Standard and Non-Standard Neutrino oscillations with NOvA

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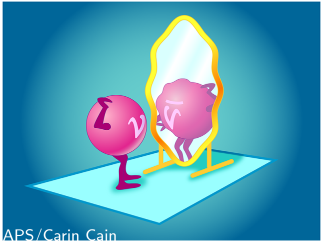
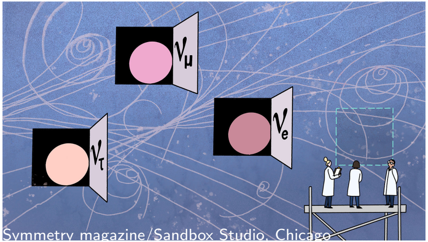
3. Bayesian Inference into the PMNS model
4. Sterile neutrinos

Open Questions



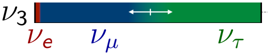
Do neutrinos violate **Charge-Parity**?

Do we understand $\boldsymbol{\nu}$ **propagation in matter**?



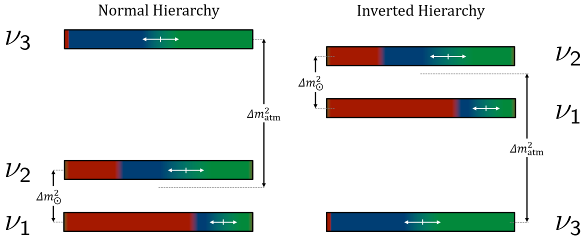
Is there a light, **sterile neutrino**?

How are the **nuetrino mass states ordered**?



How $\boldsymbol{\nu_\mu/\nu_\tau}$ **mix** into the mass states?

Neutrino oscillation physics



- Flavour eigenstates; ν_e, ν_μ and ν_τ (interact)
- Mass eigenstates; ν_1, ν_2 and ν_3 (propagate)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{atmospheric, beam}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{reactor, beam}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{solar, reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

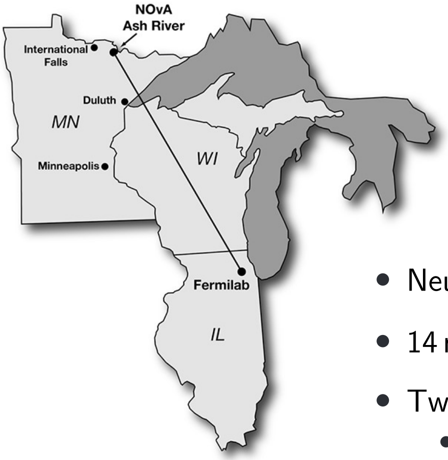
$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

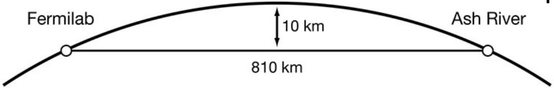
atmospheric, beam: Super-K, IceCube, Opera, **NOvA**, T2K

reactor, beam: Double Chooz, Daya Bay, RENO, **NOvA**, T2K

solar, reactor: Super-K, SNO, KamLAND

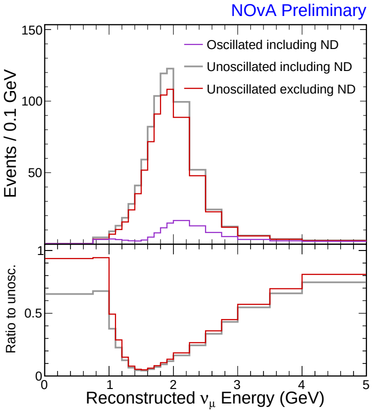
- θ_{23}: Larger or smaller than 45? Important for $\nu_\tau - \nu_\mu$ symmetries.
- δ_{CP}: Potential contribution to matter-antimatter asymmetry in the universe.
- $\pm\Delta m^2_{32}$: Symmetries in neutrino physics, consequences for 2β decay search.





- Neutrino beam from Fermilab's NuMI Beamline.
- 14 mrad off-axis beam narrowly peaked at ∼2 GeV.
- Two functionally identical detectors:
  - Near Detector (ND), 0.3 kton, 1 km baseline.
  - Far detector (FD), 14 kton, 810 km baseline.

ν_μ signal



Location of the dip: $|\Delta m^2_{32}|$

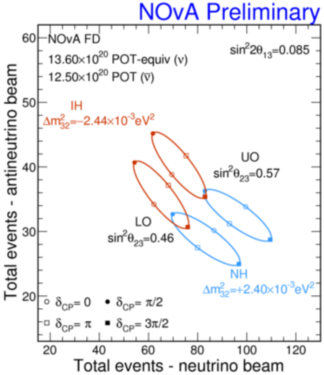
(does not depend on the sign)

Depth of the dip: $\sin^2(2\theta_{23})$

Difficult to separate $\theta_{23} > 45$ and $\theta_{23} < 45$

Is $\nu_\mu = \nu_\tau$ in ν_3 mass state?

ν_e signal



Combination of ν_e and $\bar{\nu}_e$ excess;

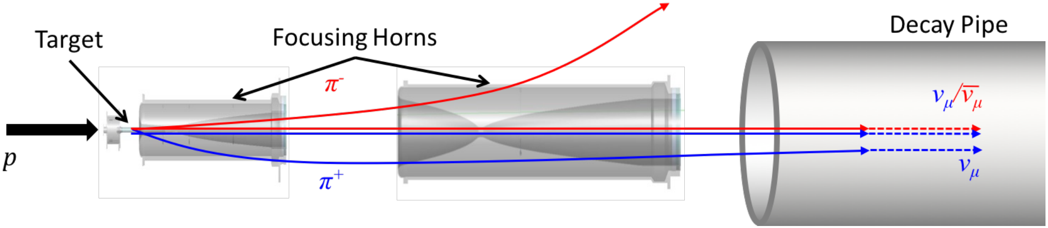
$\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$, δ_{CP}

Good dependence on the sign of Δm^2_{32}

Channel for CP violation detection

NuMI Neutrino beamline

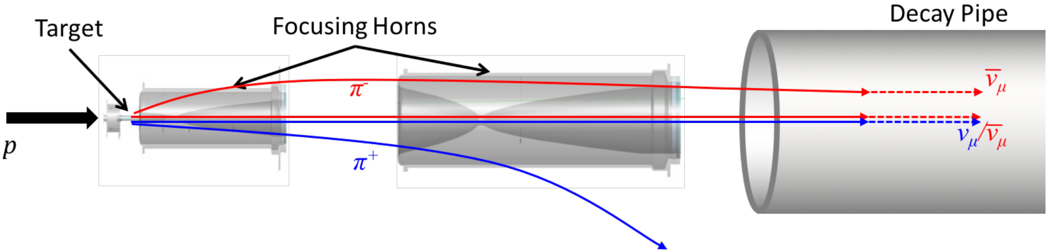
Focusing +ve mesons to get mostly ν_μ (Neutrino mode)



- Beam of 120 GeV protons incident on carbon target.
- Focusing +ve or -ve mesons to obtain mostly ν_μ or $\bar{\nu}_\mu$.
  - Achieved by reversing the polarity of the magnetic horns.
- Neutrinos appear from the decaying mesons. 675 m decay pipe.

