BERKELEY LAB

The T2K Oscillation Analysis and Future Prospects

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APS Division of Particles & Fields Meeting

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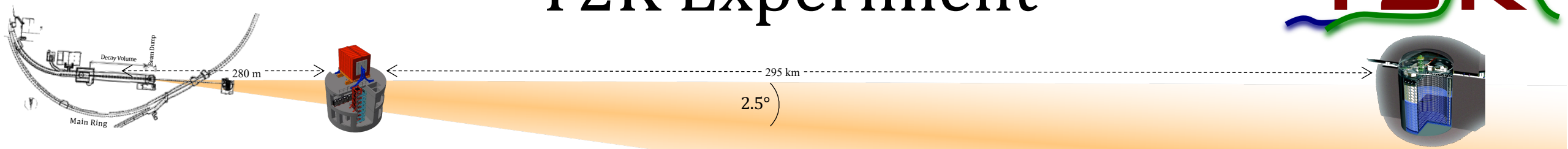
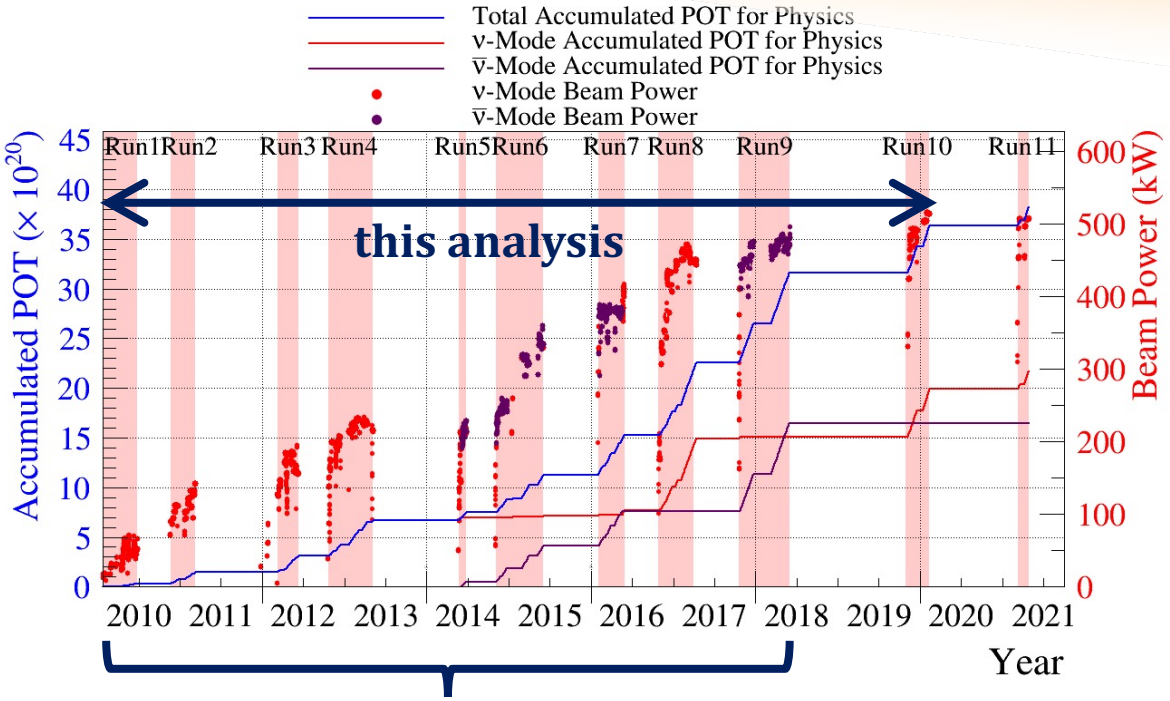
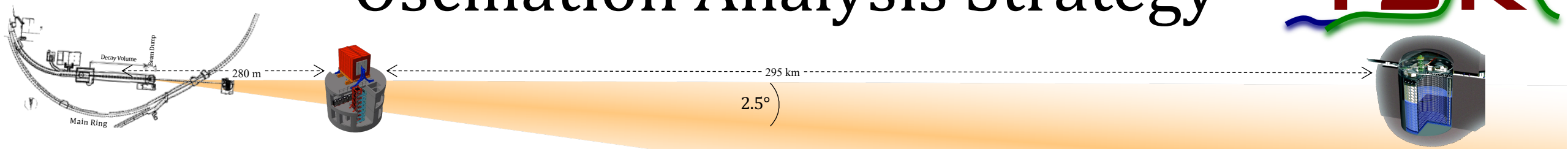
T2K Experiment



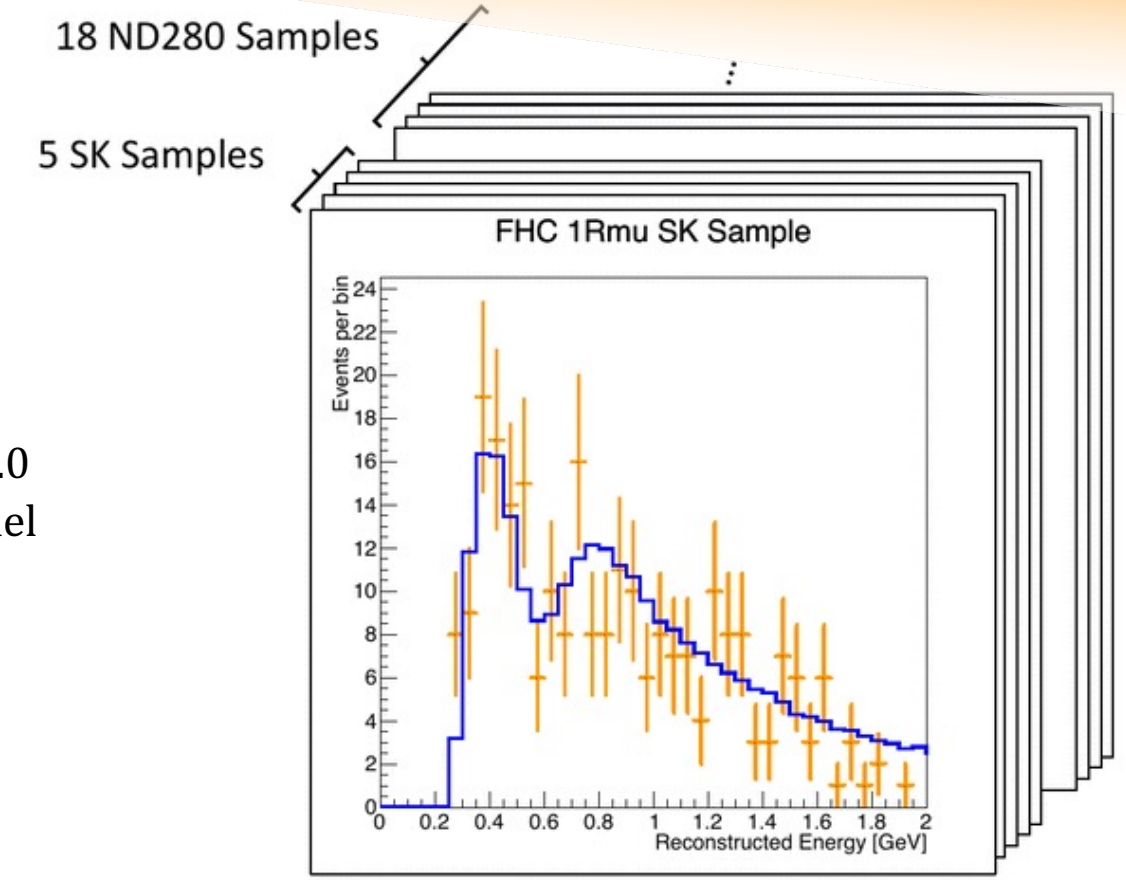
1) Intense neutrino beam produced at the J-PARC facility and sent across Japan from Tokai to Kamioka
2) A near detector complex to monitor the neutrino beam, sample the unoscillated flux, and study neutrino-nucleus interactions
3) A 50-kt water Cherenkov far detector under 2.7 km water equivalent overburden



