T2K+NOvA Joint Measurement of Neutrino Oscillation Parameters

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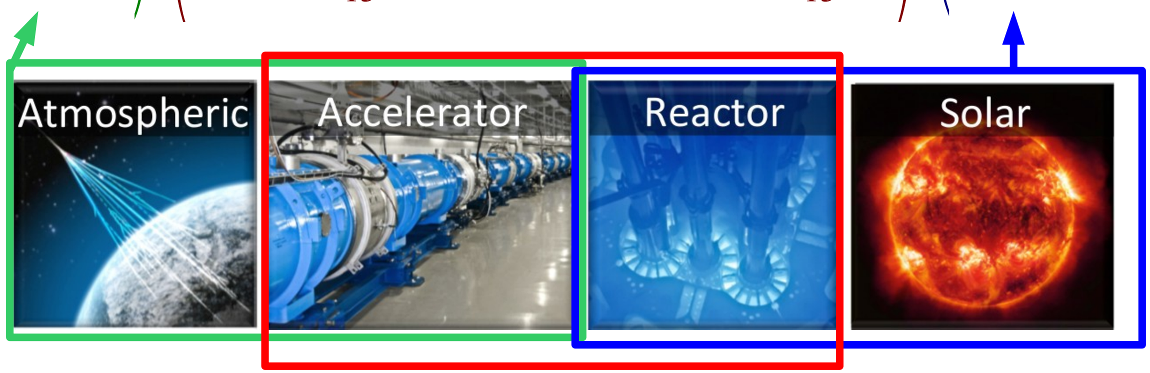
Motivation: neutrino oscillations

- As you probably know, **neutrinos oscillate** (change flavour during propagation)
- mixing between **weak** (interacting) and **mass** (propagating) eigenstates:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



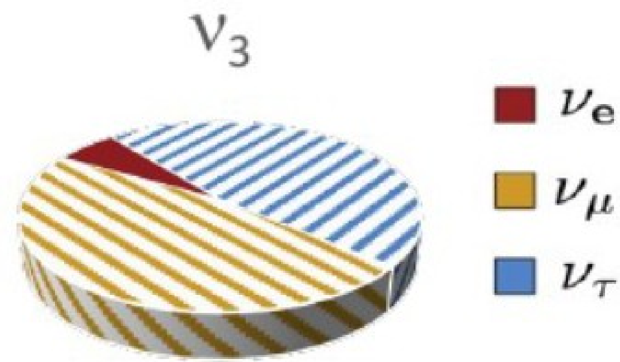
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum \mathcal{O}_{ij}\sin^2\frac{\Delta m_{ij}^2 L}{4E} \pm 2\sum \mathcal{U}_{ij}\sin 2\frac{\Delta m_{ij}^2 L}{4E}$$

CP-conserving　　CP-violating

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

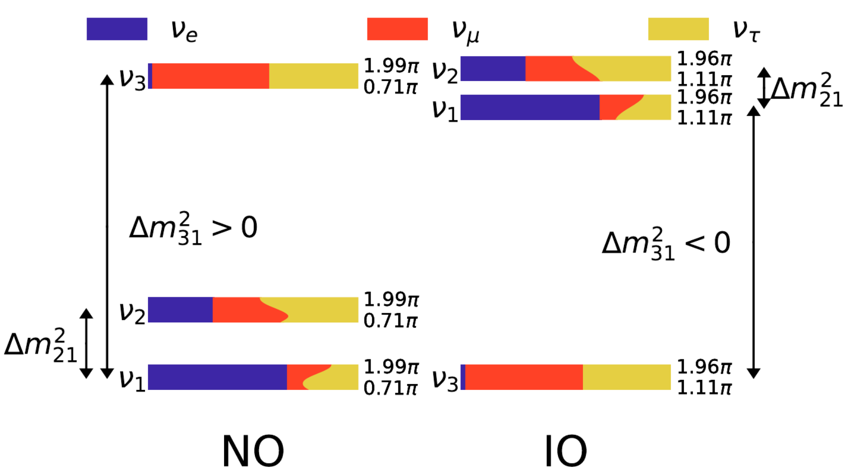
Long baseline experiments

- accelerator muon neutrino beams, E ~1 GeV
- baseline L ~100-1000 km



Is θ_{23} mixing maximal? μ-τ symmetry?
Is $\theta_{23} \lessgtr 45°$?

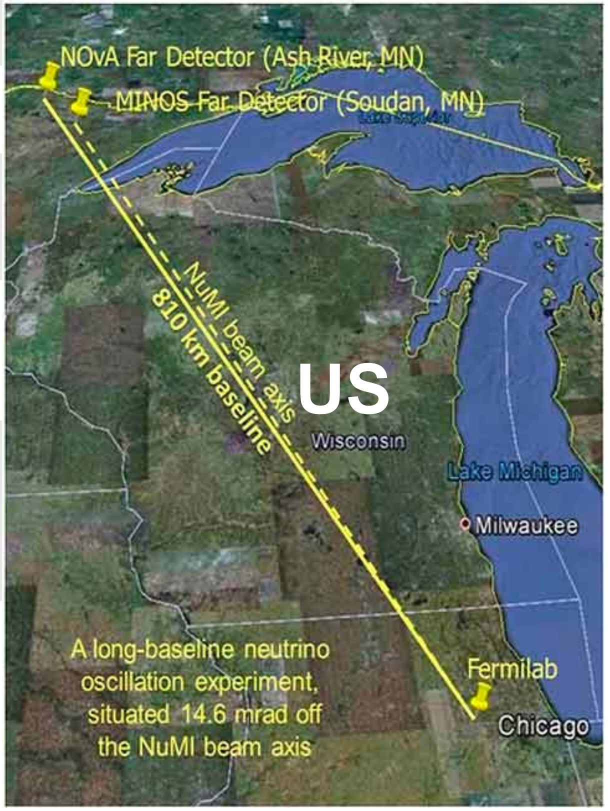
What is the ordering of the ν masses?
Normal (NO) or inverted (IO)?



Is there significant CP violation in the lepton sector?

T2K and NOvA

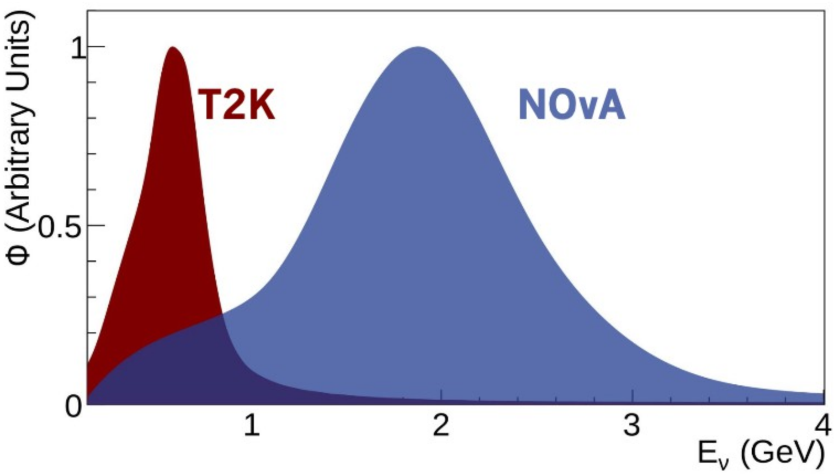
	T2K	NOvA
Baseline	**295** km	**810** km
Peak energy	**600** MeV	**2** GeV
e/μ identification	Cherenkov ring shape	convolutional neural network
Neutrino energy reconstruction	two-body formula for QE or resonant interactions	calorimetric
Near Detector	multi-purpose (TPC, FGD, ECAL) magnetized	extruded plastic cells filled with liquid scintillator
Far Detector	50 kton Water Cherenkov	14 kton scintillator

