Latest Neutrino Oscillation Results from NOvA

Blois 2024

Margot MacMahon for the NOvA Collaboration

22/10/2024

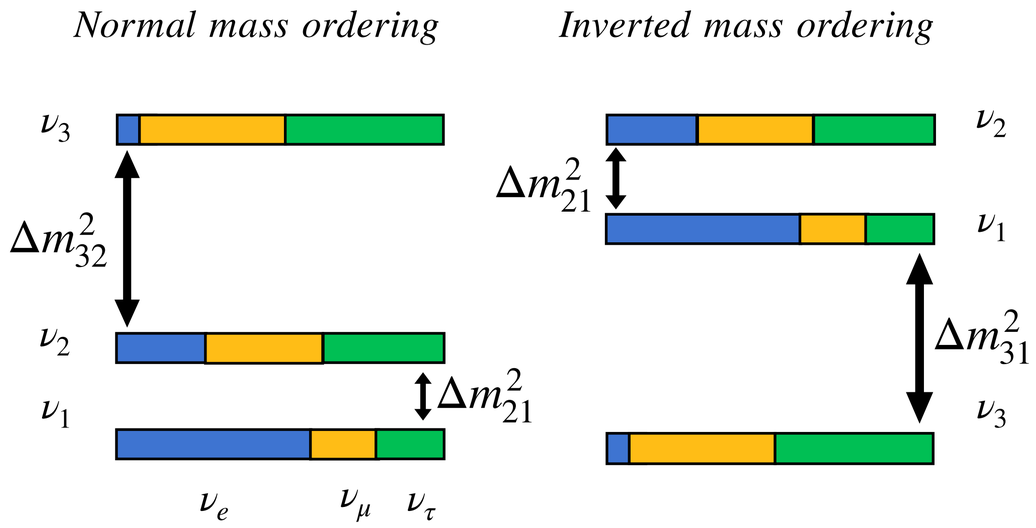
Neutrinos

Neutrinos

Are there more neutrino flavours?

Neutrinos

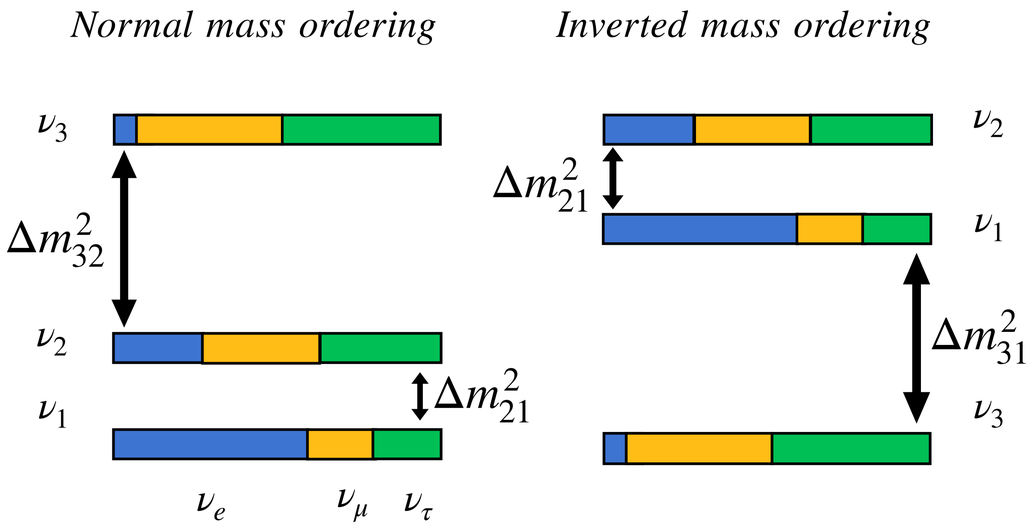
Are there more neutrino flavours?



What is the ordering of the neutrino mass states?

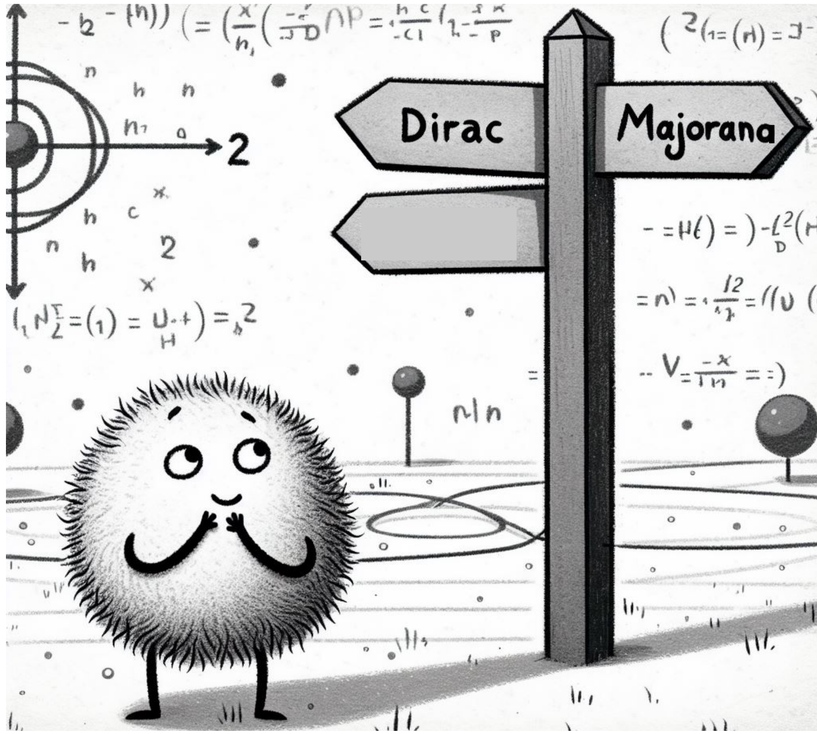
Neutrinos

Are there more neutrino flavours?



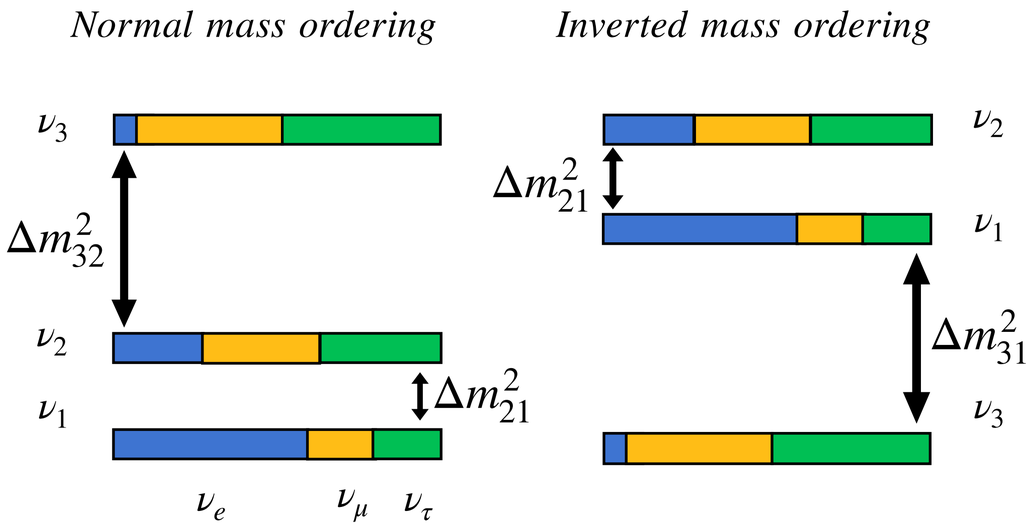
What is the ordering of the neutrino mass states?

Are neutrinos Dirac or Majorana?



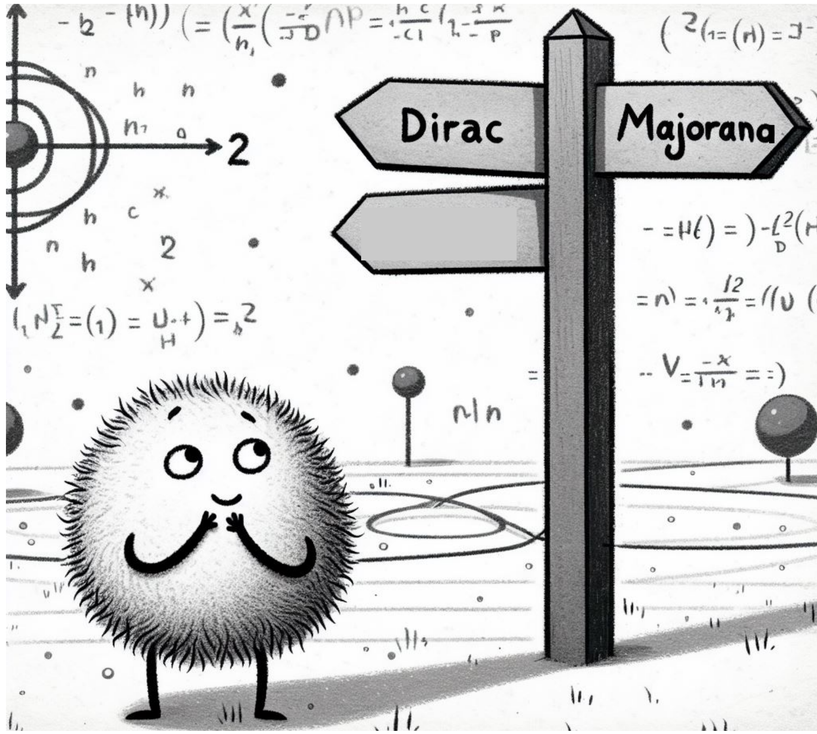
Neutrinos

Are there more neutrino flavours?



What is the ordering of the neutrino mass states?

Are neutrinos Dirac or Majorana?



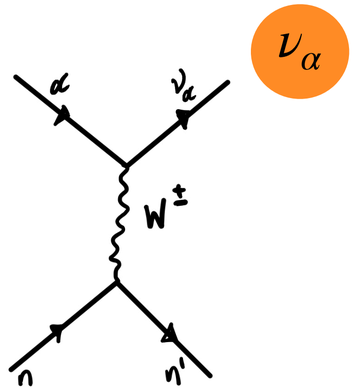
δ_{CP}

Is there Charge-Parity violation in the lepton sector?

Neutrino Oscillations

Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

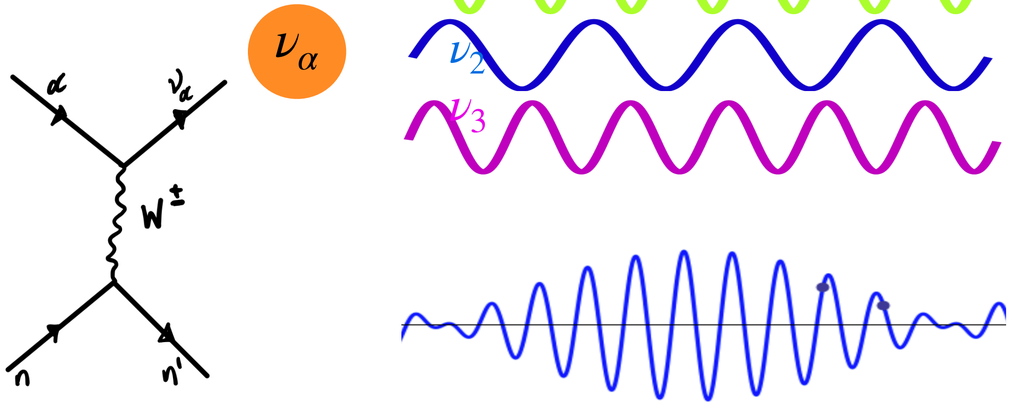
Neutrino Oscillations



ν_α

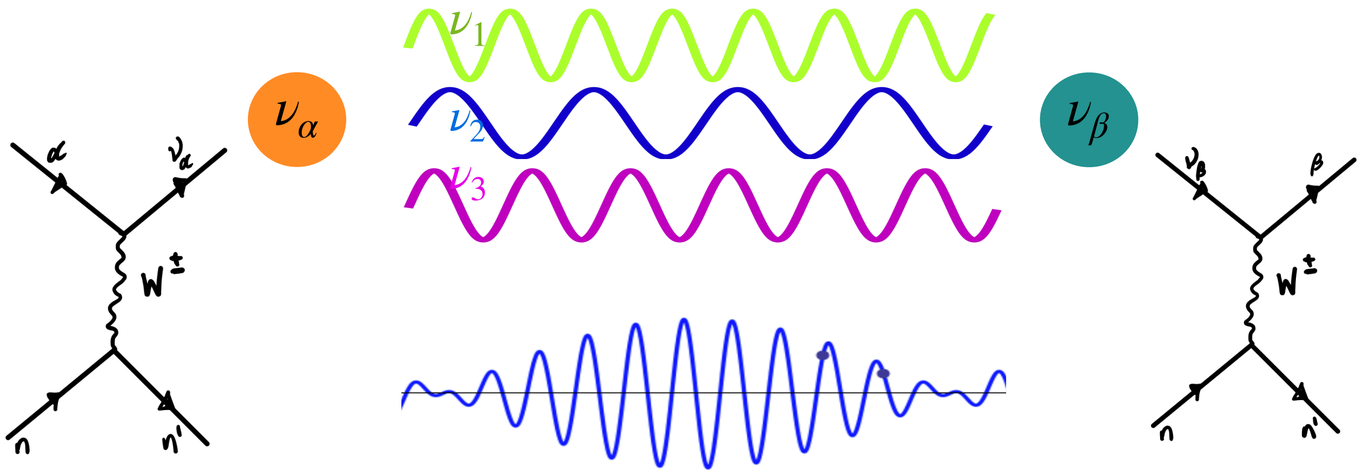
Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

