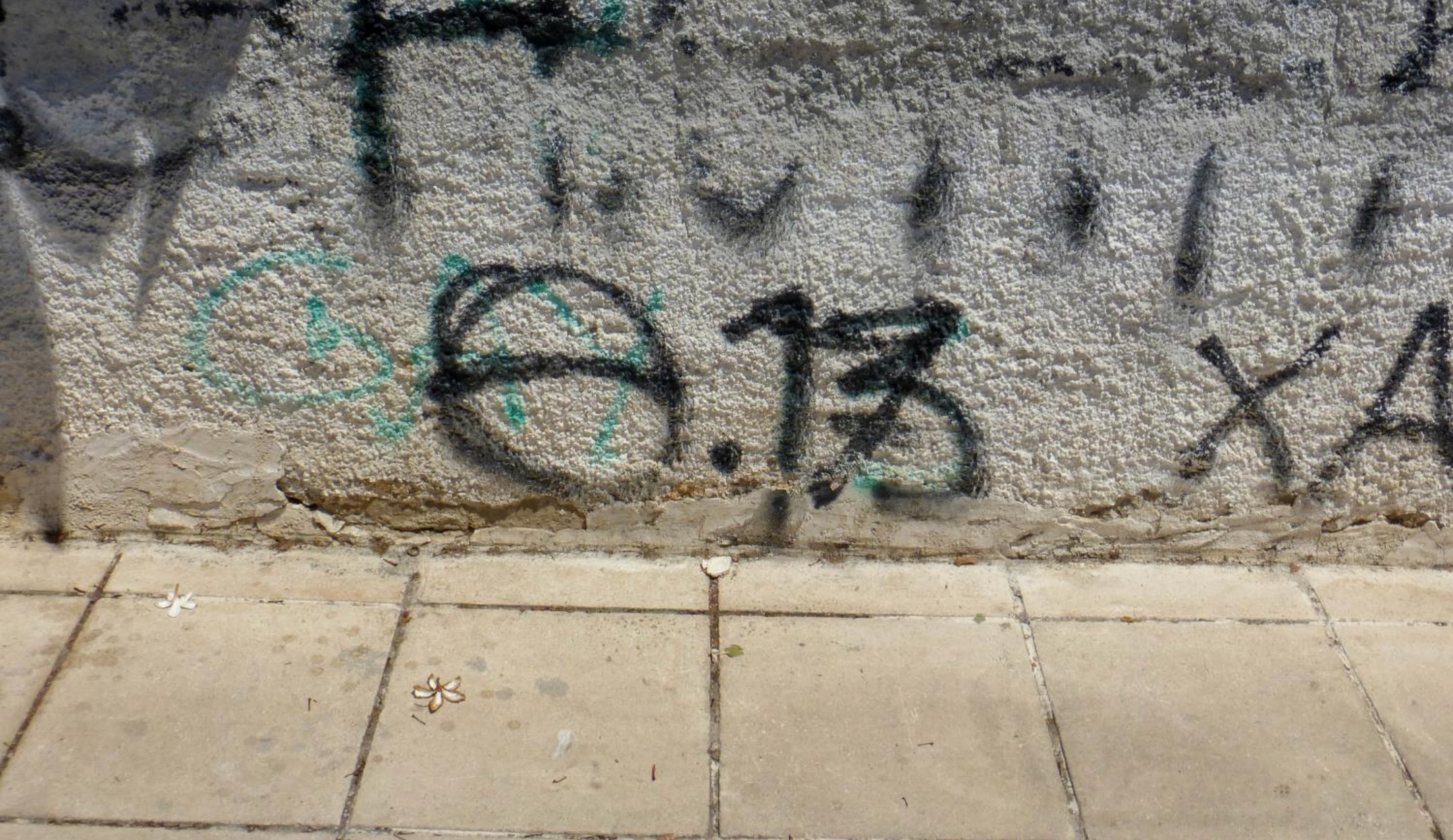
Latest results from the T2K neutrino experiment

Dean Karlen / University of Victoria & TRIUMF
Representing the T2K collaboration

7th International Conference on New Frontiers in Physics, Crete

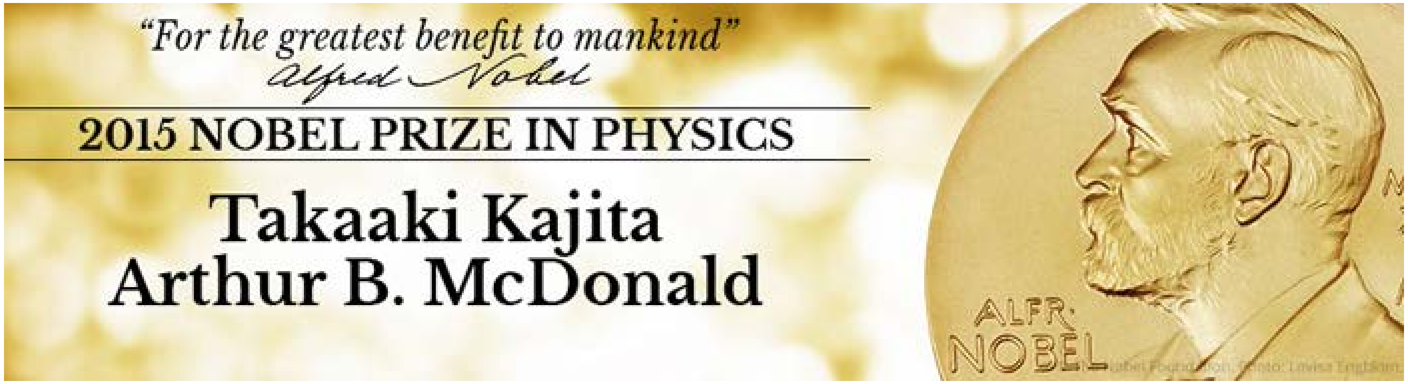


Introduction to lepton mixing

Lepton mixing

Measurements of natural neutrinos (atmospheric and solar) by the Super-Kamiokande and Sudbury Neutrino Observatory experiments established that:

- leptons mix
- neutrinos have mass



Lepton mixing

Lepton mixing is described by the PMNS matrix

- Each flavour state is a linear combination of mass states:

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

Flavour state
$\alpha = e, \mu, \tau$

PMNS lepton
mixing matrix

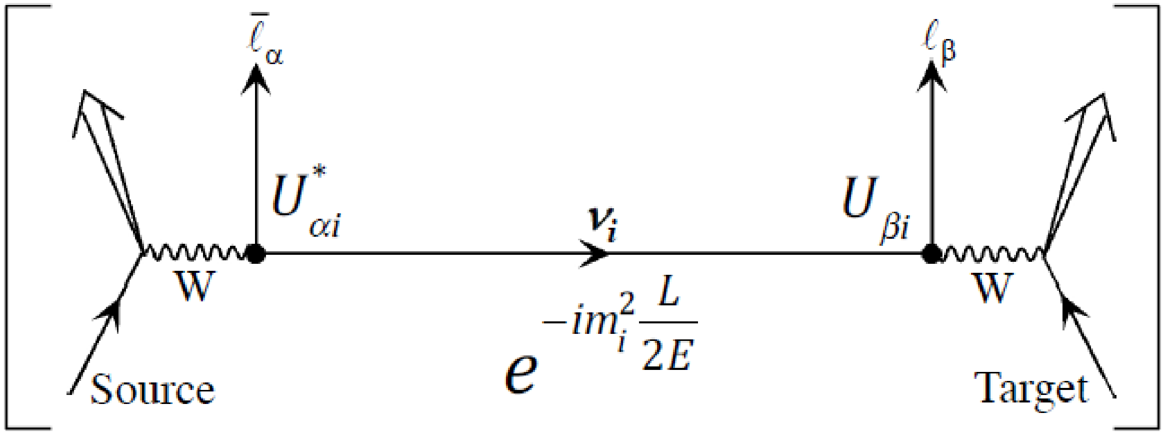
Mass state
i= $1, 2, 3$

Because of this mixing, a neutrino produced with a definite flavour can be detected as another flavour: neutrino oscillation…

Lepton mixing

The vacuum amplitude for neutrino flavour change is

$$\text{Amp}\left(\nu_\alpha \to \nu_\beta\right) = \sum_i \text{Amp}$$



B. Kayser

$$= \sum_i U^*_{\alpha i}\, e^{-im_i^2 \frac{L}{2E}}\, U_{\beta i}$$

Lepton mixing

The vacuum probability for neutrino flavour change is

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

- Oscillation implies non-degenerate neutrino masses
- Probability depends on baseline (L) and neutrino energy (E)

Lepton mixing

The PMNS matrix is usually parameterized as:

"Atmospheric" "Solar"

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

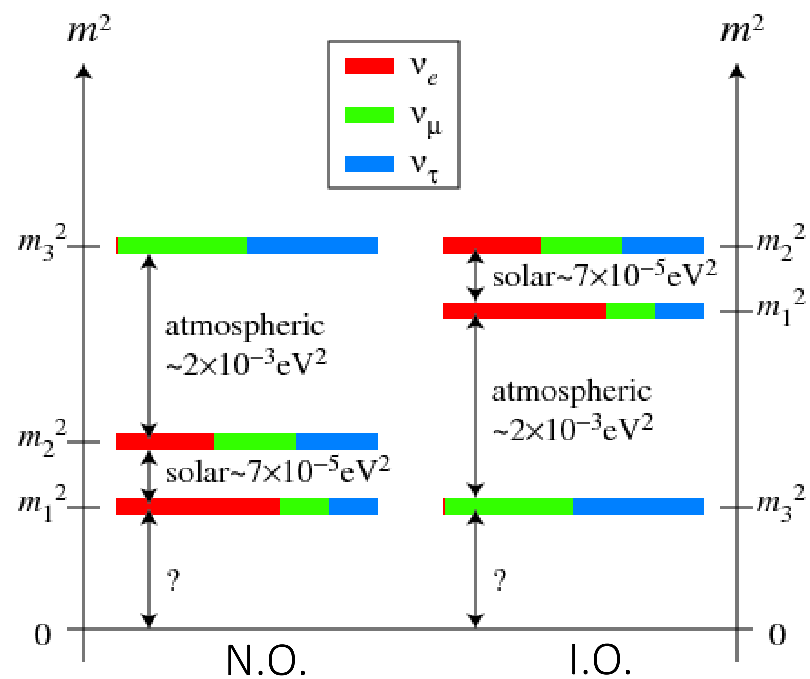
$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

Two mass scales found:

- Two possible mass orderings

  Normal Ordering (N.O.)

  Inverted Ordering (I.O.)



Experiments with artificial neutrinos

Experiments with artificial neutrinos

Experiments with artificial neutrinos have improved measurements of lepton mixing in the past decade:

Reactor experiments

- Daya Bay, Reno, Double Chooz

Long baseline neutrino beam experiments

- K2K, T2K, Minos, NOvA

Established that mixing is complete ($\sin\theta_{13} \neq 0$)

Not yet established the mass ordering and whether there is CP violation:

- If $\sin\delta_{\mathrm{CP}} \neq 0$ then $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

Experiments with artificial neutrinos

Schematic for the "best design":

- parallel beam of mono-energetic neutrinos of one flavour
- two identical detectors, unambiguous charged-lepton id
- adjustable energy or distance to map out mixing parameters

$$P(\nu_\alpha \to \nu_\beta | L, E) = \frac{N_\beta^{\text{far}}}{N_\alpha^{\text{near}}} \times \frac{\phi^{\text{near}}}{\phi^{\text{far}}} \frac{\sigma_\alpha}{\sigma_\beta} \frac{\varepsilon_\alpha}{\varepsilon_\beta} = \frac{N_\beta^{\text{far}}}{N_\alpha^{\text{near}}} \times \frac{\sigma_\alpha}{\sigma_\beta} \frac{\varepsilon_\alpha}{\varepsilon_\beta}$$

$\rightarrow$ small or zero systematic uncertainty from neutrino flux (ϕ), cross sections (σ), and detector efficiency (ε)

Experiments with artificial neutrinos

parallel beams not possible:

- after production, neutrino direction cannot be controlled
- for long baseline experiments, near/far flux ratio can be O(10^6) – necessitating different detector designs

mono-energetic neutrinos not possible in general:

- must model the neutrino spectrum and accurately estimate the energy of each interacting neutrino
- T2K beam design reduces systematics arising from this:

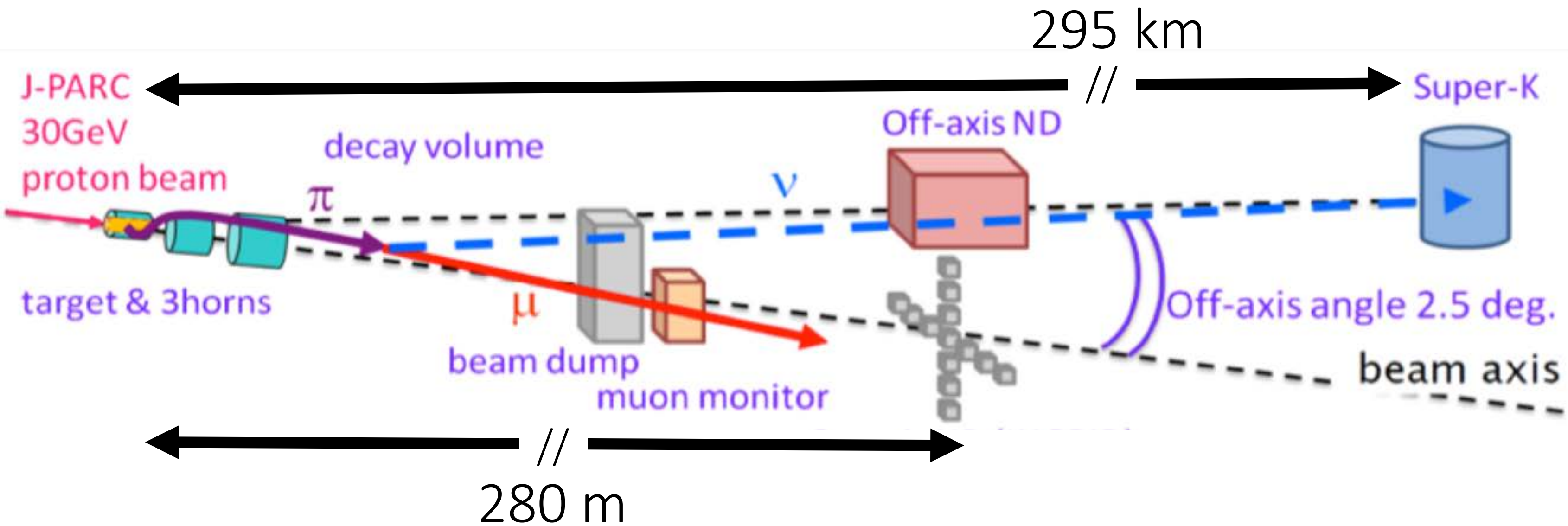
  narrow band beam at energies where quasi-elastic scattering dominates

near and far detector design reduces systematics:

- only need <u>relative</u> fluxes/cross sections/efficiencies

The T2K experiment

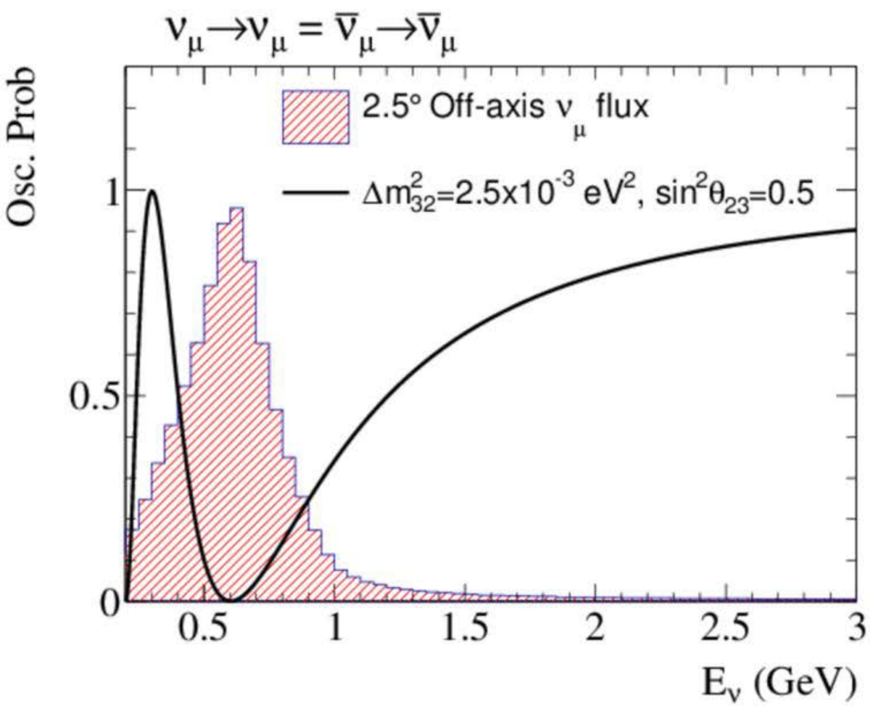
T2K experiment

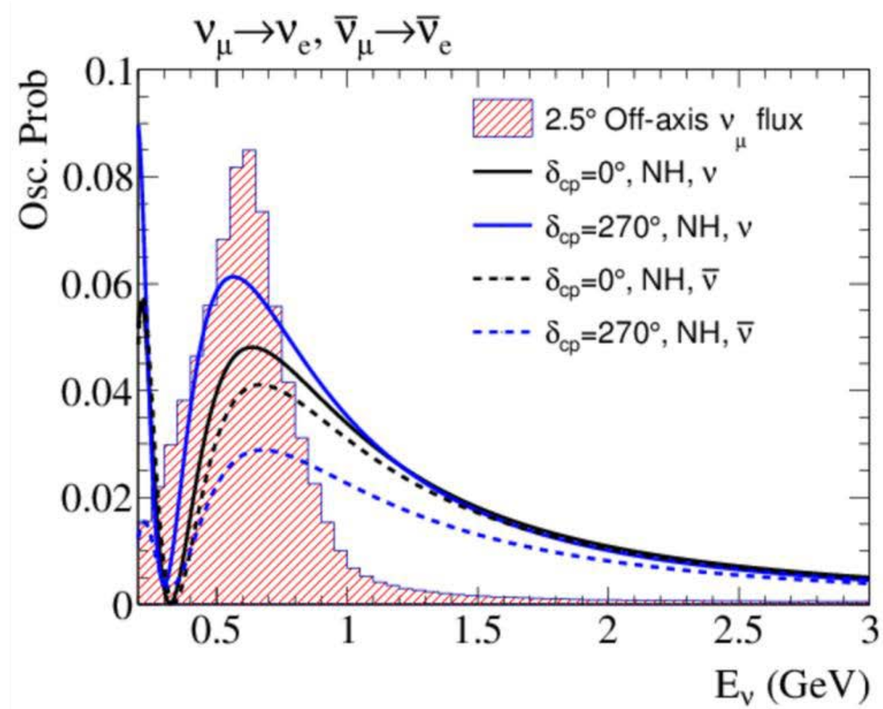


- 30 GeV protons from JPARC strike target to produce hadrons
- $\pi^+(\pi^-)$ [sign-selected by magnetic horns] decay to produce neutrinos (anti-neutrinos) towards Super-Kamiokande
- near detectors measure neutrino properties prior to oscillation
- far detector (SK) measures the effect of lepton mixing

T2K is an “off-axis” experiment

2.5° off axis angle chosen to optimize sensitivity to oscillation parameters for the 295 km baseline

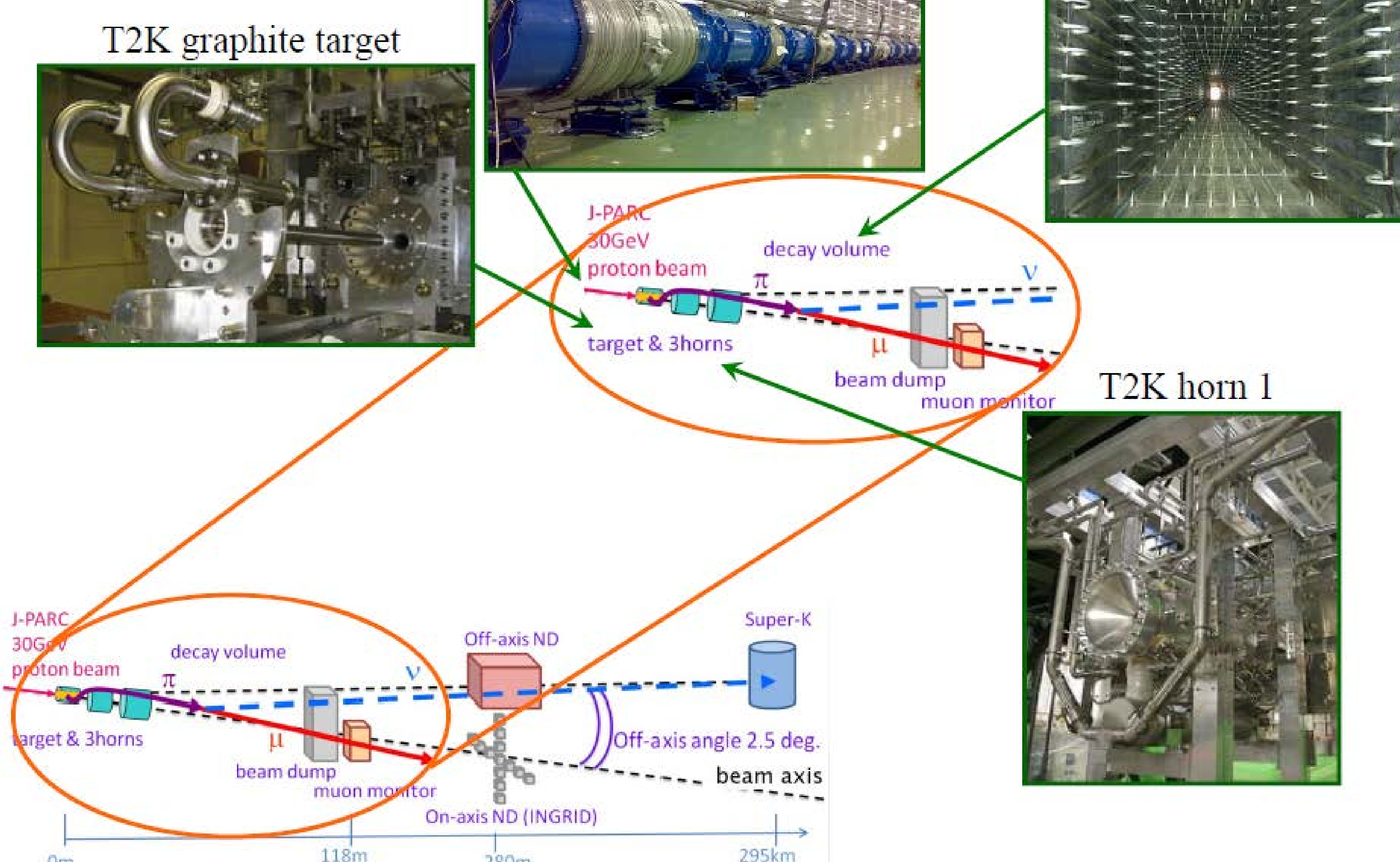




- $P(\nu_\mu \to \nu_e)$ depends on δ_{CP} and to a lesser extent, the mass ordering

