New NOvA Results with 10 Years of Data

Jeremy Wolcott
Tufts University
for the NOvA Collaboration

This document was prepared by the NOvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.
Recent NOvA -T2K Joint Fit Results

Jeremy Wolcott
Tufts University

for the NOvA & T2K Collaborations
NOvA and T2K are complementary

Compared to T2K*, NOvA has **Higher $E_{\nu}$**

* See previous talk for more on T2K
NOvA and T2K are complementary

Compared to T2K*, NOvA has **Higher** $E_{\nu}$
(and a corresponding longer baseline)

**Larger matter effects**

T2K: $L=295$ km, $E=0.6$ GeV

NOvA: $L=810$ km, $E=2.0$ GeV

*See previous talk for more on T2K*
NOvA and T2K are complementary

Compared to T2K*, NOvA has Higher $E_\nu$

Larger matter effects

T2K: $L=295$ km, $E=0.6$ GeV

- More antineutrinos
- More final-state pions

NOvA: $L=810$ km, $E=2.0$ GeV

- Inverted ordering
- Normal ordering

Also...

- More antineutrinos
- More final-state pions

(see overflow slides)

Stronger mass ordering sensitivity;
more $\delta_{CP}$ degeneracy

* See previous talk for more on T2K
NOvA and T2K are complementary

Compared to T2K*, NOvA uses a different experimental approach

* See previous talk for more on T2K
NOvA and T2K are complementary

Compared to T2K*, NOvA uses a different experimental approach

**NOvA**
active scintillator calorimeters

- see significant energy from both lepton and hadron systems: “calorimetric” $E_\nu$ reconstruction
- & functionally equivalent detectors
  - shared uncertainties mostly cancel

**T2K**
water Cherenkov FD

- see only lepton energy: “kinematic” $E_\nu$ reconstruction

* See [previous talk](#) for more on T2K

Hybrid gas TPC & scintillator tracker ND

ND+FD shared uncertainties explicitly fitted & constrained via model
NOvA-T2K joint fit: PMNS parameters

Joint fit splits the difference b/w NOvA-only & T2K-only in NO; improves constraint in IO

NOvA only: Phys. Rev. D106, 032004 (2022)

“assuming IO is true”
(does not include relative probability of IO vs. NO)
NOvA-T2K joint fit: takeaways

Advancing the precision frontier on $|\Delta m_{32}^2|$<2% measurement!

<table>
<thead>
<tr>
<th>Inverted mass ordering</th>
<th>2.477±0.005</th>
<th>1.4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOvA+T2K$^{[1]}$</td>
<td>2.53 ± 0.05</td>
<td>2.0%</td>
</tr>
<tr>
<td>T2K$^{[2]}$</td>
<td>2.44 ± 0.05</td>
<td>2.0%</td>
</tr>
<tr>
<td>NOvA$^{[3]}$</td>
<td>2.45 ± 0.08</td>
<td>3.1%</td>
</tr>
<tr>
<td>MINOS+$^{[4]}$</td>
<td>2.40 ± 0.04</td>
<td>1.9%</td>
</tr>
<tr>
<td>IceCube$^{[6]}$</td>
<td>2.48±0.007 -0.060</td>
<td>2.4%</td>
</tr>
<tr>
<td>SuperK+T2K$^{[5]}$</td>
<td>2.48 ± 0.12</td>
<td>3.6%</td>
</tr>
<tr>
<td>Daya Bay$^{[7]}$ nGd</td>
<td>2.571±0.006</td>
<td>2.3%</td>
</tr>
<tr>
<td>RENO$^{[8]}$ nGd</td>
<td>2.79 ± 0.12</td>
<td>4.3%</td>
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<tr>
<td>RENO$^{[9]}$ nH</td>
<td>2.58 ± 0.28 -0.32</td>
<td>11.6%</td>
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[1] KEK IPNS seminar, FNAL JETP seminar
NOvA-T2K joint fit: takeaways

