Recent Oscillation Results at T2K

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Neutrino Oscillations

Two sets of eigenstates for neutrinos: mass & flavor

- Flavor states interact
- Mass states propagate

Flavor | Mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & -0 & \cos\theta_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Related through the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

Similar to CKM matrix for quarks

Measurable parameters: Δm^2_{32}, Δm^2_{21}, θ_{12}, θ_{13}, θ_{23}, δ_{CP}

Mixing angles

$\theta_{23} = 45.8 \pm 3.2°$

$\theta_{12} = 33.4 \pm 0.9°$

$\theta_{13} = 8.9 \pm 0.4°$

Mass splittings $\Delta m^2_{ij} = m^2_i - m^2_j$

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

$|\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3} eV^2$

Remaining Questions

Sign of Δm_{32}^2 still unknown:

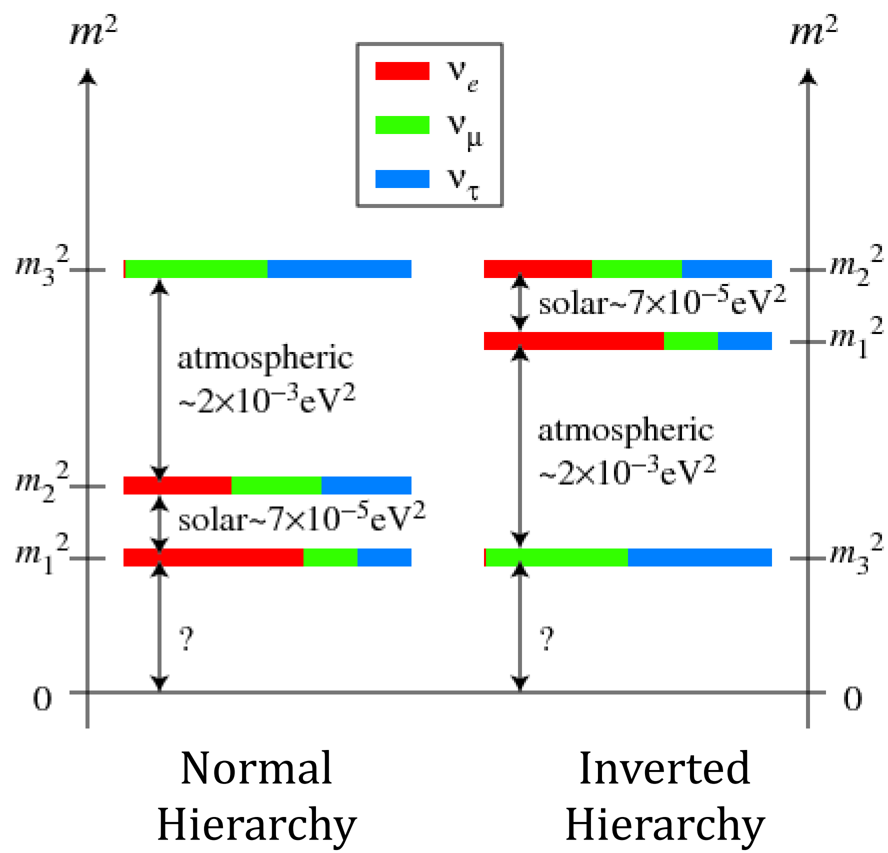
- What is the ordering of the neutrino masses?
- What are the absolute neutrino masses?

Value of δ_{CP} unknown:

- If not equal to 0:
  - CP violation in the neutrino sector
  - Difference in oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

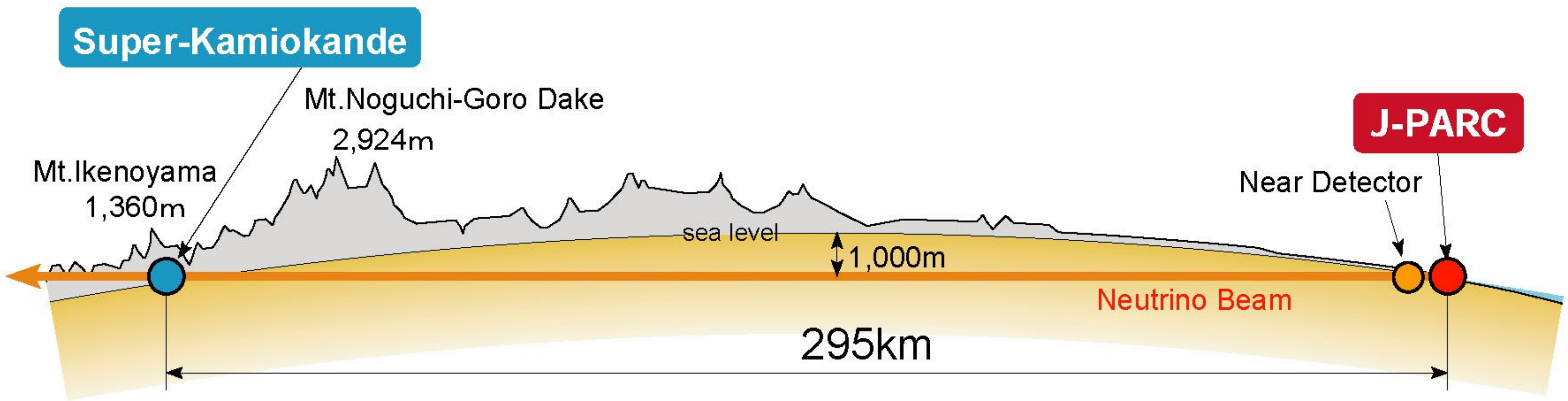
Exact size of the other oscillation parameters:

- Is θ_{23} maximal (45°)?



$$P_{\nu_a \rightarrow \nu_b}(L,E) = \left| \sum_{j,k} U^*_{aj} U_{bj} U_{ak} U^*_{bk} e^{-i\frac{\Delta m^2_{jk} L}{2E}} \right|$$

The T2K Experiment

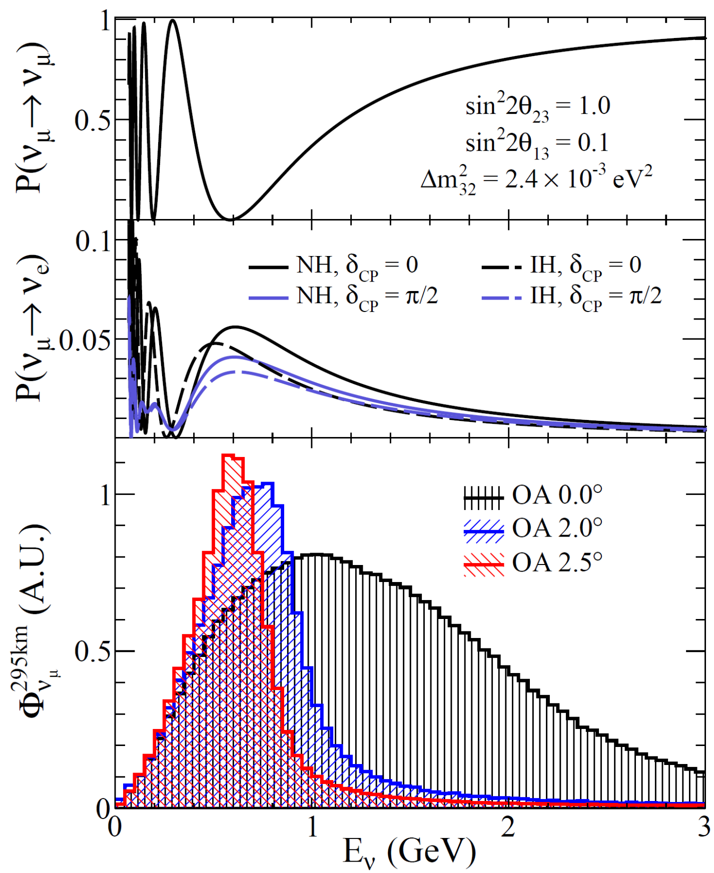


T2K is a long-baseline neutrino experiment with a 600 MeV narrow band muon neutrino beam

