mathscr{B}_{ij} \sin \frac{\Delta m^2_{ij} L}{2E_\nu}}_{\text{CP violating}}$$

ν or $\bar{\nu}$

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



Disappearance

- Look for decrease in neutrino flux.

Appearance

- Look for increase in neutrino flux.

Neutrino Oscillations in a Nutshell

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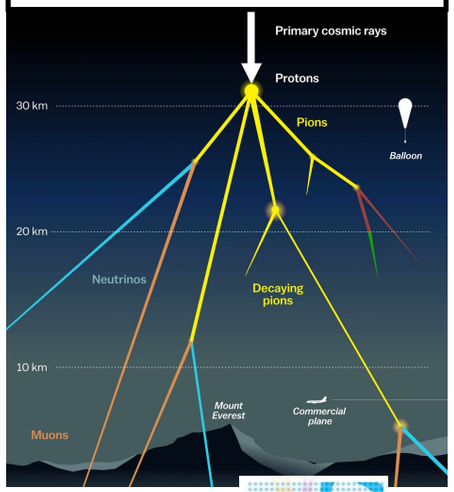
Δm^2_{23} Δm^2_{12}

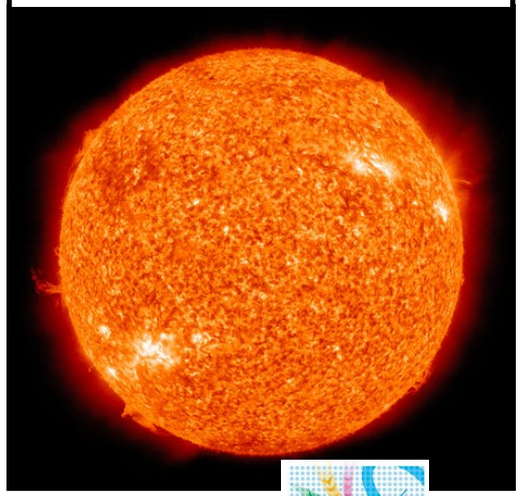
Atmospheric



Accelerator

Reactor

Solar



Different experiments have different typical L/E, allowing to explore different sets of parameters

Current Knowledge & Challenges

Hyper-Kamiokande

Entering in the era of precision ν measurements

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \cdot \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix} \cdot \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \cdot \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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$\delta_{CP} : 39\%[100\%]$ $\quad$ $|\Delta m^2_{3\ell}| : 2.2\%\,[6.7\%]$ $\quad$ $\Delta m^2_{21} : 5.5\%\,[16\%]$

https://arxiv.org/pdf/2007.14792.pdf

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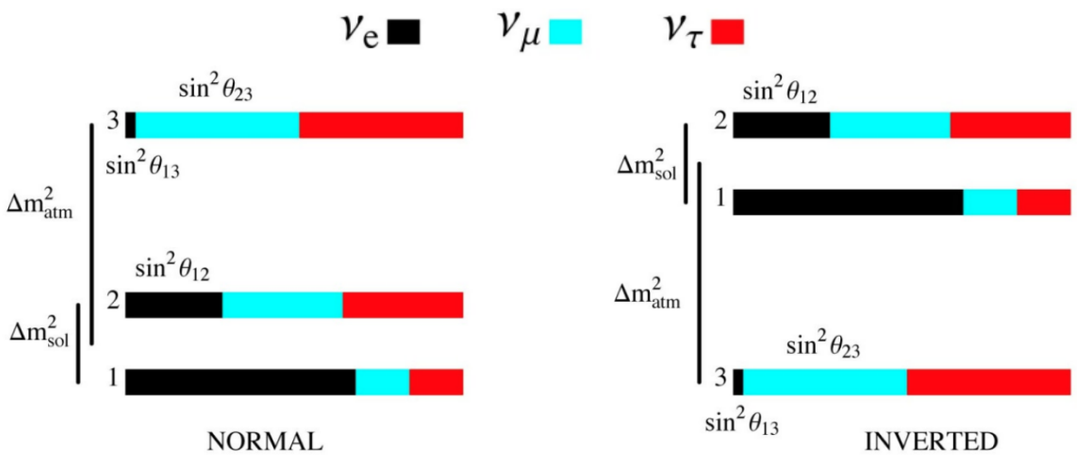
Which is the MO?



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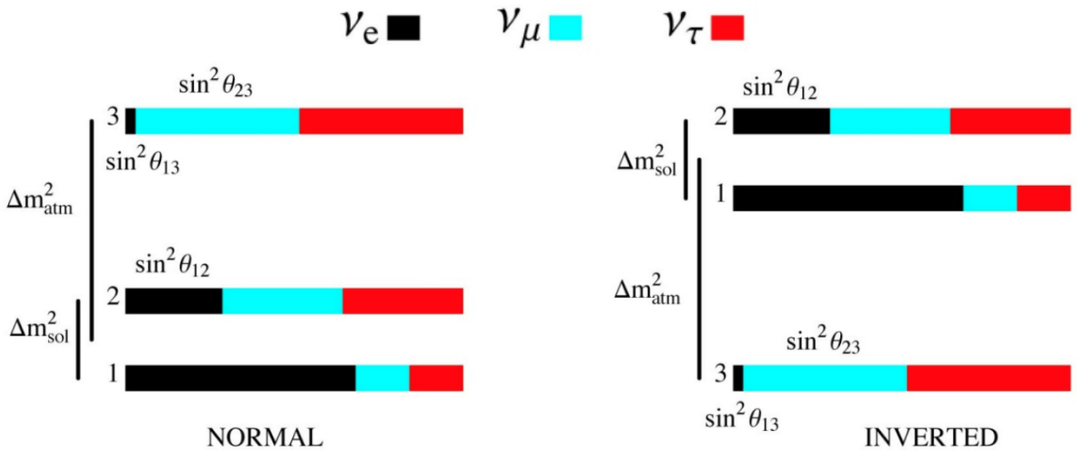
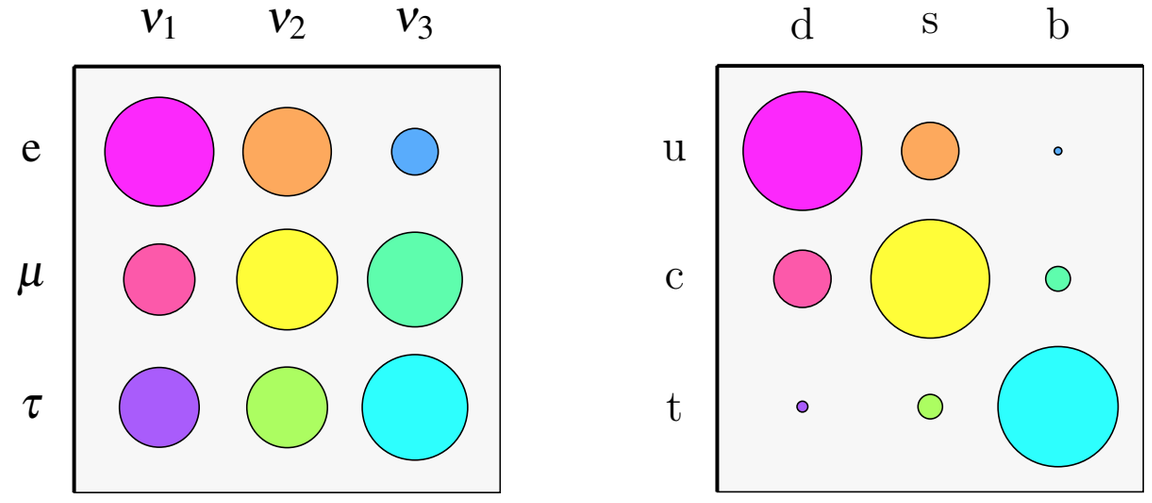


Flavor pattern?



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Are neutrino oscillations CP-violating?

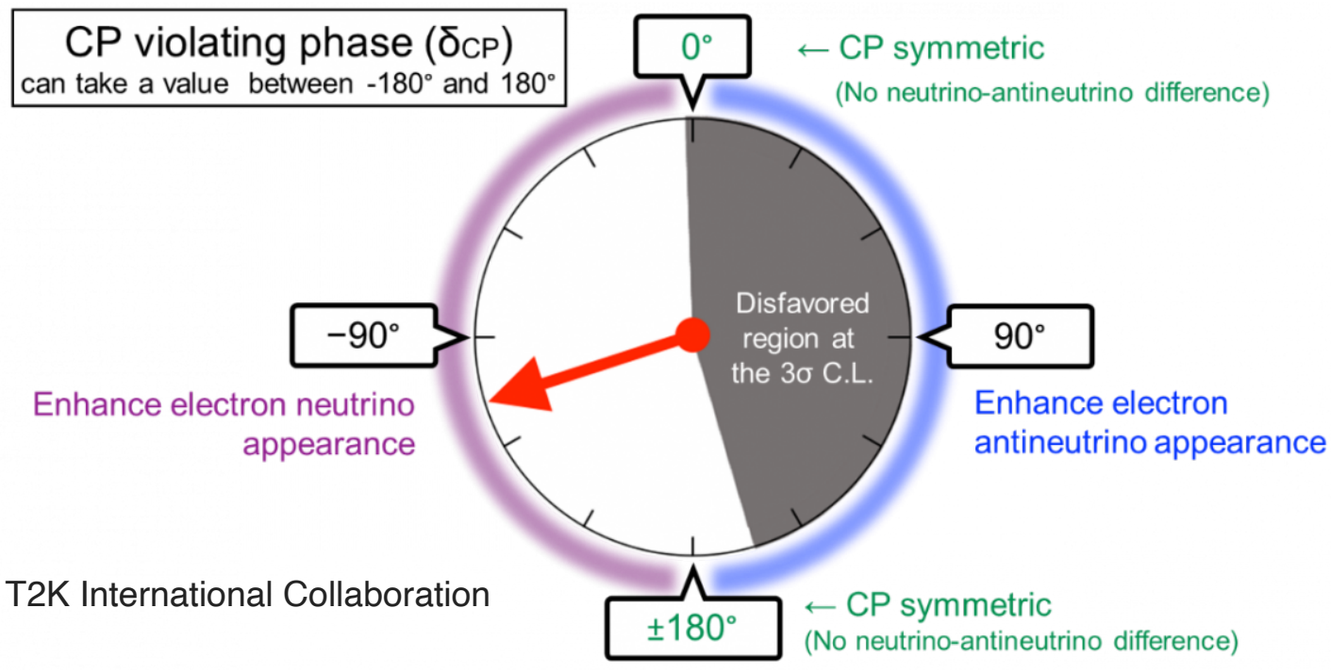
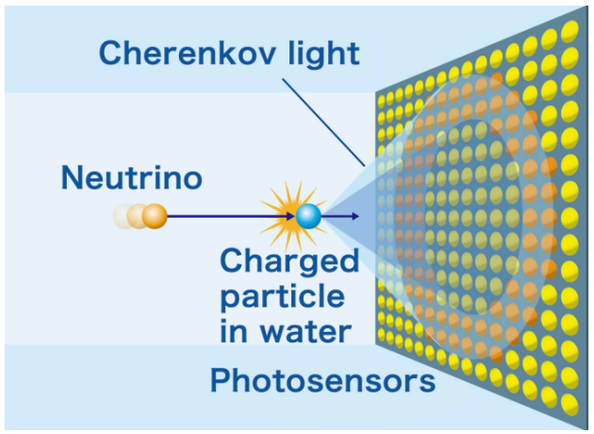


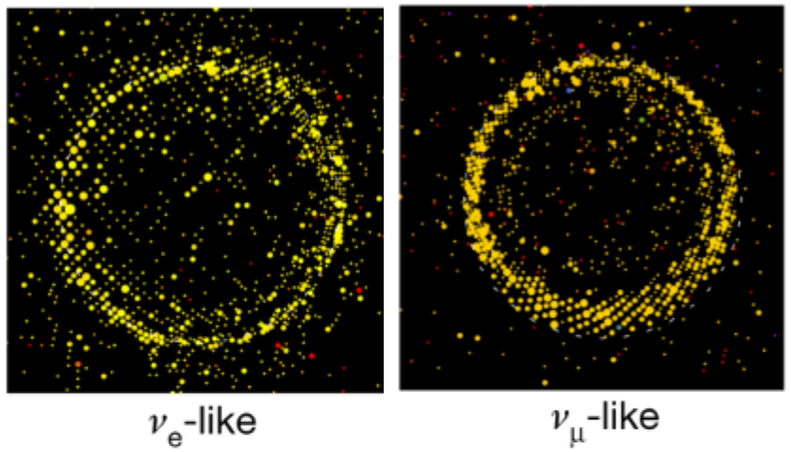
Image Credit: T2K International Collaboration

Kamioka Water Cherenkov Experiments

Hyper-Kamiokande

Particle ID depends on ring

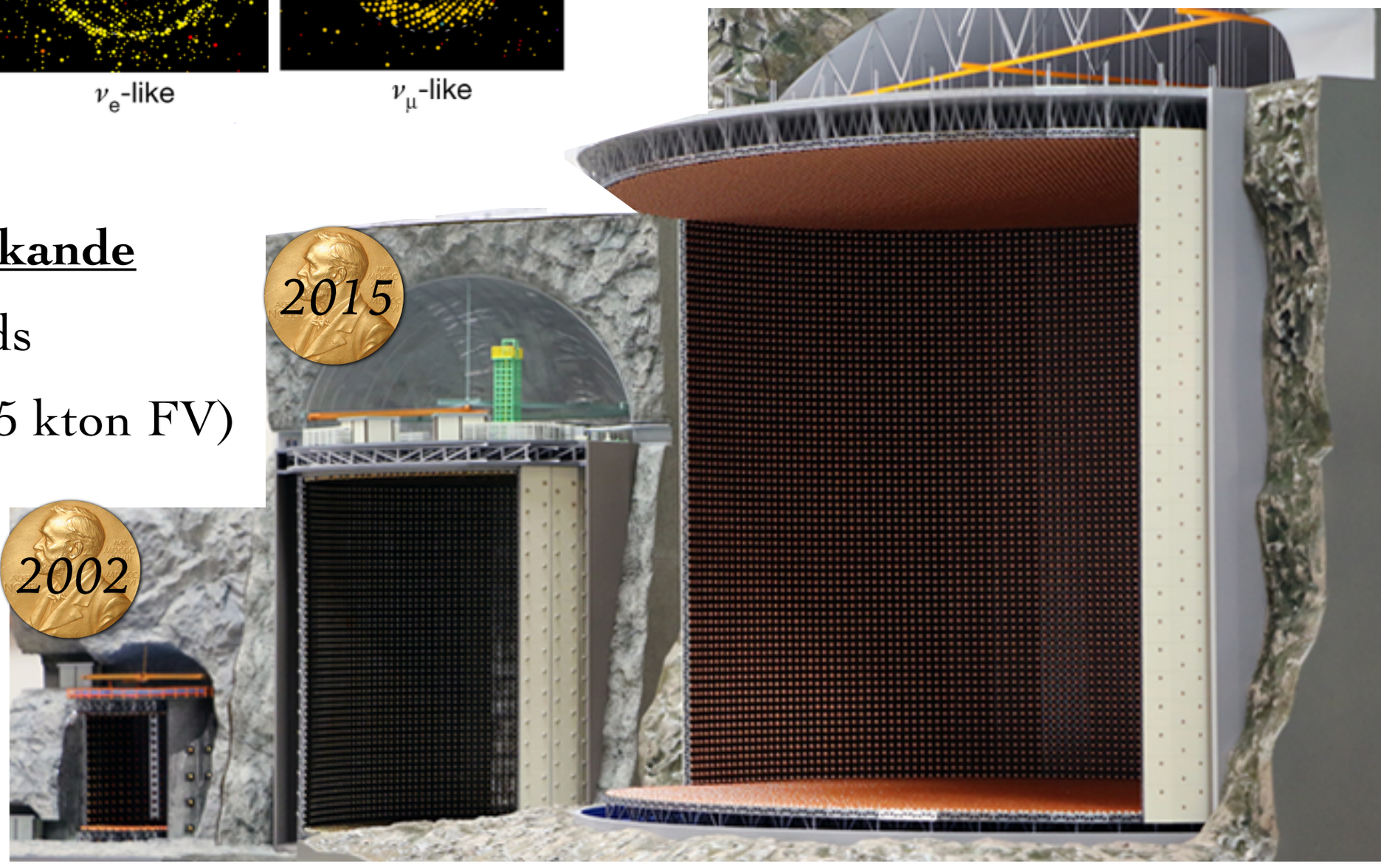




Hyper-Kamiokande

- 2027 onwards
- 258 kton (188 kton FV)

x8



x20

Super-Kamiokande

- 1996 onwards
- 50 kton (22.5 kton FV)

KamiokaNDE

- 1983-1996
- 3 kton

Kamioka Water Cherenkov Experiments

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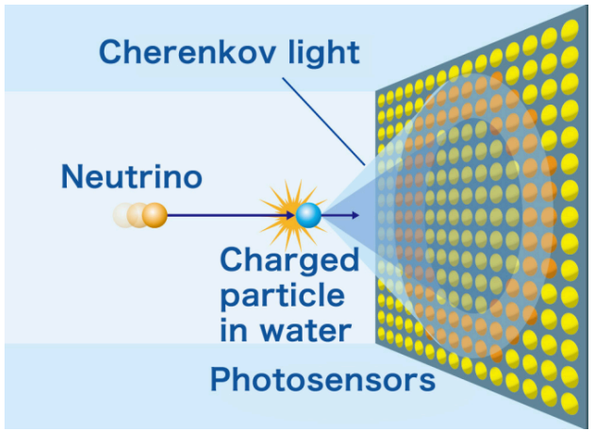

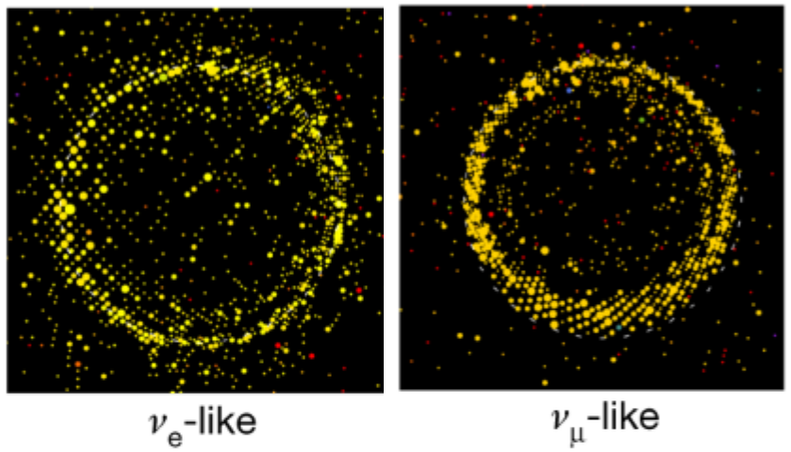

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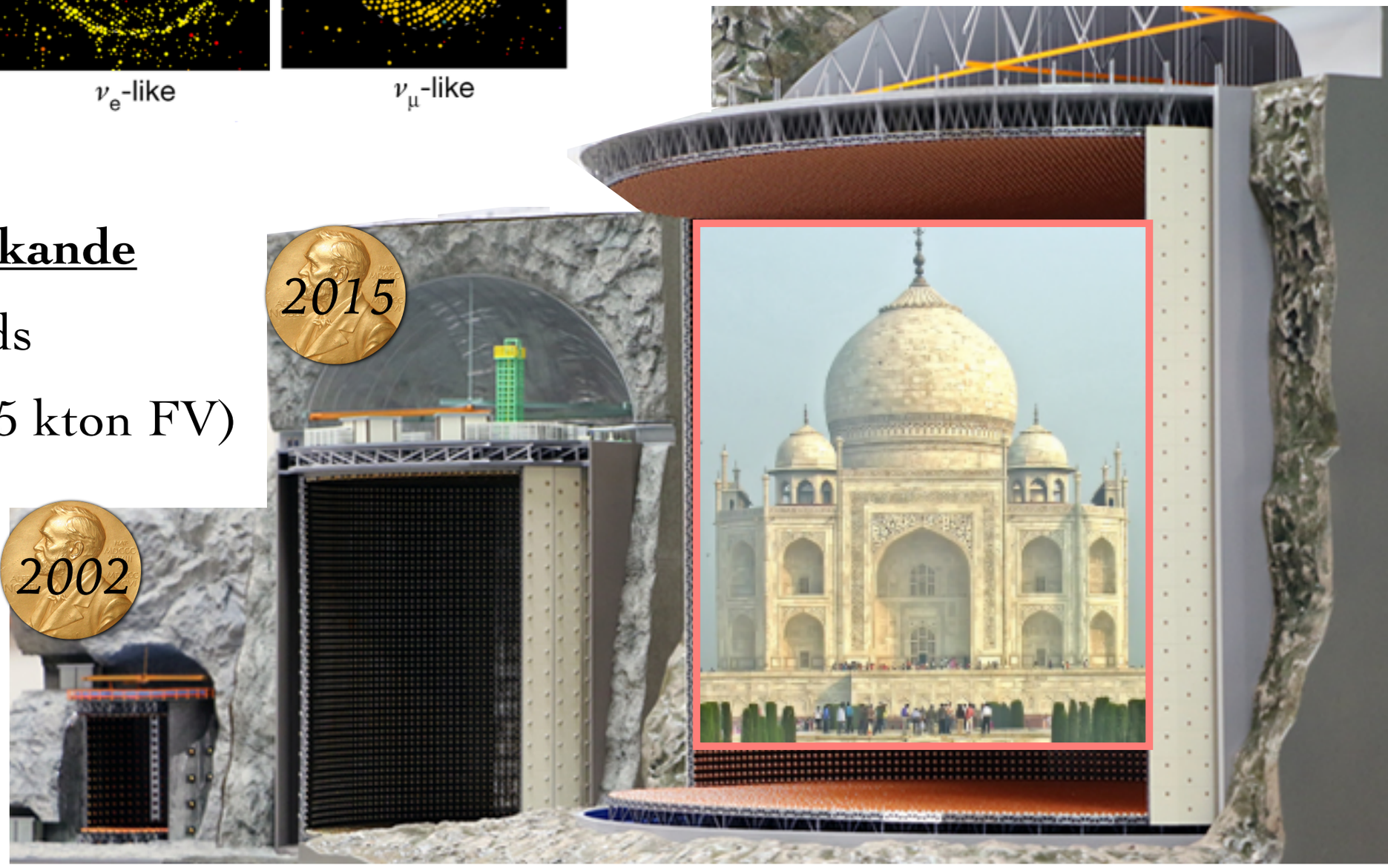