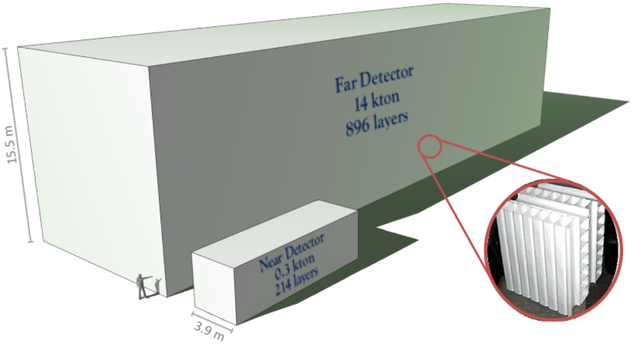
NuMI Neutrino beamline

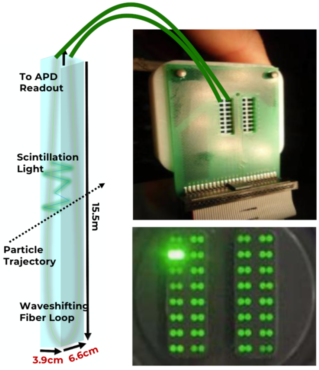
Focusing -ve mesons to get mostly $\bar{\nu}_\mu$ (Antineutrino mode)



- Beam of 120 GeV protons incident on carbon target.
- Focusing +ve or -ve mesons to obtain mostly ν_μ or $\bar{\nu}_\mu$.
  - Achieved by reversing the polarity of the magnetic horns.
- Neutrinos appear from the decaying mesons. 675 m decay pipe.

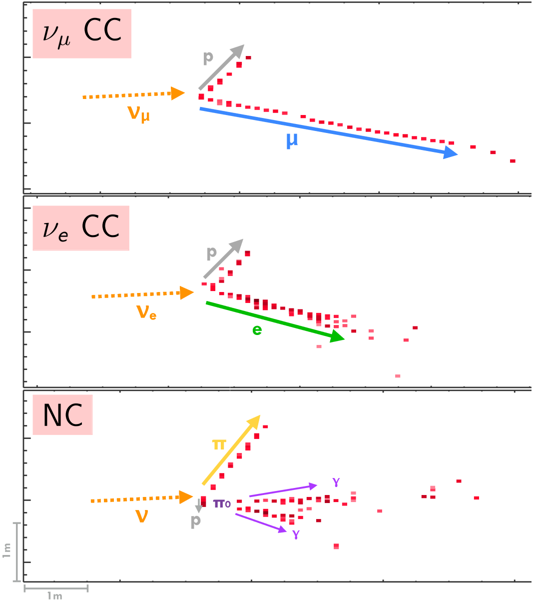
NOvA Detectors



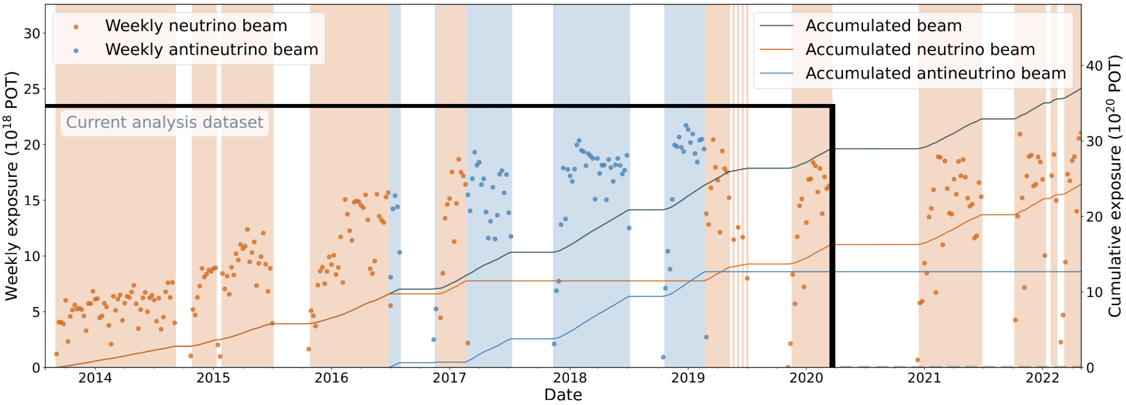


- Extruded cells filled with liquid scintillator, with 62% active volume.
- Wavelength-shifting fibre collects and transports light to Avalanche photodiode.
  - Each APD sees 32 NOvA cells.
- Cells with alternating horizontal & vertical planes for 3D reconstruction.
- Optimized for electron showers.

Event topologies

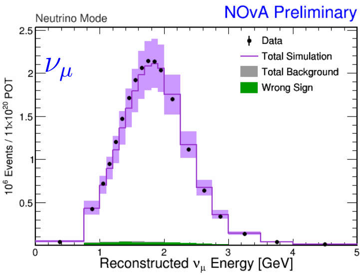


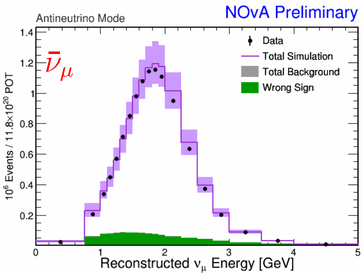
- Modern **convolutional neural network (CNN)** techniques used to identify neutrino flavour.
- Learns features of different event topologies.
- Data-driven validations based on ND and FD control samples.
- New test beam data will help with future validations/improvements.

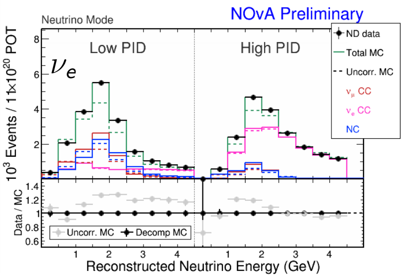


- Collected 37×10^{20} protons-on-target up to date.
- Data up to early 2020 included in the analysis shown here.
  - 13.6×10^{20} in ν-beam mode.
  - 12.5×10^{20} in $\bar{\nu}$-beam mode.

Near detector data

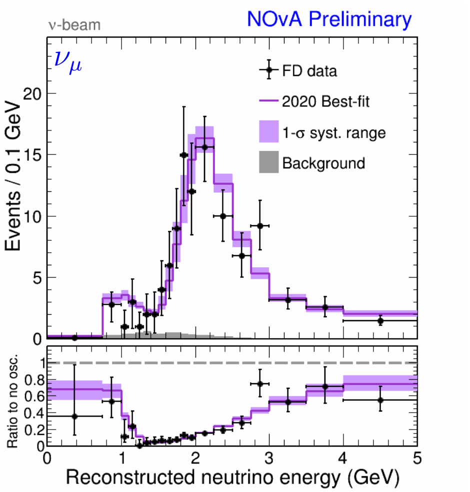




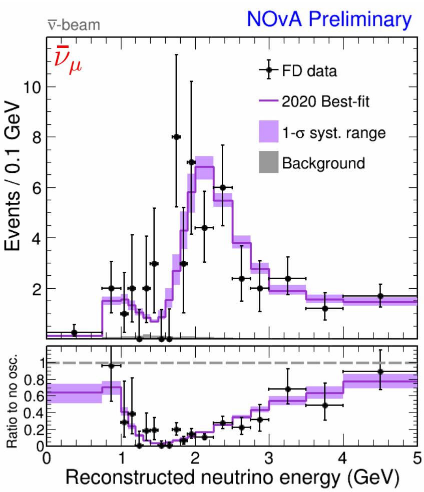


- ν_μ and $\bar{\nu}_\mu$ ND samples are used to correct the FD unoscillated predictions via extrapolation.
- We can then apply the $P(\nu_\mu \to \nu_e)$ curve to the corrected predictions.
- The ν_e samples are used to correct the irreducible ν_e background in the beam at the FD.
- The ν_e samples also used to estimate how the backgrounds to the ν_e appearance oscillate.

