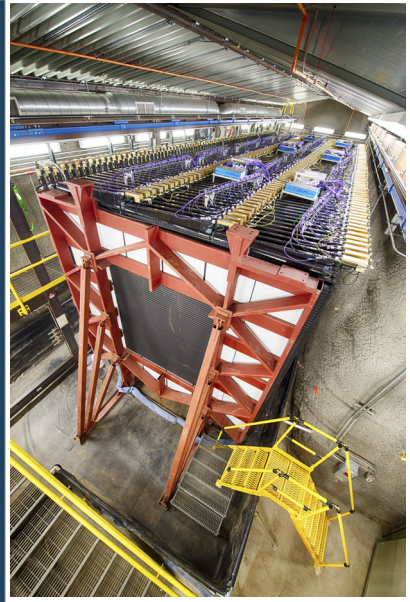
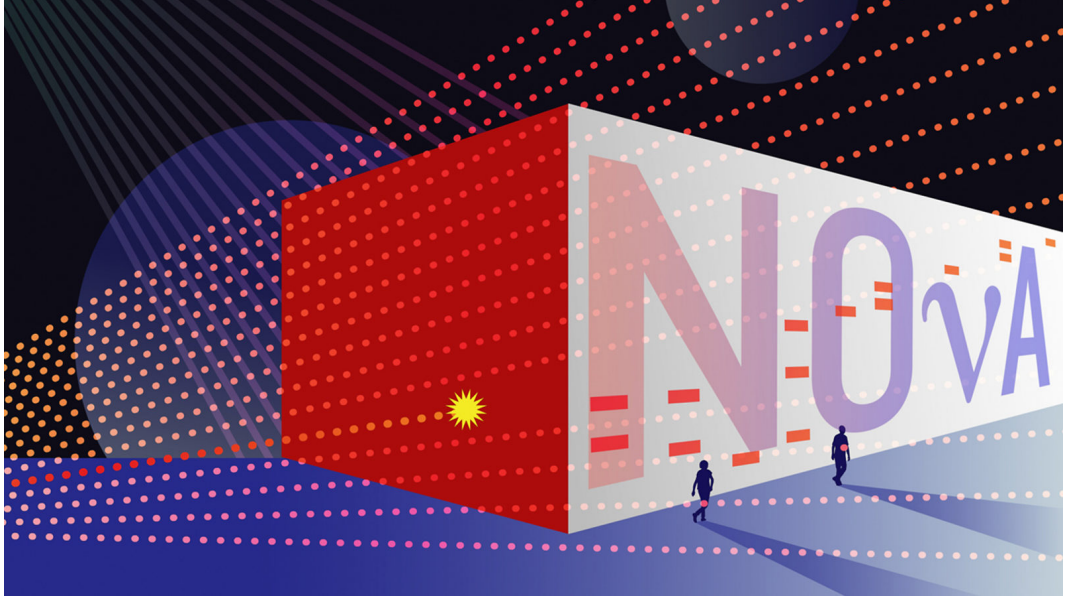
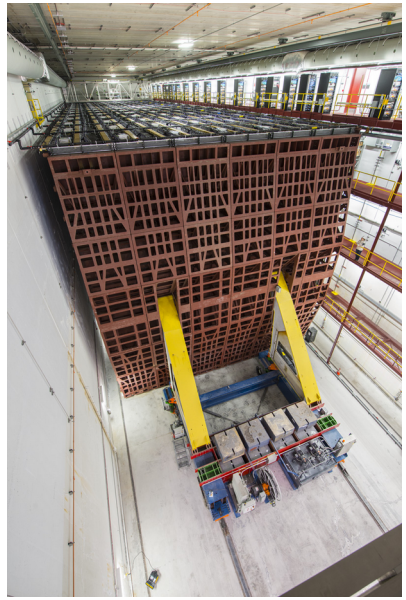






Latest 3-Flavor Neutrino Oscillation Results

Richa Sharma
Panjab University, Chandigarh
For the NOvA Collaboration

NuFACT

Aug 5, 2022

Standard Picture of 3 flavor Mixing

Flavor Eigenstates (interact)

Mass Eigenstates (propagate)

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

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric, beam}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor, beam}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, reactor}}$$

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

Standard Picture of 3 flavor Mixing

Flavor Eigenstates (interact) | Mass Eigenstates (propagate)

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

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

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

Oscillation frequencies proportional to mass square splittings.

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(1.27\frac{\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(1.27\frac{\Delta m^2_{ij}L}{E}\right)$$

Current knowledge, from global fit to oscillation data

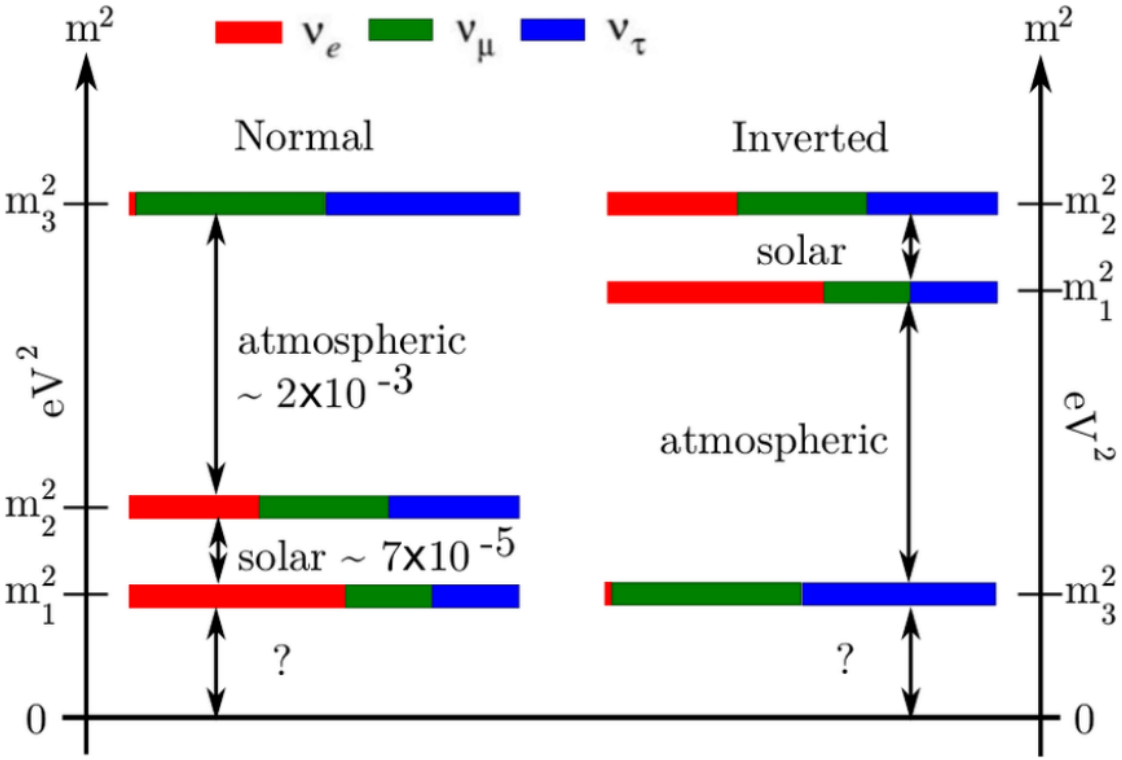
$$\sin^2\theta_{23} = 0.573^{+0.018}_{-0.023}$$
$$\sin^2\theta_{13} = 0.02220^{+0.00068}_{-0.00062}$$
$$\sin^2\theta_{12} = 0.304^{+0.013}_{-0.012}$$

NuFIT 5.1 (2021), www.nu-fit.org
JHEP 09 (2020) 178 [arXiv:2007.14792]