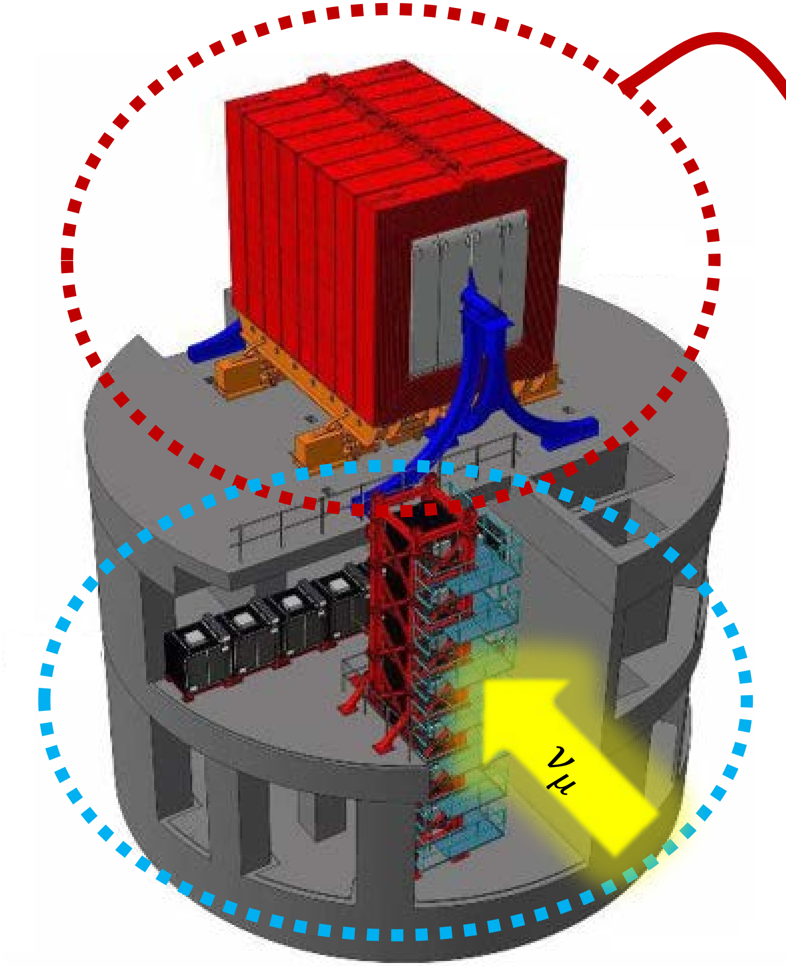
T2K beamline

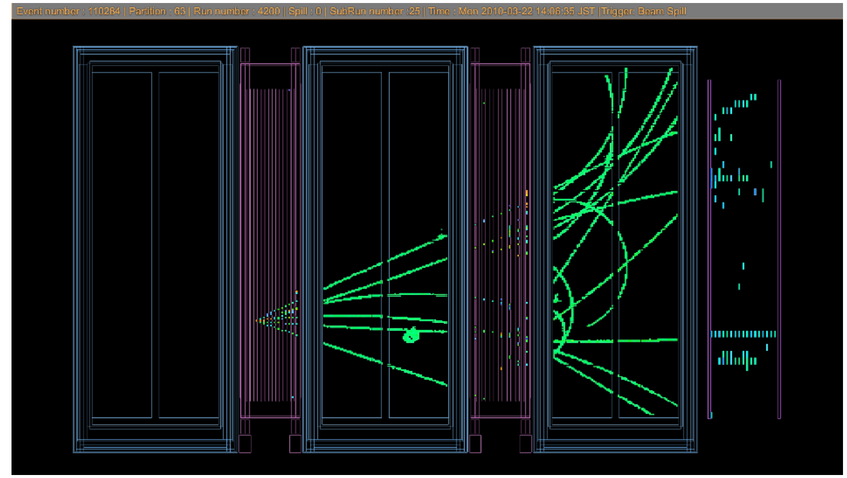
- J-PARC Lab

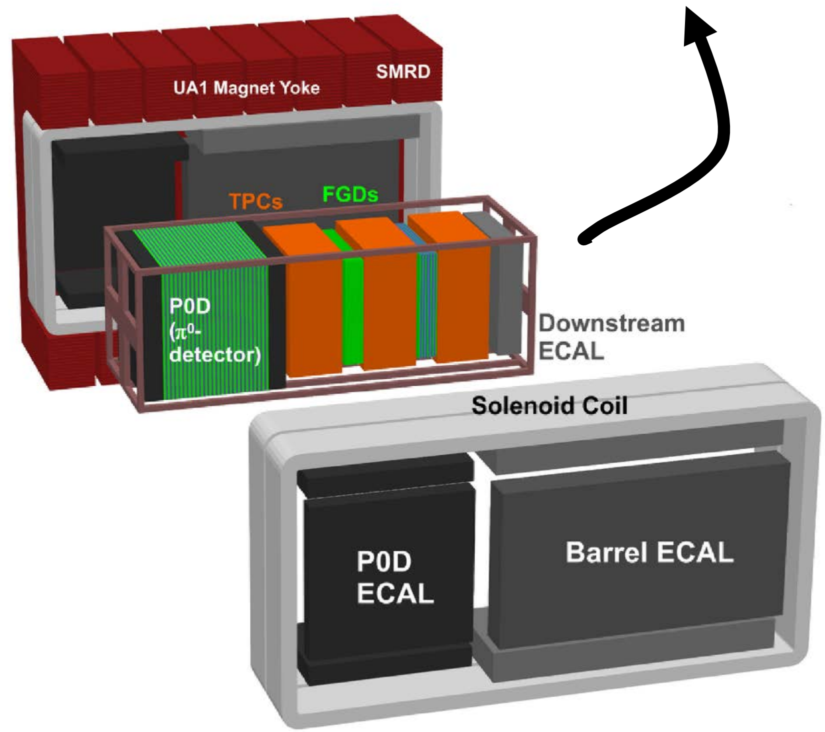


T2K near detectors

ND280 off-axis detector



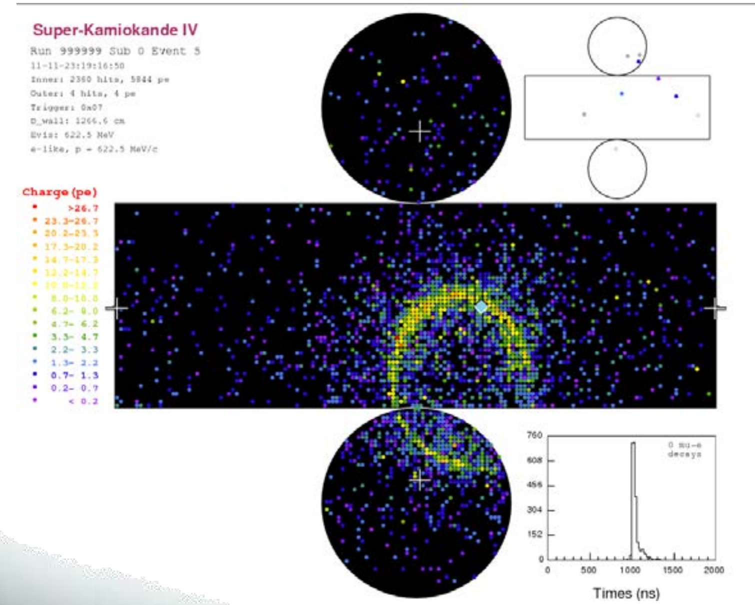


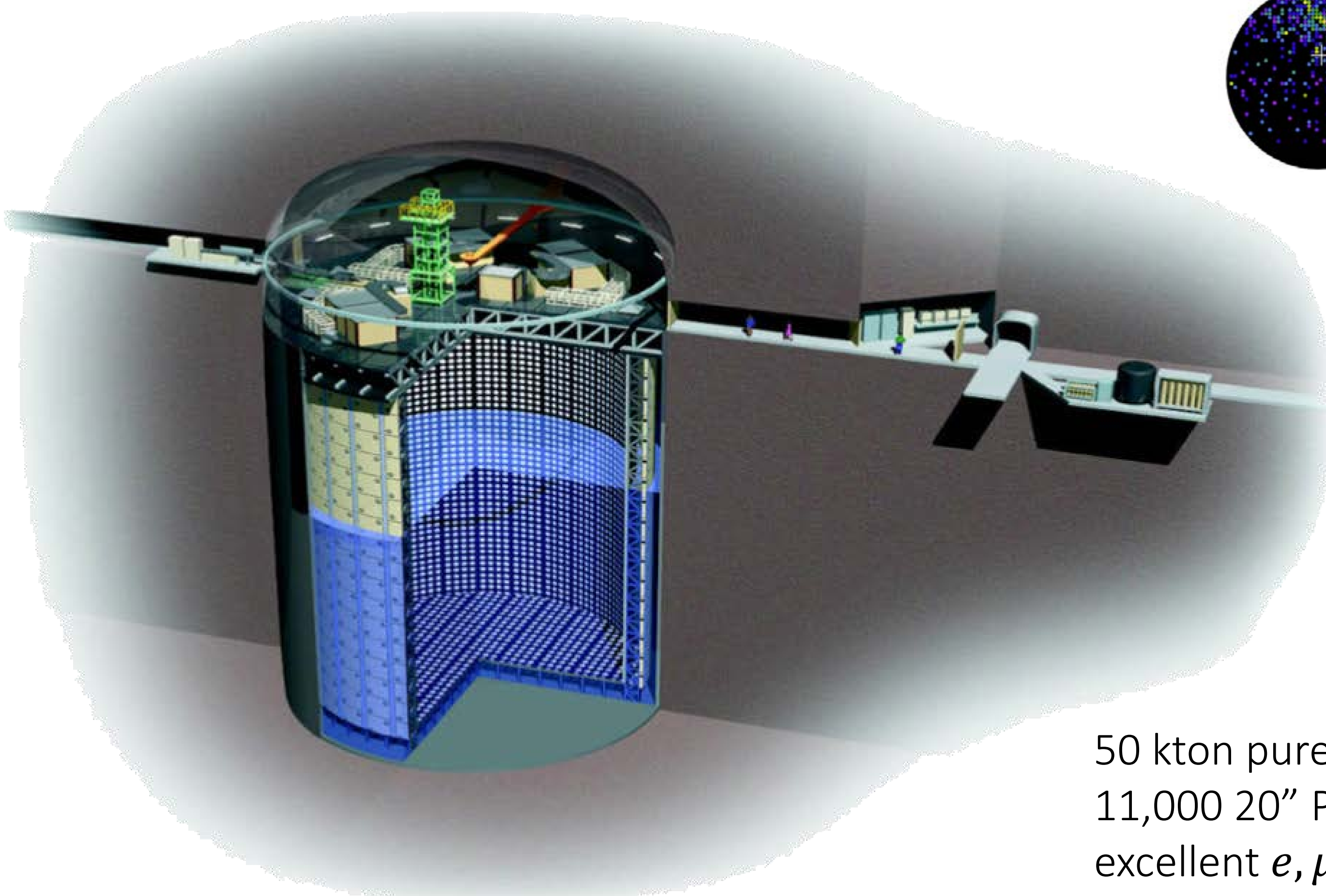


INGRID on-axis detector

T2K far detector

Super-Kamiokande (@295 km)



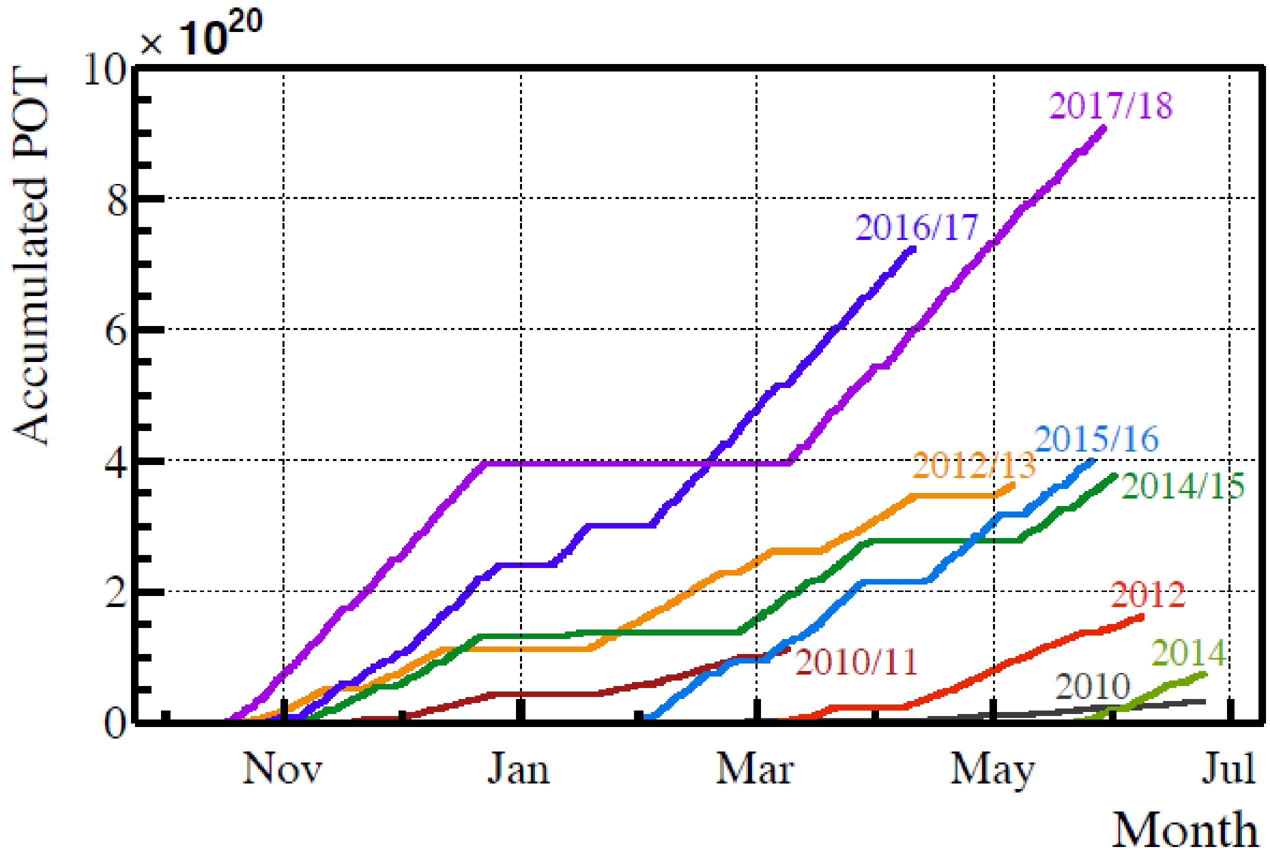


50 kton pure water
11,000 20" PMTs
excellent e, μ separation

T2K data collection

Accumulated number of protons on target (POT)

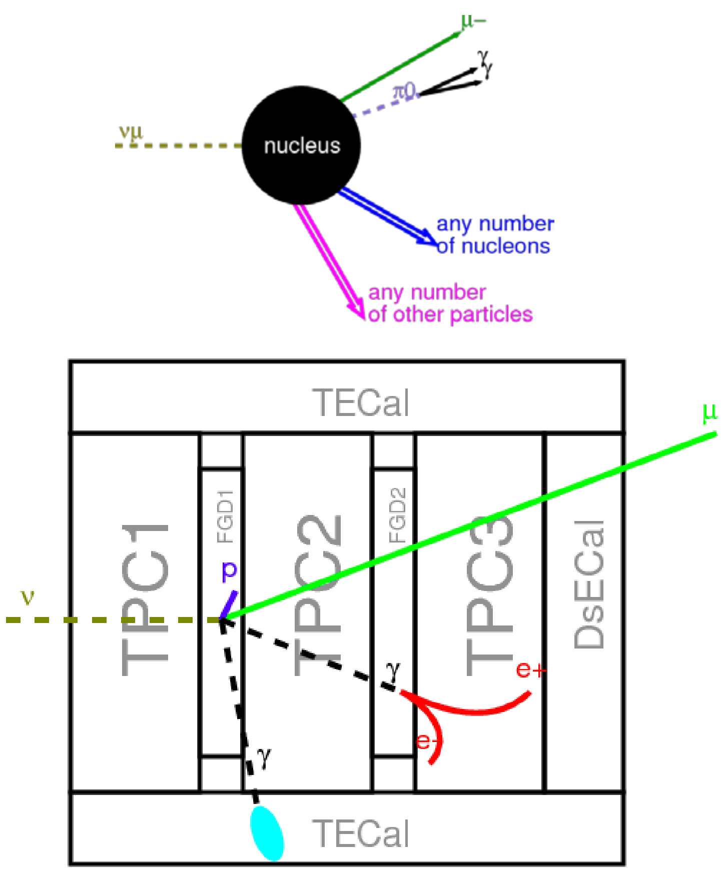
- beam power steadily increasing (achieved 500 kW)
- total: 3.16×10^{21} POT, roughly 50:50 $\nu : \bar{\nu}$ modes

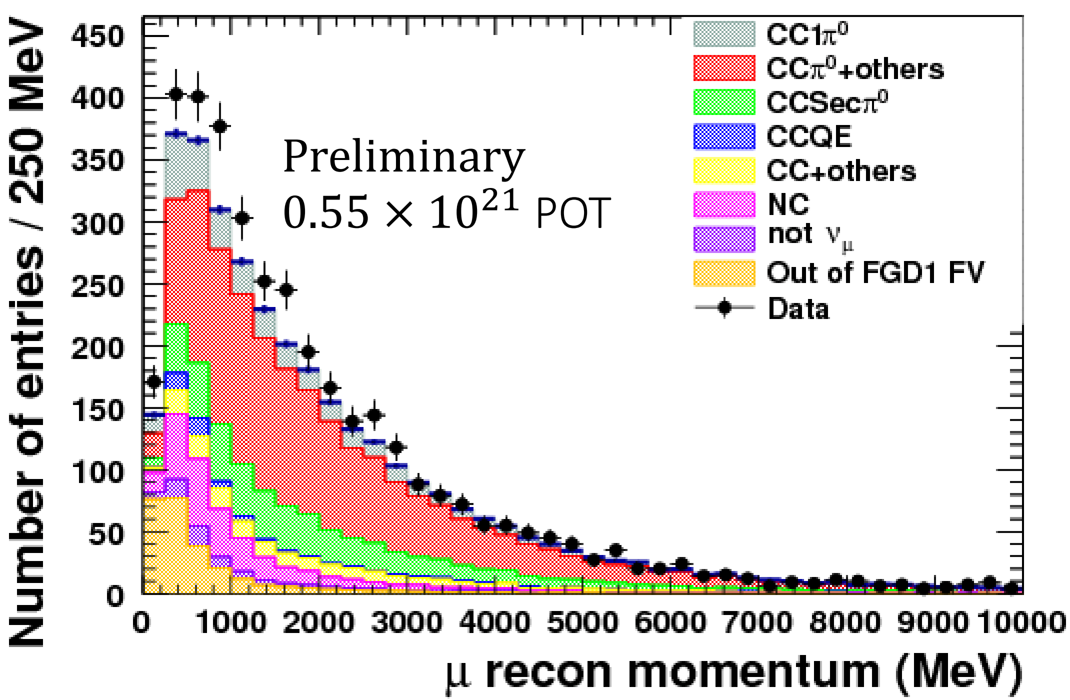


T2K results

T2K ν cross section measurements

Event rate measurements in ND280 test and refine neutrino interaction models. One example:





$$\sigma_{\text{Data}}/\sigma_{\text{NEUT}} = 1.18 \pm 0.03\ (\text{stat})\ ^{+0.22}_{-0.21}\ (\text{sys})$$

T2K ν oscillation analyses

To measure neutrino oscillation we model:

- neutrino flux
- neutrino interactions, and
- performance of the near and far detectors

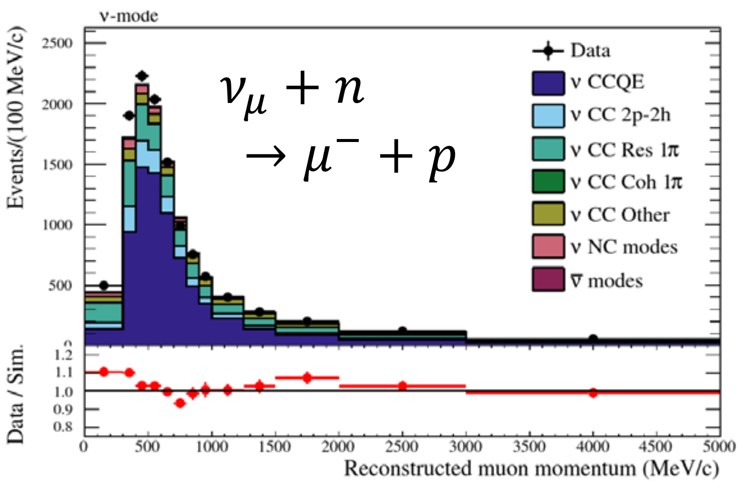
Our models include systematic parameters to encapsulate our uncertainty (both theoretical and experimental)

