Latest Results from T2K

Helen O'Keeffe, Lancaster University,
On behalf of the T2K collaboration
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Neutrino Oscillations

Neutrinos can change flavour during their propagation

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

$\theta_{23} = (45\pm3)°$
$|\Delta m^2_{32}| = (2.52\pm0.04)\times10^{-3}$ eV^2

$\theta_{13} = (8.5\pm0.15)°$
$|\Delta m^2_{31}| = (2.52\pm0.04)\times10^{-3}$ eV^2

$\theta_{12} = (33.6\pm0.8)°$
$\Delta m^2_{21} = (7.50\pm0.18)\times10^{-5}$ eV^2

$$\Delta m^2_{ji} = m^2_j - m^2_i \quad c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

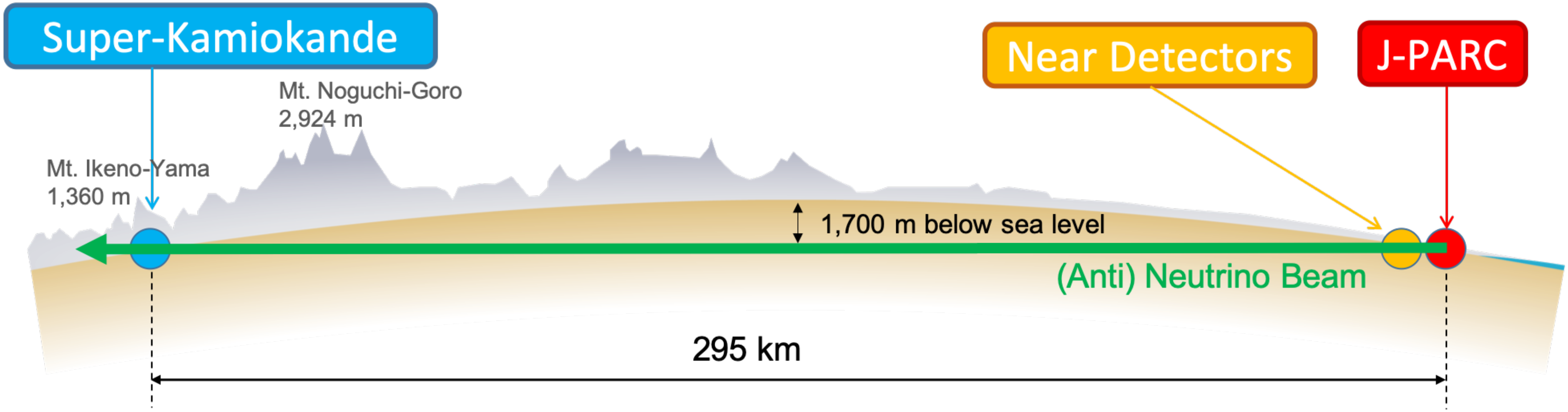
Infer parameters via measurement of probability, P:

$$P(\nu_\alpha \to \nu_\beta) = P(E, L, \Delta m^2_{ji}, \theta_{ij})$$

Unanswered questions:

θ_{23} octant, δ_{CP} = ?, Mass ordering

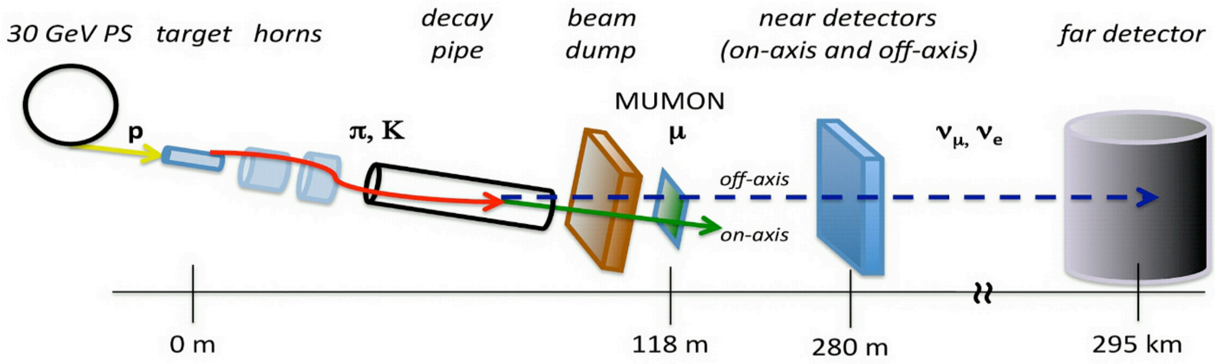
Tokai to Kamioka (T2K) experiment



Measurements to be made by T2K:

- Anti-ν_e appearance and probe CP violation
- Improved measurements of Δm^2_{32}, θ_{23} and θ_{13}
- Precision cross-section measurements at near detector
- Searches for exotic phenomenon

