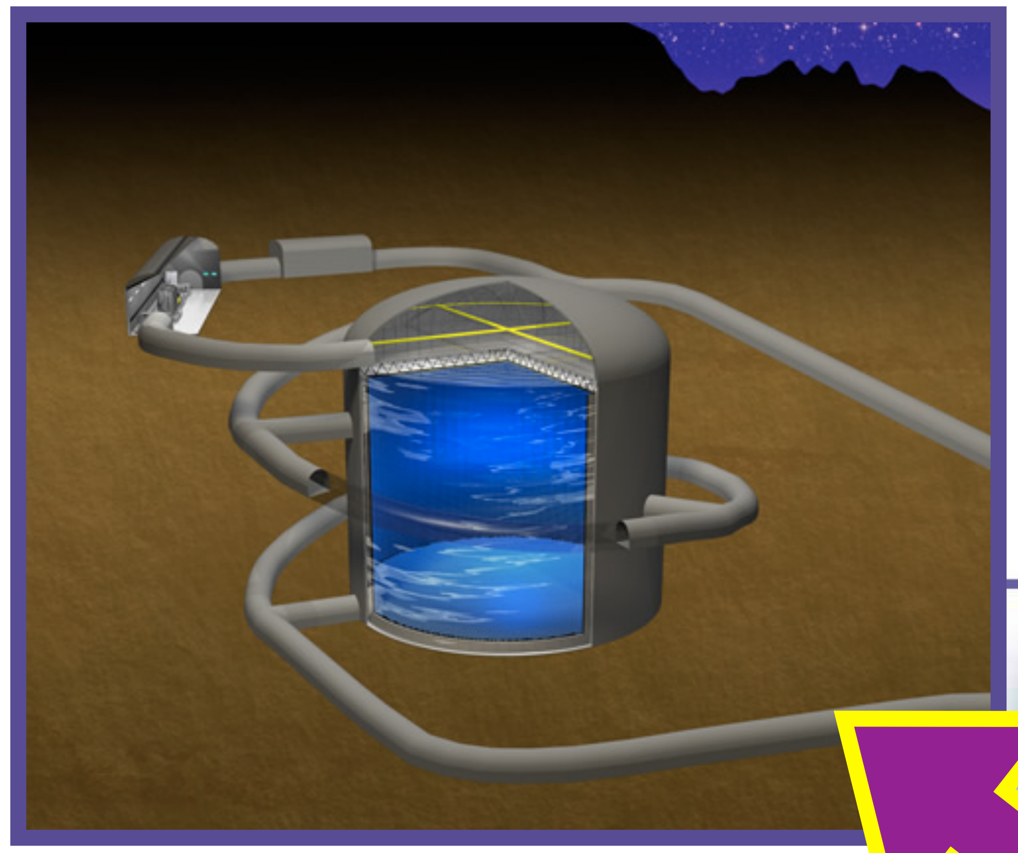
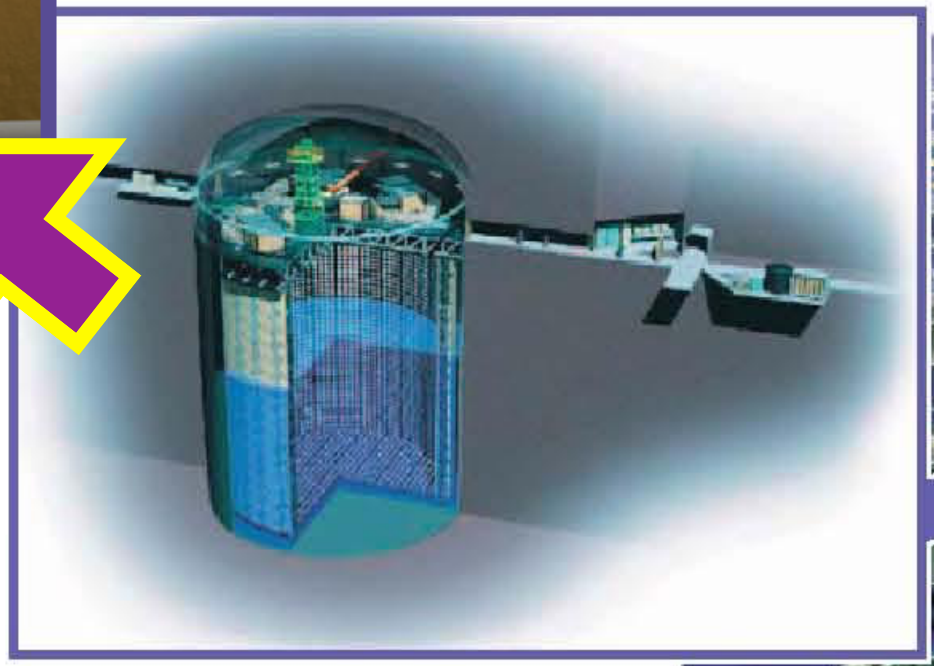
Neutrino Oscillations at the T2K and Hyper-Kamiokande Experiments

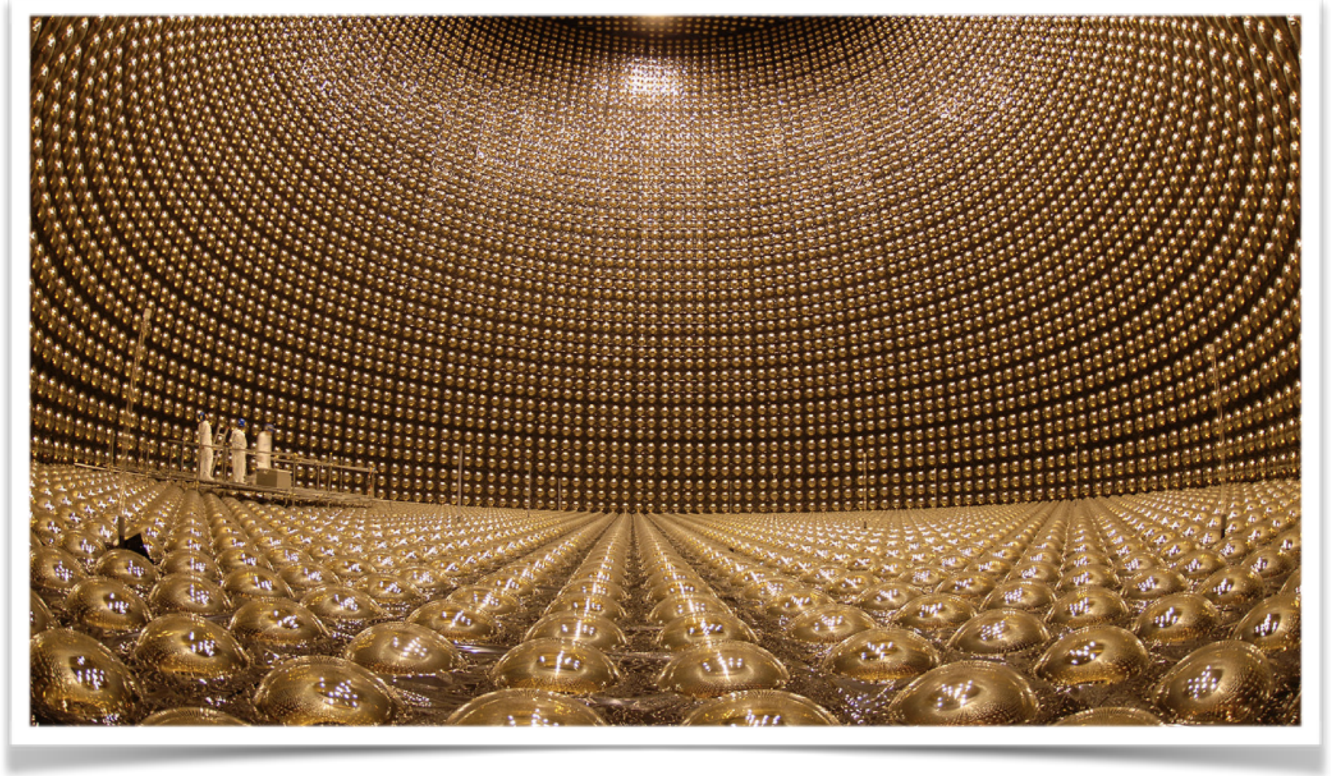


Hyper-Kamiokande



Super-Kamiokande
(ICRR, Univ. Tokyo)

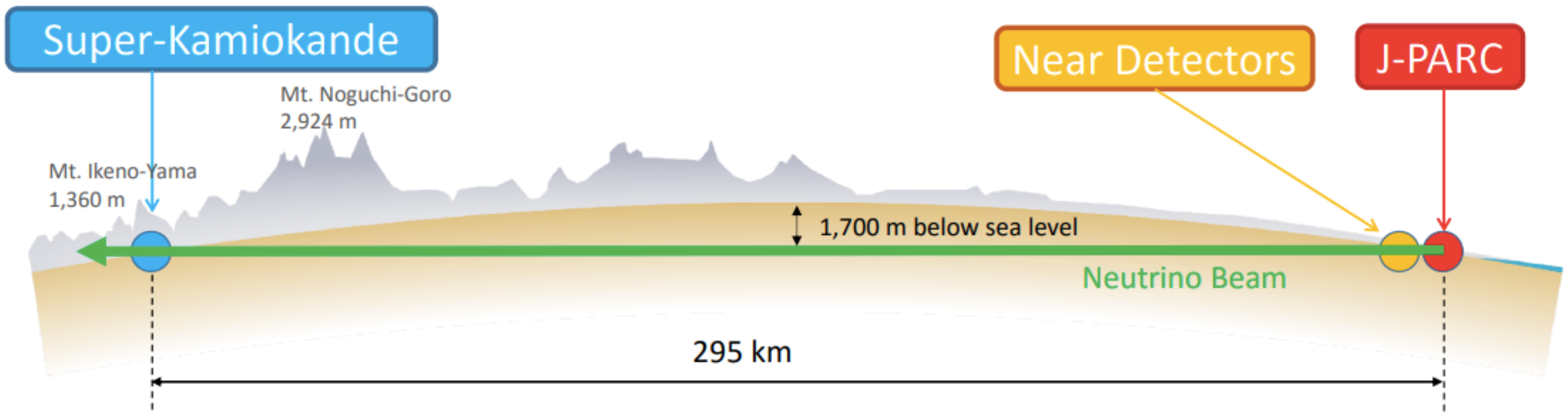
J-PARC Main Ring
(KEK-JAEA, Tokai)



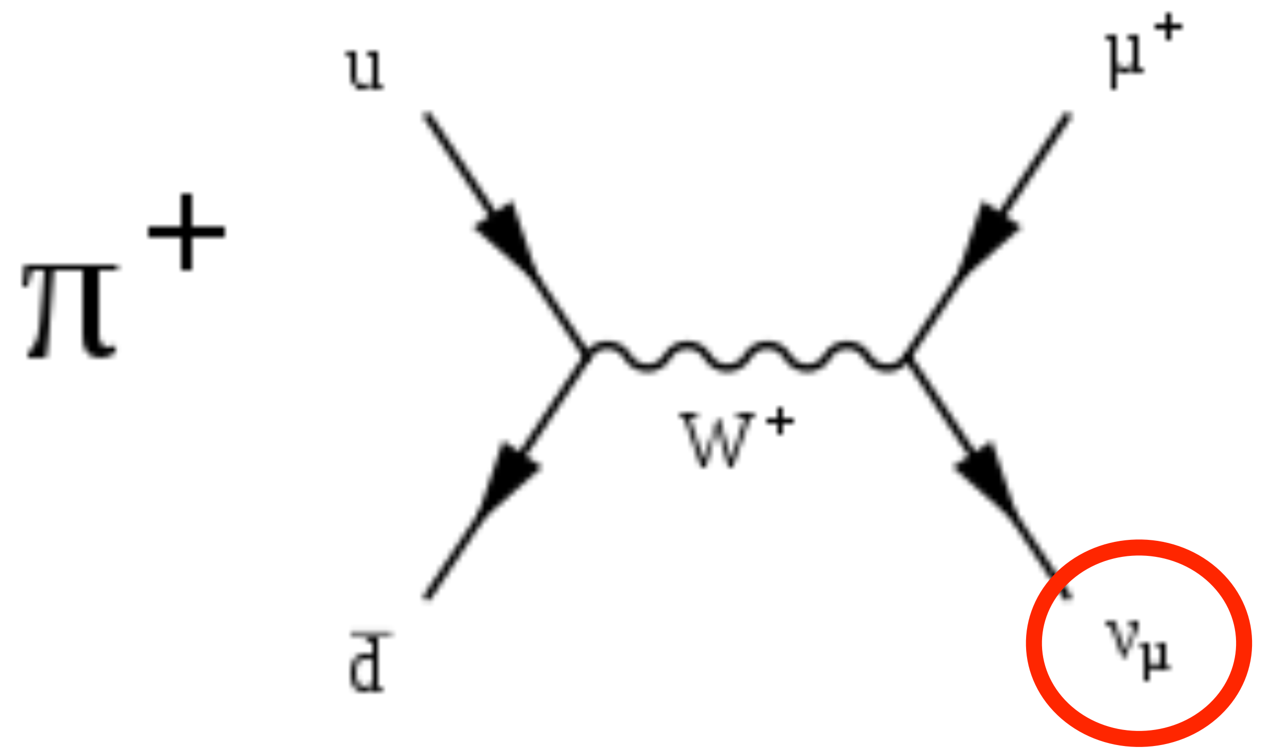
Mark Hartz
TRIUMF & Kavli IPMU, University of Tokyo

CAP-PPD, June 9, 2020

Neutrino Oscillation Experiments

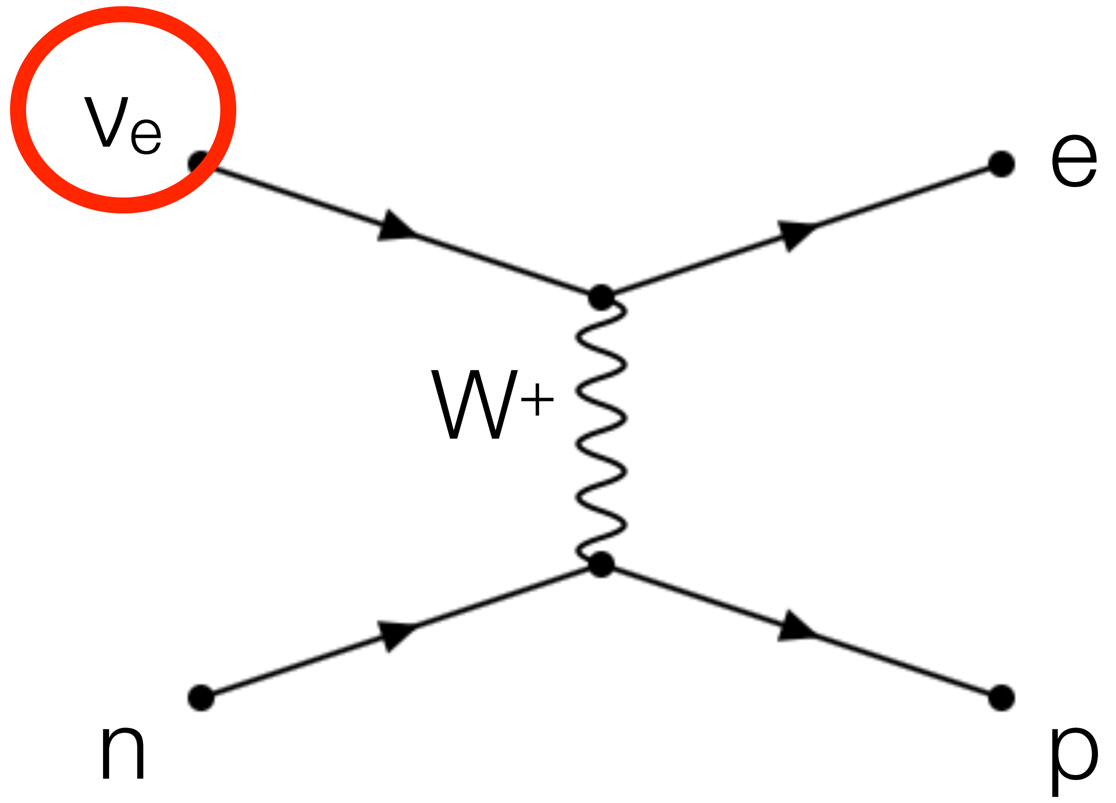


Over hundreds of km baselines, study change of neutrino flavor through oscillations



ν_1, ν_2, ν_3

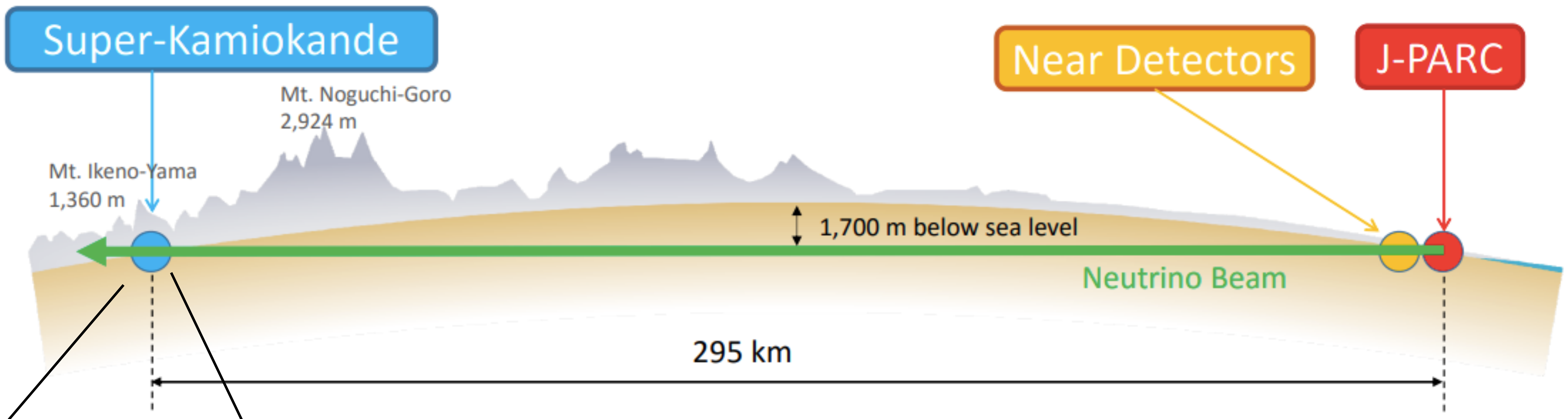
Mass states propagate with relative phases

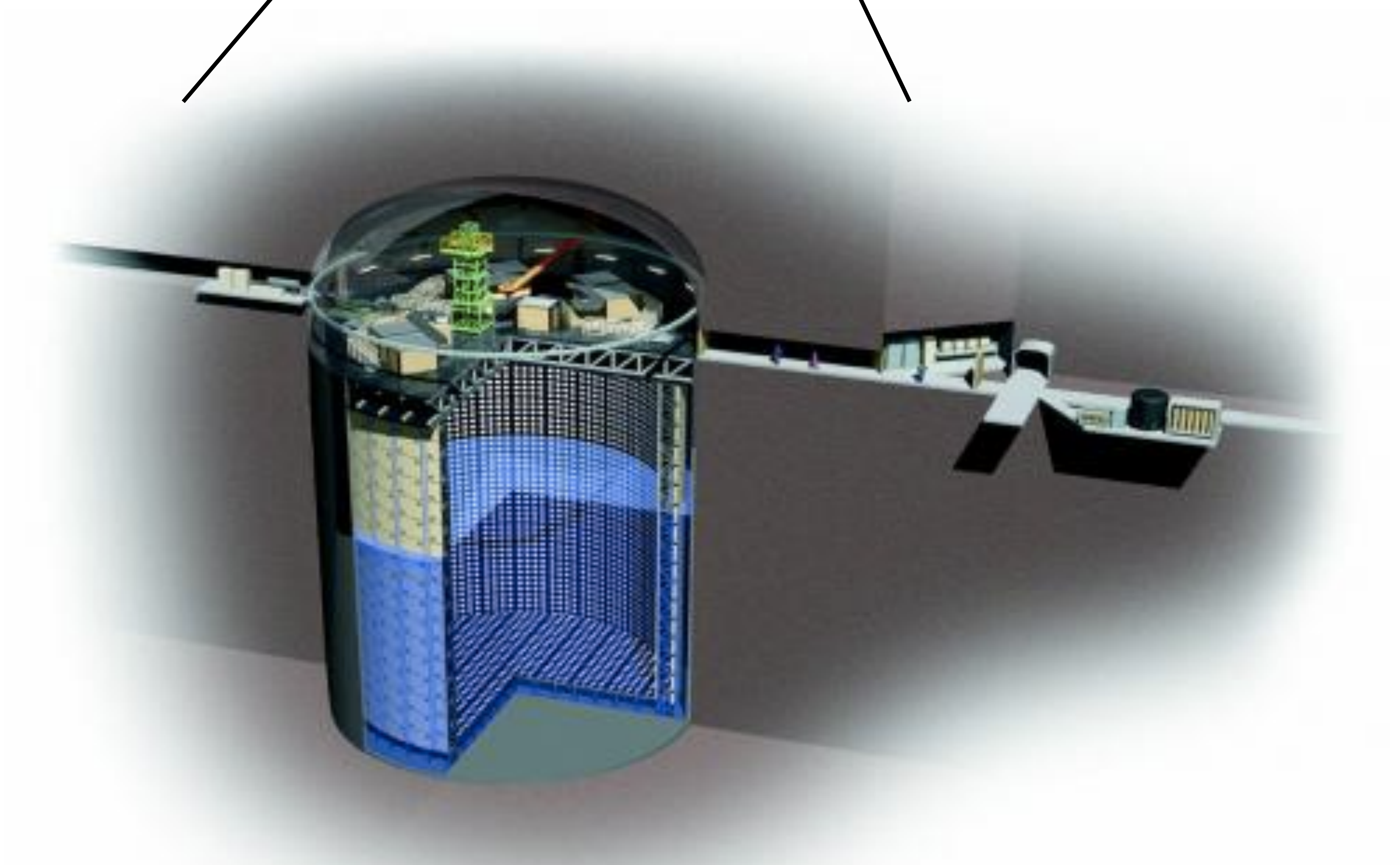


Produce neutrinos as weak states

Interact as weak eigenstates

General Purpose Experiments





Super-Kamiokande (Far Detector)

- Far detectors are general purpose experiments:
  - Atmospheric neutrinos
  - Supernova neutrinos
  - Solar neutrinos
  - Nucleon decay searches
  - Dark matter searches
  - ….

Neutrino Oscillation Parameters

PMNS mixing matrix in standard 3-neutrino mixing framework:

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

Accessible through neutrino oscillations

$s_{12} = \sin\theta_{12}$, etc.

