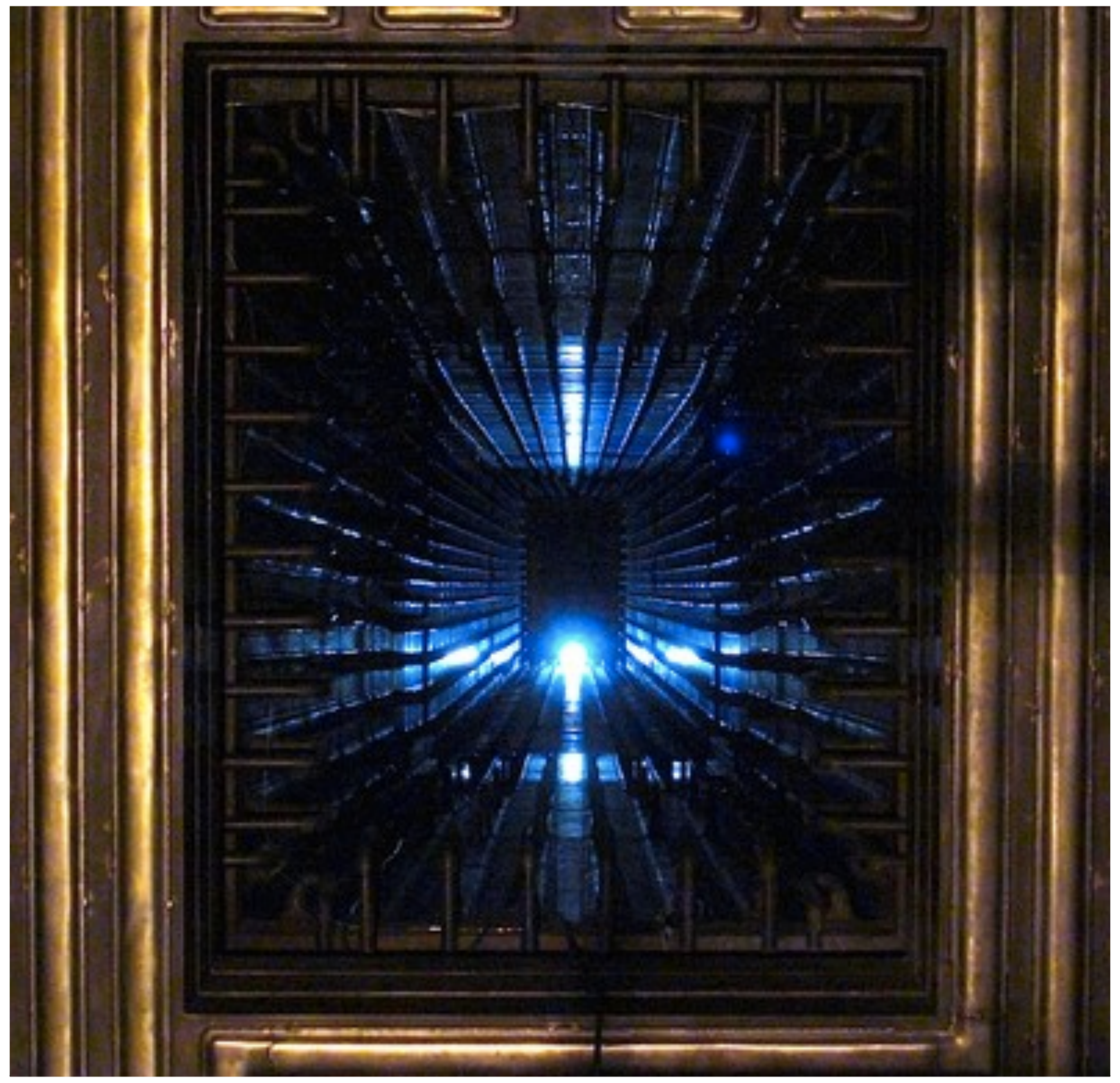
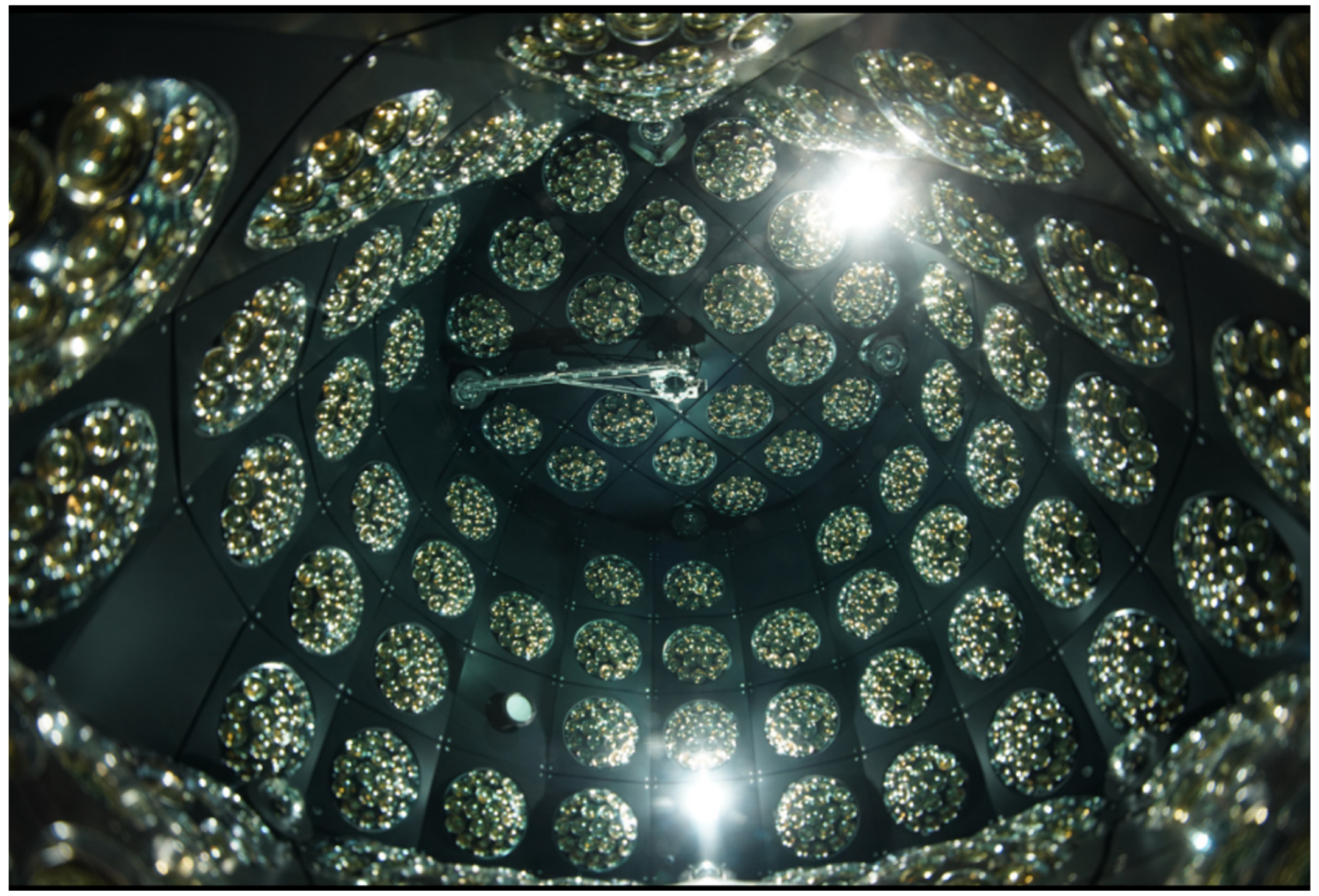
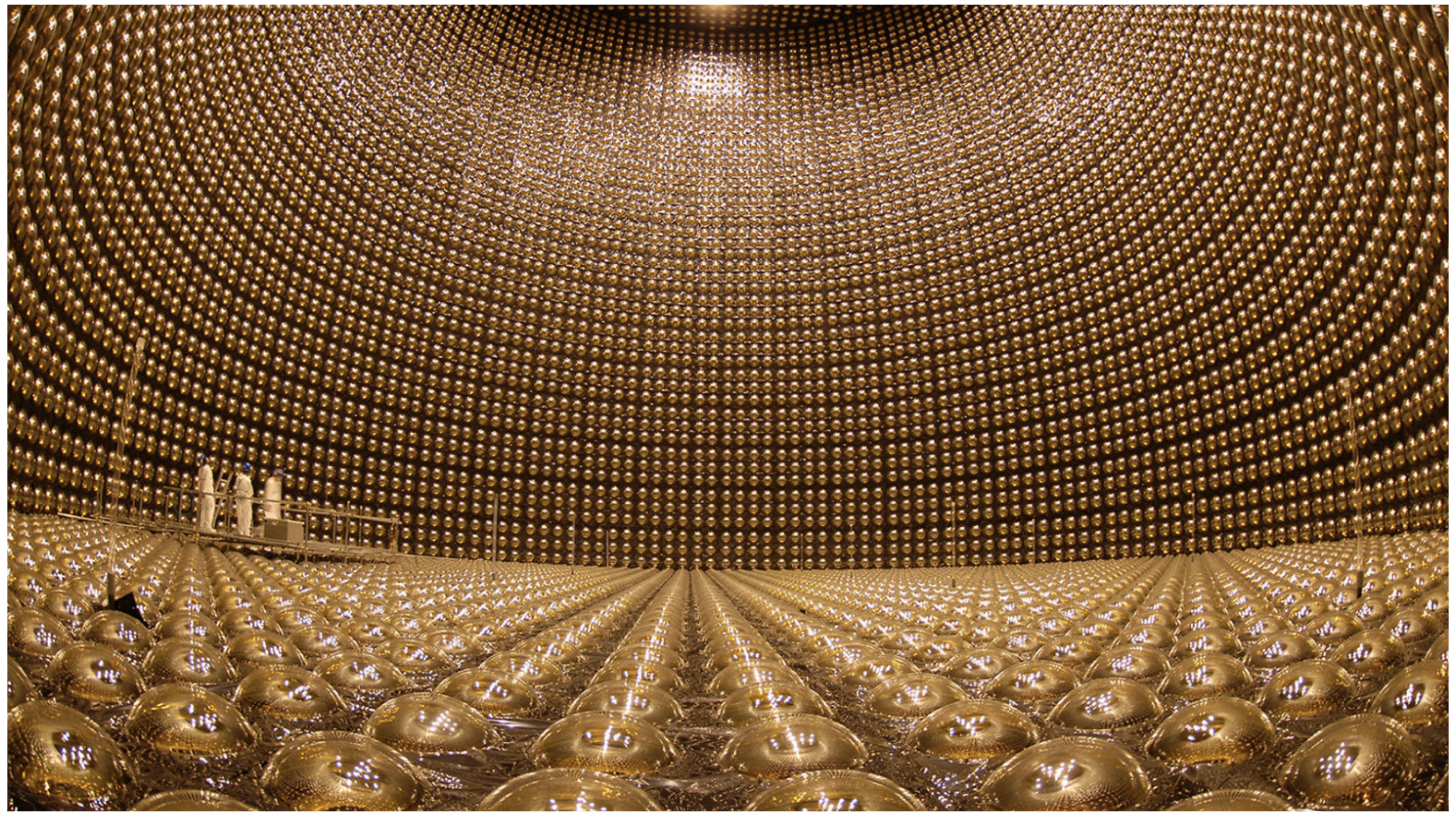
Long Baseline Neutrino Physics at T2K and Hyper-Kamiokande







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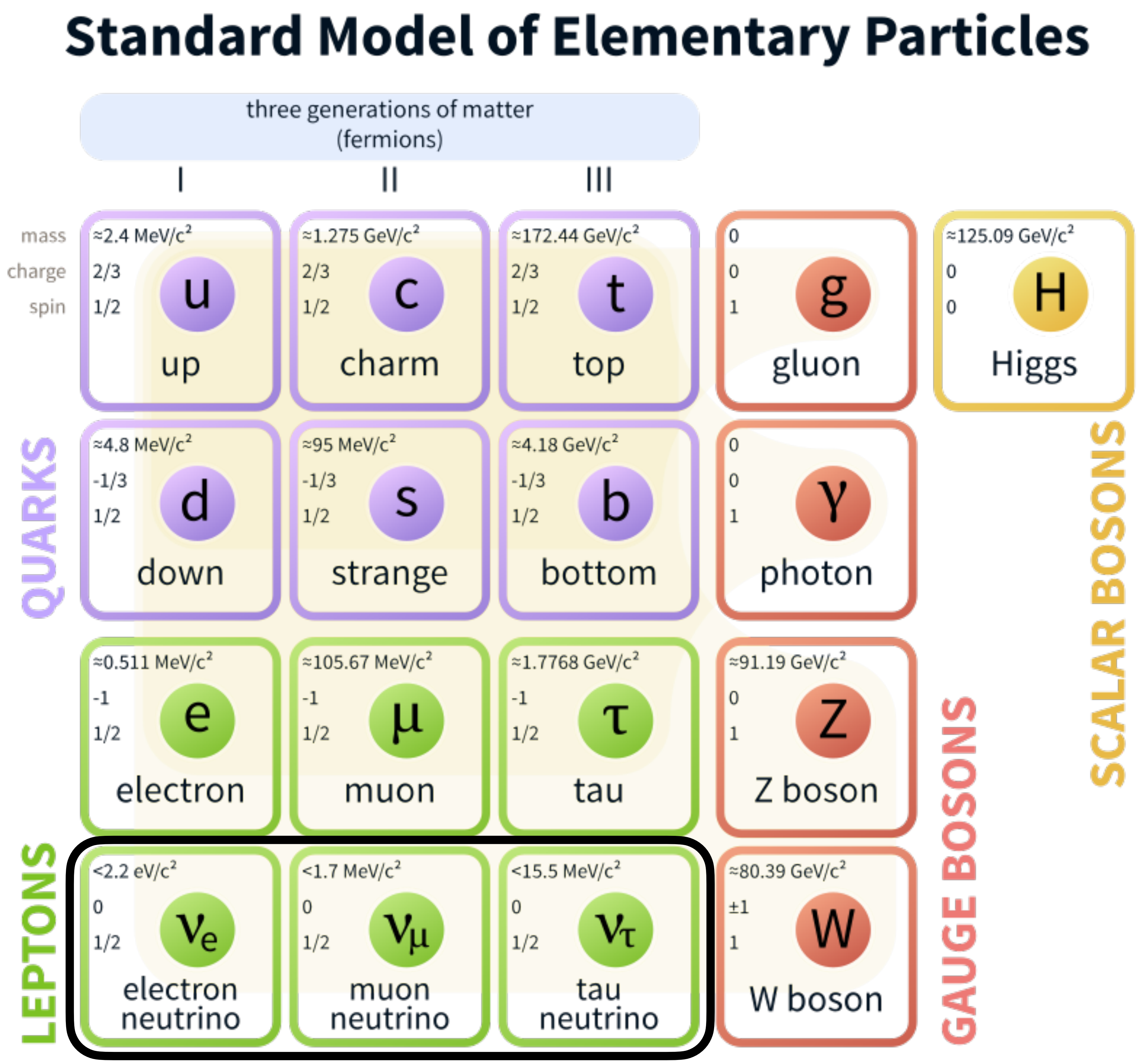
TRIUMF & KMI, Nagoya University

T2K

The 6th KMI International Symposium
March 5, 2025

Hyper-Kamiokande

Fundamental Physics with Neutrinos



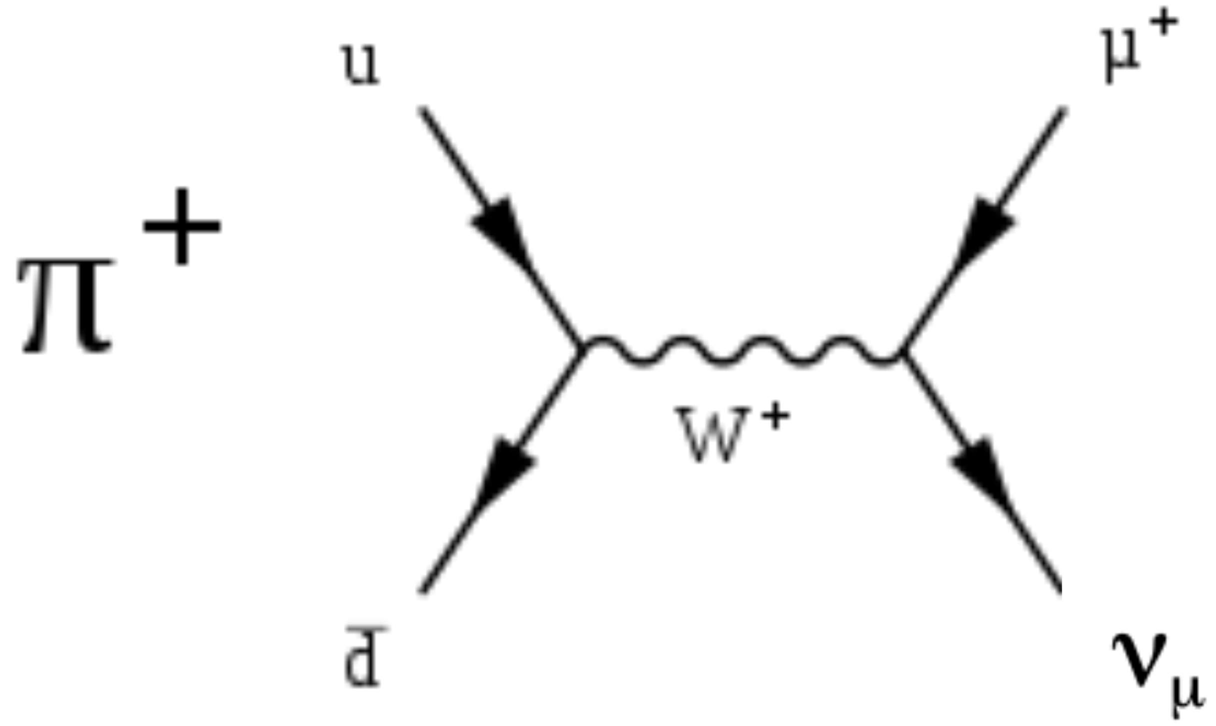
- Many remaining questions in fundamental physics involve neutrinos:
  - What is the mechanism for neutrinos acquiring mass?
  - Do right-handed neutrinos exist and could they be dark matter?
  - Do neutrinos play a role in leptogenensis and the asymmetry between matter & antimatter in the universe
- The Standard Model parameters of neutrino masses and flavour mixing are still not precisely measured

Neutrino Oscillations

- A neutrino state of definite flavour is a mixture of states of definite mass:

$$|\nu_\alpha\rangle = \sum_{i=1}^{i=3} U^*_{\alpha i} |\nu_i\rangle$$

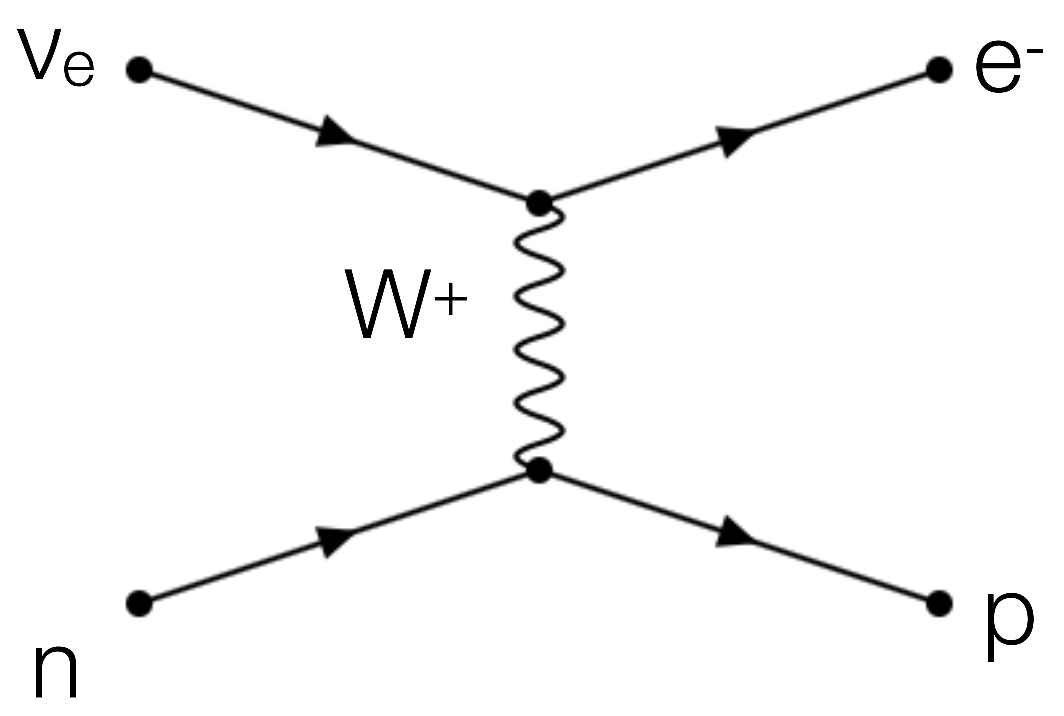
Flavour state Mass states



ν_1, ν_2, ν_3

Propagate as mixture of mass states

$$\nu_\mu = U_{\mu,1}\nu_1 + U_{\mu,2}\nu_2 + U_{\mu,3}\nu_3$$



Produce neutrinos as weak eigenstates

Interact as weak eigenstates

- Mass states propagate with relative phase that depends on mass squared differences, **$\Delta m^2_{ij} = m^2_i - m^2_j$**

- **Flavour composition changes during propagation**

Parameterization of Oscillations

Pontecorvo–Maki–Nakagawa–**Sakata** mixing matrix:

$$U=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s^{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

Accessible through neutrino oscillations
($s_{12} = \sin\theta_{12}$, etc.)

Majorana phases if neutrinos are Majorana particles

δ, α_{21} and α_{31} may introduce new sources of CP violation

The flavor content of states oscillate as they traverse matter or vacuum:

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

Dependence on mass squared differences of mass states, distance and energy

Open Questions

Mixing angle measurements (PDG):

$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$

$\sin^2\theta_{23} = 0.553^{+0.016}_{-0.024}$

$\sin^2\theta_{13} = 0.0219 \pm 0.007$

Do the mixing angles indicate underlying symmetry?

The value of θ_{23} is close to 45º

What is the value of δ? Is there CP violation in neutrino oscillations?

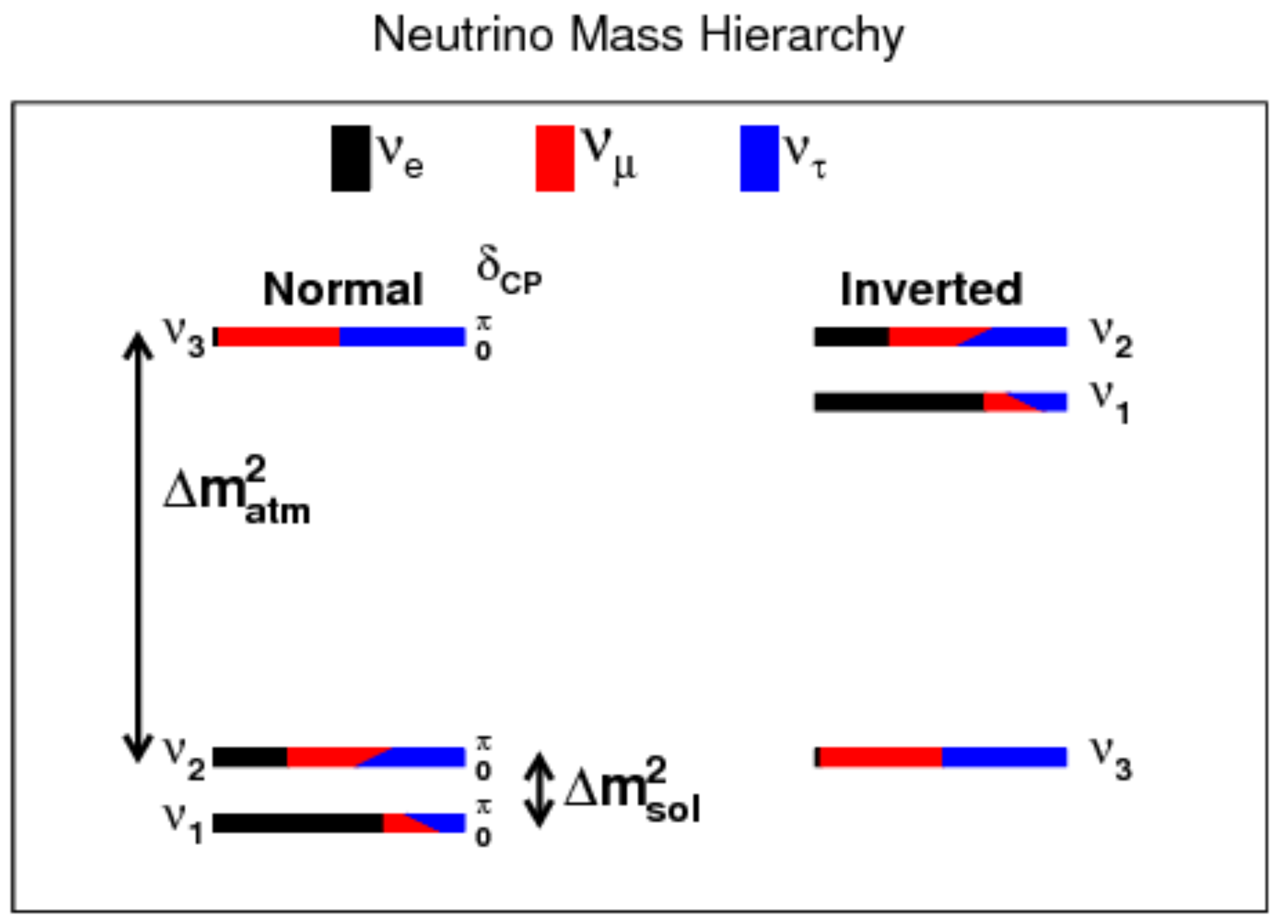
Mass splitting measurements (PDG):