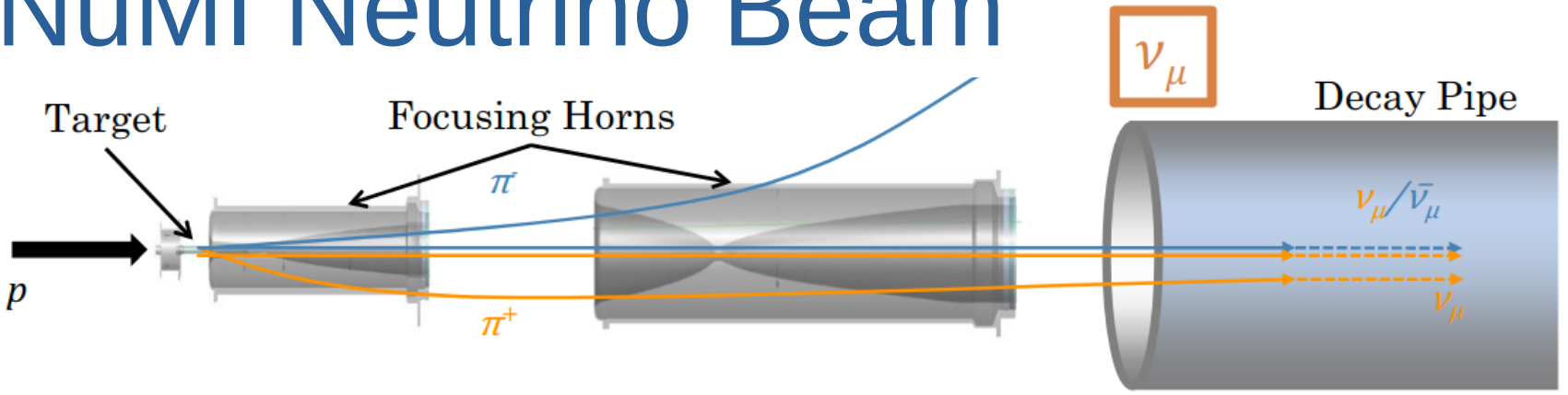
Open Questions

- **The sign of the larger mass splitting is unknown**
- **$\theta_{23} \neq 45°$?** : Its octant would determine whether ν_μ or ν_τ couples more strongly to ν_3
- **$\delta_{CP} \neq 0$?**: Charge-Parity symmetry violation.

Observe ν_e ($\bar{\nu}_e$) appearance and ν_μ ($\bar{\nu}_\mu$) disappearance



NuMI Neutrino Beam



Flux 1-5 GeV

96.3% ν_μ

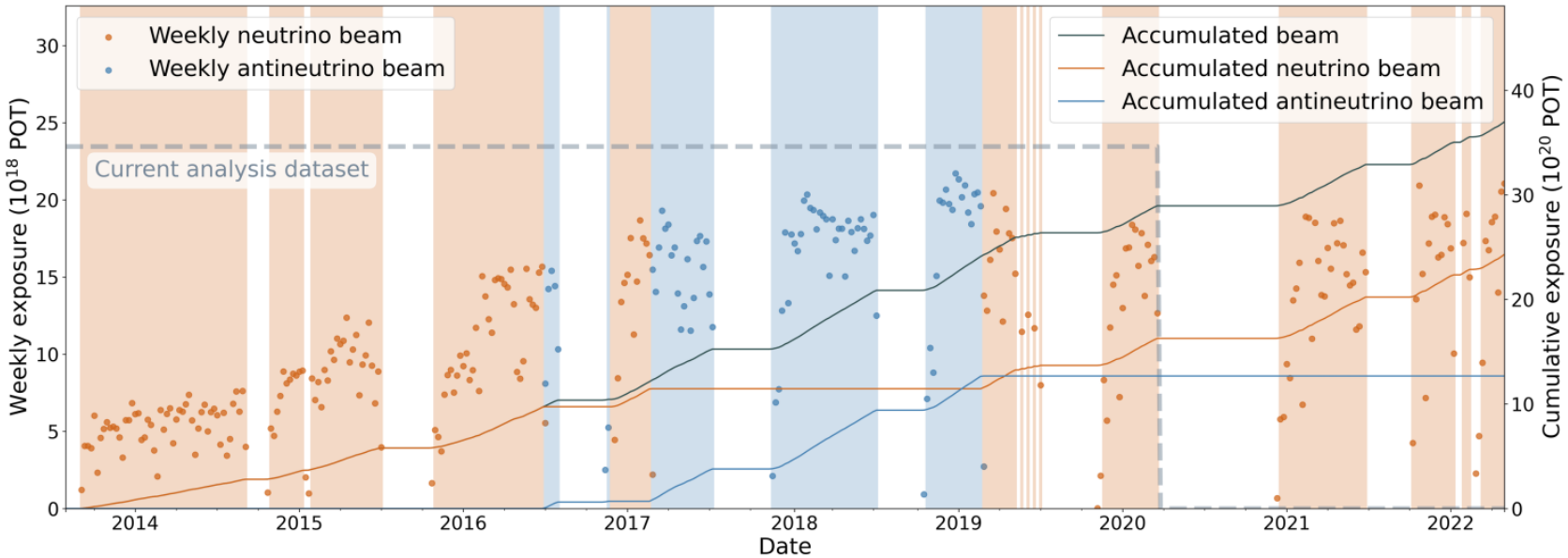
2.5% $\bar{\nu}_\mu$

1.1% $\nu_e + \bar{\nu}_e$

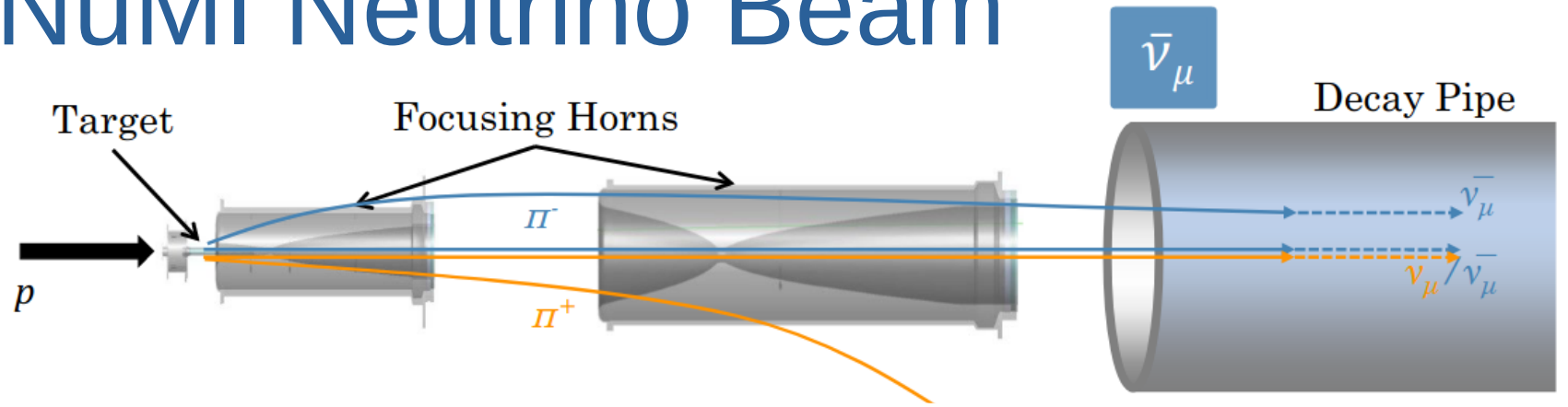
Analysed Exposure (POT)

