Recent Results from the T2K Experiment

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Neutrino Oscillation

- Neutrinos propagate as mass states (ν_1 , ν_2, ν_3) and interact as flavour states (ν_e , ν_μ , ν_τ)
- Mass states are a superposition of flavour states (and vice-versa)

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$ → Neutrino with mass *i = (1, 2, 3)*

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$ → Neutrino with flavor α = *(electron, muon, tau)*

PMNS matrix

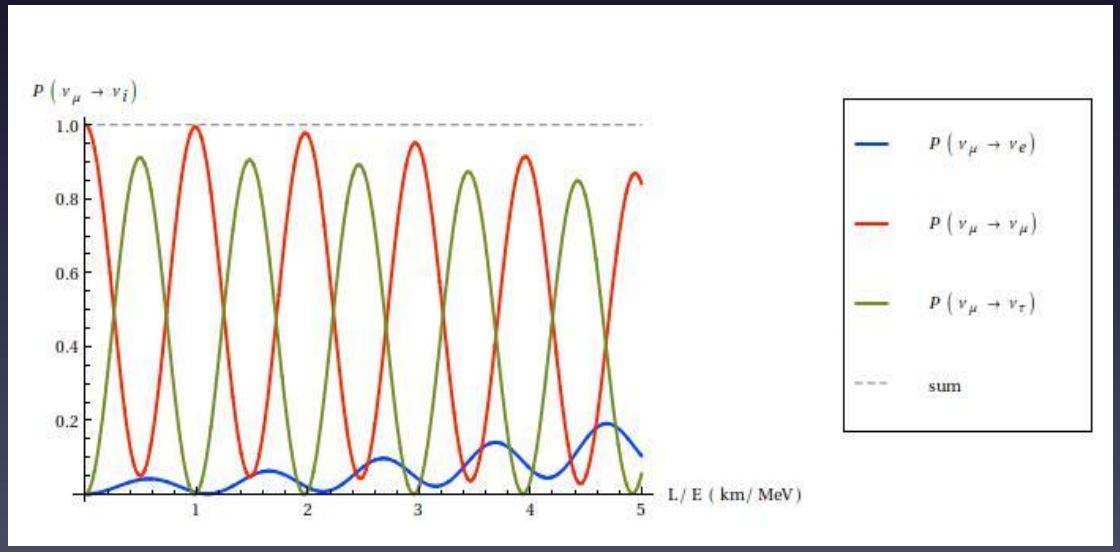
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric and accelerators}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactors and accelerators}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar and reactors}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

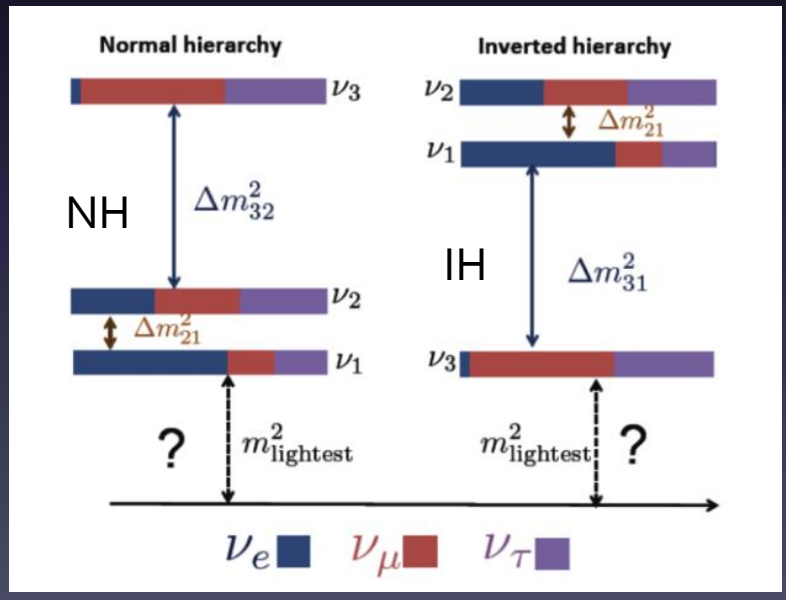
$U_{\alpha i}$ → neutrino mixing matrix, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, δ = CP phase

Oscillation Probability

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

$$\Delta m^2_{21} = \Delta m^2_{31} - \Delta m^2_{32}$$
Δm^2_{21} is small $\rightarrow \Delta m^2_{32} \approx \Delta m^2_{31}$