Existing Experiments

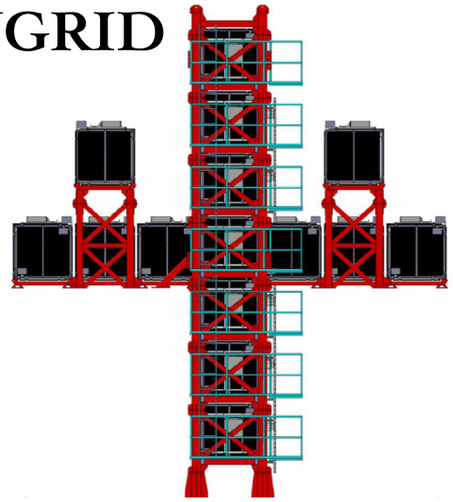
Hyper-Kamiokande

Existing Experiments

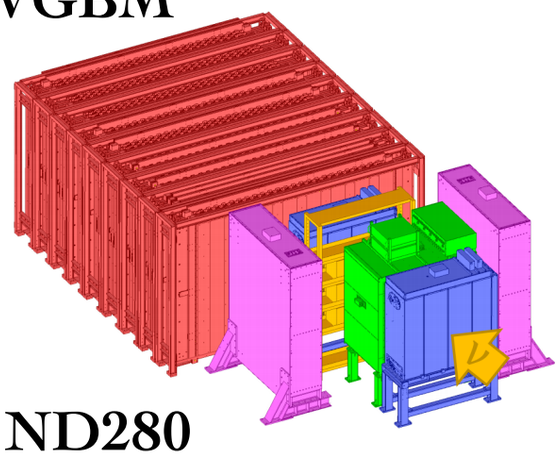
Hyper-Kamiokande

Near Detectors

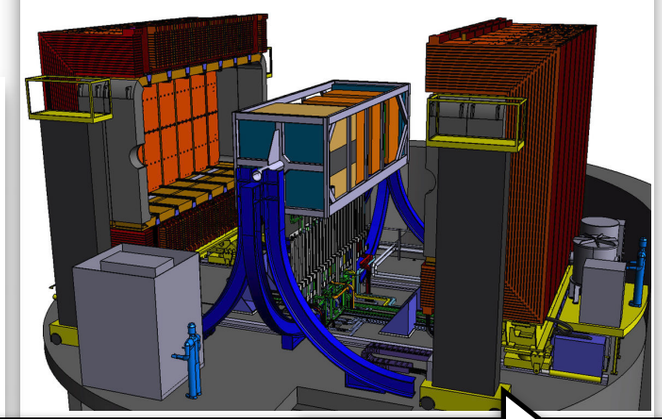
INGRID



WGBM



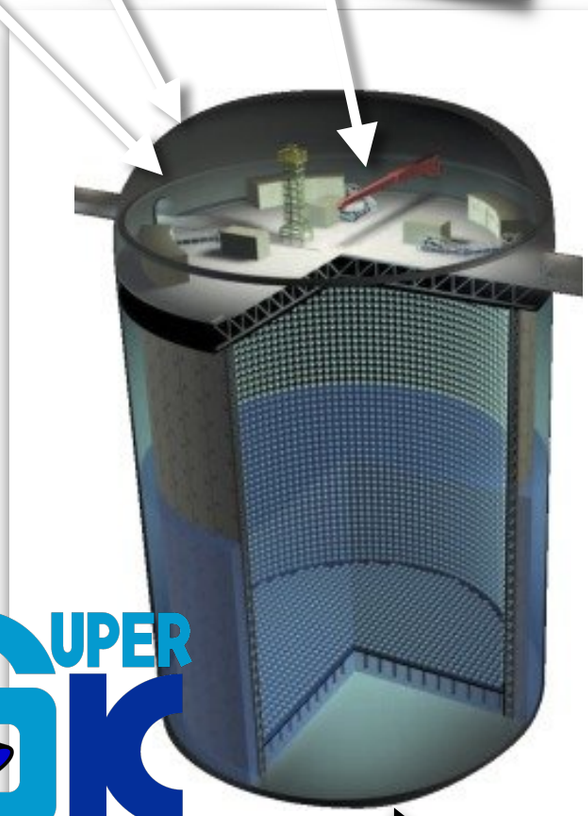
ND280



大強度陽子加速器施設

J-PARC

Japan Proton Accelerator Research Complex



SUPER-K

280 m — T2K — 295 km

The Hyper-Kamiokande Experiment

Hyper-Kamiokande

Hyper-Kamiokande

- Extremely broad physics program combining and extending capabilities of SK and T2K

大強度陽子加速器施設
J-PARC
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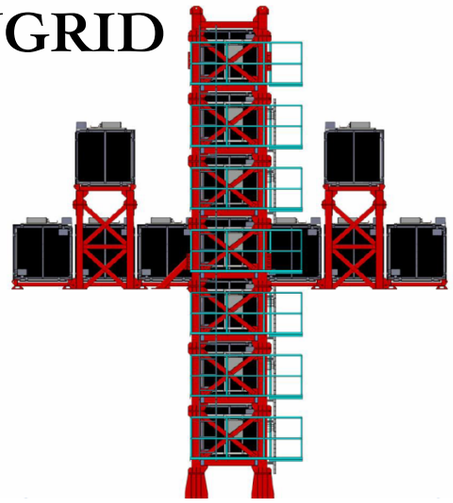
Near Detectors

INGRID



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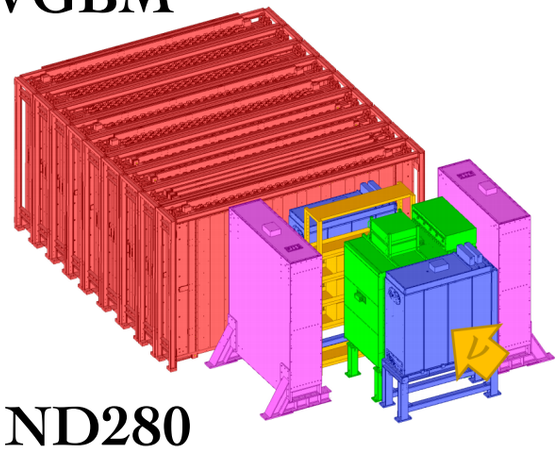

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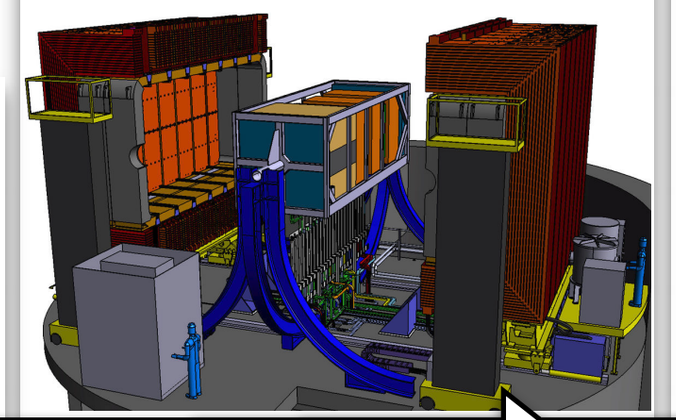
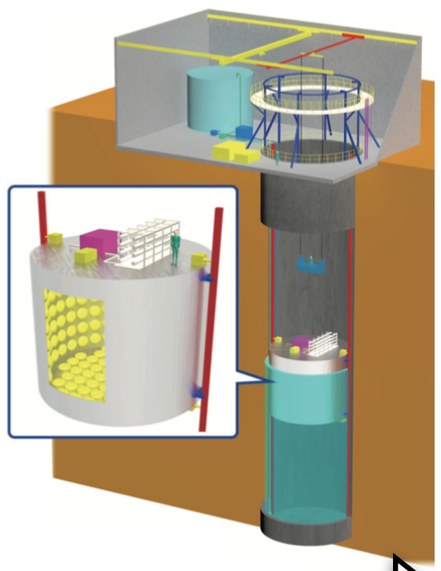
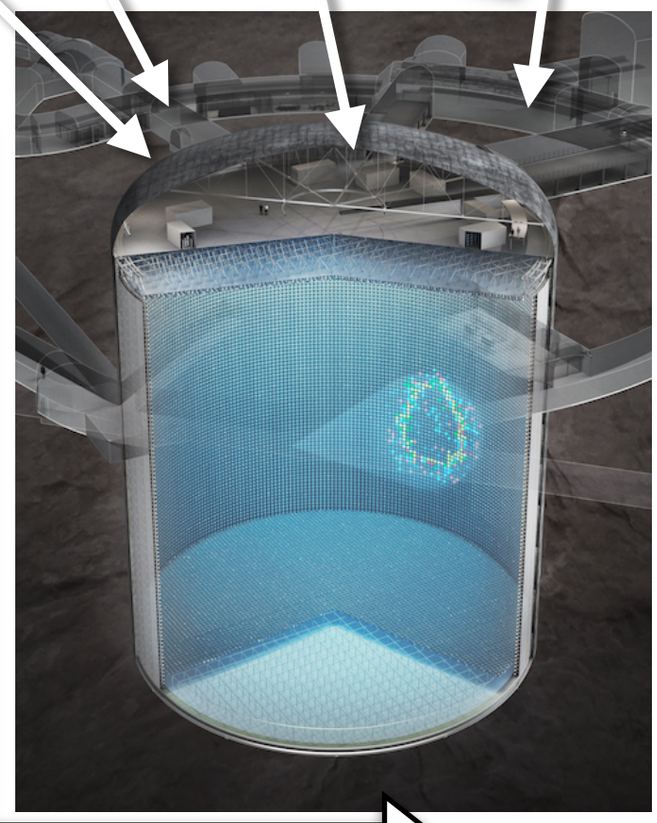


Intermediate Detector

IWCD





280 m ~1 km 295 km

The Hyper-Kamiokande Status

2020

HK MoU signed

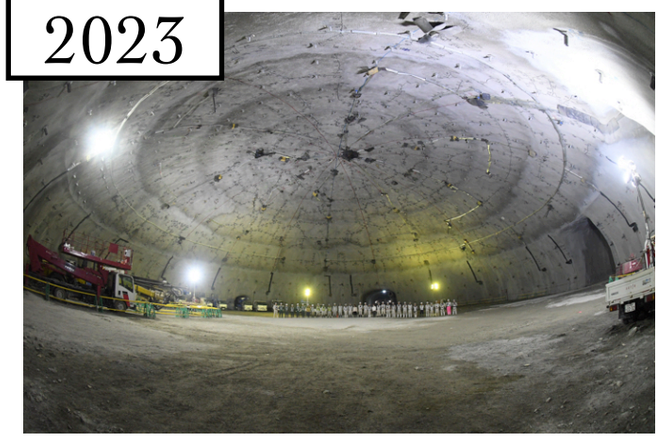
2021

Started PMT production

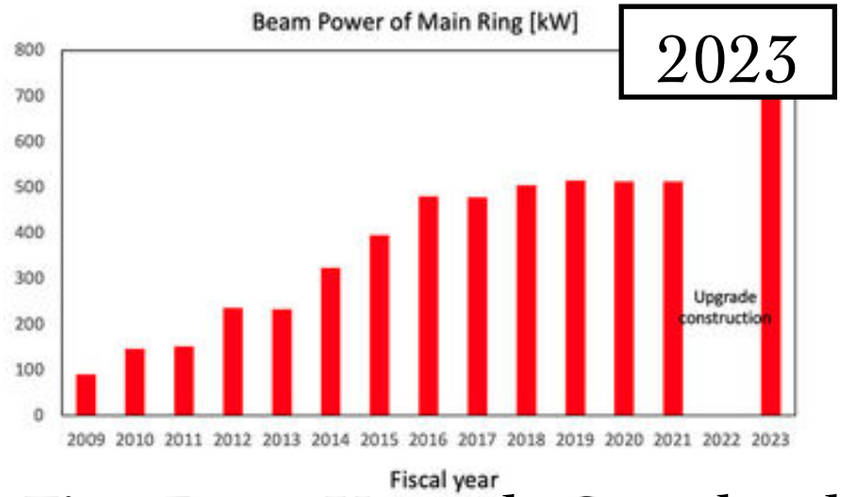
2022

Dome Center Reached

2023

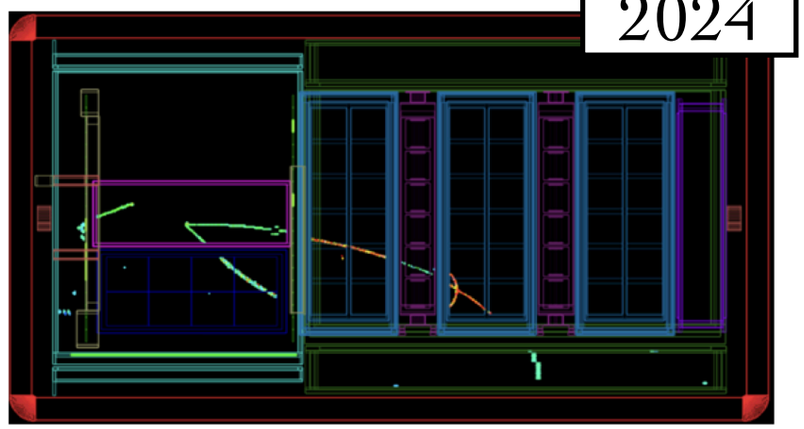


Cavern Dome Completed



First Beam Upgrade Completed

2024



ND280 upgrade completed

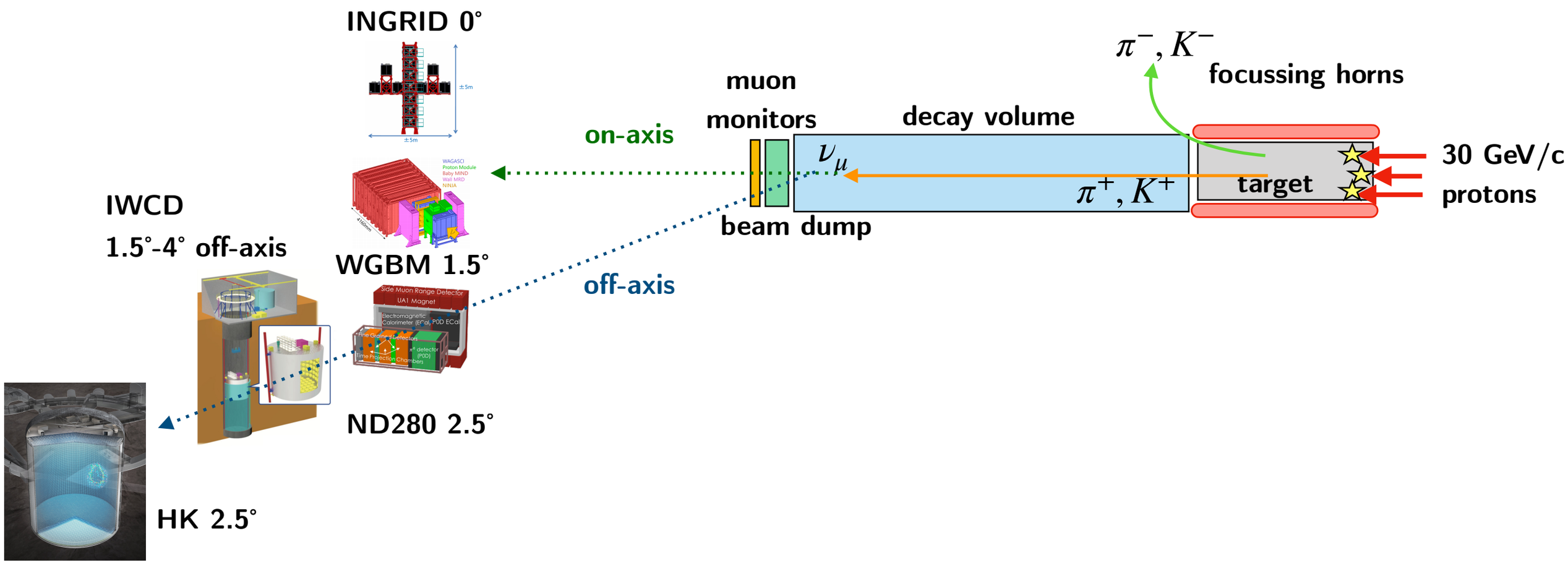
Next Steps

2024 → 2025 → 2026 → 2027

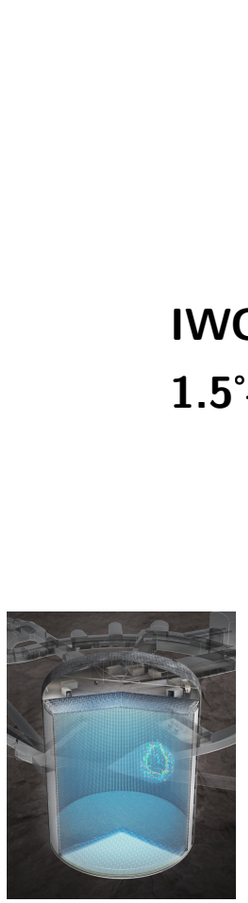
Tank Construction	Installation	H_2O Filling

~600 researchers, 22 countries

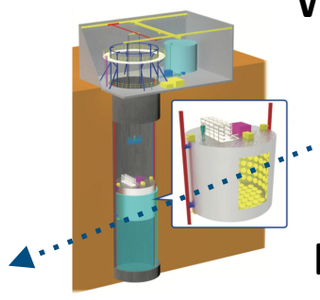
Beam


INGRID 0°
±5m
±5m
WAGASCI
Proton Module
Baby MIND
Wall MRD
NINJA
WGBM 1.5°
IWCD
1.5°-4° off-axis
Side Muon Range Detector
UA1 Magnet
Electromagnetic
Calorimeter (ECal, P0D ECal)
Fine Grained Detectors
π⁰ detector
(P0D)
Time Projection Chambers
ND280 2.5°
HK 2.5°
on-axis
off-axis
muon
monitors
beam dump
decay volume
ν_μ
π^+, K^+
π^-, K^-
focussing horns
target
30 GeV/c
protons