Three mixing angles θ_{12}, θ_{13}, θ_{23}

Majorana phases if neutrinos are Majorana particles

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

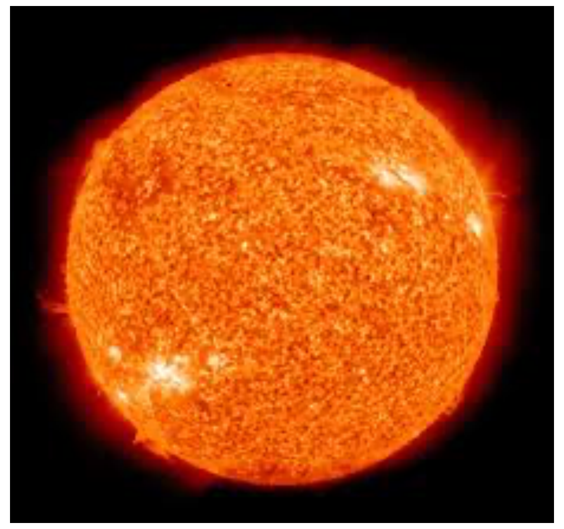
The flavor content of states oscillate as they traverse matter or vacuum:

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

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

Neutrino Sources and Measurements

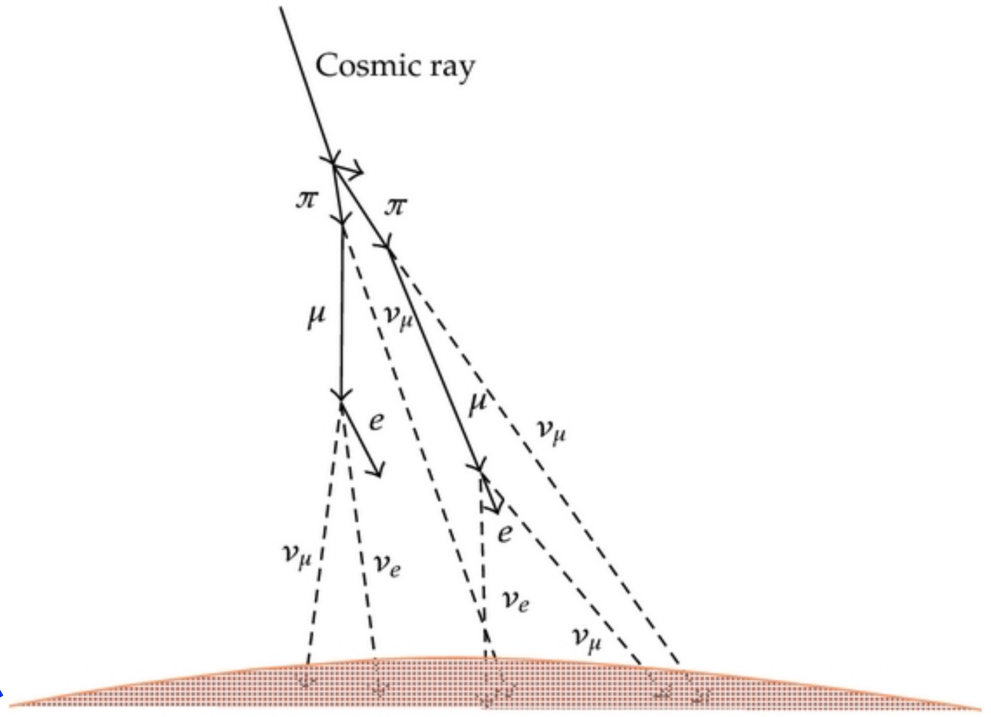
Solar



Reactor

Accelerator

Atmospheric



$\theta_{12} = 33.65^o \pm 0.80^o$

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

$\theta_{13} = 8.49^o \pm 0.14^o$

$\Delta m^2_{32} = (2.45 \pm 0.05) \times 10^{-3}\,\text{eV}^2$

or

$\Delta m^2_{32} = (-2.52 \pm 0.05) \times 10^{-3}\,\text{eV}^2$

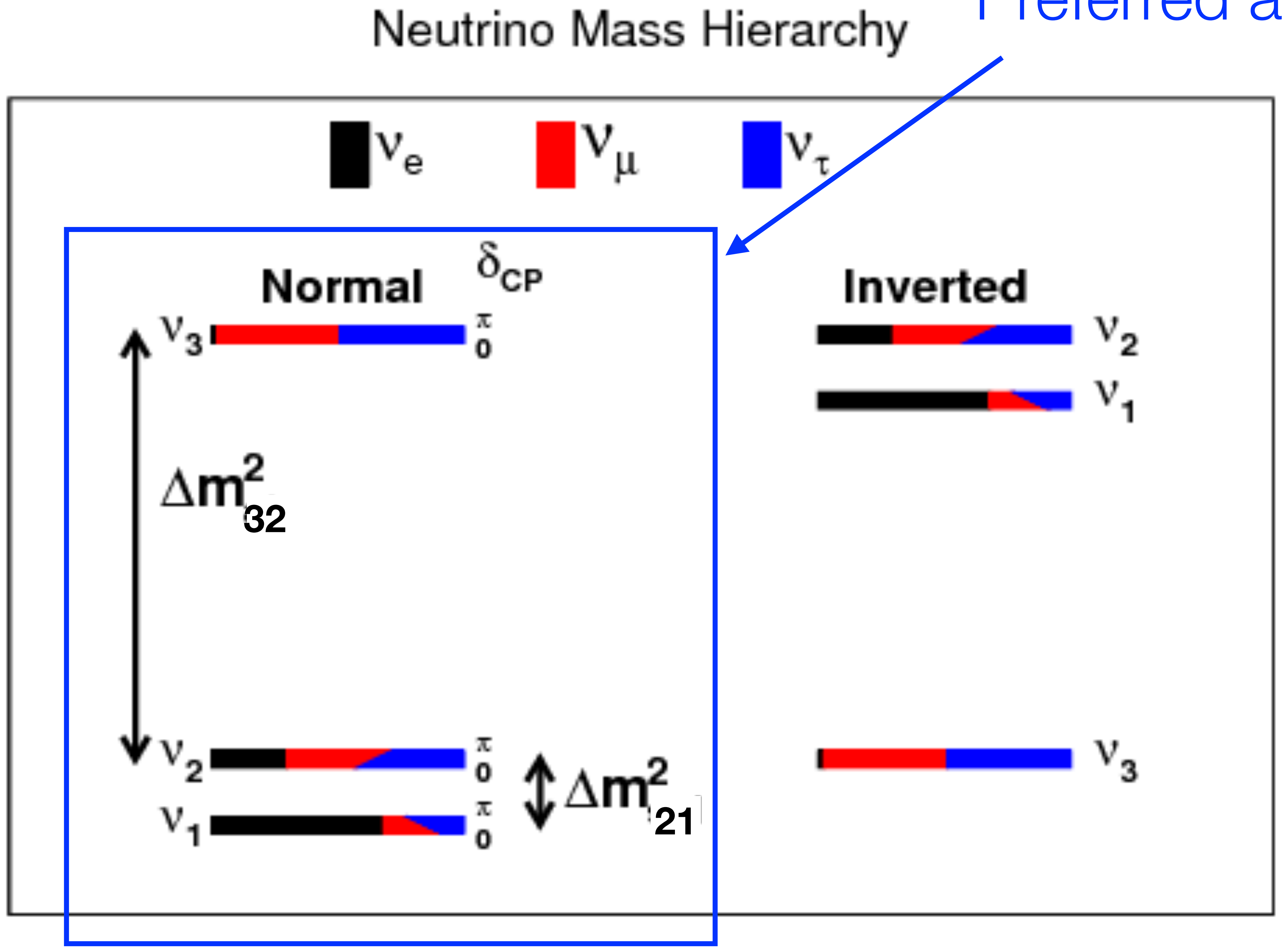
$\theta_{23} = 47.1^o \pm 1.6^o$

$\delta_{cp} = ??$

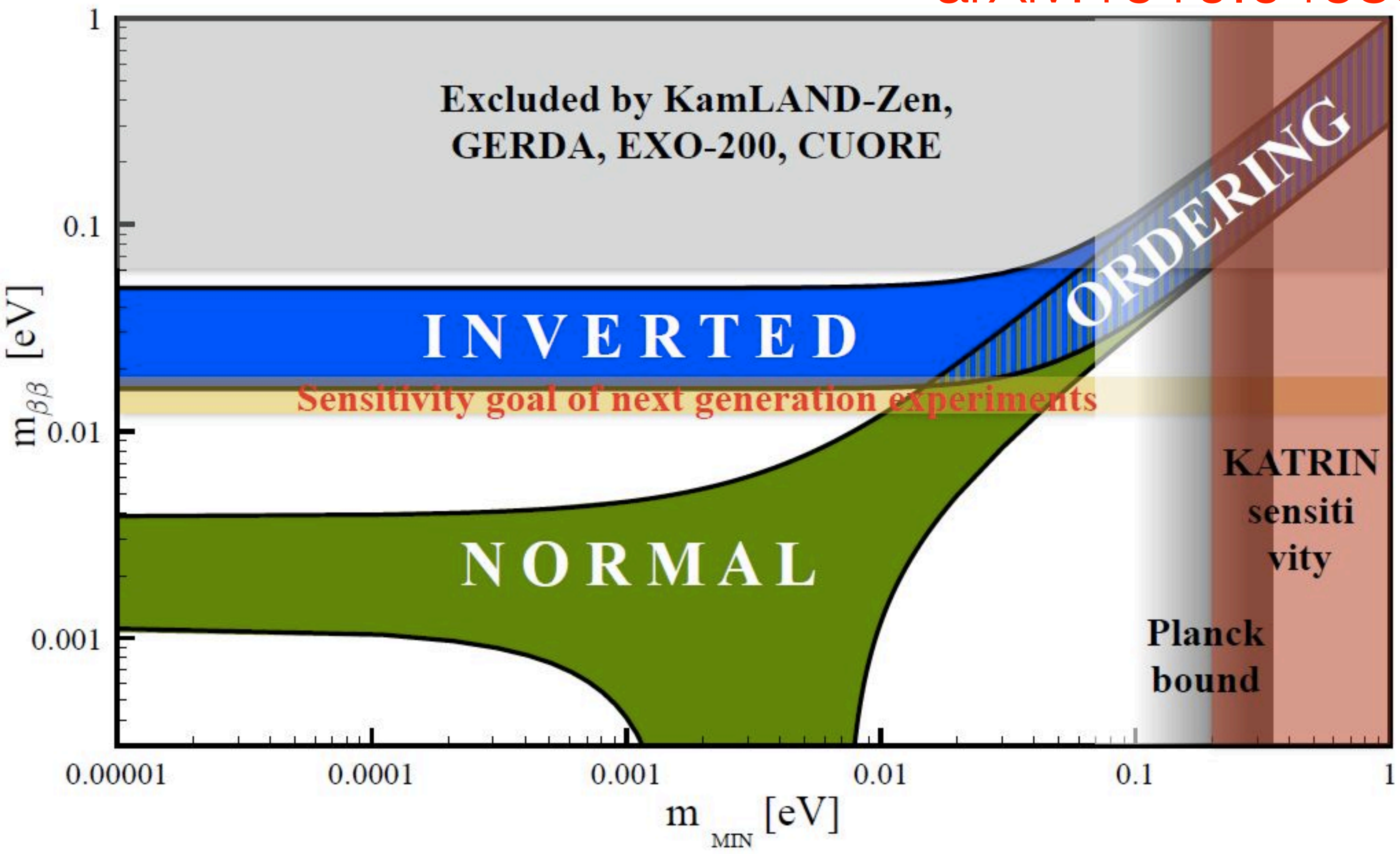
New source of CP violation?

Mass Hierarchy (Ordering)

Preferred at ~3σ significance in global fits



arXiv:1910.04688



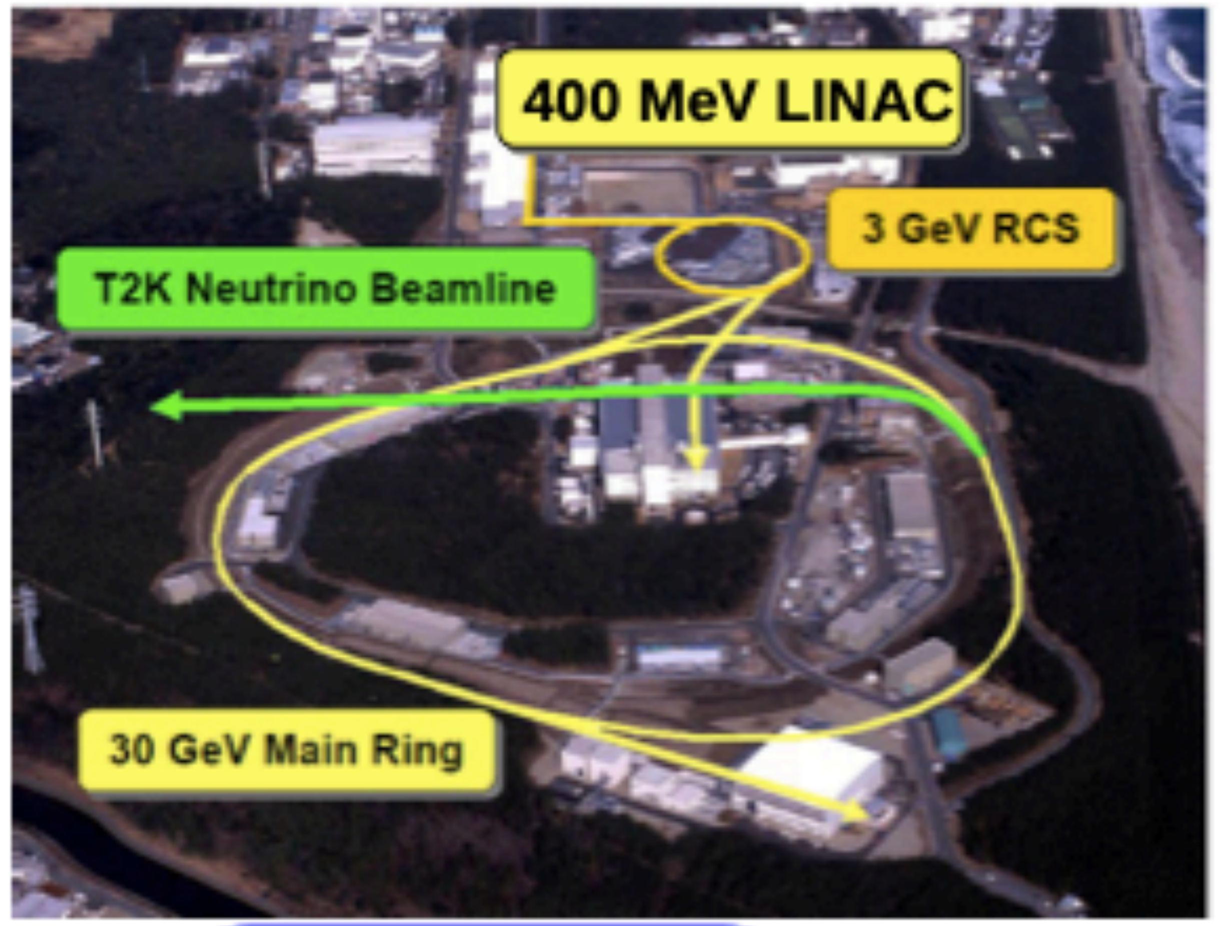
- Sensitive to mass ordering through oscillation effect when neutrinos propagate through matter
- Important interplay with neutrinoless double beta decay experiments

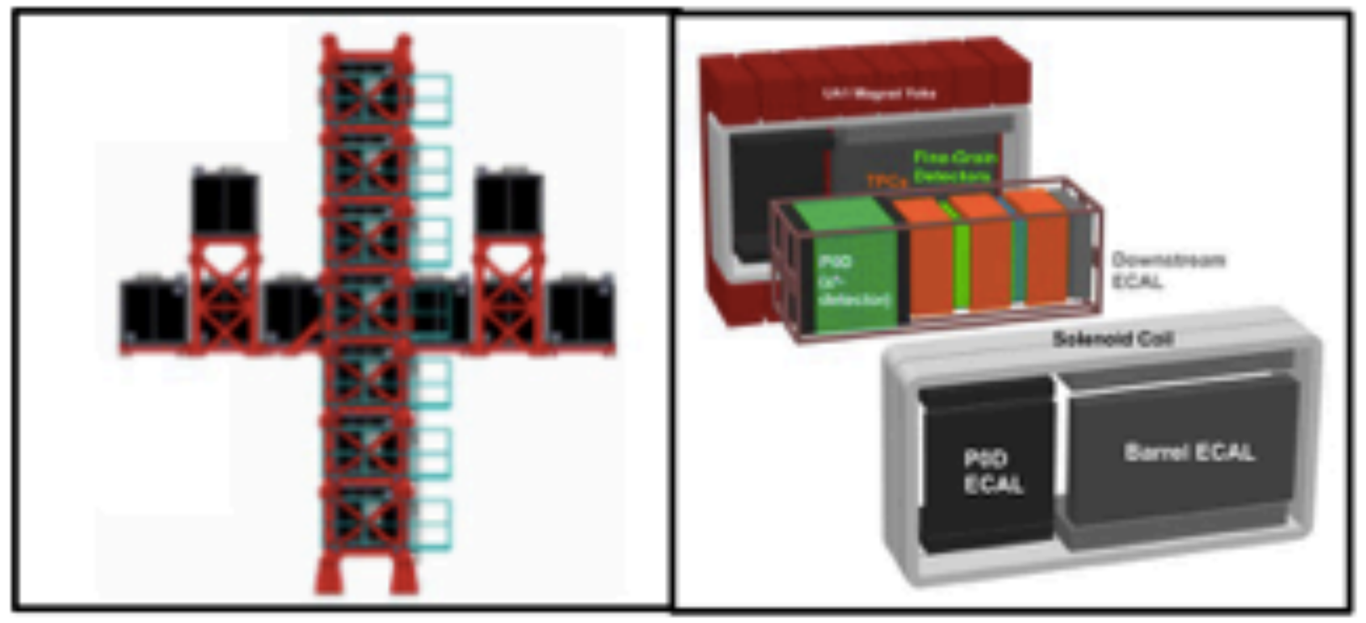
Long Baseline Neutrinos at T2K

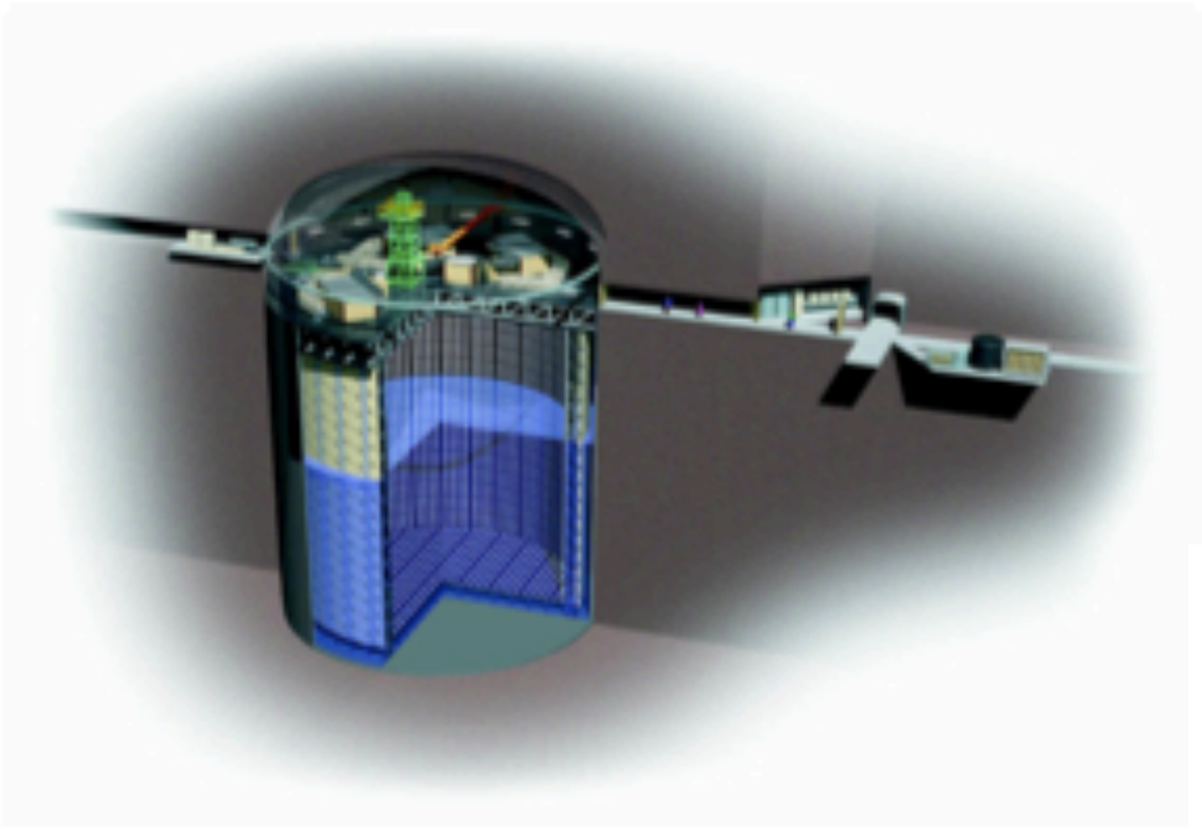
ND280 Near Detector

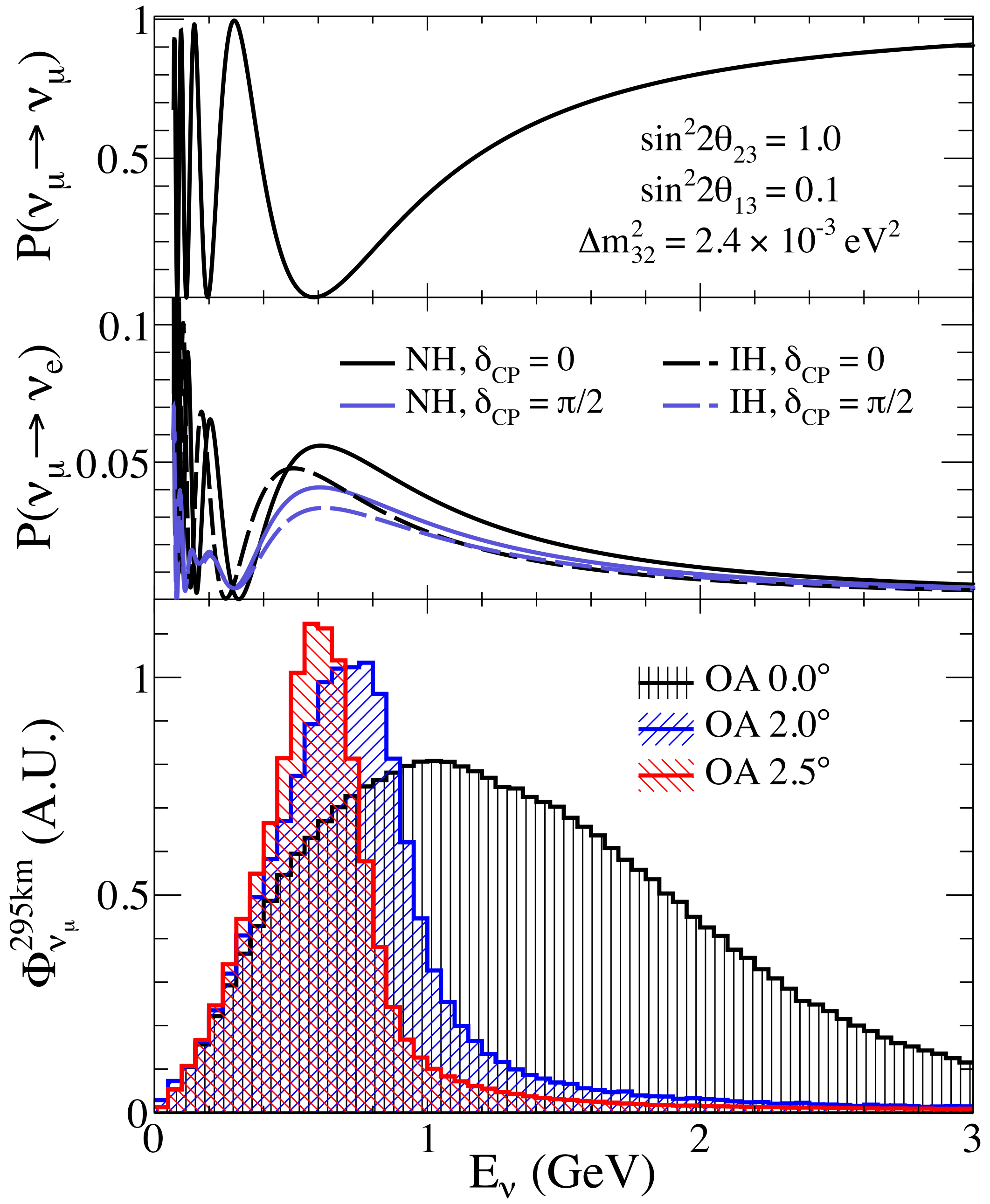
~500 members, 69 Institutes, 12 countries