$\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\ eV^2$

$\Delta m^2_{32} = -2.53 \pm 0.03 \times 10^{-3}\ eV^2$

or

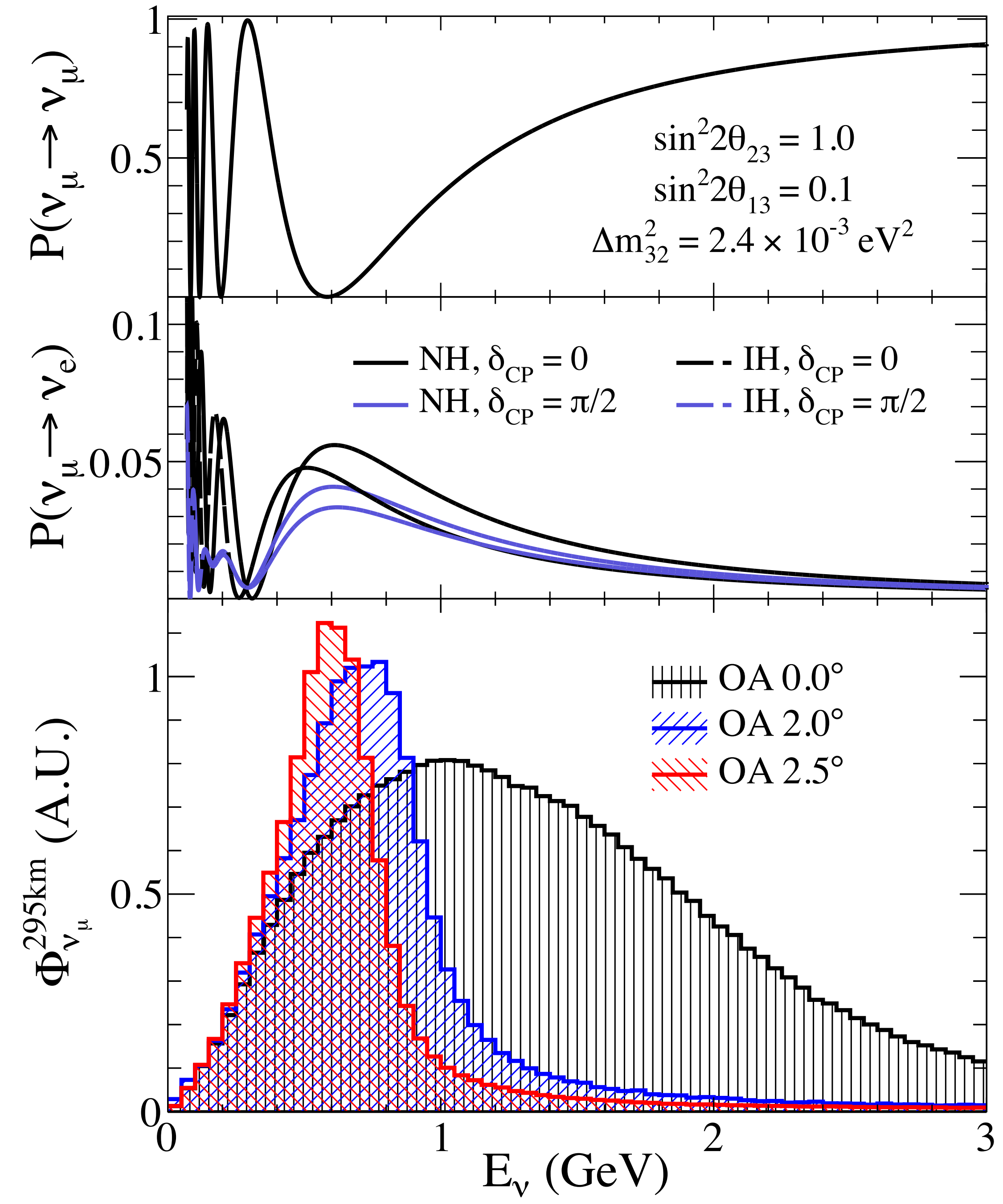
$\Delta m^2_{32} = 2.46 \pm 0.03 \times 10^{-3}\ eV^2$



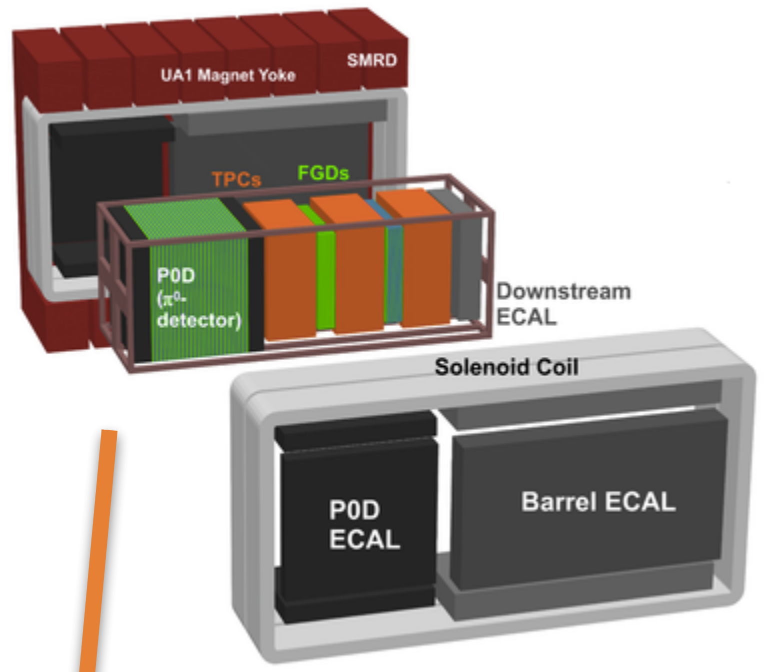
Is the ordering normal or inverted?

Neutrino Oscillations at T2K

571 members from 74 institutions from 15 countries



ND280 Near Detector



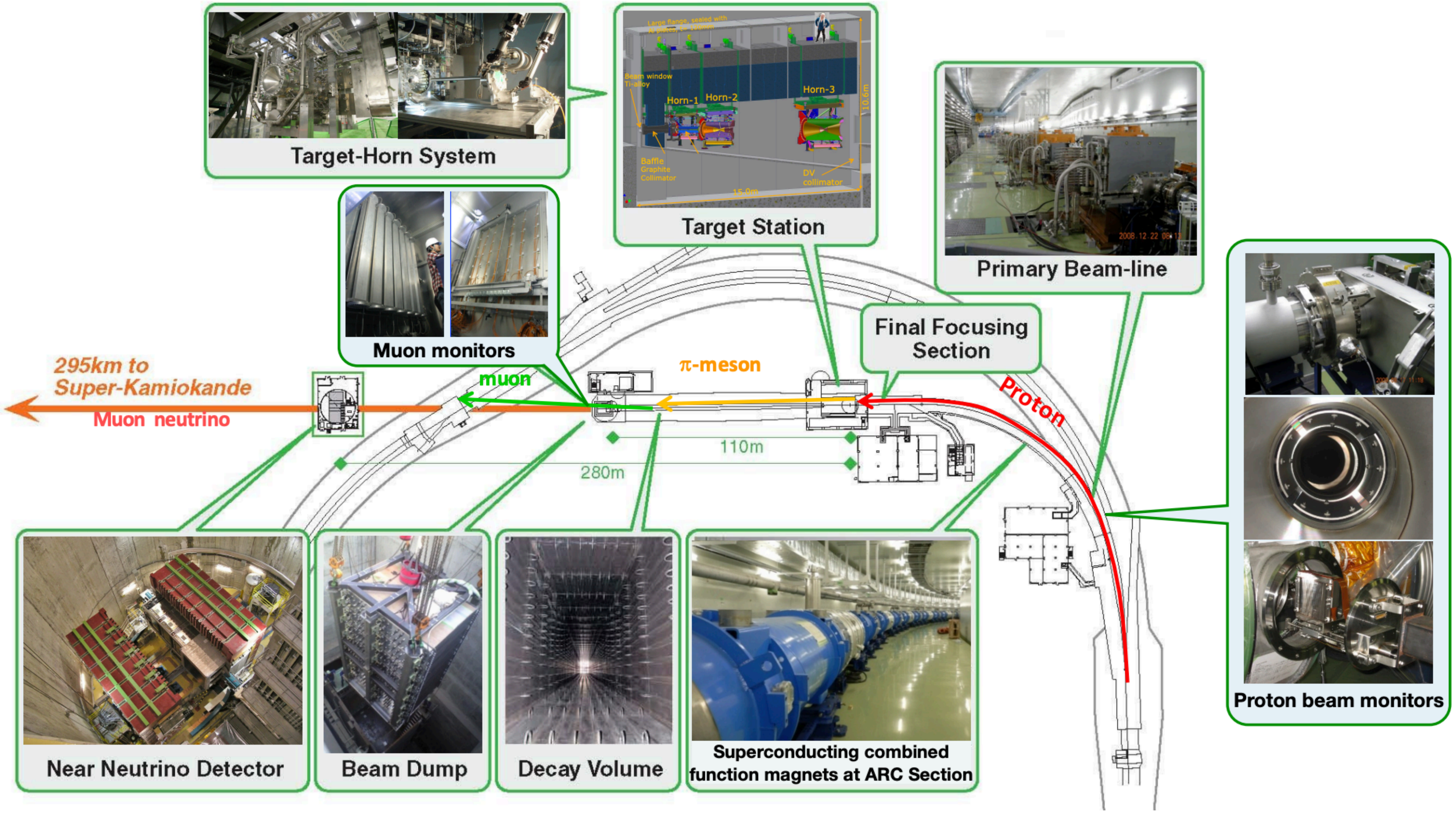
Neutrino Oscillation Modes:

CP violation in Neutrino Oscillations

$$P_{\mu\to e} = \boxed{\sin^2\theta_{23}} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \boxed{\mp} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin^2 2\theta_{13} \sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \boxed{\sin\delta_{CP}} + \ldots$$

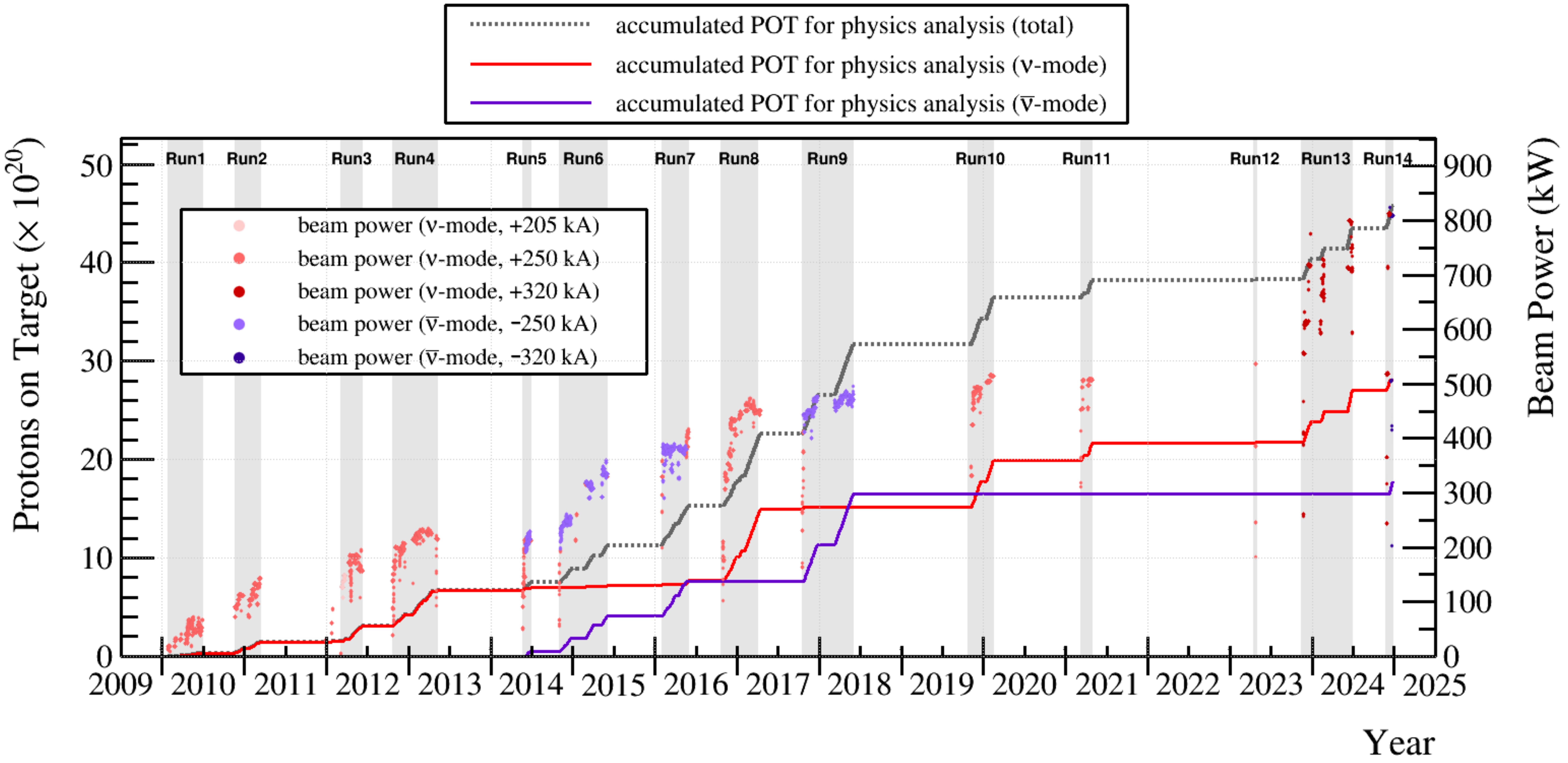
$$P_{\mu\to\mu} = 1 - \left(\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23} \cos 2\theta_{23} \sin^2 2\theta_{13}\right) \sin^2\left(\frac{\boxed{\Delta m^2_{32}} L}{4E_\nu}\right) + \ldots$$

Neutrino Beam Generation



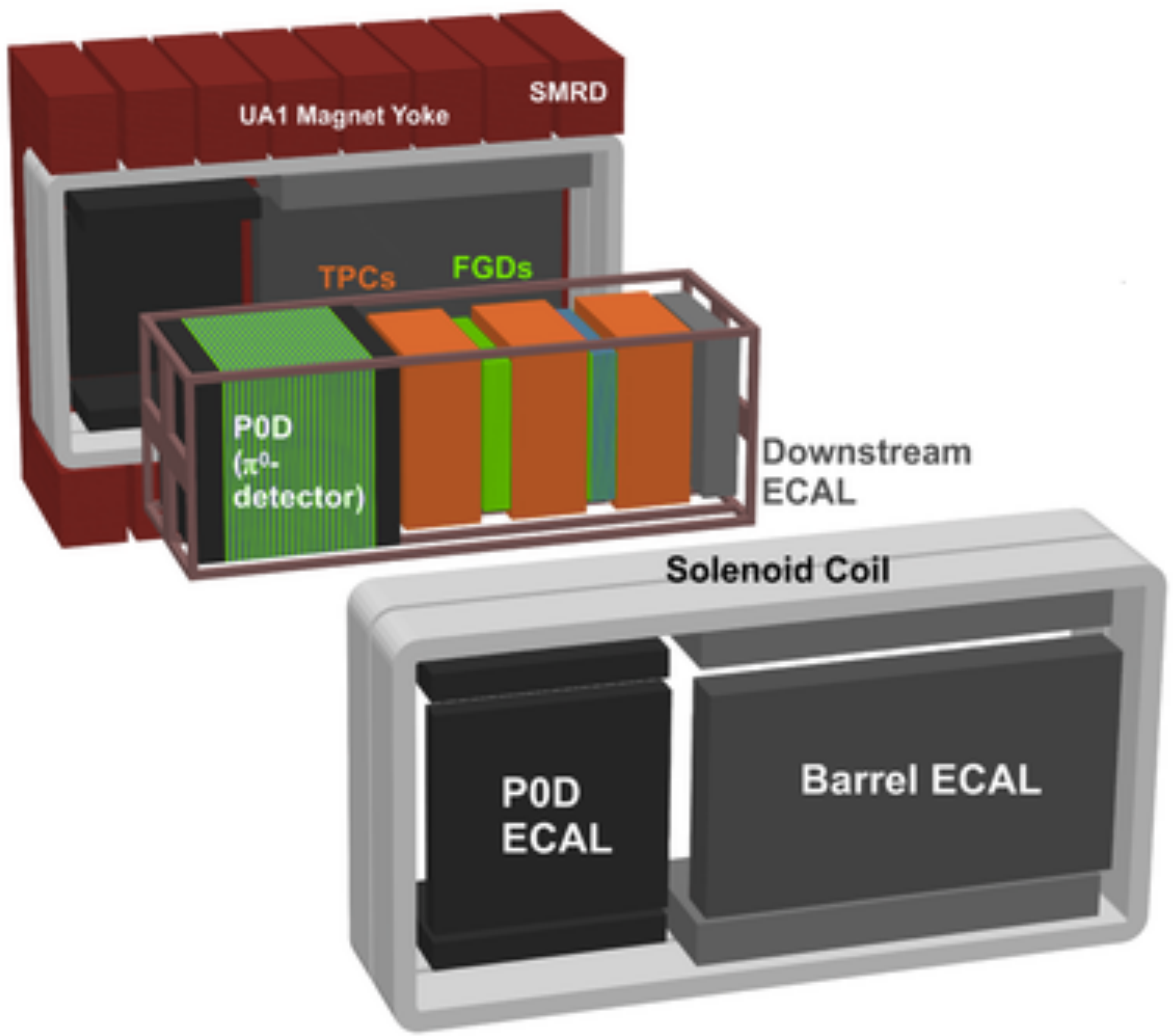
- Neutrino beam generated at J-PARC with 30 GeV protons colliding with a graphite target
- 3 magnetic horns focus positive or negative pions/kaons to produce neutrino or antineutrino beam

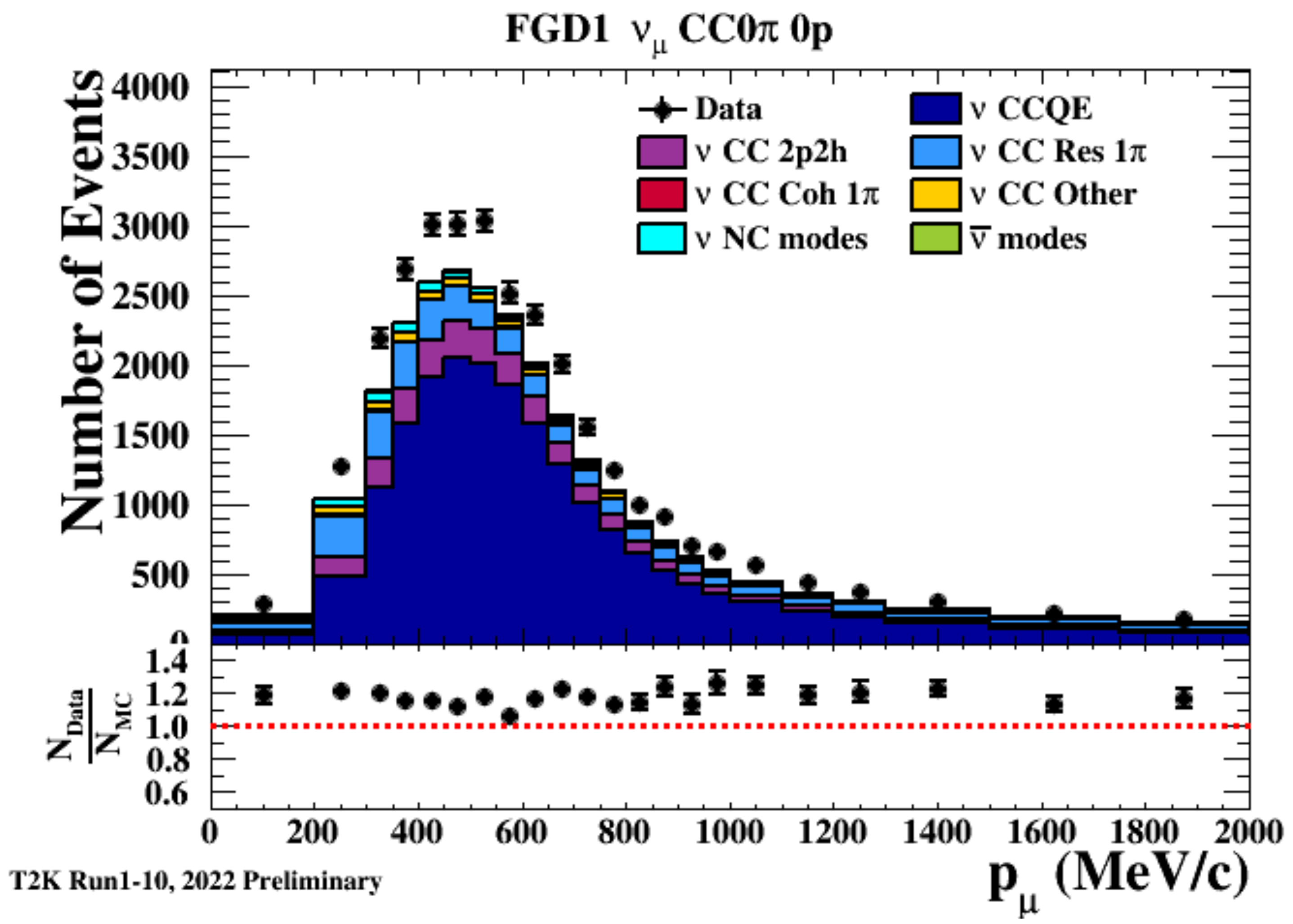
J-PARC Beam Delivery

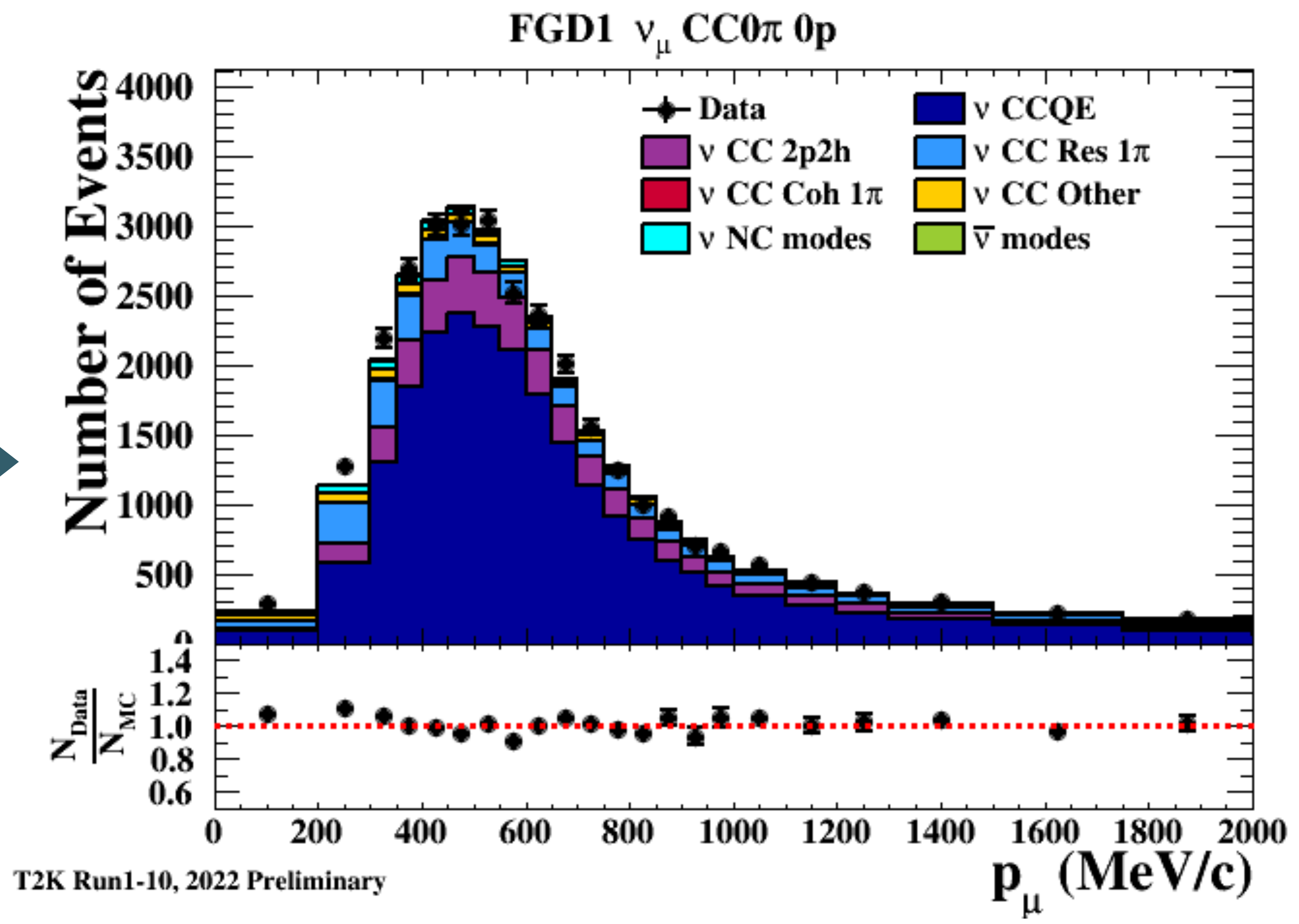


- Upgrade of the J-PARC main ring RF and magnets to achieve higher protons-per-spill and increased repetition rate
- Achieved record operation of >800 kW!

