# Recent results concerning search for CP violation in accelerator neutrino experiments

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# Outline

- Neutrino oscillations.
- Accelerator neutrinos: oscillations, CP violation.
- T2K experiment and results.
- NOvA results.
- Future prospects in search for CP violation.

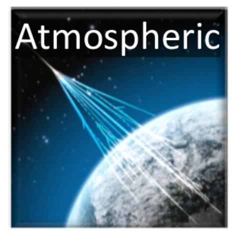
# Neutrino oscillations

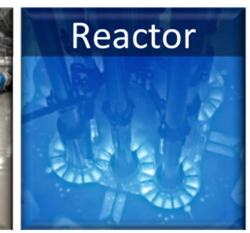
Flavor Mass

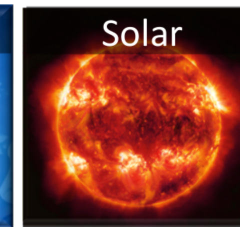
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U_{PMNS}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Pontercorvo
Maki
Nakagawa
Sakata
matrix








Probability of flavor change:

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

$\Delta m^2_{ij} = m^2_i - m^2_j$ $\quad i = 1,2,3$ $\quad \alpha,\beta = e,\mu,\tau$

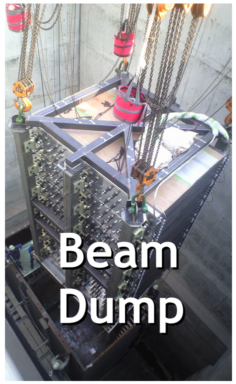
# Knowns & unknowns in oscillations

| Parameter | best-fit | $3\sigma$ |
|---|---|---|
| $\Delta m^2_{21}$ [$10^{-5}$ eV $^2$] | 7.37 | 6.93 – 7.97 |
| $\|\Delta m^2\|$ [$10^{-3}$ eV $^2$] | 2.50 (2.46) | 2.37 – 2.63 (2.33 – 2.60) |
| $\sin^2\theta_{12}$ | 0.297 | 0.250 – 0.354 |
| $\sin^2\theta_{23}$, $\Delta m^2 > 0$ | 0.437 | 0.379 – 0.616 |
| $\sin^2\theta_{23}$, $\Delta m^2 < 0$ | 0.569 | 0.383 – 0.637 |
| $\sin^2\theta_{13}$, $\Delta m^2 > 0$ | 0.0214 | 0.0185 – 0.0246 |
| $\sin^2\theta_{13}$, $\Delta m^2 < 0$ | 0.0218 | 0.0186 – 0.0248 |
| $\delta/\pi$ | 1.35 (1.32) | (0.92 – 1.99) |
| | | ((0.83 – 1.99)) |

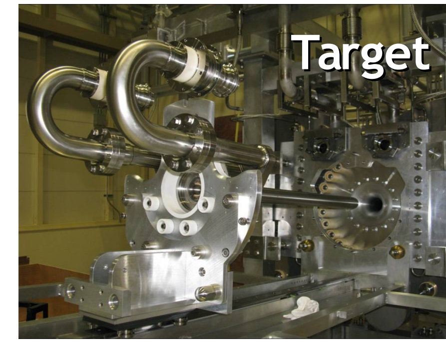
**PDG 2016**
($\Delta m^2 = \Delta m^2_{32}$)

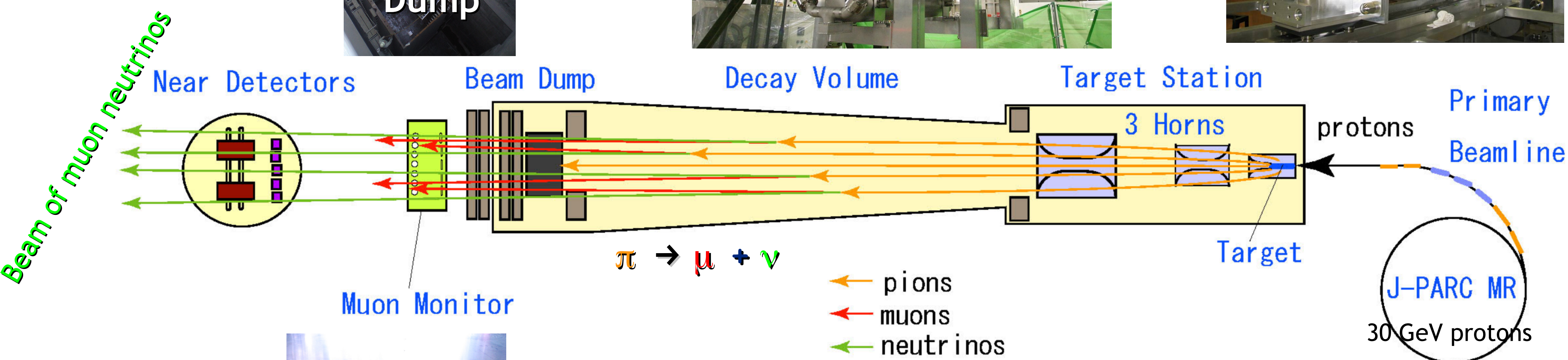
- What we don't know:
  - Is $\delta_{CP} \neq 0,\pi$ (CP violation in neutrino sector) ?
  - Is $\theta_{23} = 45^\circ$(maximal mixing, $\theta_{23}$ octant)?
  - Normal: $\mathbf{m_3 > m_2} > m_1$ (N.H.) or inverted: $m_2 > \mathbf{m_1 > m_3}$ (I.H.) mass hierarchy (matter effects allow to distinguish between them)

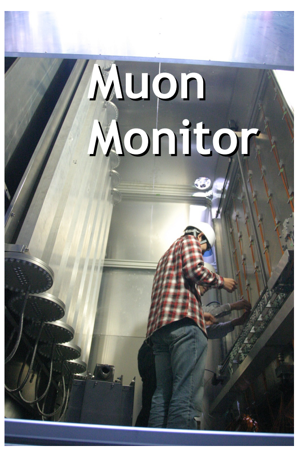
# How to make neutrinos with accelerators?