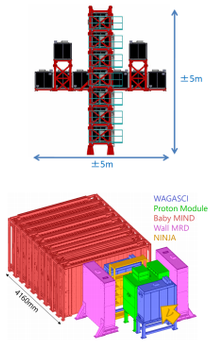
Beam



HK 2.5°

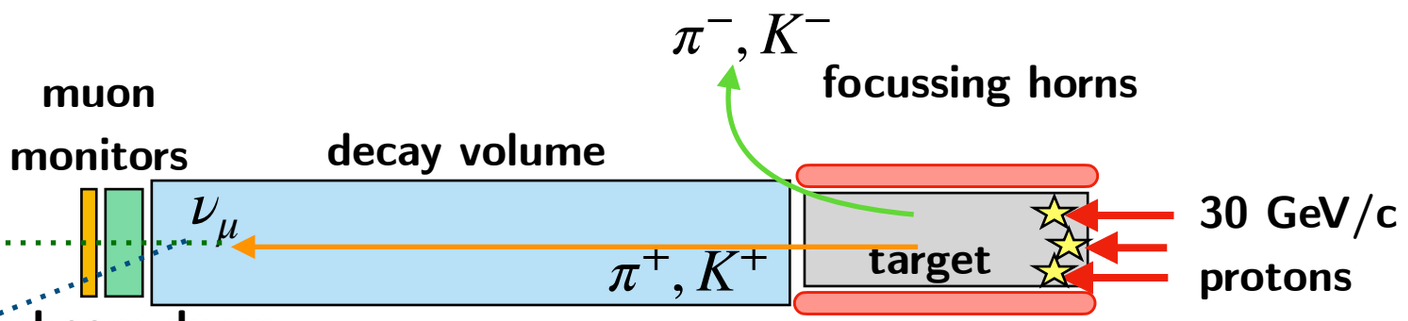


IWCD
1.5°-4° off-axis

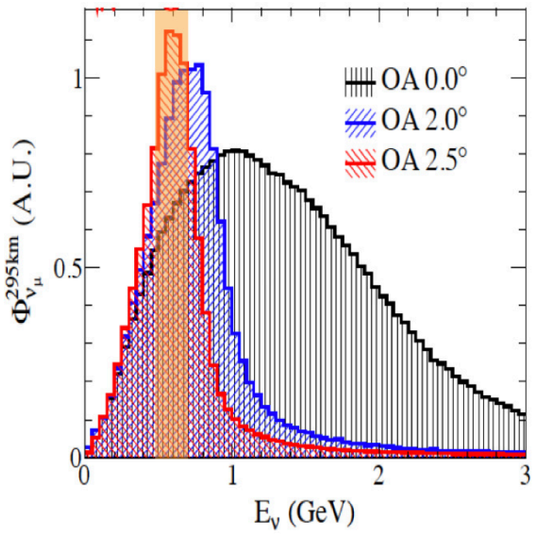


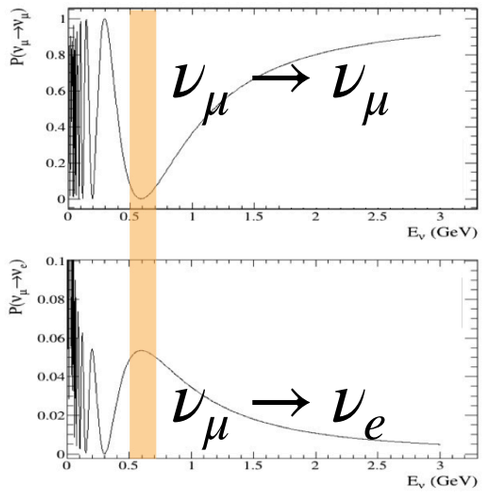
on-axis

off-axis

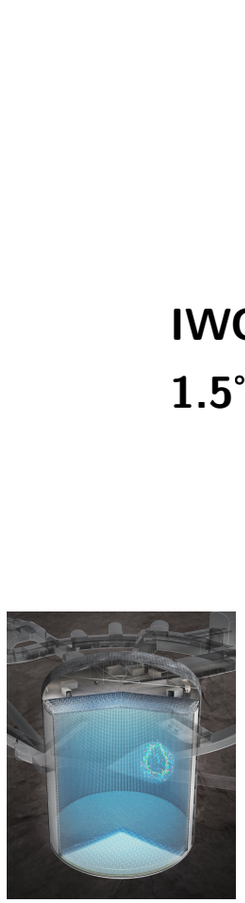


Typical beam energy $E_\nu \approx 0.6$ GeV



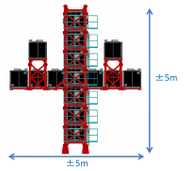


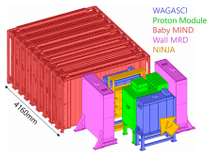
Beam



HK 2.5°

INGRID 0°

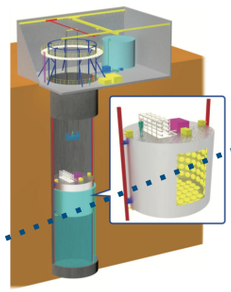


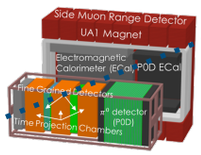


WGBM 1.5°

IWCD

1.5°-4° off-axis

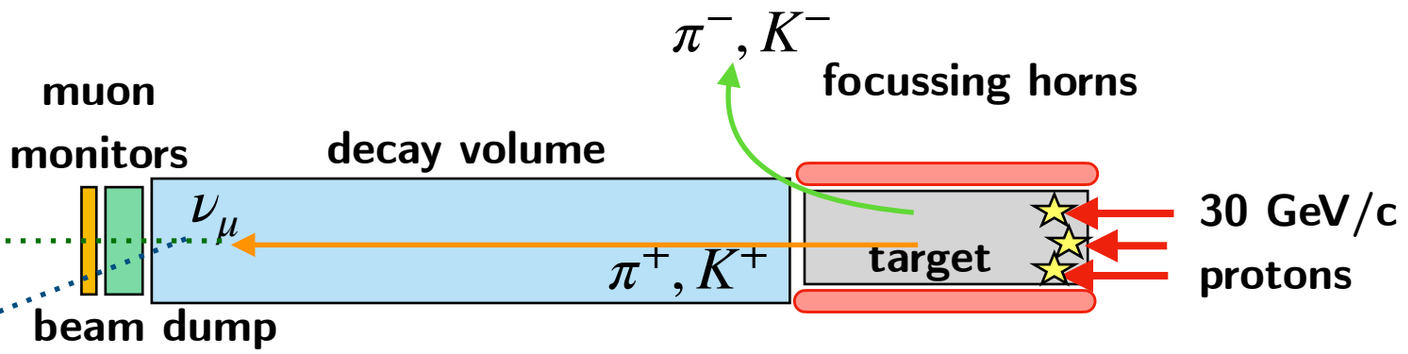




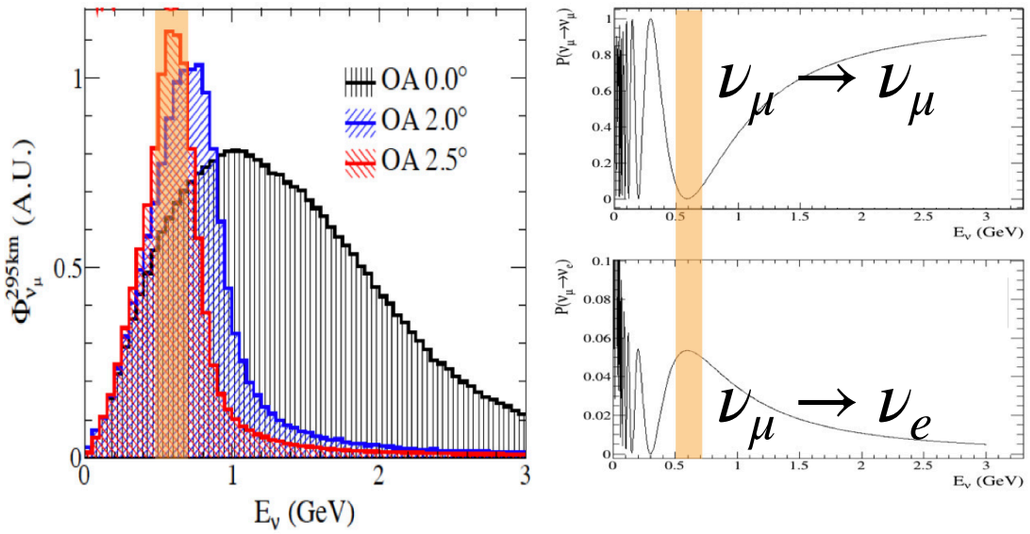
ND280 2.5°

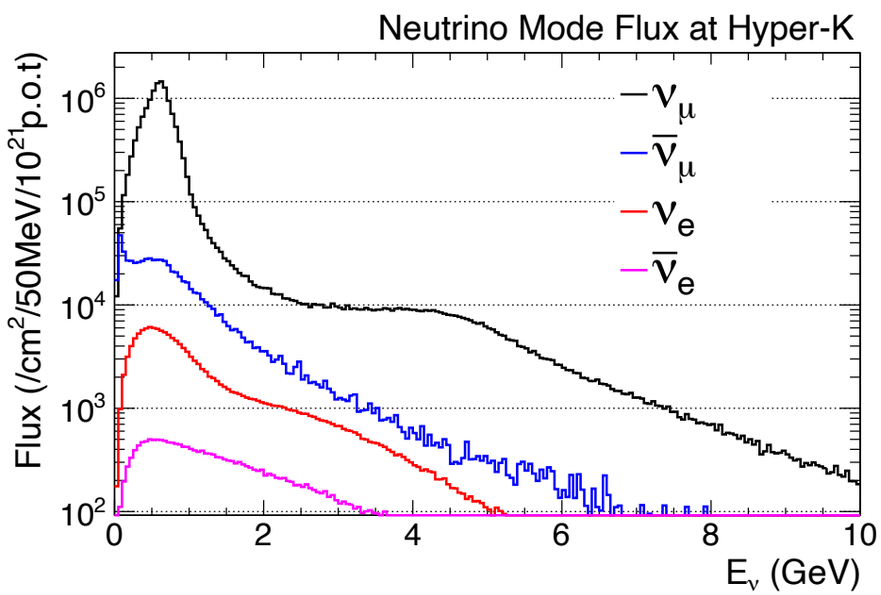
on-axis

off-axis



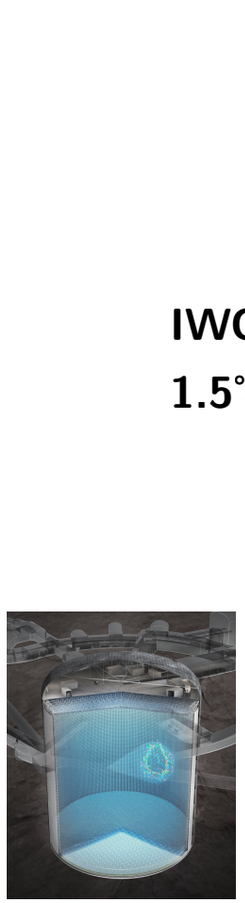
Typical beam energy $E_\nu \approx 0.6$ GeV



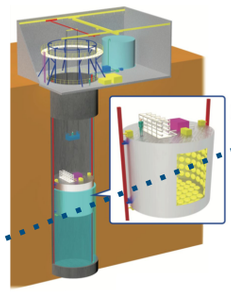


Highly pure ν_μ or $\bar{\nu}_\mu$ beam

Beam



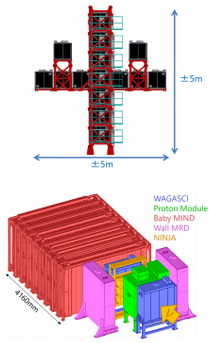
HK 2.5°



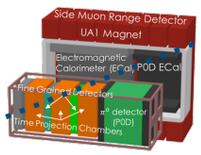
ND280 2.5°

IWCD

1.5°-4° off-axis



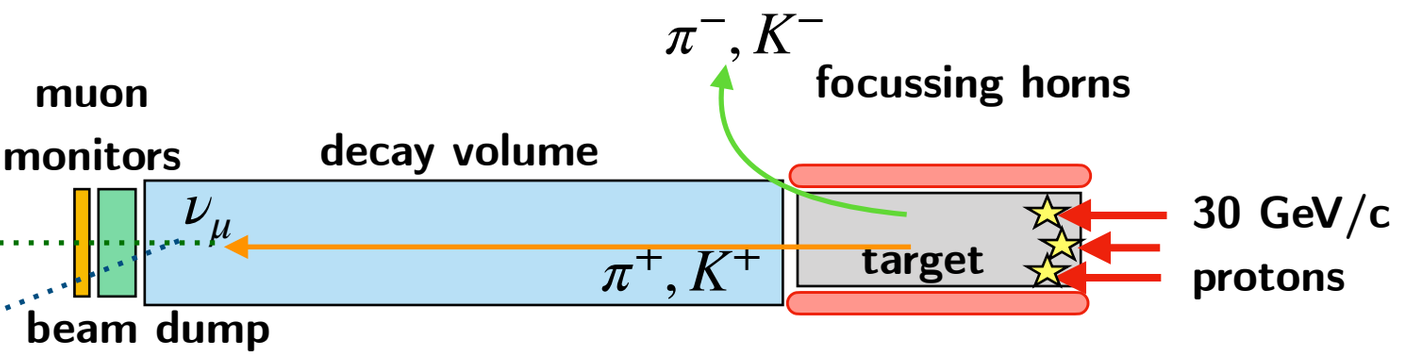
WGBM 1.5°



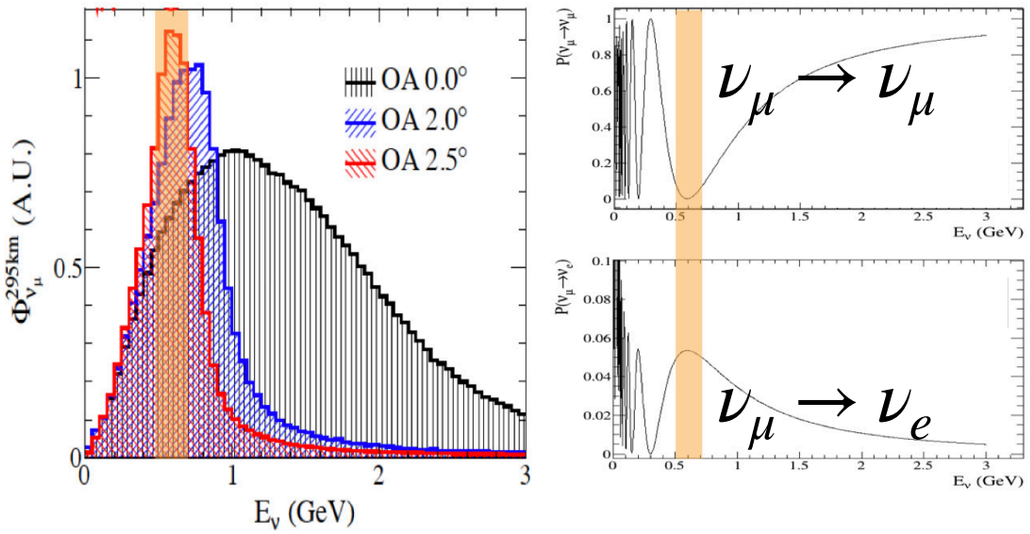
INGRID 0°

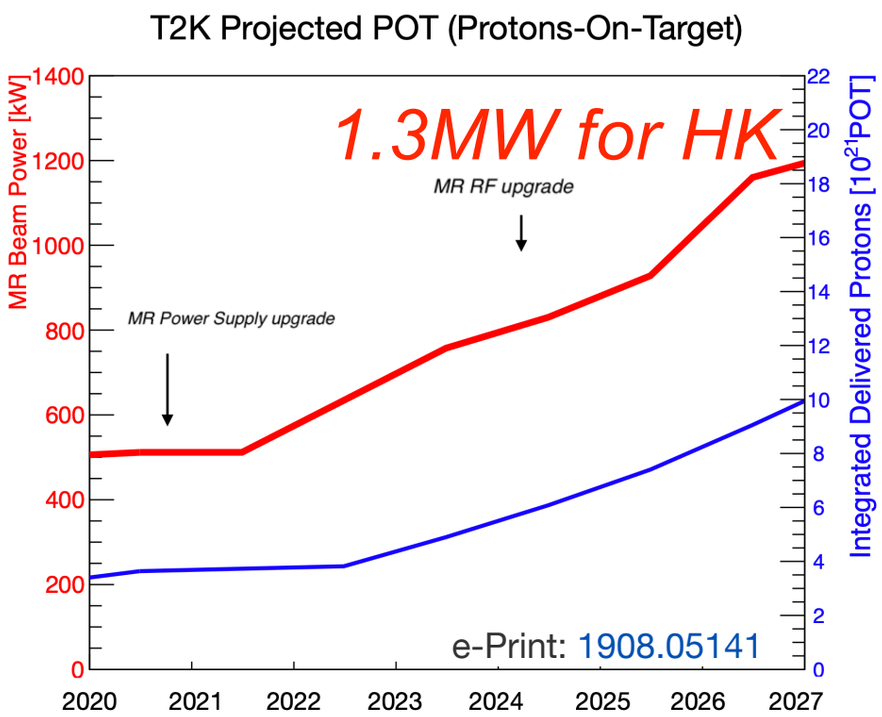
on-axis

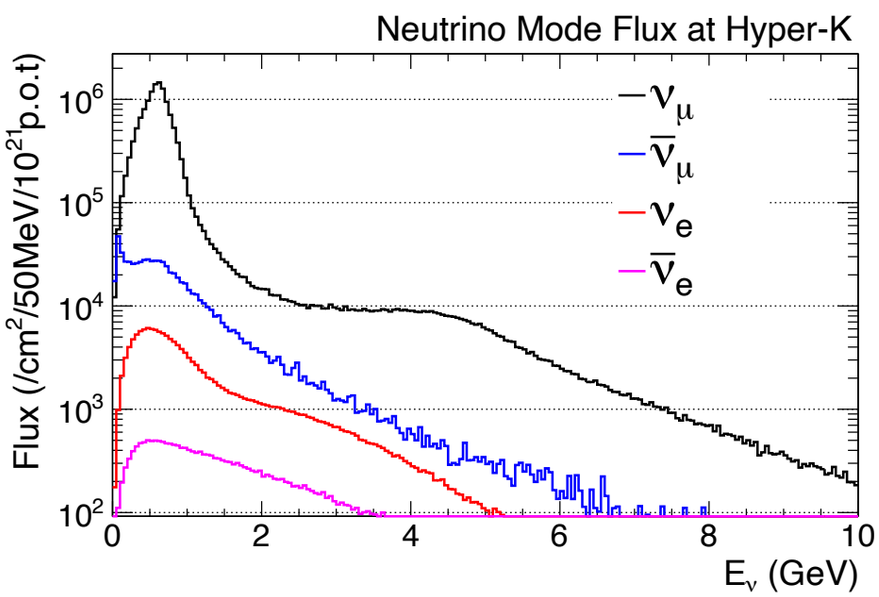
off-axis



Typical beam energy $E_\nu \approx 0.6$ GeV







Highly pure ν_μ or $\bar{\nu}_\mu$ beam

The role of the near detectors

Hyper-Kamiokande

Event rate prediction

$$N_i^{exp}(E_\nu) = \underbrace{P(\nu_\alpha \to \nu_\beta)}_{\text{Oscillation probability}} \times \sigma_i(E_\nu) \times \underbrace{\Phi_\nu(E_\nu)}_{\text{Neutrino flux}} \times \epsilon_i(E_\nu)$$

$N_i^{exp}(E_\nu)$: Expected event rate

$\sigma_i(E_\nu)$: Interaction cross-section

$\epsilon_i(E_\nu)$: Detector efficiency

In the near detector

$$P(\nu_\alpha \to \nu_\beta) \simeq 1$$

We get to learn about

$$\sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$$

The role of the near detectors

Hyper-Kamiokande

Event rate prediction

$$N_i^{exp}(E_\nu) = P(\nu_\alpha \to \nu_\beta) \times \sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$$

Oscillation probability — Neutrino flux

Expected event rate — Interaction cross-section — Detector efficiency

In the near detector

$$P(\nu_\alpha \to \nu_\beta) \simeq 1$$

We get to learn about

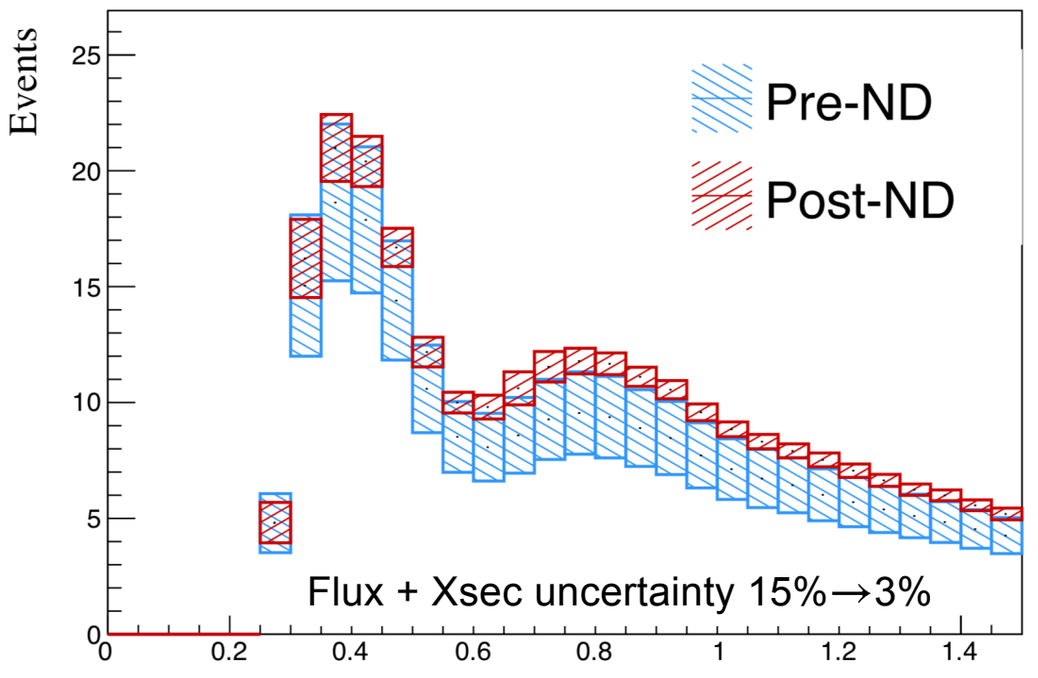
$$\sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$$

Uncertainties in T2K (arXiv:2101.03779)

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI+SI+PN	2.2	2.0	3.0	2.3	11.4	1.6
Flux + Xsec (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
Nucleon Removal Energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23} + \Delta m^2_{21}$	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All Systematics	5.1	4.5	8.8	7.1	18.4	6.0

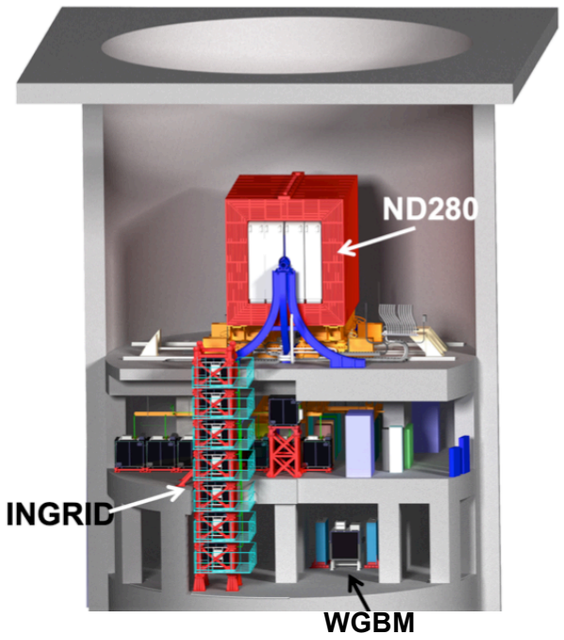
Only possible thanks to ND constraint:

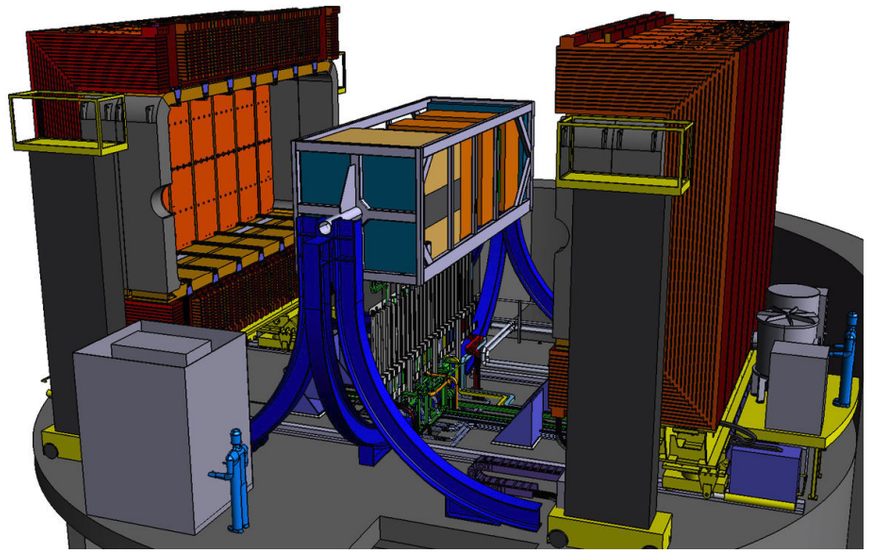
Flux + Xsec (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2

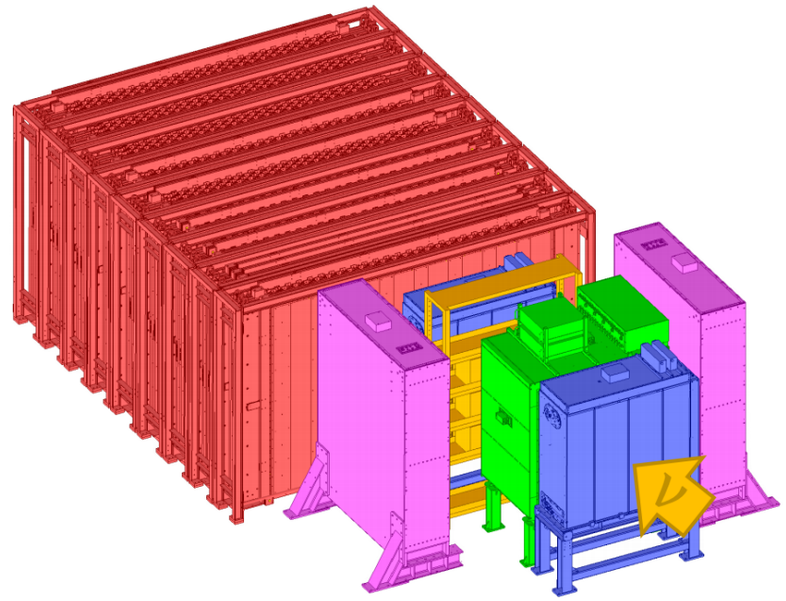


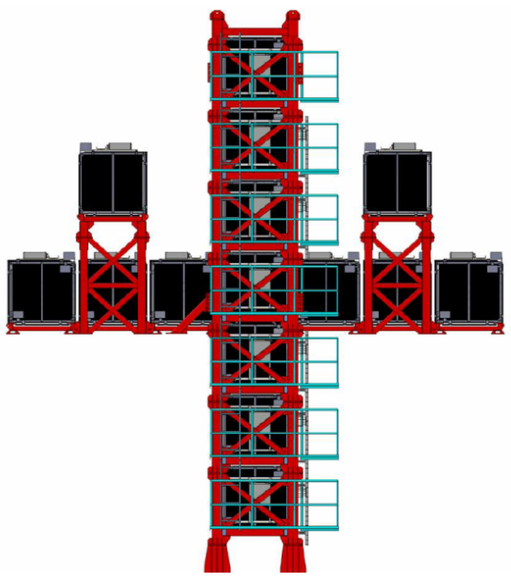
Phys.Rev.D 103 (2021) 1, L011101 • e-Print: 2008.07921

Near Detectors









INGRID

- Beam Direction, Intensity and Stability.