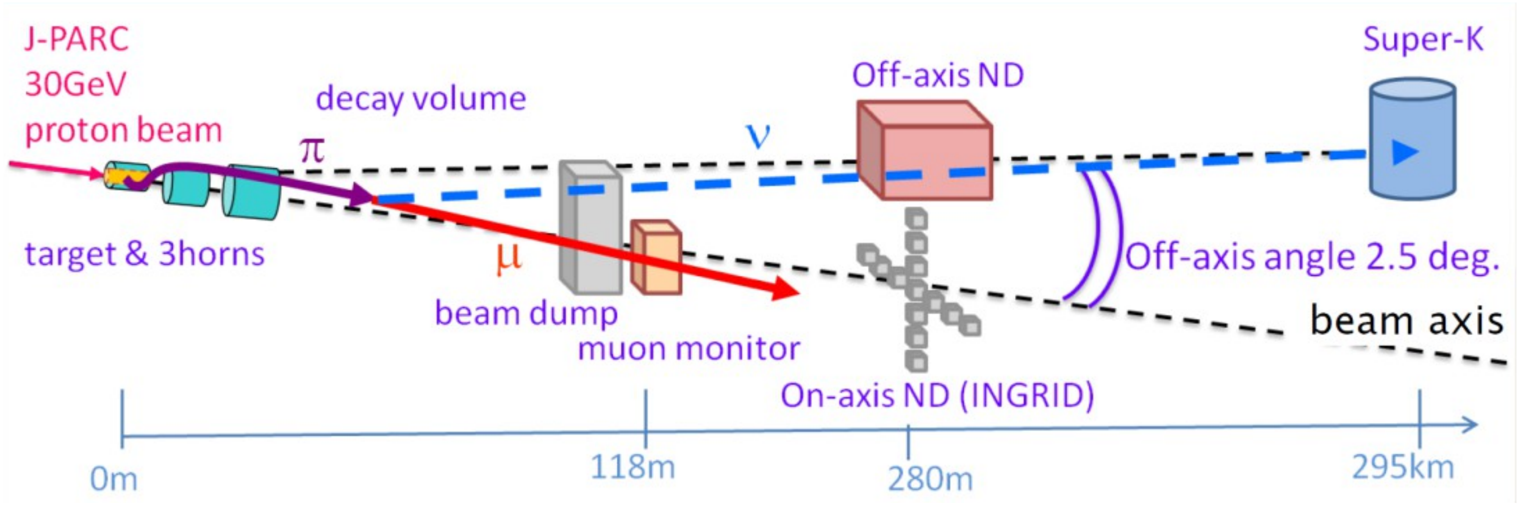
- Detectors 2.5° off axis from neutrino beam
- Near detector at 280 m from beam source
- Far detector 295 km from source

Neutrino energy spectrum tuned to hit oscillation maximum at far detector

$$P_{\nu_a \to \nu_b}(L, E) = \left| \sum_{j,k} U^*_{aj} U_{bj} U_{ak} U^*_{bk} e^{-i\frac{\Delta m^2_{jk} L}{2E}} \right|$$

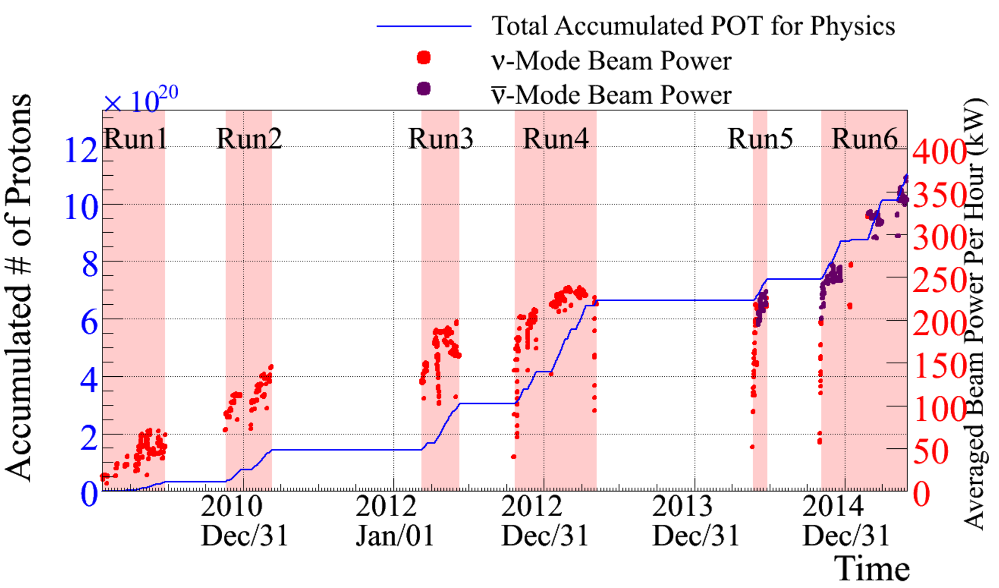


The Off-Axis Beam



30 GeV proton beam situated at J-PARC

- Protons collide with target, producing pions and other mesons
- These decay to neutrinos
- Can run in neutrino or antineutrino mode

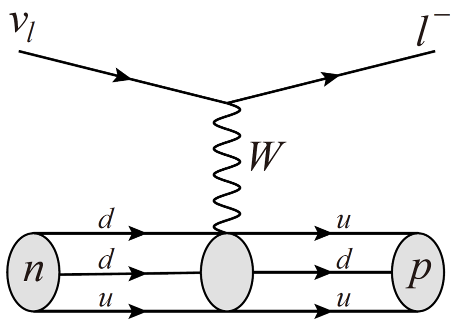


Neutrino Interactions at T2K

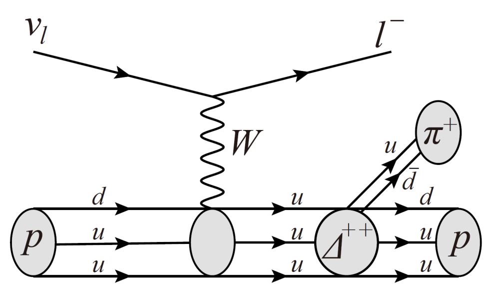
T2K looks for final-state leptons from charged-current interactions.

- Identified via topology at both near and far detectors
- Important for both cross-section and oscillation analyses

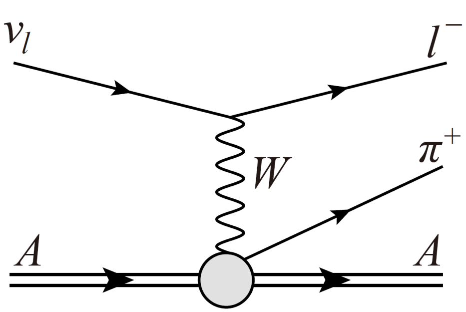
Cross-sections not well measured – need to use near detector to normalize.