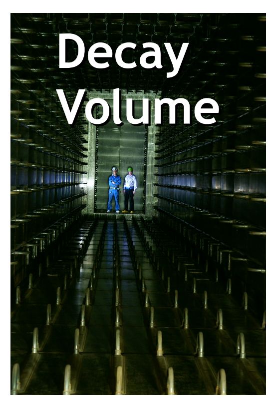






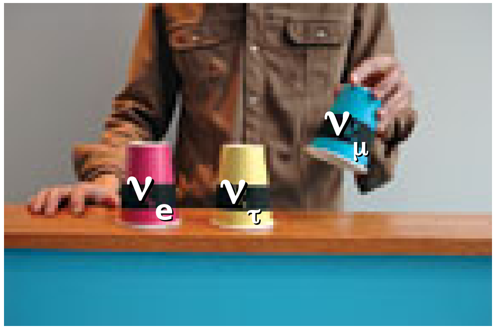




# Accelerator neutrino oscillations

Disappearance of muon neutrinos from the beam

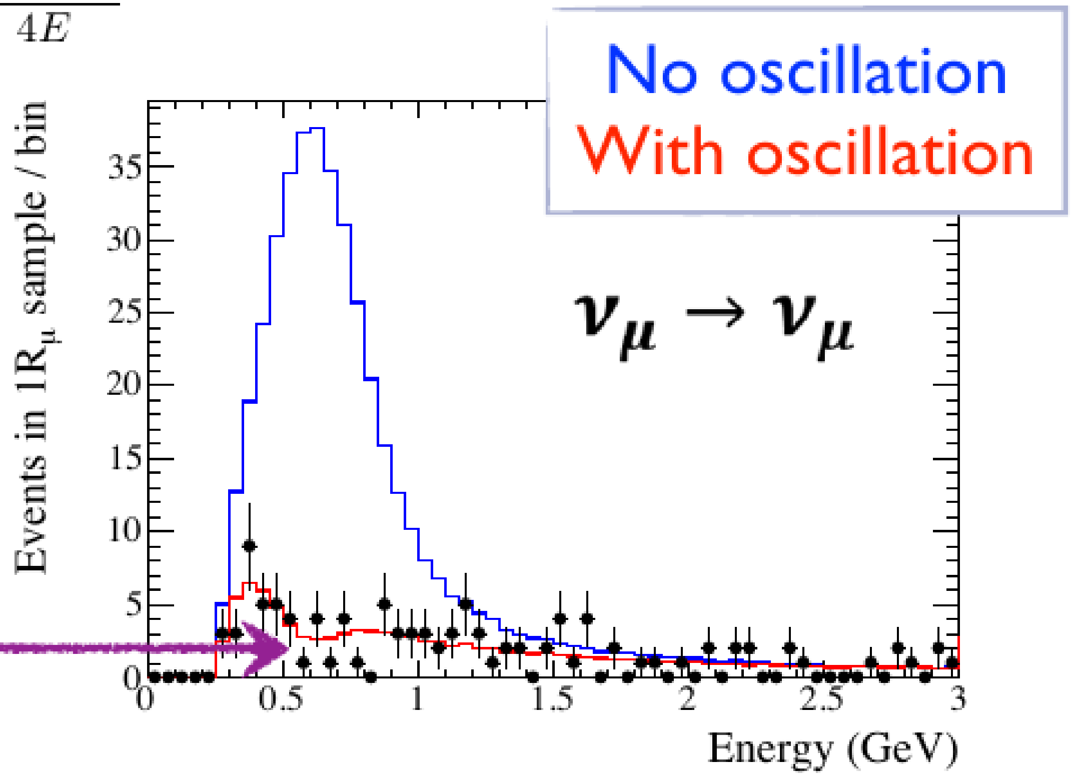
($\nu_\mu$ disappearance)




$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

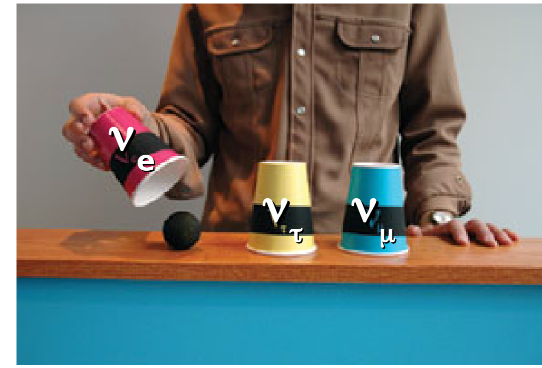
Location of min: $\Delta m^2_{32}$

Depth of min: $\sin^2 2\theta_{23}$



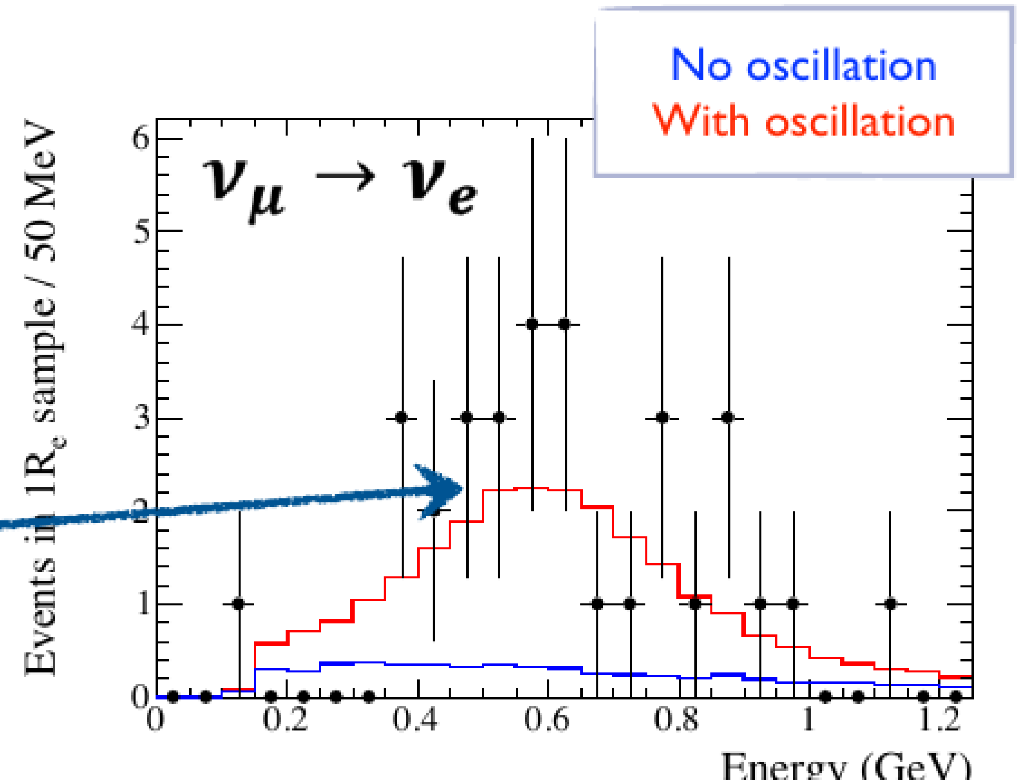
# Accelerator neutrino oscillations

Electron neutrino appearance in the muon neutrino beam
($\nu_e$ appearance)




$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E} \\
& (+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13} \\
& \times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big] \\
& + (\text{CP-even, solar, matter effect terms})
\end{aligned}
$$

Magnitude of the peak
$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, $\delta_{CP}$

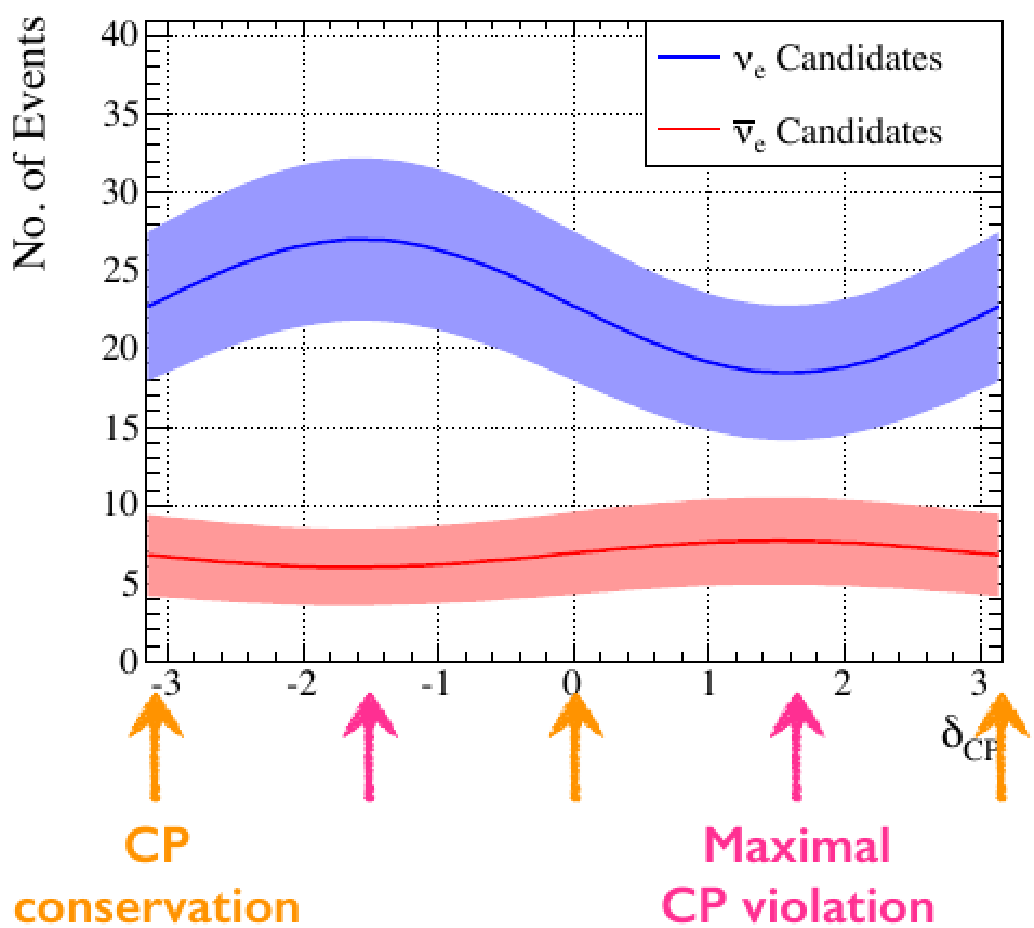


# CP violation in accelerator neutrino oscillations?

$$CPV: \quad P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$
$$(+)-\left[ \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \times \sin \frac{\Delta m^2_{21} L}{4E} \sin^2 \frac{\Delta m^2_{32} L}{4E} \sin\delta_{CP} \right]$$
$$+ \text{(CP-even, solar, matter effect terms)}$$

