T2K+NOvA Joint Measurement of Neutrino Oscillation Parameters

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Neutrino Oscillation and (All Sort of) Motivations

Neutrino mixing in 3ν-paradigm

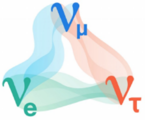


Image by Symmetry Magazine

Flavor Eigenstates — Mass Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

Measured from the following neutrino sources

Atmospheric

Accelerator

Reactor

Solar

Image by Symmetry Magazine

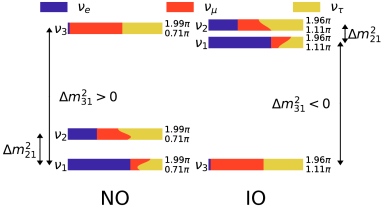
Studying neutrino oscillation within 3ν-paradigm

Long-baseline accelerator experiments with $L/E \sim 10^{2-3}$ km/GeV are sensitive to

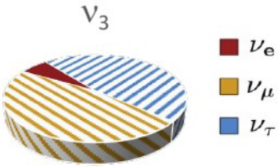
Δm^2_{32}, NO/IO

What is the ordering of the ν masses?

Normal (NO) or inverted (IO)?



θ_{23}

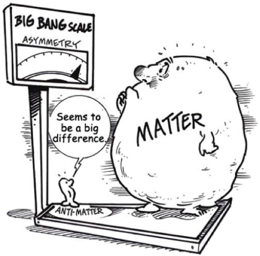


Is 23 mixing maximal? $\mu\tau$ symmetry?

Is $\theta_{23} \lessgtr 45^\circ$?

δ_{CP}

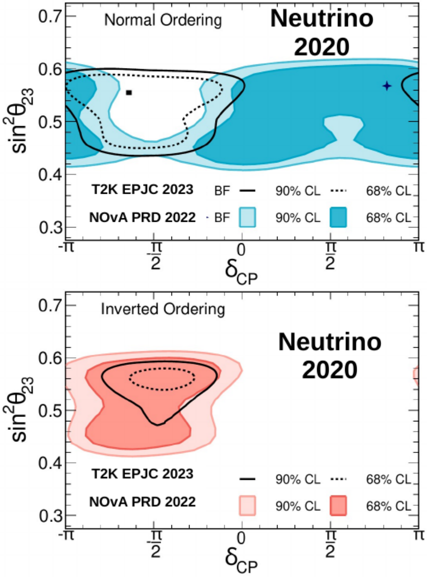
Is there significant CP violation in the lepton sector?



... also θ_{13}

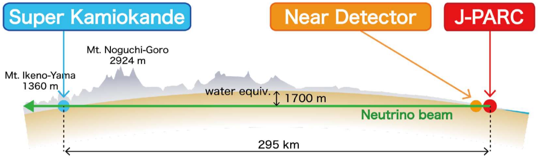
Motivation to combine

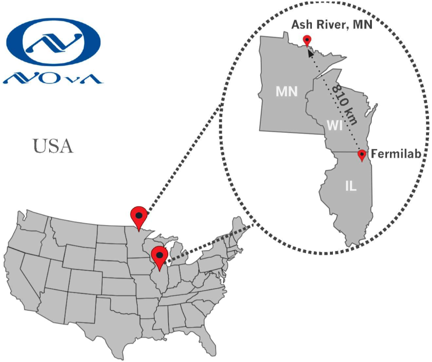
- Different experimental setups of oscillation baseline and energies lead to **different physics sensitivity**
  - NOvA mass ordering sensitivity
  - T2K CP-violation sensitivity
- **Full implementation of**
  - **Consistent statistical inference** across the full dimensionality
  - Each experiments' **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
- **Roughly doubled statistical power of individual experiments**

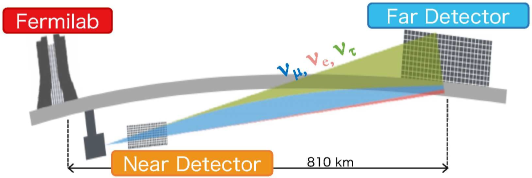


The T2K and NOvA Experiments


Japan
Kamioka
295 km
Tokai


Super Kamiokande
Near Detector
J-PARC
Mt. Noguchi-Goro
2924 m
Mt. Ikeno-Yama
1360 m
water equiv.
1700 m
Neutrino beam
295 km


USA
Ash River, MN
MN
810 km
WI
Fermilab
IL


Fermilab
Far Detector
ν_μ, ν_e, ν_τ
Near Detector
810 km

Neutrino energies

- Both experiments have their detectors located slightly off-axis (2.5° T2K, 0.84° NOvA) to get narrow and highly pure $\nu_\mu/\bar{\nu}_\mu$ spectra

  NOvA peak at ~ 2 **GeV**

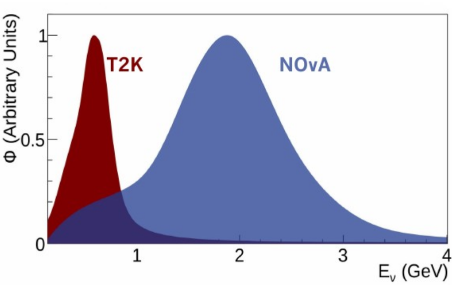
  T2K peak at ~ 0.6 **GeV**

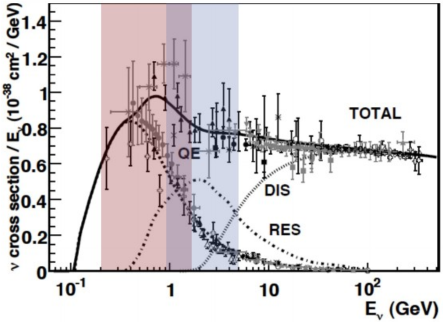
- Different ν energy corresponds to different phenomenological **types of interactions**

  NOvA:
  transition region, mixture of QE, 2p2h, RES π production and DIS

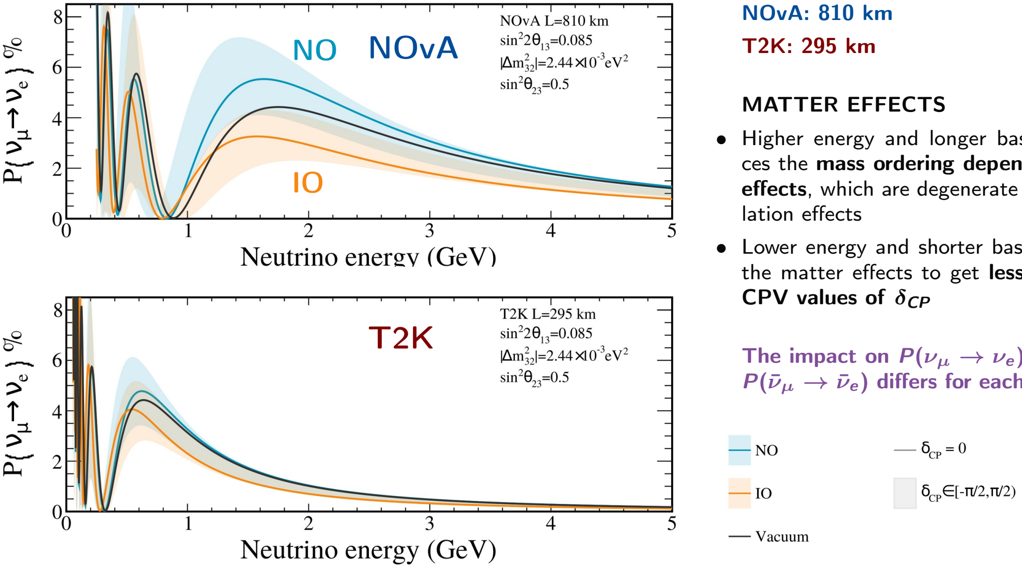
  T2K:
  mostly QE with 2p2h and RES
  DIS in tail

Neutrino flux





Baselines



NOvA: 810 km

T2K: 295 km

MATTER EFFECTS

- Higher energy and longer baseline enhances the **mass ordering dependent matter effects**, which are degenerate with CP violation effects
- Lower energy and shorter baseline reduces the matter effects to get **less degenerate CPV values of δ_{CP}**

The impact on $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ differs for each experiment

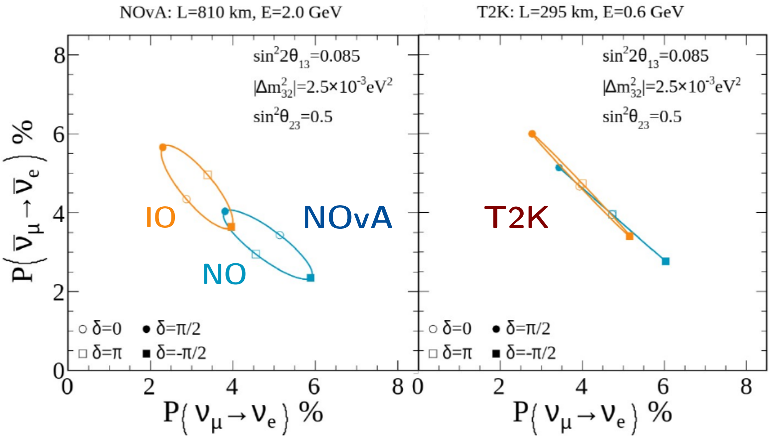
Lifting degeneracies

- Different **energies** and **baselines** give different oscillation probabilities and parameter sensitivity

  NOvA:
  - Better mass ordering sensitivity
  - Degenerate for around $\delta_{CP} = \pi/2$ and $-\pi/2$ (CPV)

  T2K:
  - Better δ_{CP} sensitivity
  - Degenerate for around $\delta_{CP} = 0$ and π (no-CPV)