Oscillation Analysis Strategy



- Model event distributions at the near and far detectors:
  - Flux
    - NEW: NA61/SHINE hadroproduction measurements on replica T2K target reduces flux uncertainty at far detector from 8% → 5%
      Eur.Phys.J.C 76 (2016) 11, 617
  - ν-nucleus interactions
    - Many improvements to the interaction model in NEUT 5.4.0
    - Tuned spectral function for CCQE nuclear initial state model
    - Effect of nuclear removal energy now modeled in detail
    - …
  - Detector
  - Oscillation (PMNS)

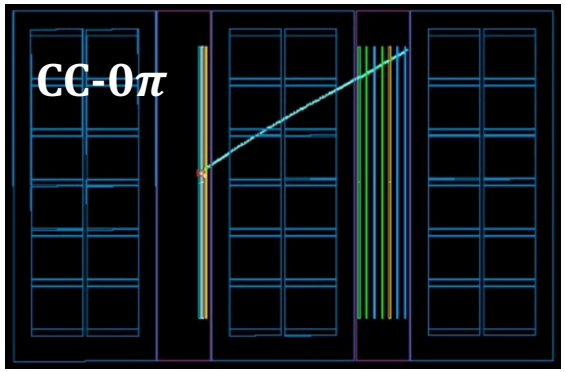


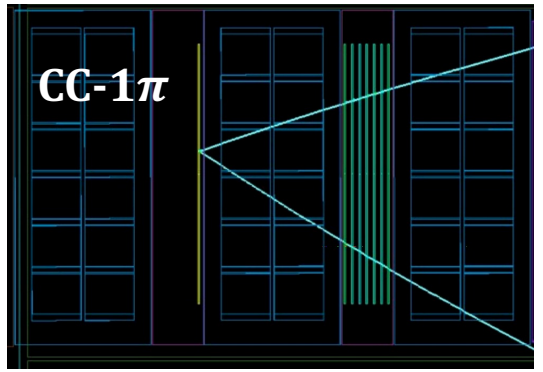
Oscillation Analysis Strategy

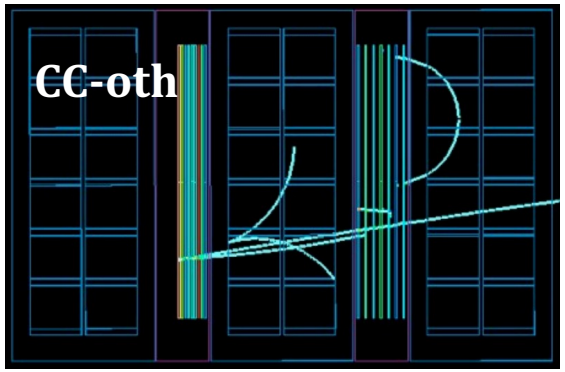
- Sample unoscillated flux with a near detector complex to constrain flux and interaction systematic parameters of the model

ND280 samples

	ν_μ events in ν-mode	$\bar{\nu}_\mu$ events in $\bar{\nu}$-mode	$\bar{\nu}_\mu$ events in ν-mode
FGD1 (scintillator)	CC-0π	CC-0π	CC-0π
	CC-1π	CC-1π	CC-1π
	CC-oth	CC-oth	CC-oth
FGD 2 (scintillator + H_20)	CC-0π	CC-0π	CC-0π
	CC-1π	CC-1π	CC-1π
	CC-oth	CC-oth	CC-oth







Oscillation Analysis Strategy

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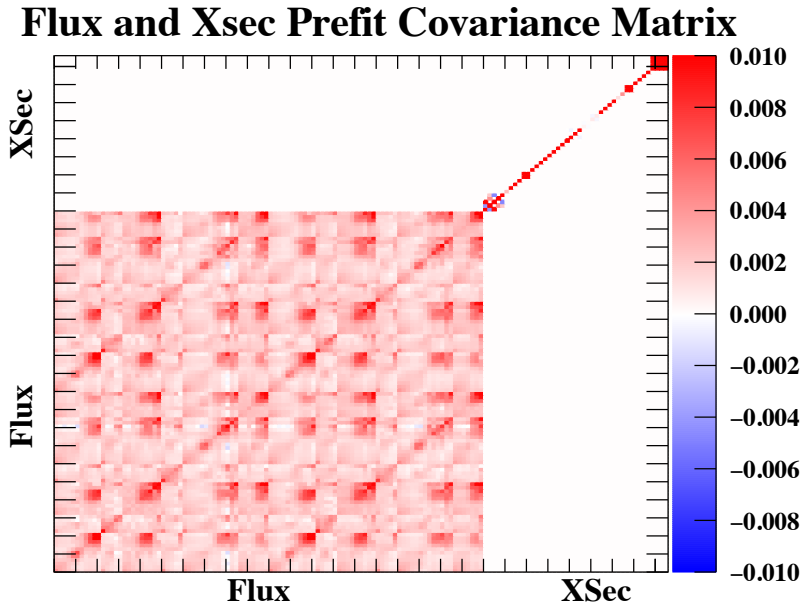
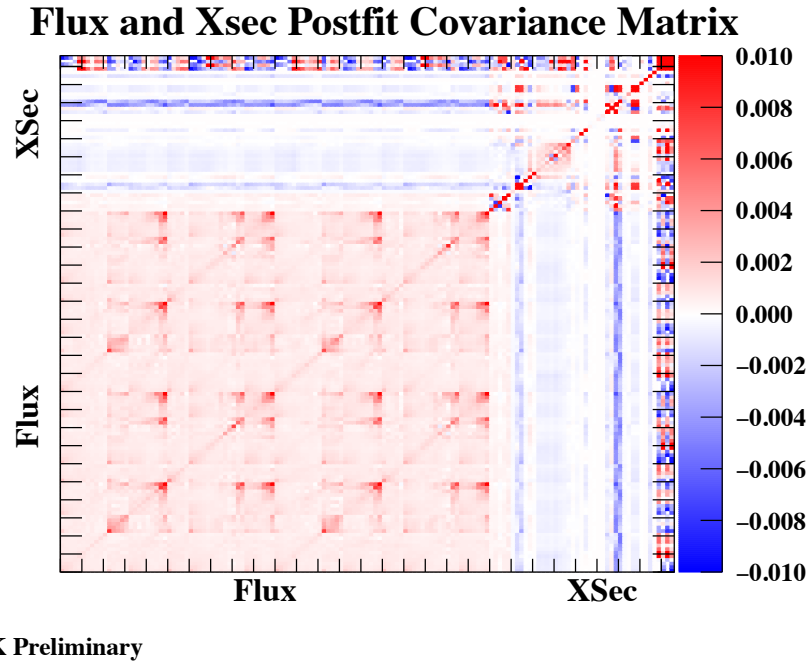
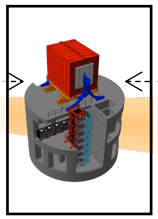