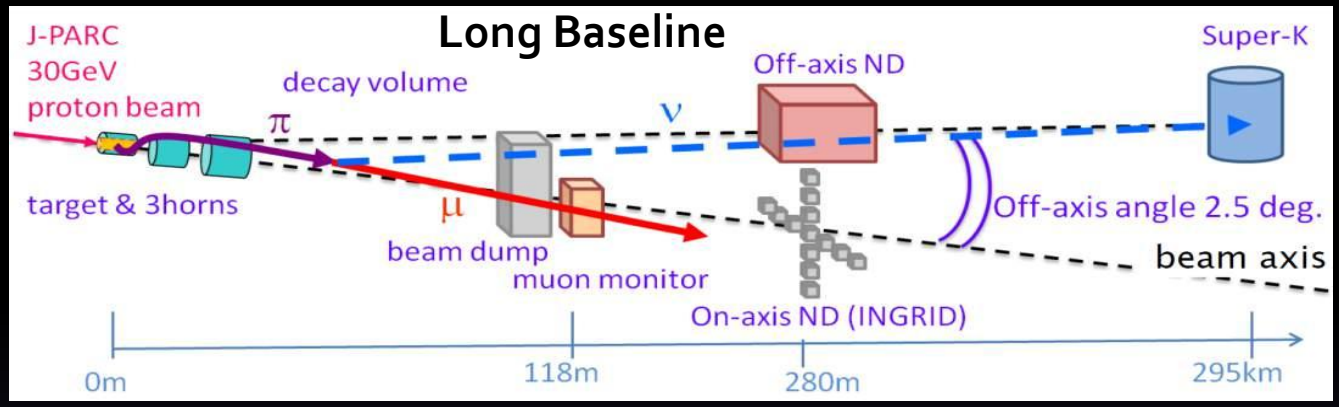




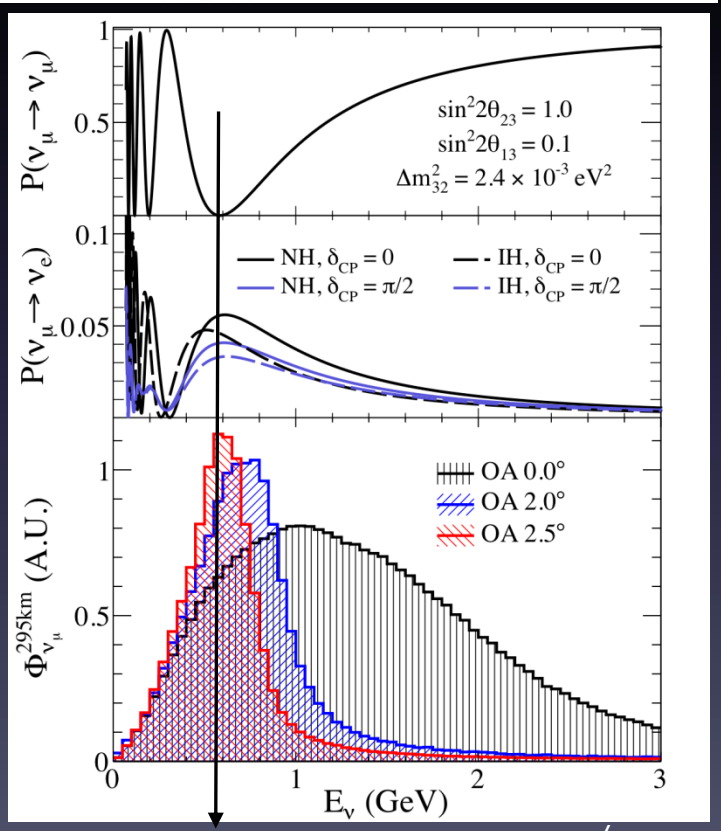
T2K Experiment

Protons hit a target → pions → ν_μ beam

3 magnetic horns:
Forward polarity → ν_μ
Reverse polarity → $\bar{\nu}_\mu$



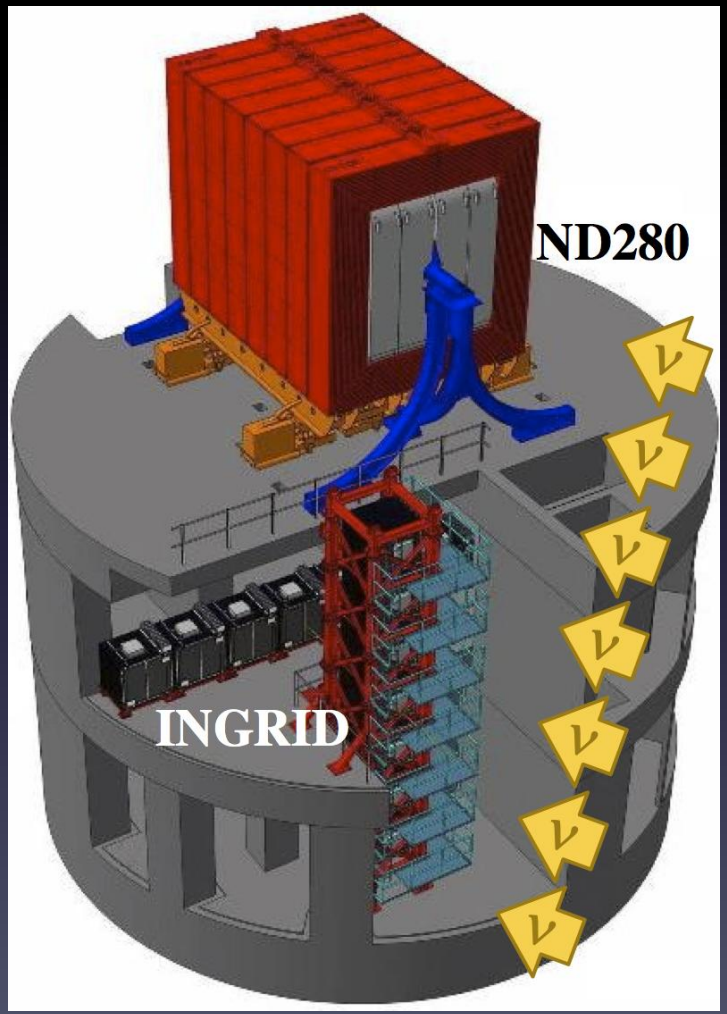
- Off-axis concept -> angle selected to probe maximum oscillation probablity (E ≈ 600 MeV; L = 295 Km)
- Also suitable to study electron neutrino appearance
- Measure unoscillated/oscillated neutrino fluxes with Near/Far Detectors.

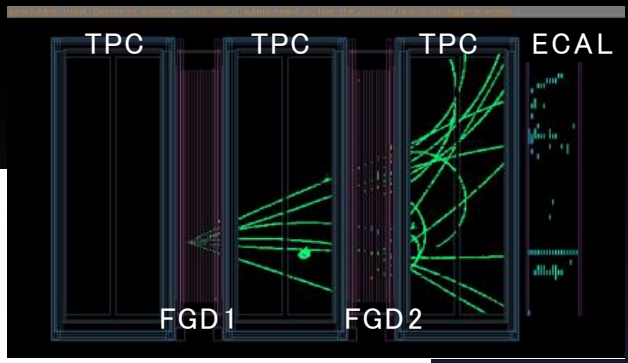


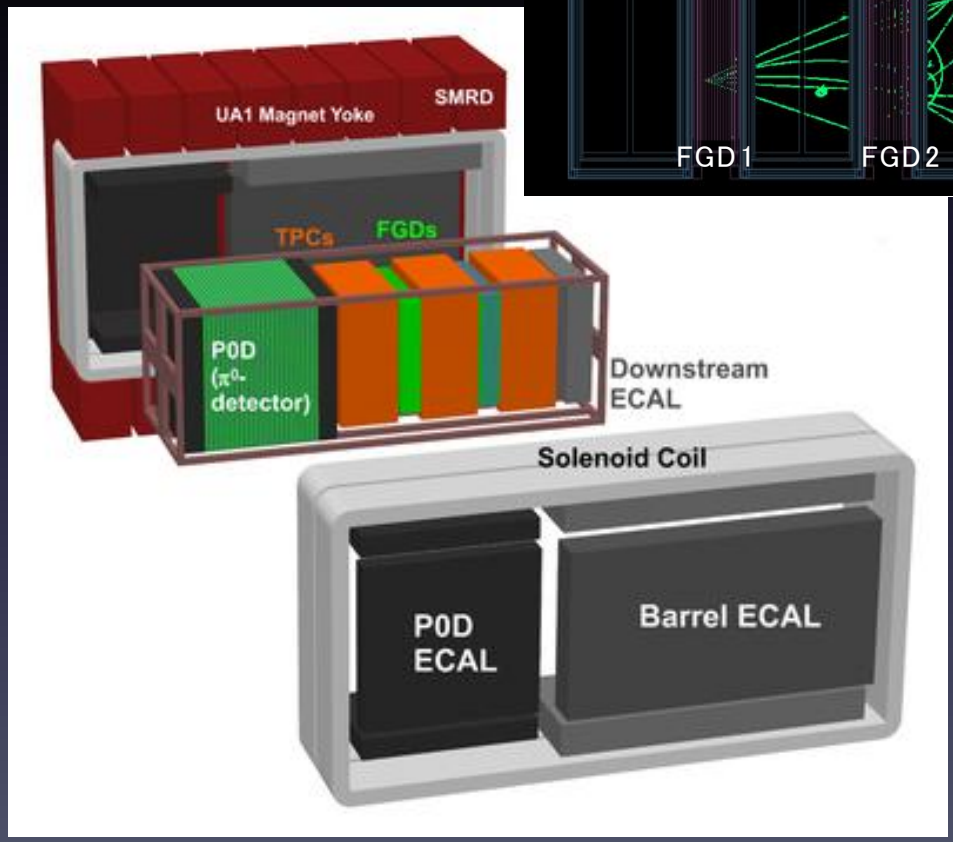
T2K neutrino energy peak

Near Detector

- Tracking + Calorimetry + Muon + Beam Monitoring (including water targets)
- ND280 (off-axis) (magnetized) : Cross section and flux measurements → Constrain uncertainties
- INGRID (on-axis): Monitor beam stability and direction