Near Detector Constraint





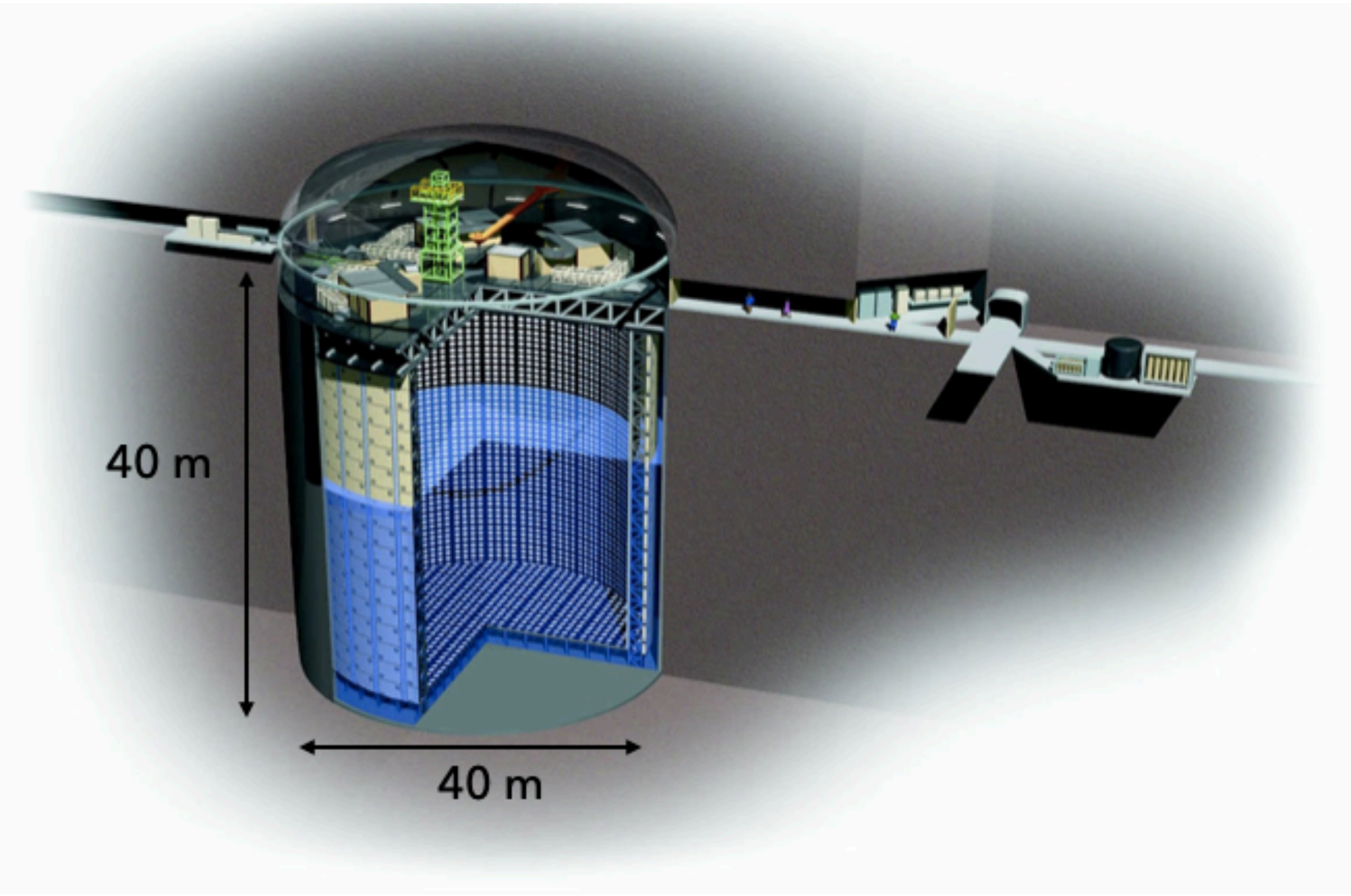


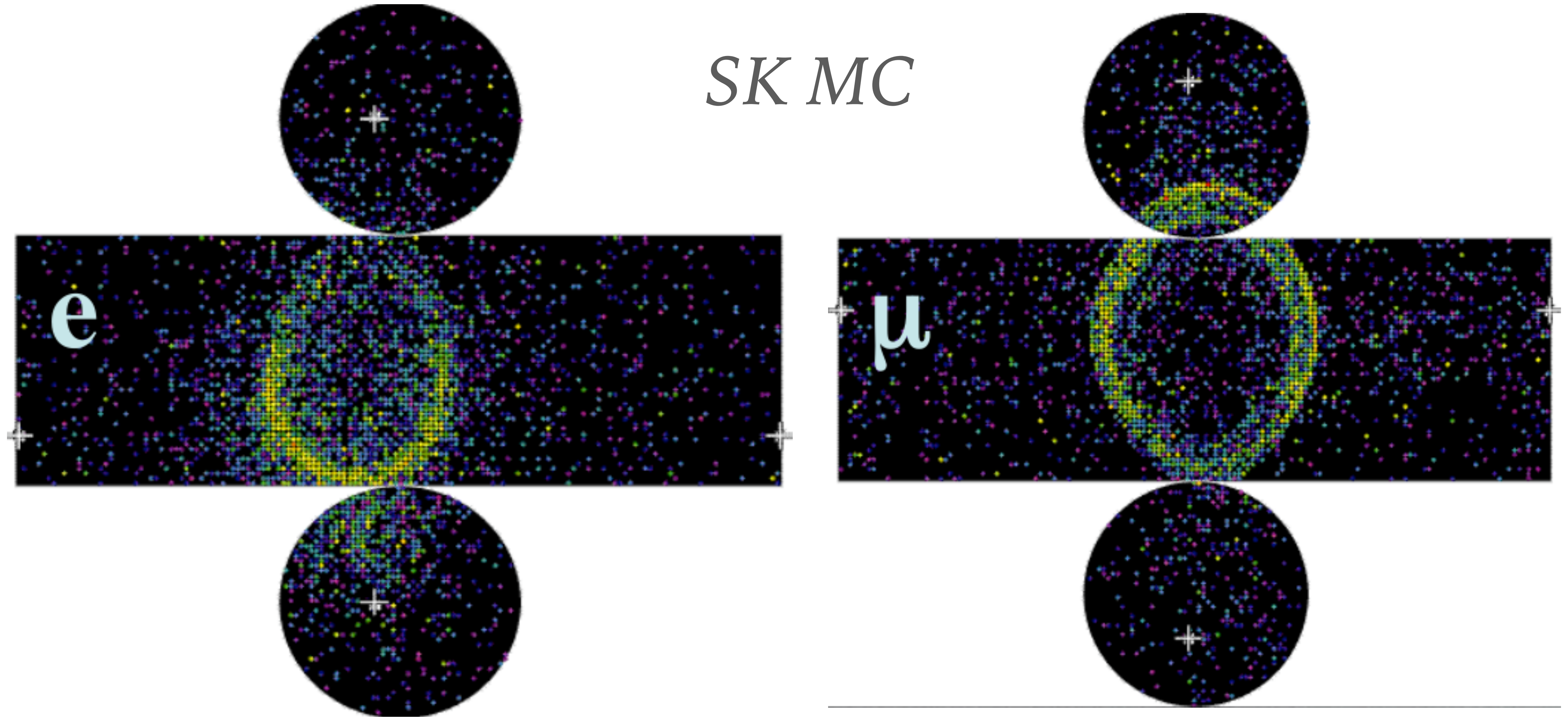
- Models of neutrino production and interactions are source of systematic uncertainty
- Data from ND280 near detector is used to constrain models of the neutrino production and neutrino interactions

Magnetized tracking detector with scintillator targets (FGDs) and tracking time projection chambers (TPCs)

Super-K Detector

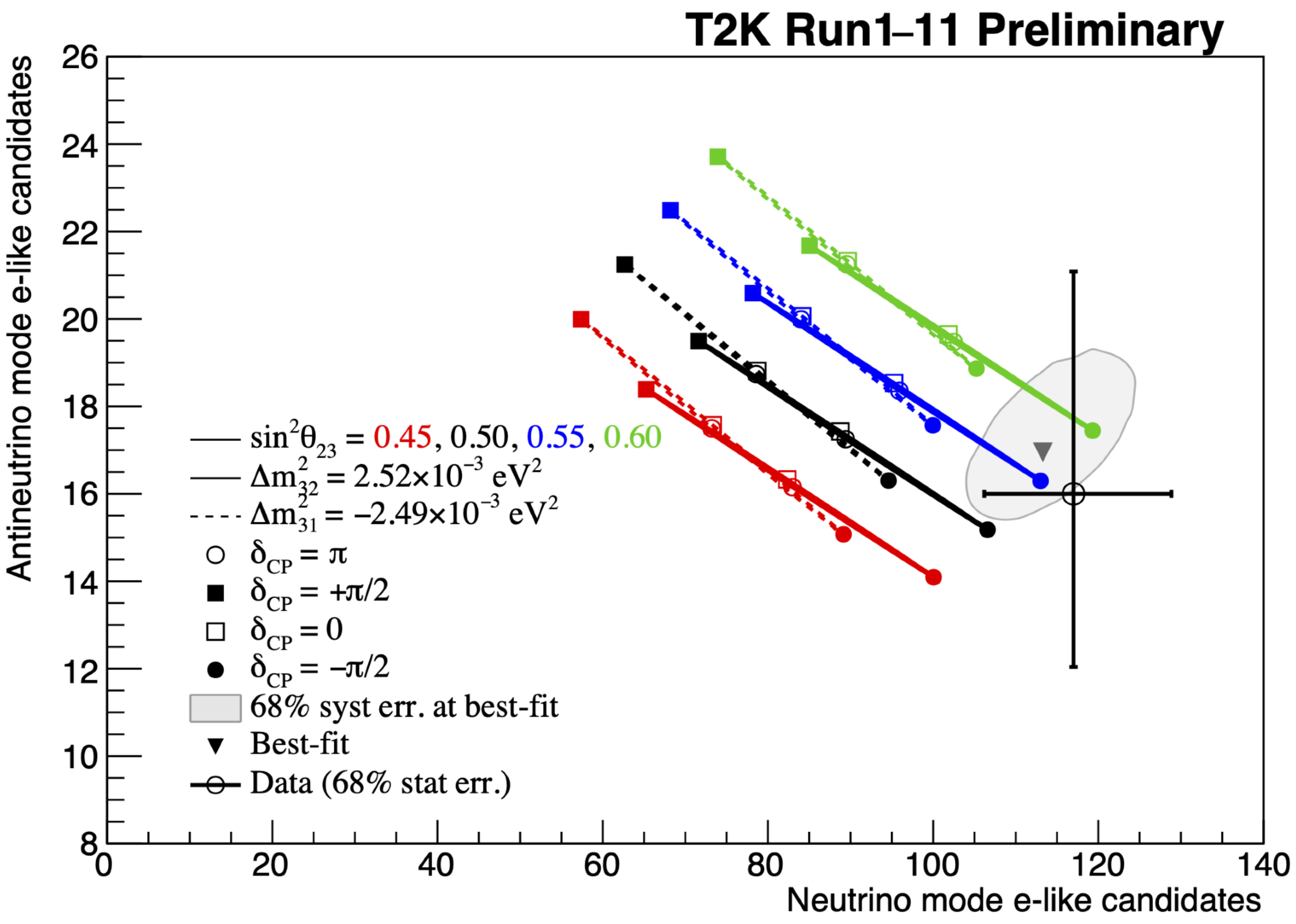
- 22.5 kton fiducial mass water Cherenkov detector
- Located 295 km from J-PARC at 2.5 degrees off-axis
- 11,000 50-cm PMTs used to image Cherenkov light from neutrino interaction products
- Excellent particle identification performance necessary for selection of electron (anti)neutrino candidates
- T2K is one of many accomplishments with Super-K detector (see Nakahata-san's talk)

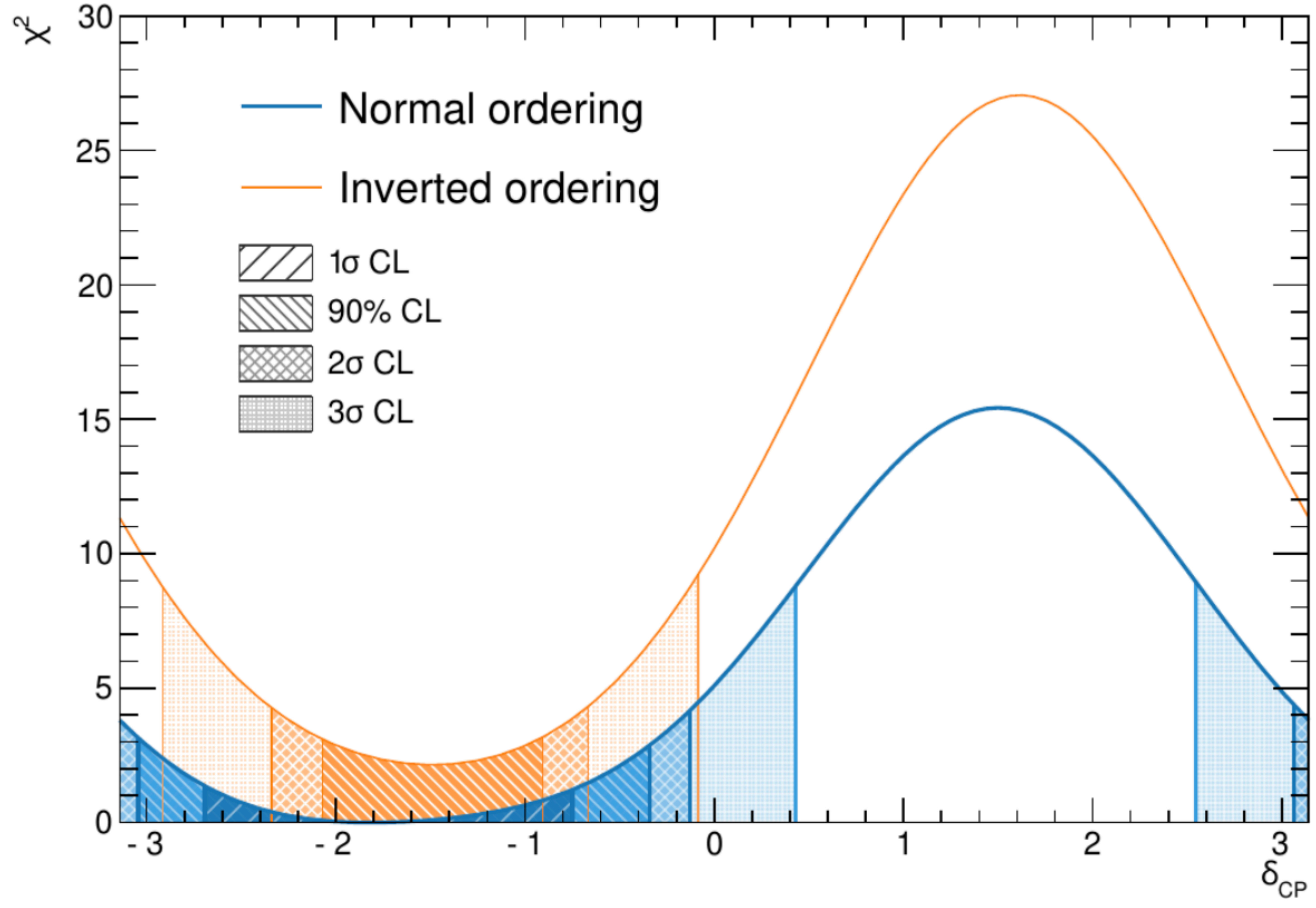




T2K Results

Eur. Phys. J. C 83 (2023) 9, 782





- T2K observes **117 electron neutrino** candidates and **16 electron antineutrino** candidates
- Results are consistent with large CP violation with **~1/2 of possible values disfavoured at 2σ significance**

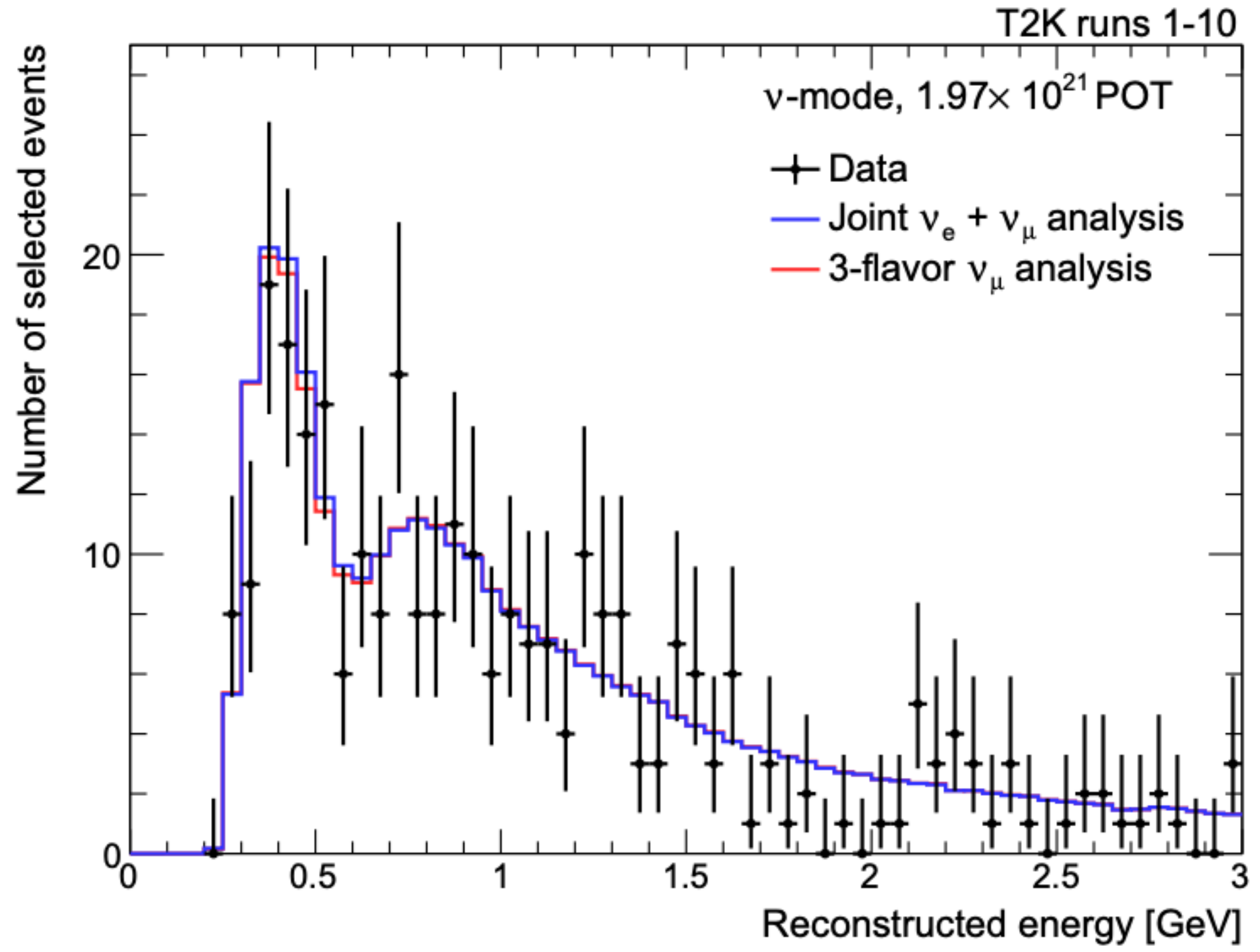
Δm^2_{32} & θ_{23}

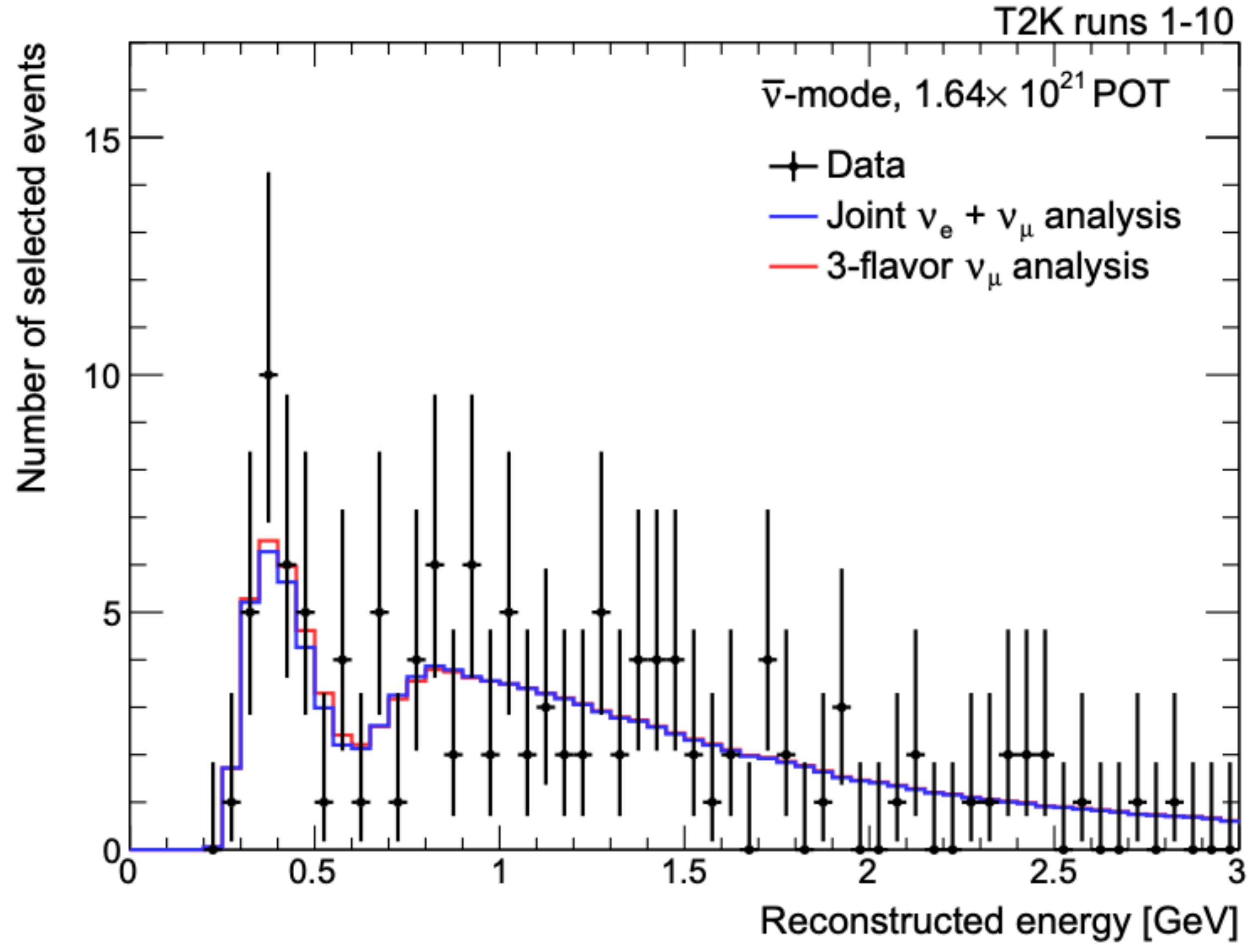
Eur. Phys. J. C **83 (2023) 9, 782**

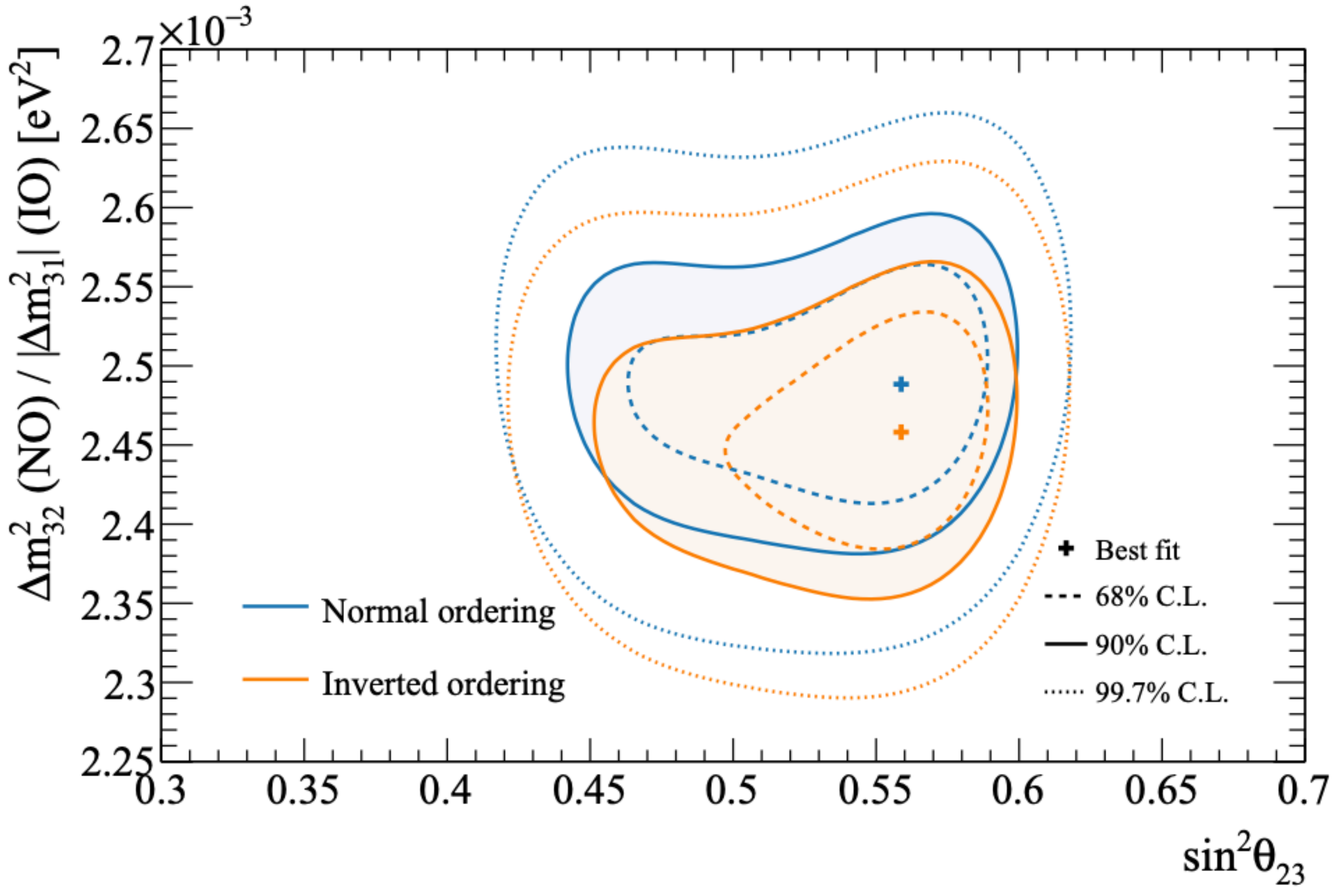
- T2K measurement of θ_{23} remains consistent with maximal mixing

$$\Delta m^2_{32} = 2.494^{+0.041}_{-0.058} \times 10^{-3}\ \mathrm{eV}^2$$

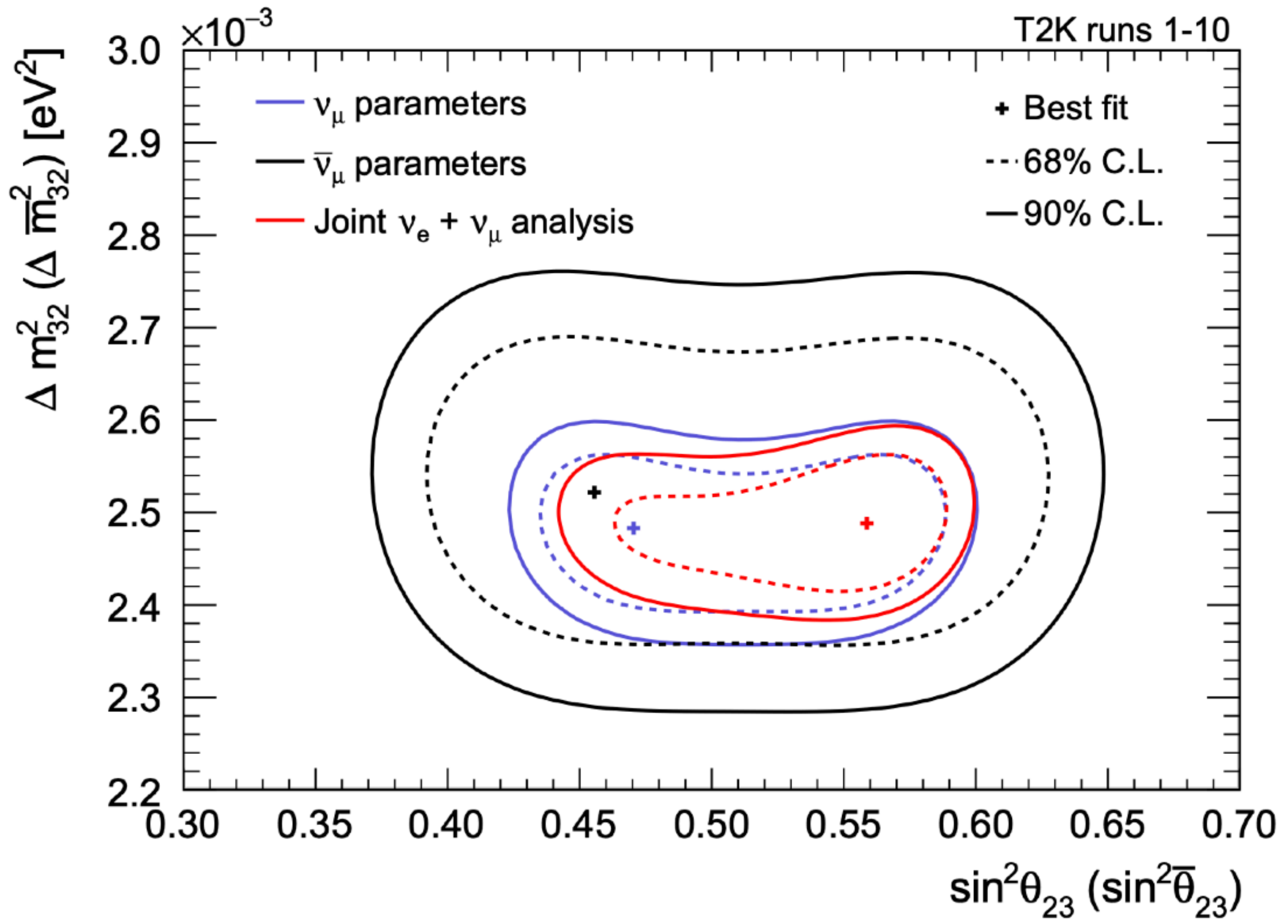
- T2K shows a slight preference for normal ordering with posterior probability of 0.81
- Separate fits of parameters for neutrinos and antineutrinos show consistent results (no CPT violation)