Neutrino Oscillations



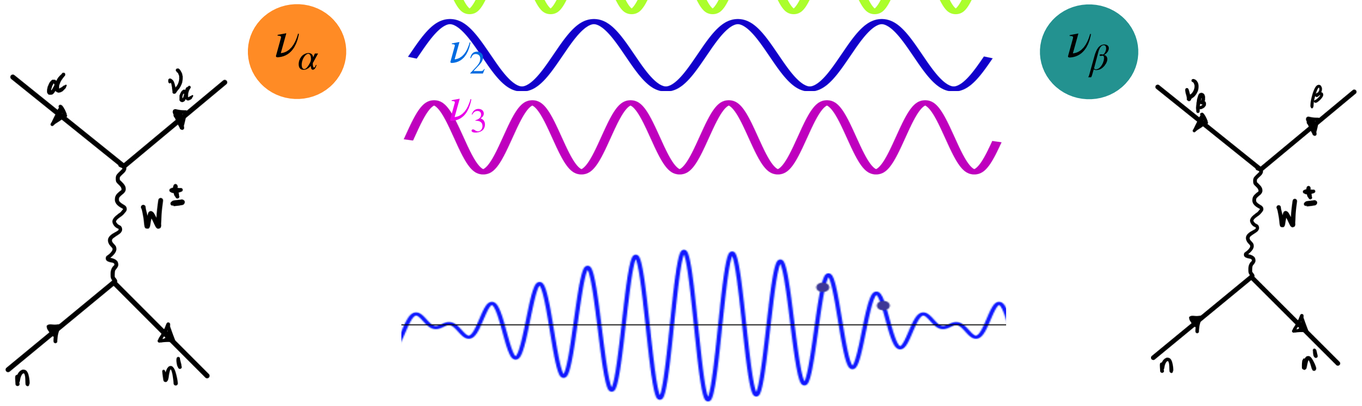
Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

Neutrino Oscillations



Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

Neutrino Oscillations

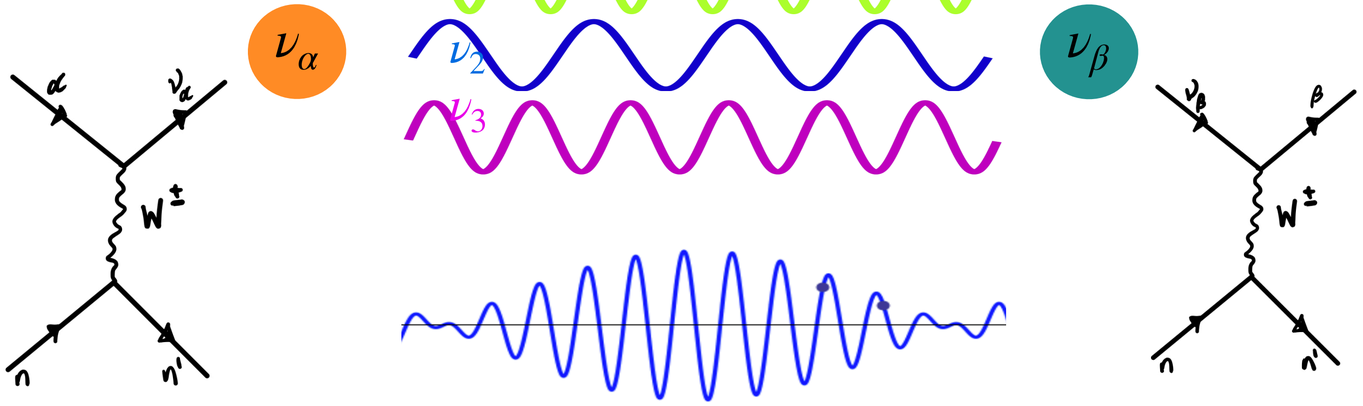


Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing between mass and flavour states is determined by PMNS matrix

Neutrino Oscillations



Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

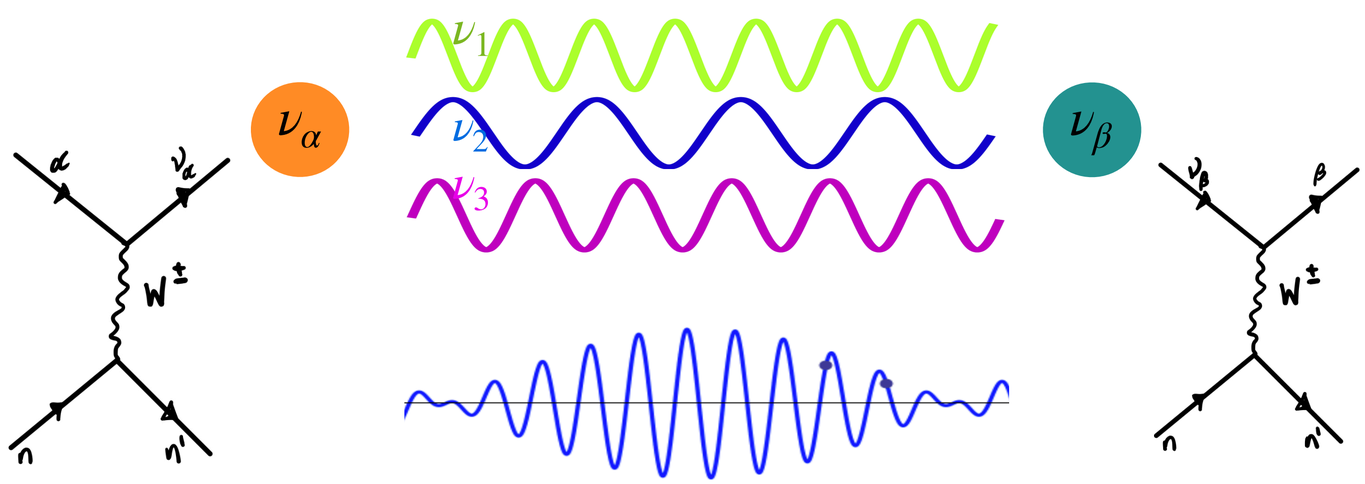
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing between mass and flavour states is determined by PMNS matrix

$U_{PMNS} \ni \theta_{12}, \theta_{13}, \theta_{23}$ 3 mixing angles

δ_{CP} 1 CP violating(?) phase

Neutrino Oscillations



Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>k} \mathbb{R}\{U^*_{\alpha j}U_{\beta j}U_{\alpha k}U^*_{\beta k}\sin^2(\frac{\Delta m^2_{jk}L}{4E})$$

$$+2\sum_{j>k} \mathbb{I}\{U^*_{\alpha j}U_{\beta j}U_{\alpha k}U^*_{\beta k}\sin(\frac{\Delta m^2_{jk}L}{2E})$$

Oscillation probability depends on mixing angles, CP phase and mass splittings

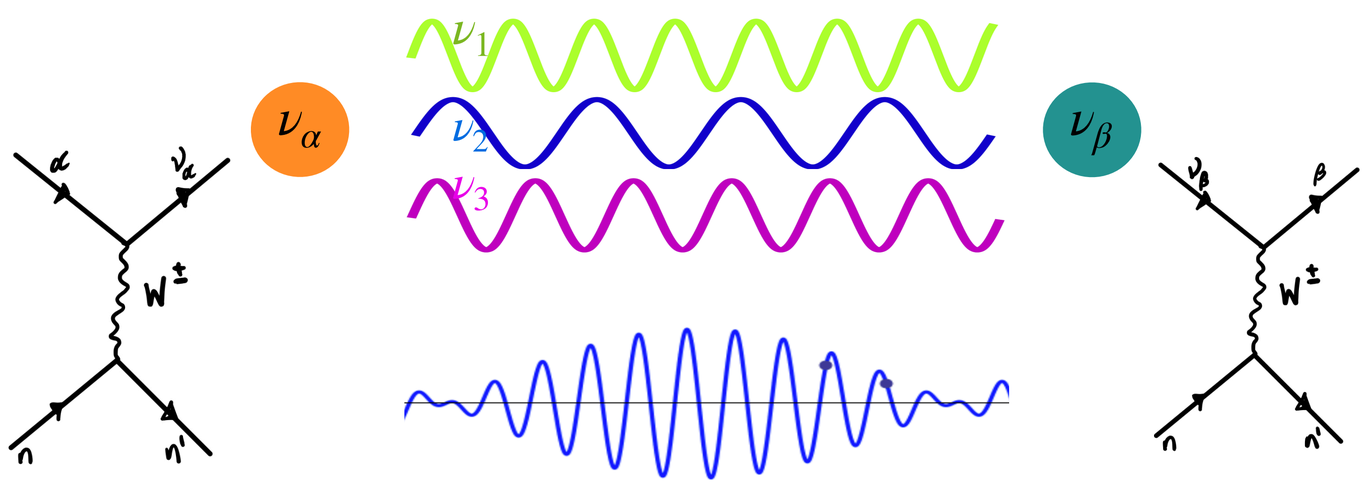
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}}_{U_{PMNS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mixing between mass and flavour states is determined by PMNS matrix

$U_{PMNS} \ni \theta_{12}, \theta_{13}, \theta_{23}$ 3 mixing angles

δ_{CP} 1 CP violating(?) phase

Neutrino Oscillations



Neutrinos interact in a flavour eigenstate, but propagate in a superposition of mass eigenstates

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>k} \mathbb{R}\{U^*_{\alpha j}U_{\beta j}U_{\alpha k}U^*_{\beta k}\sin^2(\frac{\Delta m^2_{jk}L}{4E})$$

$$+2\sum_{j>k} \mathbb{I}\{U^*_{\alpha j}U_{\beta j}U_{\alpha k}U^*_{\beta k}\sin(\frac{\Delta m^2_{jk}L}{2E})$$

Oscillation probability depends on mixing angles, CP phase and mass splittings

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}}_{U_{PMNS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mixing between mass and flavour states is determined by PMNS matrix

$U_{PMNS} \ni \theta_{12}, \theta_{13}, \theta_{23}$ **3 mixing angles**

δ_{CP} **1 CP violating(?) phase**

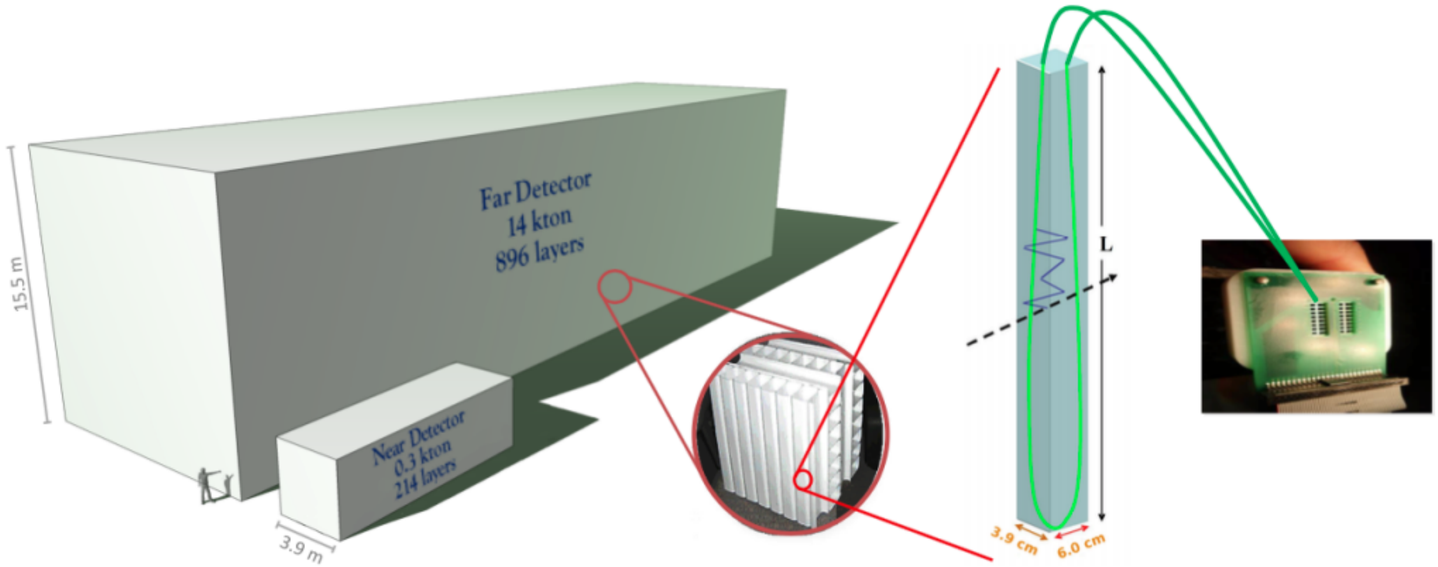
θ_{12} constraints from solar and reactor neutrinos

θ_{13} very well measured by reactor experiments

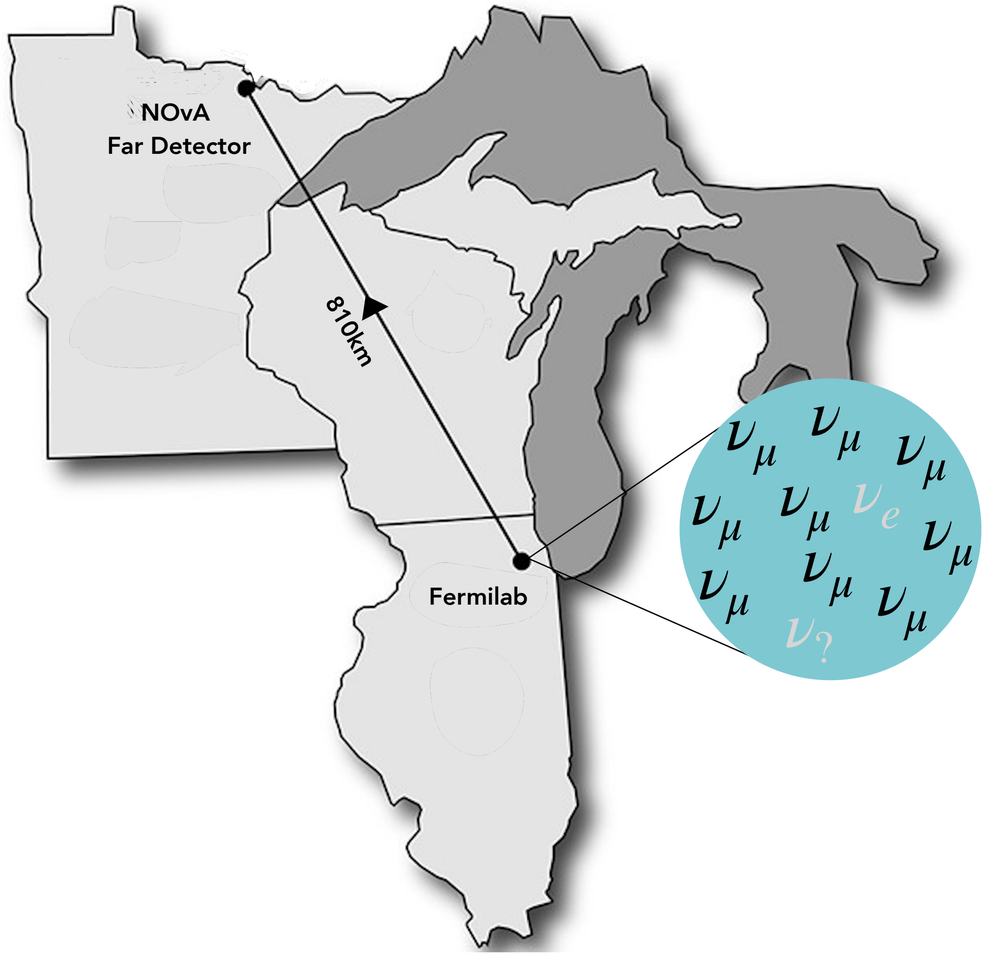
θ_{23} constraints from beam and atmospheric neutrinos

