An Overview of the T2K Experiment

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for the T2K Collaboration

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Neutrino Physics

CP2023

Neutrino oscillations occur due to the mixing of the flavour and mass eigenstates, with the amplitude relating the PMNS mixing matrix, shown below.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor + Long Baseline}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{ij} = \cos(\theta_{ij})$$
$$s_{ij} = \sin(\theta_{ij})$$

6 Oscillation parameters

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

Key questions:

1. What is the value of δ_{CP}?
2. What is the sign of Δm^2_{32}?
3. What is the value of θ_{23}?

Probability Formula

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$
$$\mp 1.27\Delta m^2_{32}\frac{L}{E_\nu}8J_{CP}\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$

Changes for $\nu/\bar{\nu}$

Jarlskog Invariant:

$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{\rm CP}$

normal ordering (NO) **inverted ordering (IO)**

6 Oscillation parameters

Key questions:

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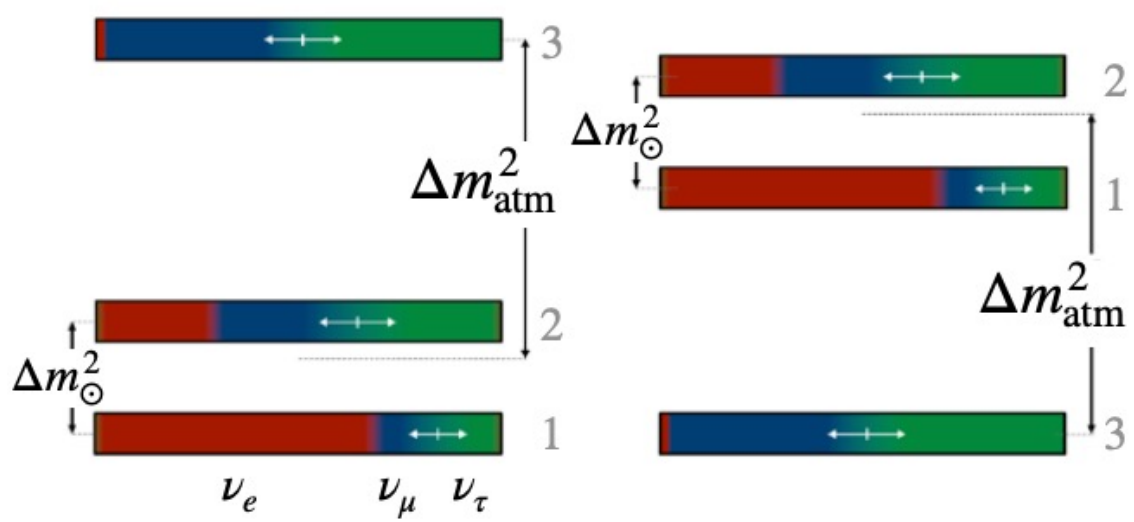
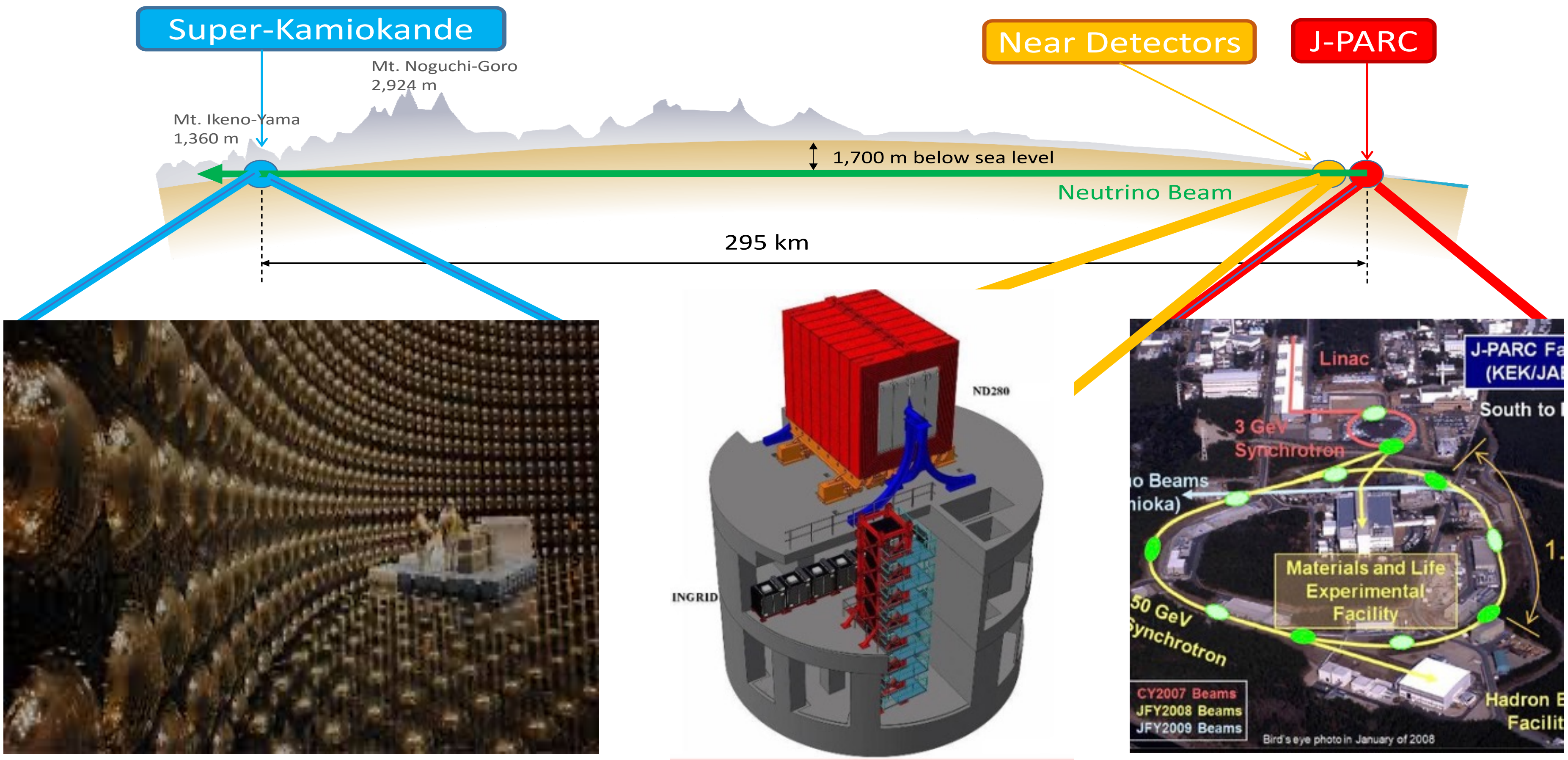


T2K Overview

A Long baseline neutrino experiment situated in Japan.
International collaboration of ~500 Members from 78 Institutes In 12 Countries.



T2K Overview

For δ_{CP} we look at $\nu_e/\bar{\nu}_e$ appearance.

$\nu_e, \nu_e, \nu_\mu, \nu_\mu, \nu_\mu$

$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu$

$\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

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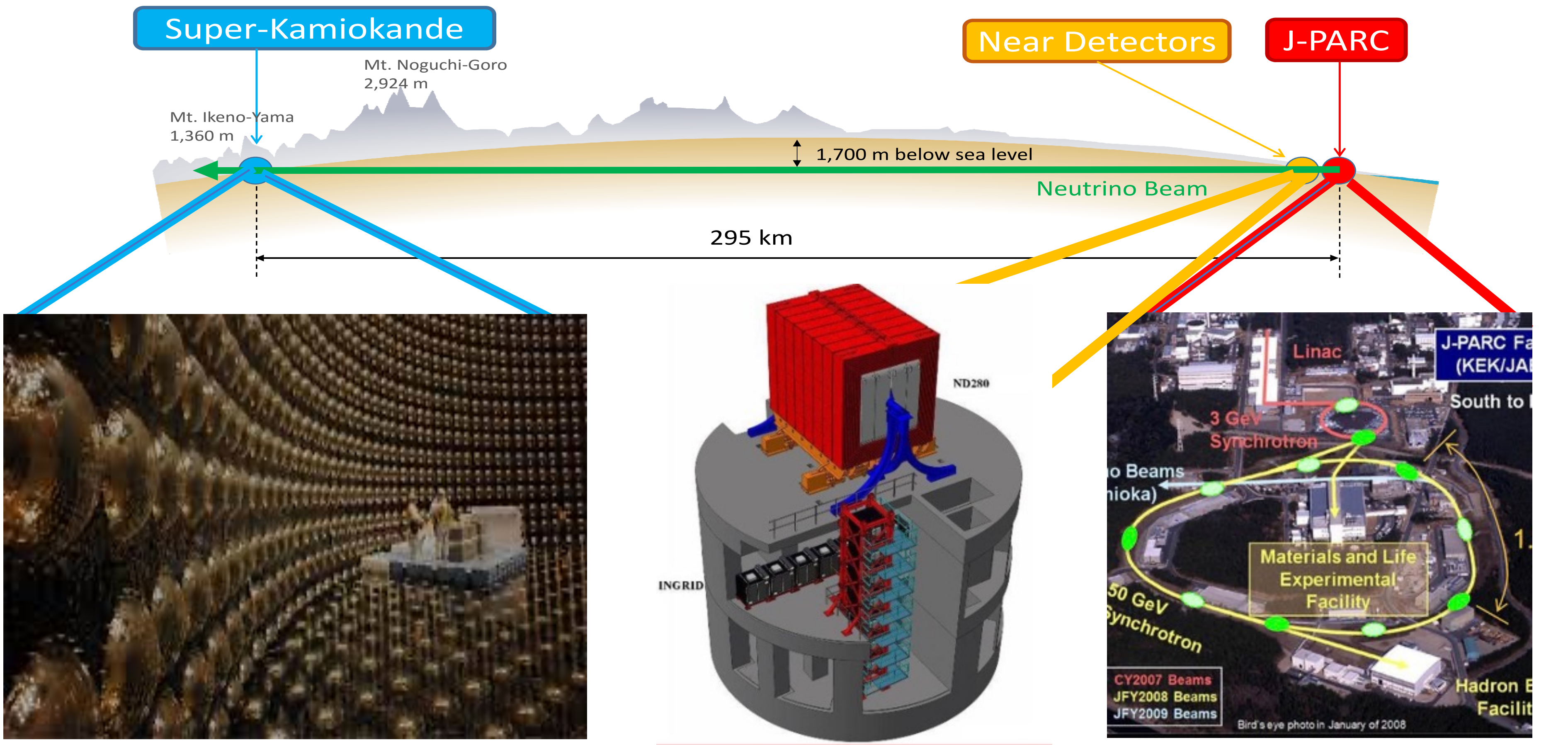
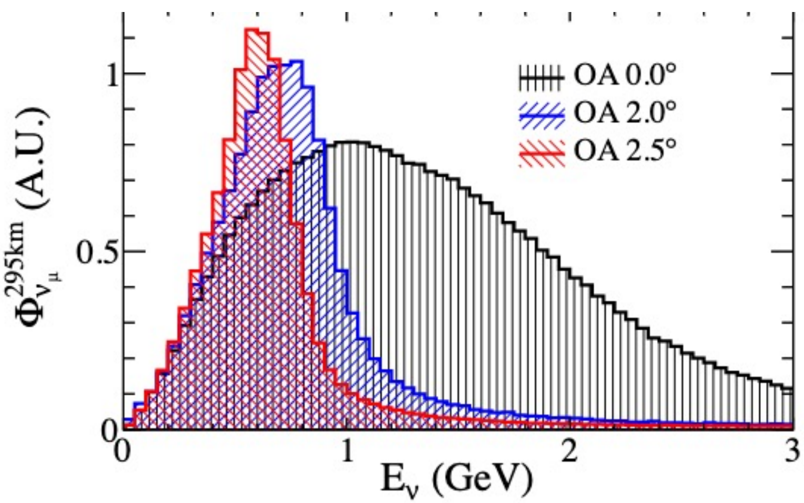
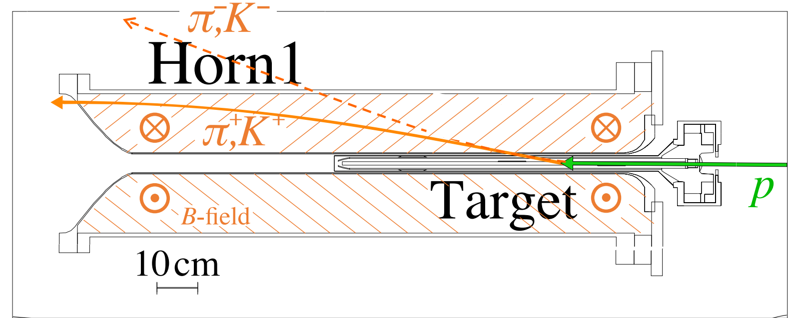


