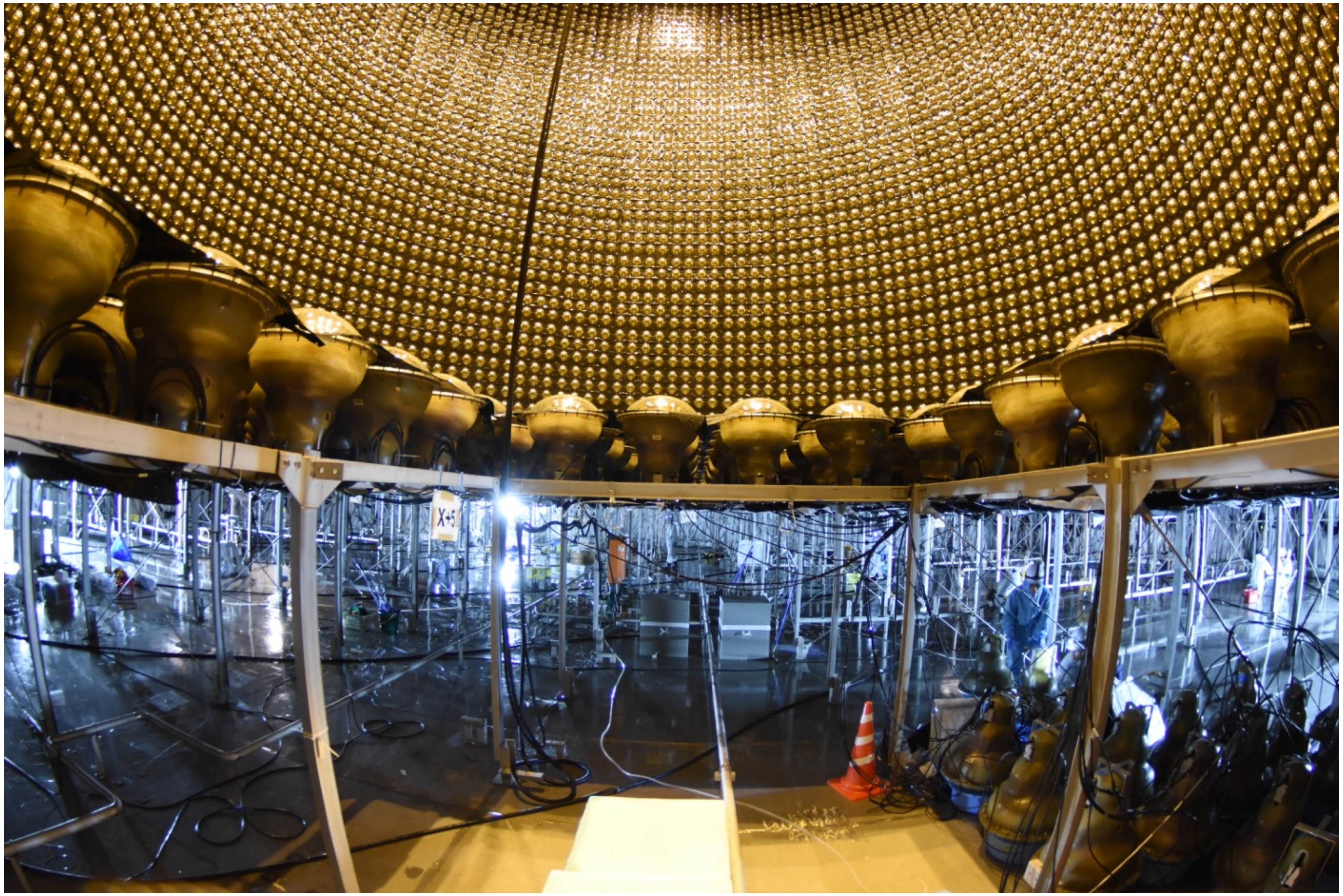
Recent results from long-baseline neutrino oscillation experiments



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Oct. 22, 2018

DBD18

Contents

- Introduction:
  - Neutrino mixing
  - Two leading accelerator-based long-baseline experiments: T2K and NOvA
- Recent oscillation results from T2K and NOvA
- (Near) future prospects
- Summary

Neutrino Mixing

- Neutrino flavor (weak) eigenstates and mass eigenstates are mixed

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

Weak eigenstate (α = e, μ, τ) — $|\nu_\alpha\rangle$

Mass eigenstate (i = 1, 2, 3) — $|\nu_i\rangle$

MNS mixing matrix — $U_{\alpha i}$

- Neutrinos change their flavor as they travel (neutrino oscillation)
- Natural interferometer to explore fundamental nature of neutrinos

Two neutrino case: $P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$

Amplitude ($\sin^2 2\theta$)

Frequency (Δm^2)

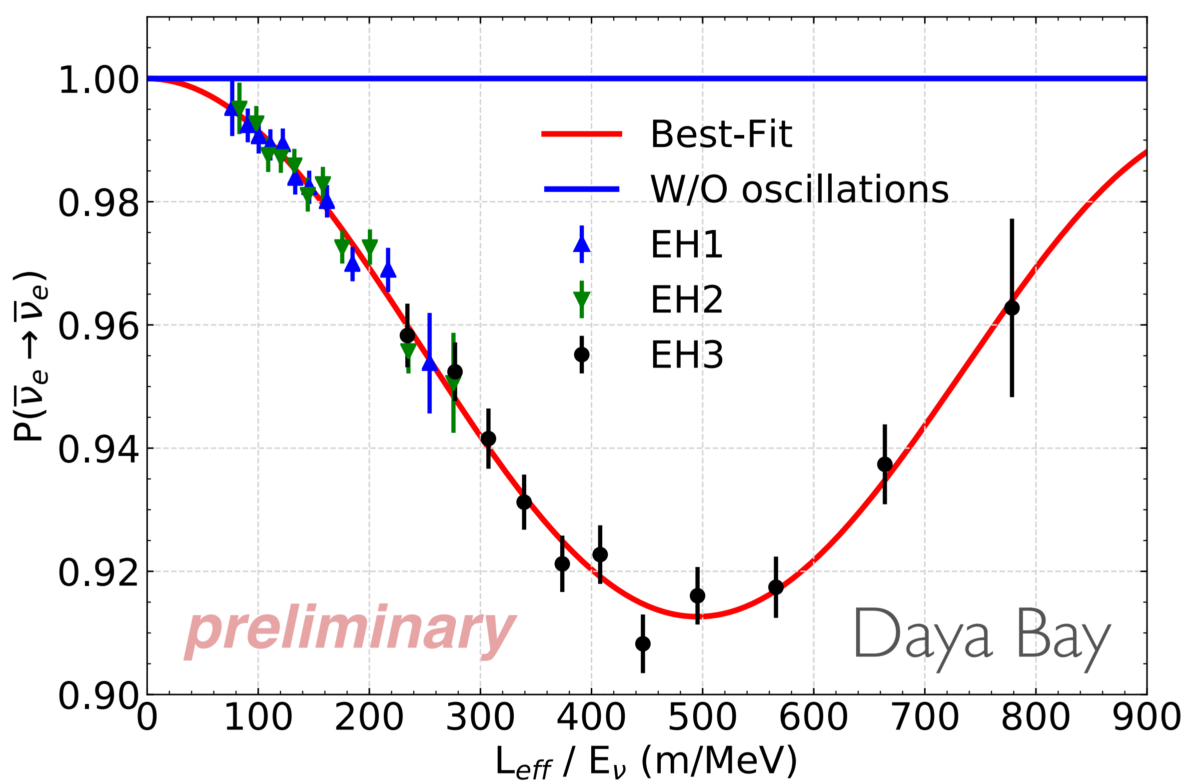


Figure taken from J. P. Ochoa's presentation at Neutrino2018

θ	**: mixing angle**
Δm²	**: mass squared difference**
L	: the distance traveled
E	: the energy of neutrino

Neutrino Mixing

All the three angles are finally observed!

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

$\theta_{13} \sim 9^o$
Reactor ν

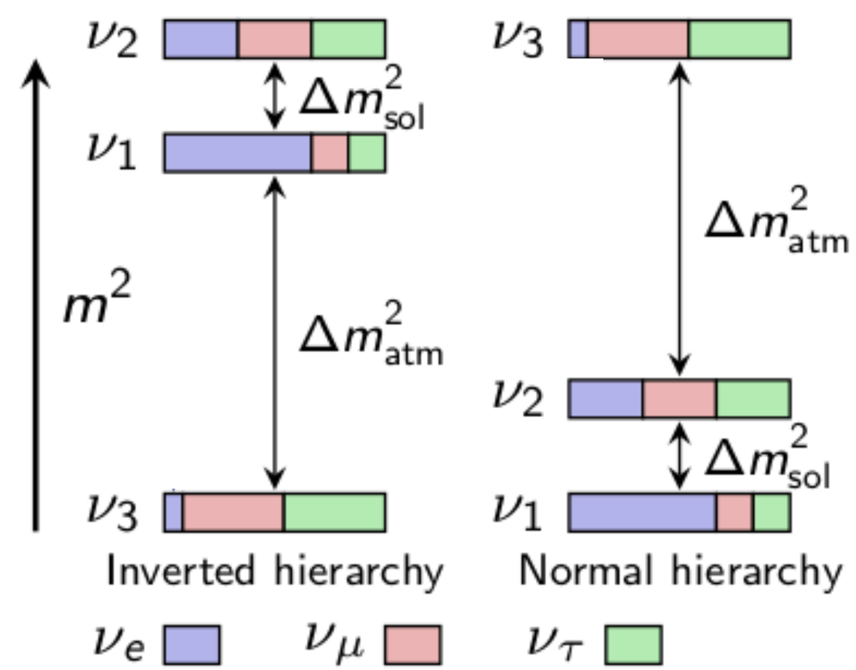
$\theta_{12} \approx 35^o$
Solar ν
Reactor ν

$\Delta m^2_{32} \sim \Delta m^2_{31} \sim 2.5 \times 10^{-3}$ eV^2

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2

Still many open questions:

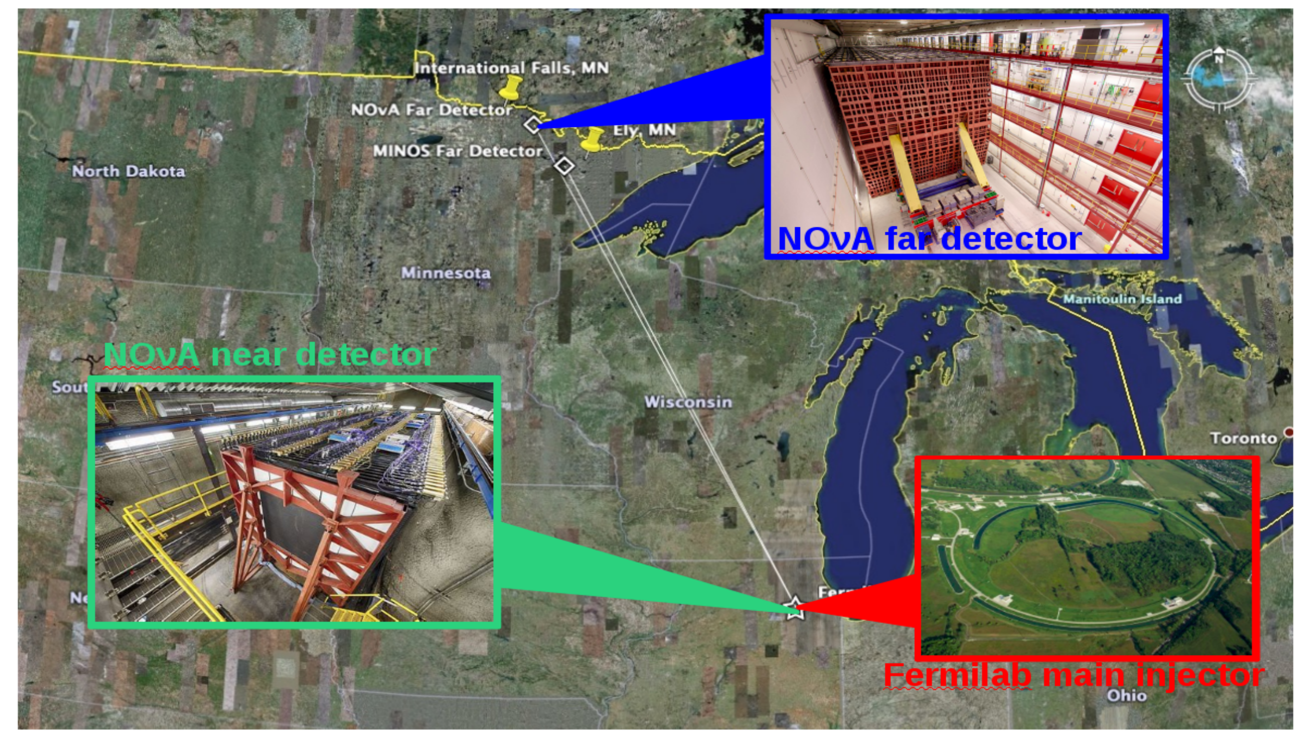
- What is the CP-violation phase, δ ?
- What is the absolute mass scale/ordering?
- What is the origin of neutrino mass?
- Are there any extra spices?



Accelerator-based long-baseline neutrino oscillation experiments

T2K

NOvA



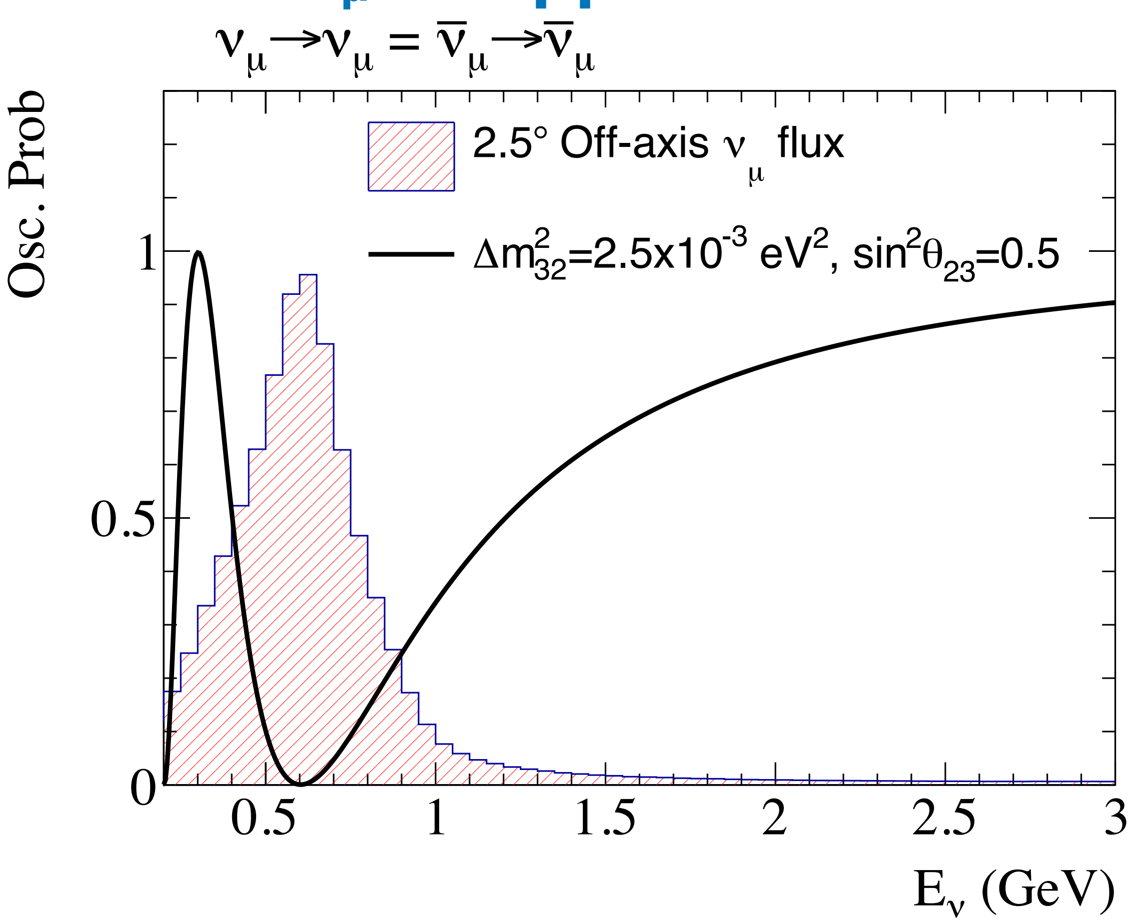
- High-intensity muon (anti-)neutrino beam produced by smashing protons to fixed targets
- Near detectors to constrain the beam flux, and measure oscillation at the far detectors
- Both uses off-axis narrow-band neutrino beam.