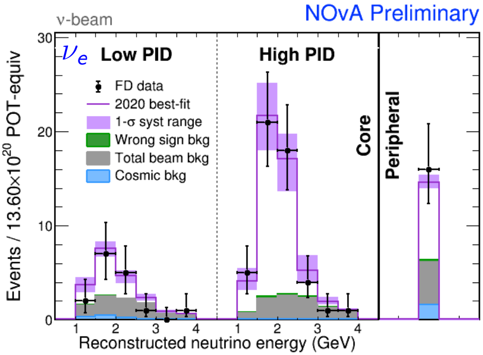
Far detector data Muon neutrinos

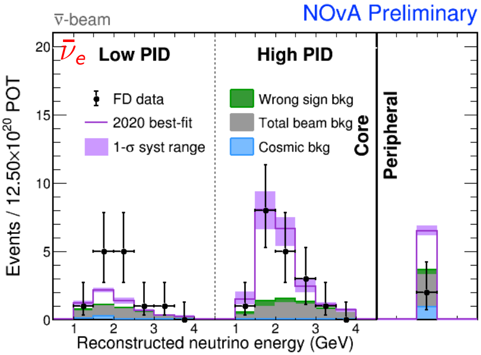


- Observed: 211
- Best Fit Prediction: 222.3
- Background: 8.2



- Observed: 105
- Best Fit Prediction: 105.4
- Background: 2.1





- Observed: 82
- Best Fit Prediction: 85.8
- Background: 26.8

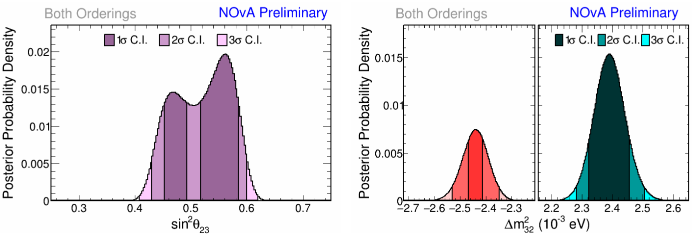
- Observed: 33
- Best Fit Prediction: 33.2
- Background: 14

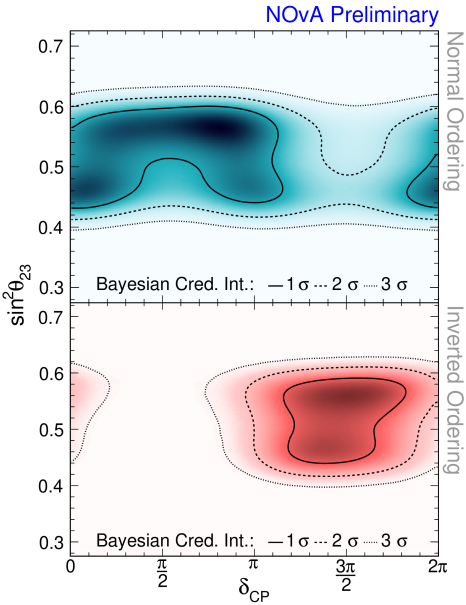
$> 4\,\sigma$ evidence of electron antineutrino appearance

Results

Standard PMNS results

Both Orderings | Normal Ordering | Inverted Ordering





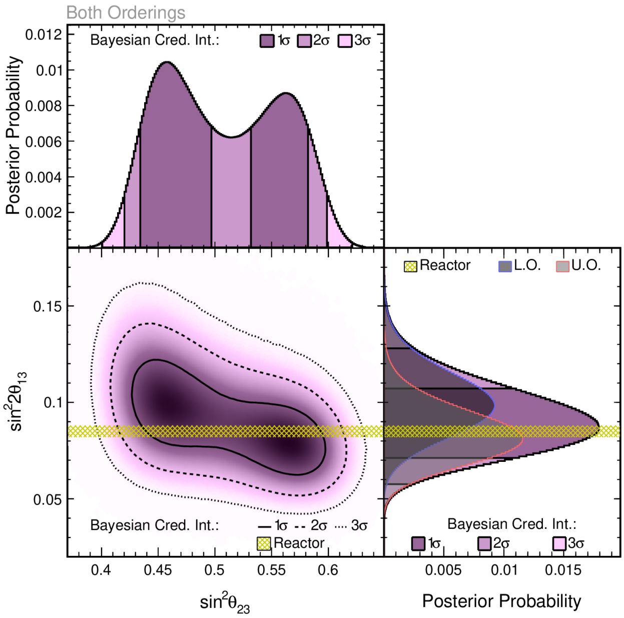
- General conclusions compatible with the 2020 Frequentist analysis.
- Prefer upper octant and normal mass ordering.
- Neither preference is significant, below $\sim 1\,\sigma$.
- "Not worth more than a bare mention" *

	N. Ordering	I. Ordering	
U. Octant	41.7%	20.9%	62.6%
L. Octant	25.8%	11.5%	37.4%
	67.5%	32.5%	

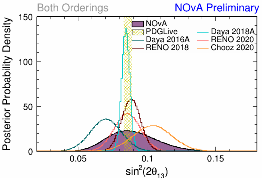
* Jeffreys ISBN:9780191589676, Raftery & Kass doi:10.2307/2291091

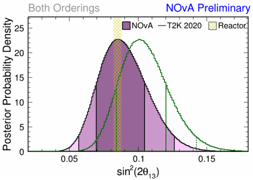
First NOvA-only θ_{13} measurement

Both Orderings | Normal Ordering | Inverted Ordering



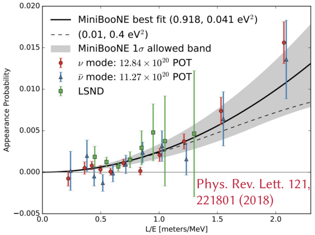
- $\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$
- NOvA in a good agreement with the reactor experiments.
- No tensions between short-distance $P(\bar{\nu}_e \to \bar{\nu}_e)$ and long-distance $P(\nu_\mu \to \nu_e)$ & $P(\bar{\nu}_\mu \to \bar{\nu}_e)$.