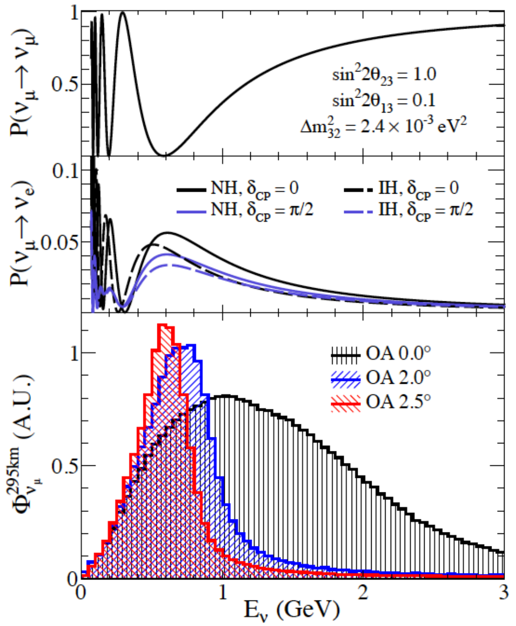
T2K neutrino beam



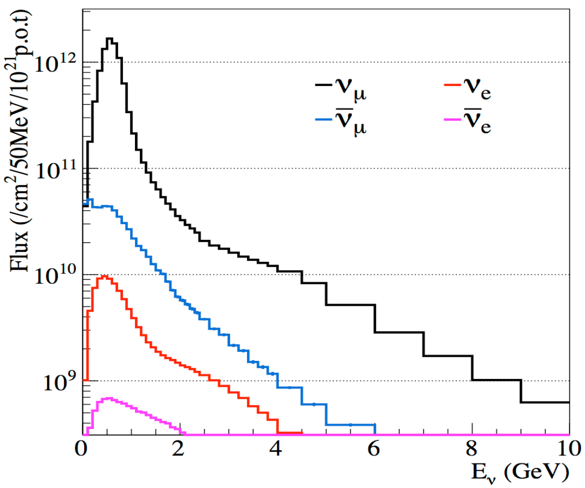
High-purity ν_μ beam

Reverse horn current to produce anti-ν_μ beam

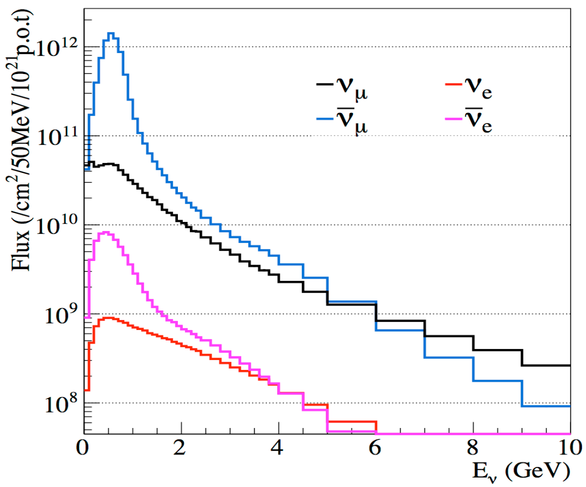
Place detectors 2.5° off the beam axis



Neutrino-mode flux at ND280



Antineutrino-mode flux at ND280



Dedicated hadron production measurements from NA61/SHINE

(Eur. Phys. J. C76 (2016) no.2, 84)