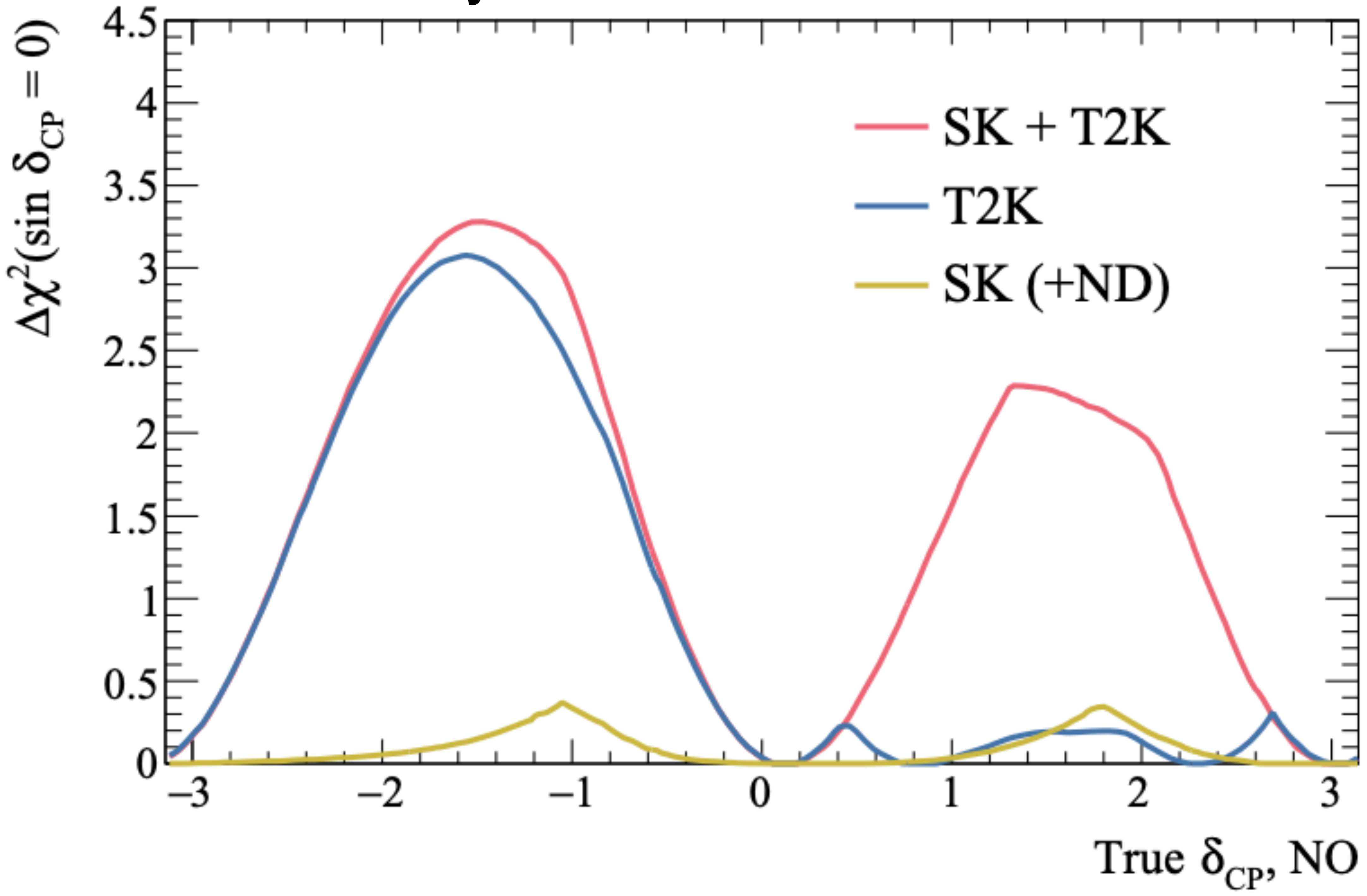
Phys. Rev. D 108 (2023) 7, 072011

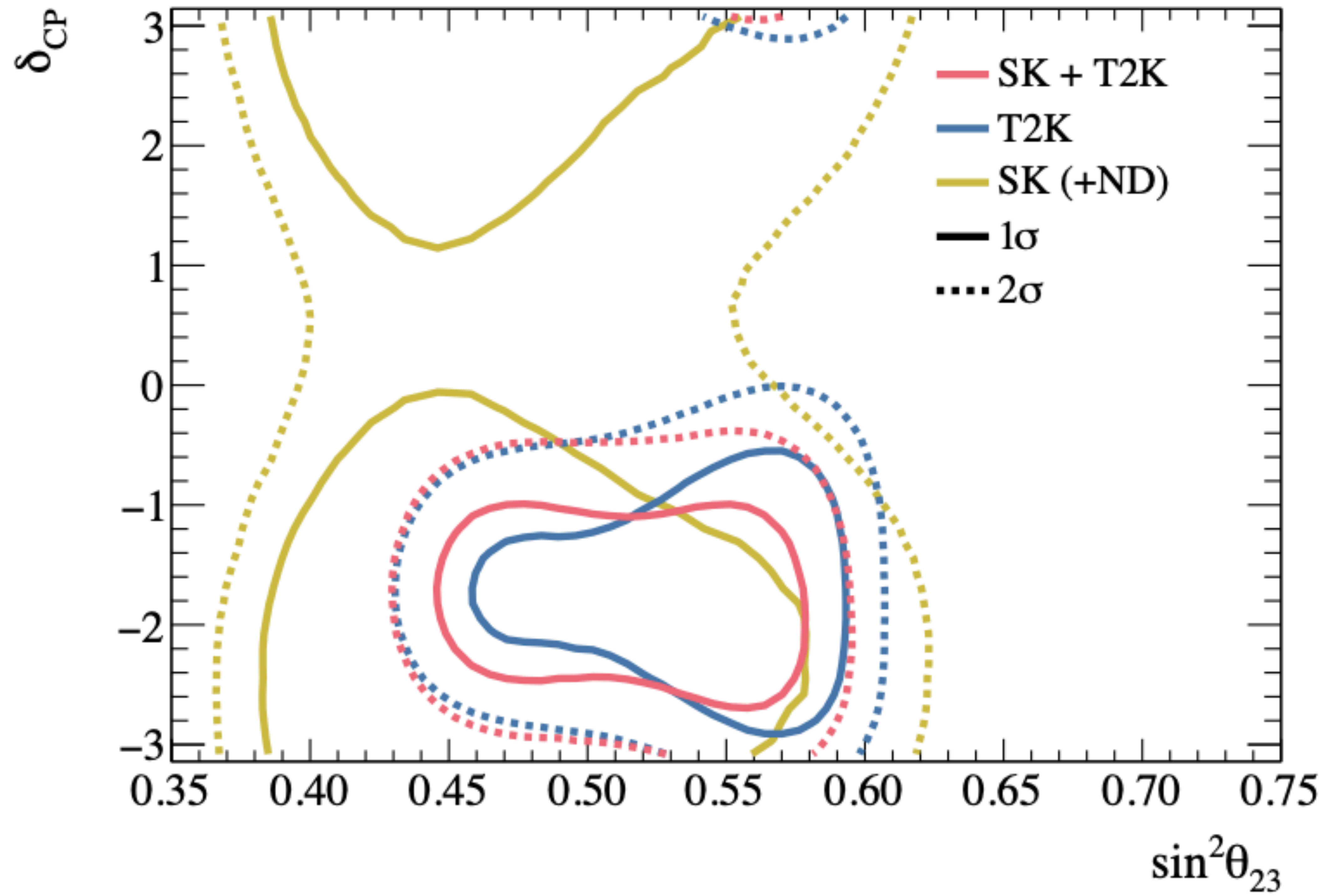


Joint Result: T2K & Super-K

Phys. Rev. Lett. 134 (2025) 1, 011801

Sensitivity to exclude CP conservation





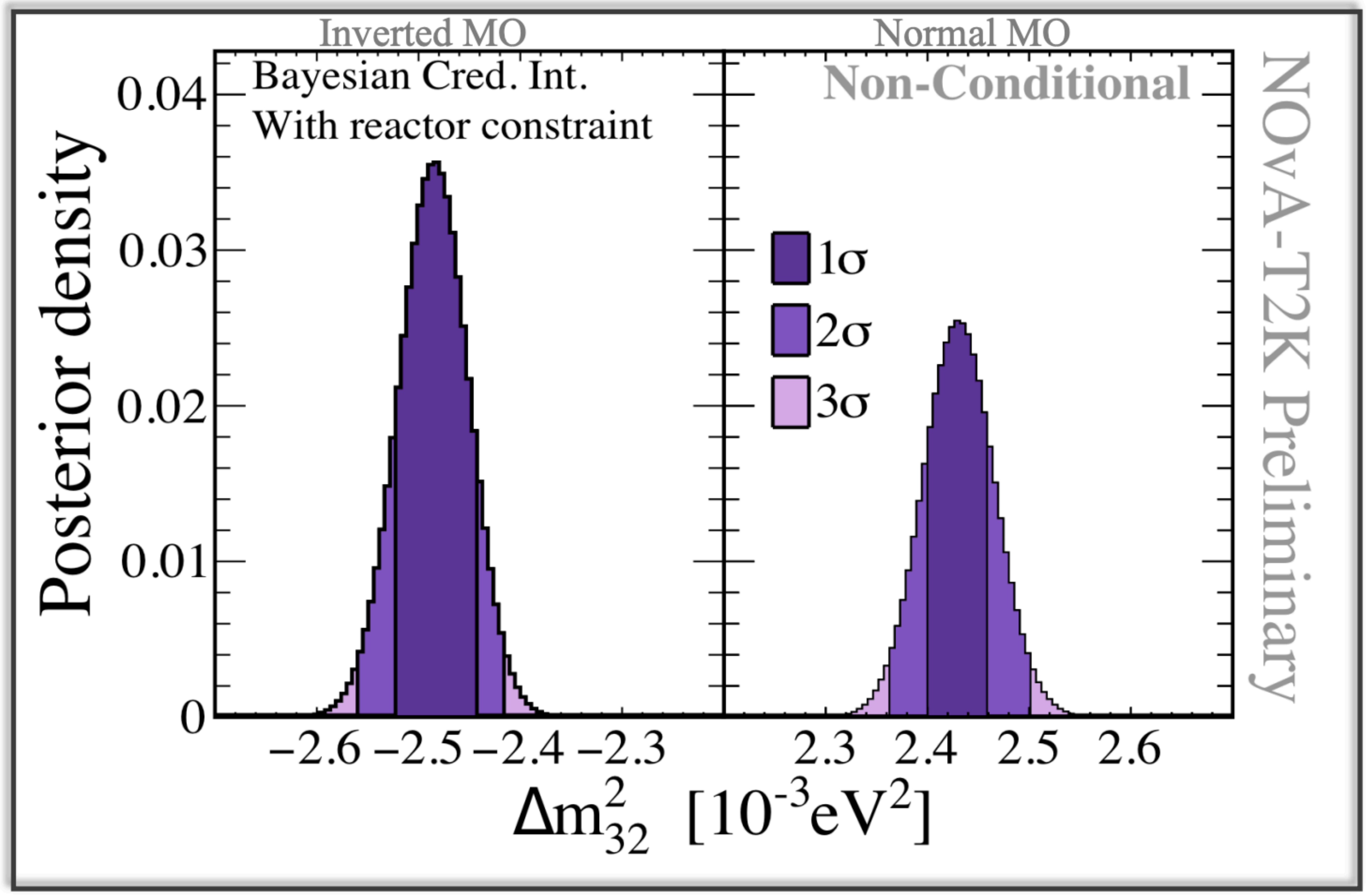
- Super-K atmospheric neutrino data has improved sensitivity to the mass ordering compared to T2K
- Data at different L/E breaks degeneracies
- Combined data shows a similar preference for δ and $\sin^2\theta_{23}$ values
- Preference for normal ordering

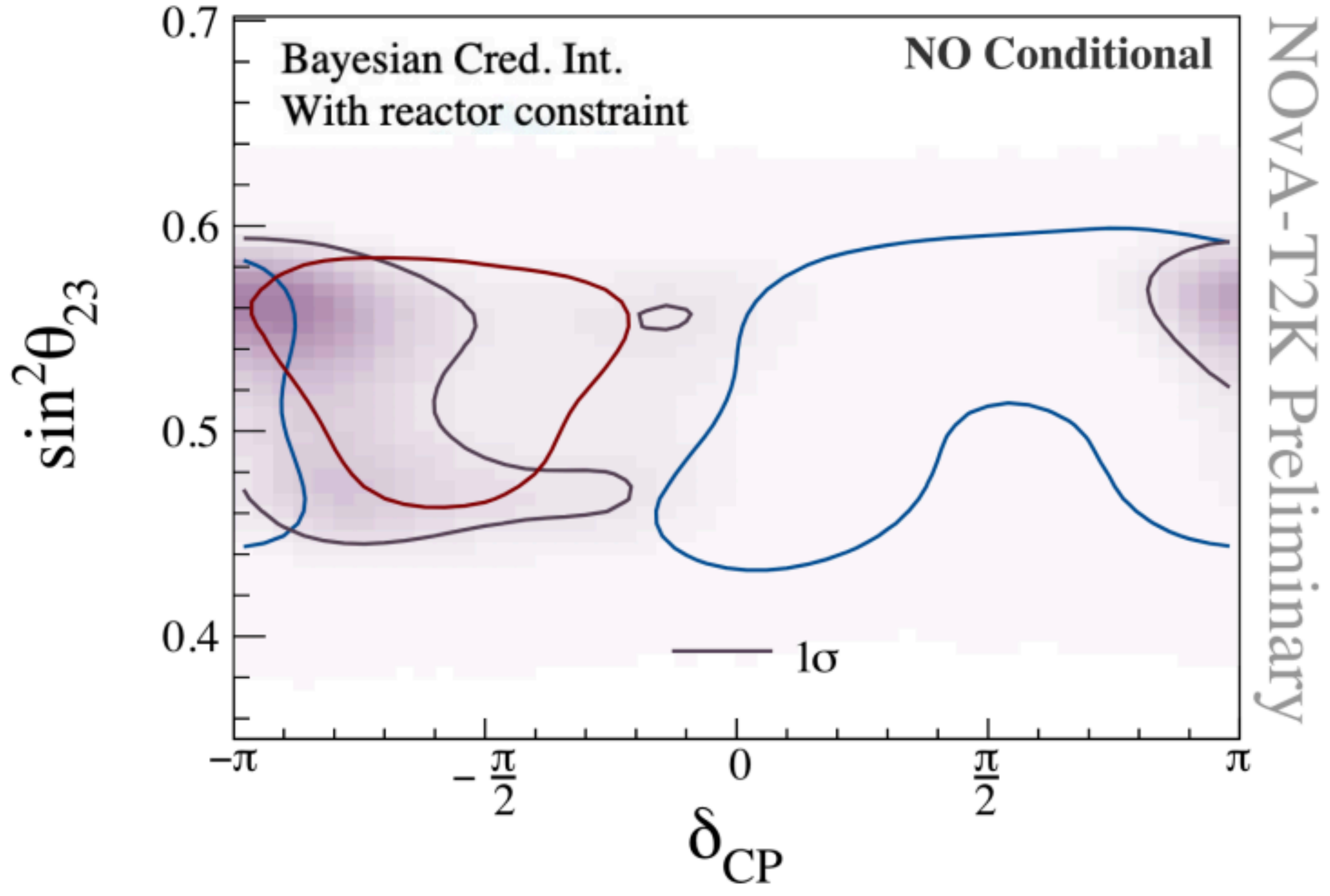
Posterior probability for mass ordering

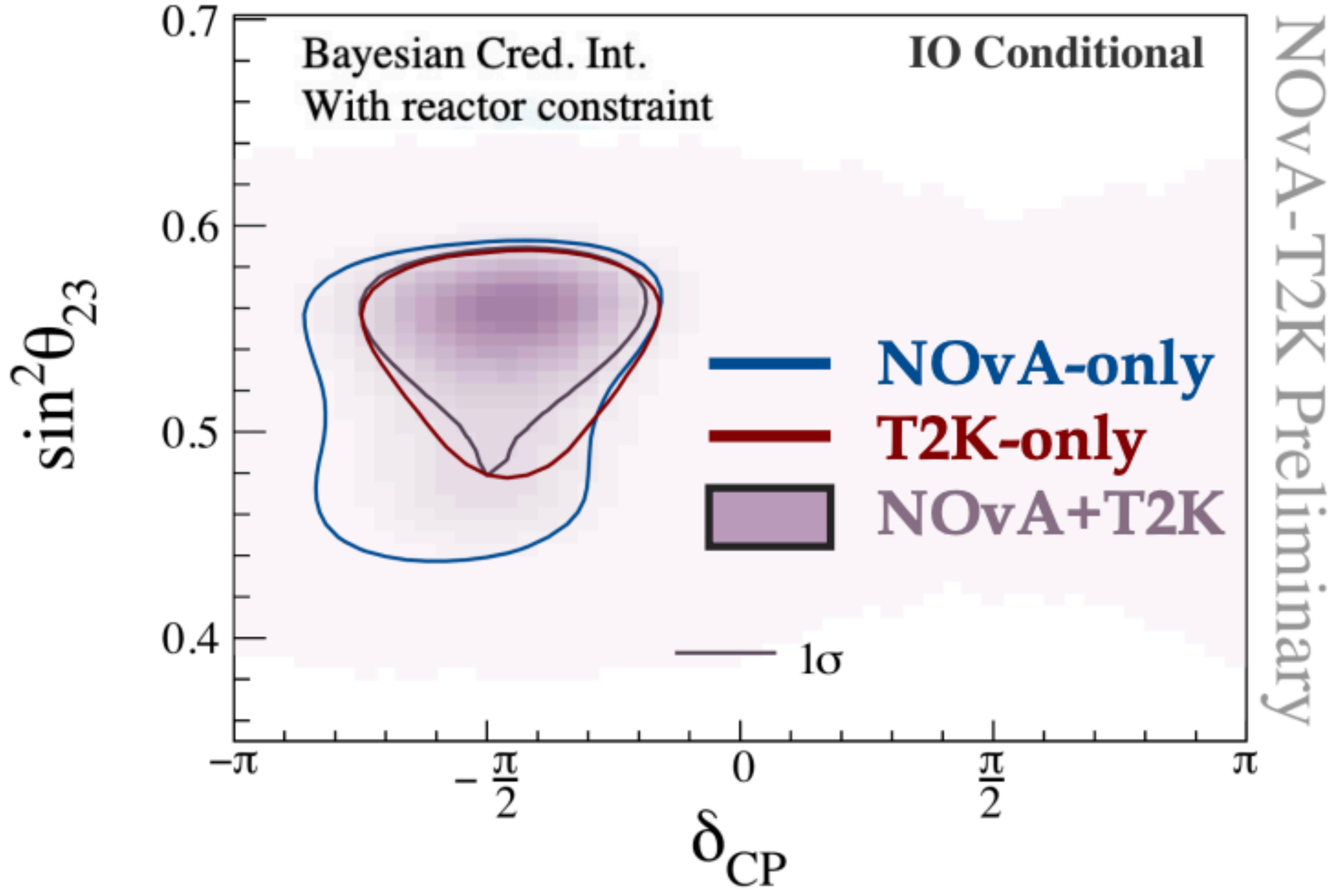
	SK only	T2K only	SK+T2K
Upper octant	0.318 (0.337)	0.785 (0.761)	0.611 (0.639)
Normal ordering	0.654 (0.633)	0.832 (0.822)	0.900 (0.887)

Joint Result: T2K & NOvA

FNAL, Joint Theory-Experiment Seminar

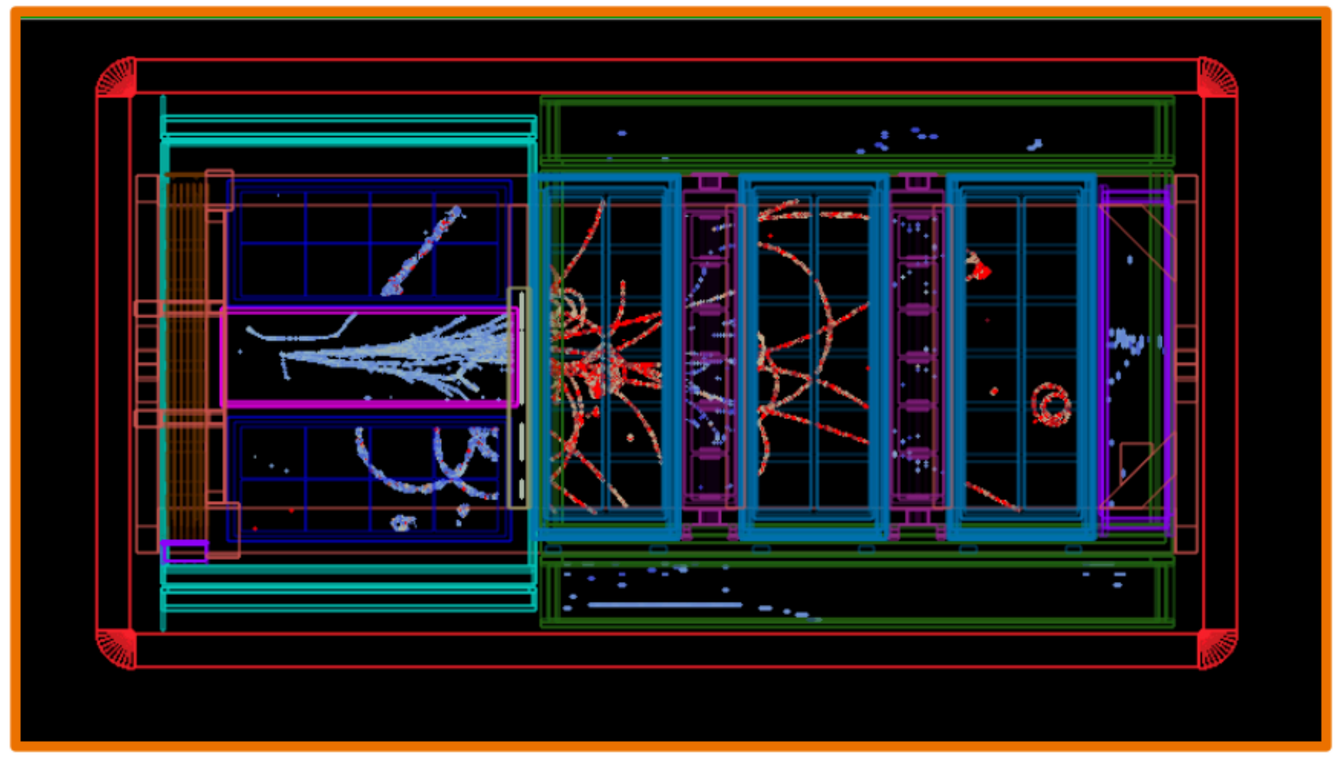


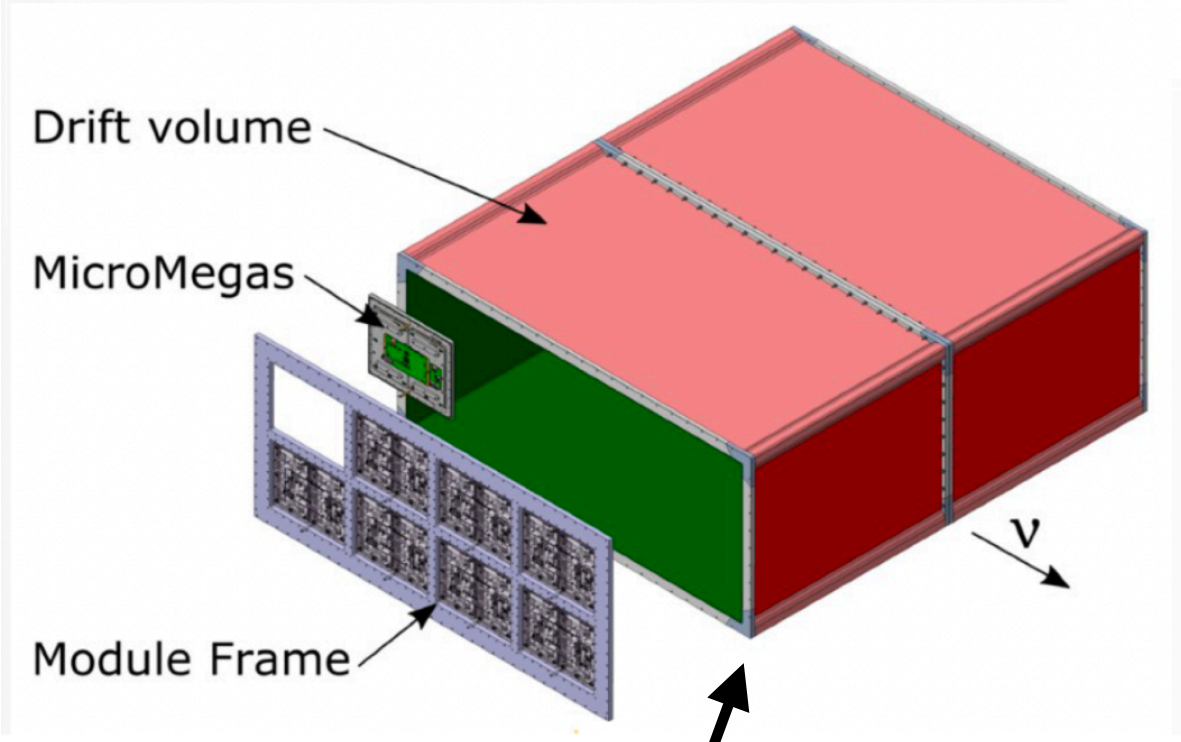


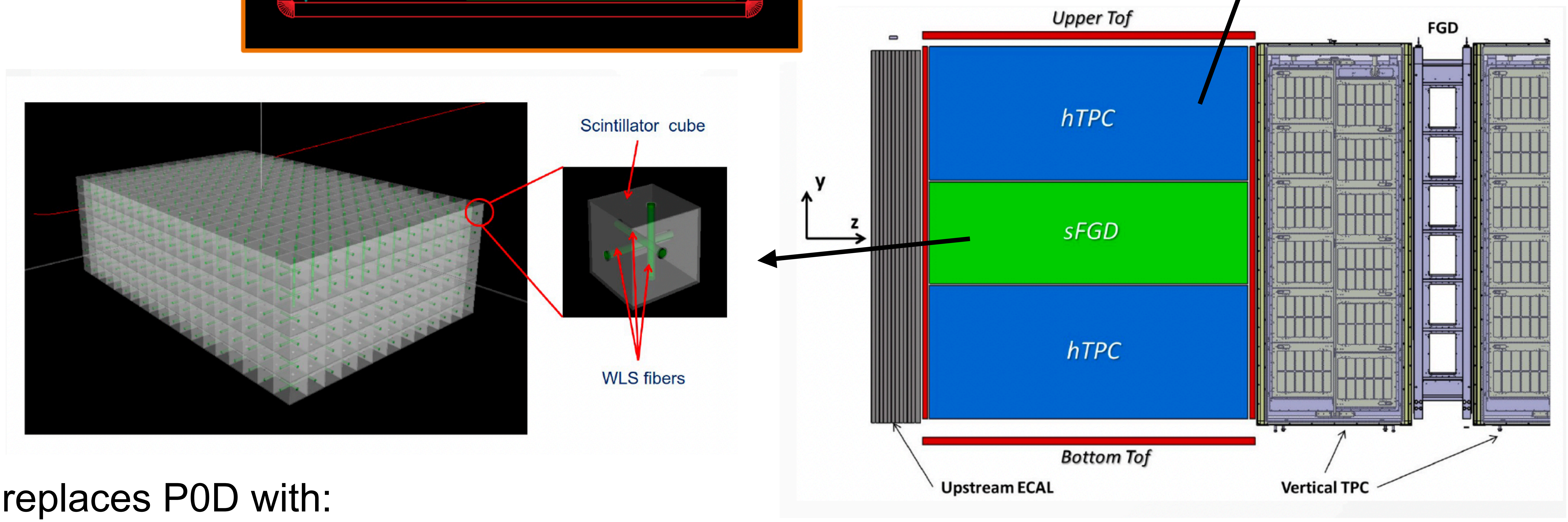


- T2K and NOvA experiments have completed a joint analysis with a paper coming soon
- Combined result shows essentially no preference between normal and inverted ordering
- Preferred δ values are limited in inverted ordering hypothesis