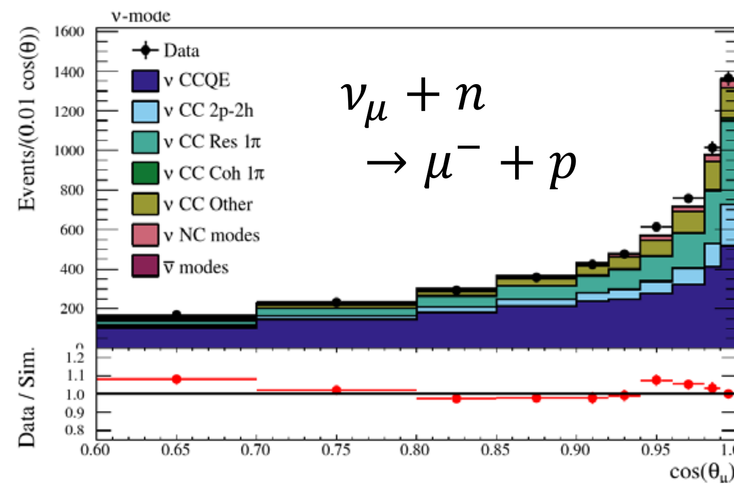
- Some of the systematic parameters are constrained using external data (for example, hadron production measurements by NA61)

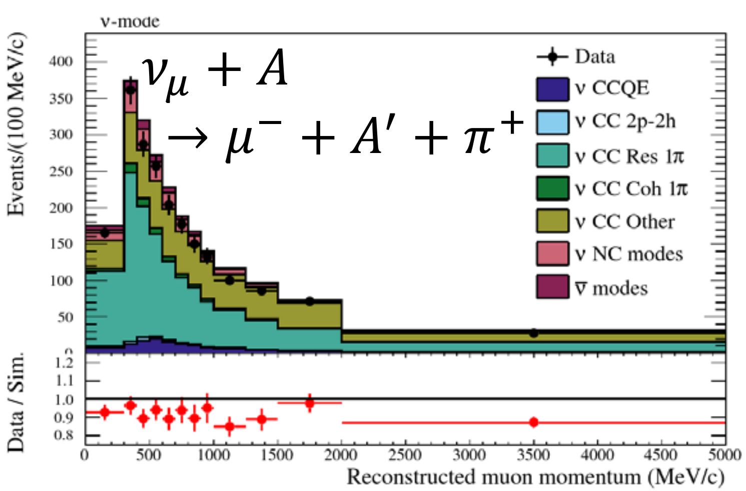
We measure kinematic distributions of the leptons from different categories of neutrino interactions in the near and far detectors to form likelihood functions

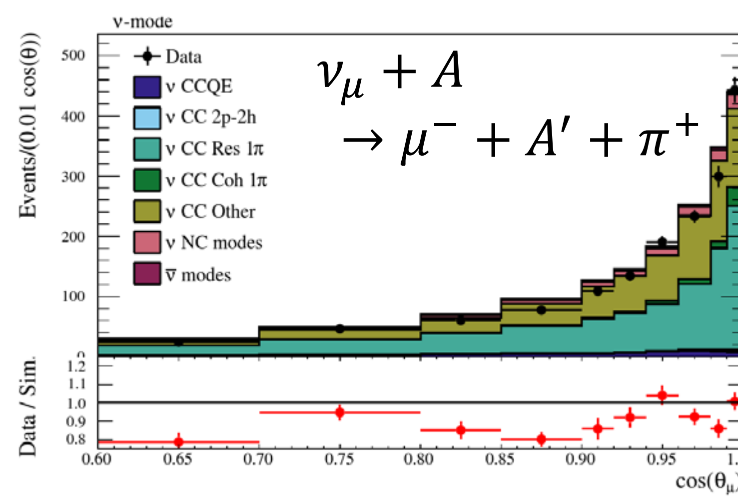
- The functions are used for Frequentist and Bayesian interpretation for the physics parameters while marginalizing over the systematic parameters

ND280 μ^- kinematics (nominal model)





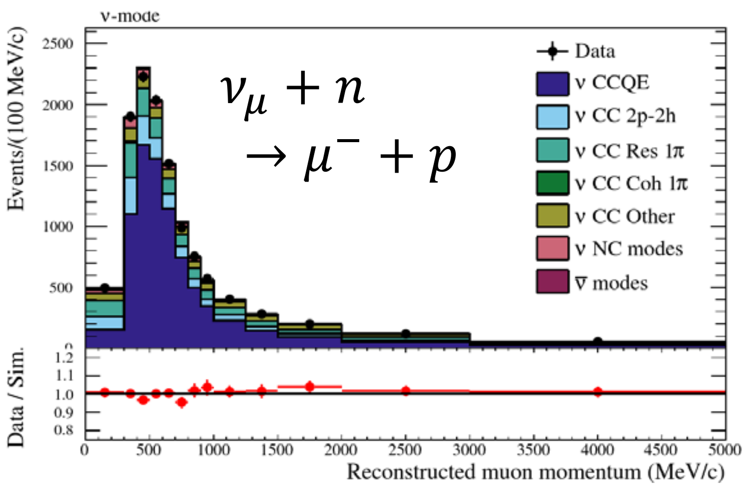


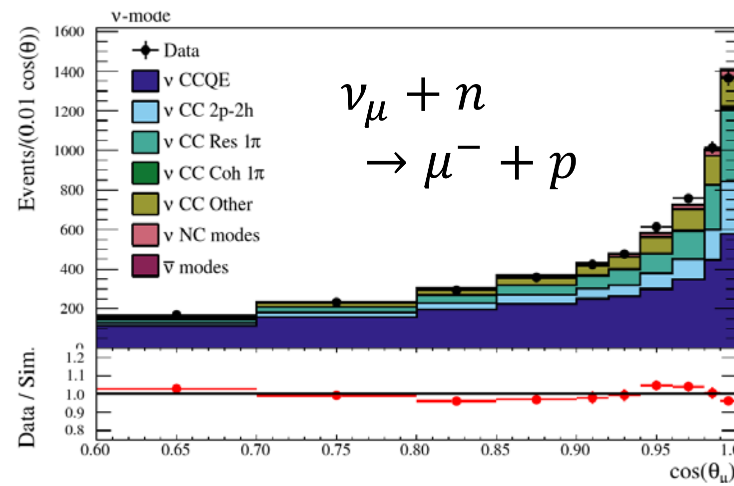


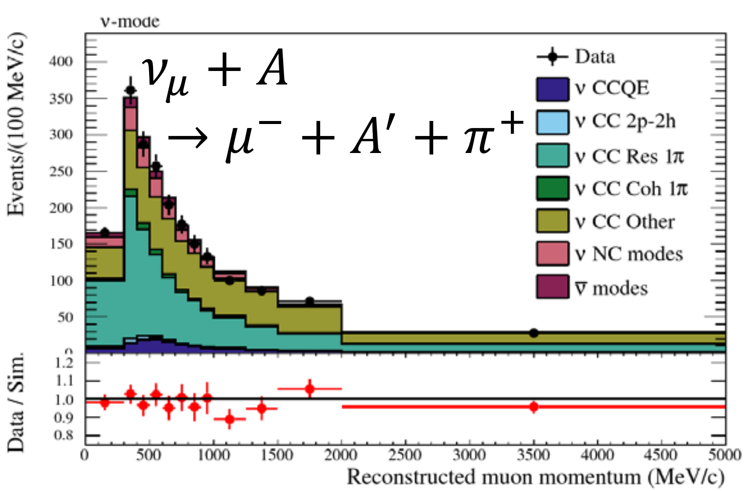
PRELIMINARY p_μ (MeV/c)

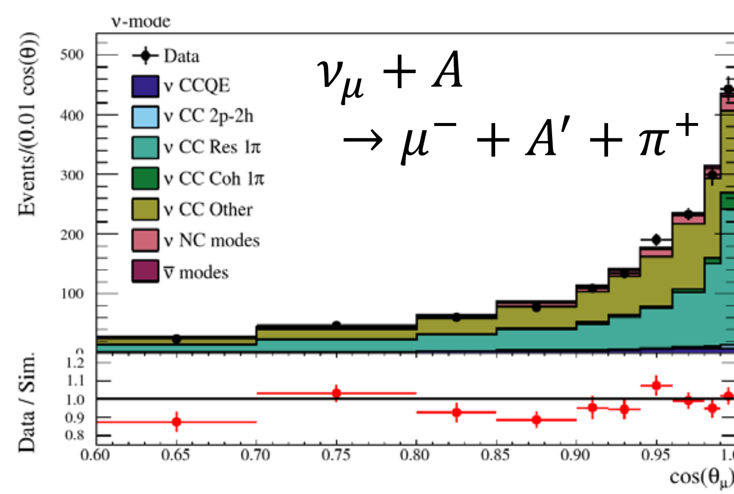
PRELIMINARY $\cos\theta_\mu$

ND280 μ^- kinematics (fitted model)





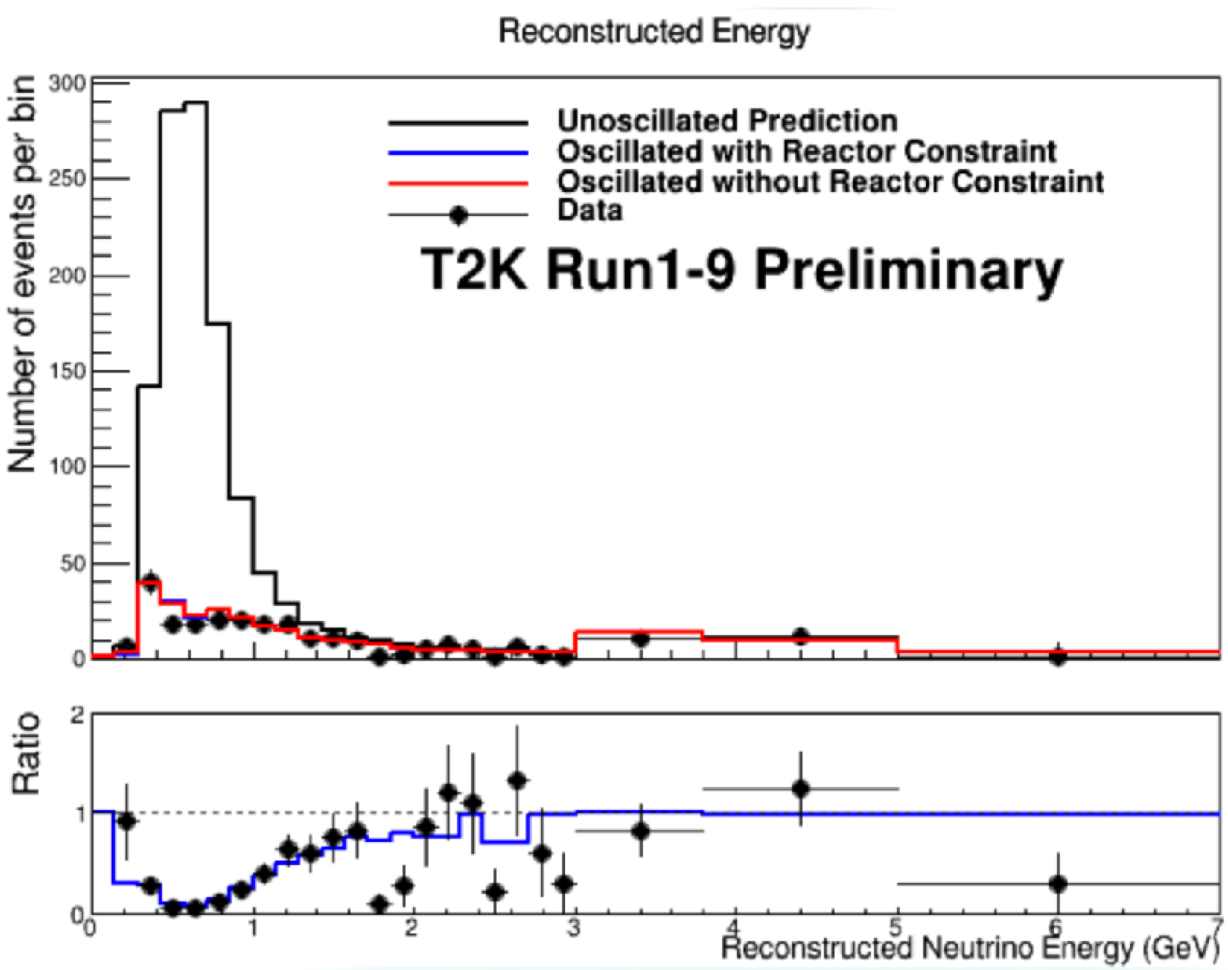




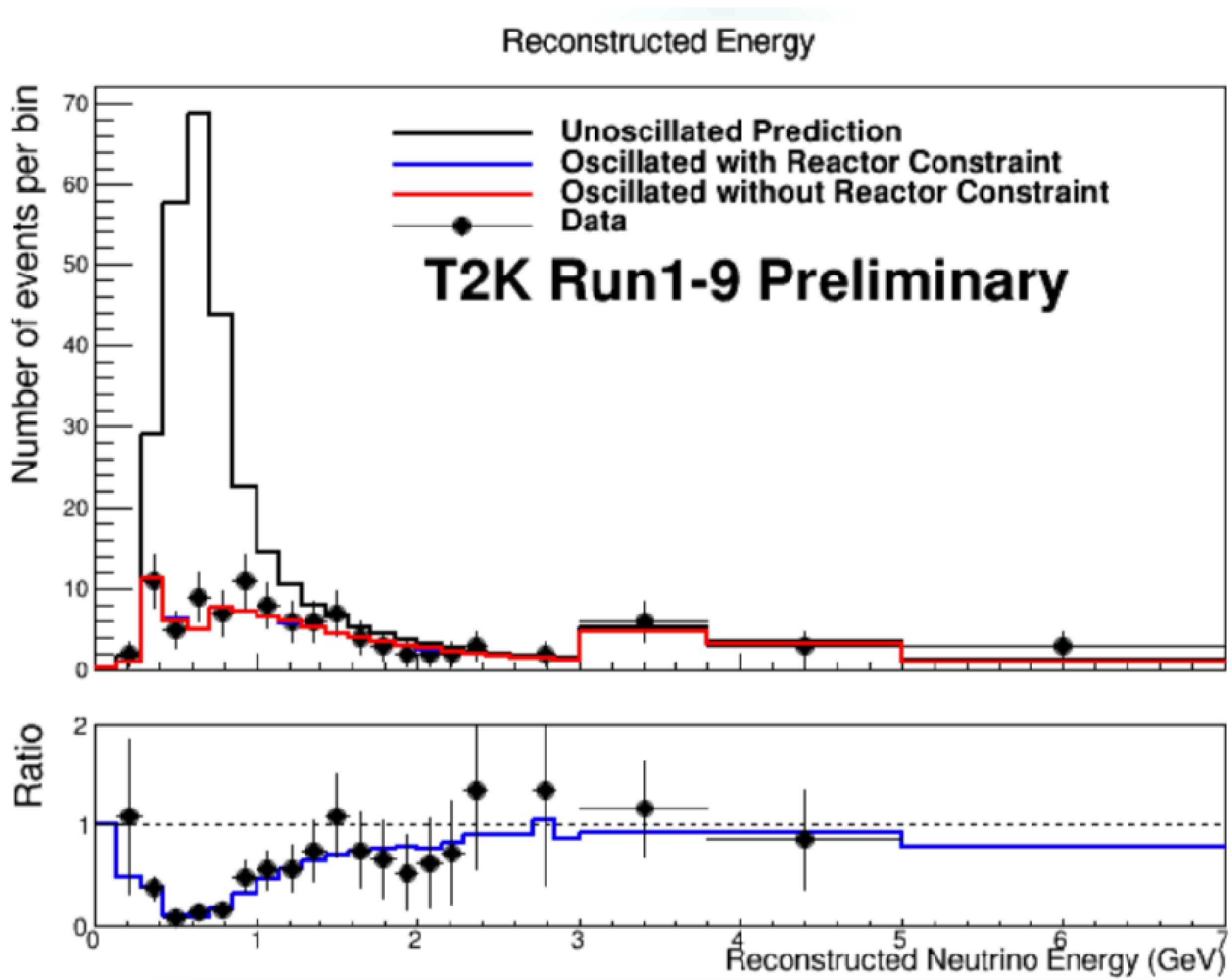
PRELIMINARY p_μ (MeV/c)