	Baseline	Peak energy
T2K	295 km	~ 600 MeV
NOvA	810 km	~ 2 GeV

Oscillation signatures

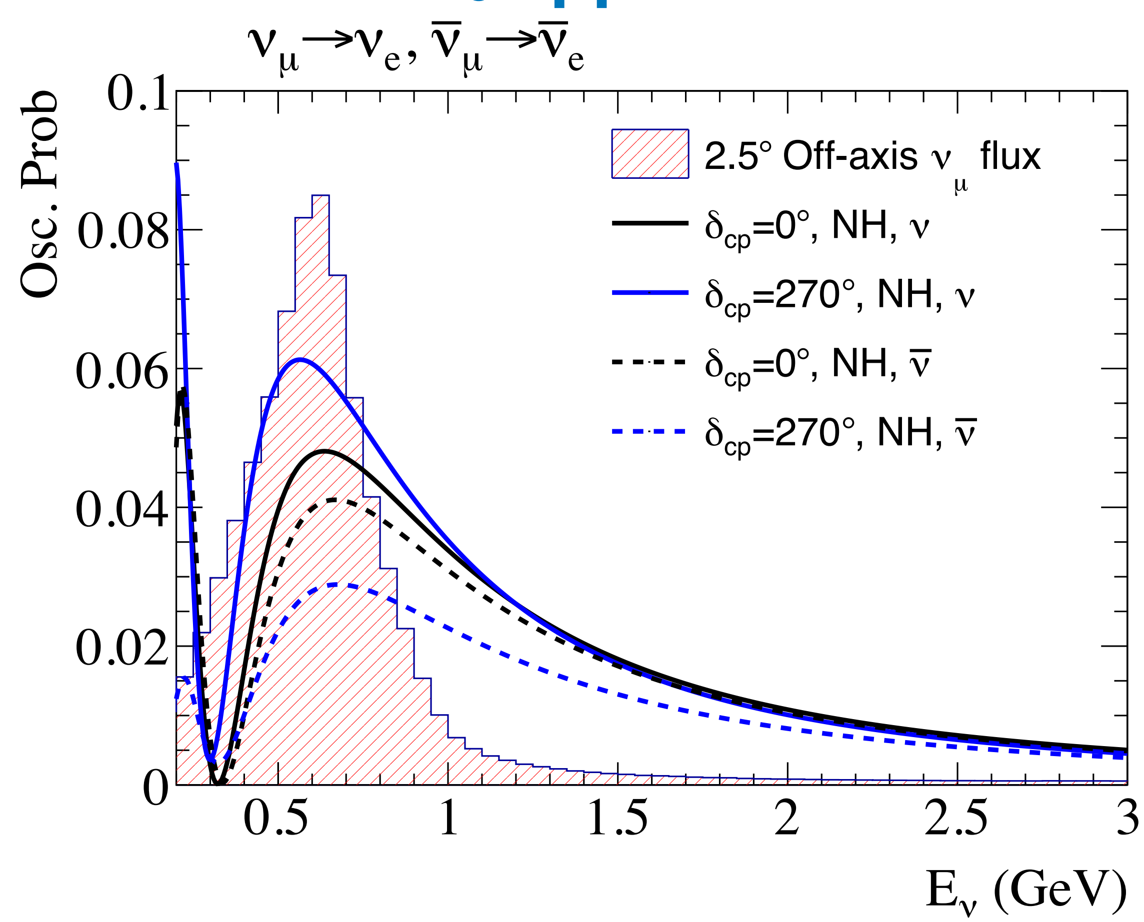
Example for the T2K beam

ν_μ disappearance



- Precision measurement of $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$
- Can test CPT symmetry

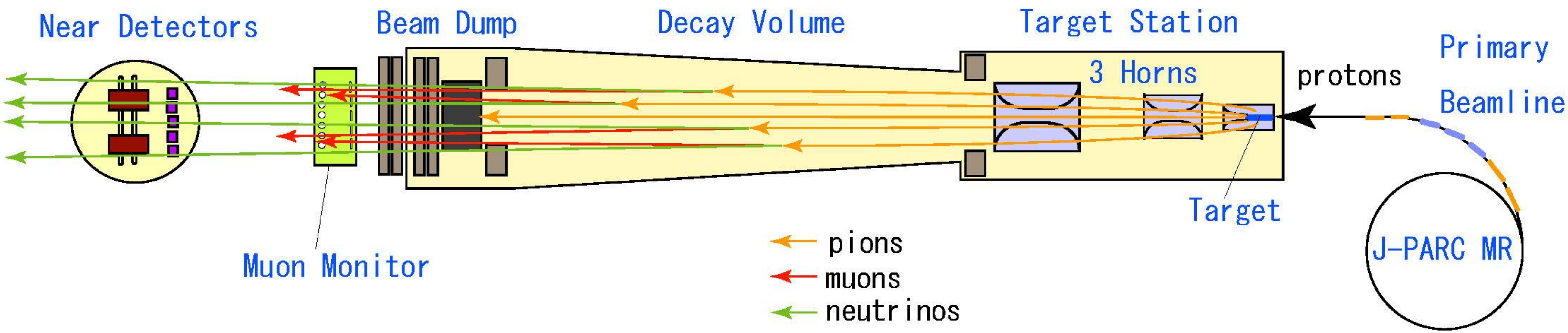
ν_e appearance



- Sensitivity to $\mathbf{\sin^2 2\theta_{13}}$, CP violating phase **$\delta$**, **$\theta_{23}$ octant**, and **mass ordering** through the matter effect
- Important to have multiple experiments to disentangle impacts of those parameters

Experimental apparatus and performance

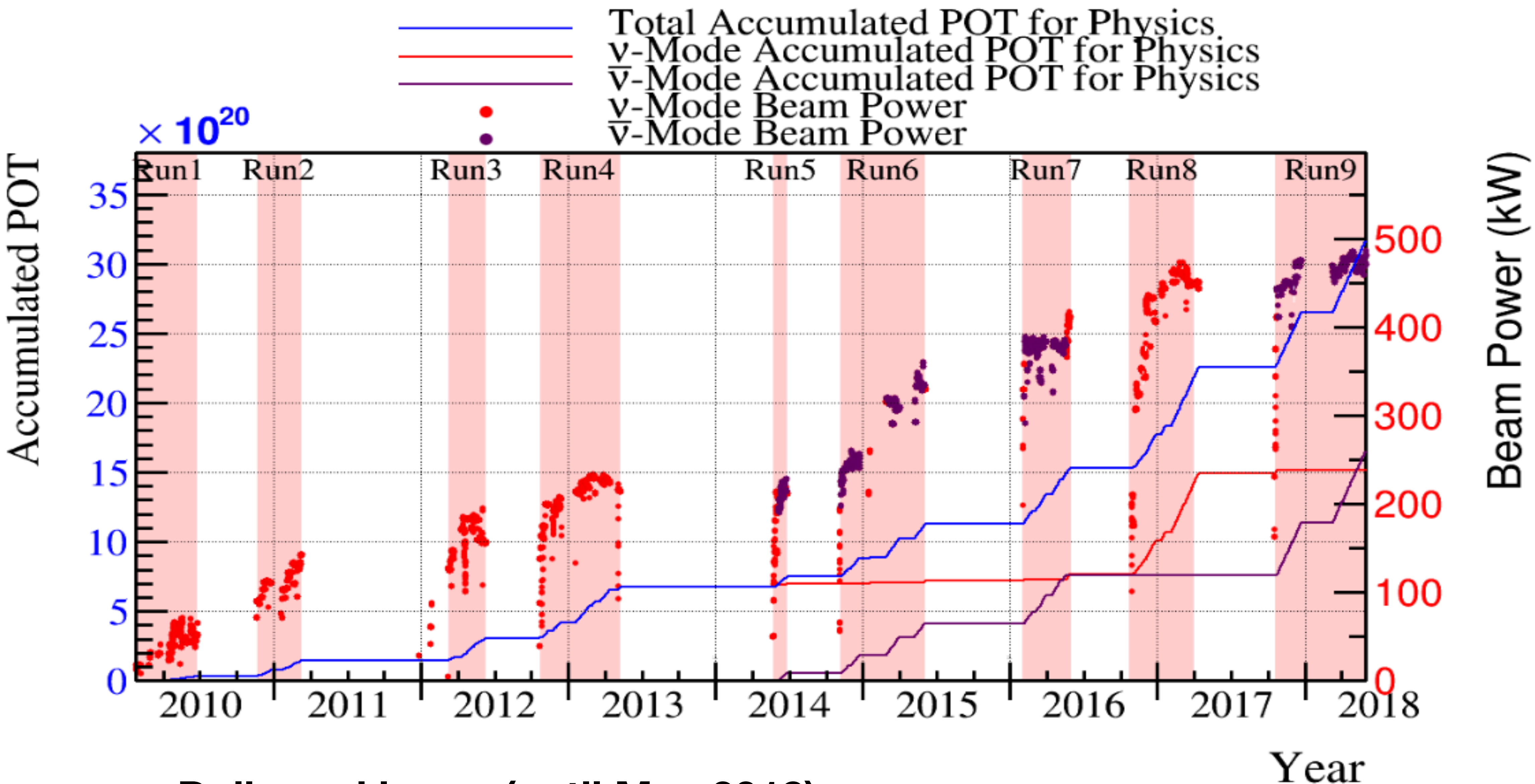
T2K neutrino beamline at J-PARC



- 30 GeV protons extracted from J-PARC Maing Ring smashes a graphite target
- Secondary $\pi^{+/-}$ are focused by three magnetic horns, and decay into $\mu^{+/-}$ and $\overset{(-)}{\nu}_\mu$ in the decay volume
- Muon detector monitors beam stability.

Can switch neutrino mode and anti-neutrino mode by switching the horn current

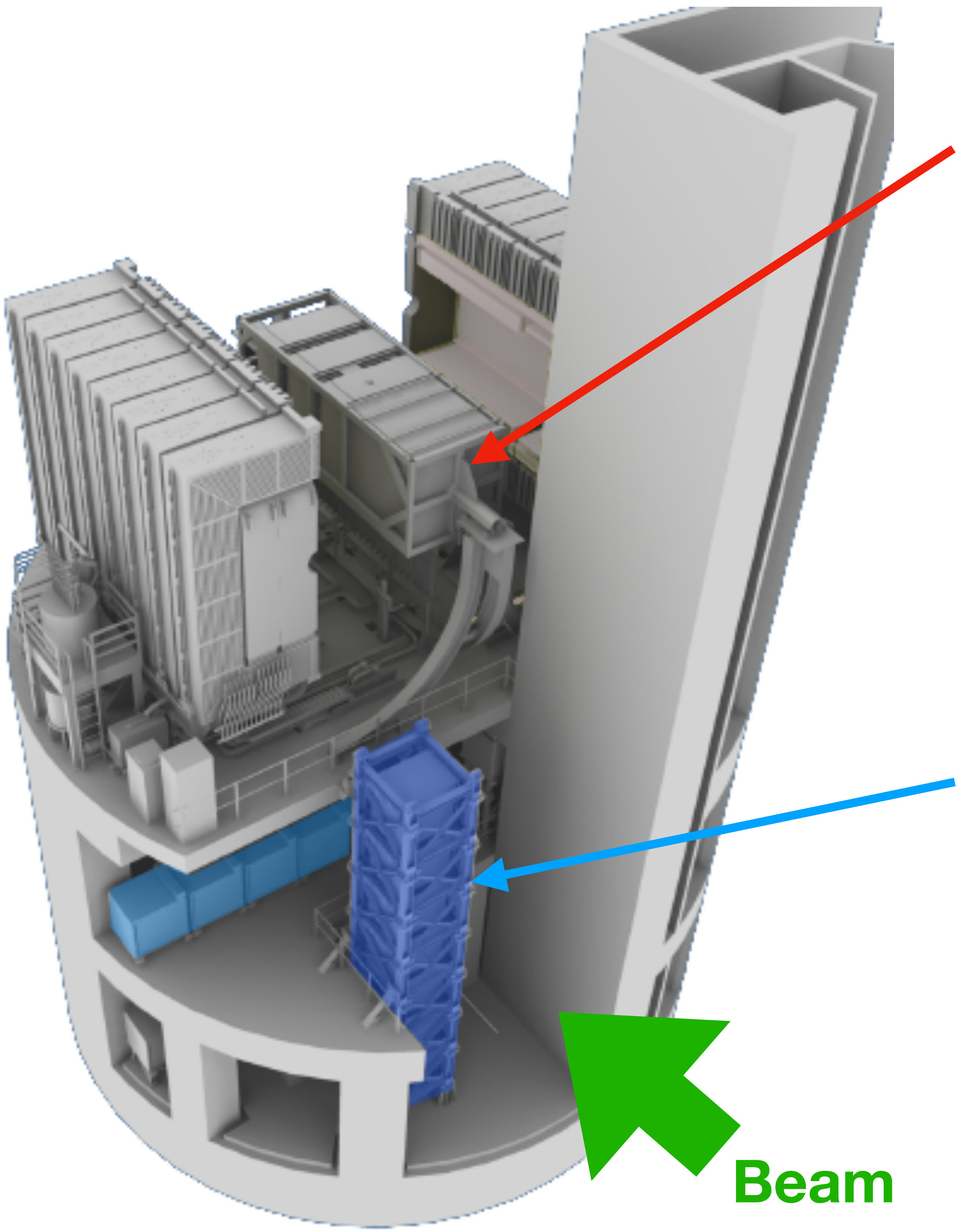
T2K beam delivery



- **Delivered beam (until May 2018)**
  - 1.51 x 10^{21} POT neutrino mode (Forward Horn Current)
  - 1.65 x 10^{21} POT antineutrino mode (Reverse Horn Current)
- **Used for the latest oscillation analysis:**
  - 1.49 x 10^{21} POT neutrino mode
  - 1.12 x 10^{21} POT antineutrino mode