$\sin\delta_{CP}$ occurs in $\nu_e$ and $\bar{\nu}_e$ appearance probability with opposite sign



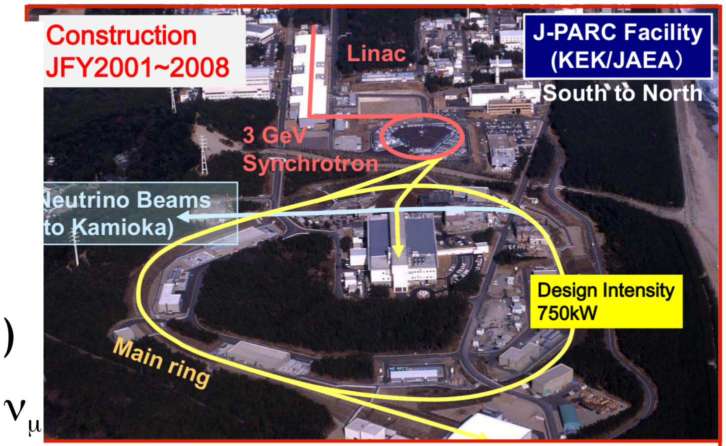

Complicated measurement → Sensitivity to measure $\delta_{CP}$ depends on:

$\delta_{CP}$ true value, $\theta_{23}$ true value, mass ordering

# T2K experiment overview

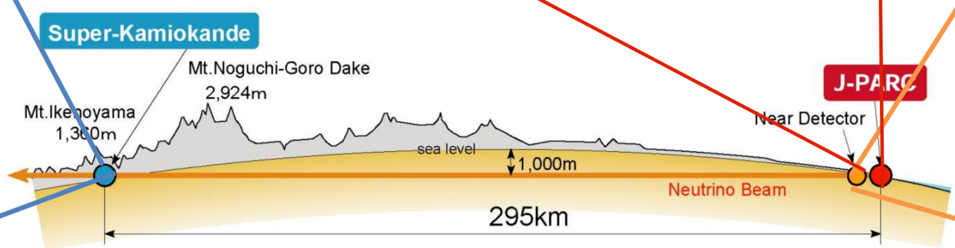
- 11 countries,
- 59 institutions
- ~500 people

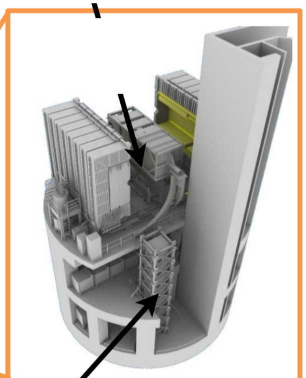
- Long-baseline (L=295 km)
- Almost pure accelerator $\nu_\mu$ beam (<1% $\nu_e$)




- Main goals:
  - Measure $\theta_{13}$ and estimate $\delta_{CP}$ through $\nu_e$ appearance
  - Measure $\theta_{23}$ through $\nu_\mu$ disappearance