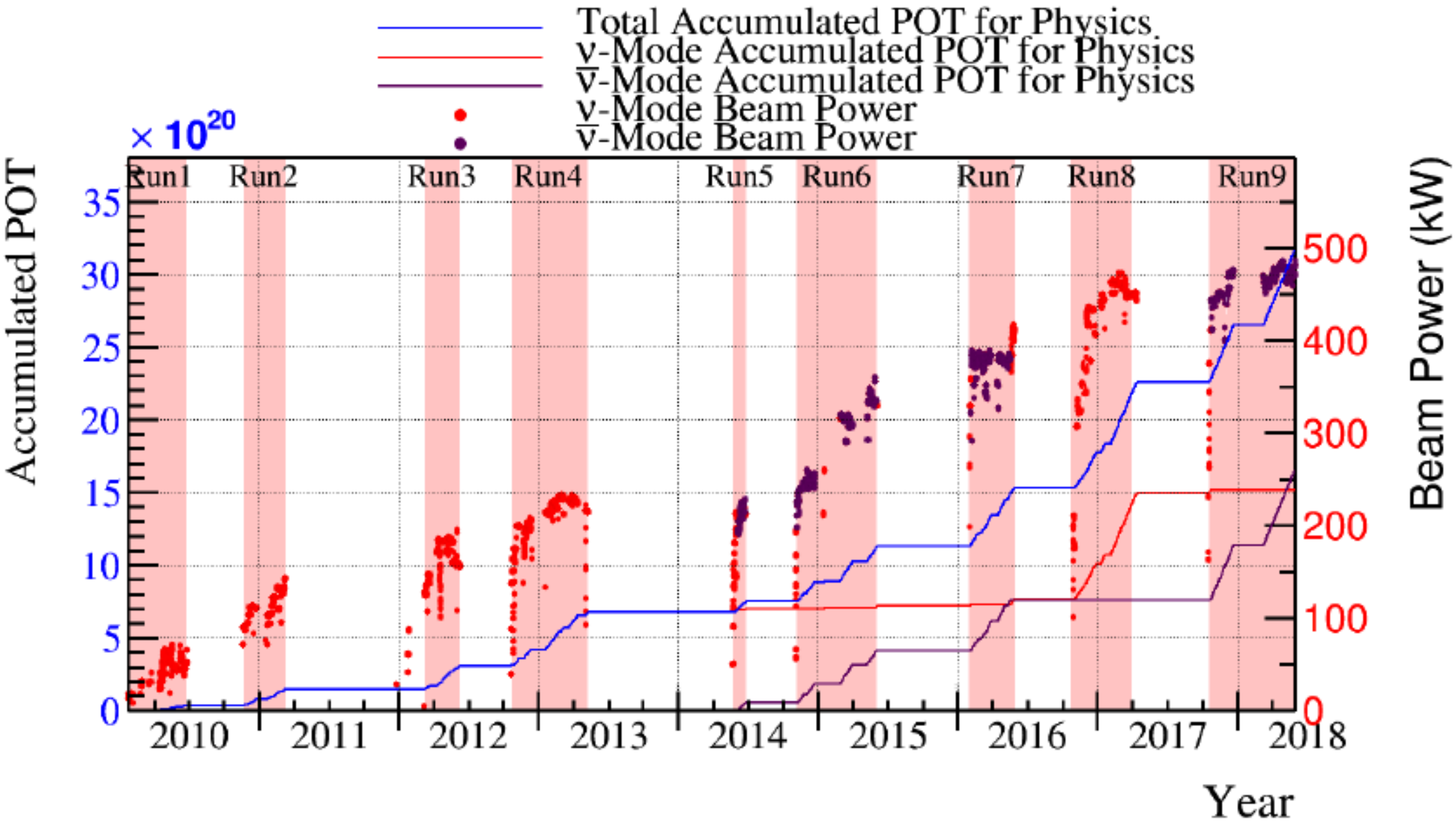
T2K beam performance

Protons on target, to date

Neutrino mode = 1.51 x 10^{21}

Anti-neutrino mode = 1.65 x 10^{21}

Beam power of 500 kW



Near detectors

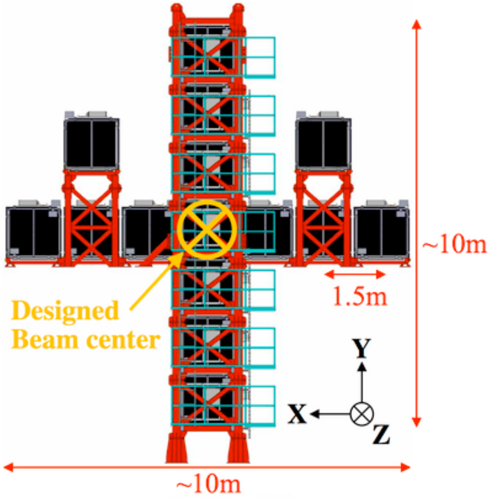
Located 280 m downstream of target

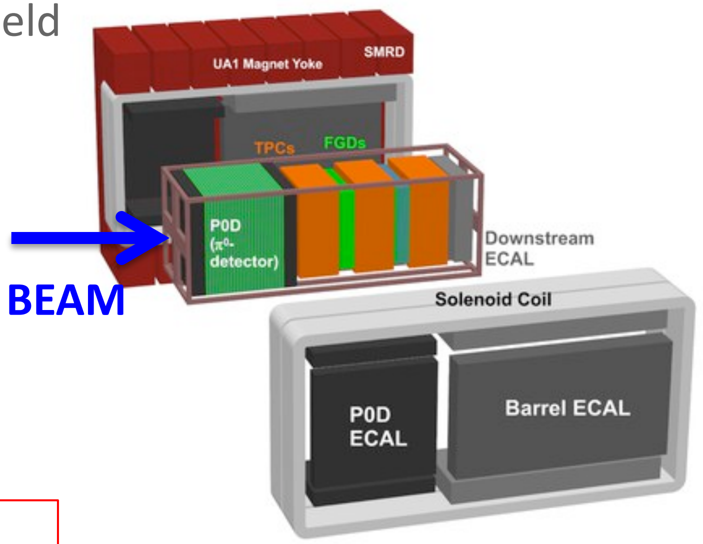
INGRID on-axis detector

- Monitor beam direction/stability
- Constrain flux systematics and beam direction

ND280 off-axis detector

- Same direction as Super-K, 2.5° off-axis
- Comprised of five sub-detectors in a 0.2 T magnetic field
- Measurements of neutrino interaction properties, intrinsic ν_e backgrounds and wrong-sign background
- Predict spectrum at far detector





$$\underbrace{N_{ND}}_{\text{Number of events}} \propto \underbrace{\phi(E)}_{\text{Neutrino flux}} \times \underbrace{\sigma(E)}_{\text{Interaction cross section}} \times \underbrace{\epsilon_{ND}(E)}_{\text{Detector efficiency}}$$

Far detector: Super-Kamiokande

Super-Kamiokande far detector

- 2.5° off-axis
- 50 kton water-Cherenkov detector
- No magnetic field
- Excellent μ/e separation

<1% μ misidentified as e

$$N_{FD} \propto \phi(E) \times \sigma(E) \times \epsilon_{FD}(E) \times P(\nu_\alpha \to \nu_\beta; E; \theta_{ij}, \Delta m^2_{ji})$$