T2K near complex

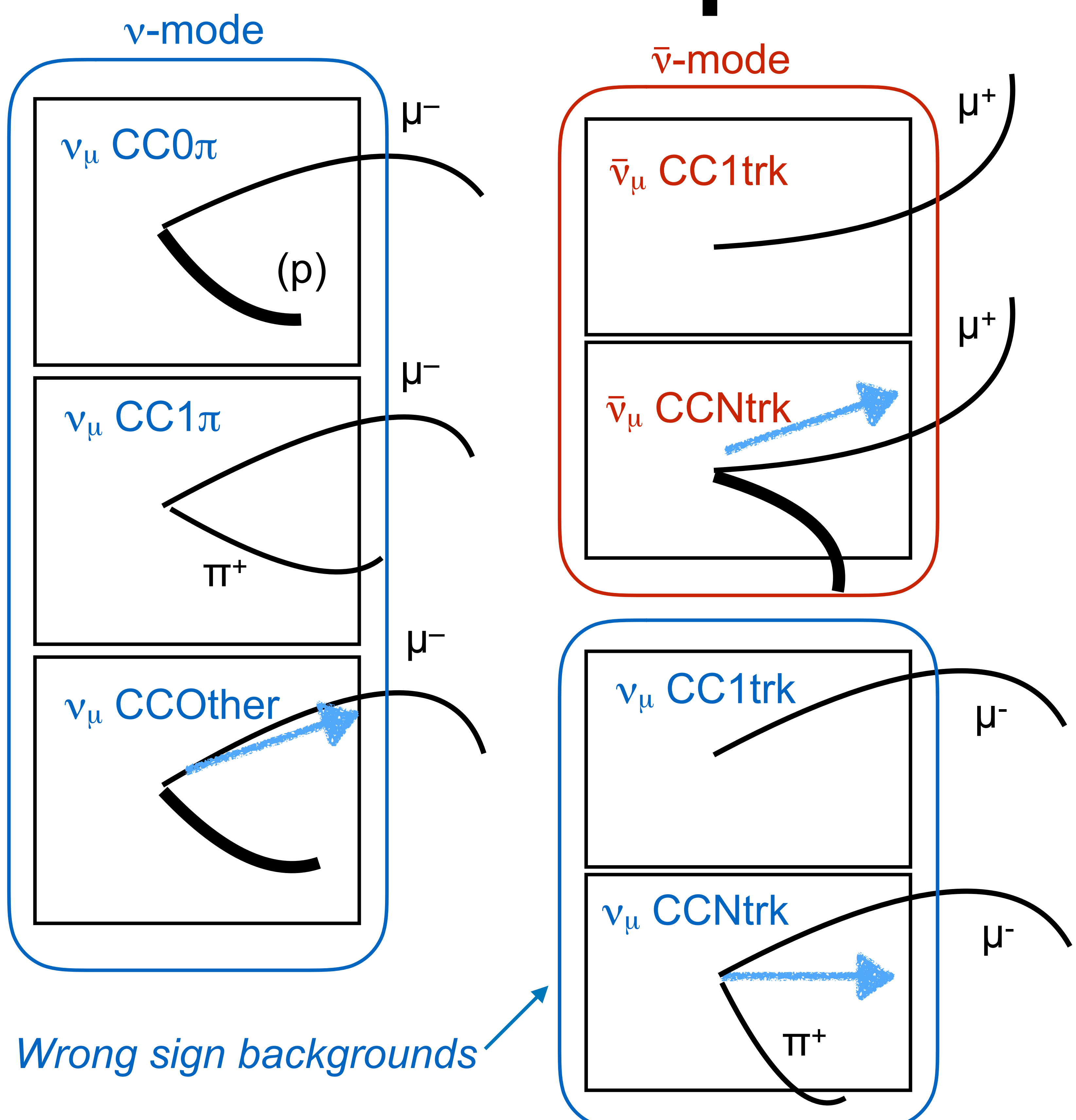
T2K Near Detector complex consists of off-axis (ND280) and on-axis (INGRID) detectors



- **ND280**
  - Measures flux at SK direction before oscillation
  - Detector placed in 0.2 T magnetic field
  - Tracker consists of 2 fine-grained detectors (FGDs) and 3 TPCs
  - Plastic and Water targets
- **INGRID**
  - Measures beam profile and direction
  - Array of 9-ton iron-scintillator sandwich detectors

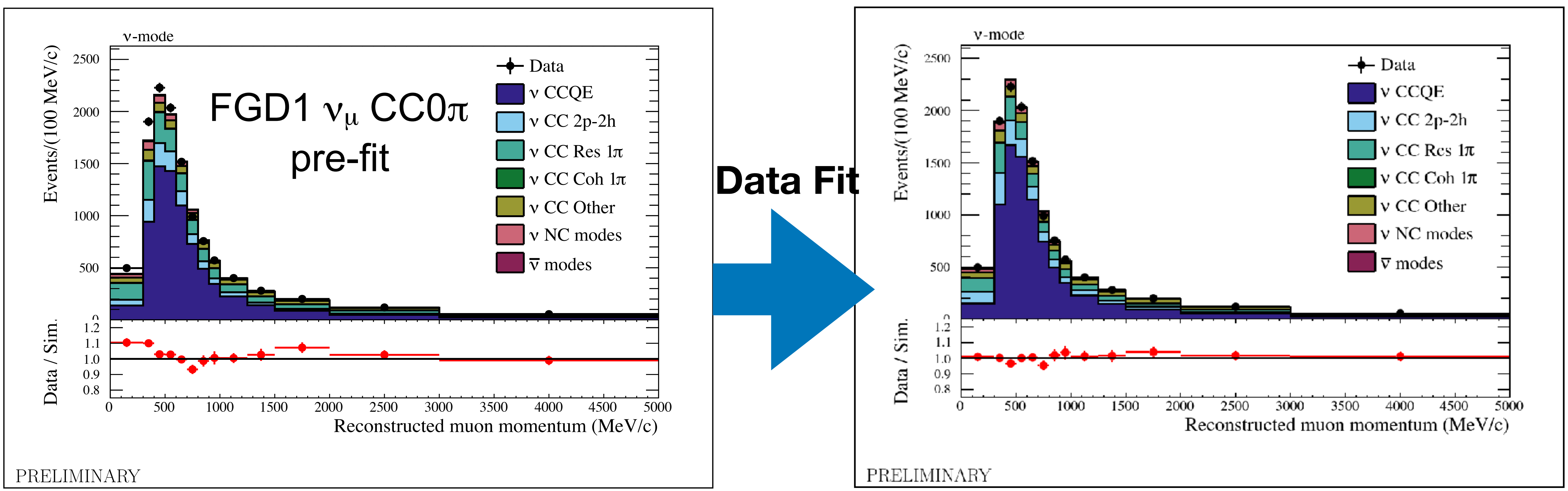
T2K ND280 data samples

- 14 total ND280 data samples used by oscillation analysis fit
- ν-mode (FHC)
  - sort by π^+ multiplicity
  - 2 fine-grained detectors (FGDs) (C,O)
  - ➡ 6 samples
- $\bar{\nu}$-mode (RHC)
  - sort by muon charge
  - sort by number of tracks
  - 2 FGDs (C,O)
  - ➡ 8 samples

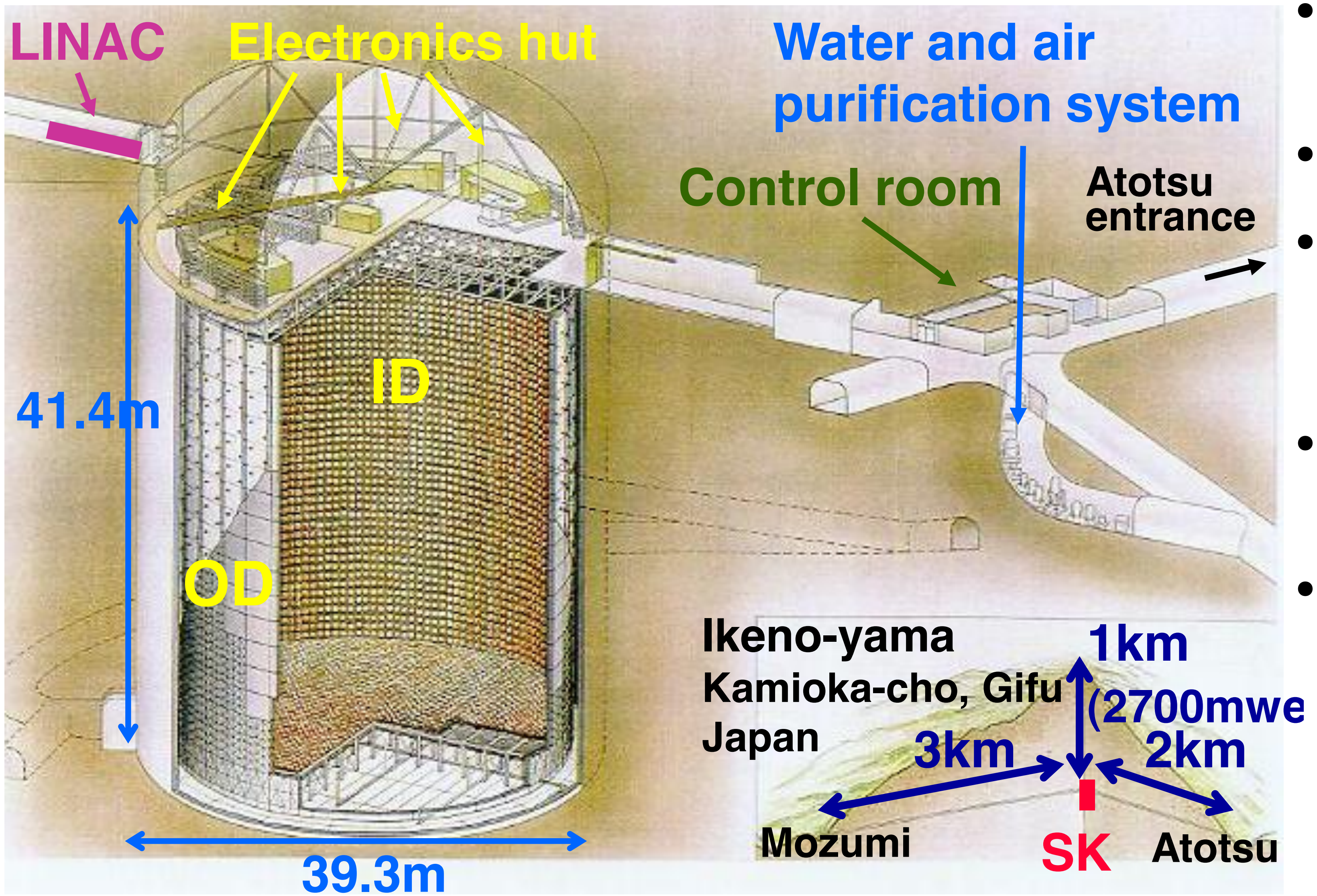


ND280 data fitting

- The 14 ND 280 samples are used to constrain neutrino flux and cross-section
- After the fit, the flux and cross-section uncertainty at the far detector reduced to ~5% from ~15%
- Also measures neutrino interaction cross-sections



Super-Kamiokande (T2K far detector)



- 50-kton water Cherenkov detector
- Overburden: 2700 mwe
- Inner Detector covered by > 11000 20" PMTs (40% photo coverage)
- Outer detector equipped with ~2000 8”PMTs and act as veto
- Can detect neutrinos for wide energy rage
  - Solar neutrinos
  - Supernova neutrinos
  - Atmospheric/**Accelerator neutrinos**