T2K Overview









J-PARC accelerator complex and neutrino beamline

ν_μ 2.5° ν_μ

On-axis: INGRID

Off-axis: ND280

Super-Kamiokande

0 — 280m — 295 km

ν production

Near detectors

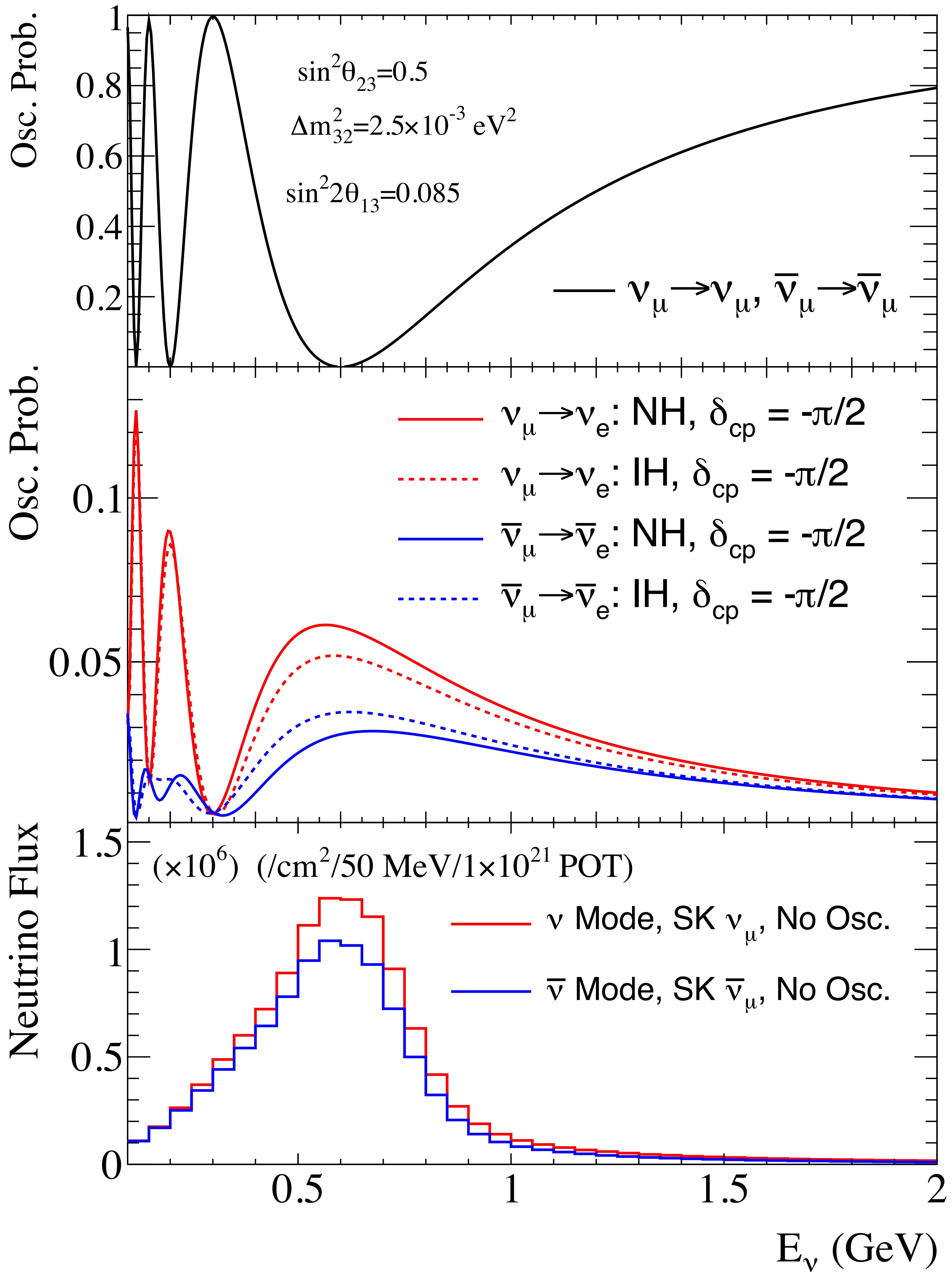
Far detector

- Characterise ν beam
- Constrain systematic uncertainties

Study ν oscillations

Off-axis beam

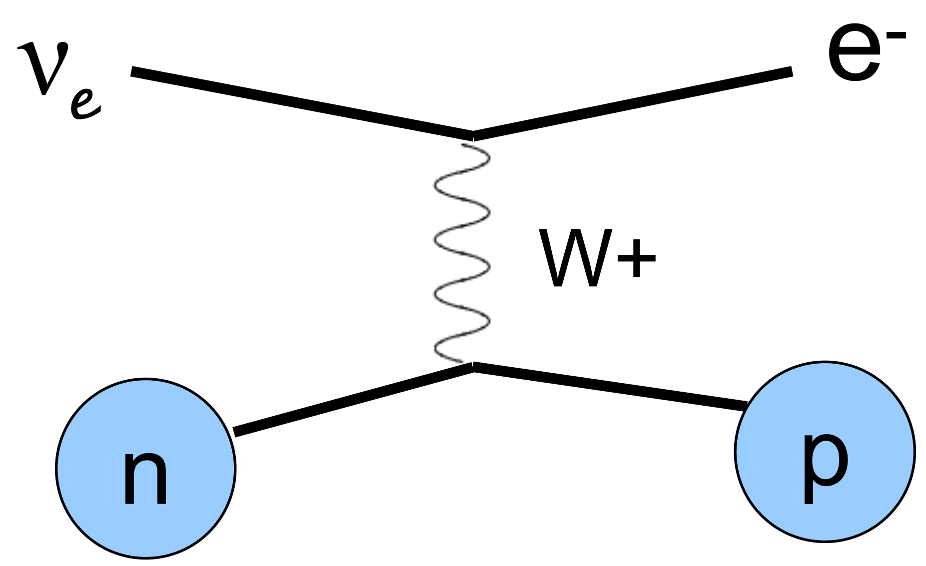
Neutrino Oscillations at T2K



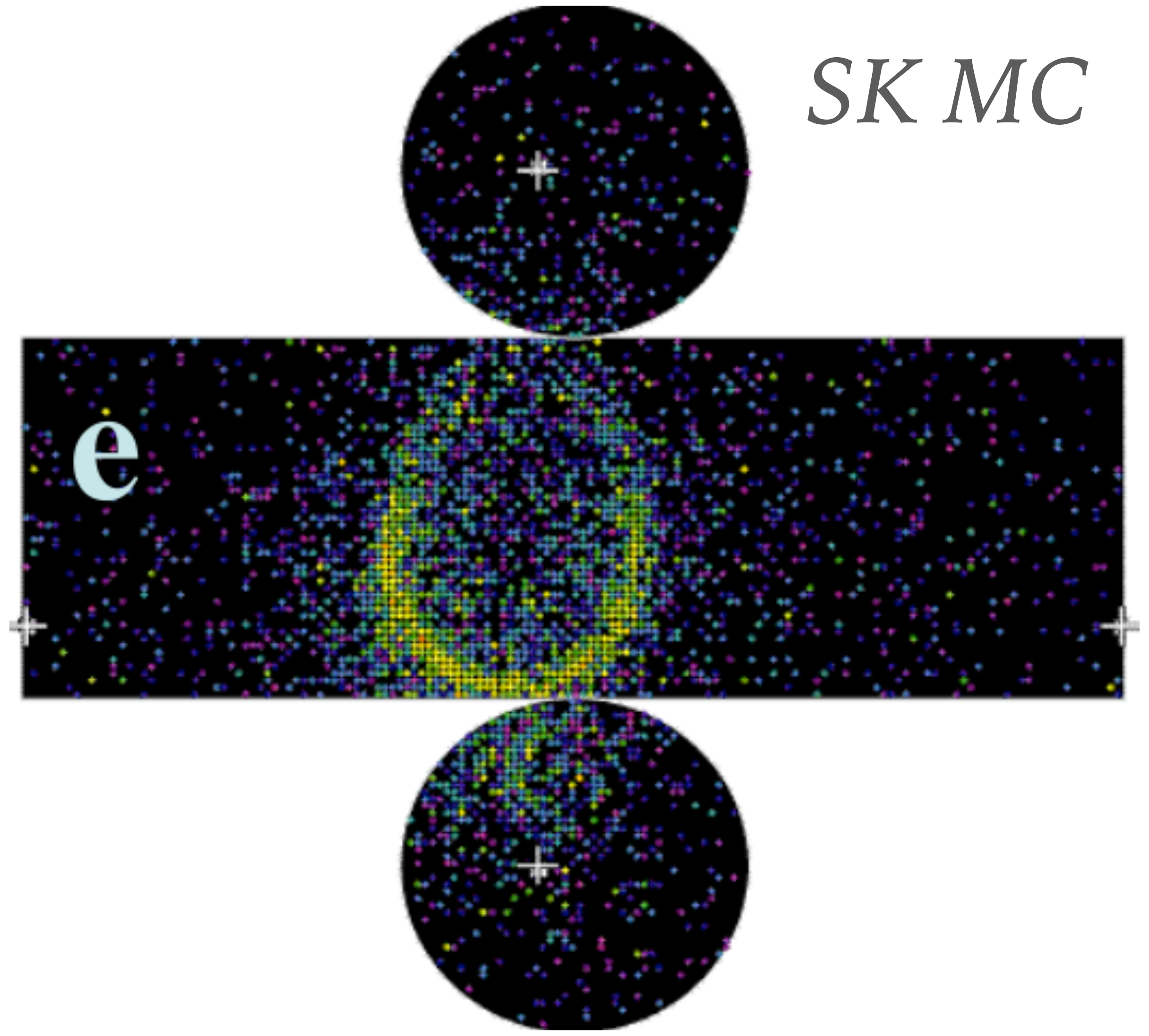
- **Muon (anti)neutrino survival** depends on $\sin^2(2\theta_{23})$ and Δm^2_{32}
- **Electron (anti)neutrino appearance**
  - $\sin^2(\theta_{23})$, $\sin^2(2\theta_{13})$ and Δm^2_{32} in leading term
  - Sub-leading dependence on δ_{cp}
    - CP conservation at $\delta_{cp}=0,\pi$
    - Maximal CP violation at $\delta_{cp}=-\pi/2,\pi/2$
  - Matter effect → dependence on the mass hierarchy
    - Normal Hierarchy (NH): enhanced rate for neutrinos, decreased for antineutrinos

Neutrino Detection at Super-K

Electron neutrino appearance signal:

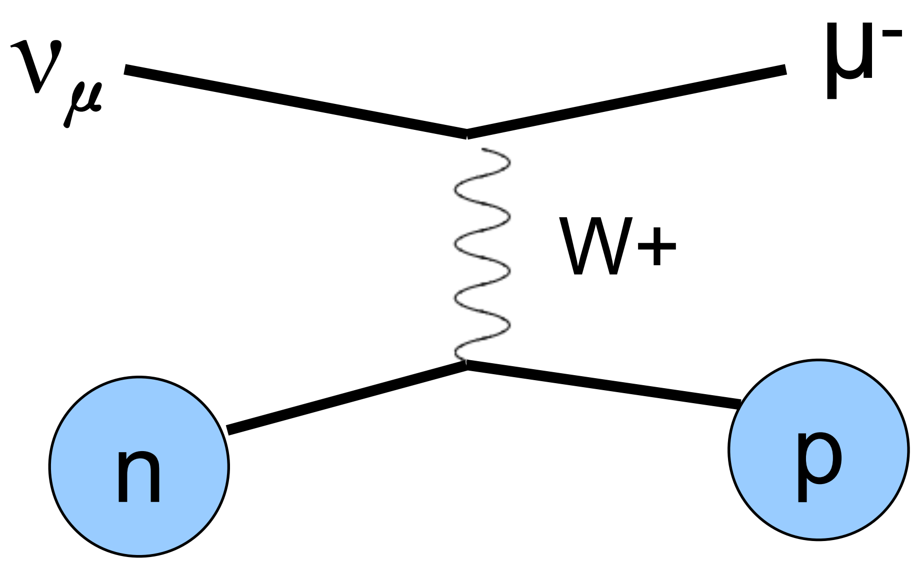


Detected electron produces a shower: “fuzzy” ring

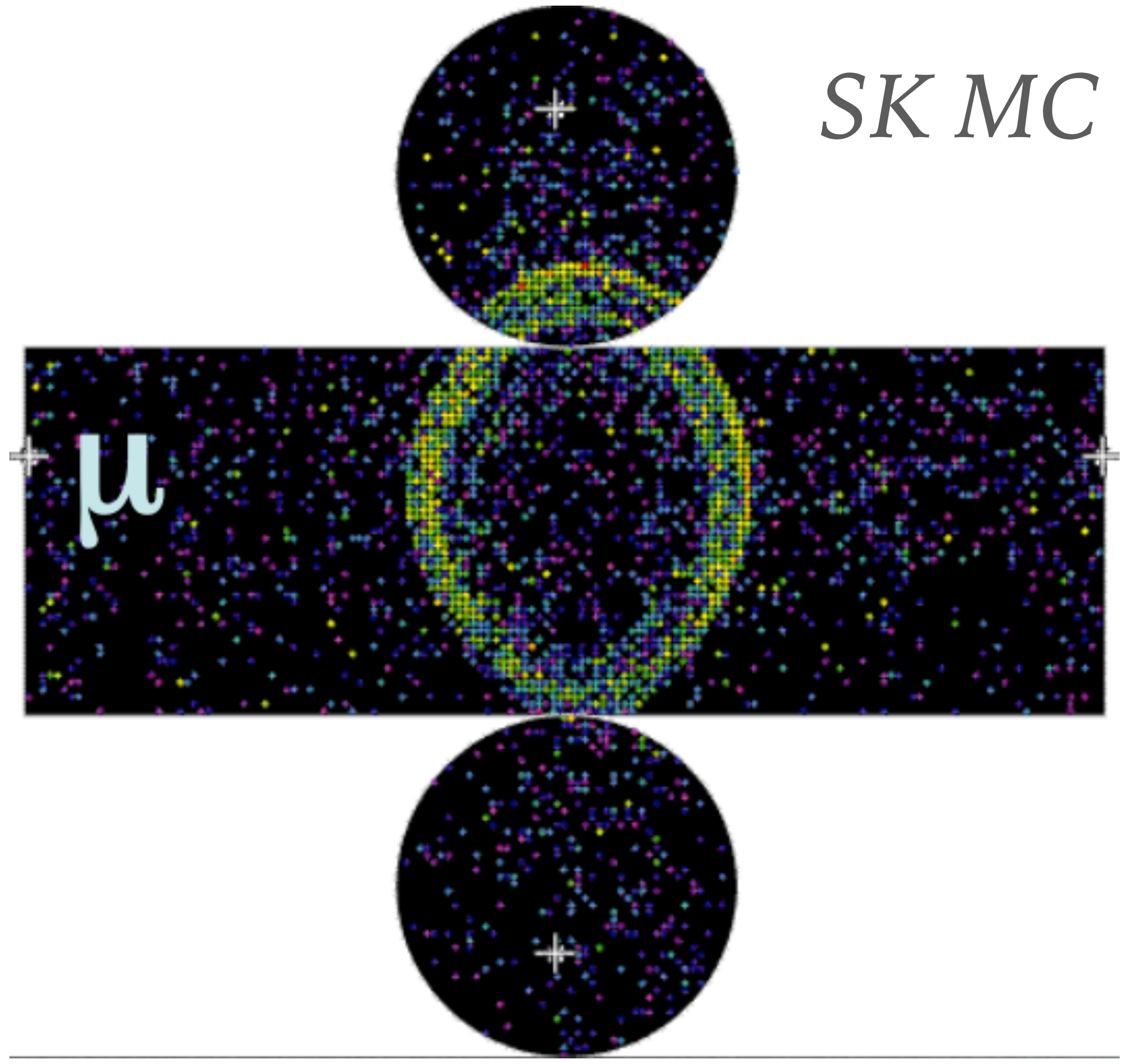


SK MC

Muon neutrino survival signal:



Detected muon produces a sharp ring

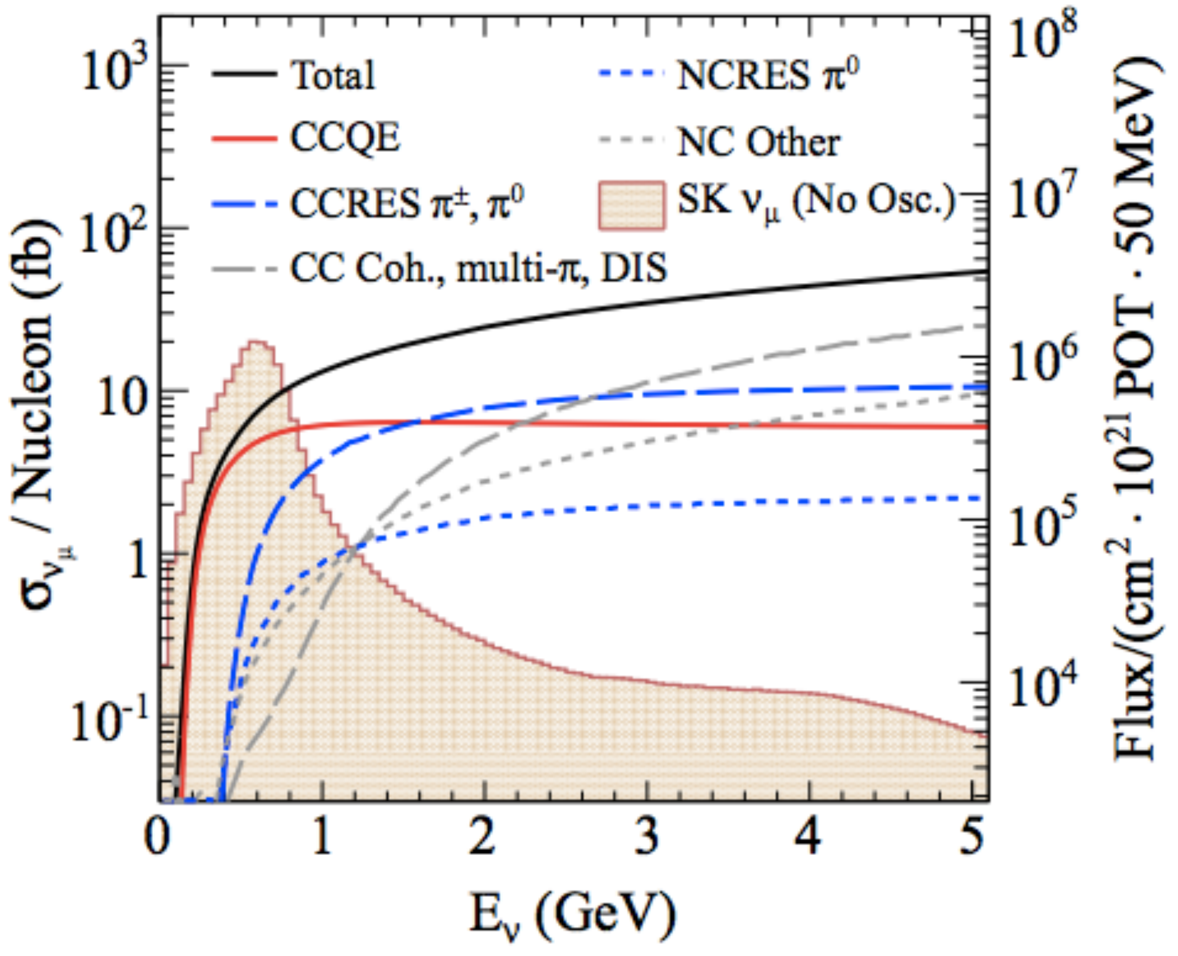


SK MC

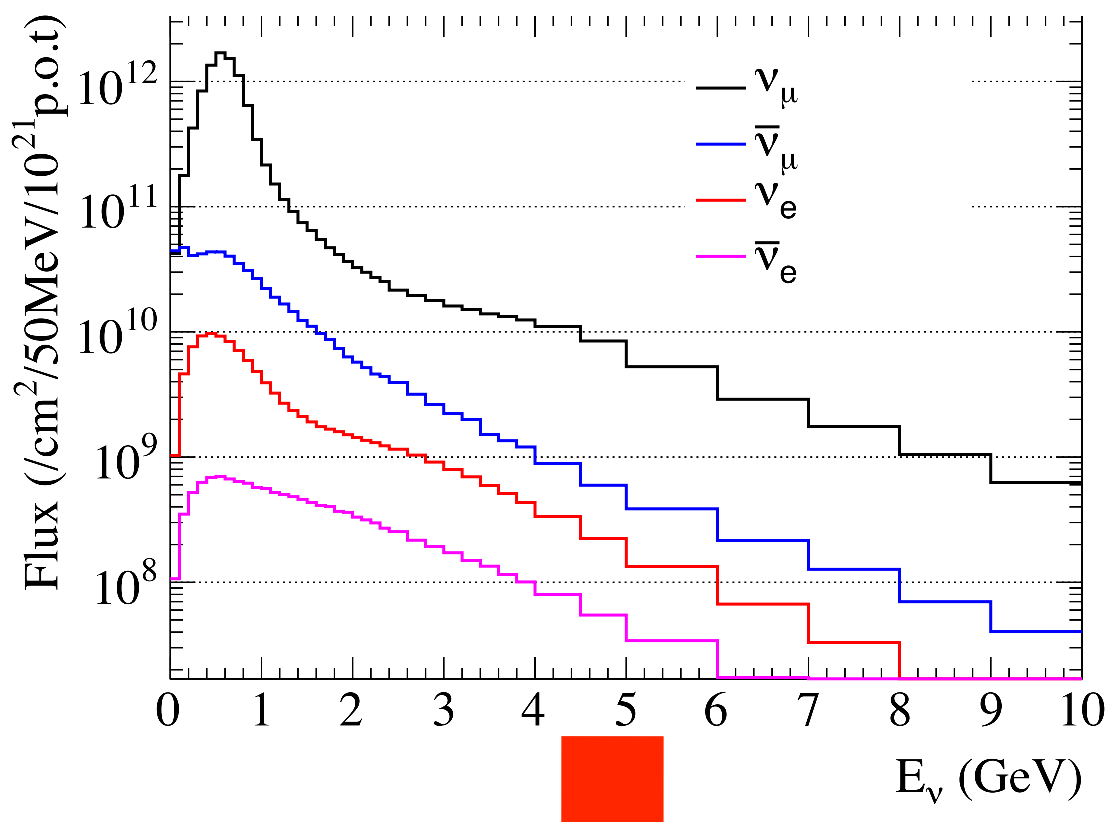
Likelihood-based reconstruction development led by TRIUMF

Using Near Detector Data

Neutrino-nucleus Interaction Model

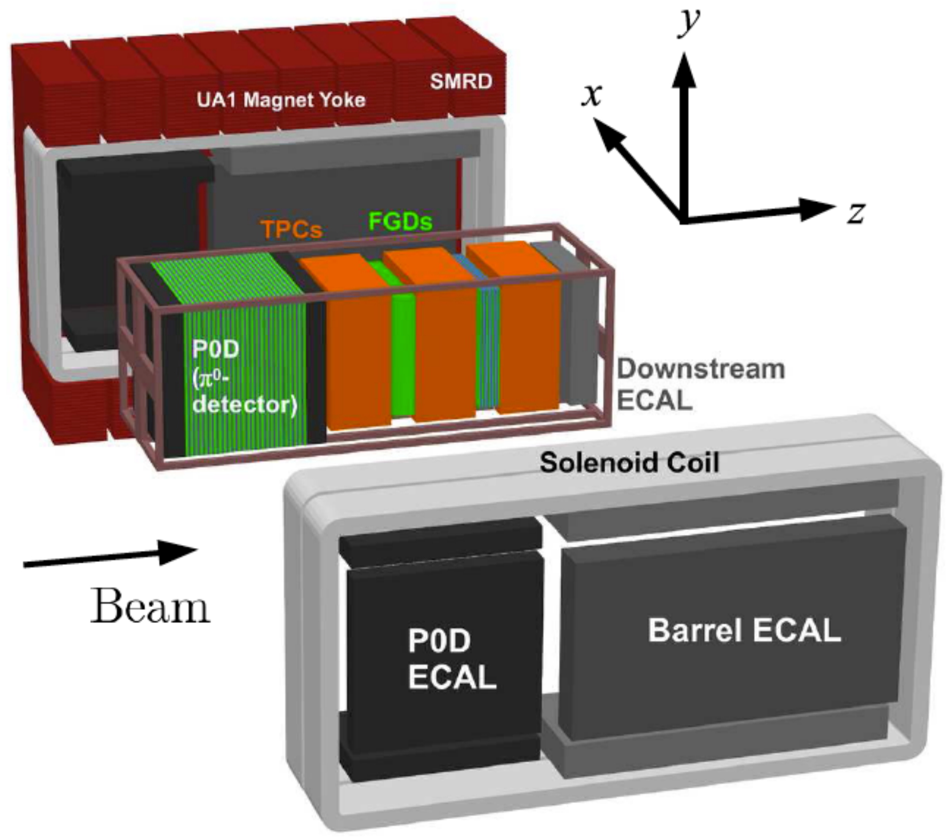


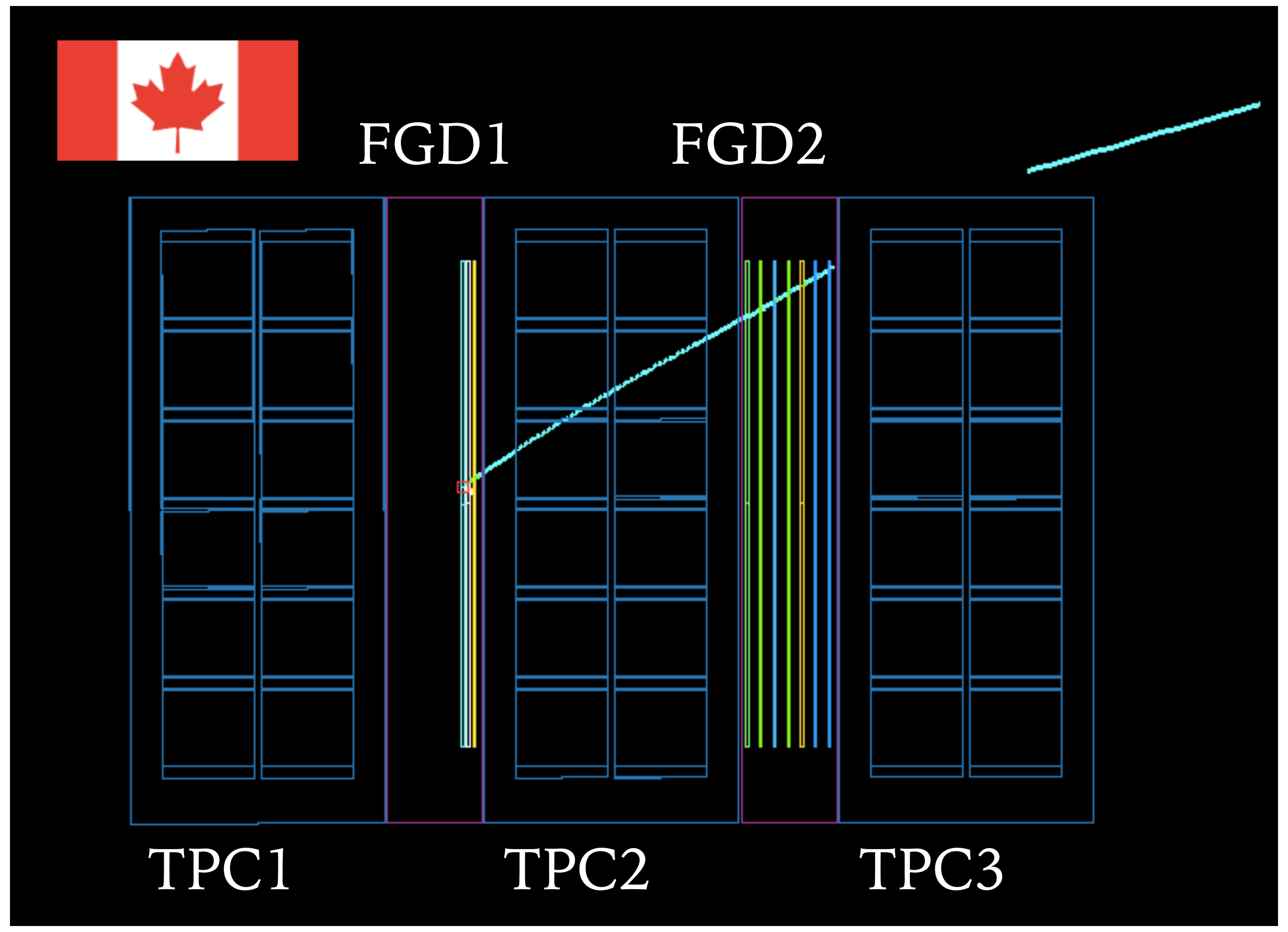
Neutrino Flux Model

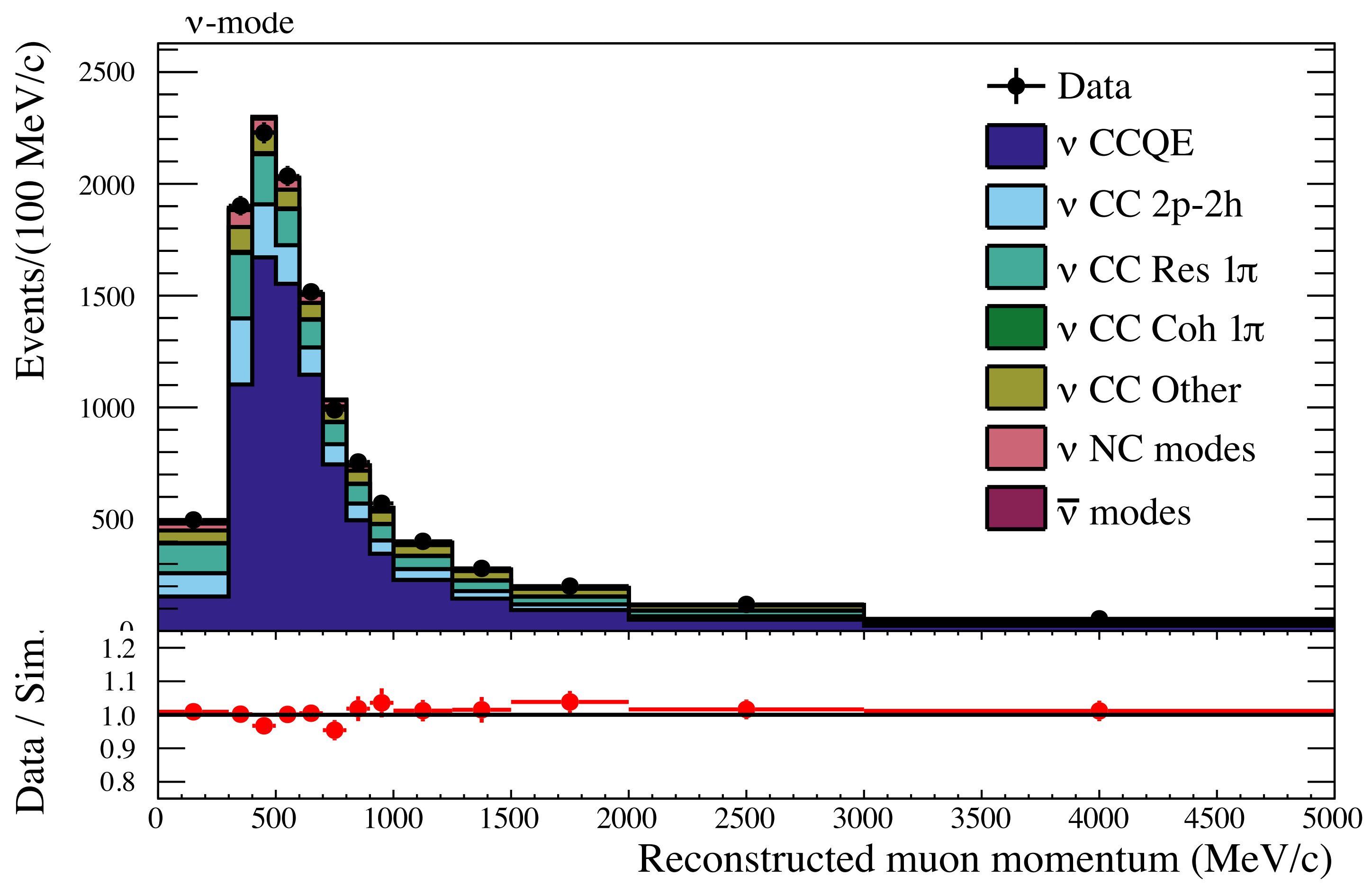


Fit to ND280 data constrains neutrino flux parameters and interaction model parameters