Advancing the precision frontier on $|\Delta m^2_{32}|$ <2% measurement!

| Inverted mass ordering | $|\Delta m^2_{32}|$, $10^{-3} \text{ eV}^2$ |
|------------------------|------------------------------------------|
| NOvA+T2K$^{[1]}$      | 2.477 $\pm$ 0.005, 1.4%                |
| T2K$^{[2]}$            | 2.53 $\pm$ 0.05, 2.0%                   |
| NOvA$^{[3]}$           | 2.44 $\pm$ 0.05, 2.0%                   |
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| Daya Bay$^{[8]}$ nGd  | 2.571 $\pm$ 0.000, 2.3%                 |
| RENO$^{[9]}$ nGd      | 2.79 $\pm$ 0.012, 4.3%                  |
| RENO$^{[9]}$ nH       | 2.58 $\pm$ 0.28, 11.6%                  |

Mild preference for Inverted Ordering but influenced by $\theta_{13}$ constraint

- NOvA+T2K only
  - IO (71%)
- NOvA+T2K + 1D $\theta_{13}$
  - IO (57%)
- NOvA+T2K + 2D ($\theta_{13}$, $\Delta m^2_{32}$)
  - NO (59%)

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Mild preference for Inverted Ordering but influenced by $\theta_{13}$ constraint

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<td>IO (71%)</td>
<td>IO (57%)</td>
<td>NO (59%)</td>
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CP-conserving points are outside 3$\sigma$ intervals in IO
Expect CPV if ordering is inverted

[1] KEK IPNS seminar, FNAL JETP seminar
NOvA+T2K summary & outlook

• NOvA & T2K’s first joint results:
  – Yield strong constraint on $\Delta m^2_{32}$
  – Weakly prefer IO or NO depending on which reactor constraint is applied
  – Strongly favor CP violation in Inverted Ordering

[more detail also available in Feb. 16, 2024 results seminars]
Edward Atkin, KEK IPNS seminar
Zoya Vallari, FNAL JETP seminar
New NOvA Results
New NOvA Results

- Recent NOvA-T2K Joint Fit Results
  - New neutrino oscillation results from NOvA with 10 years of data
- 3 nu current global analysis

Claudio Giganti
Milano
11:10 - 11:35

Jeremy Wolcott
Milano
12:00 - 12:30
The NuMI neutrino beam

Approaching megawatt beam!
- Typically ~900 kW
- Record 959 kW

2014-2023: 10 years of beam to NOvA!
This analysis: +96% neutrino beam
\[ \nu: 26.61 \times 10^{20} \text{ POT} \]
\[ \bar{\nu}: 12.50 \times 10^{20} \text{ POT} \]
The NOvA detectors

- ND & FD are segmented liquid scintillator detectors
- $4 \times 6 \text{ cm}^2$ PVC cells $\rightarrow$ 
- $\sim 6$ samples / rad
NOvA detector characterization

Improved light production model
(Cherenkov & scintillation)
in both detectors, from dedicated bench measurements & *in situ*
stopping muon and proton tracks
NOvA detector characterization

Improved light production model
(Cherenkov & scintillation)
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 stopping muon and proton tracks

Difference between
MENATE_R* and default Geant4.10.4
informs systematic uncertainty

Expanding $\nu_e$ selection

Maximum ordering sensitivity from $\nu_e-\nu_e$ asymmetry at lower $E_\nu$

(Previous analysis had a cut reco. $E_\nu \geq 1$ GeV)

Designed new selection to retain lower-E $\nu_e$ candidates

(Uses BDT to reject backgrounds)
Expanding $\nu_e$ selection

For now, $\nu$ only
(Analogous $\nu$ sample currently too small, but future exposure gains will improve sensitivity to asymmetry)

Increases mass ordering sensitivity by $\sim$few %
(depends on oscillation parameters)

Normal MO: $\Delta m^2_{32} = +2.43 \times 10^{-3} \text{eV}^2$
Inverted MO: $\Delta m^2_{32} = -2.47 \times 10^{-3} \text{eV}^2$
Near detector observations

ND spectra reflect *unoscillated* beam

**νμ candidates**
correspond to FD νμ and νe signal

**νe candidates**
correspond to FD νe backgrounds

Dominated by beam νe (irreducible):
~50% for ν, ~70% for ν
Near detector observations

Uncertainties on single-detector measurements are large...