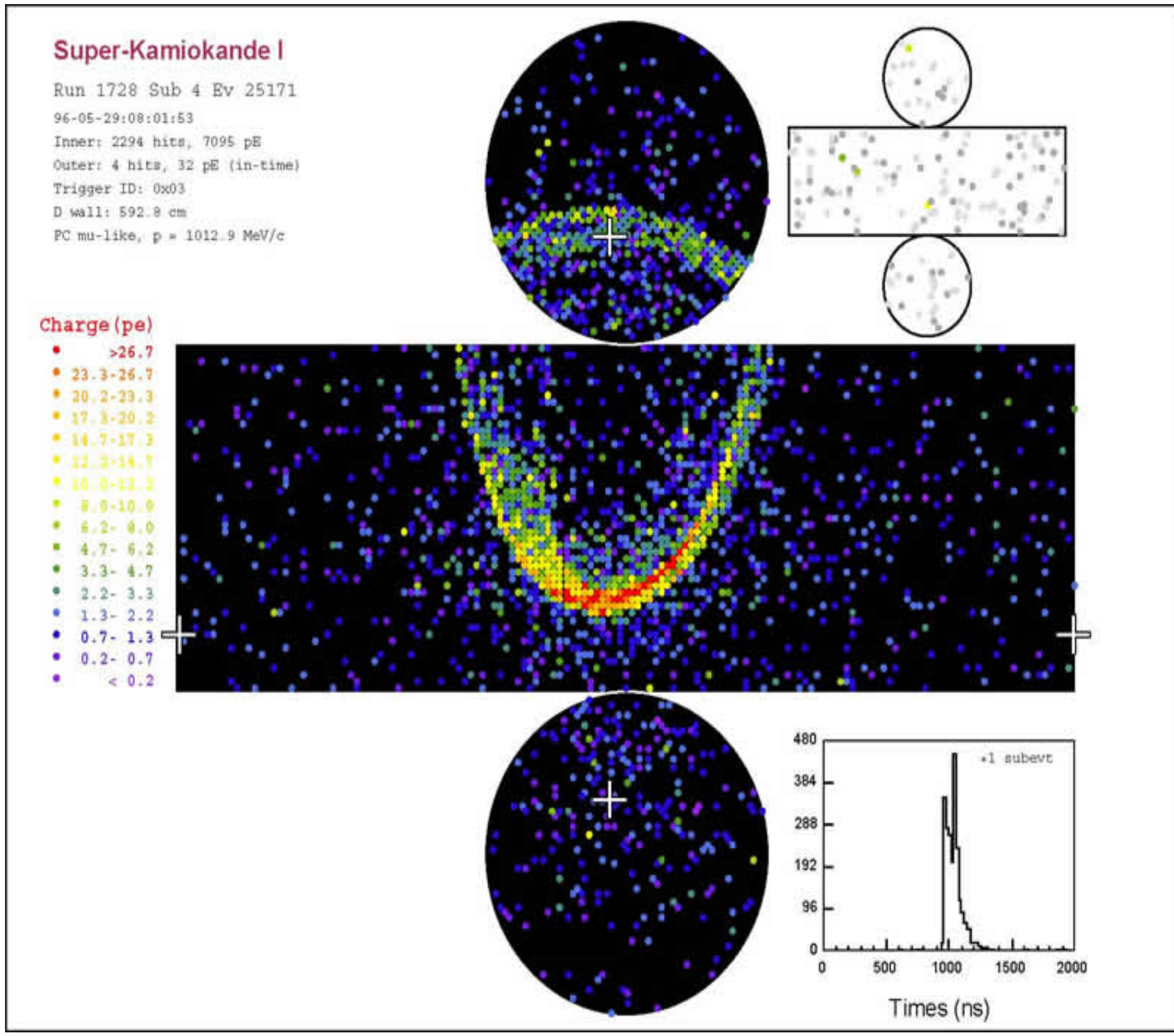
~ MeV

~ GeV

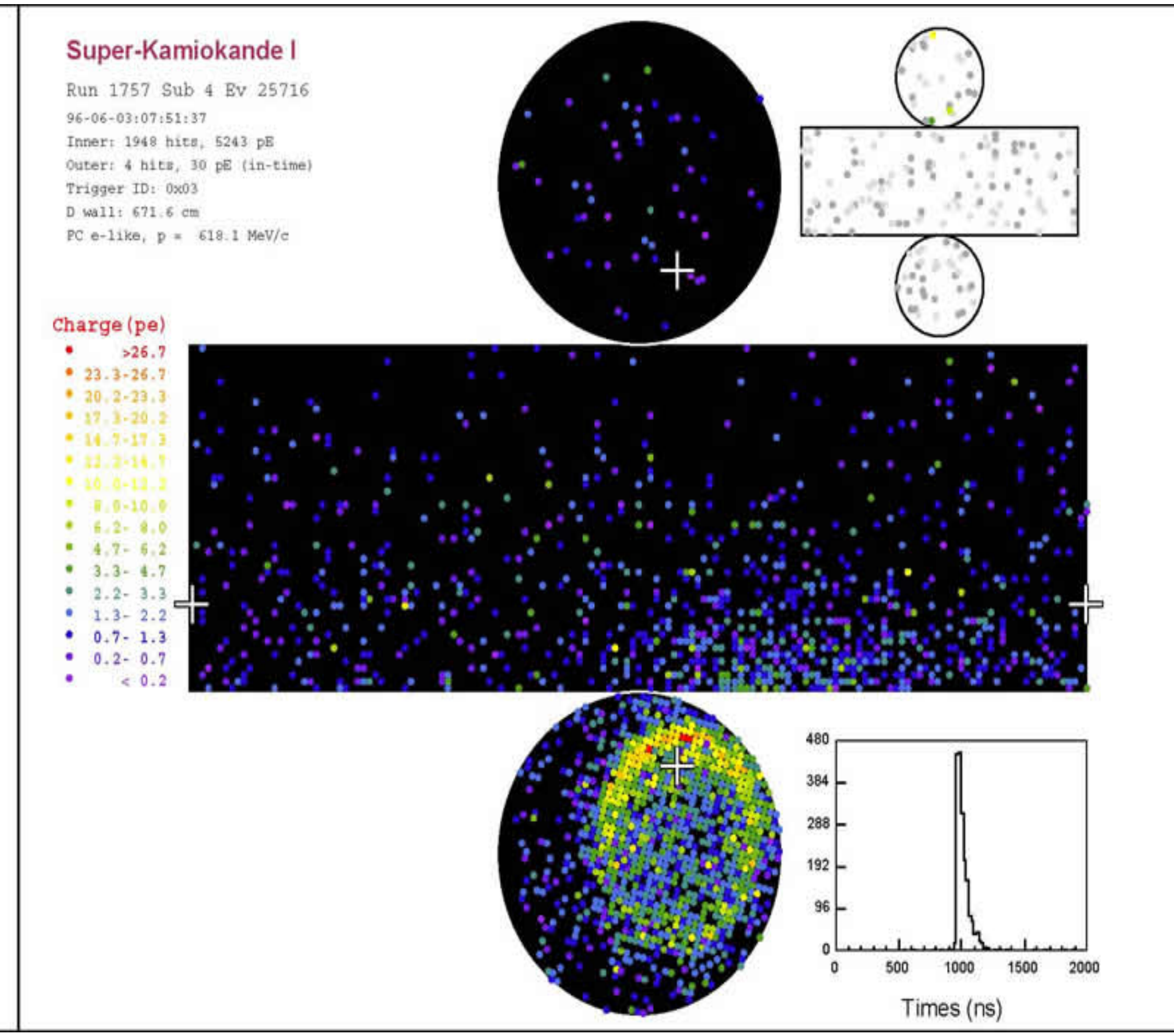
- Operational since 1996

Super-K event samples

μ-like event

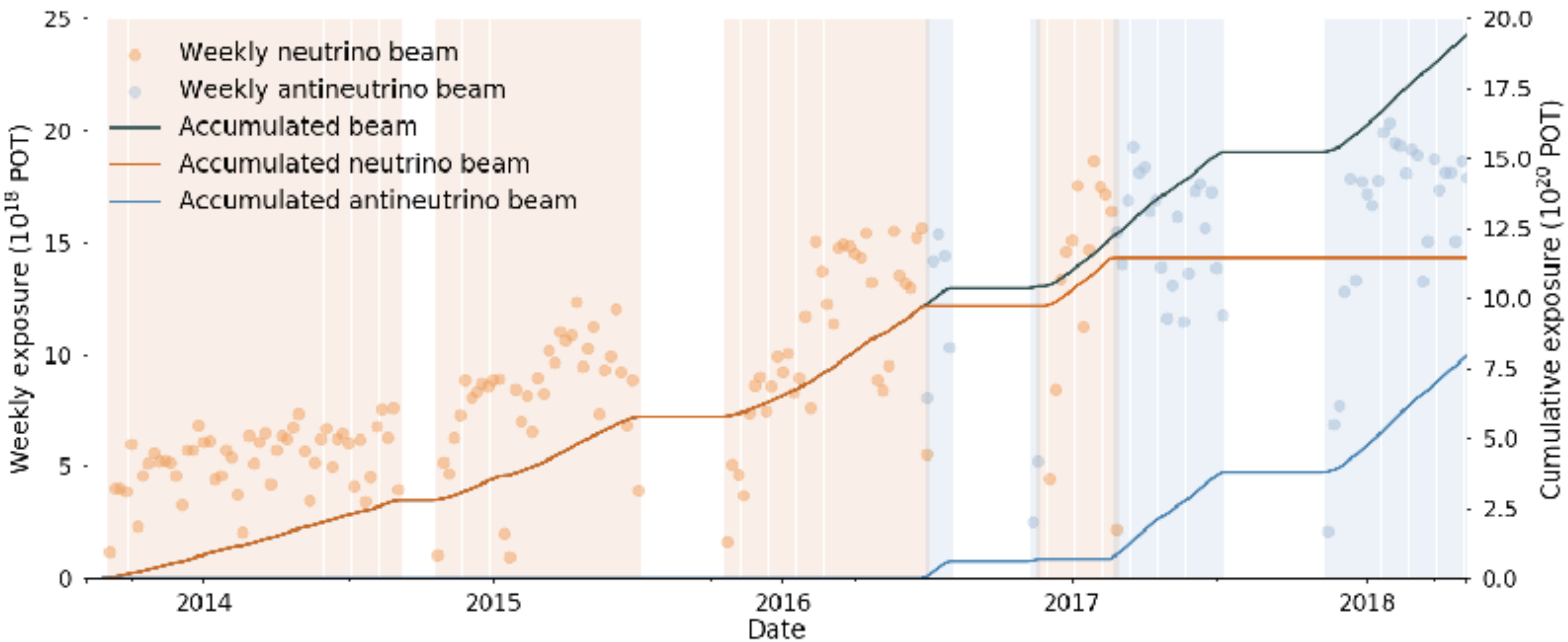


e-like event



- Utilizes ring pattern to separate muons and electrons

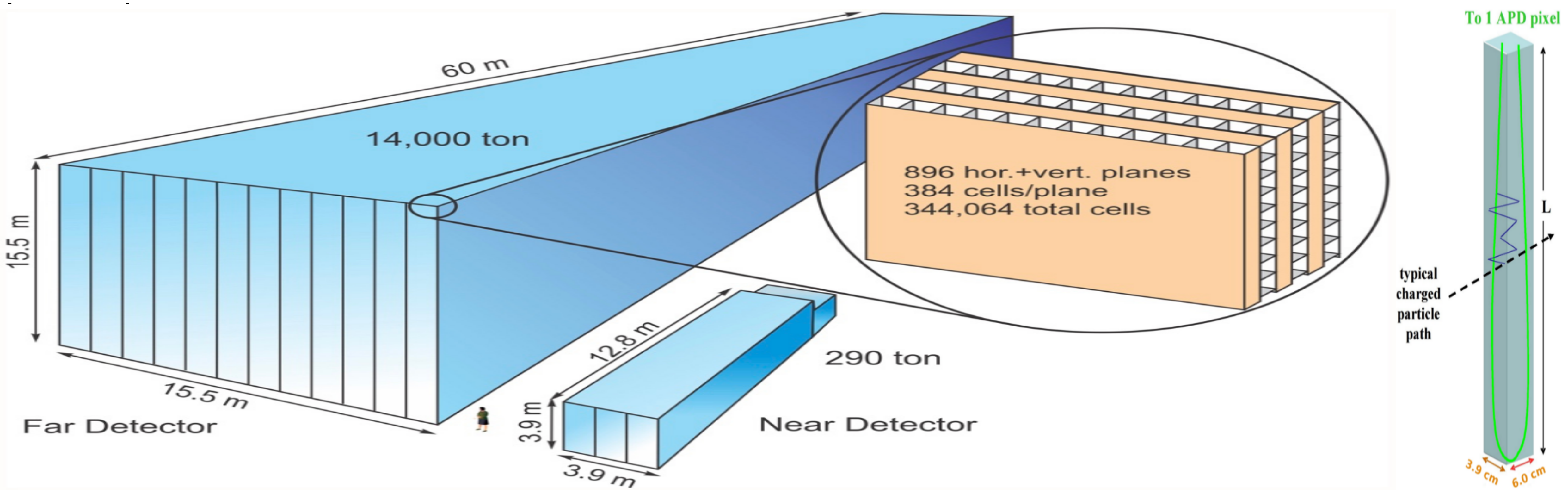
NOvA beam delivery



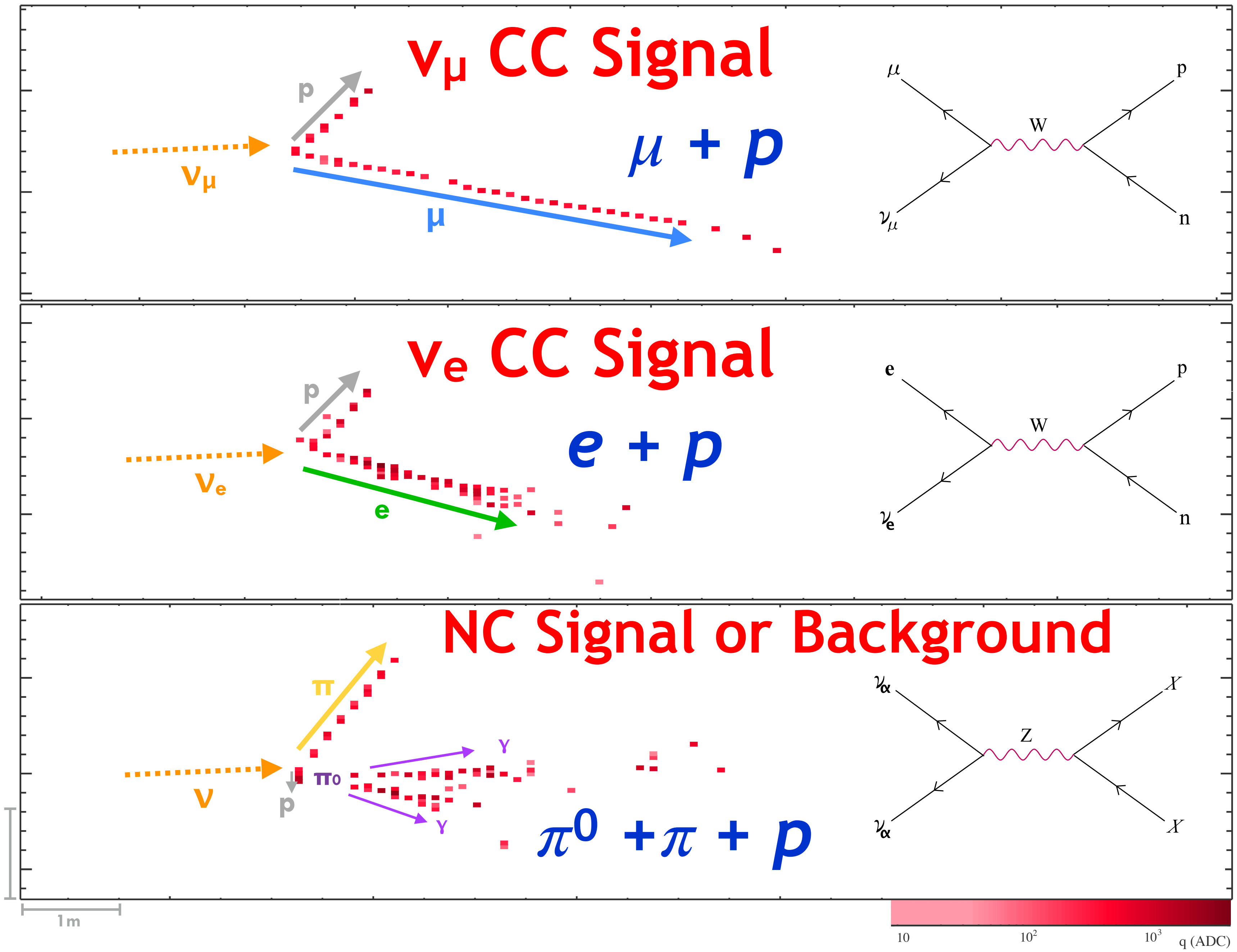
- NuMI beam running at 700 kW since Jan 2017
- Recorded POT by April 2018:
  - Neutrino mode: 8.85 x 10^{20} POT
  - Antineutrino mode: 6.9 x 10^{20} POT

NOvA Near and Far detectors

- Uses the same technology for both near and far detectors
  - PVC extrusion + Liquid scintillator
  - Layered planes of orthogonal views with 6-cm cells. Readout via WLS fibers to APDs.
- Near detector (0.3 kton)
  - 1 km from source, 100 m depth
- Far detector (14 kton)
  - 810 km from source, on the surface, 3 m.w.e. overburden.



Neutrino events at NOvA



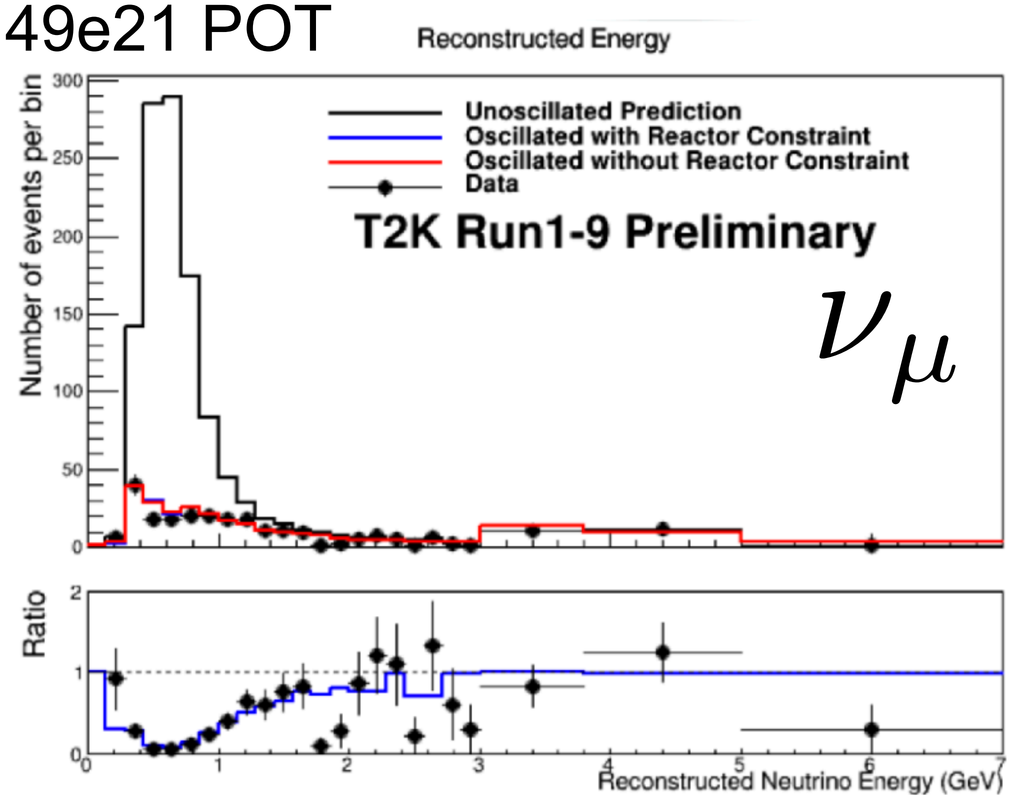
Utilizes Convolutional Neural Networks (CNN) for particle classification