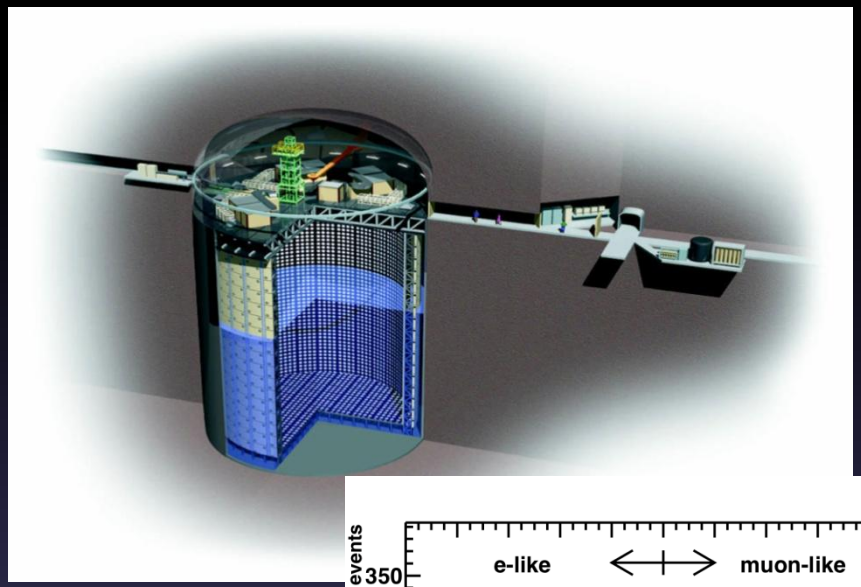


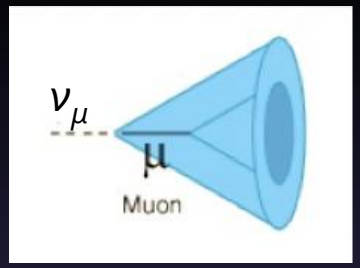


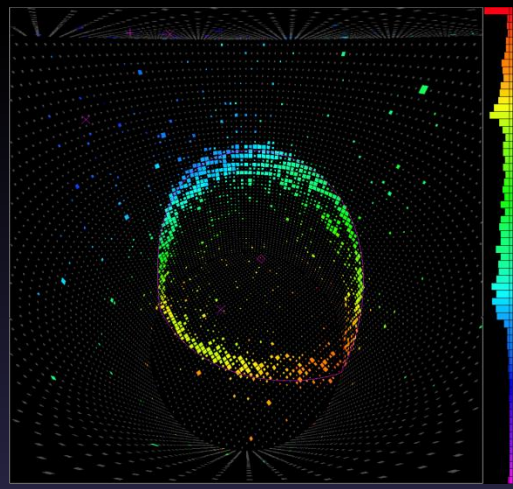


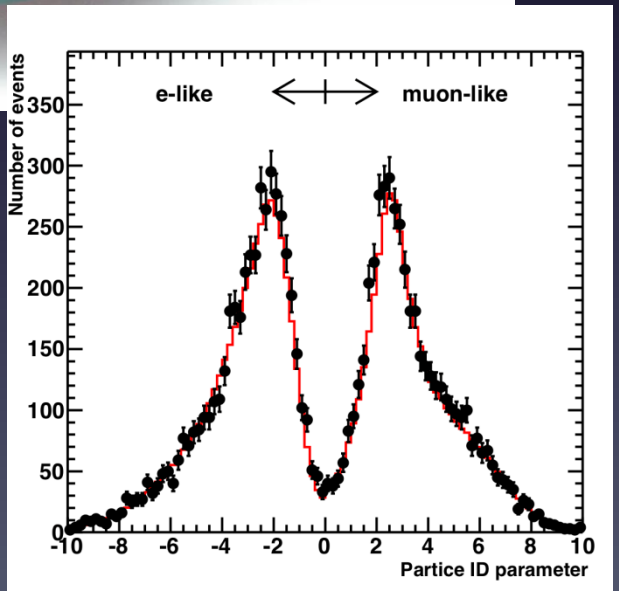
SK Detector

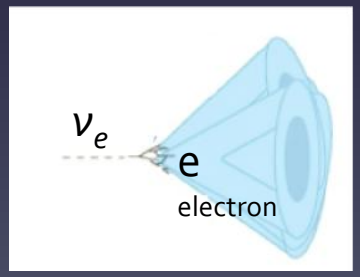
- 50 kton water Cherenkov detector; 11129 20" PMTs (32 kton inner detector); 1885 8" PMTs (18 kton outer detector – veto)
- Excellent electron/muon identification

