Most Recent T2K Results on CPV in Neutrino Sector

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Outline

- Introduction, neutrino oscillations
- T2K experiment design and analysis strategy
- Results and conclusions

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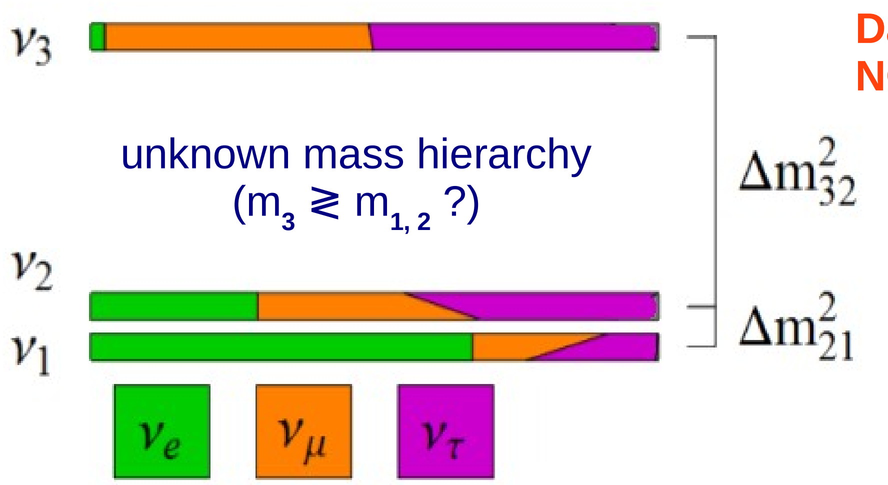
Neutrino oscillations: flavour-mass mixing

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

Super-K, K2K, MINOS, OPERA NOνA, T2K

Super-K, SNO, KamLAND

DChooz, RENO, Daya Bay, MINOS, NOνA, T2K



- c_{ij}, s_{ij} – $\cos\theta_{ij}$, $\sin\theta_{ij}$
- θ_{ij} – mixing angles, δ_{CP} – CP violation (CPV) phase
- T2K is sensitive to Δm^2_{32}, θ_{23}, θ_{13} and δ_{CP}.

Three flavour $\nu_\mu \rightarrow \nu_e$ appearance probability

$$P(\nu_\mu \rightarrow \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$

Leading including matter effect

$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP conserving

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP violating

$$+4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin^2\Delta_{21}$$

Solar

$$-8c_{13}^2 s_{13}^2 s_{23}^2 (1-2s_{13}^2)\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$

Matter effect (small)

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

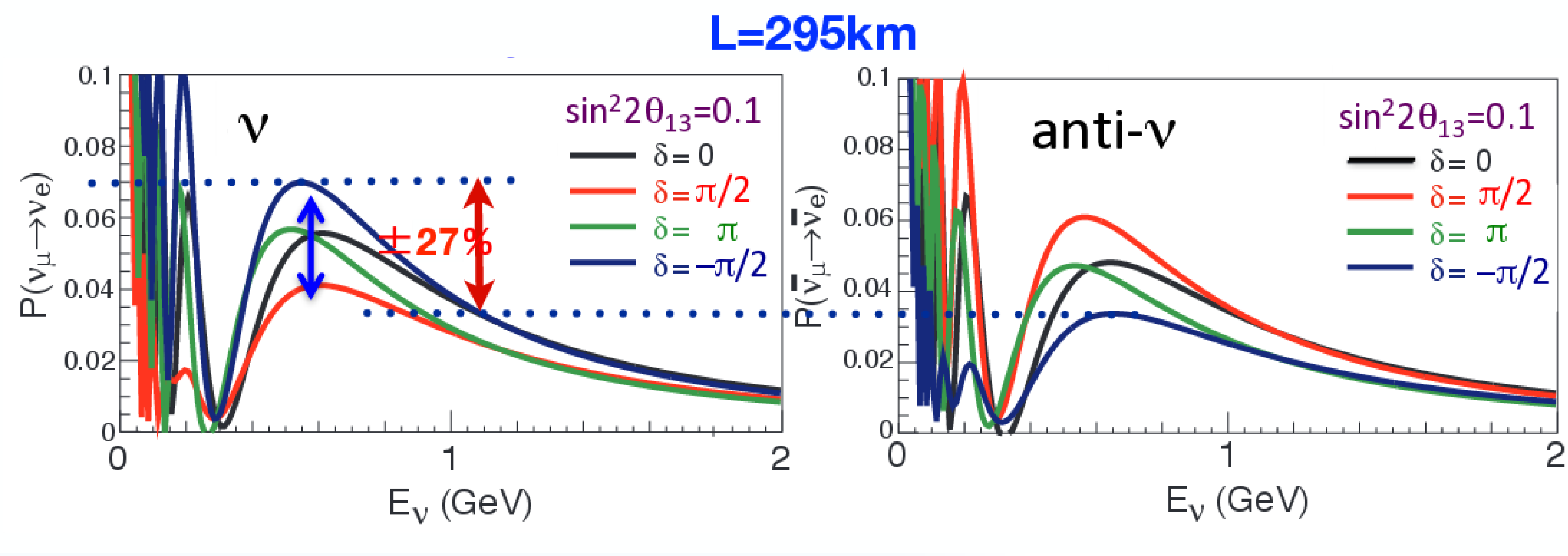
$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2\,\frac{\rho}{\mathrm{gcm}^{-3}}\,\frac{E}{GeV}$$

replace δ_{CP} by $-\delta_{CP}$ and a by $-a$ for $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

The impact of CP violation

- If δ_{CP} = 0 or π then the CP symmetry is conserved. $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ (in vacuum)
- If $\delta_{CP} = -\pi/2$ then $P(\nu_\mu \rightarrow \nu_e) > P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- If $\delta_{CP} = +\pi/2$ then $P(\nu_\mu \rightarrow \nu_e) < P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



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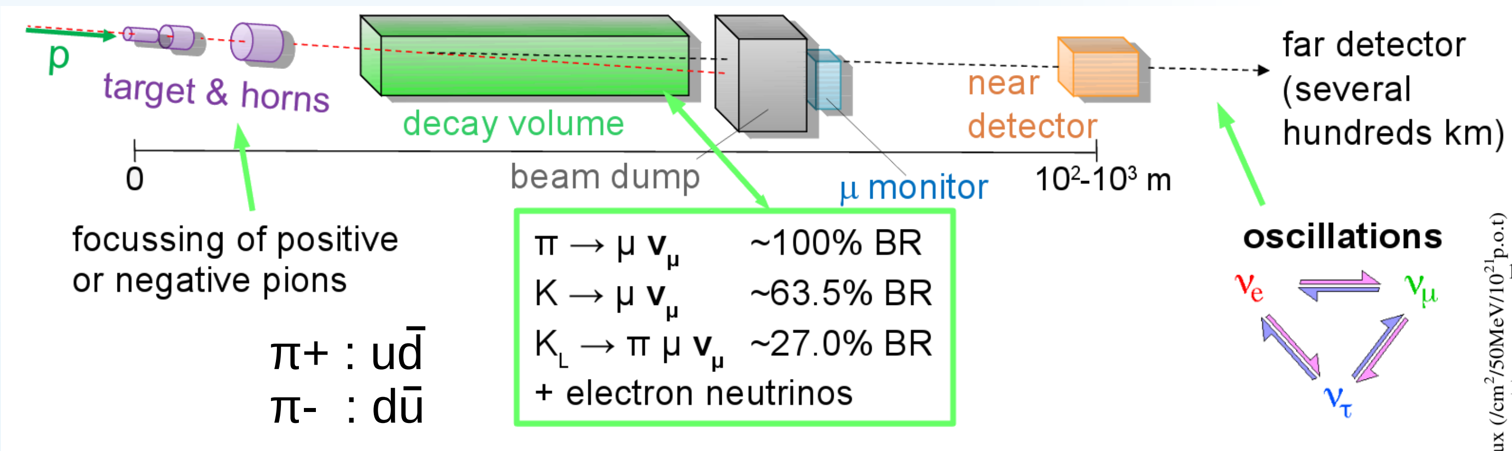
T2K experiment

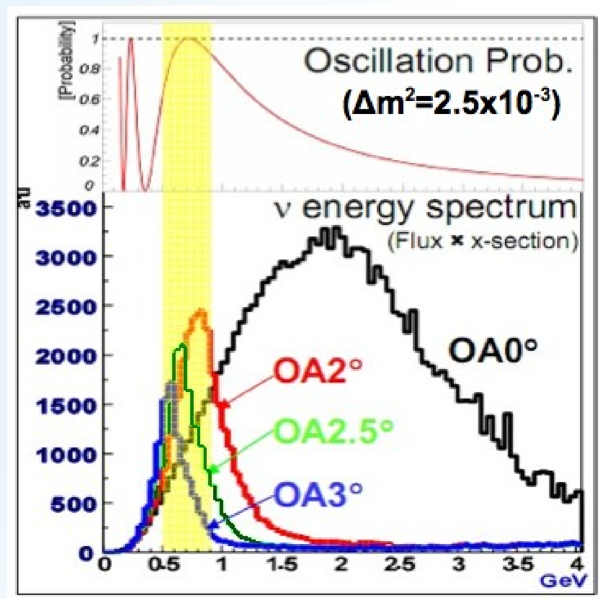
- T2K is a long-baseline neutrino experiment.
- Two near detectors are used to study beam ~280 m from the target.
- Super-Kamiokande is used as the far detector.

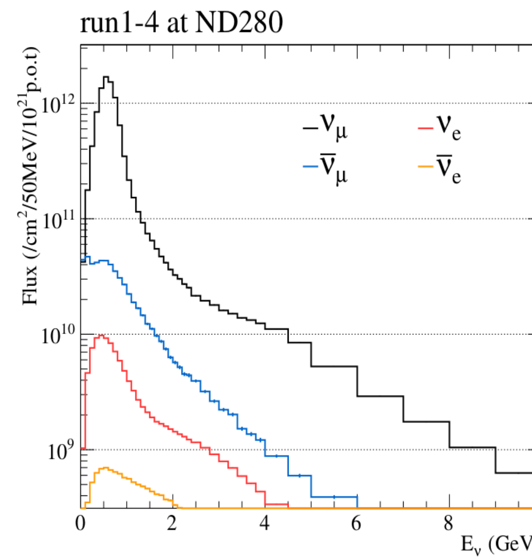
- Started taking data in 2010, ν_e appearance discovered in 2013.