Oscillation Analysis Results

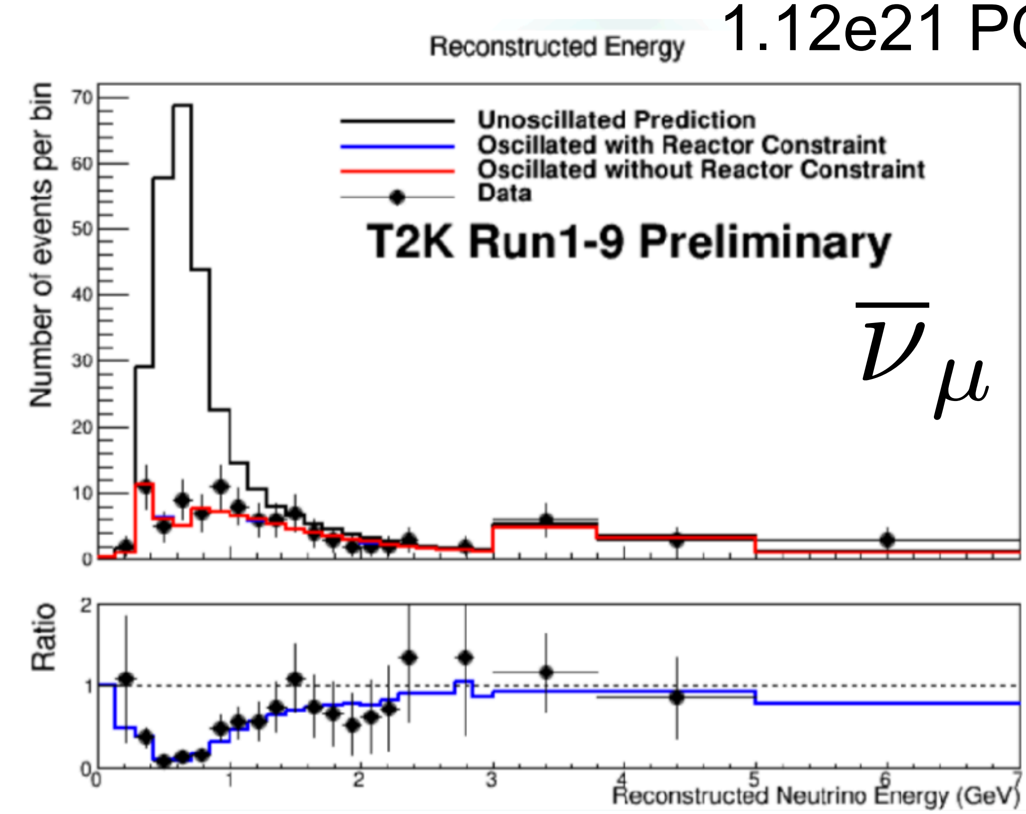
T2K disappearance analysis

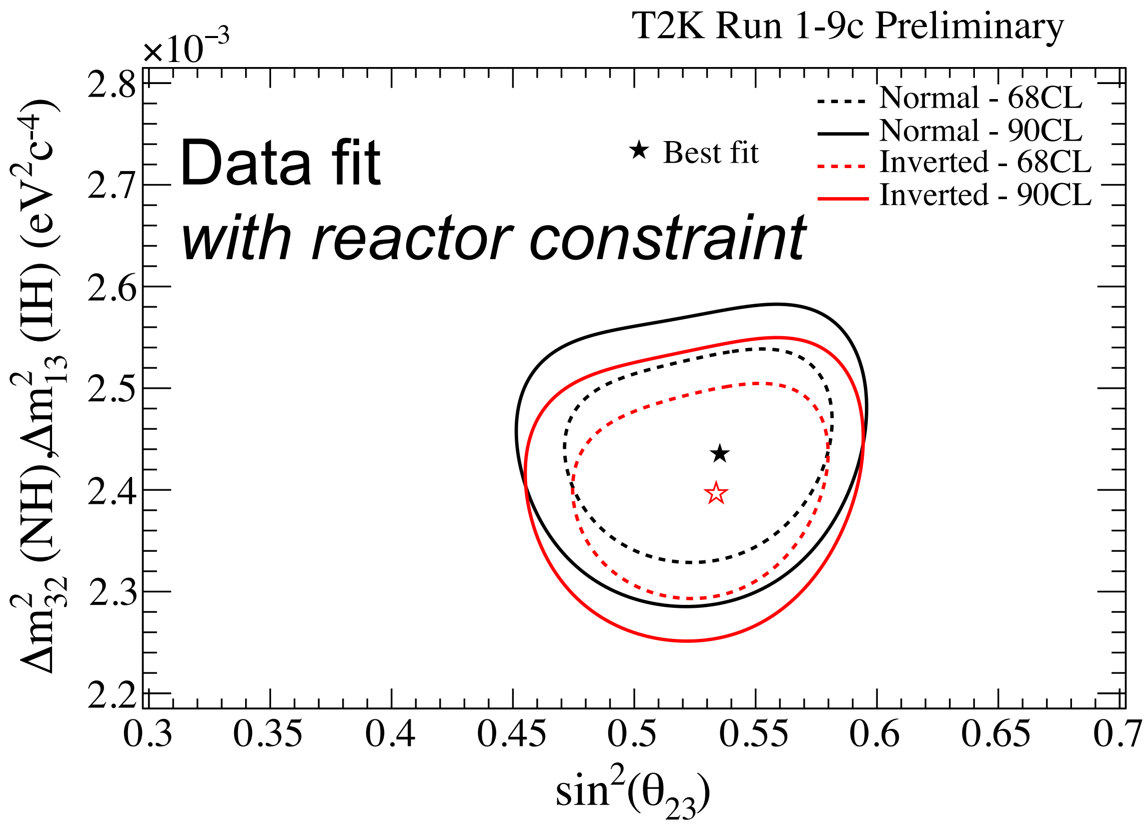
Morgan Wascko, Neutrino 2018
DOI: 10.5281/zenodo.1286752

1.49e21 POT



1.12e21 POT



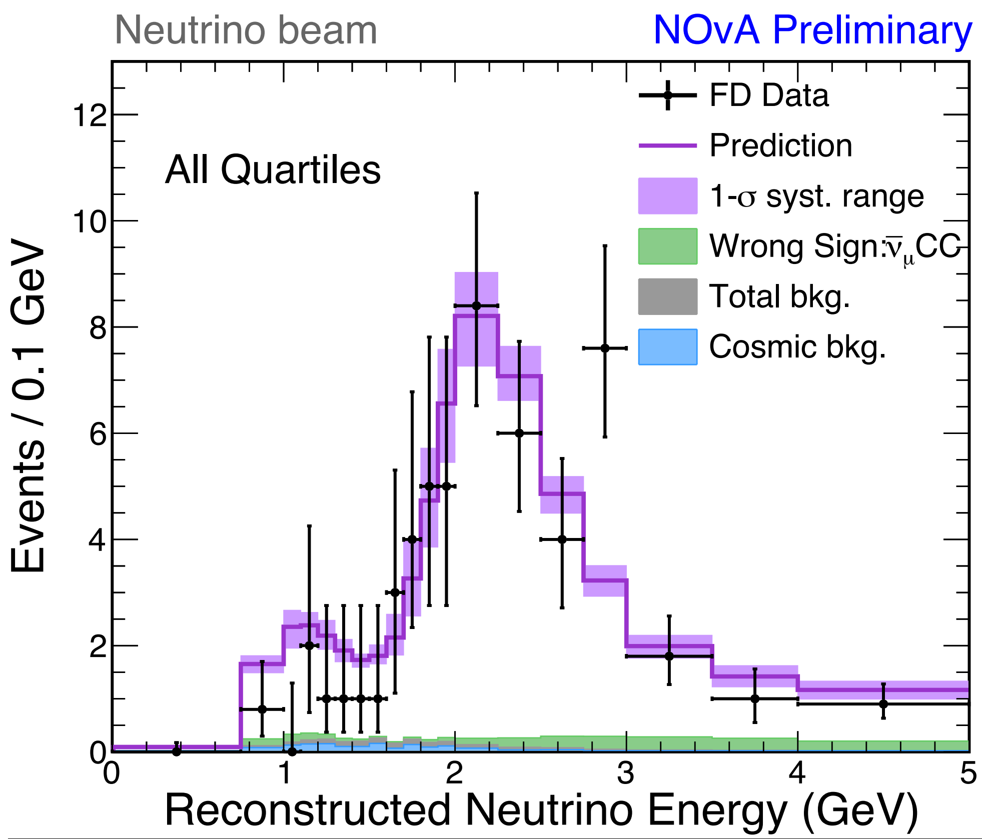


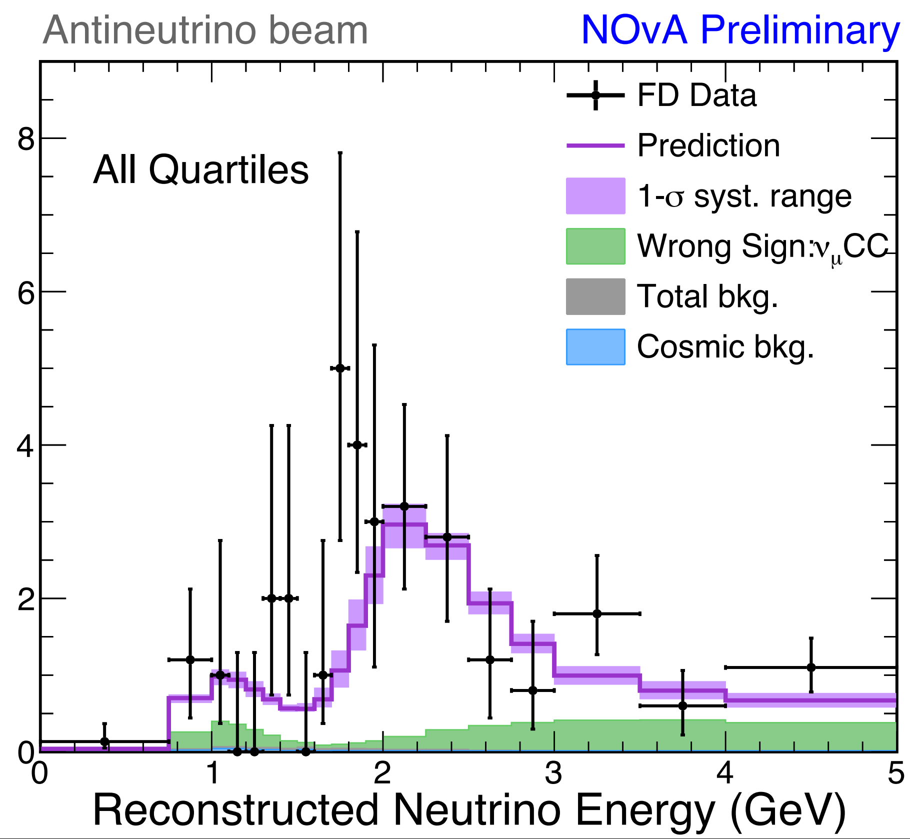
	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\|\Delta m^2\|$	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

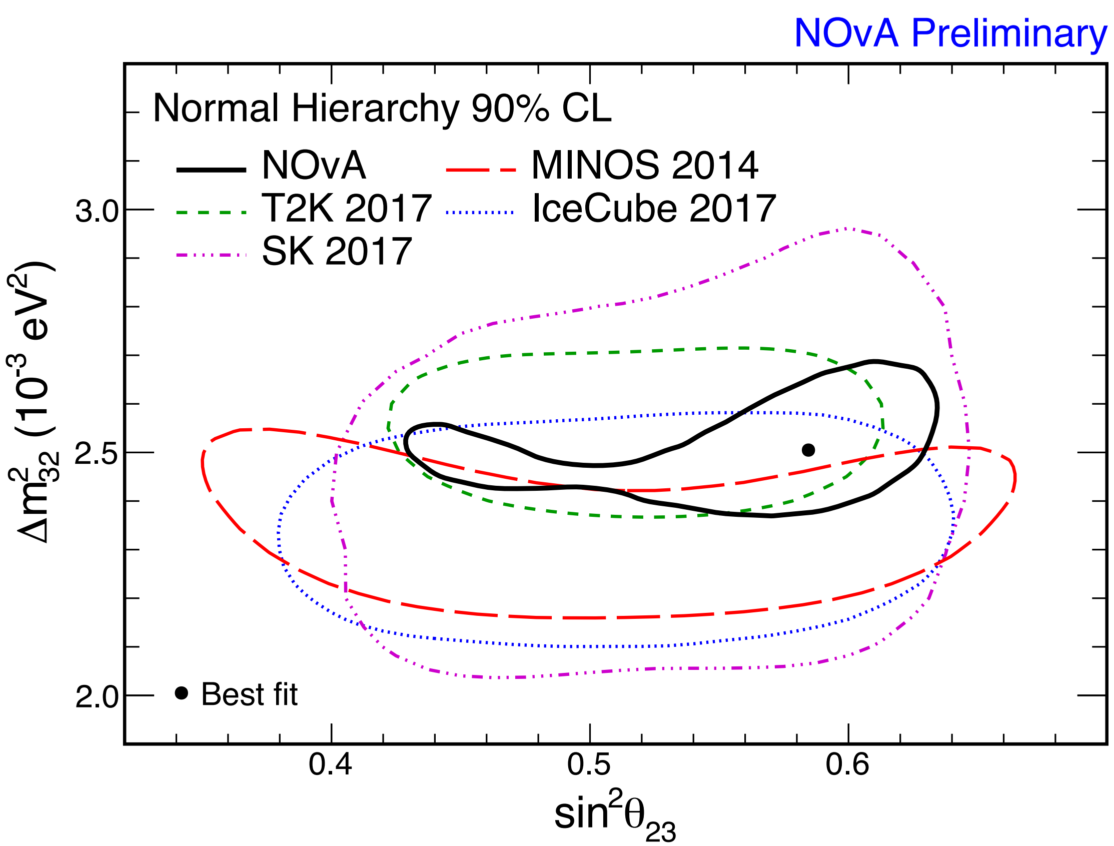
T2K result consistent with maximal mixing ($\theta_{23} = 45^o$)

NOvA disappearance analysis

Mayly Sanchez, Neutrino 2018
DOI: 10.5281/zenodo.1286758







Best fit: Normal Hierarchy

$\delta_{CP} = 0.17\pi$

$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)

$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \text{eV}^2$

90% CL region compatible with other experiments

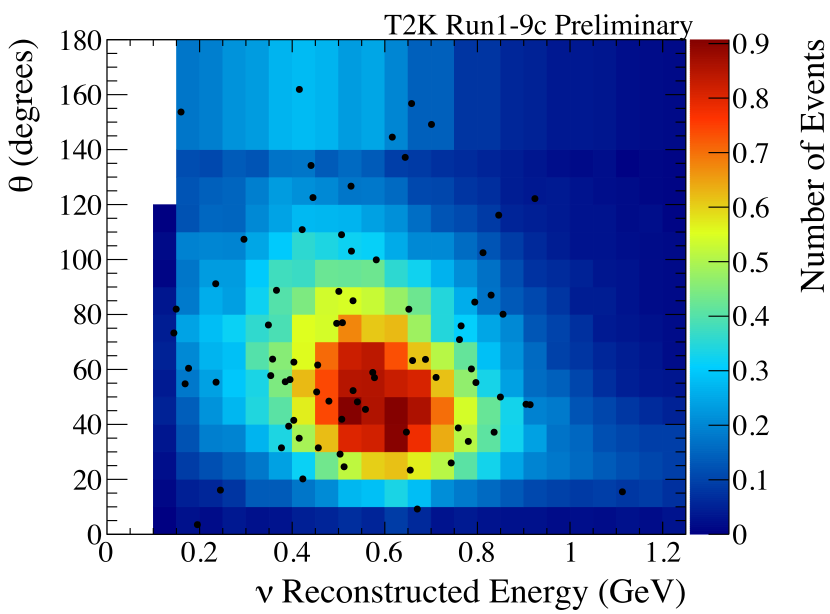
Prefer non-maximal mixing at 1.8σ

T2K appearance samples

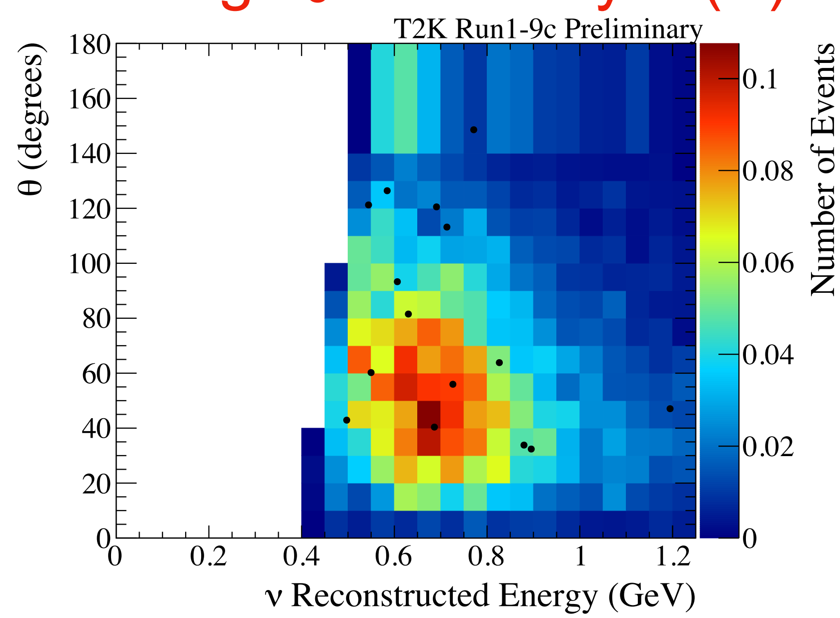
Three appearance samples used for the fit:
(1π identified with additional decay-e)