ND280 Upgrade





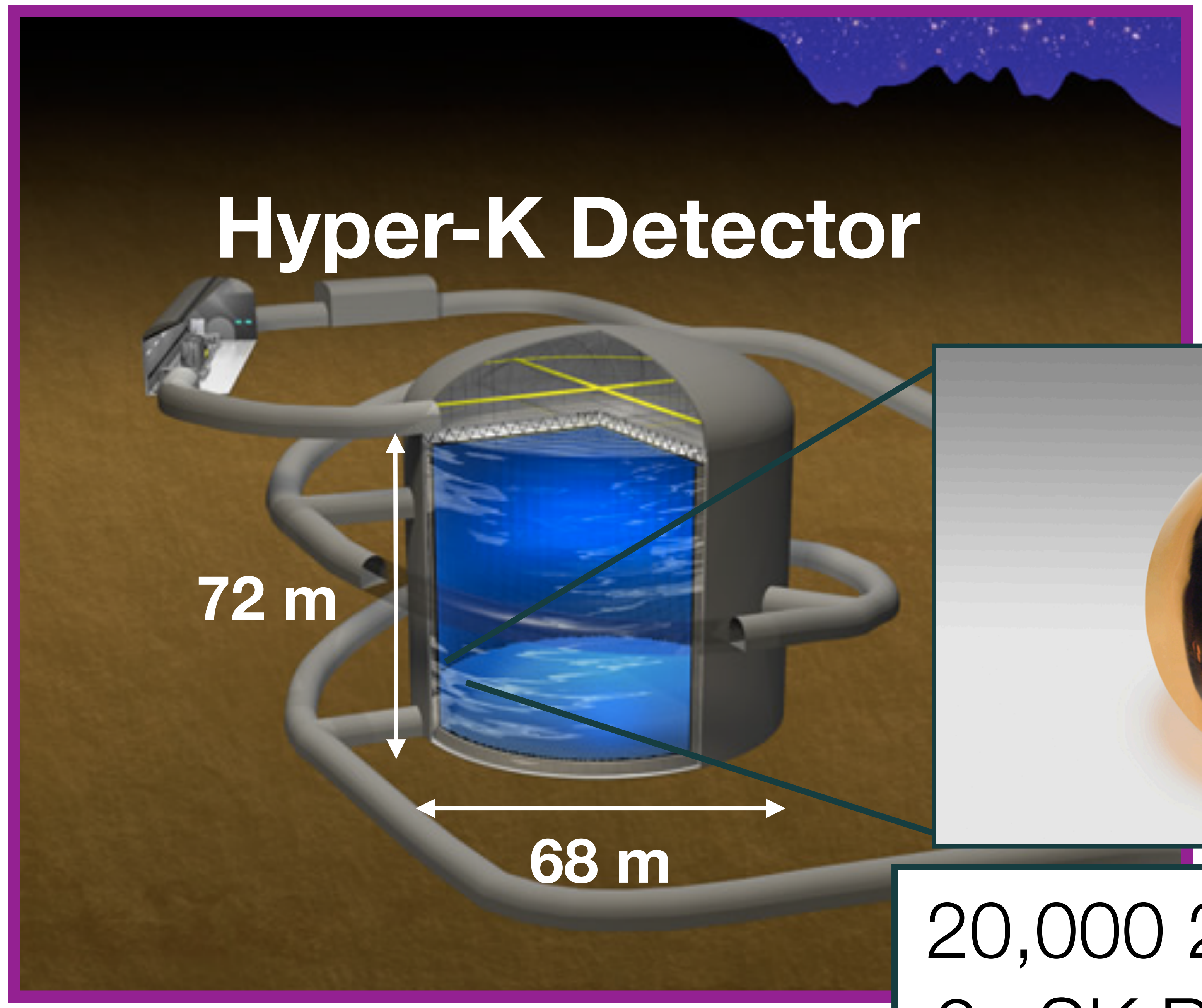


- Upgrade of ND280 detector replaces P0D with:
  - Super-FGD scintillator detector with 3 axis of light collection for precision tracking
  - High-angle TPCs to track neutrino interaction produced produced at higher angles
  - Time-of flight detectors to reconstruct particle direction and support particle identification
- Upgrades are installed and operating!

Hyper-Kamiokande

650 members from 106 institutions from 22 countries

- 260 kton detector with fiducial mass is 8x larger than Super-Kamiokande
- Neutrino beam from J-PARC will be further upgraded to 1.3 MW
- New photon detectors and intermediate detector
- Broad physics program includes
  - Accelerator neutrinos
  - Proton decay searches
  - Supernova neutrino detection
  - Atmospheric neutrino detection
  - Solar neutrino detection
  - Dark matter searches…
- Planned completion by JFY2027



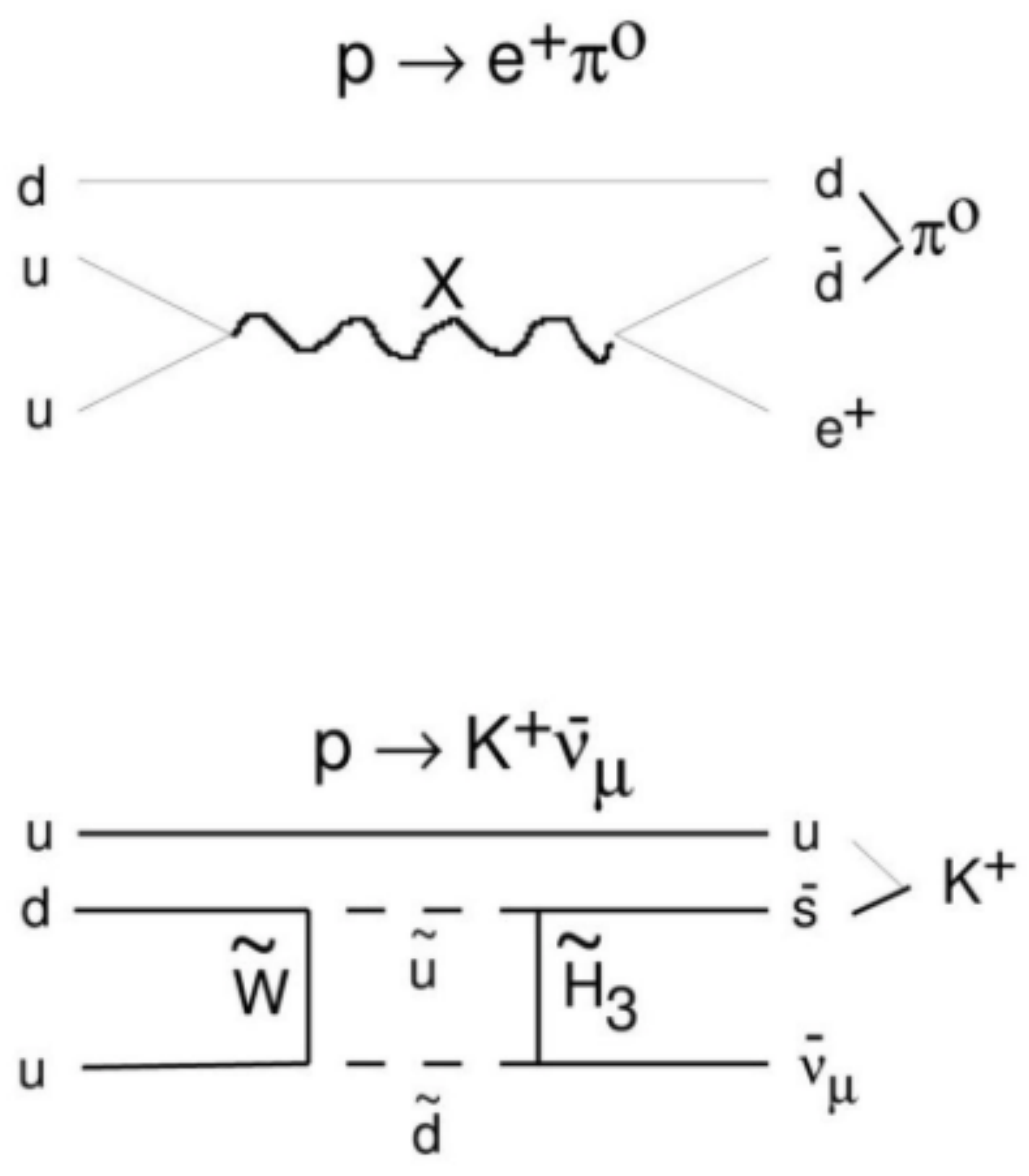
20,000 20-in. ⌀ PMTs
2x SK PMT efficiency

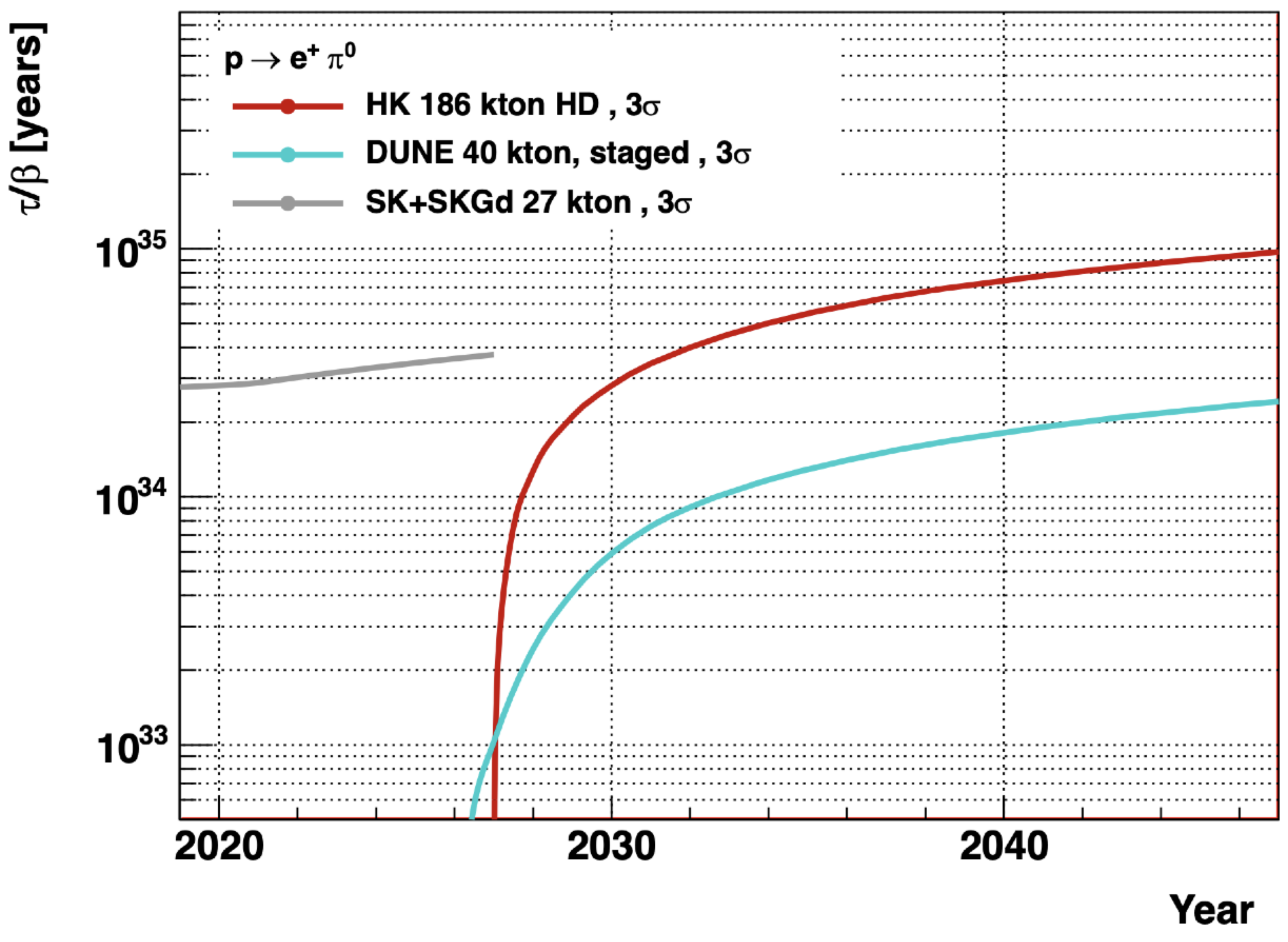
J-PARC upgrade to 1.3 MW beam power

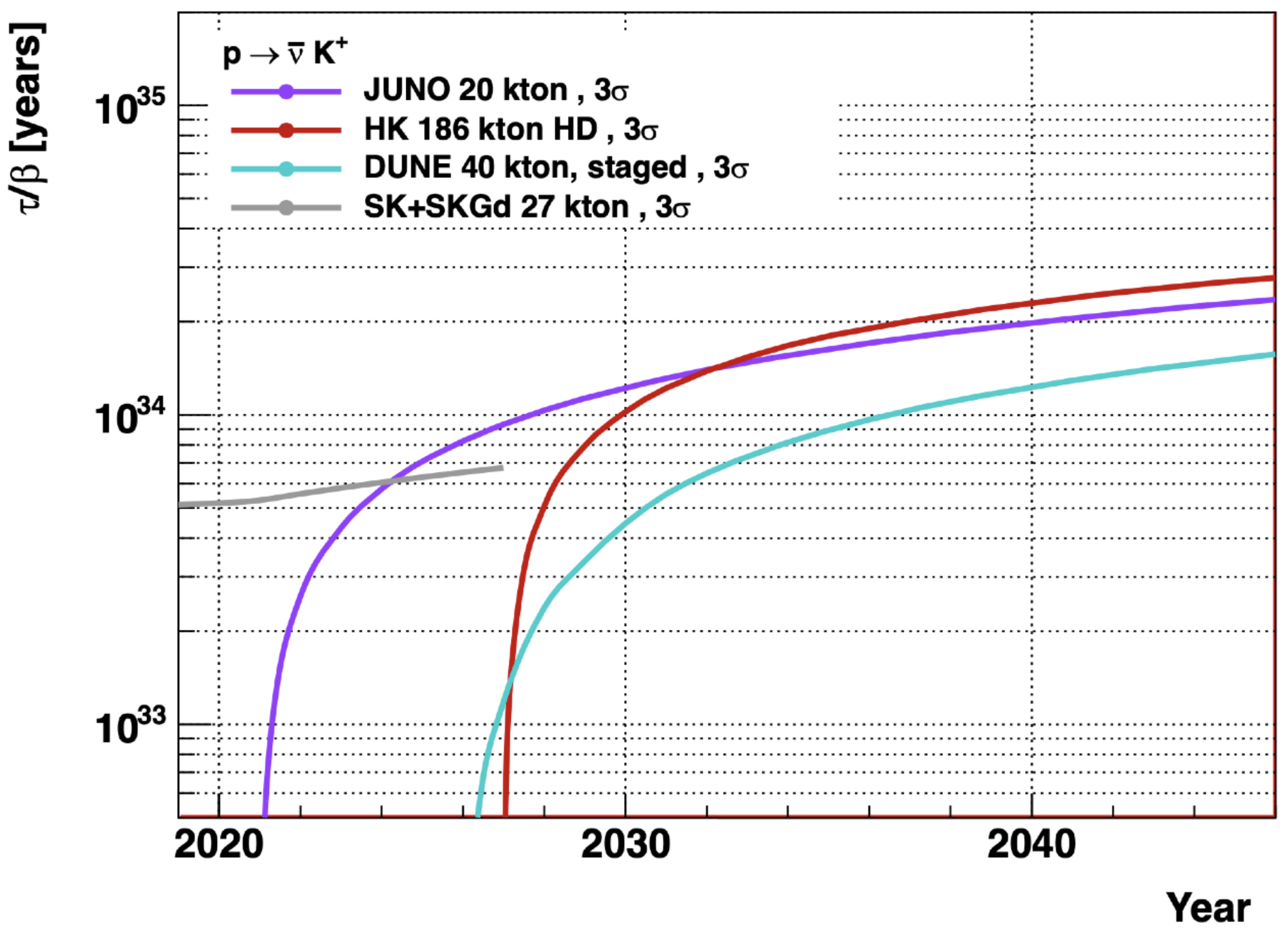
Proton Decay at Hyper-Kamiokande

The original Kamiokande experiment was built to look for proton decay predicted by Grand Unified Theories (GUTs) - not found yet

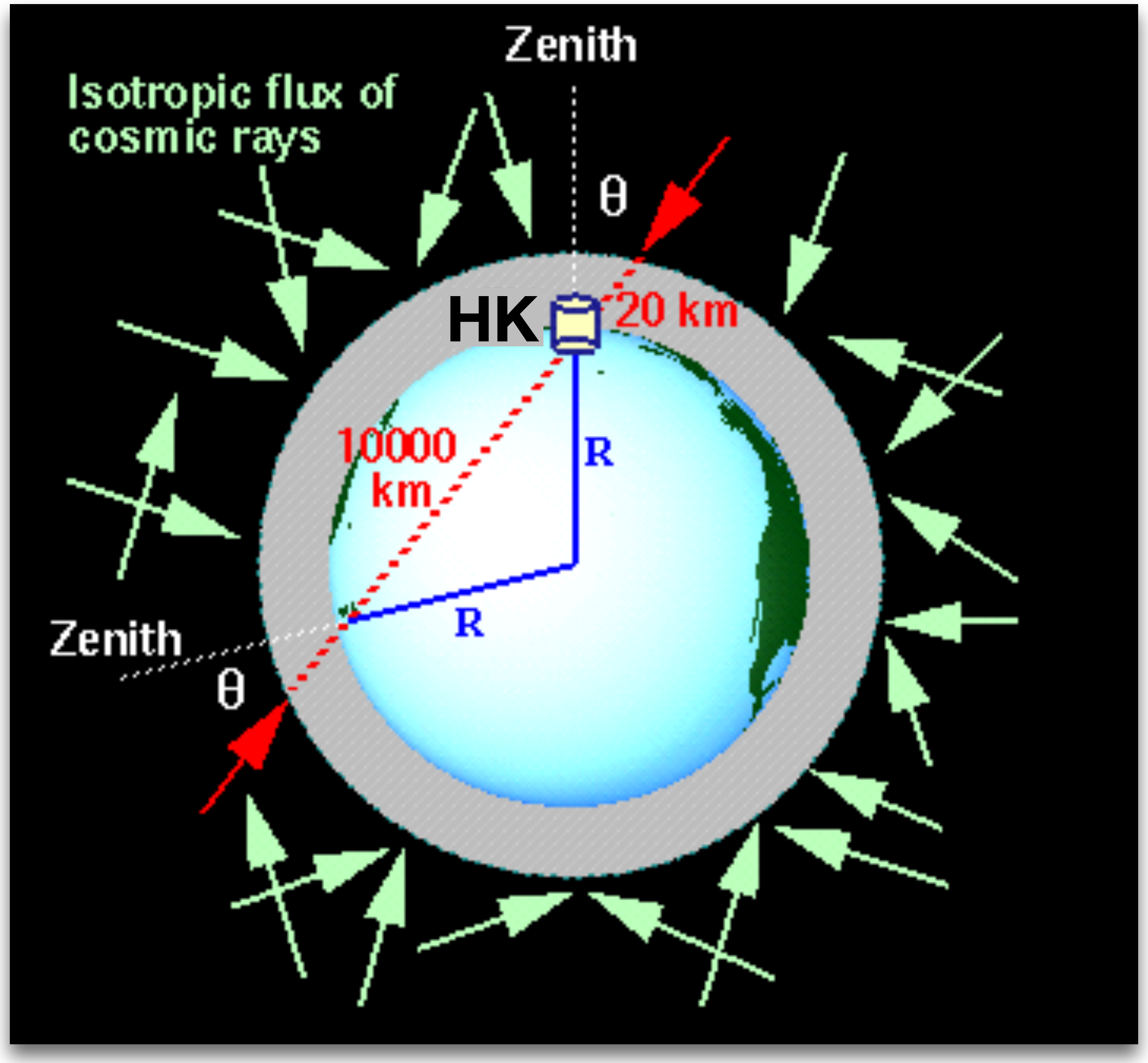
With 8x larger mass than Super-K, will be able to push proton lifetime sensitivity by almost an order of magnitude