δ_{CP} constraints from reactor and beam neutrinos

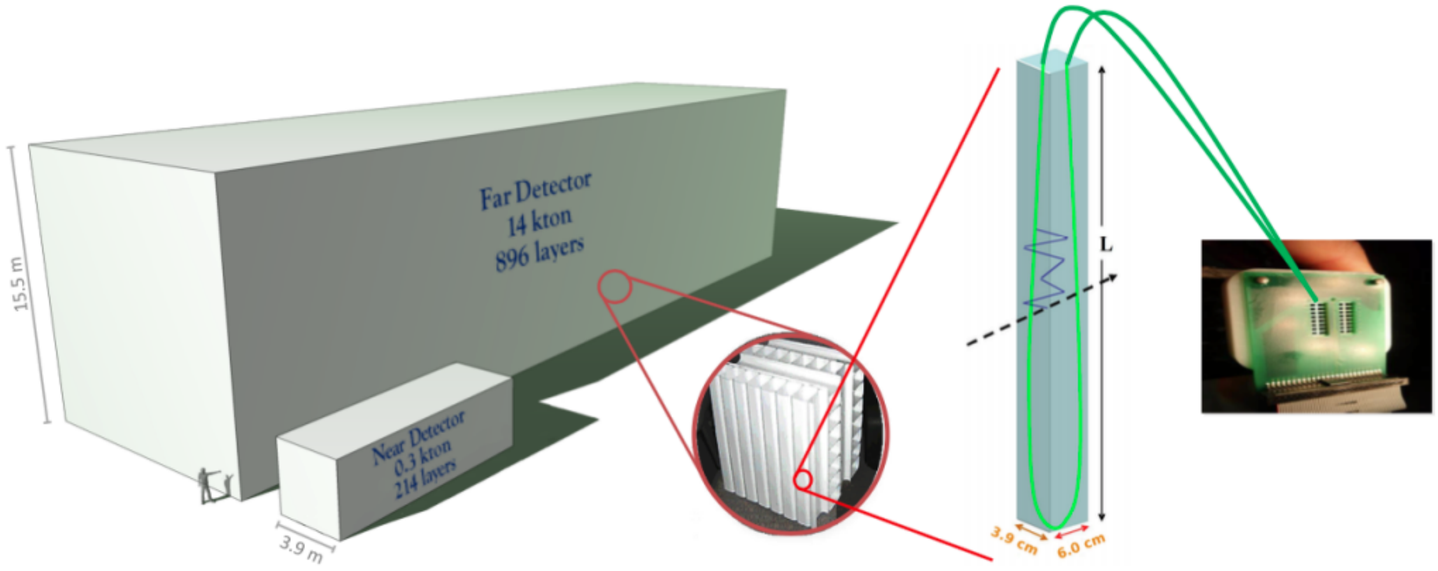
NOvA Experiment



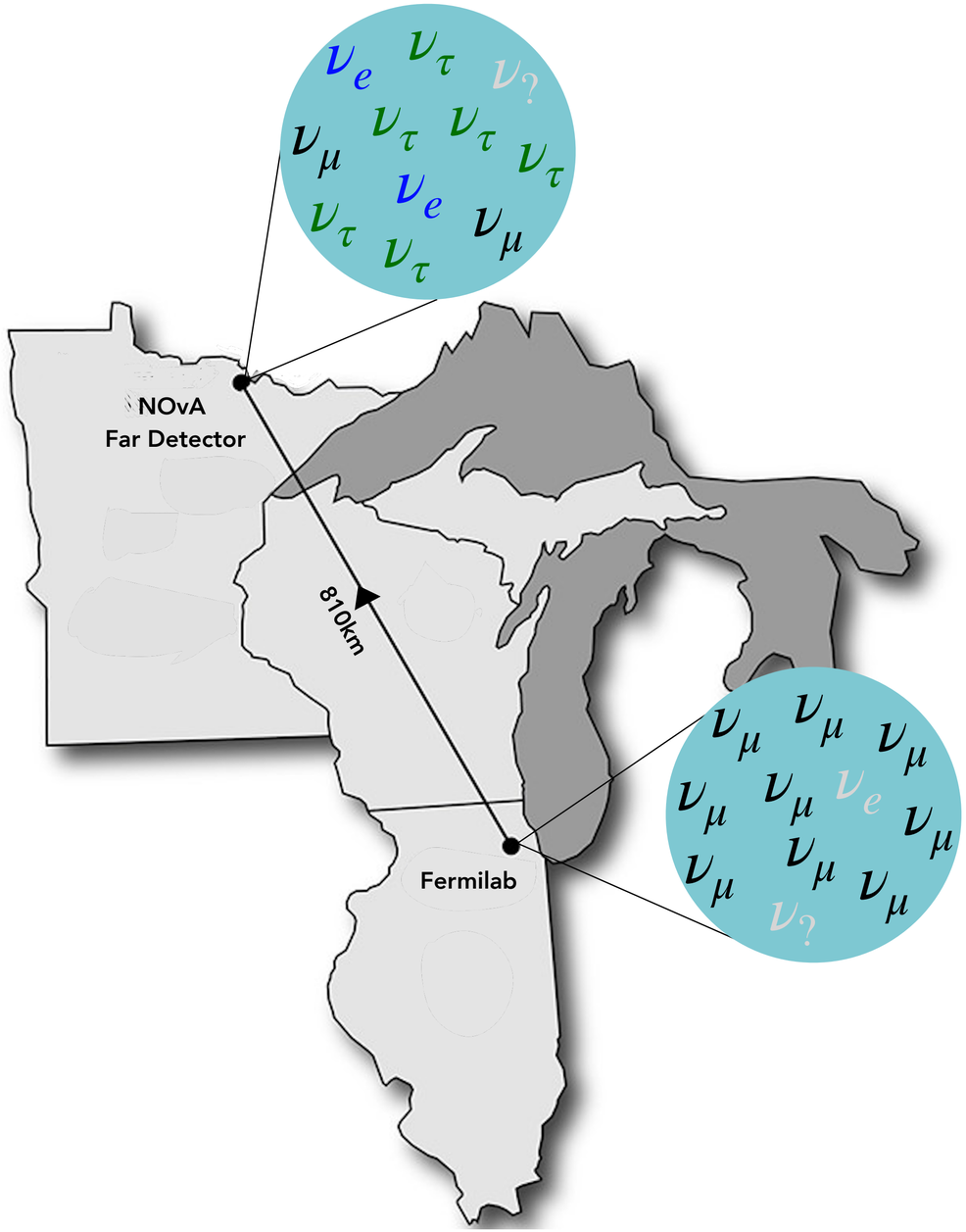
NOvA Experiment



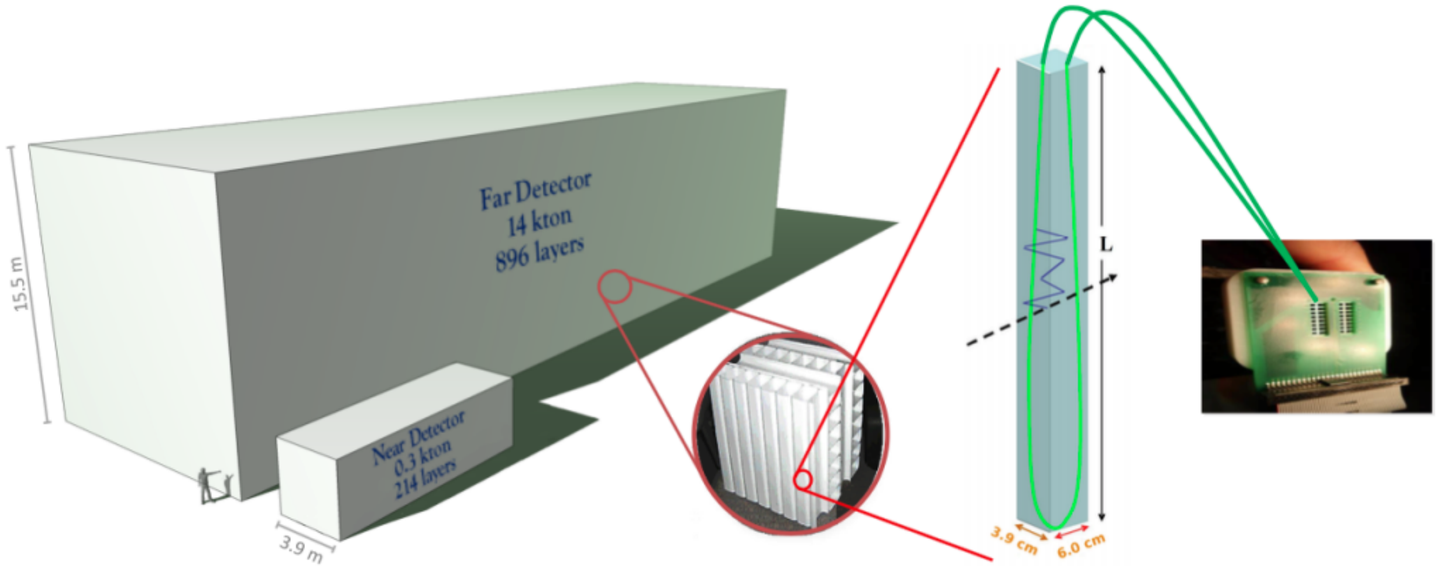
- NuMI beamline produces high purity beam of ν_μ or $\bar{\nu}_\mu$