Near Detector Fit



Oscillation Analysis Strategy

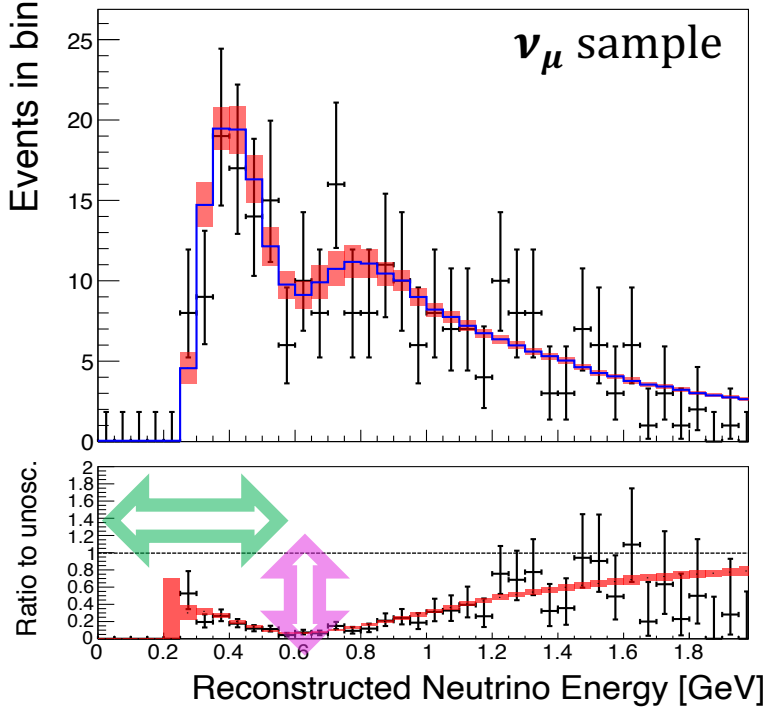


- Sample unoscillated flux with a near detector complex to constrain flux and interaction systematic parameters of the model

Far Detector Sample	ν_μ	ν_e	ν_e + 1 d. e.	$\bar{\nu}_\mu$	$\bar{\nu}_e$
Systematic uncertainty on event rate ***before*** ND fit	11.1%	13.0%	18.7%	11.3%	12.1%
Systematic uncertainty on event rate ***after*** ND fit	3.0%	4.7%	14.3%	4.0%	5.9%

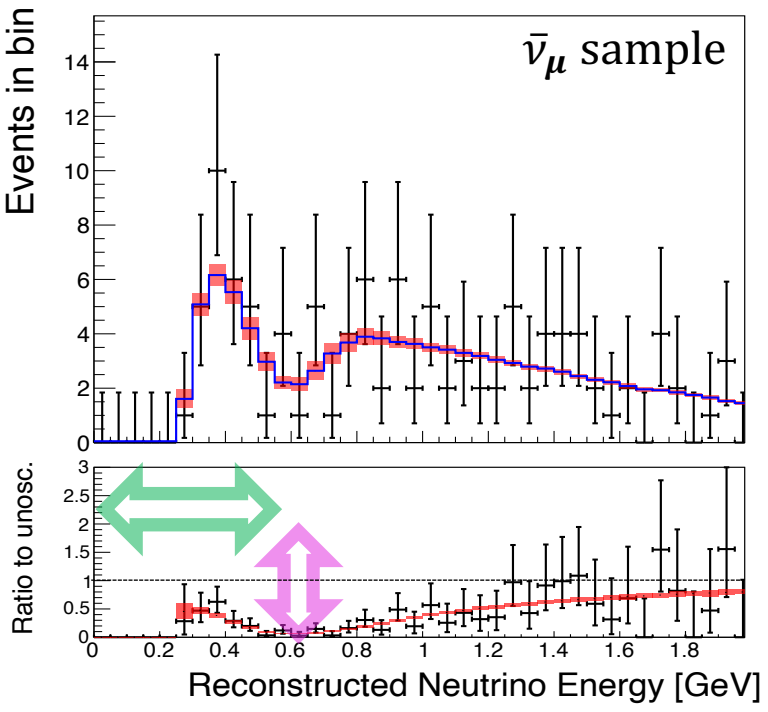
Oscillation Analysis Strategy

- With improved model constraints, certain details of the far detector samples can be more confidently associated with oscillation effects



$\nu_\mu/\bar{\nu}_\mu$ disappearance:

- **$\sin^2(2\theta_{23})$ ↔ depth of the dip**
- **Δm^2_{32} ↔ energy at which dip occurs**



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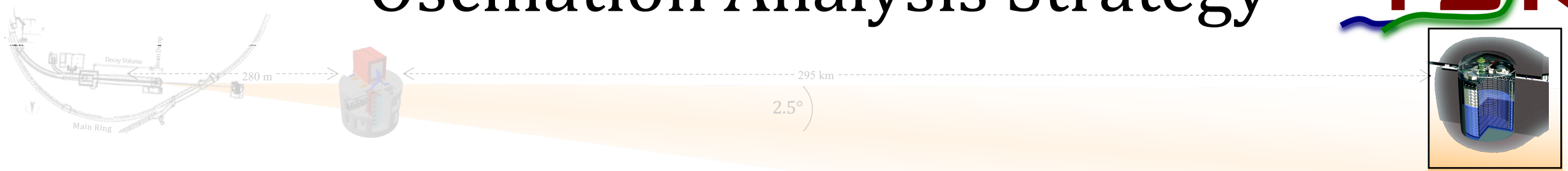

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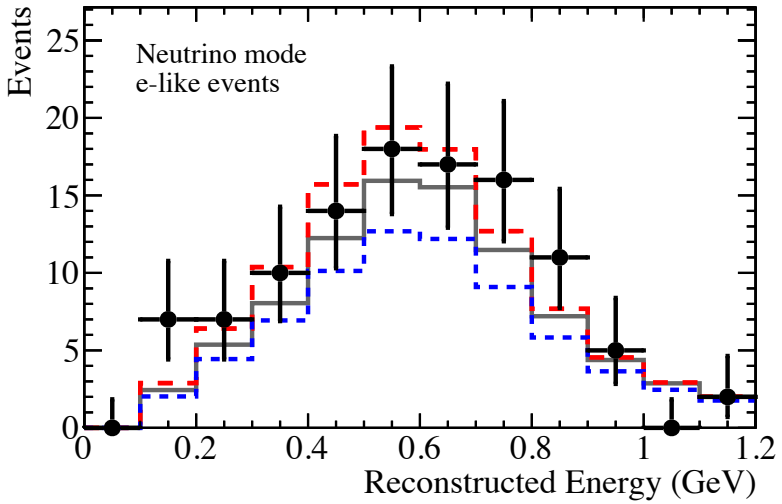
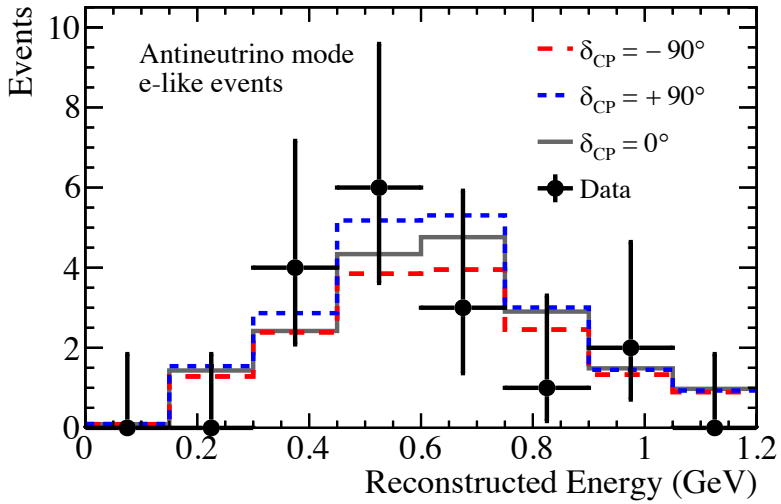
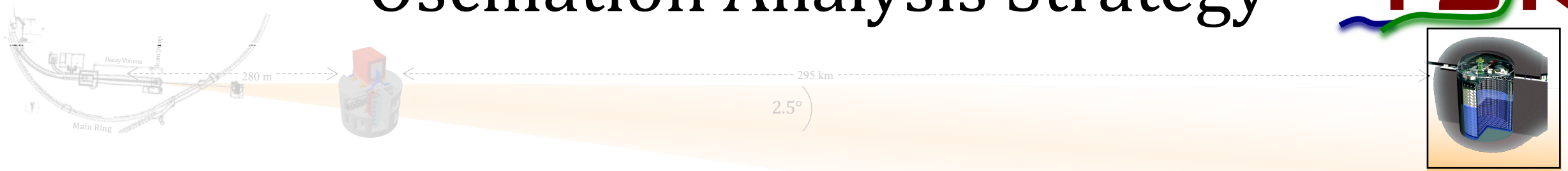