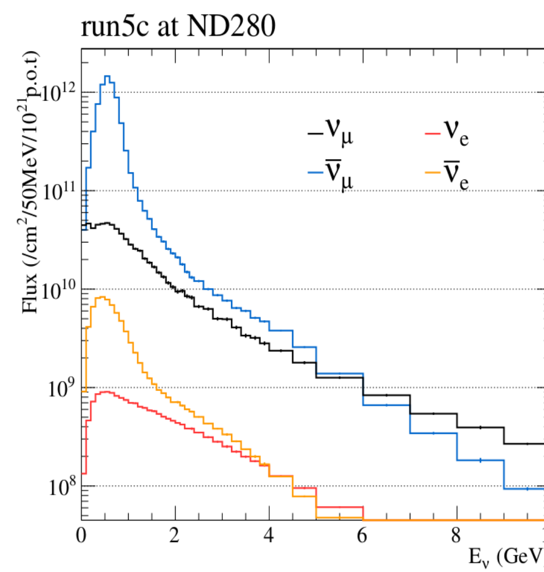
T2K beam



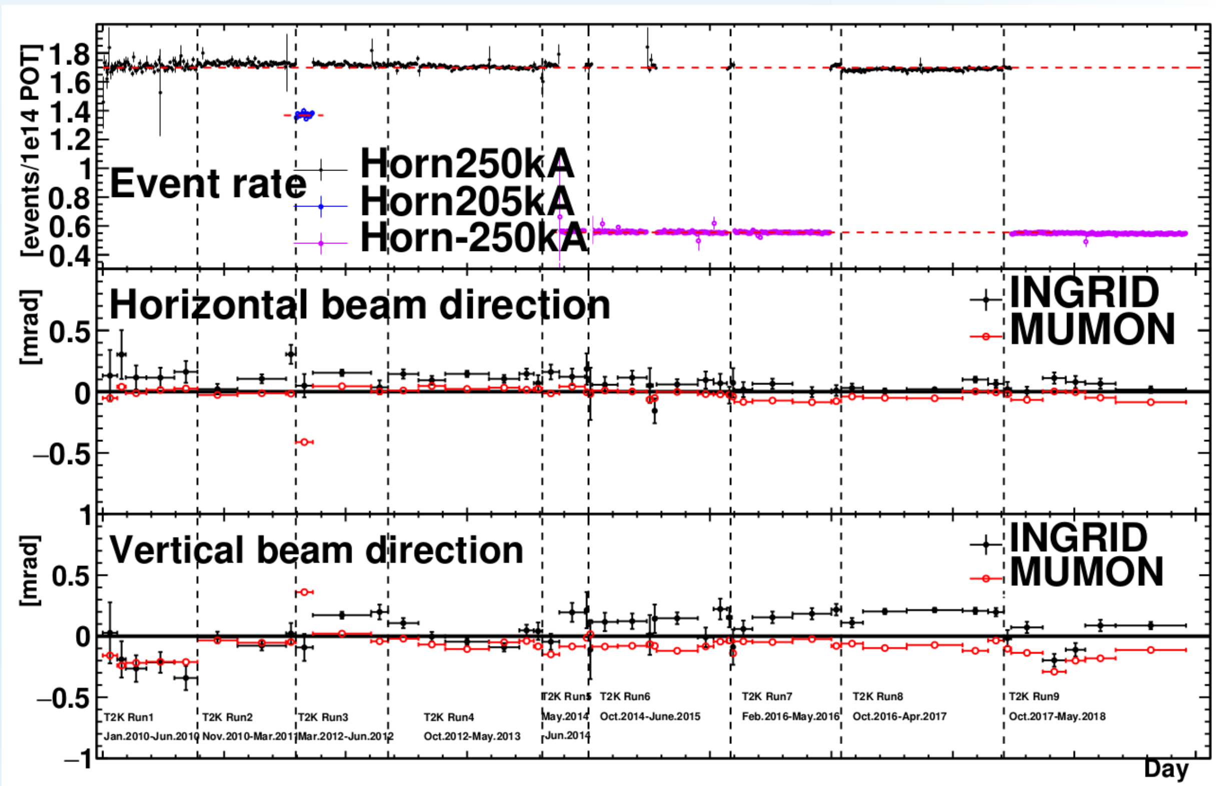
- Beam used in neutrino or anti-neutrino mode.
- Around T2K beam peak (~600 MeV), mostly CC quasielastic (CCQE) and resonant reactions occur.
- Off-axis strategy enhances sensitivity to oscillation effect at the far detector and CCQE interactions and reduces background.

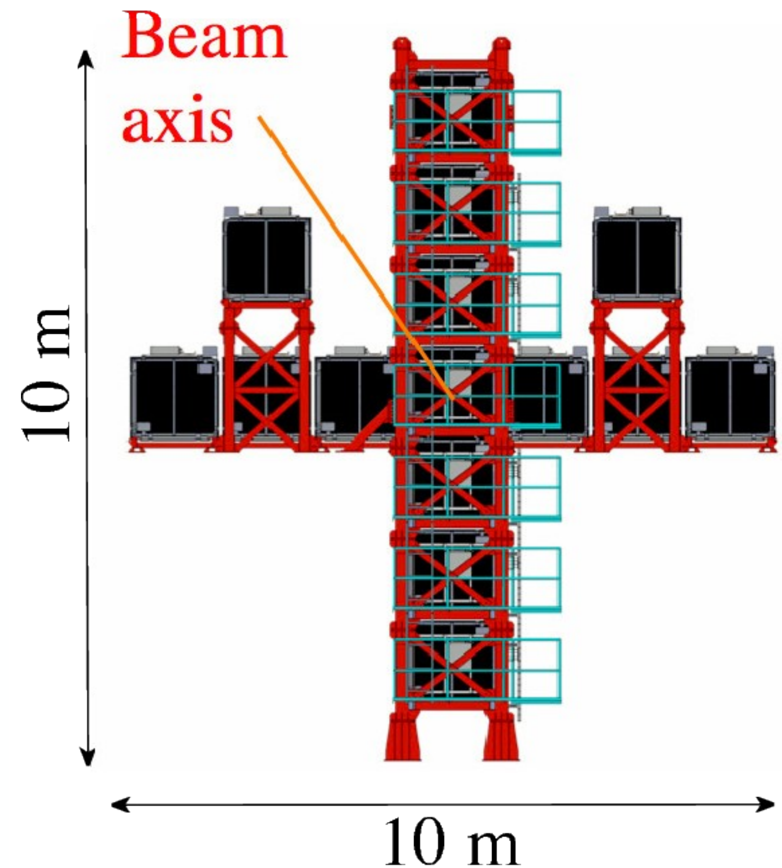






On-axis near detector: INGRID

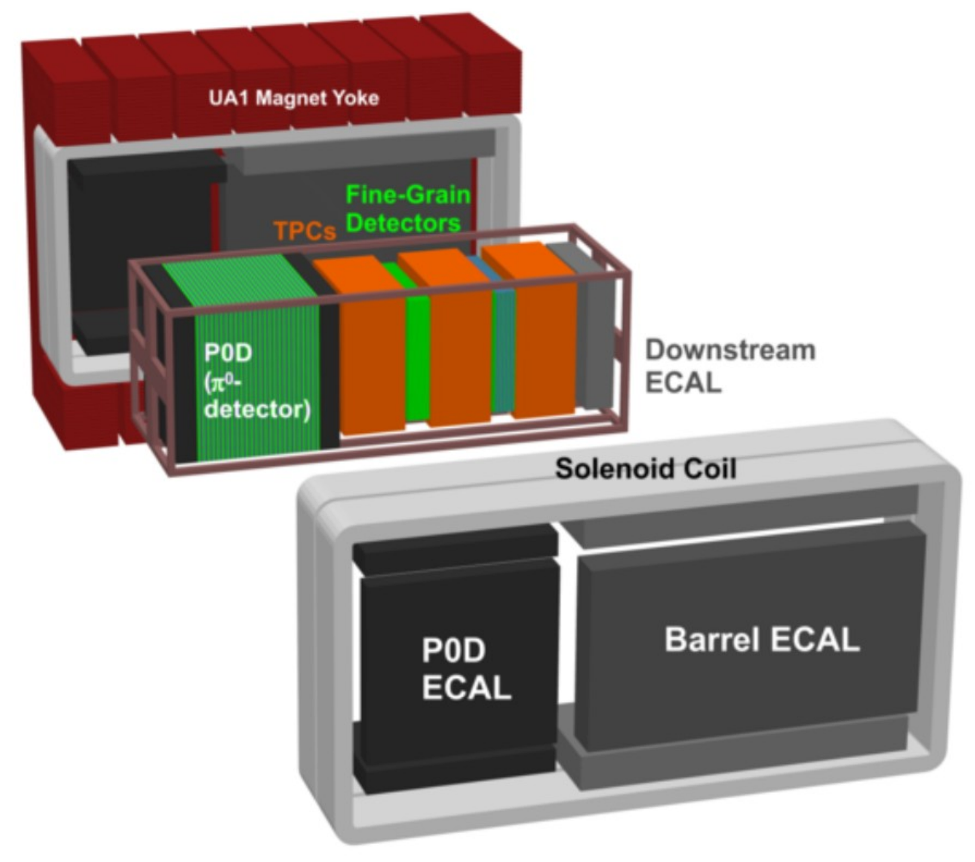




- Cross-shaped detector composed of 16 Fe/scintillator and 1 scintillator modules.
- Monitors beam's direction, profile and intensity.