... but ND data forms basis for model correction & constraint
Constraining predictions

Correcting ND simulation to agree with data in reco $E_{\nu}$...

... via Far/Near transformation that comprises well understood effects (beam divergence, detector acceptance) + oscillations

... results in constrained FD $E_{\nu}$ prediction highly correlated with ND correction.
Constraining predictions

Constrain nominal prediction and effect of systematic uncertainties

- Shift all elements of sim., then redo constraint
- Since post-correction all variations forced to agree at ND, spread at FD is reduced
- Effects that are not shared between detectors unaffected, or increase in some cases (e.g.: calibration)

Subdivide or use different samples to better account for ND/FD differences:

- νμ: differences in resolution, acceptance subdivide by E_{had}/E_{ν} × |p_{t}| [12 bins]
- νe bknds: different oscillation behavior constrain vs’ parent π and K (beam νe); subdivide by Michel electron multiplicity (νμ, NC)
Systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>νμ count uncertainty (%)</th>
<th>νe count uncertainty (%)</th>
</tr>
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<tbody>
<tr>
<td>Lepton Reconstruction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron Uncertainty</td>
<td></td>
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<td>Detector Response</td>
<td></td>
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<td>Beam Flux</td>
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<td></td>
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<tr>
<td>Near-Far Uncor.</td>
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<td></td>
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<td>Systematic Uncertainty</td>
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</tr>
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For νμ selection:
- Not Extrapolated: [Graph]
- Extrapolated: [Graph]

For νe selection:
- Not Extrapolated: [Graph]
- Extrapolated: [Graph]
Systematic uncertainties

Include improvements to light, neutron propagation models mentioned previously

Lepton Reconstruction
Neutron Uncertainty
Detector Response
Beam Flux
Detector Calibration
Neutrino Cross Sections
Near-Far Uncor.
Systematic Uncertainty

ν-beam
NOvA Preliminary

ν_μ Selection All Quarters

Total ν_μ count uncertainty (%)

ν-Selection
NOvA Preliminary

ν_μ Selection

Total ν_e count uncertainty (%)
Systematic uncertainties

Based on GENIE 3.0.6 with data-driven adjustments (see overflow slides)

New: additional pion-production related systematic uncertainties

415. New RES and DIS uncertainties for NOvA cross-section model
Maria Martinez Casales (Fermilab), Michael Dolce
6/18/24, 5:30 PM
Far detector observations: $\nu_\mu$

384 $\nu_\mu$ data candidates
(11.3 background)

106 $\nu_\mu$ data candidates
(1.7 background)

3-flavor oscillations describe these data well: Bayesian posterior predictive $p$-value = 0.54
Far detector observations: $\nu_e$

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<thead>
<tr>
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<td>1.8</td>
<td>1.6 – 2.8</td>
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<tr>
<td>Beam bknd.</td>
<td>53.7</td>
<td></td>
</tr>
<tr>
<td>Cosmic bknd.</td>
<td>6.2</td>
<td></td>
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<td>2.1</td>
<td>1.0 – 3.2</td>
</tr>
<tr>
<td>Beam bknd.</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Cosmic bknd.</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>
Far detector observations: $\nu_e$

Data favors region where matter & CP violation effects oppose one another.

Future $\nu$ data will be critical for disentangling.