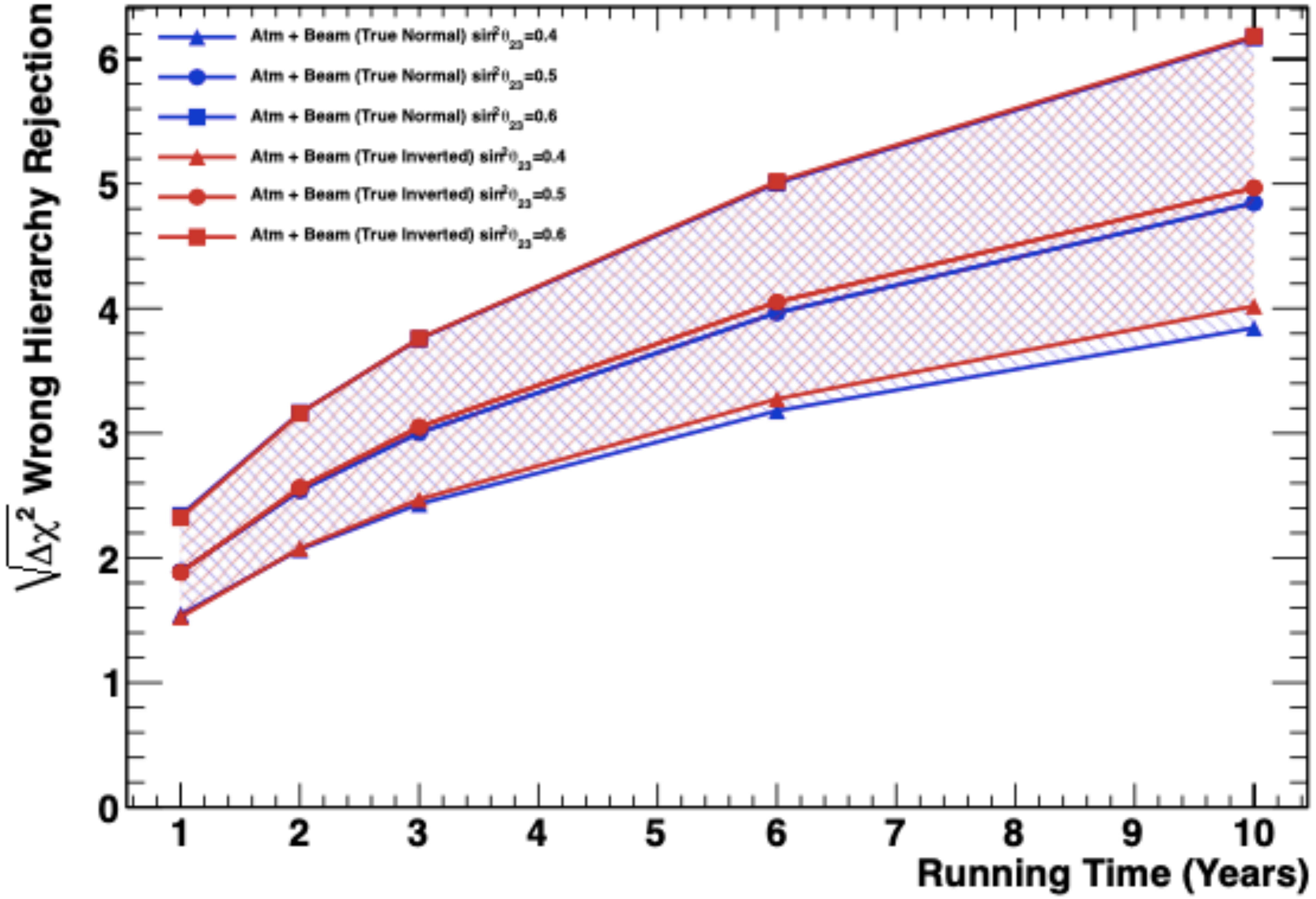






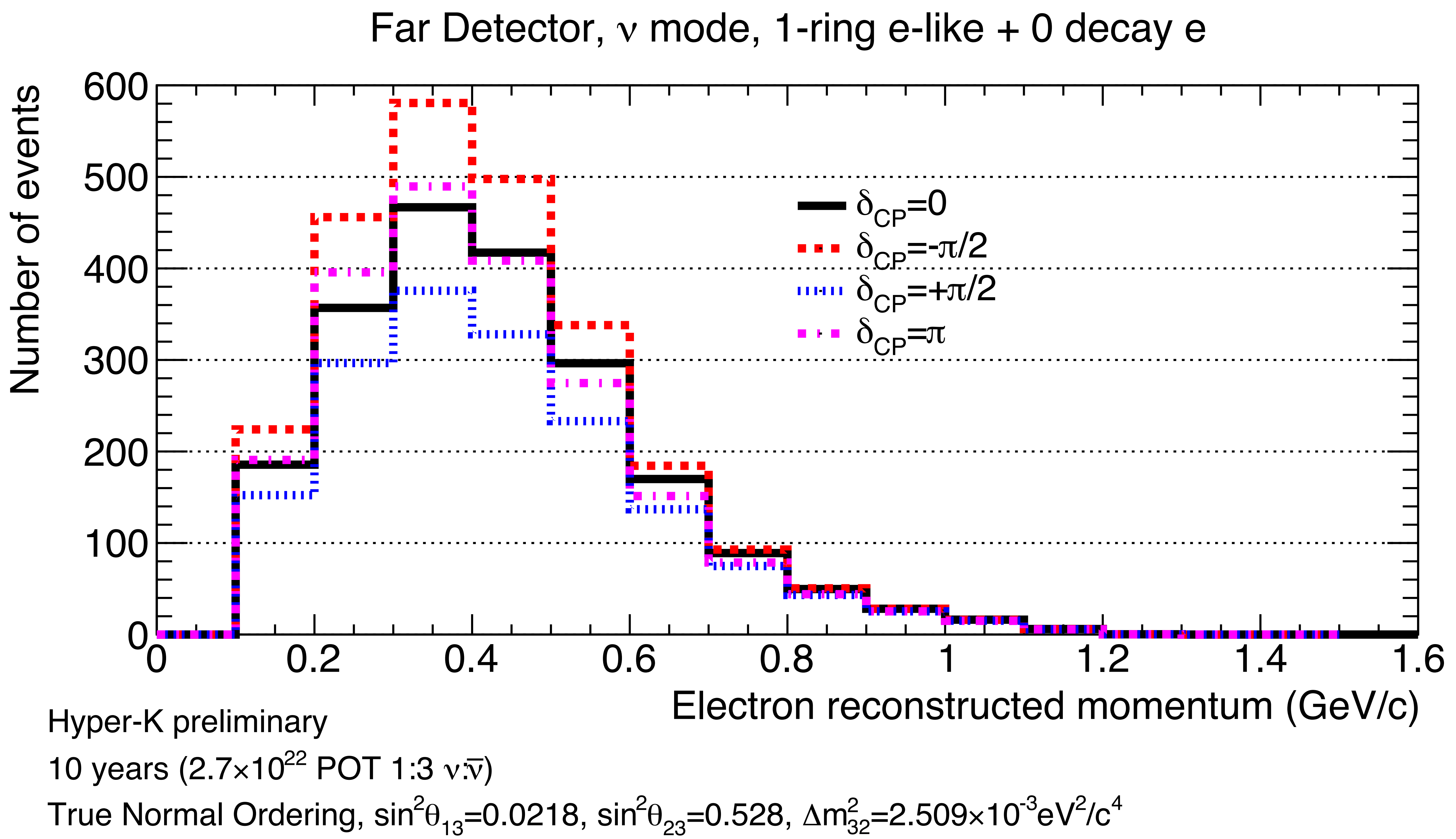
Atmospheric Neutrinos

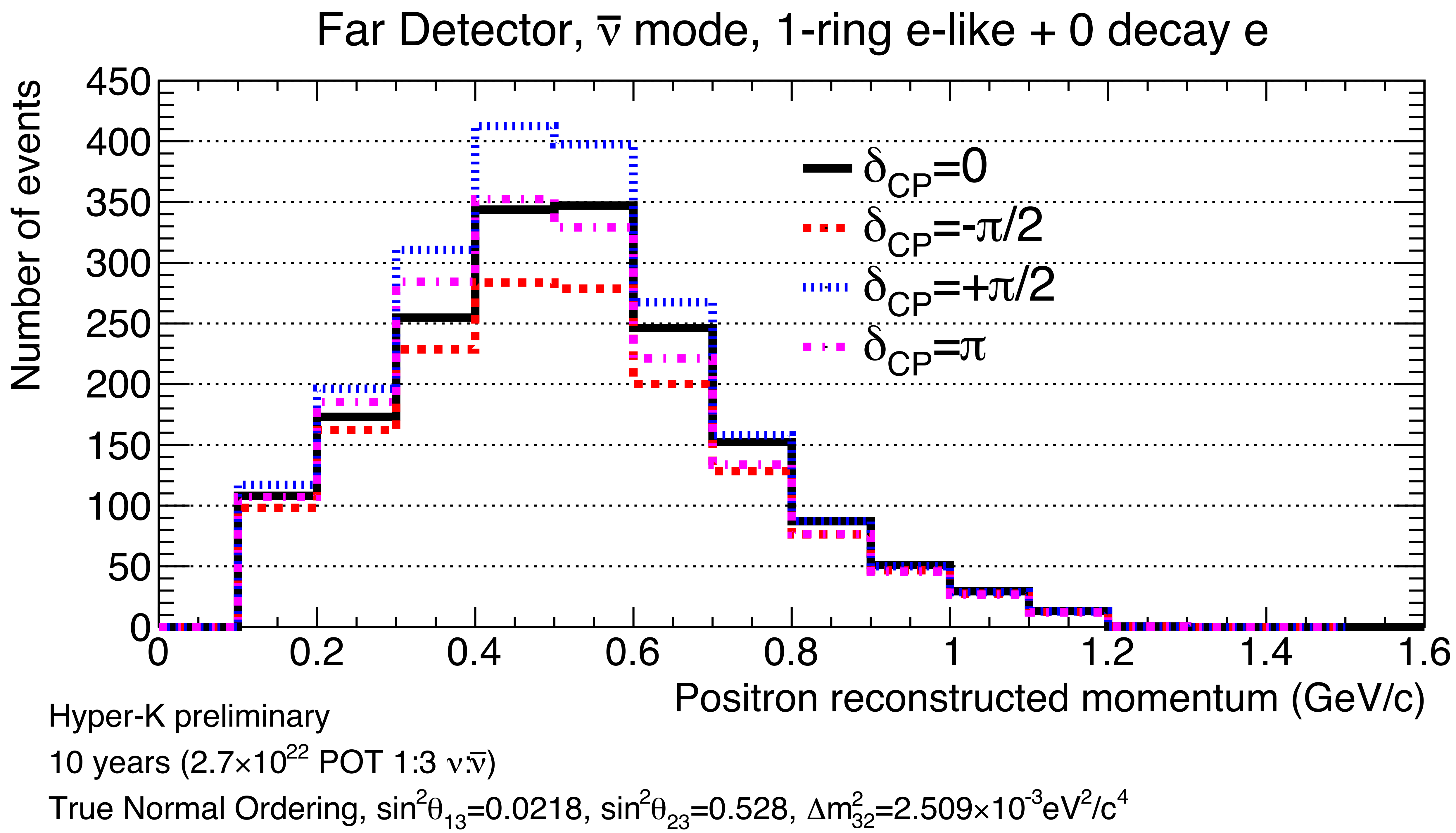




- Longer baselines and higher energies are accessible with atmospheric neutrinos
- Improves sensitivity to the mass ordering
- **>4σ rejection of the wrong hierarchy after 10 years**

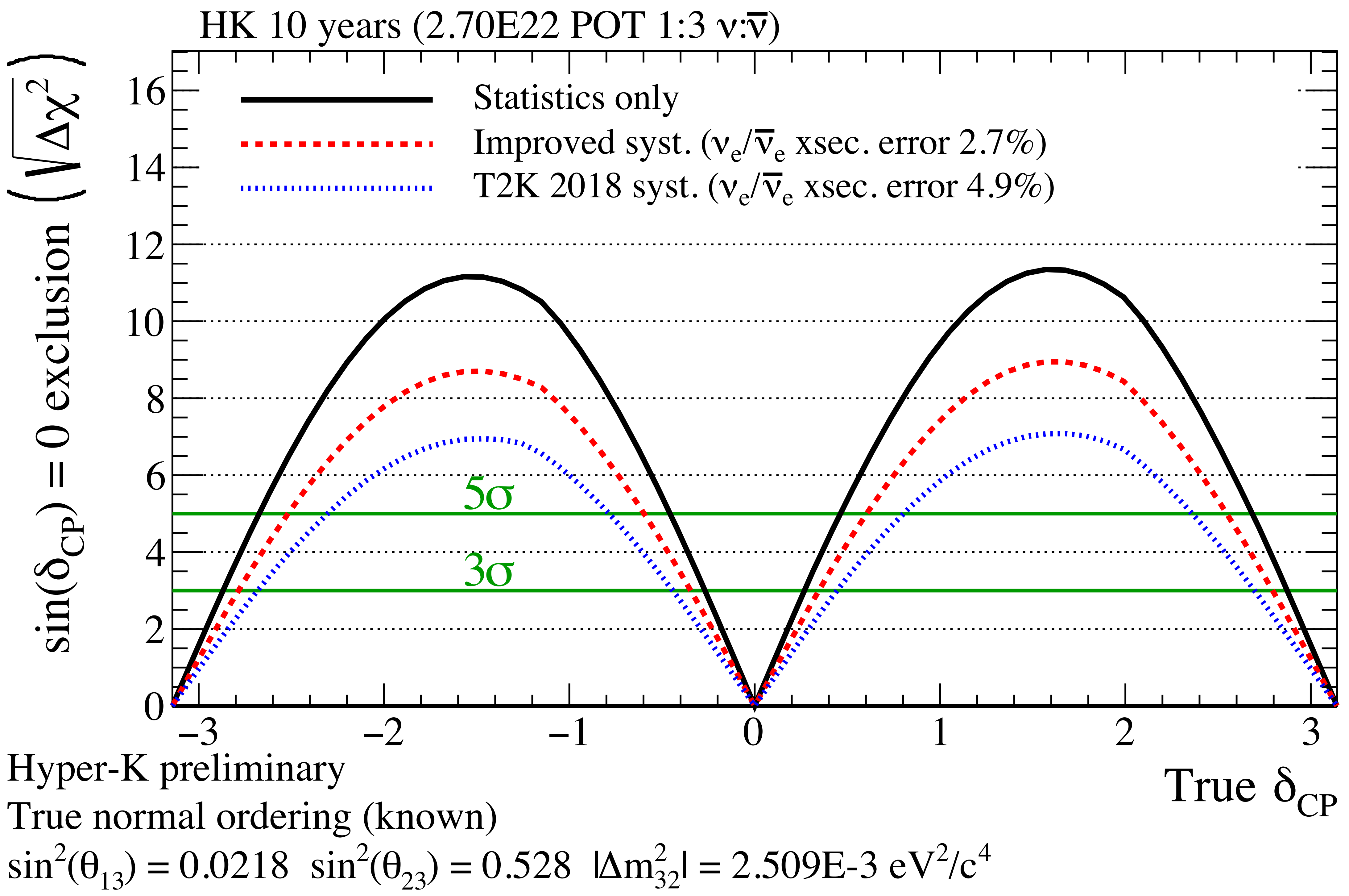
CP Violation at Hyper-K

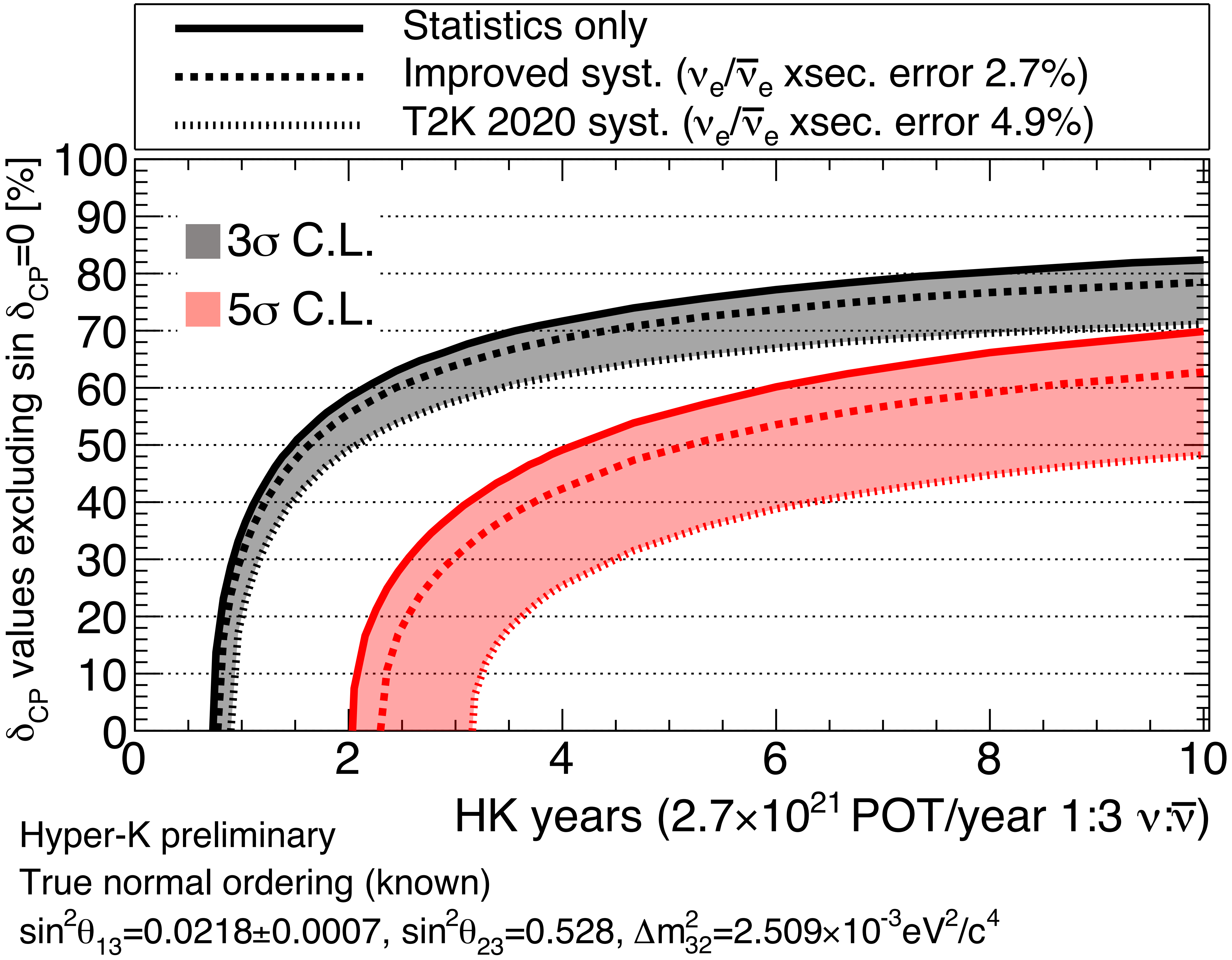




- Recall that T2K has observed ~100 candidate events
- Hyper-K will observe ~2000 electron neutrino and electron antineutrino candidates each
  - 3% statistical error on the CP violation measurement is achieved
  - **Controlling systematic errors is critical: T2K's current errors are ~6%**

CP Violation Sensitivity

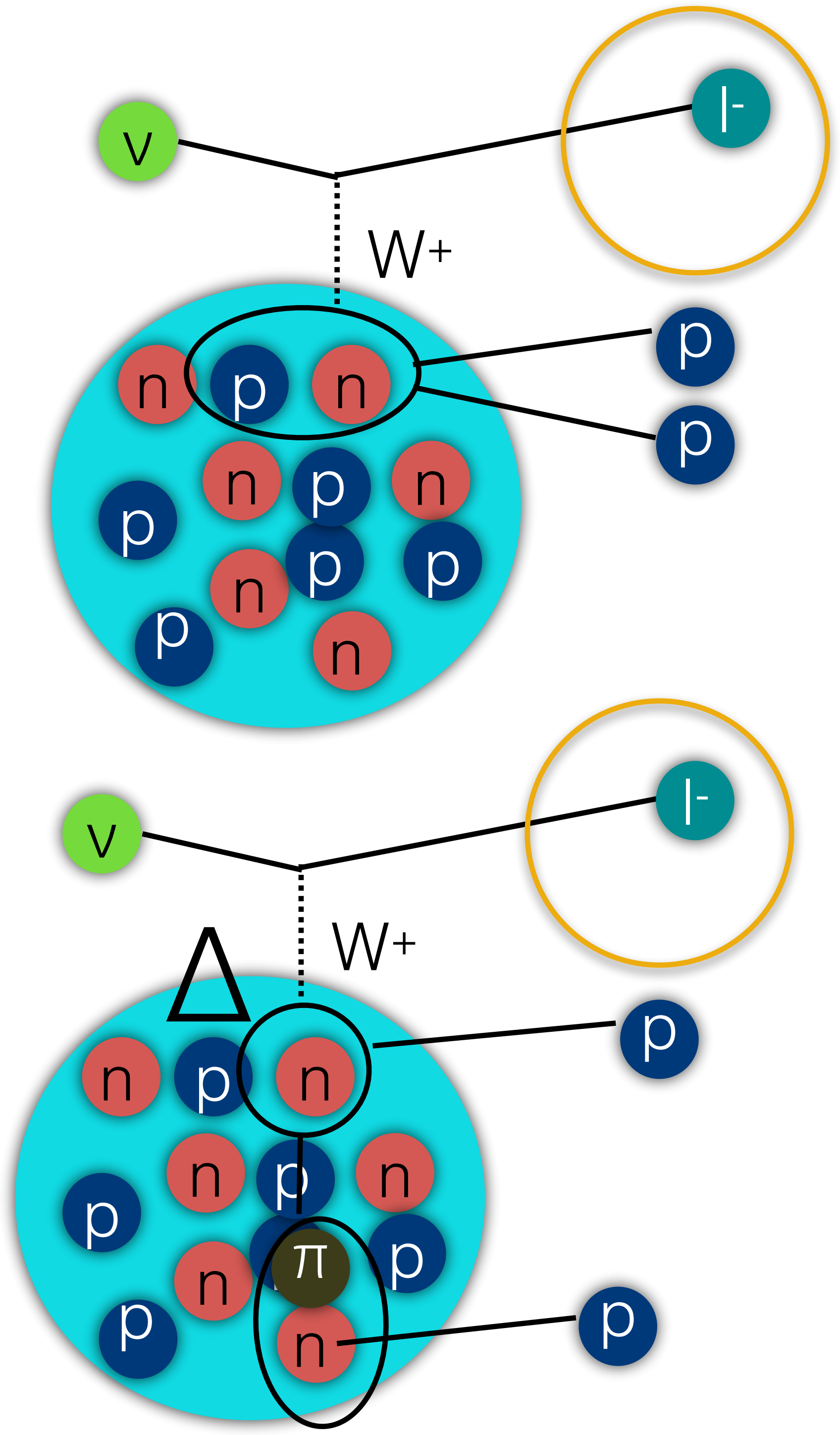




- **5σ CP violation** discovery potential for **~60% of δcp** values assuming improvement in systematic uncertainties
- Capability to discover CP violation depends strongly on the control of systematic uncertainties - important challenge for Hyper-K

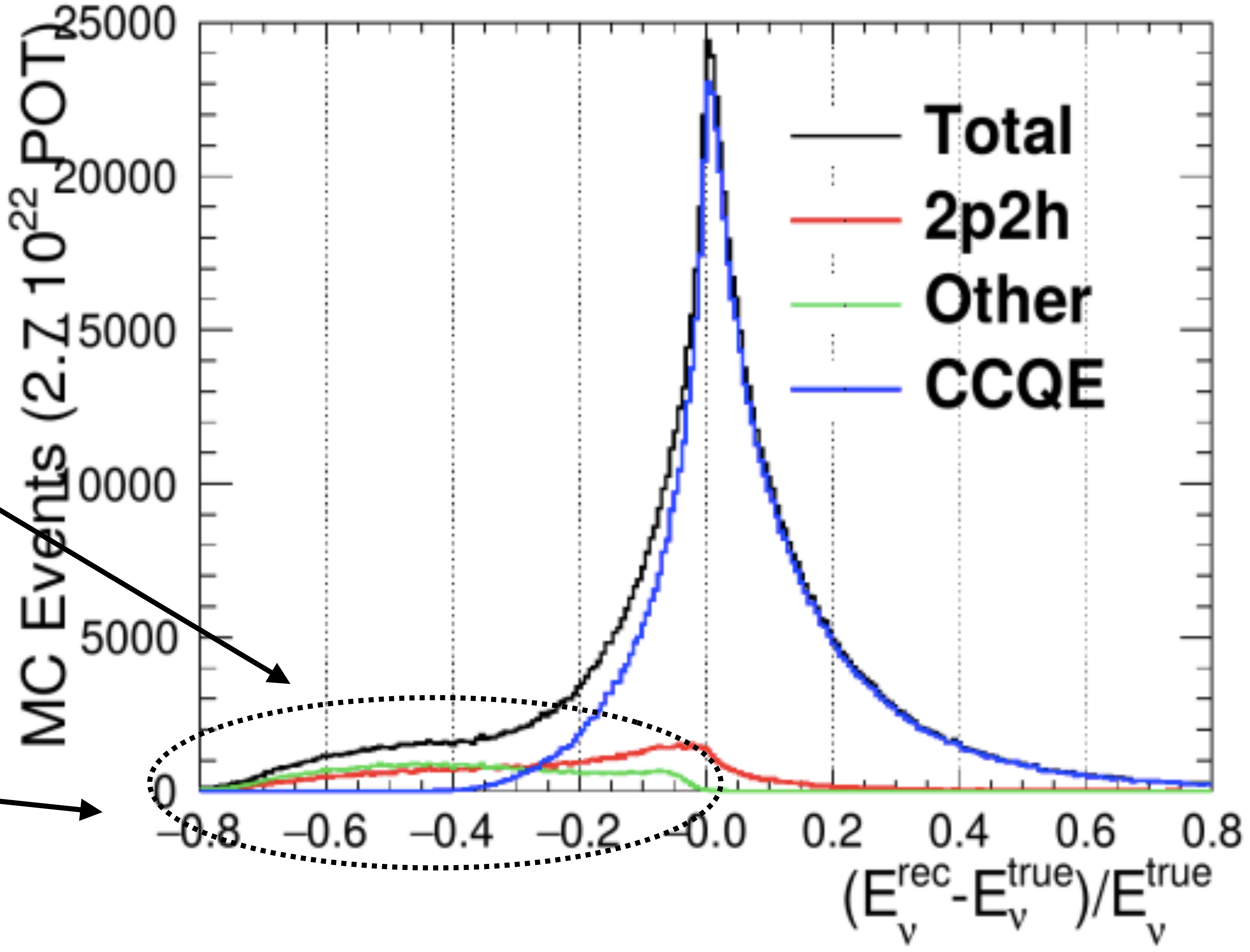
Challenge: Energy Reconstruction

- Oscillations depend on neutrino energy
- Energy in neutrino beam is not fixed to a single value
- We must infer neutrino energy from particles we observe in detectors
- If we make the quasi-elastic assumption, inferred energy will be biased for other processes



Scattering on correlated pairs of nucleons "multi-nucleon or 2p-2h"

Pion production, where pion is absorbed in nucleus



Challenge: Energy Reconstruction

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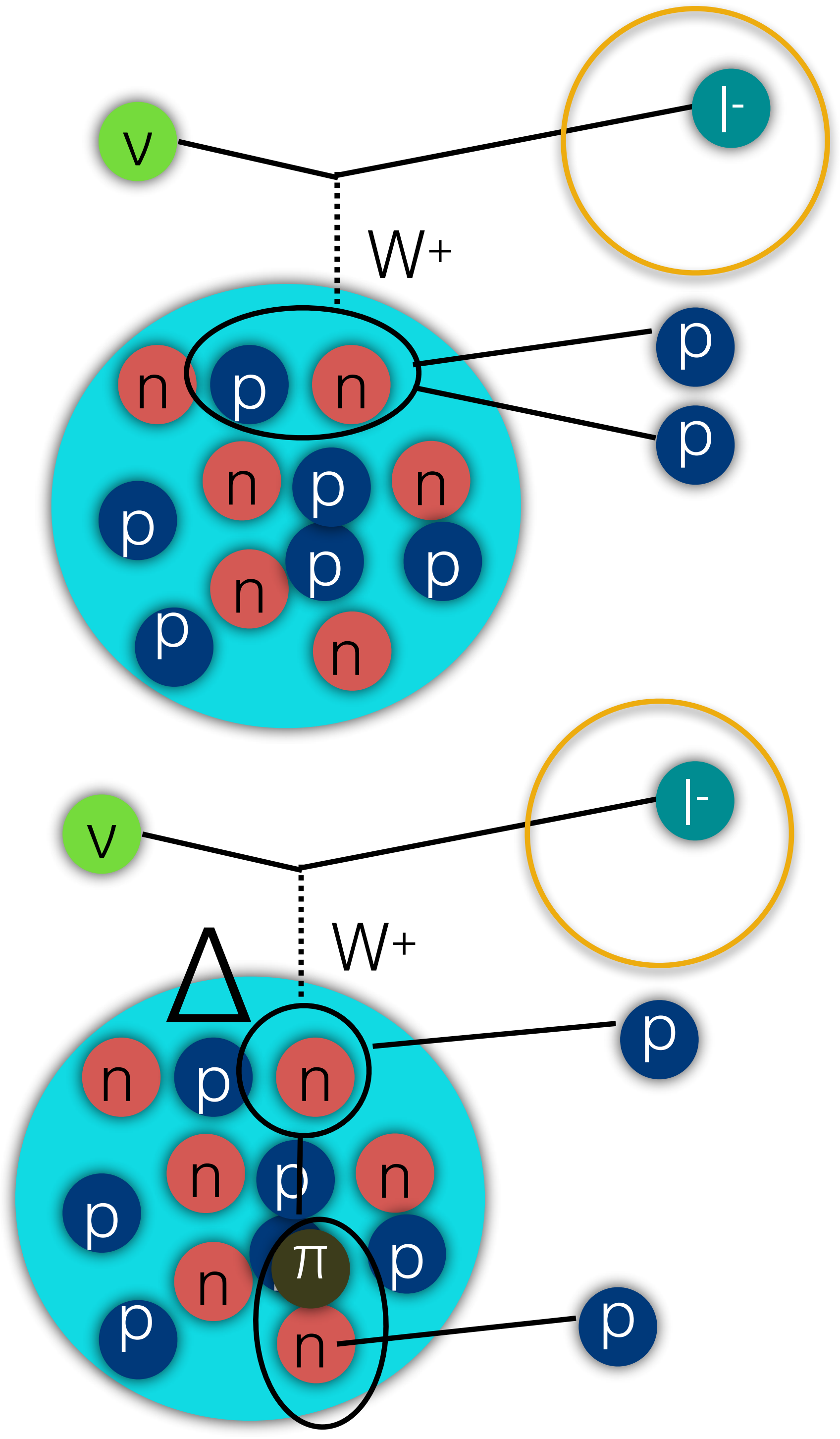
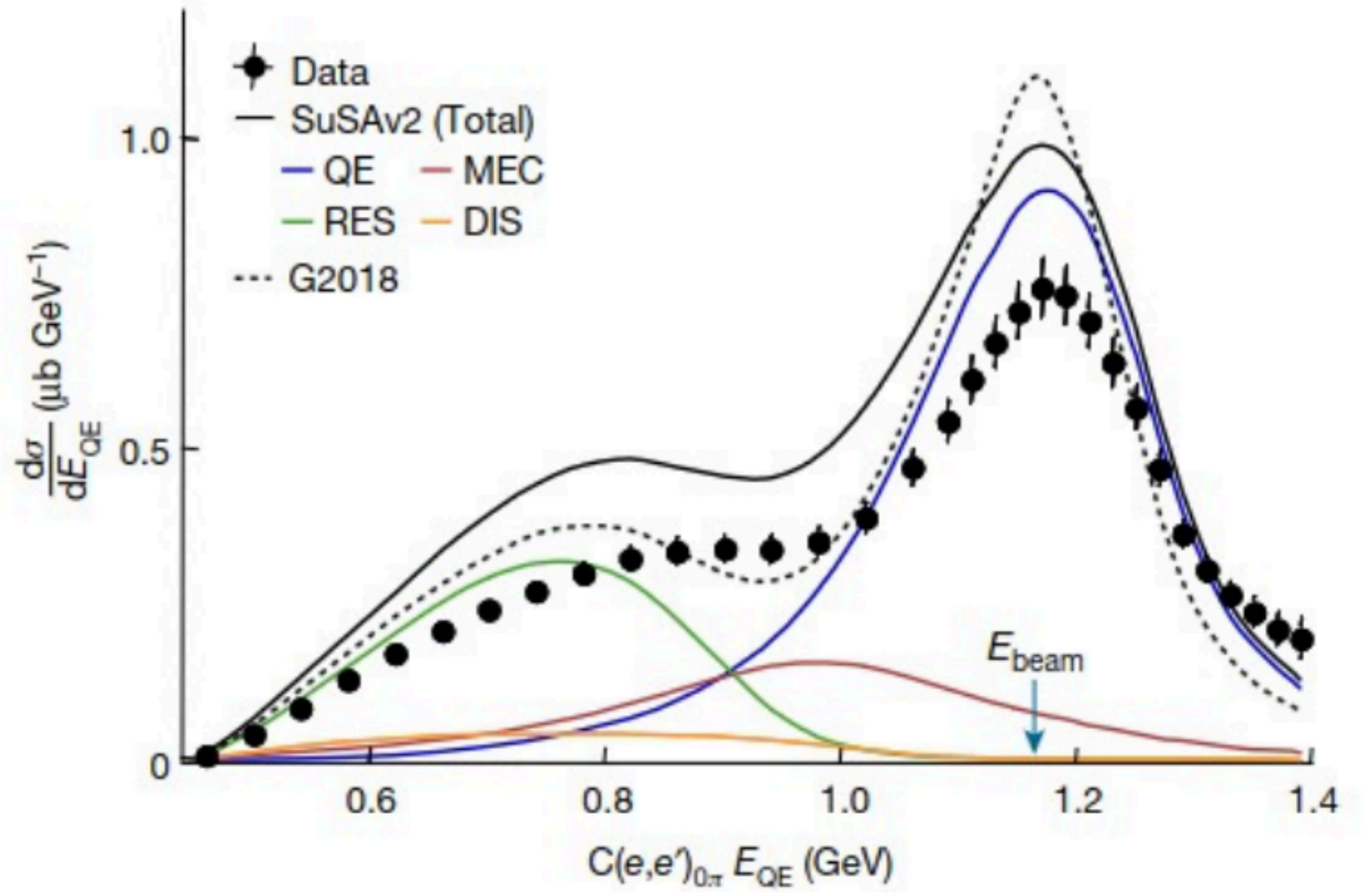