Morgan Wascko, Neutrino 2018
DOI: 10.5281/zenodo.1286752

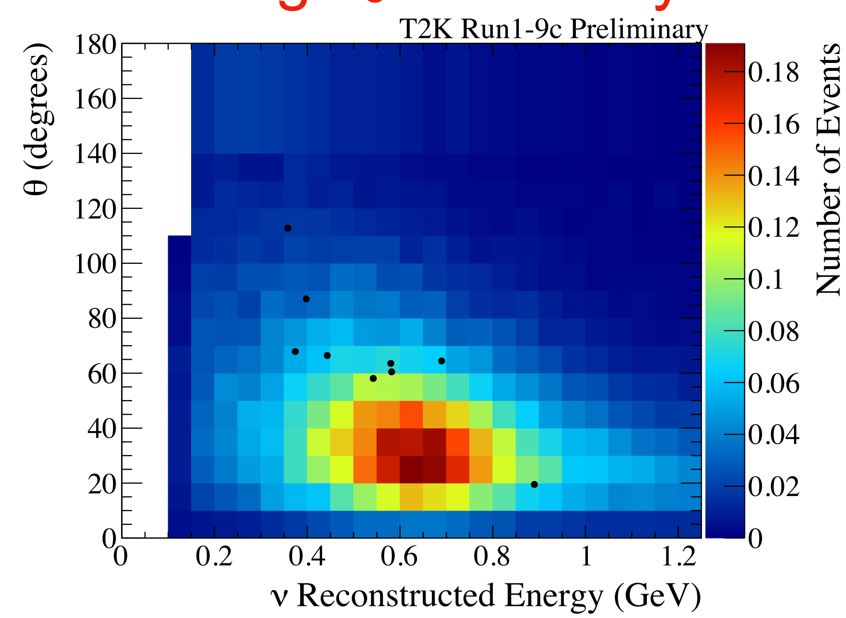
1Ring ν_e + 0 decay-e



1Ring ν_e + 1 decay-e (π)



1Ring $\overline{\nu}_e$ + 0 decay-e



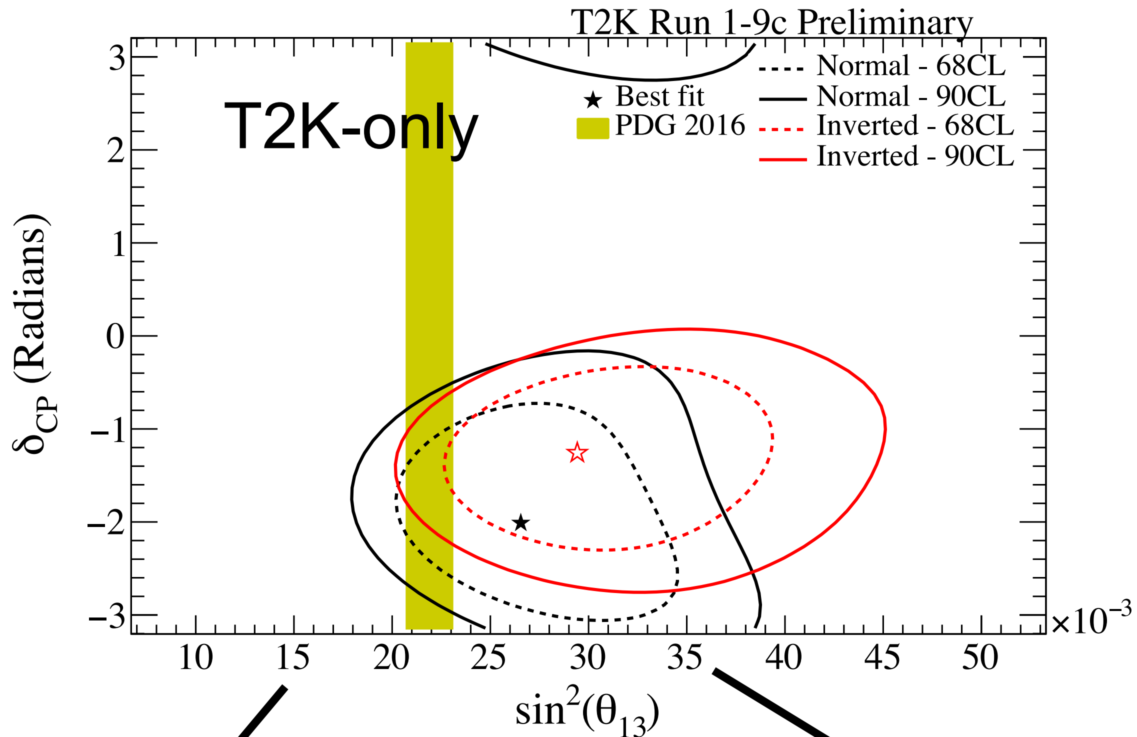
Sample	Prediction				Data
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	
1Ring ν_e, 0 decay-e	73.8	61.6	50.0	62.2	**75**
1Ring ν_e, 1 decay-e	6.9	6.0	4.9	5.8	**15**
1Ring $\overline{\nu}_e$, 0 decay-e	11.8	13.4	14.9	13.2	**9**

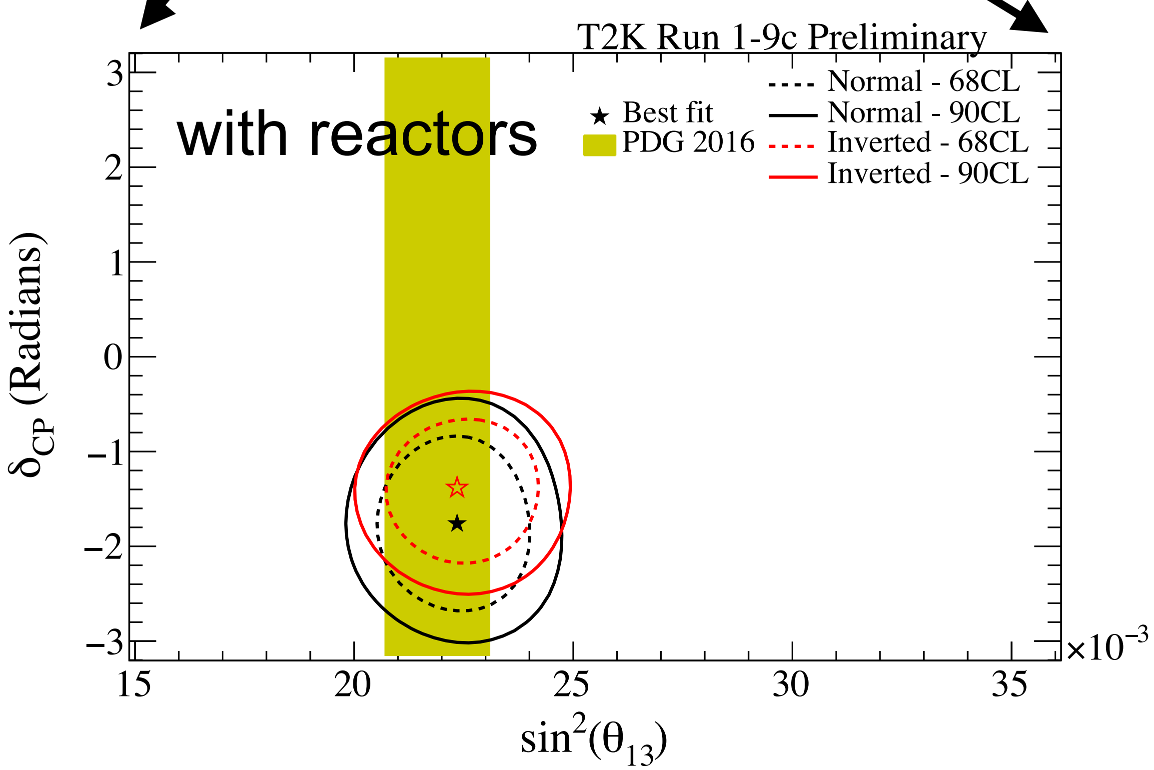
Compared with the predictions, observed more events in the neutrino mode, less events in the antineutrino mode

T2K Appearance results

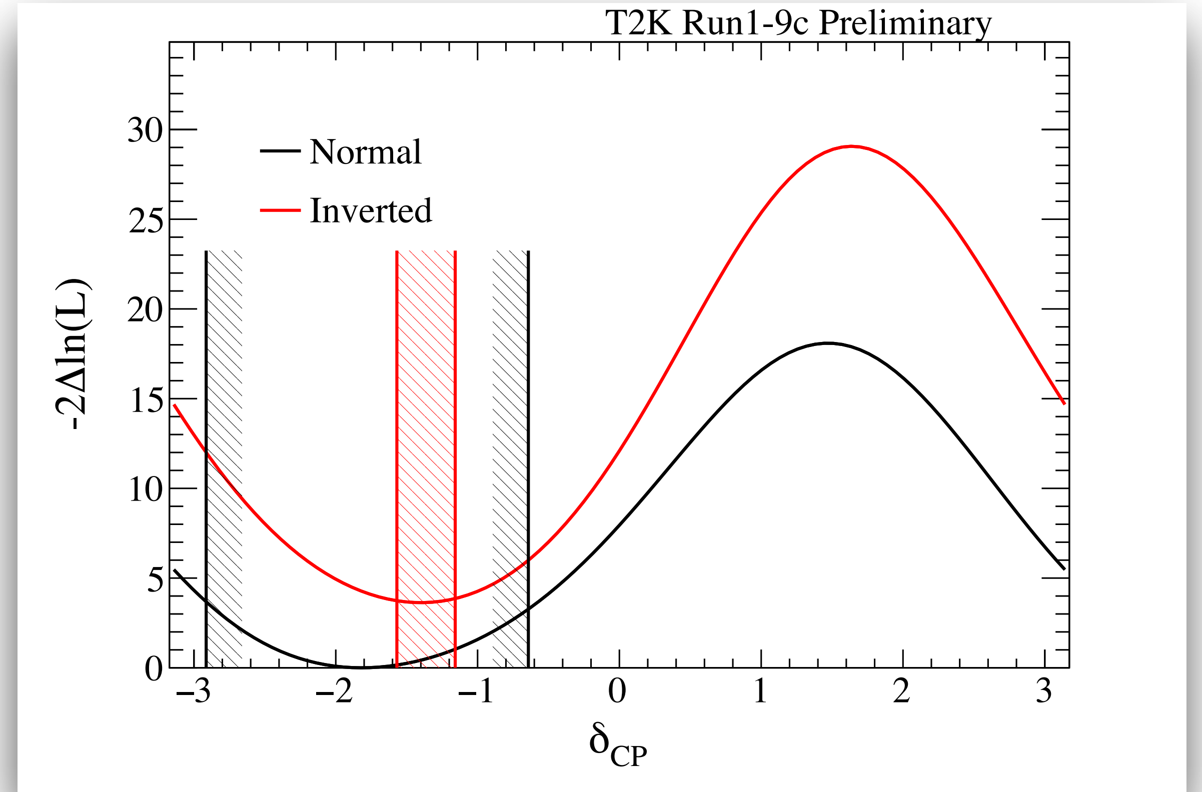
Morgan Wascko, Neutrino 2018
DOI: 10.5281/zenodo.1286752

DATA FIT





Data fit w/ reactor constraints



CP conserving values excluded by > 2σ for both hierarchy assumptions

T2K Posterior Probabilities

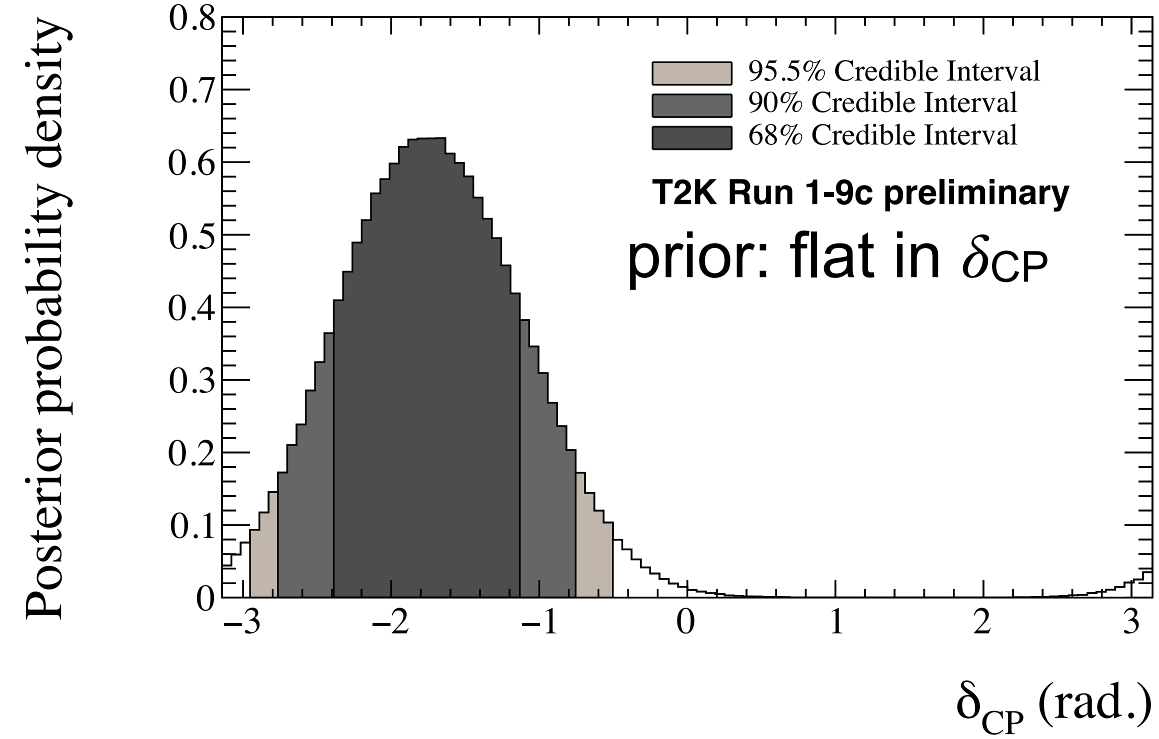
Morgan Wascko, Neutrino 2018
DOI: 10.5281/zenodo.1286752

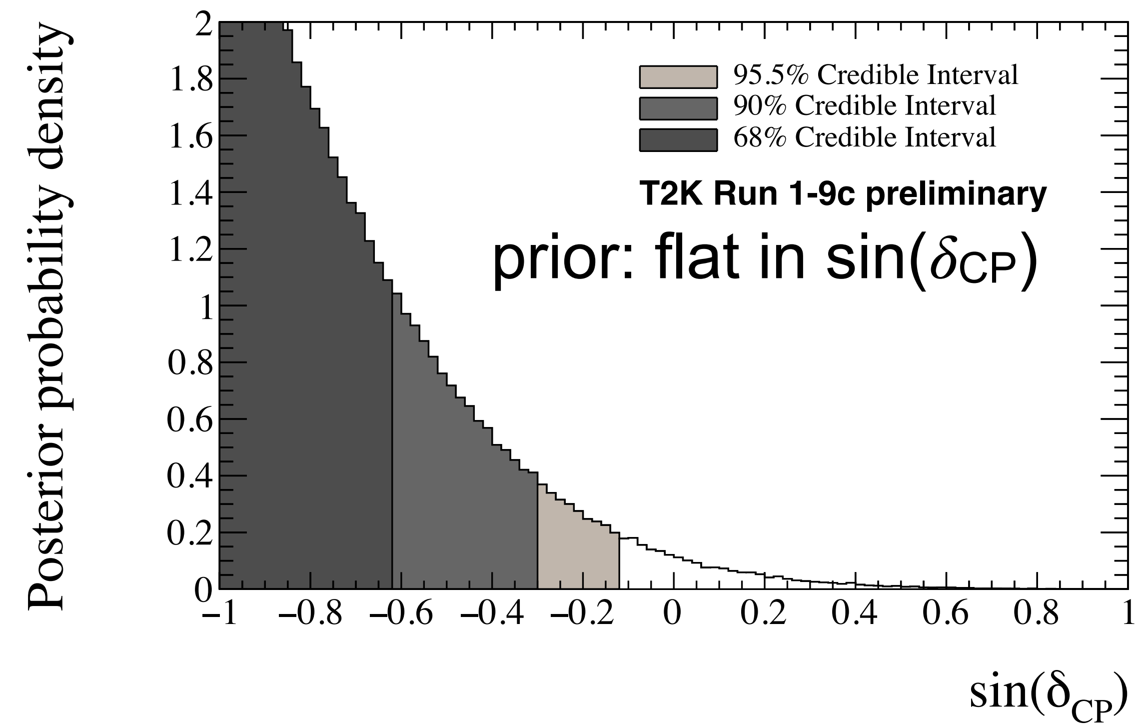
- Prior probability assumption of δ_{CP} does not affect 2σ exclusion of CP conservation