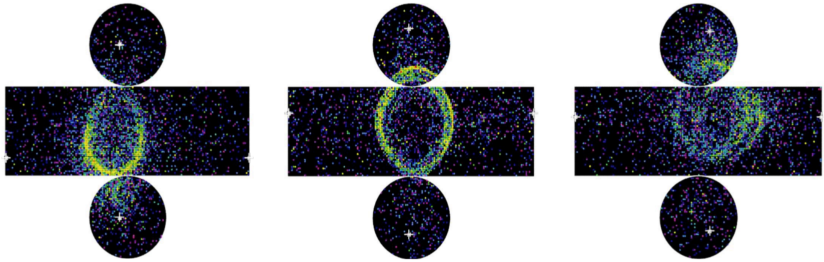
Number of events

Neutrino flux

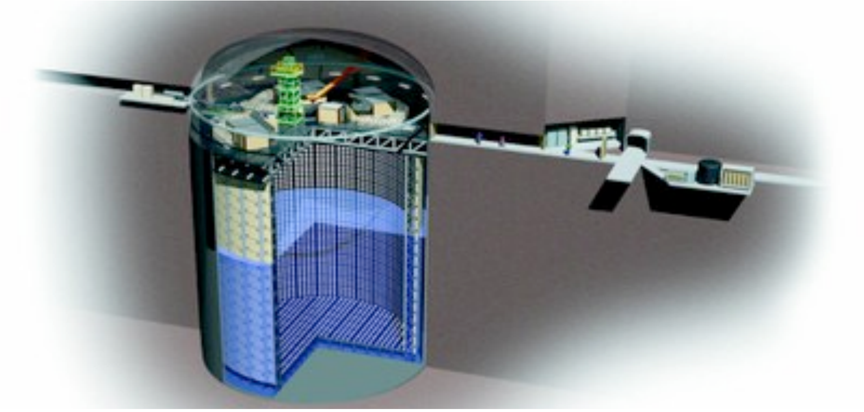
Interaction cross section

Detector efficiency

Oscillation probability



Electron ***Muon*** π^0



5 different Charged Current (CC) samples used

ν mode

CCQE 1 μ-like ring, ≤ 1decay e

CCQE 1 e-like ring, 0 decay e

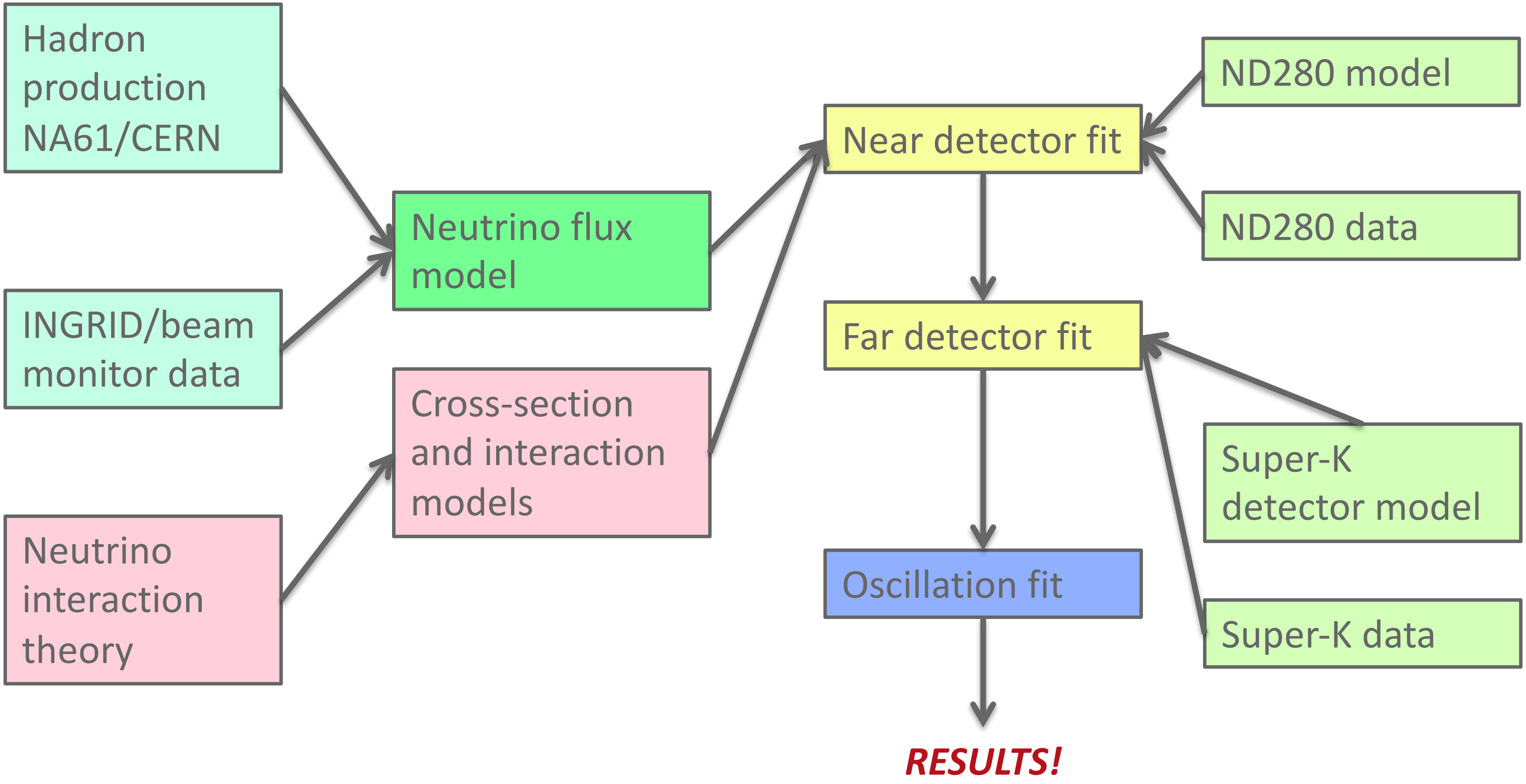
CC1π 1 e-like ring, 1 decay e

anti-ν mode

CCQE 1 μ-like ring, ≤ 1 decay e

CCQE 1 e-like ring, 0 decay e

T2K analysis strategy



Hadron production NA61/CERN

INGRID/beam monitor data

Neutrino interaction theory

Neutrino flux model

Cross-section and interaction models

Near detector fit

ND280 model

ND280 data

Far detector fit

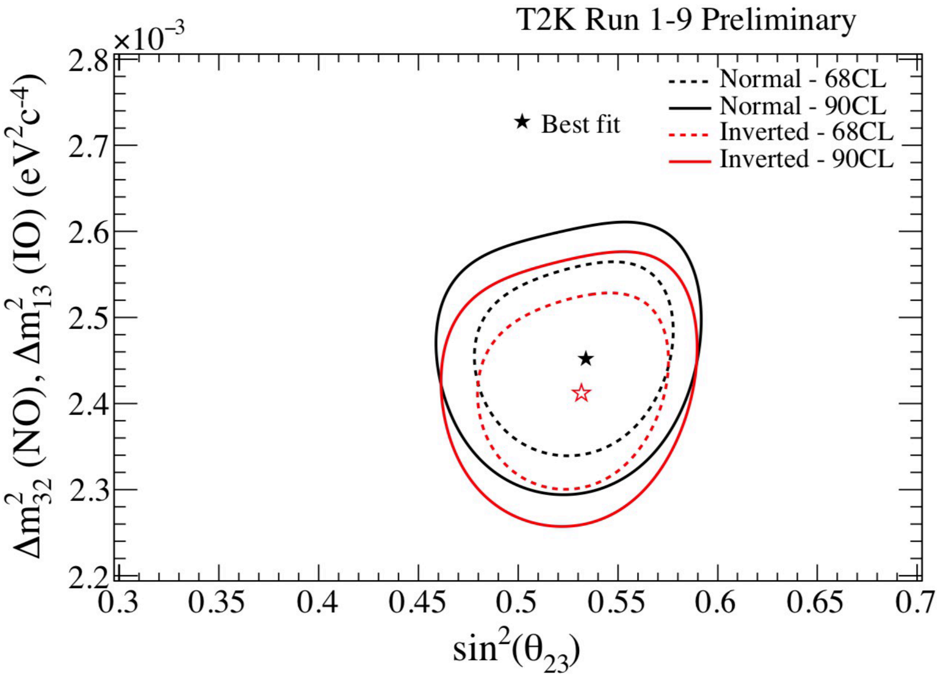
Super-K detector model

Super-K data

Oscillation fit

RESULTS!

Results: Atmospheric parameters