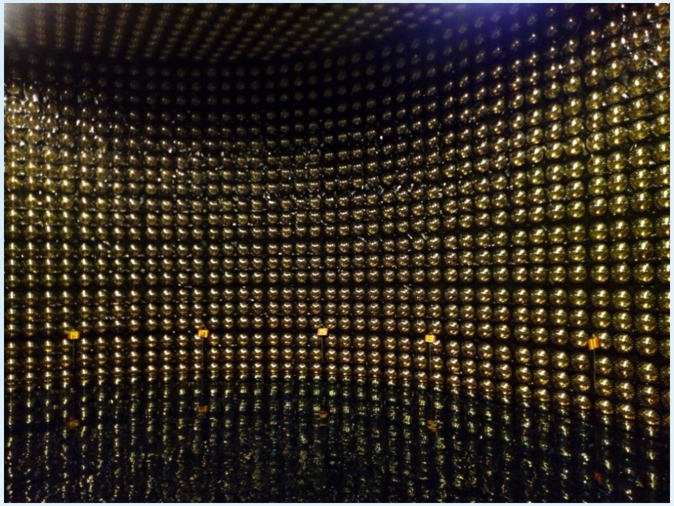
Off-axis near detector: ND280

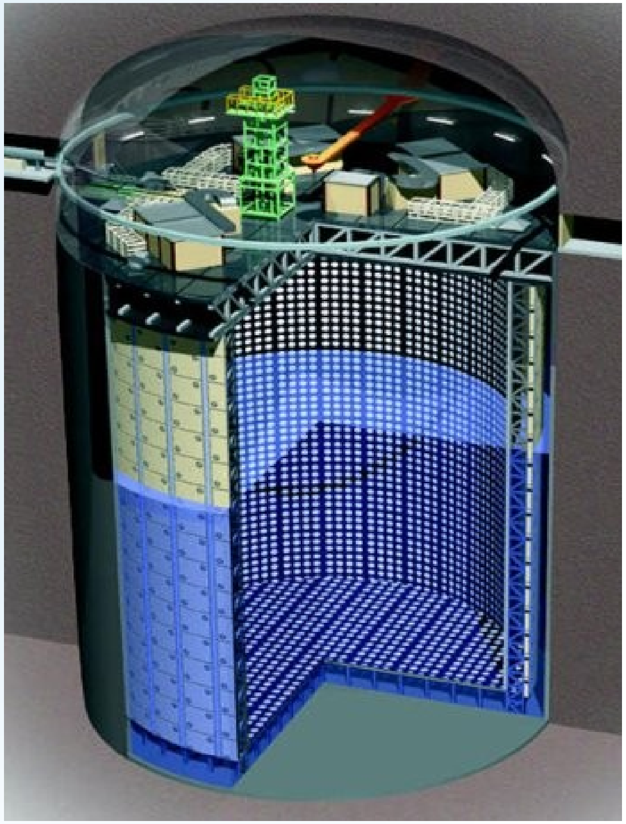
- ND280 is a multipurpose detector used to constrain the off-axis flux and neutrino interaction model.
- Oscillation analysis is impacted by CC interaction measurements in the tracker, made of two FGDs (fine grained detectors - scintillators) and three gaseous TPCs.
- Magnetic field B = 0.2 T.
- FGDs serve as targets and provide good vertex and track resolution.
- Energy loss in the TPCs allows for particle identification.

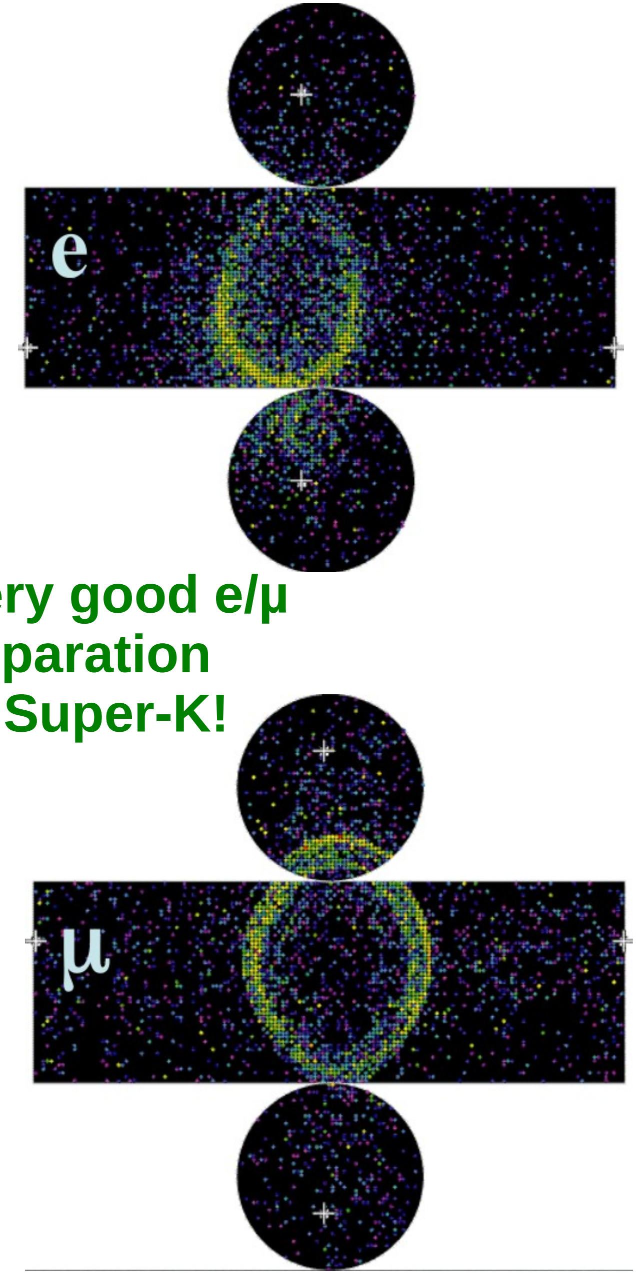


Far detector: Super-Kamiokande

- 50 kton water Cherenkov detector
- Over 10000 PMTs measure the Cherenkov light inside the tank.





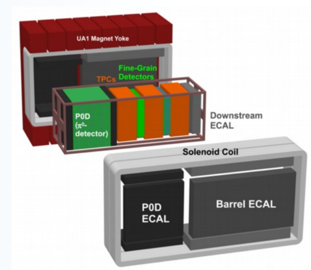


Very good e/μ separation in Super-K!

- Searching for CCQE events or ν_e appearance with single pion production (decay electron signature).
  $\nu_l + n \rightarrow l^- + p$,
  $\bar{\nu}_l + p \rightarrow l^+ + n$,
  $\nu_e + p \rightarrow e^- + \pi^+ + p$