13.6×10^{20} neutrino mode

12.5×10^{20} antineutrino mode



NuMI Neutrino Beam



Flux 1-5 GeV

15.2% ν_μ

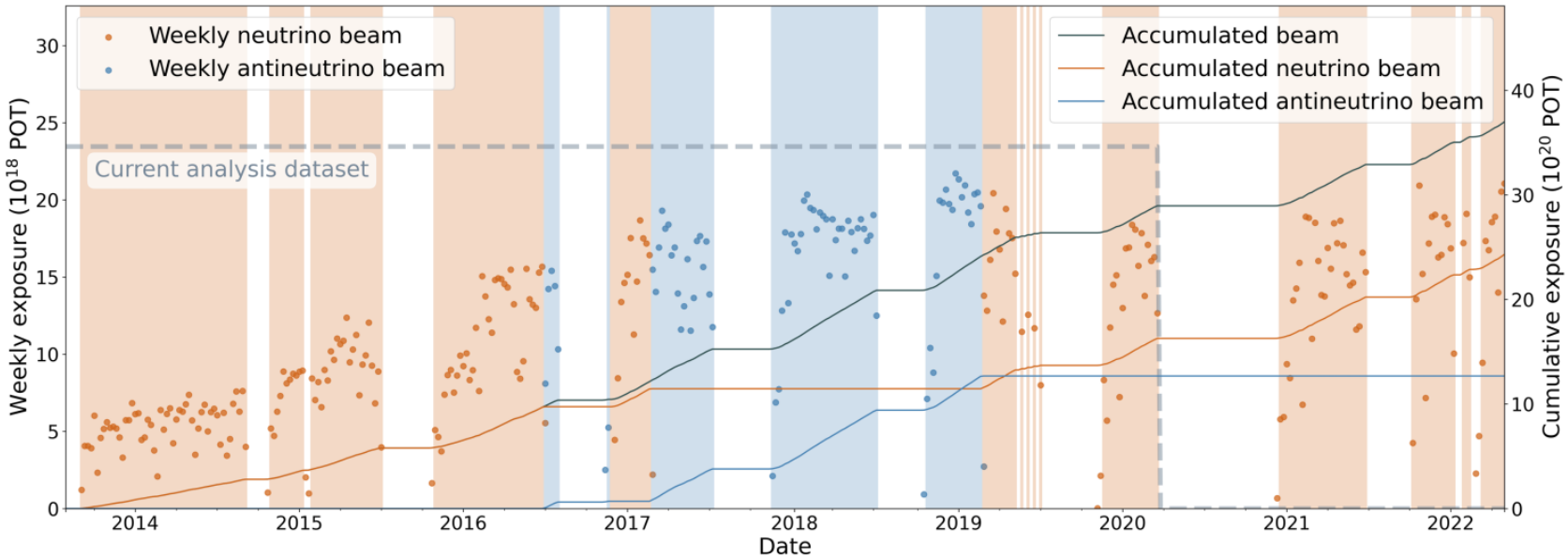
83.5% $\bar{\nu}_\mu$

1.3% ν_e + $\bar{\nu}_e$

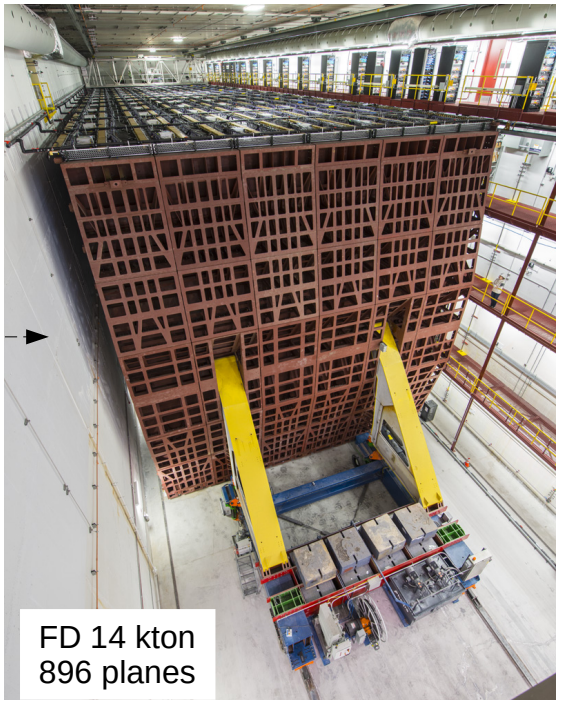
Analysed Exposure (POT)