PRELIMINARY $\cos\theta_\mu$

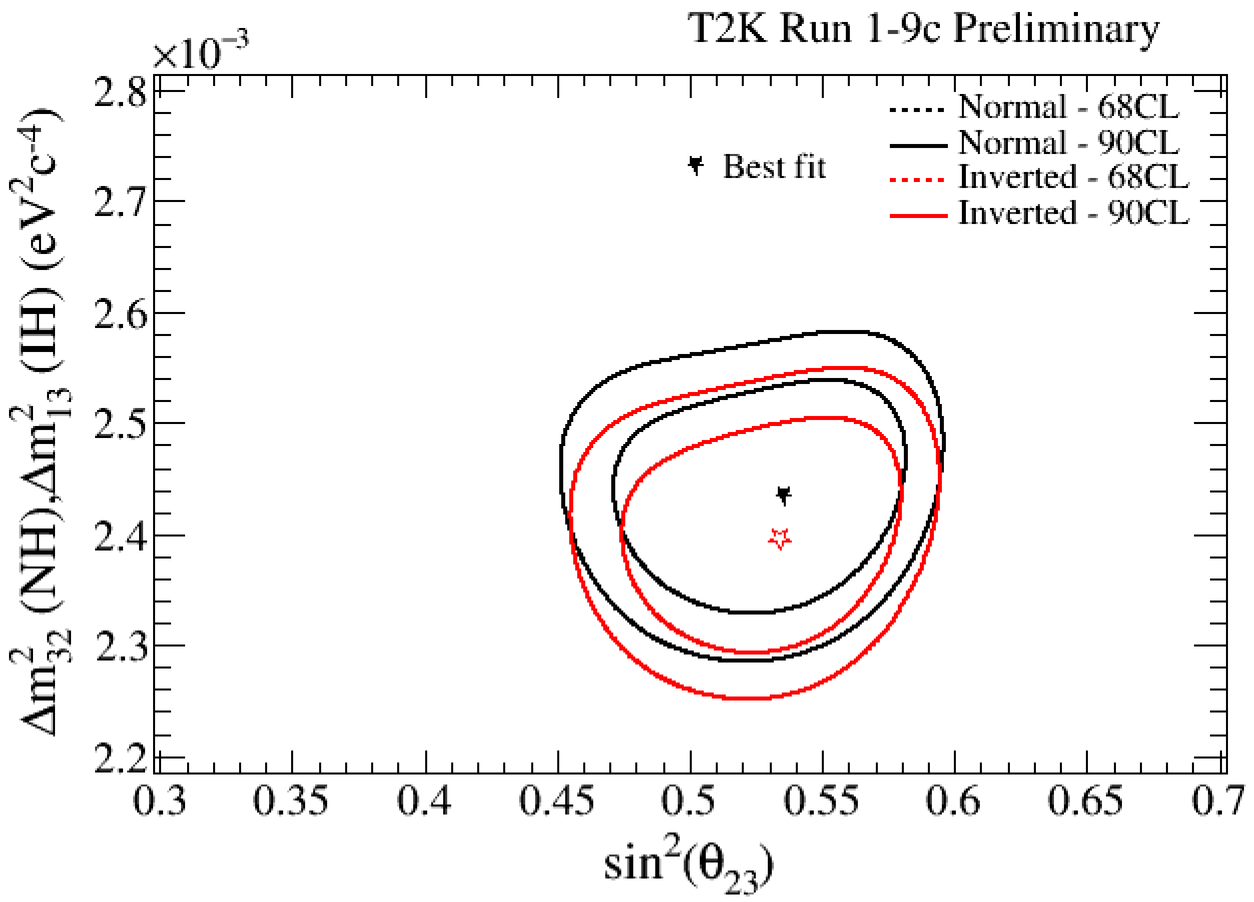
SK ν_μ spectrum (1.49×10^{21} POT)



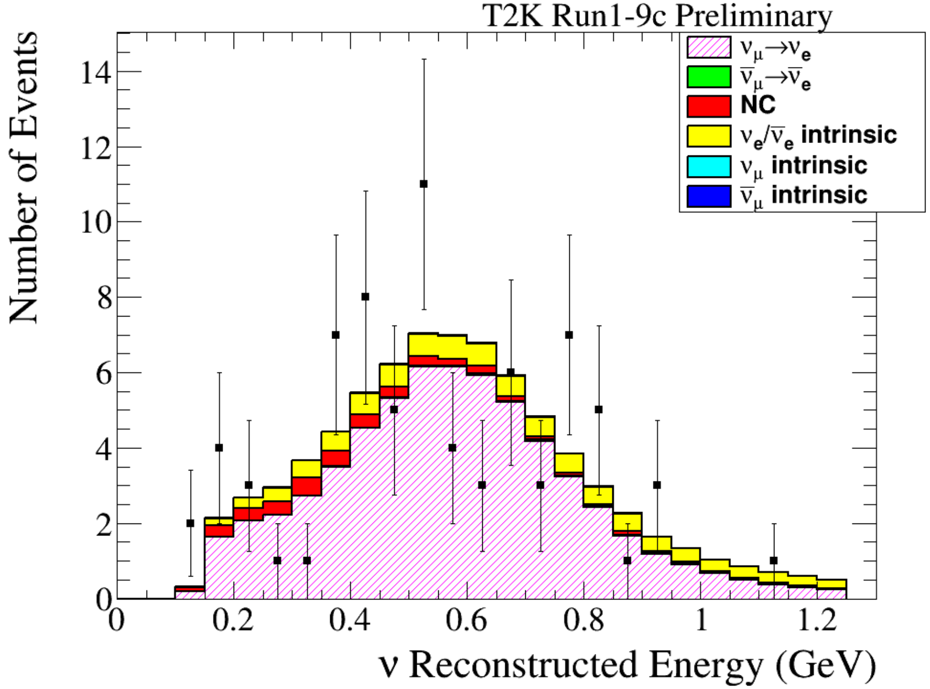
SK $\bar{\nu}_\mu$ spectrum (1.12×10^{21} POT)

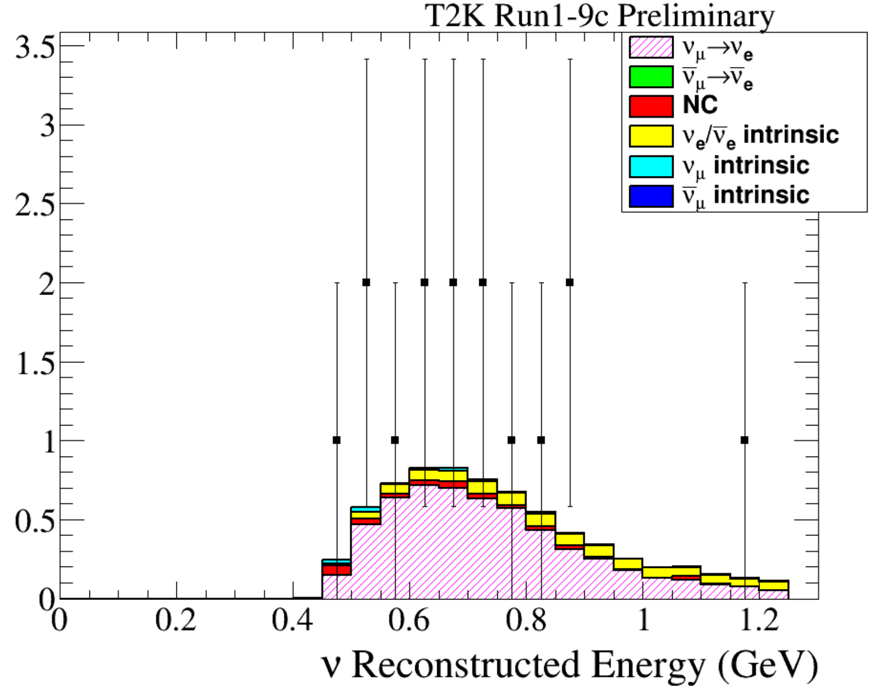


“Atmospheric” oscillation parameters



SK ν_e spectrum (1.49×10^{21} POT)