**J-PARC (Neutrino production)**

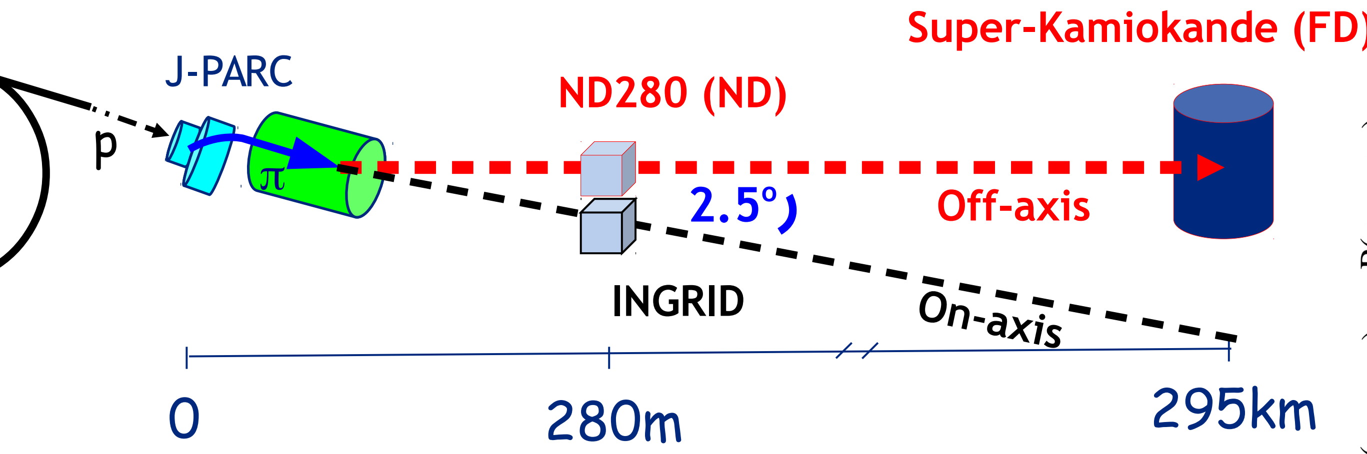


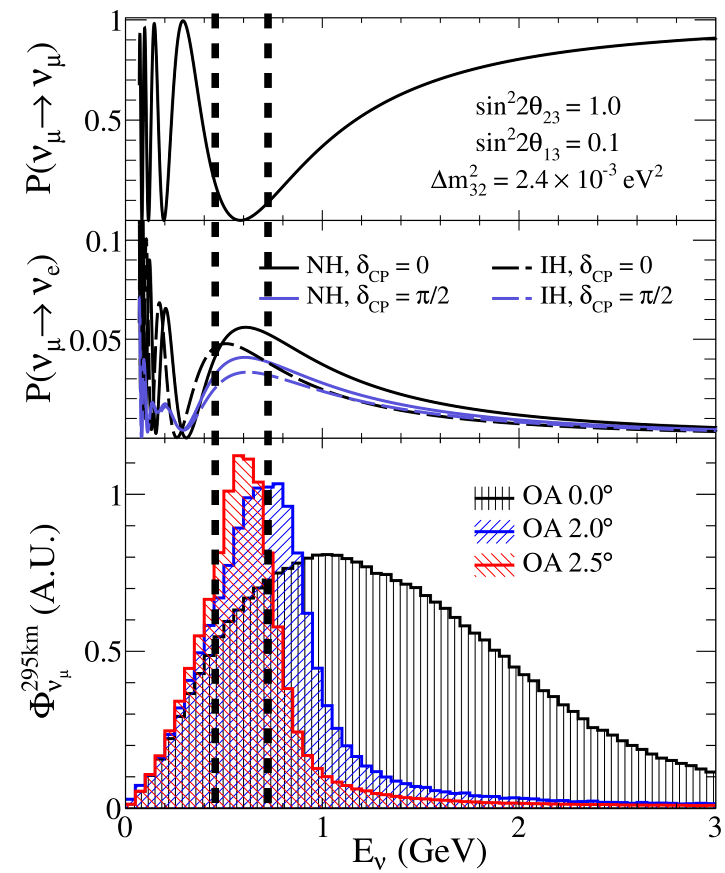



**Far detector**

**Near detectors**

# T2K beam & design

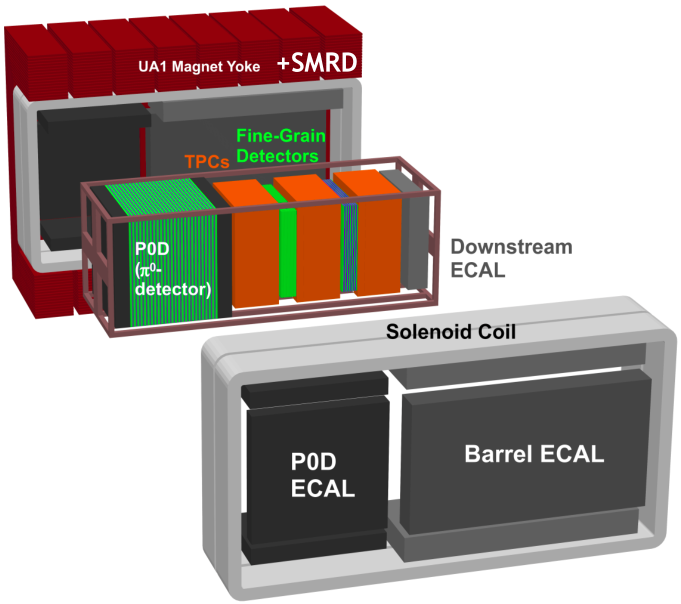


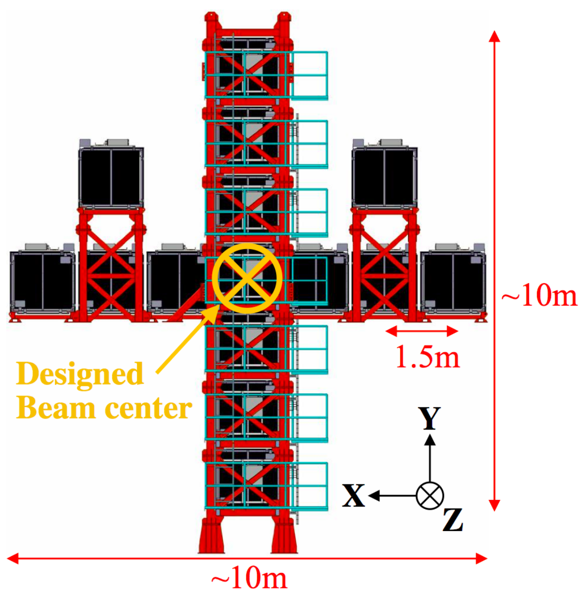




- Pre-oscillation measurement: neutrino spectrum @ Near detector (280m)
- Post-oscillation measurement: neutrino spectrum @ Far detector (295km)

Oscillation probabilities and **neutrino flux peaked at maximum disappearance and appearance**

# T2K near detectors

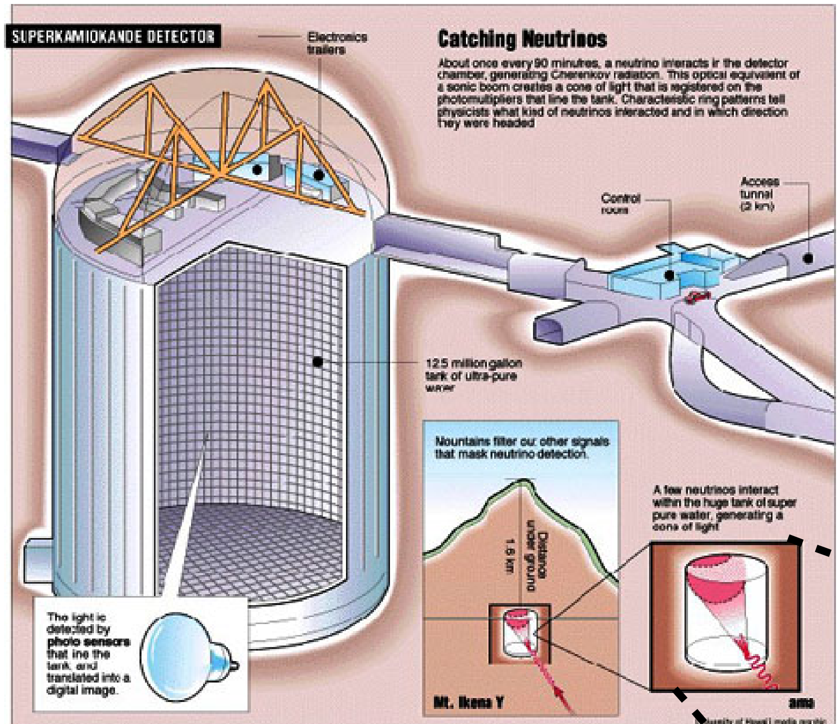



- **ND280** off-axis near detector:
  - Several sub-detectors in 0.2T magnetic field:
    - Tracker (TPCs & FGDs), Pizero Detector (P0D), Electromagnetic Calorimeter (ECAL), Side Muon Range Detector (SMRD)
  - **Goal: Measure neutrino spectrum before the oscillation occurs**
  - Measure intrinsic $\nu_e$ contamination in the beam
  - Neutrino cross section measurements

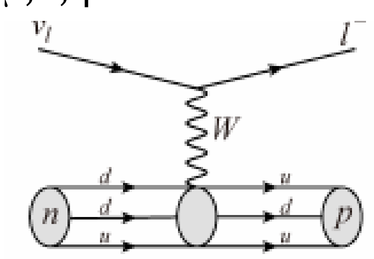
- **INGRID** on-axis near detector:
  - 16 modules (iron/scintillator sandwich) + additional scintillator-only module (proton module)
  - Count neutrinos by reconstructing muons from $\nu_\mu$ interactions
  - Monitor beam rate, direction and stability

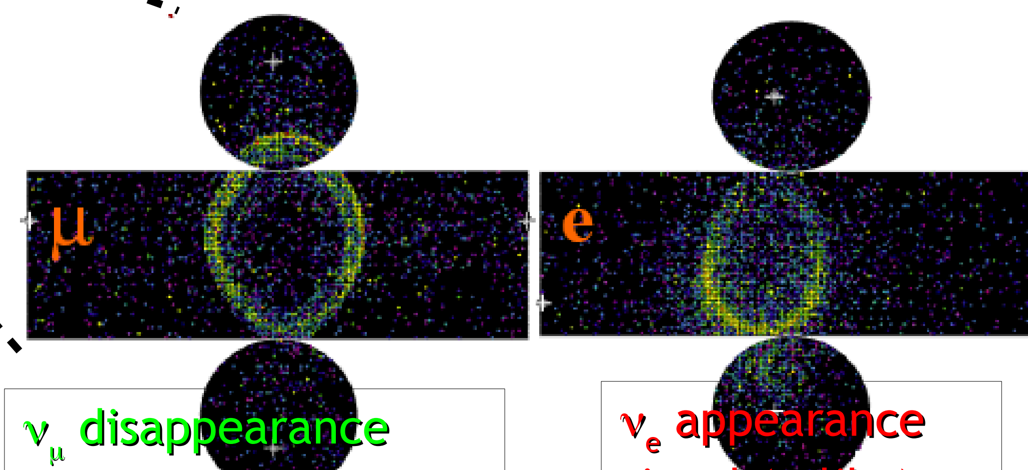
# T2K far detector




- **Super-Kamiokande (Super-K)** far detector:
  - Operating since 1996 with well understood detector and technology
  - 50 kt (22.5 kt FV) water Cherenkov technology
  - > 11 000 photomultipliers
  - Very good electron/muon separation (<1% $\nu_\mu$ identified as $\nu_e$)
  - **Goal: Measure neutrino event spectrum after oscillations occured**

Signal
(l=μ,e; proton below threshold)

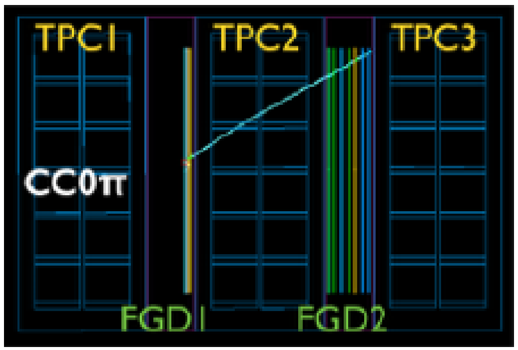


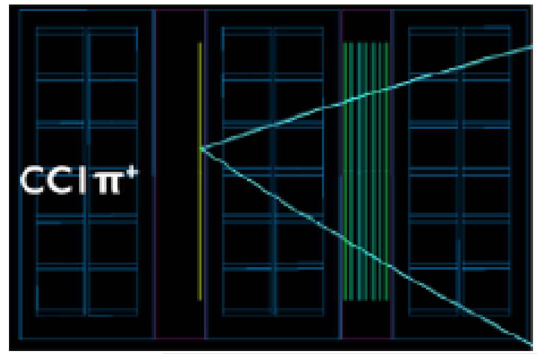

$\nu_\mu$ disappearance signal (μ-like)

$\nu_e$ appearance signal (e-like)