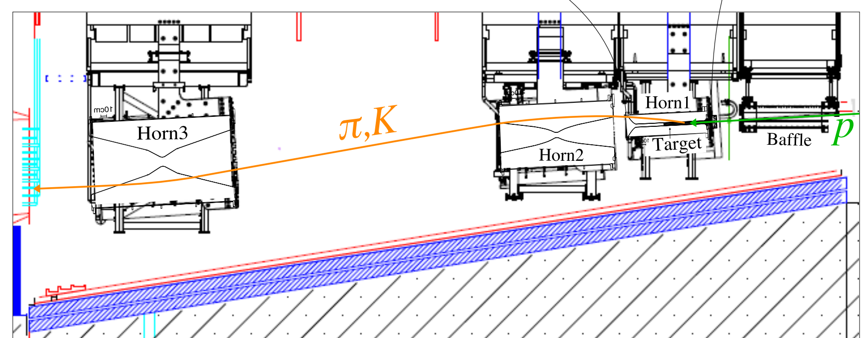
J-PARC Beam

30 GeV protons collide with the 90 cm producing hadrons.

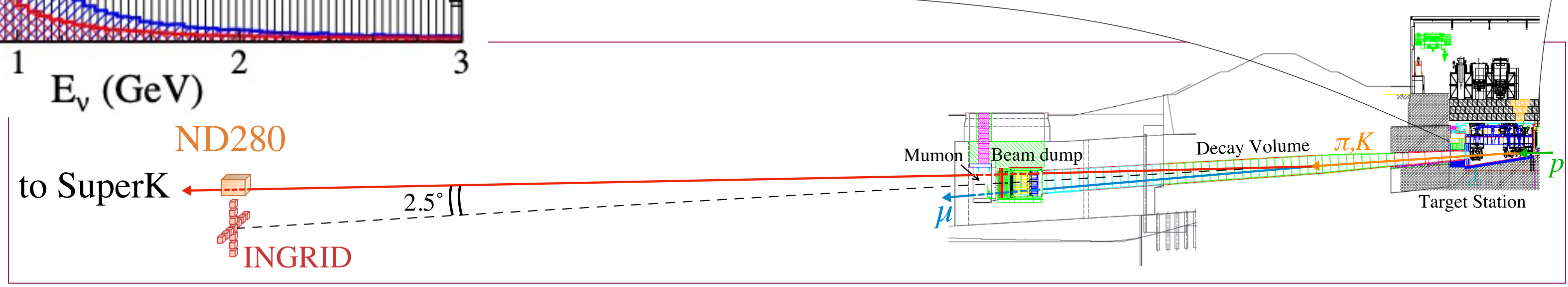
Polarity of horns defines the particle targets which further decay. π^+ and K^+ produce ν_μ, π^- and K^- produce $\bar{\nu}_\mu$.



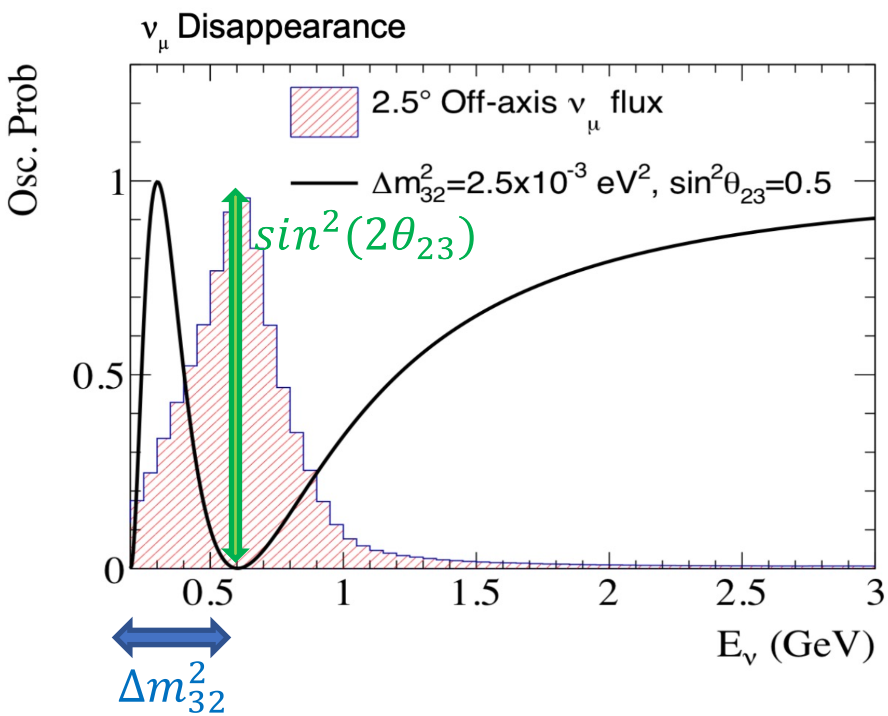


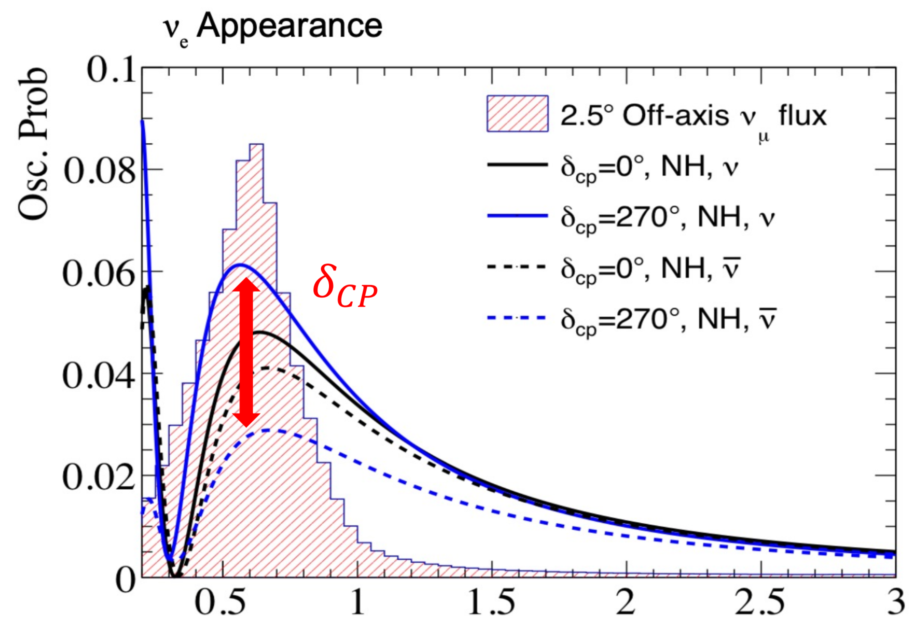


Off-axis Technique.



Sensitivities

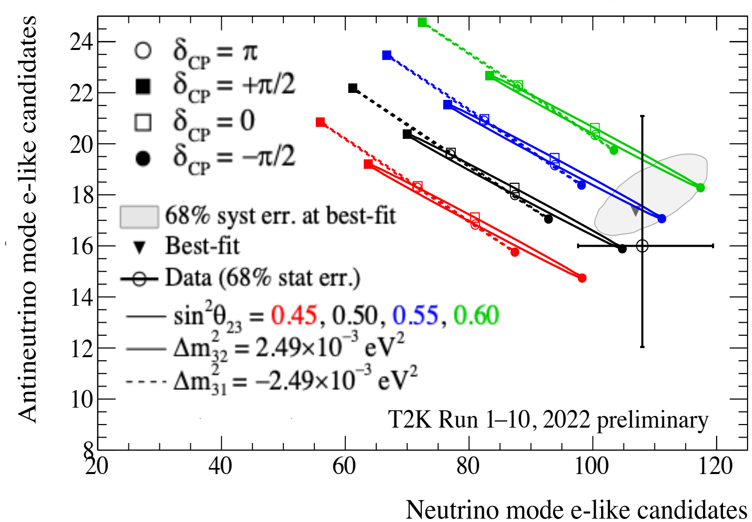




Looking at both ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance, T2K has sensitivity to θ_{23}, δ_{CP}, θ_{13} and Δm^2_{32}

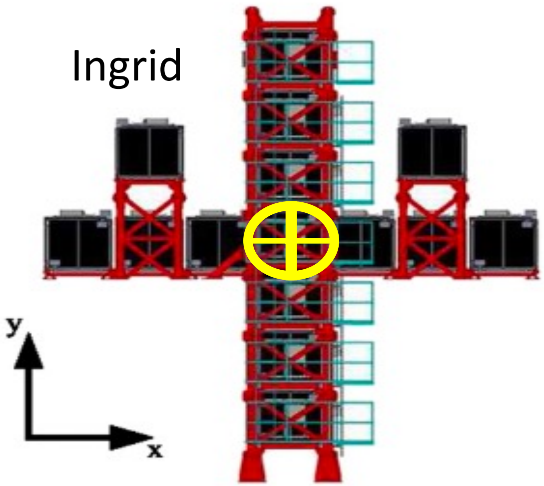
If $\delta_{CP} = \frac{\pi}{2}$, **fewer** neutrinos and **more** anti-neutrinos.

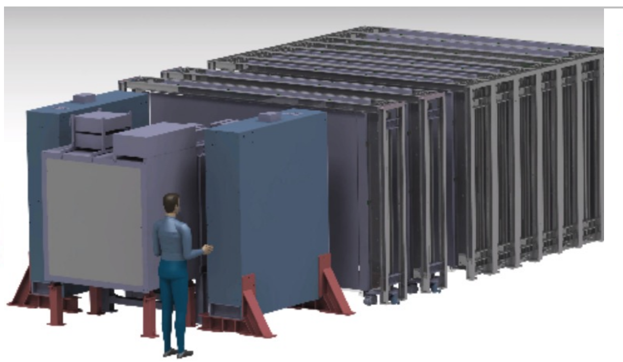
If $\delta_{CP} = -\frac{\pi}{2}$, **more** neutrinos and **fewer** anti-neutrinos.



Near Detectors

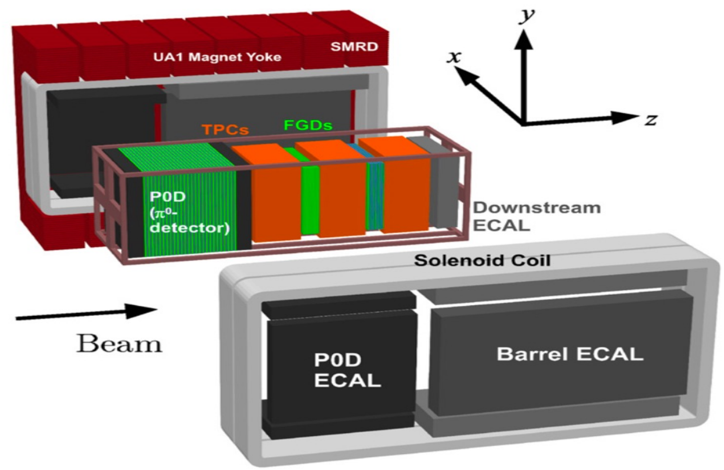
Ingrid





WAGASCI-BabyMIND

ND280



On axis detector.

Ingrid measures beam intensity and beam direction.

14 identical Iron and plastic scintillator detectors.

1.5^o off axis from beamline.

Water target, used for extra cross-section measurements.

Intermediate off axis, higher neutrino energies.

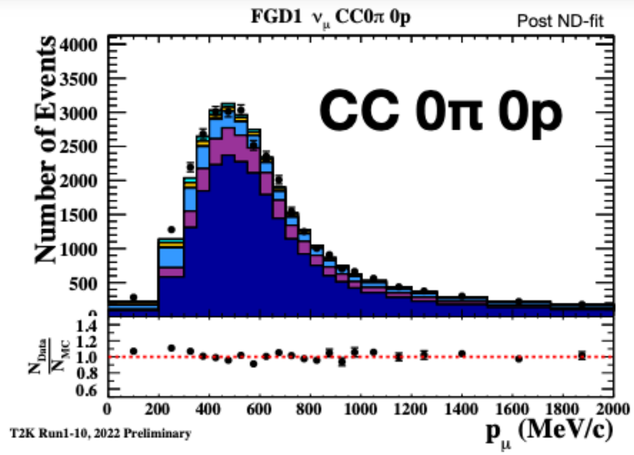
2.5^o off axis detector .