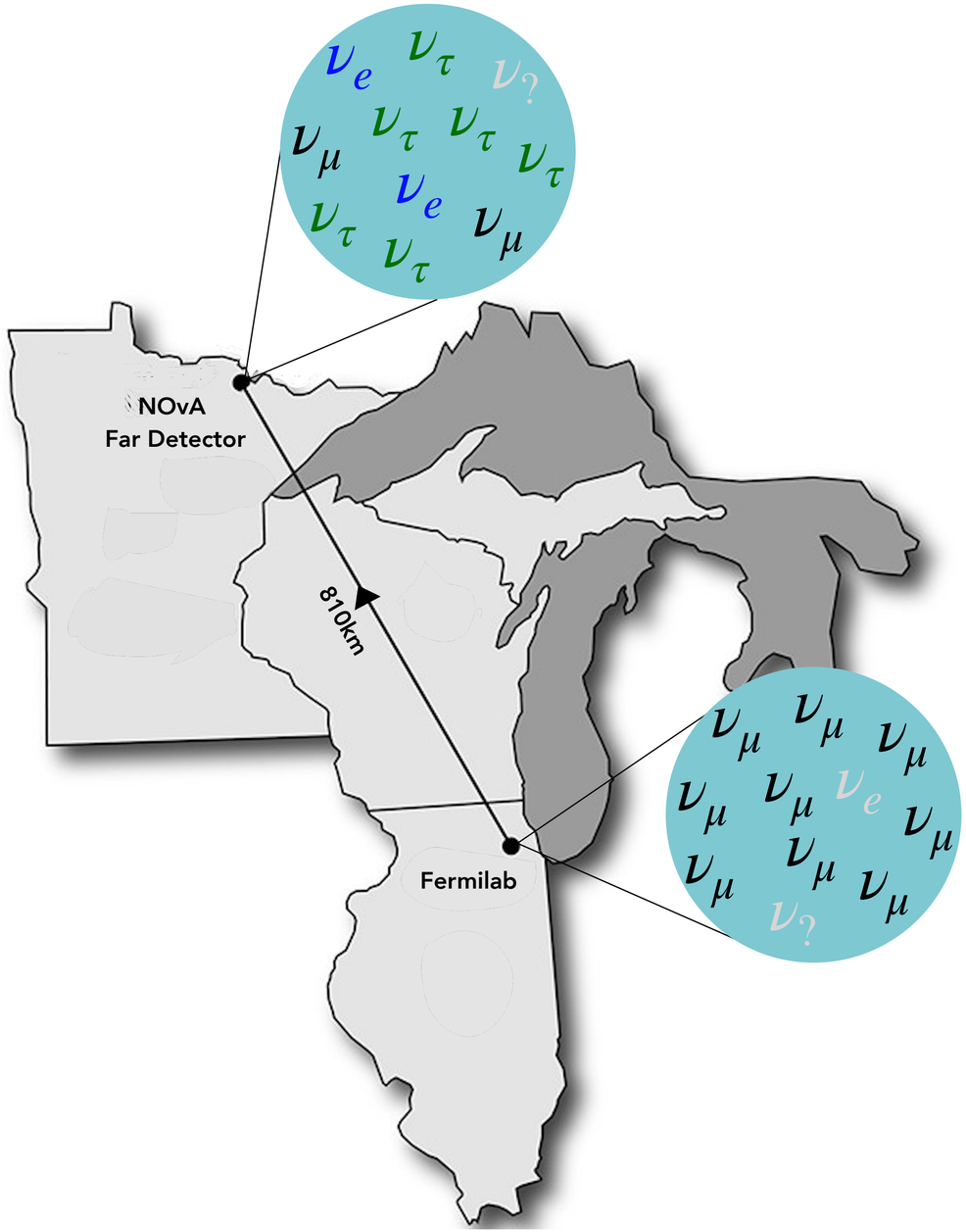
NOvA Experiment



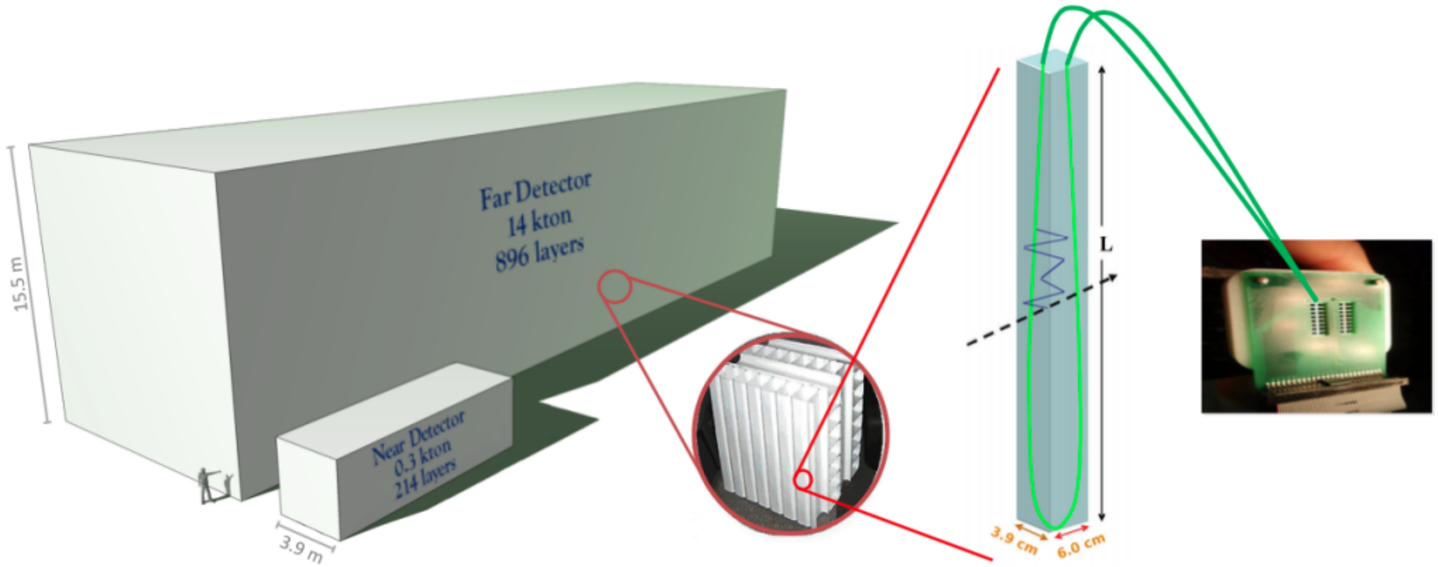
- NuMI beamline produces high purity beam of ν_μ or $\bar{\nu}_\mu$
- Neutrinos pass through near detector before travelling 810km to the functionally identical far detector in Minnesota



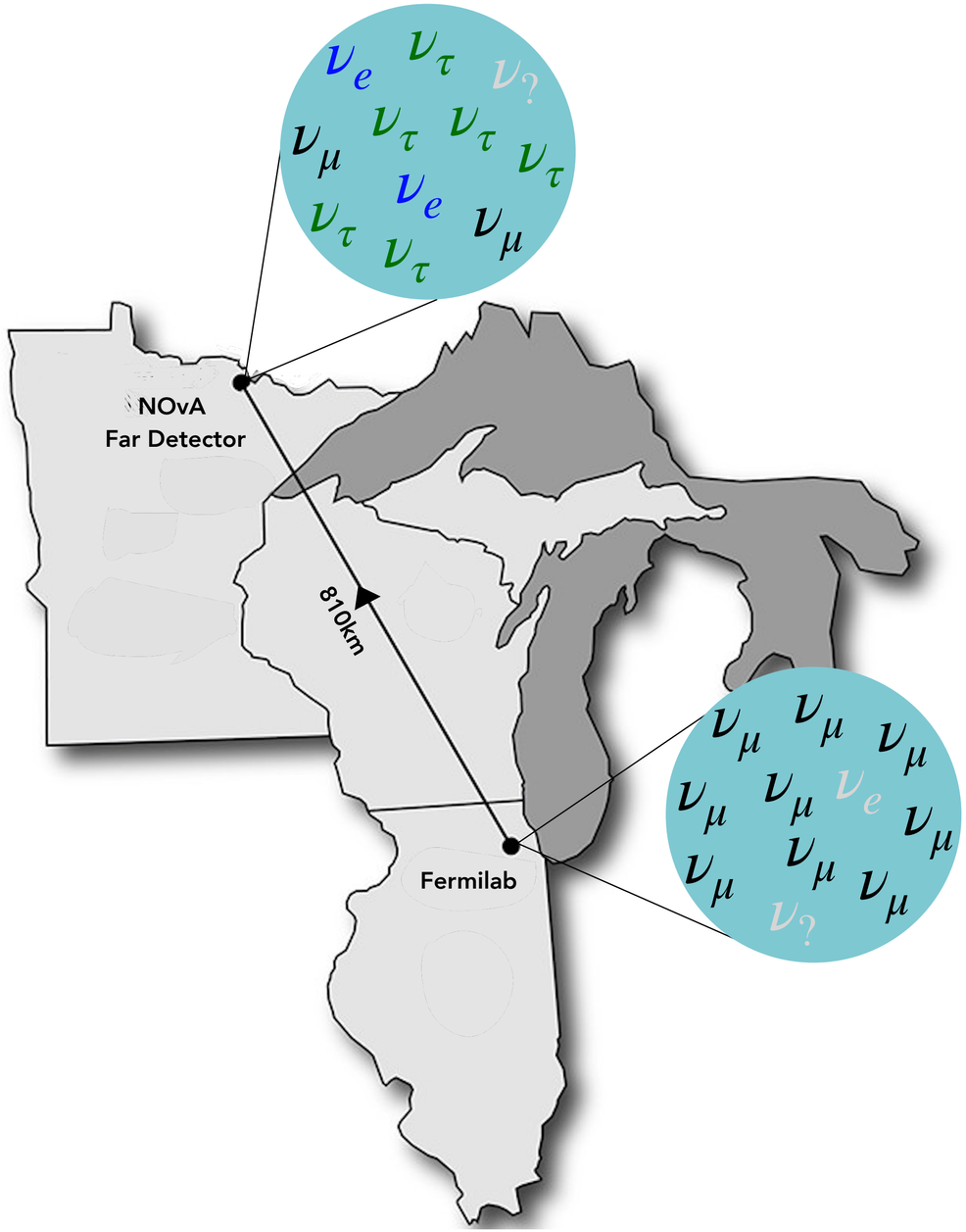
NOvA Experiment



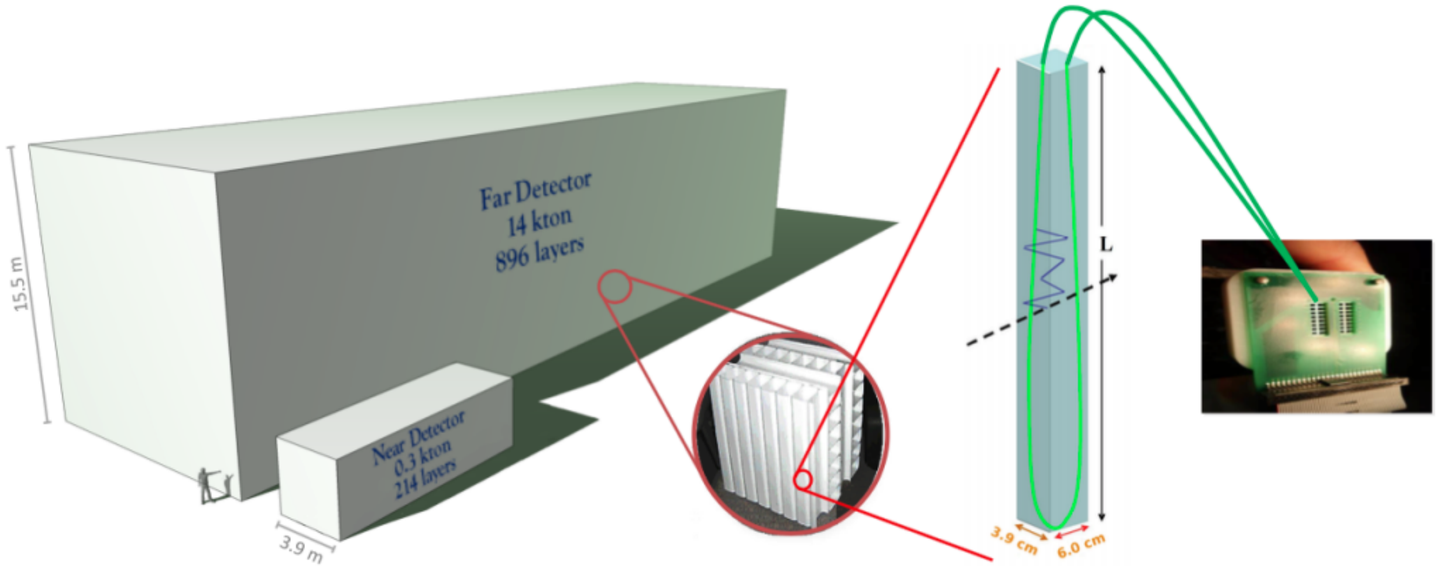
- NuMI beamline produces high purity beam of ν_μ or $\bar{\nu}_\mu$
- Neutrinos pass through near detector before travelling 810km to the functionally identical far detector in Minnesota
- Detectors are placed 14mrad off axis, meaning incident neutrino energy is narrowly peaked at 2GeV.



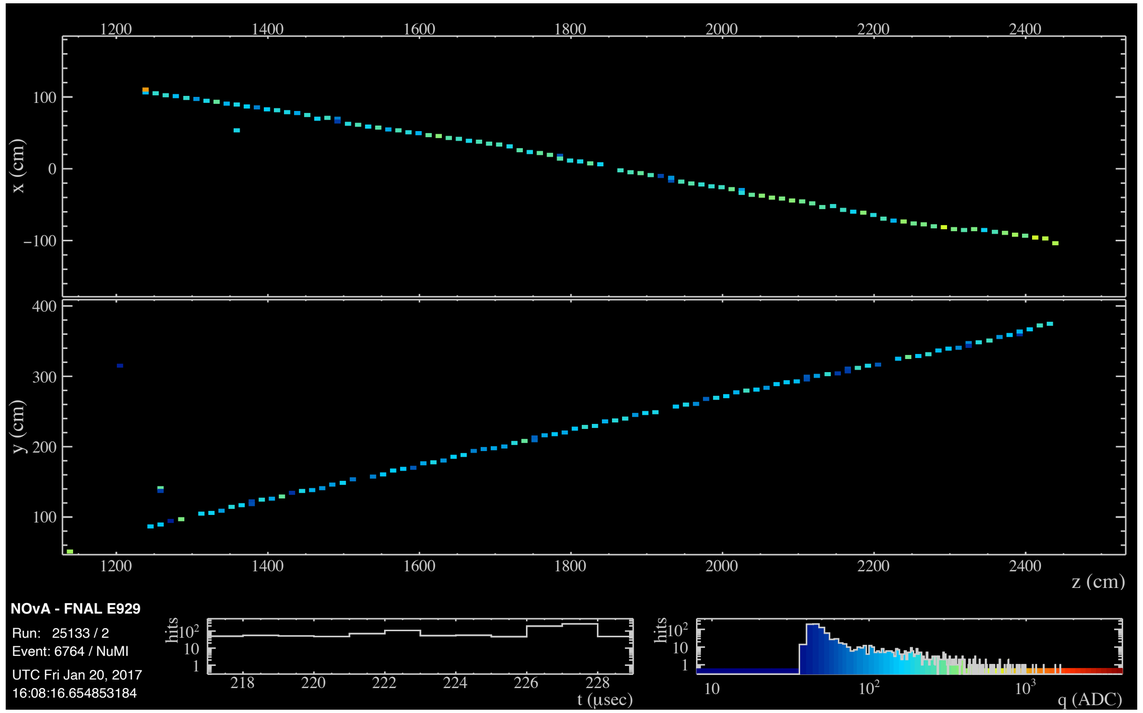
NOvA Experiment



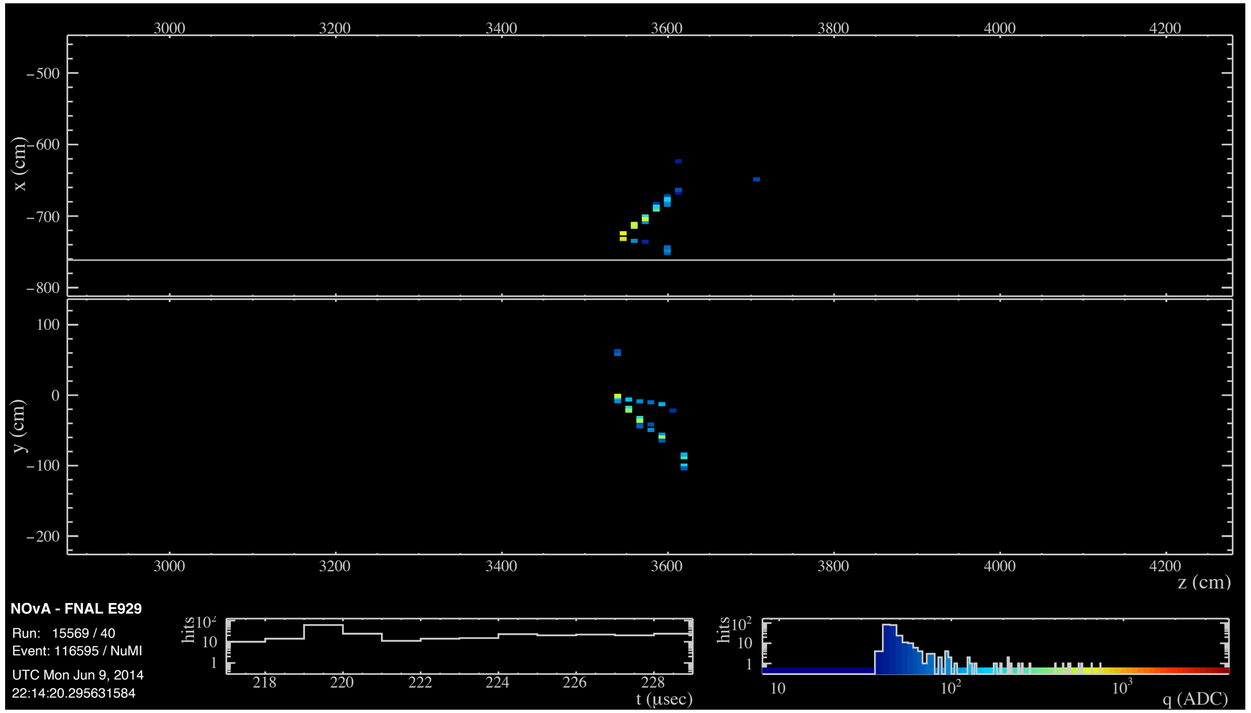
- NuMI beamline produces high purity beam of ν_μ or $\bar{\nu}_\mu$
- Neutrinos pass through near detector before travelling 810km to the functionally identical far detector in Minnesota
- Detectors are placed 14mrad off axis, meaning incident neutrino energy is narrowly peaked at 2GeV.
- Neutrino interactions in detectors produce scintillation light which is collected by wavelength shifting fibres, then amplified and read out by the connected avalanche photodiode pixel.