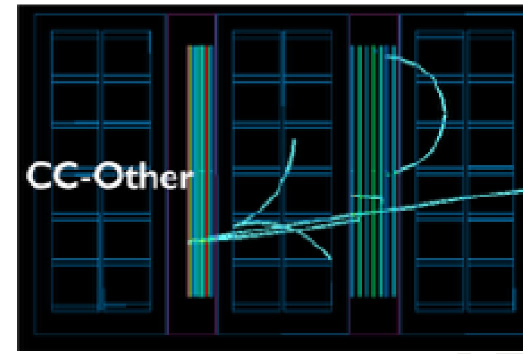
# Near detector data



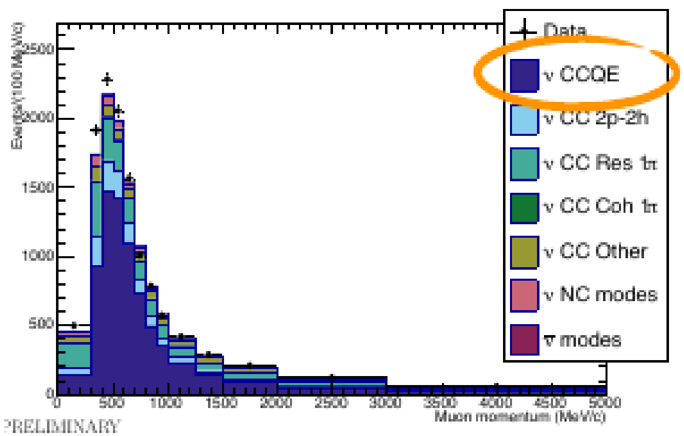

CC interaction with no π in final state

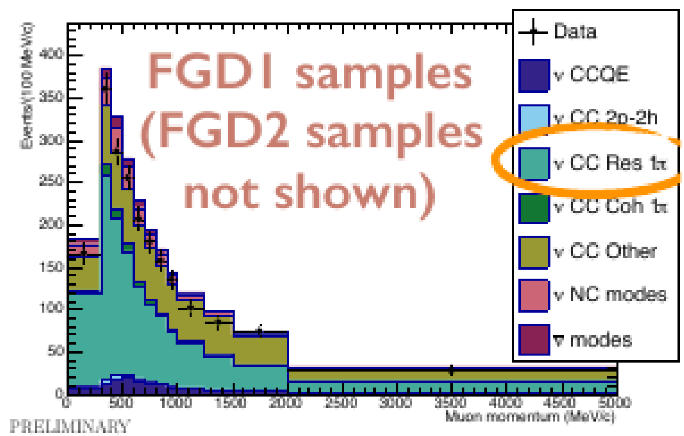


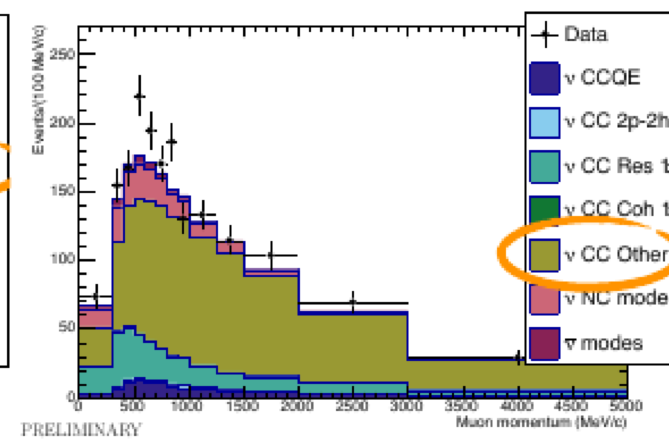

CC interaction with one $\pi^+$ in final state




All other CC interactions



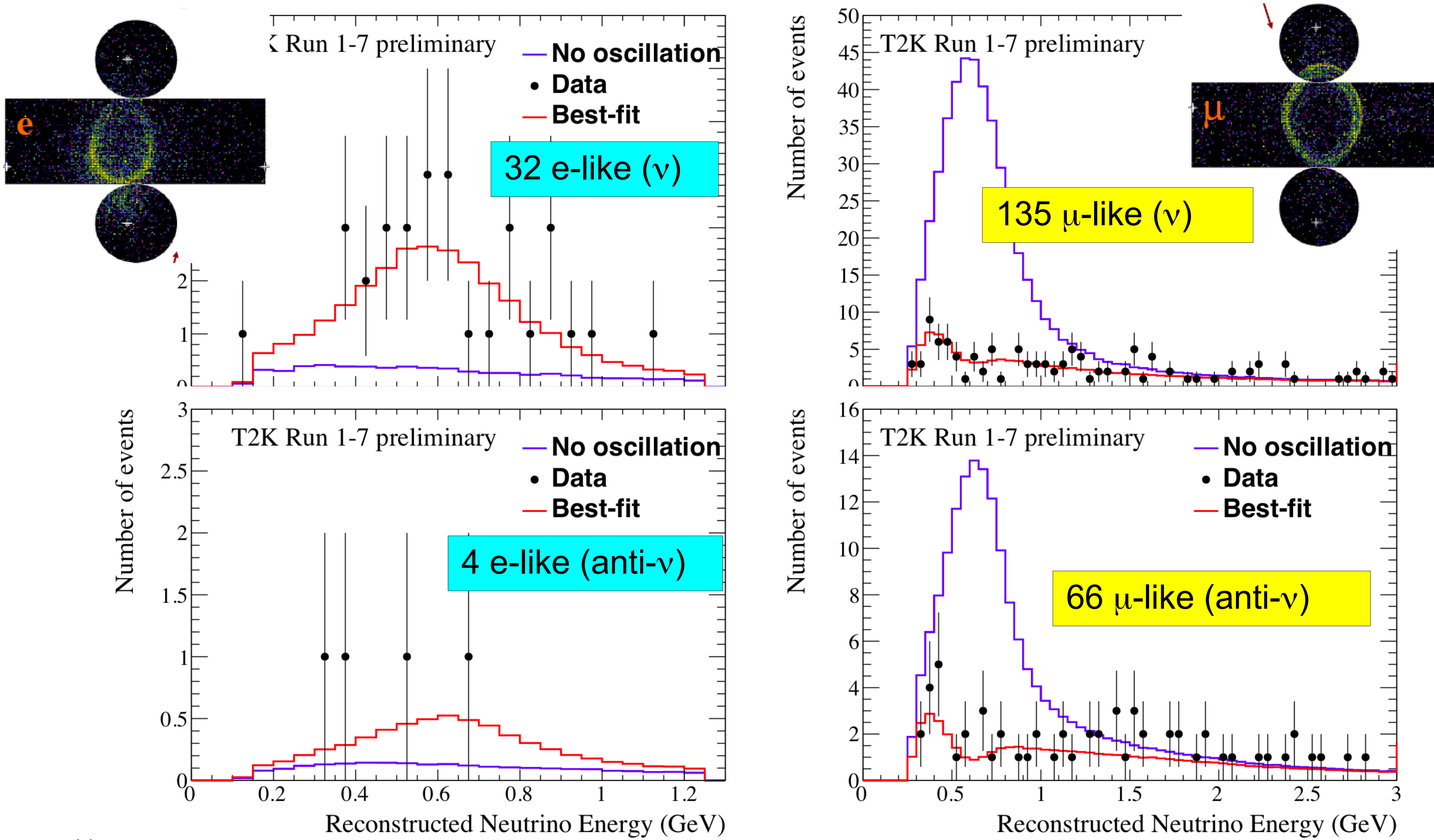



# Near detector & systematic errors

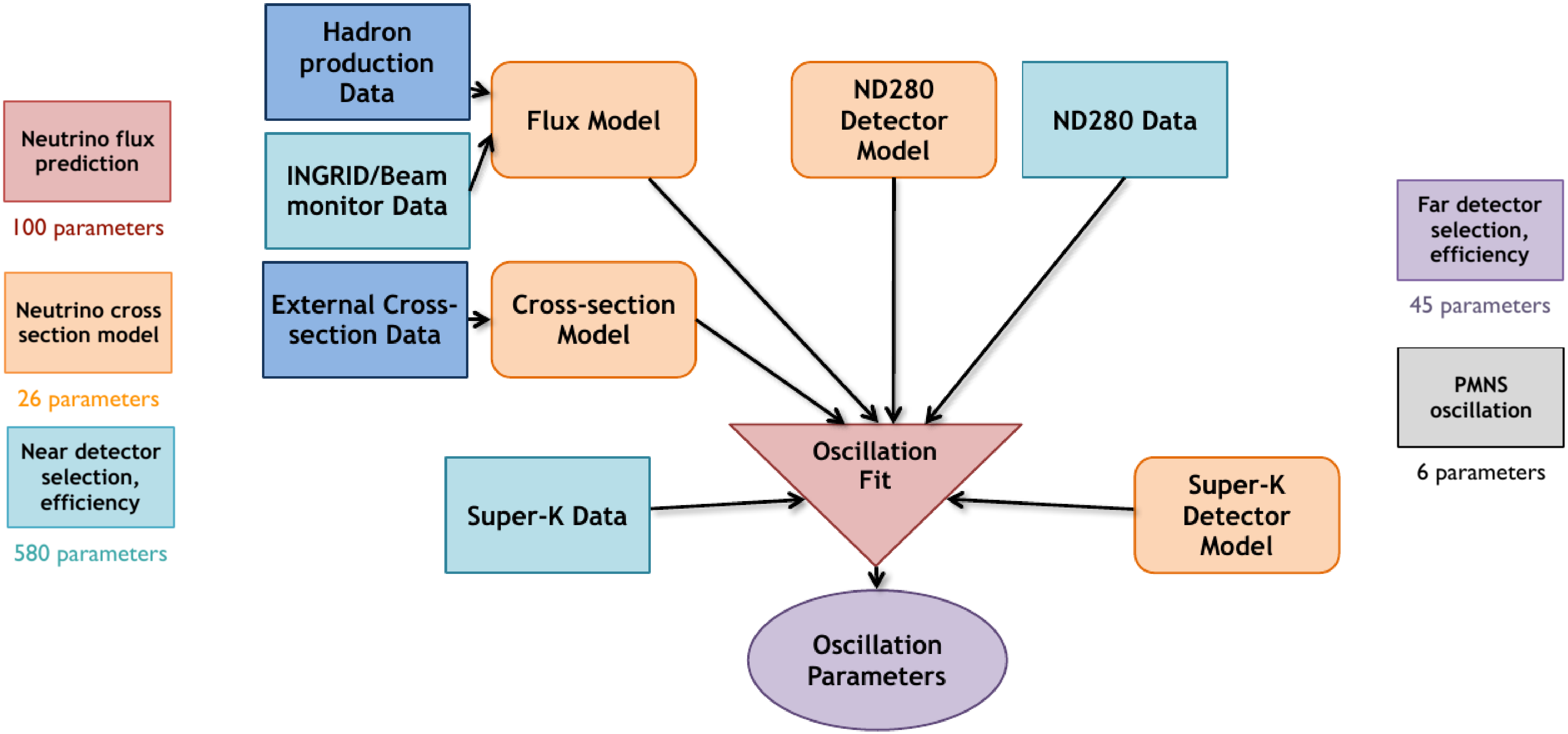
| uncertainty on # of events (%) | | $\nu_\mu$ | $\nu_e$ | anti-$\nu_\mu$ | anti-$\nu_e$ |
|---|---|---|---|---|---|
| flux | w/o ND280 | 7.6 | 8.9 | 7.1 | 8.0 |
| cross section | w/o ND280 | 7.7 | 7.2 | 9.3 | 10.1 |
| flux and cross section | **with ND280** | **2.9** | **4.2** | **3.4** | **4.6** |
| final/sec. hadronic int. | - | 1.5 | 2.5 | 2.1 | 2.5 |
| Super-K detector | - | 3.9 | 2.4 | 3.3 | 3.1 |
| total | **w/o ND280** | **12.0** | **11.9** | **12.5** | **13.7** |
| total | **with ND280** | **5.0** | **5.4** | **5.2** | **6.2** |

- Significant reduction of systematic uncertainties with near detector constraints.