- Reactor constraints on θ_{13}
- Compatible with maximal mixing

	Normal ordering	Inverted ordering
$\sin^2\theta_{23}$	0.532	0.532
$\lvert\Delta m^2_{32}\rvert \times 10^{-3}$ eV²	2.452	N/A
$\lvert\Delta m^2_{31}\rvert \times 10^{-3}$ eV²	N/A	2.432

Results: Anti-ν_e appearance

For anti-ν_e events observed in runs 1-9

Define β such that

β = 1: PMNS anti-ν_e appearance

β = 0: No anti-ν_e appearance

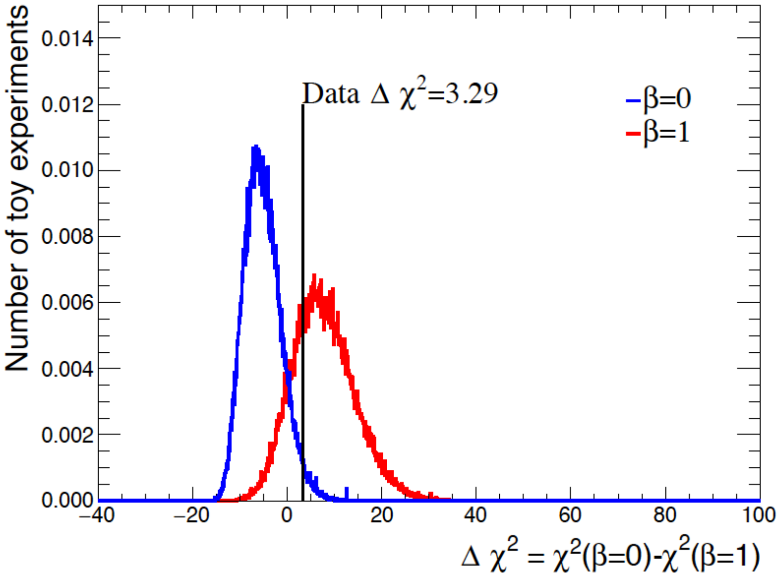
Expectations:

β = 1: 17.1 events

β = 0: 7.7 events

Not statistically significant

Data agrees with both hypotheses



Analysis	P-value for β = 0 (σ)	P-value for β = 1 (σ)
Rate+shape	0.024 (2.25σ)	0.261 (1.12σ)

Results: $\sin^2 \theta_{13}$

T2K only $\sin^2 \theta_{13}$:

Normal ordering: 0.0268

Inverted ordering: 0.0300

PDG2018 best fit point(s) $\sin^2 \theta_{13}$:

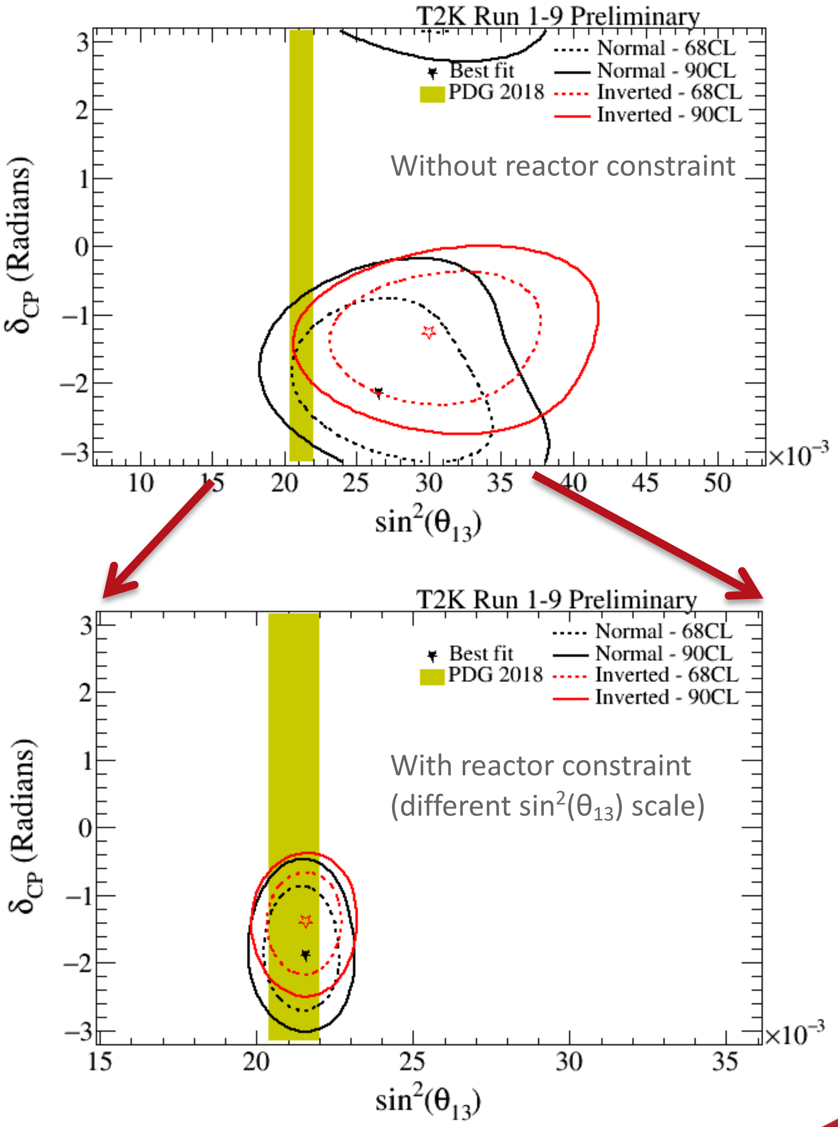
Normal ordering: 0.0215

Inverted ordering: 0.0216

T2K-only data excludes some δ_{CP} parameter space at 90% C.L.

Adding reactor measurement improves constraint

Preference shown for $\delta_{CP} \sim -\pi/2$



Results: δ_{CP}

Confidence intervals for the results with reactor constraint are calculated using Feldman Cousins method

Best fit point

Normal ordering: -1.885 radians

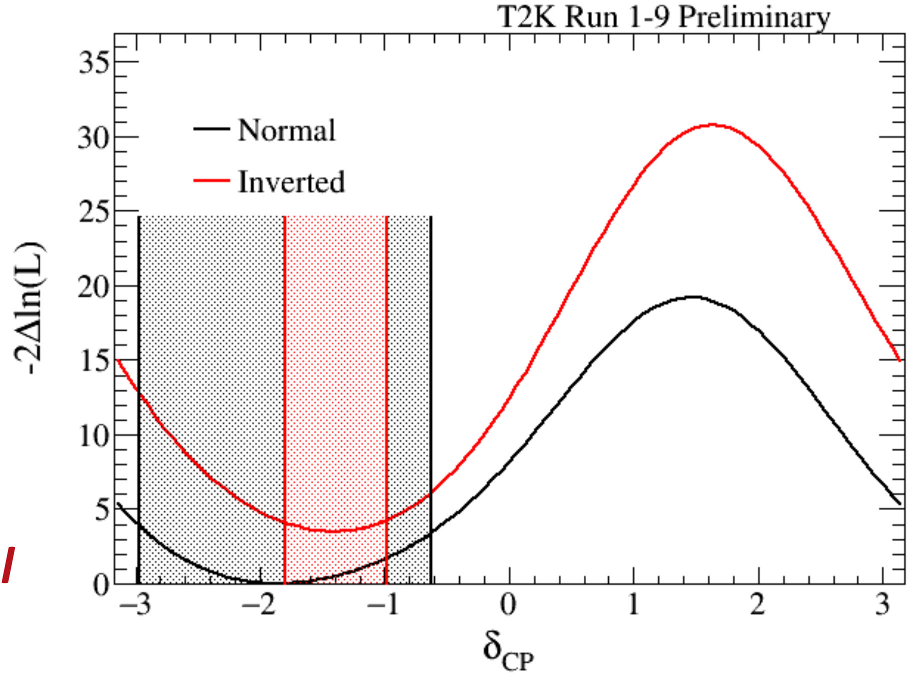
Inverted ordering: -1.382 radians

Normal ordering 2σ confidence interval

$[-2.97, -0.63]$ radians

Inverted ordering 2σ confidence interval

$[-1.78 \;\; - 0.98]$ radians



CP conserving values (0,π) fall outside of 2σ confidence intervals

Summary

Updated oscillation analyses using 3.1x10^{21} POT (50% ν, 50% anti- ν)

- Analysis excludes CP conserving values at 2σ
- Maximal mixing is preferred by T2K

Exciting programme of neutrino oscillation physics still to come!