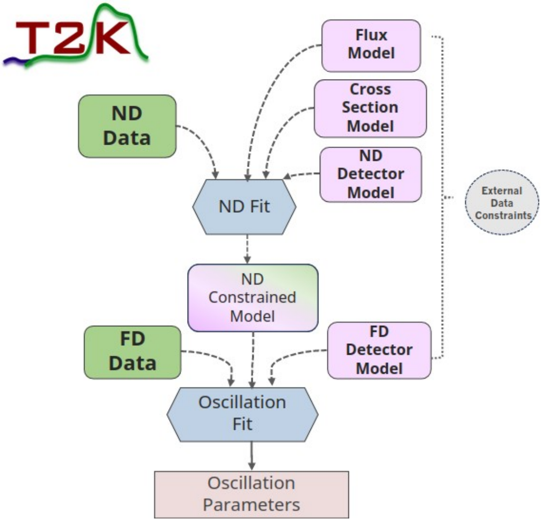
- Joint analysis probes both spaces **lifting degeneracies of individual experiments**

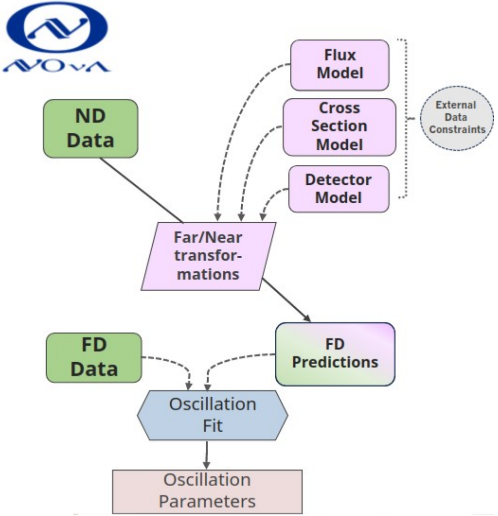


The Joint Analysis

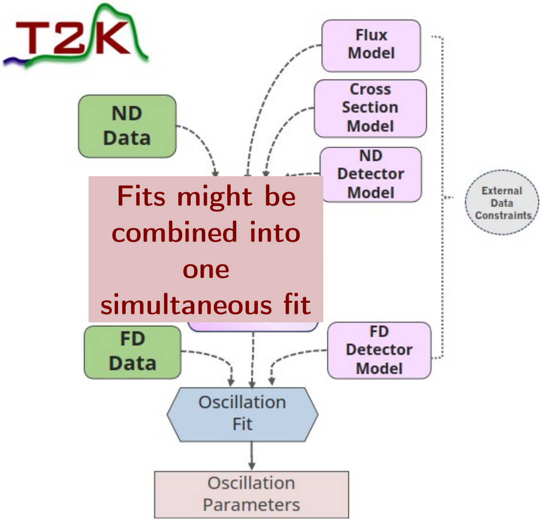
Based on 2020 analyses *EPJC 83 782* (T2K), *PRD 106 032004* (NOvA)

T2K vs NOvA analysis strategy

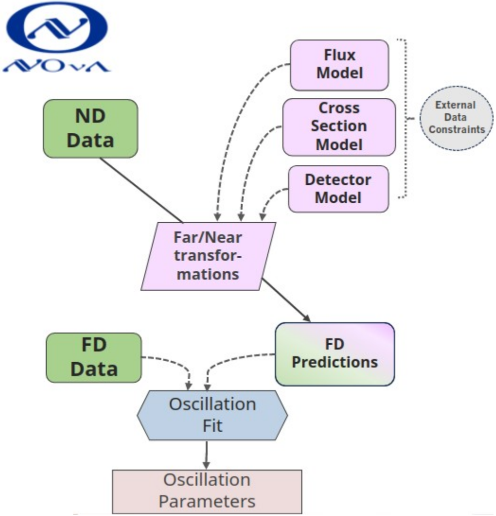




T2K vs NOvA analysis strategy

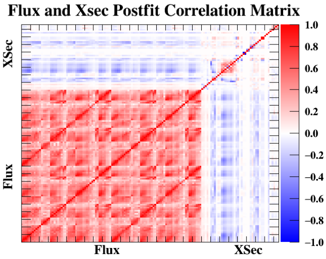


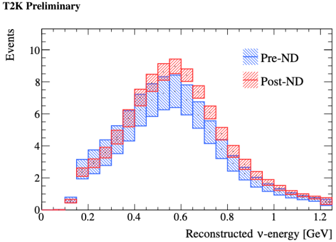
Fits might be combined into one simultaneous fit

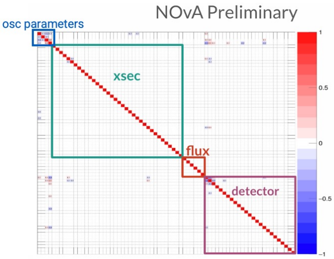


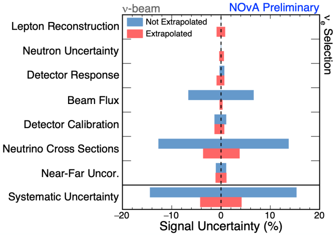
T2K vs NOvA analysis strategy

Different approaches have a similar impact on the resulting systematic uncerts









Joint analysis strategy

Based on Bayesian versions of 2020 analyses: T2K: *EPJC 83 782* NOvA: *PRD 110 012005*

Full statistical treatment of experiments integrated via containerized environment:

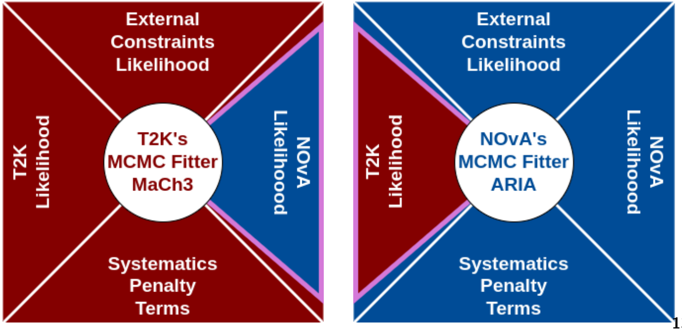
- **Each experiment can run the other's analysis** through an analysis software container
- **Full access to Monte-Carlo and data** while preserving each experiments' unique analysis approach

Two Bayesian Markov Chain Monte Carlo (MCMC) fitters: MaCh3 (T2K) and ARIA (NOvA)

Both give the same output format:

- Results are presented as **posterior densities** and **credible intervals** (regions) for parameters of interest
- Discrete model preferences (neutrino mass ordering, θ_{23} octant) presented with **Bayes factors**

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



Models and systematics

What? When? How much? . . . to correlate common physics parameters between the two experiments?

FLUX MODEL	• Different energies • Different external data tuning • Different treatment in the analysis	$\Rightarrow$	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	$\Rightarrow$	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	$\Rightarrow$	Investigate the impact of correlations in the joint analysis

Checks on impact of correlations in interaction models

Strategy

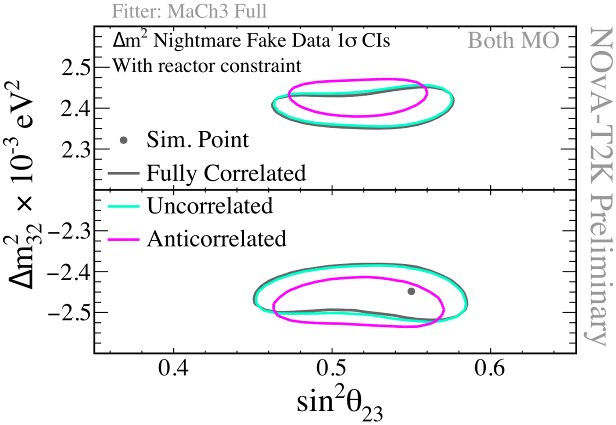
- Study parameters and their inter-experimental correlations with a significant impact on the parameters of interest δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32}

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

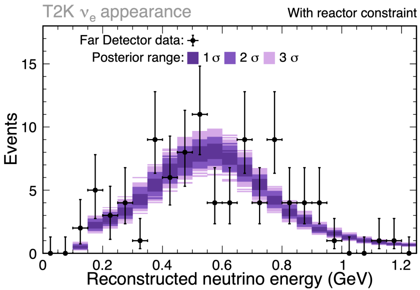


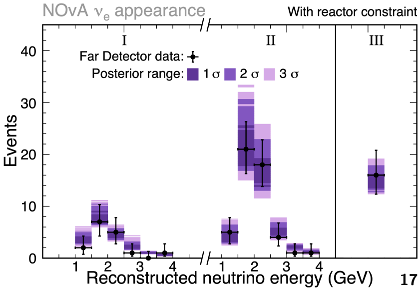
Results

Goodness of fit, compatibility of datasets

- Joint analysis uses data collected by each experiment until 2020
  NOvA: 1.36 (ν) + 1.25 $(\bar{\nu})$ $\times 10^{21}$ POT
  T2K: 1.97 (ν) + 1.63 $(\bar{\nu})$ $\times 10^{21}$ POT
- Using posterior predictive p-values (PPP) to assess the goodness of fit (good PPP is around 0.5)
- **The data from both experiments is described well by the joint fit**

Channel	NOvA	T2K	Total
ν_e	82	$94_{(\nu_e)}$ $14_{(\nu_e 1\pi)}$	**190**
$\bar{\nu}_e$	33	16	**49**
ν_μ	211	318	**529**
$\bar{\nu}_\mu$	105	137	**242**





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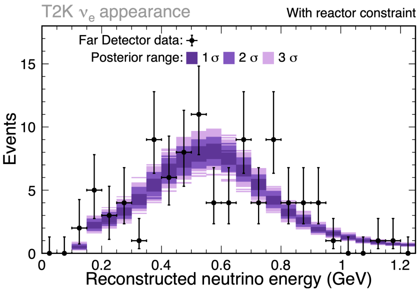
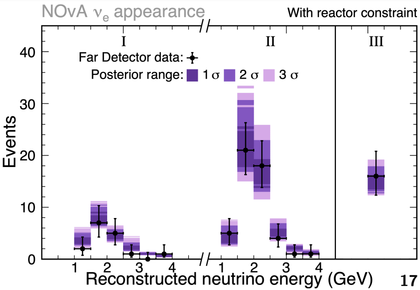
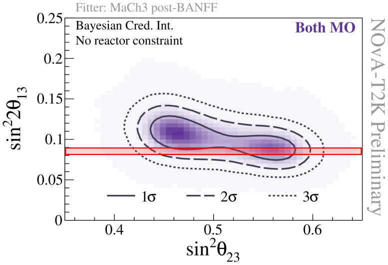
Channel	P-value NOvA	P-value T2K	P-value Combined
ν_e	0.90	$0.19_{(\nu_e)}$ $0.79_{(\nu_e 1\pi)}$	**0.62**
$\bar{\nu}_e$	0.21	0.67	**0.40**
ν_μ	0.68	0.48	**0.62**
$\bar{\nu}_\mu$	0.38	0.87	**0.72**
All	0.64	0.72	**0.75**