Event displays



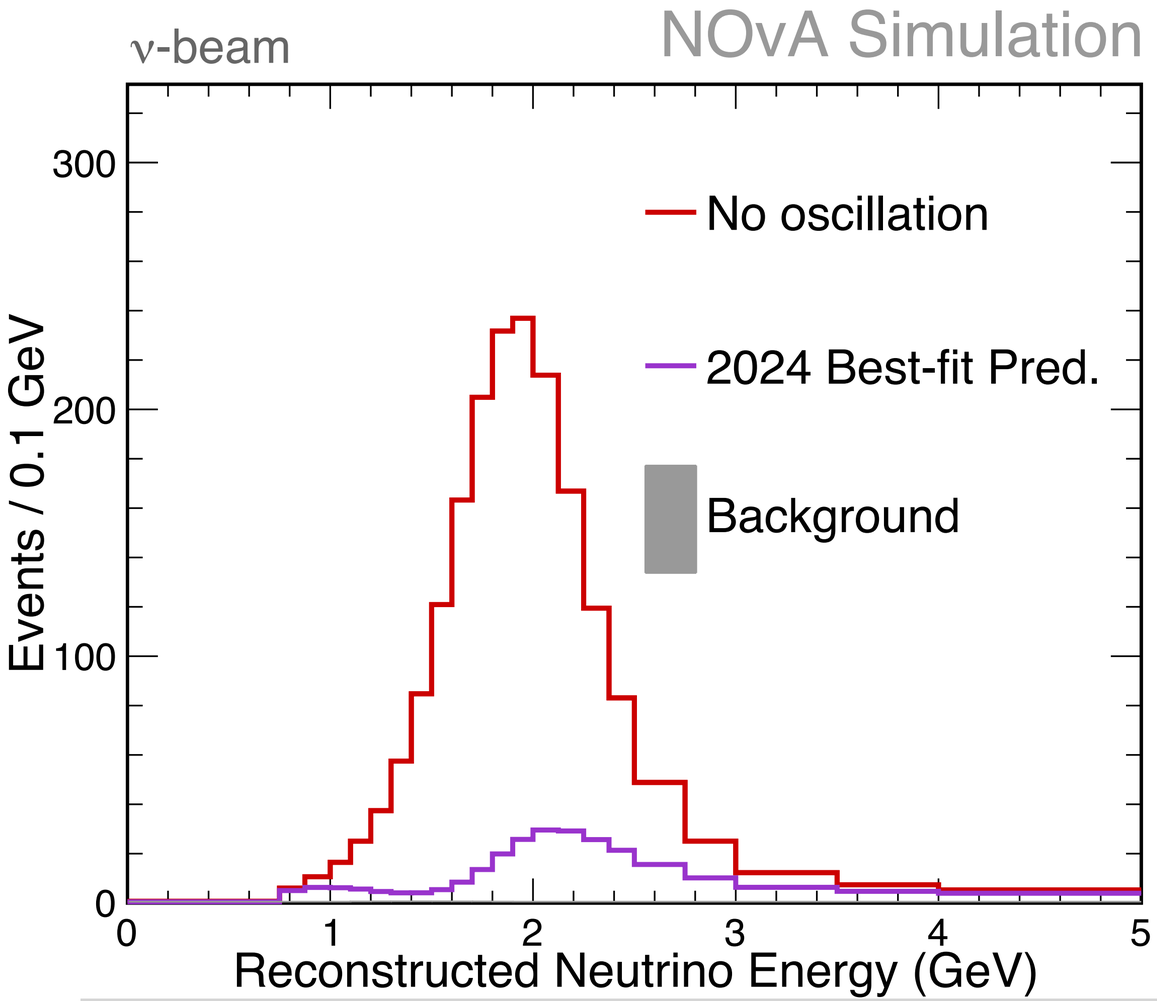
ν_μ CC candiate event



ν_e CC candidate event

Neutrino Oscillations

$\nu_\mu(\bar{\nu}_\mu)$ disappearance (survival)

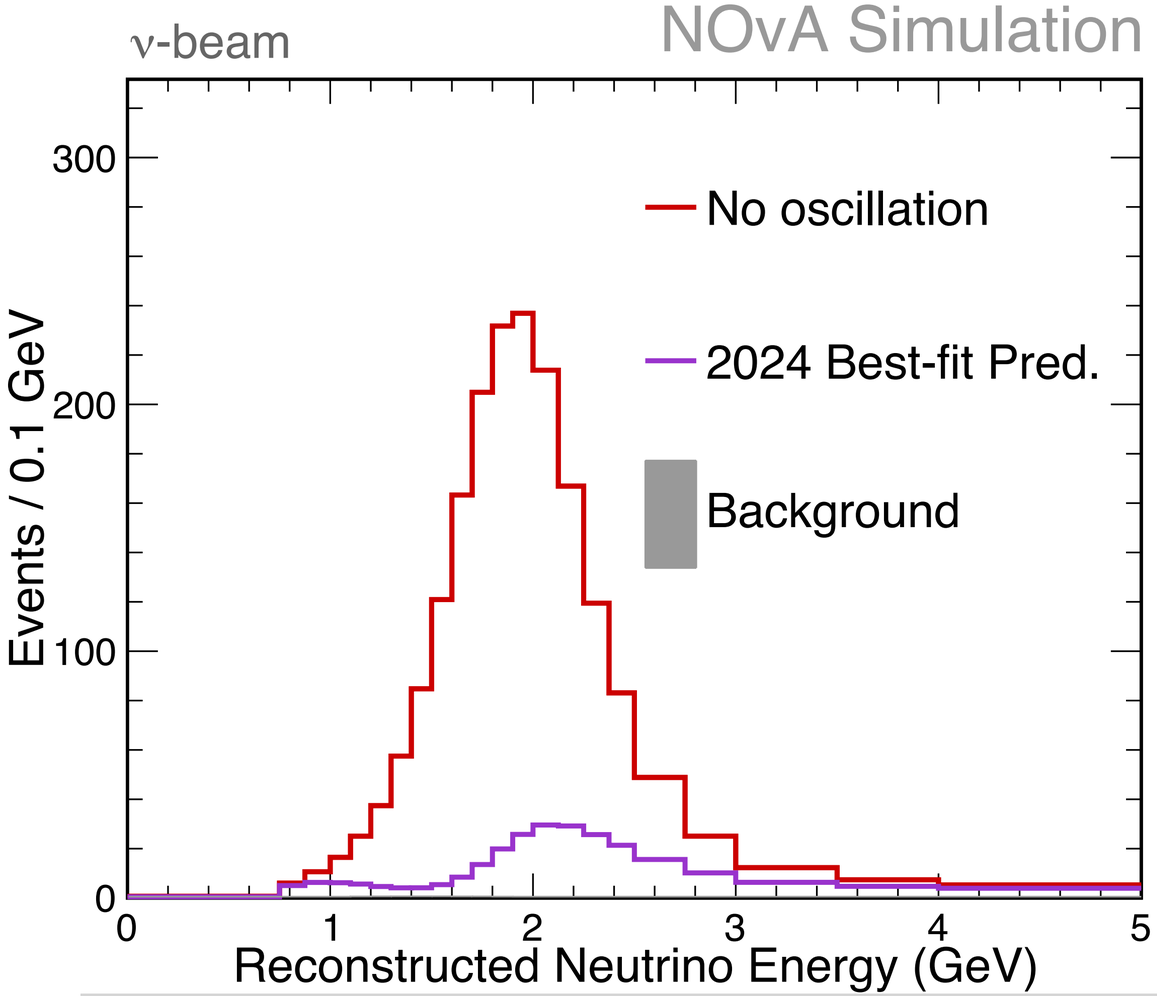


Position of dip $\rightarrow |\Delta m^2_{32}|$

Depth of dip $\rightarrow \sin^2 2\theta_{23}$: difficult to discern $\theta_{23} < 45$ or $\theta_{23} > 45$ (important for $\nu_\mu \leftrightarrow \nu_\tau$ symmetries)

Neutrino Oscillations

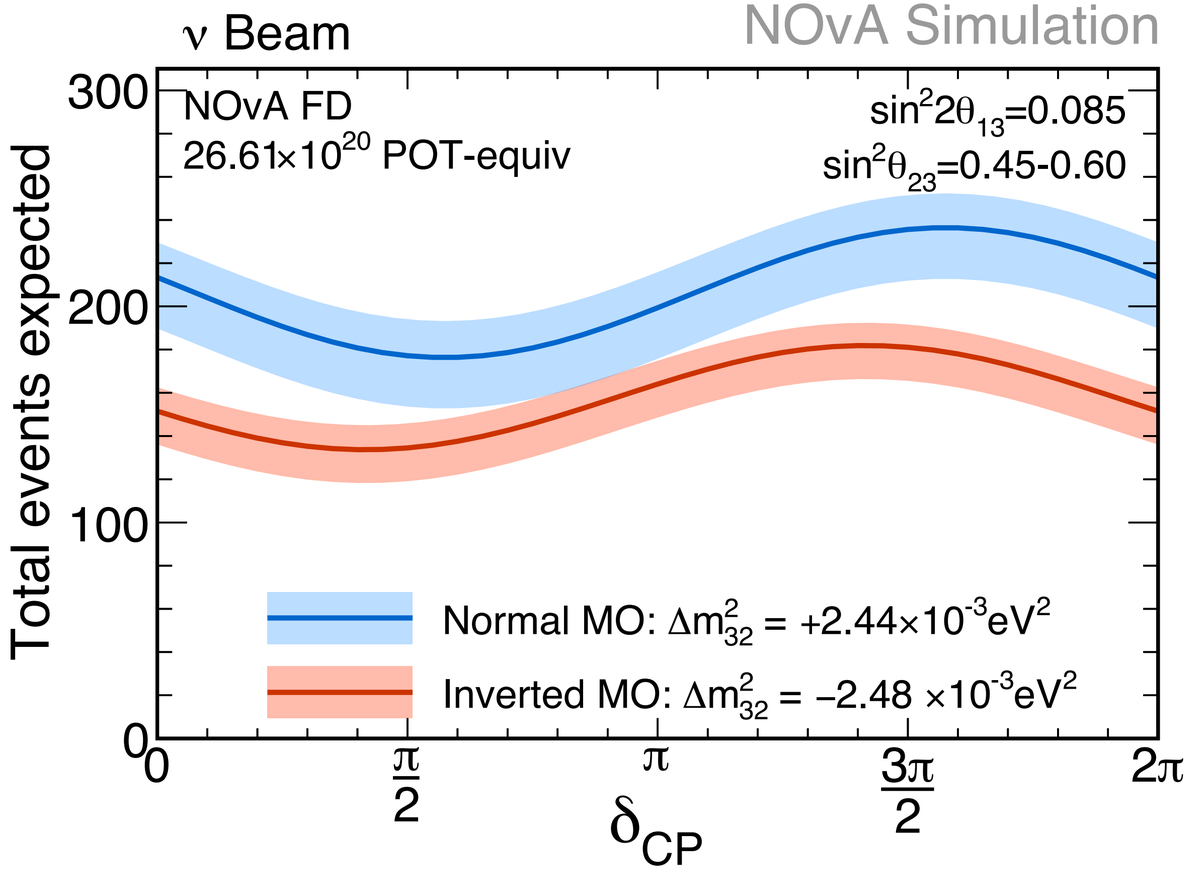
$\nu_\mu(\bar{\nu}_\mu)$ disappearance (survival)



Position of dip $\rightarrow |\Delta m^2_{32}|$

Depth of dip $\rightarrow \sin^2 2\theta_{23}$: difficult to discern $\theta_{23} < 45$ or $\theta_{23} > 45$ (important for $\nu_\mu \leftrightarrow \nu_\tau$ symmetries)

$\nu_e(\bar{\nu}_e)$ appearance

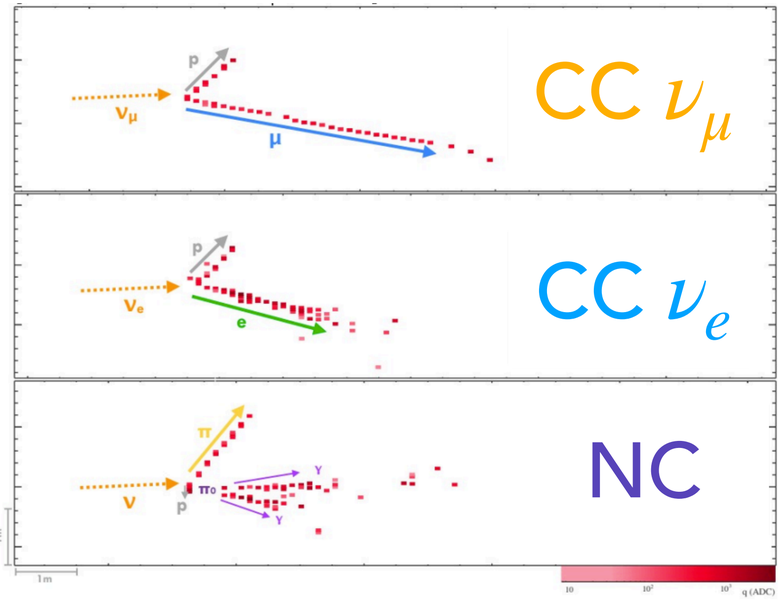


ν_e and $\bar{\nu}_e$ appearance $\rightarrow \sin^2\theta_{23}$ octant, $\sin^2\theta_{13}, \delta_{CP}$