32 $\nu_e$ data candidates

181 $\nu_e$ data candidates
Extracting oscillation parameters

Goal:

$\Delta m_{32}^2$, $\sin^2 \theta_{23}$, $\sin^2 2\theta_{13}$, $\delta_{CP}$
Extracting oscillation parameters

Bayesian Markov Chain Monte Carlo (marginalization) (technique described in arXiv:2311.07835)

Frequentist $\chi^2$ minimization (profiled Feldman-Cousins) (technique described in arXiv:2207.14353)

Bayesian credible regions $\to \Delta m_{32}^2, \sin^2 \theta_{23}, \sin^2 2\theta_{13}, \delta_{CP} \to$ frequentist confidence regions

450. Bayesian Fit for the NOvA Three Flavor Oscillation Analysis
Ben Jargowsky (University Of Calif.,, Liudmila Kolupaeva
6/18/24, 5:30 PM

456. Determination of the neutrino oscillation parameters through the unified approach of Feldman and Cousins by the NOvA Experiment
Mr Andrew Dye (The University of Mi.,, Mr Luiz R. Prais (The University of Mi...
6/18/24, 5:30 PM
Extracting oscillation parameters

**Bayesian**
Markov Chain
Monte Carlo
(marginalization)
(technique described in arXiv:2311.07835)

**Frequentist**
χ² minimization
(profiled Feldman-Cousins)
(technique described in arXiv:2207.14353)

Bayesian credible regions
→ \(\Delta m_{32}^2, \sin^2 \theta_{23}, \sin^2 2\theta_{13}, \delta_{CP}\)
→ frequentist confidence regions

Consider three \(\theta_{13}\) possibilities:

- \(\theta_{13}\) unconstrained
  (NOvA only)
- Daya Bay
  1D \(\theta_{13}\) constraint
  \(\sin^2 2\theta_{13} = 0.0851 \pm 0.0024\)
- or
- Daya Bay
  2D \((\Delta m_{32}^2, \theta_{13})\) constraint

Other mixing parameters:
- \(\sin^2 \theta_{12} = 0.307\) (PDG 2023)
- \(\Delta m_{21}^2 = 7.53 \times 10^{-5} \text{ eV}^2\) (PDG 2023)
- \(\rho = 2.74 \text{ g/cm}^3\) (CRUST1.0)

Daya Bay
1D \(\theta_{13}\) constraint
\(\sin^2 2\theta_{13} = 0.0851 \pm 0.0024\)

Daya Bay
2D \((\Delta m_{32}^2, \theta_{13})\) constraint

PRL 130, 161802
Oscillation parameter results
NOvA 2024 summary & outlook

- First new NOvA neutrino oscillation measurement since 2020
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data
  - Updated simulation, including improved light response model and neutron propagation uncertainty
  - New low-energy $\nu_e$ candidate sample

Most precise single-experiment
First new NOvA neutrino oscillation measurement since 2020
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Most precise single-experiment
**403. Medium Energy Neutron Detector Response in NOvA**  
Miranda Rabelhofer, Andrew Sutton

**406. Recent Advancements in Machine Learning Techniques Utilised in NOvA**  
Alejandro Yankelevich, Alexander Booth, Alexander Shmakov, Ashley Back, Erin Ewart, Wenjie Wu

**138. PISCES two-detector covariance matrix fit for the NOvA Experiment**  
Miriama Rajaoalisoa

**415. New RES and DIS uncertainties for NOvA cross-section model**  
Maria Martinez Casales, Michael Dolce

**450. Bayesian Fit for the NOvA Three Flavor Oscillation Analysis**  
Ben Jargowsky, Liudmila Kolupaeva

**456. Determination of the neutrino oscillation parameters through the unified approach of Feldman and Cousins by the NOvA Experiment**  
Andrew Dye, Luis R. Prais

**455. Pions in the NOvA test beam**  
David Dueñas

**411. Muon neutrino charged-current cross measurement with zero mesons in NOvA**  
Sebastian Sanchez-Falero

**565. Characterization of Charged Pions with the NOvA Detectors**  
Camilo Cortés Parra, Rafael Maldonado Agudelo, Juan Villamil Santiago, Enrique Arrieta Diaz

**475. Constraining Neutral Current Uncertainties for Future Sterile Neutrino Search at NOvA Experiment**  
Shivam Chauhary, Stella Oh