Models checked with electron scattering data

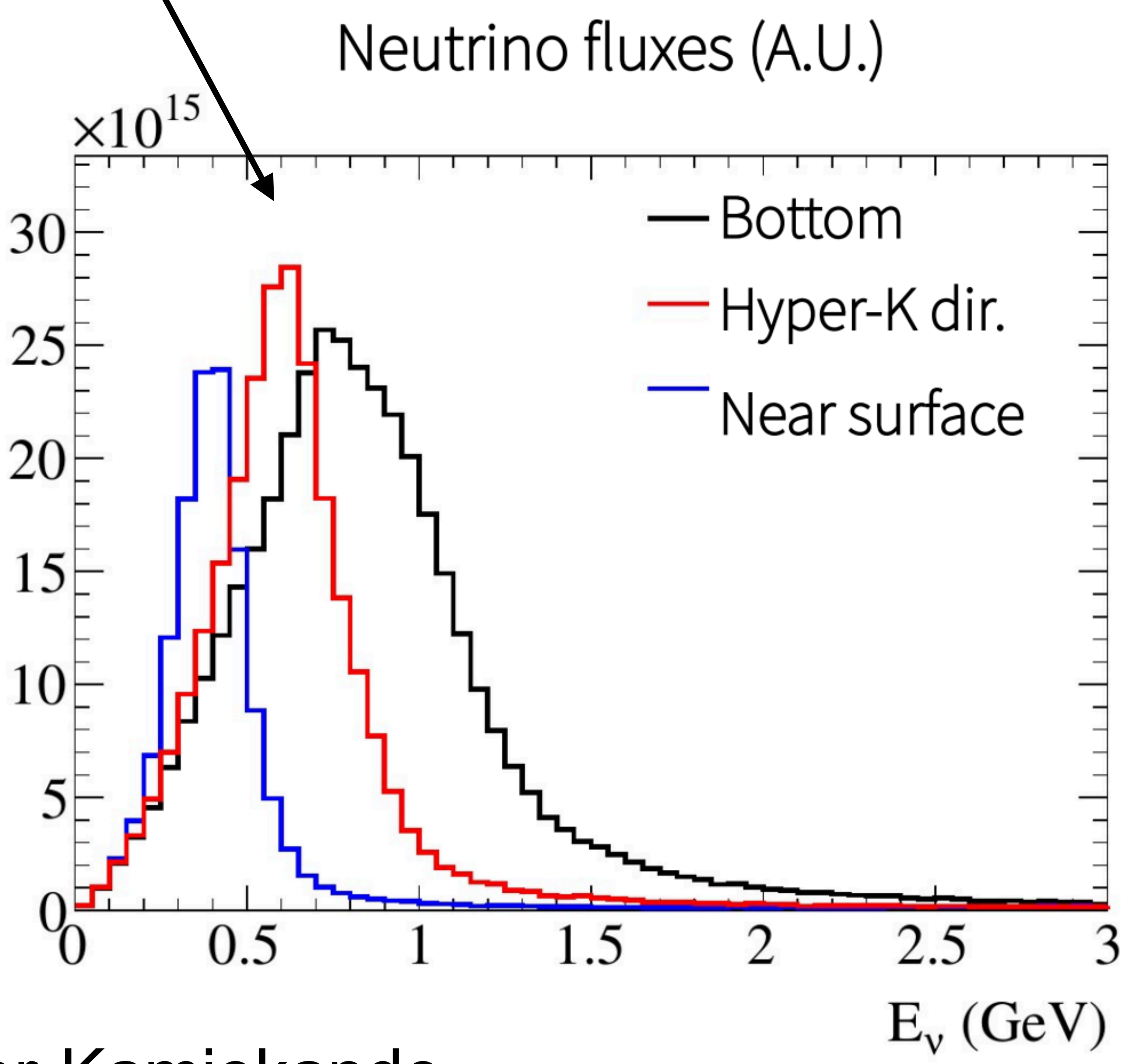
Show large variations and often significant disagreements with data

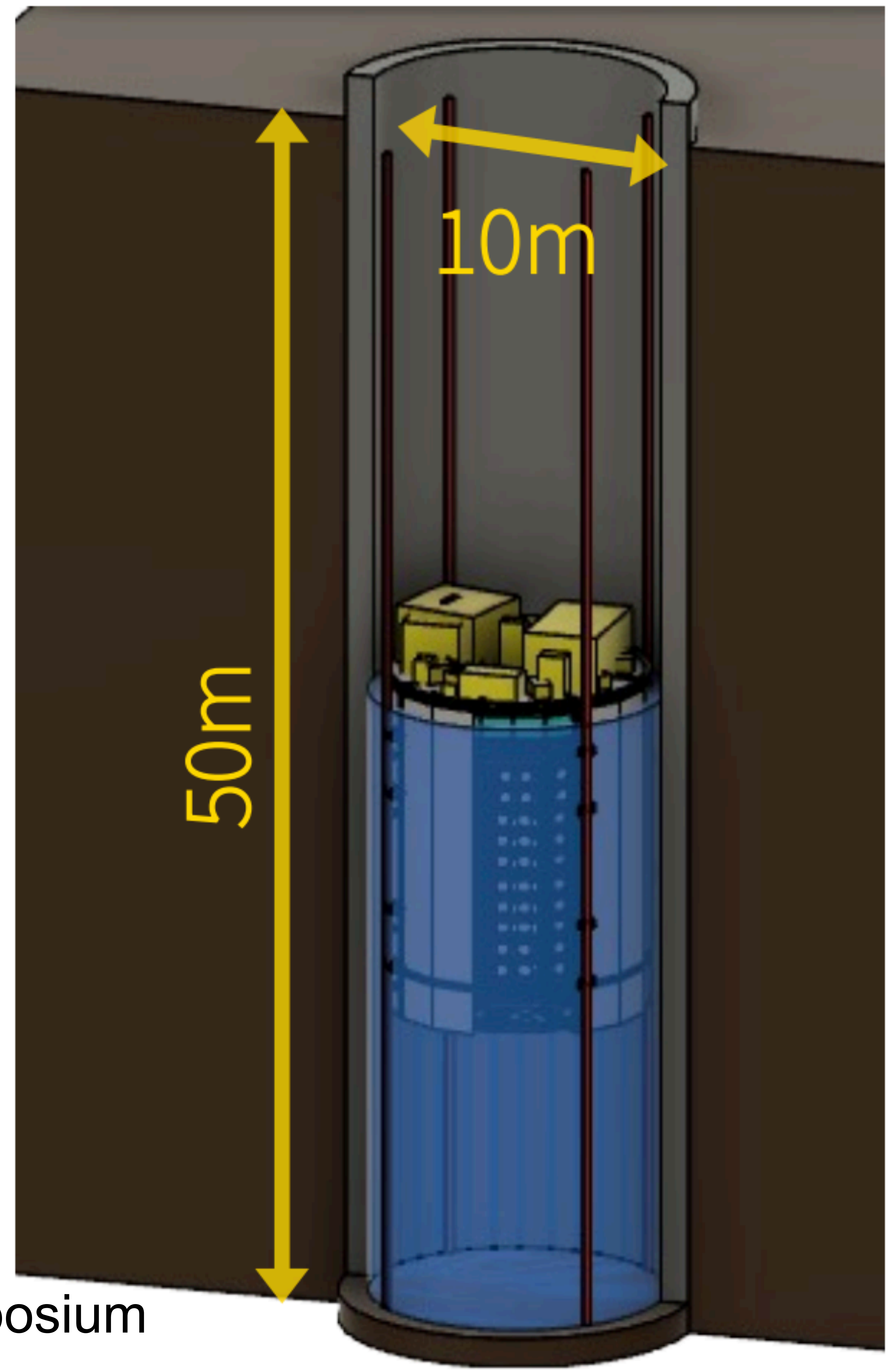


Nature volume 599, pages 565–570 (2021)

Solution: Intermediate Water Cherenkov Detector

- Water Cherenkov detector located 850 m downstream of neutrino target
- Detector can move vertically in the neutrino beam
- Capability to move vertically allows different neutrino energies to be probed

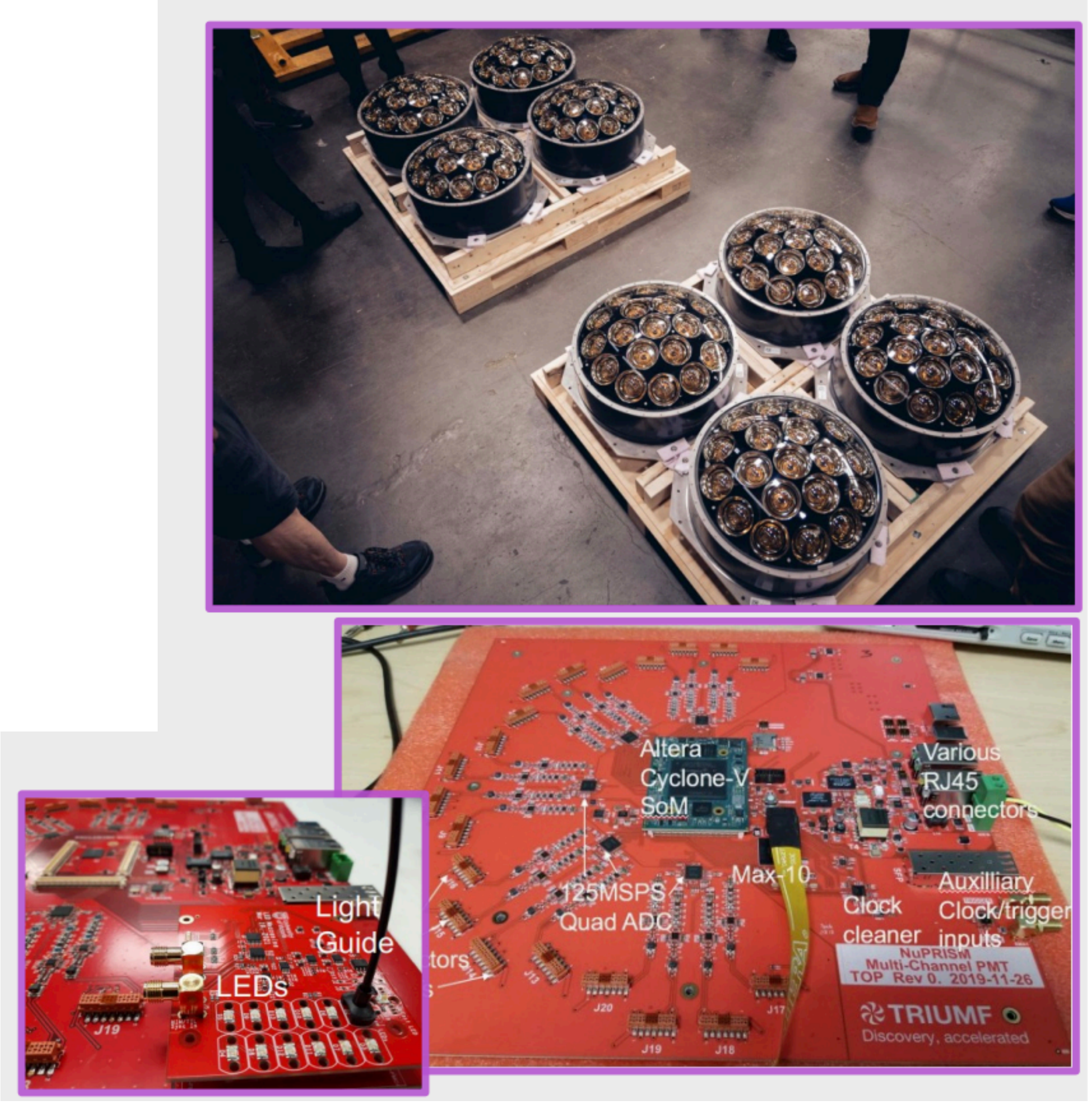


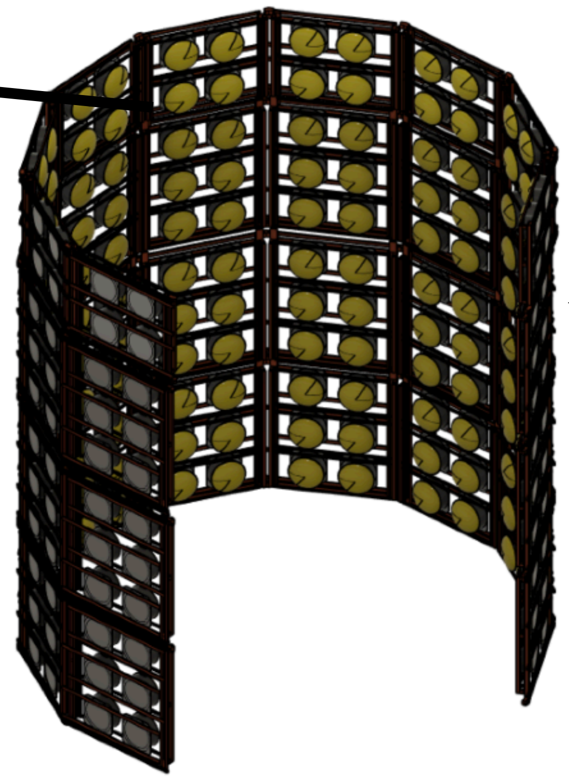


IWCD Detector Technologies

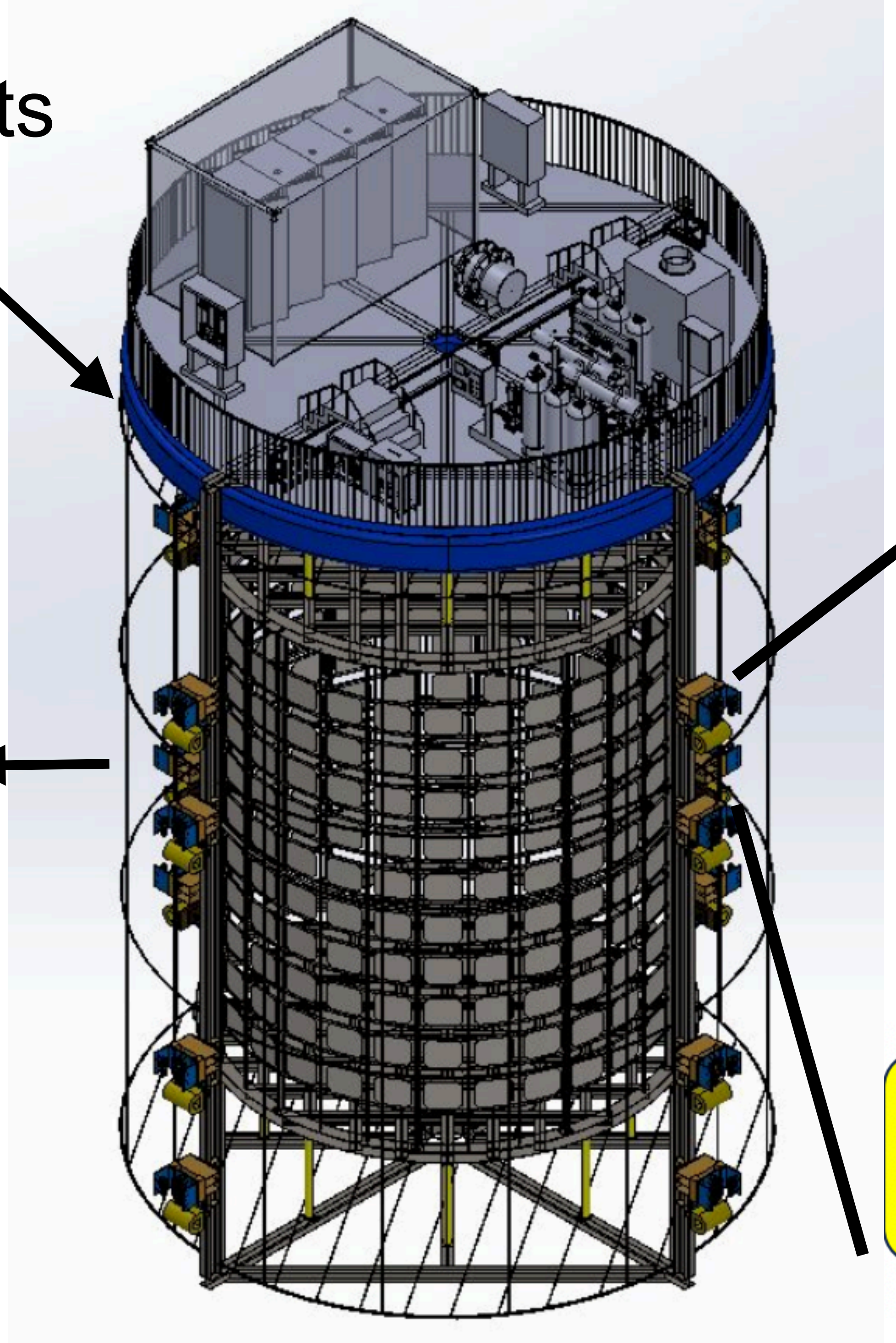
- IWCD uses many tried and true water Cherenkov technologies with its own unique challenges
  - Flotation compartments and rail and free bearing system for controlling detector position
  - Multi-PMT photosensors with good spatial and timing resolution containing 19 8-cm diameter PMTs and integrated electronics

Multi-PMT photosensor modules and main electronics board

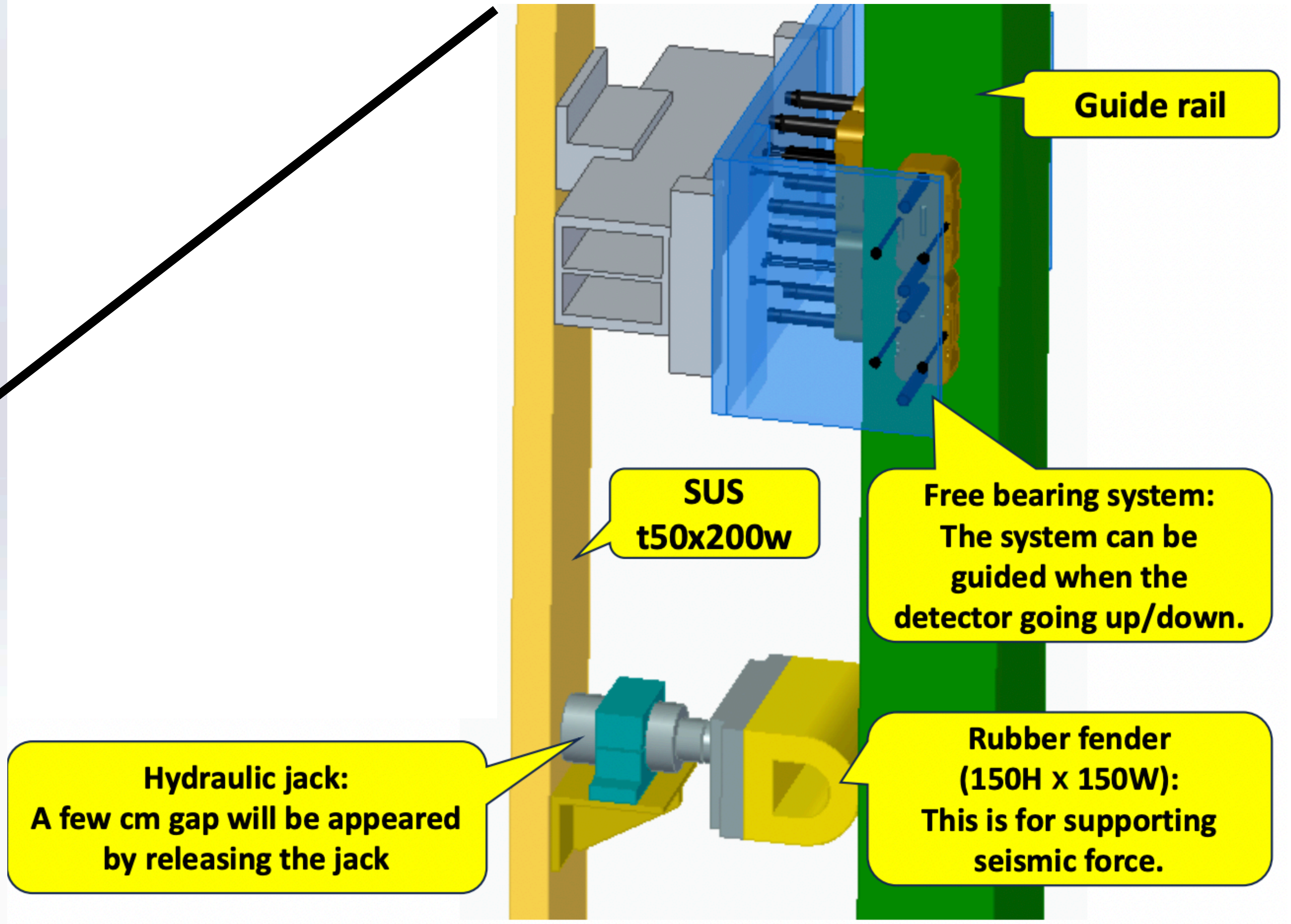




Flotation compartments



Rail and free bearing system

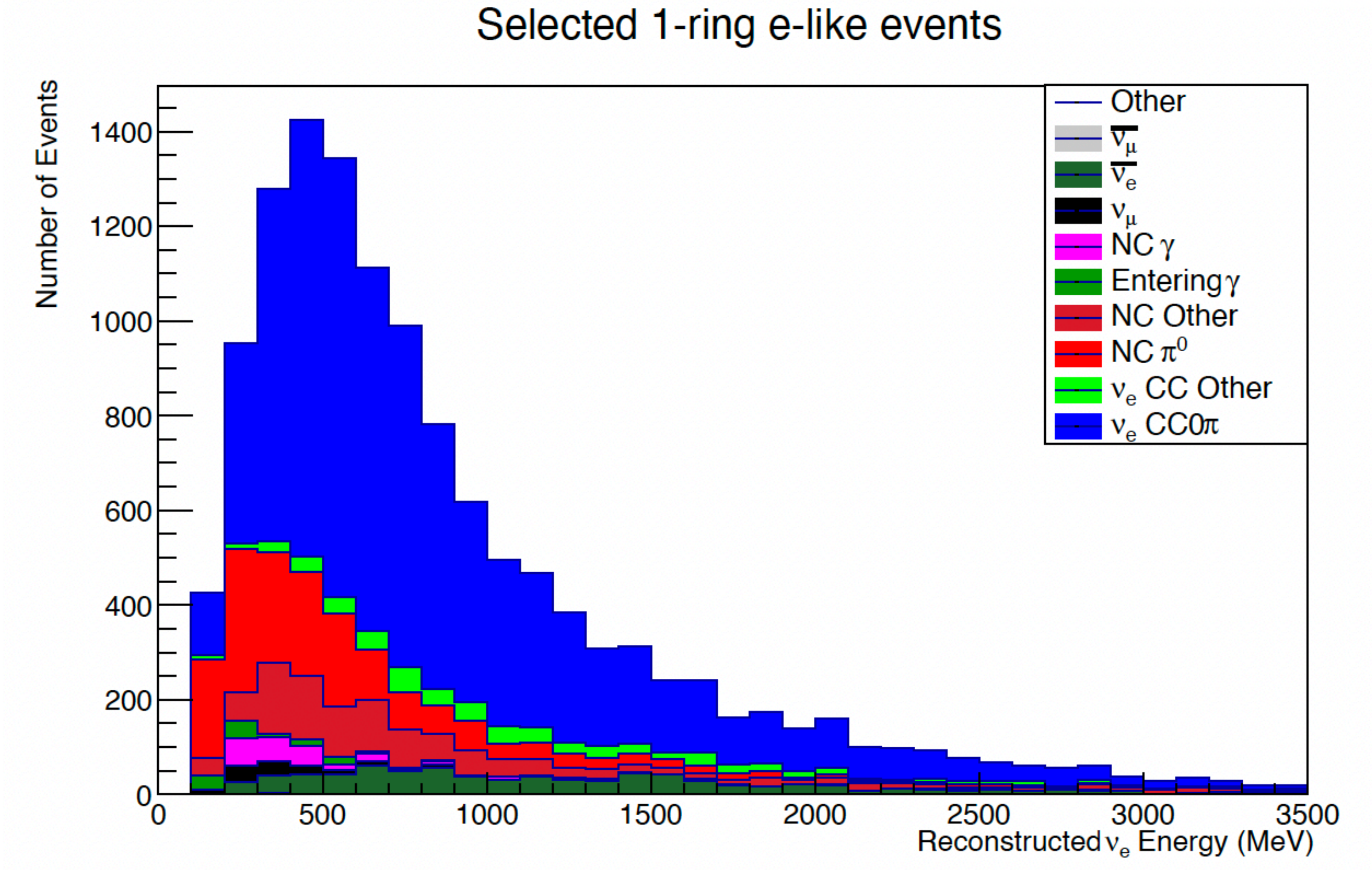


IWCD Physics Program

Hyper-K CP violation measurement depends on: $P_{\nu_\mu \to \nu_e}(E_\nu),\ P_{\bar{\nu}_\mu \to \bar{\nu}_e}(E_{\bar{\nu}})$