$\nu_e/\bar{\nu}_e$ appearance:

- **Provides sensitivity to CPV (δ_{CP}), θ_{23}-octant, mass hierarchy**

Oscillation Analysis Strategy



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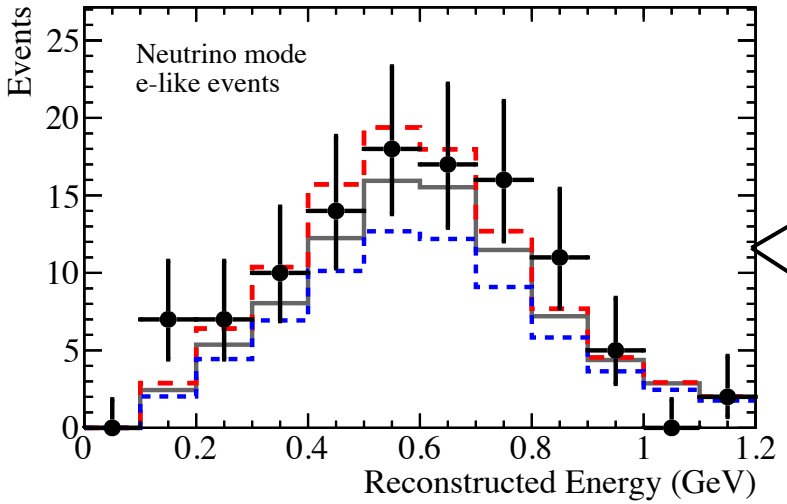
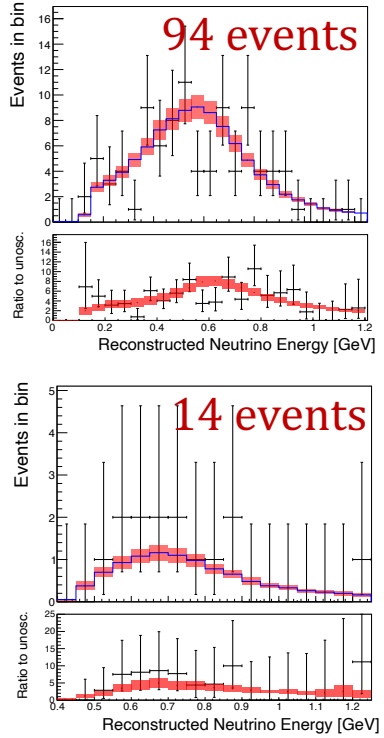




- Neutrino mode ν_e appearance sample further split based on the presence of a decay electron from pion decay
- Energy reconstruction accounts for pion production
- No corresponding antineutrino mode splitting due to absorption

Fitting Frameworks

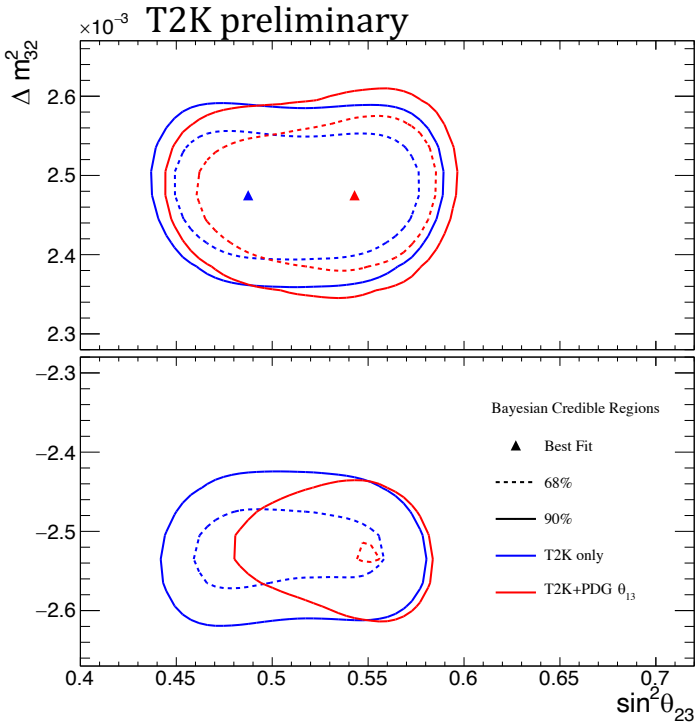
- 3 fitters in T2K that make different analysis choices
  - Frequentist vs. Bayesian
  - Sample binning*
  - Likelihood optimization/evaluation
  - Incorporation of ND information
- Following slides will present MaCh3's Bayesian results

MaCh3	P-Theta	VALOR
Bayesian	Frequentist (Bayesian capable)	Frequentist
ν_μ-like: E_{rec} ν_e-like: $E_{rec} - \theta$	ν_μ-like: $E_{rec} - \theta$ ν_e-like: $p - \theta$	ν_μ-like: E_{rec} ν_e-like: $E_{rec} - \theta$
Markov Chain Monte Carlo	Gradient descent algorithm/grid search	Gradient descent algorithm/grid search
Simultaneous fit of ND and FD	Covariance matrix	Covariance matrix

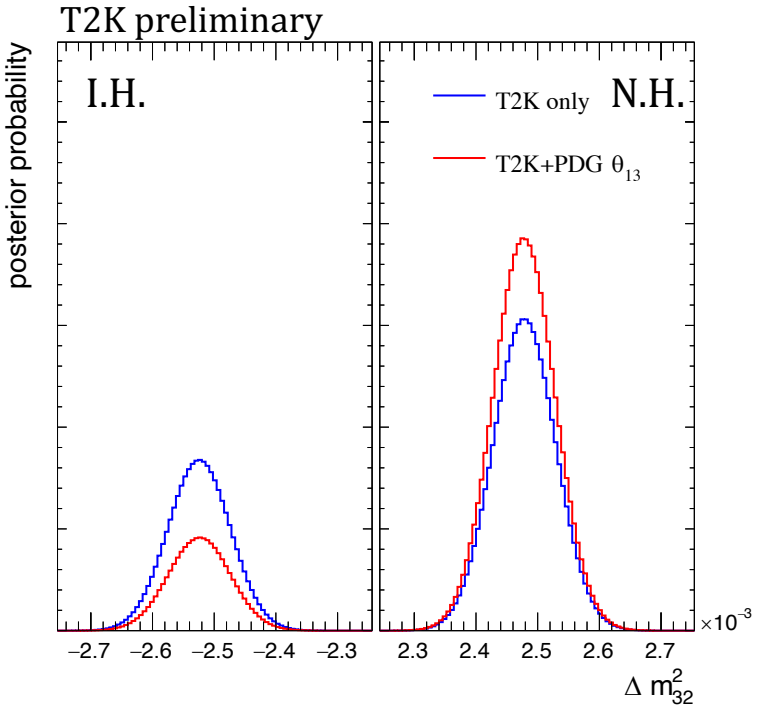
* θ: angle of charged lepton wrt neutrino
p: momentum of charged lepton
E_{rec}: reconstructed neutrino energy