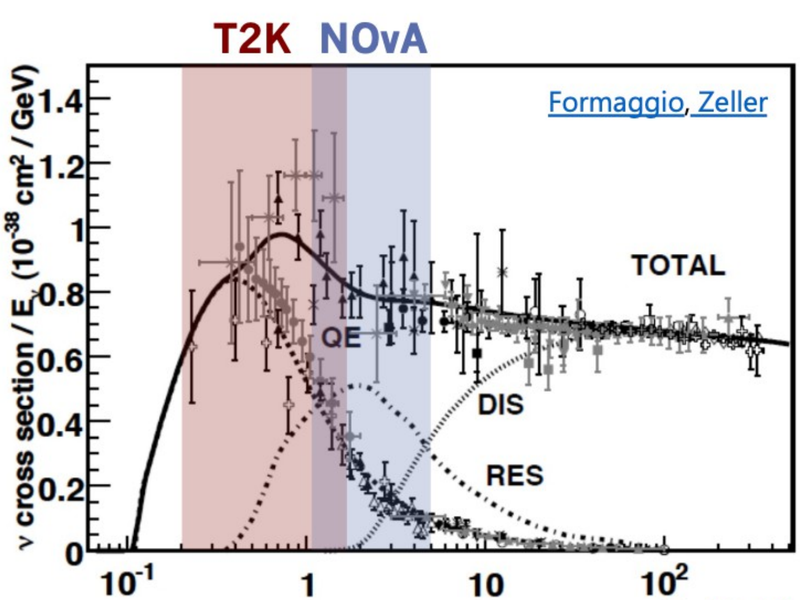


T2K vs NOvA

	T2K	NOvA
reactions	QE (also 2p2h, RES)	mix
CP effect	32%	22%
Matter effect	9%	29%

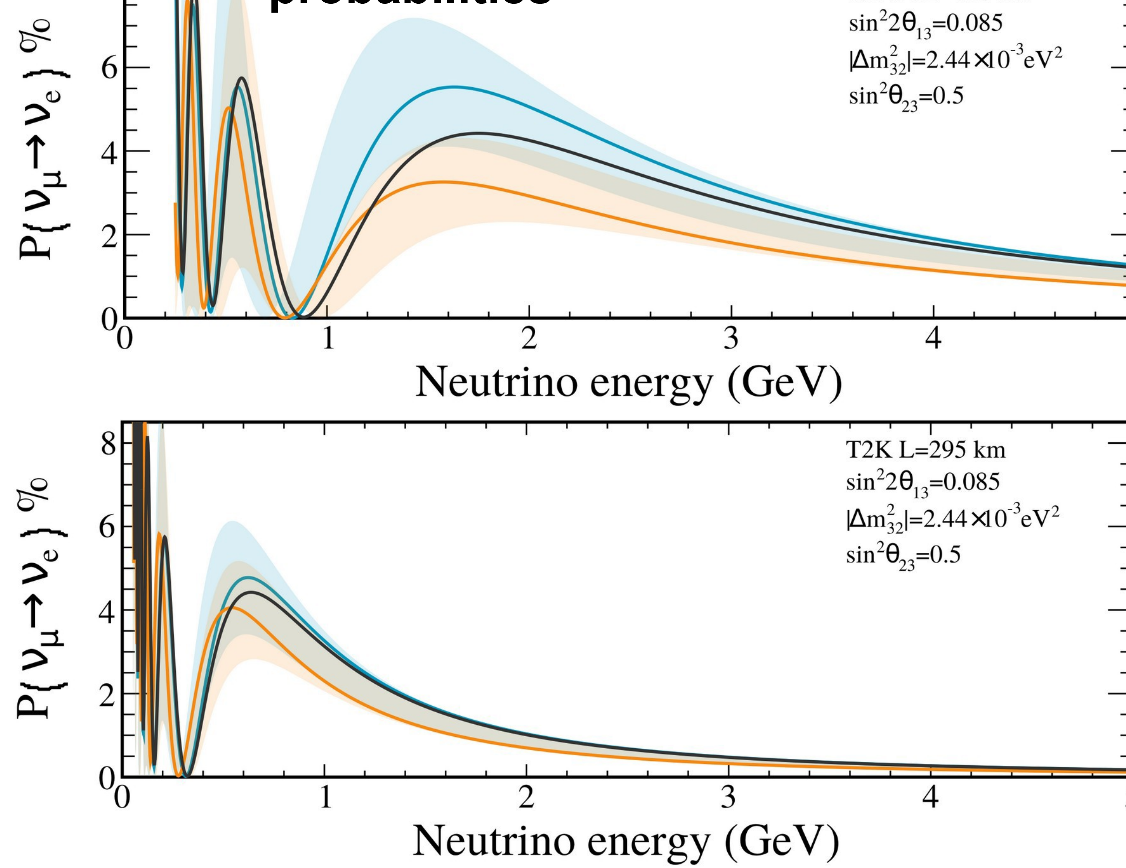
neutrino spectrum





cross sections

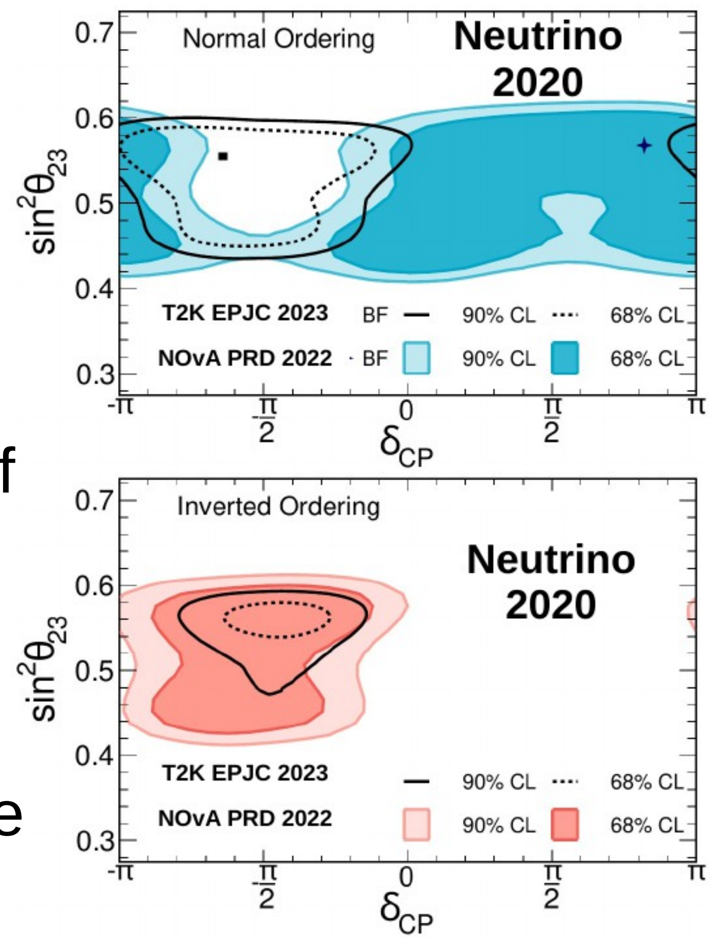
appearance probabilities



Joint analysis

Different setups of oscillation baseline and energies
→ different physics sensitivity

- NOvA → mass ordering
  - degenerations around δ_{CP} = π/2 and −π/2
- T2K → CP-violation
  - degenerations around δ_{CP} = 0 and π