Asymmetry of appearance gives handle on sign of Δm^2_{32} and δ_{CP}

Event reconstruction and analysis

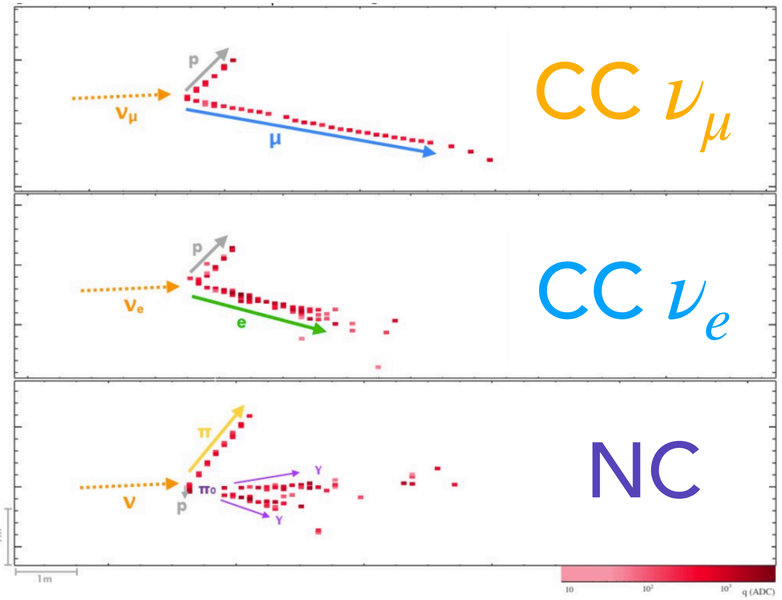
Event reconstruction and analysis

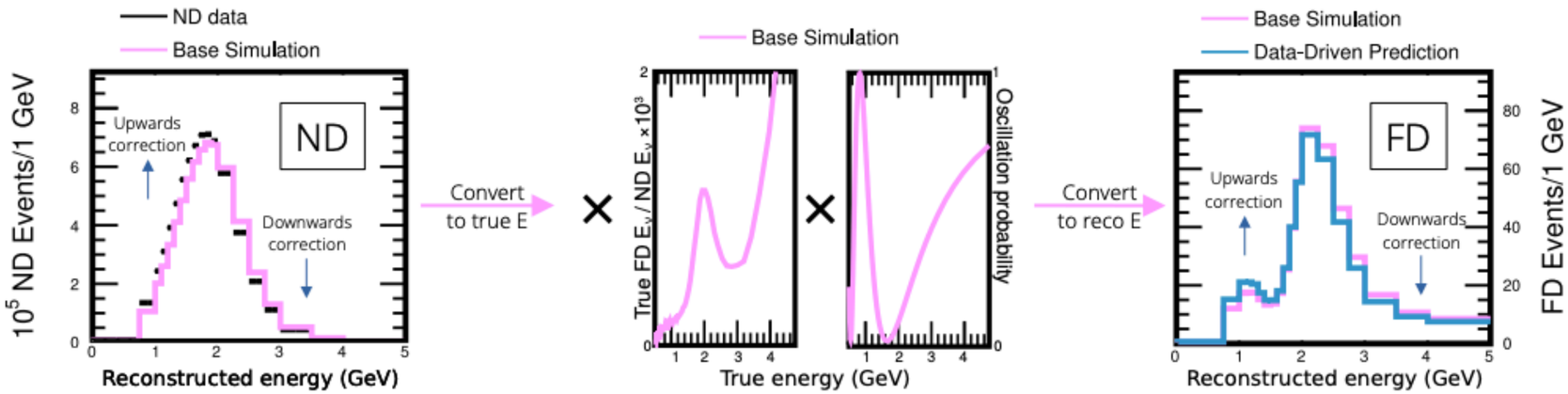


Use convolutional neural networks for:

- **rejection of background events from cosmic ray muons**
- **Neutrino interaction flavour identification**
- **Particle identification**

Event reconstruction and analysis





J. Wolcott

Use convolutional neural networks for:

- **rejection of background events from cosmic ray muons**
- **Neutrino interaction flavour identification**
- **Particle identification**

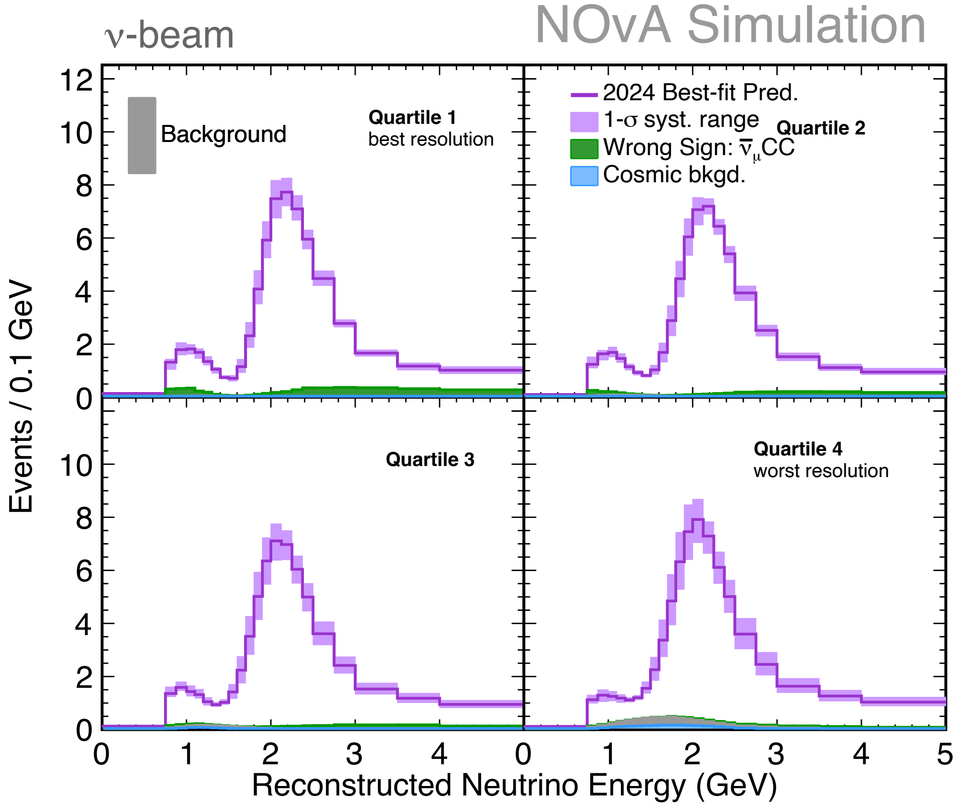
Correct Near detector Monte Carlo to match near detector data

- **Extrapolate** these corrections to Far Detector predictions (take into account beam divergence, detector performance + oscillations)
- gives FD E_ν prediction with constrained systematic uncertainties

Compare FD data to predicted rates of neutrino events to extract oscillation parameters using Bayesian or Frequentist statistics

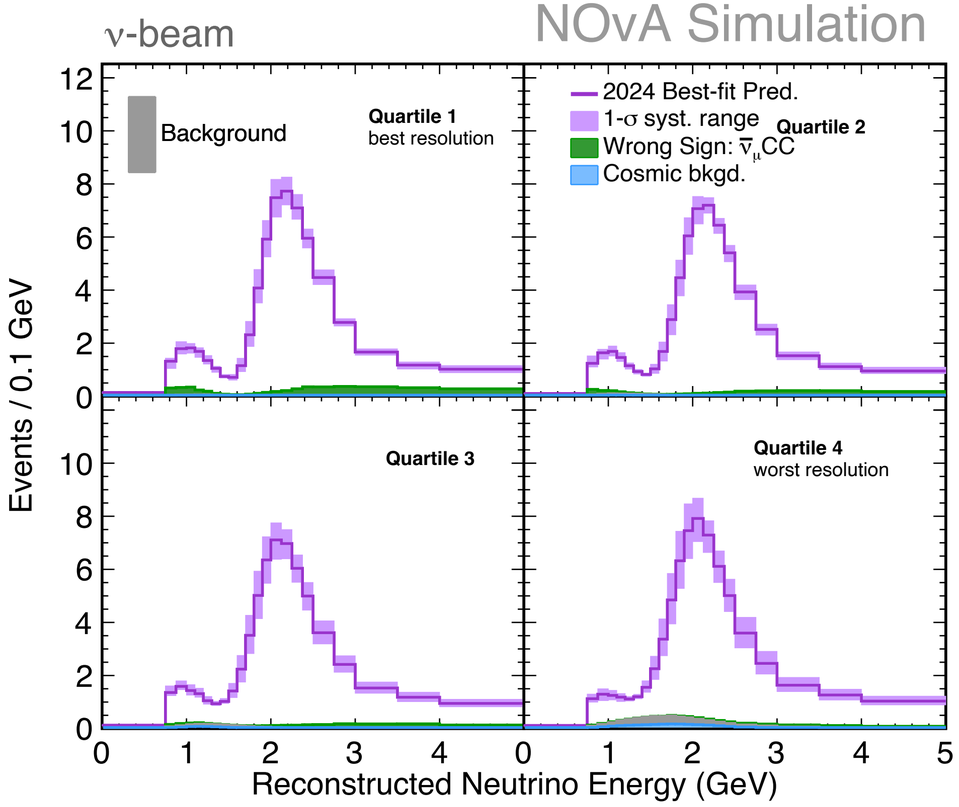
Increasing sensitivity

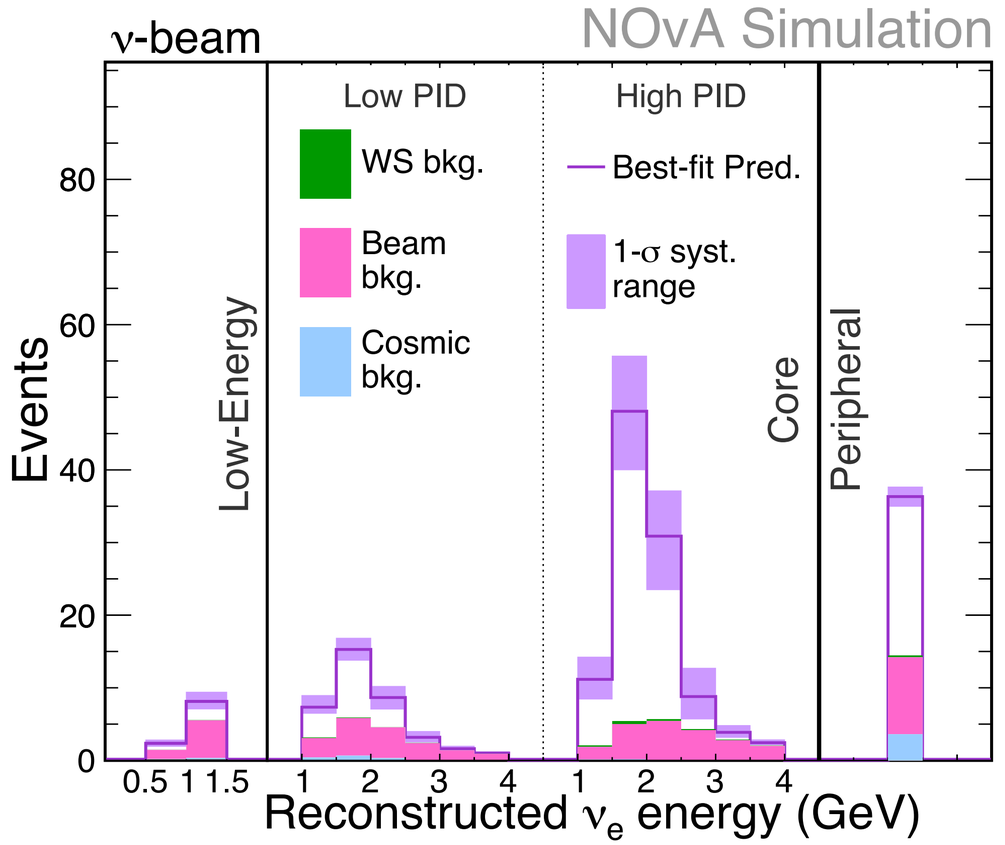
Increasing sensitivity



Parameters extracted from $\nu_\mu/\overline{\nu}_\mu$ data depend on distribution **shape** → bin ν_μ by hadronic energy fraction (i.e. energy resolution)

Increasing sensitivity

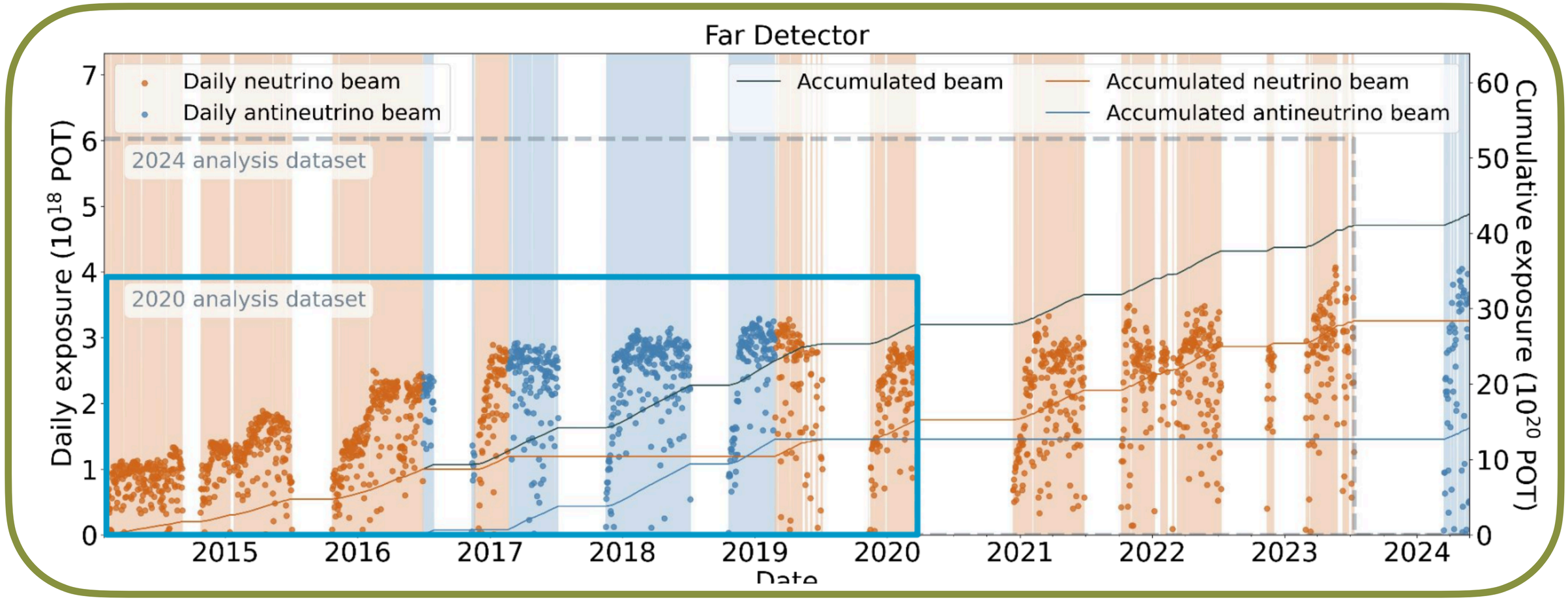




Parameters extracted from $\nu_\mu/\overline{\nu}_\mu$ data depend on distribution **shape** → bin ν_μ by hadronic energy fraction (i.e. energy resolution)

Parameters extracted from $\nu_e/\overline{\nu}_e$ data depend on **event counts**→ bin ν_e by sample purity (i.e. signal/background)

New for 2024



More data!