**574. Charged-pion cross-section measurements in the NOvA near detector**  
Palash Roy, Mathew Muether

NOvA collaboration, Feb. 2024
Overflow
NOvA/T2K $E_\nu$ differences: implications

**NOvA has larger matter effects**

**T2K**: $L=295$ km, $E=0.6$ GeV

- $\sin^2\theta_{13}=0.085$
- $|\Delta m^2_{13}|=2.5\times10^{-3}$ eV$^2$
- $\sin^2\theta_{23}=0.5$

**NOvA**

- $L=810$ km, $E=2.0$ GeV

**Inverted ordering**
- $\delta=0$, $\delta=\pi/2$
- $\delta=\pi$, $\delta=-\pi/2$

**Normal ordering**

**NOvA sees more antineutrinos**

**NOvA** has more final-state pions

**T2K** has antineutrinos

---

**Flux ($\nu$ / m$^2$ / 10^12 POT)**

- SK flux
- NOvA FD flux

**Fraction of total $\sigma_{\nu_\mu}$ (CC)**

- DIS
- RES
- MEC
- QE

**Neutrino energy (GeV)**

**Total CC cross section (10^{-32} cm$^2$)**

- $\nu_\mu$ flux
- $\bar{\nu}_\mu$ flux

- NOvA FD
- SuperK

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June 17, 2024 / NEUTRINO ’24

J. Wolcott / Tufts U.
## NOvA numerical results

<table>
<thead>
<tr>
<th>Bayesian results</th>
<th>NOvA only</th>
<th>Daya Bay 1D</th>
<th>Daya Bay 2D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prob.</td>
<td>BF</td>
<td>Prob.</td>
</tr>
<tr>
<td>( \theta_{23} &gt; 0.5 ) preference</td>
<td>57%</td>
<td>1.3</td>
<td>69%</td>
</tr>
<tr>
<td>N.O. preference</td>
<td>69%</td>
<td>2.2</td>
<td>76%</td>
</tr>
</tbody>
</table>

### Frequentist results

<table>
<thead>
<tr>
<th>(w/ Daya Bay 1D ( \theta_{13} ) constraint)</th>
<th>N.O.</th>
<th>I.O.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m^2_{32} / 10^{-3} \text{ eV}^2 )</td>
<td>+2.43 3</td>
<td>+0.03 5</td>
</tr>
<tr>
<td>( \sin^2 \theta_{23} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \delta_\text{CP} / \pi )</td>
<td>0.88</td>
<td>1.51</td>
</tr>
<tr>
<td>Rejection significance (( \sigma ))</td>
<td>—</td>
<td>1.36</td>
</tr>
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</table>
Multinucleon knockout

“2p2h”
Knock out two nucleons with an elastic-like interaction.

Lots of recent progress on theory, but no model in GENIE (yet) describes extant data well

Employ fits to NOvA ND data in the meantime

Only minor updates from 2020
[Detailed discussion of 2020 technique in NuSTEC CTGWG Seminar Dec. 14, 2022 (J. Wolcott)]
FSI tuning & uncertainties

- Only minor updates from 2020
- Detailed discussion of 2020 technique in NuSTEC CTGWG Seminar Dec. 14, 2022

**Tuning**
- Adjust nominal prediction to agree better with pion scattering data at low energies where most relevant for NOvA
- Construct uncertainty bands in same spirit as work from T2K
  [Phys. Rev. D99, 052007]

**Impact**
- 5-10% effect on pion kinematics
- Ultimately subdominant for calorimetric $E_\nu$ reco. used in NOvA
Alternate CCQE model: CRPA (1)

- Continuum Random Phase Approximation (CRPA)
- Improved treatment of low-momentum-transfer nuclear dynamics
- Opens additional phase space

*Phys. Rev. C92, 024606
†Phys. Rev. D106, 073001
Alternate CCQE model: CRPA (2)