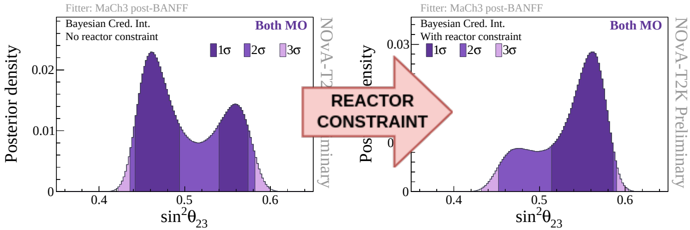


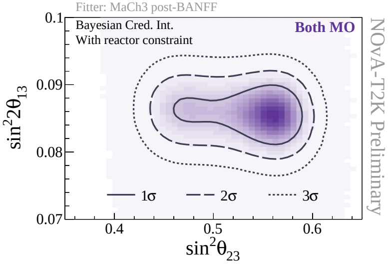


Mixing angles and reactor constraint

- $\sin^2 2\theta_{13}$ value consistent with reactor measurements, but not competitive
- Using PDG 2020 average $\sin^2 2\theta_{13} = 0.0850 \pm 0.0027$ as an external reactor constraint (RC) to change prior
- Using $\sin^2 2\theta_{13}$ RC has a large impact on the $\sin^2\theta_{23}$ octant preference, otherwise nearly degenerate
- **Bayes factor of 3.6 for upper octant preference (modest)** with RC
- From now on, **all results with RC**



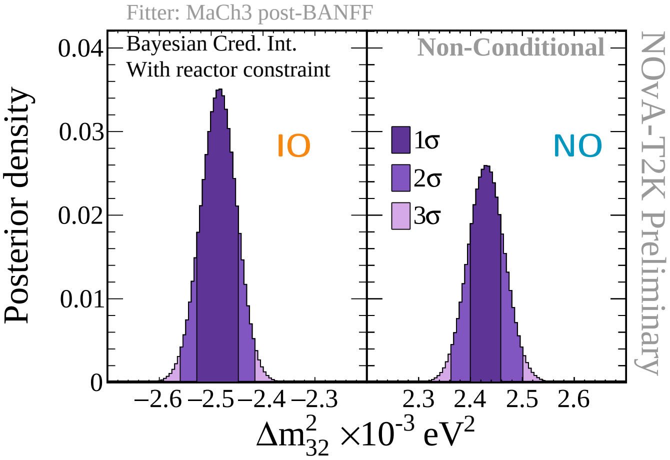




Δm^2_{32}

- Using posterior probability distribution integral in each Δm^2_{32} hyperplane to calculate Bayes factor for IO/NO preference
- **Very weak preference for IO, Bayes factor 1.3**
- **Posterior probability 57% for $\Delta m^2_{32} < 0$**
- **Posterior probability 43% for $\Delta m^2_{32} > 0$**

- Consistent with other measurements
- **Smallest uncertainty in $\Delta m^2_{32} < 2$ %** (newest NOvA 2024 results competitive)



Marginalizing over $\Delta m^2_{32} \lessgtr 0$ separately leads to NO/IO **"conditional" credible regions**

$$\Delta m^2_{32}\big|_{\mathrm{IO}} = -2.48^{+0.03}_{-0.04} \times 10^{-3}\ \mathrm{eV}^2$$

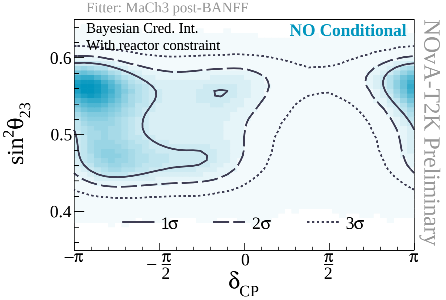
$$\Delta m^2_{32}\big|_{\mathrm{NO}} = 2.43^{+0.04}_{-0.03} \times 10^{-3}\ \mathrm{eV}^2$$

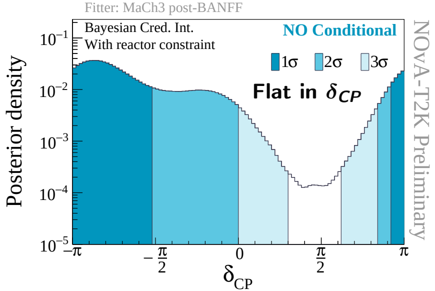
δ_{CP}

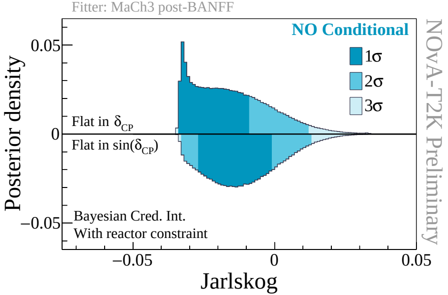
- **Neither ordering** has a preference for δ_{CP} values around $+\pi/2$ (outside 3σ CI)
- **Normal ordering** allows for a **broad range** of possible δ_{CP}
- **For inverted ordering CP-conserving δ_{CP} values outside 3σ CIs**
- Independent measurement with Jarlskog invariant

$$J_{CP} = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}; \qquad s_{ij} = \sin\theta_{ij},\, c_{ij} = \cos\theta_{ij}$$

- Robust under change of δ_{CP} prior







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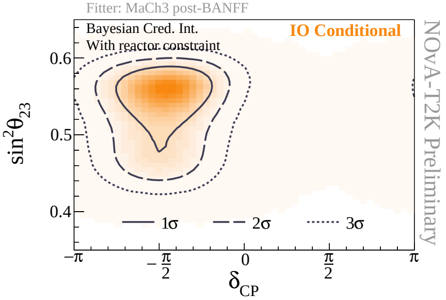
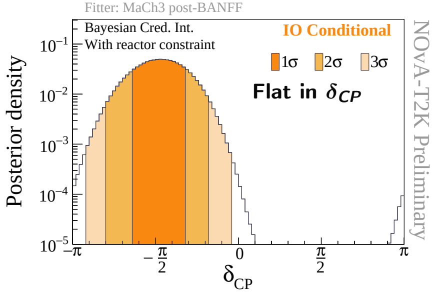
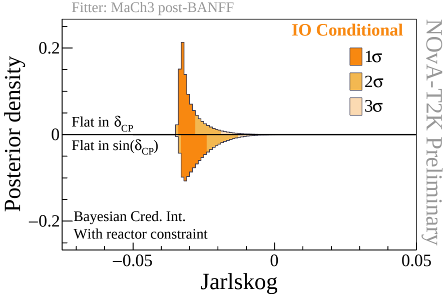
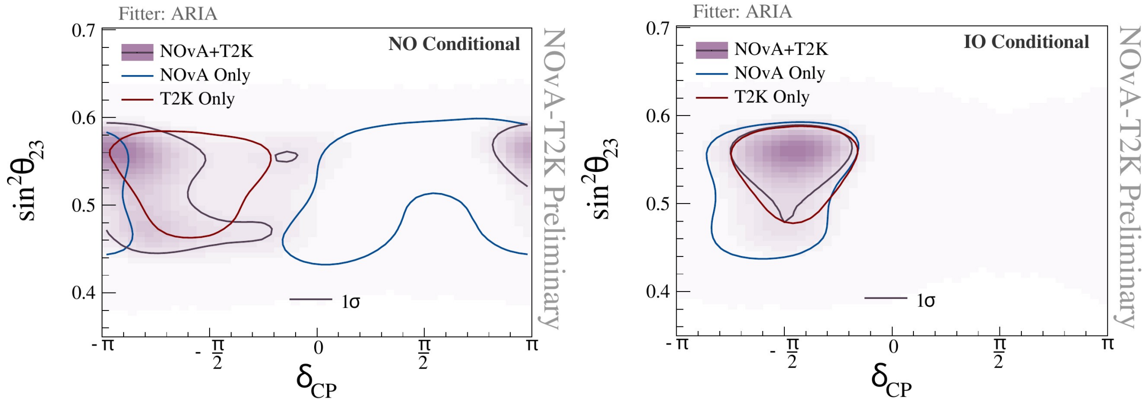






Comparison to NOvA-only and T2K-only results

The joint fit is well in agreement with both individual fits



Conclusions

Conclusions

- Joint T2K and NOvA analysis results show compatibility of both experiments' datasets within a 3ν-paradigm
- Good posterior predictive p-value

SUMMARY OF RESULTS

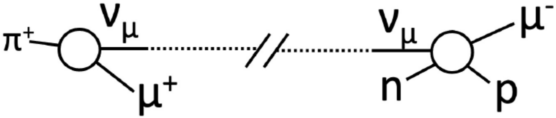
- **No strong preference for mass ordering**
  Bayes factor 1.3 for IO not statistically significant
- New Δm^2_{32} precision < 2 %
- About 1σ (Bayes factor 3.6) preference for $\theta_{23} > 45^\circ$
- $\delta_{CP} = \pi/2$ **disfavored at** 3σ
- CP conserving values of $\delta_{CP} = 0, \pi$ lies outside the 3σ CI in the case of IO

OUTLOOK

- Expected to double the statistics from both experiments in coming years
- Knowledge sharing and exchange of information resulted in a deeper understanding of each experiment
- Actively exploring the scope and timeline for the next steps to bring the joint analysis forward

BACKUP

Disappearance oscillation probabilities



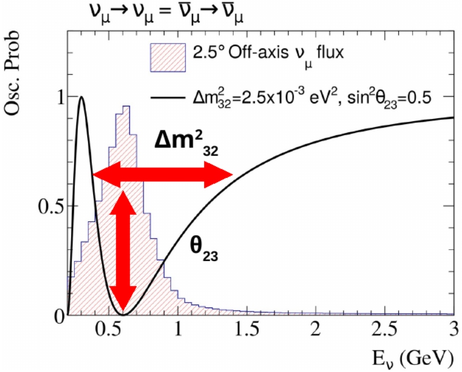
Leading order $\sin^2 2\theta_{23}$ and Δm^2_{32}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$\sin^2 2\theta_{23}$:
mixing angles rule the oscillation amplitude