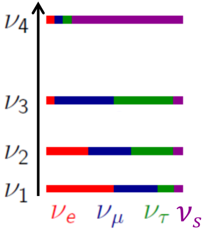


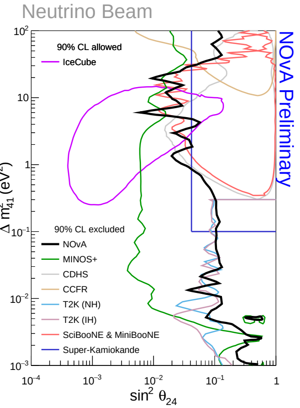


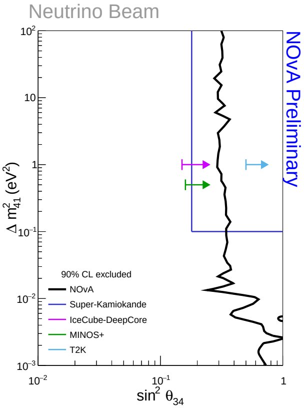
Anomalous neutrino event rates in the short-baseline experiments

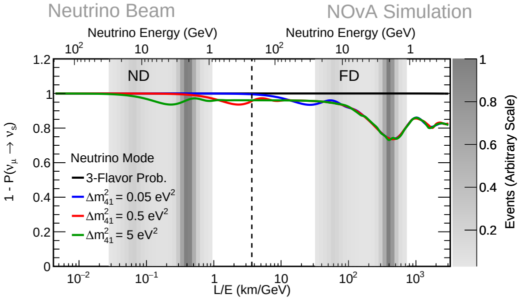
- ν_μ disappearance could occur in the near detector at large Δm^2_{41}.
- No evidence of sterile neutrinos found.
- Competitive results for Δm^2_{41}, θ_{24} & θ_{34}











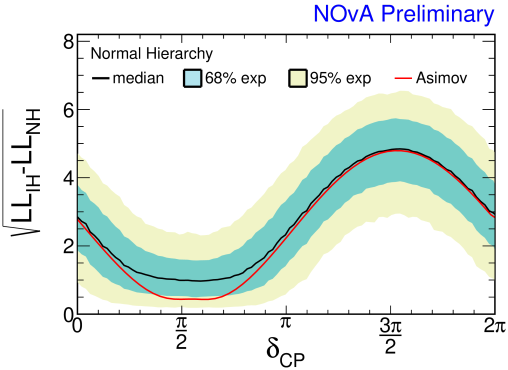
Bright Future

- NOvA Test-Beam to measure detector response.

- MW-capable horn and target installed.
  - New power record reached last year!

- Expect $> 2\times$ more in both ν and $\bar{\nu}$ data.
  - Analysed 26e20 POT.
  - 11e20 POT more collected since.
  - Goal by 2027: 67–72e9 POT.

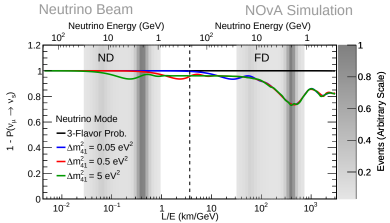
- NOvA-T2K effort to produce joint result.

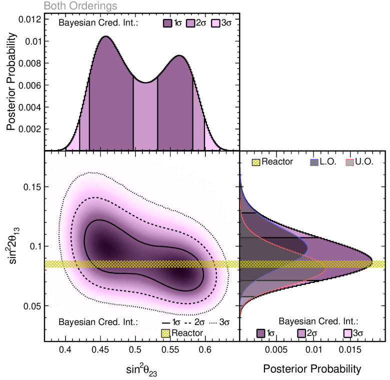


- **Competitive constraints on 3+1 sterile neutrinos.**
  - NOvA data consistent with no sterile neutrinos.

- First NOvA-only measurement of θ_{13}
  $\mathbf{\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}}$

- **PMNS formalism explains NOvA data very well:**
  - No tension between Accelerator and Reactor neutrinos.
  - No high preference for either CP-Violation or CP-Conservation.
  - Good model-data agreement.





Thank you!

BACKUPS

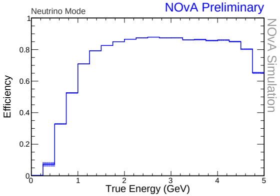
Event identification

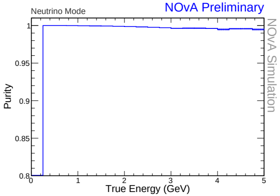
Pre-selections:

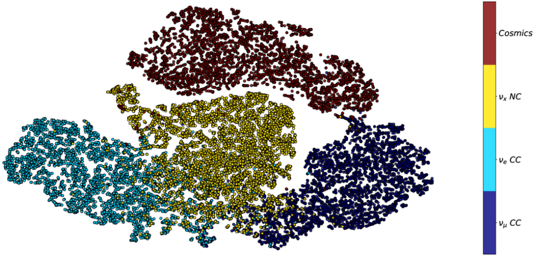
- Contained inside the detector.
- Inside of the beam spill-window.
- Cosmic particles rejection via BDT.

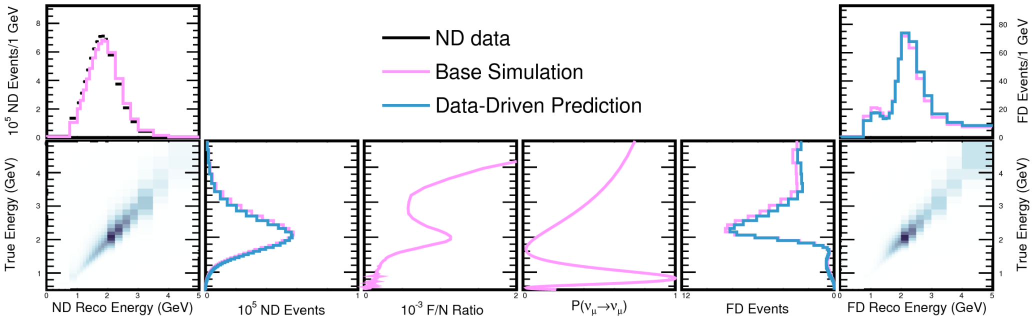
Event Identification:

- Modern CNN techniques used to identify neutrino flavour.
- Learns features of different event topologies.
- Data-driven validations based on ND and FD control samples.
- Results in high purity samples.

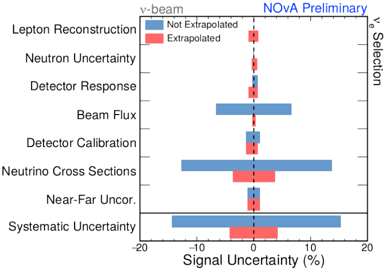


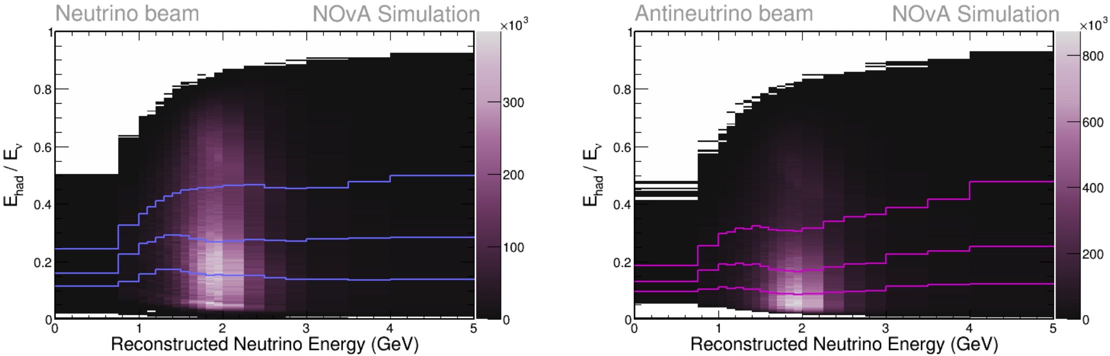






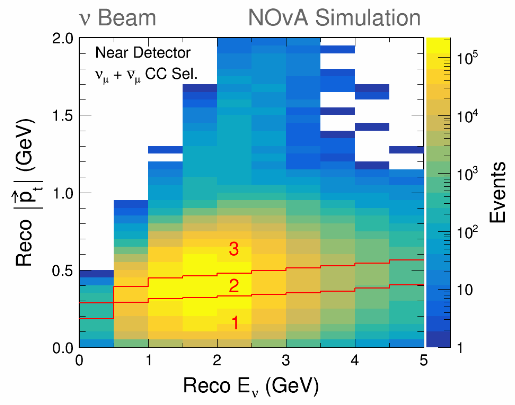
- Take advantage of detector similarity to extrapolate ND predictions to FD.
- Many systematic effects e.g. cross-sections, flux and efficiency are shared.
- Helps dealing with the "unknown unknowns".
- Extrapolate different kinematic samples separately to deal with Near/Far acceptance differences.