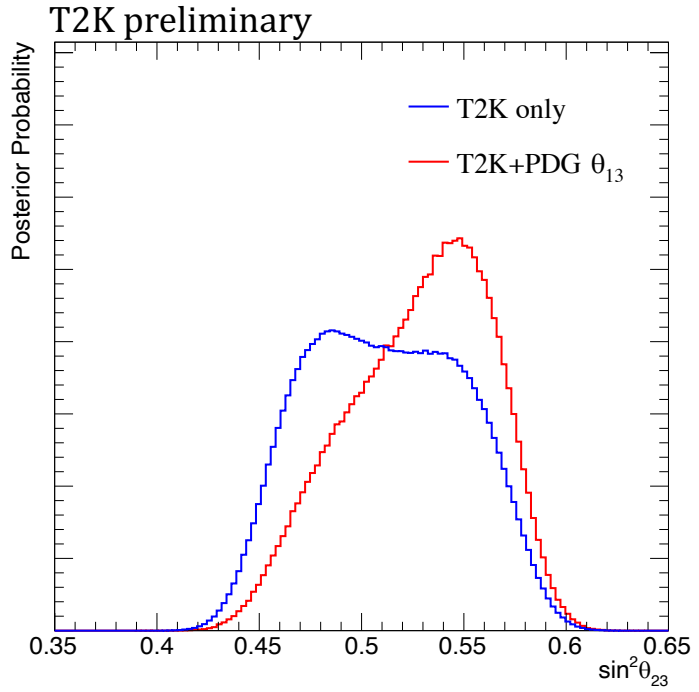
Run 1-10 Results

- Showing results from
  - **T2K data only fit** – flat priors on 4 oscillation parameters of interest
  - **T2K + reactor constraint** – puts a Gaussian prior on $\sin^2\theta_{13}$ based on PDG world average



T2K Runs 1-10





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Fraction of posterior probability corresponding to different discrete hypotheses of mass hierarchy and θ_{23}-octant, from priors with(out) PDG constraint on $\sin^2\theta_{13}$.

T2K Runs 1-10

T2K preliminary

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH	0.195 (0.260)	0.613 (0.387)	0.808 (0.647)
IH	0.035 (0.152)	0.157 (0.201)	0.192 (0.353)
Sum	0.230 (0.412)	0.770 (0.588)	1.000

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Bayes' Factor for normal hierarchy:

$$\frac{0.808}{0.192} = 4.21$$

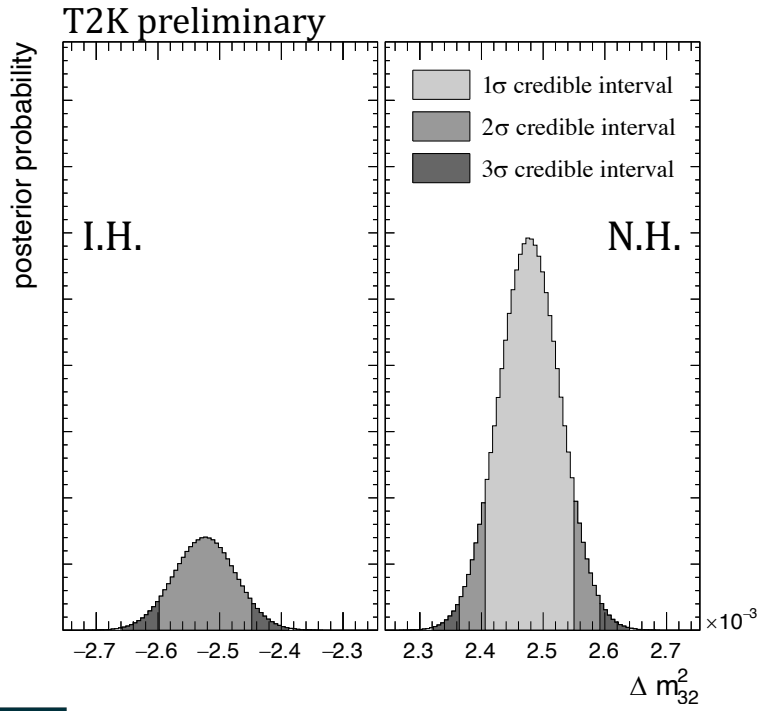
Bayes' Factor for upper θ_{23}-octant:

$$\frac{0.770}{0.230} = 3.35$$

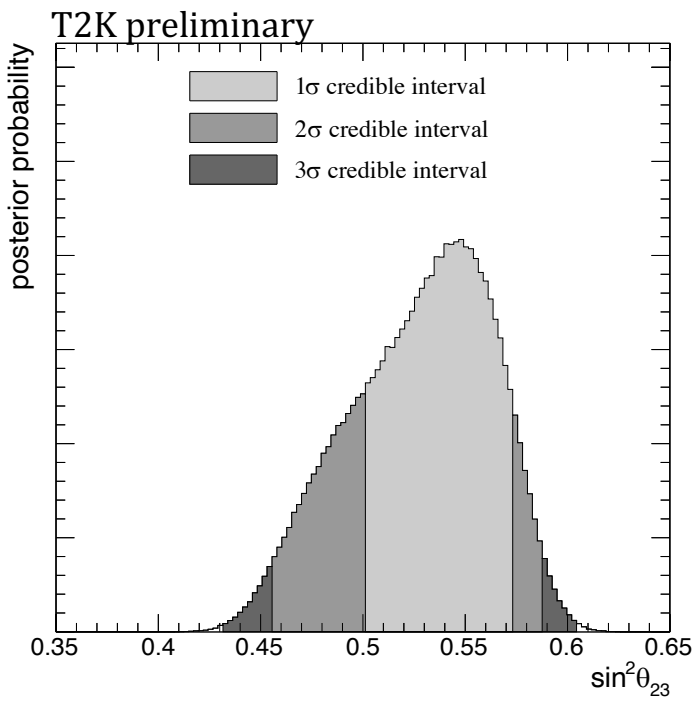
Run 1-10 Results

- 1D marginalized posterior distributions (with reactor constraint) for oscillation parameters of interest with credible intervals indicated.

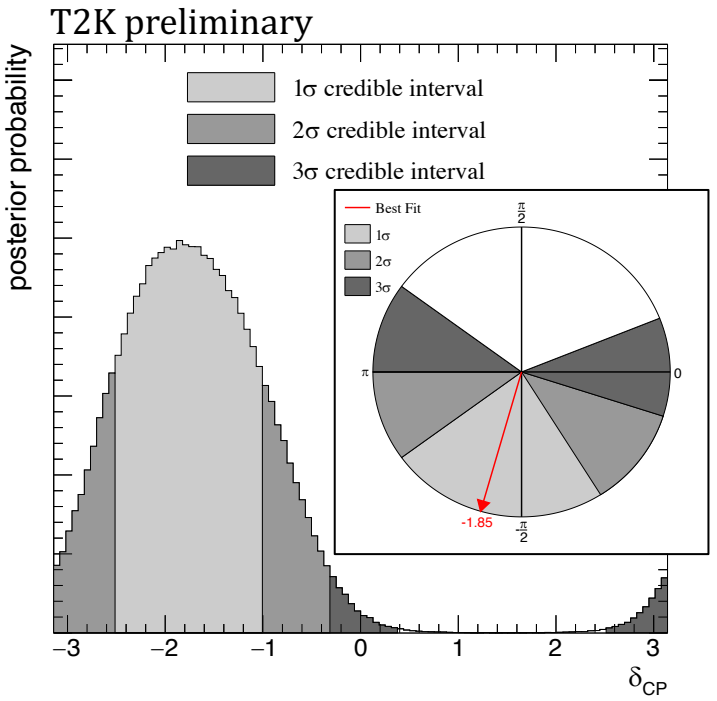
- Entire 1σ region in normal hierarchy ($\Delta m^2_{32} > 0$):



- Entire 1σ region in upper θ_{23}-octant ($\sin^2\theta_{23} > 0.5$):