Opposite to "global fits", a full implementation of

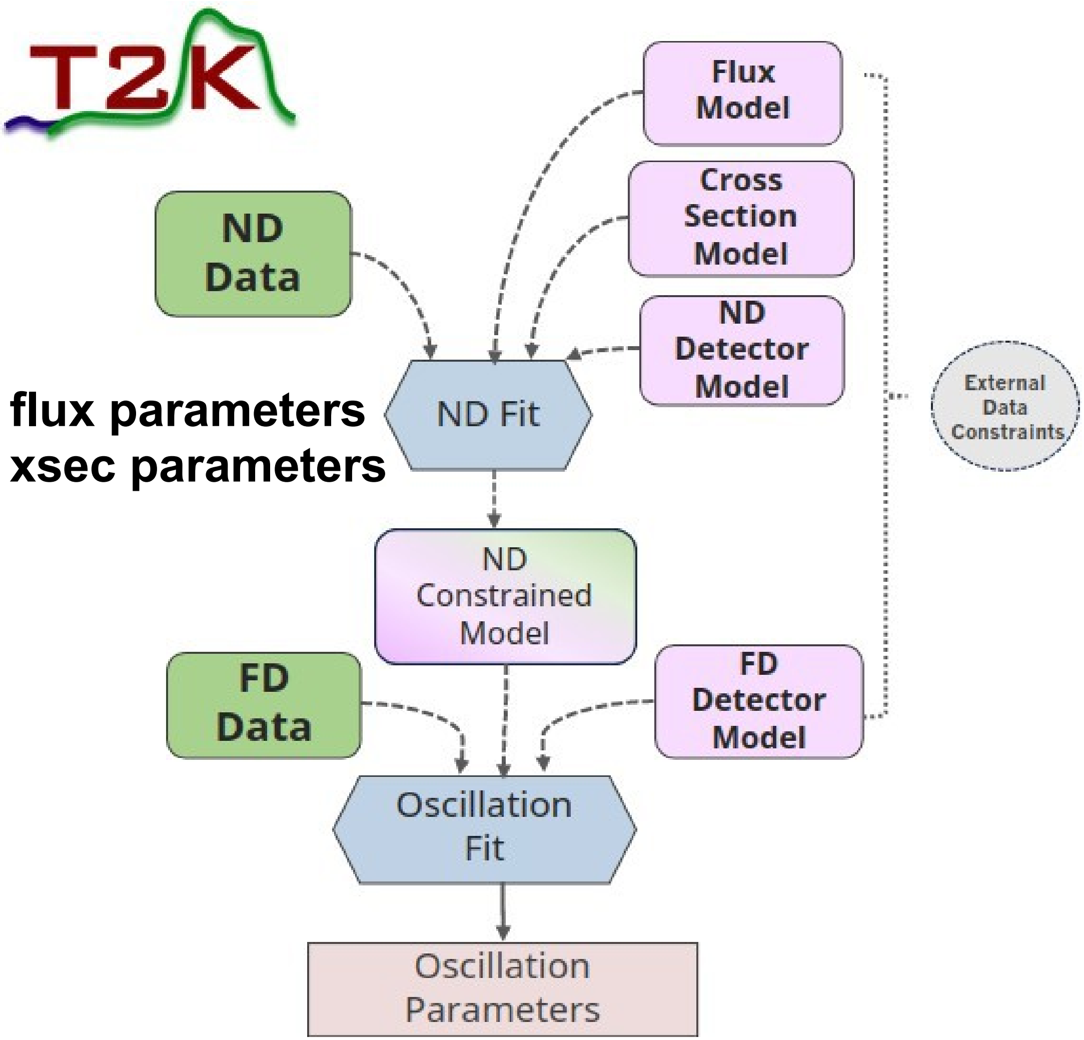
- consistent statistical inference across the full dimensionality
- each experiments' detailed likelihood
- energy reconstruction and detector response

In-depth review of

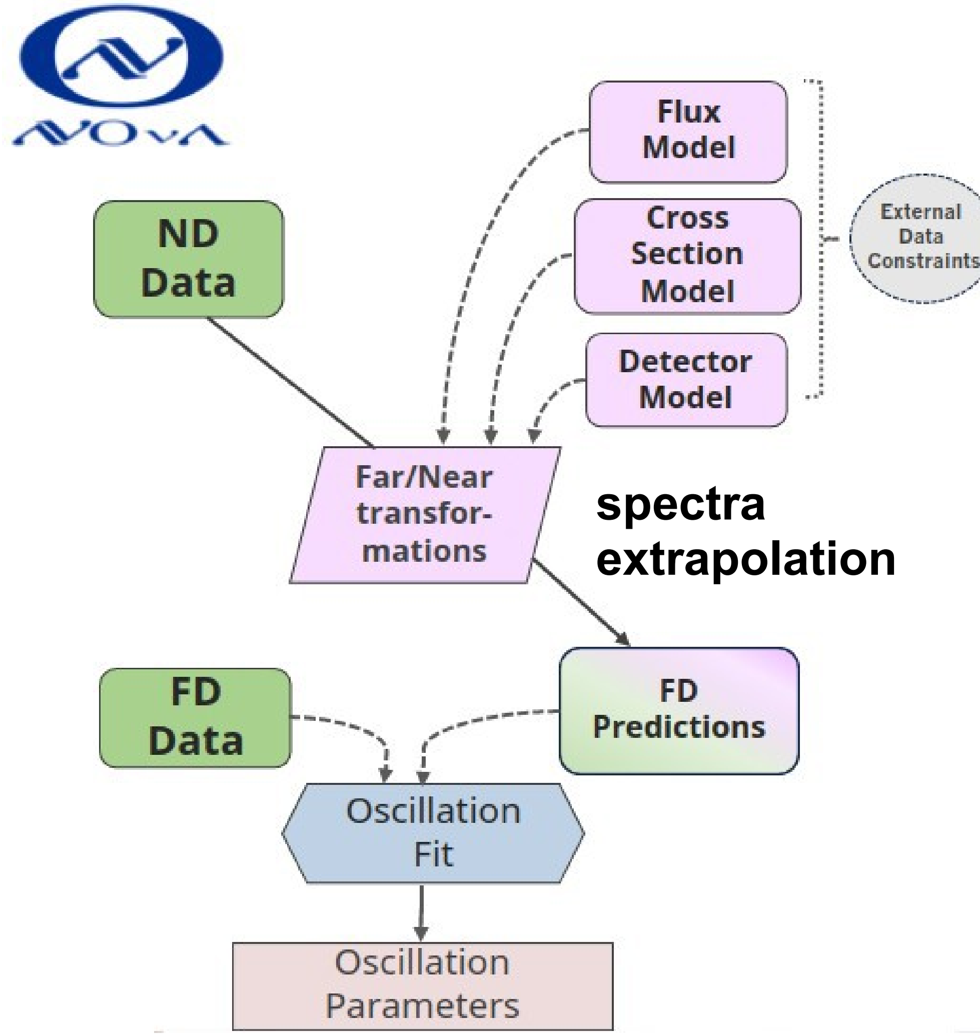
- Models, systematic uncertainties and their possible correlations
- Different analysis strategies driven by different detector designs

Last, not least: roughly doubled statistical power of individual experiments

Analysis strategies



flux parameters
xsec parameters



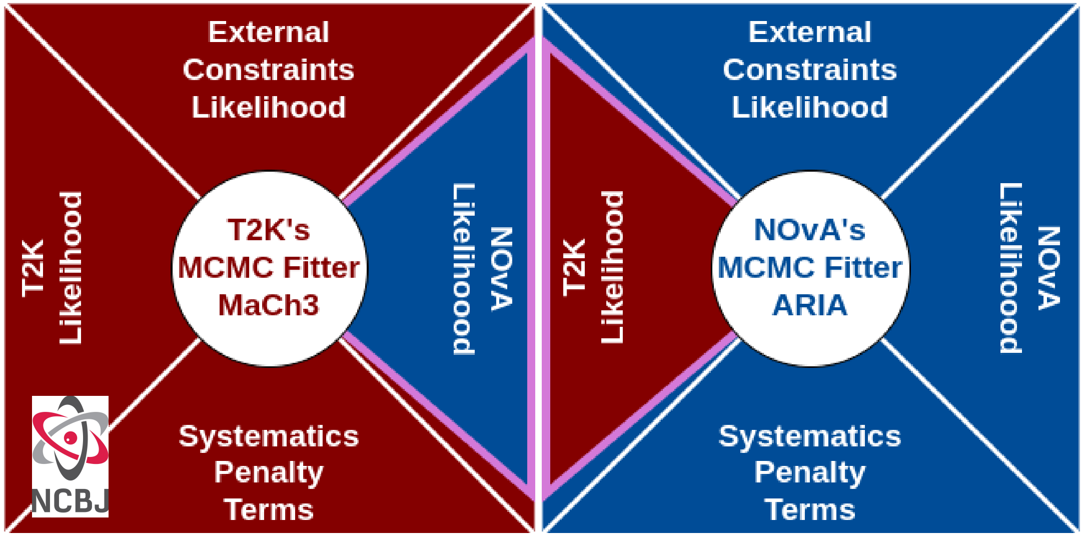
spectra
extrapolation

Analysis method

- Based on Bayesian versions of 2020 analyses: T2K: EPJC 83 782 and NOvA: PRD 110 012005
- Full statistical treatment of experiments integrated via containerized environment:
  - Each experiment can run the other's analysis through an analysis software container
  - Full access to Monte-Carlo and data while preserving each experiments' unique analysis approach

Two Bayesian Markov Chain Monte Carlo fitters

- Results presented as posterior densities and credible intervals (regions) for parameters of interest
- Discrete model preferences (neutrino mass ordering, θ23 octant) presented with Bayes factors



Multiple analysis streams and independent implementation of the framework provides rigorous validation