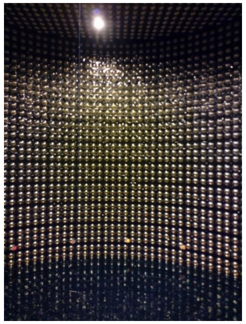
Analysis strategy

NA61/SHINE external data



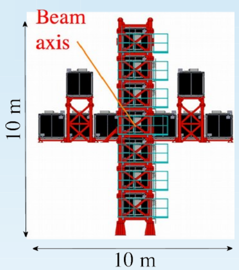
ND280 detector model

ND280 data



Super-K detector model

INGRID & Beam monitor data



Neutrino flux model

ND280 Fit
systematics
~2x smaller

Super-K data

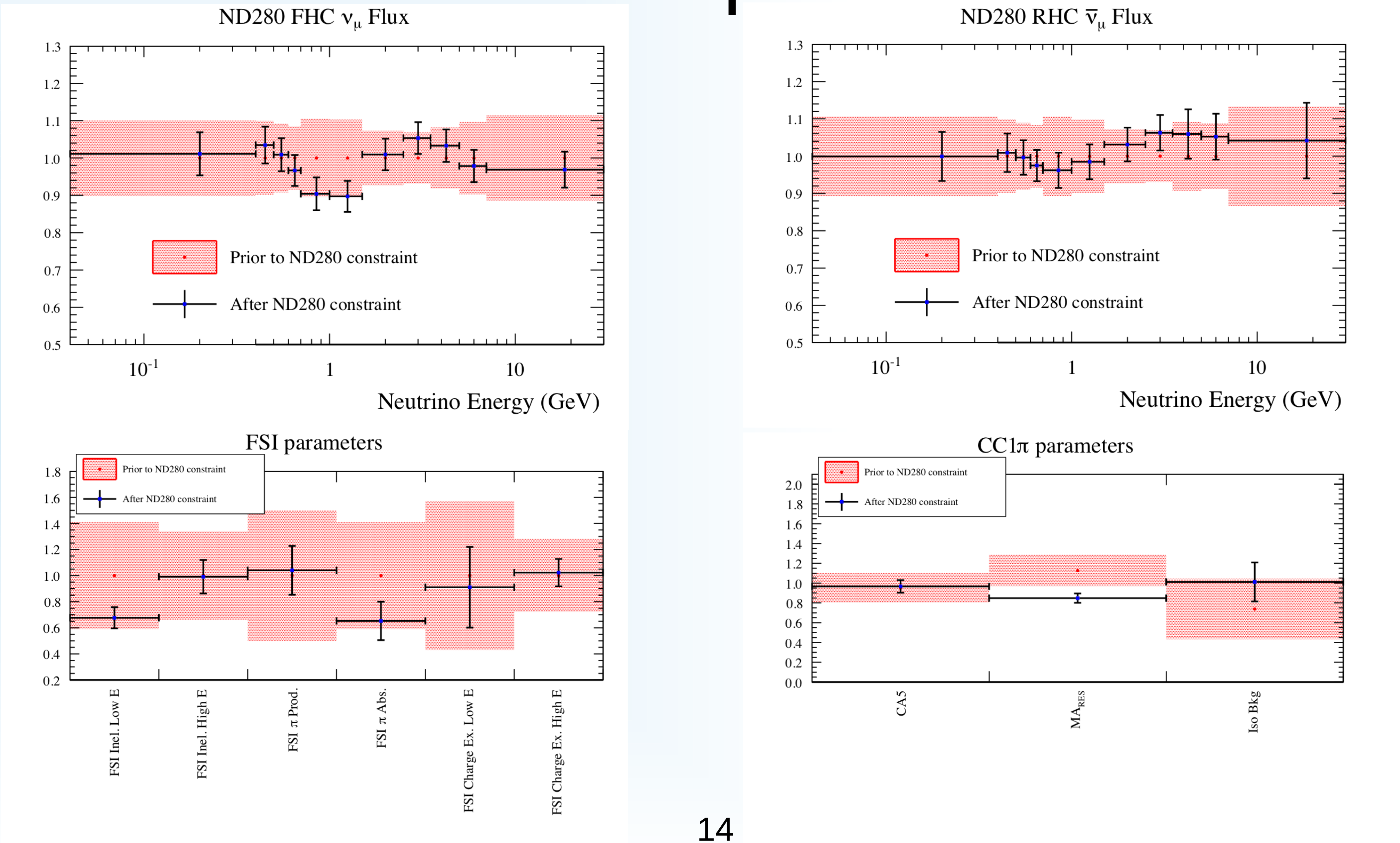
Cross-section model

External cross-section data

Oscillation Fit

Oscillation parameters

ND280 constraint of flux and cross-section parameters



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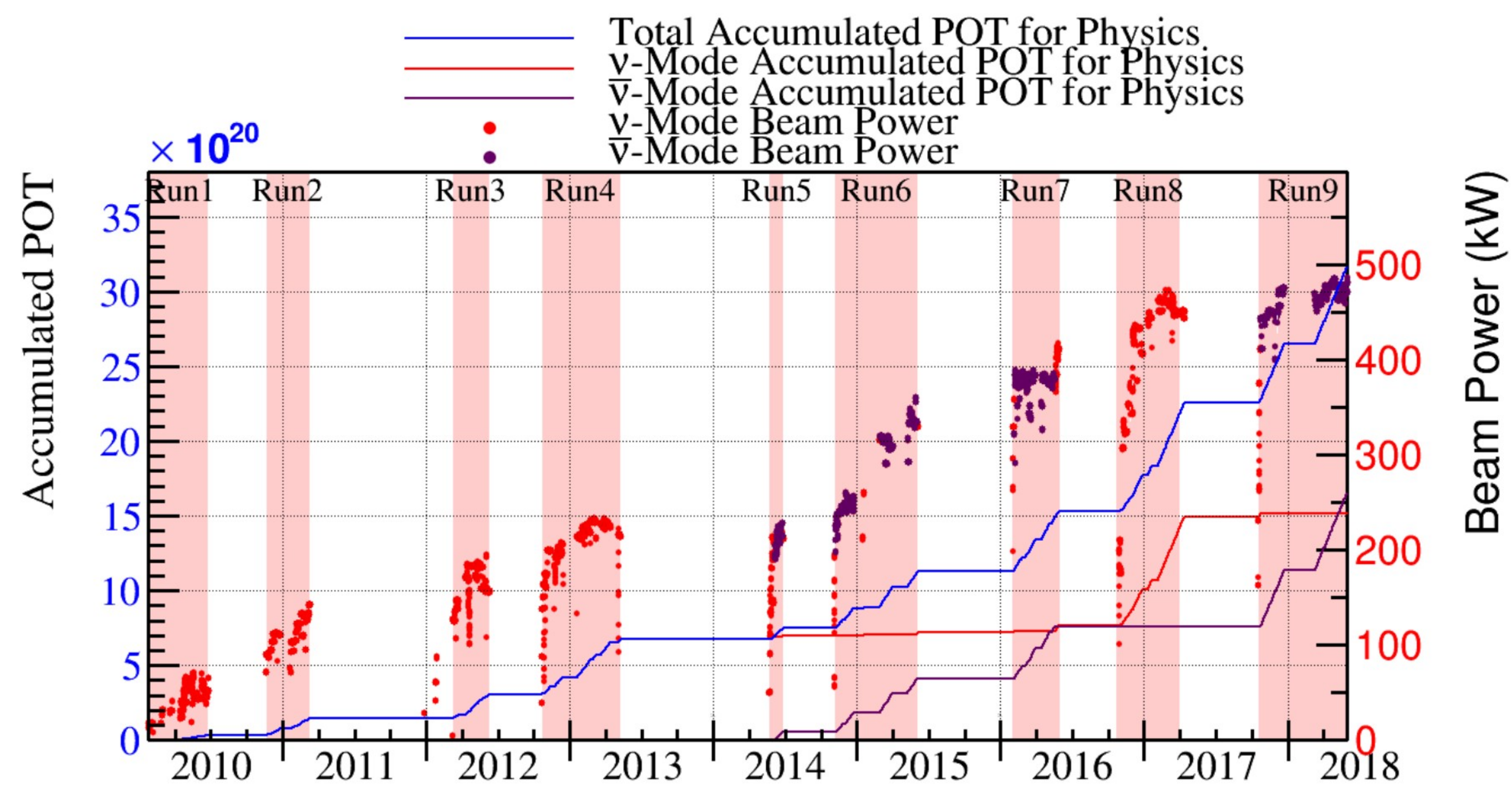
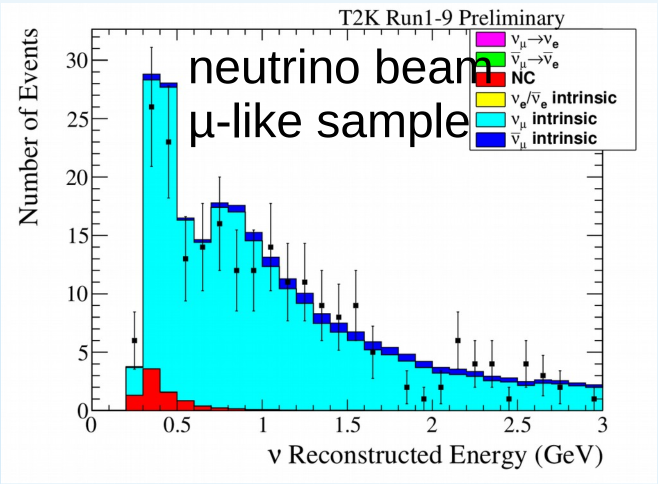
Collected statistics

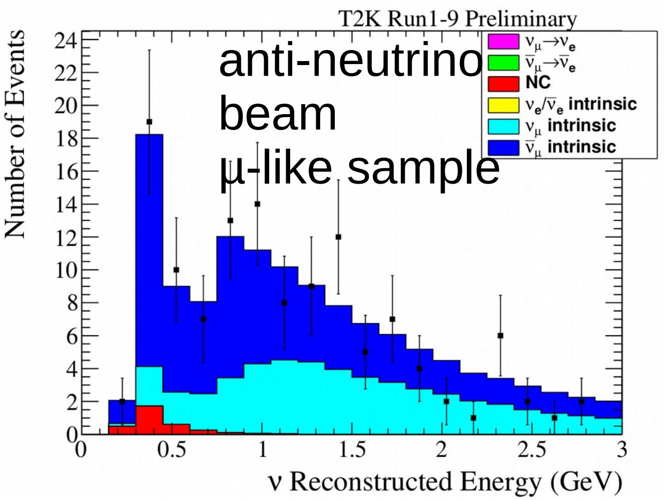


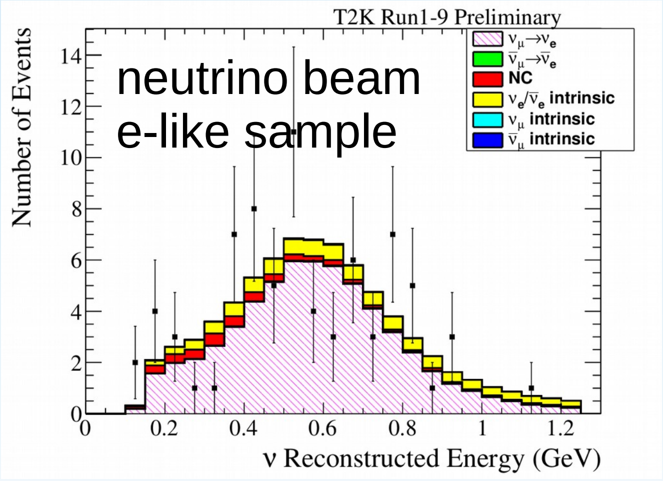
- 3.16×10^{21} Protons On Target (POT) collected so far.
  - 1.51×10^{21} for neutrino, 1.65×10^{21} for anti-neutrino beam mode.
- Oscillation results based on 3.13×10^{21} POT.
  - 1.49×10^{21} for neutrino, 1.63×10^{21} for anti-neutrino beam mode.

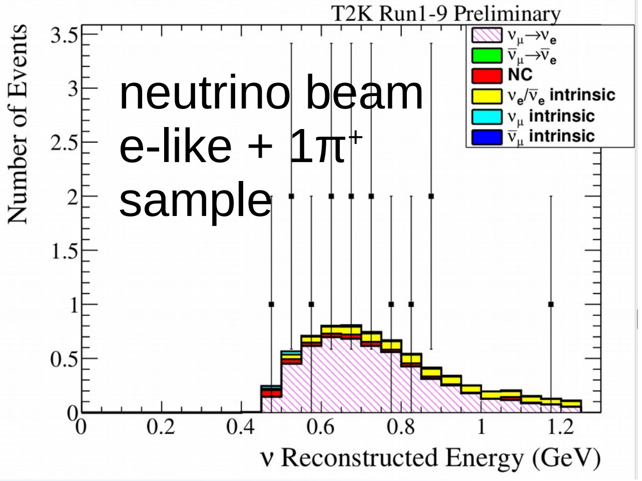
Super-K fit to data

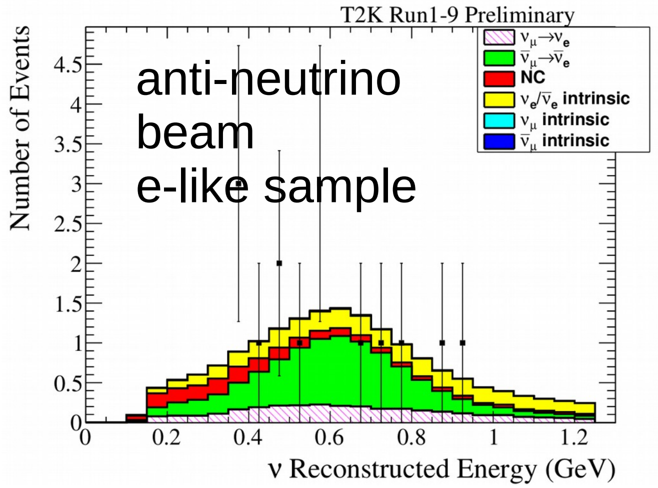


- Fit simultaneously 5 samples.
- Oscillation and systematic parameters are shared between them.







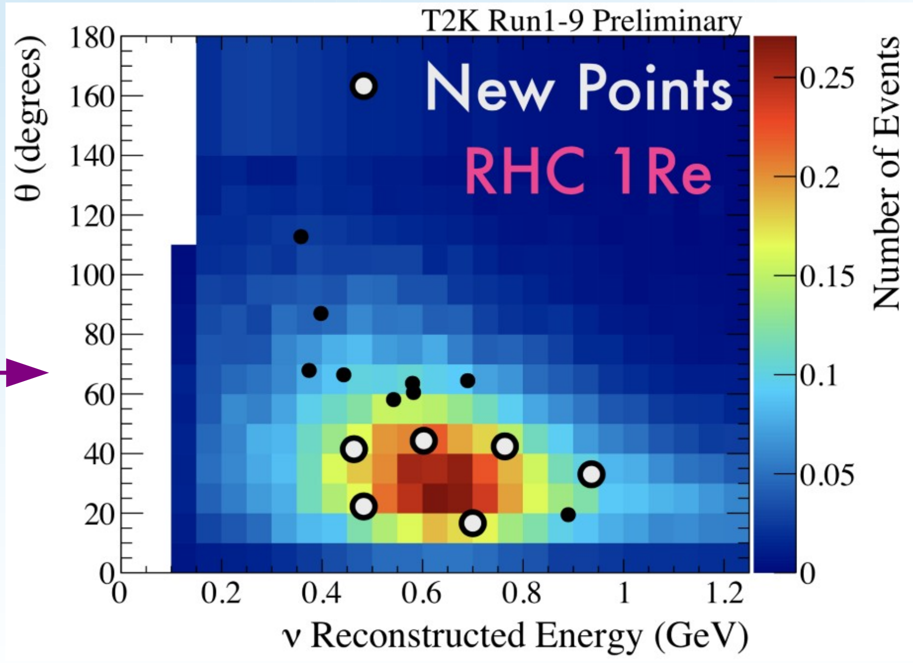


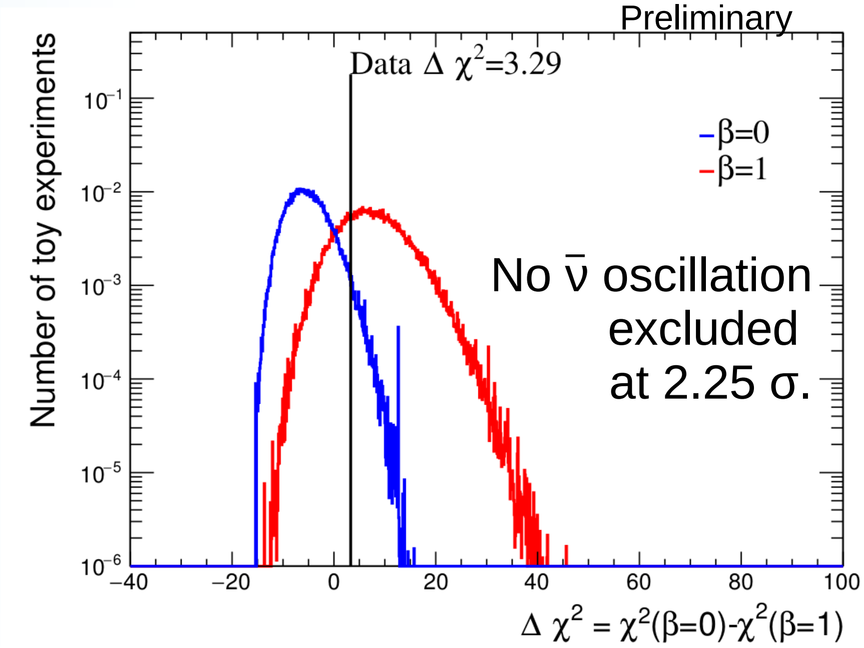
For the MC distributions above:

Normal Hierarchy, $\delta = -\pi/2$, $\sin^2\Theta_{23} = 0.528$, $\sin^2\Theta_{13} = 0.0212$

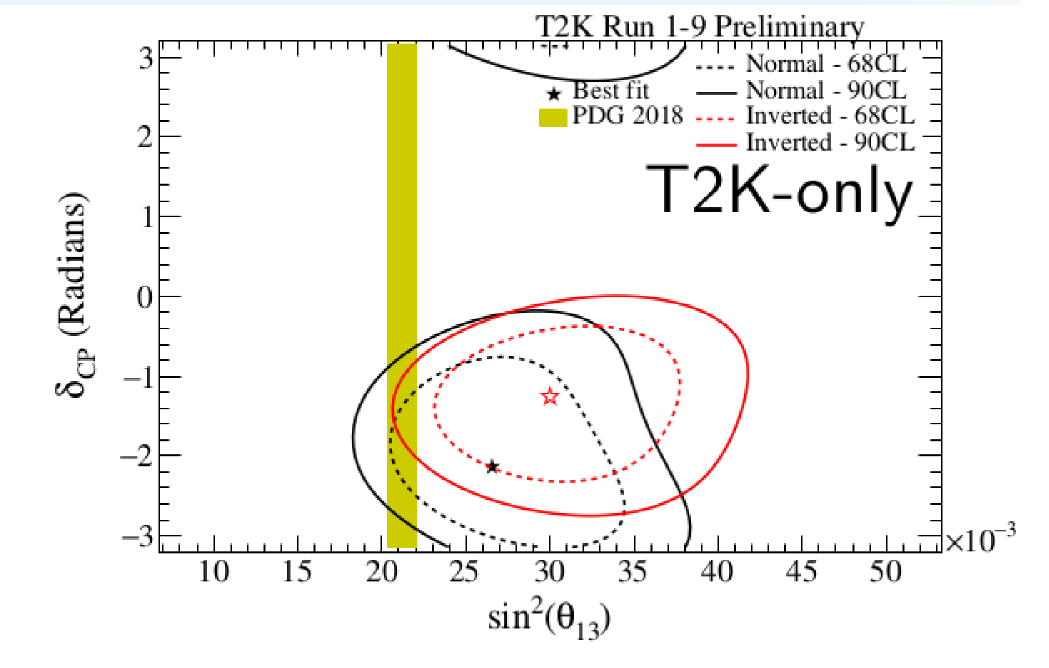
Super-K collected events

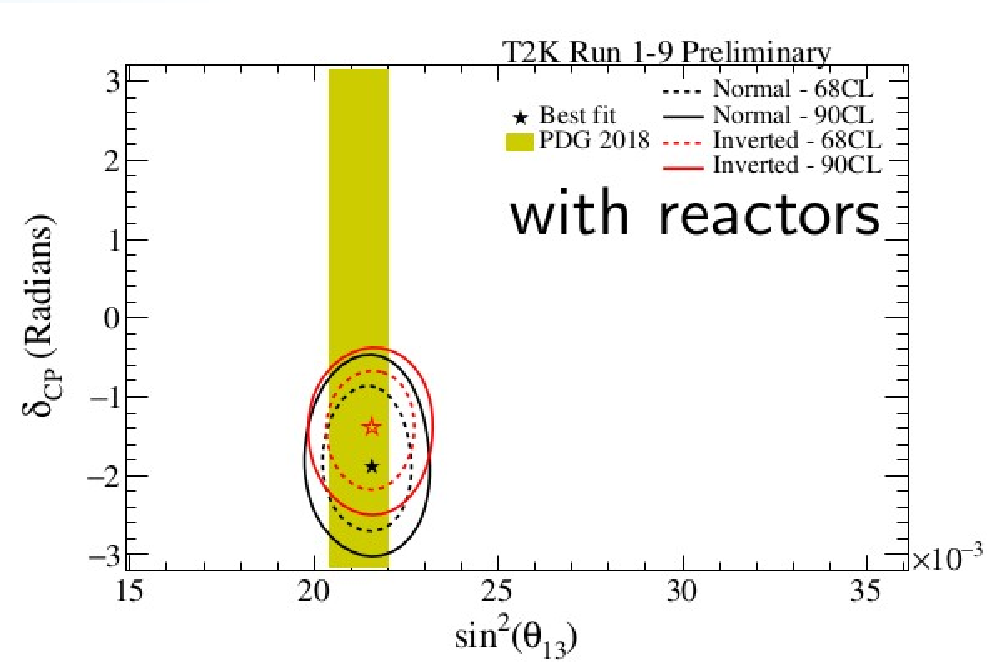
Sample	Predicted				Observed	Systematic uncertainty for prediction
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = π		
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
$\bar{\nu}$ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
$\bar{\nu}$ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + $1\pi^+$	7.0	6.1	4.9	5.9	15	18.4%





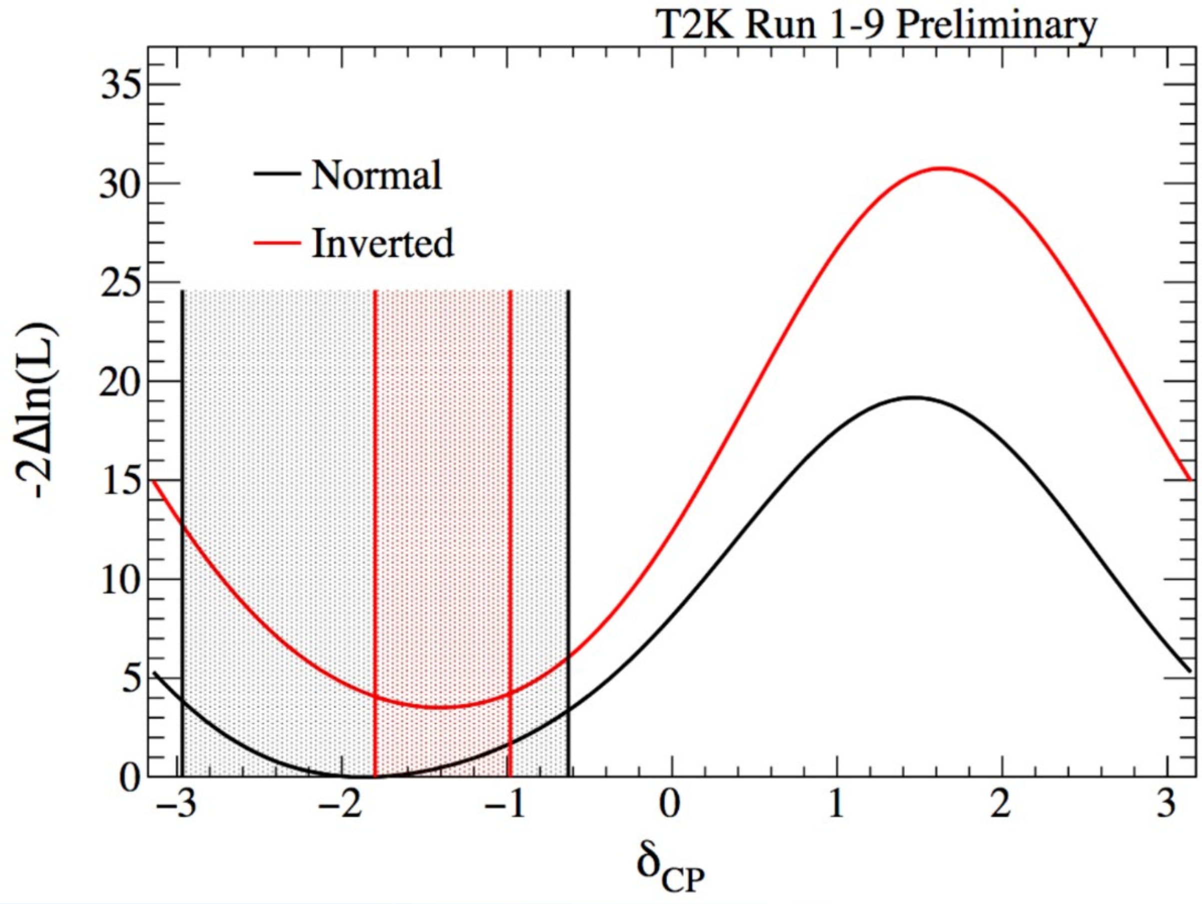
Results: δ_{CP} vs θ_{13}





- T2K results are in agreement with θ_{13} value measured in reactor experiments.
- Best fit (T2K-only): $\sin^2\theta_{13}$ = 0.0268 for NH, 0.0300 for IH.
- Reactor constraint: $\sin^2\theta_{13}$ = 0.0212.
- **Updated the reactor constraint on $\sin^2\theta_{13}$ to match PDG2018 values.**