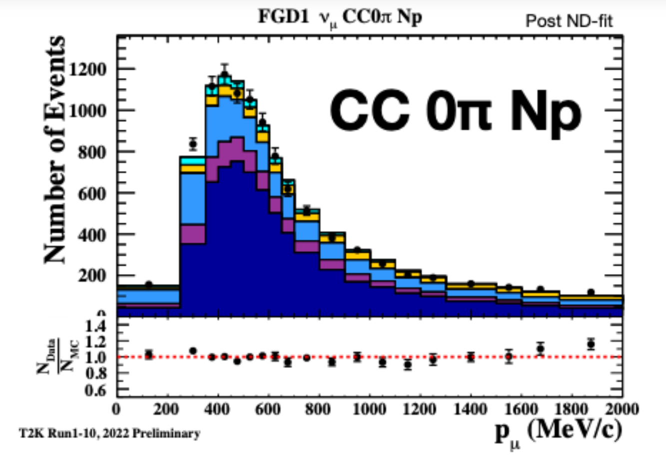
Fully magnetized for particle charge sensitivity.

Two different target materials, C and C+O, allows for cross-section measurements.

Near Detector Samples (some)

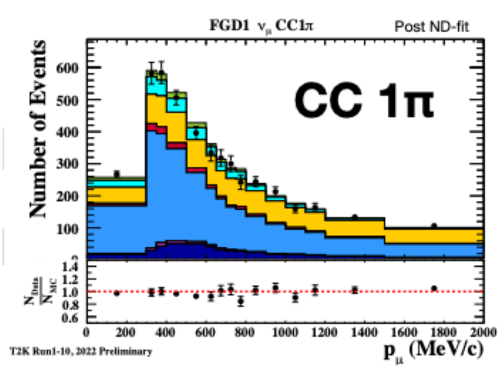
Improved to 22 samples, 18 in previous analysis round.

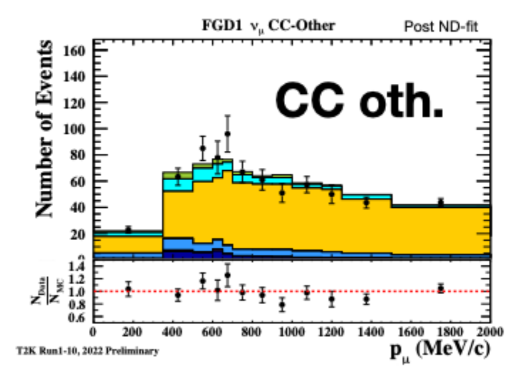


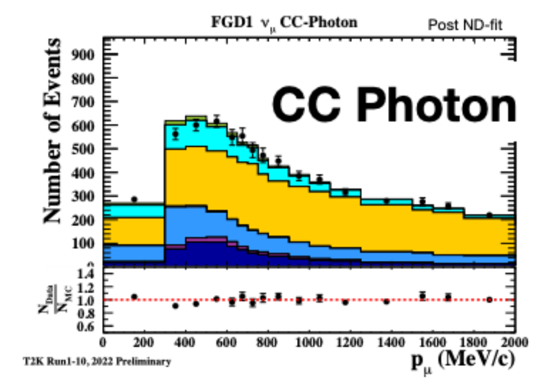


CC = Charged Current

NC = Neutral Current



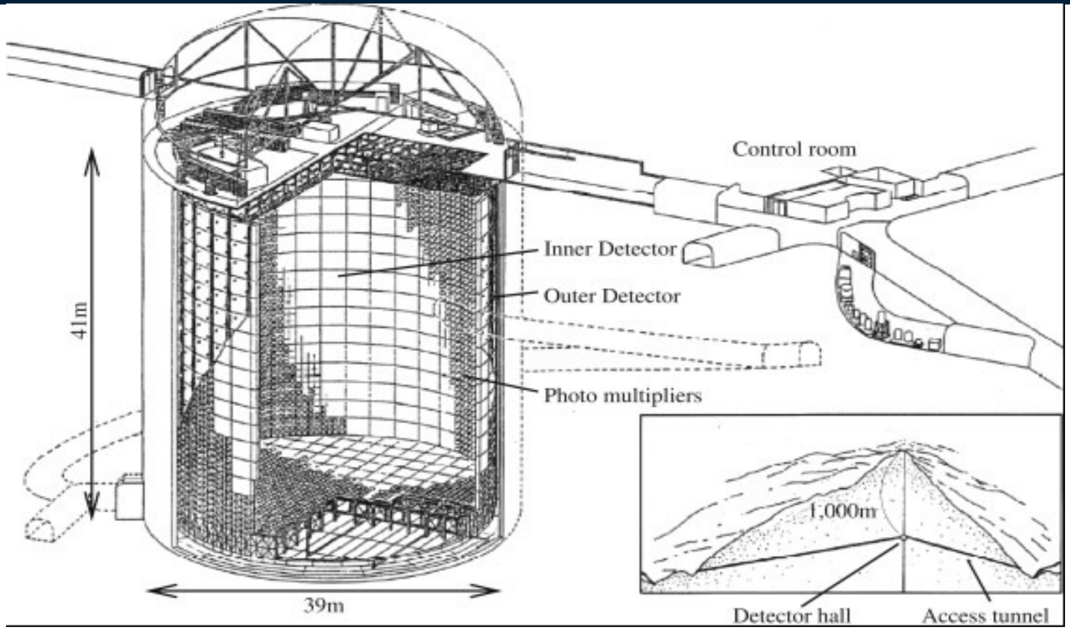




New information about proton and photon tagging.

Dominated by CC quasi-elastic (CCQE) interactions, followed by 2p2h, CC Resonant (CCRES) and CC Deep inelastic scattering (CCDIS).

Super Kamiokande

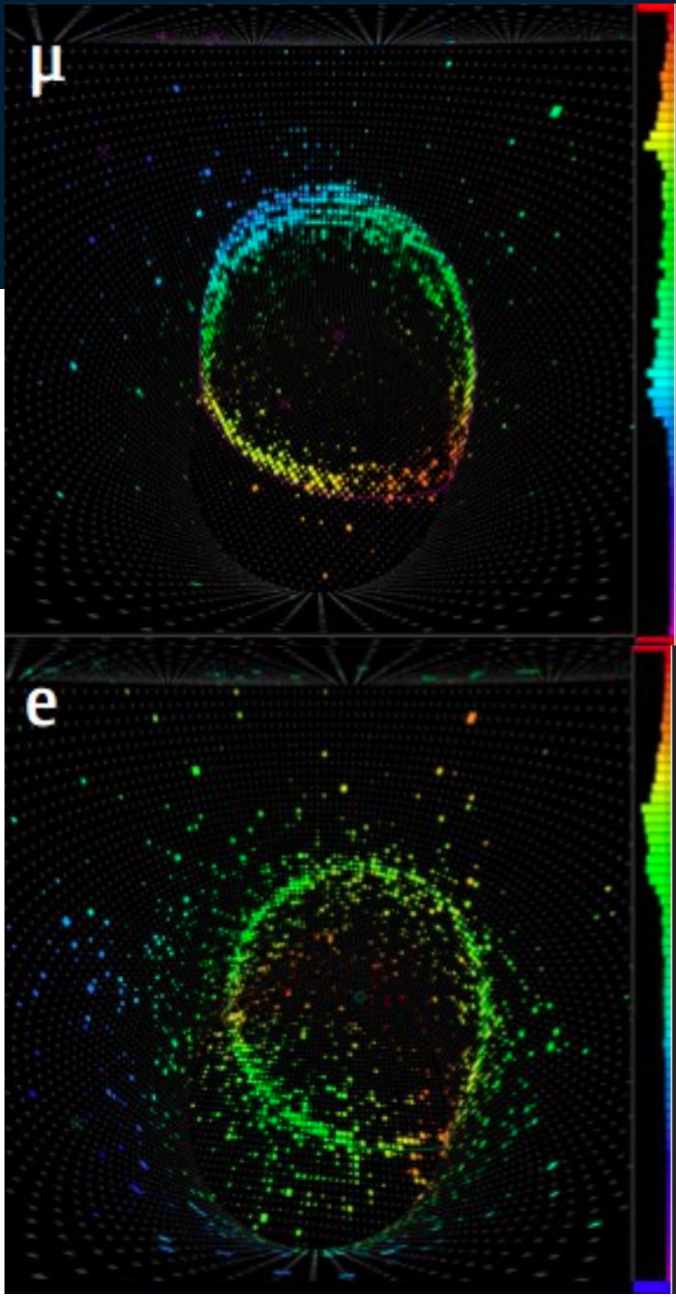


50kt Water Cherenkov detector.

11,000 20” PMT’s in Inner detector.

Good PID given shape of leptonic Cherenkov rings.

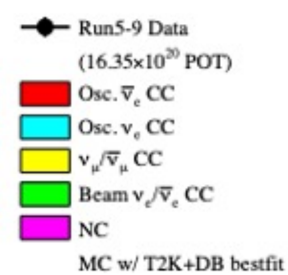
Can reconstruct neutrino energy thanks to lepton momentum and known beam direction.

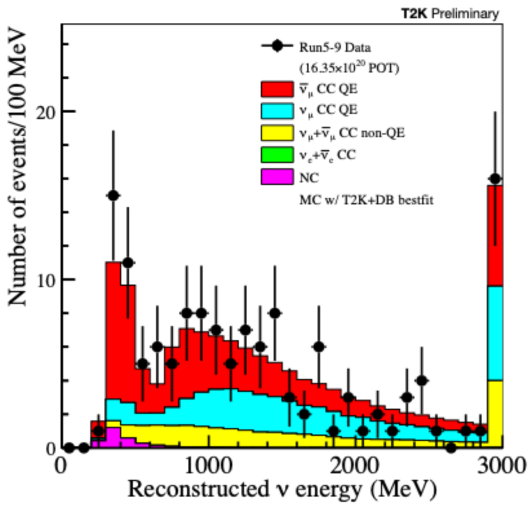


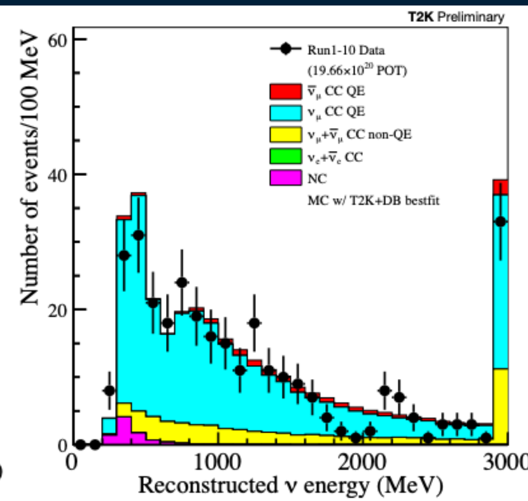
Now doped with Gadolinium!