	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31} < 0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

- Bayes factor for NH/IH is 7.9

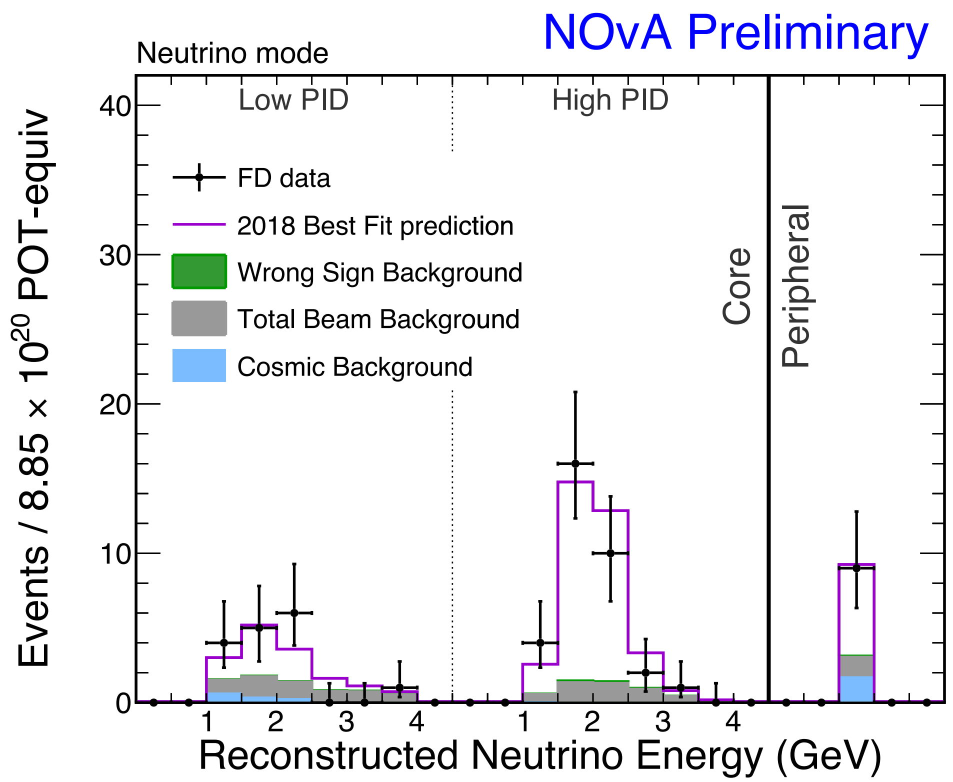
- ~50% more antineutrino data to be included soon



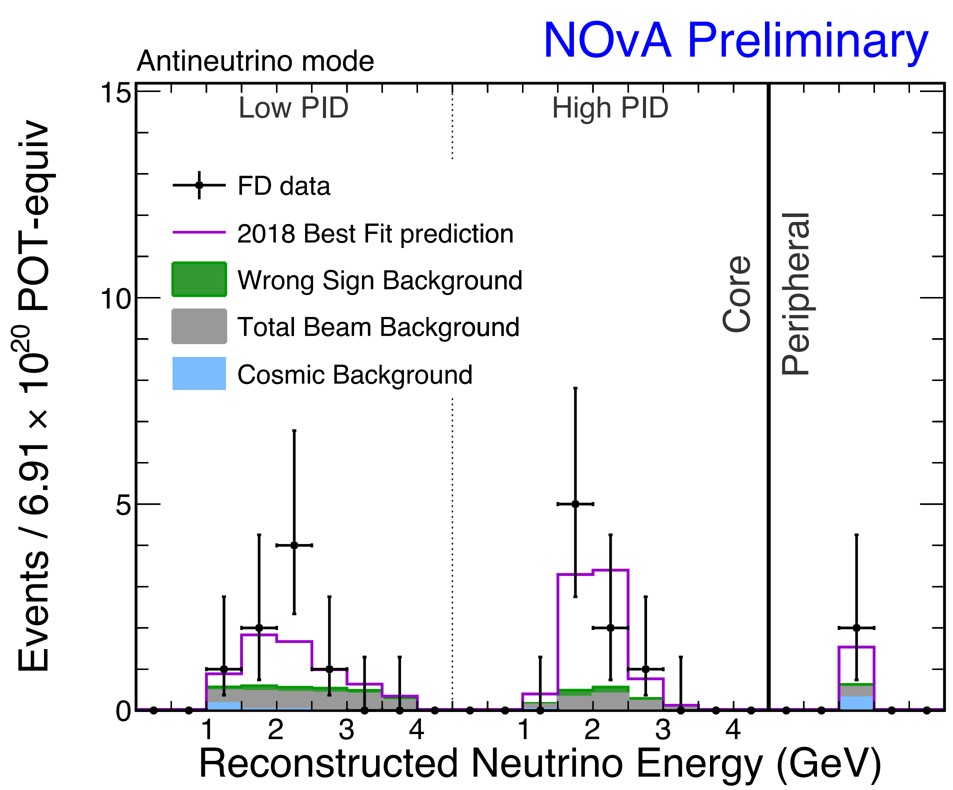


NOvA appearance samples

Mayly Sanchez, Neutrino 2018
DOI: 10.5281/zenodo.1286758



Neutrino mode:
53 events observed
w/ 15 expected backgrounds

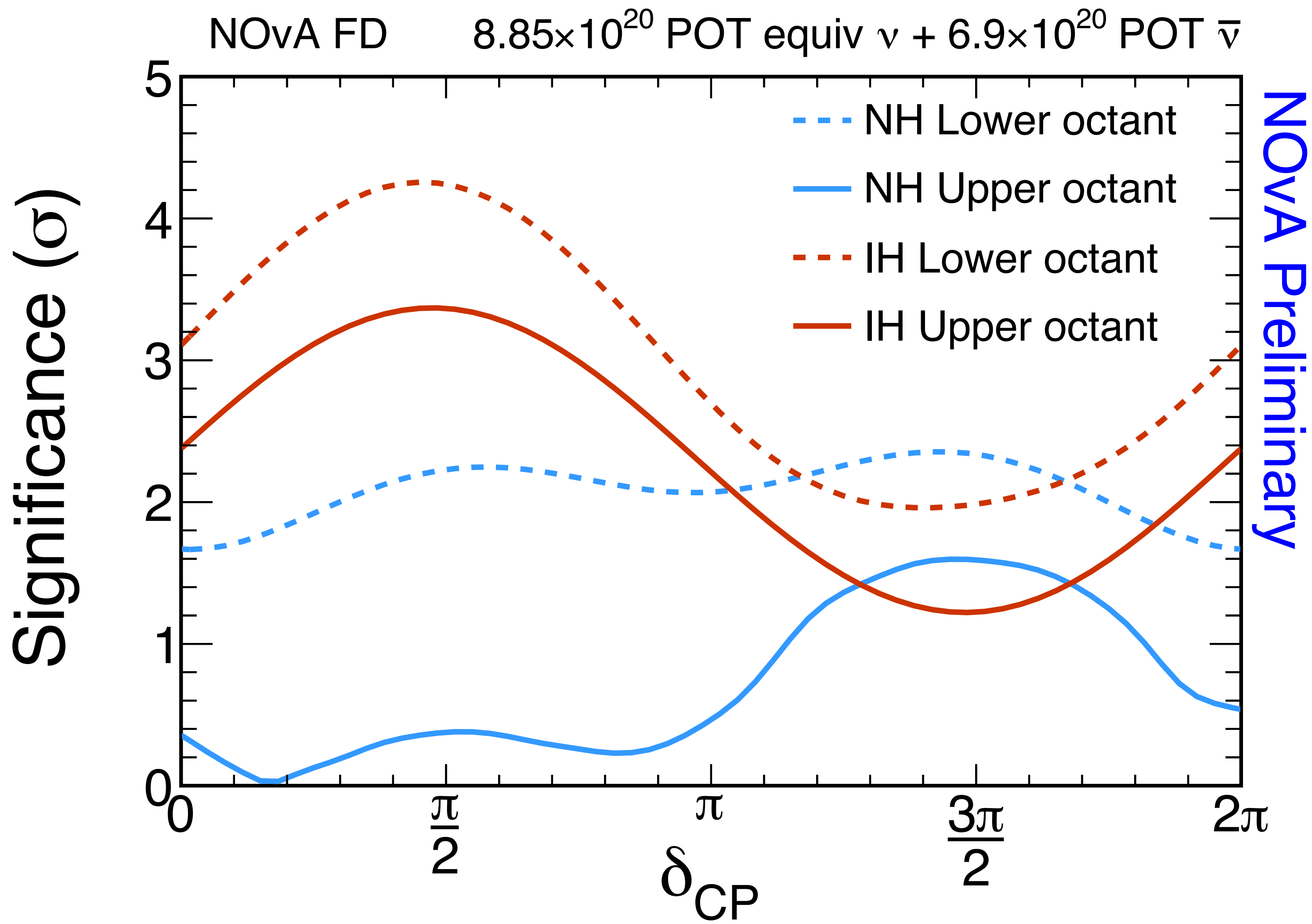


Antineutrino mode:
18 events observed
w/ 5.3 expected backgrounds

> 4σ evidence of electron antineutrino appearance

NOvA δ_{cp} and NH results

Mayly Sanchez, Neutrino 2018
DOI: 10.5281/zenodo.1286758



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$\sin^2\theta_{23}$ = 0.58±0.03 (UO)

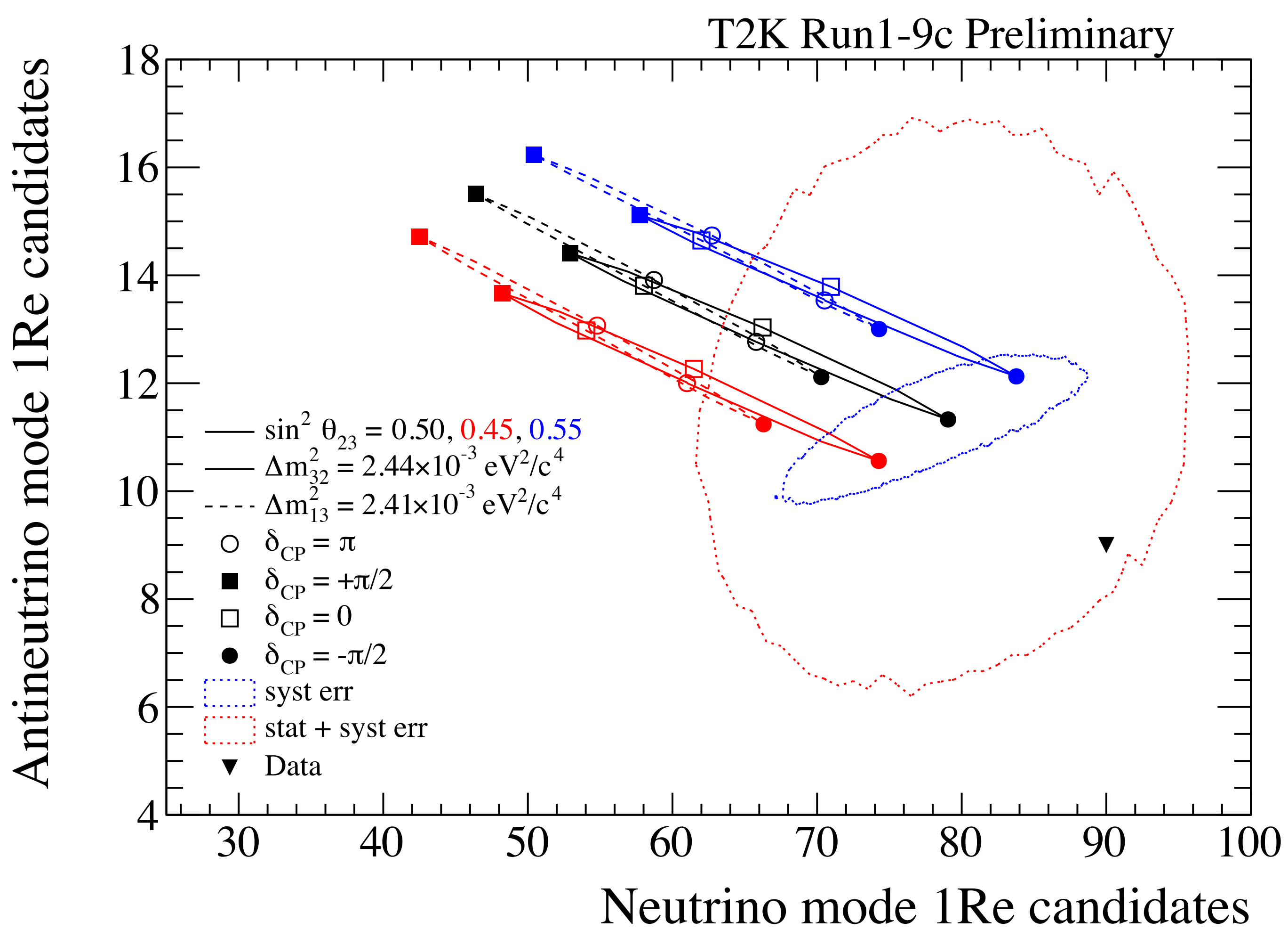
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08})\cdot 10^{-3}\ eV^2$

Prefer NH by 1.8σ

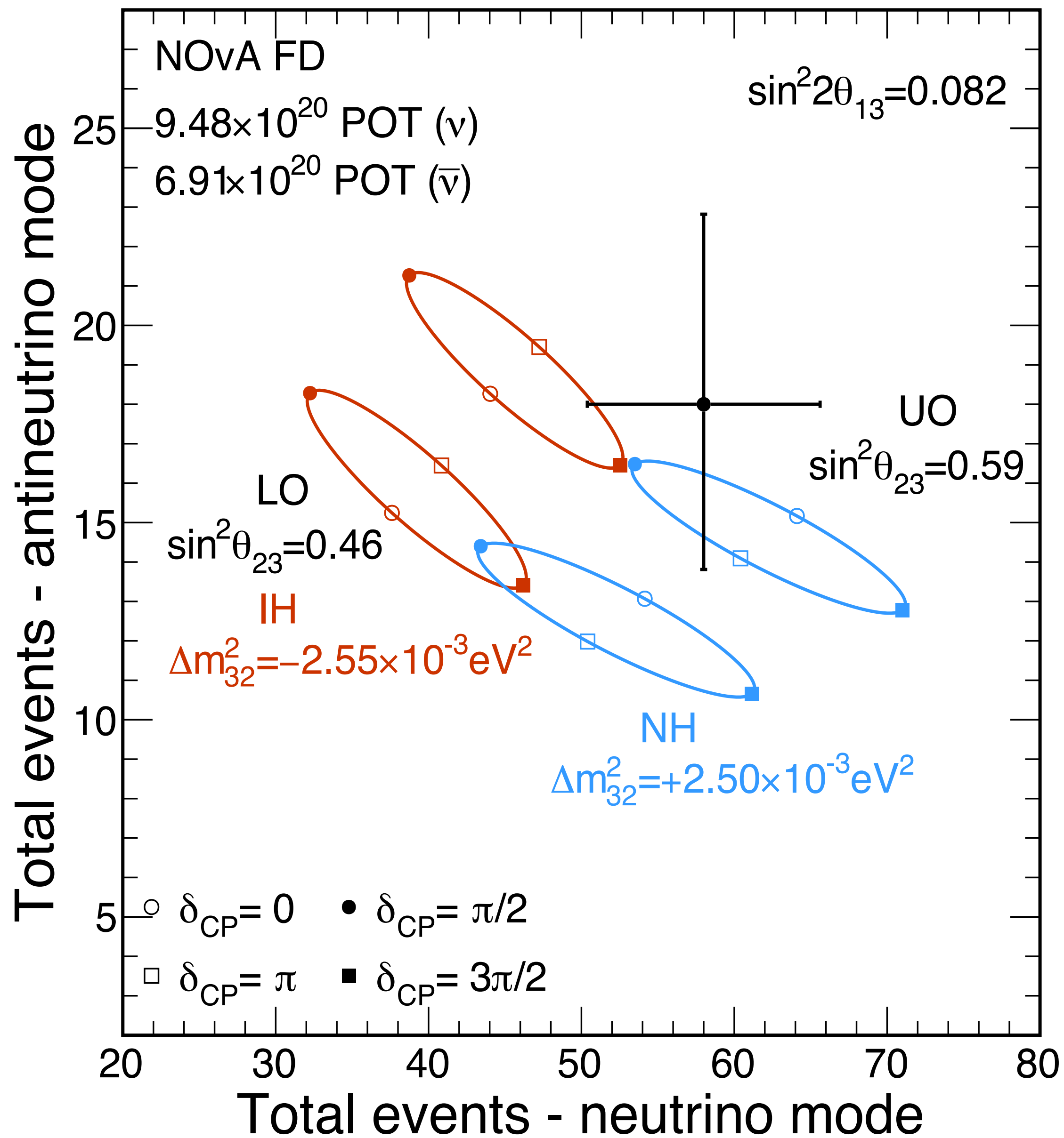
Exclude δ=π/2 in the IH at > 3σ

T2K and NOvA appearance samples

T2K



NOvA



Stay tuned for how those evolves with more statistics and improved analyses!