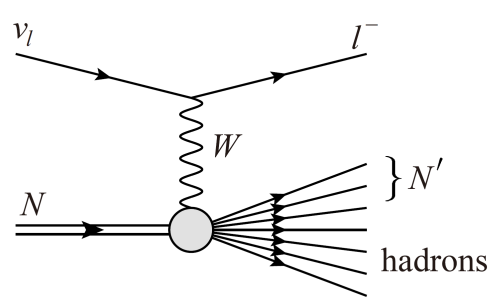
Charged-current quasielastic



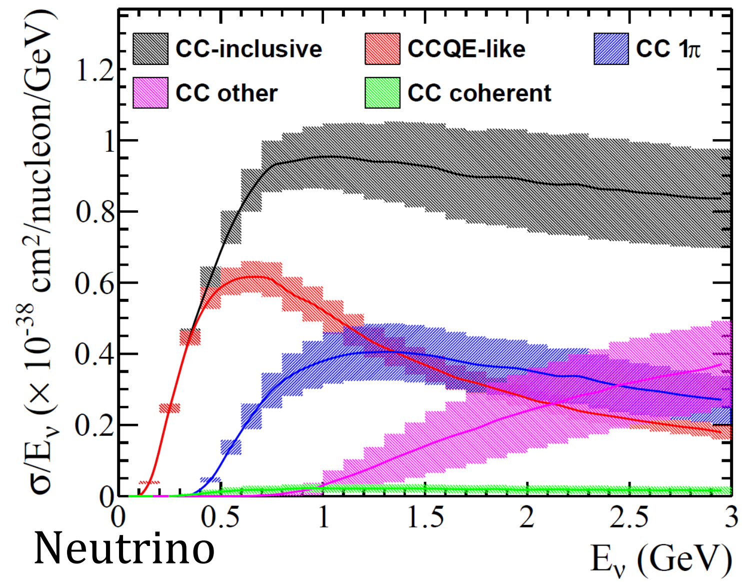
Resonant

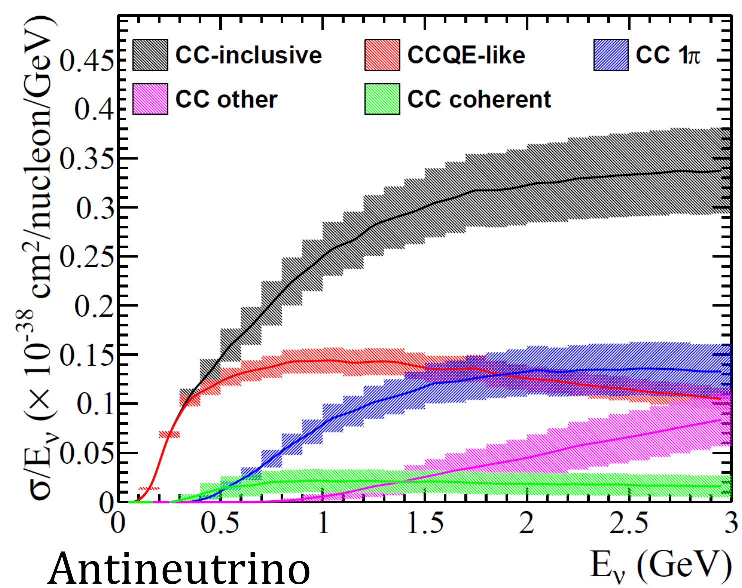


Coherent



DIS





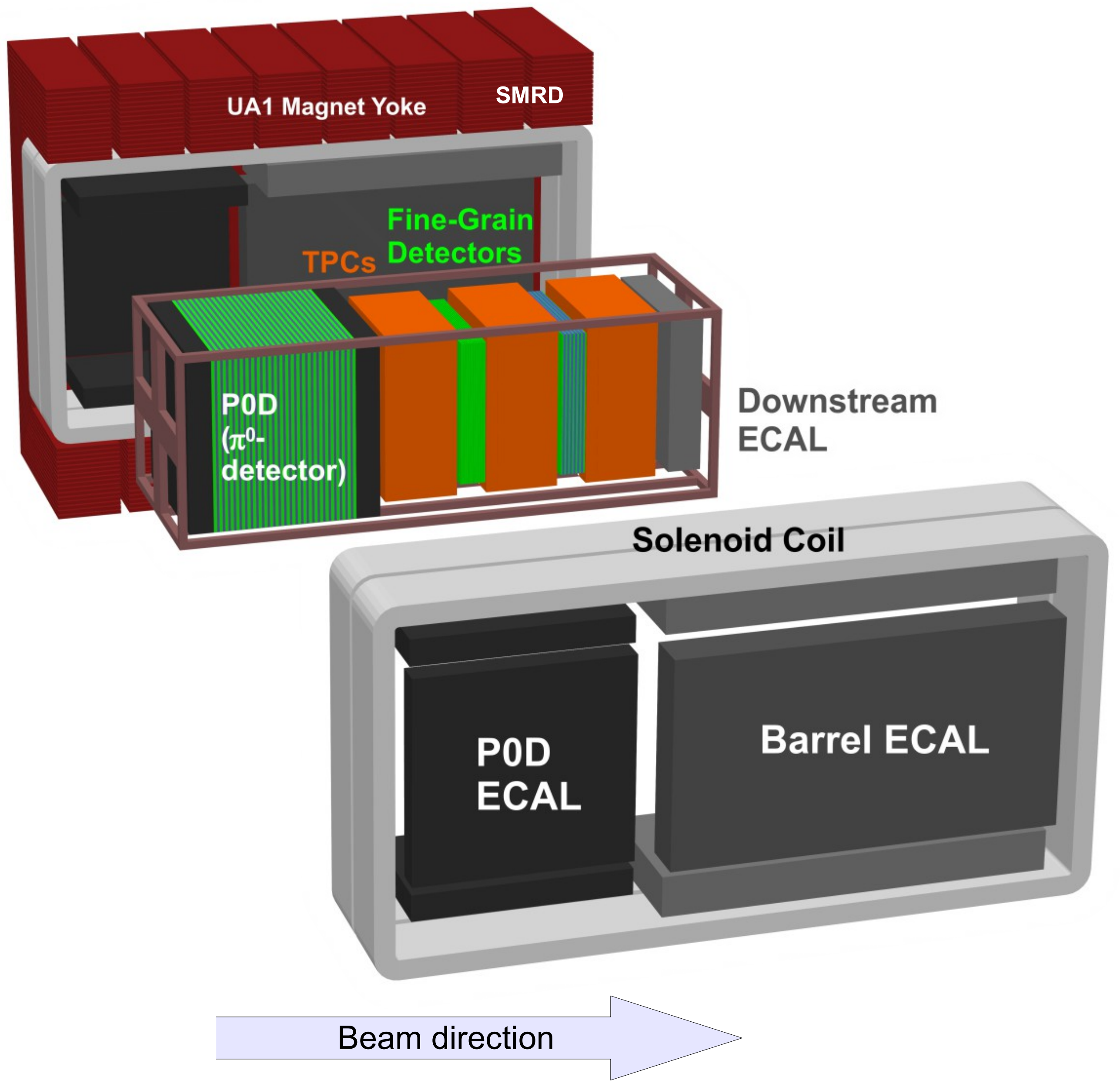
The Near Detectors at 280m

Off-axis from beam at 2.5° and 280 meters from neutrino production target.

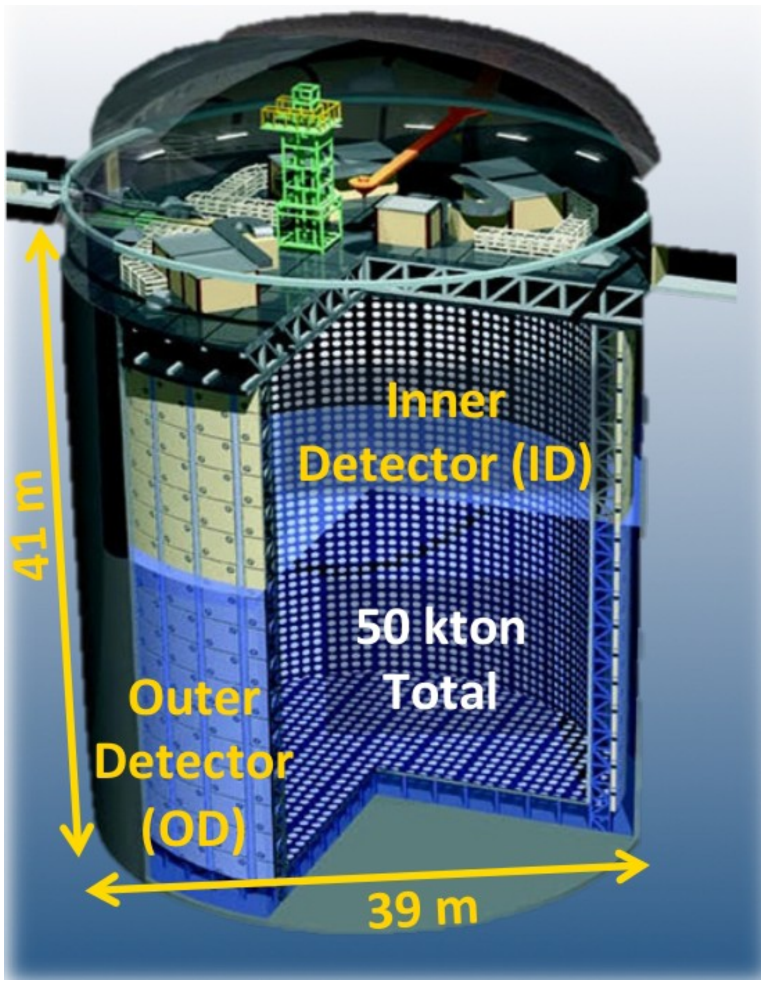
- Provides improved constraints on flux and cross-section models.