- We are currently at the limit of the detector systematics → need of the near detector upgrade to further reduce systematic errors

# Super-K (far detector) data



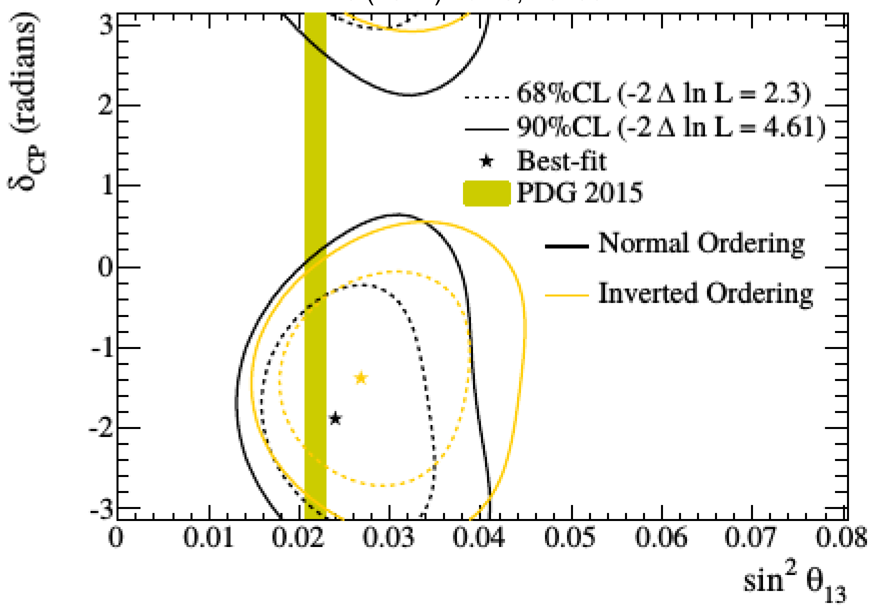
# Oscillation fit




- Two independent fitting strategies with different statistics: frequentist, Bayesian.
- Three data binning approaches (1D: neutrino energy, 2D: neutrino energy + outgoing lepton angle, outgoing lepton momentum + outgoing lepton angle)
- Long validation procedure: predicted event rate comparisons across fitters, ”Asimov” fits, fake data fits, ...

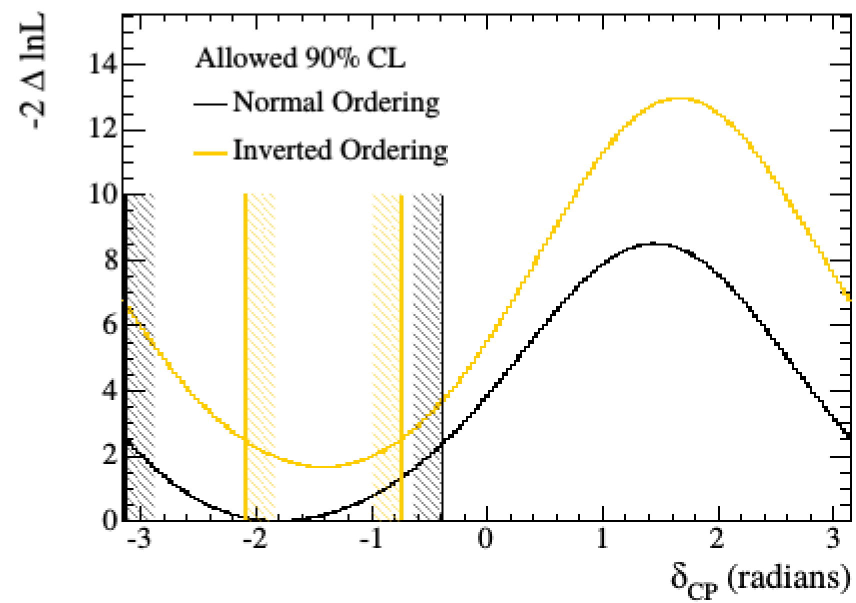
# T2K results on CP violation

PRL 118 (2017) no.15, 151801




- $\theta_{13}$ value consistent with the measurements from reactor experiments
- T2K measurement + reactor constraint → $\delta_{CP}$ allowed values (90% C.L.):
  - $\delta_{CP}$= [-3.13, -0.39] N.H.
  - $\delta_{CP}$=[-2.09, -0.74] I.H.
- T2K favors $\delta_{CP}$ = $-\pi/2$ (maximal CP violation)
- But still not statistically significant → need more data...