Δm^2_{32} :
squared mass-splittings rule the oscillation frequency

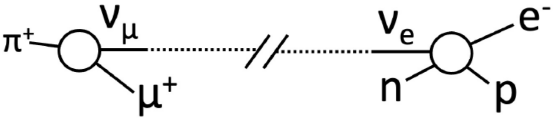
Max $\sin^2\theta_{23} = 1$ corresponds to maximal mixing of $\theta_{23} = 45°$



$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

Squared mass-splittings of neutrino masses

Appearance oscillation probabilities



Leading order $\sin^2\theta_{23}, \sin^2 2\theta_{13}$ and Δm^2_{32} in vacuum

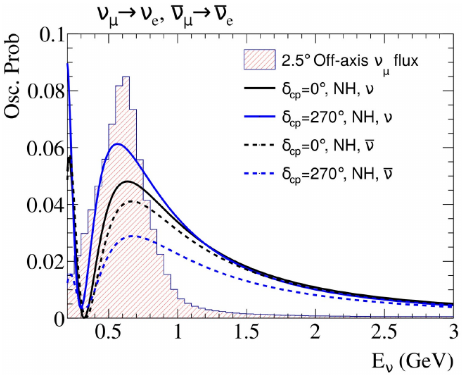
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

+ δ_{CP} dependent terms CP violating
+ δ_{CP} dependent terms CP conserving
+ other terms

$\delta_{CP} = \pi/2$: less $\nu_\mu \to \nu_e$, more $\bar{\nu}_\mu \to \bar{\nu}_e$
$\delta_{CP} = -\pi/2$: more $\nu_\mu \to \nu_e$, less $\bar{\nu}_\mu \to \bar{\nu}_e$

Matter effects

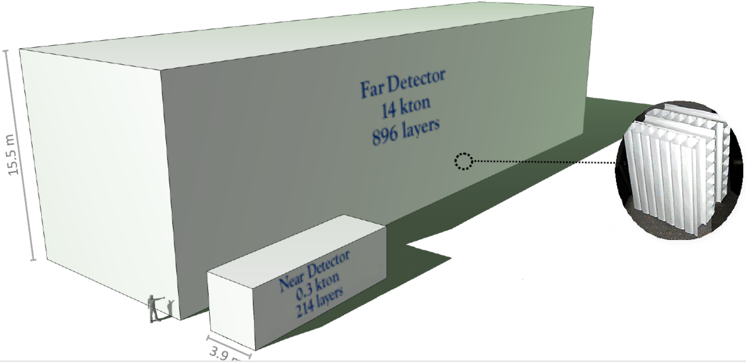
ν_e coherent forward scattering on pseudo-free electrons of matter modify $\nu_\mu \to \nu_e$, depends on the **sign of Δm^2_{32}** (mass ordering)

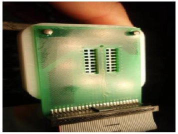


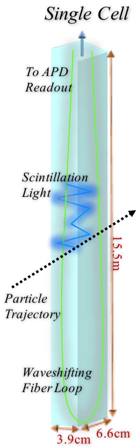
NOvA vs T2K Comparison

Experiment	**NOvA**	**T2K**
Country Laboratory Started	USA Fermilab 2014	Japan KEK, J-PARC 2010
Baseline ν energy peak Off angle	810 km 2 GeV 0.84° / 14.6 mrad	295 km 0.6 GeV 2.5° / 43.6 mrad
ν Source $\nu + \bar{\nu}$ POT 2020	120 GeV protons, max 760 kW $(1.36 + 1.25) \times 10^{21}$	30 GeV protons, max 515 kW $(1.97 + 1.63) \times 10^{21}$
Near Detector	**NOvA ND** liquid scintillator tracking calorimeter NO MAGNET	**ND280** TPC trackers targets of pl. scintillator or water magnetized to distinguish $\nu_\mu/\bar{\nu}_\mu$
Far Detector	**NOvA FD** 14 kt liquid scintillator tracking calorimeter	**SuperK** 50 (22.5) kt water Cherenkov 13k (11k) PMTs
ν interactions	QE, 2p2h, RES, DIS mix	Mostly QE, 2p2h and RES bkg
Near-to-far	Direct correction of FD MC based on the ND data (F/N trans.)	Fit to ND data which constrains the interaction and flux parameters
Energy estimator	Lepton and hadronic calorimetry	Lepton kinematics (elastic)

NOvA detectors

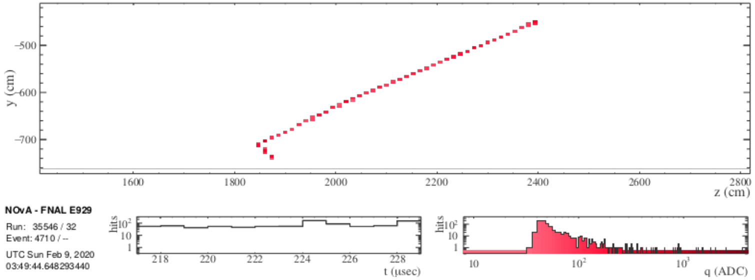


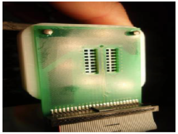


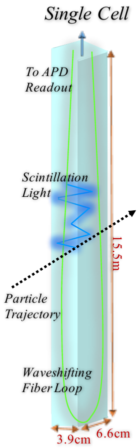


- Two functionally similar detectors 810 km apart – **Near (ND)** and **Far (FD)**
- FD on the surface, ND about 100 m underground
- Consist of extruded plastic cells with alternating vertical and horizontal orientation for 3D reconstruction of neutrino interactions
- Filled with liquid scintillator, tracking calorimeter with 65% active mass (FD 14 kton, ND 0.3 kton)
- Energy estimation from μ range, EM and hadronic shower calorimetry

NOvA detectors







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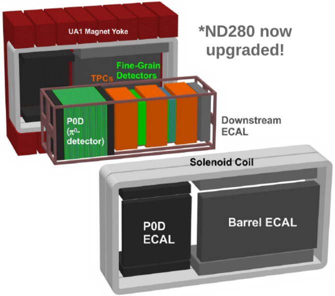
T2K detectors

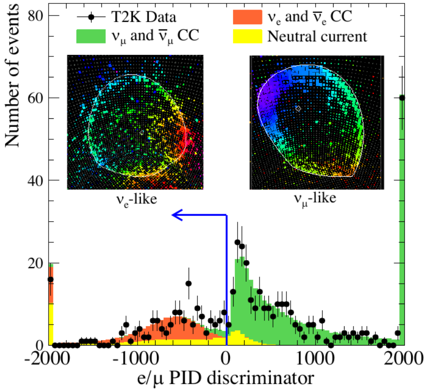
ND280

- TPC tracker with excellent PID
- Plastic scintillator target (C) + water layers (O)
- **MAGNETIZED** to distinguish ν_μ and $\bar{\nu}_\mu$
- Selected neutrino events with reconstructed μ track and number of π: CC1μ0π, CC1μ1π, CC1π



*ND280 now upgraded!

Adapted from arXiv:1910.03887v2

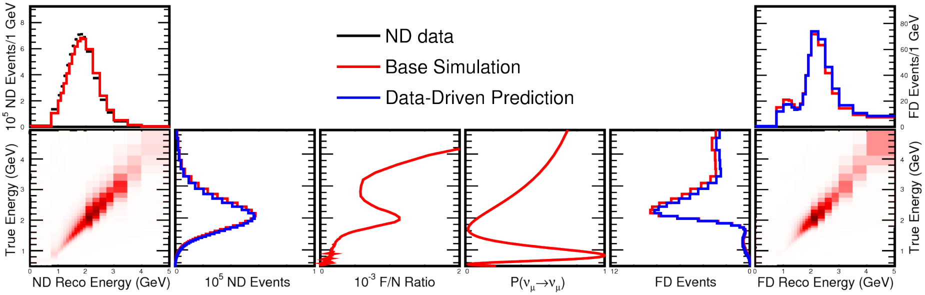


Super-Kamiokande

- 50kt water Cherenkov detector
- Excellent μ/e-like Cherenkov rings separation (ν_μ vs ν_e CC interactions)
- Reconstruction from lepton kinematics

NOvA analysis strategy

- ND sees the neutrino spectrum as a combination of **neutrino *flux*** from NuMI, **CC *cross sections***, ***detector acceptance*** and ***selection efficiency***
- The ND measured spectra are used to correct FD MC oscillated predictions using the **Far/Near (F/N)** transformation
- Due to functional similarity of both detectors, this procedure largely cancels detector correlated uncertainties (ν flux and cross sections)