Able to differentiate between neutrino and antineutrino events:

- 0.2 T magnetic field
- Constrains neutrino background for antineutrino oscillation analysis.



The Far Detector at Super-Kamiokande



50 kton water Cherenkov detector:

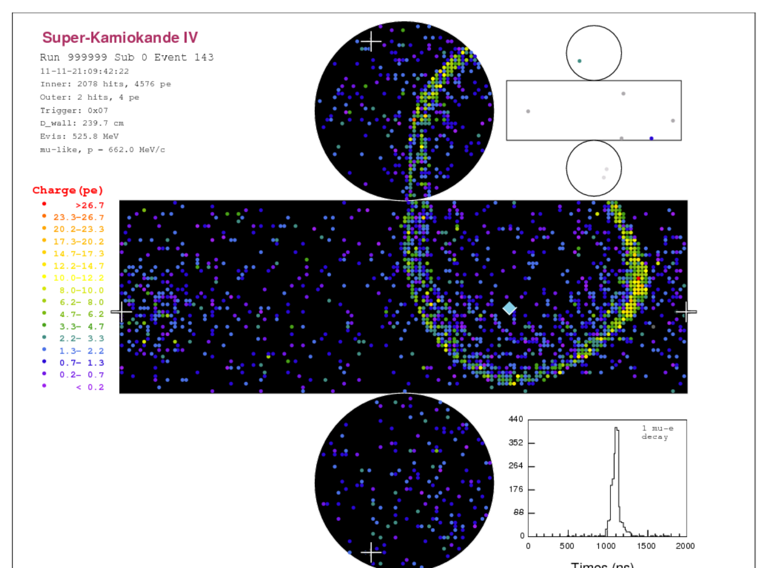
- 22.5 kton fiducial volume

Provides T2K event selection.

Good muon/electron separation.

Cannot separate $\nu/\bar{\nu}$ on an event by event basis:

- No charge ID
- No magnetic field



Event display from Monte Carlo

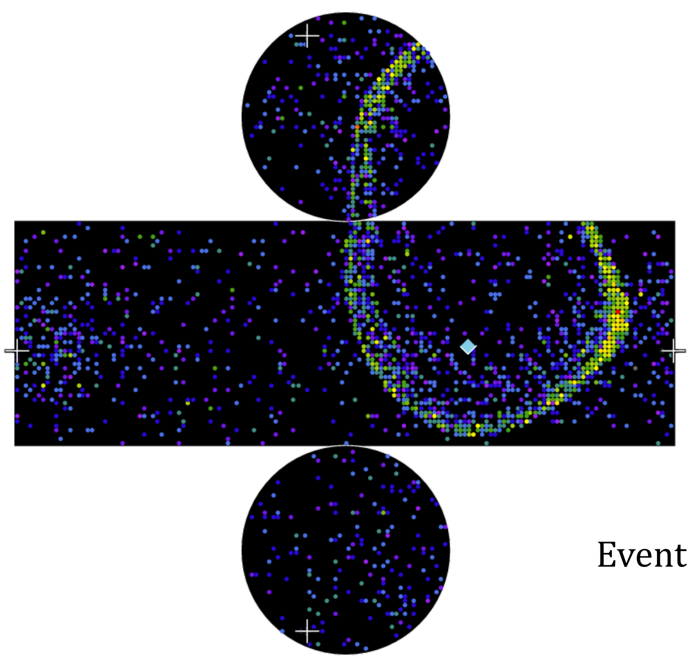
Selection at SK

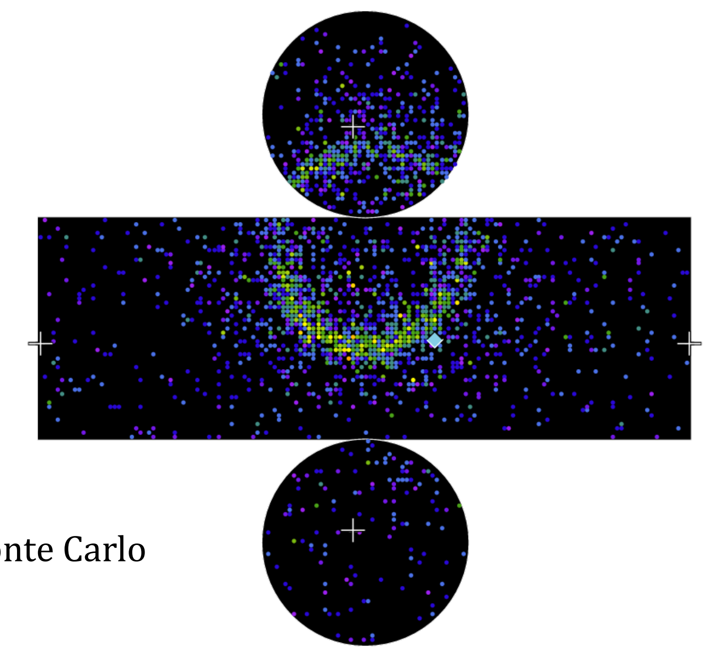
μ-like

- Single reconstructed muon-like ring
- P_μ > 200 MeV/c
- One or less decay electrons

e-like

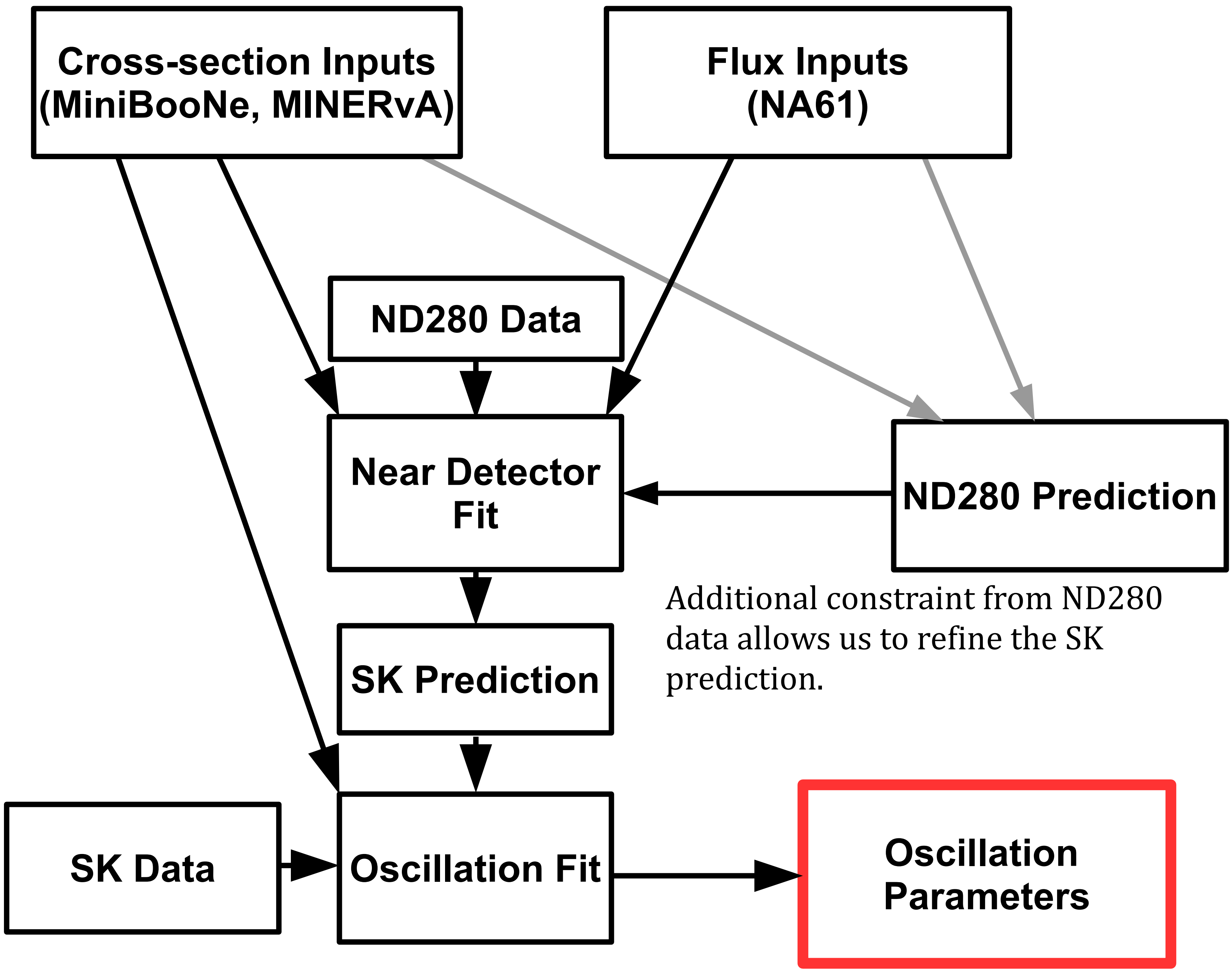
- Single reconstructed electron-like ring, with $E_{visible}$ > 100 MeV
- Reconstructed $E_{neutrino}$ <1250 MeV
- No decay electrons
- Not π_0-like