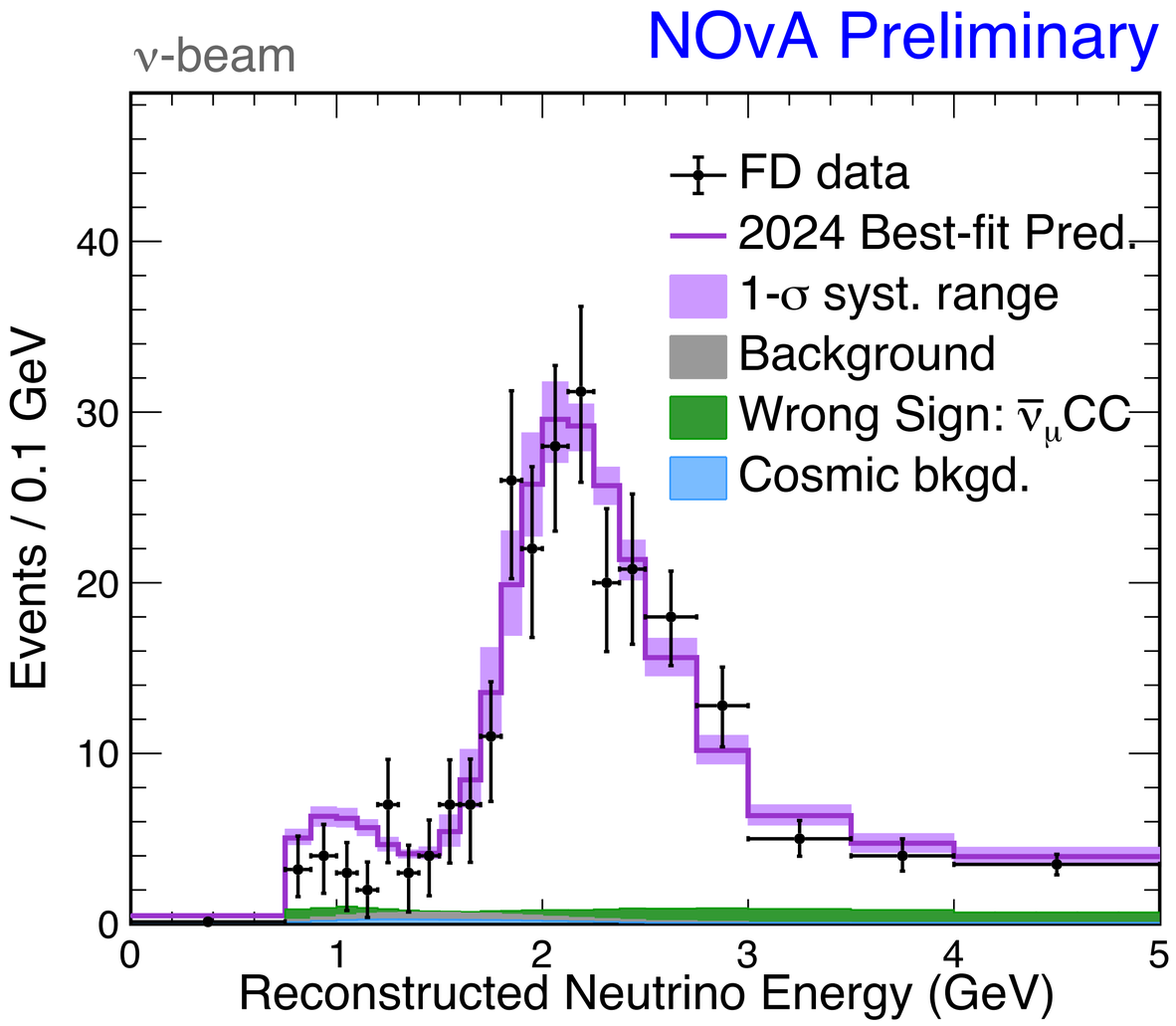
Improved detector simulations

Improved uncertainty predictions

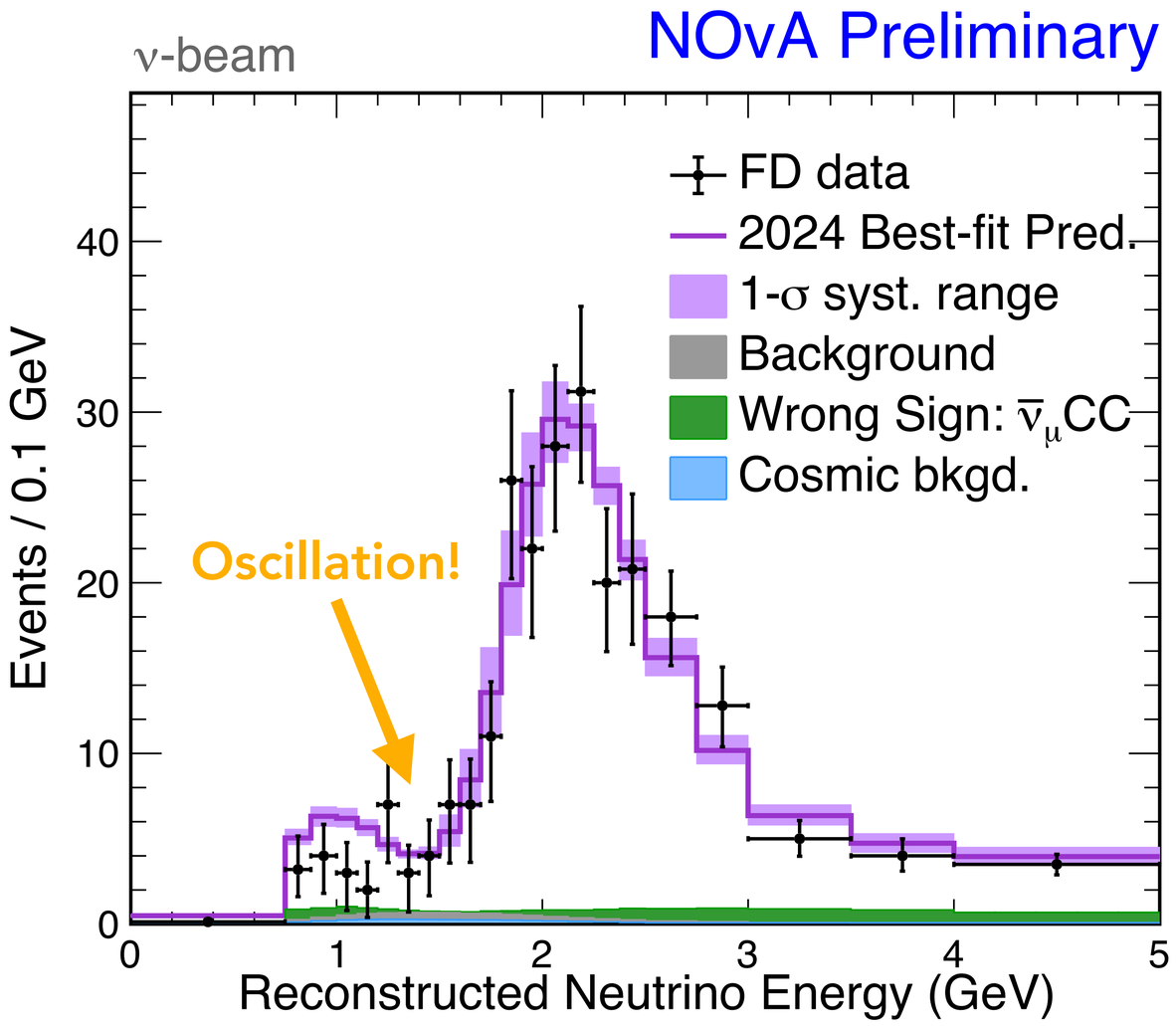
New Selection

2024 ν_μ events

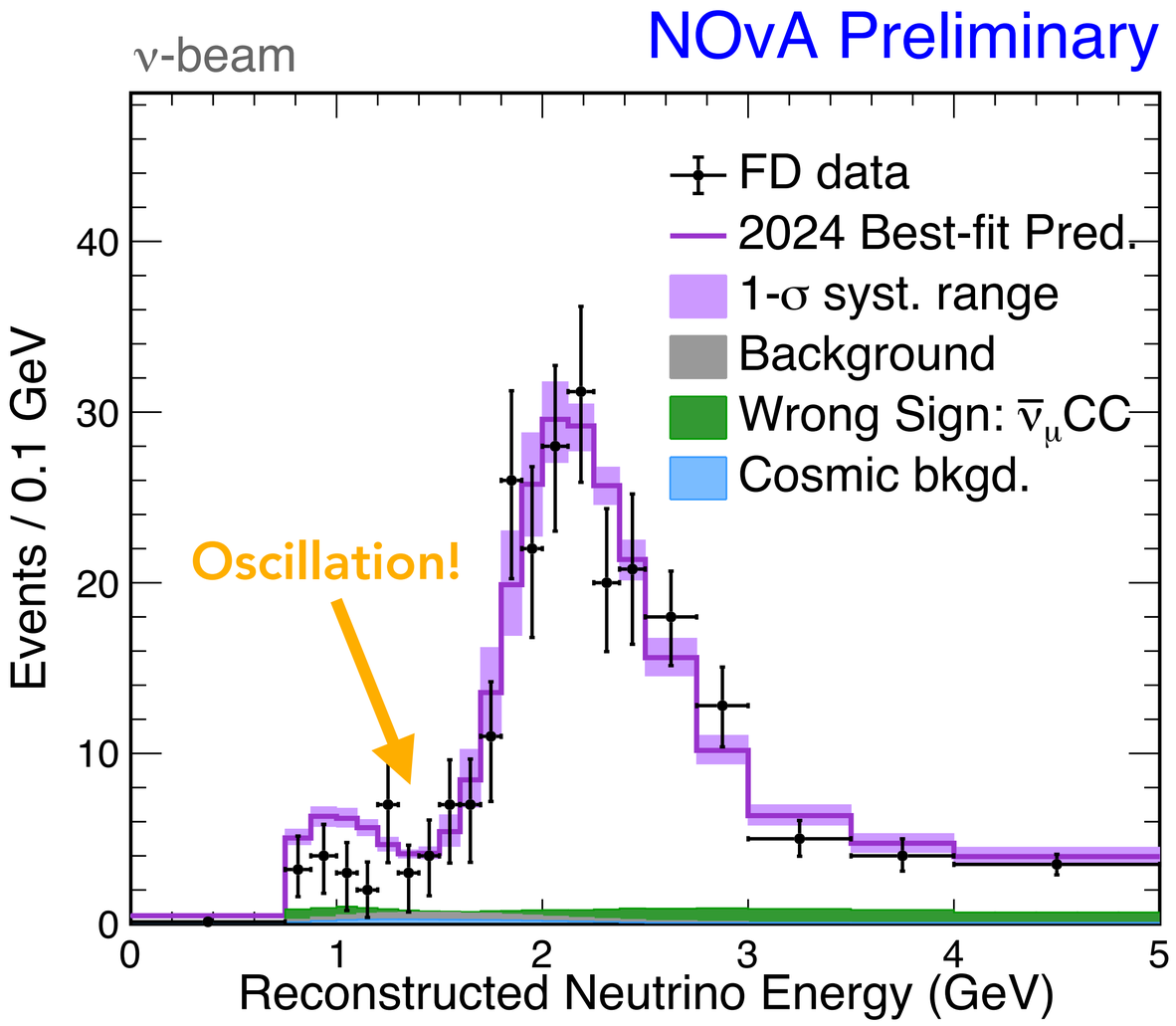
2024 ν_μ events



2024 ν_μ events

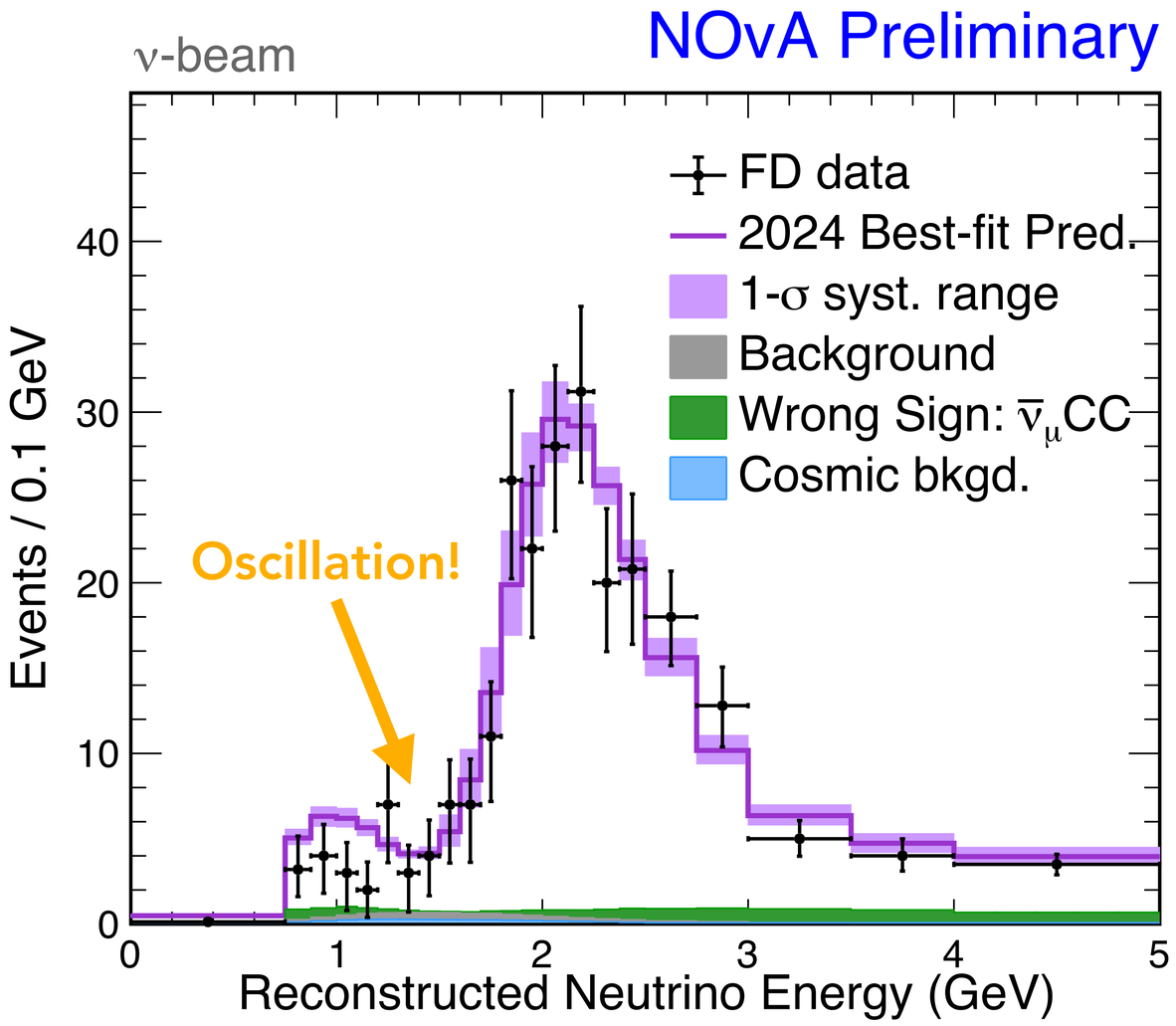