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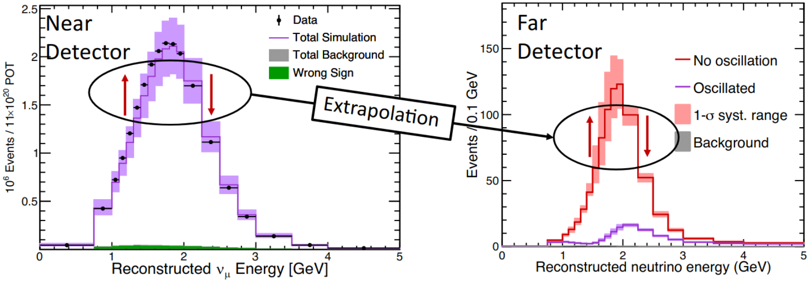
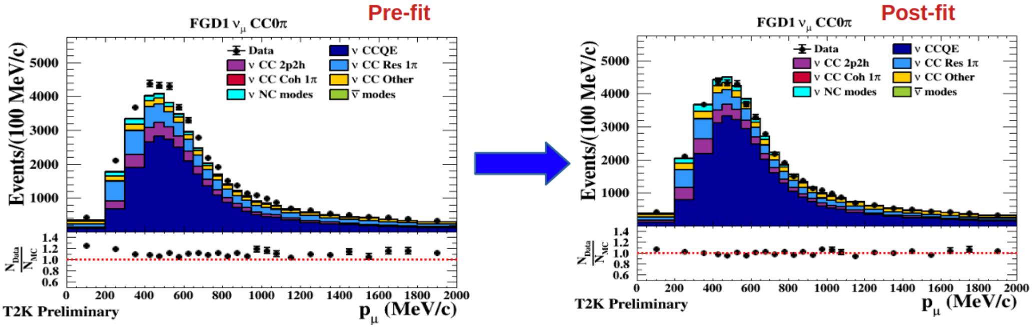
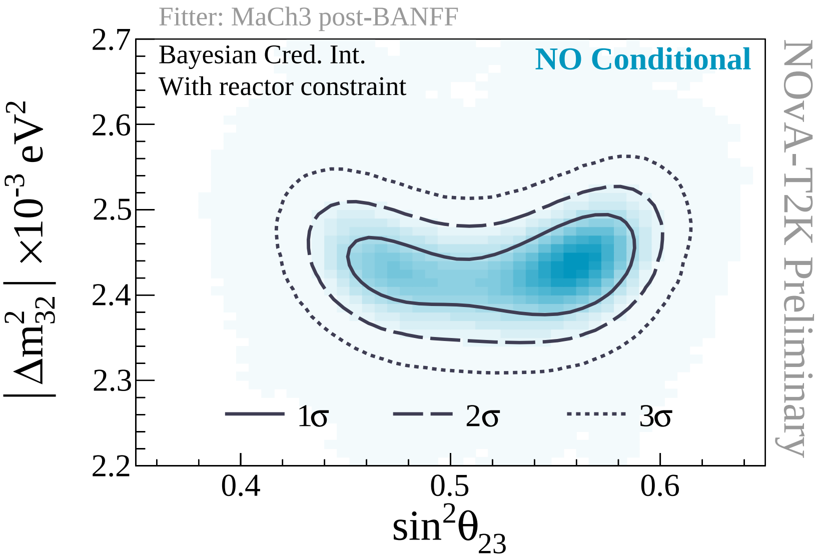


T2K analysis strategy

- **Fit to ND280 data move the model parameters** from their -pre-fit values and also **constrain them**
- This data fit might be **sequential** (ND fit → constrained model → FD fit) or **simultaneous** (ND+FD data simultaneous fit)



Δm^2_{32} vs. $\sin^2\theta_{23}$



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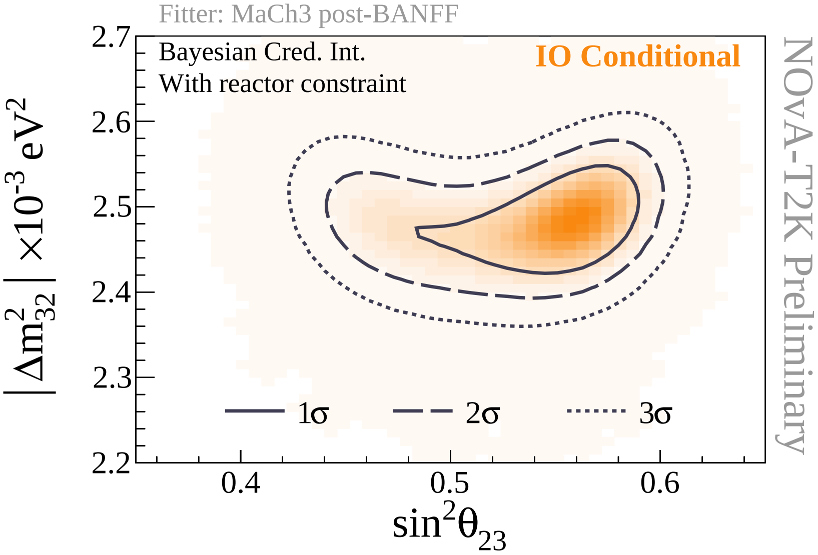
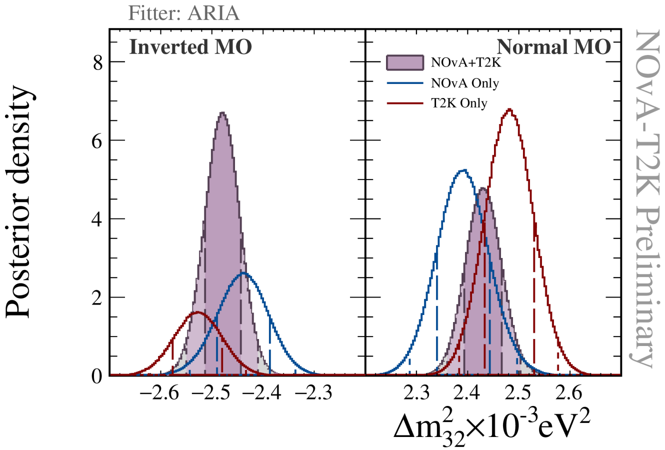


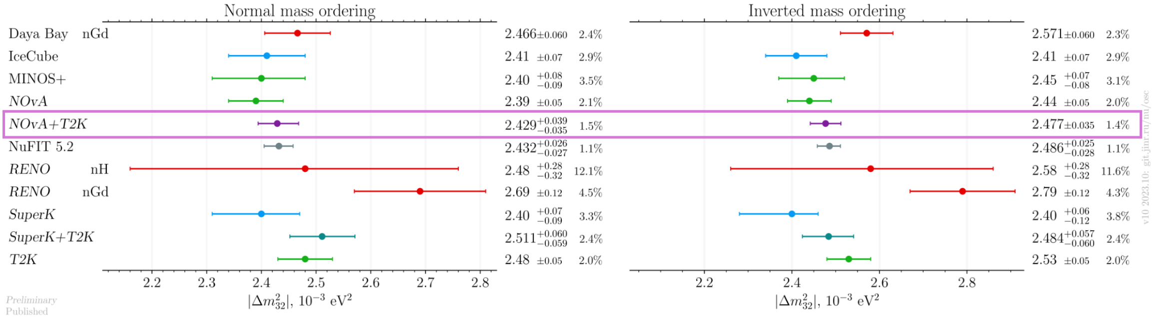
Comparison to NOvA-only and T2K-only results



- Joint analysis flips the preference for the IO
- T2K and NOvA individually prefer NO
- **Joint analysis enhances Δm^2_{32} precision**

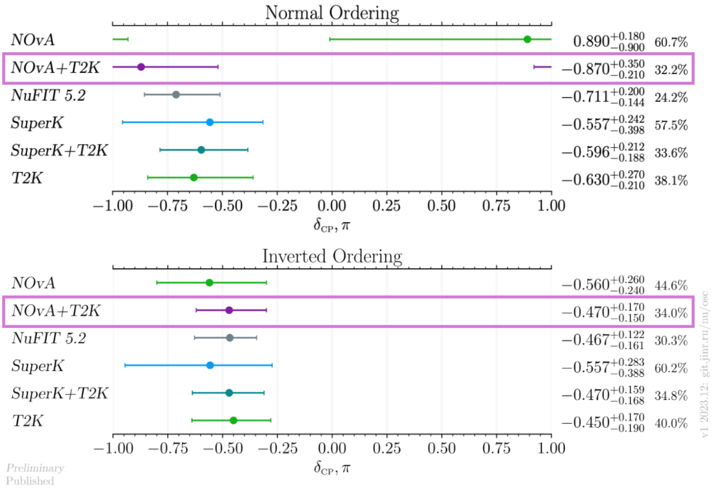
Δm^2_{32} global comparisons

- Δm^2_{32} measurements are largely consistent across different experiments
- This analysis **has smallest uncertainty in Δm^2_{32}** (newest NOvA 2024 results competitive)
- Showing 1σ CIs for Δm^2_{32} for both orderings conditionally

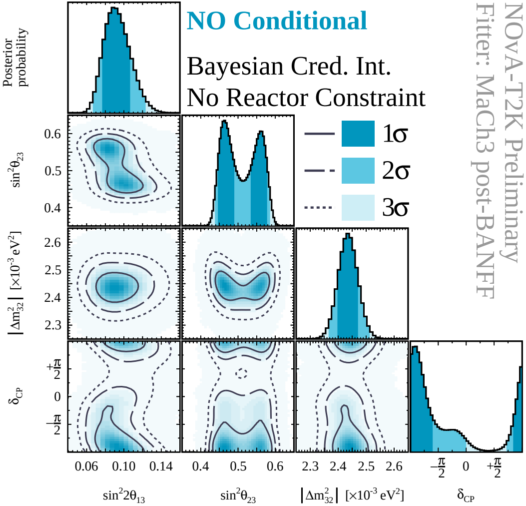


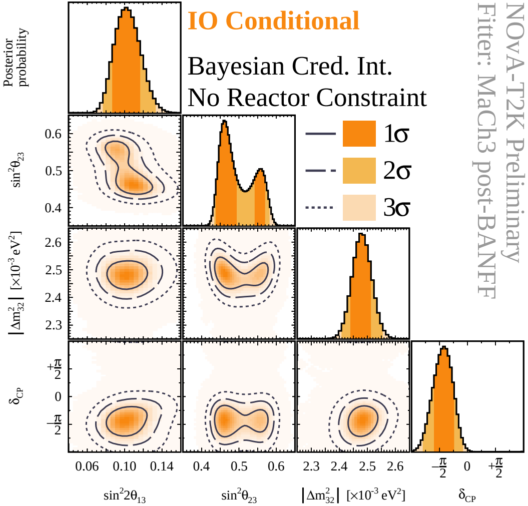
δ_{CP} global comparisons

- δ_{CP} measurements are consistent across many experiments and joint analyses
- Precision is still limited by the low statistics