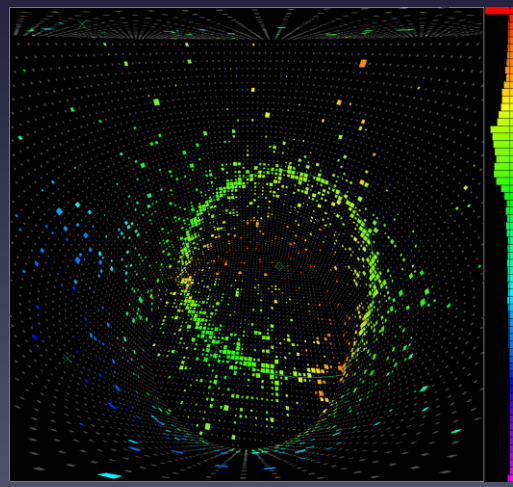




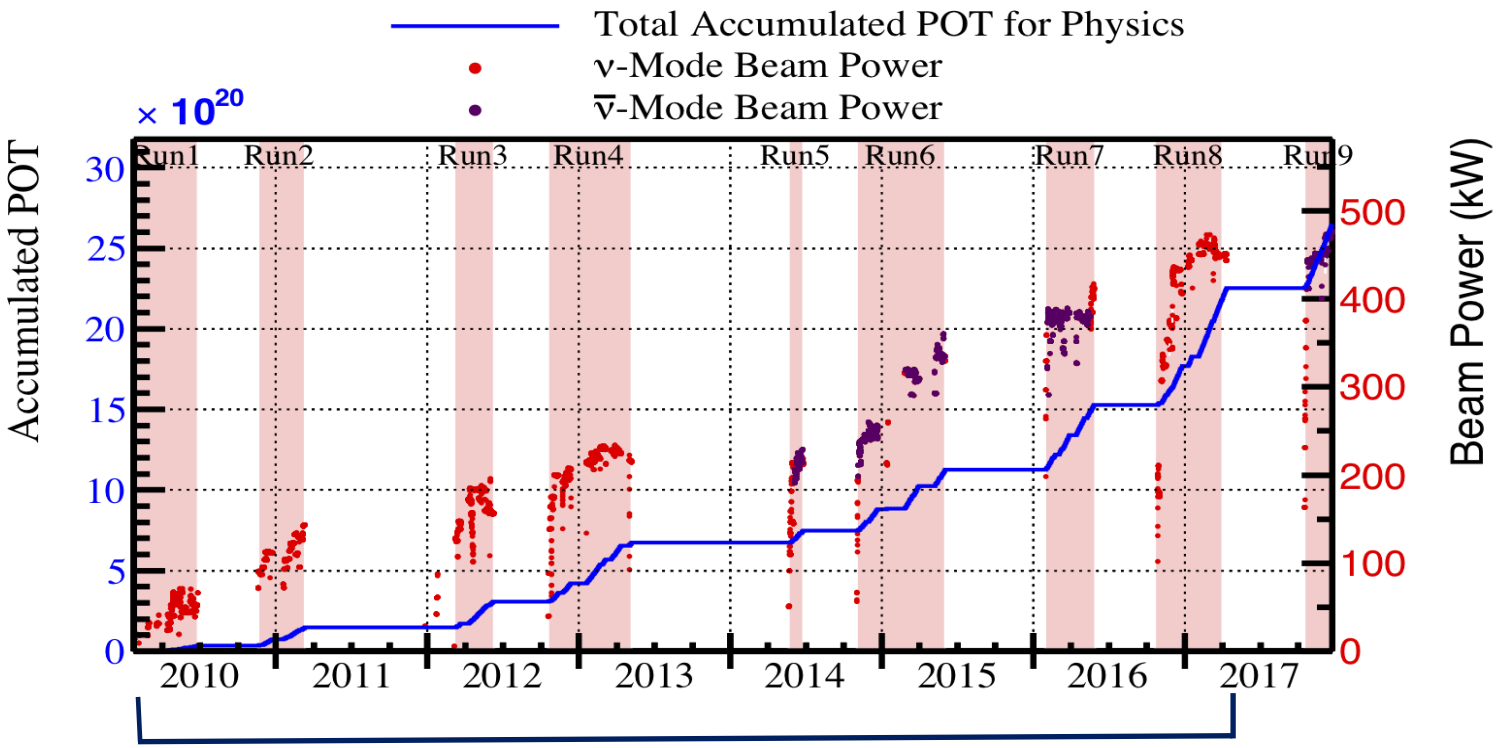








T2K Data (PoT - Protons-on-Target)



Runs 1-8 (These analyses) → 2.2 x 10^{21} POT (2/3 ν_μ ; 1/3 $\bar{\nu}_\mu$)

23 Jan. 2010 - 22 Dec. 2017

POT total: 2.65 x 10^{21}

ν-mode 1.51 x 10^{21} (57.14%)

$\bar{\nu}$-mode 1.14 x 10^{21} (42.86%)

Currently operating at ~470 kW

Oscillation Probability in T2K

$\nu_\mu \rightarrow \nu_e$ (appearence): $\theta_{13}, \delta_{CP}, \theta_{23}$ octant; mass hierarchy

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

$$-\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Leading including matter effect

CP violating

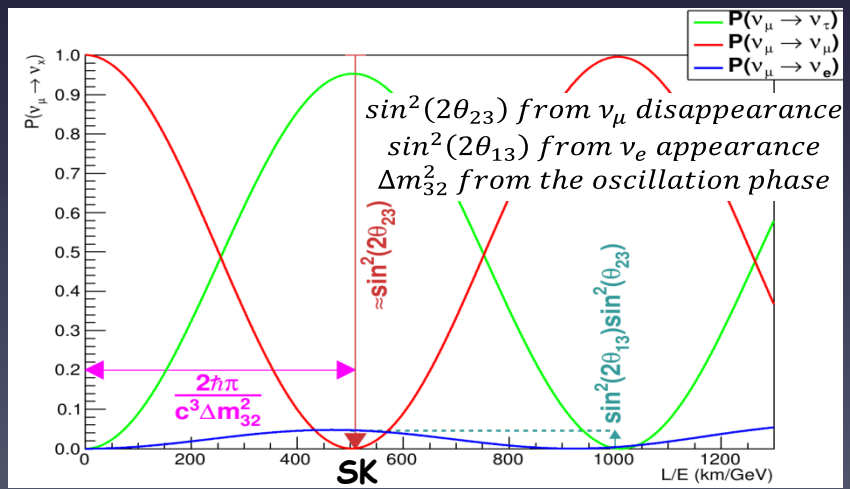
$$a \equiv 2\sqrt{2} G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{g\mathrm{cm}^{-3}} \frac{E}{GeV}$$

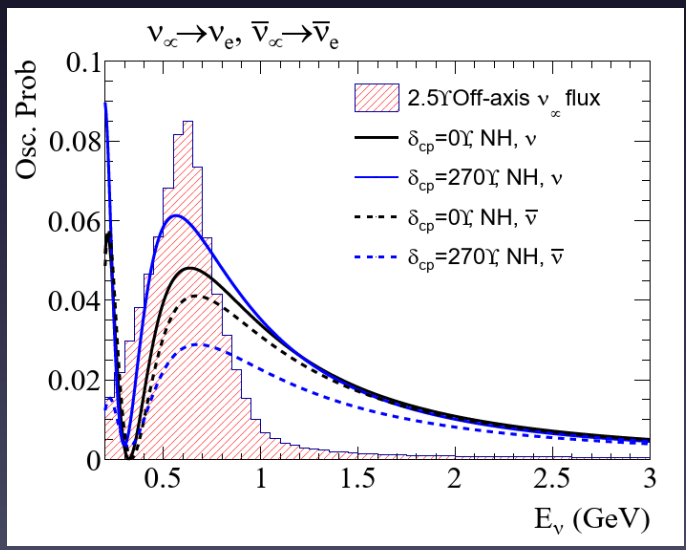
Replace δ by -δ and a by $-a$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$\nu_\mu \rightarrow \nu_\mu$ (disappearence): $\theta_{23}, \Delta m^2_{23}$

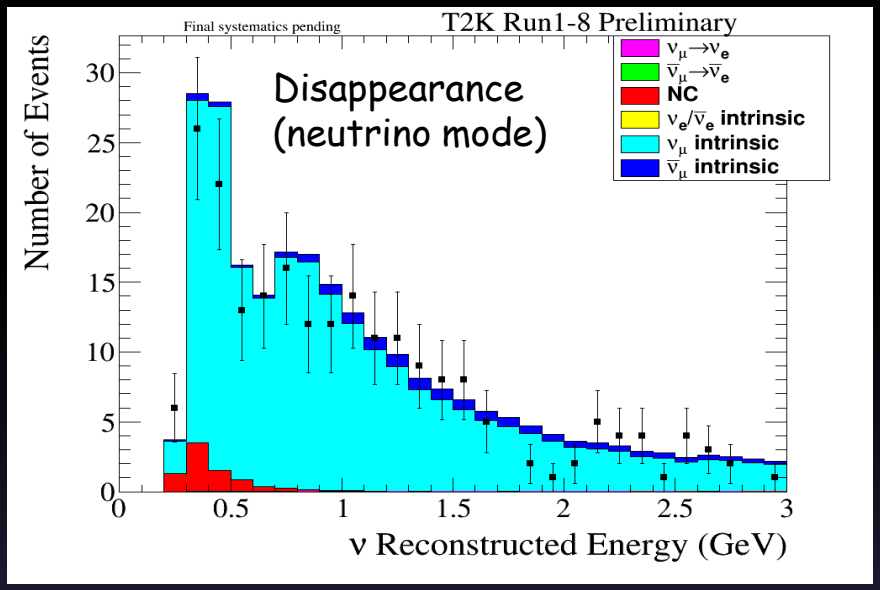
$$P(n_m \rightarrow n_m) \sim 1 - \left(\cos^4 q_{13} \cdot \sin^2 2q_{23} + \sin^2 2q_{13} \cdot \sin^2 q_{23}\right) \cdot \sin^2 \frac{Dm^2_{31} \cdot L}{4E}$$