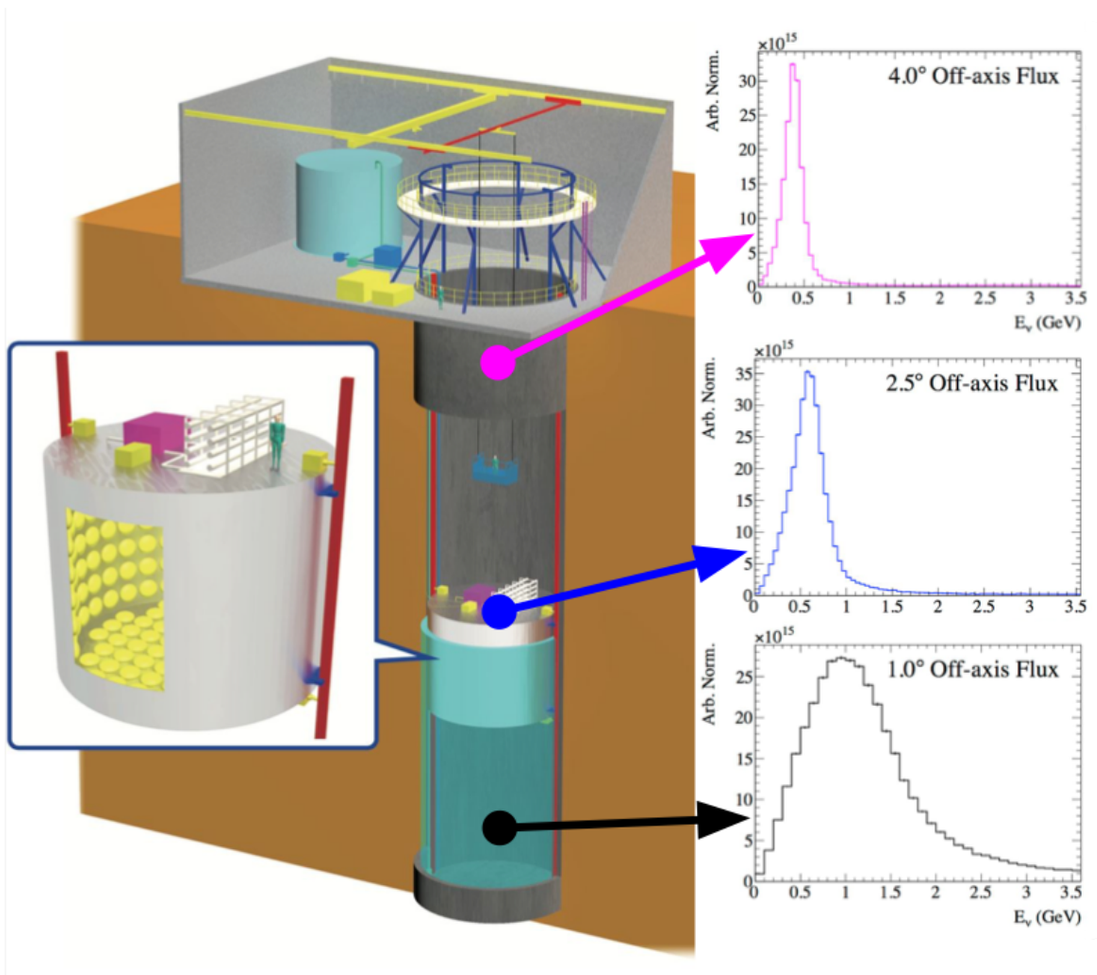
ND280

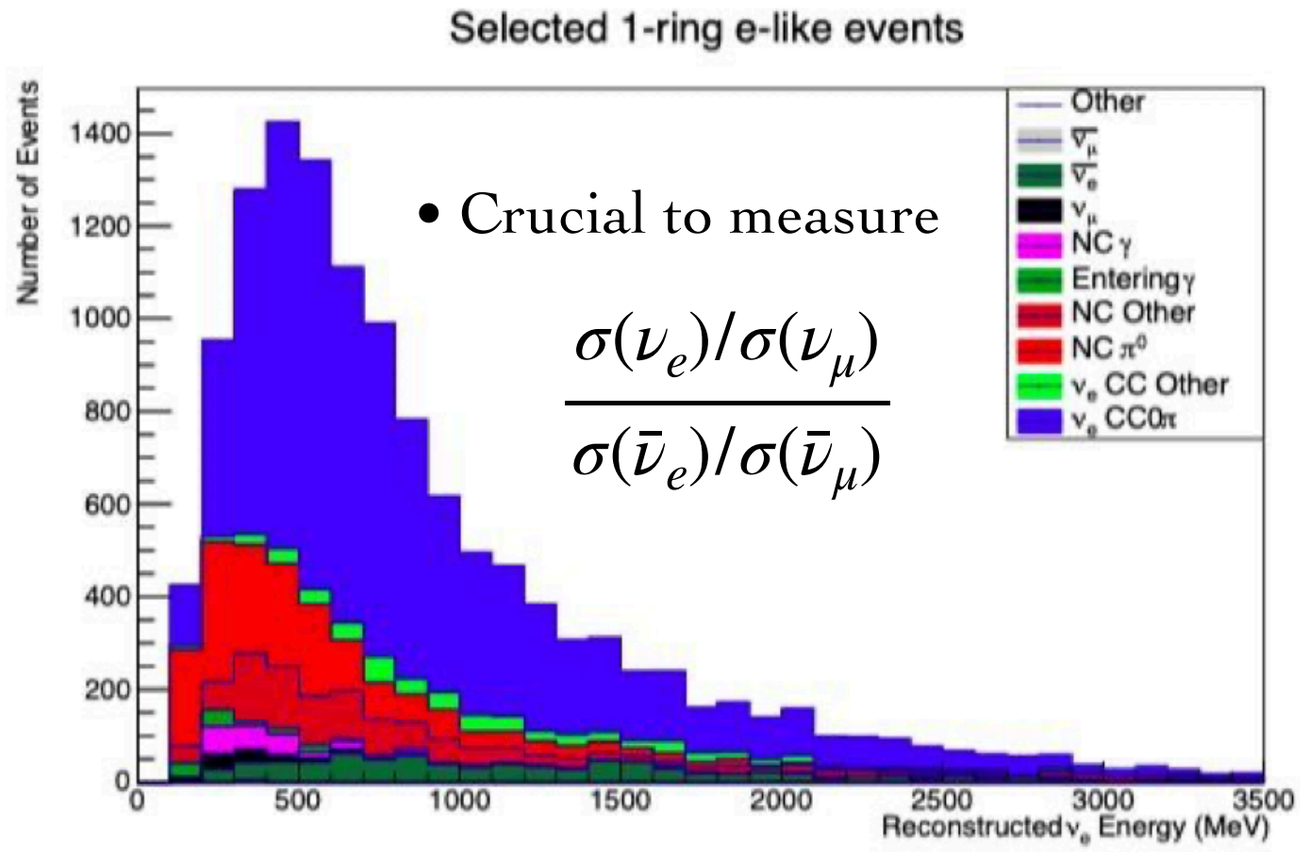
- Main near detector, has been crucial for T2K.
- Detailed measurements of neutrino interactions in plastic and water.
- >20 neutrino cross section publications in the last decade.
- Magnetized detector with excellent PID and angular coverage.

WGBM

- New detector, collecting most of its data recently.
- Meant to complement ND280: Additional plastic and water targets at different off-axis.
- Magnetized detector with high forward acceptance.
- Hosts water-based nuclear emulsion NINJA experiment.

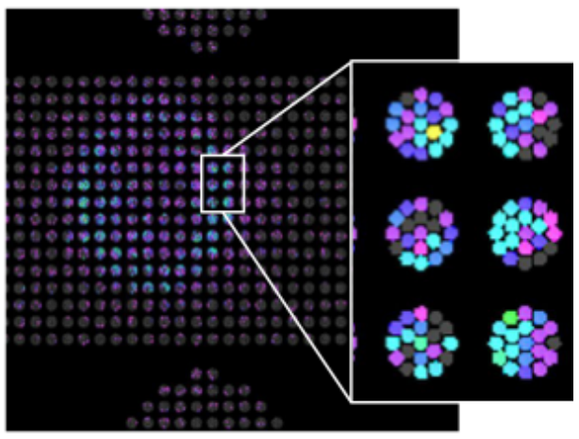
IWCD

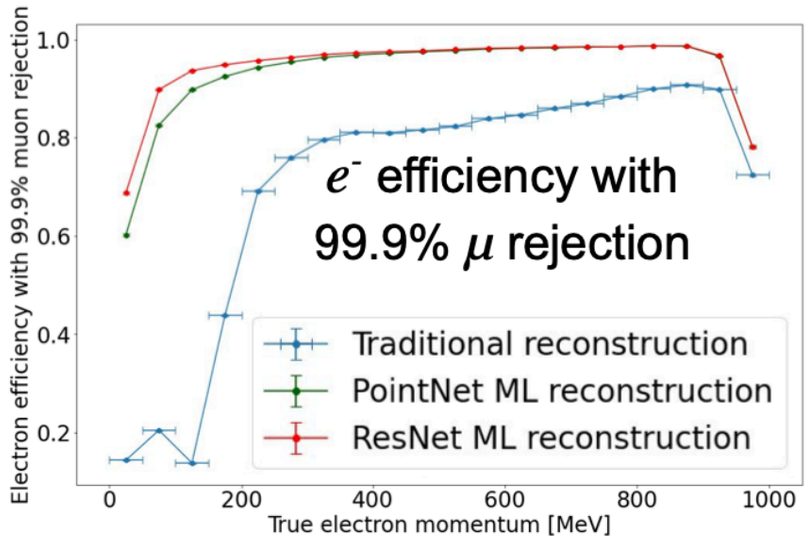




- Crucial to measure

$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$

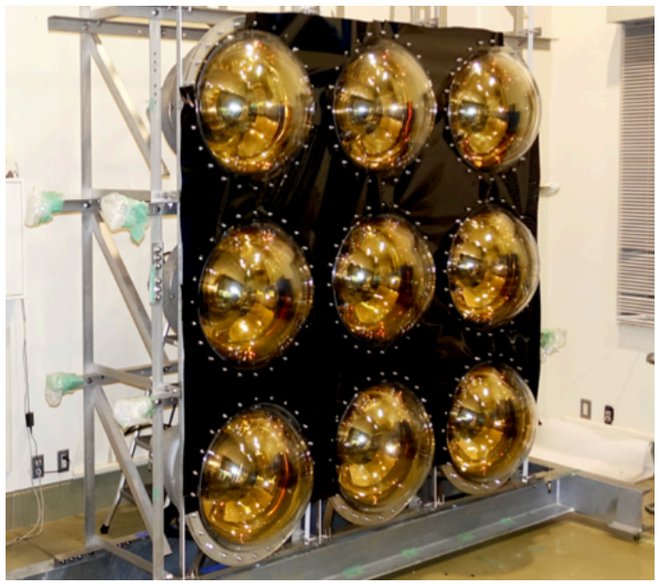




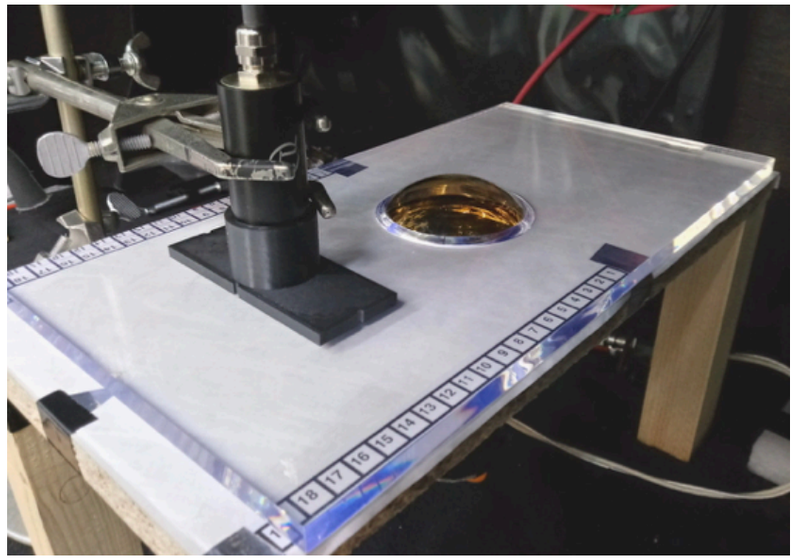
N.Prouse Lepton-Photon 2021

Hyper-K Far Detector R&D

- 20k 50cm PMTs with 2.6ns time resolution and 2× SK PMTs efficiency.

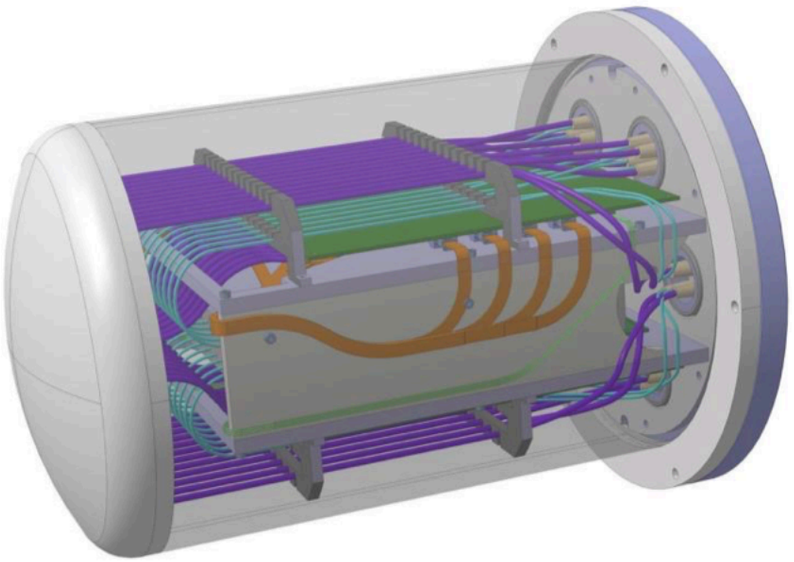


- 8 cm PMTs+WLS for OD

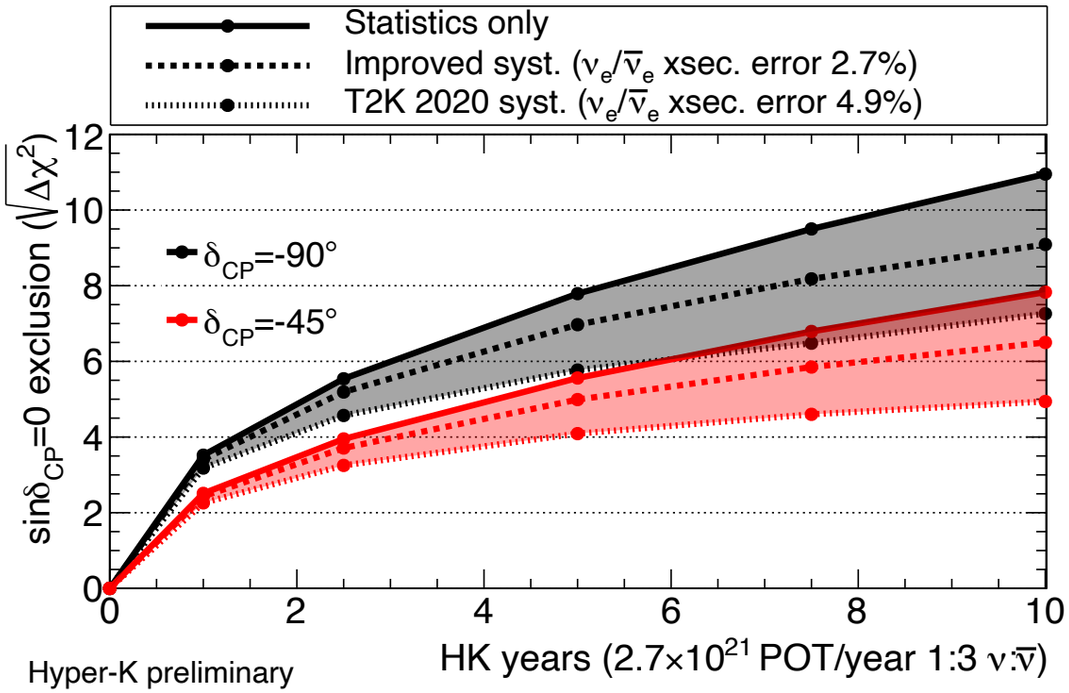


- mPMTs with 19 8cm PMTs: Direction information + improved spatial and timing resolution.

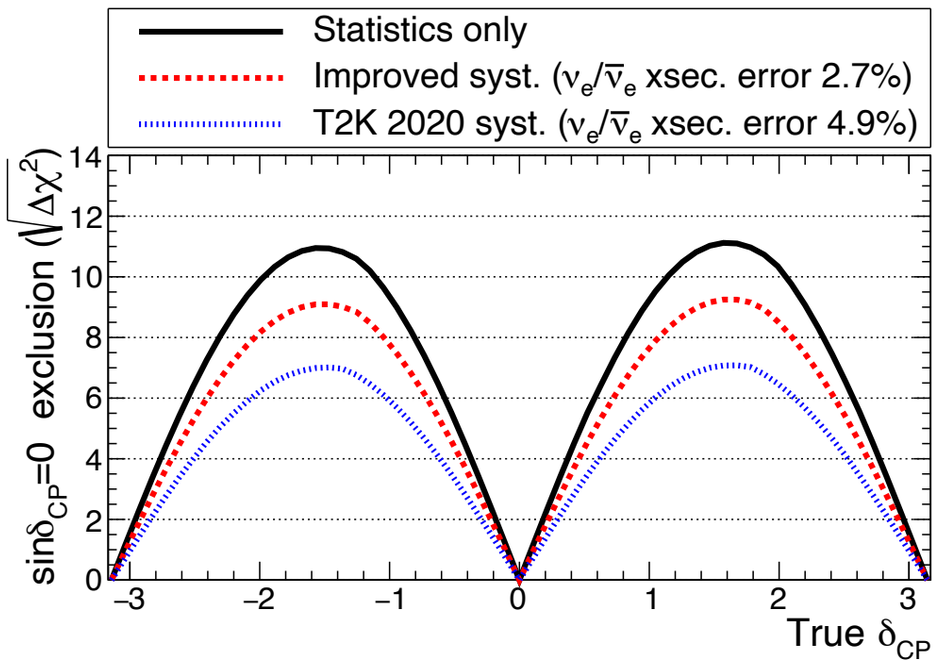
- Underwater electronics.