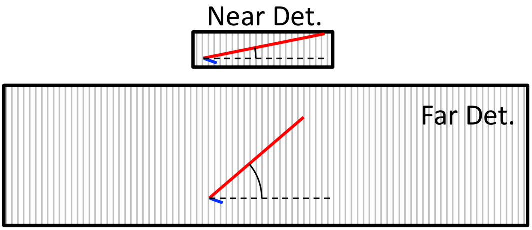




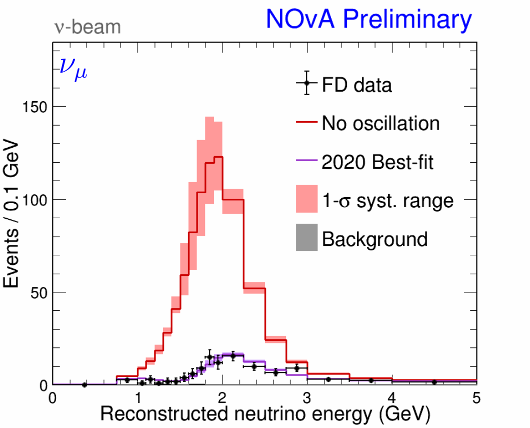
- The energy resolution varies between the detectors.
- Extrapolation split in four E_{had}/E_{ν} quartiles.
- Matches the Hadronic energy resolution between ND and FD.

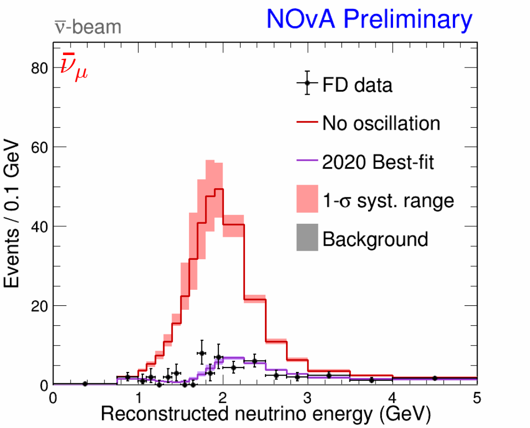
ND→FD Extrapolation: Lepton $|p_T|$





- Different lepton angle distributions due to the difference in detectors' size.
- Extrapolation split in three ranges of lepton transverse momenta.
- Done separately for each $E_{\rm had}$ quartile.
- Matches the detector acceptances between ND and FD.





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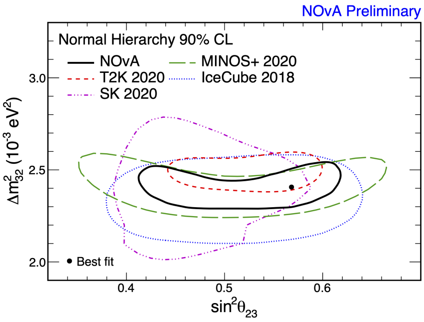
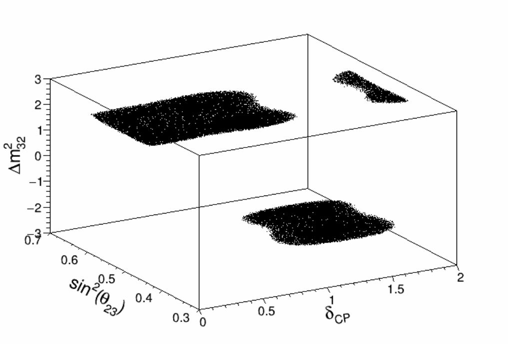
Fitting/Sampling techniques



- NOvA fits 10 data samples: $4\nu_\mu$, $4\bar{\nu}_\mu$, $1\nu_e$ and $1\bar{\nu}_e$.
- All the previous NOvA results were Frequentist with use of profiling.
- New Bayesian frameworks implemented in NOvA.
- New studies now easier: Jarlskog-Invariant, NOvA-only θ_{13}, Bayes factors and possibly more!
- Other experiments often provide Marginalized and/or Bayesian results.



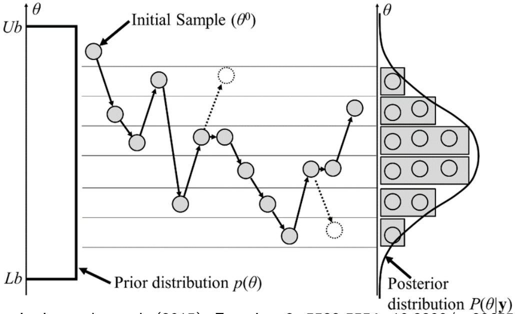
Bayes Theorem:

$$\mathcal{P}(\vec{\theta}|D) \approx \mathcal{P}(D|\vec{\theta})\mathcal{P}(\vec{a})$$

$$Posterior \approx Likelihood \times Prior$$

$$Posterior \approx e^{-\frac{\chi^2}{2}} \times Prior$$

- Bayesian results given in terms of posterior probability distributions.
- Need to produce N-dimensional probability distribution for marginalized results.
- MCMC generates samples on N-dimensional.
  - Sample density corresponds to posterior probability density.



L. Jaewook et. al. (2015). Energies. 8. 5538-5554. 10.3390/en8065538.

Bayes Theorem:

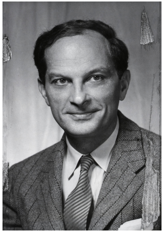
$$\mathcal{P}(\vec{\theta}|D) \approx \mathcal{P}(D|\vec{\theta})\mathcal{P}(\vec{a})$$

$$Posterior \approx Likelihood \times Prior$$

$$Posterior \approx e^{-\frac{\chi^2}{2}} \times Prior$$

- MCMC generates samples by iteratively deviating parameters from their previous values.
- At each iteration we can either accept, or reject the step.
  - Accept: new step added to the end of the chain.
  - Reject: previous values repeated at the end of the chain.
- Over time, this "chain" ensemble starts resembling posterior probability.