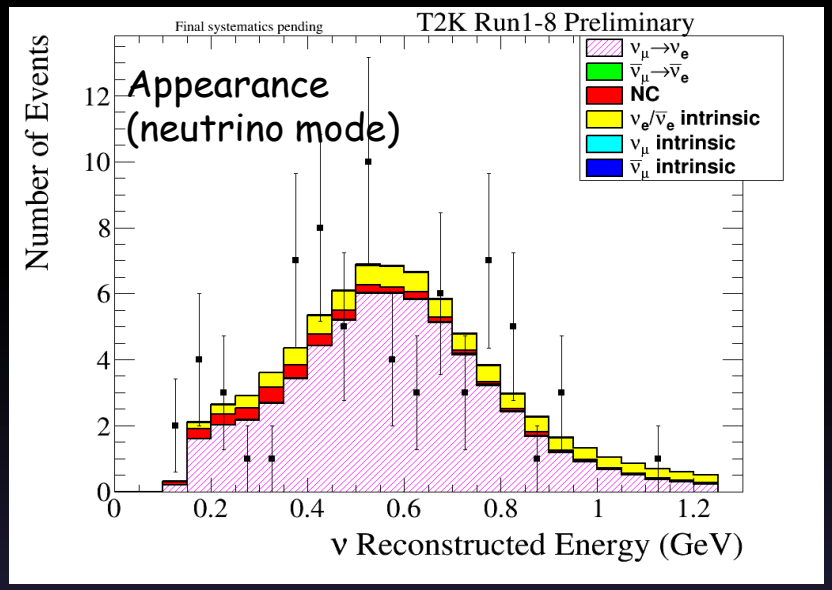
$$\Delta m^2 \approx \Delta m^2_{32} \approx \Delta m^2_{31}$$

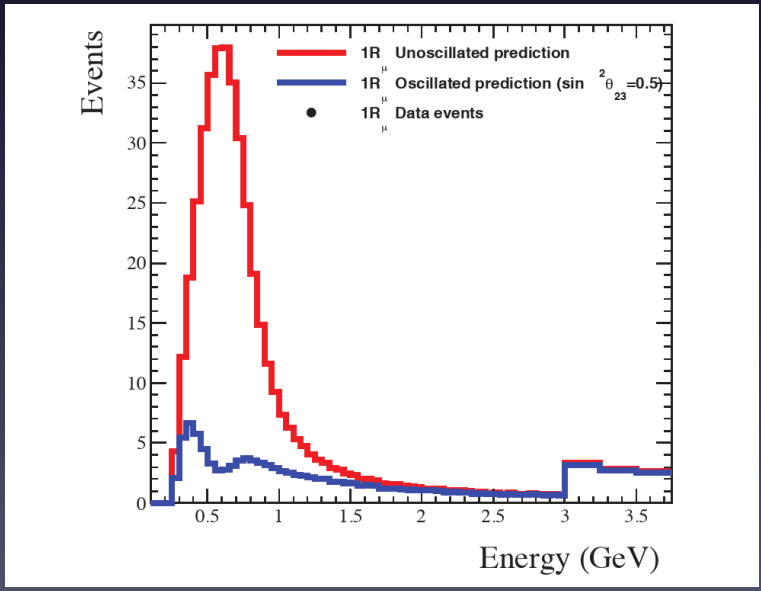


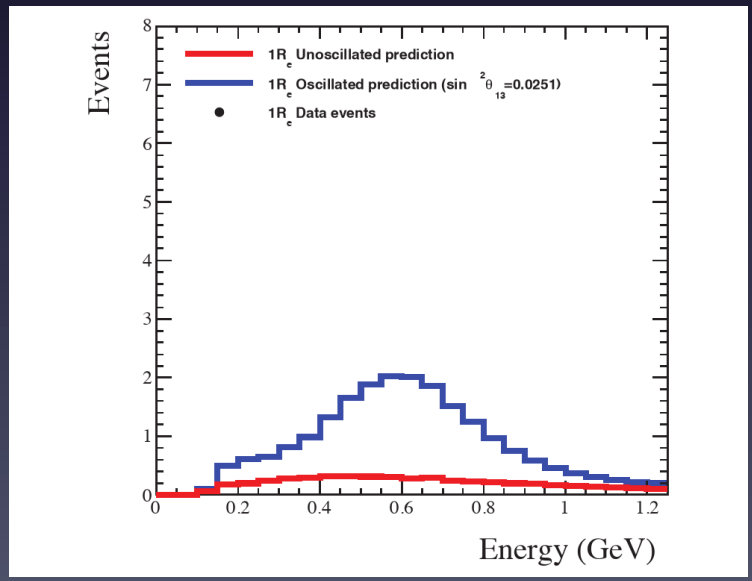


Oscillation Spectra in SK (Far Detector)









Data Analysis Strategy

- Oscillation Parameters: Compare number N^{ν} of neutrinos between Near Detector (ND) and Far Detector (FD):

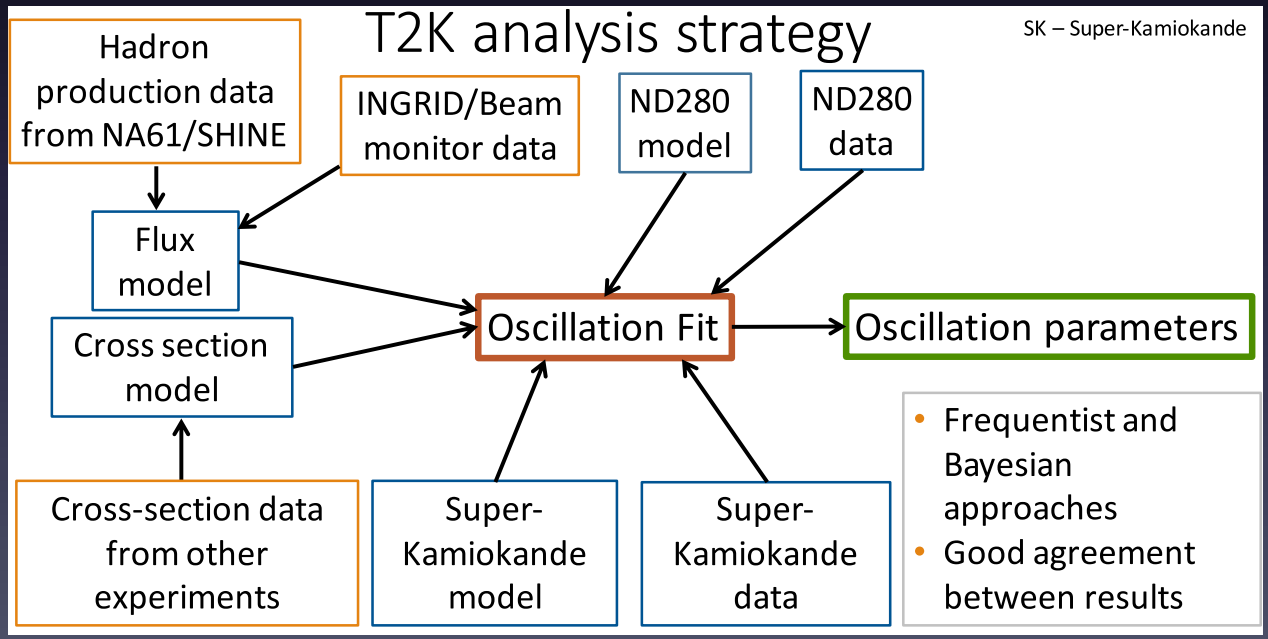
$$N^{\nu}_{ND} = (flux^{\nu}_{ND})(\sigma^{\nu}_{ND})(\varepsilon_{ND})$$

$$N^{\nu}_{FD} = (flux^{\nu}_{FD})(\sigma^{\nu}_{FD})(\varepsilon_{FD})(P_{osc})$$