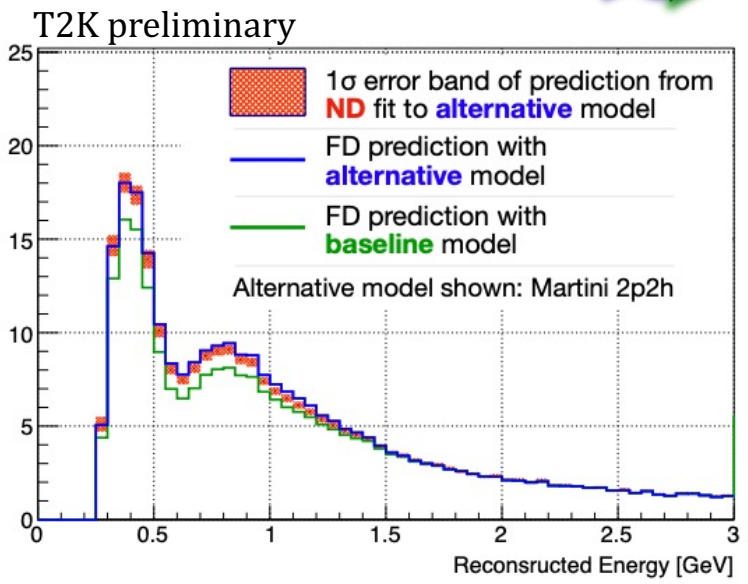


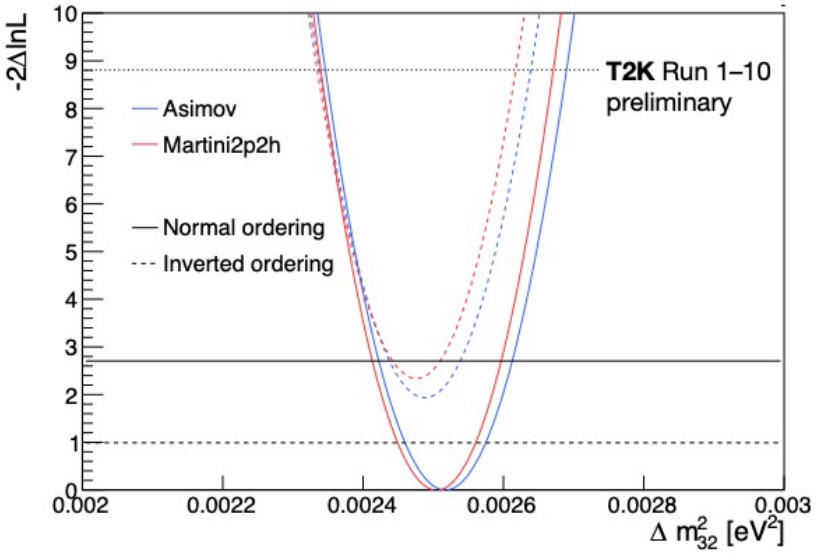
- CP conserving values ruled out at 90%.
- 35% of values around $\delta_{CP} \sim \pi/2$ ruled out at 3σ.



Robustness Studies

- The robustness of the reported results against mismodeling of ν-nucleus interactions are studied with fits to simulated data sets
  - Fits to simulated data from alternative interaction models (theory- or data-driven) are compared to those from the tuned-T2K model prediction
  - No significant biases observed for θ_{23}, θ_{13}
  - No significant bias observed for δ_{CP}
    - Largest change in $\Delta\chi^2$ would move left (right) edge of 90% interval by 0.073 (0.080) radians
  - Small bias in Δm^2_{32} → apply Gaussian smearing with $\sigma = 1.4\times10^{-5}\,\mathrm{eV}^2$





Future Analysis Prospects

- Continuing to improve flux and cross section models
  - E.g. incorporating NA61/SHINE replica target constraints on $K^{\pm}$, proton production
- New selections/samples
  - ND280 – proton and photon tagging to better separate event topologies
    - ND280 upgrade will provide more event details
  - Super-Kamiokande – charged current ν_μ + single charged pion
- Joint analyses with other experiments can break degeneracies and enhance physics reach by exploiting differences (e.g. strength of matter effect)
  - NOνA
  - Super-Kamiokande (SK)

T2K + NOνA Joint Analysis

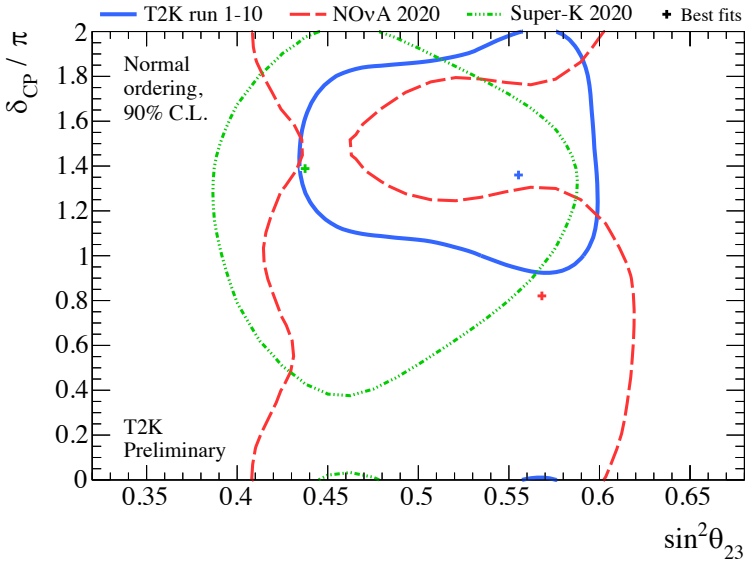
- T2K and NOνA have individual strengths that can complement one another
- A joint analysis between the two experiments is being pursued
  - A joint framework has been developed to allow full likelihood surface sharing between analyses
- Testing key assumptions
  - Does either individual experiment's extrapolation, systematic uncertainty need reassessing with the extra statistical sensitivity
  - Does choice of systematic correlations between experiment impact the results at current statistics?
- Snowmass LOI 2020:
  - The projected timescale for a first NOνA-T2K joint analysis is 2021-2022

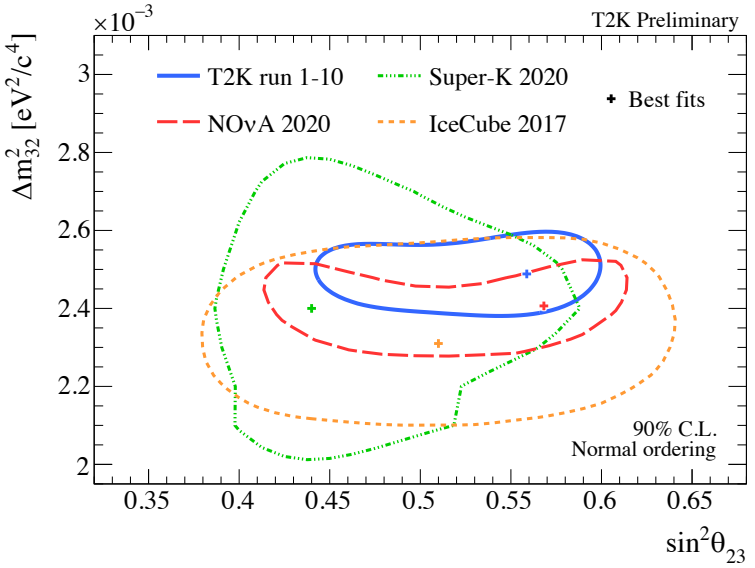
T2K+SK Joint Analysis

- Joint analysis of T2K beam data and SK atmospheric data being pursued
- Investigating importance of correlations between low energy atmospheric and beam samples in the treatment of relevant detector systematics
- Analysis will use a consistent interaction model where applicable
  - ND280 may constrain low energy atmospheric systematics
  - Constraints from high energy samples from SK alone