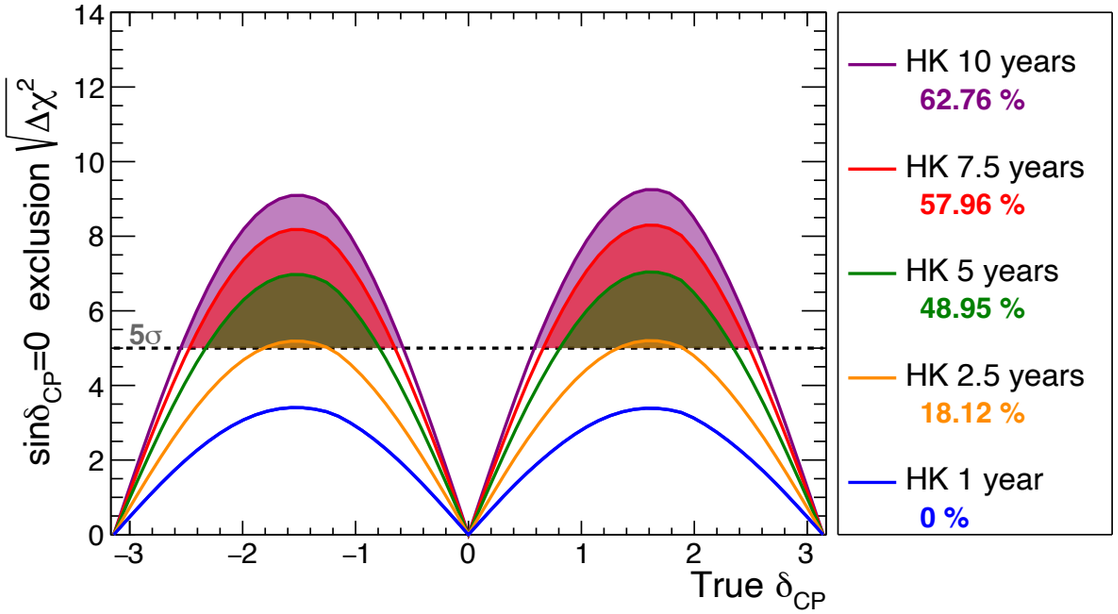
Accelerator Neutrino Physics - δ_{CP}



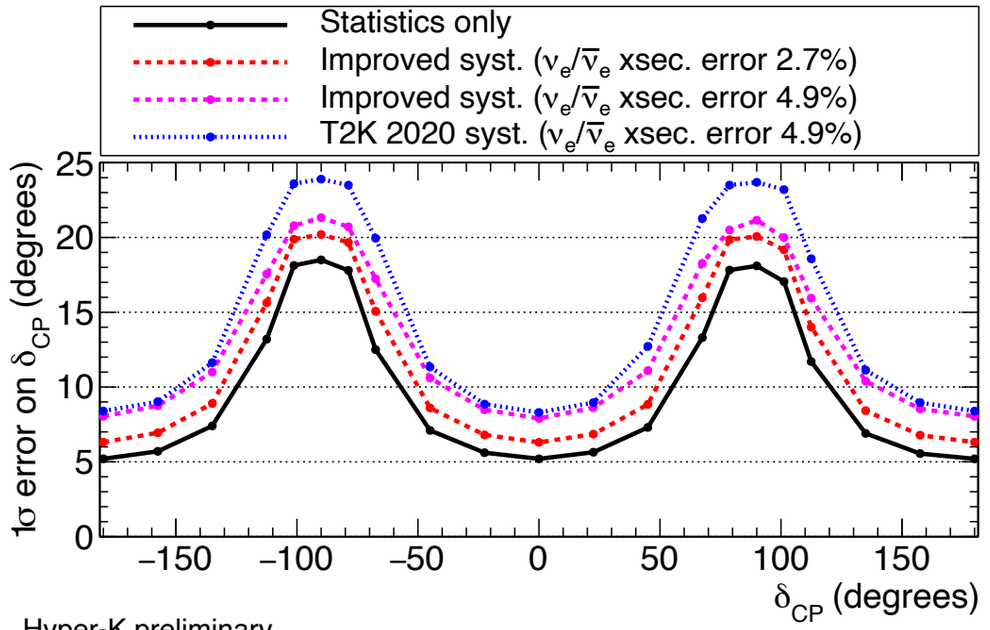
Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4



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



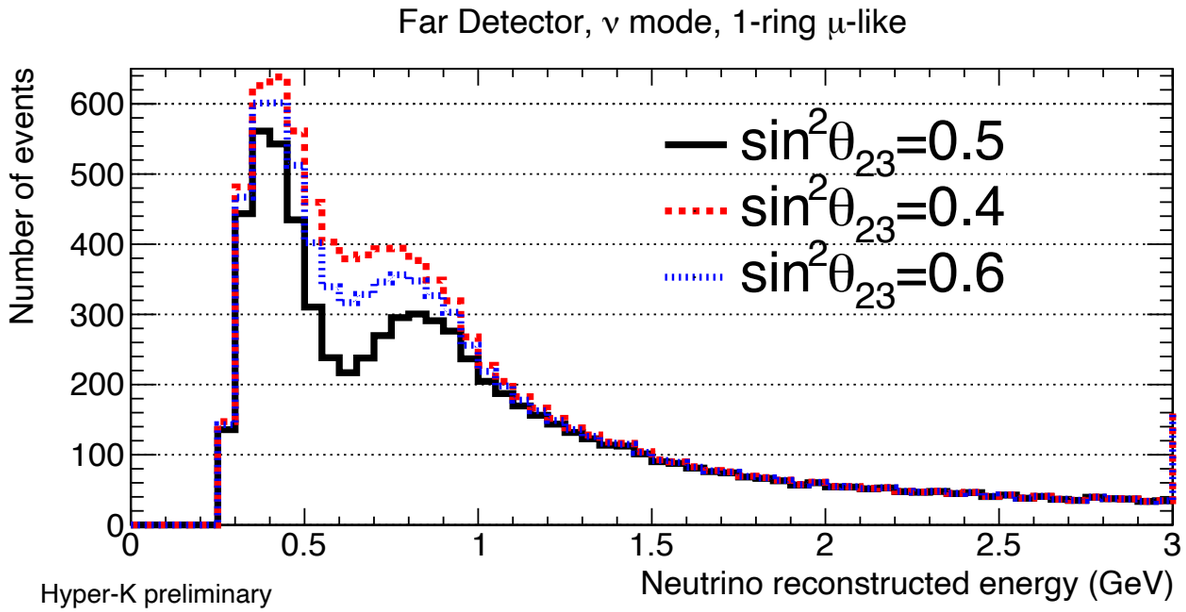
Hyper-K preliminary
True normal ordering (known), Improved systematics
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4



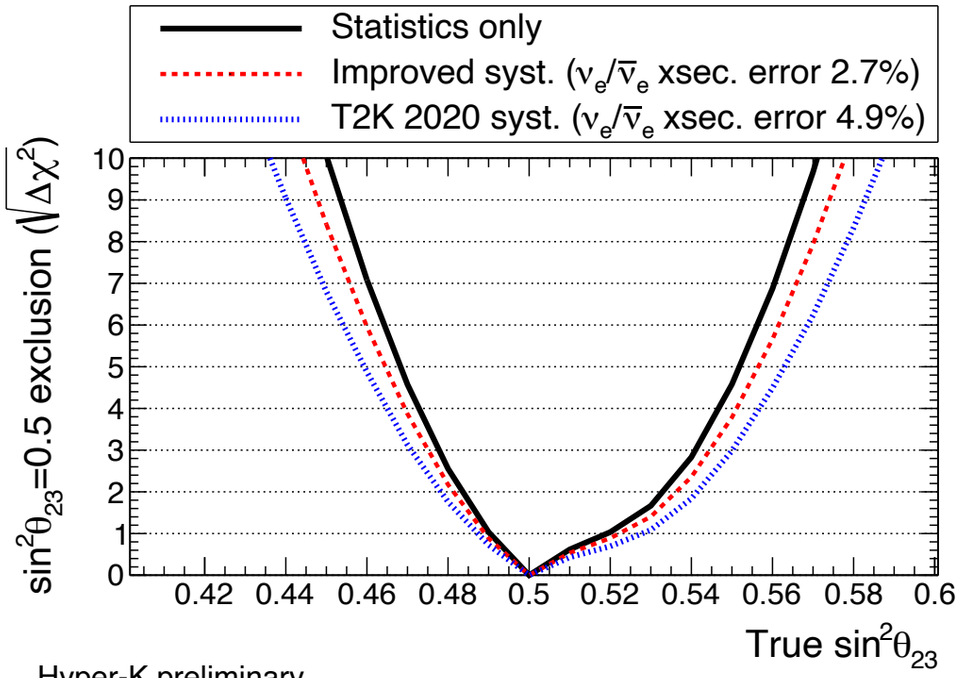
Hyper-K preliminary
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4

$\sin^2\theta_{23}$ & Δm^2_{23}

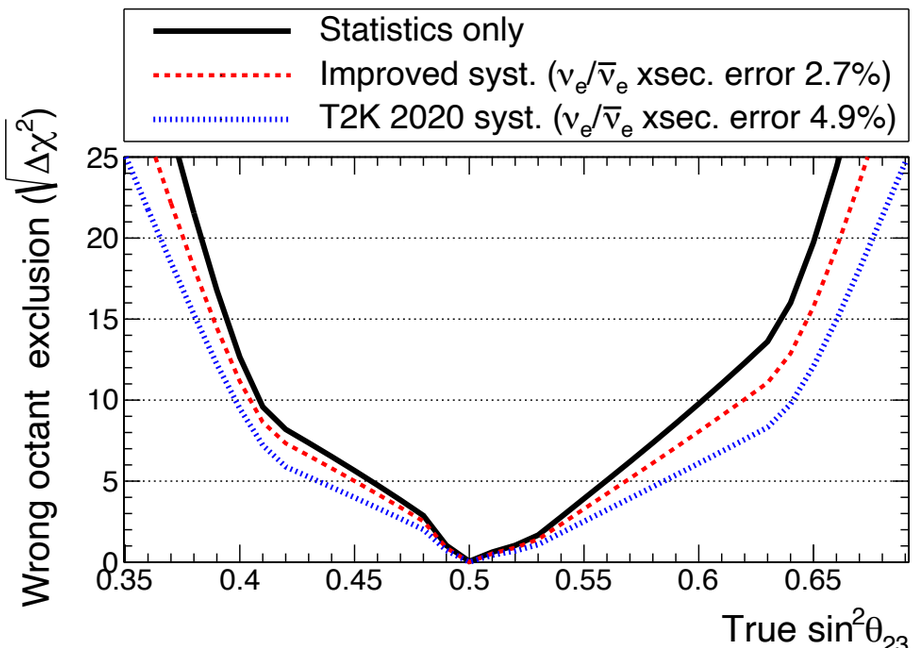
Hyper-Kamiokande



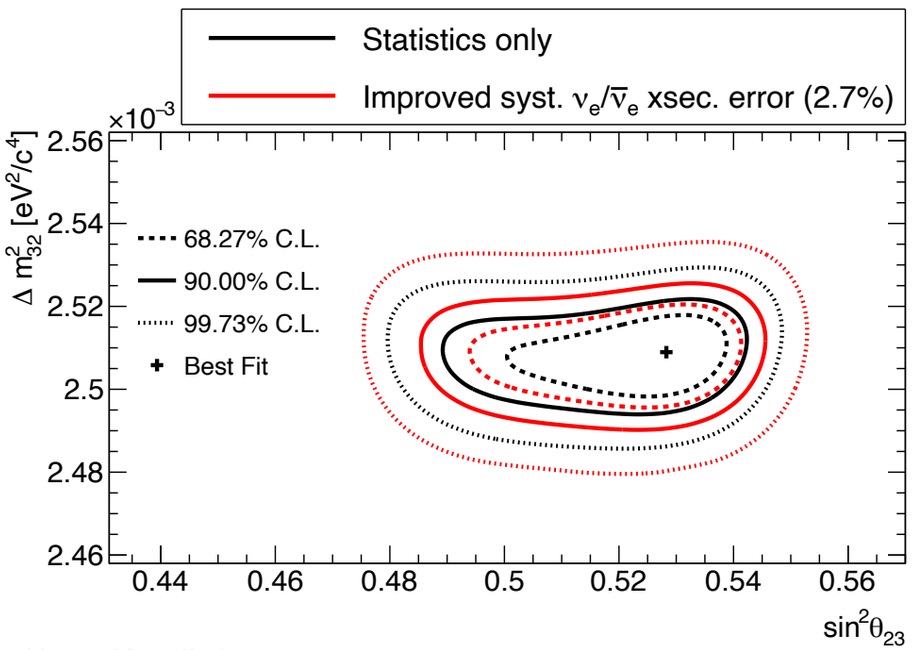
Hyper-K preliminary
10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
Normal Ordering, $\sin^2\theta_{13}=0.0218$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$, $\delta_{CP}=-1.601$



Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\delta_{CP}=-1.601$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$



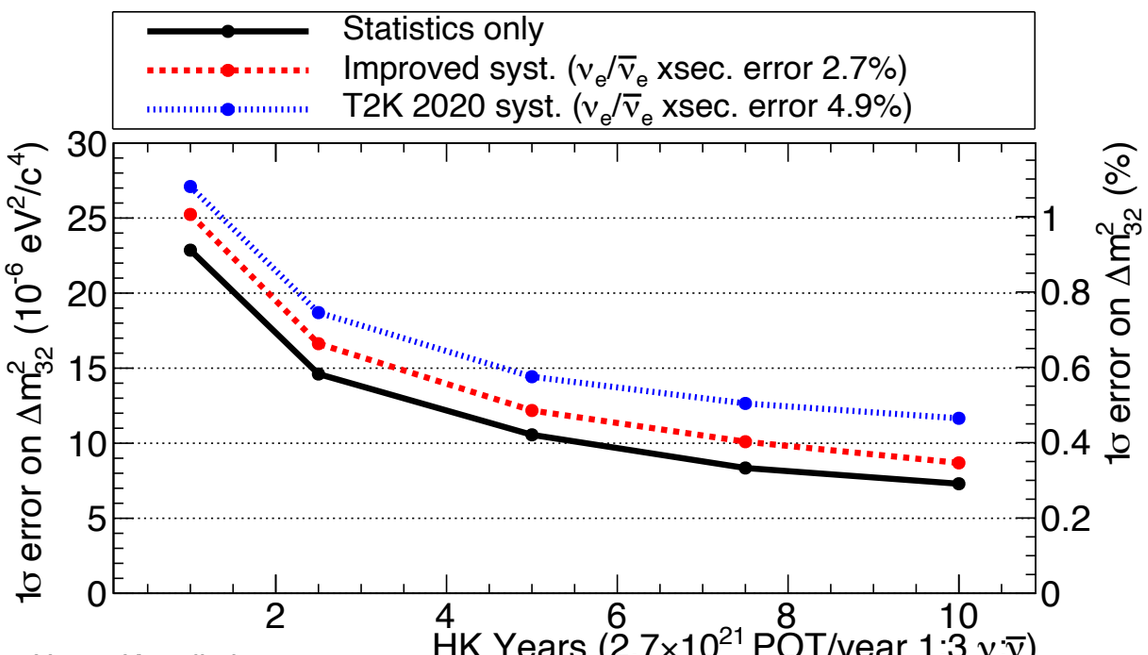
Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\delta_{CP}=-1.601$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$



Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$, $\delta_{CP}=-1.601$

Mass Ordering via Δm^2_{23}

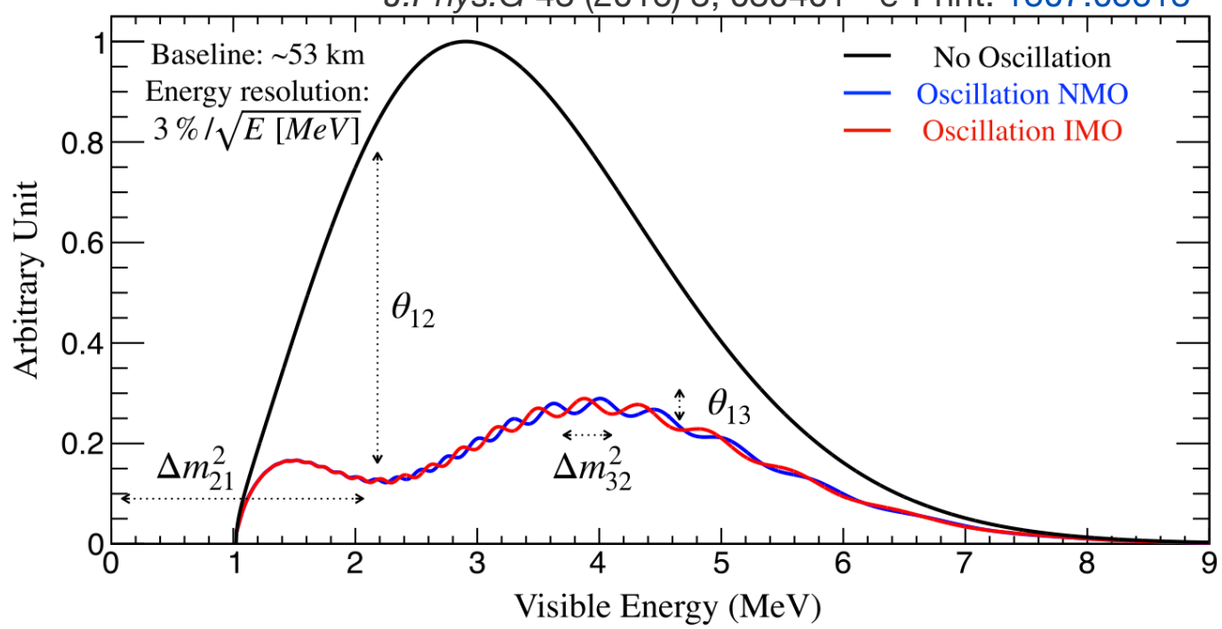
Hyper-Kamiokande



True normal ordering (known)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4, δ_{CP}=-1.601

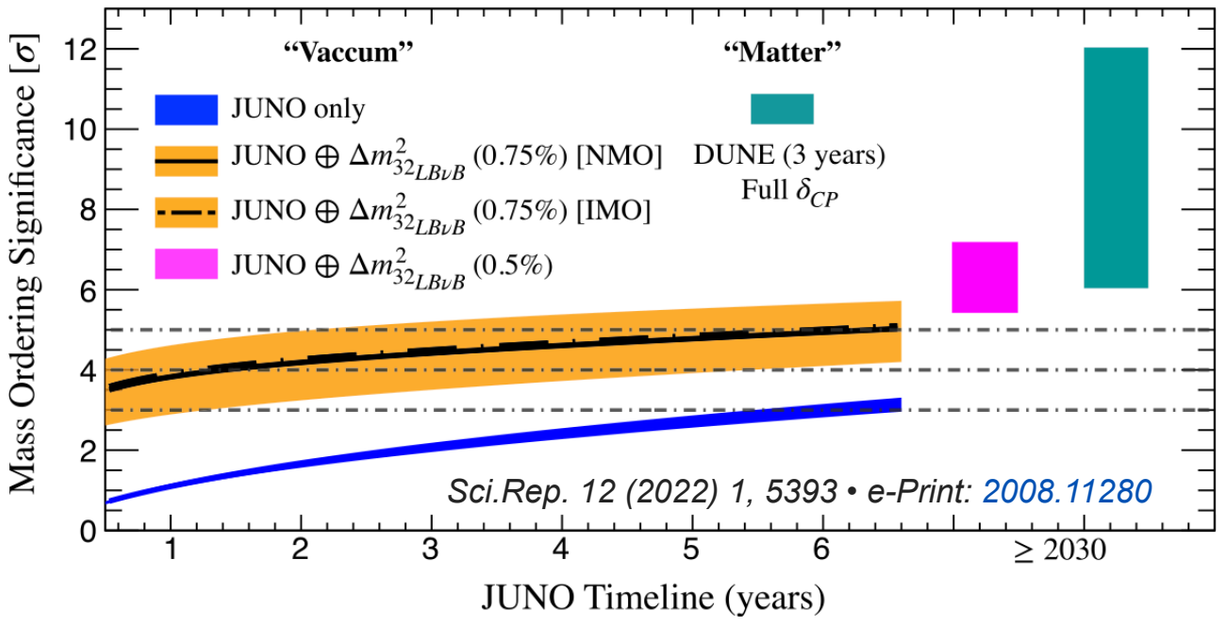
JUNO

J.Phys.G 43 (2016) 3, 030401 • e-Print: 1507.05613



- Hyper-K capable of measuring Δm^2_{23} with 0.5% before 2032.
- First $>5\sigma$ measurement of mass ordering expected to be done by JUNO with Hyper-Kamiokande's Δm^2_{23} constraint.