Cross section

Detector efficiency

Oscillation Probability



From Maria Antonova, ICPPA-2017

Data Analysis Strategy

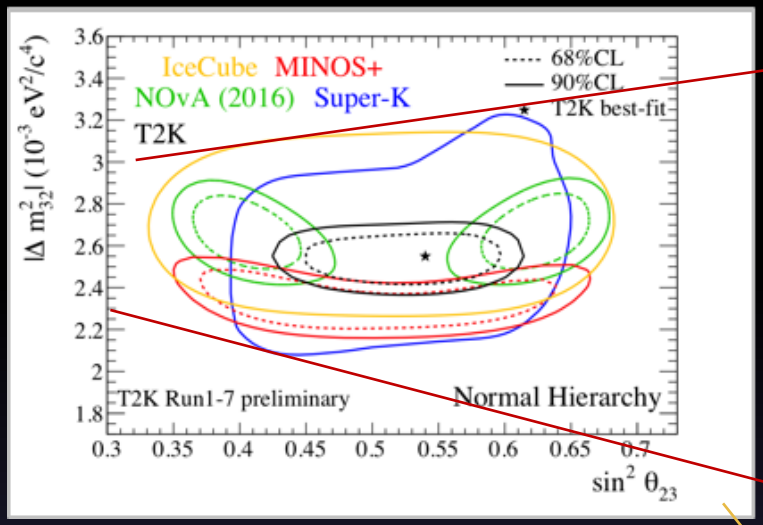
Simultaneous fit to neutrino and anti-neutrino mode at ND280 and SK using maximum binned likelihood

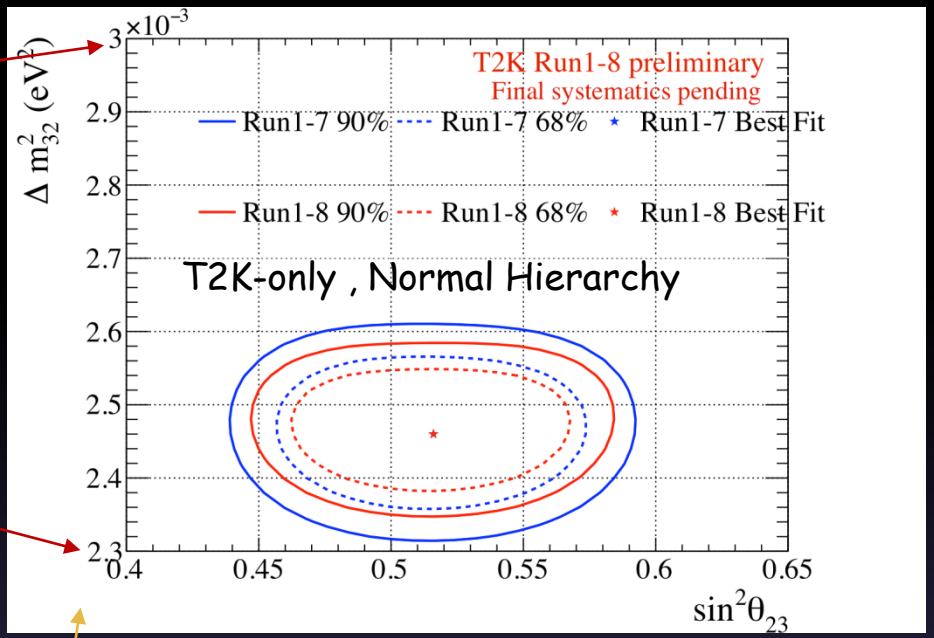
- Gaussian priors for $sin^2(\theta_{12}), \Delta m^2_{12}$ based on their PDG values

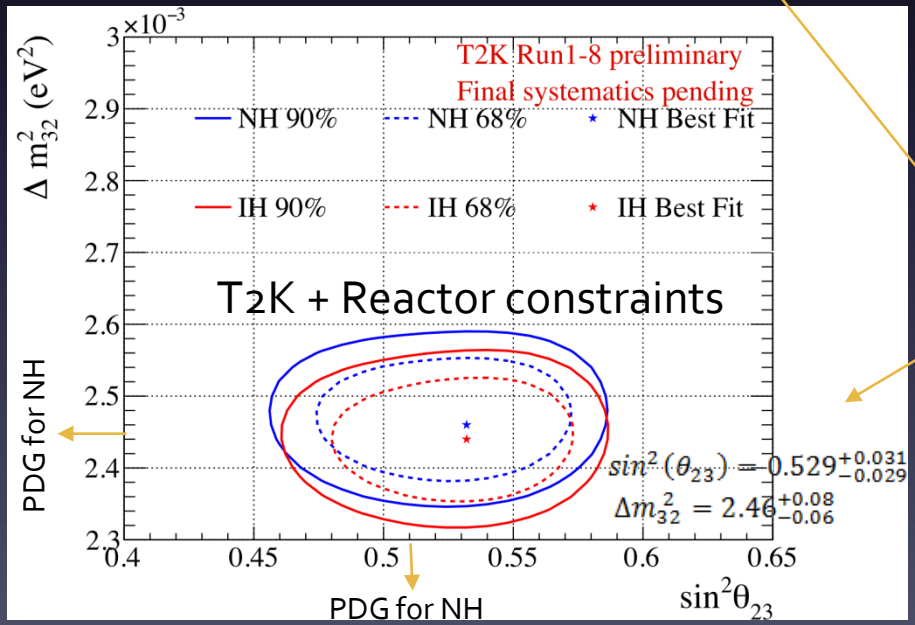
-**T2K-only** (without reactor constraint): Flat priors (bounded by their physically allowed values) for $sin^2(\theta_{13}), sin^2(\theta_{23}), \Delta m^2_{32}, \delta_{CP}$

- **T2K + Reactor**: Gaussian prior for $sin^2(\theta_{13})$ based on its PDG values reported from reactor experiments ($sin^2(2\theta_{13}) = 0.0857 \pm 0.0046$)

Measurements of $sin^2(\theta_{23}), \Delta m^2_{23}$ (Contour Plot)