13.6×10^{20} neutrino mode

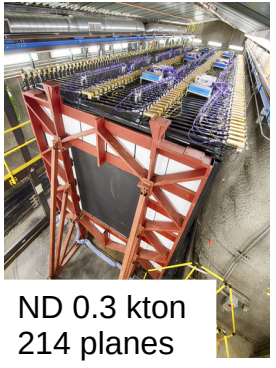
12.5×10^{20} antineutrino mode



NOvA Experiment

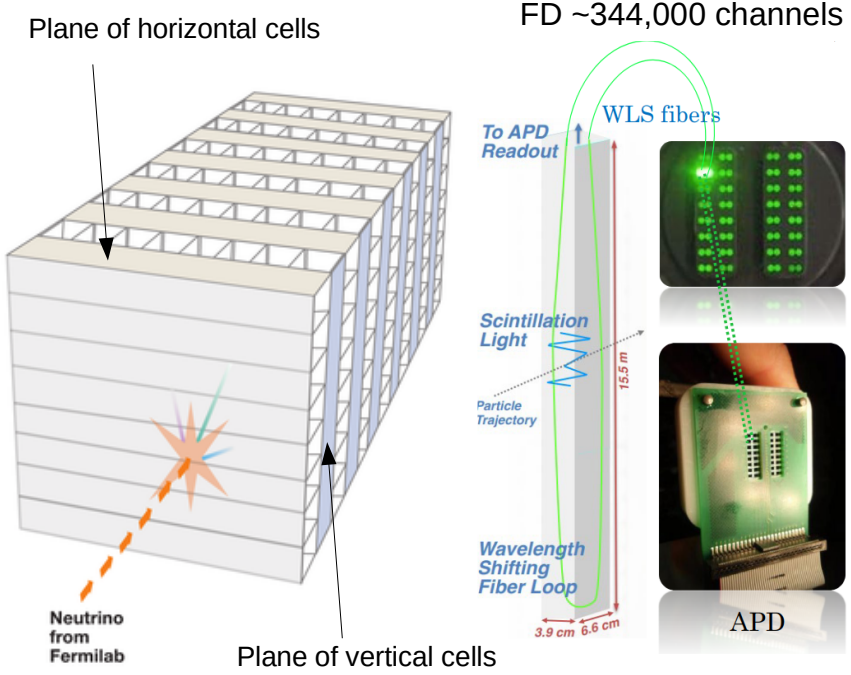


FD 14 kton
896 planes



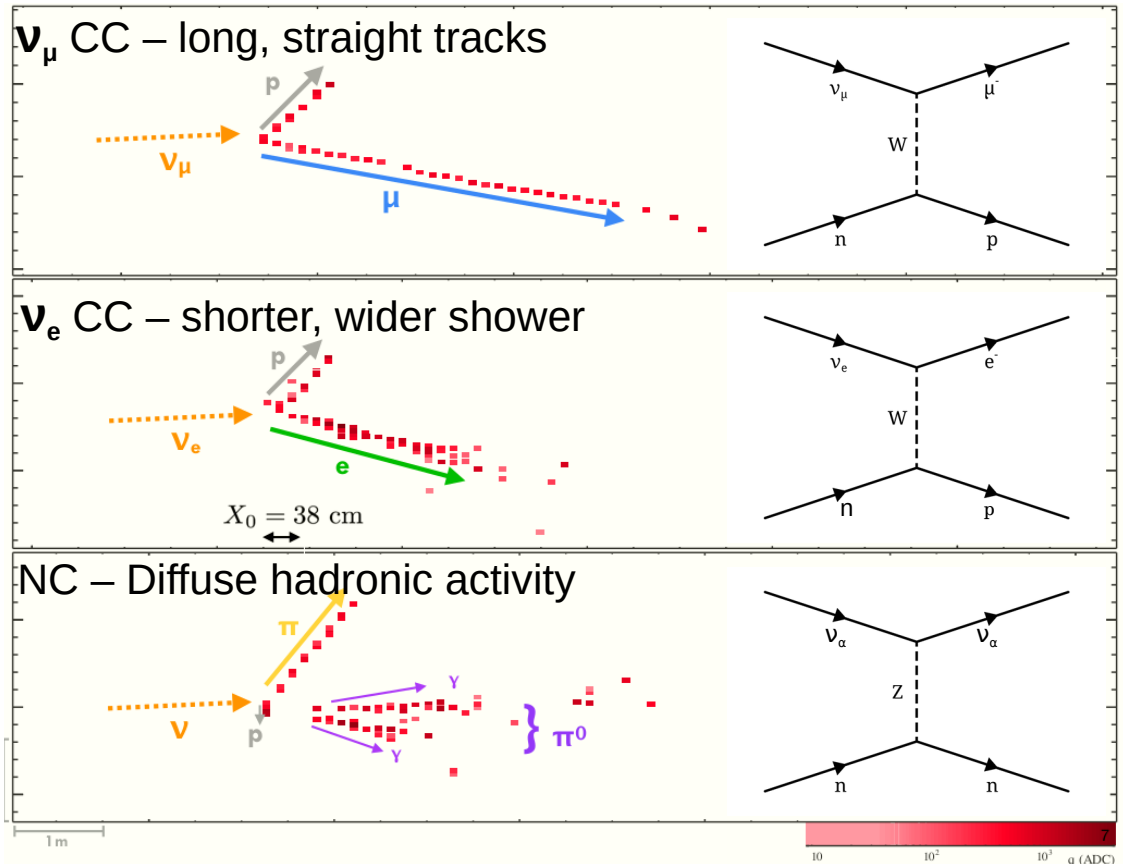
ND 0.3 kton
214 planes

ND ~20,000 channels
FD ~344,000 channels



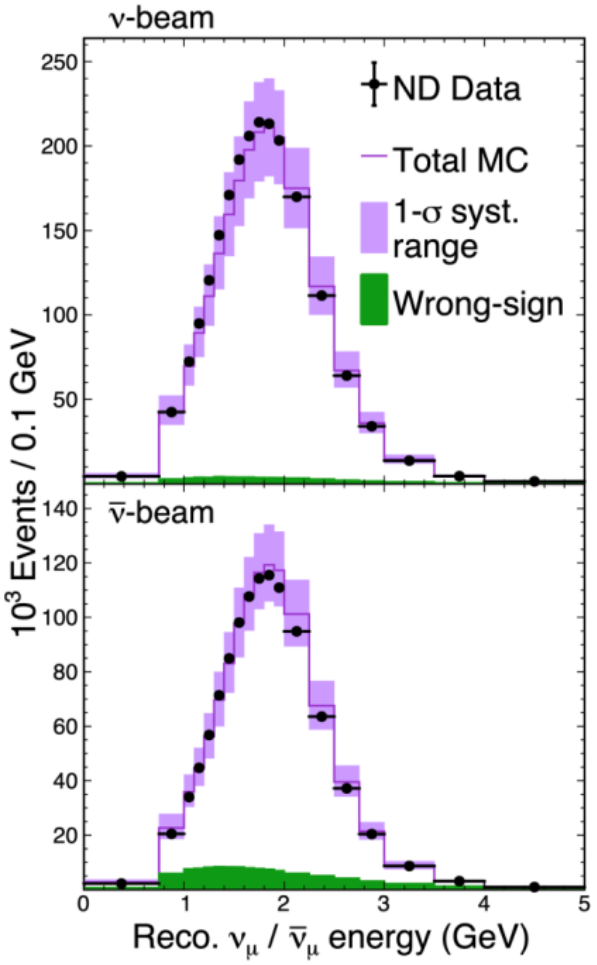
- PVC extrusions filled with liquid scintillator(mineral oil + 5% pseudocumene)
- Each cell readout by a wavelength shifting fiber onto one pixel of a 32 pixel avalanche photodiode

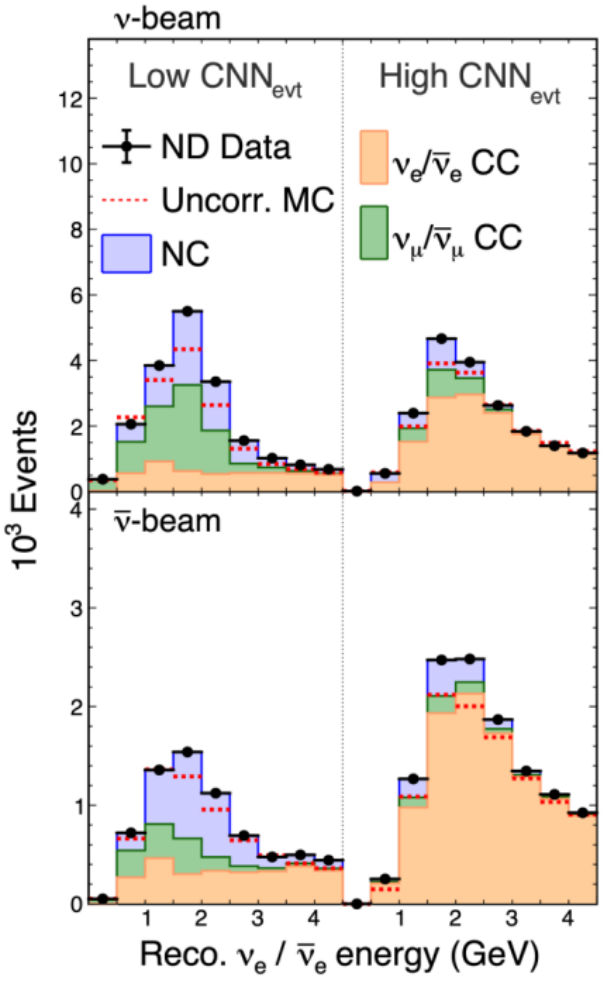
Event Classification



- Candidate events are required to:
  - Be in time with the beam
  - Be contained in the detector
  - Pass data quality cuts
- A CNN_{evt} used to classify events into ν_eCC, ν_μ CC, NC or cosmogenic.
- The scores of the CNN_{evt} are used to form two independent samples of neutrinos and antineutrino events.
- Another CNN, in addition to BDT, to reduce cosmic background in the FD.
  - Cosmic background < 5%

ND Data





Both neutrino and antineutrino mode data used.