Uncertainties and correlations

FLUX MODEL	• Different energies • Different external data tuning • Different treatment in the analysis	⇒	No significant correlations between the experiments

DETECTOR MODEL	• Different detector designs and technologies
	• Different selections
	  ∘ Inclusive vs exclusive outgoing π
	• Different reconstruction techniques
	  ∘ Calorimetry vs lepton kinematics
		⇒	No significant correlations between the experiments

CROSS-SECTION MODEL	• Expecting correlations from common physics • Different interaction models and generators ∘ Optimized for different energies • Systematics designed for individual models and analysis approaches	⇒	Investigate the impact of correlations in the joint analysis

NCBJ

Checks on impact of correlations in interaction models

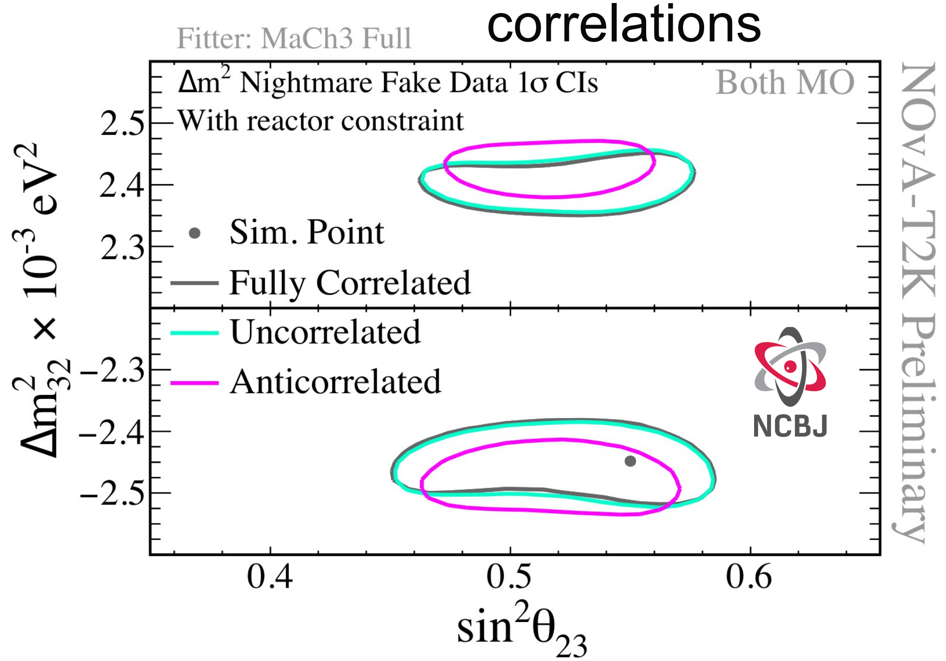
Strategy to study parameters and their inter-experimental correlations with a significant impact on the parameters of interest δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32}

Fully correlating ν_μ/ν_e and $\bar{\nu}_\mu/\bar{\nu}_e$ cross-section uncertainties, treatment is identical (large δ_{CP} impact)

Otherwise, no direct mapping of the systematic parameters between the experiments

- Fabricated, simulated and studied a fully correlated bias for Δm^2_{32} or $\sin^2\theta_{23}$
- Impact of correlations merits further investigation for future analyses with increased statistics
- Given current (2020) statistics, the overall sensitivity gains from correctly correlating systematics would be small, while incorrectly correlating leads to bias

One example of a study to assess the importance of inter-experimental correlations

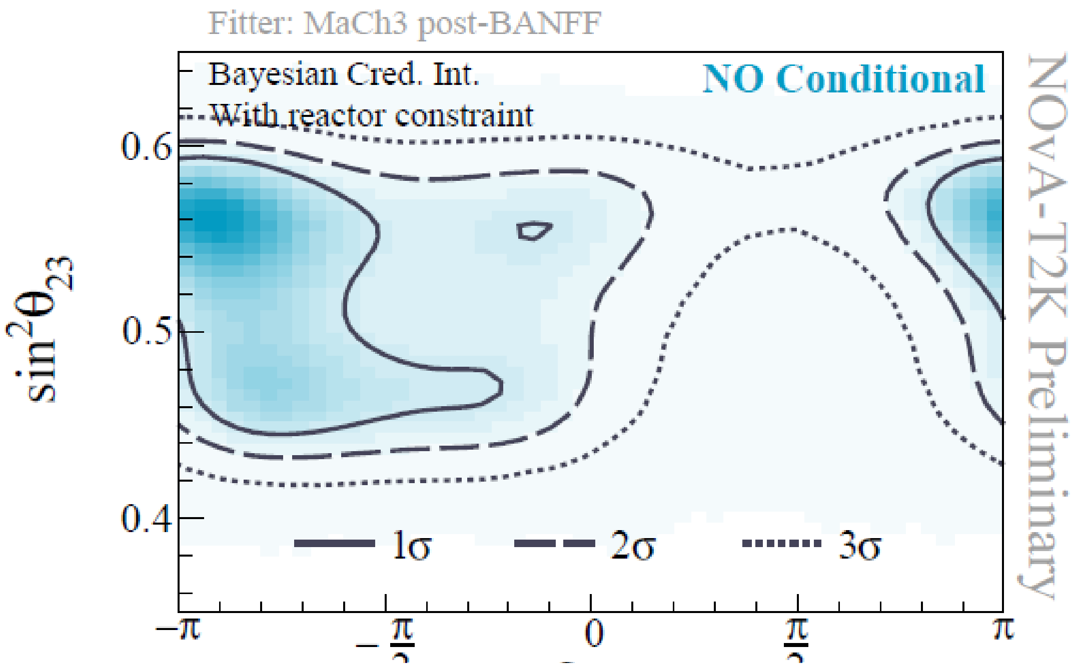


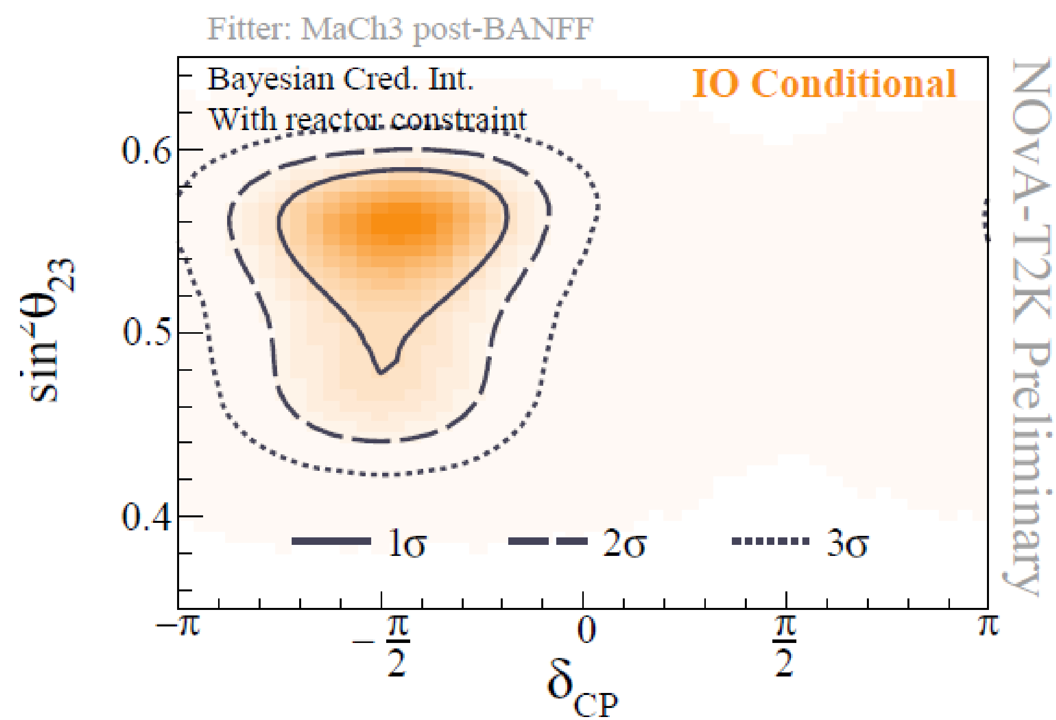
Summary of NCBJ contributions

- MaCh3 development
- MaCh3 software container preparation and validation
- fake data studies
  - testing the impact of alternate physics models
  - development of common FDS validation tools to check pre-defined criteria for measuring neutrino oscillation parameters
  - “mock data” studies to assess the impact of inter-experimental correlations of heuristic systematic nuisance parameters with significant impact on the neutrino oscillation parameters measurements, so-called “Nightmare parameters studies”.
- other analysis validations
- extracting credible intervals and regions, calculating discrete model preferences, and producing overlays and comparisons of different fit setups or results from different experiments.