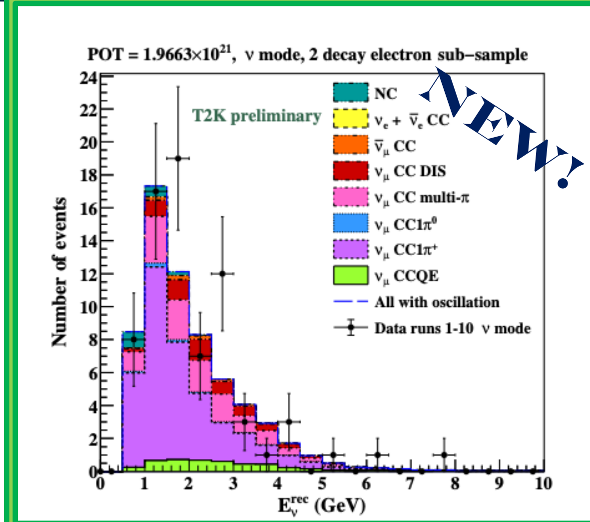
Far Detector Samples

CP2023

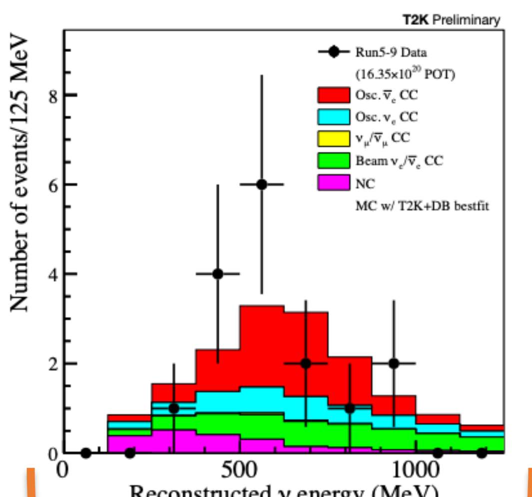




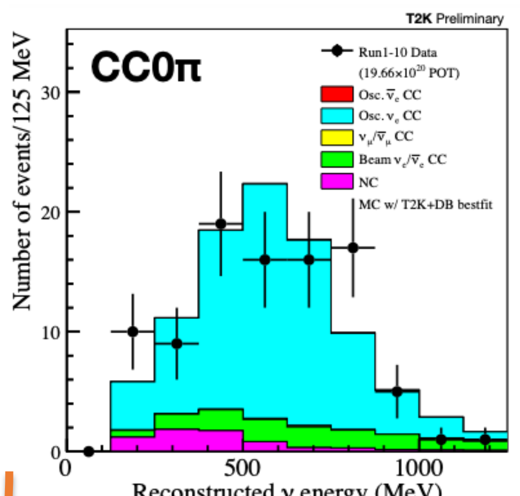


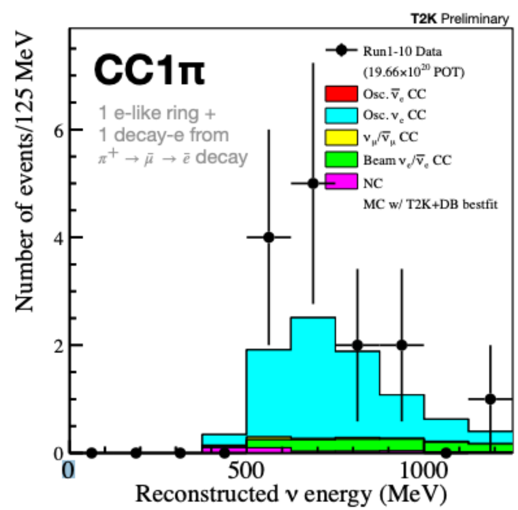


μ - like



$\bar{\nu}$

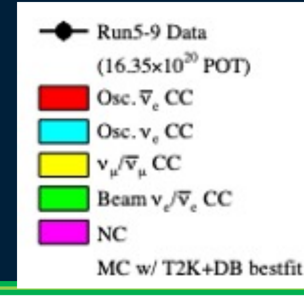


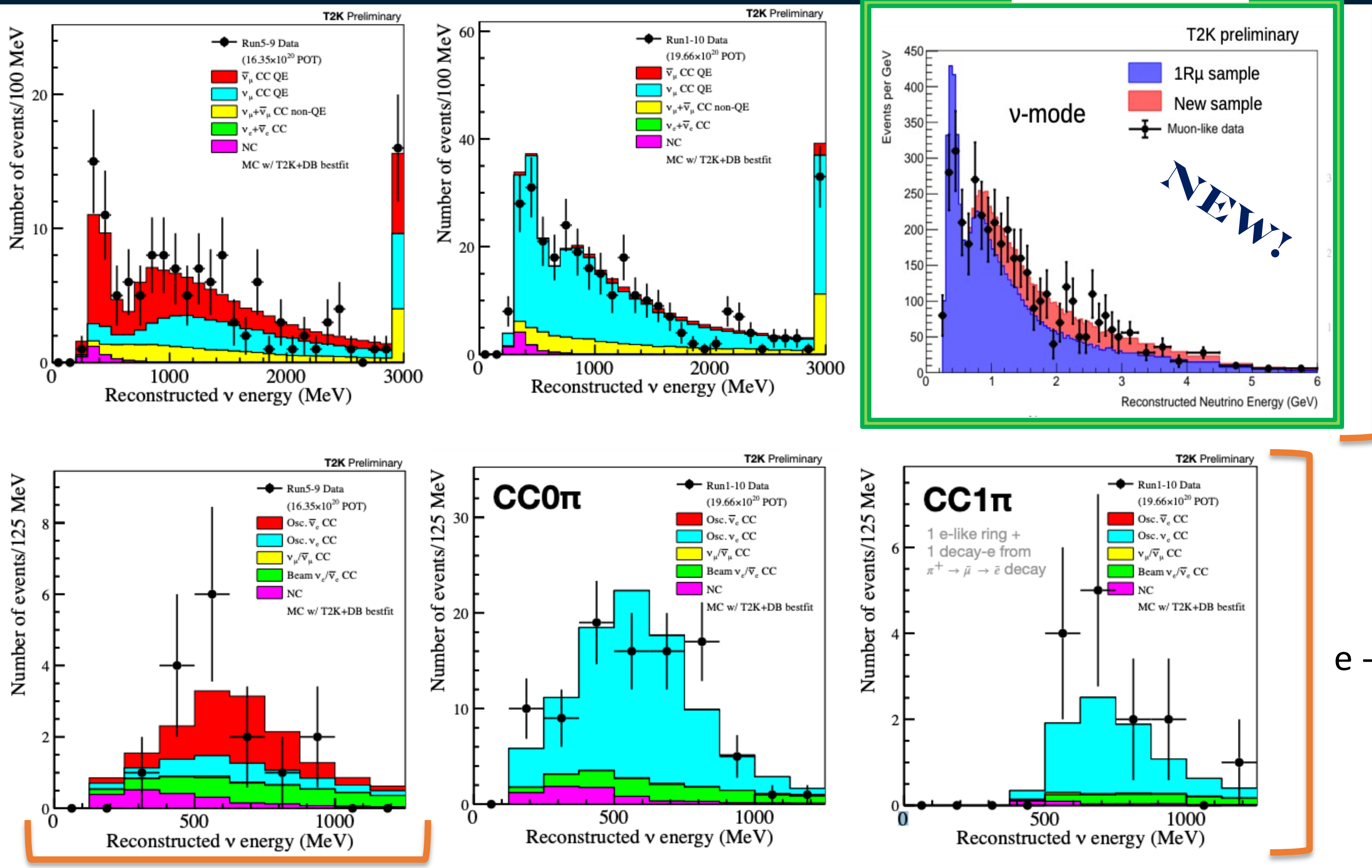


e - like

Far Detector Samples

CP2023



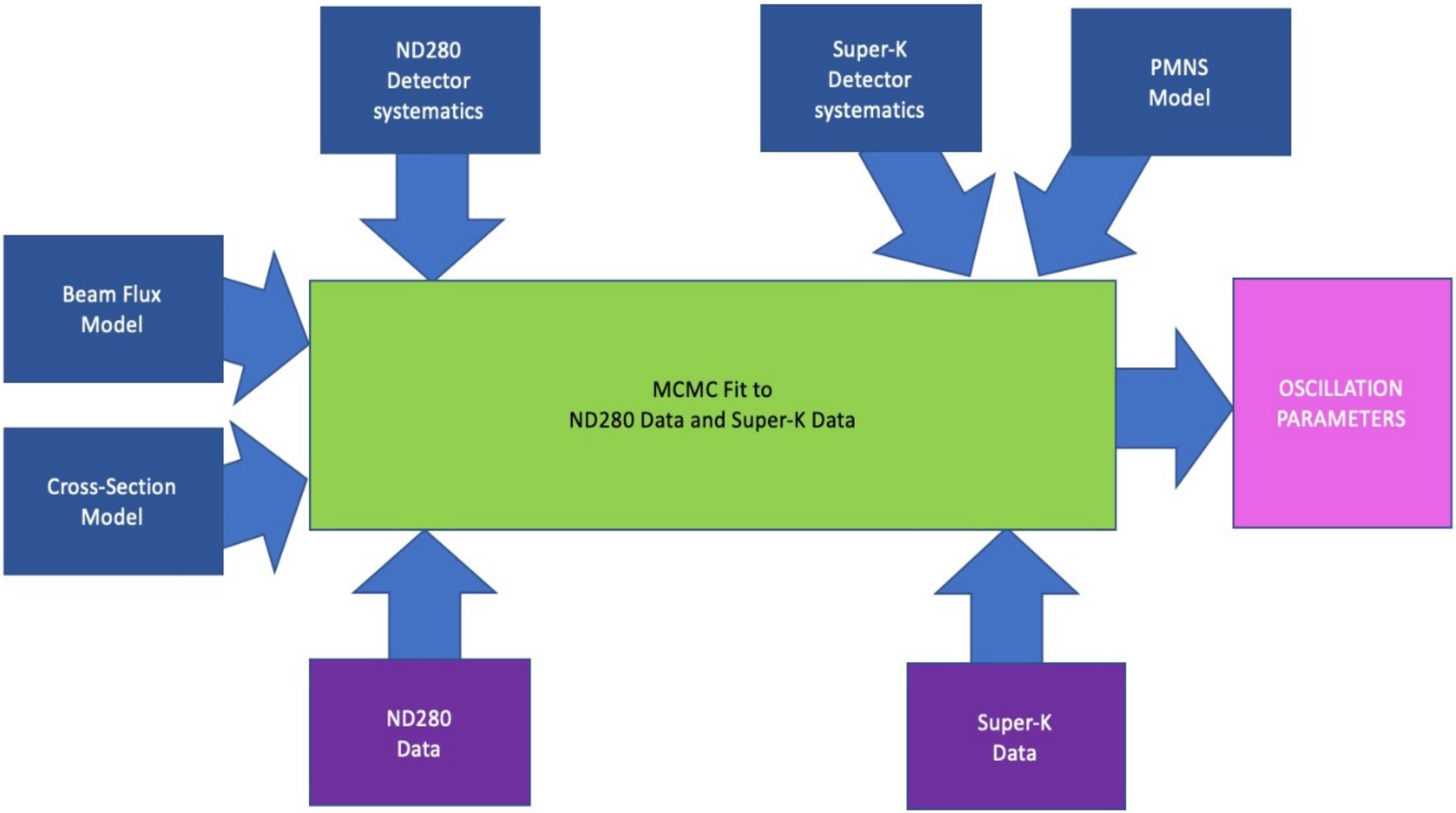


μ - like

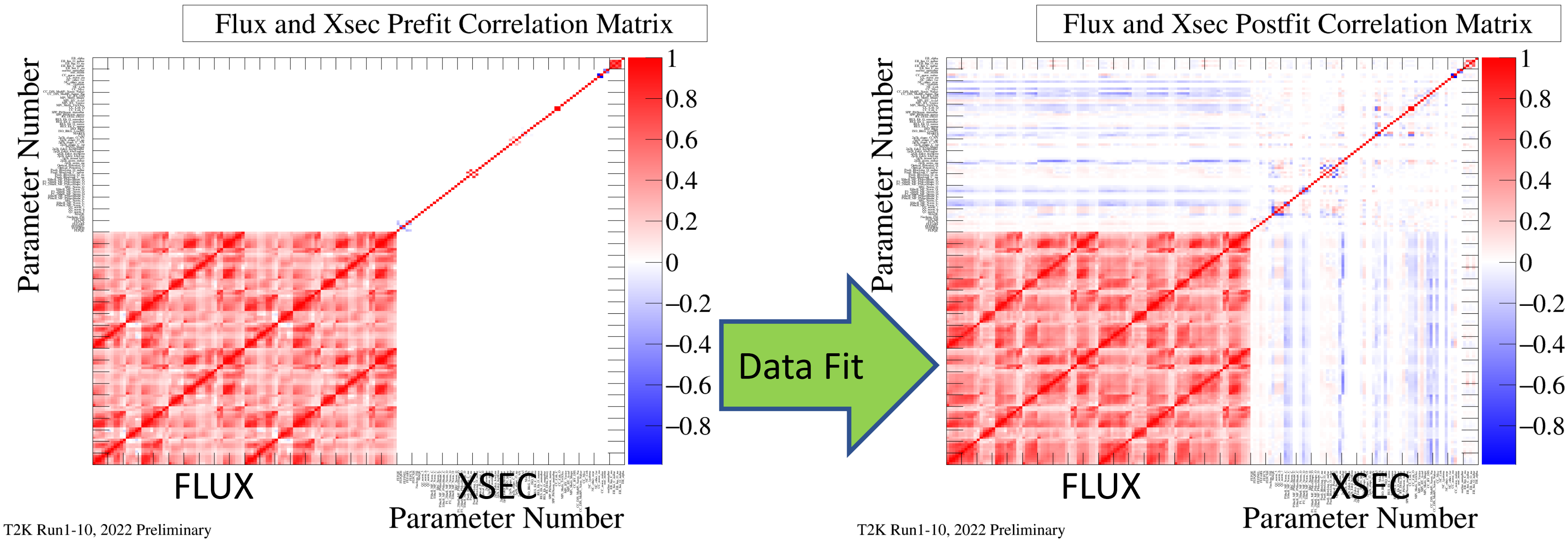
e - like

$\bar{\nu}$

Oscillation Analysis



Near Detector Fit

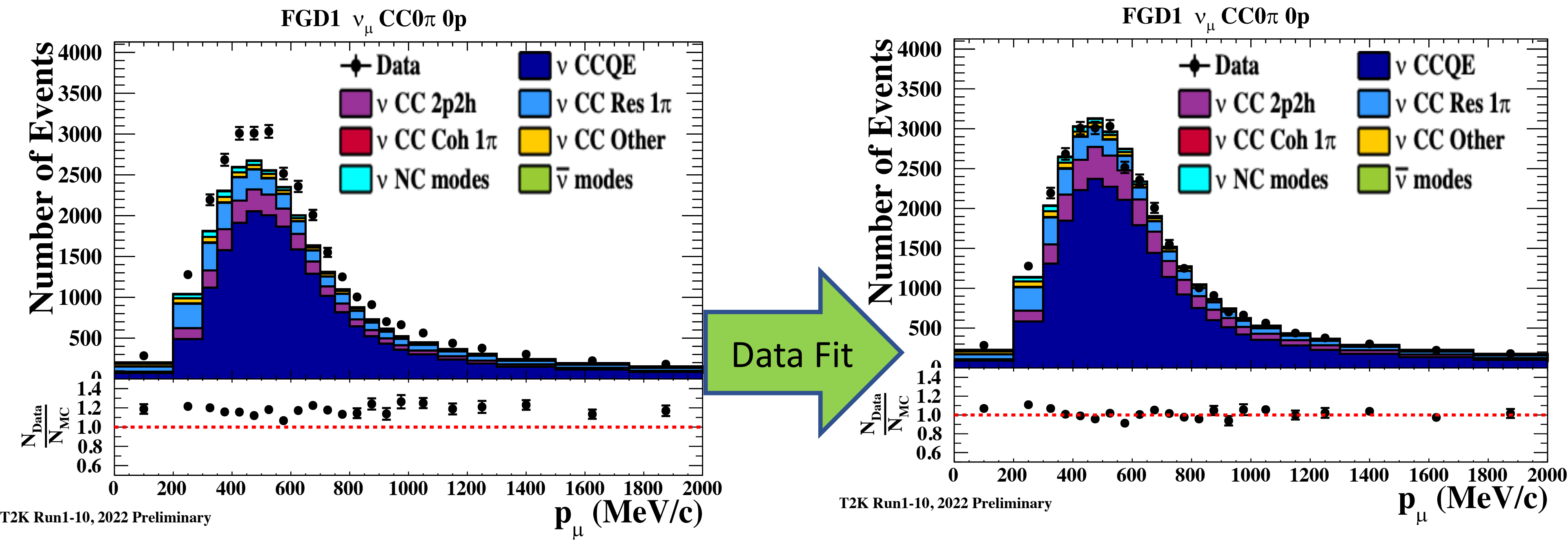


Accounts for anti-correlation between cross-section and flux models, will also change prior and error values.

Important to tune the model to the ND data, it reduces the uncertainty in the far detector predictions!