Simulated ND spectra corrected to ND data and extrapolated to FD. Extrapolation accounts for

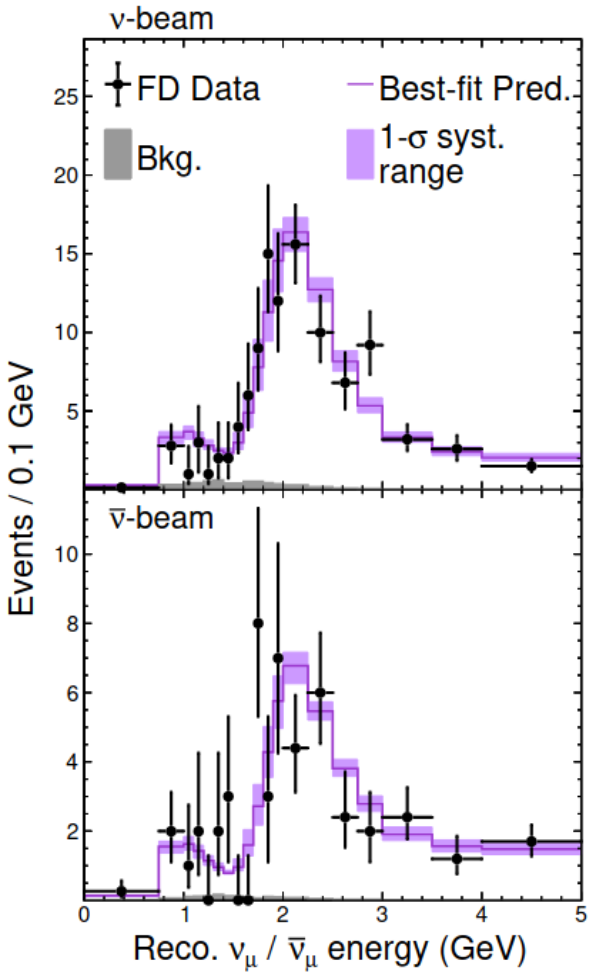
- Energy Smearing
- Acceptance and selection efficiency
- Beam divergence

Data-driven FD predictions for

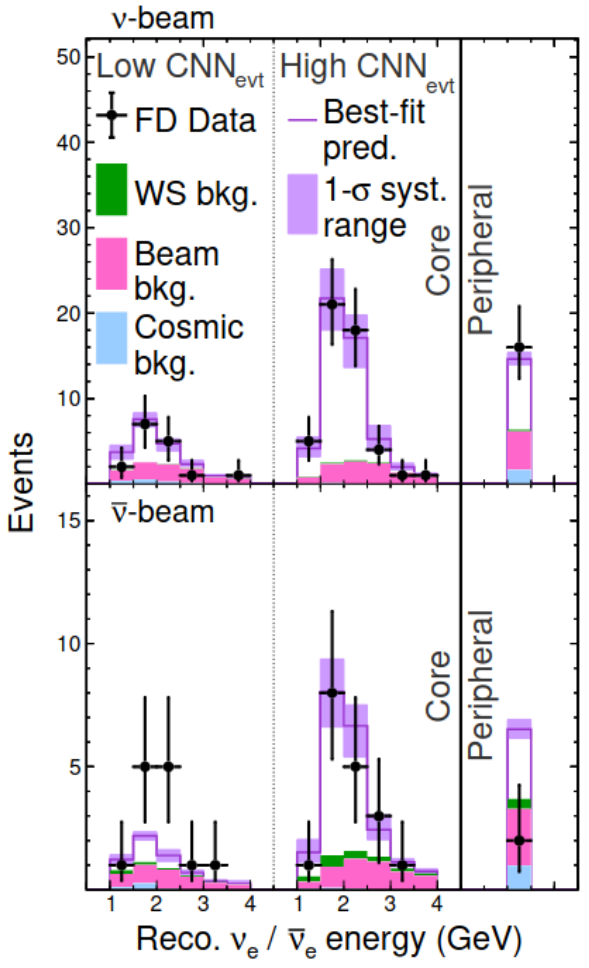
- ν_μ ($\bar{\nu}_\mu$) disappearance
- ν_e ($\bar{\nu}_e$) appearance
- Beam backgrounds

FD Data

211 ν_μ cand.
(8 bkgd)



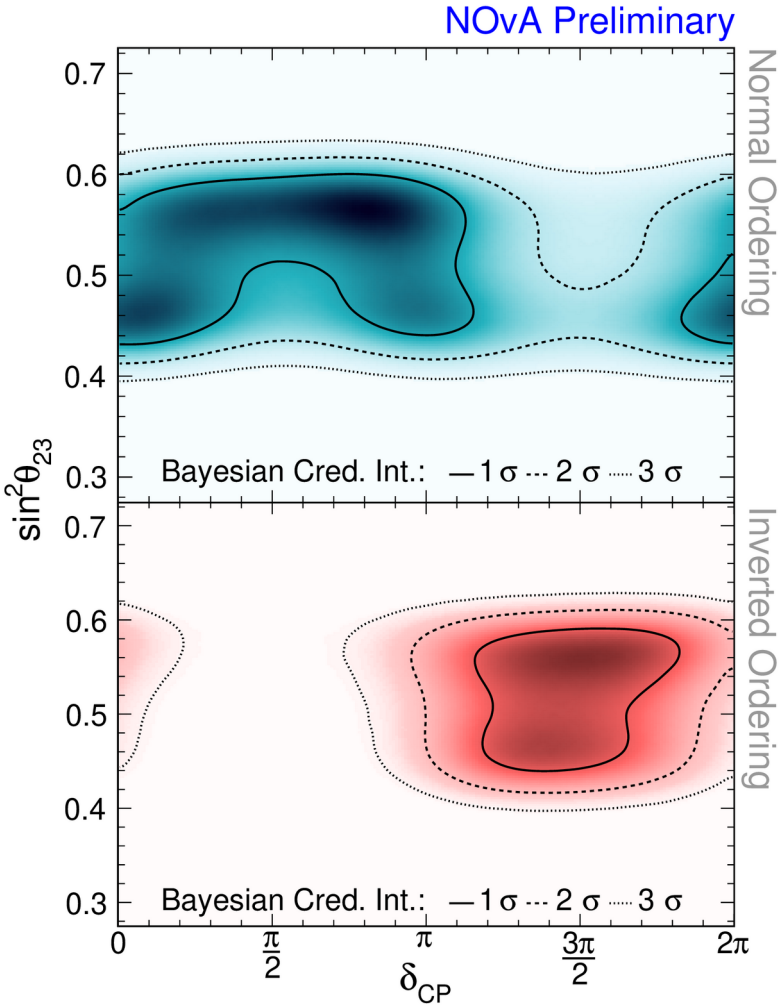
105 $\bar{\nu}_\mu$ cand.
(2 bkgd)



82 ν_e cand.
(27 bkgd)

33 $\bar{\nu}_e$ cand.
(14 bkgd)