- Tested impact on NOvA analysis with fake data
  - Compared extrapolated CRPA prediction to extrapolated nominal
  - Spectral impact is well within extrapolated uncertainty budget
Pion production uncertainties

Introduce 3 pion-production related systematic uncertainties for 2024

- Relative strength of Δ vs non-Δ resonant production (1 uncertainty)
  → Shift Δ and non-Δ resonances ±20% independently
  - Default GENIE: all resonances affected together
  - Overcounts Δ-specific uncertainty somewhat with other GENIE knobs, but “conservative”
- Charged vs. neutral hadron production in RES, DIS (2 uncertainties)
  - Shift ratio of RES Δ-channel proton/neutron final states by ±5%
  - Shift composition of proton/neutron final states in DIS
- Moderate impacts on pion-rich subsamples, but overall effect on uncertainty budget is minor

415. New RES and DIS uncertainties for NOvA cross-section model

Maria Martínez Casales (Fermilab), Michael Dolce
6/18/24, 5:30 PM
Neutron propagation

In situ ND neutron candidate sample

- 44% of primary neutrons deposit visible energy in NOvA (but deposited energy ~uncorrelated w/ primary KE)
- Simple cuts on number of cells illuminated (1 ≥ N_{cells} ≥ 5) and distance from vertex (≥ 20cm)
- Select ~pure sample (61%) at high efficiency (73%) (relative to visible neutrons)

Compare simulations of deposited energy to in situ ND data sample

- Two options:
  - stock Geant4.10.4 (QGSP-BERT)
  - Geant4.10.4 with MENATE_R* neutron inelastic scattering cross section model (~20-100 MeV)
- MENATE_R agrees well with NOvA data in shape (significant improvement over G4)
- Biggest difference b/w MENATE and G4 is in photon production
- Difference between MENATE_R and GEANT4.10.4 used as input to systematic uncertainty

- Normalization inflated to also cover residual data/sim. difference
- Residual normalization difference may also suggest issue with neutron production simulation (GENIE)
ND data distributions

**νμ candidates**

- 6.5M candidates
- Reco. νμ / \( \bar{\nu}_\mu \) energy (GeV)

**νe candidates**

- 94K candidates
- 17K candidates
- Reconstructed νe energy (GeV)

---

**νe candidates**

- NOvA Preliminary

**νμ candidates**

- NOvA Preliminary
FD data: $\nu_\mu$ in $E_{\text{had}}/E_v$ quantiles

Extrapolation procedure is performed in $|p_t|$ subpopulations of $E_{\text{had}}/E_v$ quartiles

Resolutions range from Q1 6.5% (5.4%) to Q4 12.6% (11.2%) in $\nu$ ($\bar{\nu}$) mode
Bayesian posterior predictive $p$-values

- **Procedure:**
  - Throw pseudoexperiments (PSE) w/ Poisson fluctuations from each MCMC sample’s parameter set $\theta_i$
  - Make predictions for energy spectra
  - Compute $\chi^2(\text{PSE}_i, \text{Asimov}_i)$ and $\chi^2(\text{data, Asimov}_i)$ for each MCMC sample $i$
  - $p =$ fraction of points where $\chi^2_{\text{pseudodata}} > \chi^2_{\text{data}}$
  - **Asymptotic expectation is $p = 0.5$**
  - Deviations from 0.5 can indicate insufficient or excessive model freedom can push higher or lower
  - Large fluctuations can also push away from 0.5 (as in lowE $\nu_e$, $\nu_e$ samples here)

3-flavor oscillations + NOvA systematic uncertainty model represents NOvA data well
Bayesian priors

Intent is to use “uninformed” prior where NOvA data constrains parameter
– Typically: uniform
→ \( \theta_{23}, \Delta m^2_{32}, \delta_{\text{CP}} \) marginals: uniform in those variables
– In Jarlskog more complex: \( J \propto \sin \delta_{\text{CP}} \). Uniform in \( \delta_{\text{CP}} \) or \( \sin \delta_{\text{CP}} \)?
→ test both