Arianna Rosenbluth



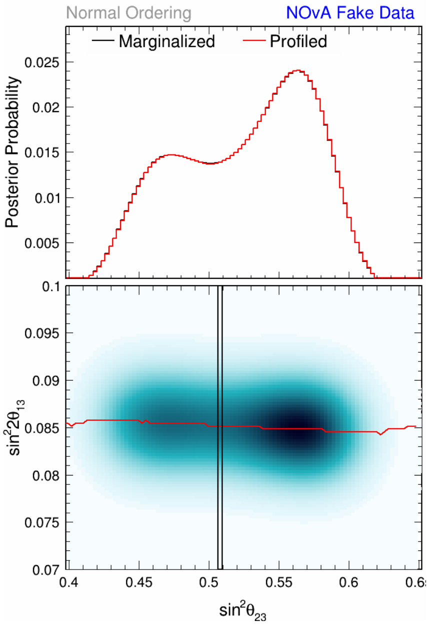
Stanislaw Ulam

- Two algorithms in NOvA: Metropolis-Hastings and Hamiltonian MCMC.
- Hamiltonian MCMC is based on Stan library (https://mc-stan.org).
  - Stanislaw Ulam invented the methods of Monte-Carlo.
- Metropolis-Hastings was written from scratch in-house.
  - Named Aria after Arianna Rosenbluth, who first implemented the method.
- Importantly, both algorithms produce identical results.

References: Metropolis-Hastings doi:10.1063/1.1699114, Hamiltonian doi:10.1016/0370-2693(87)91197-X

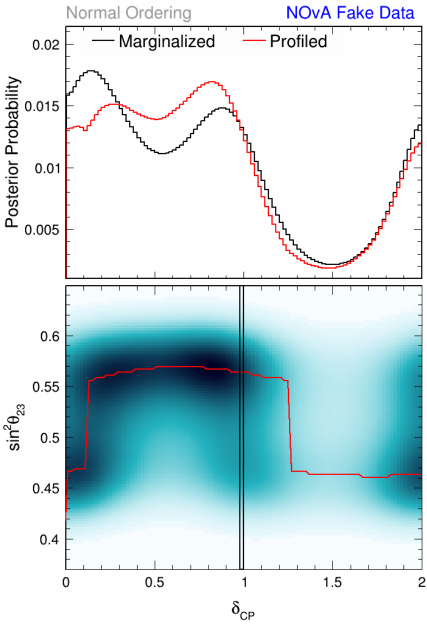
Bayesian vs Frequentist, Marginalization vs Profiling

- MCMC uses marginalization rather than profiling.
  - Not necessarily reserved to Bayesian methods!
  - Profiling: Maximize parameters not shown.
  - Marginalization: Integrate over parameters not shown.
- Example: marginalizing/profiling over $\sin^2 2\theta_{13}$.
  - Line of best fit to profile over $\sin^2 2\theta_{13}$.
  - Box with probabilities to sum over for marginalization.
- Use posterior probability densities, not χ^2.
  - Bayes. Credible Intervals vs Freq. Confidence Levels.



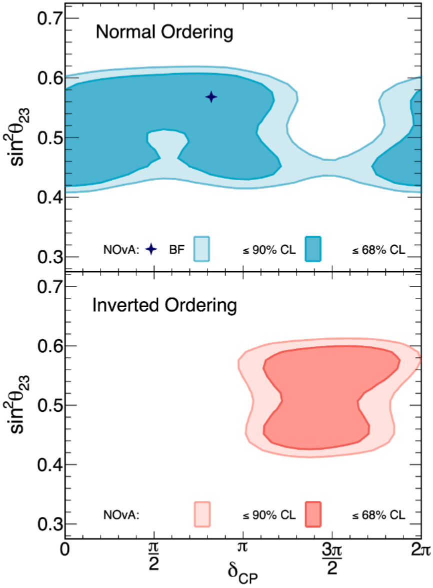
Bayesian vs Frequentist, Marginalization vs Profiling

- MCMC uses marginalization rather than profiling.
    - Not necessarily reserved to Bayesian methods!
    - Profiling: Maximize parameters not shown.
    - Marginalization: Integrate over parameters not shown.
- Example: marginalizing/profiling over $\sin^2\theta_{23}$.
    - Line of best fit to profile over $\sin^2\theta_{23}$.
    - Box with probabilities to sum over for marginalization.
- Use posterior probability densities, not χ^2.
    - Bayes. Credible Intervals vs Freq. Confidence Levels.

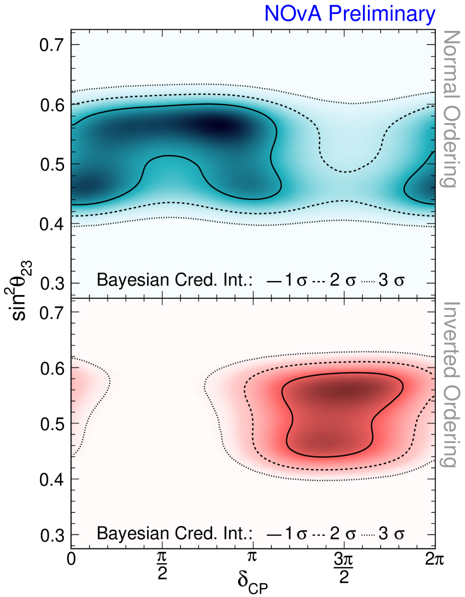


Both Orderings | Normal Ordering | Inverted Ordering

Frequentist result

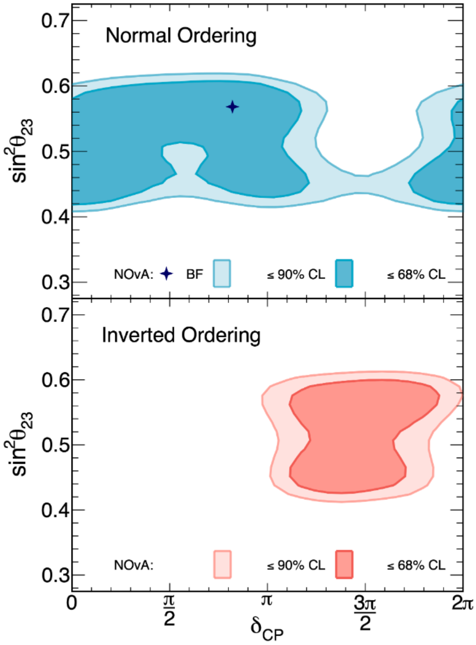


Bayesian result



Frequentist results reference: arXiv:2108.08219

2020 Frequentist Results

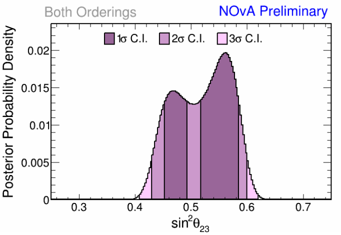


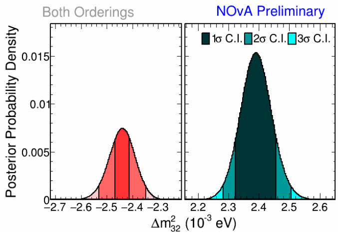
Best fit:

- Normal mass ordering.
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} eV^2$
- $sin^2\theta_{32} = 0.57^{+0.04}_{-0.03}$
- $\delta_{\mathrm{CP}} = 0.82\pi$
  - Disfavour IO $\delta_{\mathrm{CP}} = \pi/2$ at $> 3\sigma$.
  - Disfavour NO $\delta_{\mathrm{CP}} = 3\pi/2$ at $2\,\sigma$.