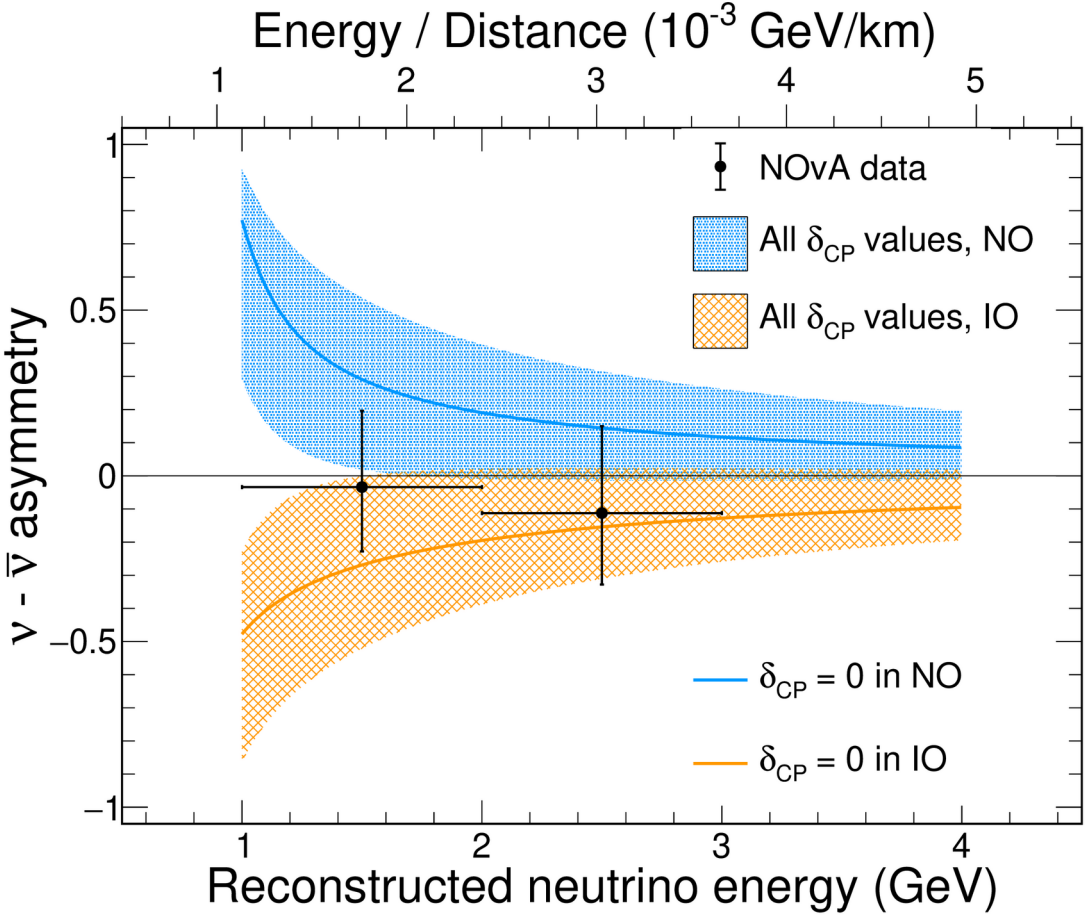
Results



- **Markov Chain Monte Carlo Bayesian Analysis**
  - **Conclusions the same as frequentist results**
- **Weak preference for Normal Ordering, Upper θ_{23} Octant**
- **The inverted mass ordering with $\delta_{CP} = \pi/2$ is excluded at more than 3σ ;**

  normal ordering with $\delta_{CP} = 3\pi/2$ is disfavored at 2σ

Appearance Asymmetry

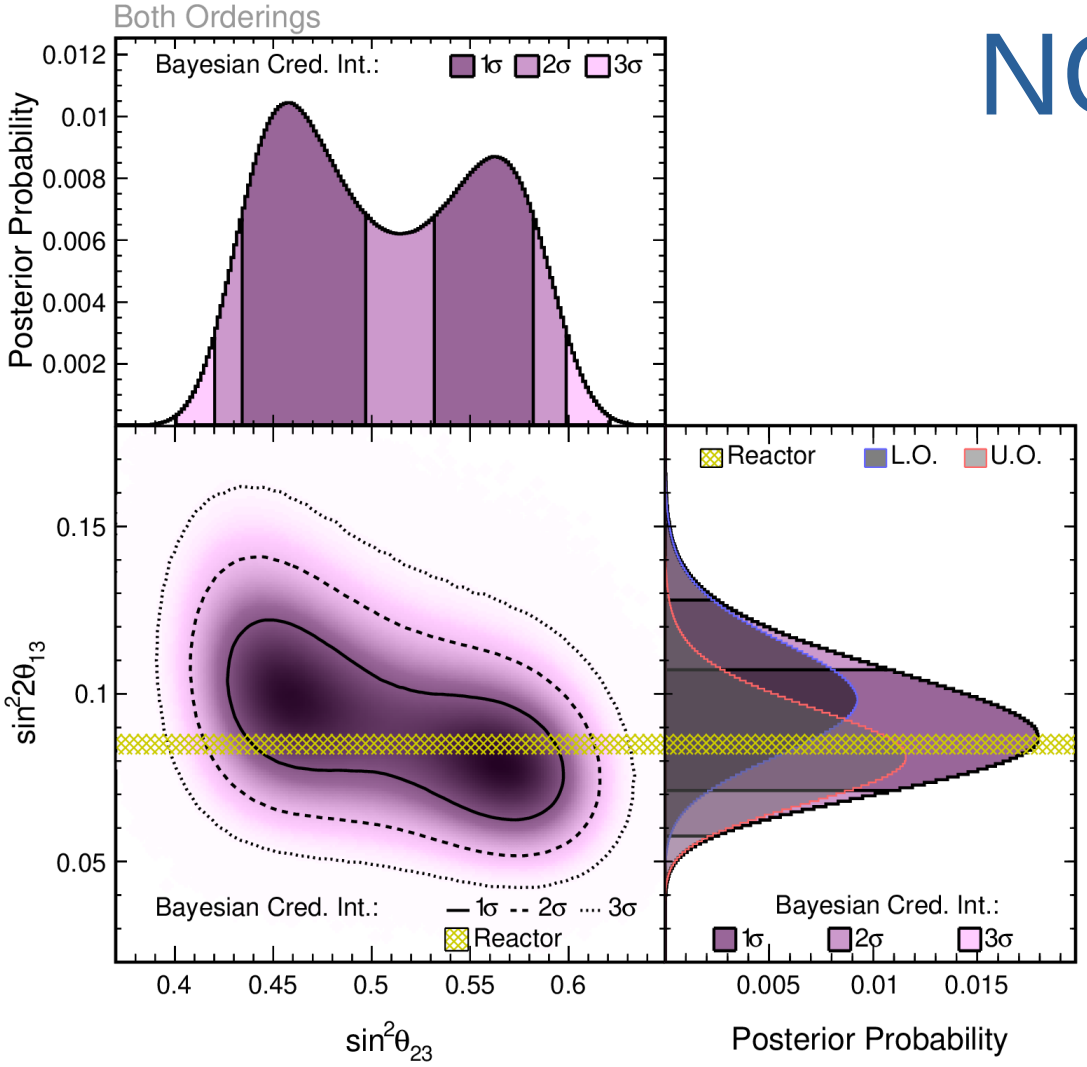


Defined as

$$P(\nu_e)-P(\bar{\nu}_e)/P(\nu_e)+P(\bar{\nu}_e)$$

No ν_e – $\bar{\nu}_e$ asymmetry to 25% precision

Disfavour mass ordering-δ CP combinations with large asymmetry



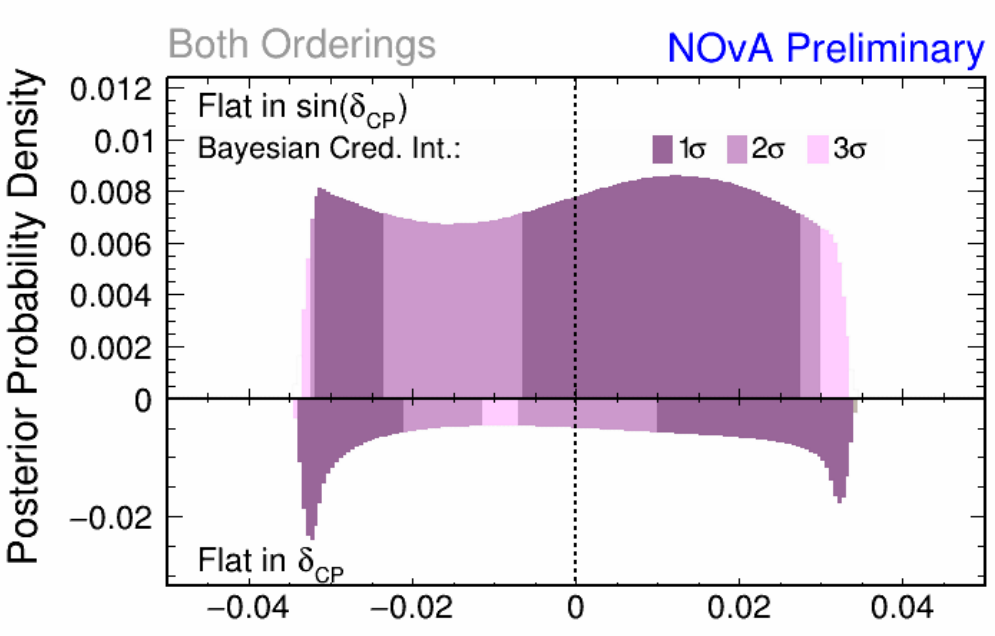
NOvA-only θ_{13} vs θ_{23}

- Bayesian framework makes this type of analysis very easy.
- **Larger θ_{13} would favour lower octant for θ_{23} and vice versa**

$$\sin^2\theta_{13} = 0.085^{+0.020}_{-0.016}$$

- **Consistent with reactor experiments**

Jalrskog Invariant



$J = \cos\theta_{12} \cos^2\theta_{13} \cos\theta_{23} \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta_{CP}$