ND280 Data

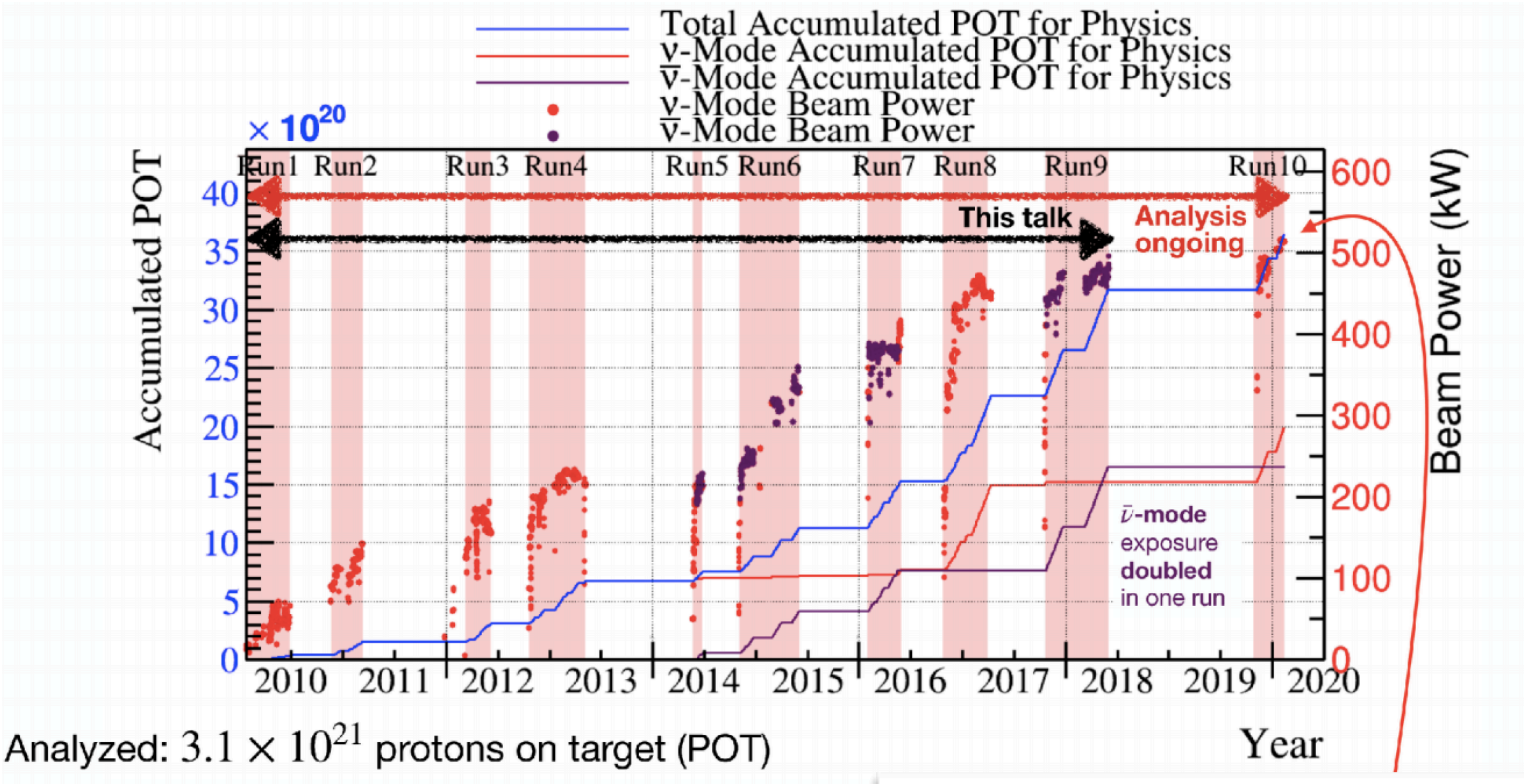






PRELIMINARY

T2K Data Collected



Analysis shown today: 3.1x10[21] POT, 50%/50% neutrino/antineutrino

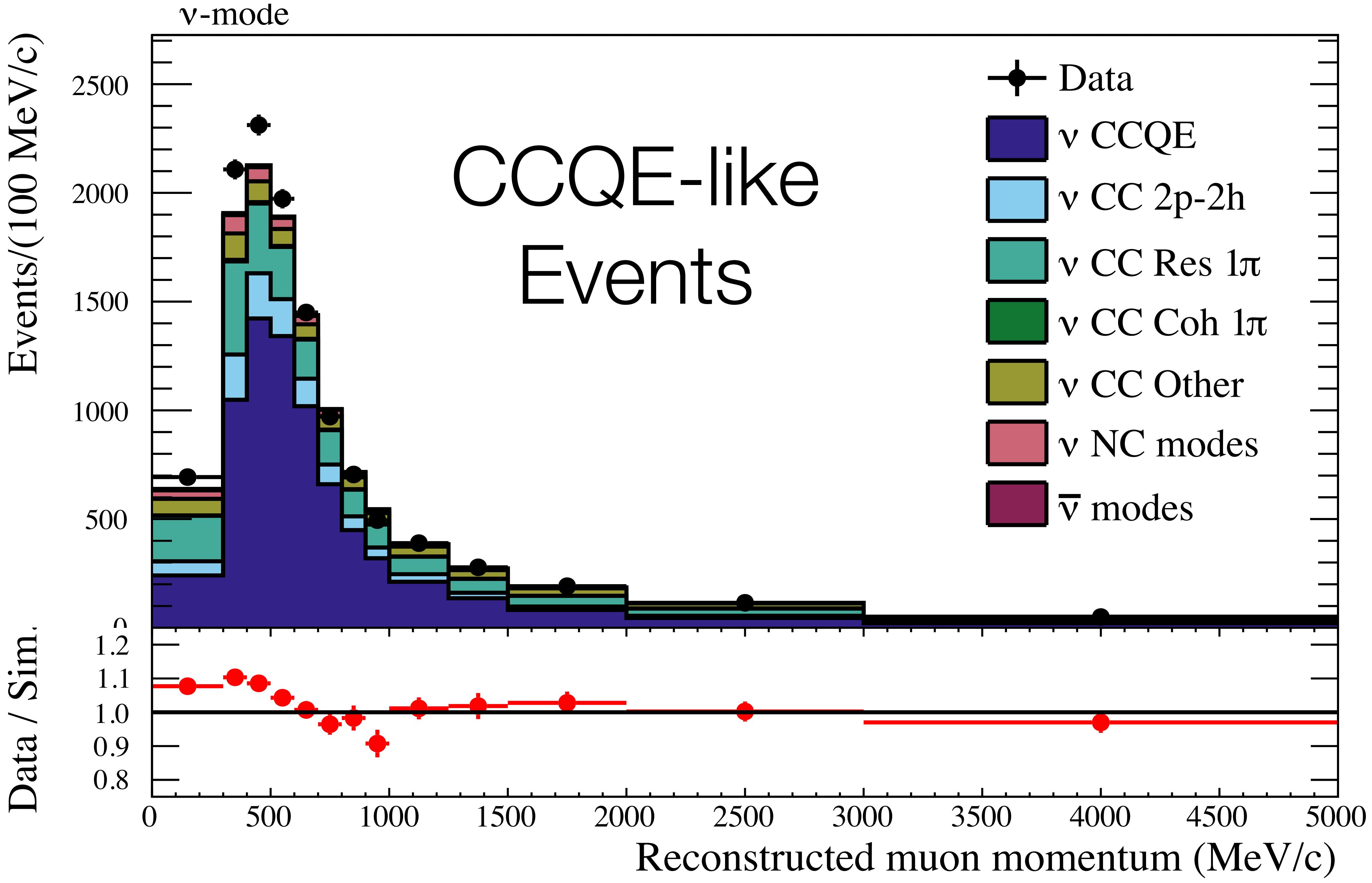
Data collected through 2018

Future analysis: 33% increase in neutrino mode statistics

Accelerator has achieved 515 kW stable operation in 2019

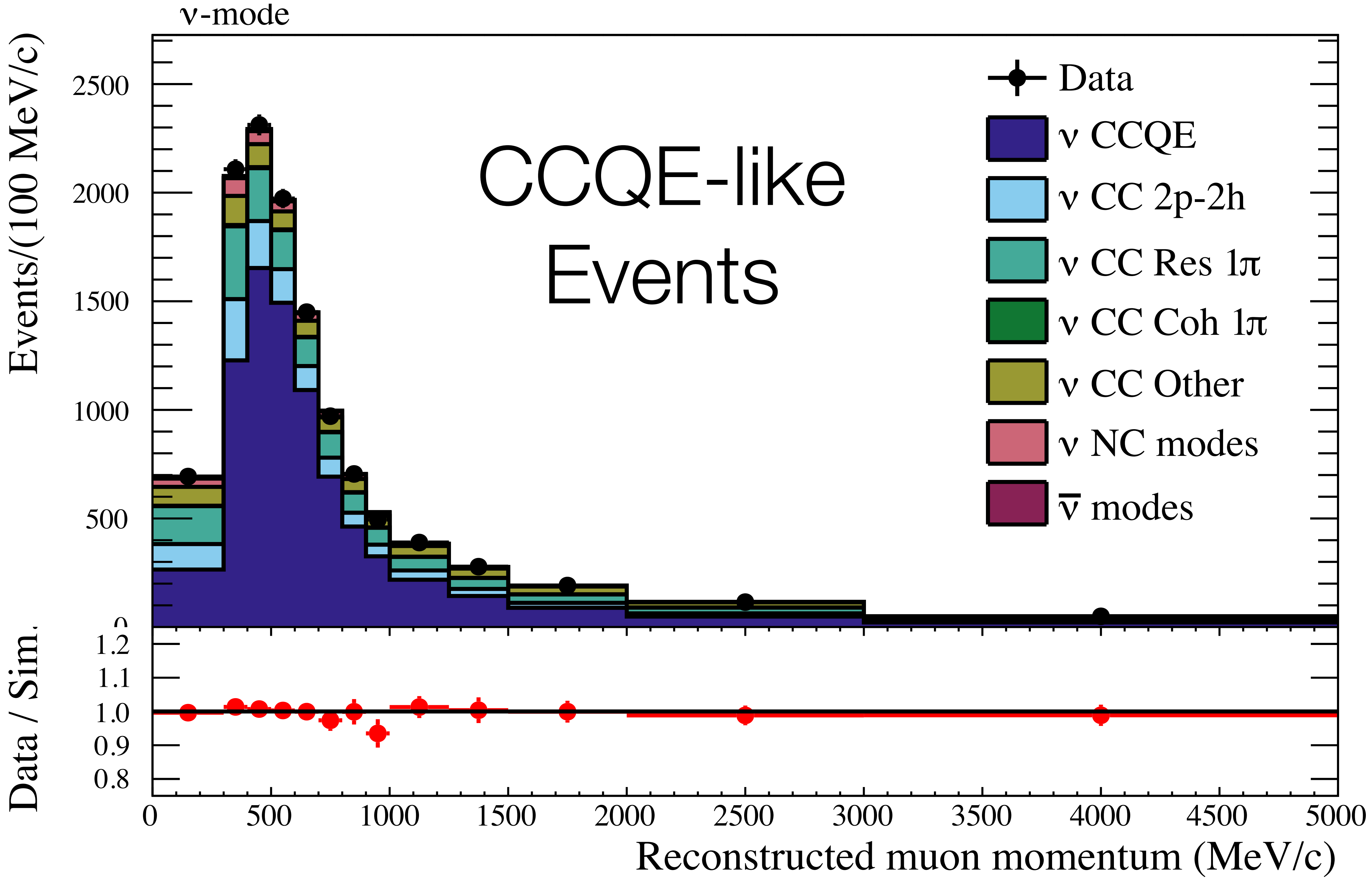
Fitted ND280 Data - Neutrino Mode

Before Fit



PRELIMINARY

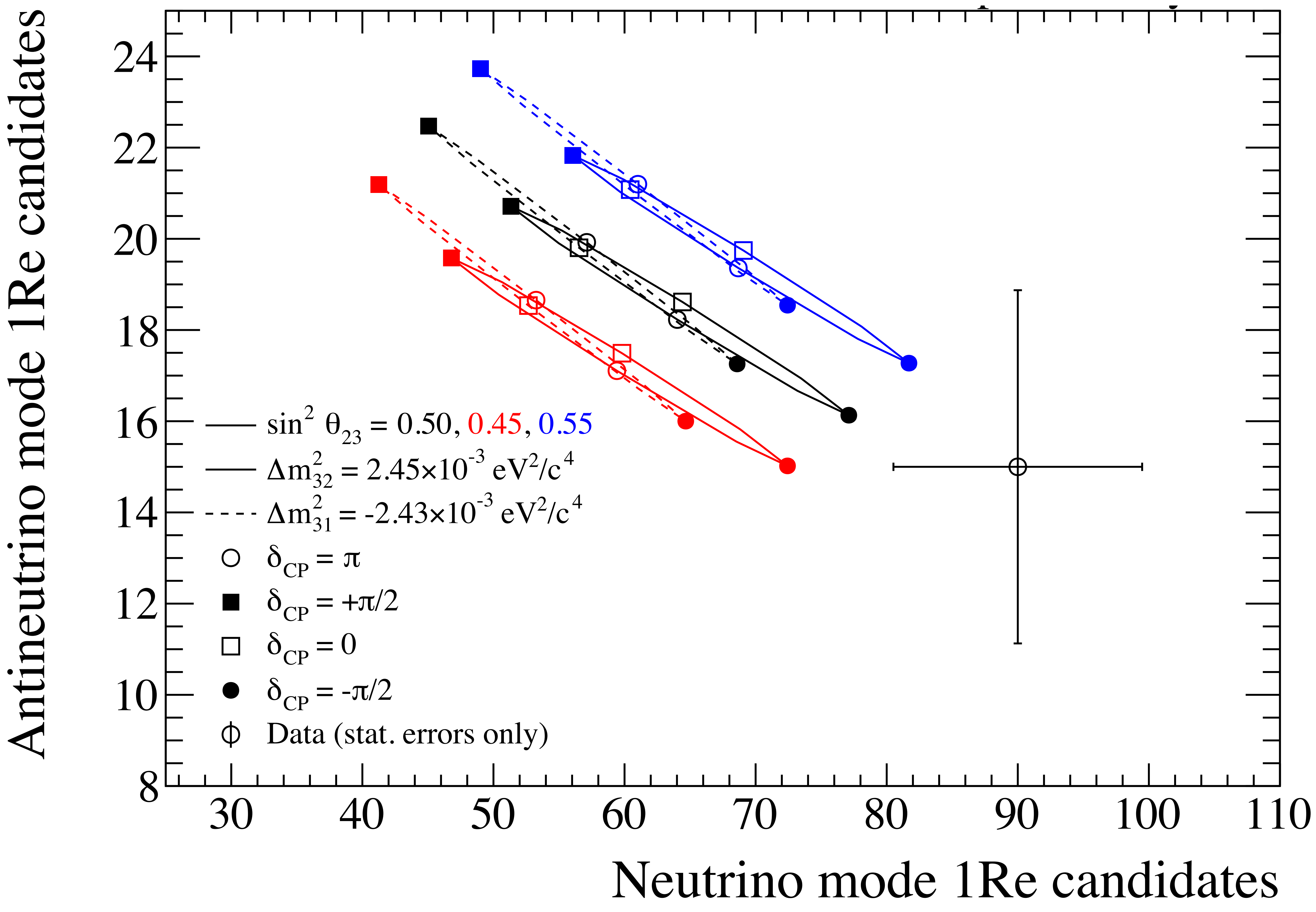
After Fit



PRELIMINARY

Model-data agreement significantly improved by fit of model to data

What We Observe

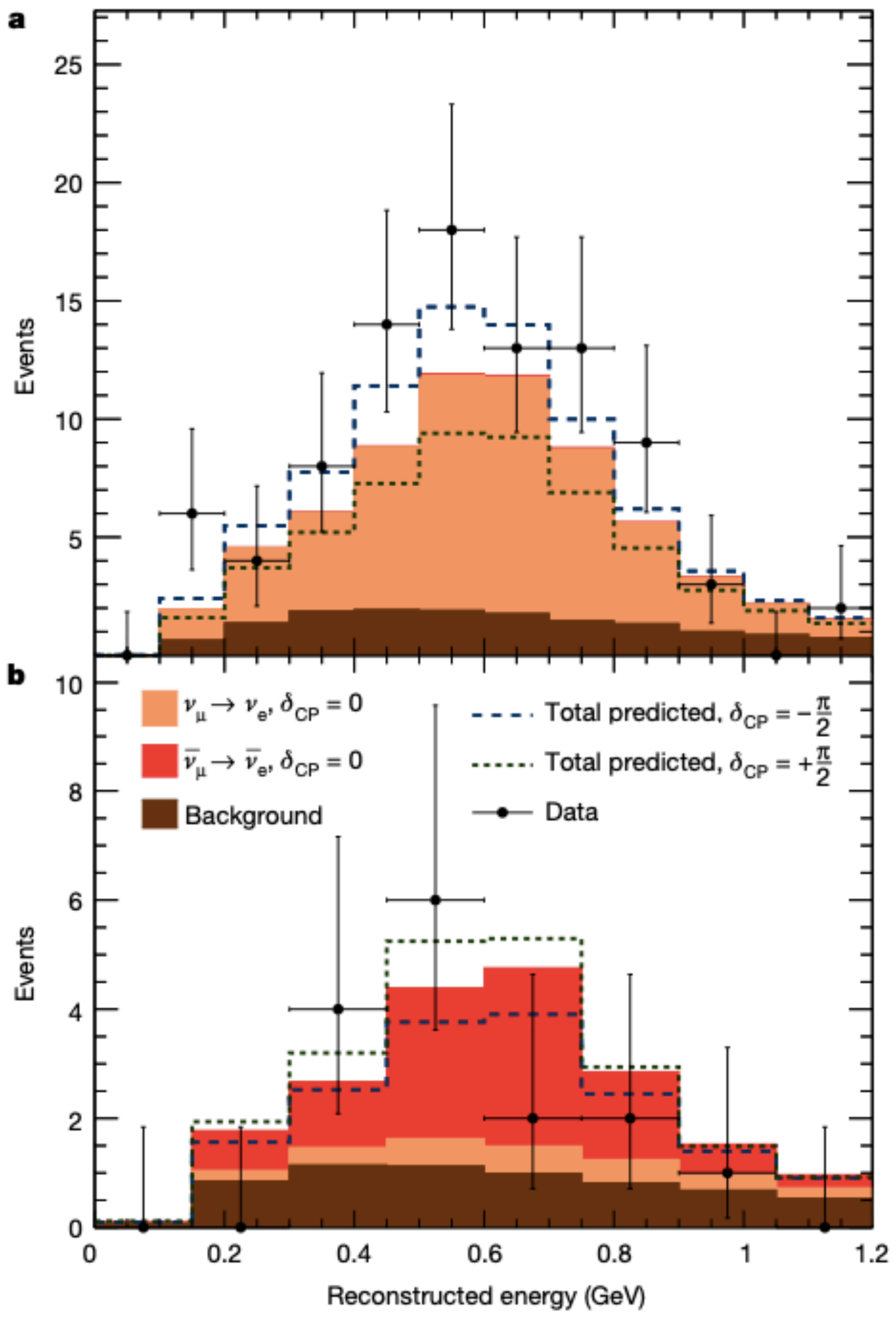


Predictions for $\delta_{cp} = -\pi/2$

c	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

- Results largely consistent with $\delta_{cp} = -\pi/2$ hypothesis
- Observe 15 events in the single decay electron sample when 7 predicted
  - Probability of fluctuation this large or larger in any of 5 samples is 7%

What We Observe



Neutrino

Antineutrino

Predictions for $\delta_{cp} = -\pi/2$

c	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
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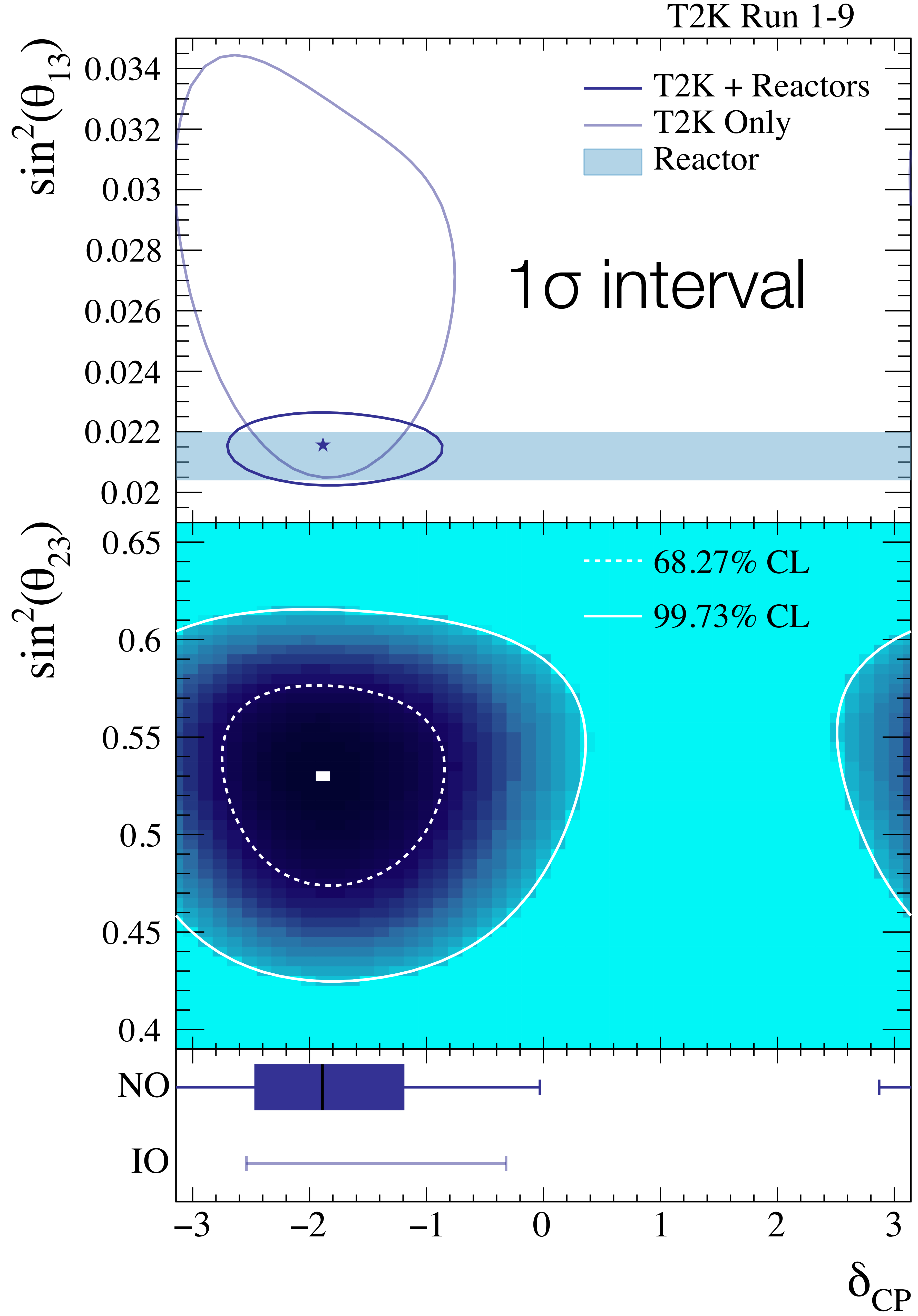
T2K Results δ_{cp}