| | $\delta_{CP}=-\pi/2$ | $\delta_{CP}=0$ | $\delta_{CP}=\pi/2$ | $\delta_{CP}=\pi$ | Observed |
|---|---|---|---|---|---|
| $\nu_e$ | 28.7 | 24.2 | 19.6 | 24.1 | 32 |
| anti-$\nu_e$ | 6.0 | 6.9 | 7.7 | 6.8 | 4 |

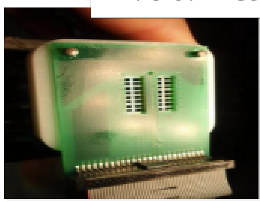


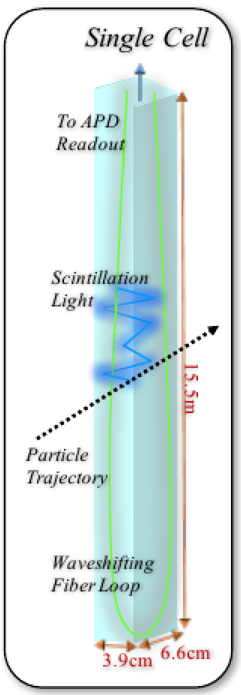

PRL 118 (2017) no.15, 151801

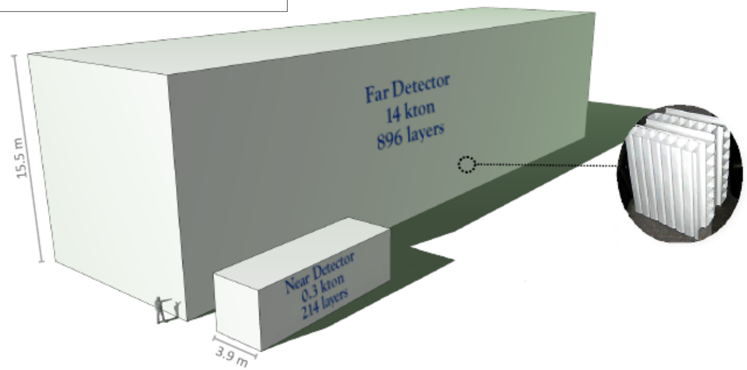
- More $\nu_e$ candidates than predicted
- Fewer anti-$\nu_e$ candidates than predicted

# NOvA experiment

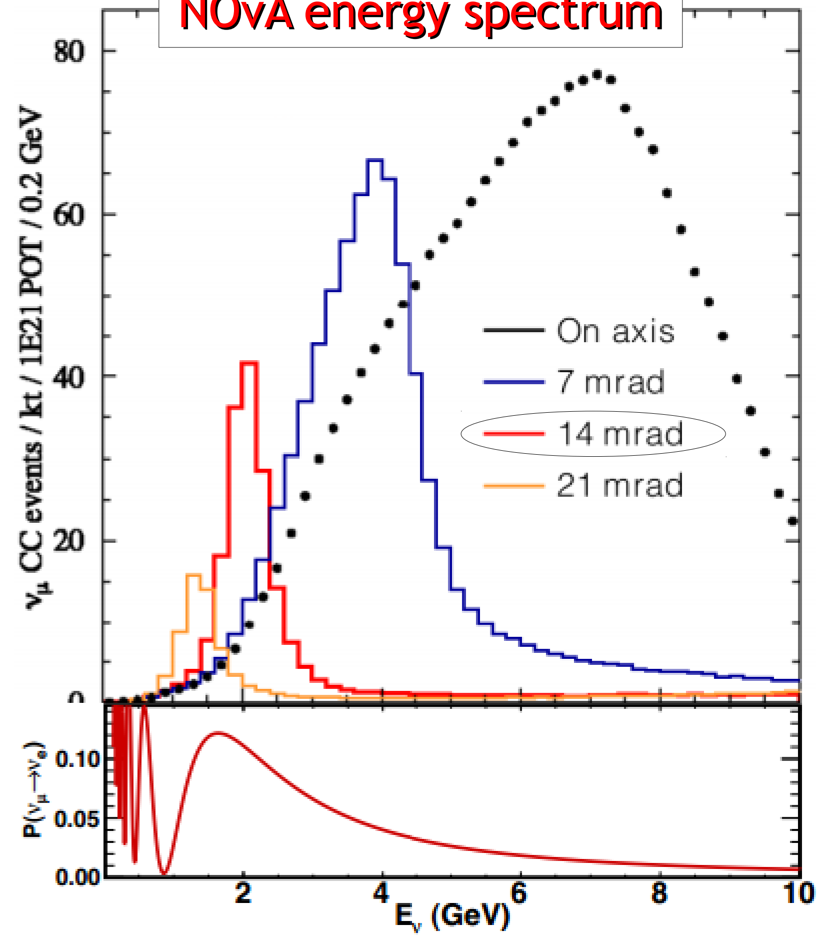
## Near & far detector





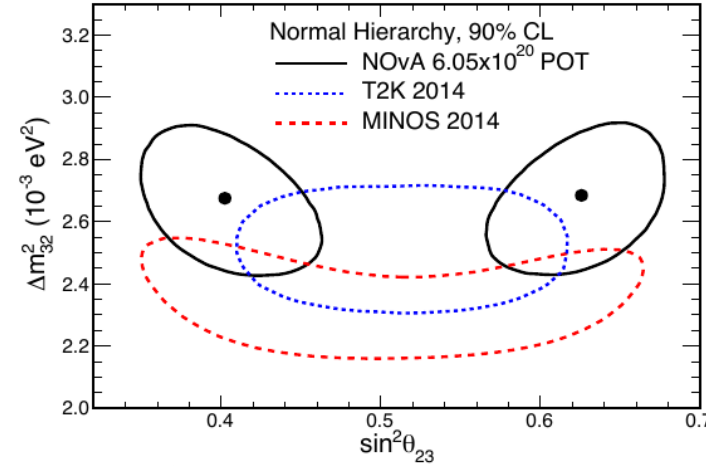




- Accelerator neutrino beam NuMI from Fermilab
- Two functionally identical detectors: near (@1 km) & far (@810 km)
- Longer baseline (810km) with additional larger matter effects on oscillation probabilities
- Extruded plastic cells filled with liquid scintillator → alternating horizontal and vertical orientation

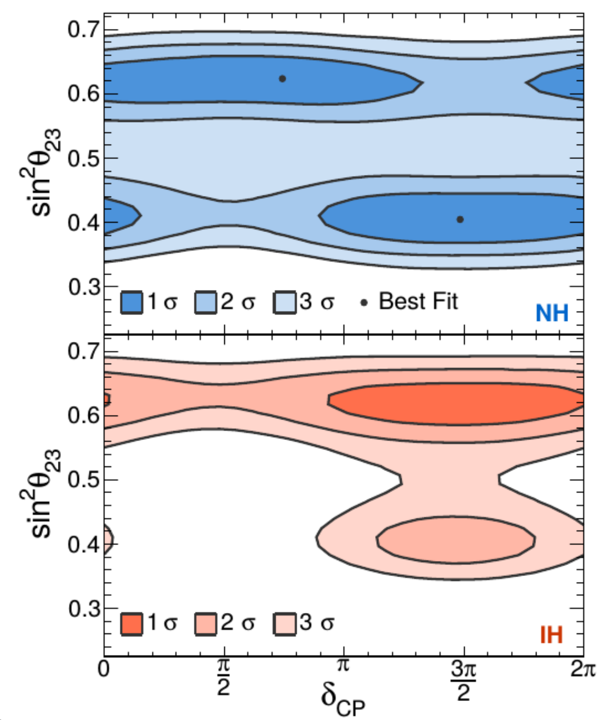


# NOvA results

- T2K's $\theta_{23}$ best fit is close to maximal mixing ($\theta_{23}=\pi/4$).
- NOvA recently reported their $\theta_{23}$ measurement. They have two degenerate solutions for Normal Hierarchy. The maximal mixing is disfavored at $2.6\sigma$.
- Influence on the $\delta_{CP}$ measurement → two degenerate points for Normal Hierarchy $\delta_{CP}= 1.48\pi$ ($\sin^2\theta_{23}=0.404$), $\delta_{CP}= 0.74\pi$ ($\sin^2\theta_{23}=0.623$) with lower significance than T2K.