- Another way of showing CP violation
- Invariant under different paramterizations
  - Of interest to theorists
- J=0: CP-Conservation. J≠0: CP-Violation

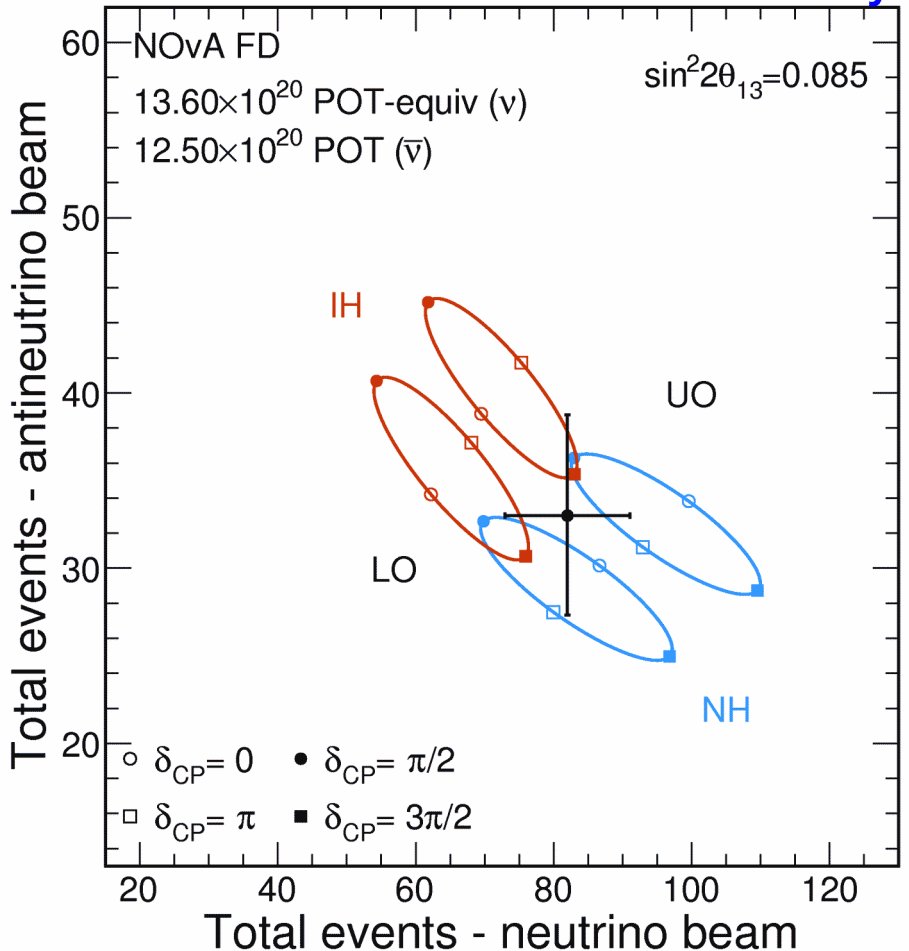
Reference: Neutrino Mixing Anarchy arXiv:1204.1249

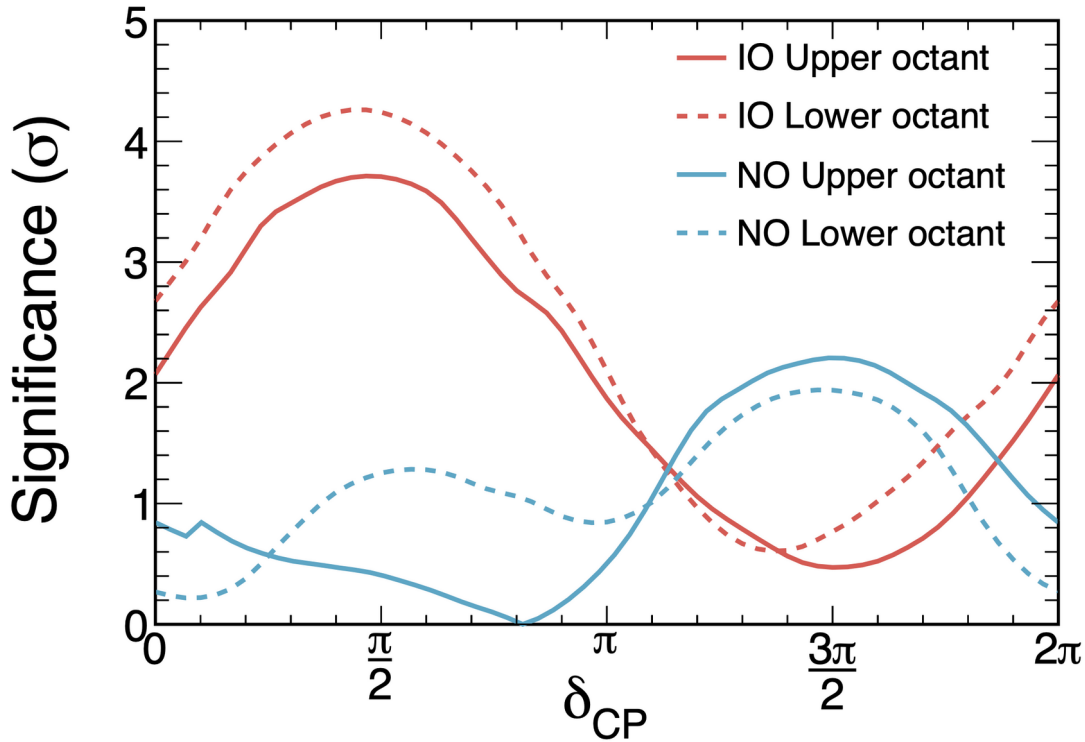
Summary

- Results from the new Bayesian MCMC framework for NovA.
- Measured $\sin^2\theta_{13} = 0.085^{+0.020}_{-0.016}$
  - Consistent with reactor experiments
- Appearance symmetry consistent with zero to 25% precision.
- New way of showing CP violation. No preference for CP conservation or violation
- More to come:
  - NOvA – T2K joint fit in progress
  - We've already taken a lot more data
  - Continue to improve measurements!