Results: MO and CPV

- The joint fit is well in agreement with both individual fits
- Neither ordering has a preferen for δ_{CP} values around +π/2 (outside 3σ CI)
- Normal ordering allows for a broad range of possible δ_{CP}
- For inverted ordering CP-conserving δ_{CP} values outside 3σ CIs

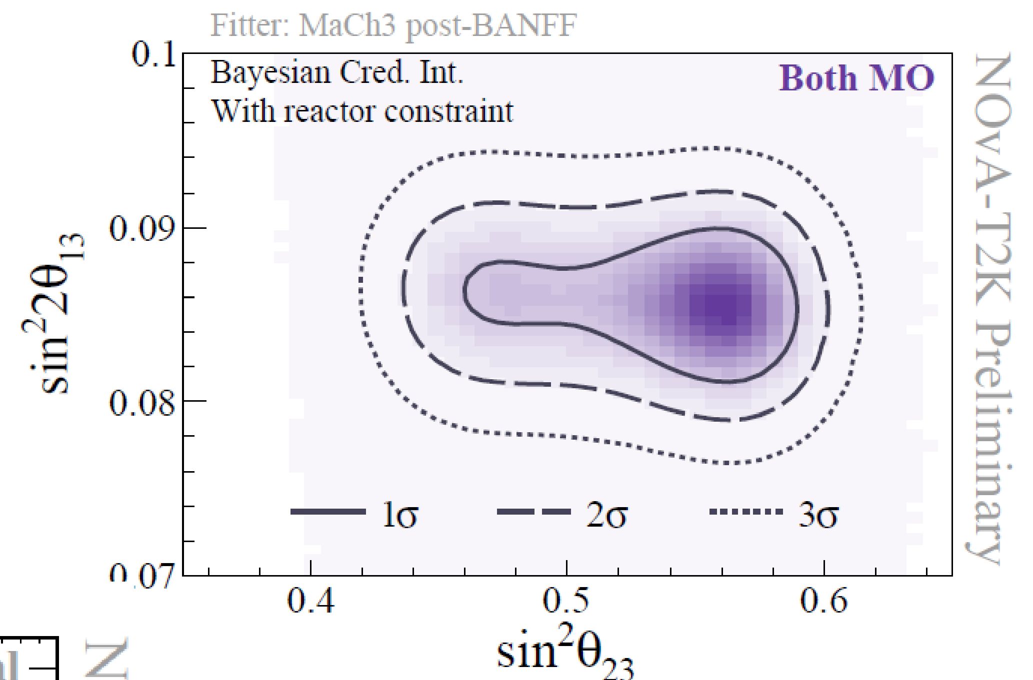


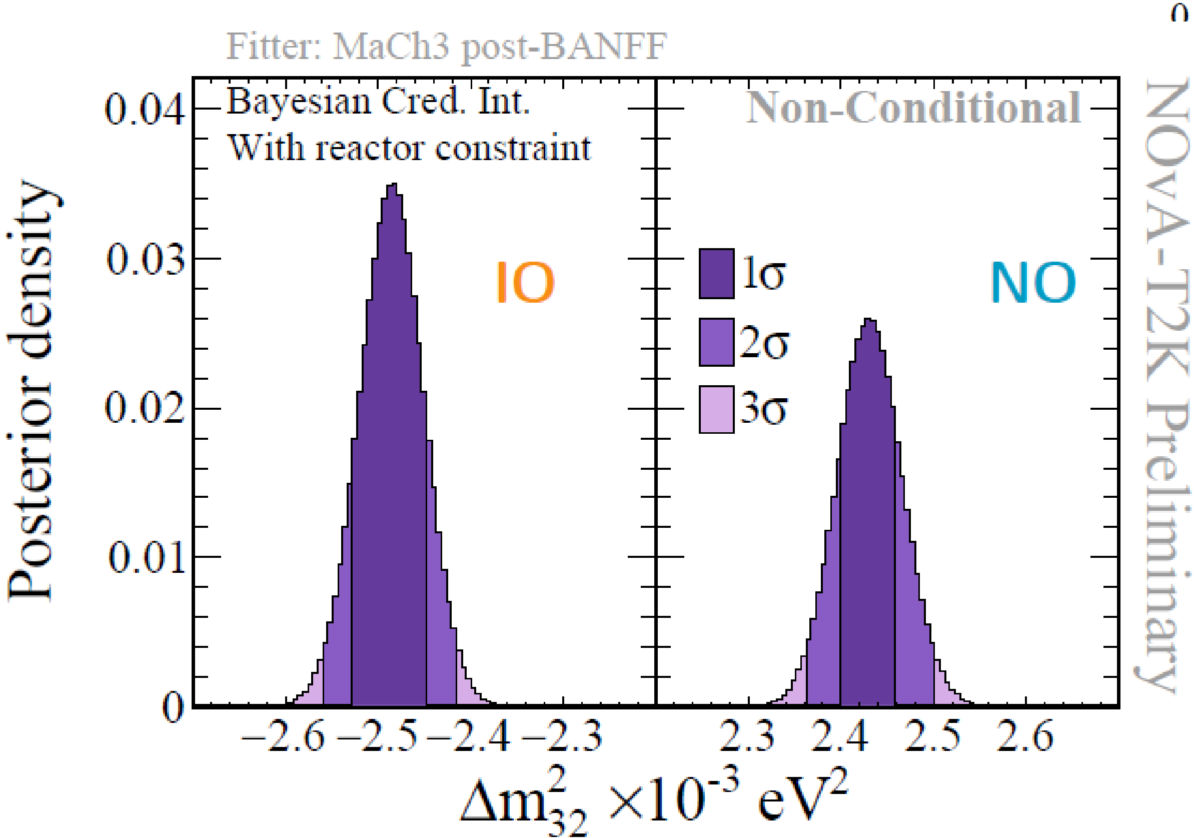


Results: θ_{23} and Δm^2_{32}

- Bayes factor of **3.6** for upper octant preference (modest) with RC
- Very weak preference for IO,