Nature 580 (2020) 7803, 339-344

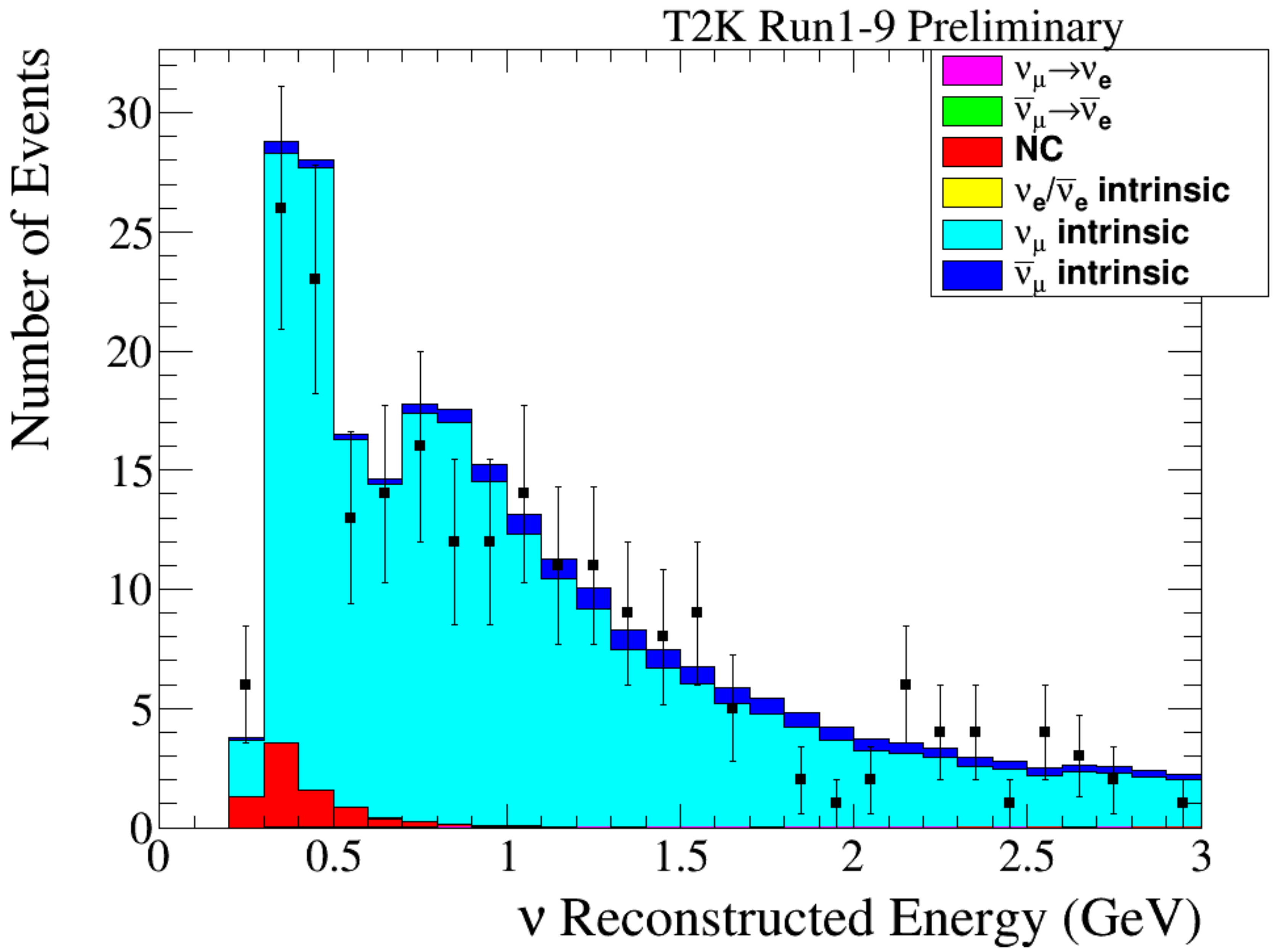


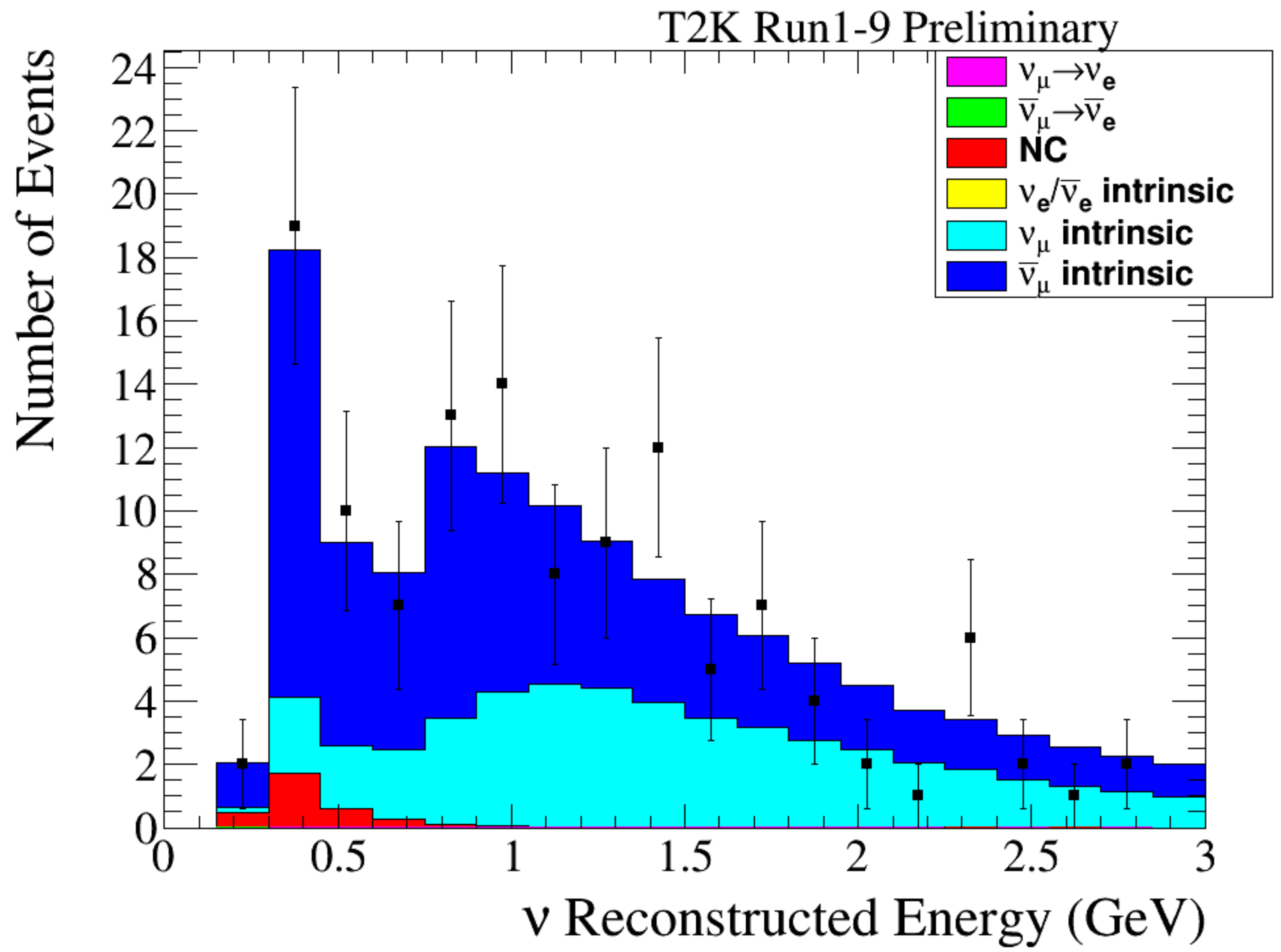
- Include constraint on θ_{13} from reactor experiments

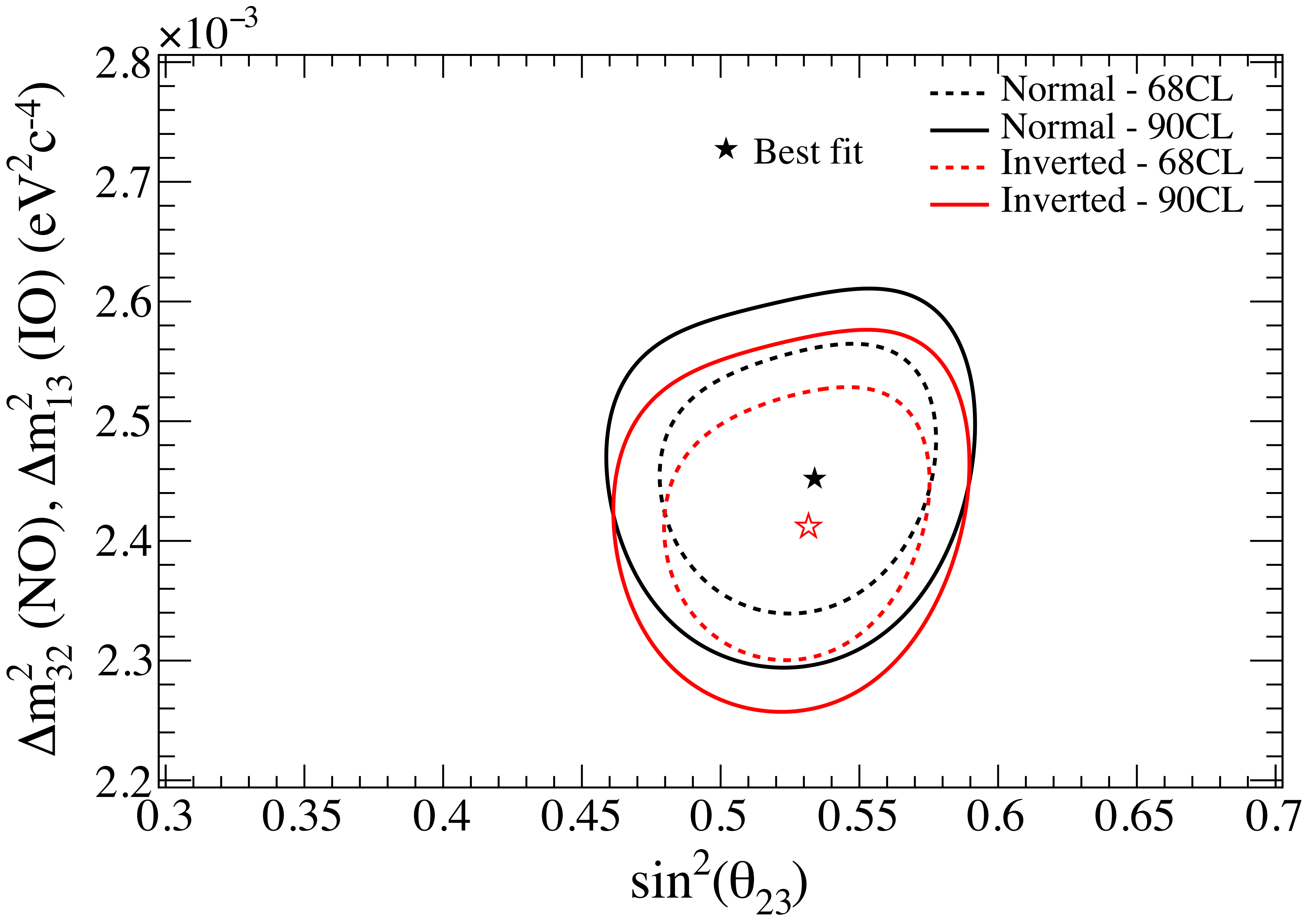
3σ range for δ_{cp}
NH: [–3.41, –0.03]
IH: [–2.54, –0.32]

- CP conserving value δ_{cp} = -π is still included in 3σ interval
- Both CP conserving values (δ_{cp} = 0,-π) are disfavored at 2σ
- Normal mass hierarchy preferred with posterior probability of 0.89

T2K Results - Atmospheric Parameters

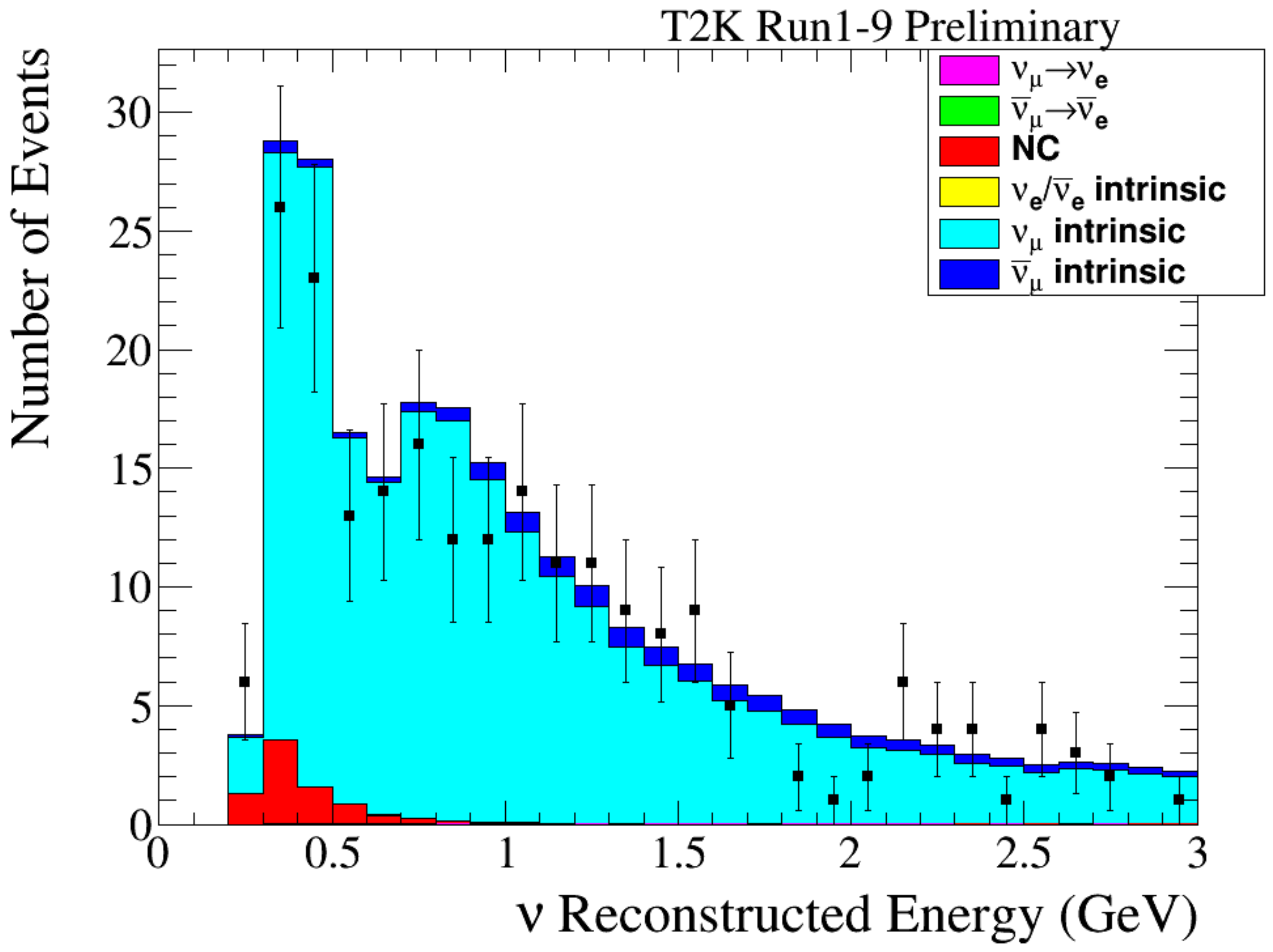


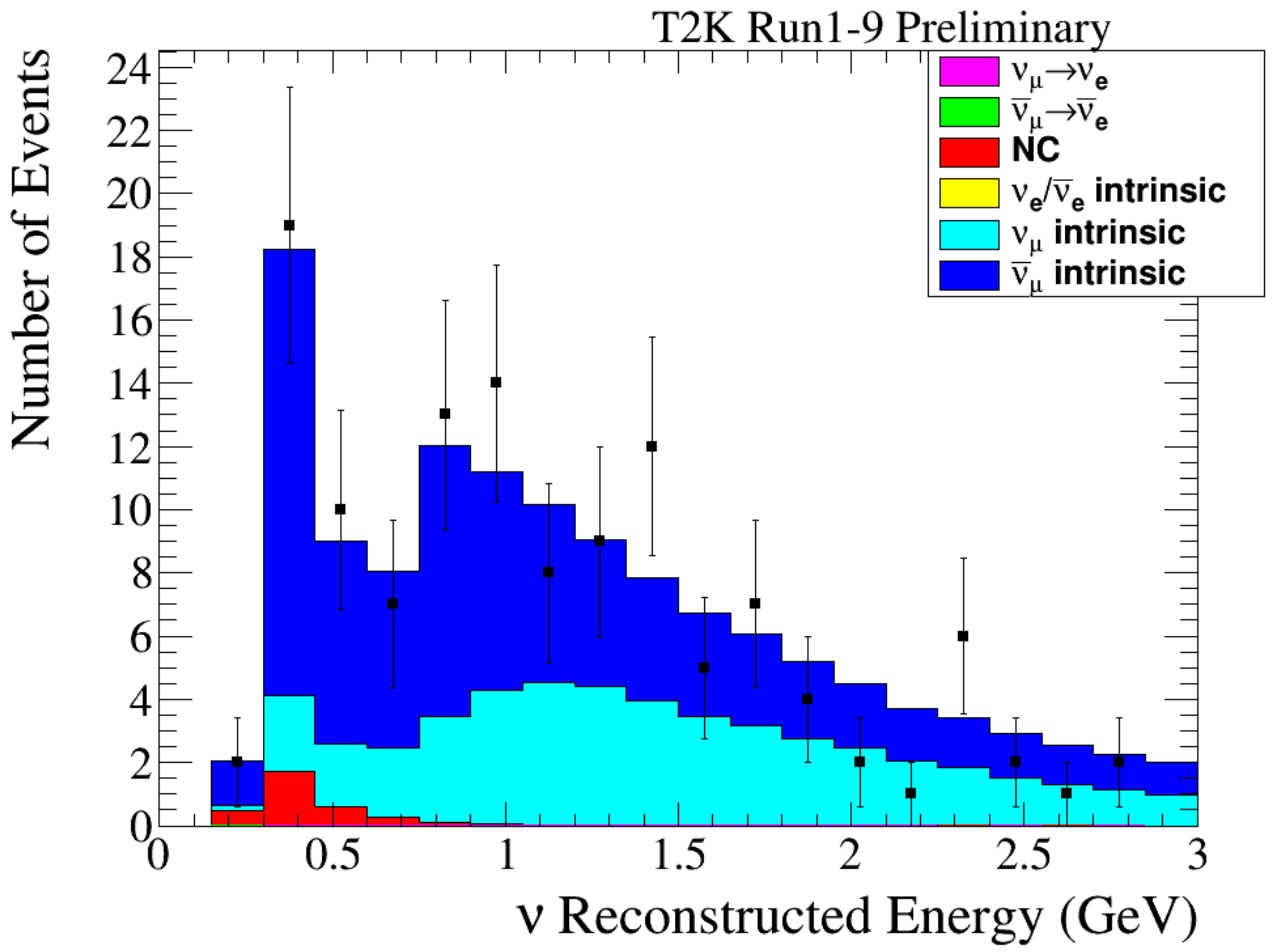




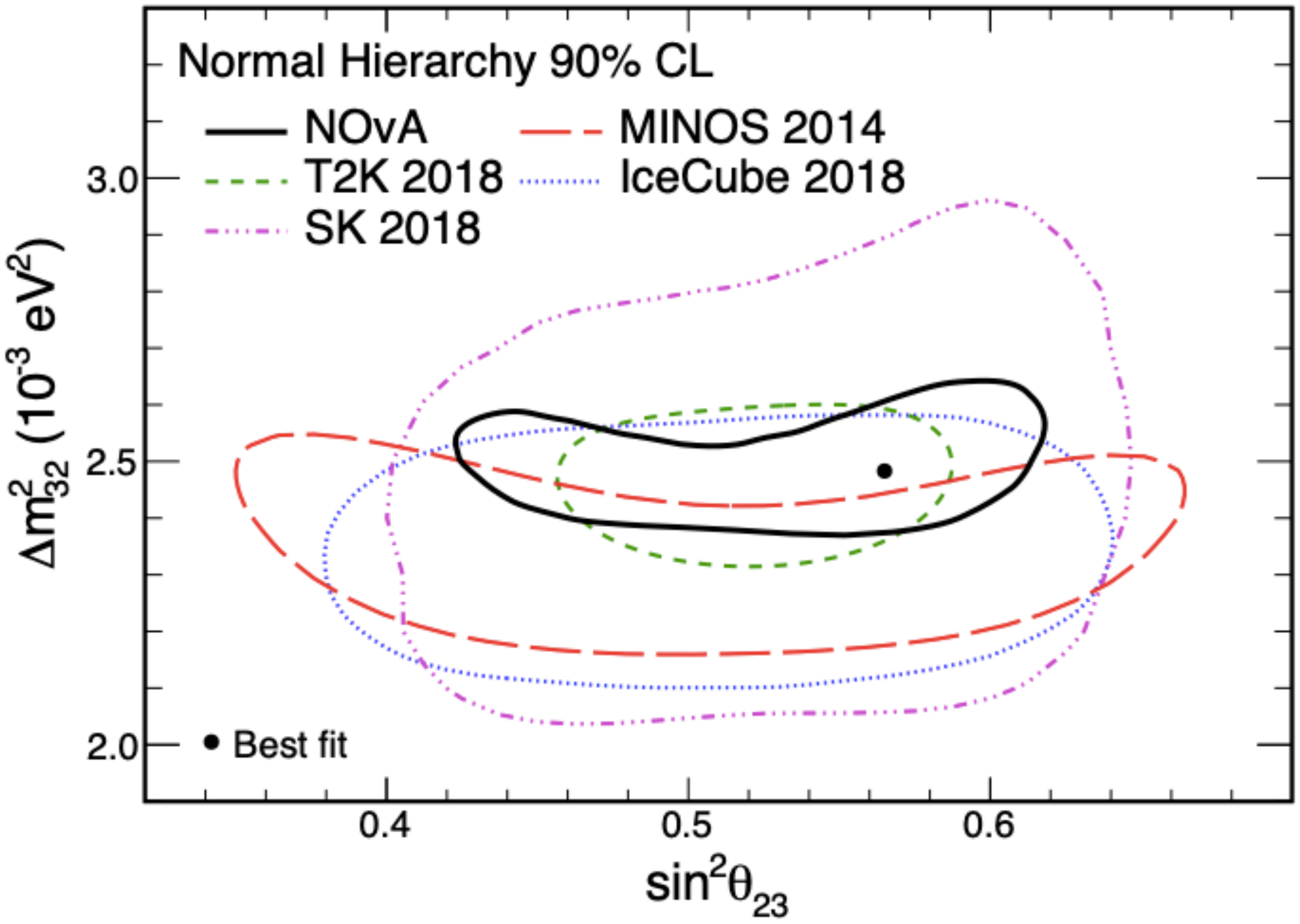
- T2K measures $\sin^2\theta_{23}=0.53+0.03-0.04$
- Remains consistent with 45° at the 1 sigma level

T2K Results - Atmospheric Parameters





NOvA: Phys. Rev. Lett. 123 (2019) no.15, 151803



Hyper-K In Canada

- Hyper-K Canada group formed in 2018
  - Supported by NSERC project grant
- Currently 11 faculty from 8 institutes - looking to grow
- Hyper-K is now an IPP project

Hyper-K In Canada



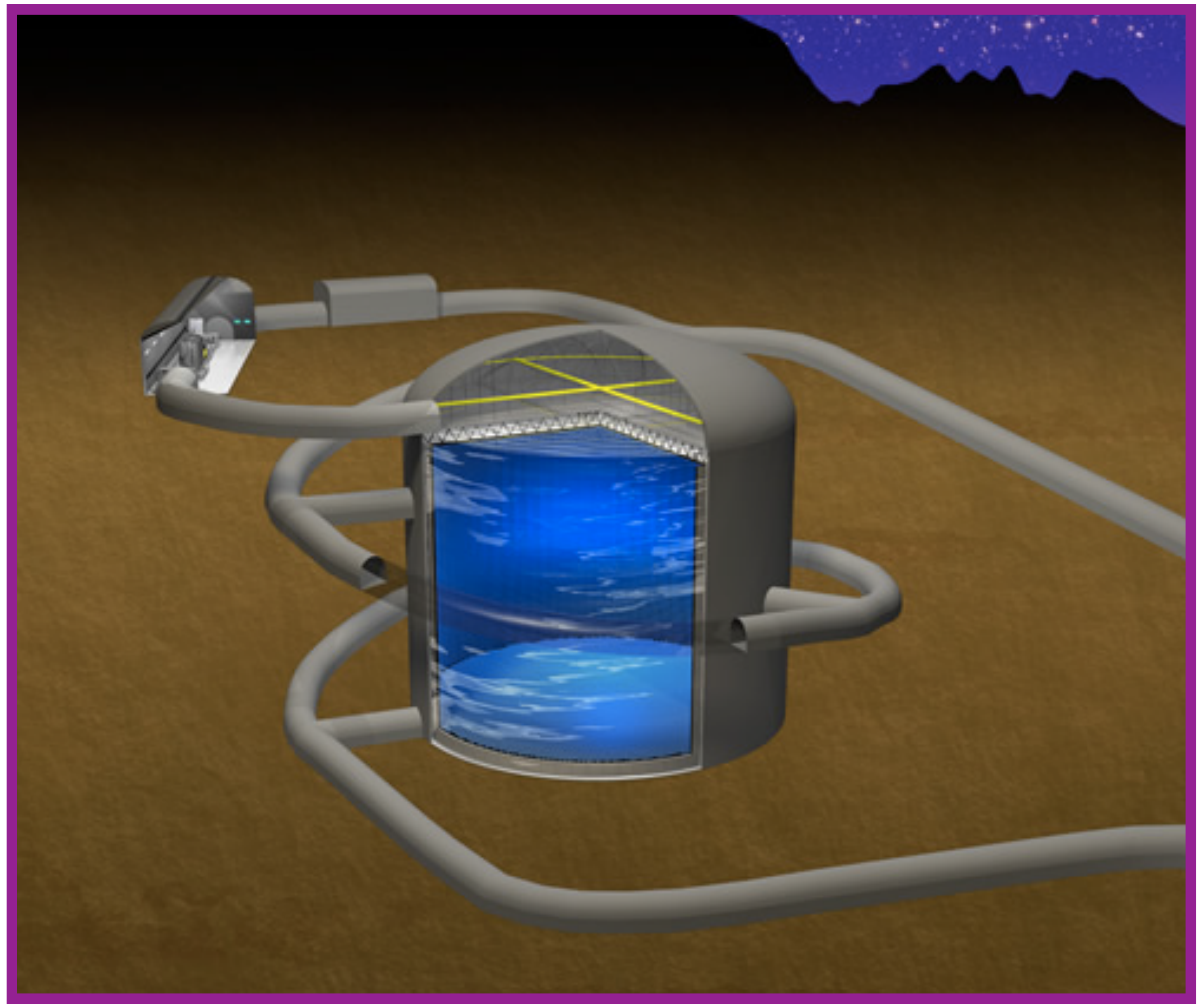
Hyper-K Canada Collaboration

TRIUMF · University of Toronto · University of Victoria · York Université University · The University of Winnipeg · BCIT British Columbia Institute of Technology · Carleton University · University of Regina