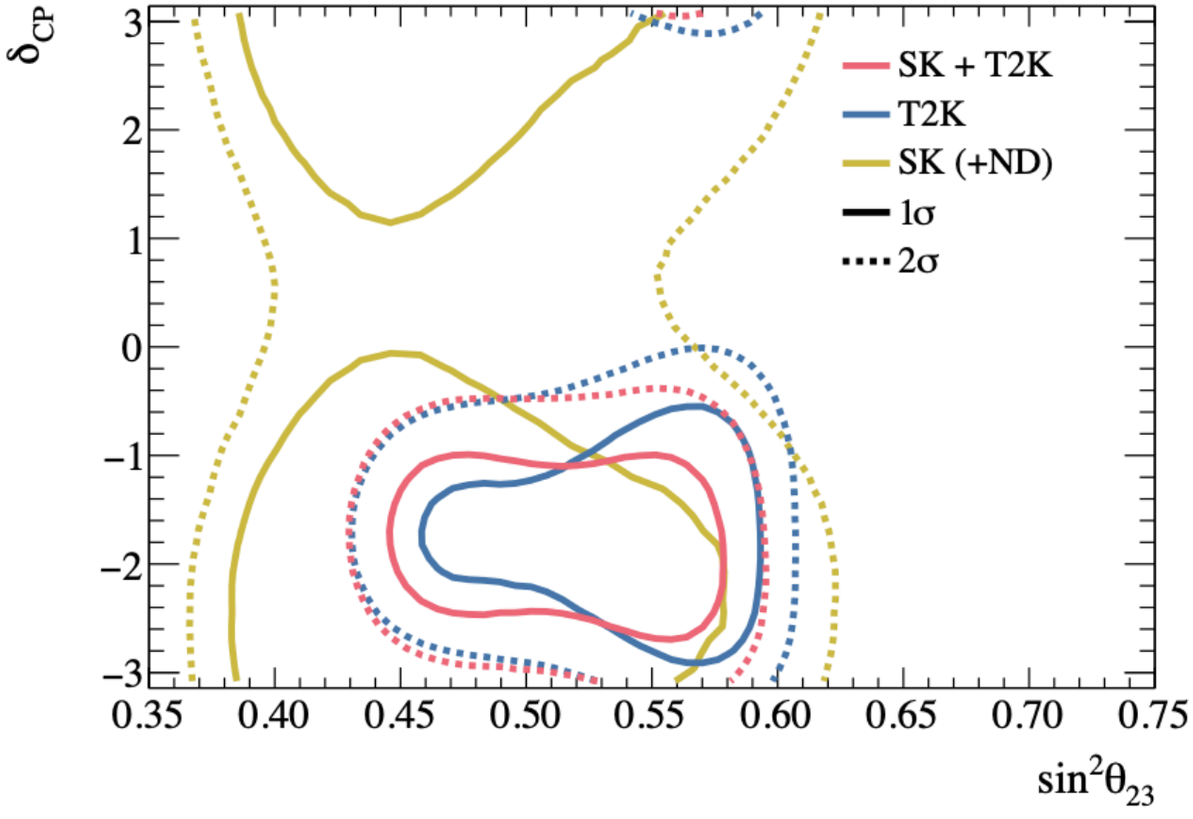
Hyper-Kamiokande + JUNO

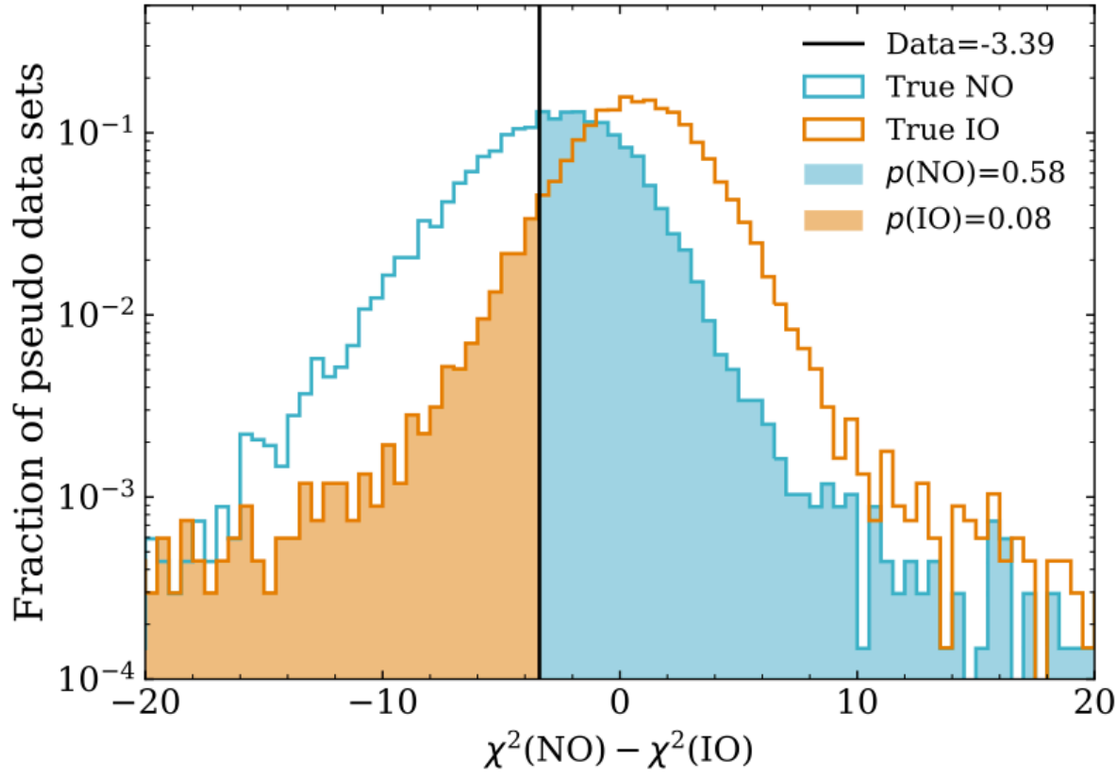


Mass Ordering via Beam + Cosmics

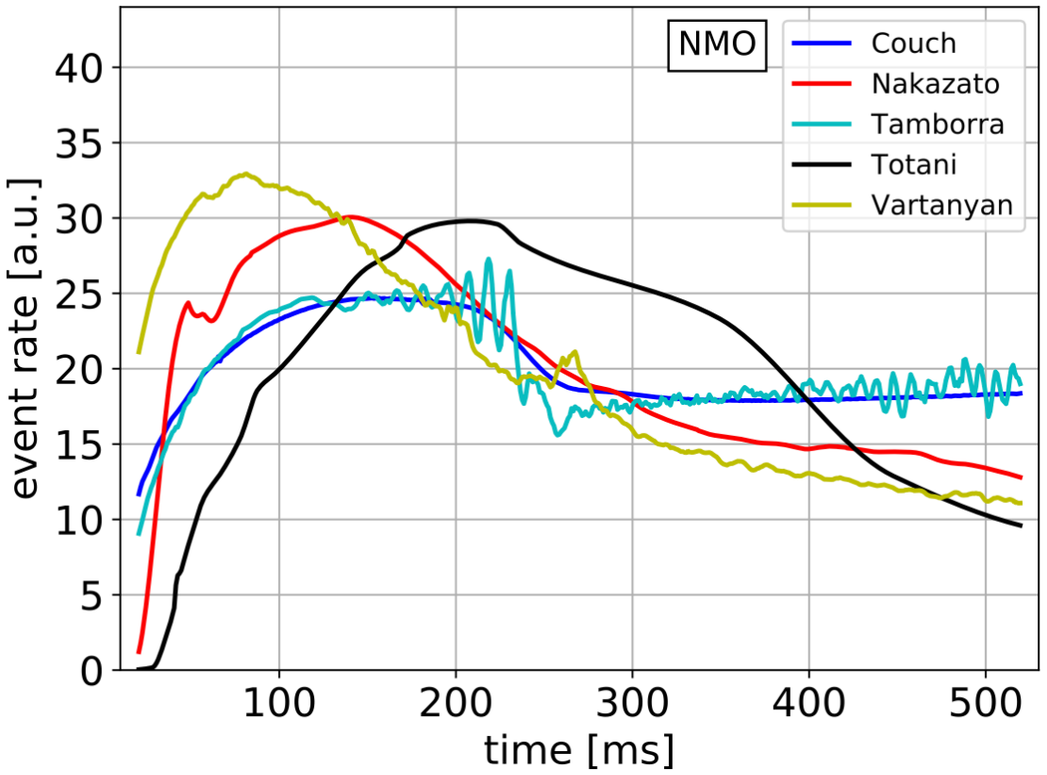
- T2K + SK joint fit has recently shown great improvement by combining beam and atmospheric neutrinos.
- This will be a usual practice in Hyper-Kamiokande.

e-Print: 2405.12488

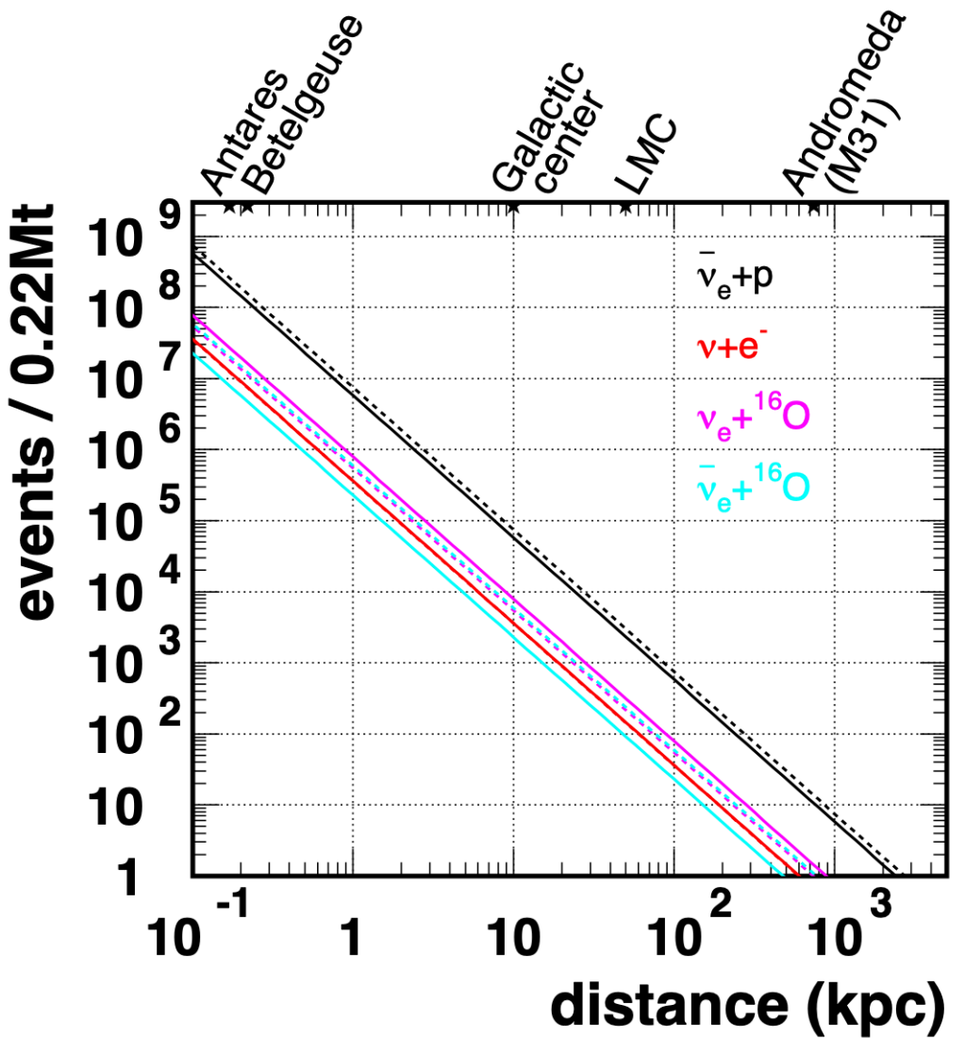




Neutrino Astrophysics



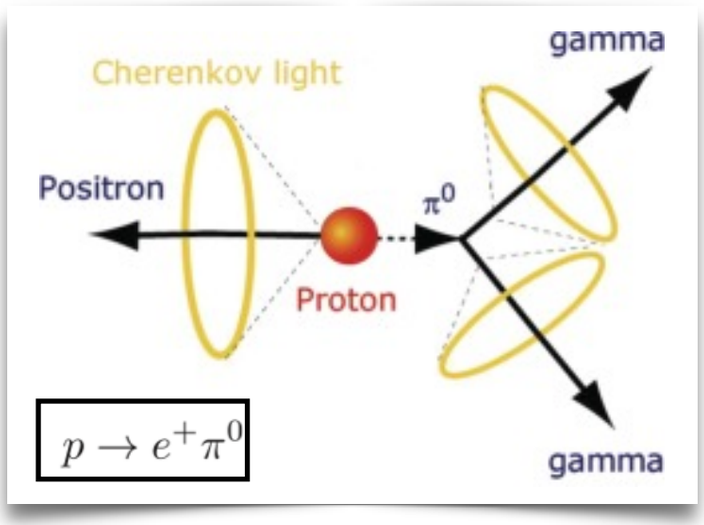
- Very rich SN physics if we get lucky.
- Exceptional data quality and statistics at HK.
- Great complementarity with other experiments (JUNO, DUNE, IceCube).

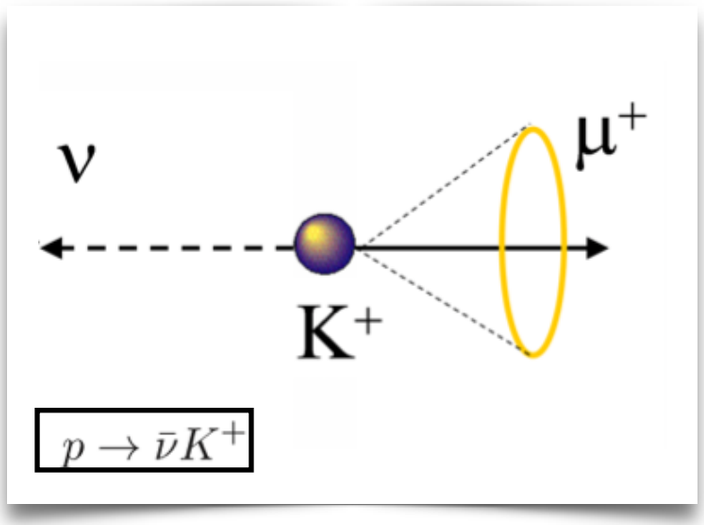


True Model \ Reconstructed Model	Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
Inverted	Couch	**99.9**	0.1	0.0	0.0	0.0
	Nakazato	0.0	**100.0**	0.0	0.0	0.0
	Tamborra	0.0	0.0	**97.4**	0.1	2.5
	Totani	0.0	0.0	0.0	**100.0**	0.0
	Vartanyan	0.0	0.0	0.8	0.0	**99.2**

Astrophys.J. 916 (2021) 1, 15 • e-Print: 2101.05269

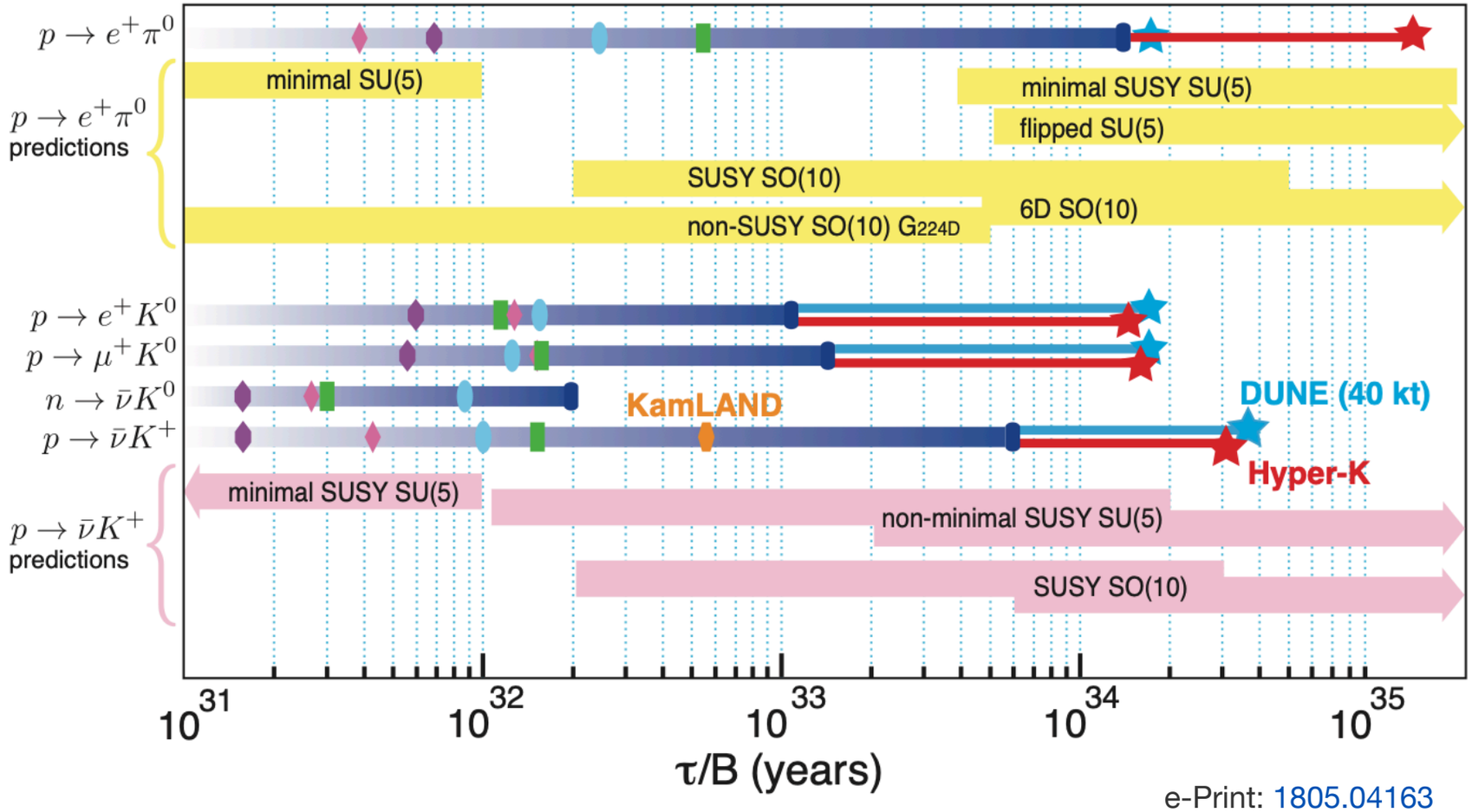
Proton Decay





- Searches for GUT signatures will continue in HK.
- ~1 order of magnitude sensitivity increase in π^0 and K^+ signatures.

Soudan Frejus Kamiokande IMB Super-K Hyper-K



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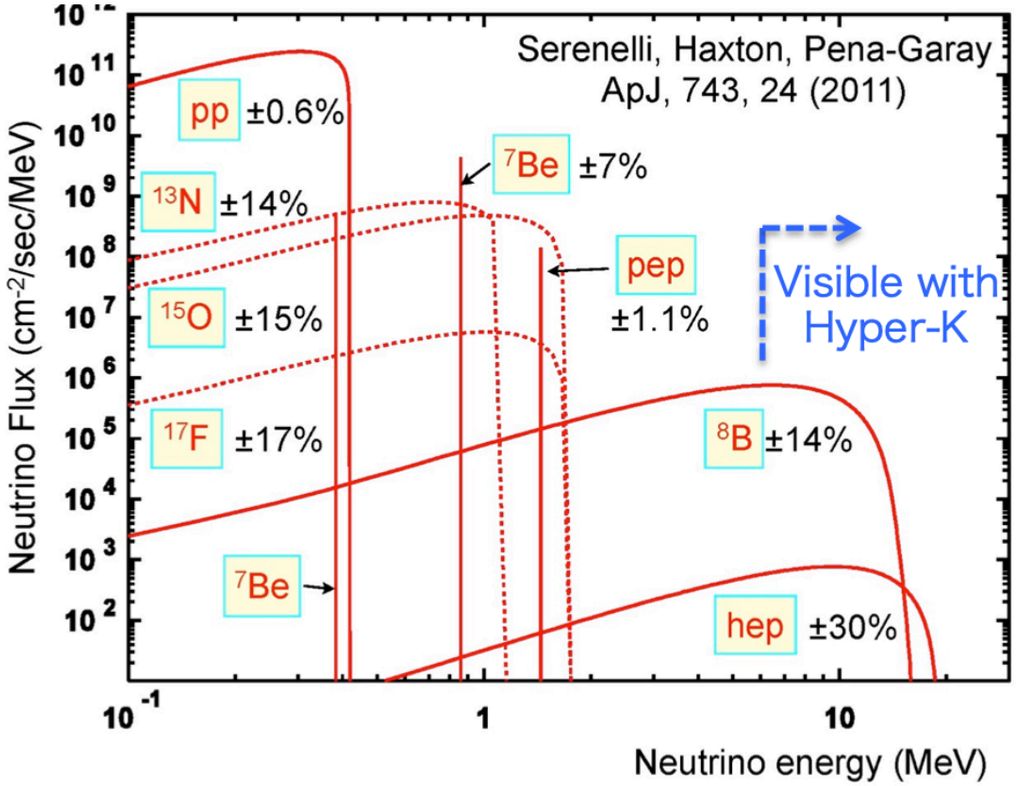
Solar Neutrinos