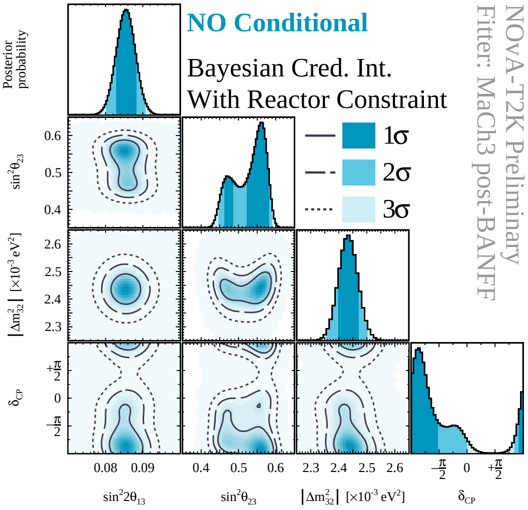


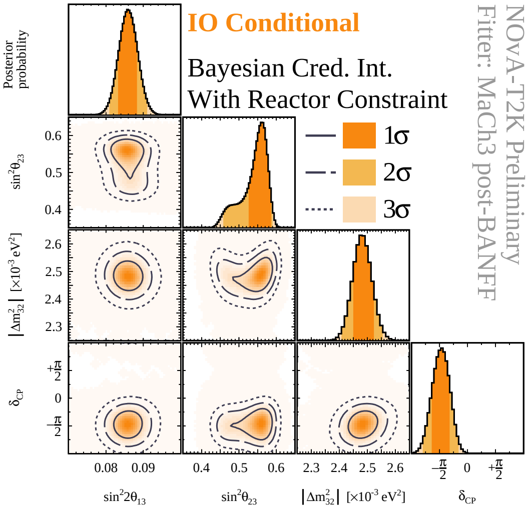
Results w/o reactor constraint, triangle plots



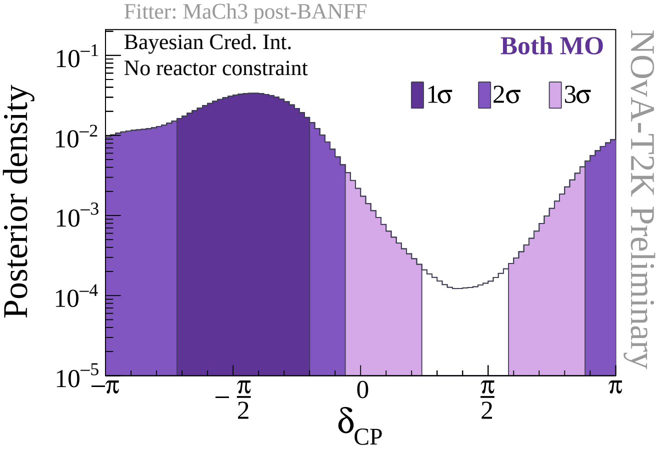


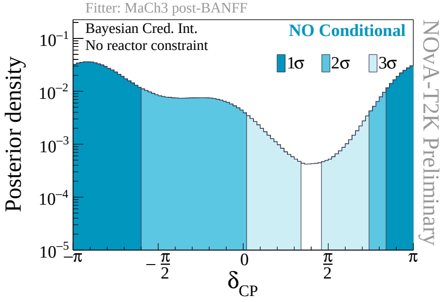
Results with reactor constraint, triangle plots

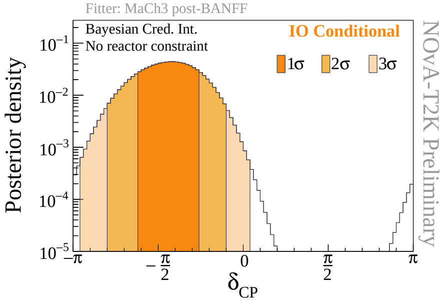




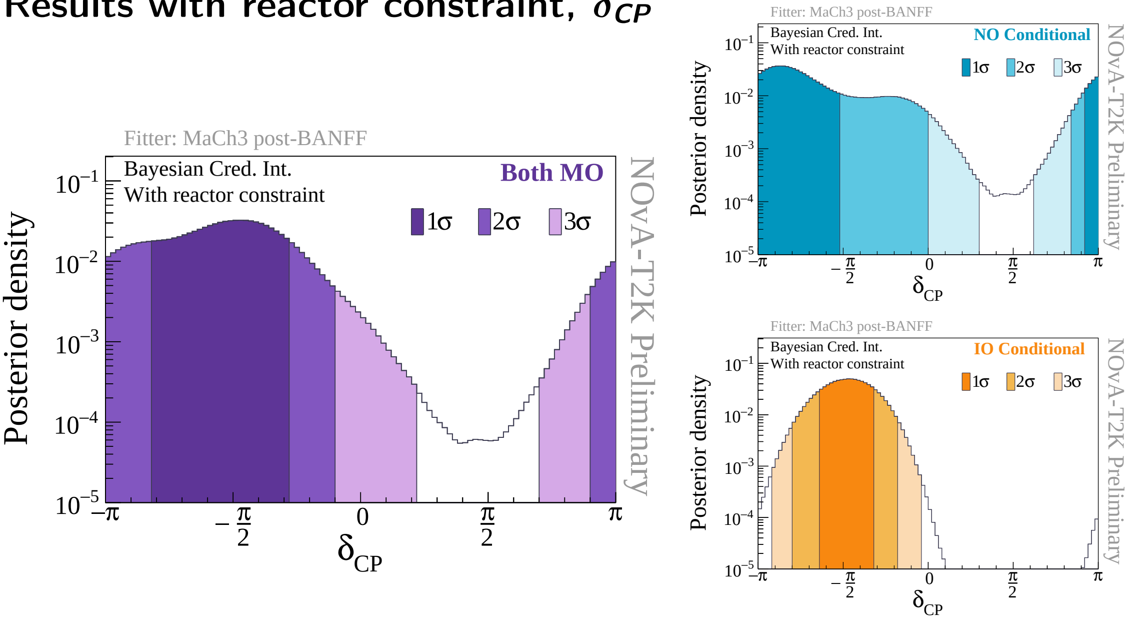
Results w/o reactor constraint, δ_{CP}





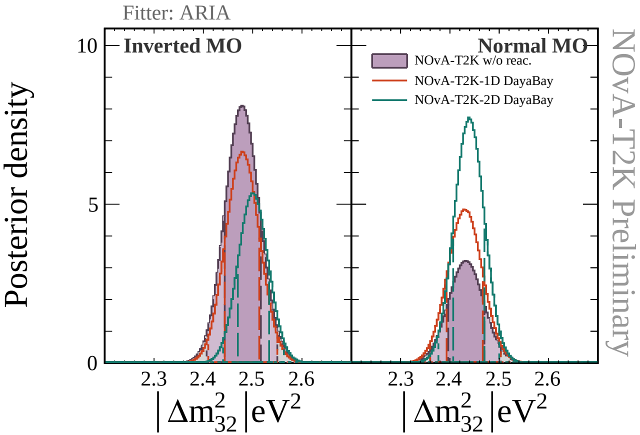


Results with reactor constraint, δ_{CP}



Daya Bay 2D constraints $\sin^2 2\theta_{13}$ and Δm^2_{32}

	NO RC	**1D** RC	**2D** RC
Mass ordering	2.4 71%:29% IO:NO	1.3 57%:43% IO:NO	1.4 59%:41% NO:IO
θ_{23} octant	1.2 54%:46% LO:UO	3.6 78%:22% UO:LO	3.2 76%:24% UO:LO



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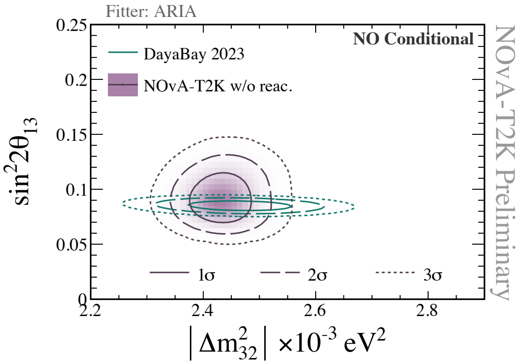
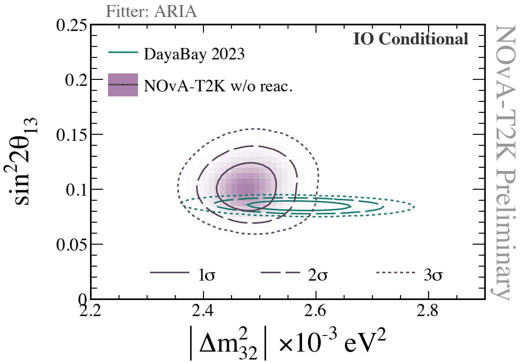
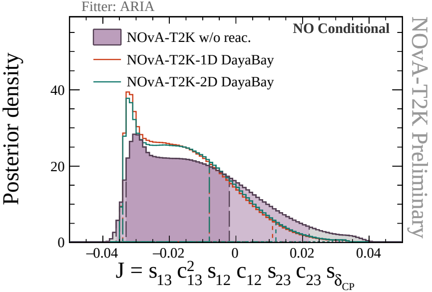
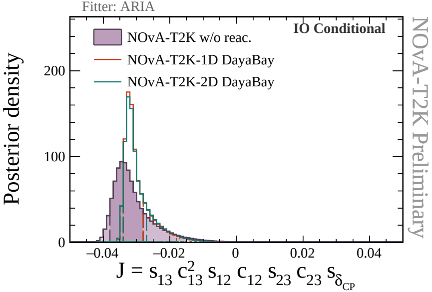