- Hyper-K Canada group formed in 2018
  - Supported by NSERC project grant
- Currently 11 faculty from 8 institutes - looking to grow
- Hyper-K is now an IPP project

Hyper-Kamiokande

- Fiducial mass is **8x larger than Super-Kamiokande**
- Neutrino beam from J-PARC will be **2.5 times more intense** (1.3 MW proton beam)
- New **photon detectors and near detectors**
- **20x the rate** of long baseline neutrinos than the T2K experiment
- Not just accelerator-based neutrino experiment:
  - Proton decay searches
  - Supernova neutrino detection
  - Atmospheric neutrino detection
  - Solar neutrino detection
  - Dark matter search
  - …



Hyper-K approved in January 2020
Construction phase has started!
Start of operation planned in 2027

Hyper-K Design Report: arXiv:1805.04163

Hyper-K Construction

Hyper-Kamiokande

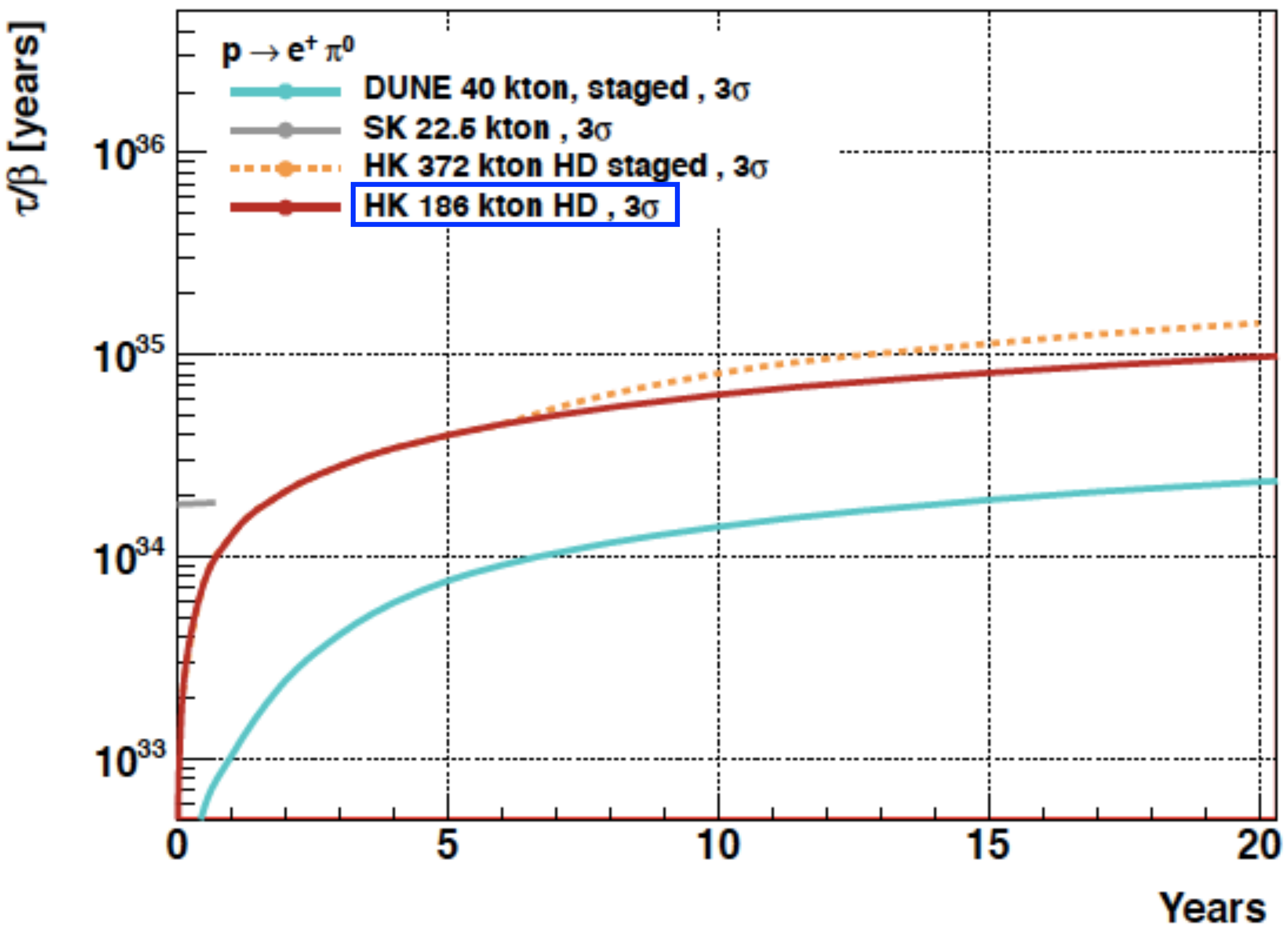
Construction of the entrance yard is proceeding!

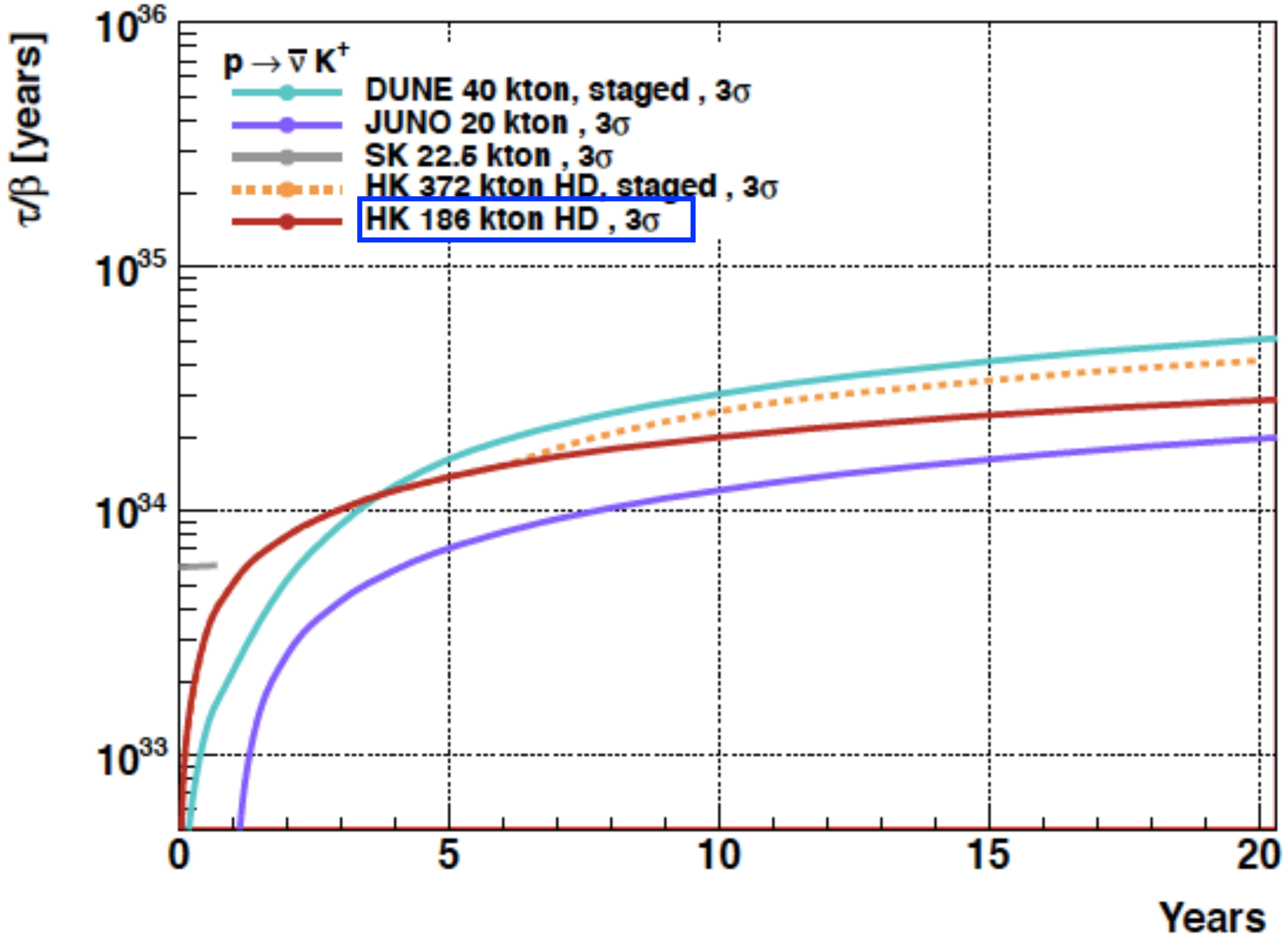
Access tunnel construction to start in FY2021

Access tunnel entrance

Proton Decay

Discovery Potential

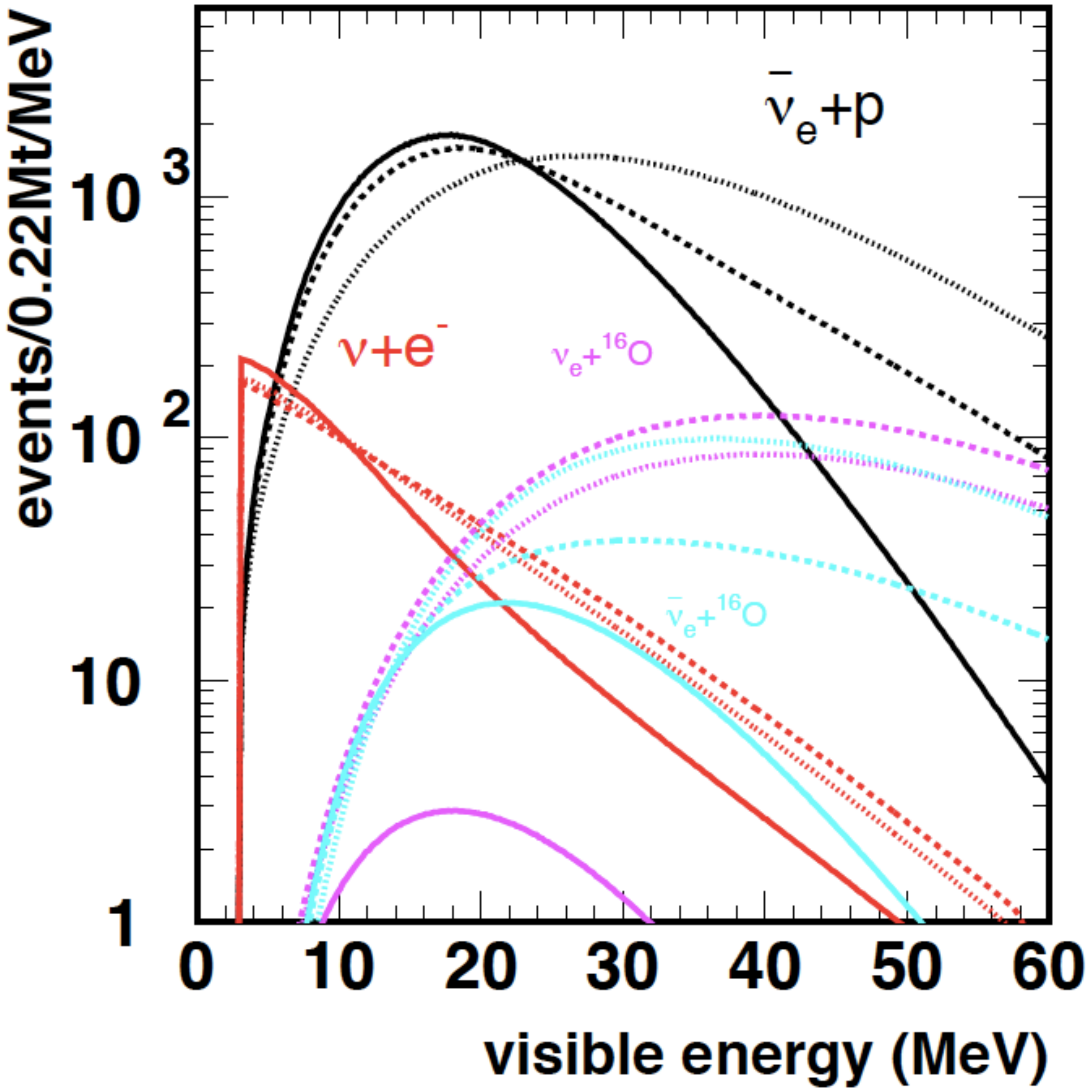


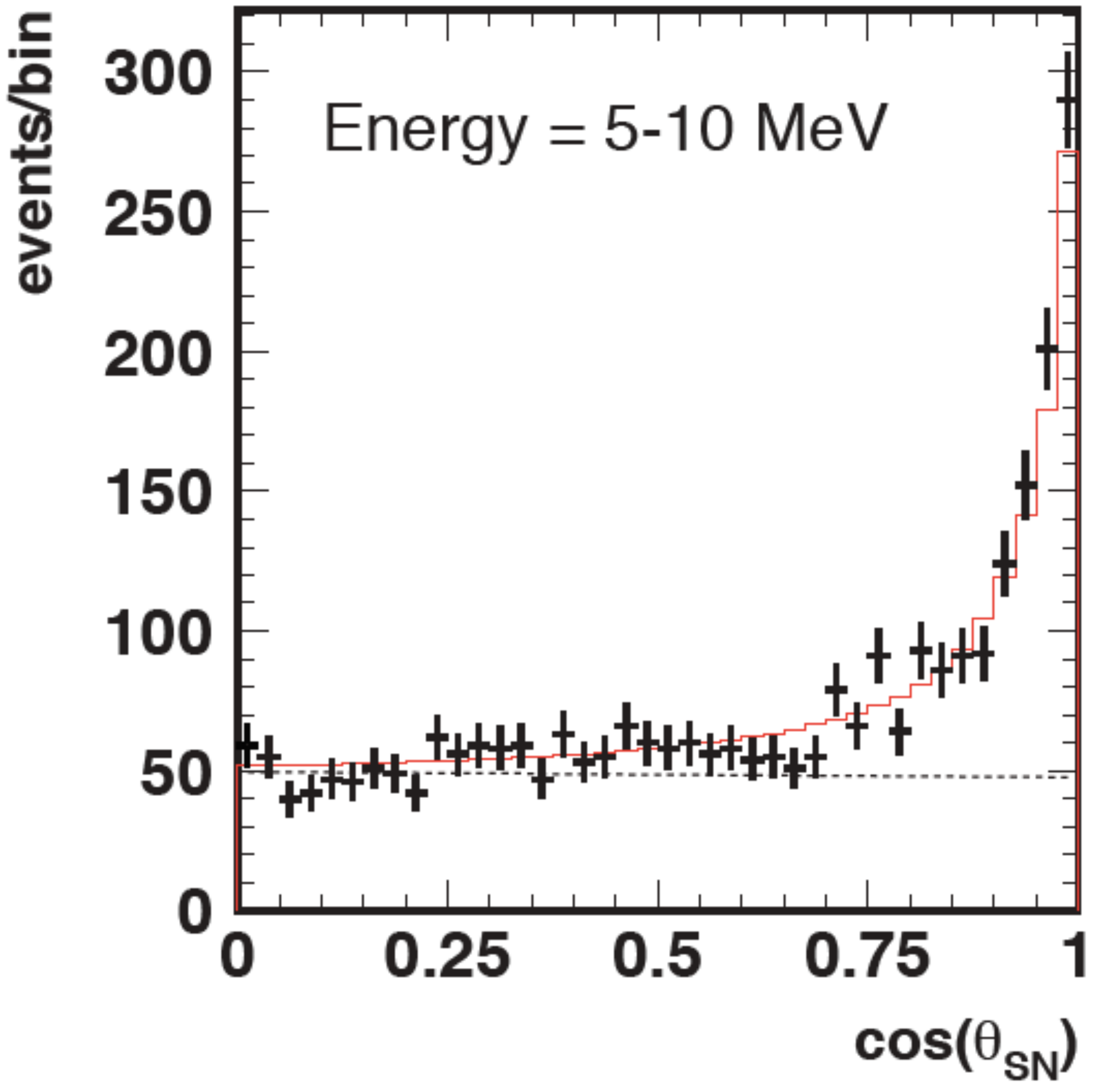


- Hyper-K excels in the $p \rightarrow e^+\pi^0$ channel, very high efficiency
- Largest fiducial mass

- Hyper-K is competitive $p \rightarrow \nu K^+$ channel, very high efficiency
- DUNE has potential for better efficiency since kaon is visible

Supernova Burst Neutrino



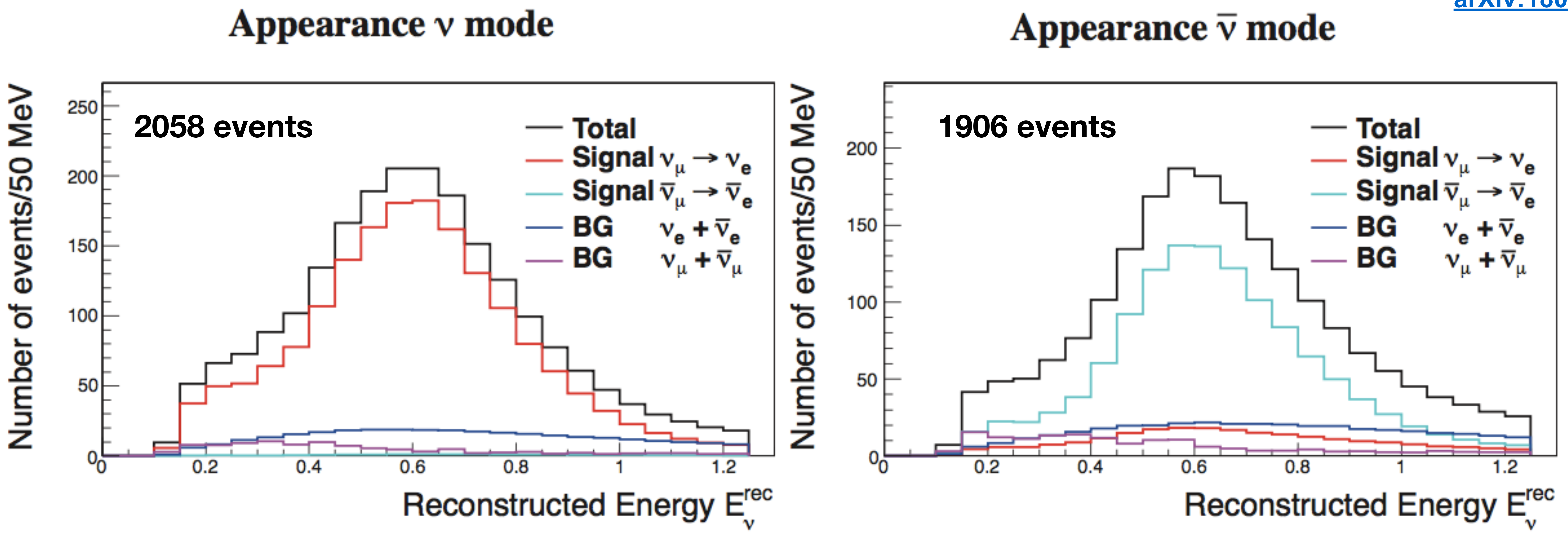


- Inverse beta decay and neutrino-electron scattering channels
- 54k-90k events for 10 kpc distant supernova
- ~10 neutrino events for supernova in Andromeda

- Neutrino-electron scattering introduces pointing capability
- 1.0-1.3 degree accuracy for 10 kpc distant supernova

CP Violation at Hyper-K

arXiv:1805.04163

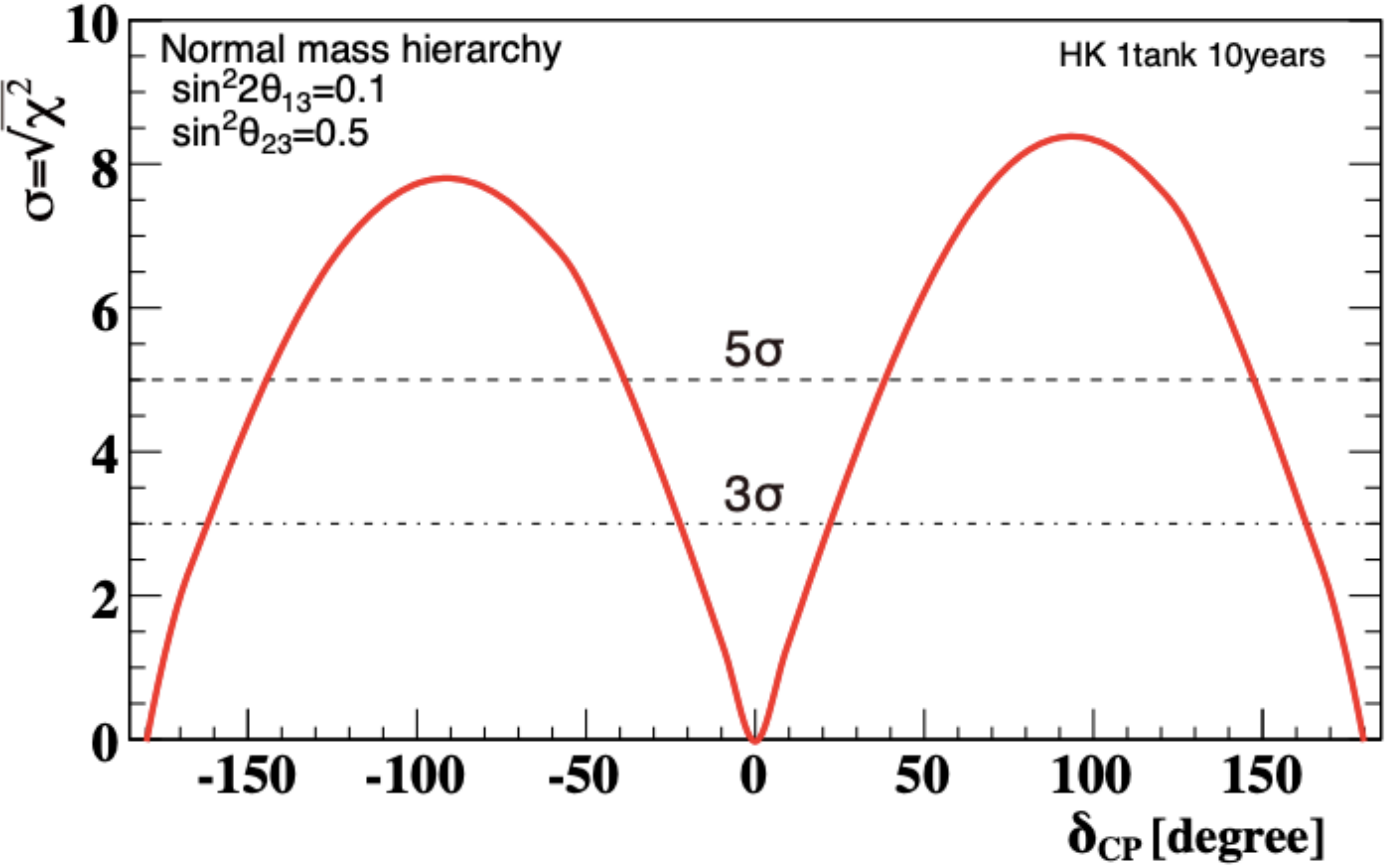


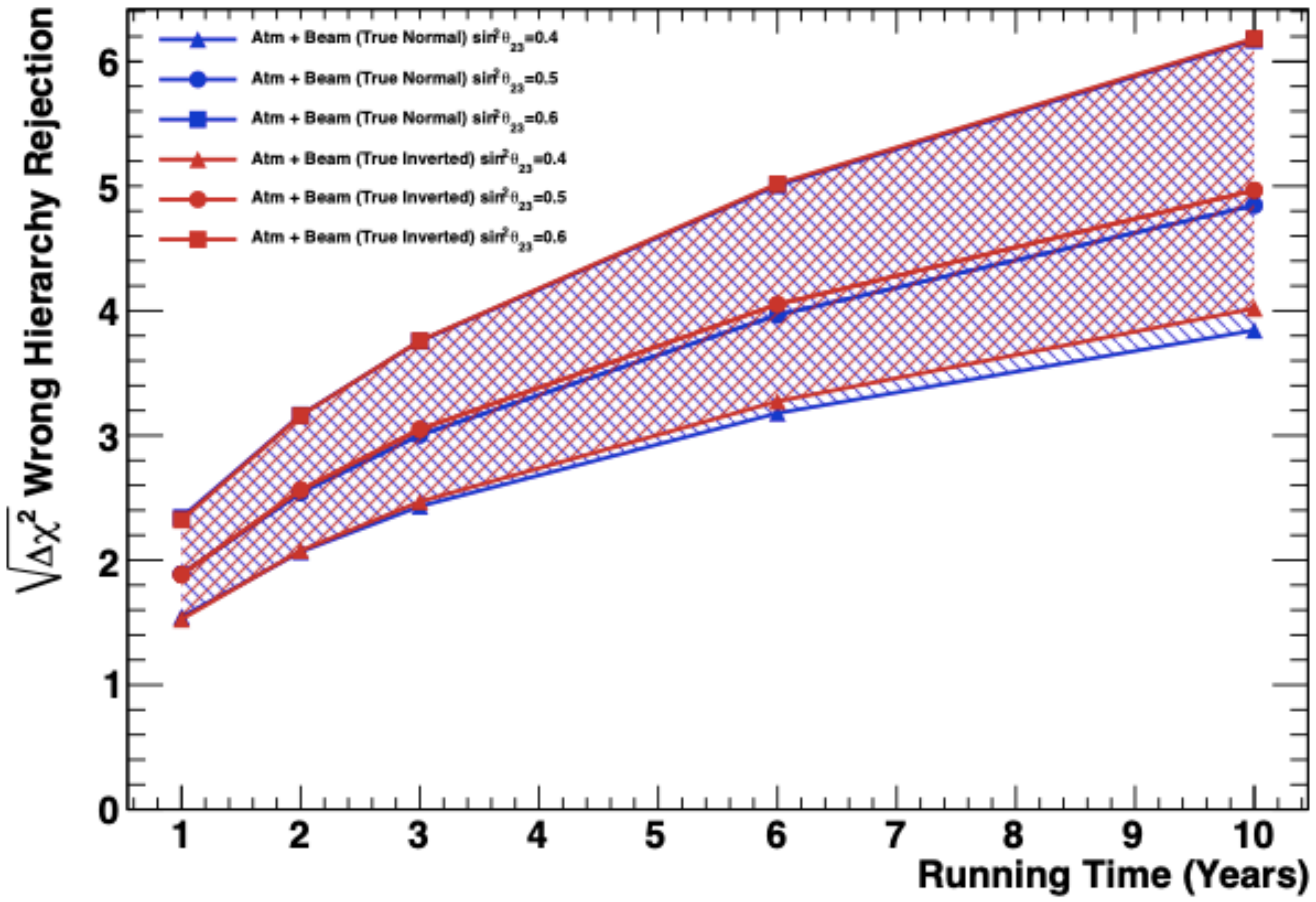
- Recall that T2K and NOvA are observing 10’s of candidate events
- Hyper-K will observe ~2000 electron neutrino and electron antineutrino candidates each
  - 3% statistical error on the CP violation measurement is achieved
  - Controlling systematic errors is critical: T2K’s current errors are ~6%