Event displays from Monte Carlo

Oscillation Analysis Structure



Additional constraint from ND280 data allows us to refine the SK prediction.

T2K systematic uncertainty (Run5-6 $\bar{\nu}_\mu$ disappearance)

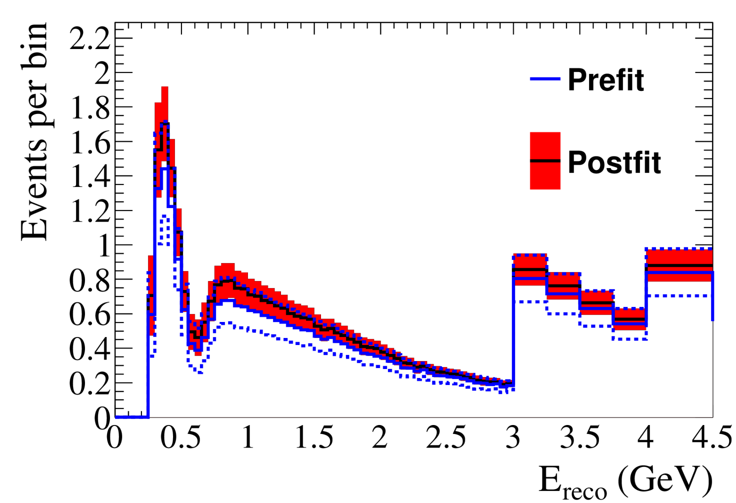
The ND280 Fit allows reduction of common systematics from 9% to 3%.

Not all cross-section uncertainties can be reduced:

- Different targets in the current ND280 (carbon) and SK (water) analyses
- ND280 analysis improvements will aim to reduce this SK-only cross-section uncertainty

		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) × (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK only)	10.0 %	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

Fractional error on number-of-event prediction



Joint ν_μ Disappearance/ν_e Appearance Result

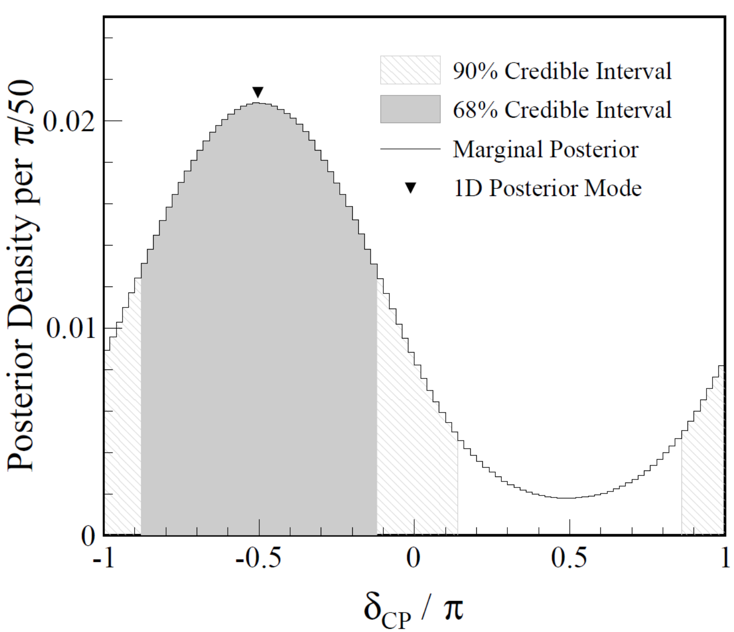
Fitting both the T2K ν_μ and ν_e results simultaneously:

Without reactor constraints:

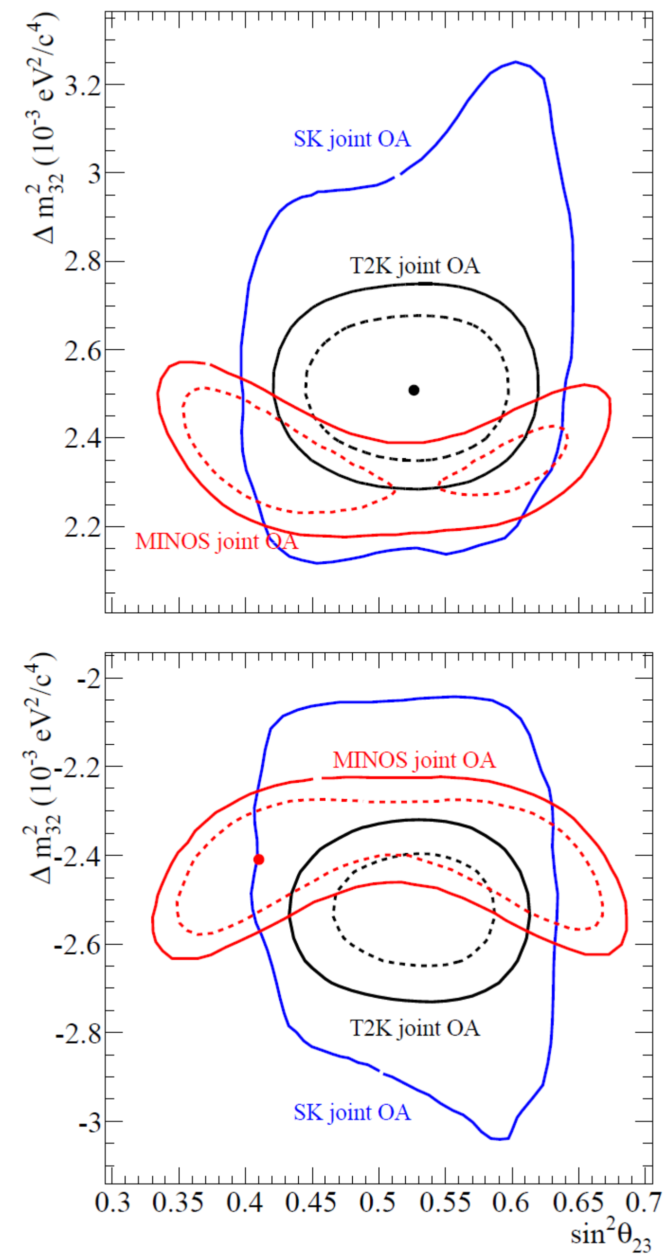
- World best precision for $\sin^2(\theta_{23})$, maximal mixing