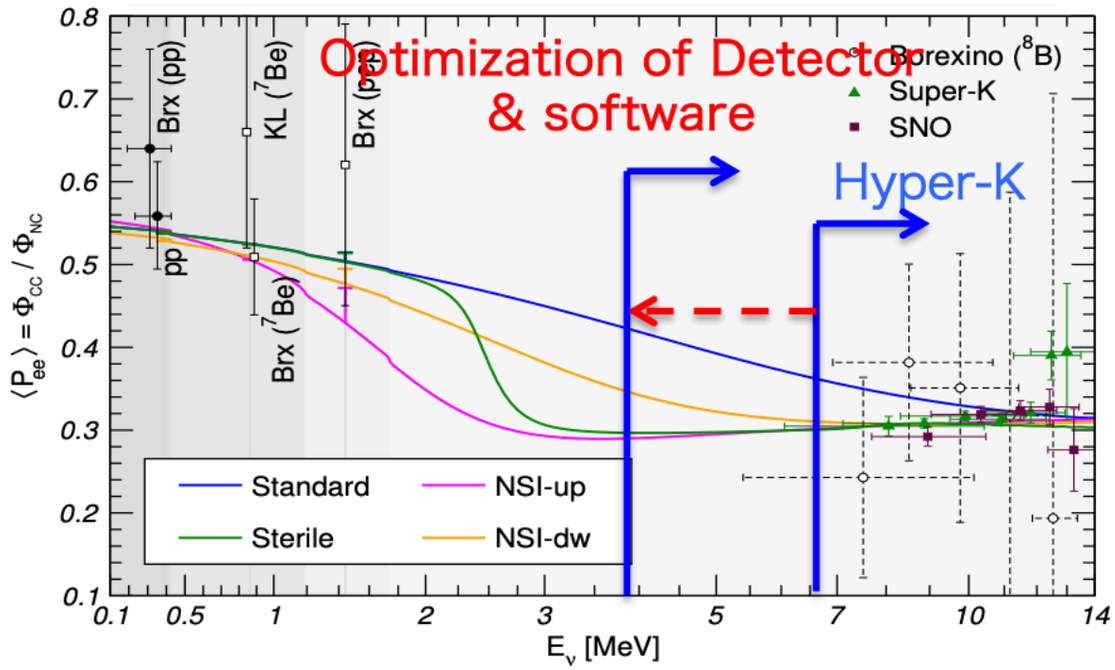
T.Yano ICHEP 2020

Hyper-Kamiokande

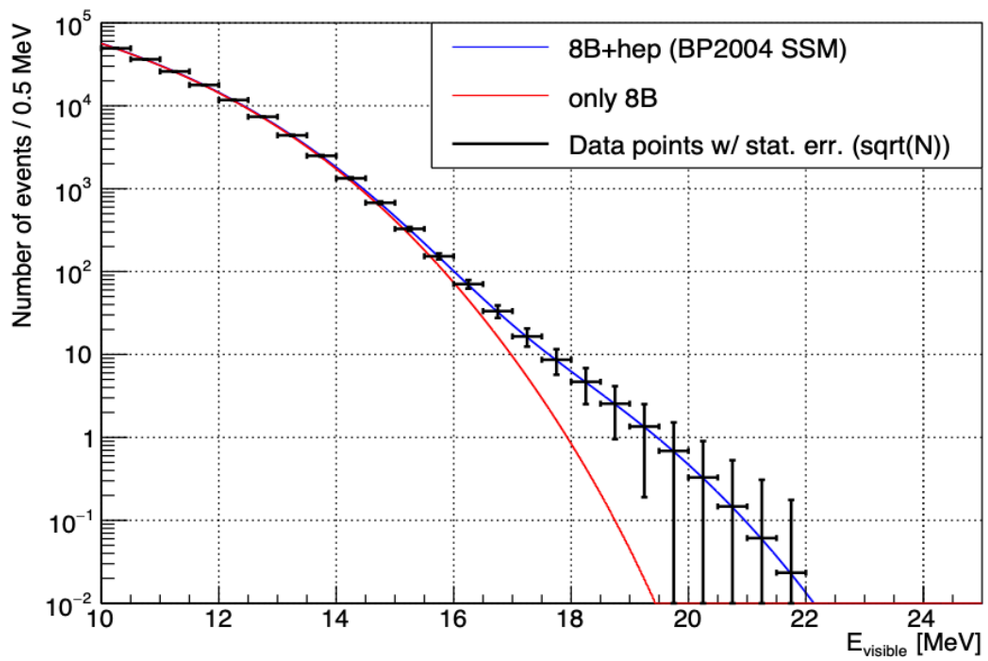
130 ν ev./day/tank, E_{vis}>4.5MeV

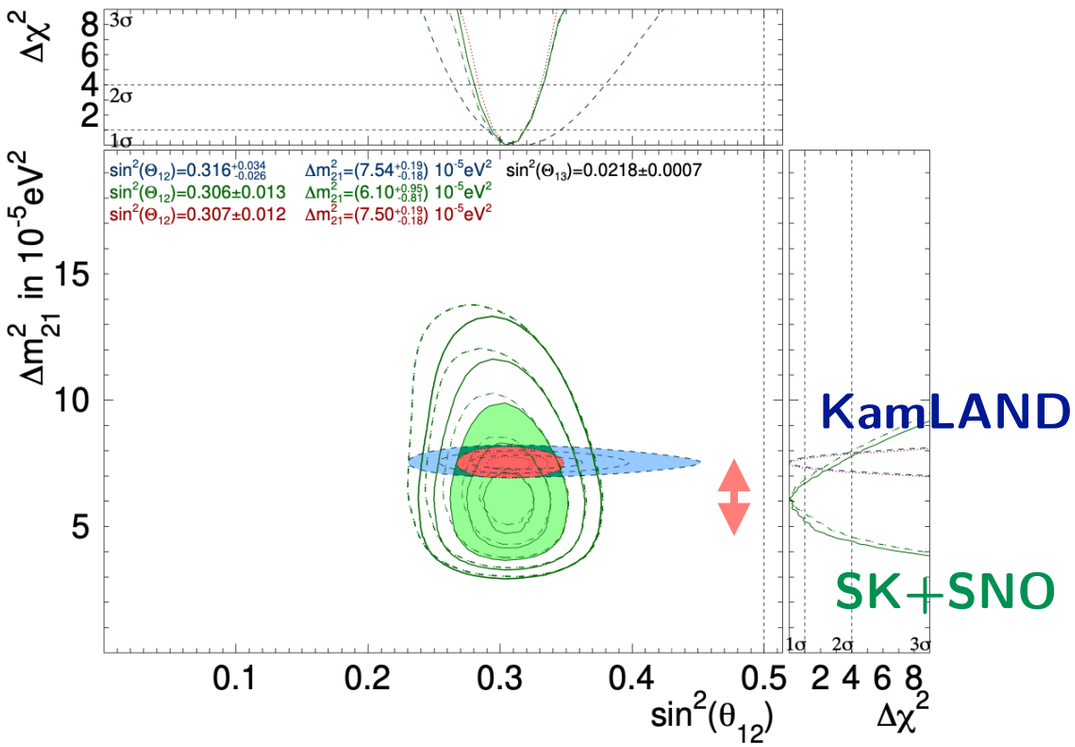
(15 ν ev./day in SK-I ~ IV)





8B and Hep nu spectrum, HK 10 years





Summary

- Hyper-Kamiokande is the next-generation neutrino experiment in Japan.
  - 258 kton water Cherenkov detector.
  - 1.3MW neutrino (or antineutrino) beam from JPARC.
  - Greatly upgraded and additional near detectors.

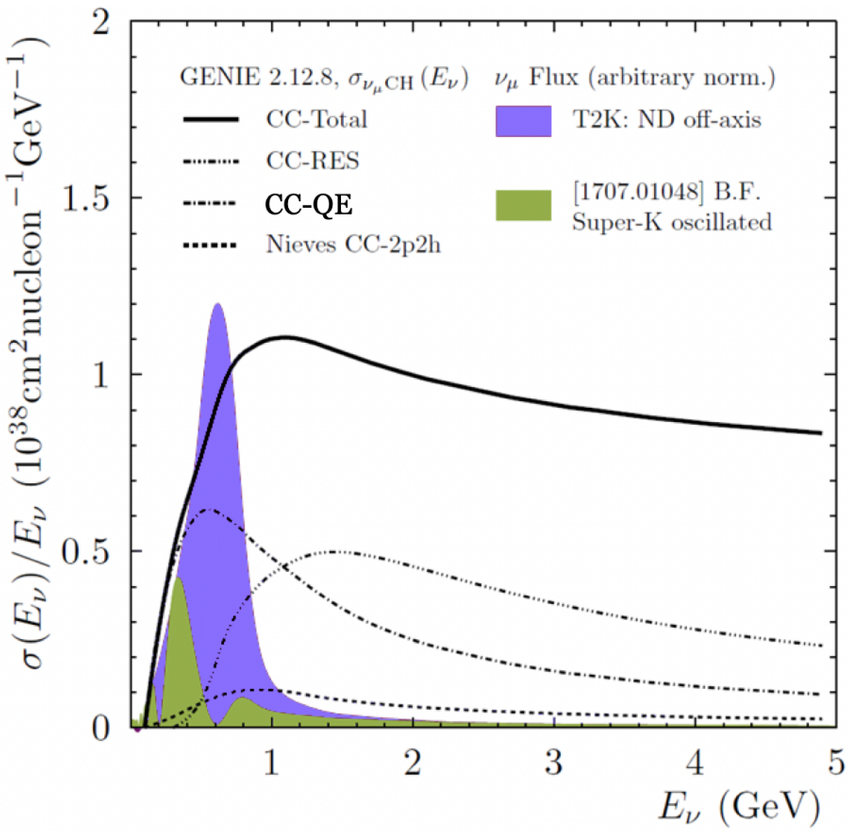
- Currently under construction, operation scheduled for 2027 and goes according to plan.
- Intense R&D program ongoing for all HK detectors.

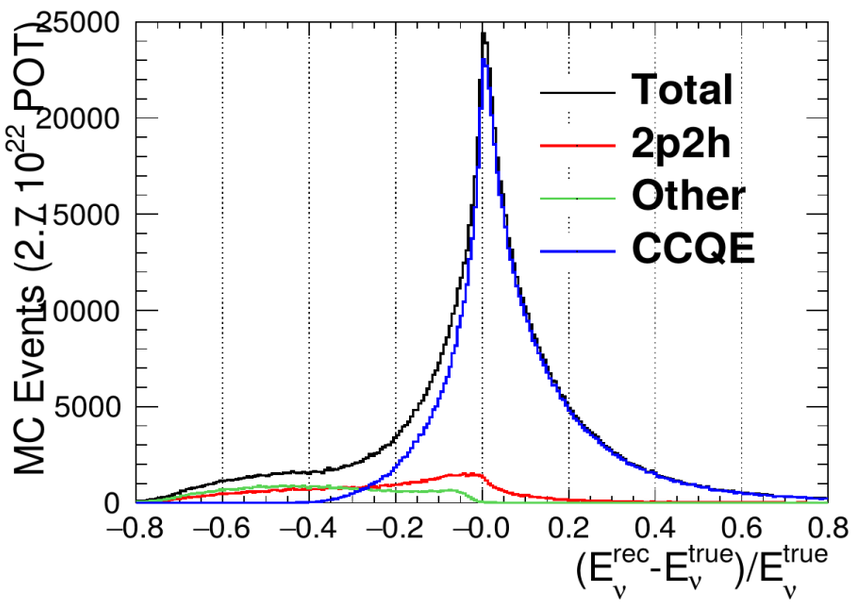
- Incredibly rich physics program:
  - Neutrino oscillations: CP violation, Δm^2_{23}, θ_{23}, mass ordering.
  - Neutrino astrophysics: Supernova bursts, solar neutrinos, relic neutrinos.
  - Proton decay limits extended by an order of magnitude.

- New collaborators are welcome!

Back Up Slides

Cross-sections $E_\nu \approx 1$ GeV

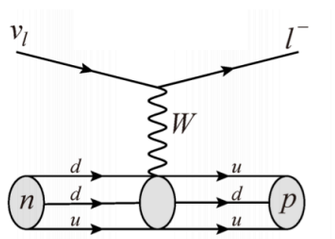




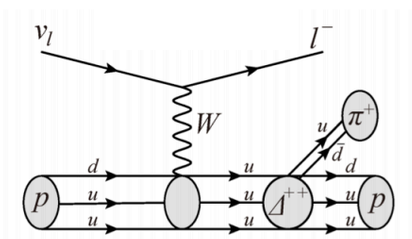
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Interactions with a single nucleon

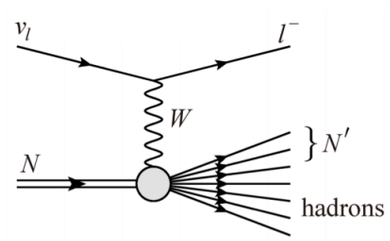
CC-QE



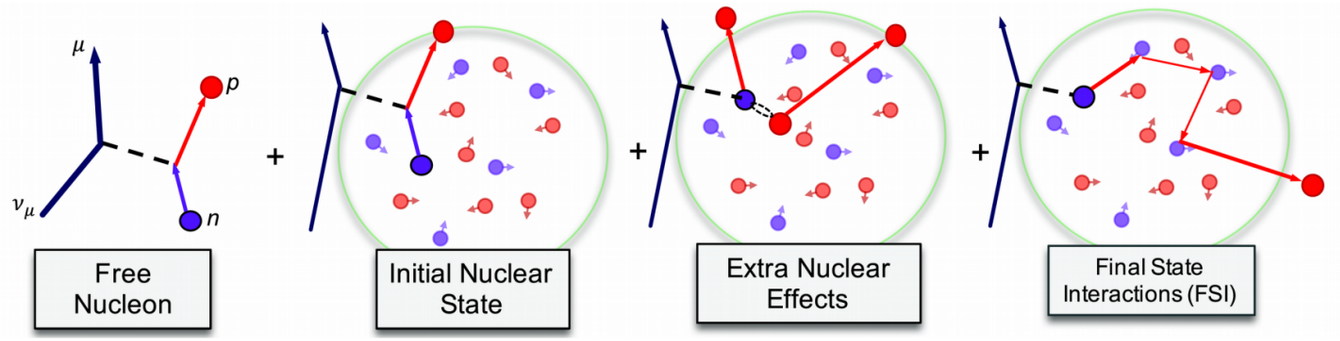
CC-RES



CC-DIS

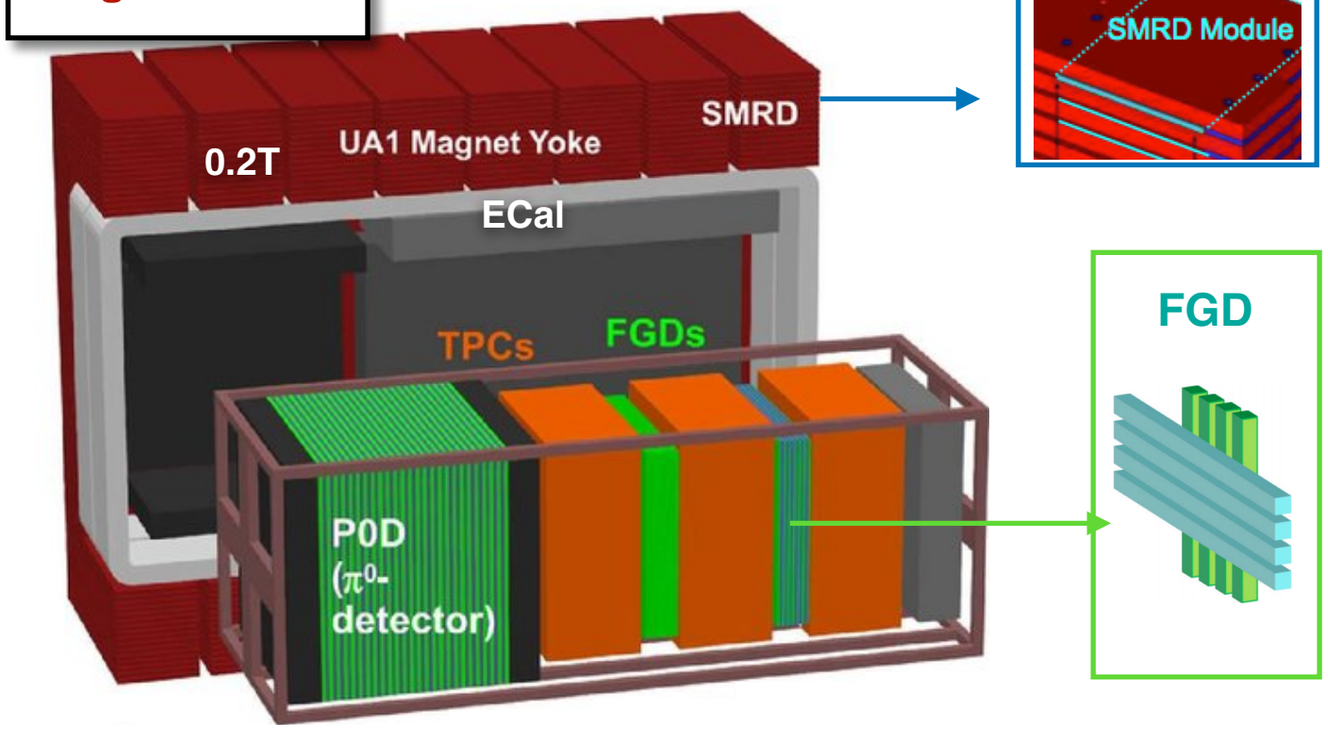


Multi-nucleon effects

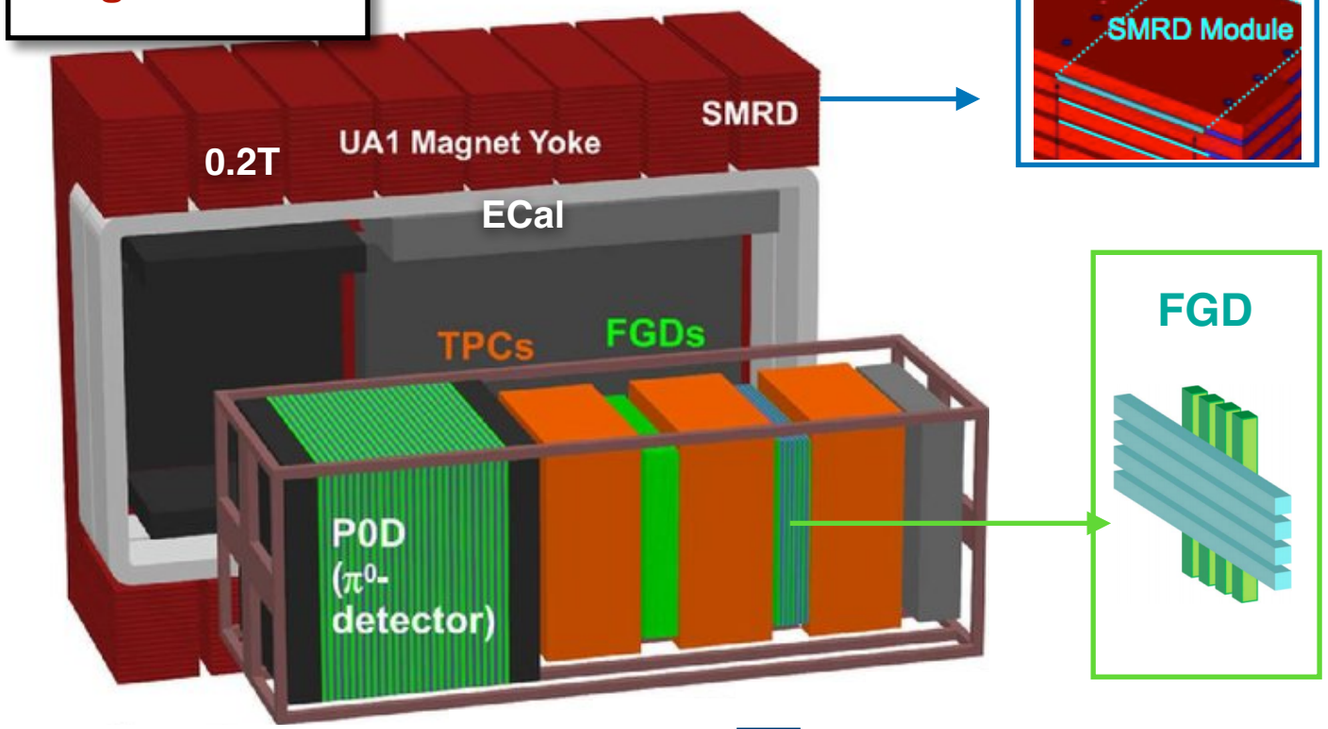


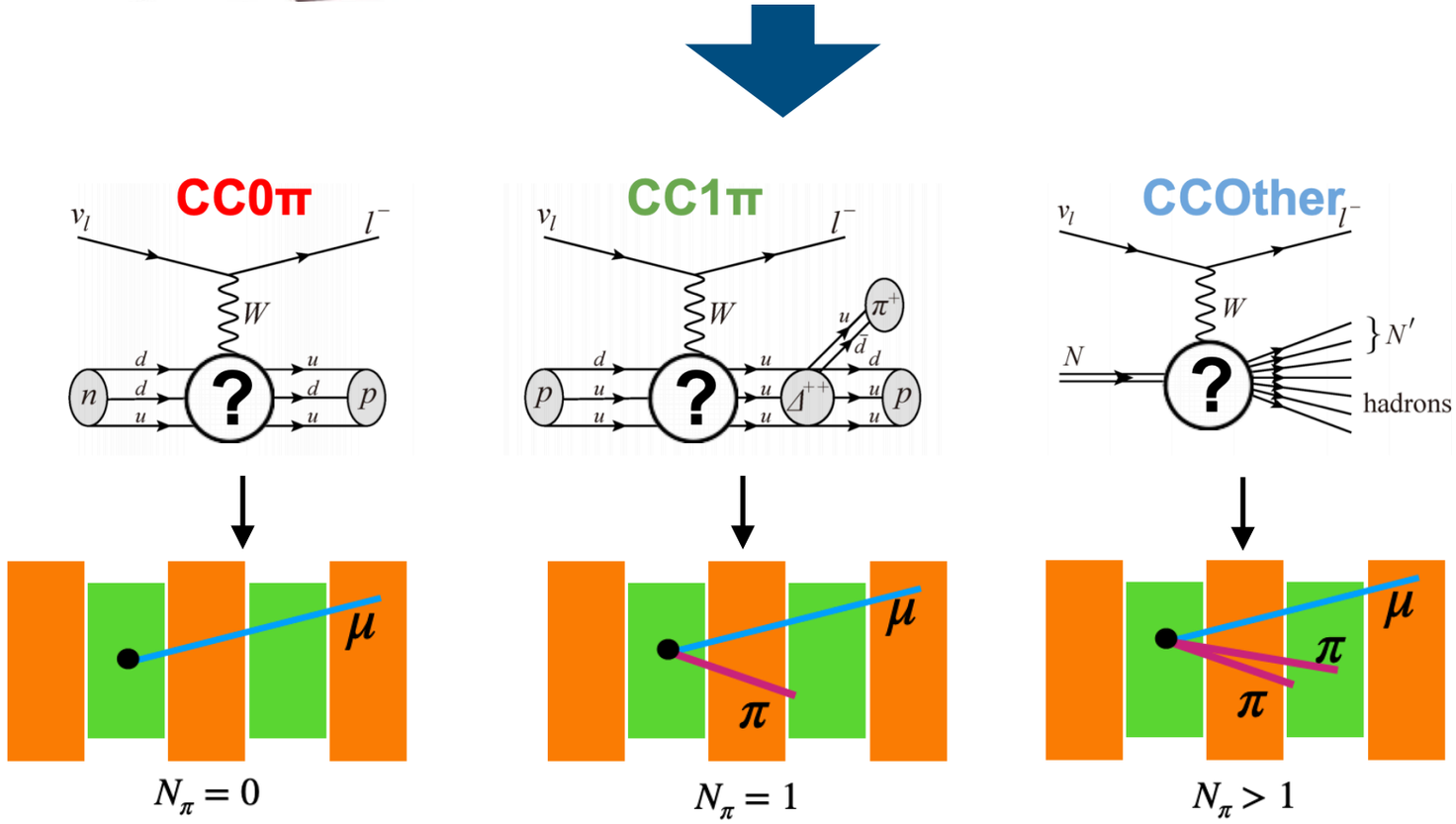
Understanding interactions is crucial!