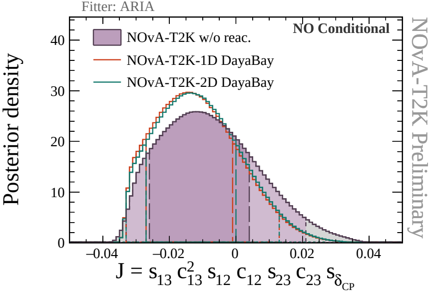
Daya Bay 2D constraints Jarlskog

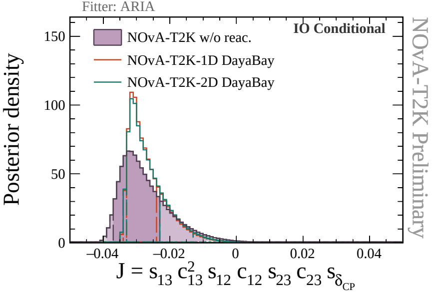
Prior flat in δ_{CP}



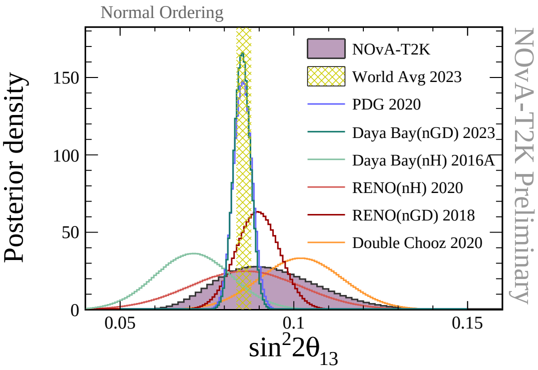


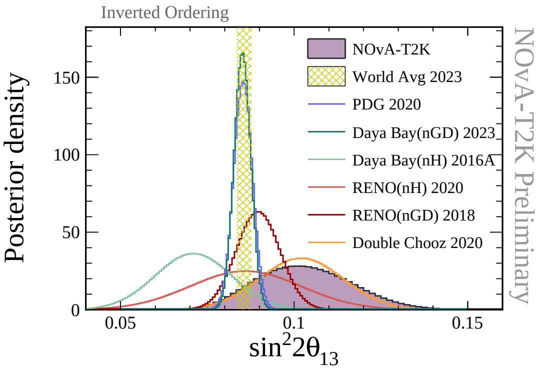
Prior flat in $\sin\delta_{CP}$



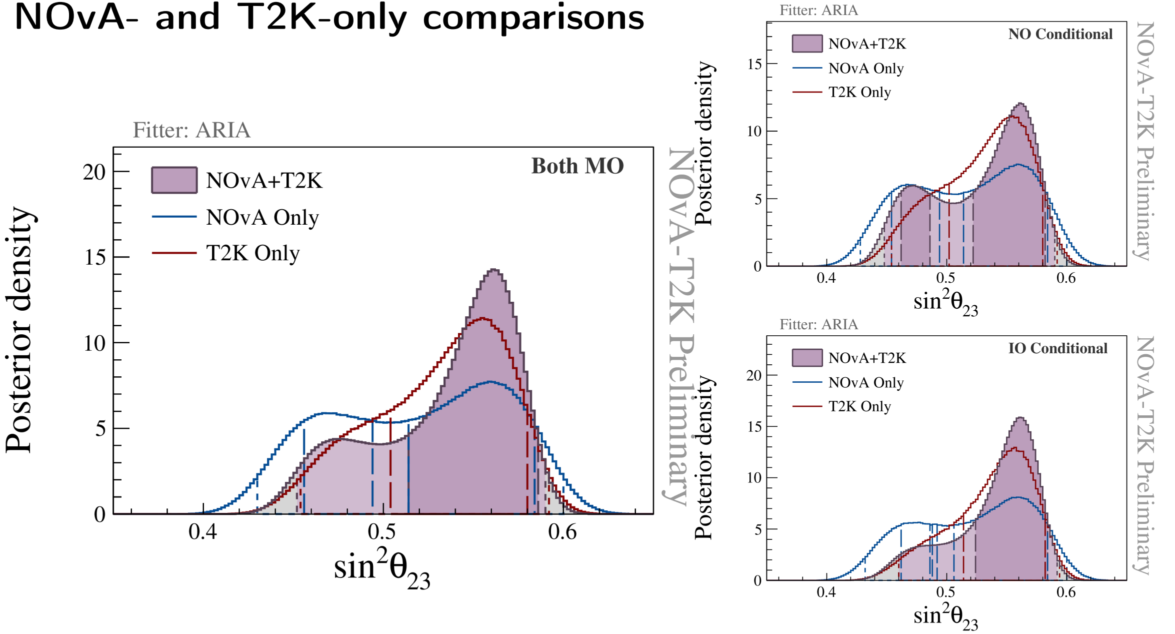


$\sin^2 2\theta_{13}$ comparisons





NOvA- and T2K-only comparisons



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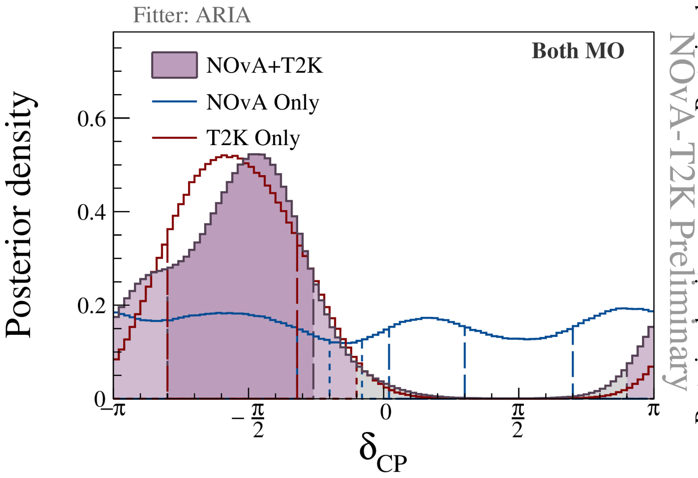
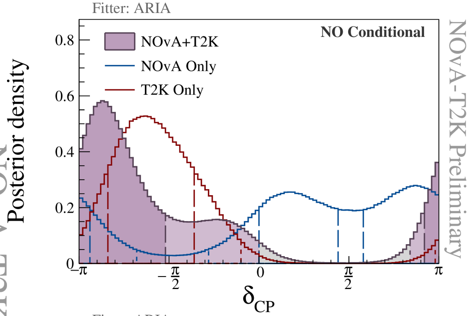
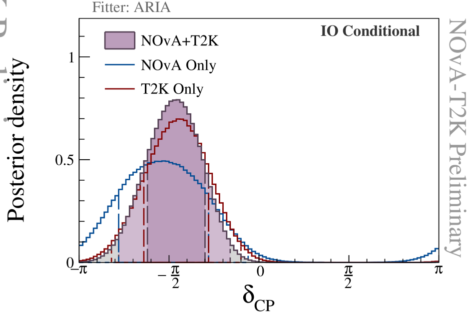
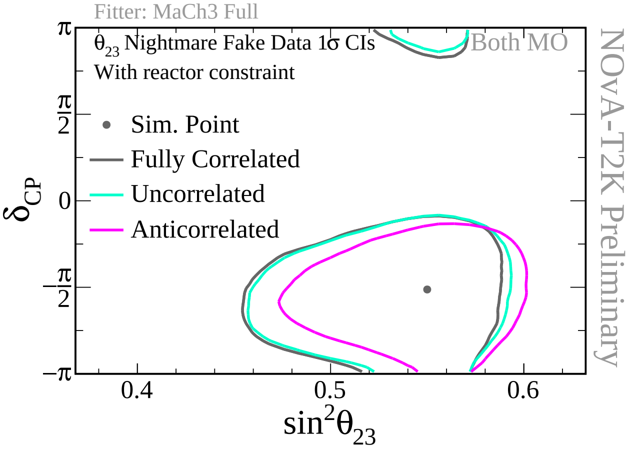


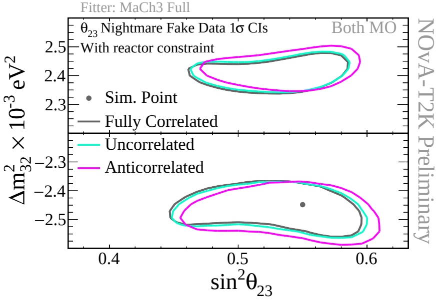


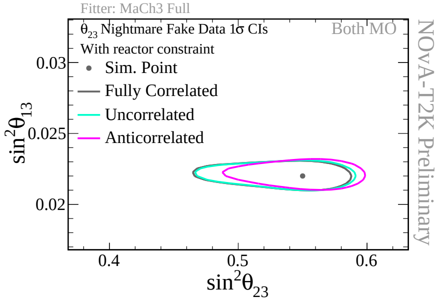


Correlation studies, θ_{23} nightmare

Derived as a 15% normalization systematic between 0.4 and 0.8 GeV for T2K and as an inflated neutron tagging systematic for NOvA

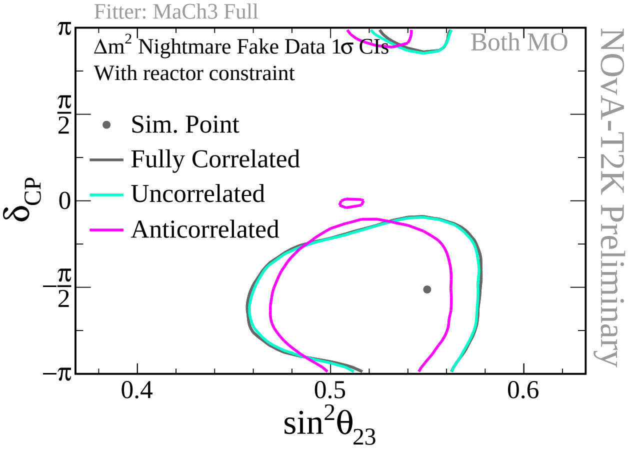


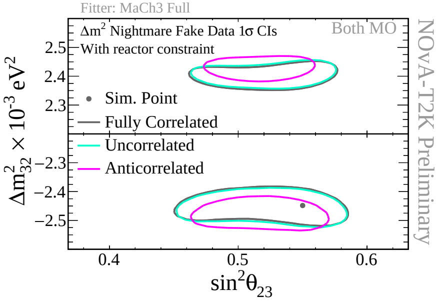


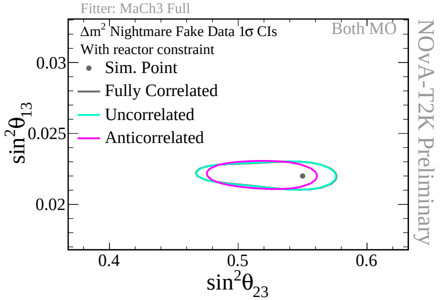


Correlation studies, Δm^2_{32} nightmare

Derived as a 10% energy scale systematic for T2K
and as an inflated neutron tagging systematic for NOvA







Checks on alternative models

- Evaluate the robustness of the analysis against alternative models
- Generate mock data for both experiments by changing MC simulation with several sets of oscillation parameters
- Fit the mock data and check the impact on the results

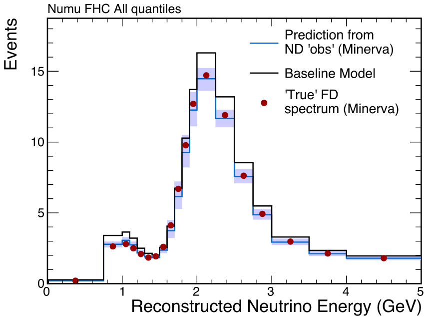
Pre-decided criteria to assess the impact

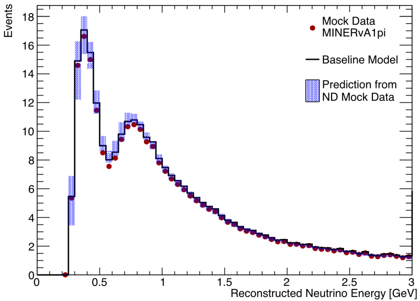
- Change in the width of 1D credible intervals $< 10\%$
- Change in central value is not larger than 50% of estimated systematic uncertainty

Example is for the suppression in single π channel seen in the MINERvA results *PRD 100 072005*

Additional tests: cross-experiment models after ND constraint, alternative nuclear response model HF-CRPA, . . .