Oscillation Measurements

arXiv:1805.04163

Known Mass Hierarchy



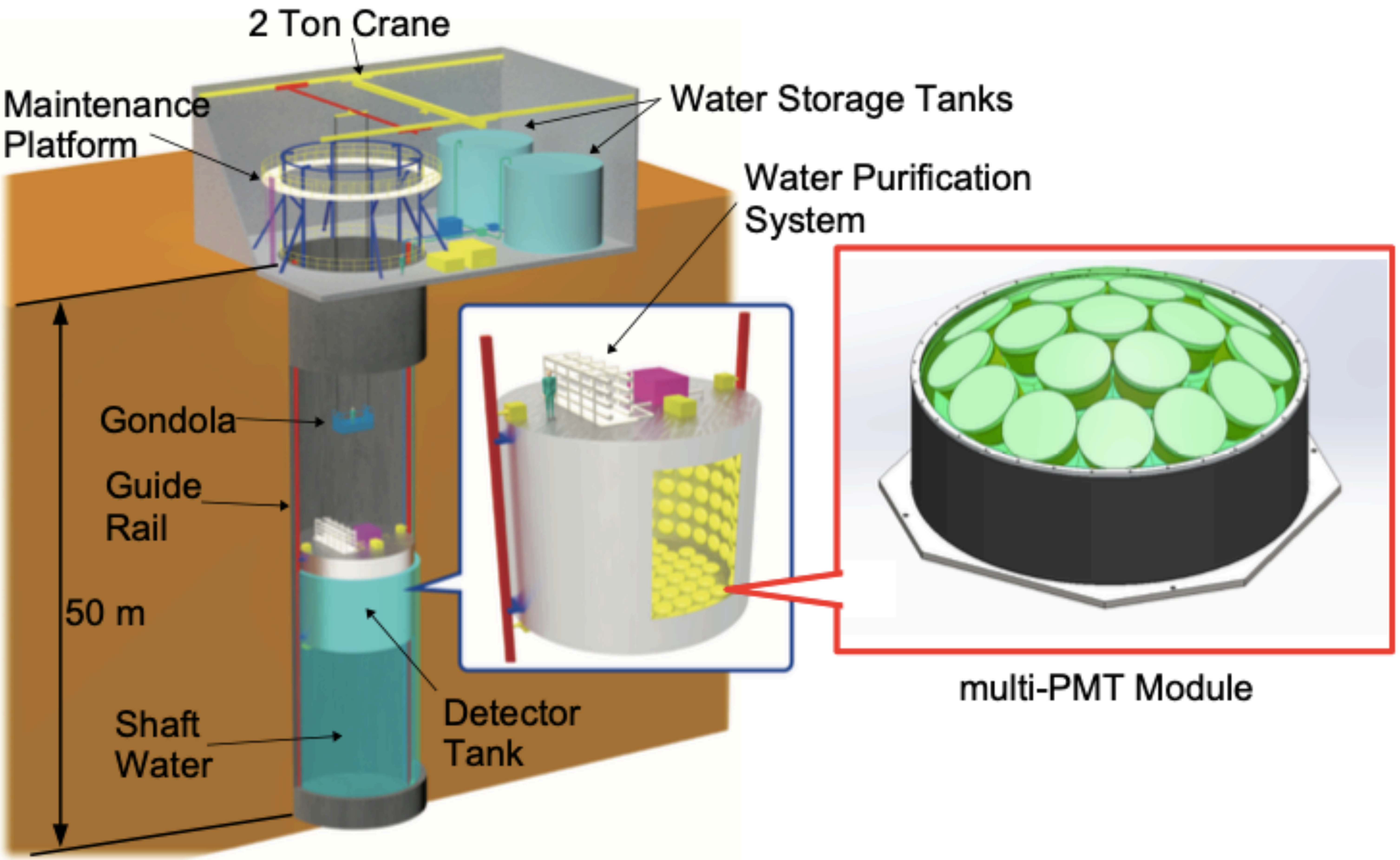


- CP violation discovery for:
  - 76% of values at 3σ
  - 57% of values at 5σ

- With atmospheric neutrino data, achieve >4σ rejection of the wrong mass hierarchy

Systematic Error Reduction with IWCD

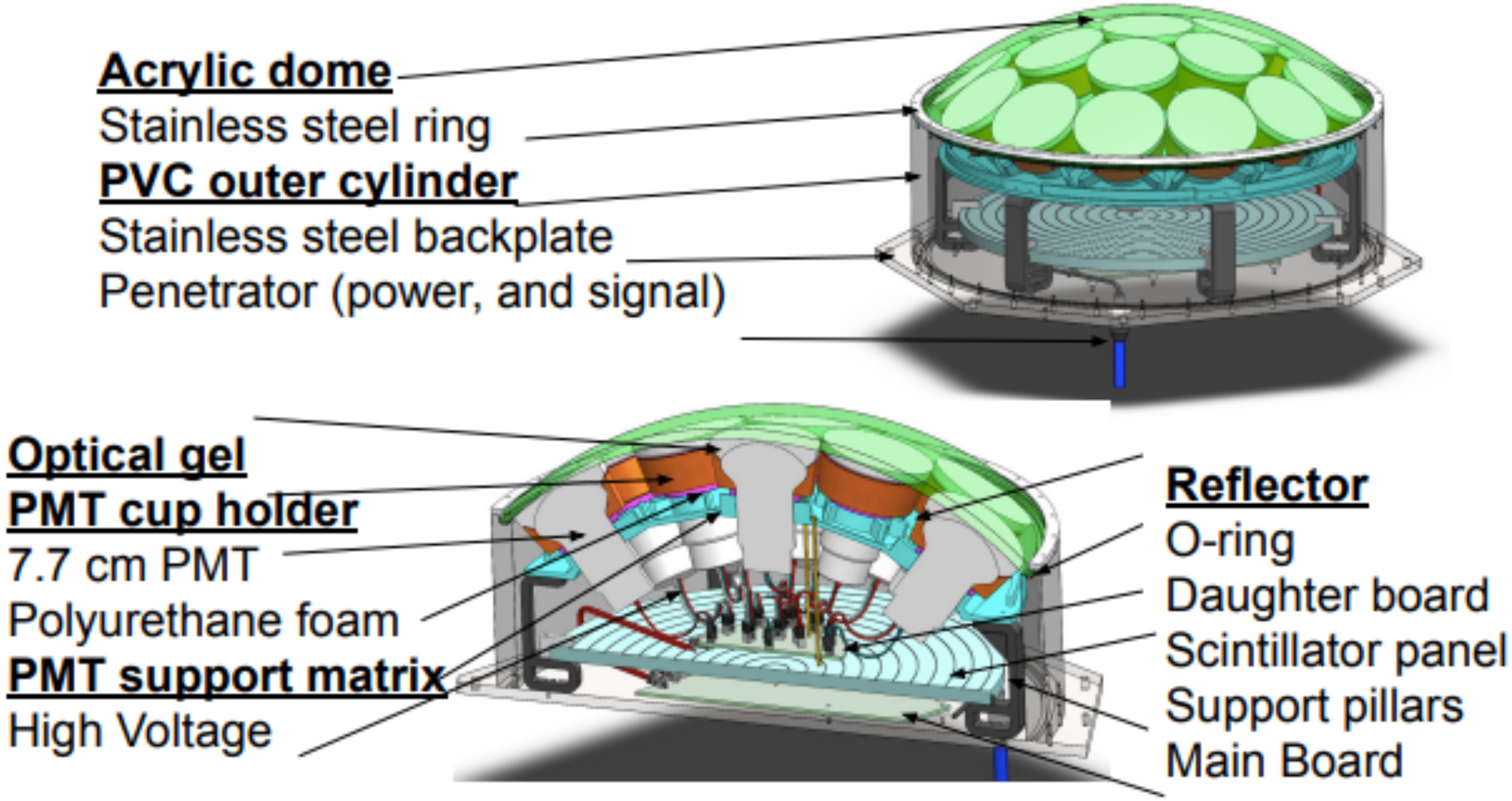
- Intermediate detector for Hyper-K
- Located about 1 km from neutrino source
- 600 ton water Cherenkov detector
- Position can be moved to different off-axis angles
- Loading with Gd to enhance neutron detection
- Using new high resolution multi-PMT modules inspired by KM3NeT
- Project led by Canadian institutes

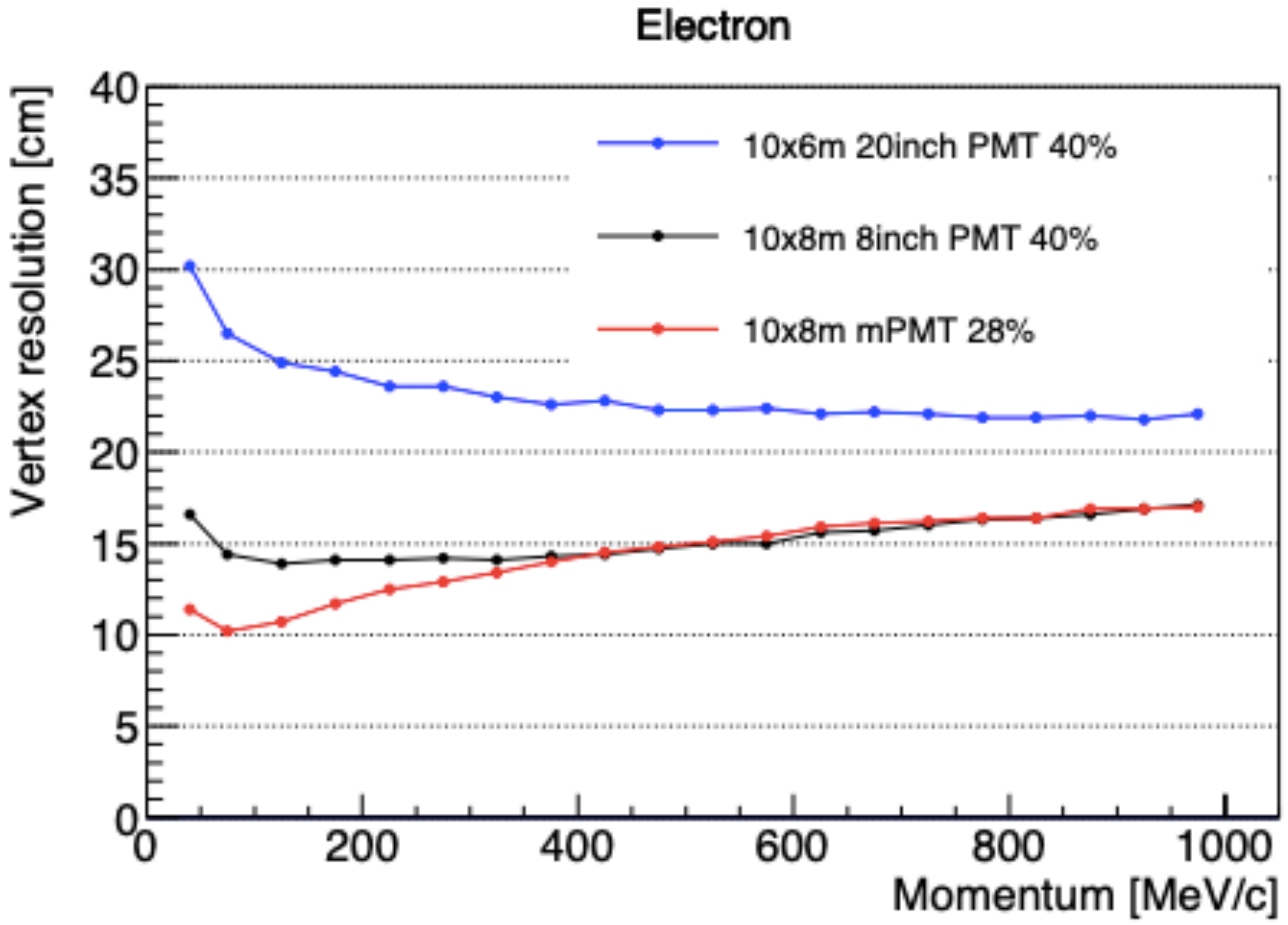


Approved Hyper-K project includes IWCD
Stage-1 approval at J-PARC as E61

https://j-parc.jp/researcher/Hadron/en/pac_1507/pdf/P61_2015-5.pdf

Multi-PMT (mPMT) Photosensor

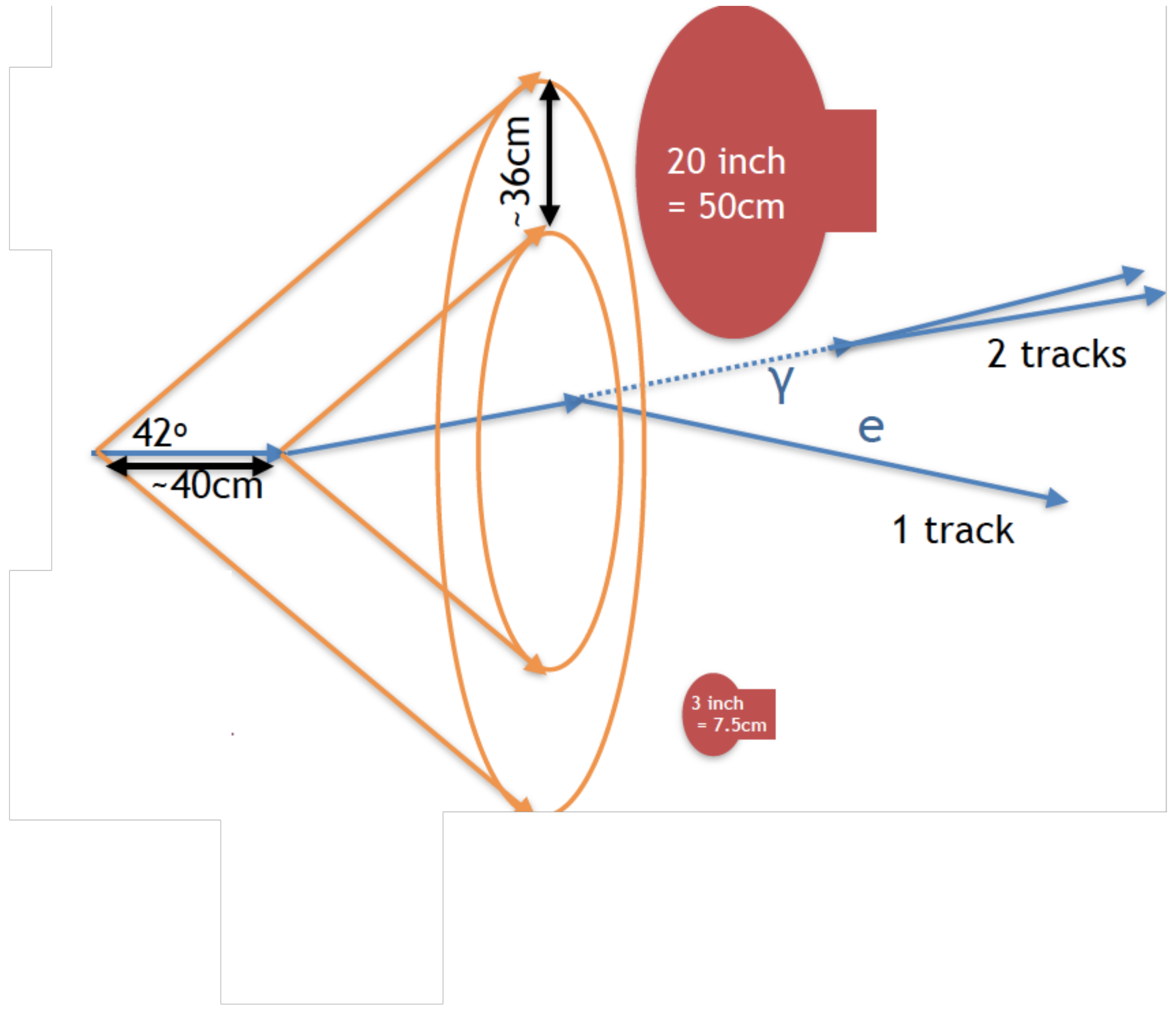


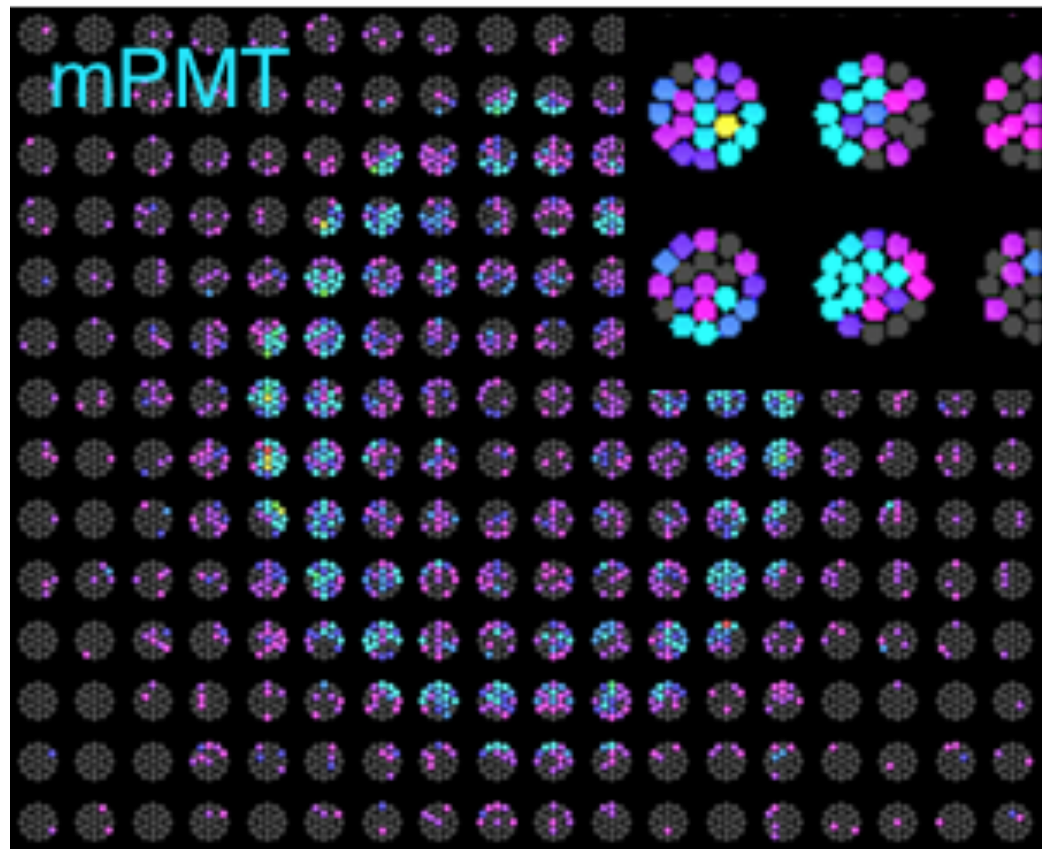


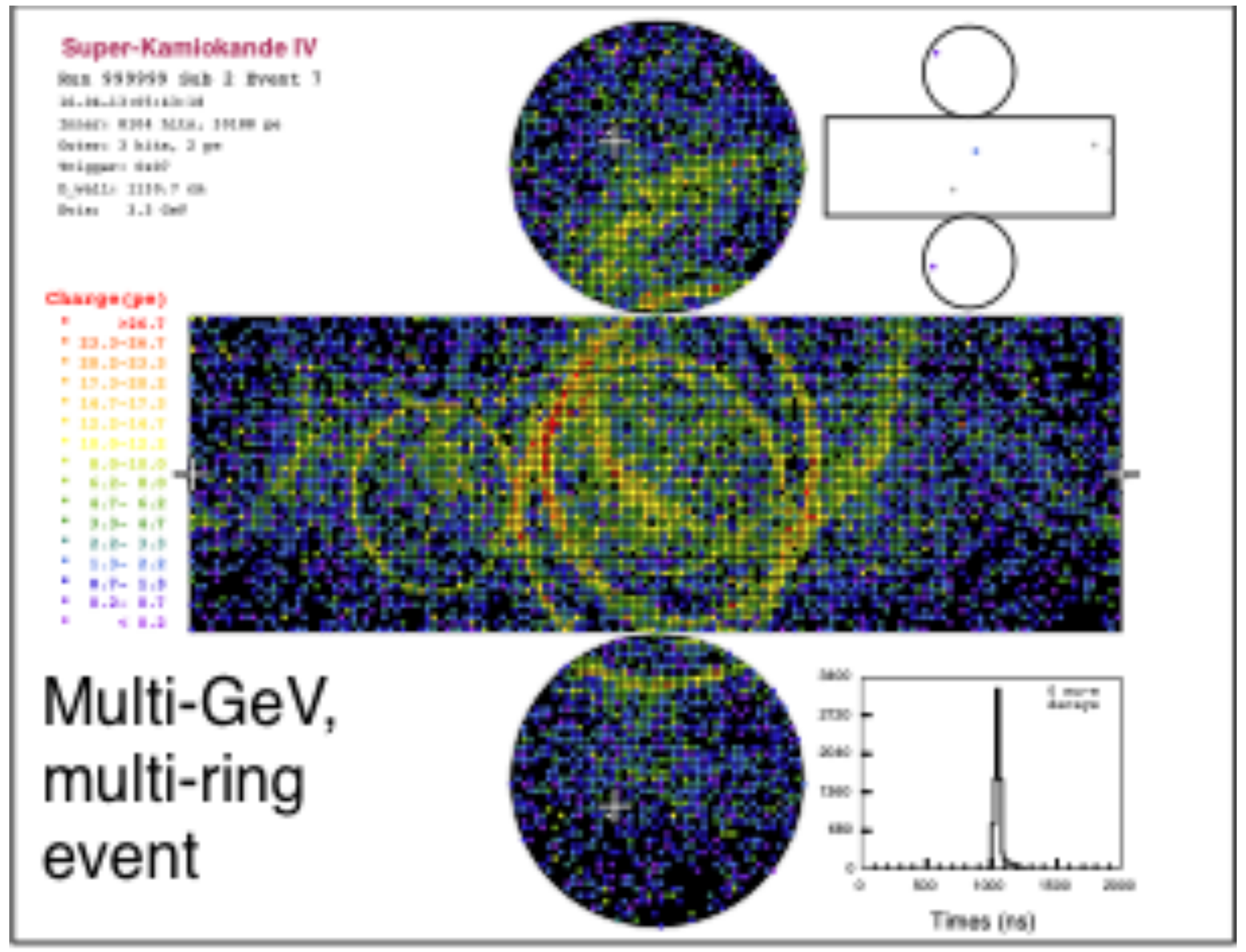
- 19 3-inch diameter PMTs integrated in module with high voltage and readout electronics
- 3-inch PMTs developed with Hamamatsu to achieve 1.7 ns FWHM timing resolution
- Improved spatial and timing resolution compared to 20-inch PMTs is necessary for detector of IWCD size
- Considered as a photodetector for Hyper-K detector as well