- T2K-II operation to 2026 to collect 20.0 x 10^{21} POT (approx. 6 times current POT).
- Upgrades to near detector
- Analysis improvements and more data
- Expect sensitivity to exclude δ_{CP} conserving values at 3σ with T2K-II

Back up slides

T2K neutrino oscillation probability

Muon neutrino disappearance

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}) \times \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Precision measurement of θ_{23} and Δm^2_{31}

Electron neutrino appearance

$$\begin{aligned}P(\nu_\mu \to \nu_e) \simeq & \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & - \alpha\sin\delta\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & + \alpha\cos\delta\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & + \mathcal{O}(\alpha^2)\end{aligned}$$

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right|$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

Matter effects included

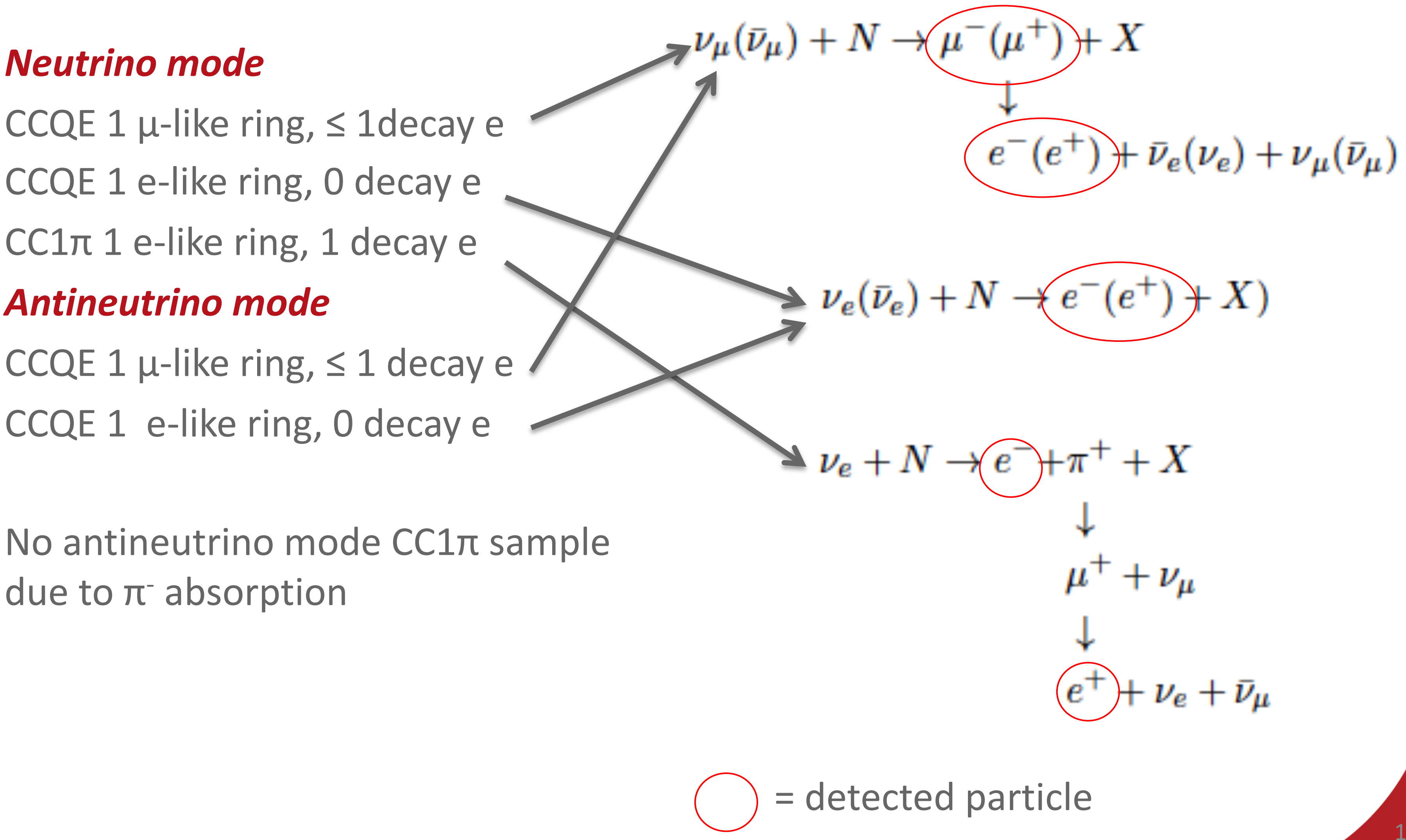
Leading term dependence on $\sin^2\theta_{13}$

If $\sin\delta \neq 0$: Asymmetry of appearance probabilities for ν and anti-ν

Observed and predicted event rates

	Predicted rates				**Observed**
Sample	**δ_{CP} = -π/2**	**δ_{CP} = 0**	**δ_{CP} = π/2**	**δ_{CP} = π**	**Events**
CCQE 1-Ring e-like ν	74.46	62.26	50.59	62.78	75
CCQE 1-Ring mu-like ν	272.34	271.97	272.30	272.74	243
CC1pi 1-Ring e-like ν	7.02	6.10	4.94	5.87	15
CCQE 1-Ring e-like anti-ν	17.15	19.57	21.75	19.33	15
CCQE 1-Ring mu-like anti-ν	139.47	139.12	139.47	139.82	140