With reactor constraints

- Constraints on δ_{CP}



NH



IH

Solid line - 90% confidence level

$\bar{\nu}_\mu$ Disappearance Results

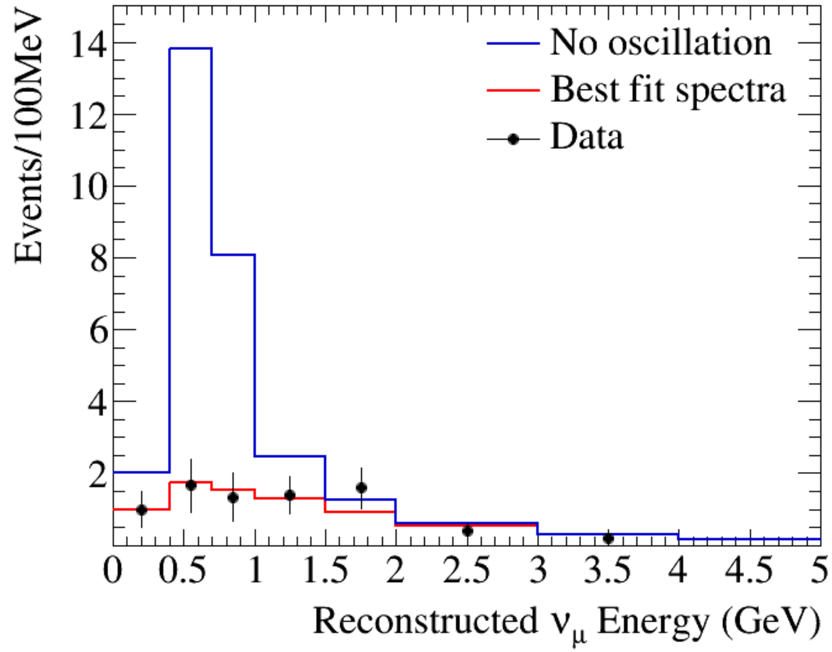
4.01 x 10^{20} protons on target in antineutrino mode.

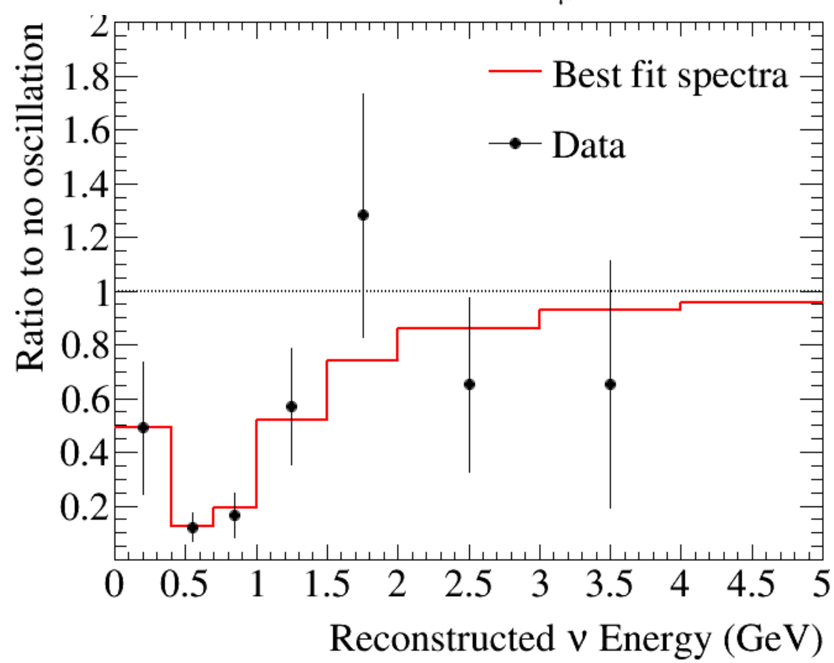
34 μ-like events seen

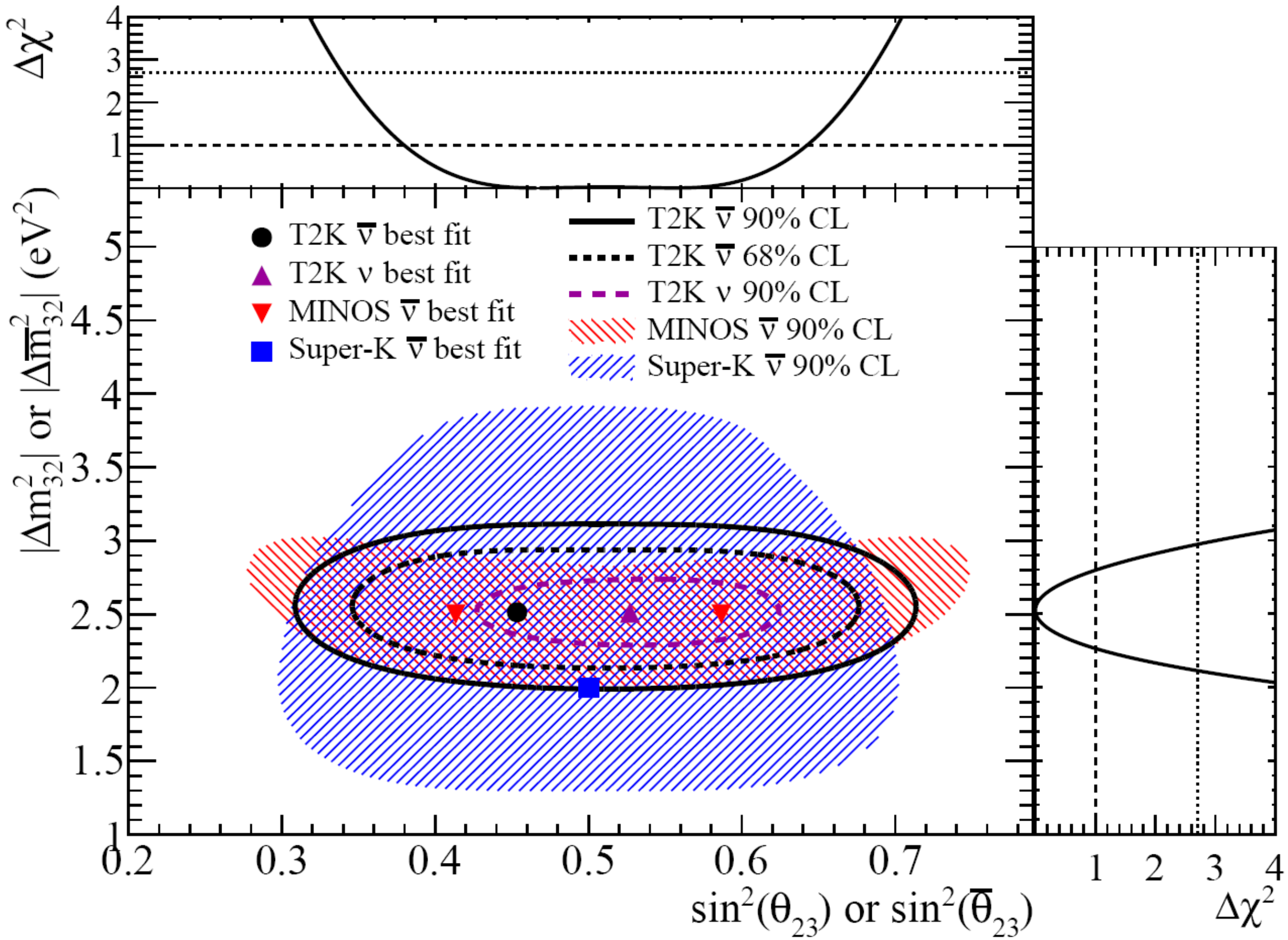
- Spectrum shows clear evidence of oscillation.

$$\sin^2(\bar{\theta}_{23}) = 0.45^{+0.19}_{-0.07}$$

$$|\Delta\bar{m}^2_{32}| = 2.51^{+0.29}_{-0.26} \times 10^{-3}\text{eV}^2$$







Result consistent with :

- MINOS results
- T2K neutrino fit results for ν_μ disappearance
- Maximal mixing