Bayes factor 1.3





Smallest uncertainty in Δm^2_{32} < 2 %

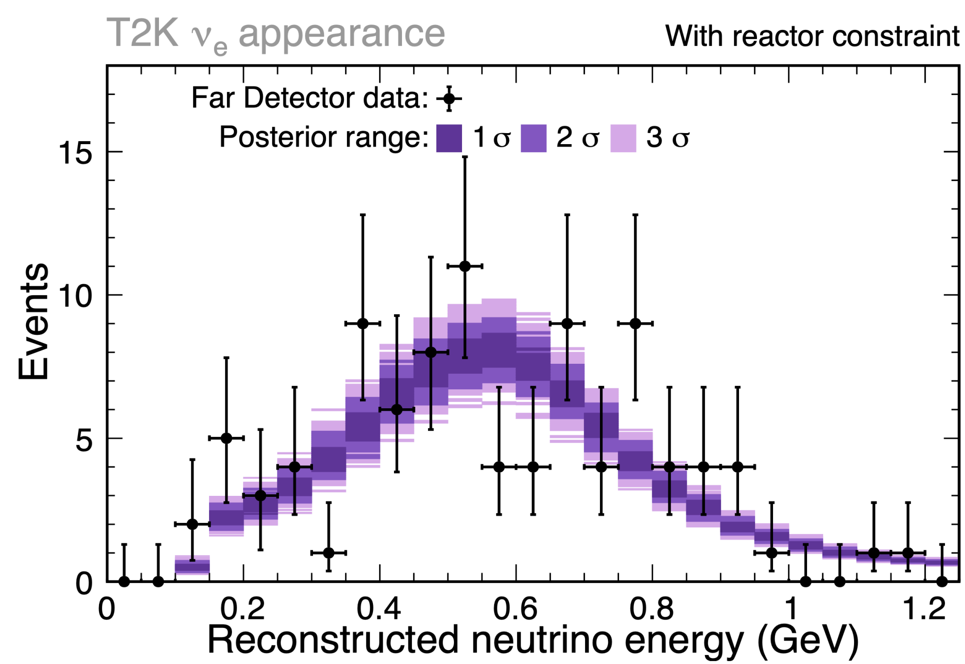
Summary and outlook

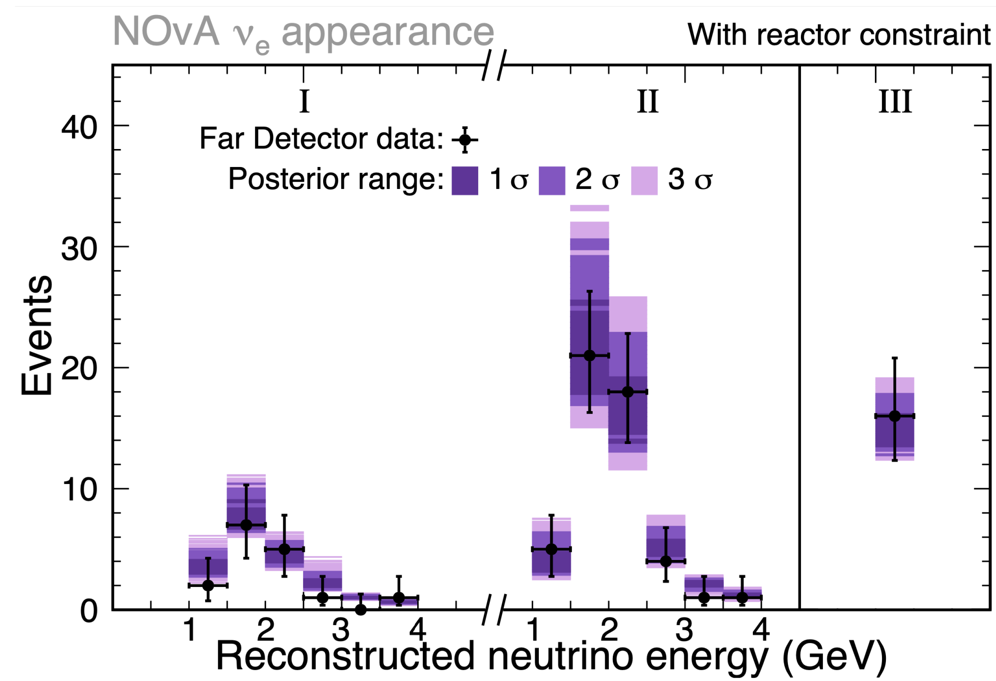
- T2K and NOvA datasets **compatible with a good posterior predictive p-value** of the fit within a standard model of three oscillating neutrinos
- results disfavor values of $\boldsymbol{\delta_{CP}}$ around $\pi/2$ at more than 3σ. CP-conserving values of $\boldsymbol{\delta_{CP}}$ (0 and π) excluded at 3σ when the inverted ordering is assumed
- new competitive precision on $\boldsymbol{\Delta m^2_{32}}$ measurement of <2%
- about 1σ (Bayes factor 3.6) preference for $\boldsymbol{\theta_{23}} > 45°$
- no statistically significant preference for either neutrino mass ordering
- **more statistics** and more profound inter-collaborative efforts to deliver high-quality results are expected from both experiments in the coming years
- T2K+NOvA also serves as an example and a base experience for the potential combined analyses of the next-generation experiments, such as DUNE and Hyper-Kamiokande

Backup slides

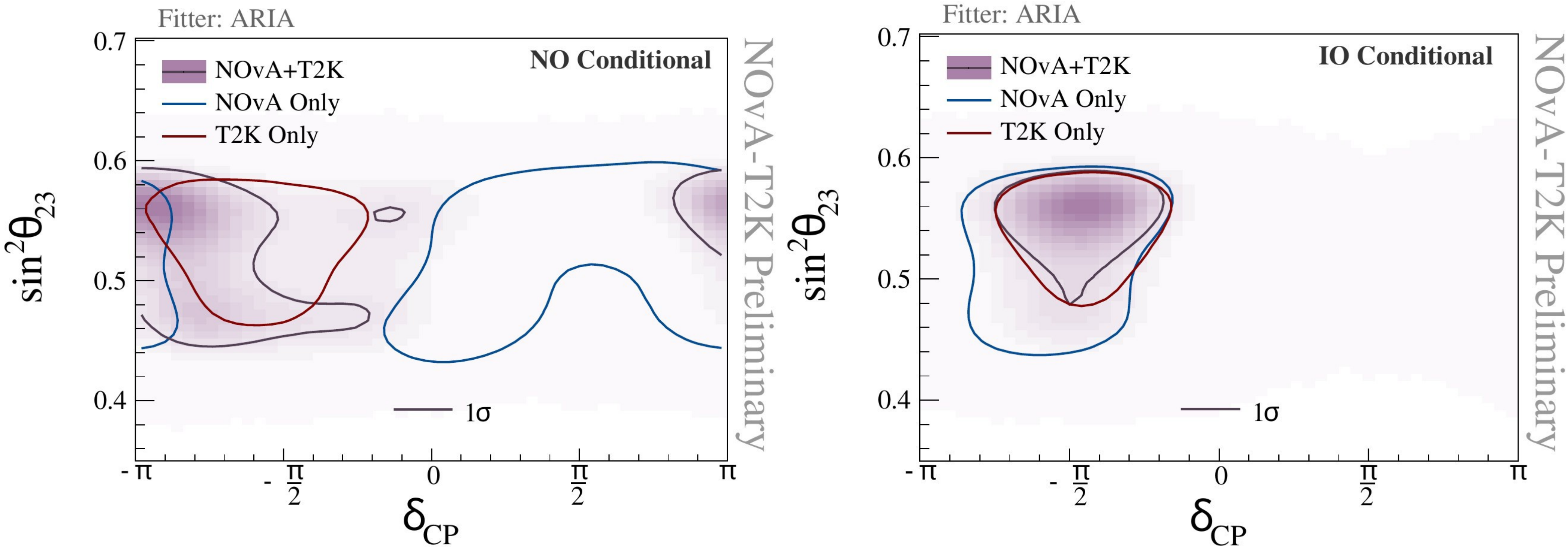
Fit results

Channel	P-value		
	NOvA	T2K	Combined
ν_e	0.90	$0.19_{(\nu_e)}$ $0.79_{(\nu_e 1\pi)}$	**0.62**
$\bar{\nu}_e$	0.21	0.67	**0.40**
ν_μ	0.68	0.48	**0.62**
$\bar{\nu}_\mu$	0.38	0.87	**0.72**
All	0.64	0.72	**0.75**