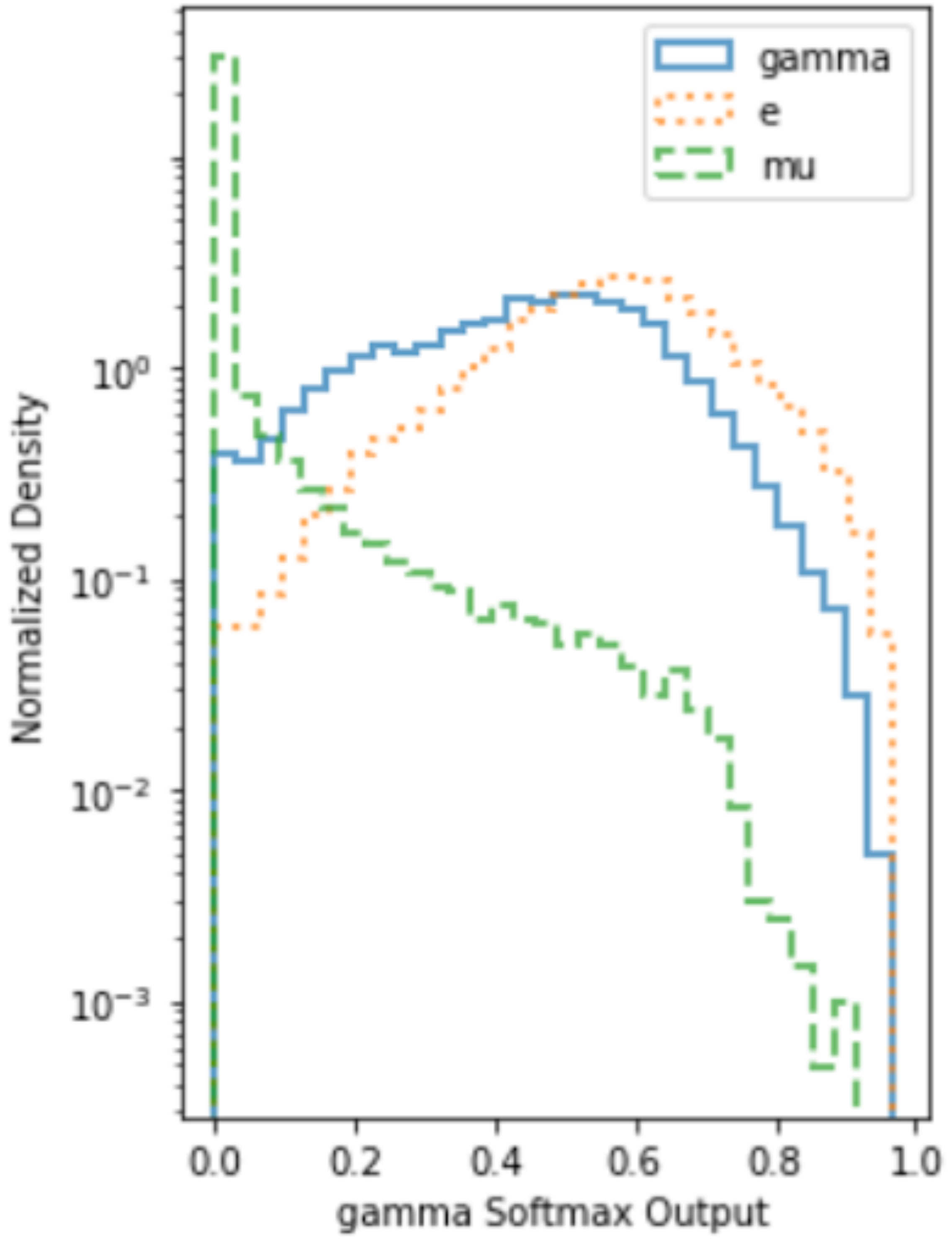
Machine Learning

- Improve reconstruction of indiscernible event topologies:
  - e/γ separation possible with improved granularity of mPMT in IWCD
  - Multi-ring: directionality of high-energy atmospheric ν, nucleon decay
  - Neutron tagging
- First application of ResNet (type of CNN) looks promising
- Investigating several architectures:
  - Graph CNN, PointNet, GAN, UNET



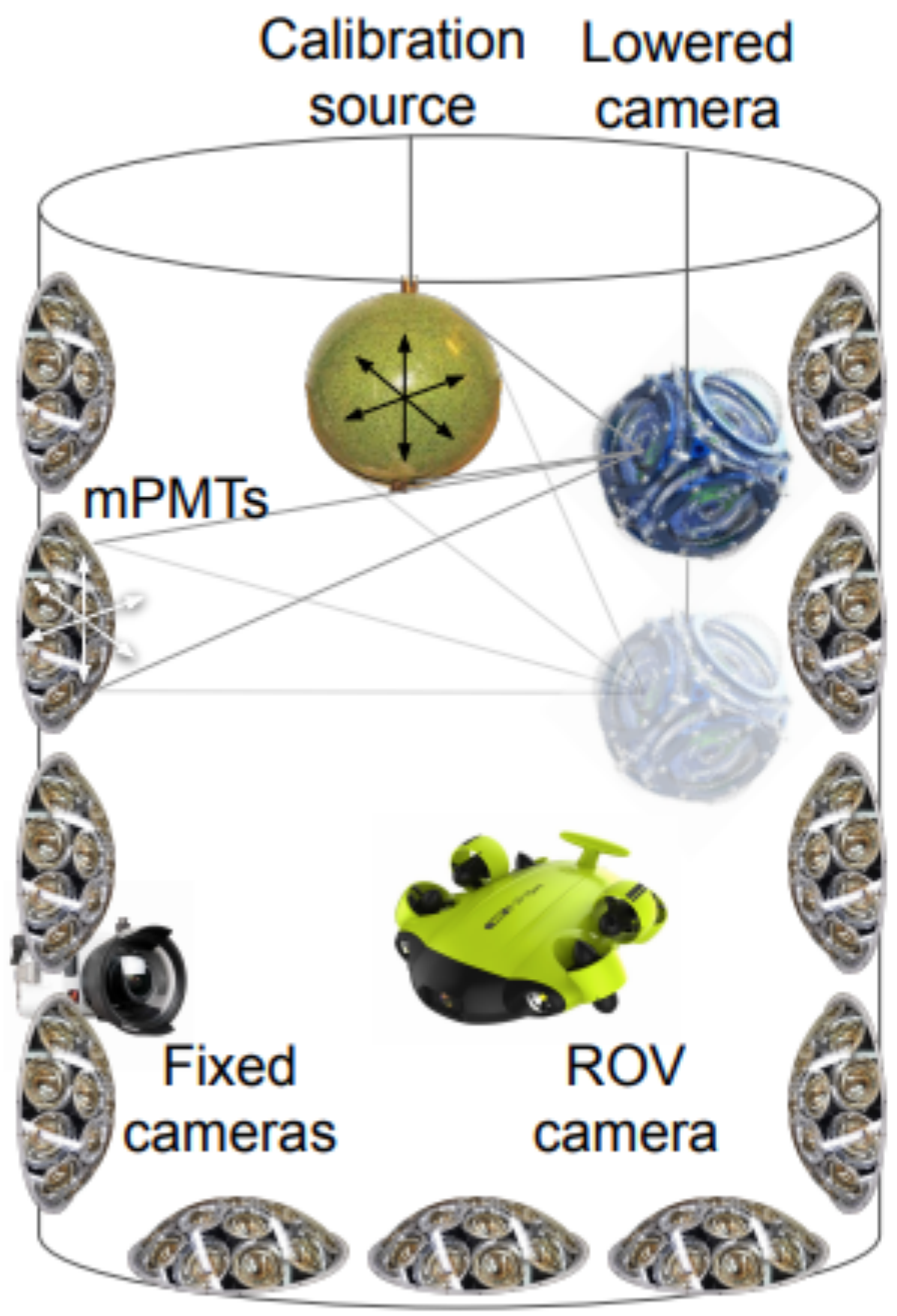


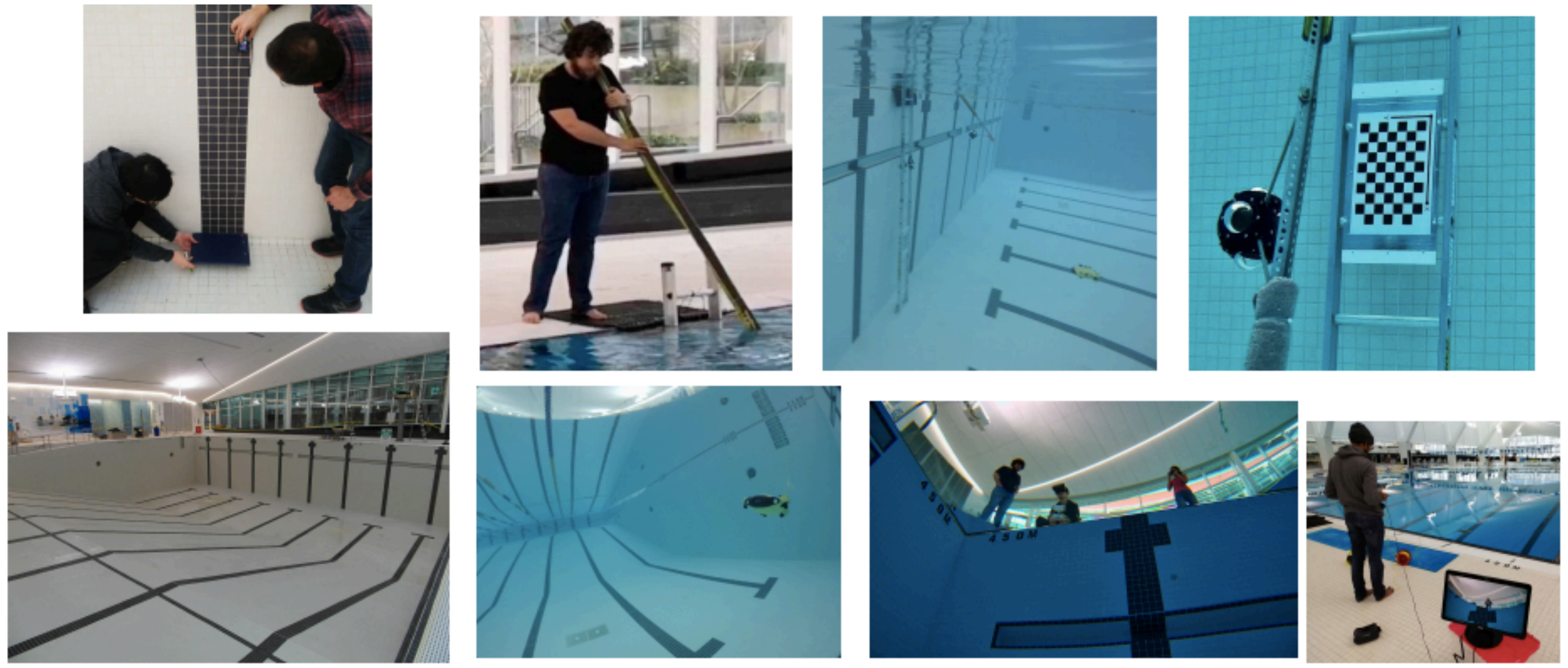




Photogrammetry Calibration

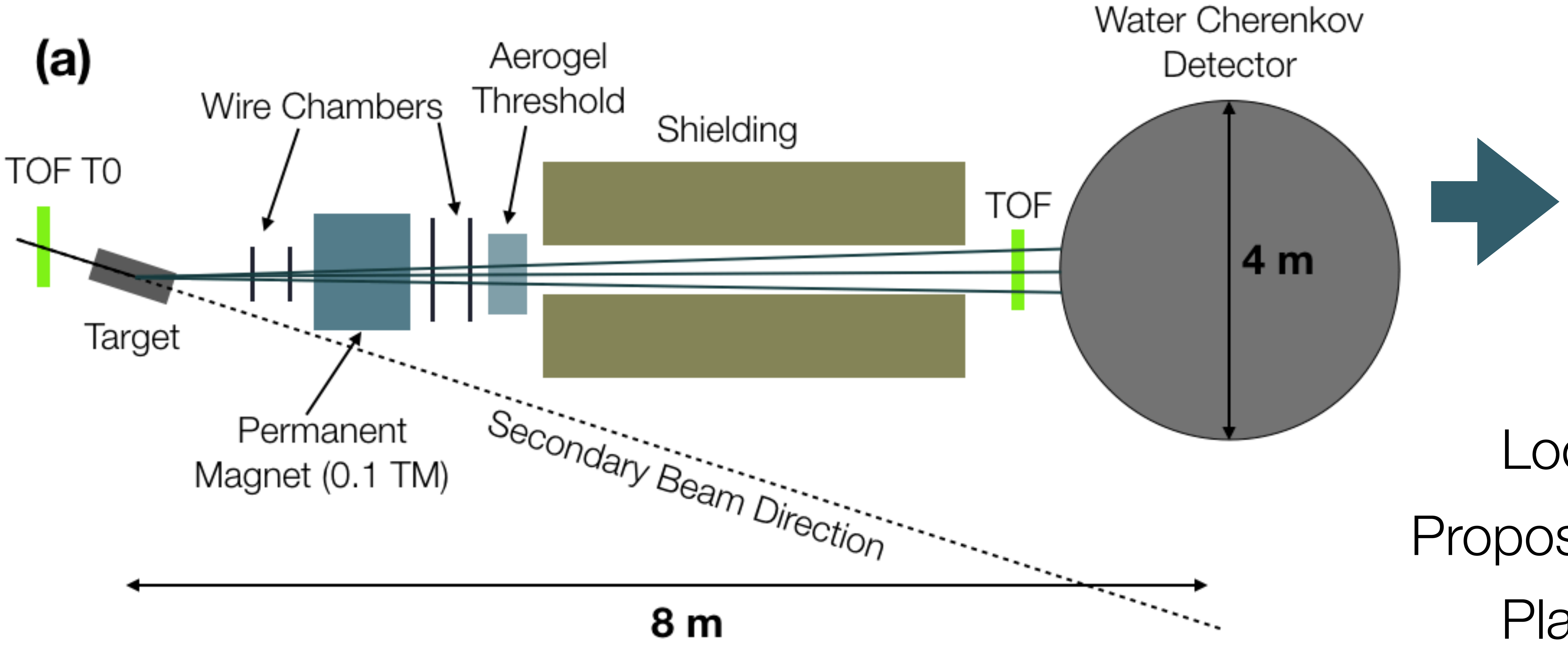
- Fiducial volume of IWCD must be known with a bias of <1 cm
- The position of all mPMTs and calibration sources must be precisely measured
- Positions can change after water filling, so need in-situ measurement
- Photogrammetry:
  - Fixed cameras and remote operated submersible take pictures of the tank interior
  - Software able to build an accurate 3-D model of the detector

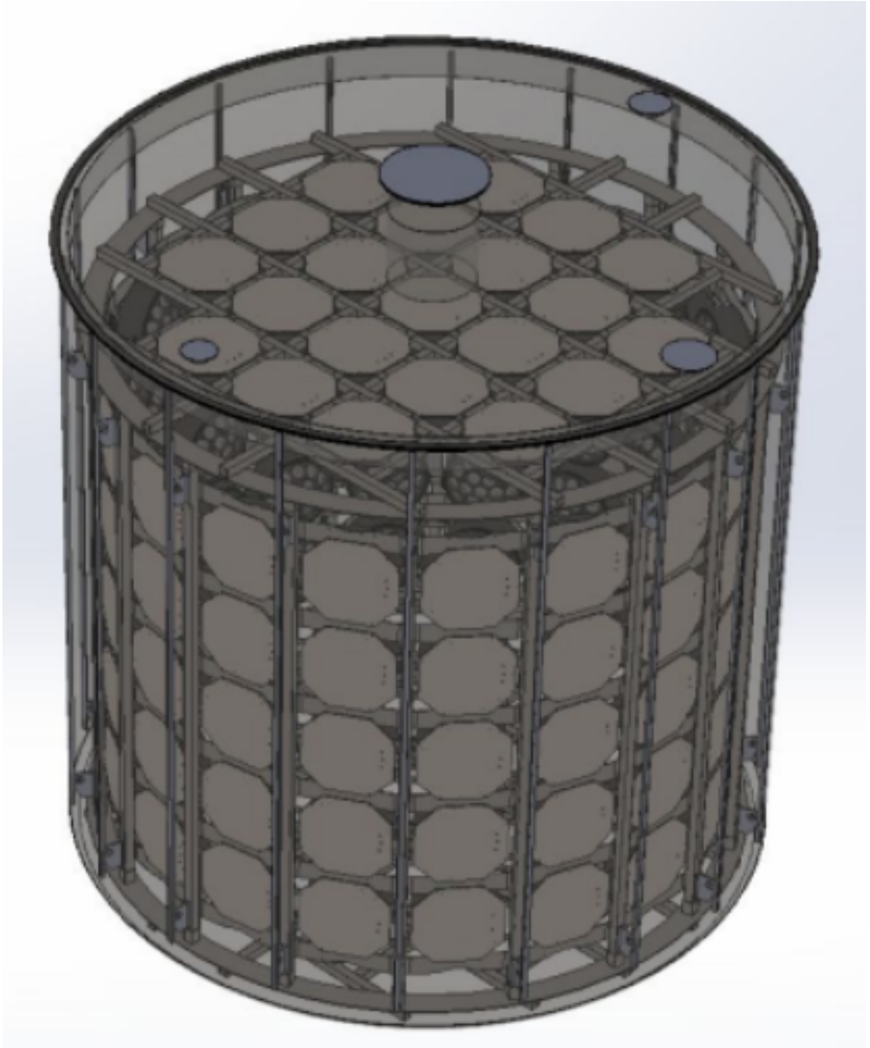




Water Cherenkov Test Experiment

- Aim for unprecedented precision to reconstruct high energy events in a water Cherenkov detector of IWCD size
- Need platform to test the hardware and validate the calibration, modeling and reconstruction techniques
- Operate detector with 4 m diameter in test beam line with incident particle fluxes of known type and moment





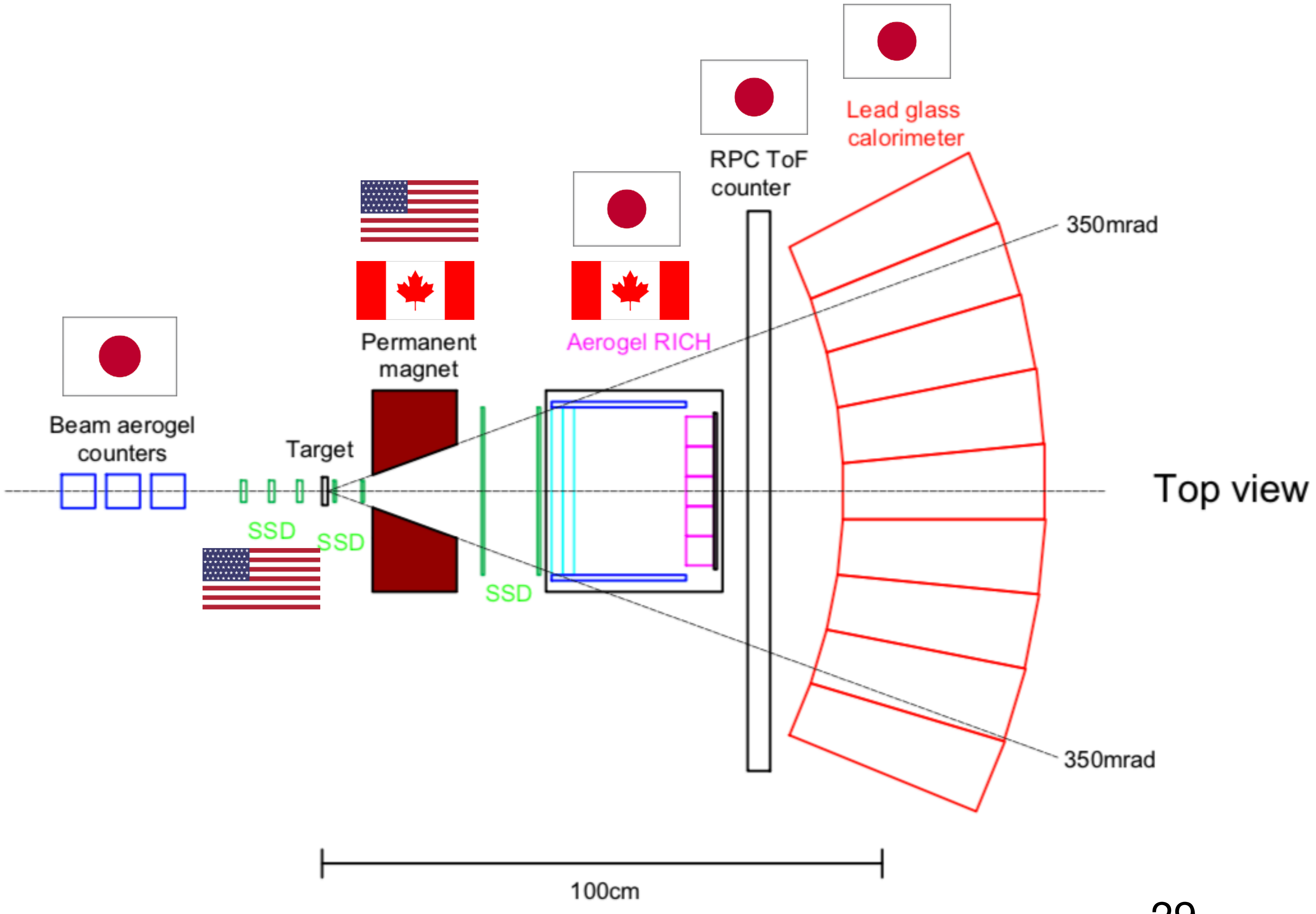
Location: CERN East Area

Proposal: CERN-SPSC-2020-005

Planned operation in 2022

EMPHATIC Experiment

- Table top hadron production experiment - improve neutrino flux simulation
- Unique application of technologies to hadron production measurements
    - Silicon strip tracking layers
    - Halbach array permanent magnet
    - Aerogel ring imaging Cherenkov detector for PID
- Operating in Fermilab MTEST beam line
    - 2018 - Pilot Run
    - 2020 - First Physics run with 100 mrad acceptance
    - 2021 - Second physics run with 400 mrad acceptance



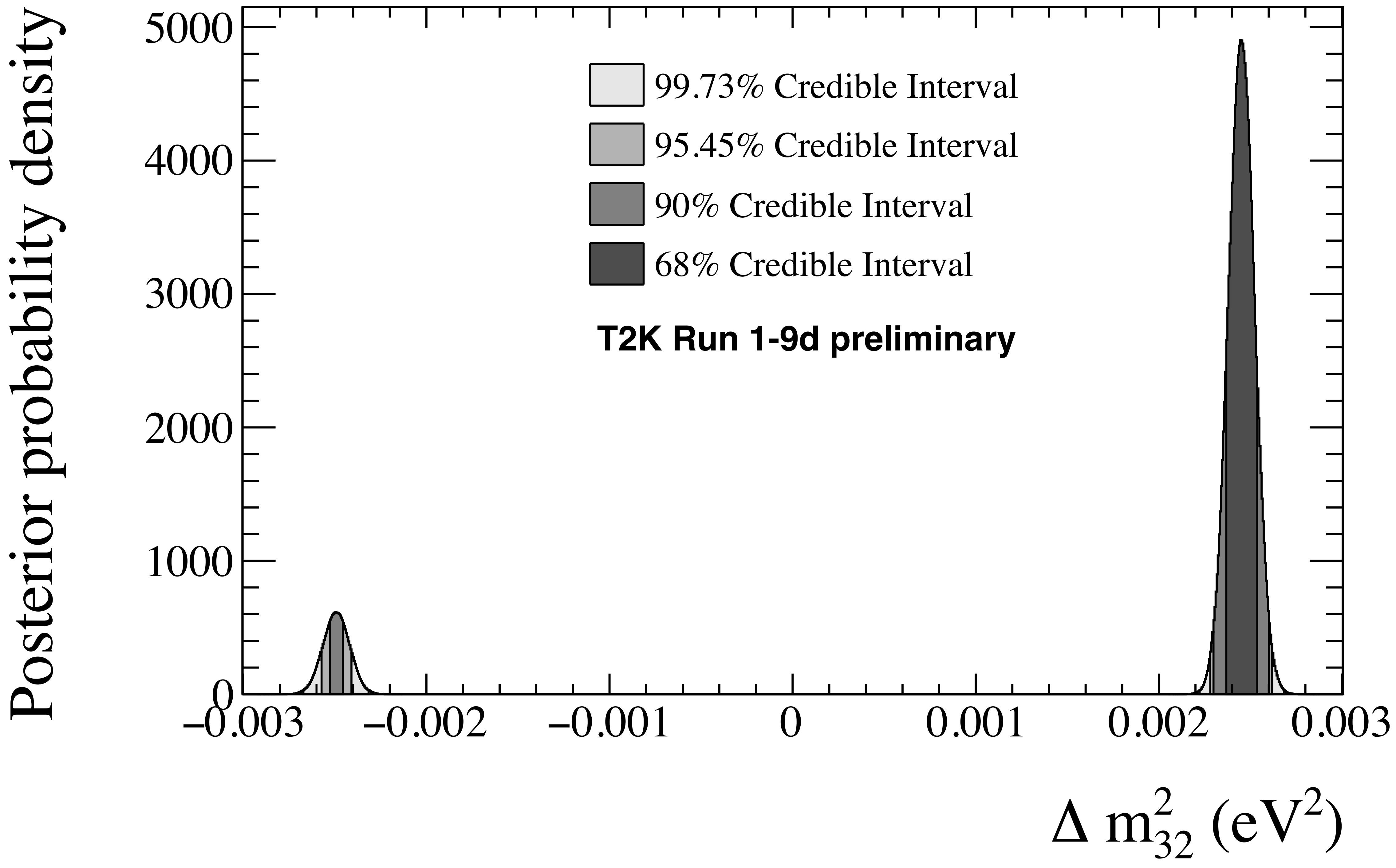
Conclusions

- T2K is providing world leading measurements of neutrino oscillations parameters
- Next phase: move to precisions measurements at Hyper-Kamiokande
  - Program includes neutrino oscillations, proton decay, supernova neutrinos, dark matter and more
  - Construction has started and planned start of operation in 2027
- Many Canadian efforts for Hyper-K focussed on control of systematic errors for precision measurements
  - Still room for new collaborators. Come join us!

Thank You

Mass Ordering Preference

- One of our analyses uses Markov Chain Monte Carlo to fit oscillation parameters
- Perform Bayesian statistical inference
  - Posterior probabilities and credible intervals
- Start with equal prior probability of normal and inverted hierarchy
- **Normal hierarchy is preferred with posterior probability of 0.89**



	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.184	0.705	0.889
IH ($\Delta m^2_{32} < 0$)	0.021	0.090	0.111
Sum	0.205	0.795	1

T2K Systematic Errors

Systematic Error Source	Uncertainty on $\nu_e/\bar{\nu}_e$ Candidates (%)
Super-K Detector Model	1.47
Pion Reinteractions	1.58
Near Detector Constrained Parameters	2.31
Nuclear Binding Energy	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	3.03
NC1γ Production	1.49
Other NC Interactions	0.18
Total	5.87

- Uncertainty on the relative rate of electron neutrino and electron antineutrino interactions
  - This is a purely theoretical estimate, no measurement
- Uncertainty on how nuclear effects impact inference of the neutrino energy