No alternate model tests failed the preset threshold bias criteria





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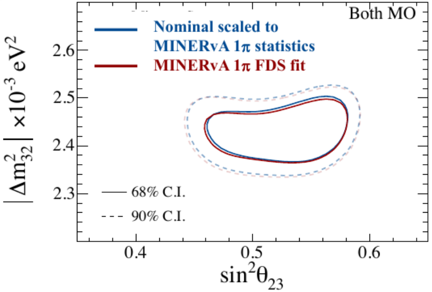
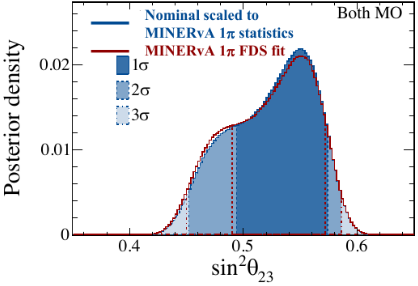




Alternative models studies

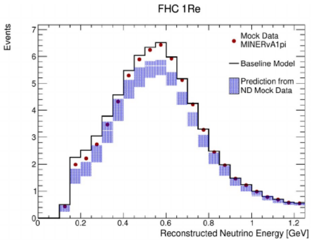
Studied 3 alternate models which gave largest biases for the T2K 2020 analysis:

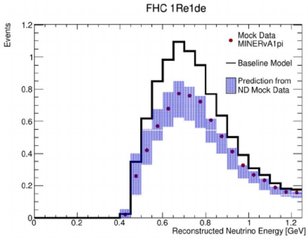
"Non-QE" ND280 CC0π data are under-predicted by the T2K pre-fit prediction. This difference can be taken accounted for by the large freedom in the CCQE model. To check this large freedom does not cause bias, an alternate model where this underprediction is attribution to only non-QE processes is produced. See *Eur.Phys.J.C 83 782* for details.

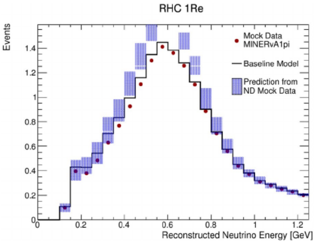
"MINERvA-1π" Suppression of CC and NC resonant pion production at low-Q2 to describe for GENIE v2 implementation of Rein-Seghal model to describe the data, *PRD 100 072005*.

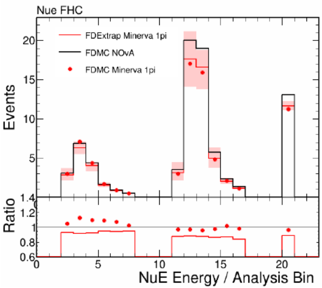
"π SI" GEANT4 model (10.1016/S0168-9002(03)01368-8) was replaced with NEUT's Salcedo–Oset (10.1016/0375-9474(88)90310-7).

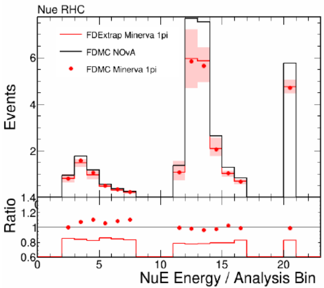
Alternative models studies, MINERvA-1π mock data







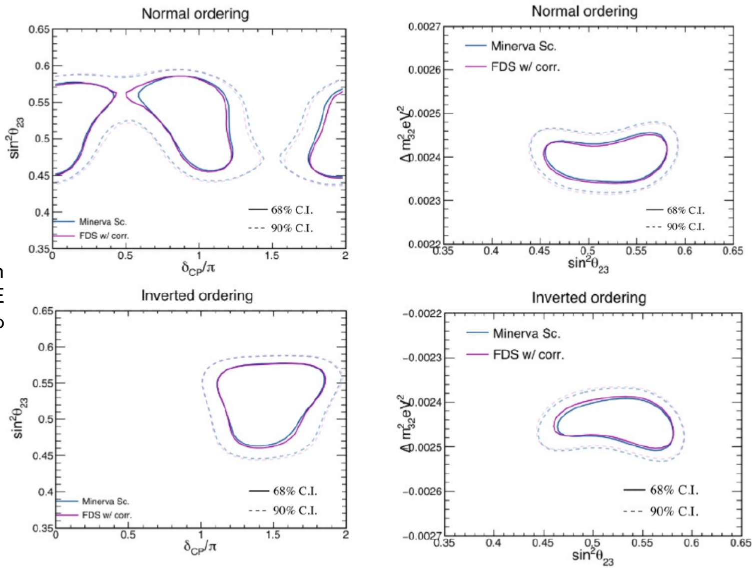




Alternative models studies, MINERvA-1π comparisons

"MINERvA-1π"

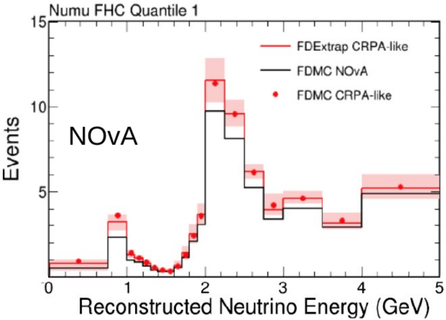
Suppression of CC and NC resonant pion production at low-Q2 to describe for GENIE v2 implementation of Rein-Seghal model to describe the data.

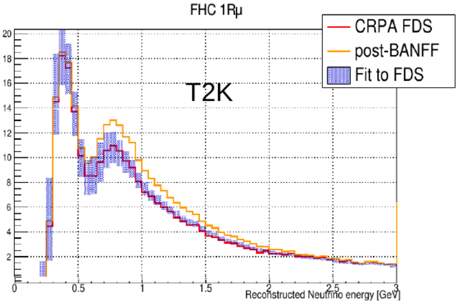


Alternative models studies, HF-CRP

Hartree Fock (HF) – Continuum Random Phase Approximation (CRPA), 10.1103/PhysRevC.92.024606

- Applies modifications to the nuclear models (Spectral Function for T2K, Local Fermi Gas for NOvA)
- Recent T2K analyses have included an additional smearing on Δm^2_{32} due to bias seen when studying this alternate model
  - T2K and NOvA independently studied the impact of this on their 2020-era analyses
  - When taken together in the context of the joint analysis, the bias is not larger than the thresholds set for any of the other alternate models





Joint analysis strategy

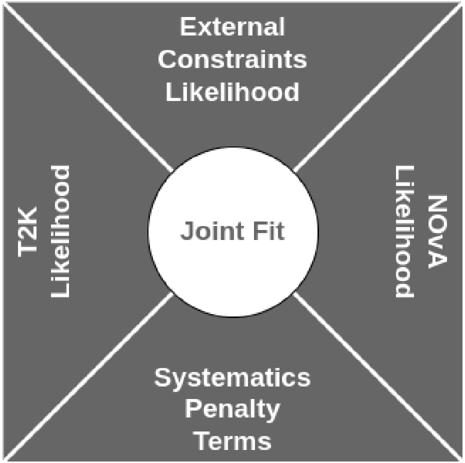
Based on Bayesian versions of 2020 analyses
T2K: *Eur.Phys.J.C 83 782*
NOvA: *arXiv:2311.07835*

Full statistical treatment of experiments

- **Poisson likelihood** from each experiment
- Prior **constraints on nuisance parameters** (systematics pulls)
- **External constraints** on θ_{13}, θ_{12} and Δm^2_{21} used as **priors** on oscillation parameters

Integrated via containerized environment

- **Each experiment can run the other's analysis** trough an analysis software container
- **Full access to Monte-Carlo and data**
- Preserving each experiments' unique analysis approach



Joint analysis strategy

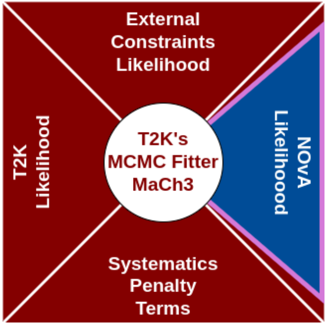
Two Bayesian Markov Chain Monte Carlo (MCMC) fitters: MaCh3 (T2K) and ARIA (NOvA)

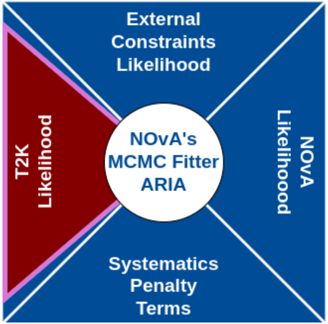
Both give the same output format

- Results are presented as **posterior densities** and **credible intervals** (regions) for parameters of interest
- Discrete model preferences (neutrino mass ordering, θ_{23} octant) presented with **Bayes factors**

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

- MaCh3 SK fit with ND280 constraints interfacing with ARIA
- ARIA fit interfacing with MaCh3 with ND280 constraints
- MaCh3 simultaneous ND280+SK fit interfacing with ARIA





Fitters comparisons