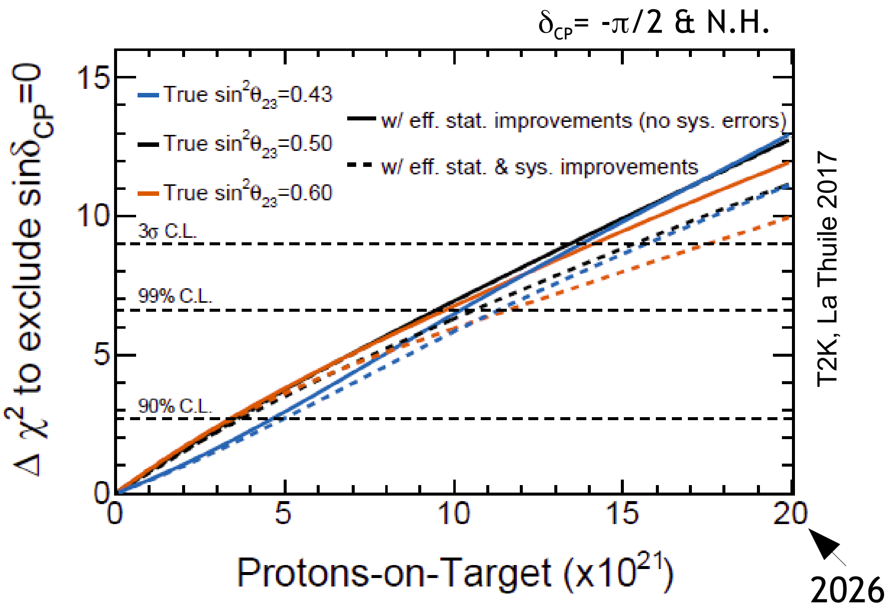


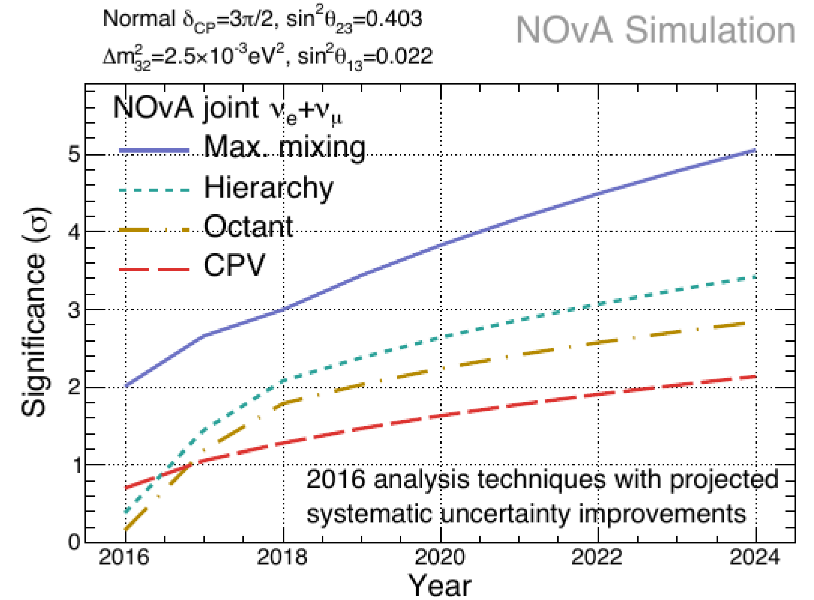

PRL 118 (2017) no.15, 151802




PRL 118 (2017) no.23, 231801

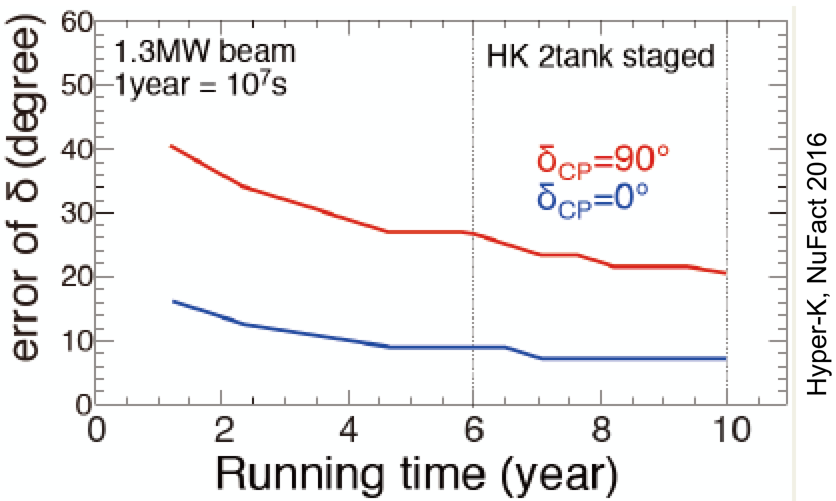
# Future potential of T2K & NOvA



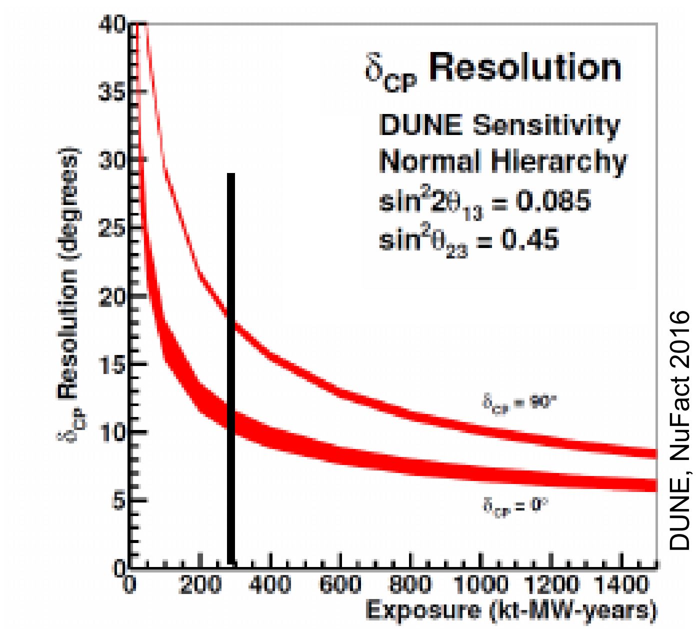




- T2K-Phase II (upgraded beam & near detector, start in ~2021) has a potential to exclude CP conservation hypothesis @ 3$\sigma$ C.L. by 2026.
- NOvA will be constantly taking data should be able to reach ~2$\sigma$ to disfavor CP conservation by 2024.
- Both experiments have ”indication” potential but in order to directly measure $\delta_{CP}$ (5$\sigma$ significance) the next generation experiments are needed...

# Longer perspectives for CPV search




- Hyper-Kamiokande (Japan):
  - Upgraded T2K setup:
    - J-PARC neutrino beam → 1.3 MW beam power
    - Near detectors → cover larger phase-space (already in T2K-II)
    - Super-Kamiokande detector → ~500 kTon Water Cherenkov (staging) Hyper-Kamiokande
  - $\delta_{CP}$ error ~7-21 degrees after ~10 years of running.
  - Expected start of the experiment ~2026.




- DUNE (USA):
  - US neutrino flagship project. Expected to launch in 2025.
  - Fermilab → SURF (South Dakota): 1300 km
  - Far detector: ~40 kton liquid argon TPC (LAr TPC) with staging, Near detector: LAr TPC/Fine-Grained tracker/HPTPC
  - Measure $\delta_{CP}$ with 6-10 degree accuracy for 10 years of exposure.

# Summary

- Large $\theta_{13}$ value opened possibility to probe CP violating phase in neutrino oscillations.
- Current accelerator neutrino experiments such as T2K and NOvA have ”indication” potential for this measurement and disfavor CP conservation:
  - T2K provides 90% C.L. intervals for $\delta_{CP}$. Current results favor $\delta_{CP} = -\pi/2$
  - NOvA also favors $\delta_{CP} = -\pi/2$ with weaker constraints but adds extra $\delta_{CP}$ solution which is related to $\theta_{23}$ degeneracy.
- T2K-Phase II should be able to exclude CP conservation at $3\sigma$ level.
- Future experiments (DUNE, Hyper-Kamiokande) will be able to measure $\delta_{CP}$ with ~7-20 degree accuracy by ~2035