1D constraints from external
Uncertainties on PMNS parameters
\( \Delta m^2_{32} \) across expts

### Normal mass ordering

<table>
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<tr>
<th>Experiment</th>
<th>Value</th>
<th>Uncertainty</th>
<th>Error</th>
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</tr>
<tr>
<td>T2K(d)</td>
<td>2.506 ± 0.052</td>
<td>0.052</td>
<td>1.8%</td>
</tr>
<tr>
<td>SuperK + T2K(d)</td>
<td>2.511 ± 0.060</td>
<td>0.059</td>
<td>2.4%</td>
</tr>
<tr>
<td>Daya Bay (n)Gd</td>
<td>2.466 ± 0.060</td>
<td>0.060</td>
<td>2.4%</td>
</tr>
<tr>
<td>MINOS+</td>
<td>2.40 ± 0.08</td>
<td>0.09</td>
<td>3.5%</td>
</tr>
<tr>
<td>SuperK(e)</td>
<td>2.40 ± 0.12</td>
<td>0.11</td>
<td>4.8%</td>
</tr>
<tr>
<td>RENO (n)Gd</td>
<td>2.69 ± 0.12</td>
<td>0.12</td>
<td>4.5%</td>
</tr>
<tr>
<td>Daya Bay (n)H</td>
<td>2.72 ± 0.14</td>
<td>0.15</td>
<td>5.3%</td>
</tr>
<tr>
<td>RENO (n)H</td>
<td>2.48 ± 0.28</td>
<td>0.32</td>
<td>12.1%</td>
</tr>
</tbody>
</table>

### Inverted mass ordering

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
<th>Uncertainty</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOvA*</td>
<td>2.472 ± 0.035</td>
<td>0.040</td>
<td>1.5%</td>
</tr>
<tr>
<td>NOvA + T2K(d)</td>
<td>2.477 ± 0.035</td>
<td>0.035</td>
<td>1.5%</td>
</tr>
<tr>
<td>IceCube</td>
<td>2.40 ± 0.05</td>
<td>0.04</td>
<td>1.9%</td>
</tr>
<tr>
<td>T2K(d)</td>
<td>2.548 ± 0.071</td>
<td>0.070</td>
<td>1.8%</td>
</tr>
<tr>
<td>SuperK + T2K(d)</td>
<td>2.484 ± 0.057</td>
<td>0.060</td>
<td>2.4%</td>
</tr>
<tr>
<td>Daya Bay (n)Gd</td>
<td>2.571 ± 0.060</td>
<td>0.060</td>
<td>2.3%</td>
</tr>
<tr>
<td>MINOS+</td>
<td>2.45 ± 0.07</td>
<td>0.08</td>
<td>3.1%</td>
</tr>
<tr>
<td>SuperK(e)</td>
<td>2.79 ± 0.12</td>
<td>0.15</td>
<td>4.3%</td>
</tr>
<tr>
<td>RENO (n)Gd</td>
<td>2.83 ± 0.14</td>
<td>0.15</td>
<td>5.1%</td>
</tr>
<tr>
<td>Daya Bay (n)H</td>
<td>2.40 ± 0.09</td>
<td>0.09</td>
<td>3.1%</td>
</tr>
<tr>
<td>RENO (n)H</td>
<td>2.58 ± 0.28</td>
<td>0.32</td>
<td>11.6%</td>
</tr>
</tbody>
</table>

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* 2024 result, PRELIMINARY
\(d\) based on 2020 ana.
\(e\) Neutrino-2022 result

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\( \Delta m^2_{32} \): the mass squared difference between the third and second neutrino mass eigenstates.
Daya Bay – NOvA correlations

Daya Bay preferred regions resolve some degeneracies in NOvA-only data
Jarlskog invariant

Jarlskog* is a parameter-independent measure of CP violation. 
- $J=0$ indicates CP conservation regardless of parameterization.
- $J \neq 0$ corresponds to CP violation.

*See, e.g., PRD 100, 053004.