$\bar{\nu}_e$ Appearance Results

Introduces a discrete parameter β

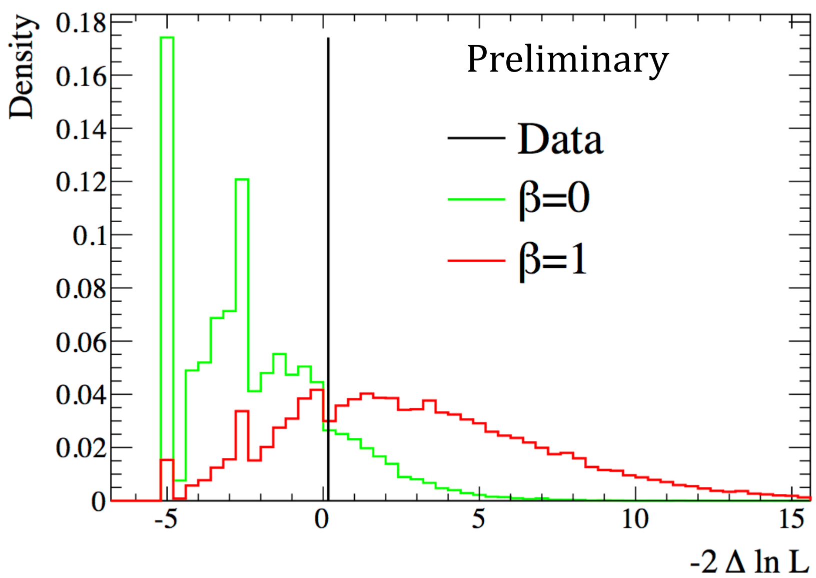
β = 0 : no $\bar{\nu}_e$ appearance

β = 1 : nominal $\bar{\nu}_e$ appearance

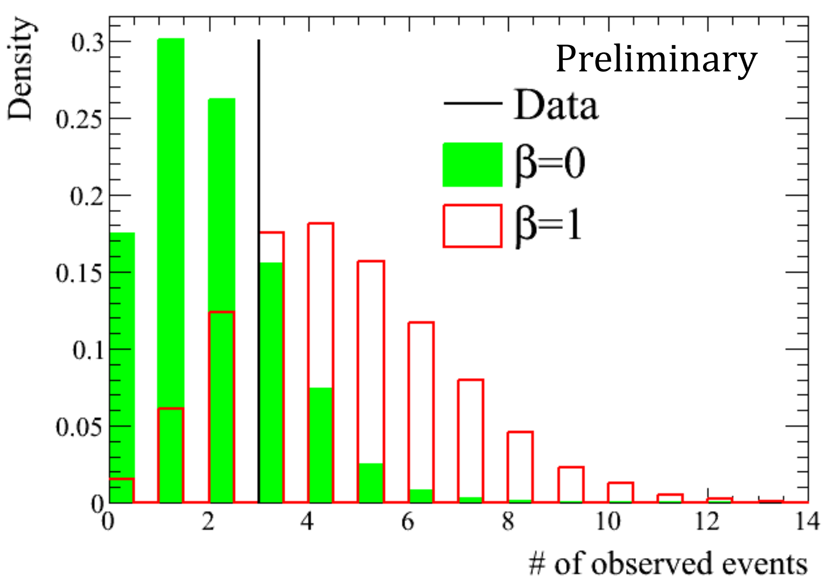
Low statistics for $\bar{\nu}_e$ appearance:

3 events seen so far

- Cannot distinguish between hypotheses at these statistics
- Need at least 2x current protons on target



	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Bkg NC	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826
Total	3.729	4.315	4.851



Conclusions

So far T2K has analyzed data from:

- 4.01×10^{20} protons on target in antineutrino mode
- 7.0×10^{20} protons on target in neutrino mode

Muon anti-neutrino disappearance results

- Consistent with previous T2K ν_μ disappearance and MINOS ν_μ disappearance

Electron anti-neutrino appearance results

- 3 events observed so far
- Statistics too low to differentiate between no-$\bar{\nu}_e$-appearance and $\bar{\nu}_e$ appearance hypotheses

T2K is currently taking more antineutrino data

Upcoming analyses:

- Including water target selection in the near detector constraint
- Full joint neutrino-antineutrino appearance and disappearance fit

Additional Slides

Event Selection at ND280

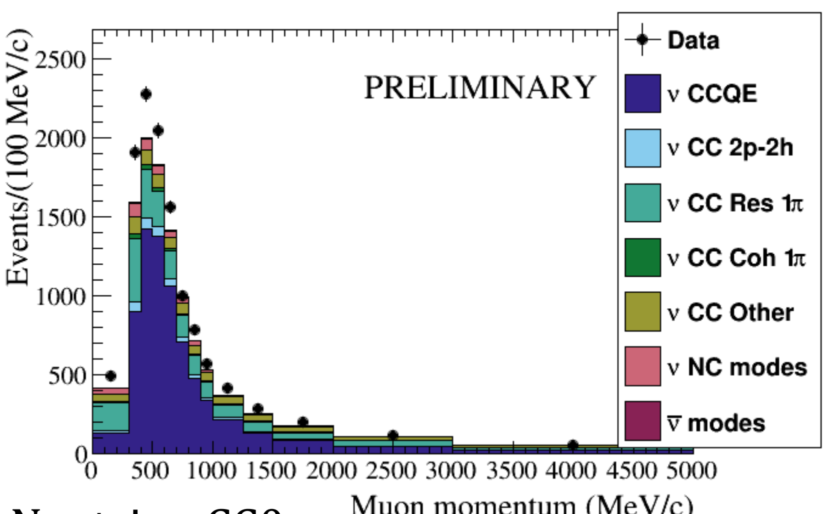
Find highest momentum muon-like track in event

- Use charge identification to separate neutrino and anti-neutrino

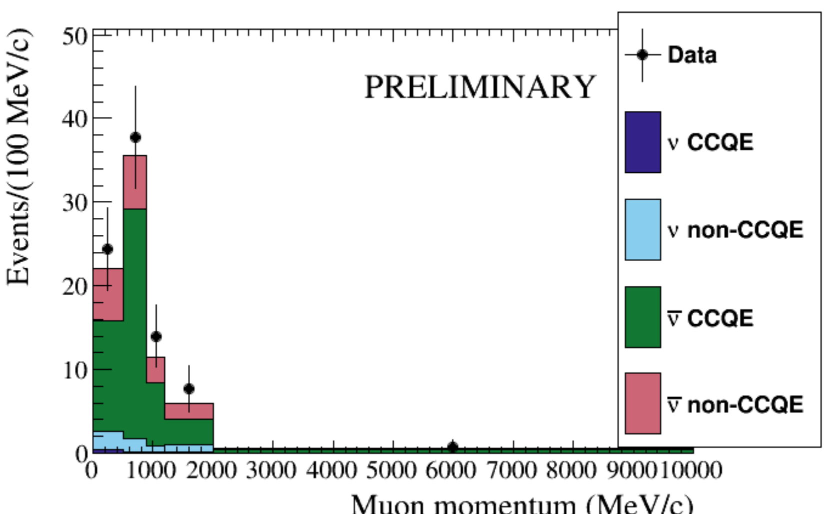
Event topology determined by number of additional tagged pions

- Neutrino mode samples are split in 0 pi, 1 pi and N-pion topologies
- Antineutrino mode samples split into 1-track (no additional tracks) and multi-track events

We select both neutrino and antineutrino events in antineutrino beam mode to constrain the neutrino background