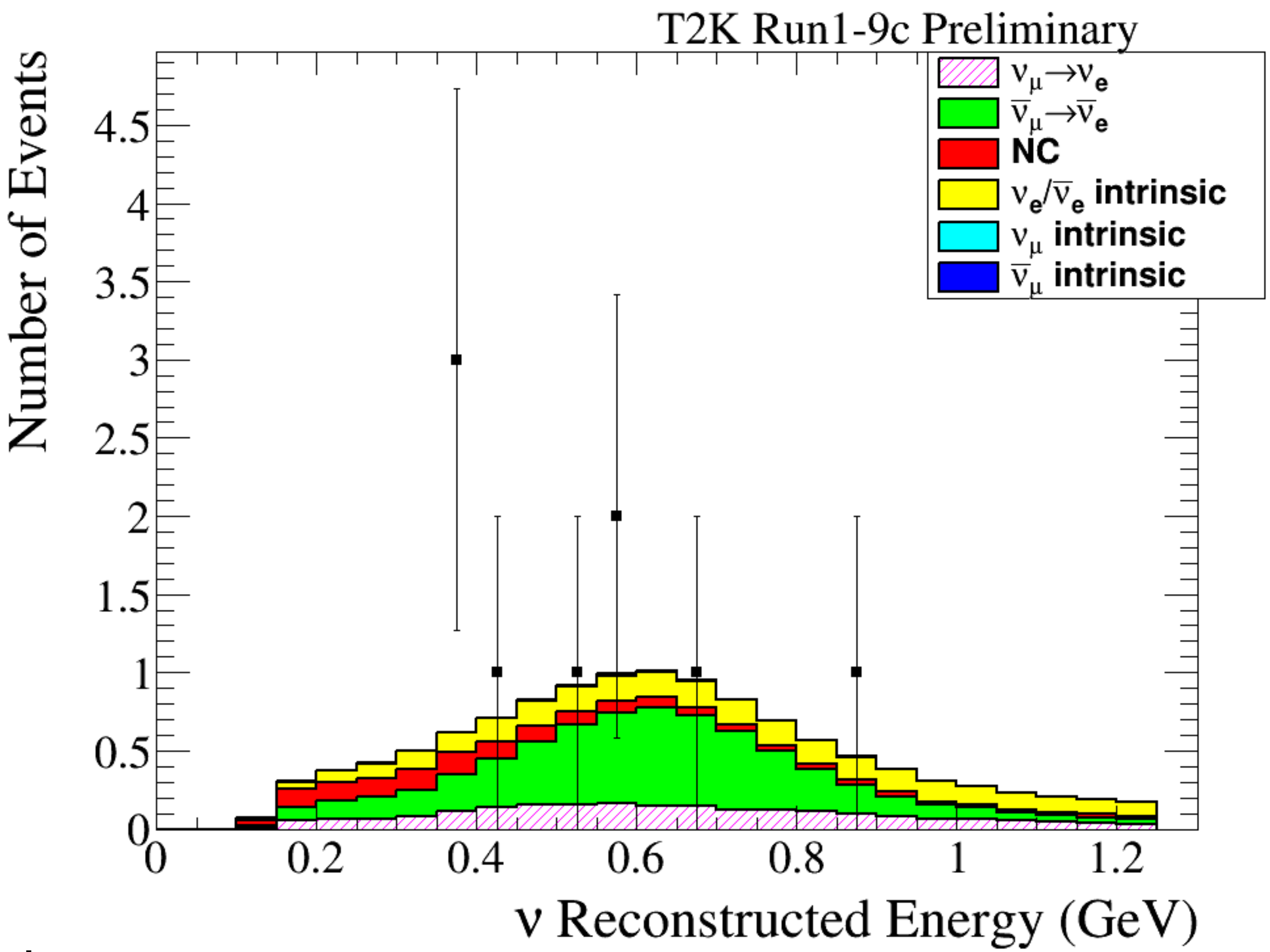




$$\nu_e + n \rightarrow e + p$$

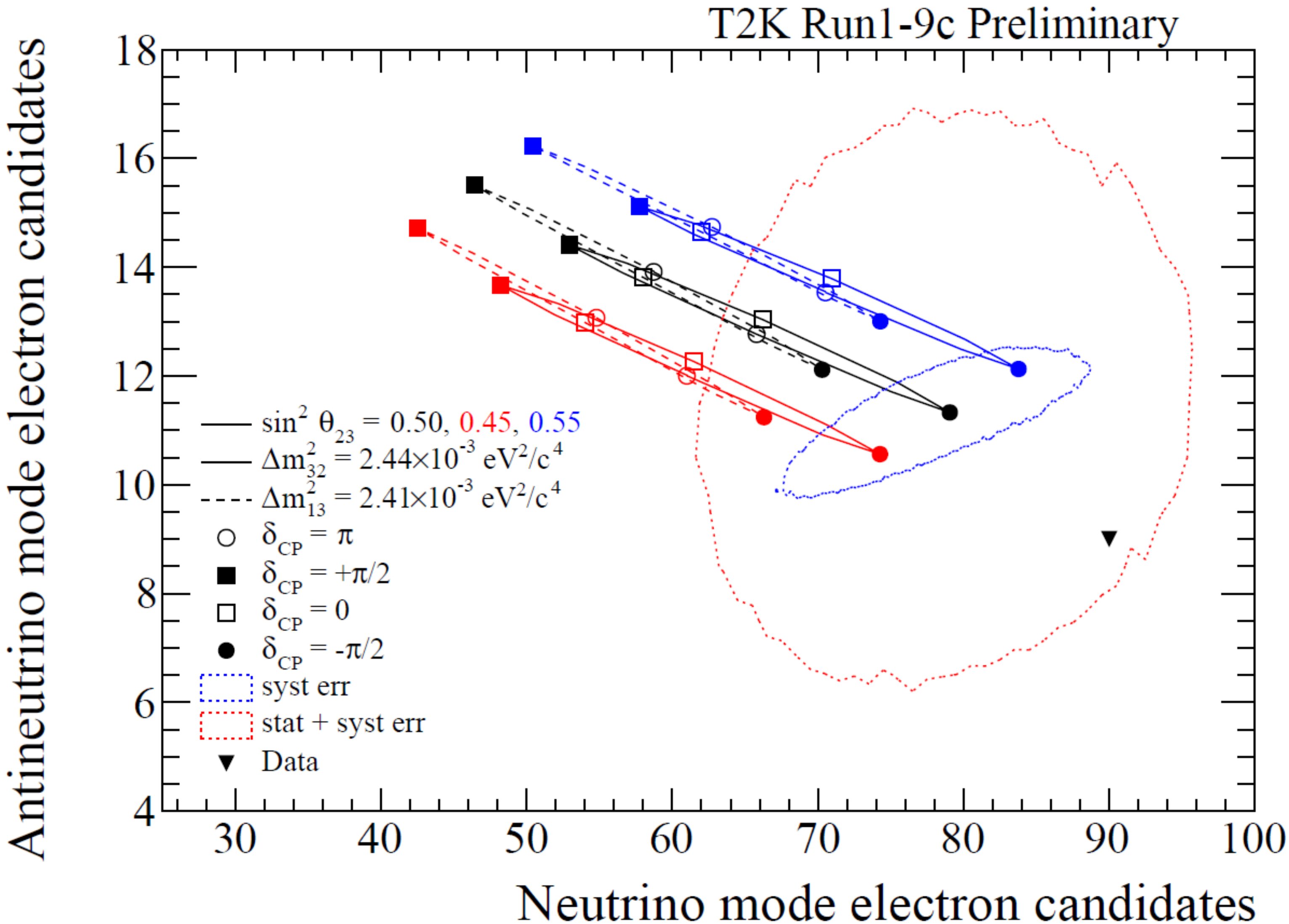
$$\nu_e + A \rightarrow e + A' + \pi^+$$

SK $\bar{\nu}_e$ spectrum (1.12×10^{21} POT)

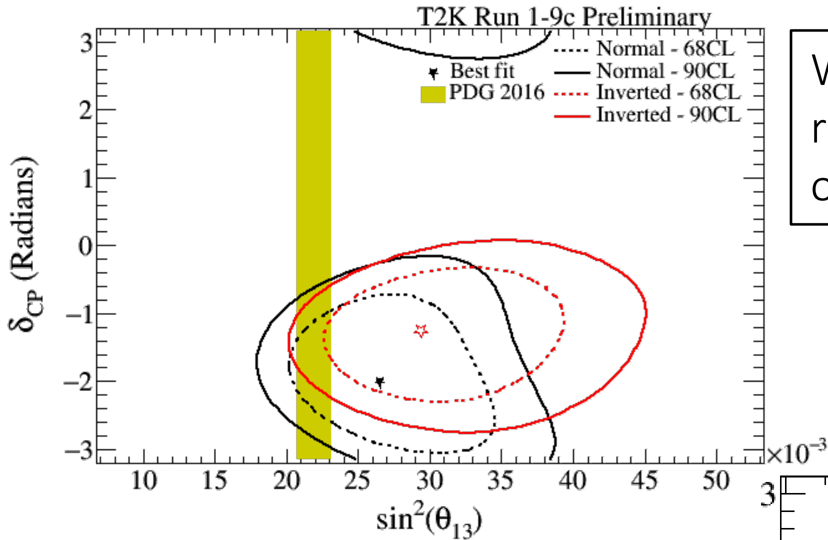


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

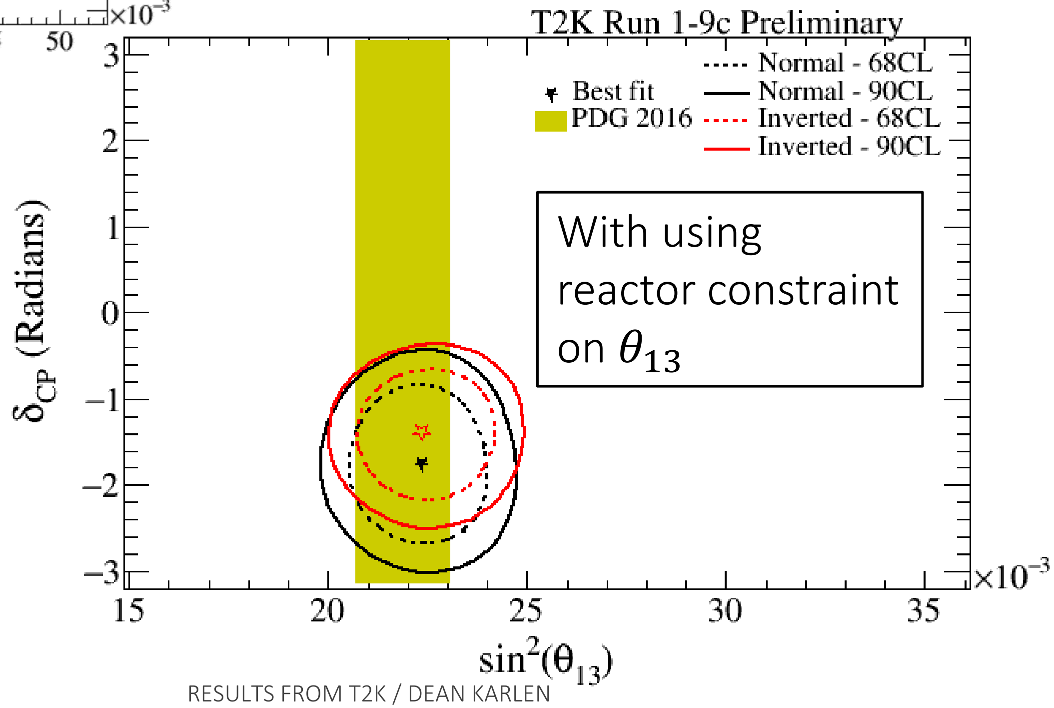
T2K SK $\bar{\nu}_e$ vs ν_e rates



T2K results on θ_{13} and δ_{CP}



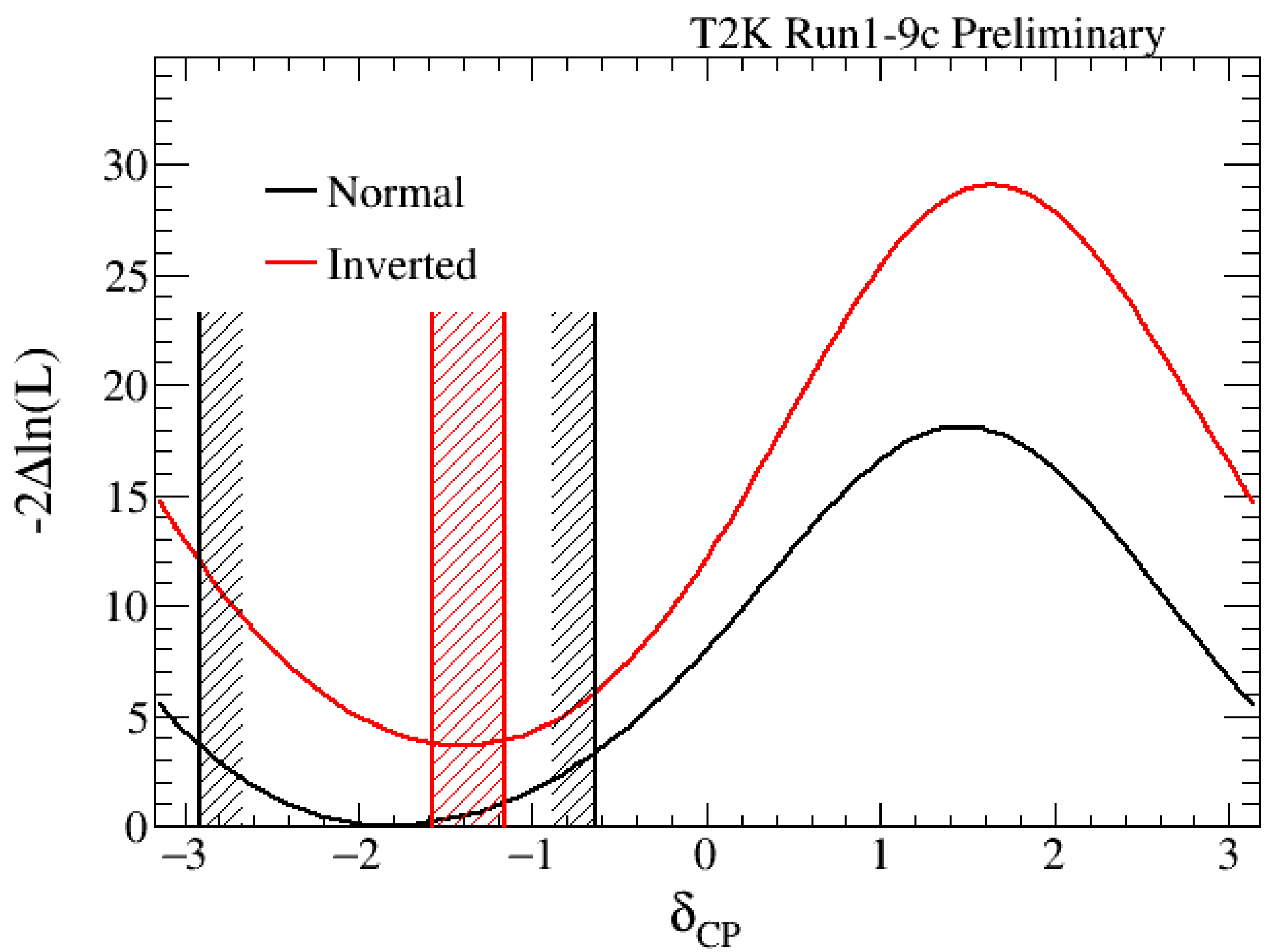
Without using reactor constraint on θ_{13}



With using reactor constraint on θ_{13}

T2K result for δ_{CP}

2σ Feldman Cousins intervals (with reactor constraint):

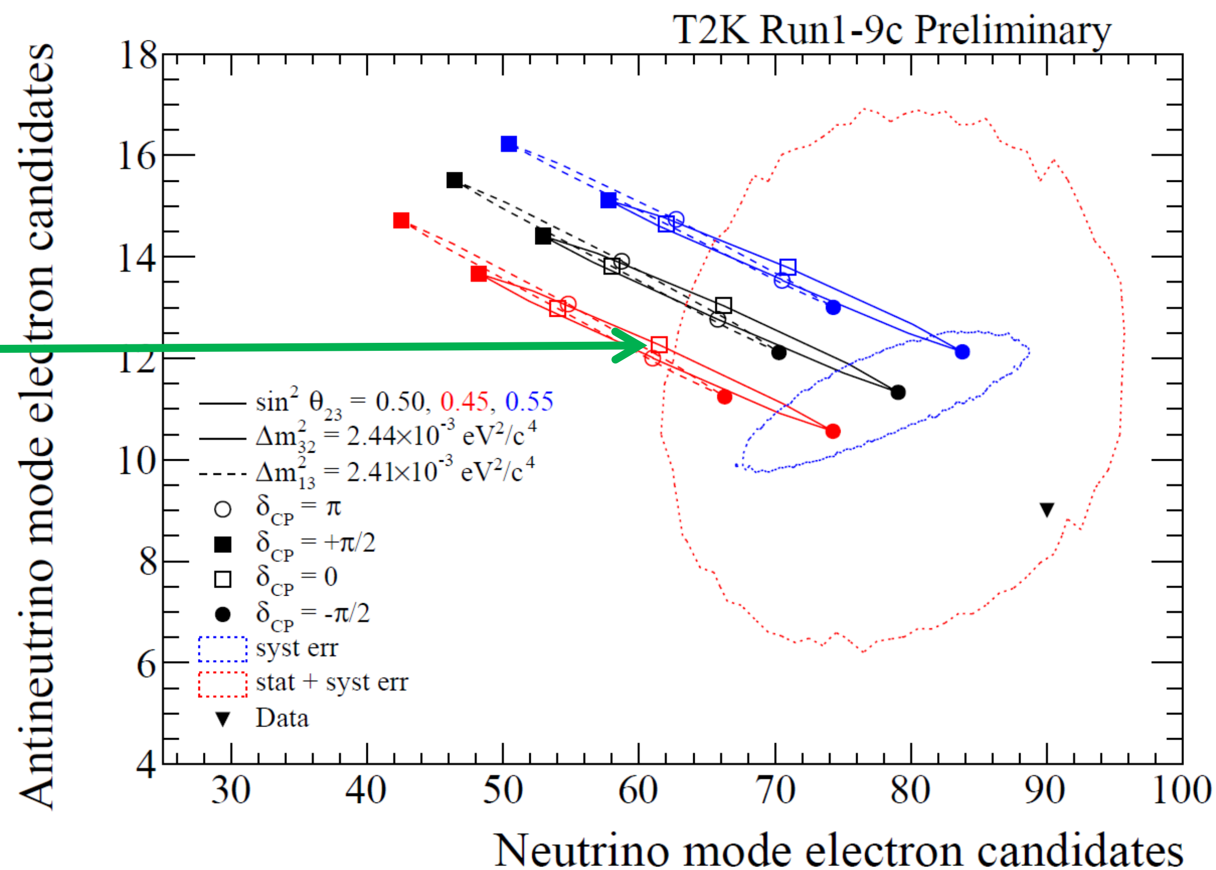


T2K sensitivity for $\sin\delta_{CP}$ & M.O.