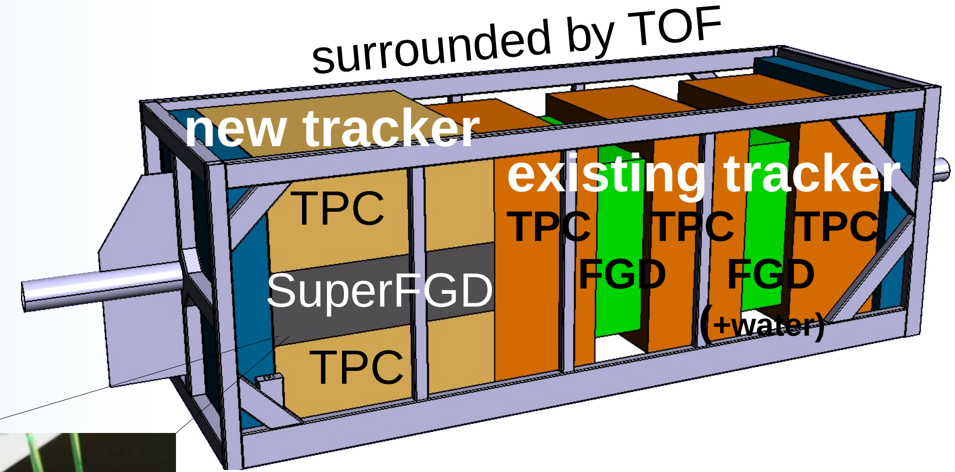
Results: δ_{CP}

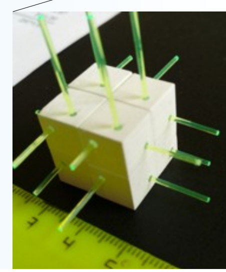


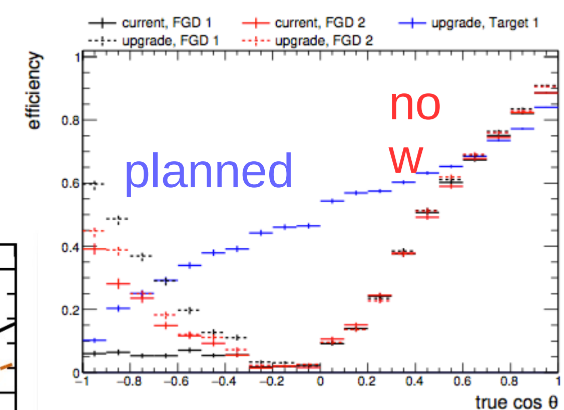
- Normal Hierarchy preferred (posterior probability: 89%)
- CP-conserving values excluded at 2σ level
- Best fit: δ_{CP} = -1.885 for NH, -1.382 for IH
- ±2σ range: [-2.966, -0.628] for NH, [-1.799, -0.979] for IH

T2K's future

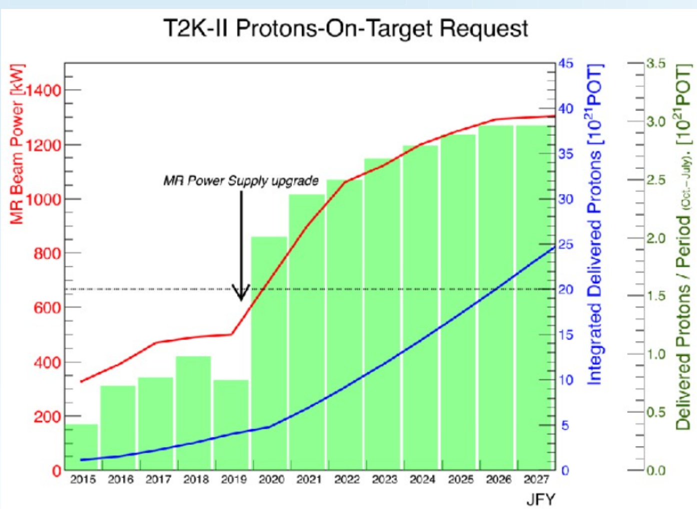
- Upgrade of ND280 for T2K Phase-II
  - SuperFGD
  - High angle TPCs
- Upgrade of Super-K
  - dissolving gadolinium
- Collected statistics shall be doubled till the 2021 (up to 7.8 E21 POT).
- Aiming for 20 E21 POT in 2026 (T2K Phase-II)

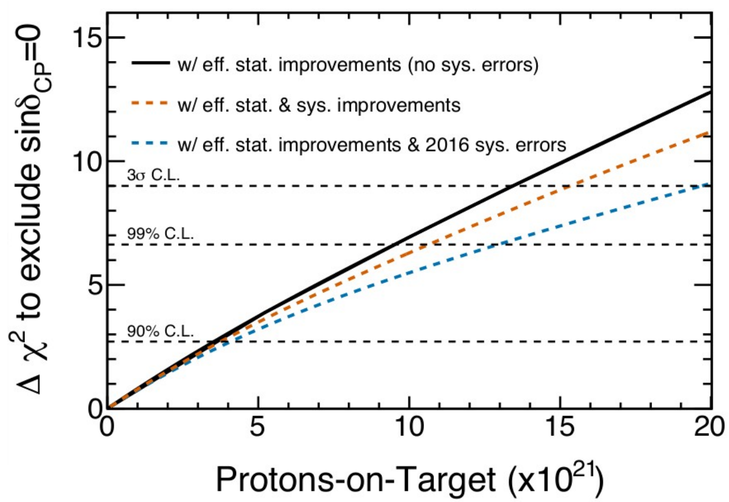






angular efficiency



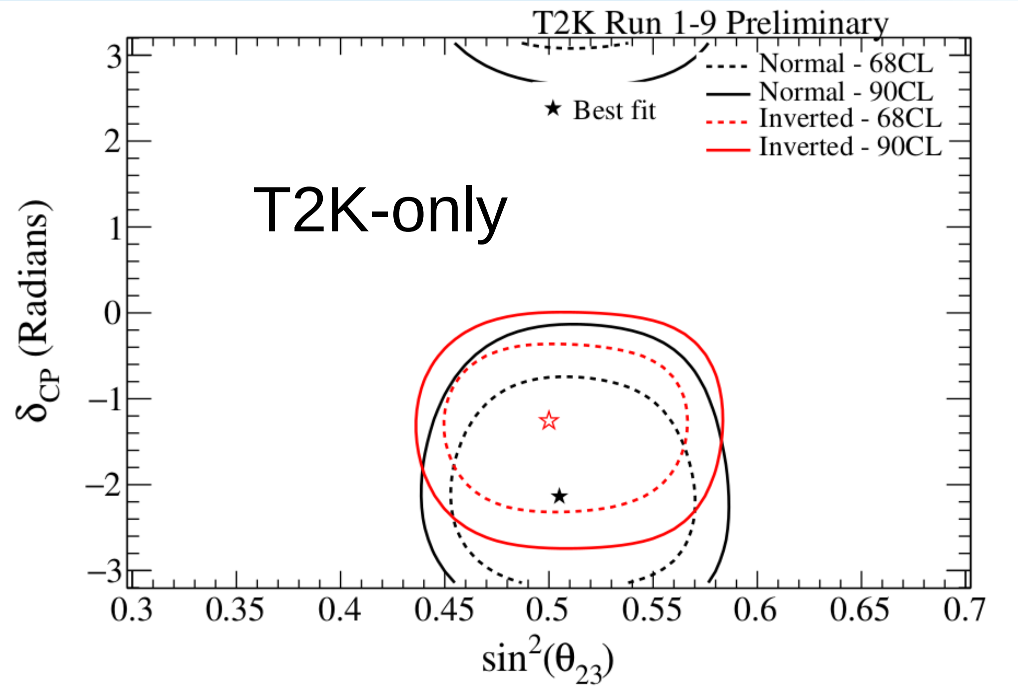


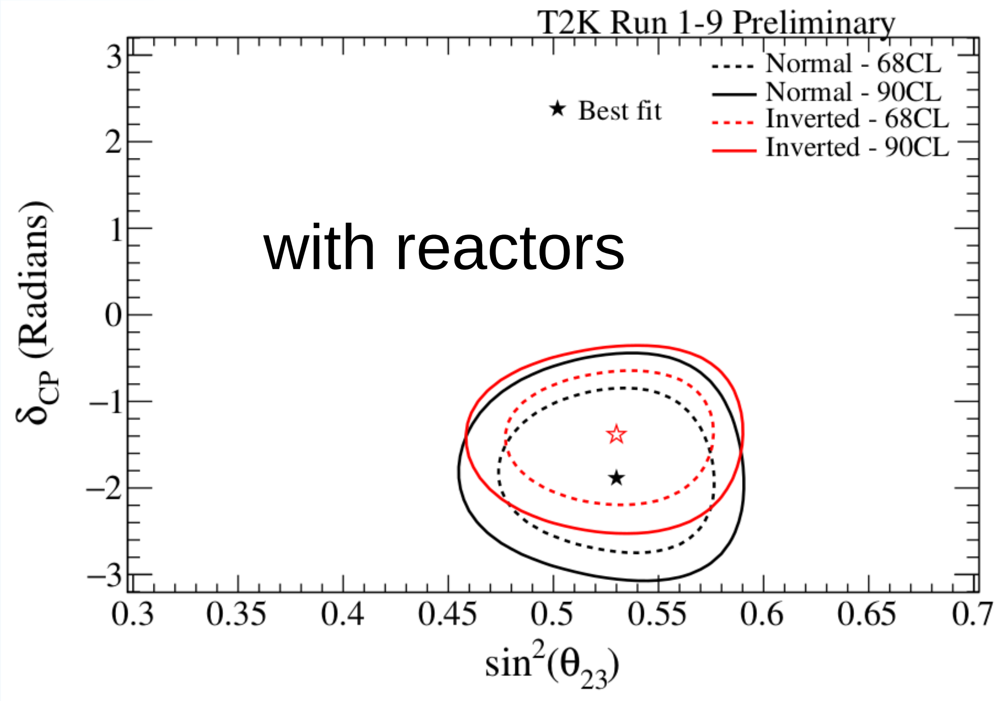
Summary

- T2K studies the CP symmetry by comparing the oscillation probabilities for neutrinos and anti-neutrinos.
- CP conservation excluded at the 2σ confidence level. Normal Hierarchy is slightly favored.
- Best fit for $\sin^2\theta_{23} = 0.532$, consistent with maximal mixing.
  - ±1σ range: [0.495, 0.562] for NH, [0.497, 0.561] for IH
- The collaboration is preparing for T2K phase-II (2021-2026).
  - ND280 upgrade
  - Super-K upgrade
  - Proton beam power upgrade