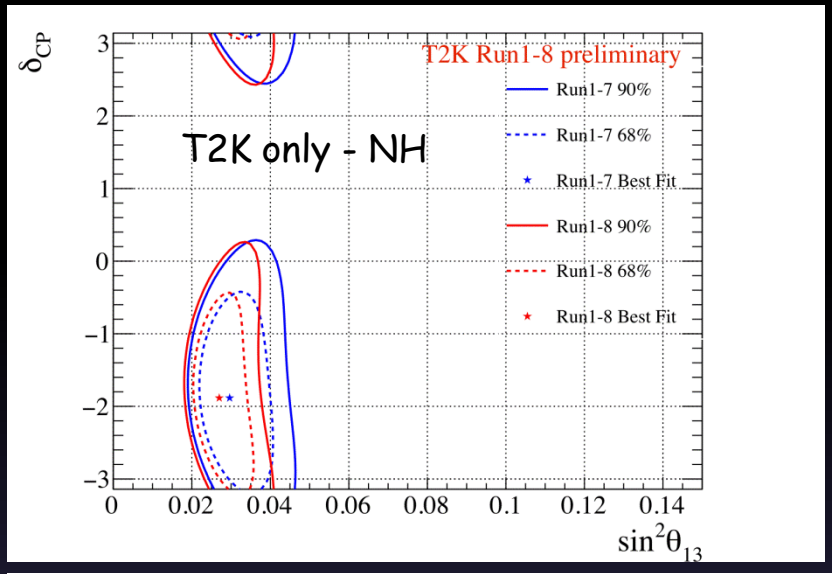


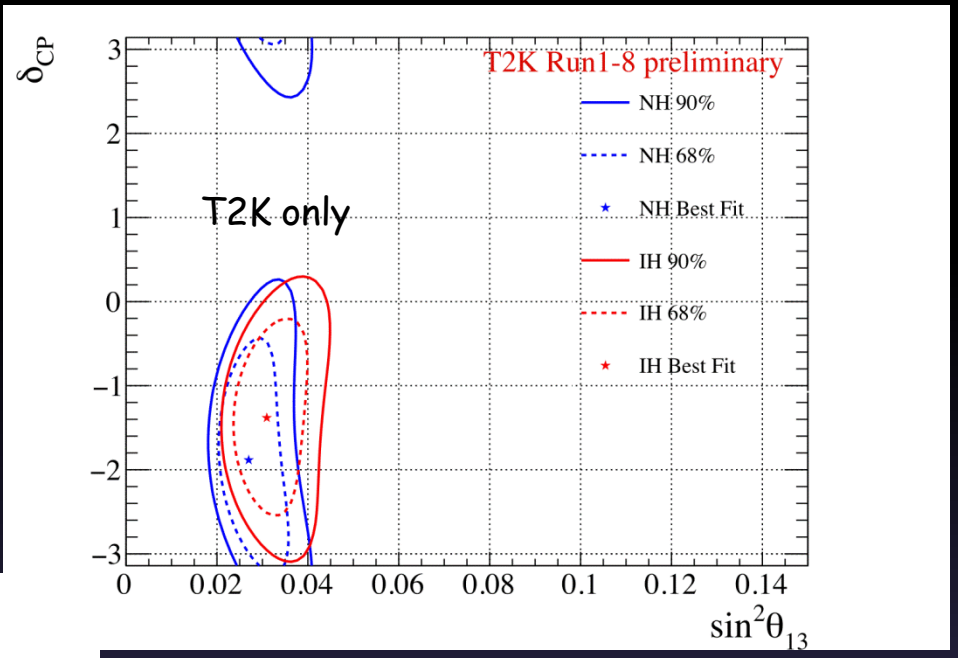


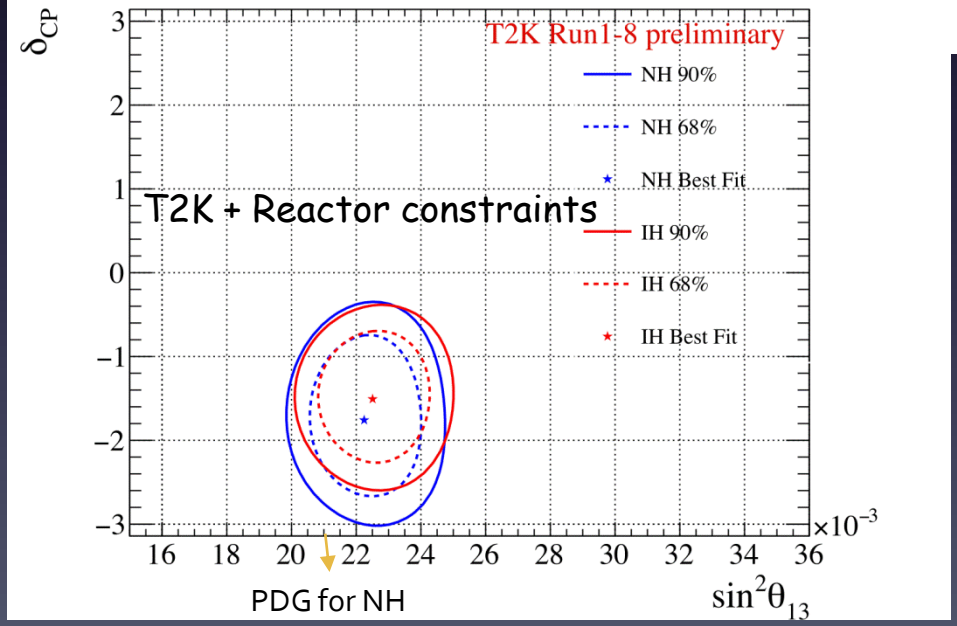


- Run 1-7 data → Results compatible between experiments
- Run 1-8 → Improvement over previous measurement (improved model, etc)
- Measurement compatible with maximal mixing ($sin^2(\theta_{23}) = 0.52$)
- Compatible with PDG values

Measurement of $sin^2(\theta_{13})$, δ_{CP} (Contour Plot)