Near Detector Fit

CP2023



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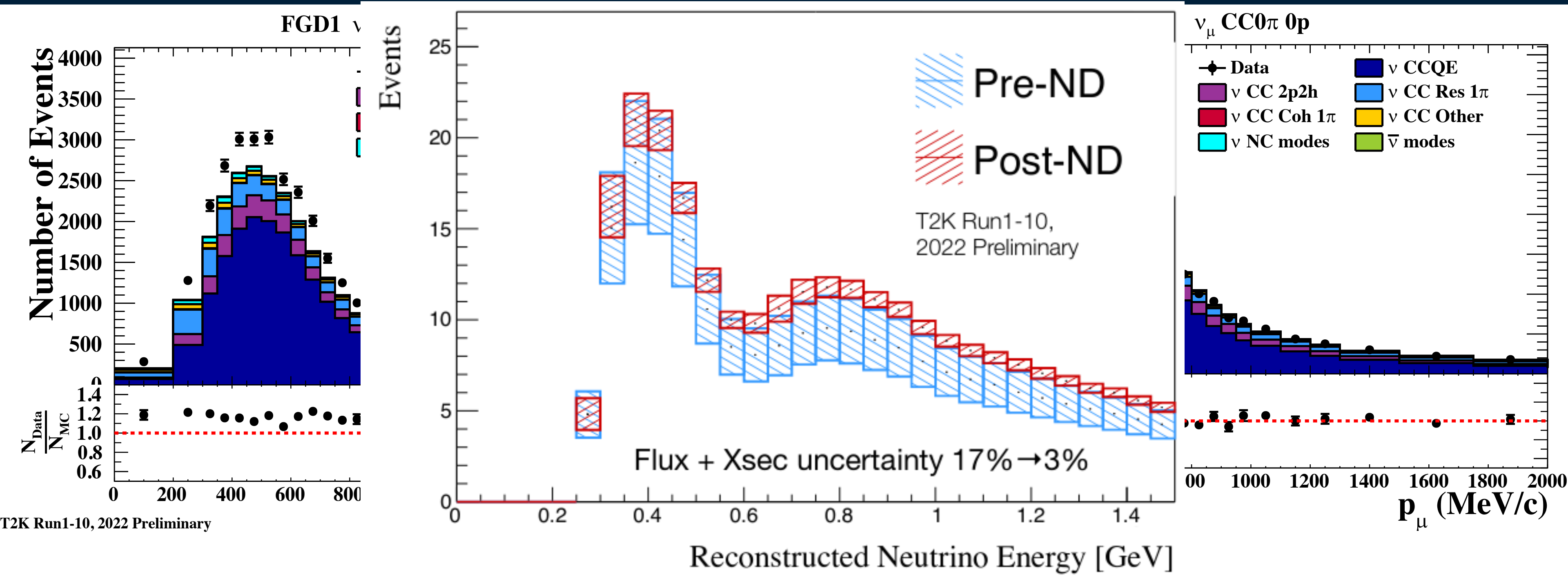

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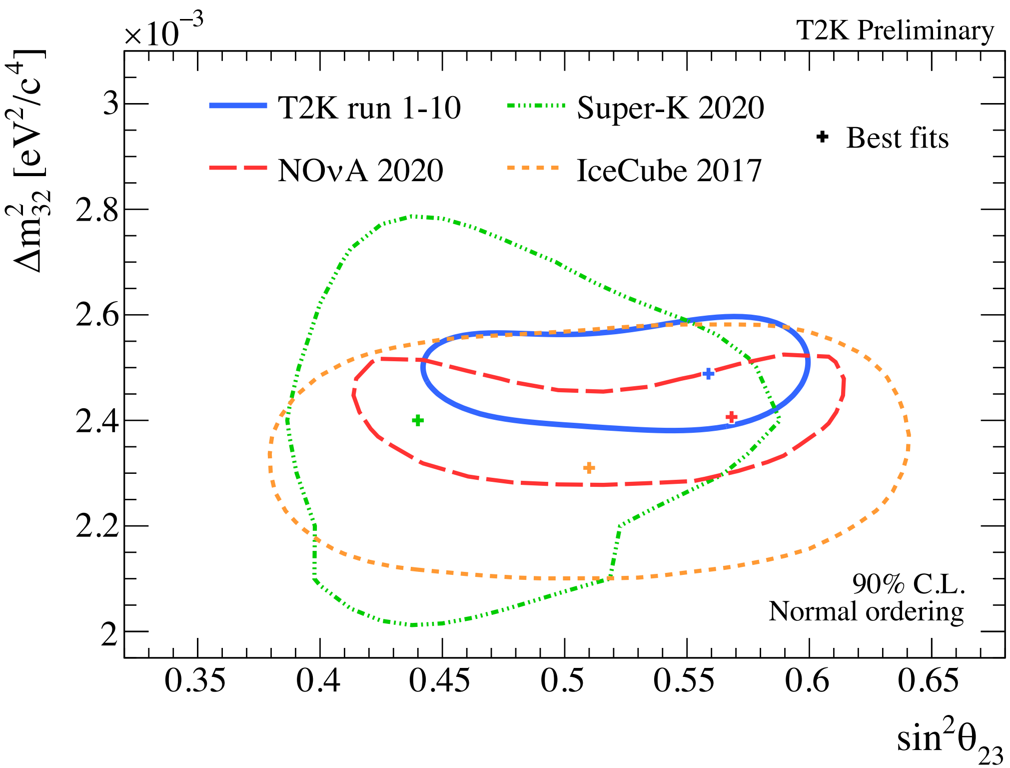
OSCILLATION RESULTS

Disappearance Channel



A world leading measurement for the Disappearance parameters.

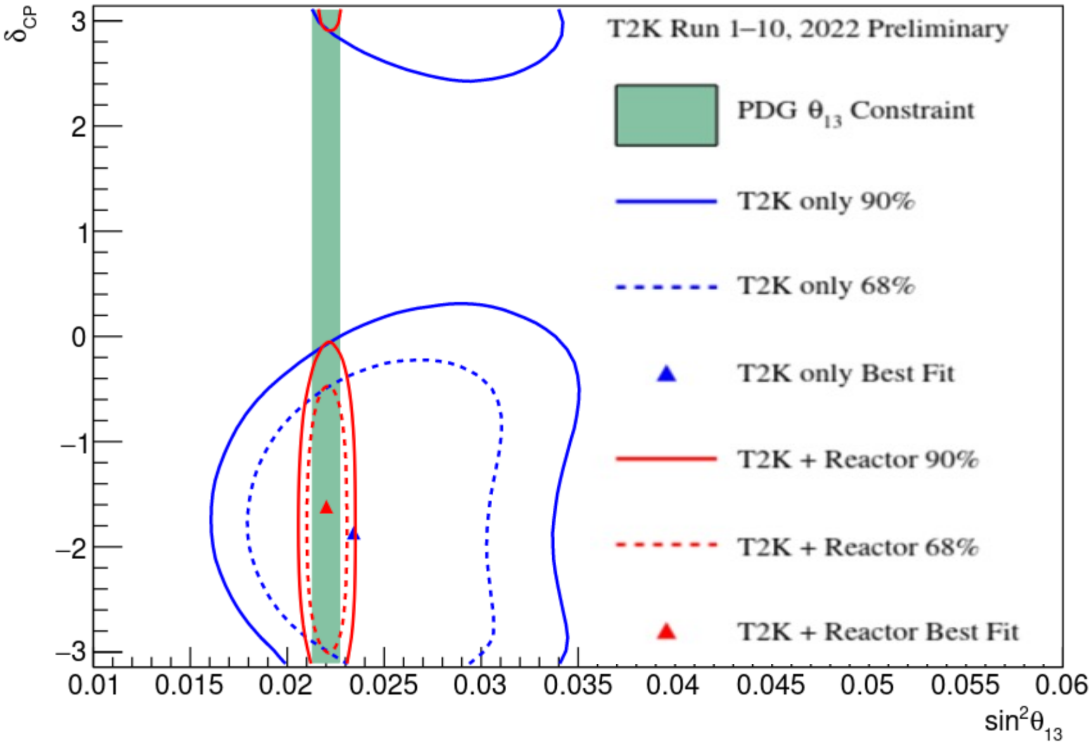
A slight preference for the Normal Ordering with a Bayes factor of 2.85.

A slight preference for the Upper Octant with a Bayes factor of 3.

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IH ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.00

Appearance Channel

CP2023



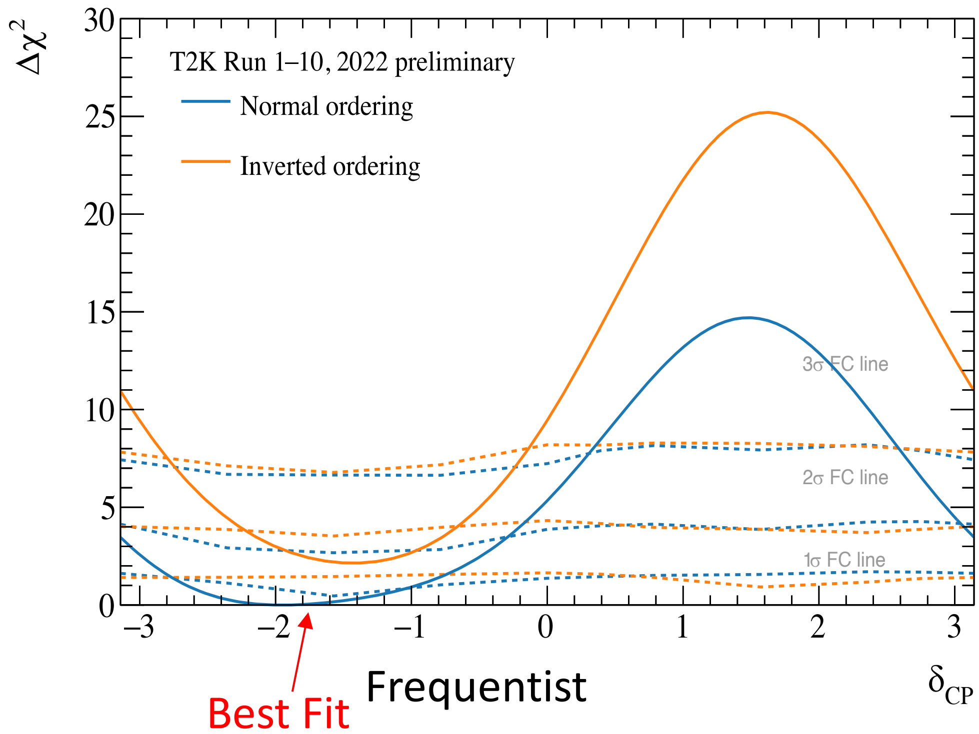
A good agreement between T2K and and the PDG's θ_{13} constraint.