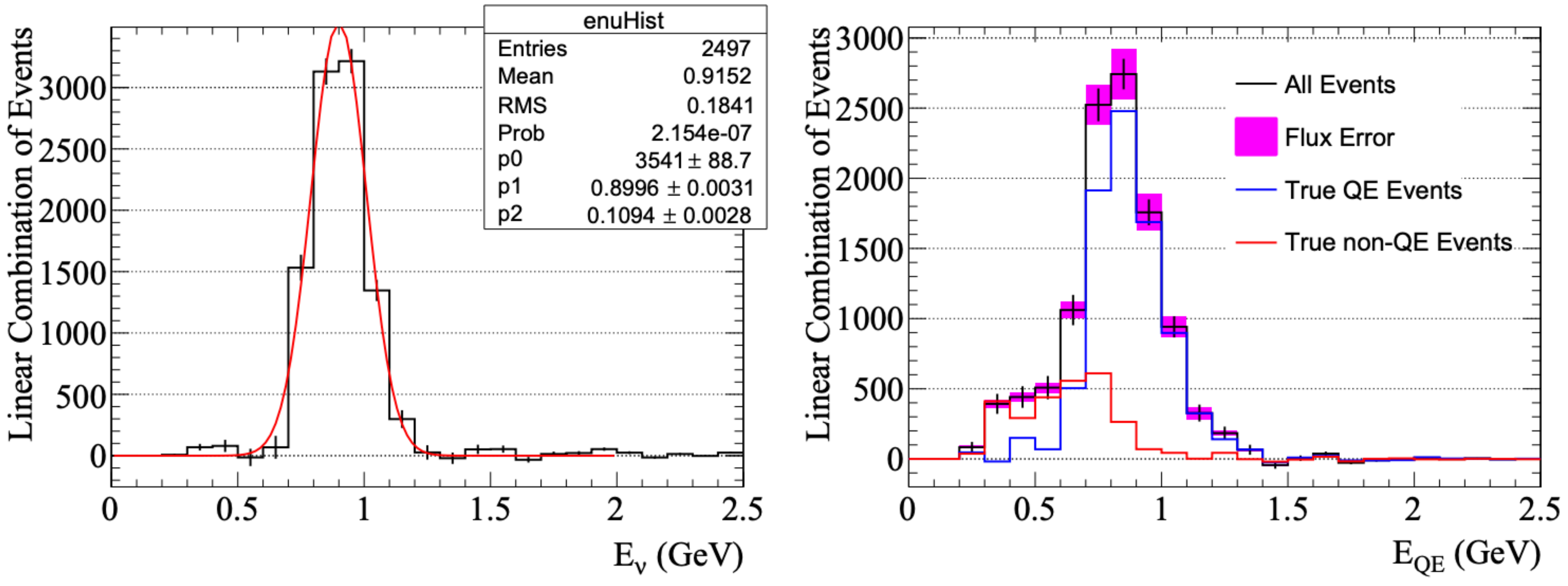
Need measurement of electron (anti)neutrino to muon (anti)neutrino interaction rates

$$\frac{\sigma_{\nu_e}(E_\nu)}{\sigma_{\nu_\mu}(E_\nu)},\ \frac{\sigma_{\bar{\nu}_e}(E_{\bar{\nu}})}{\sigma_{\bar{\nu}_\mu}(E_{\bar{\nu}})}$$



Large detector with active shielding can be used to select high statistics electron (anti)neutrino samples

Need measurements to relate reconstructed particle kinematics to neutrino energy

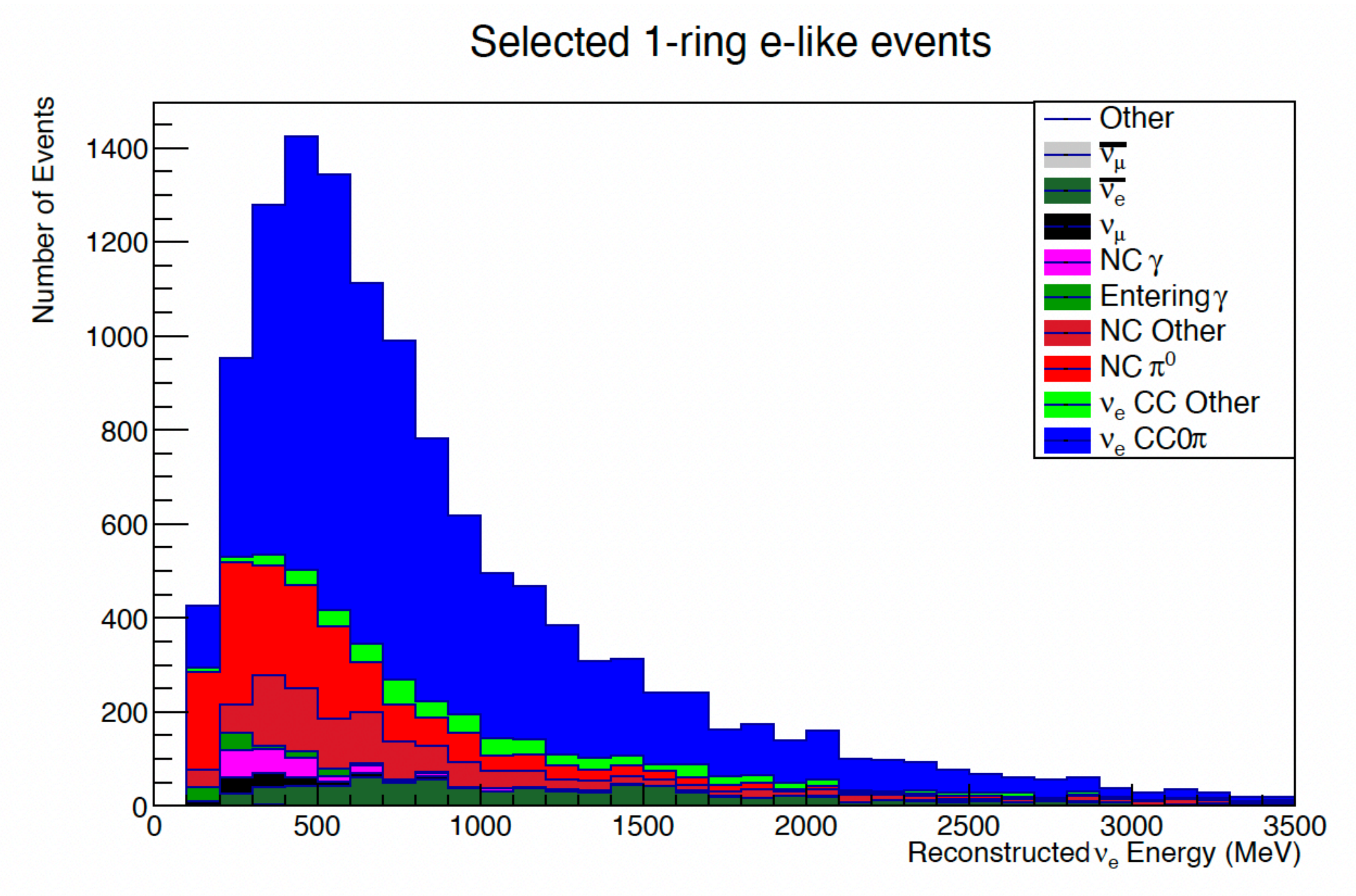


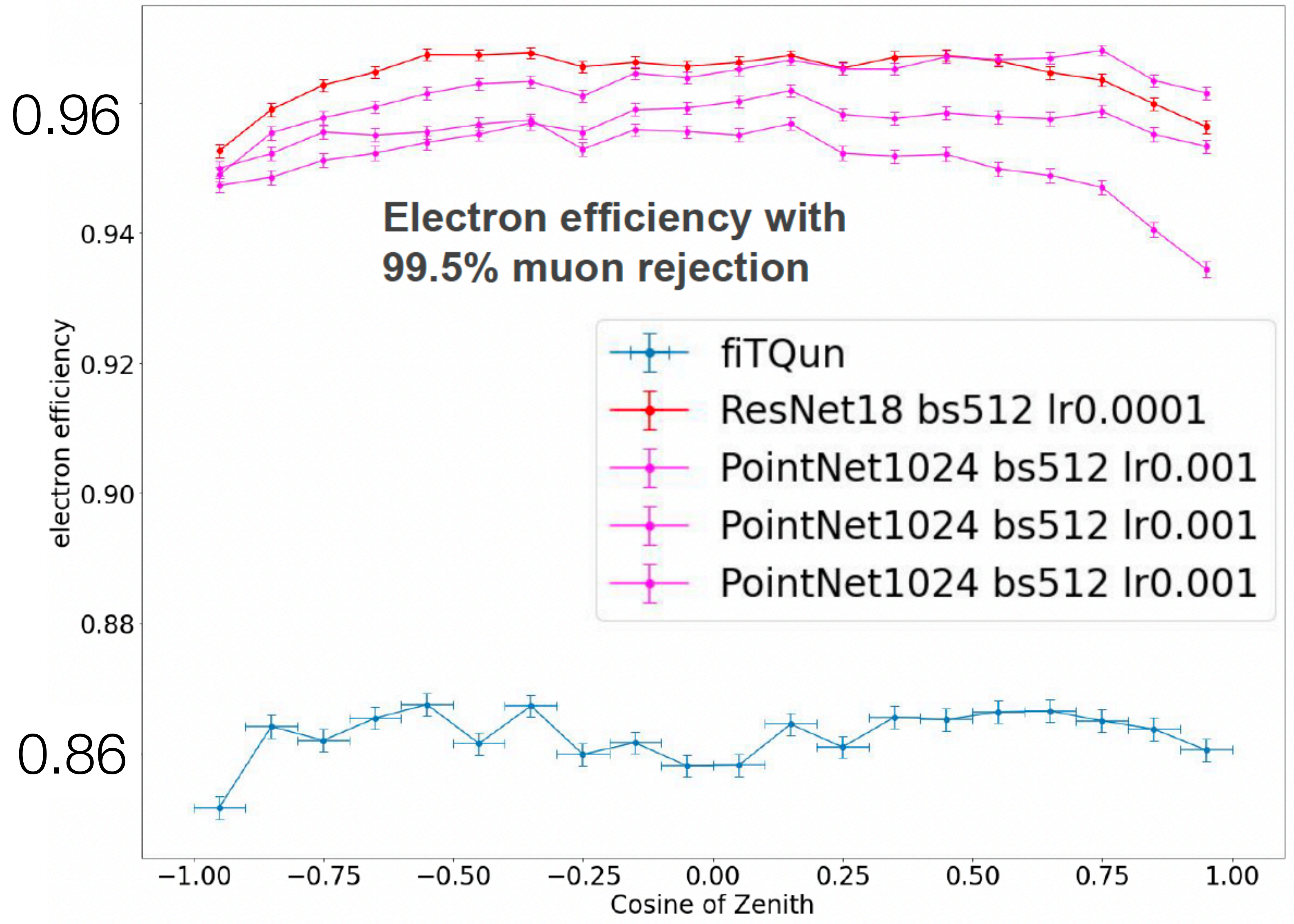
So-called NuPRISM approach uses measures at different off-axis angles to extract type of information that mono-energetic neutrino beam could provide

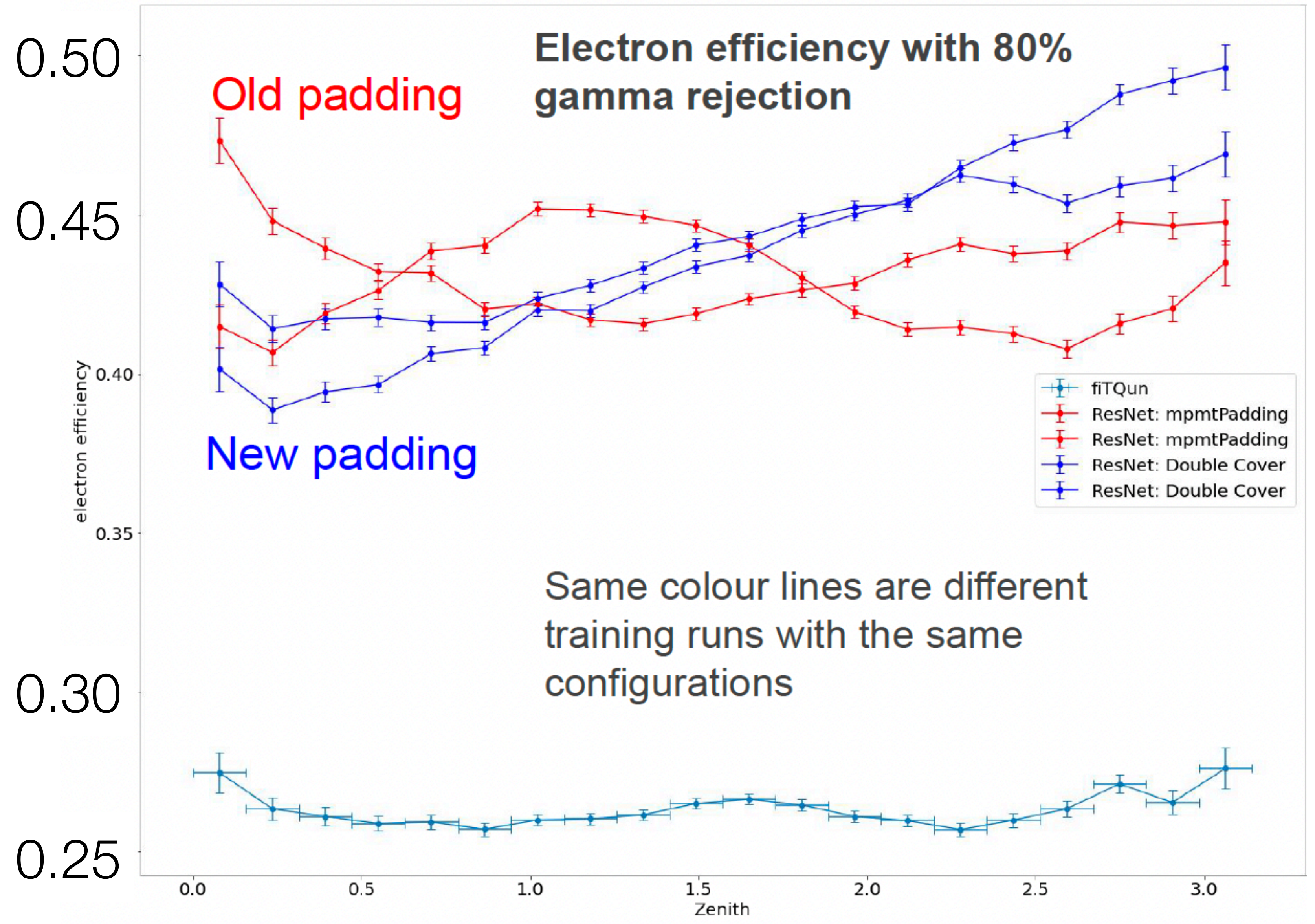
Can achieve **5% constraint on processes with large misreconstructed energy**

Machine Learning in IWCD

- In IWCD simulation, machine learning shows improved performance relative to likelihood-based reconstruction
- Major IWCD measurement is electron (anti)neutrino cross section which benefits from:
  - Good electron/muon separation
  - Capability to separate electrons and gammas, at least statistically (most backgrounds are events with gamma)



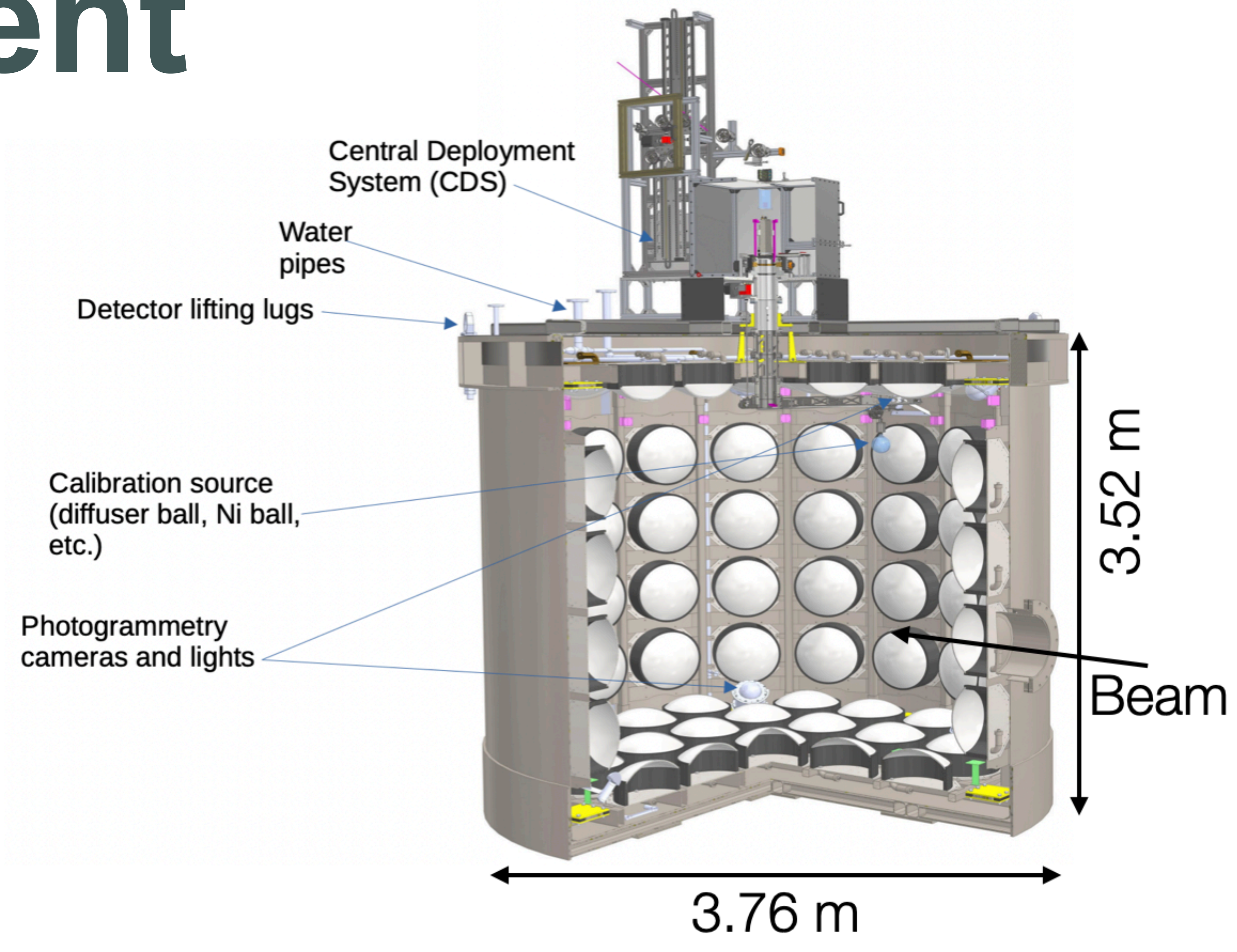


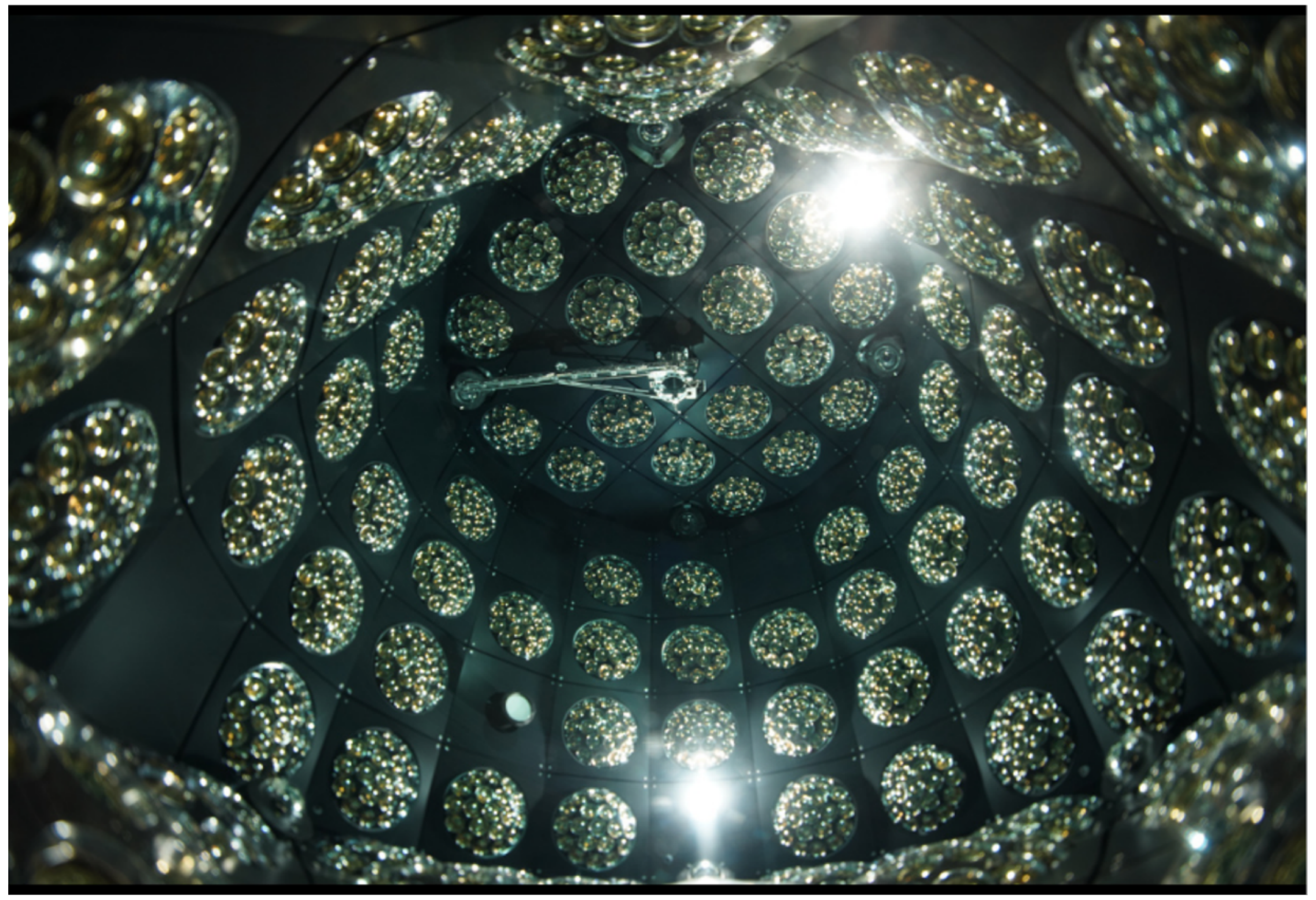


- Need experiment with known particle fluxes entering detector to confirm capability of machine learning approaches

Water Cherenkov Test Experiment

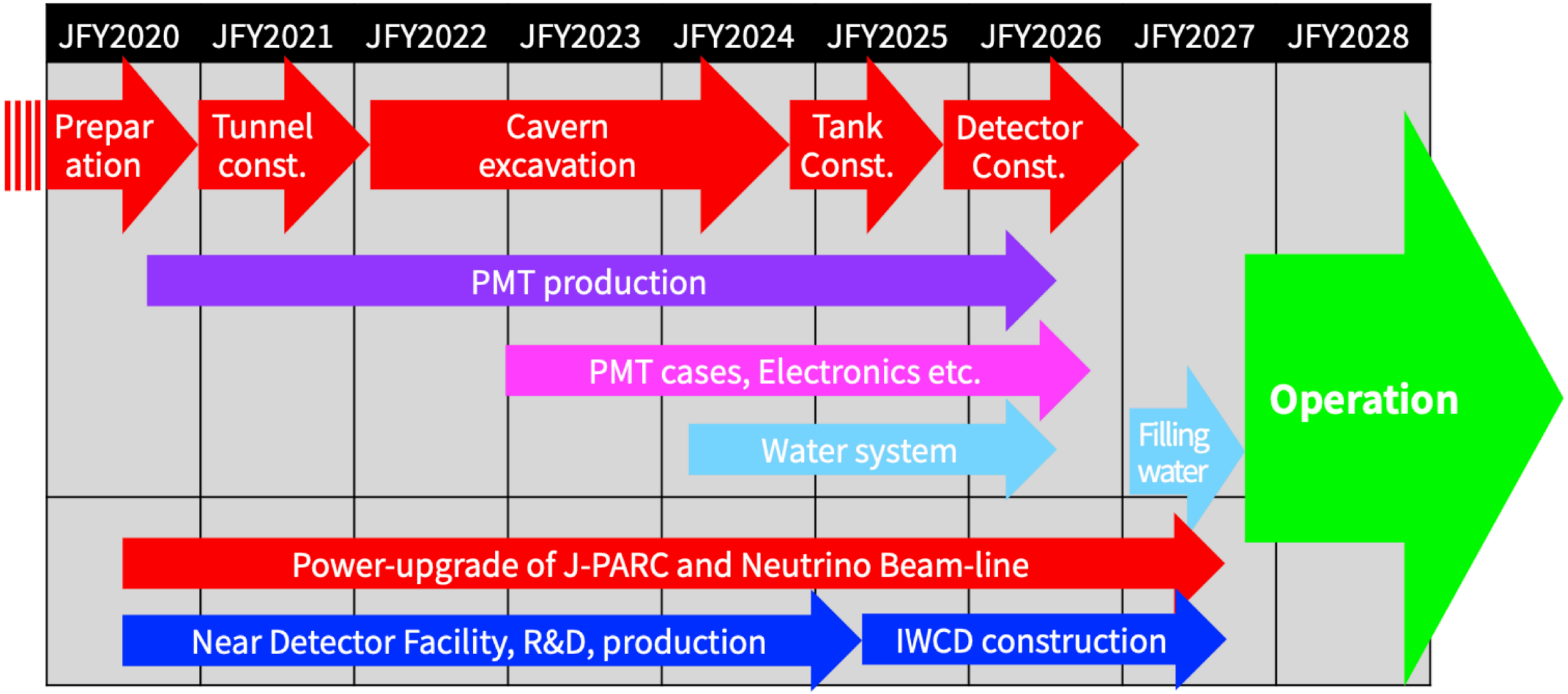
- 40 ton water Cherenkov detector - effective prototype for IWCD
- Instrumented with 96 multi-PMT photosensors
- Instrumented with calibration systems that will be used in IWCD
- Receive beam from CERN T9 beam line
  - Interested in e,π,μ,p,γ in the 0.2-1.2 GeV/c range
- Planned operation modes with pure water and loading of $Gd_2(SO_4)_3$ for enhanced neutron detection
- First operation in October-November 2024
- Main physics run in March-June 2025
- **WCTE will allow us to test calibration and event reconstruction techniques for IWCD on real data!**





Hyper-K Project Status

Water purification system “room”



- Excavation of the Hyper-K cavern is progressing well and detector components are being prepared
- Hyper-K project is progressing towards start of operation in just a few years

Summary

- Exciting time for long baseline neutrino oscillation experiments!
- Current generation experiments, including T2K, continue to improve precision of neutrino mixing and oscillation physics
- Next generation, led by Hyper-K, will make the leap to precision measurements with high statistics data samples
- Hyper-K project is progressing well, including IWCD, which will play critical role in controlling systematic uncertainties
- Look forward to Hyper-K operation in just a few years!