Summary

- Recent results from T2K data corresponding to 3.6×10^{21} protons on target
  - 54.6% ν-mode, 45.4% $\bar{\nu}$-mode
  - Slight preference for upper θ_{23}-octant and normal hierarchy
  - Exclude CP conserving values of δ_{CP} at 90% credible level and 35% of values $\sim \pi/2$ at the 3σ level
- Continuing to improve our own analysis and extending into joint analyses with SK and NOνA





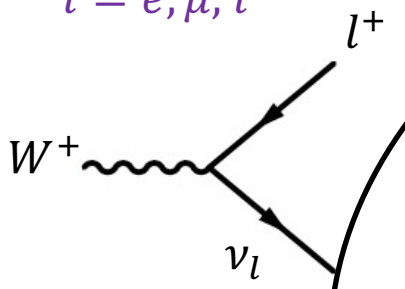
Backups

Neutrino Oscillations

produced in flavor eigenstates | *propagate in mass eigenstates* | *observed in flavor eigenstates*

flavor states

$l = e, \mu, \tau$



mass states

$i = 1, 2, 3$

$$|\alpha(0)\rangle = |\nu_l\rangle = \sum_i c_i |\nu_i\rangle$$

$$|\alpha(x)\rangle = \sum_i c_i |\nu_i\rangle e^{-ip_i \cdot x}$$

$$\Longrightarrow |\langle \nu_{l'} | \alpha(x) \rangle|^2 \neq \delta_{ll'}$$

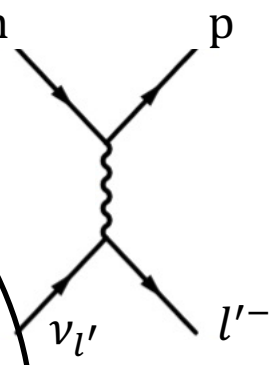
$s_{ij} \equiv \sin\theta_{ij}$

$c_{ij} \equiv \cos\theta_{ij}$

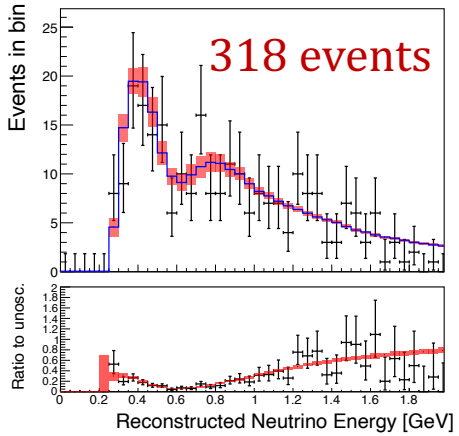
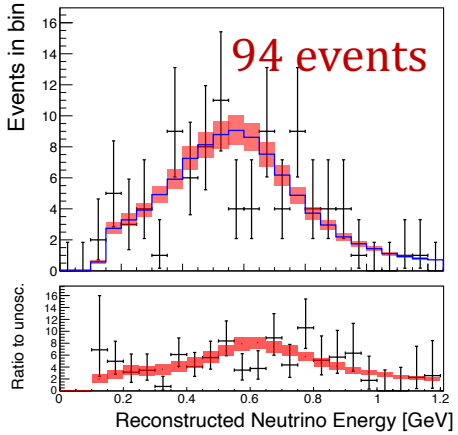
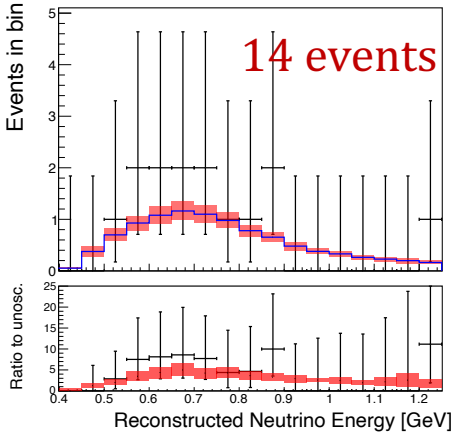
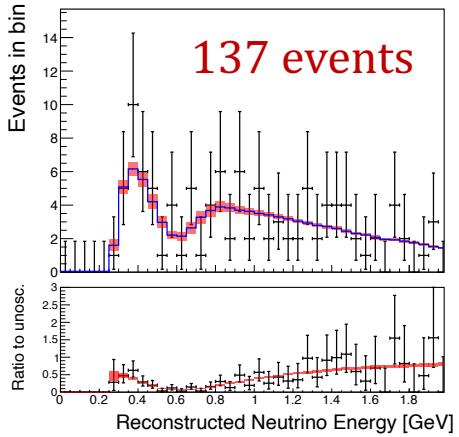
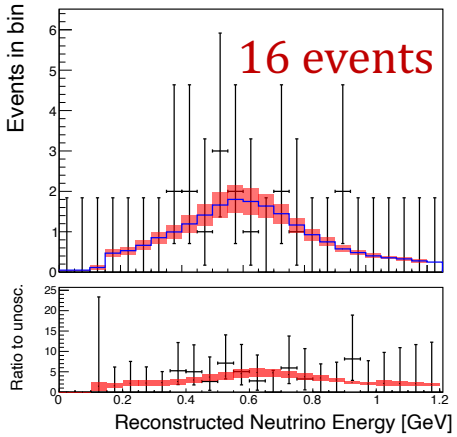
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

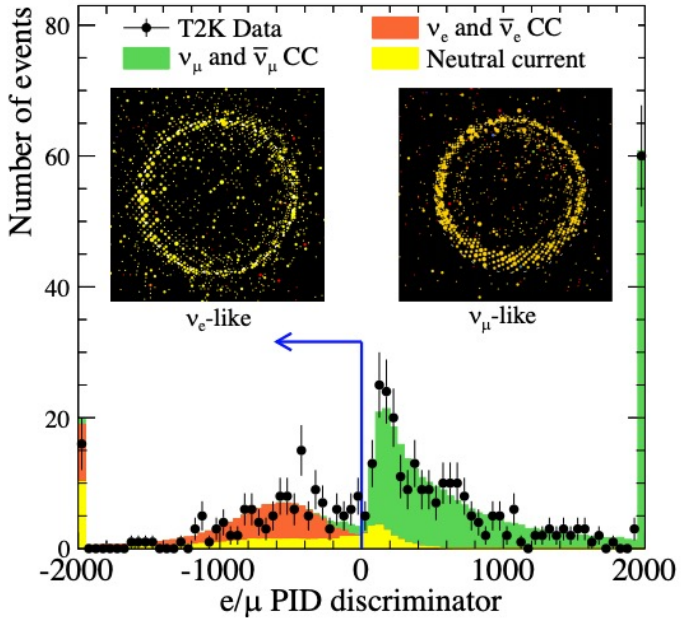
Majorana phases (no effect on oscillations)