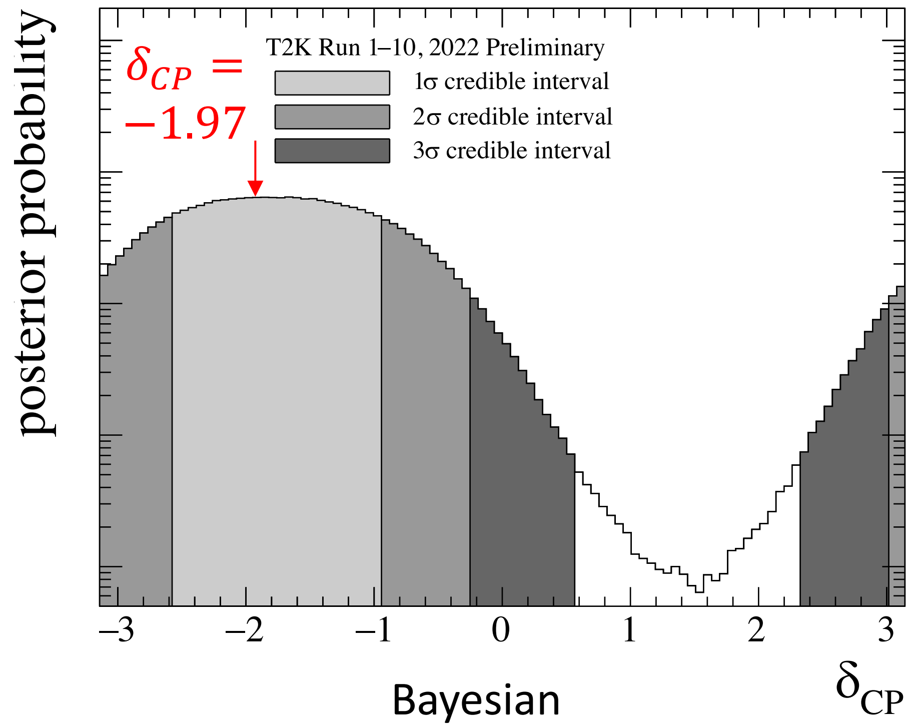
Applying reactor constraint gives a tighter constraint on other oscillation parameters too.

PDG Reactor constraint is a Gaussian:
$sin^2(\theta_{13})$ = 0.0220 $\pm$ 0.0007

All oscillation plots from here will be shown with the reactor constraint applied, T2K + Reactor.

δ_{CP} Phase



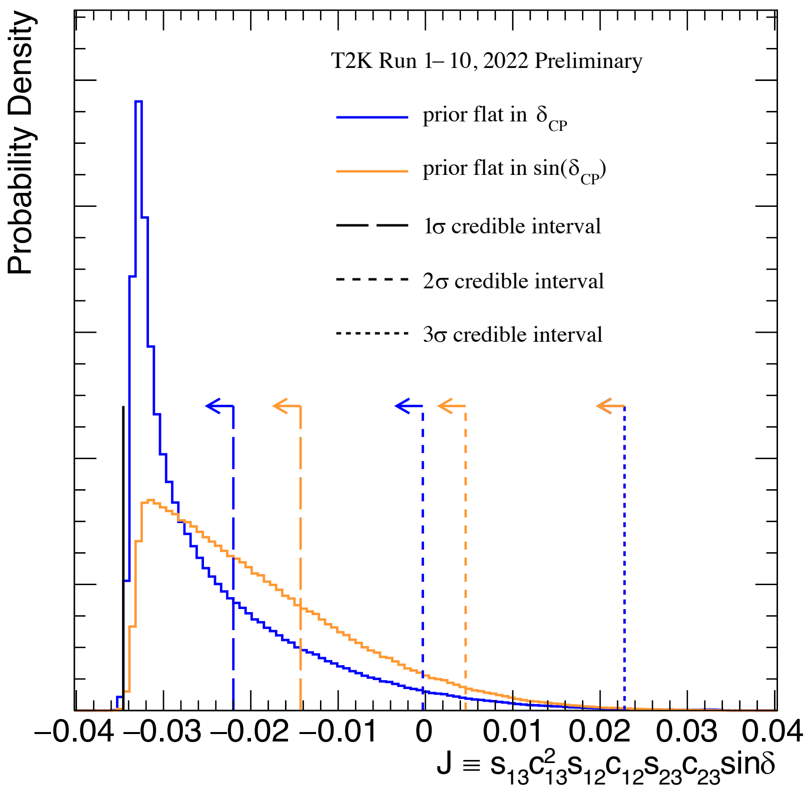


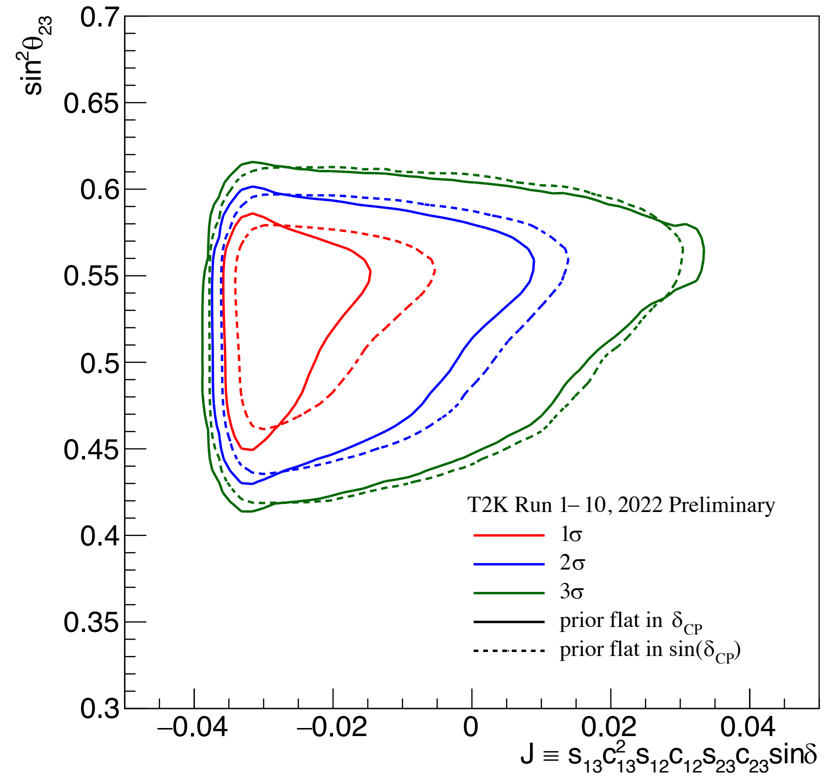
Both the Frequentist fit and Bayesian fit have a point of best fit around maximal CP violation, $-\pi/2$.

Evidenced by the posterior probability, large 3σ exclusion zones. CP conserving values of δ_{CP} are nearly excluded at the 2σ credible intervals.

Jarlskog Invariant

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$$



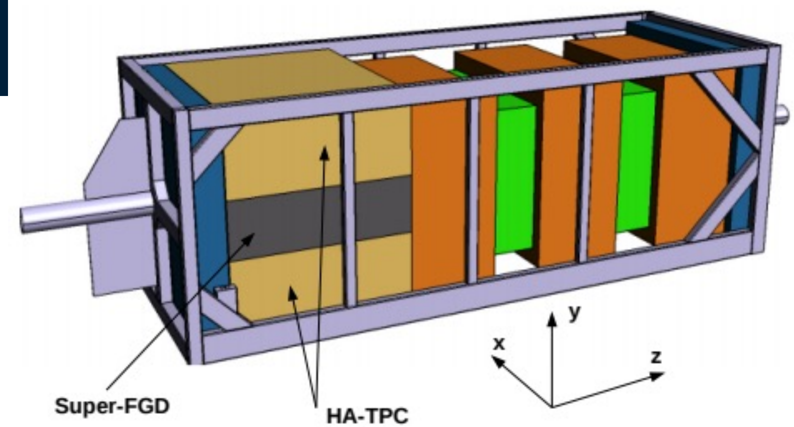


Also has measurements of Jarlskog Invariant, and the choice of prior on this.

Values of δ_{CP} conserving, $J_{CP} = 0$, included in both 2σ regions and intervals.

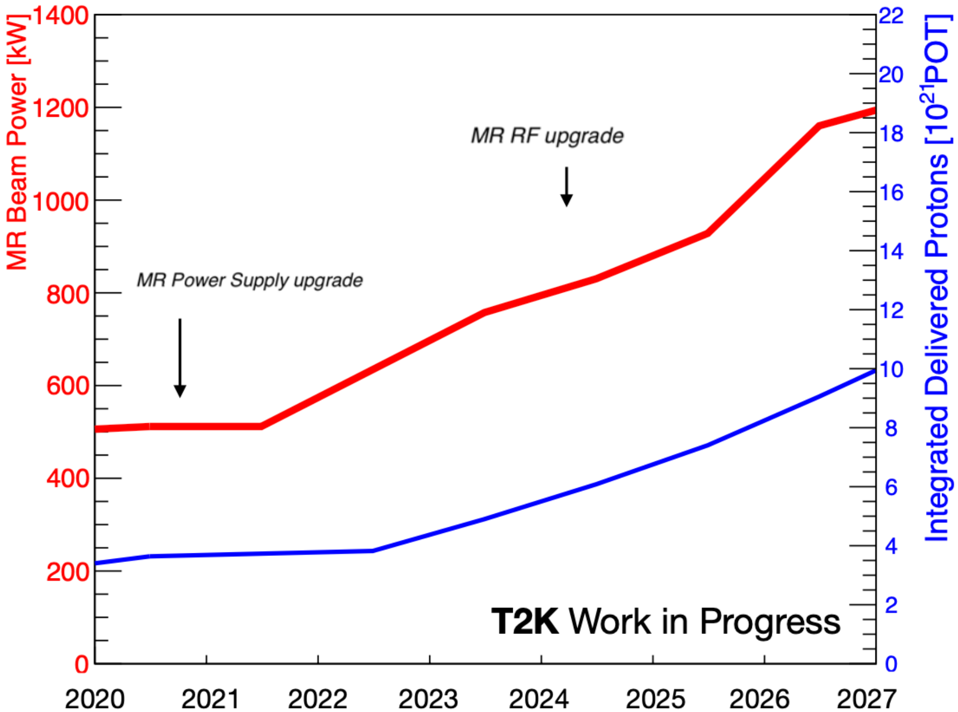
Future Plans: Upgrades

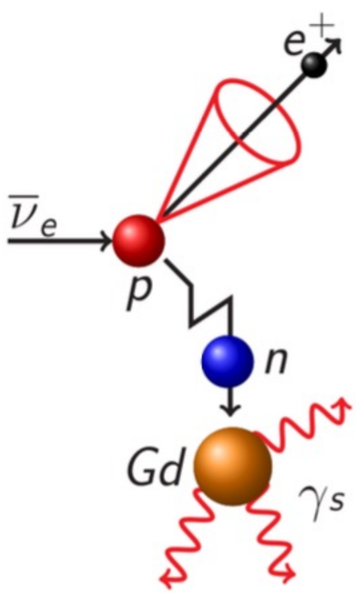
Upgrade in ND280, replacement of P0D with sFDG's and high angle TPC's!



This goes hand in hand with beam upgrade with the projection of beam power to surpass 1 MW. Also, an increase in horn current 250 kA -> 320kA.