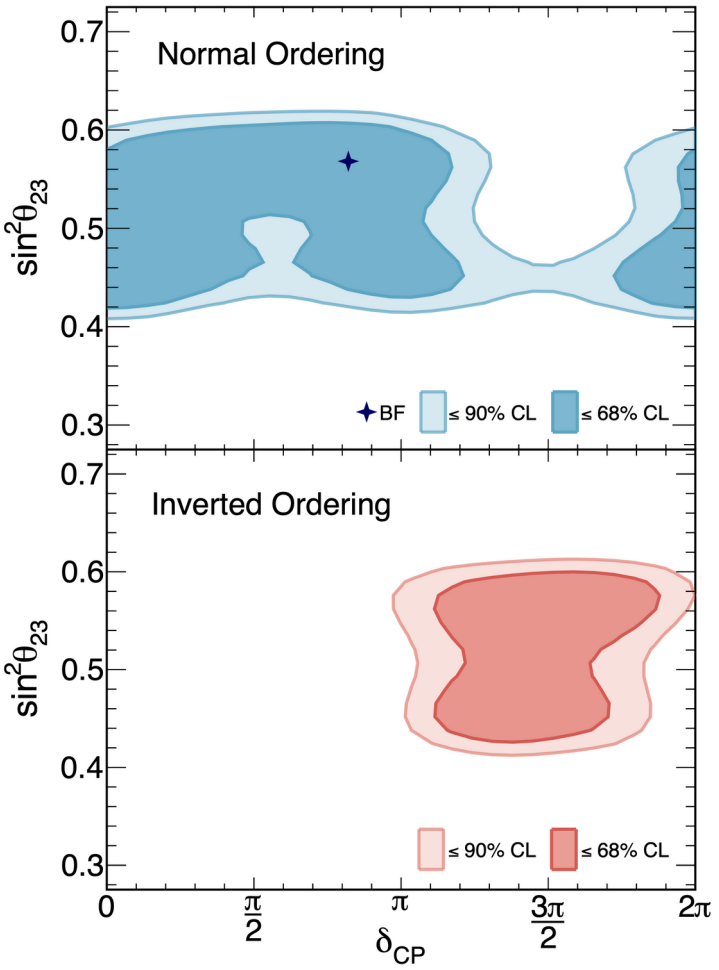
Thanks!

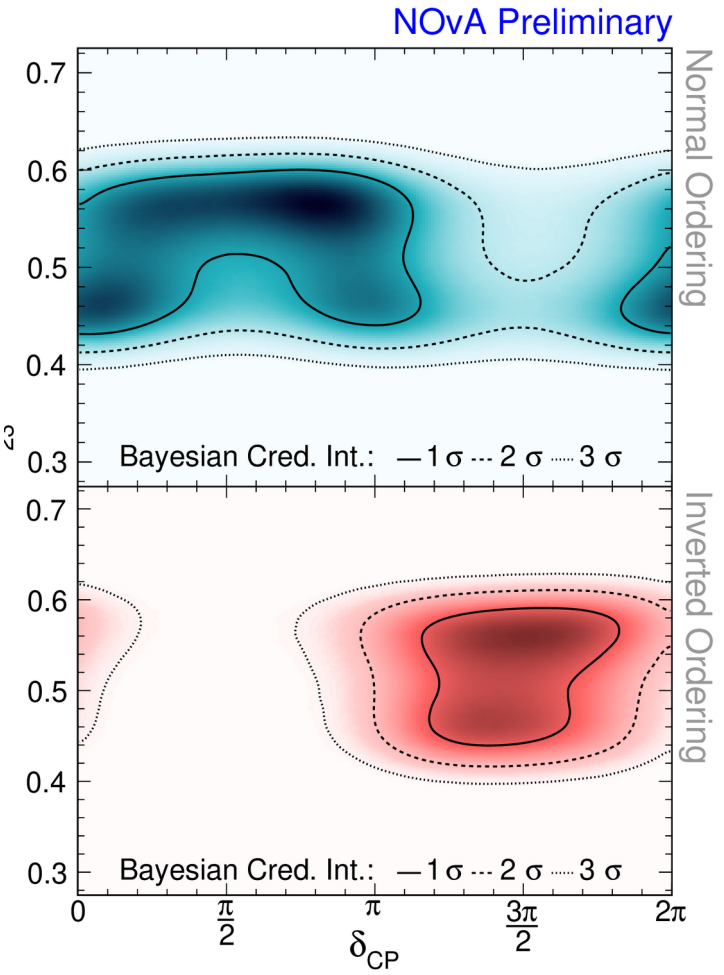
NOvA Preliminary

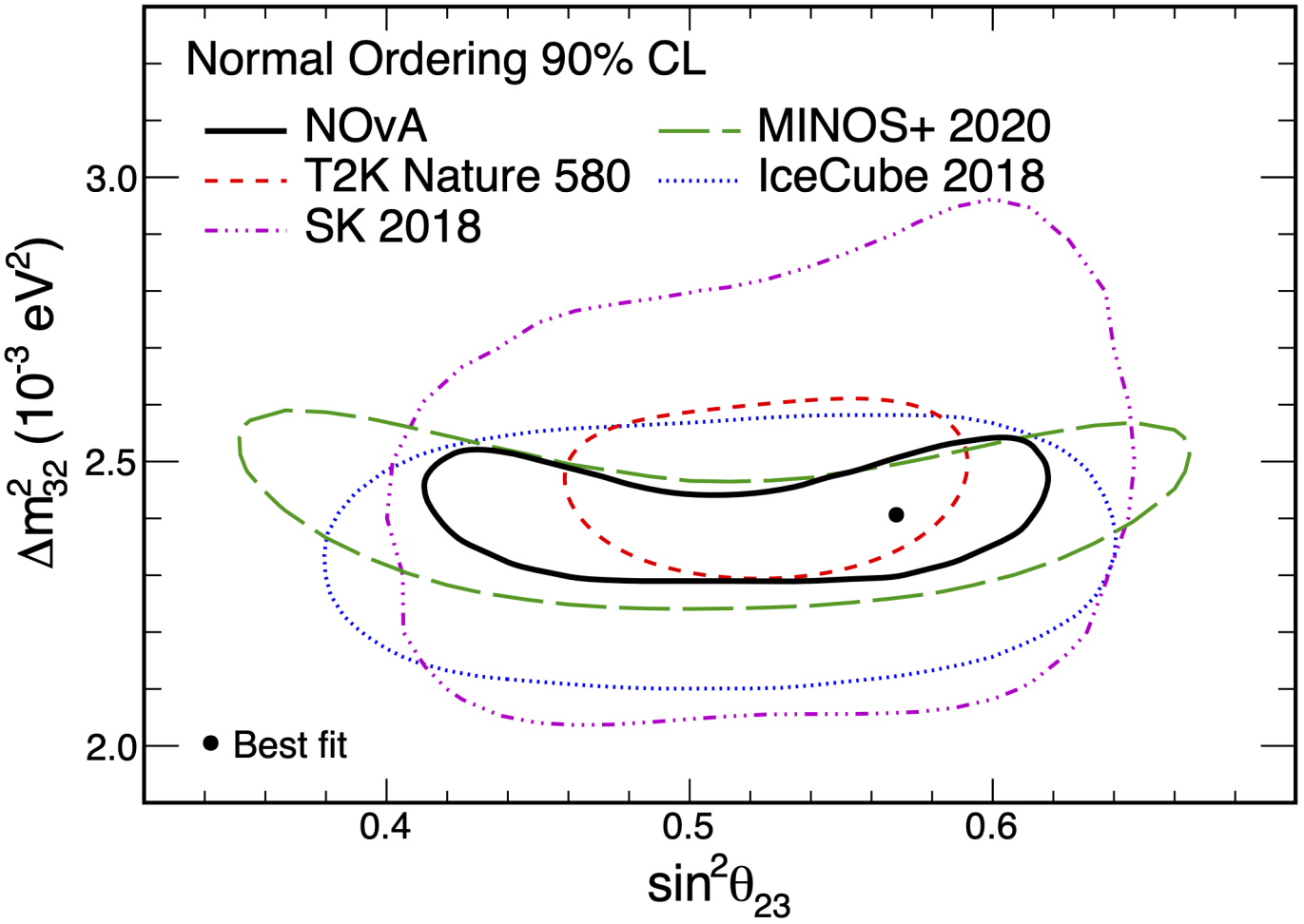




Frequentist vs Bayesian






Normal Ordering 90% CL
NOvA
T2K Nature 580
SK 2018
MINOS+ 2020
IceCube 2018
Best fit
3.0
2.5
2.0
0.4
0.5
0.6
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

Frequentist vs Bayesian