Near future prospects

- Joint T2K-NOvA analysis
- T2K extension and its near-detector upgrade
- Super-K upgrade with Gd loading

Joint T2K-NOvA analysis

- Aiming to produce full joint oscillation analysis by 2021
- Preparing for a joint working group; three workshops held so far.

T2K | Home | News | About T2K | About Neutrinos | Photos | Videos | Contact

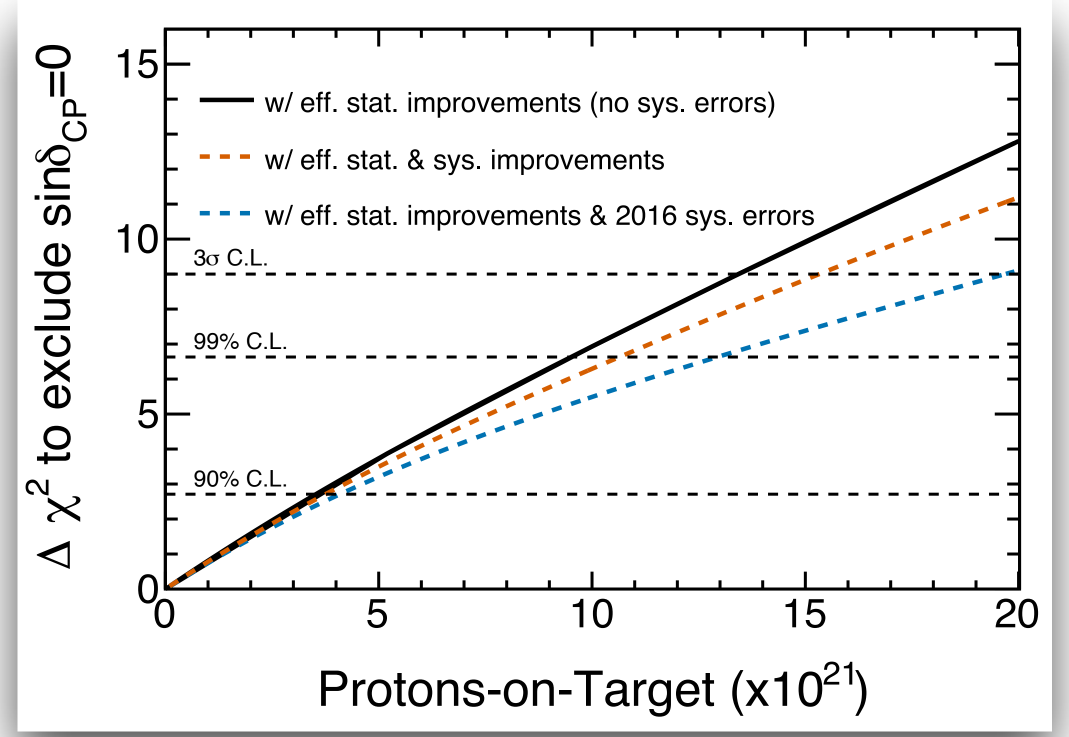
T2K and NOvA collaborations to produce joint neutrino oscillation analysis

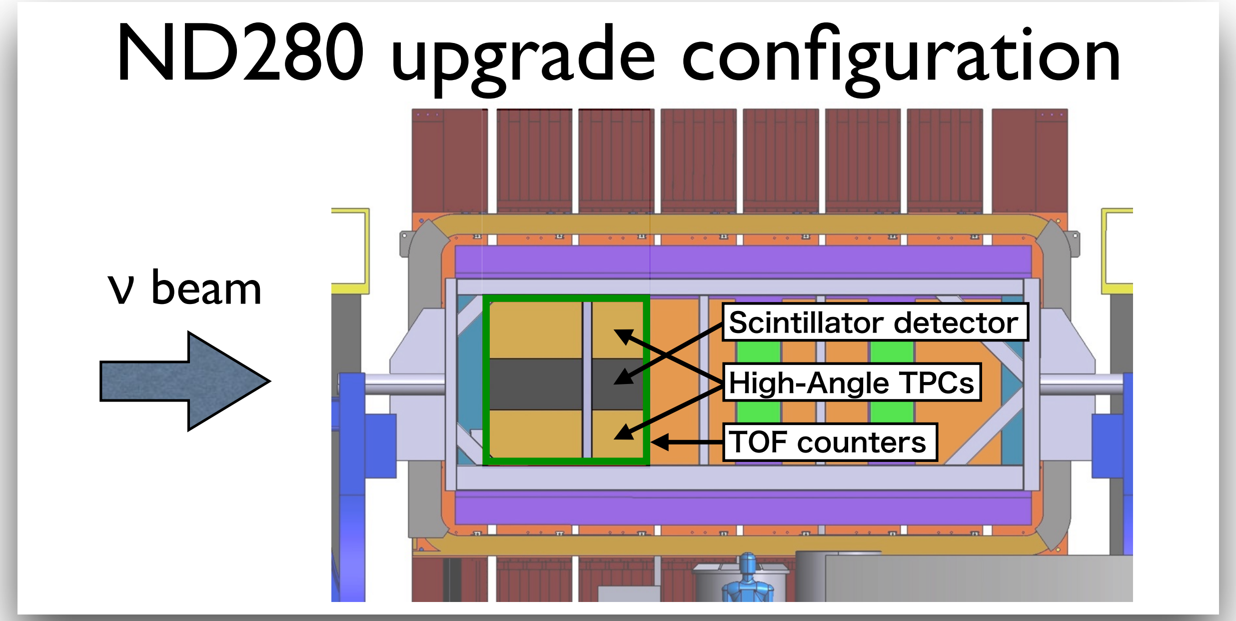
January 30, 2018

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually. The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.

T2K extension and upgrades

- T2K phase-II
    - Proposal to collect 20 x 10^{21} POT (stage-1 approved by KEK/J-PARC)
    - Will have > 3σ sensitivity for CPV
- Beam upgrade towards 1.3 MW beam power
- Near-detector upgrade
    - Required for further reducing systematics down to ~4%
    - Aiming for installation in 2021



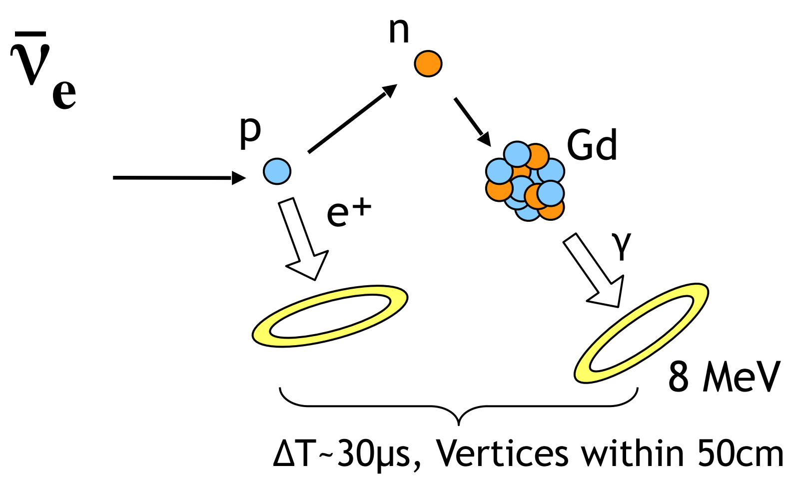


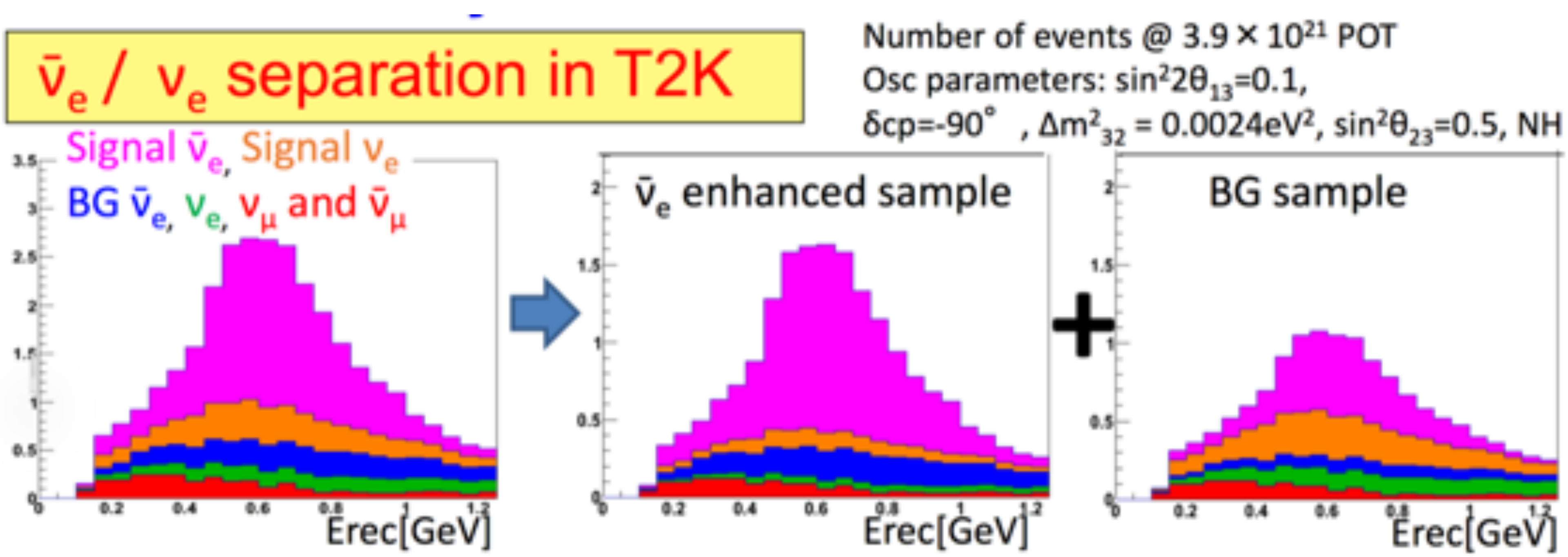
Super-K upgrade w/ Gd loading

SK-Gd project

J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110

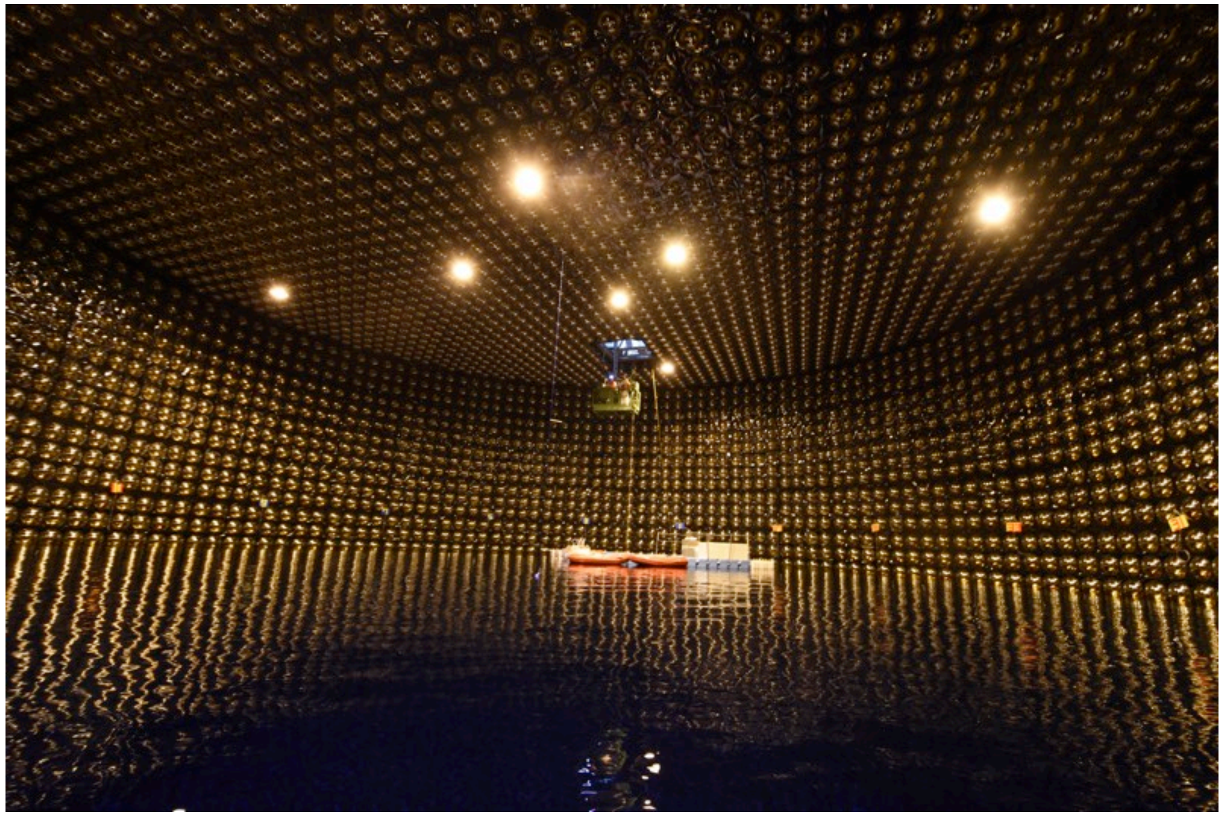
- Loading Gd to the SK pure water to enhance neutron detection capability
  - ~90% Gd capture probability with 0.1% Gd loading
- Primary goal is to detect supernova relic neutrinos
- Could also benefit T2K with:
  - Improved neutrino-antineutrino separation
  - Improved energy reconstruction
  - Improved measurement neutrino interaction





SK-Gd status

- To realize SK-Gd, a major refurbishment of the SK tank started on May 31, 2018
- The tank was opened for the first time in 12 years for:
    - Leak fixing
    - Water piping upgrades
    - PMT replacements
- Major part of refurbishment finished and started filling pure water again
- New water system for SK-Gd is now being commissioned
- Planning ongoing for initial loading of 0.01% Gd (corresponds to ~10 tons of $Gd_2(SO_4)_3$)



Summary

- Discussed recent results from the two leading long-baseline neutrino oscillation experiments: T2K and NOvA
- Interesting hints for δ_{cp}, MH and θ_{23} octants from both experiments.
- A lot more to come, including:
  - NOvA-T2K joint analysis
  - T2K upgrades
  - Gd loading to Super-K
  - And many more!

Stay tuned for the future results!