U_{PMNS}



Far Detector Samples

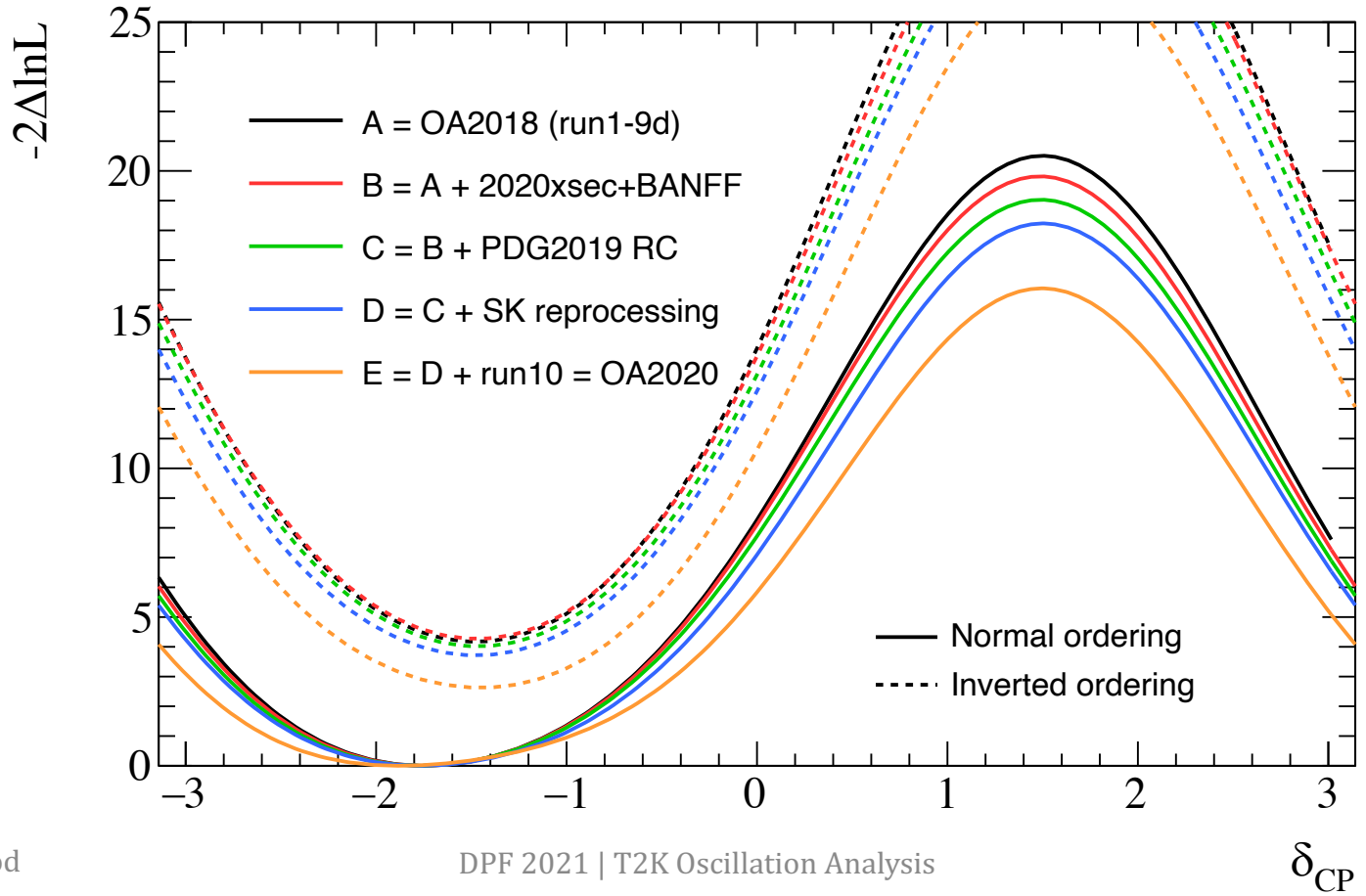
	CCQE μ-like	CCQE e-like	e-like + decay e
FHC (ν-mode)			
RHC ($\bar{\nu}$-mode)			π^- from $\bar{\nu}$ interaction typically absorbed before they decay



- fiTQun reconstruction algorithm separates muon-like rings from electron-like rings (and more)

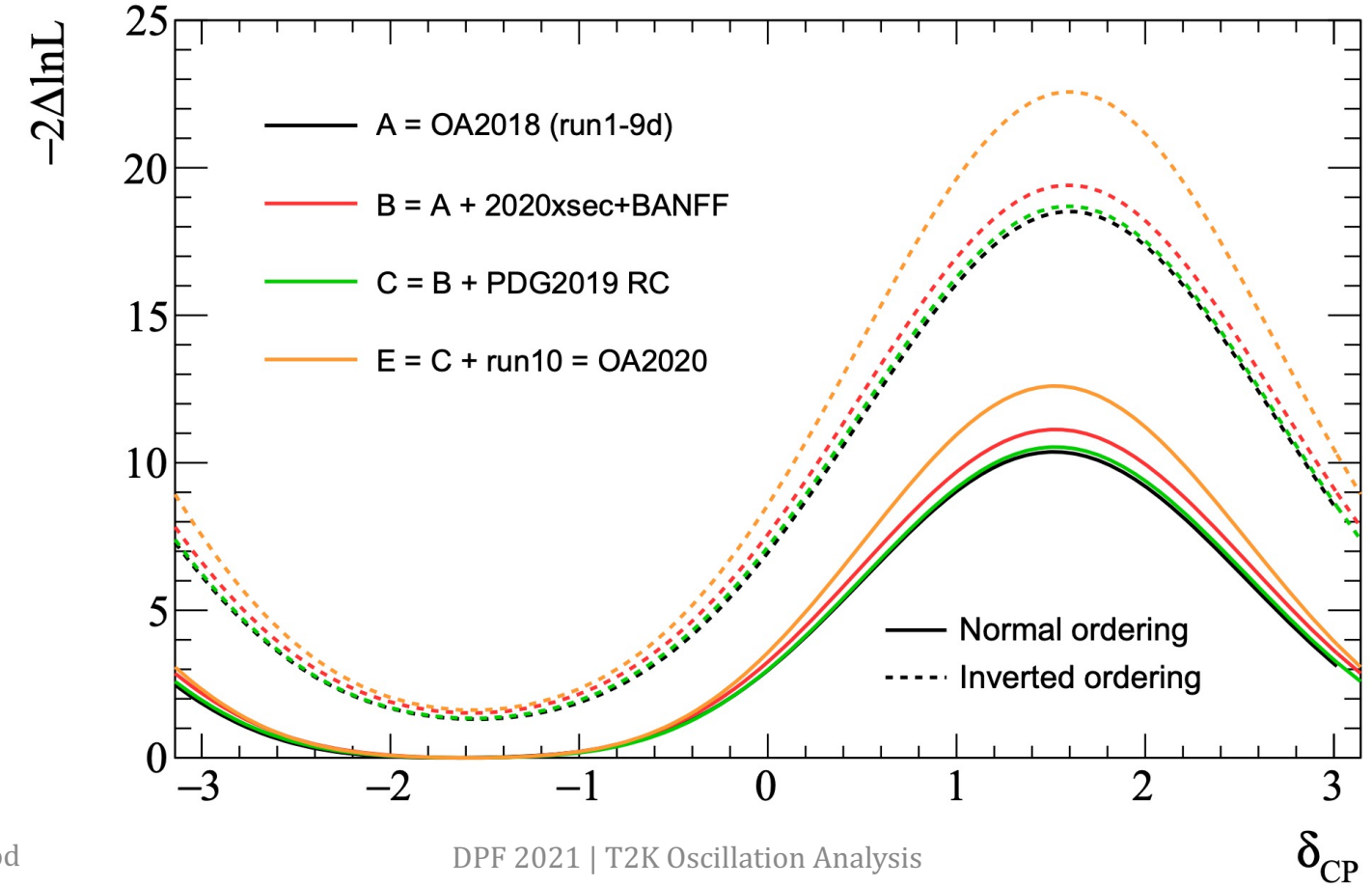
Incremental Changes to δ_{CP} - data fit

- NOTE: These are showing $\Delta\chi^2$ distributions from a frequentist analysis
- Biggest change due to run10 data



Incremental Changes to δ_{CP} - sensitivity

- NOTE: These are showing $\Delta\chi^2$ distributions from a frequentist analysis
- Biggest change due to run10 data



T2K + NOνA Joint Analysis

T2K	NOνA
Flux peaks at ~0.6 GeV	Flux peaks around 2.0 GeV
295 km baseline	810 km baseline
CCQE dominant interaction mode	Broad mix of interaction modes
NEUT	GENIE
E_{rec} from lepton kinematics	Calorimetric energy reconstruction
Different ND and FD technologies	Functionally identical ND and FD