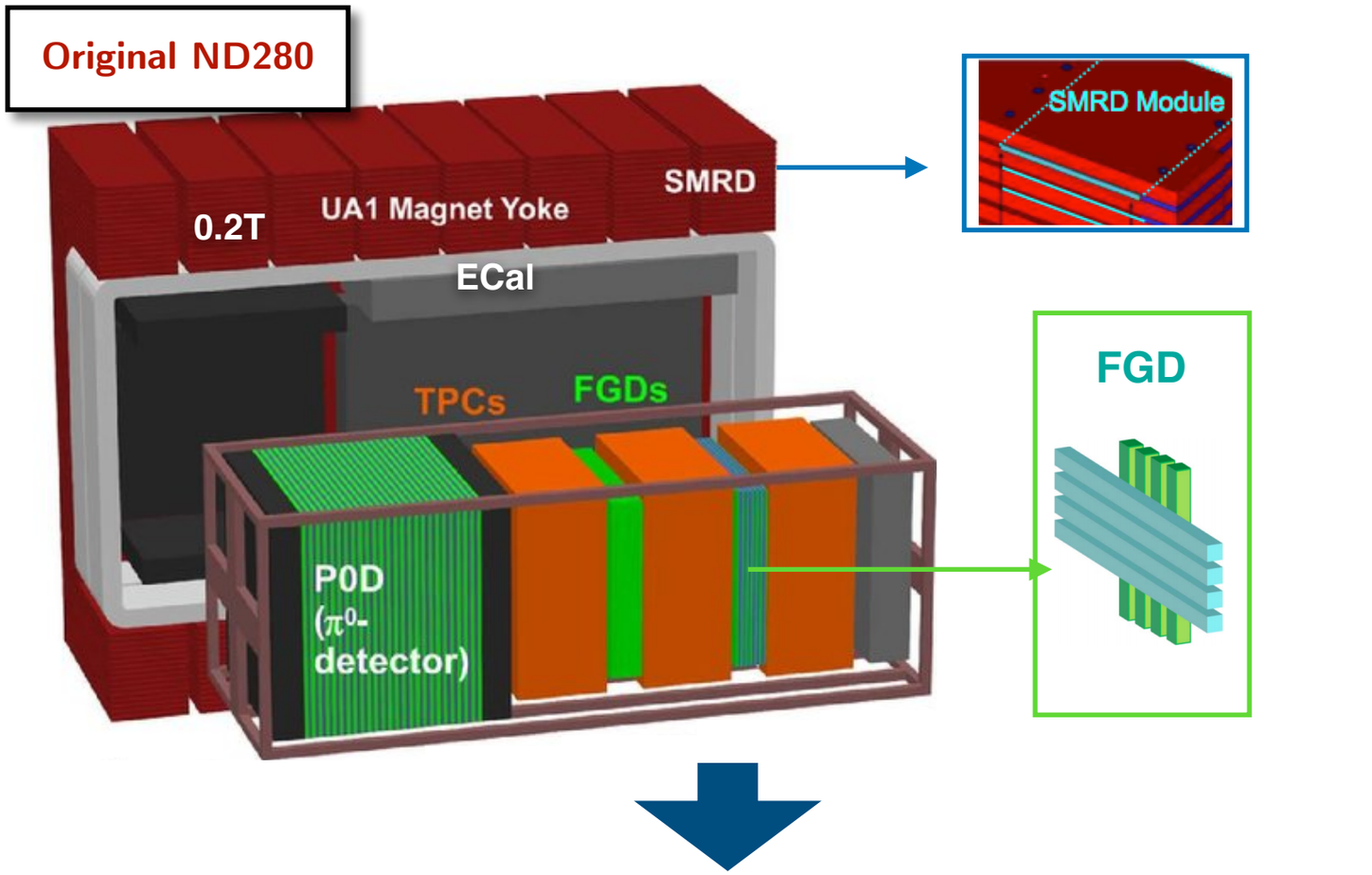
Original ND280

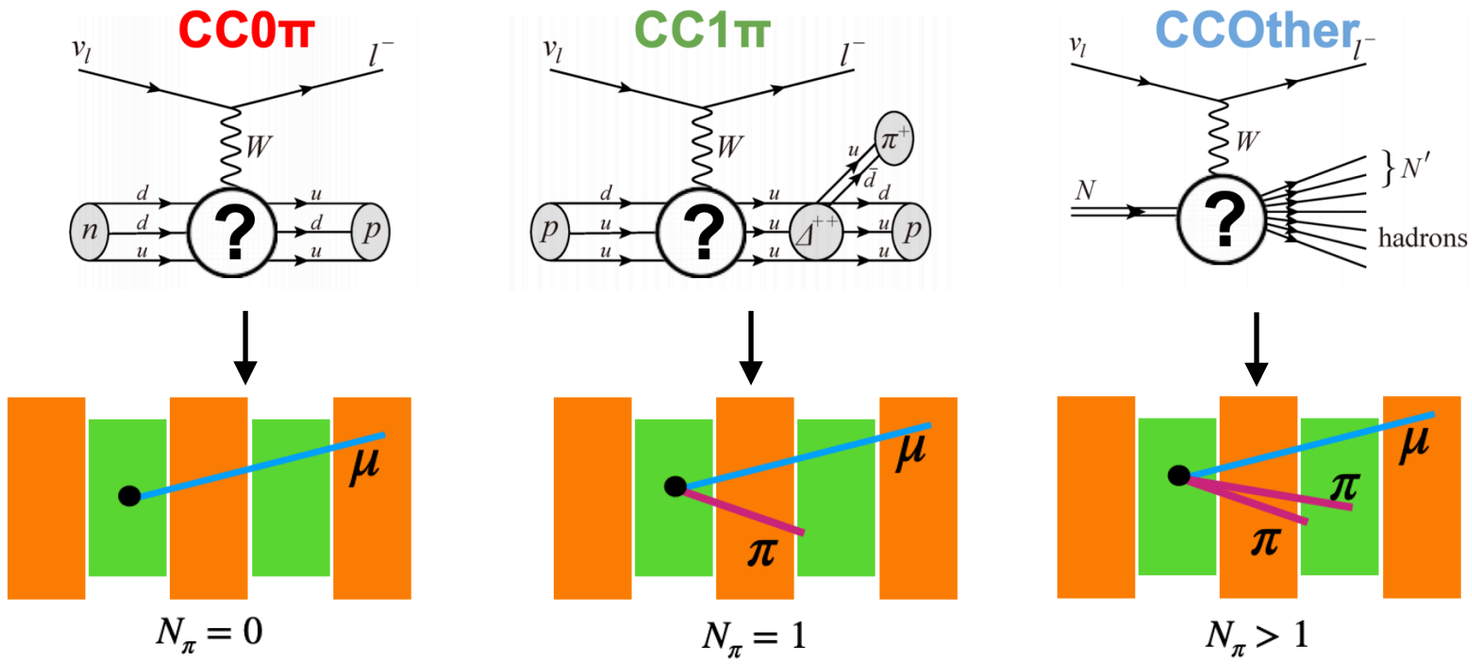


Original ND280









T2K OA results

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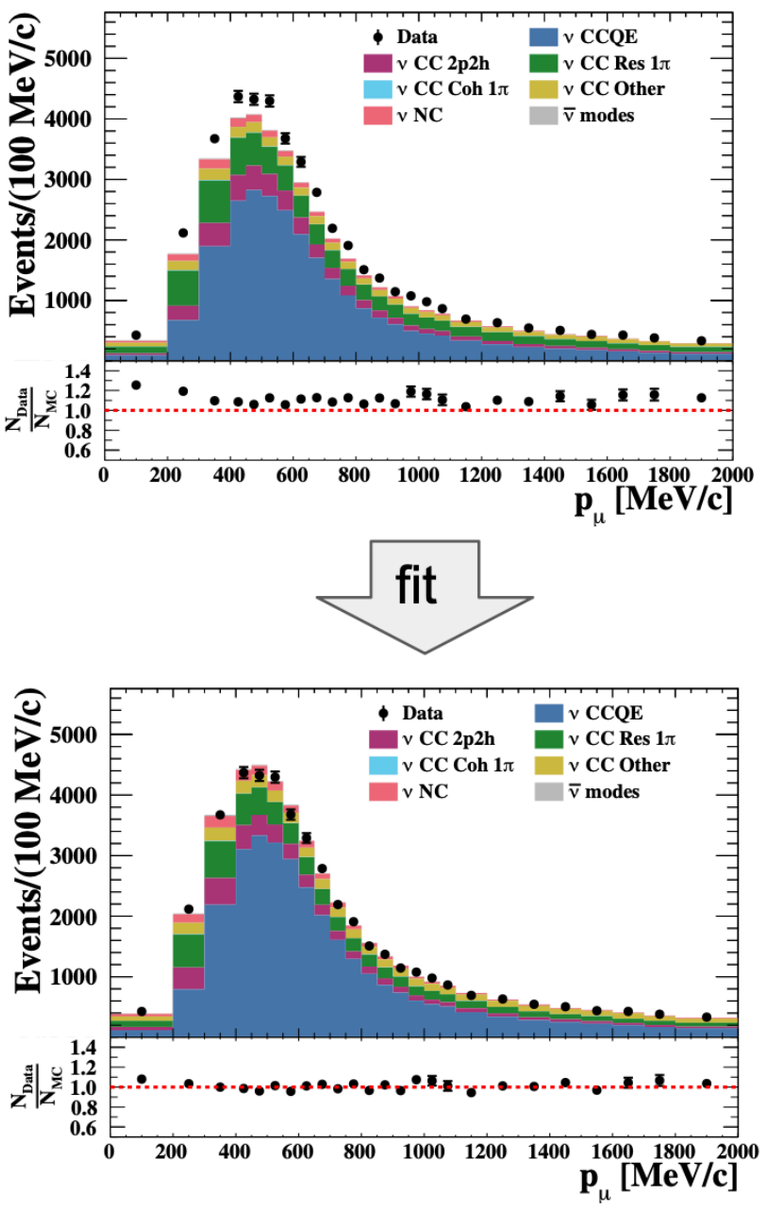
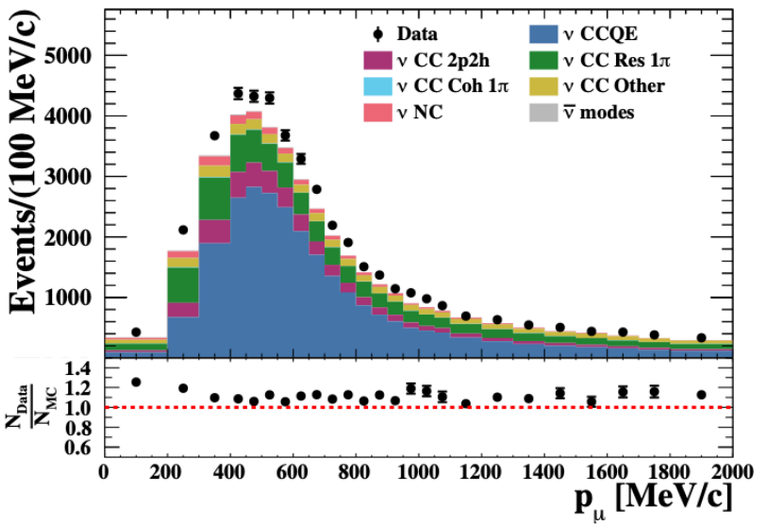
Selection	Topology	Target	Eff. (%)	Pur. (%)
ν_μ in ν-mode	0π	FGD1	48.0	71.3
		FGD2	48.0	68.2
	$1\pi^+$	FGD1	29.0	52.5
		FGD2	24.0	51.3
	Other	FGD1	30.0	71.4
		FGD2	30.0	71.2
$\overline{\nu}_\mu$ in $\overline{\nu}$-mode	0π	FGD1	70.0	74.5
		FGD2	69.0	72.7
	$1\pi^-$	FGD1	19.3	45.4
		FGD2	17.2	41.0
	Other	FGD1	26.5	26.3
		FGD2	25.2	26.0
ν_μ in $\overline{\nu}$-mode	0π	FGD1	60.3	55.9
		FGD2	60.3	52.8
	$1\pi^+$	FGD1	30.3	44.4
		FGD2	26.0	44.8
	Other	FGD1	27.4	68.3
		FGD2	27.1	69.5

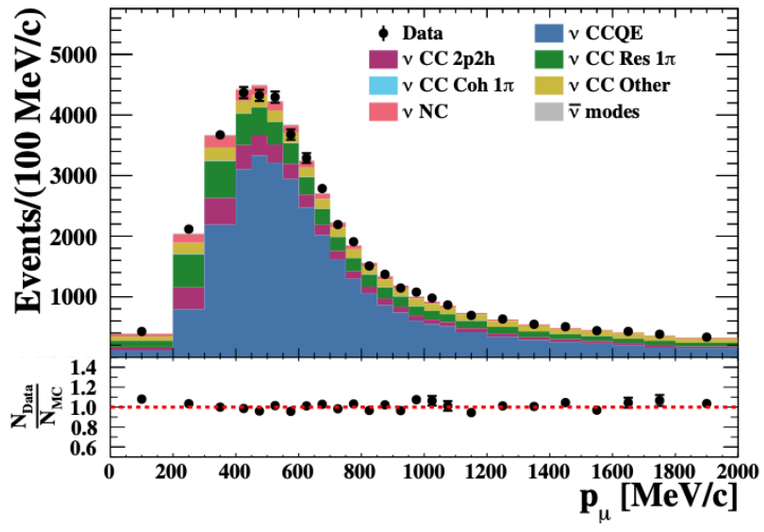
ν_μ in ν-mode
FGD1 CC0π

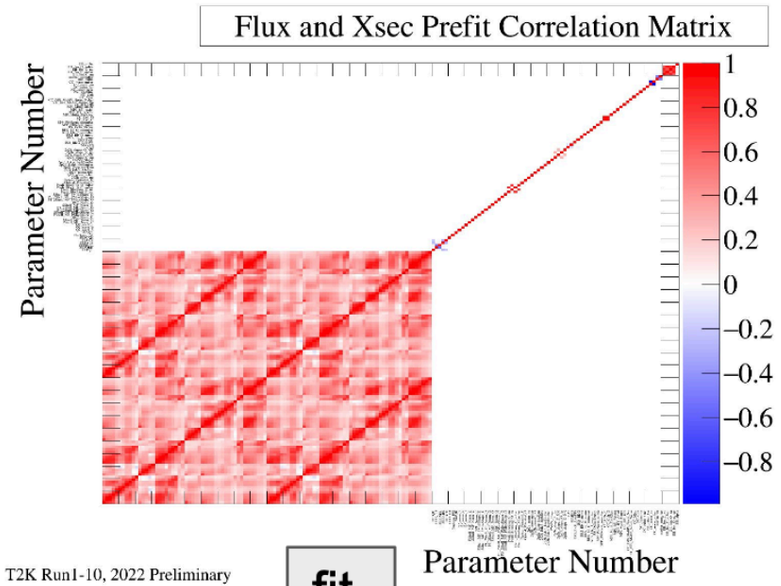


ν_μ in ν-mode
FGD1 CC0π

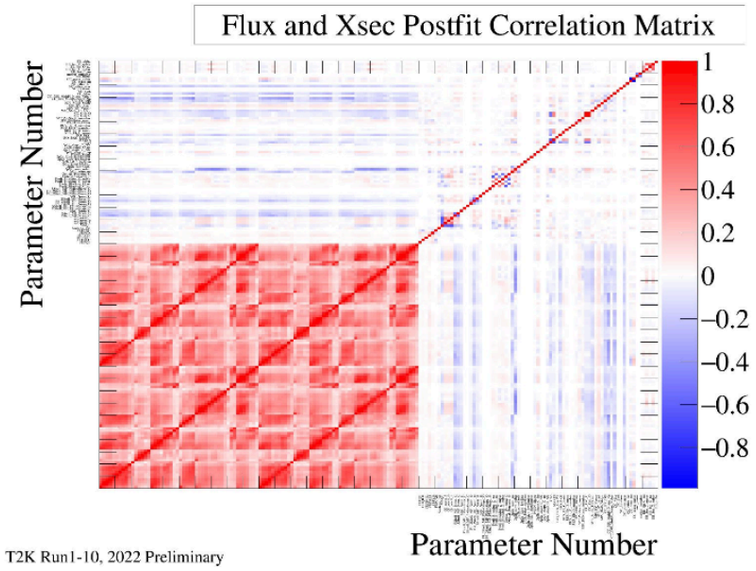


fit

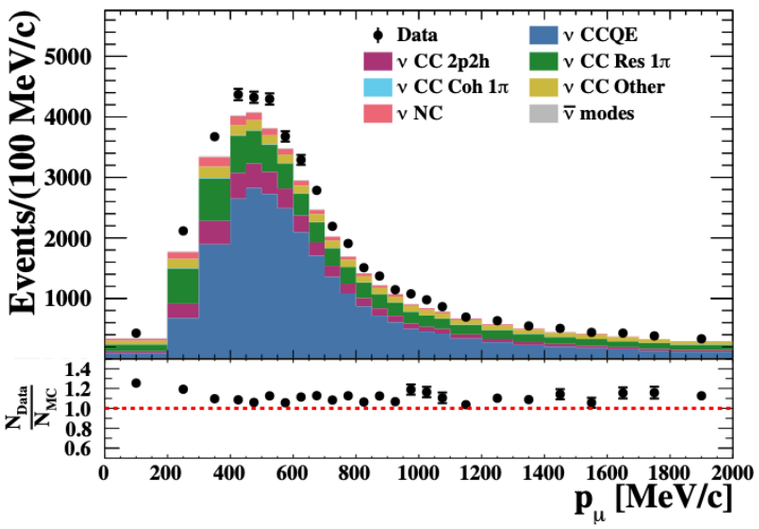




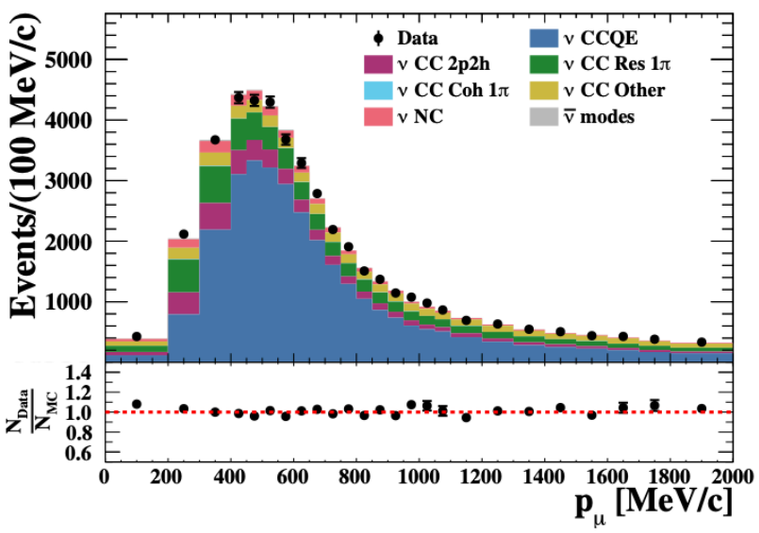
fit

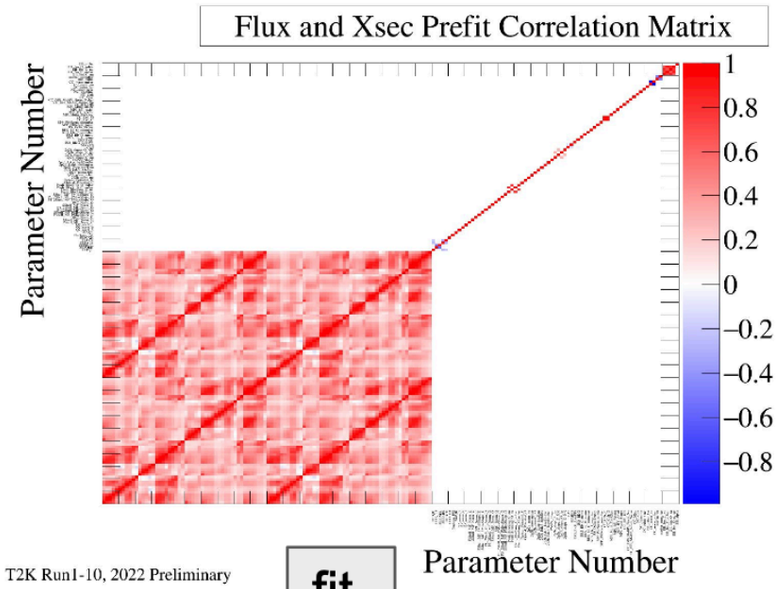


ν_μ in ν-mode
FGD1 CC0π

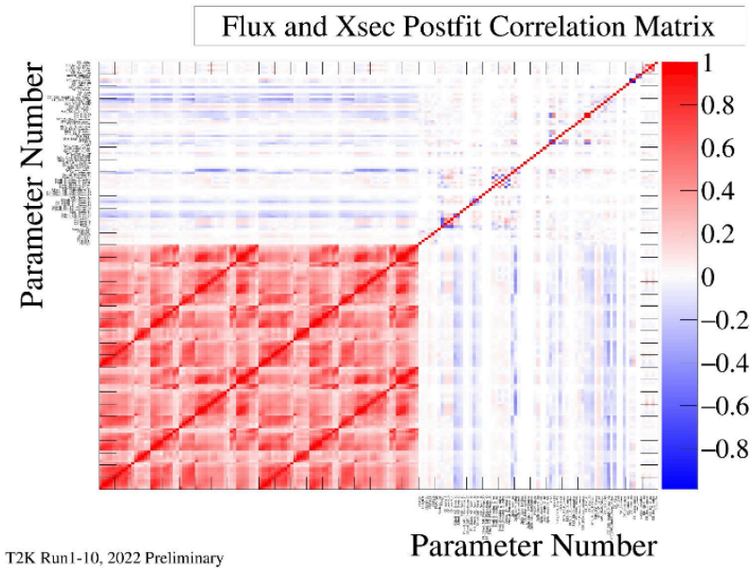


fit





fit



Prediction at Super-Kamiokande