T2K Projected POT (Protons-On-Target)





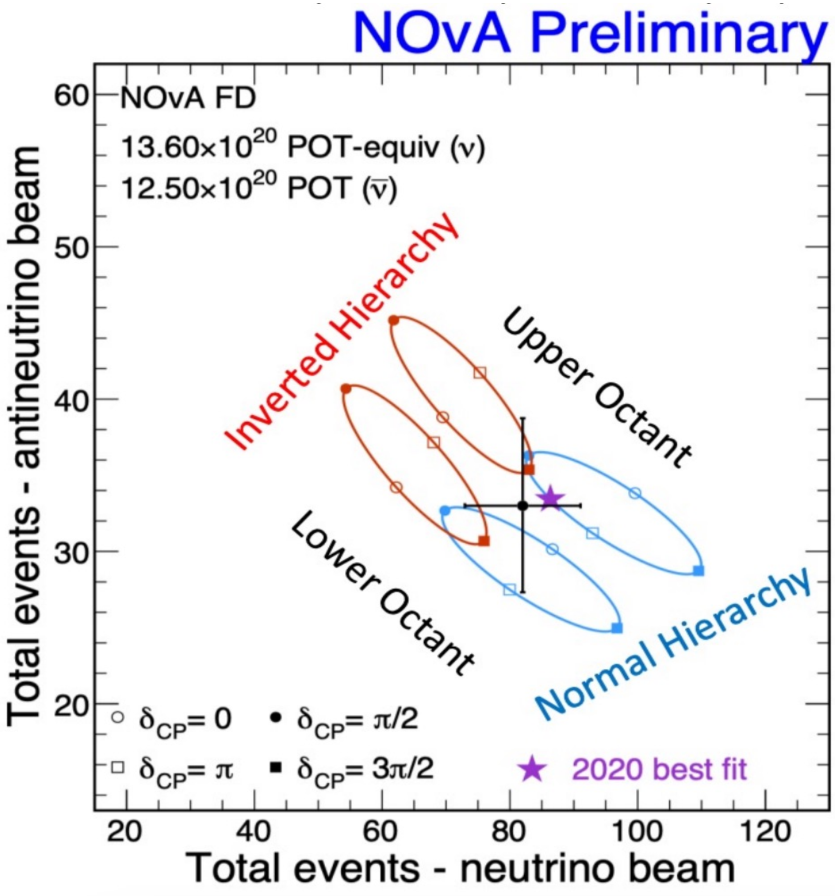
Gadolinium doping in Super-K, this will lead to improvement in neutrino/antineutrino discrimination.

Future Plans: T2K-NOvA Joint Fit

Better sensitivity when using both experiments, underway as we speak.

Different neutrino energies and baseline length and detector physics, will hopefully lead to a reduction in degeneracies. Both experiments are still statistics limited.

Results will be about soon, so stay tuned!



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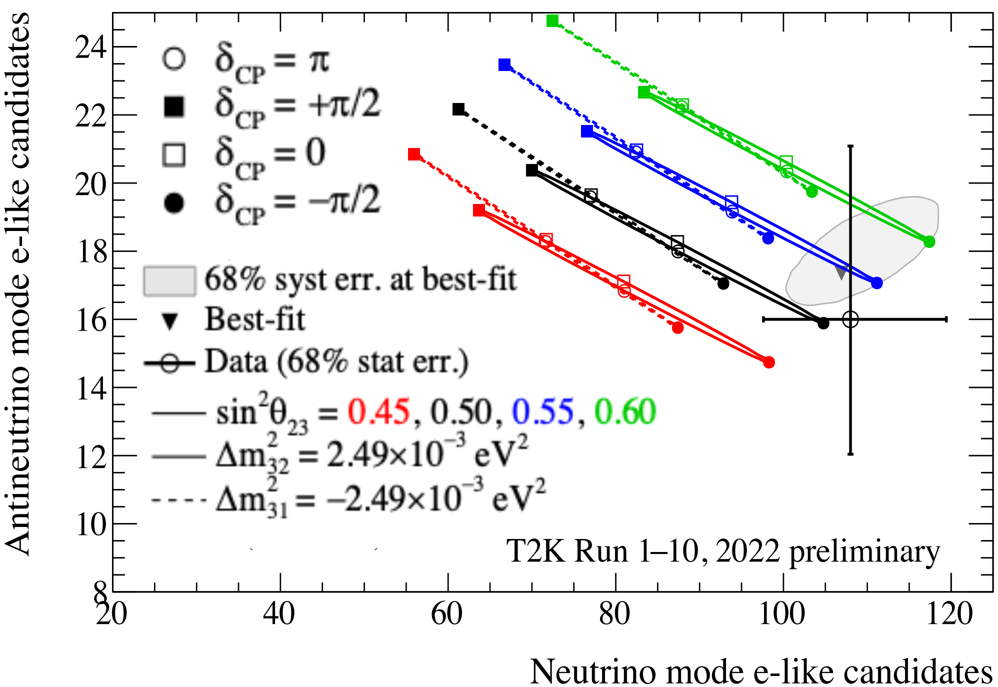

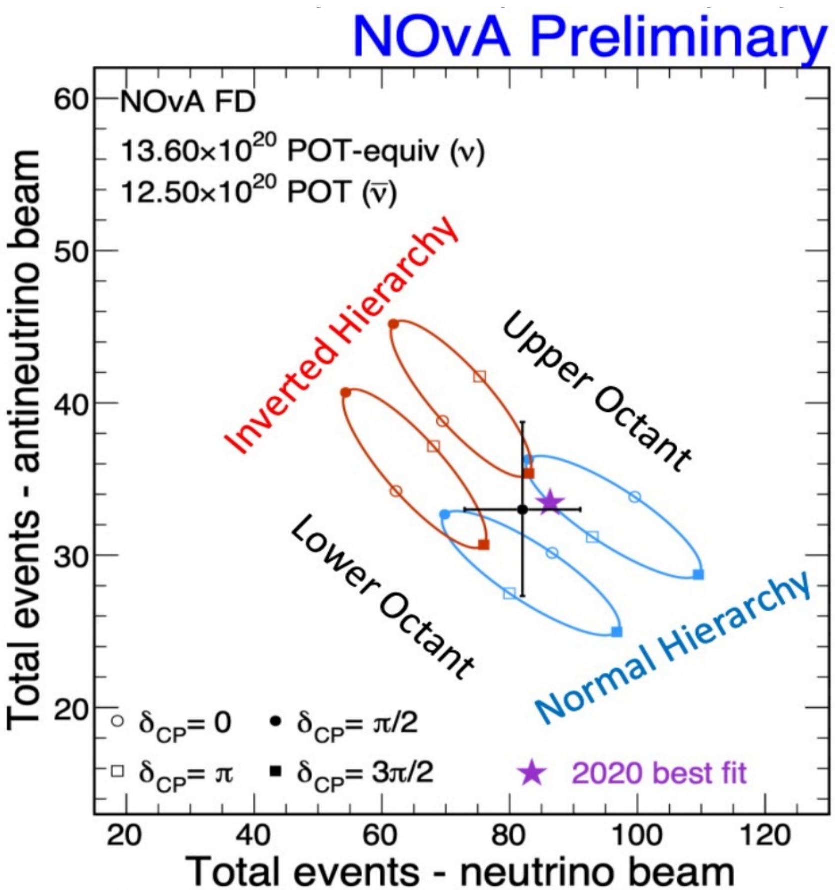

Summary

- T2K δ_{CP} best-fit point is near maximal CP violating value of $-\pi/2$.

- There is small preference for Normal Ordering and Upper Octant. A disfavour for CP conserving values, π and 0, excluding them at 90% intervals.

- T2K has many upgrades to look forward to as it enters the precision era of the experiments lifespan.

- Two high profile joint fits to keep an eye out for T2K-SK and T2K-NOvA!

Taken from a hybrid collaboration meeting, May 2022.

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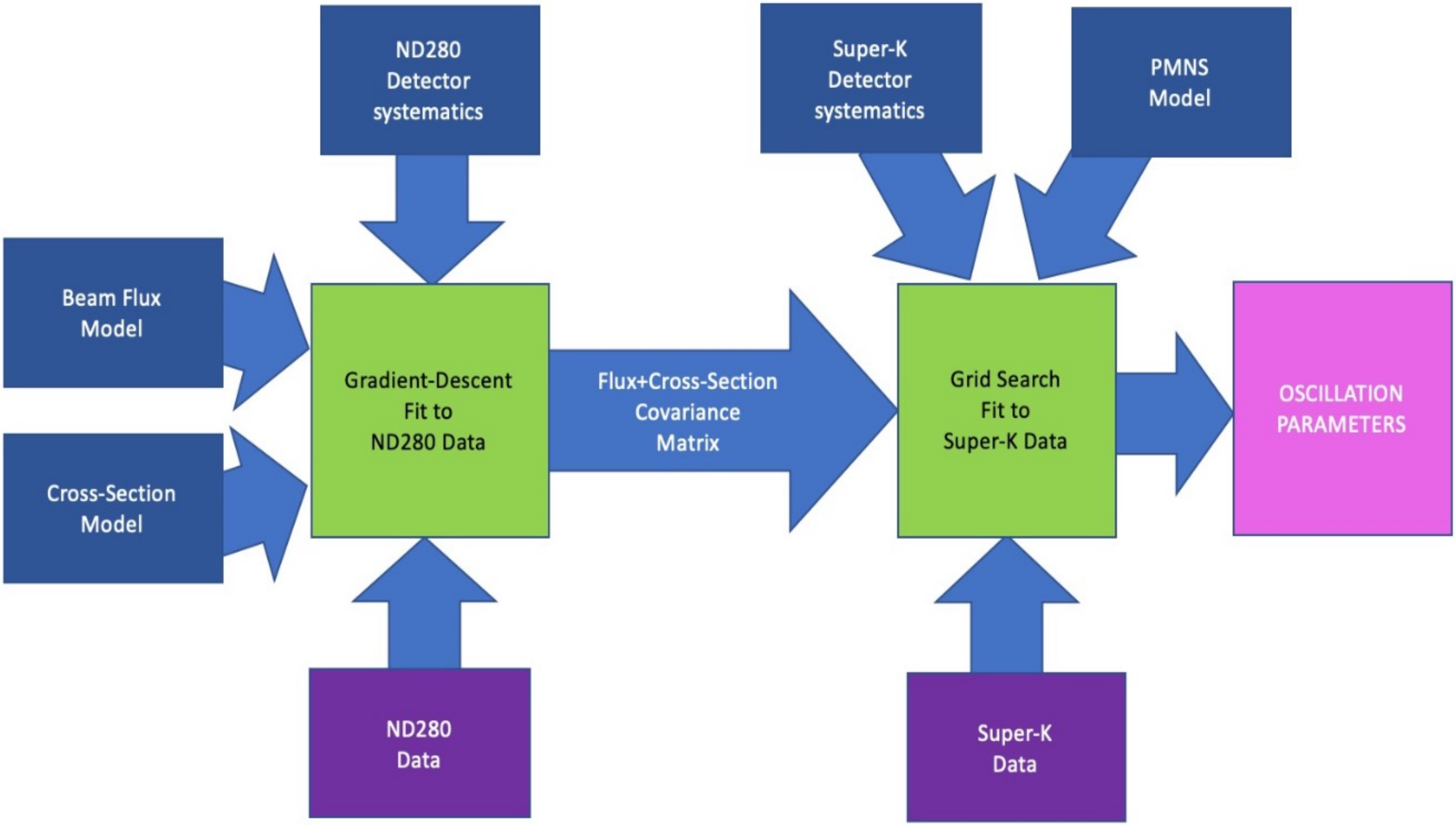
Taken in J-PARC last week!