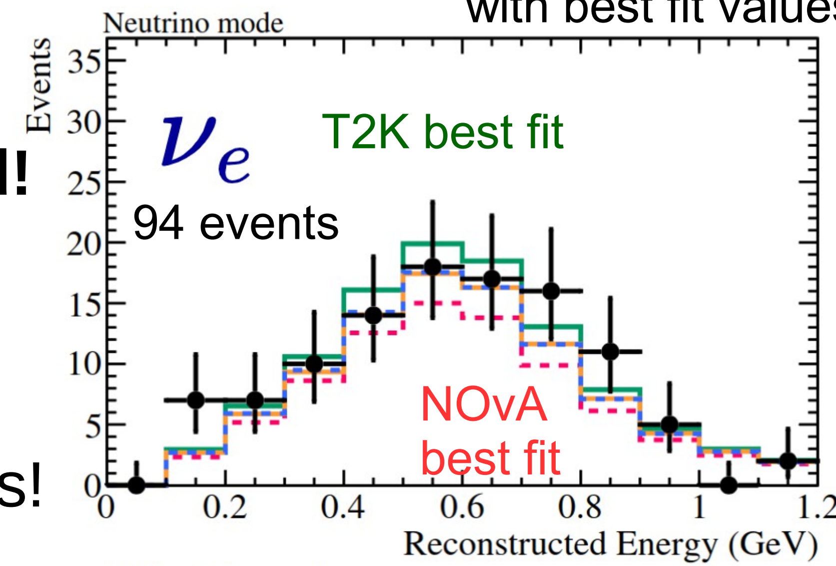
Compability of results

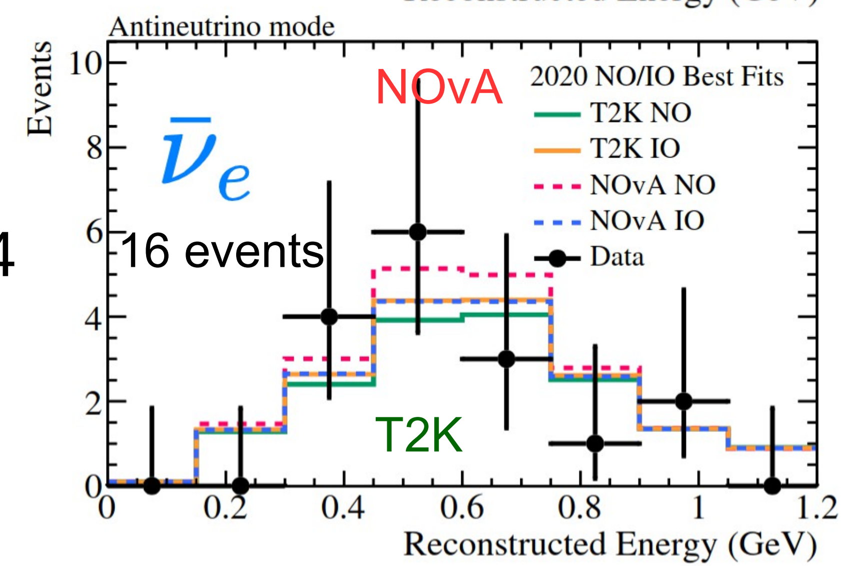


T2K vs. NOvA

points - T2K data
histograms – predictions with best fit values

- both show a **weak preference for NO**
- some tension in $\boldsymbol{\delta_{CP}}$ but remember: current results are **statistically limited!**
  - if IO: consistent preference for the 3π/2 (-π/2) region, small preference for upper octant
- **more data needed** in both experiments!



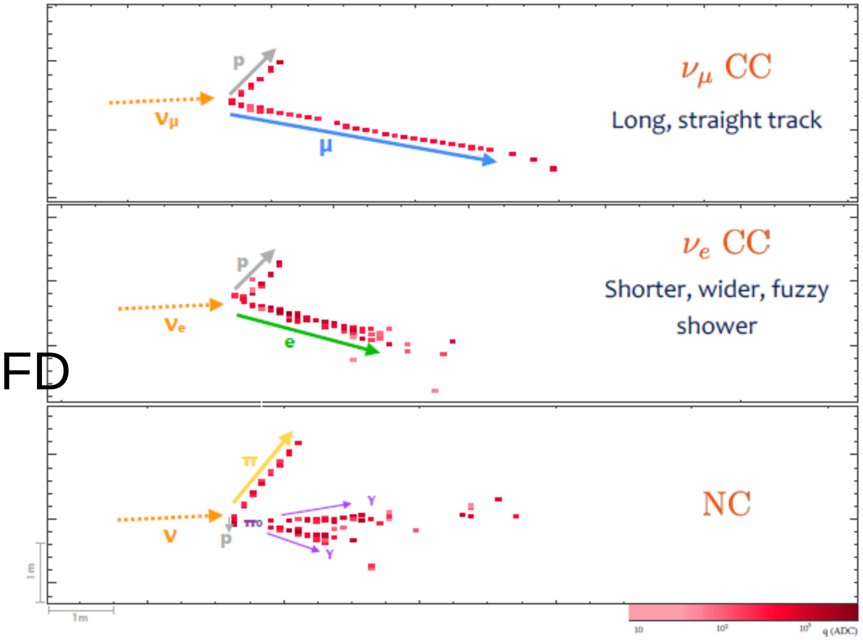


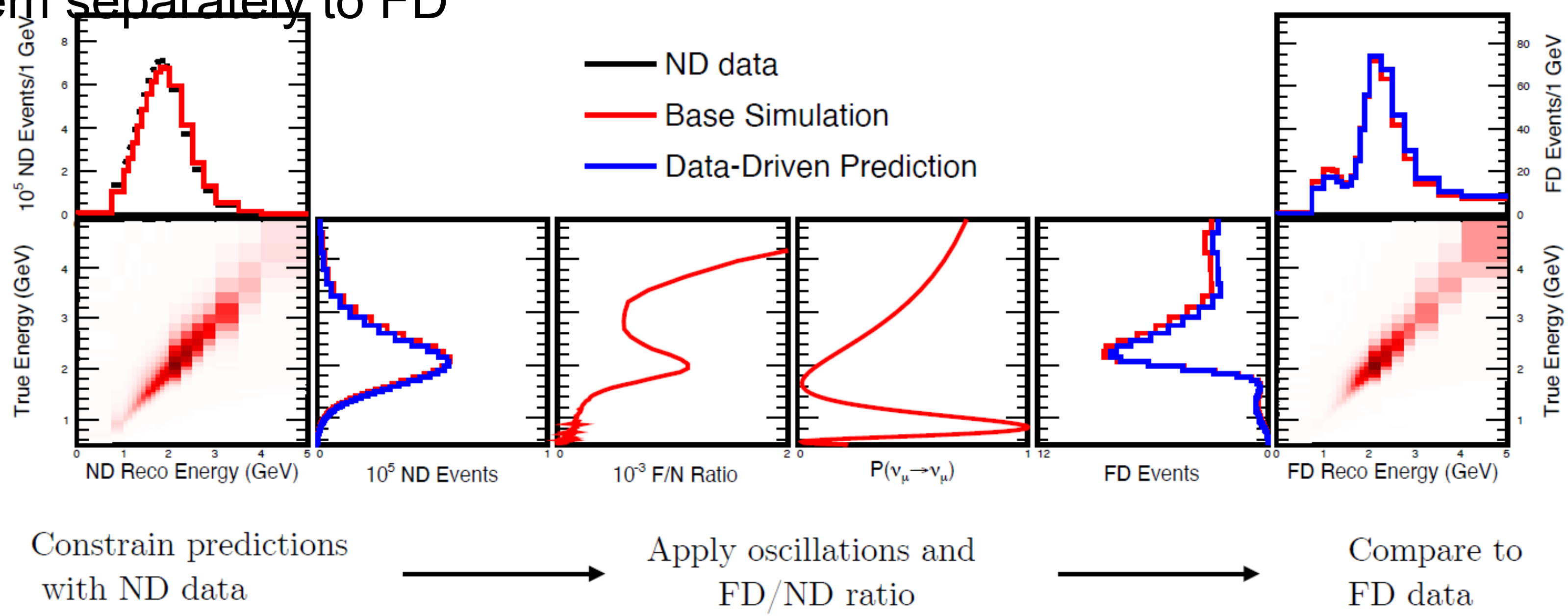
- T2K statistical update expected soon
- new analyses from both expected 2024

- Both undergoing upgrade:
  - NOvA – beam power → 900+ kW
  - T2K – beam power → 1.3 MW, ND280 upgrade, SK-Gd
  - Goal: 3σ sensitivity for CPV (T2K) and MO (NOvA)

NOvA analysis

- neutrino flavor identification: using a convolutional neural network (image recognition)
- select (anti)ν_μ and (anti)ν_e data at both ND and FD
- extrapolate the spectra from the ND to the FD
  - including the „not ν_μ CC interactions” background
  - oscillate observed ν_μ spectra
  - break down ND ν_e selected events into background sources and extrapolate them separately to FD