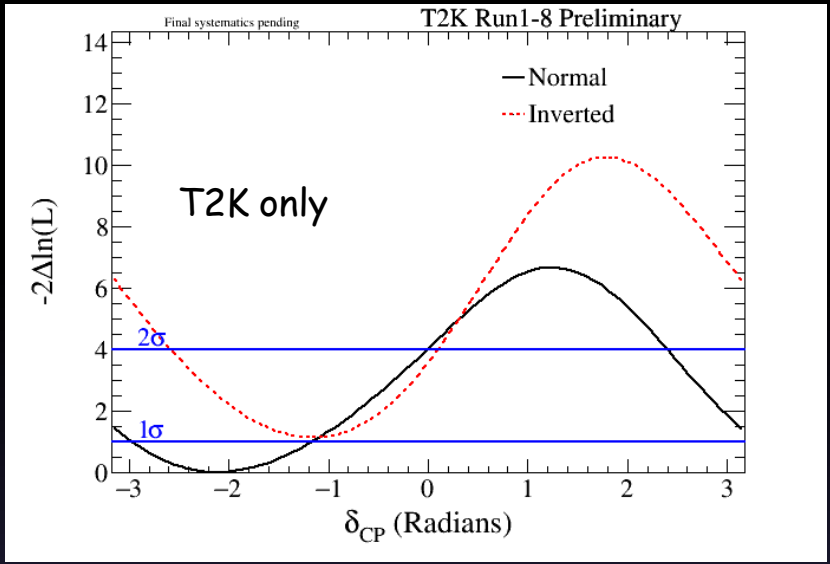


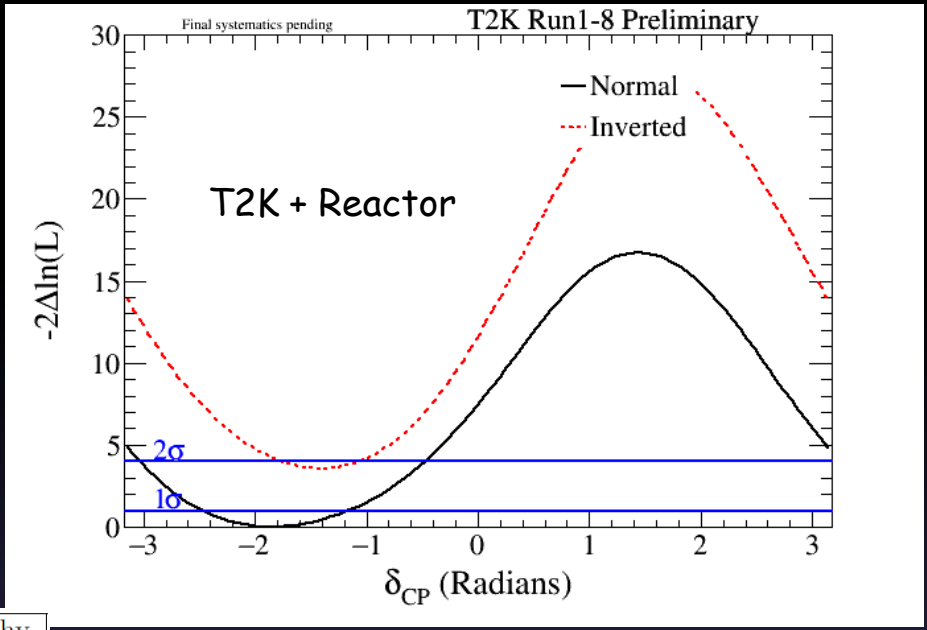


- T2K + Reactor → $sin^2(\theta_{13}) = 0.0223^{+0.0015}_{-0.0010}$

  $\delta_{CP} = -1.76$
- Compatible with PDG
- Preference for values of $\delta_{CP} \sim -\pi/2$

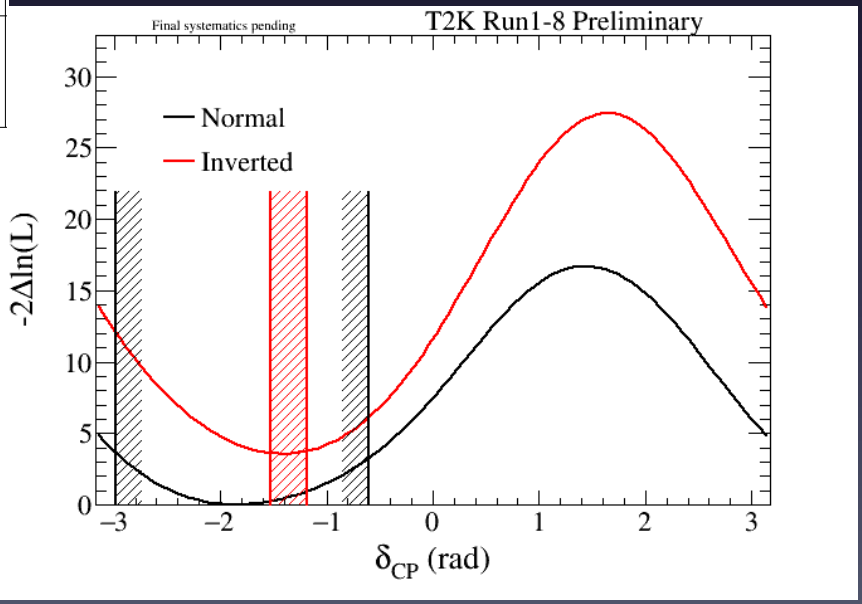
Constraints on δ_{CP}





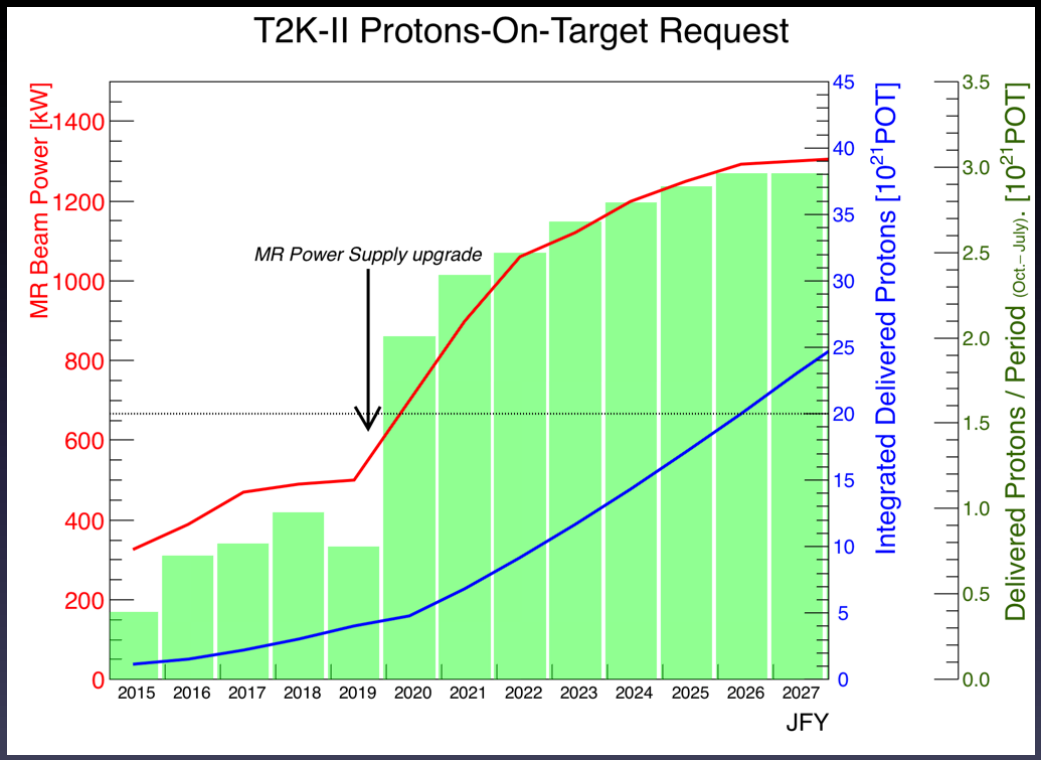
Parameter	Reactor	CL	Normal hierarchy	Inverted hierarchy
δ_{CP}	Yes	68%	$[-2.490, -1.229]$	-
δ_{CP}	Yes	90%	$[-2.805, -0.830]$	-
δ_{CP}	Yes	2σ	$[-2.981, -0.600]$	$[-1.531, -1.184]$

- Feldman-Cousins method to properly evaluate CL forT2Kn + Reactor
- δ_{CP} with preference to negative values
- $\delta_{CP} = 0, \pi$ (CP-conserving) values fall outside of the 2σ CL intervals
- Data seems to prefer Normal Hierarchy over Inverted Hierarchy:



Improving Oscillation Measurements T2K Upgrade → T2K-II

- Current analysis is limited by statistics and systematics → want to reach $\sim 3\sigma\ CL\ by\ 2025$
- Detector Upgrade
  - SK with gadolinium → neutron tagging possible → more reactions detected → better physics analysis
  - ND280 upgrade → Improved tracking and calorimetry → better cross-section measurements → better constraints on ND/FD extrapolations → better systematics
- Beam line upgrade: will go from 470 kW to 1.3 MW → better statistics



Summary

- θ_{23} compatible with oscillation maximum
- CP-conserving δ_{CP} values excluded at 2σ CL
- Data seems to prefer Normal Hierarchy
- Future prospect → T2K-II to reach 3σ CL

Backup Slides

Improving Oscillation Measurements
T2K Upgrade → T2K-II

	1-Ring μ		**1-Ring e**			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
Flux + Xsec constrained	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Osc	0.04	0.03	3.86	3.60	3.78	0.79
All Systematics	4.40	3.76	6.10	6.51	20.94	4.77
All with osc	4.40	3.76	7.27	7.44	21.24	4.85

Oscillation Spectra in SK (Far Detector)