The 5 samples at Super-K



Neutrino mode

CCQE 1 μ-like ring, ≤ 1decay e

CCQE 1 e-like ring, 0 decay e

CC1π 1 e-like ring, 1 decay e

Antineutrino mode

CCQE 1 μ-like ring, ≤ 1 decay e

CCQE 1 e-like ring, 0 decay e

No antineutrino mode CC1π sample due to π⁻ absorption

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \boxed{\mu^-(\mu^+)} + X$$

$$\downarrow$$

$$\boxed{e^-(e^+)} + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

$$\nu_e(\bar{\nu}_e) + N \rightarrow \boxed{e^-(e^+)} + X)$$

$$\nu_e + N \rightarrow \boxed{e^-} + \pi^+ + X$$

$$\downarrow$$

$$\mu^+ + \nu_\mu$$

$$\downarrow$$

$$\boxed{e^+} + \nu_e + \bar{\nu}_\mu$$

○ = detected particle

T2K-II

Extended T2K operation proposed to collect 20.0 x 10^{21}POT

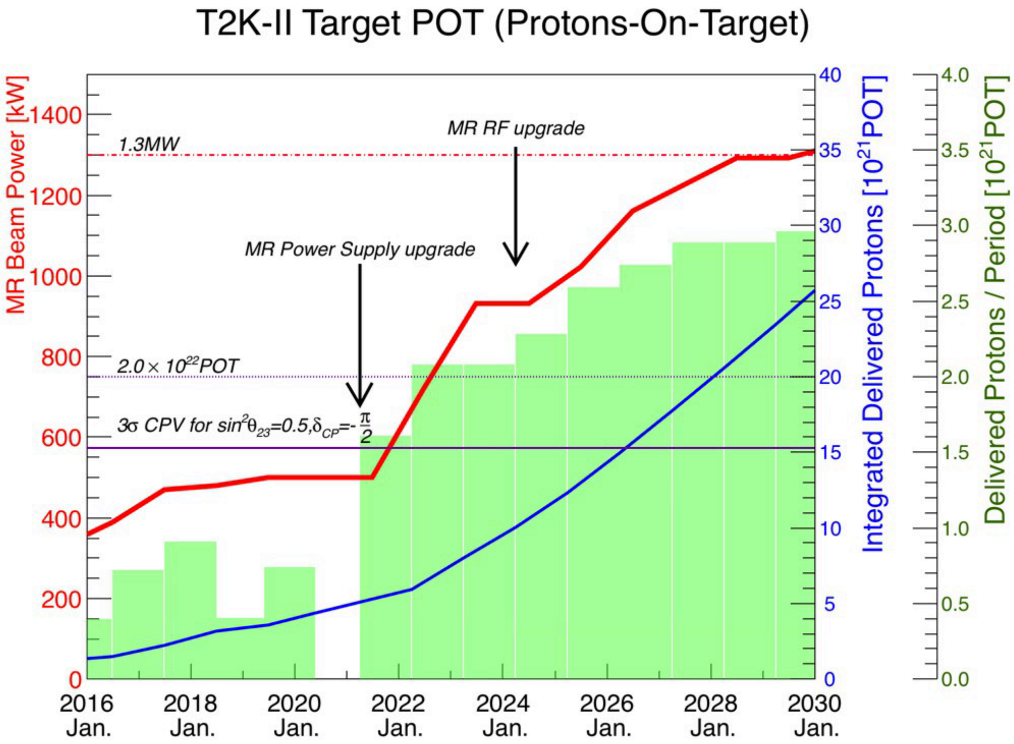
- T2K approved for 7.8 x 10^{21} POT
- Proposal to extend operations to 2026
- Expect 20.0 x 10^{21} POT to 2026

Analysis and operational improvements

Anticipate 50% increase in sensitivity

Upgrade of Main Ring power supplies

Projected beam power of 1.3 MW



T2K-II Projected sensitivities

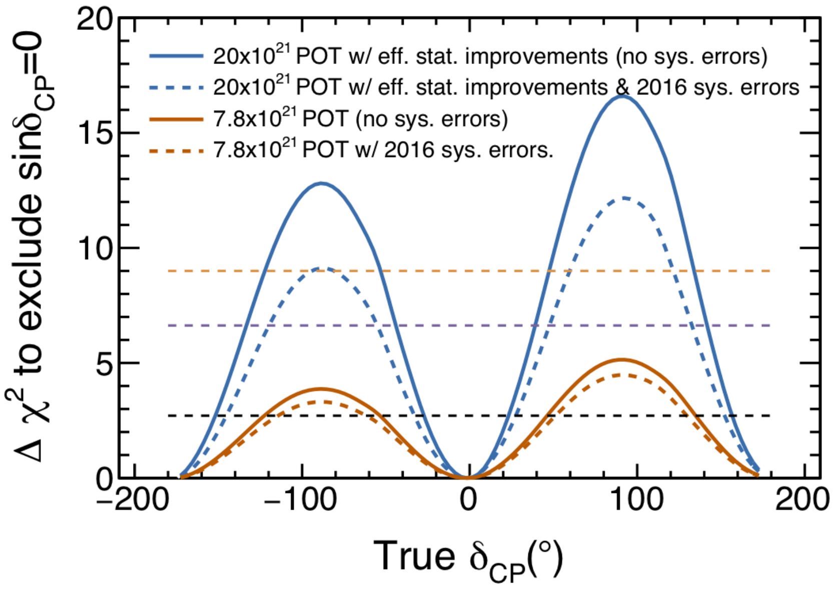
If δ_{CP} is near current best fit point

- Potential for 3σ evidence of CP violation in T2K-II

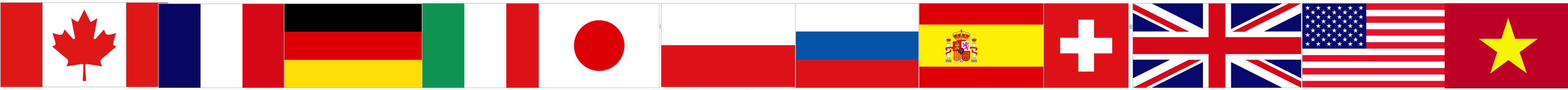
Systematic errors have a large effect on the experiment's sensitivity

- Dashed versus solid lines
- Expect systematic errors to improve

Significant reduction in atmospheric parameter space.



The T2K collaboration



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