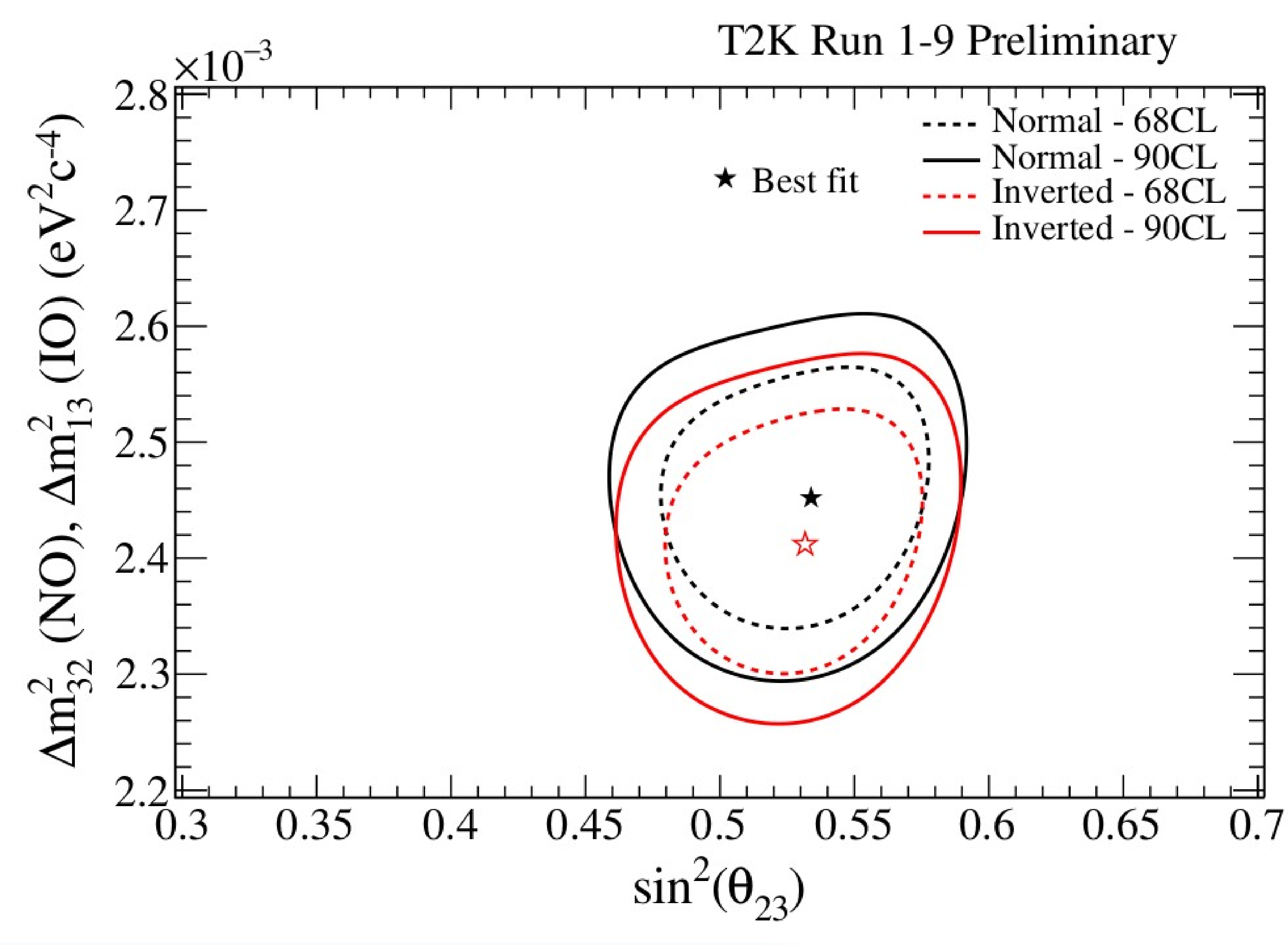
Backup

Results: δ_{CP} vs θ_{23}





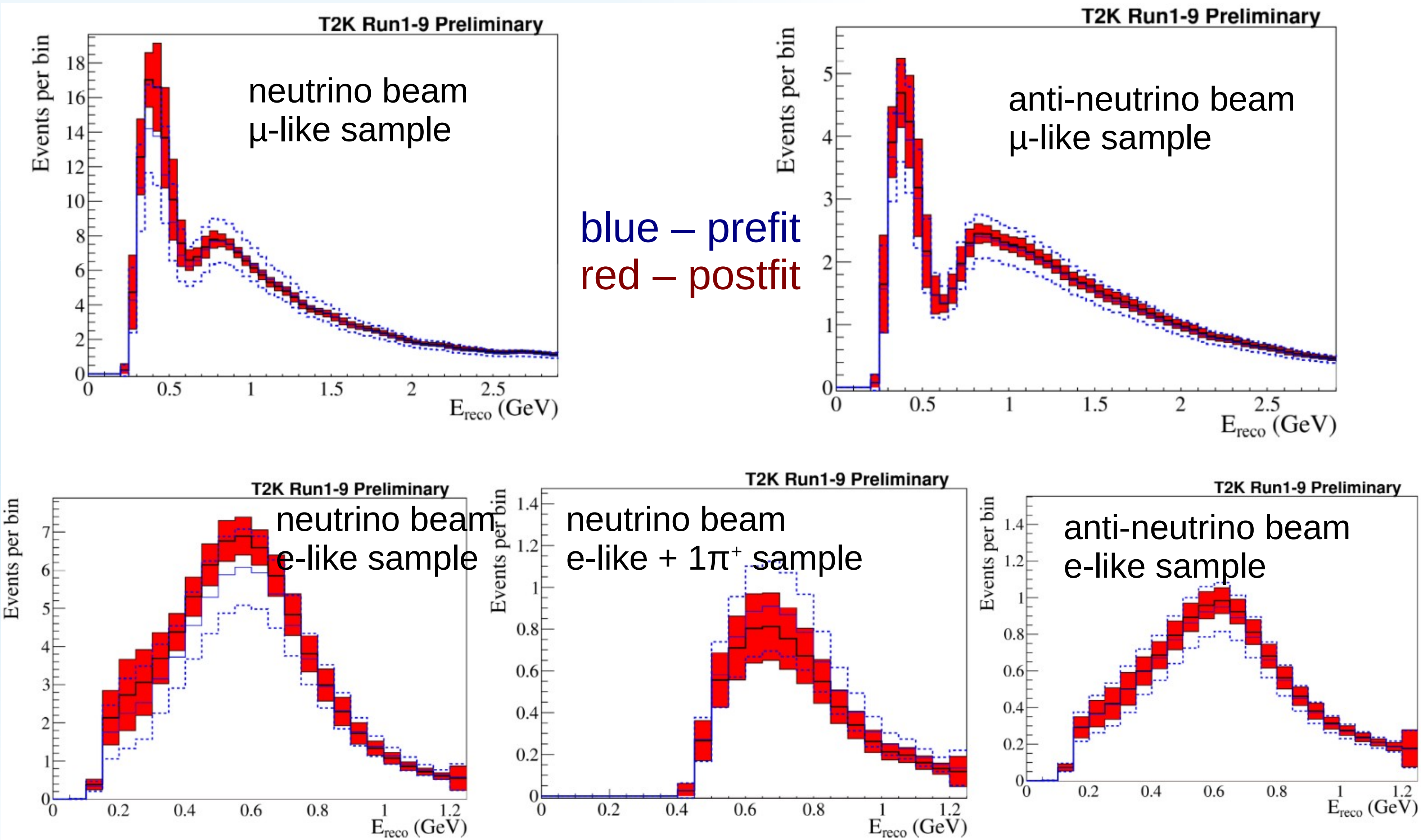
Results: Δm^2_{32} vs θ_{23}



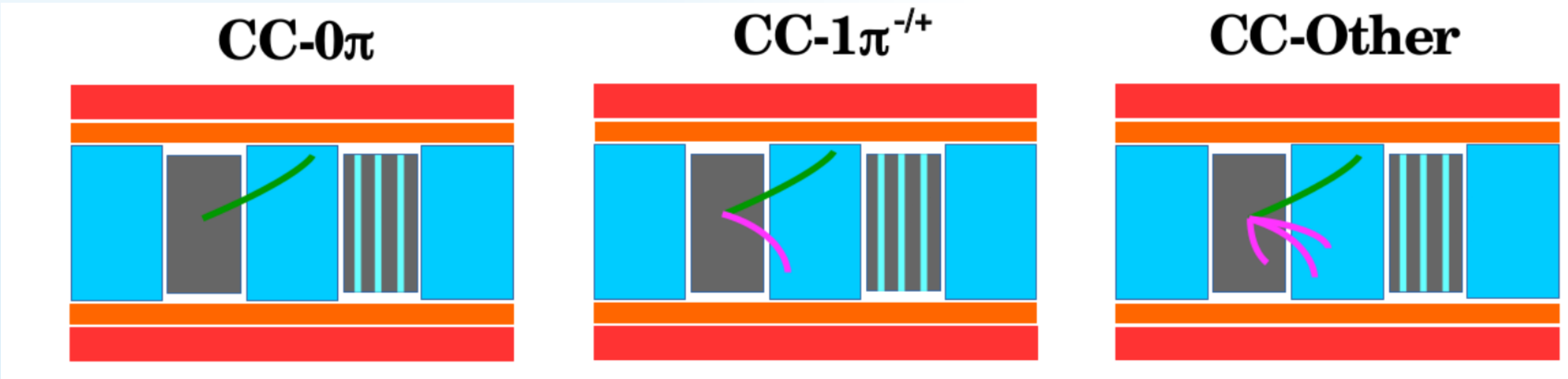
Updates since La Thuile 2018

- Increased anti-neutrino dataset
  1.12×10^{21} POT $\rightarrow$ 1.63×10^{21} POT
- Updated the reactor constraint on $\sin^2\Theta_{13}$ to match PDG2018 values.