Neutrino CC0π

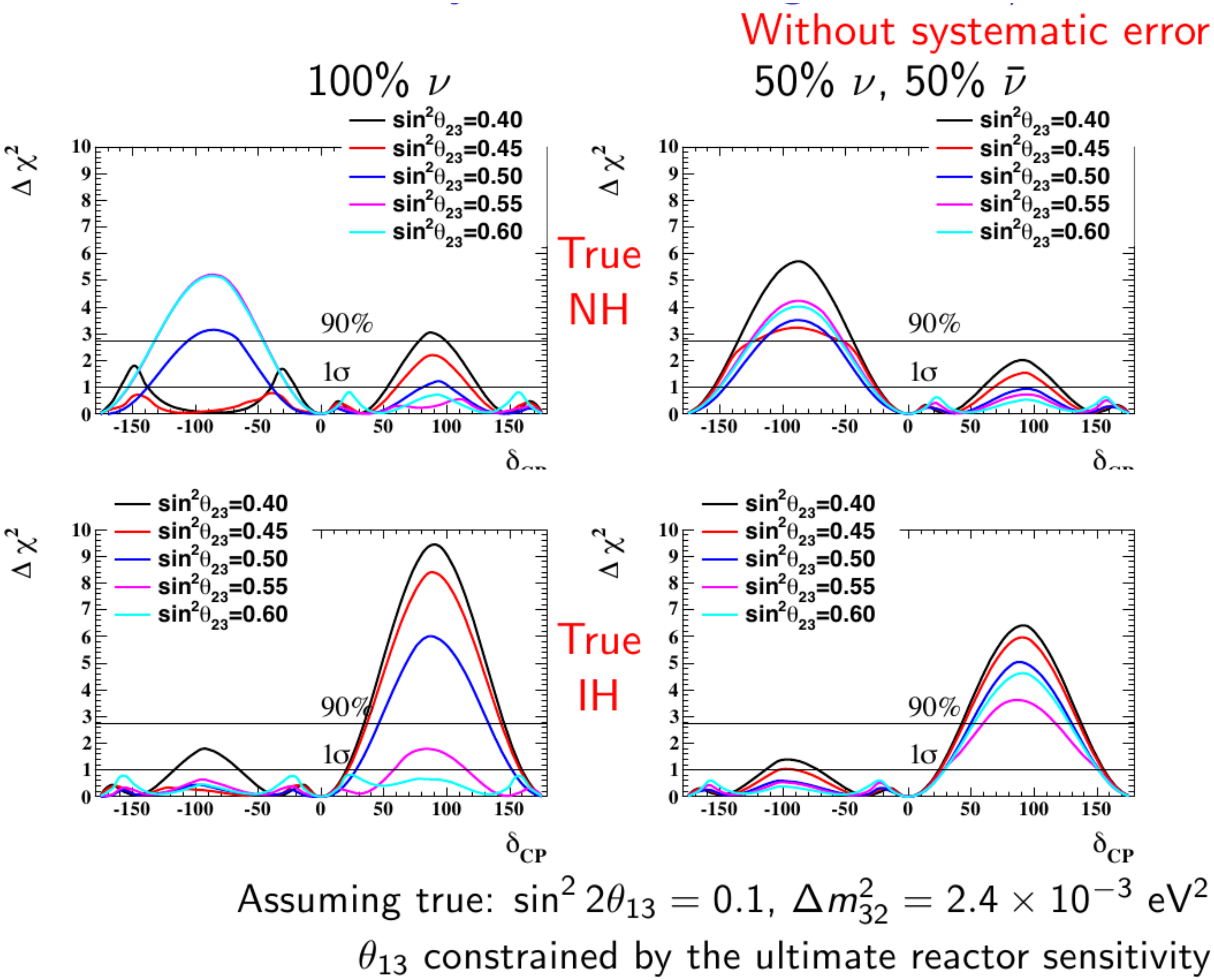


Anti-neutrino CC 1 Track

Recent Cross-section Results

- Measurement of the muon neutrino CCQE cross section with ND280 at T2K
  Phys. Rev. D 92, 112003 (2015)
- Measurement of the electron neutrino charged-current interaction rate on water with the T2K ND280 pi0 detector
  Phys. Rev. D 91, 112010 (2015)
- Measurement of the muon neutrino charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam -
  Phys. Rev. D 91, 112002 (2015)
- Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector
  Accepted by PRD (*arXiv:1509.06940*)
- Measurement of double-differential muon neutrino charged-current interactions on C8H8 without pions in the final state using the T2K off-axis beam
  Submitted to journal (*arXiv:1602.03652*)

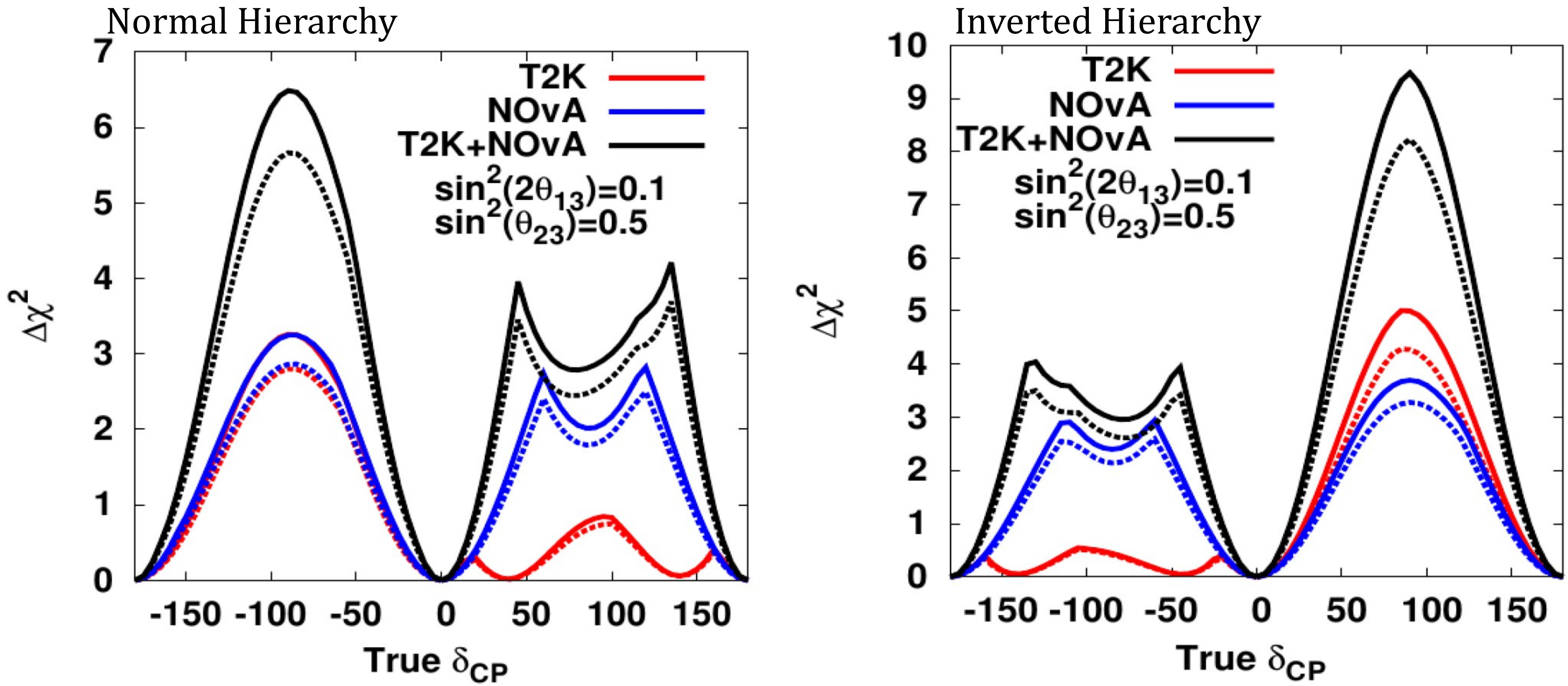
Future Sensitivity on δ_{CP} at T2K



T2K sensitivity to δ_{CP} at full statistics (7.8×10^{21} protons on target)

- Ongoing studies to find best neutrino/antineutrino running strategy to achieve best constraints
- 3σ sensitivity possible by end of T2K if δ_{CP} is maximal

Future Sensitivity on δ_{CP} at T2K



Plots shown assume 1:1 ν:ν running at T2K

Enhanced sensitivity from joint T2K + Nova fit

- Joint fit can reach 90% sensitivity to $\delta_{CP} \neq 0$