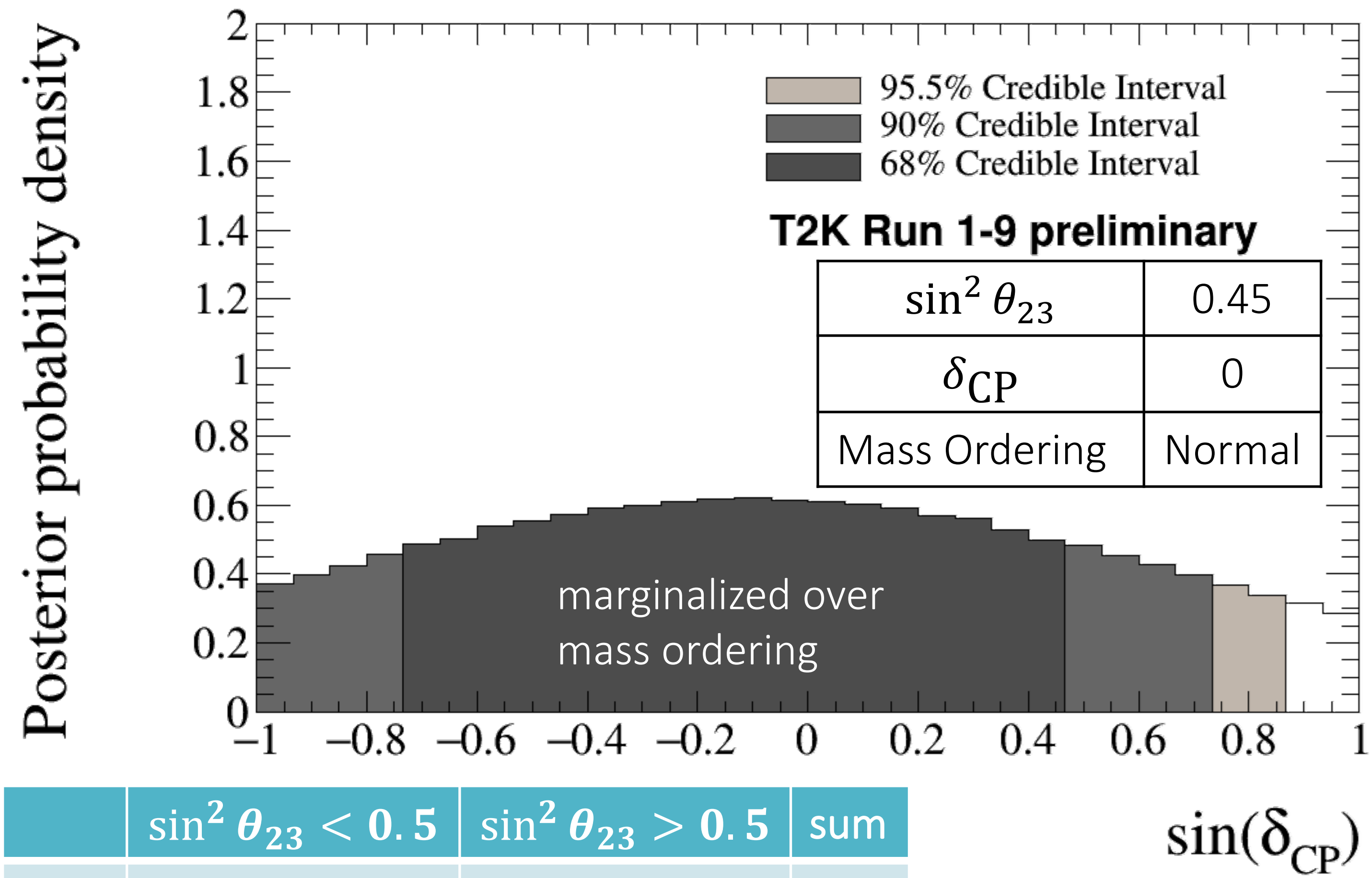
Consider expected outcomes for experiments for representative oscillation parameters

For example, this point

Assume expected numbers of events observed in all bins. With δ_{CP} unknown, cannot distinguish M.O.



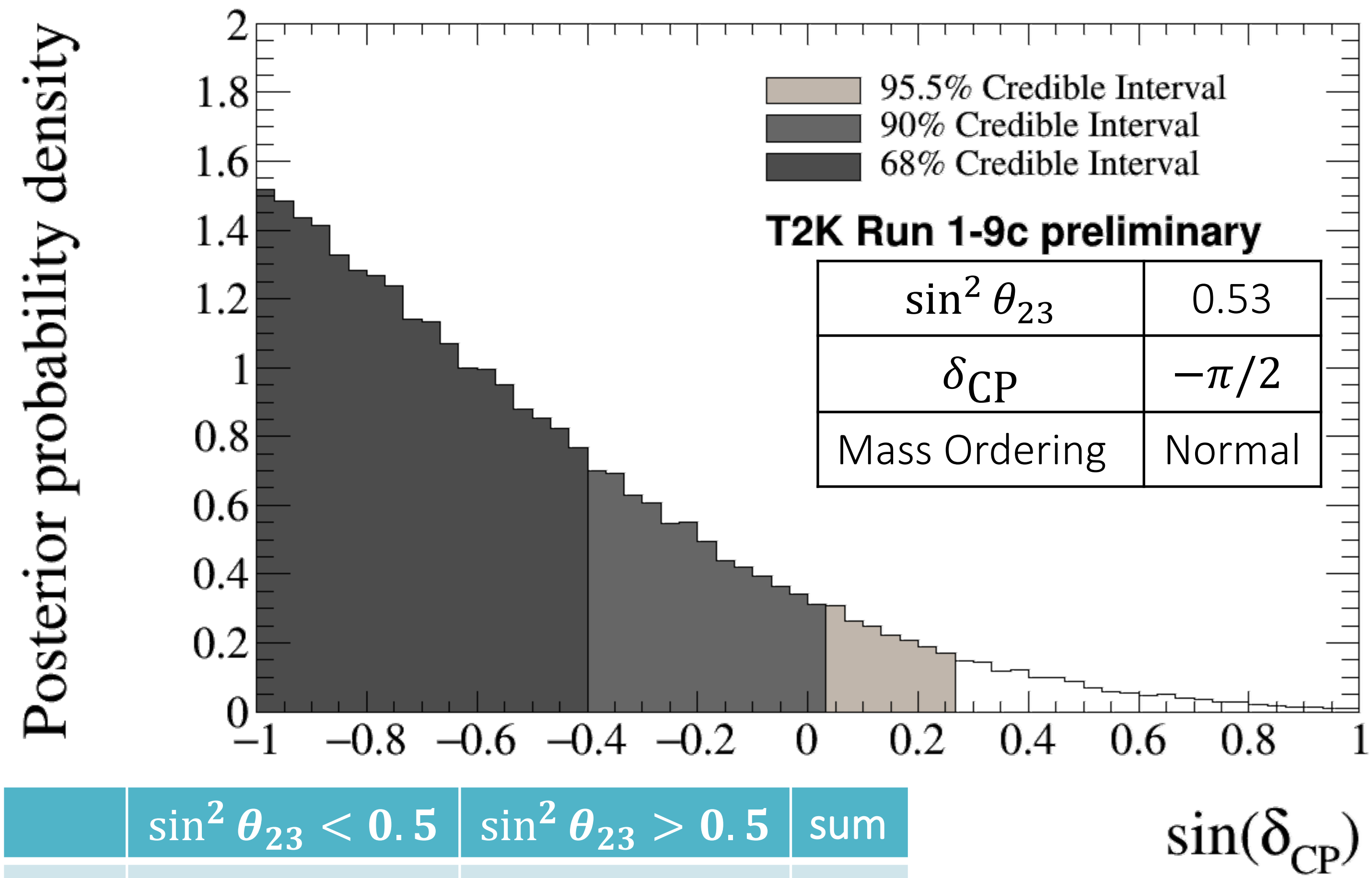
T2K sensitivity for $\sin\delta_{CP}$ & M.O.



	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	sum
N.O.	0.27	0.23	0.5
I.O.	0.25	0.25	0.5
sum	0.52	0.49	1

In this case there is very limited information about δ_{CP} and no information about MO

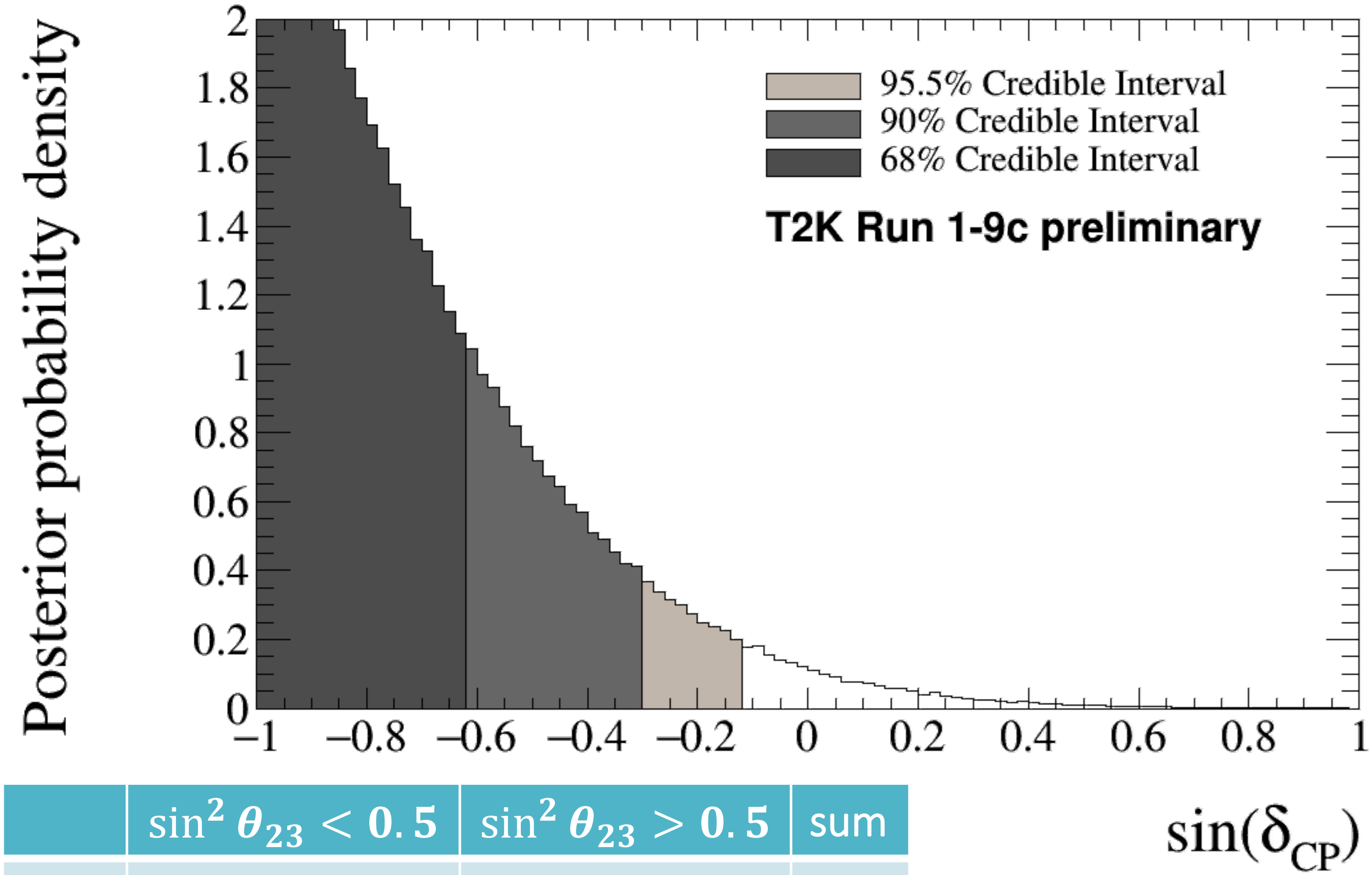
T2K sensitivity for $\sin\delta_{CP}$ & M.O.



	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	sum
N.O.	0.23	0.51	0.73
I.O.	0.07	0.20	0.27
sum	0.29	0.71	1

Expect that $\delta_{CP} = 0$ is in 90% CI and N.O. odds < 3:1

Posteriors for $\sin\delta_{CP}$ & M.O.



	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	sum
N.O.	0.20	0.68	0.89
I.O.	0.02	0.09	0.11
sum	0.23	0.77	1

Find that $\delta_{CP} = 0$ is outside 95% CI and N.O. odds > 8:1

T2K sensitivity for $\sin\delta_{\mathrm{CP}}$ & M.O.

The δ_{CP} intervals are smaller and the mass ordering posterior odds are larger than expected…

- This is due to the fact that the observed numbers of appearance events is outside the region of expected numbers for any combination of oscillation parameters

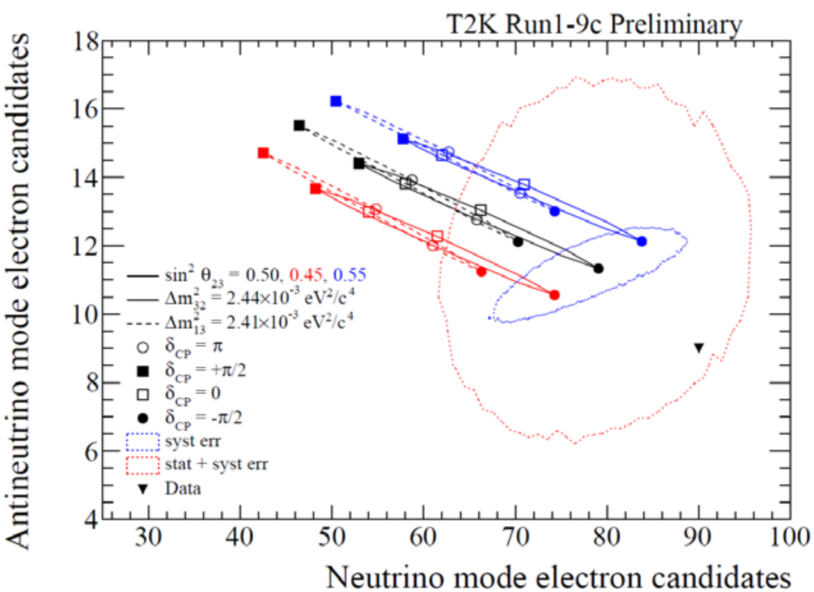
If additional data brings the appearance rates closer to expectation, the size of the δ_{CP} intervals may increase and the posterior probability for normal ordering may decrease!