Disappearance parameters' results

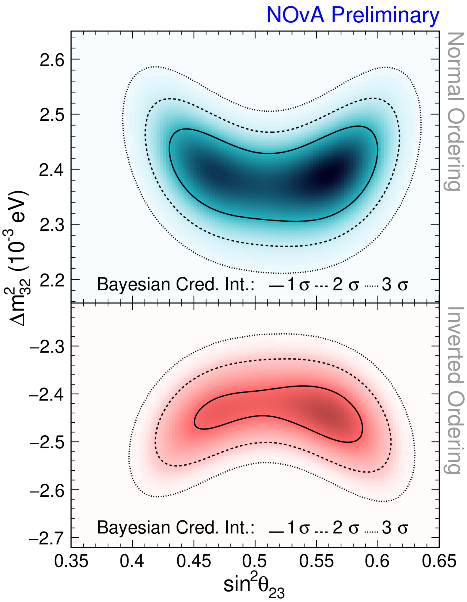
Both Orderings | Normal Ordering | Inverted Ordering





- Prefer upper octant and normal mass ordering.
- Neither preference is significant, below $\sim 1\,\sigma$.

	N. Ordering	I. Ordering	
U. Octant	41.7%	20.9%	62.6%
L. Octant	25.8%	11.5%	37.4%
	67.5%	32.5%	

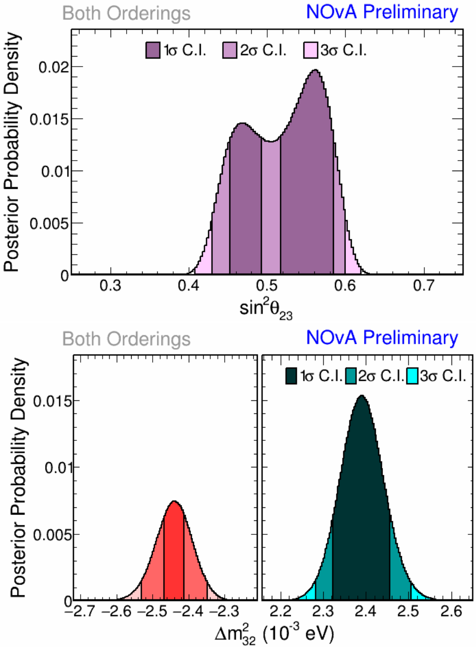


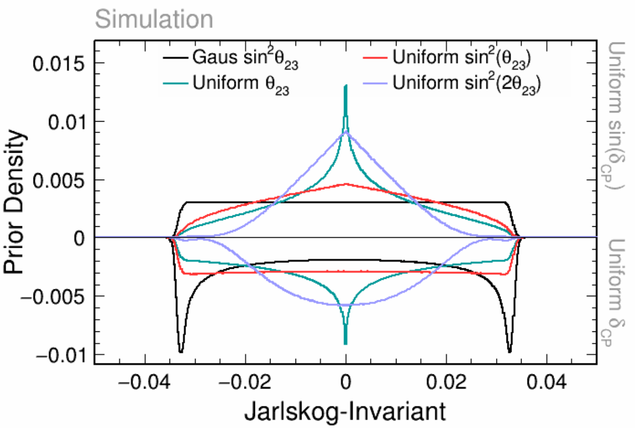
Bayes Factors

	N. Ordering	I. Ordering	
U. Octant	41.7%	20.9%	62.6%
L. Octant	25.8%	11.5%	37.4%
	67.5%	32.5%	

- Bayes Factors: odds ratio, how much more likely one model is than another.
- NO/IO: 2.1, UO/LO: 1.7
- Both can be interpreted as below 1σ or "not worth more than a bare mention" according to Jeffreys and Raftery & Kass scales.

References: Jeffreys ISBN:9780191589676,
Raftery & Kass doi:10.2307/2291091





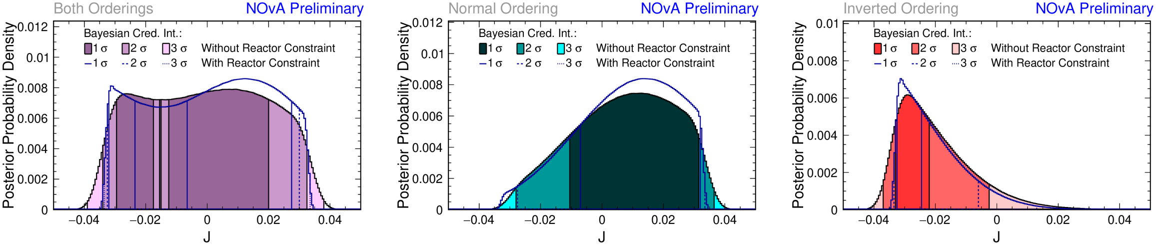
How about priors on other oscillation parameters for J?

- Changing θ priors to be uniform in θ, $\sin^2\theta$ changes the prior contribution.
- It does not, however, change the posterior – our results.
- Likelihood is stronger than the prior for high-stats data, overwhelming it.
- This does not happen for $\delta_{\rm CP}$ because we don't constrain it well.

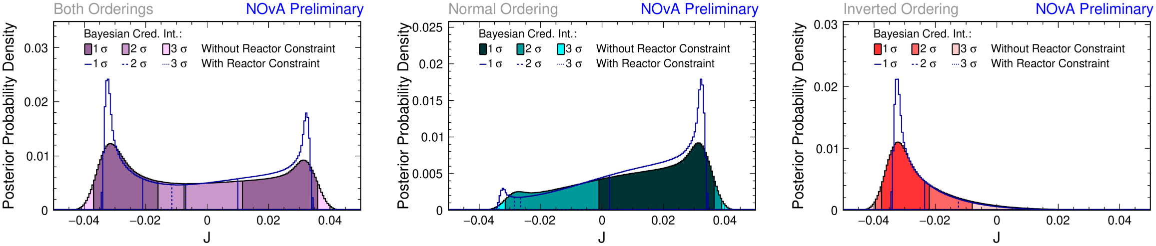
Jarlskog-Invariant
θ_{13} constraint comparisons

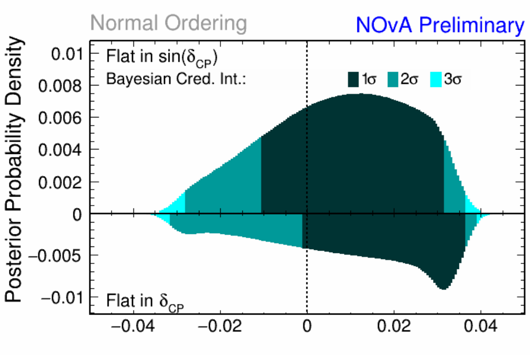
Both Orderings | Normal Ordering | Inverted Ordering

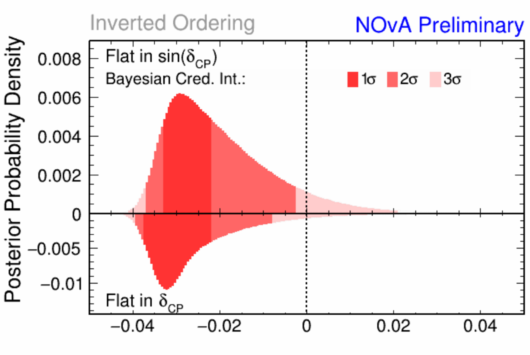
Prior uniform in $\sin(\delta_{CP})$:



Prior uniform in δ_{CP}:

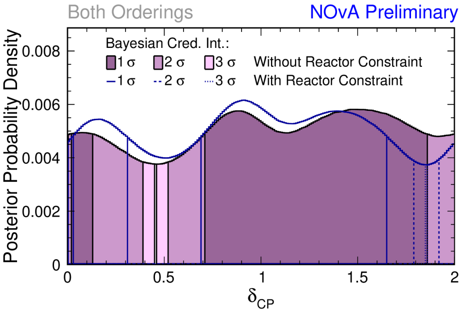


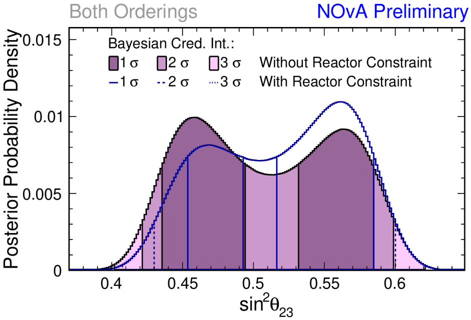




- The shape changes because θ_{13} is allowed to take more values.
- Nevertheless, the general conclusions about CP-conservation are similar.

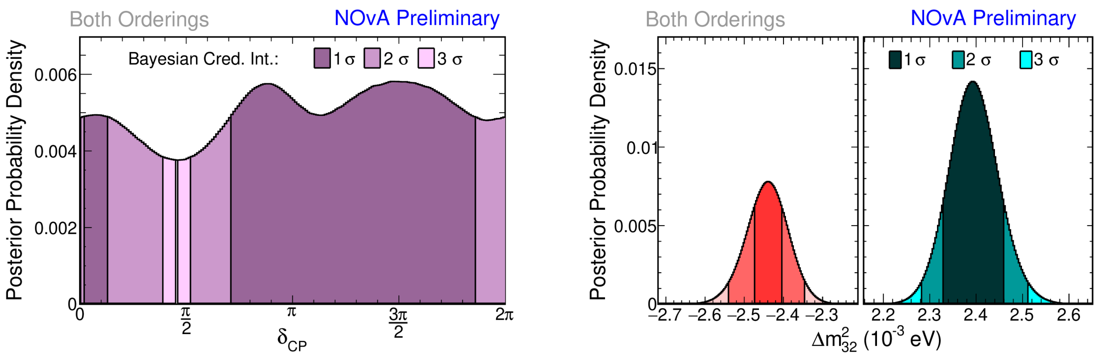
Reactor constraint comparisons



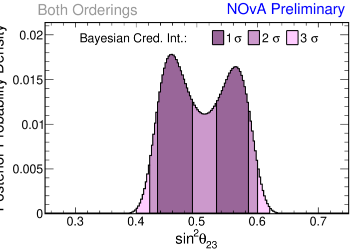


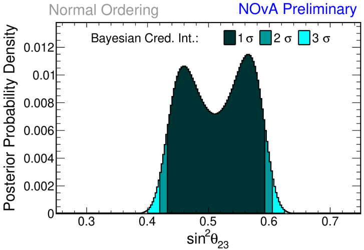
- Setting θ_{13} free does change our results slightly.
- Prefer lower octant with free θ_{13}, upper octant when constrained.
- These differences are low, however.
  - $1\,\sigma$ intervals in both octants.
  - Low Bayes Factors.

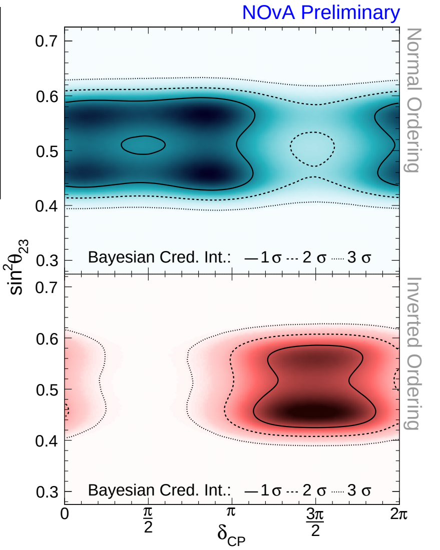
Results without Reactor Constraint



- All previous Frequentist results shown with exteranl θ_{13} constraint.
- But NOvA has sensitivity to θ_{13}! How does it affect our results?
  - Do we agree with the Reactors? Tensions in the PMNS model?
- Allowing unconstrained θ_{13} to give NOvA-only preferences:
  - δ_{CP} preferences don't change much.
  - Prefer normal mass ordering.
  - General conclusions similar to Reactor-constrained θ_{13}.





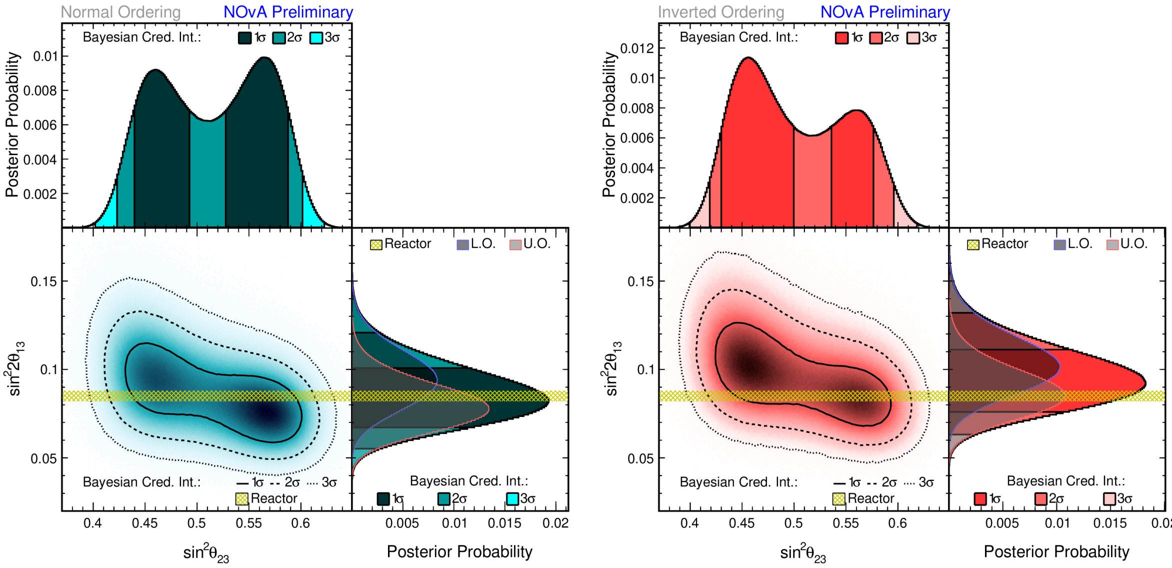


Lower octant: $\sin^2\theta_{23} < 0.5$, Upper Octant: $\sin^2\theta_{23} > 0.5$

- Prefer Lower Octant overall with NOvA-only θ_{13}
- Slight preference for Upper Octant in Normal Ordering.
- Higher preference for Lower Octant in Inverted Ordering.
- We need to look at θ_{13} to understand this.

NOvA-only θ_{13} measurements

Both Orderings | Normal Ordering | Inverted Ordering



Non-Standard Interactions: $\epsilon_{\mu\tau}$