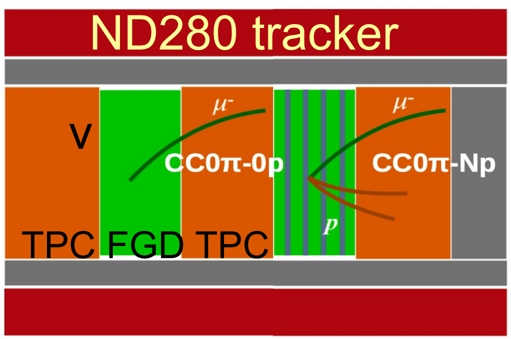




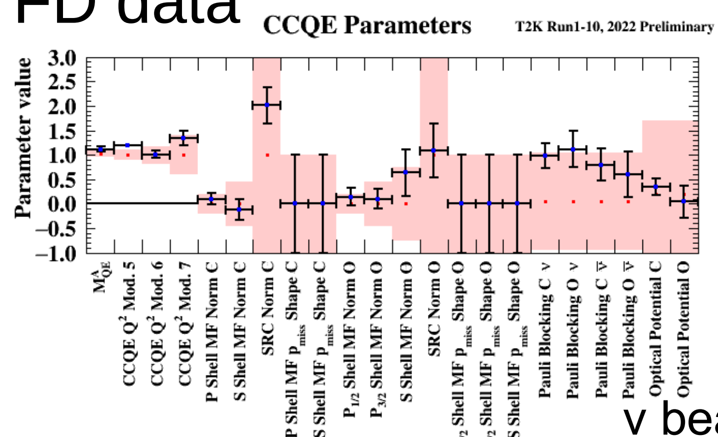
T2K Oscillation Analysis

updates in 2022

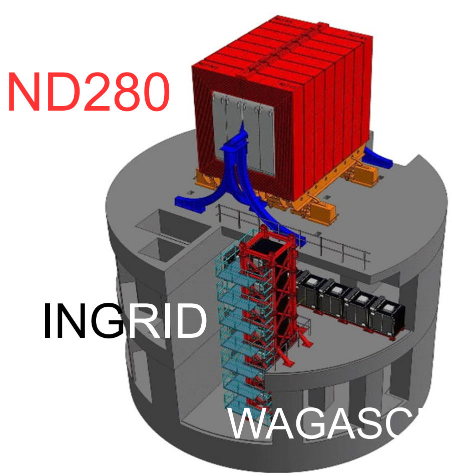
- parametrized flux and cross section models
- best values of the parameters from fit to ND280 $\nu_\mu/\bar{\nu}_\mu$ data → correct the predictions for FD → fit to FD $\nu_e/\bar{\nu}_e$ and $\nu_\mu/\bar{\nu}_\mu$ event samples (frequentist)
- OR: fit simultaneously ND280 and FD data (Bayesian fit using Markov chain MC)



Near Detector Fit



(example of some cross-section parameters)



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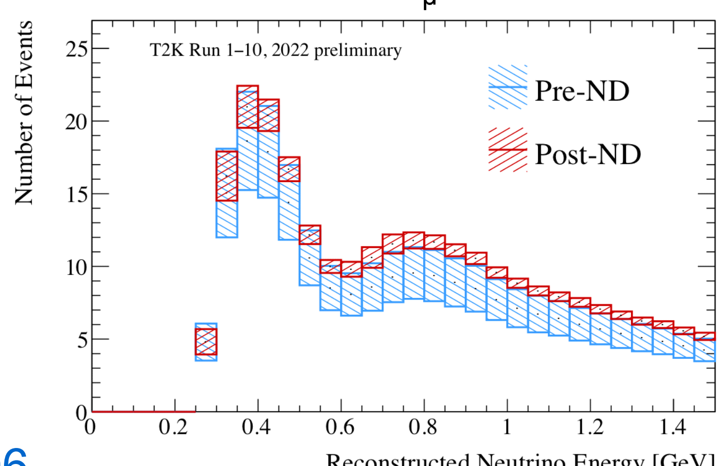
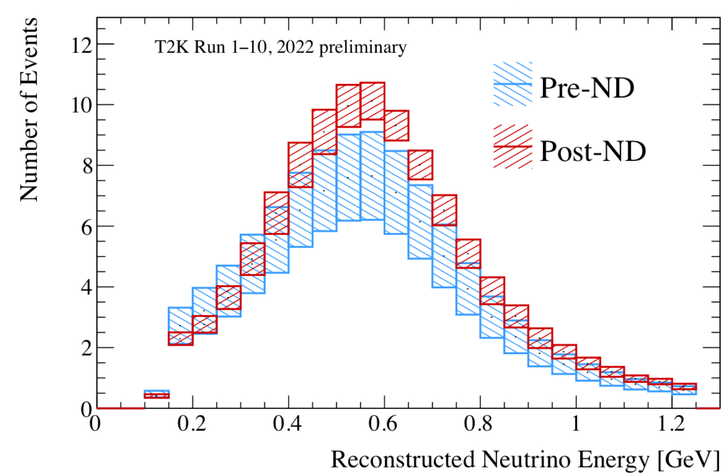
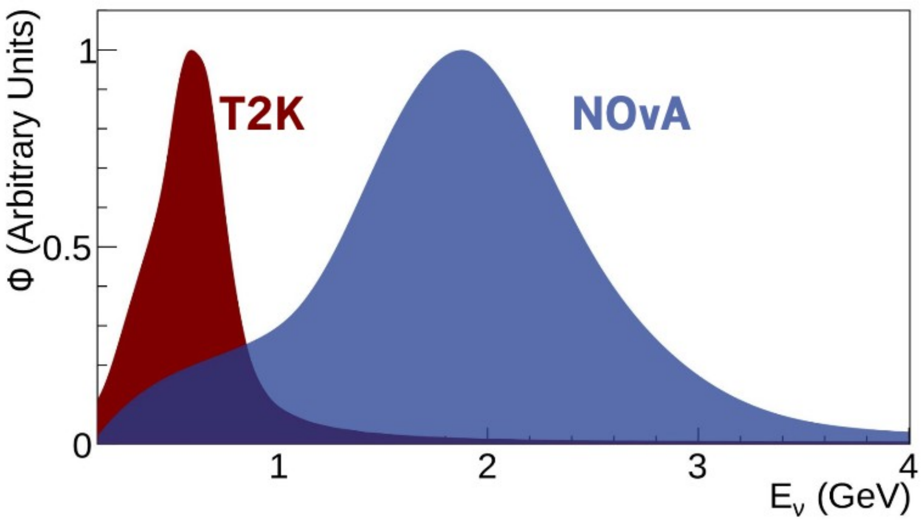
ν beam
1Ring ν_μ-like

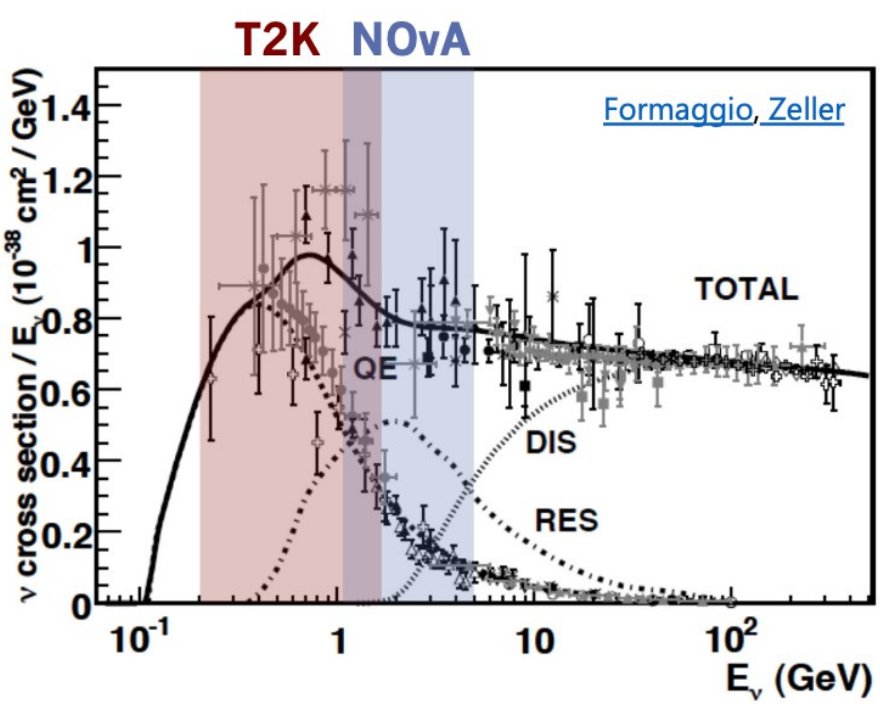


ν beam
1Ring ν_e-like



T2K vs NOvA





Neutrino energy reconstruction:
T2K: two-body formula for QE or resonant interactions
NOvA: calorimetric

e/μ identification
T2K: Cherenkov ring shape
NOvA: convolutional neural network

Number of events in (anti)ν_e appearance samples

T2K	DATA	Best fit total	δ_{CP}=0	δ_{CP}=-π/2
ν_e	**94**	**96.47**	83.56	99.06
ν_e CC1π^+	**14**	**10.47**	9.45	10.85
anti-ν_e	**16**	**17.34**	19.35	17.02

NOvA	Total observed	Best fit total	Signal	BKG
ν_e	**82**	85.8	59±2.5	26.8±1.7
anti-ν_e	**33**	33.2	19.2±0.7	14.0±1.0