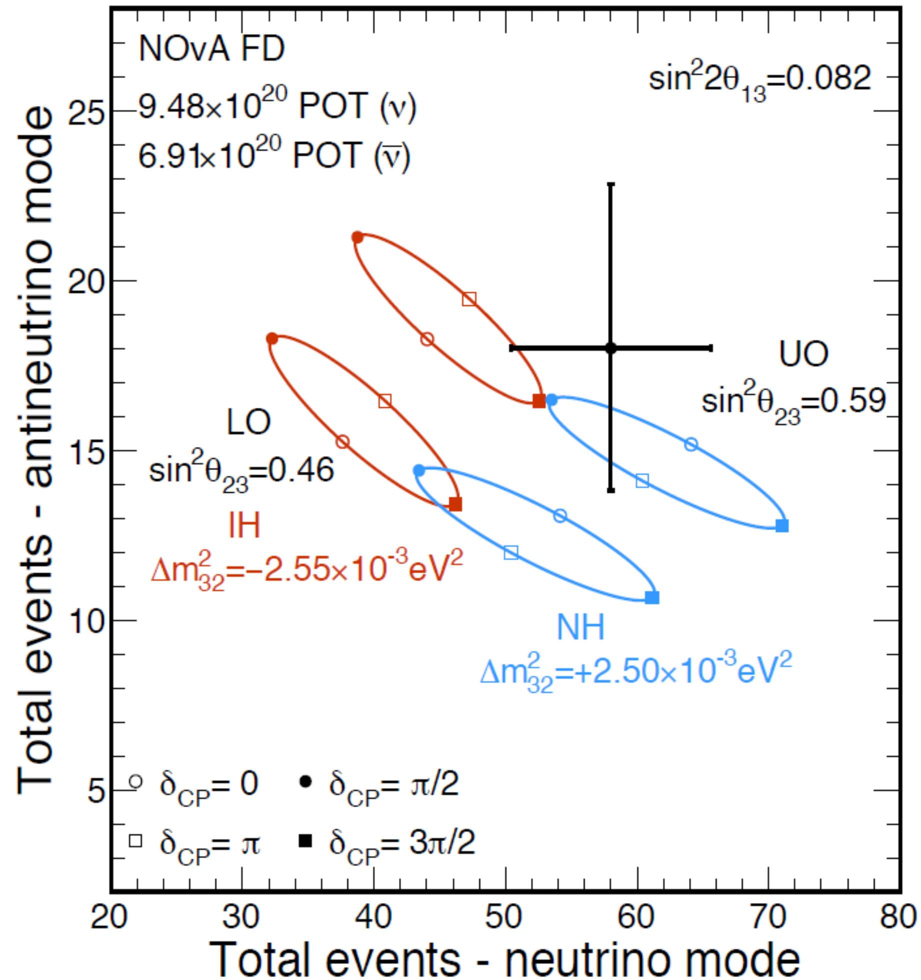
- a consequence of the physical bounds on the parameters

Recent results from NOvA

Presented at
Neutrino 2018

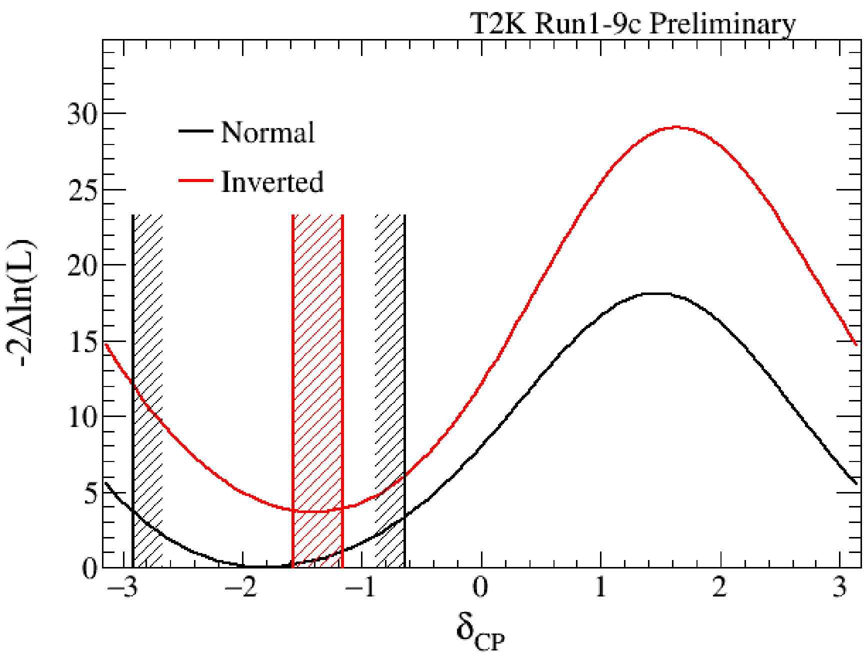
NOvA appearance result summary

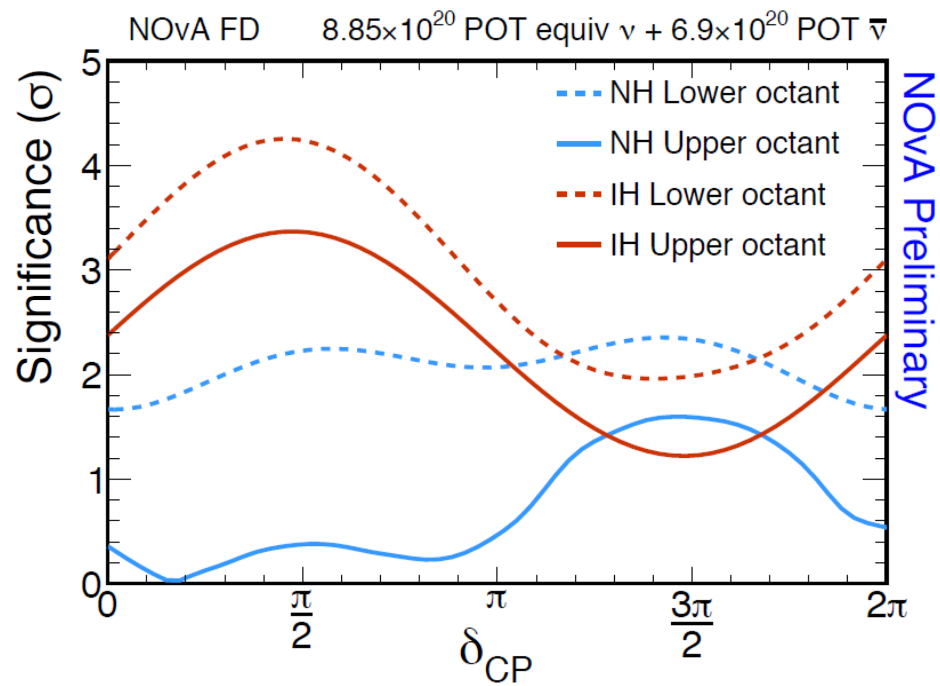




Recent results from NOvA

- T2K and NOvA data show preference for N.O. and for upper octant ($\sin^2\theta_{23} > 0.5$).
- For those choices, NOvA data disfavours $\delta_{CP} = -\frac{\pi}{2}$ (but at small significance)



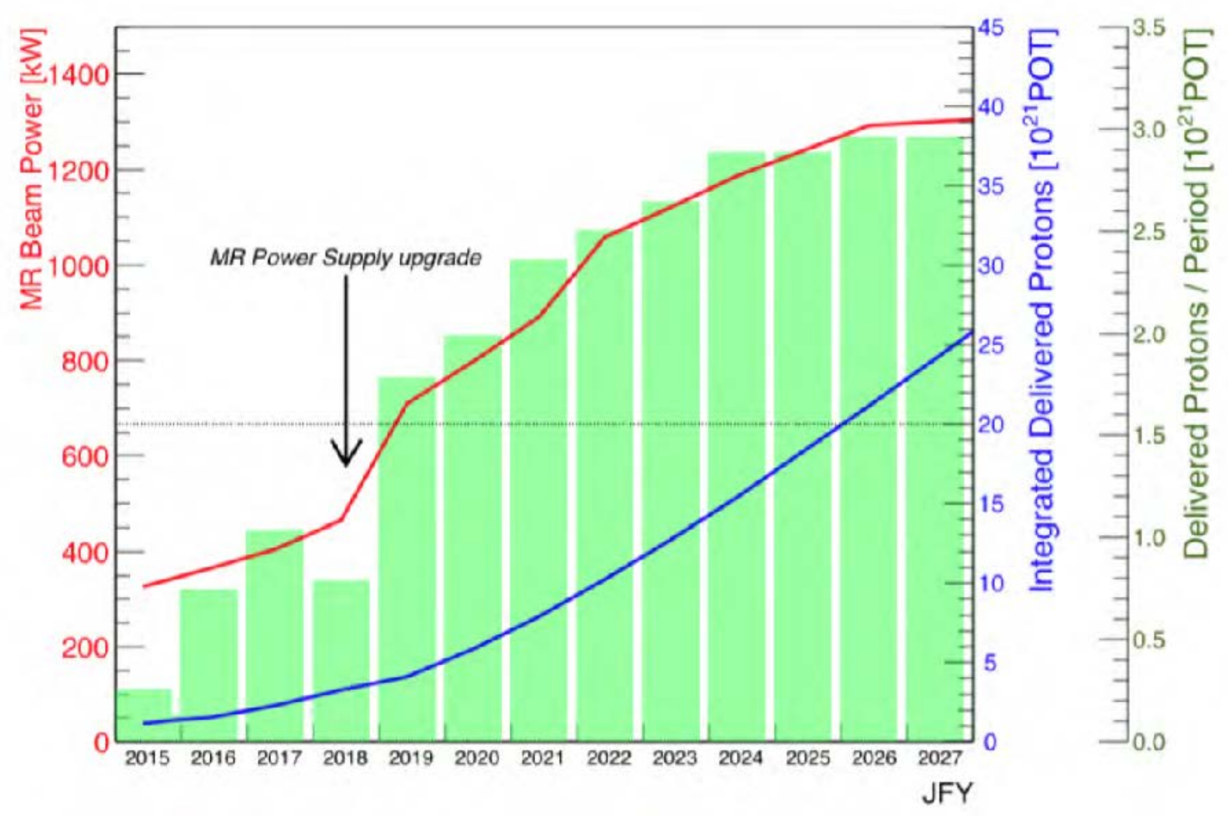


The road ahead

Future T2K

JPARC to deliver higher power beams in the future

- T2K-II (run extension) and Hyper-K under consideration
- Upgrading near and far detectors



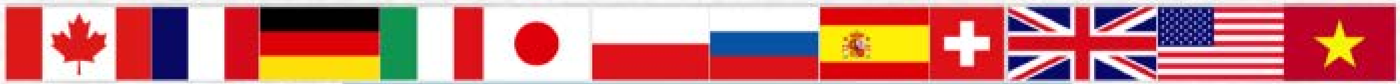
Thank you!

T2K Breakthrough Prize Party

January 28th, 2016 at Kuji Sunpia Hitachi

Backups

The T2K collaboration



~500 members, 64 Institutes, 12 countries

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U. Toronto
U. Victoria
U. Winnipeg
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INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

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Kavli IPMU
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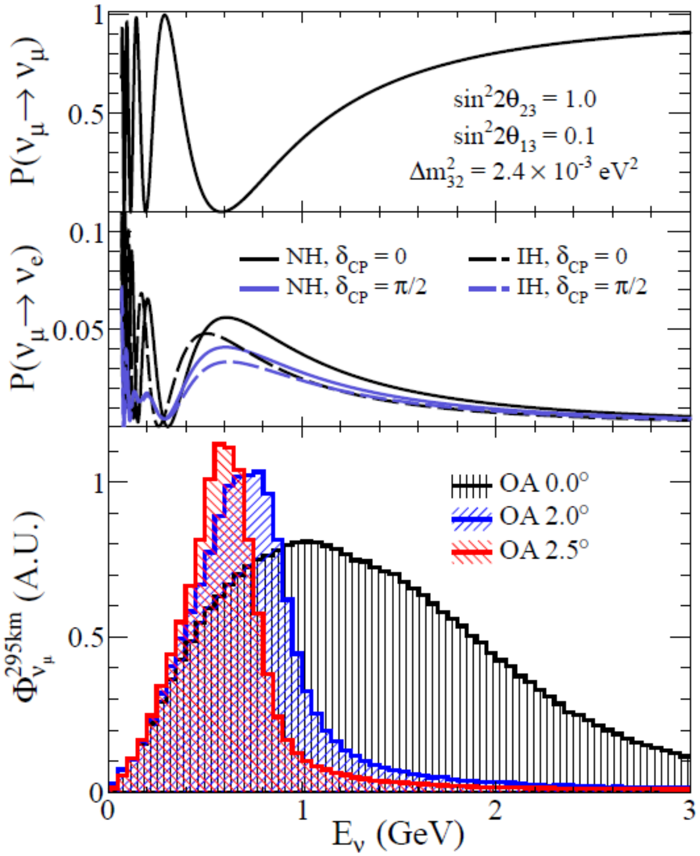
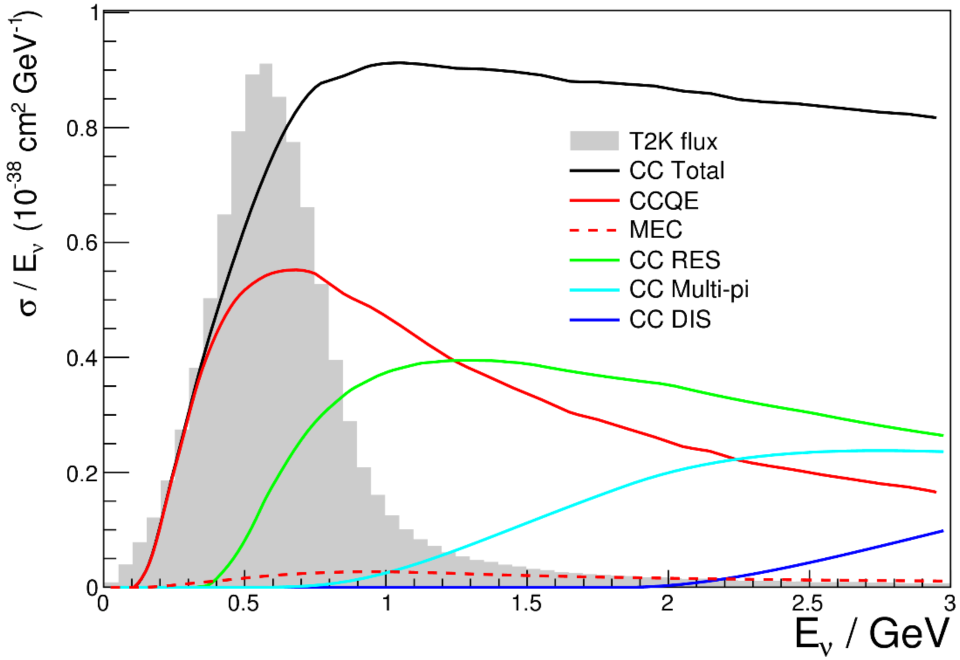
Off-axis approach

Oscillation probabilities and cross sections





SK event rates

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$
FHC μ-like sample	268.525	268.232	268.494	268.880
FHC e-like sample	73.780	61.615	50.072	62.238
RHC μ-like sample	95.528	95.306	95.529	95.770
RHC e-like sample	11.753	13.403	14.899	13.250
FHC ν_e CC1π^+-like sample	6.928	6.009	4.869	5.788

Observed
243
75
102
9
15

T2K-II sensitivity

Expected significance if $\sin\delta_{CP} = -1$