BACKUP SLIDES

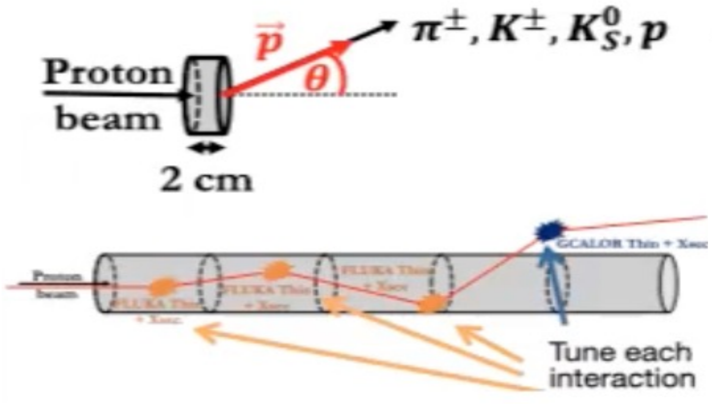
Oscillation Analysis



Flux model

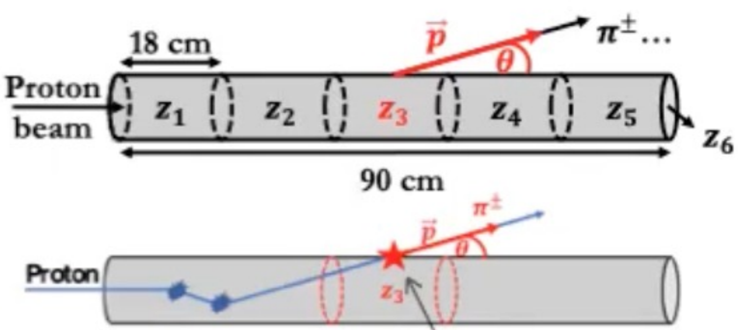
Thin target data

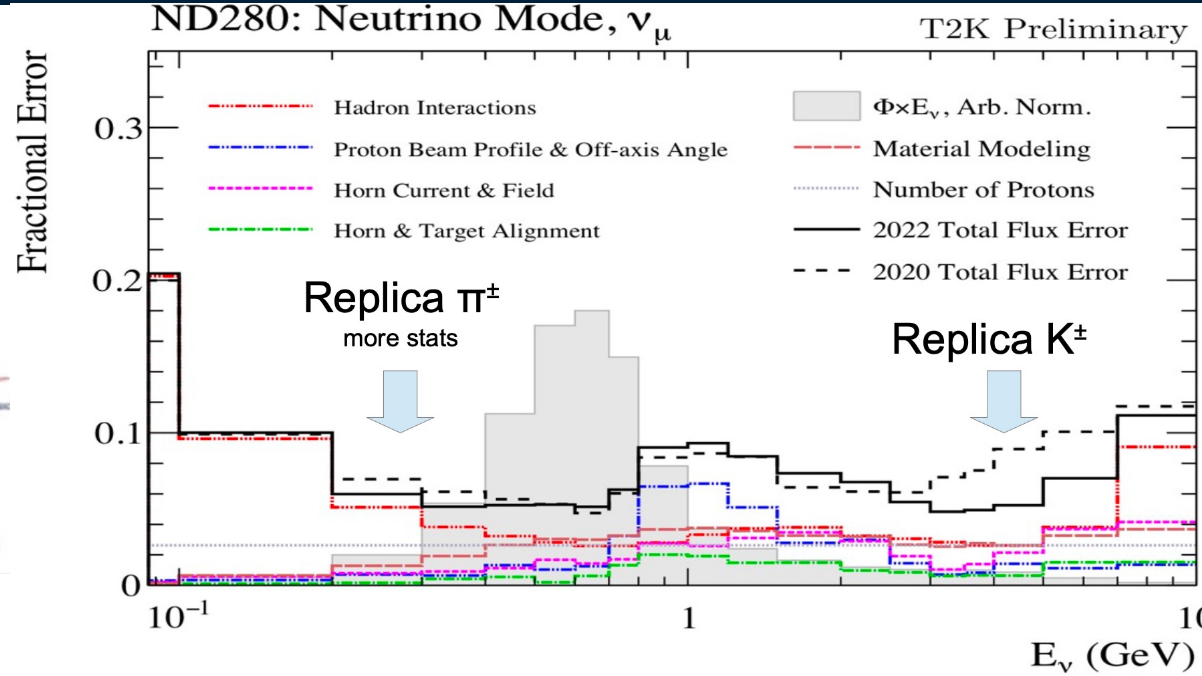
Mainly Eur. Phys. J. C (2016) 76:84



Replica target data

Eur. Phys. J. C (2016) 76:617





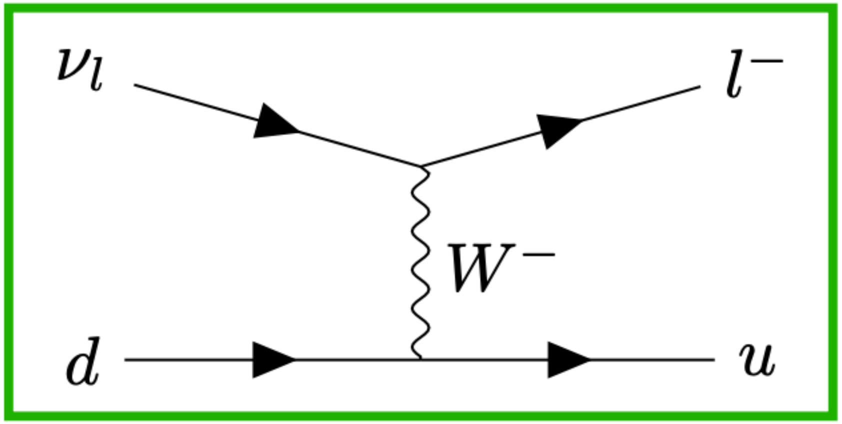
Taking external data from NA61/SHINE and other hardon production results.

Reduced uncertainty on flux model by ~5% due to switching from a thin target to a T2K replica target.

SK Reconstruction

Assuming quasi-elastic interaction with a single bound nucleon.

Known beam direction allows one to calculate reconstructed neutrino energy.



$$E_0^{\mathrm{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

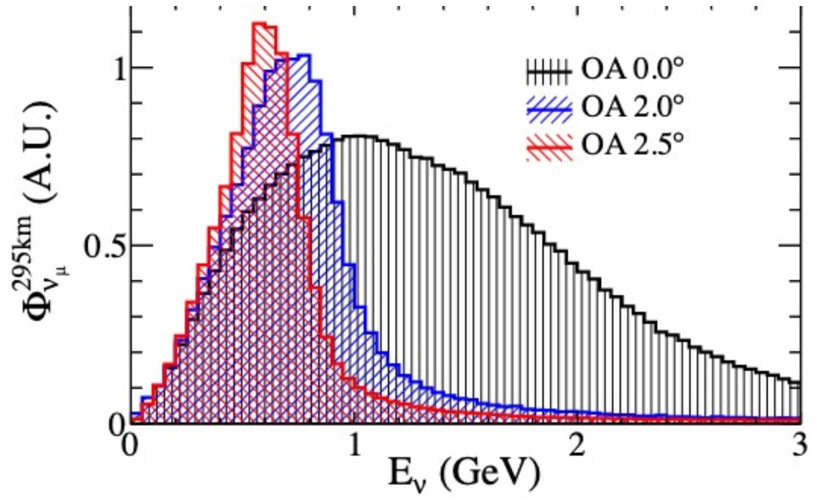
Only uses particle mass (m_p, m_n & m_e), lepton kinematics (p_l & $\cos(\theta_l)$) and binding energy (E_b).

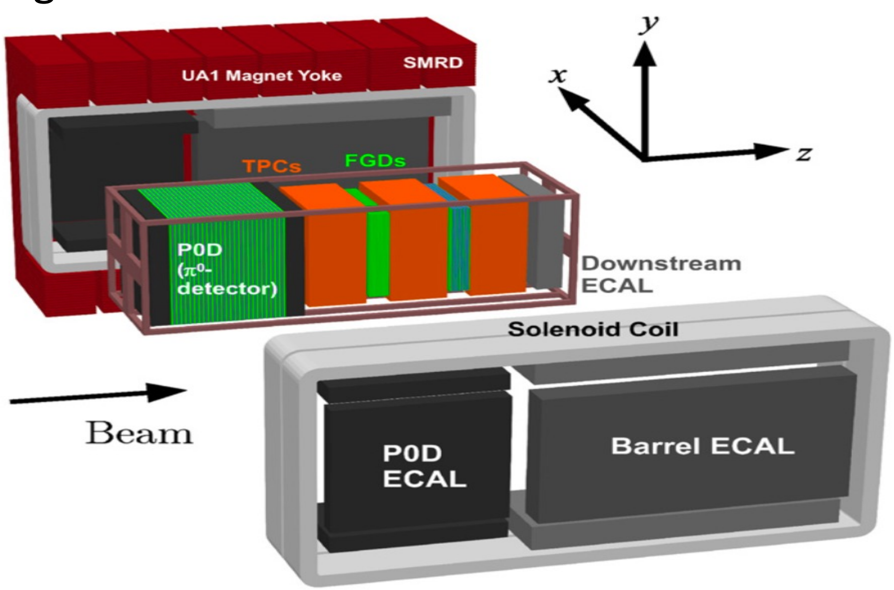
ND280

2.5^o off axis from beamline. Located 280m downstream of target.

Enveloped in 0.2 T magnetic field for charged particle sensitivity and momentum measurements.

Time Project Chambers (TPC's) allow for good particle tracking.

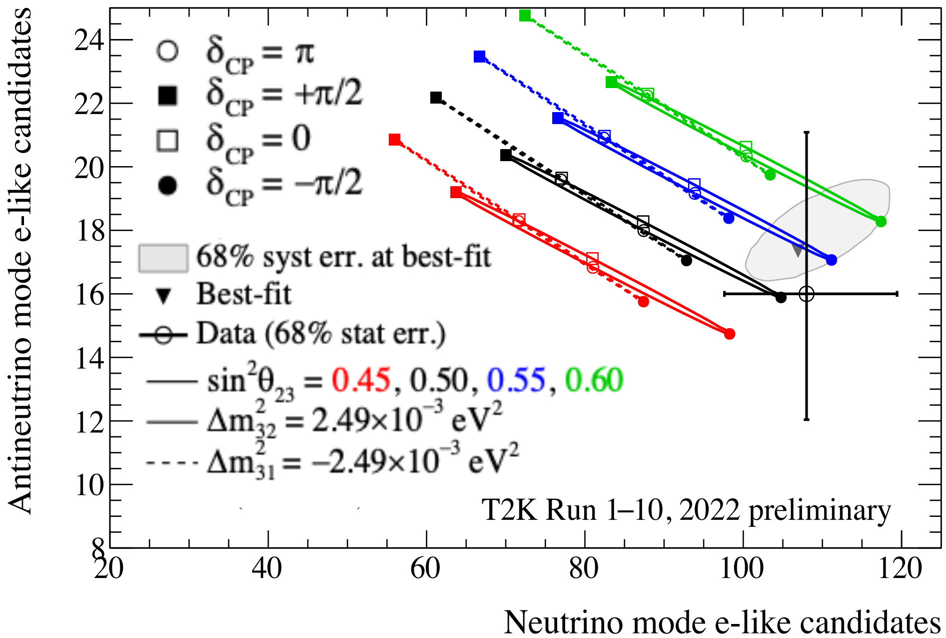




Fine Grained Detectors (FDG's) provide target mass, a C target and C+O.

P0D, a π^0 decay measurement detector.

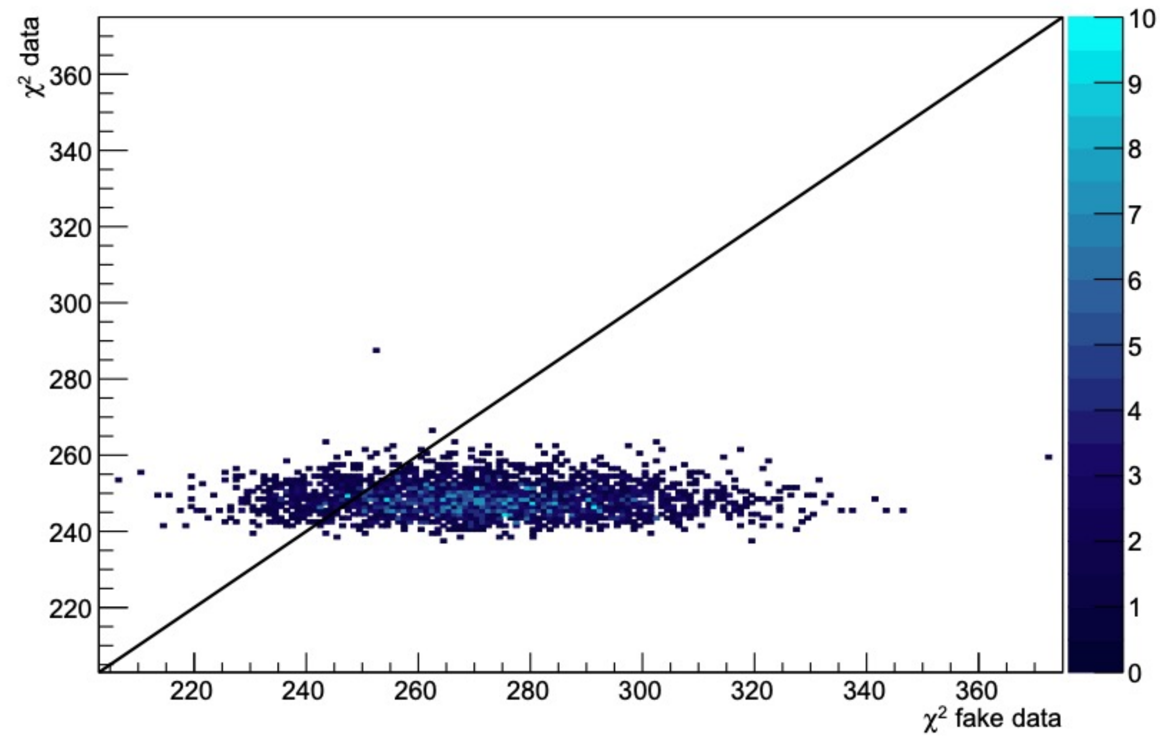
Bi-Rate Plot



Bi-rate figures shows the effect of changing some oscillation parameters.

T2K has a preference for maximal CP Violation at $-\frac{\pi}{2}$. It also highlights the large degeneracy for the mass ordering.

P-Value



T2K's Posterior predictive P-Value, our goodness of fit metric for the analysis.

Current P-value resides at 88%.