ND280 constraints for Super-K

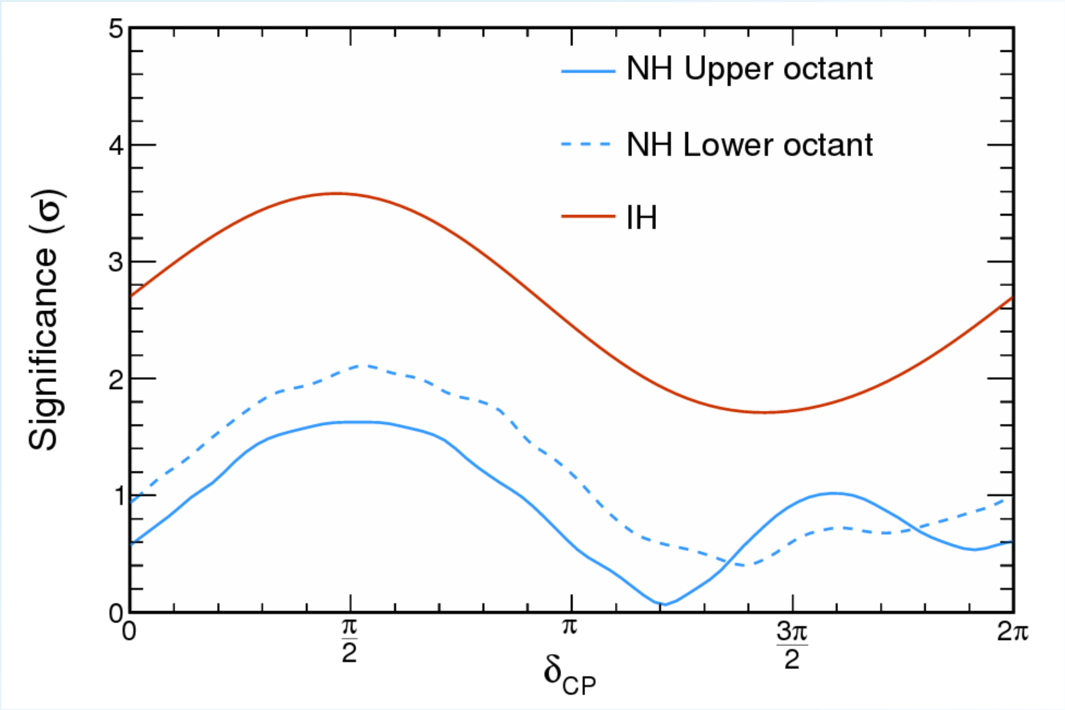


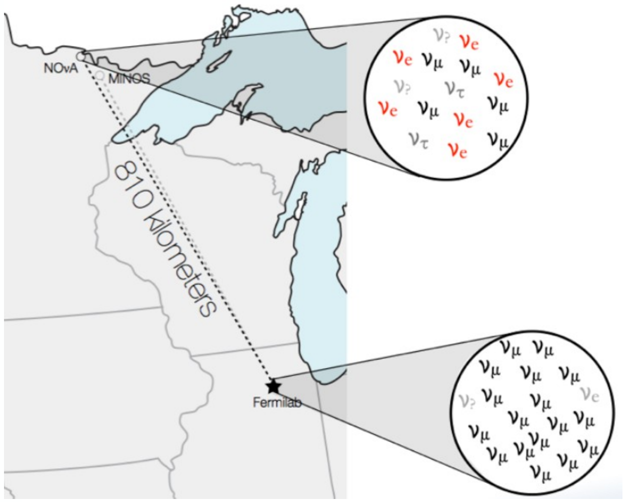
ND280 data samples

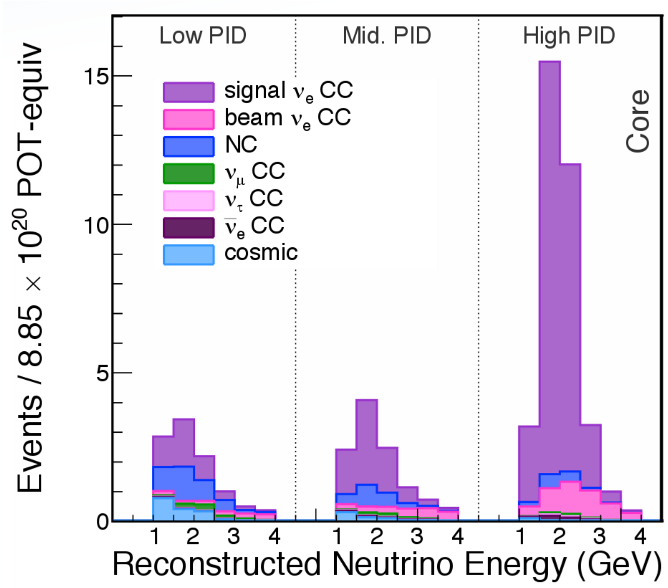


- We can't measure directly certain type of reaction. We classify event with respect to the pion multiplicity:
  - CC0π sample – enhanced with CCQE interactions
  - CC1π – enhanced with resonant interactions
  - CCother

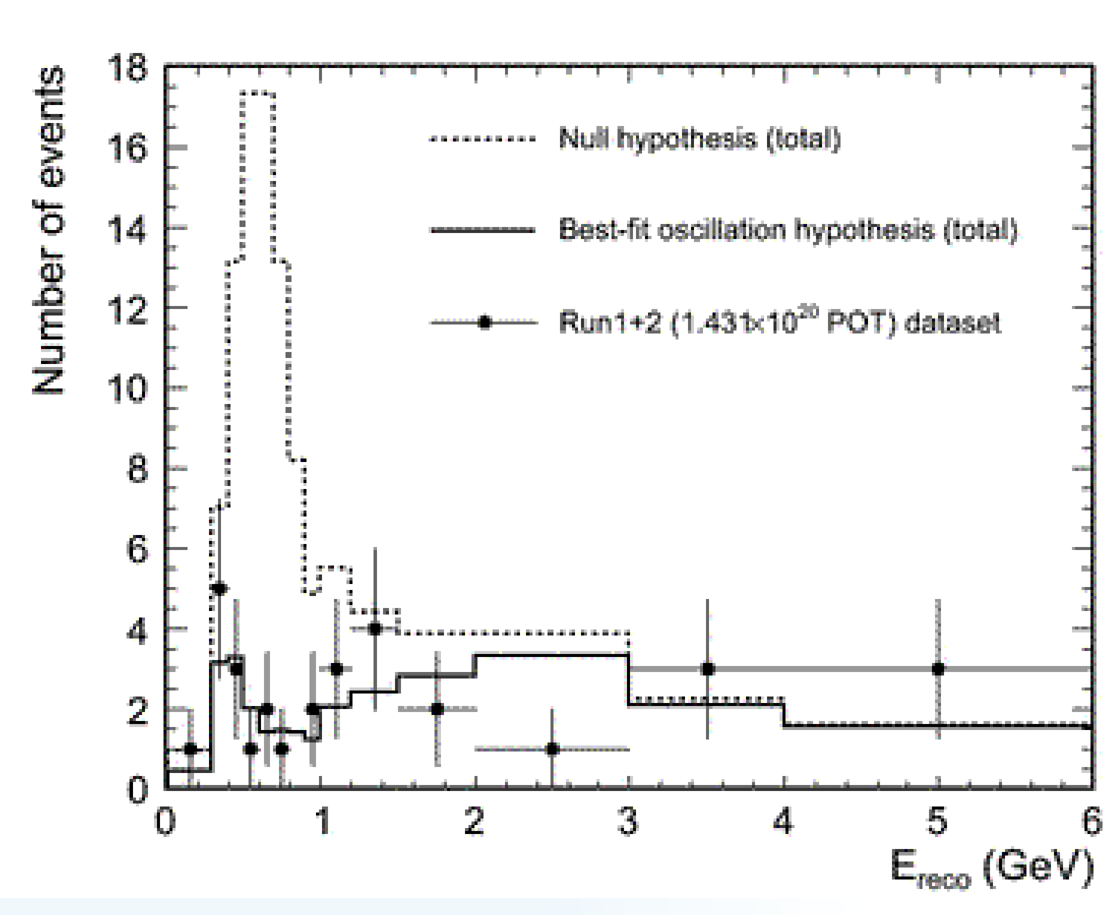
NOvA results on CPV



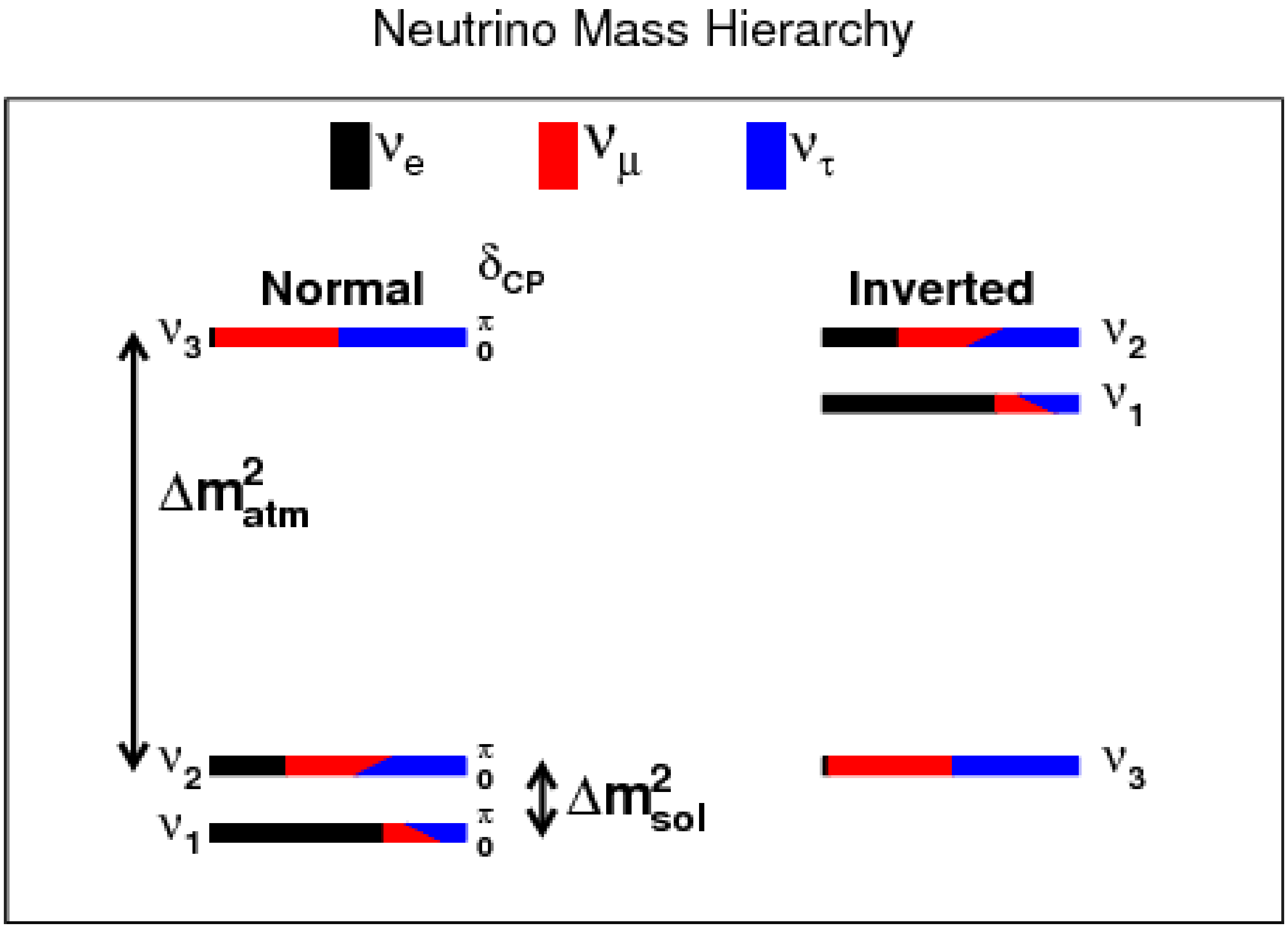




Neutrino disappearance



Mass hierarchy



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