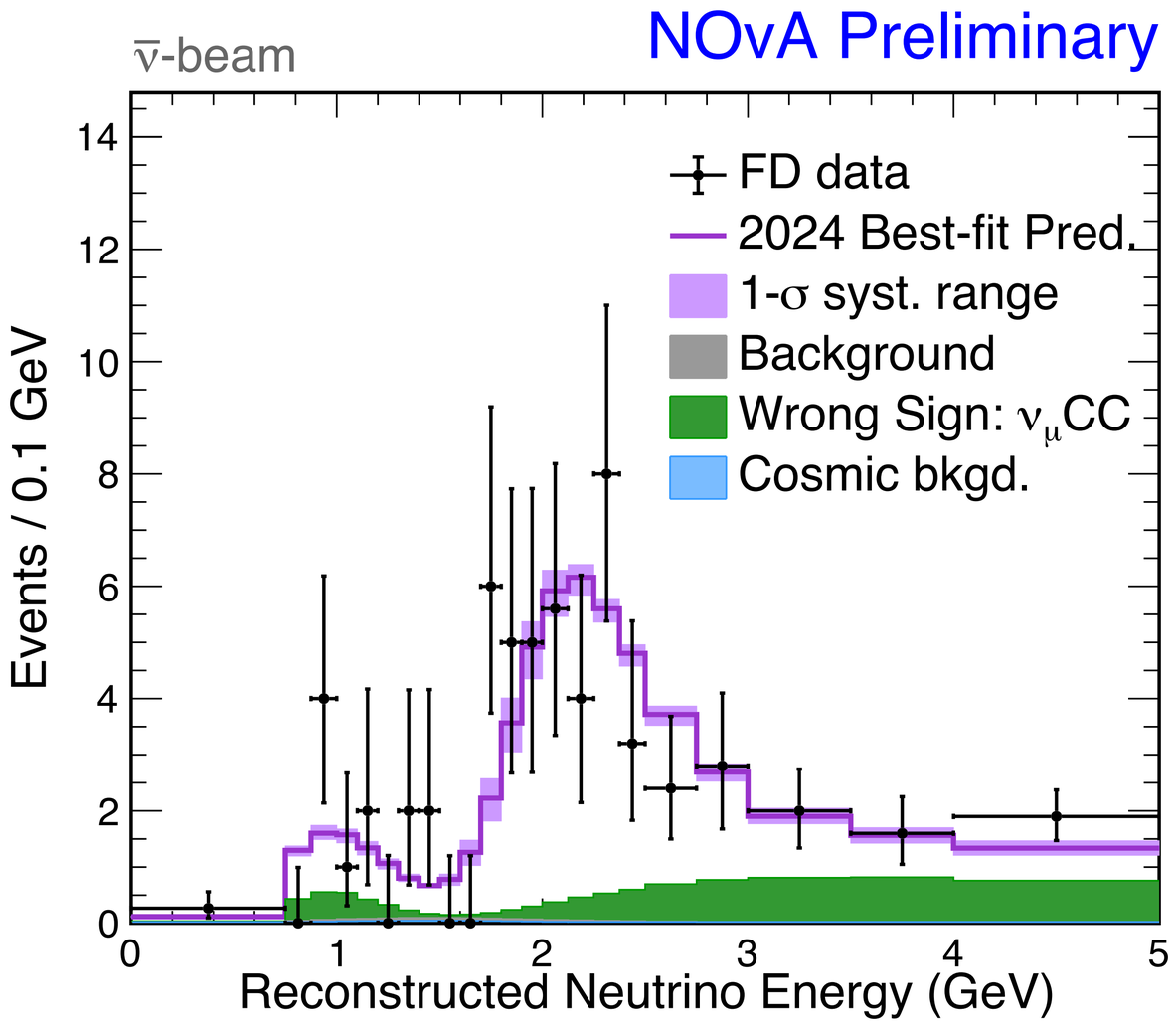
2024 ν_μ events



See 384 ν_μ signal events, expect 11.3 background events

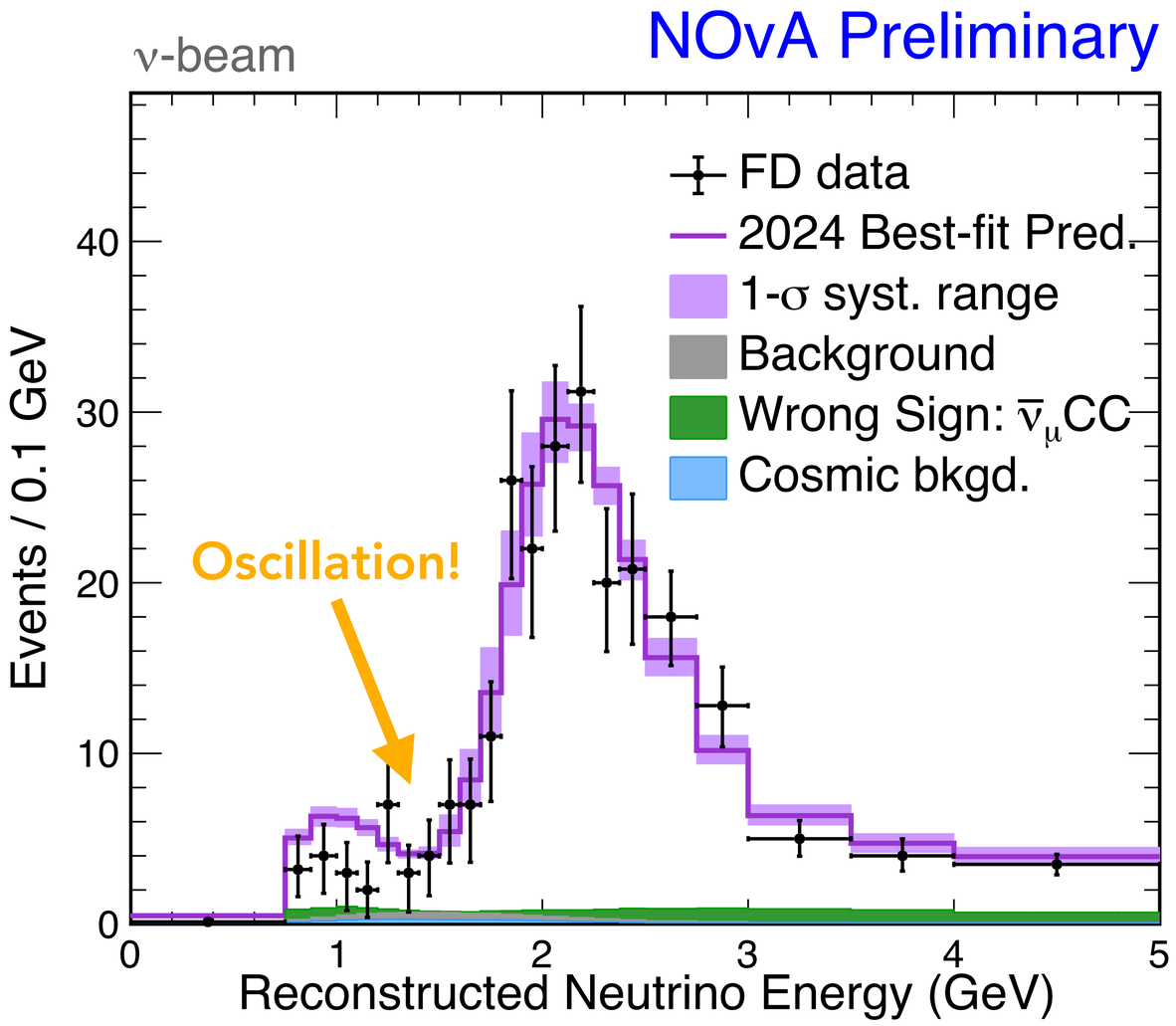
2024 ν_μ events

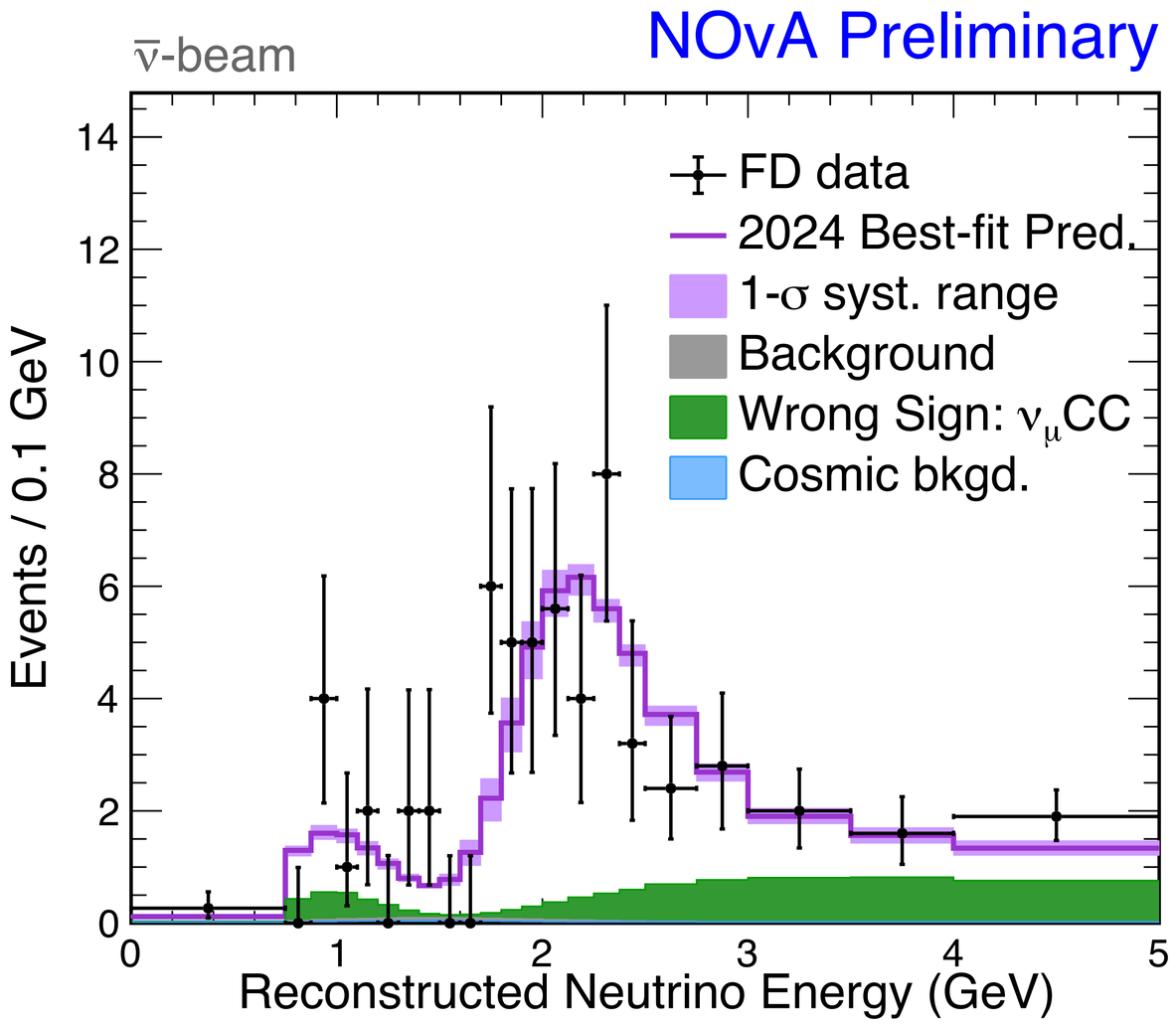




See 384 ν_μ signal events, expect 11.3 background events

2024 ν_μ events



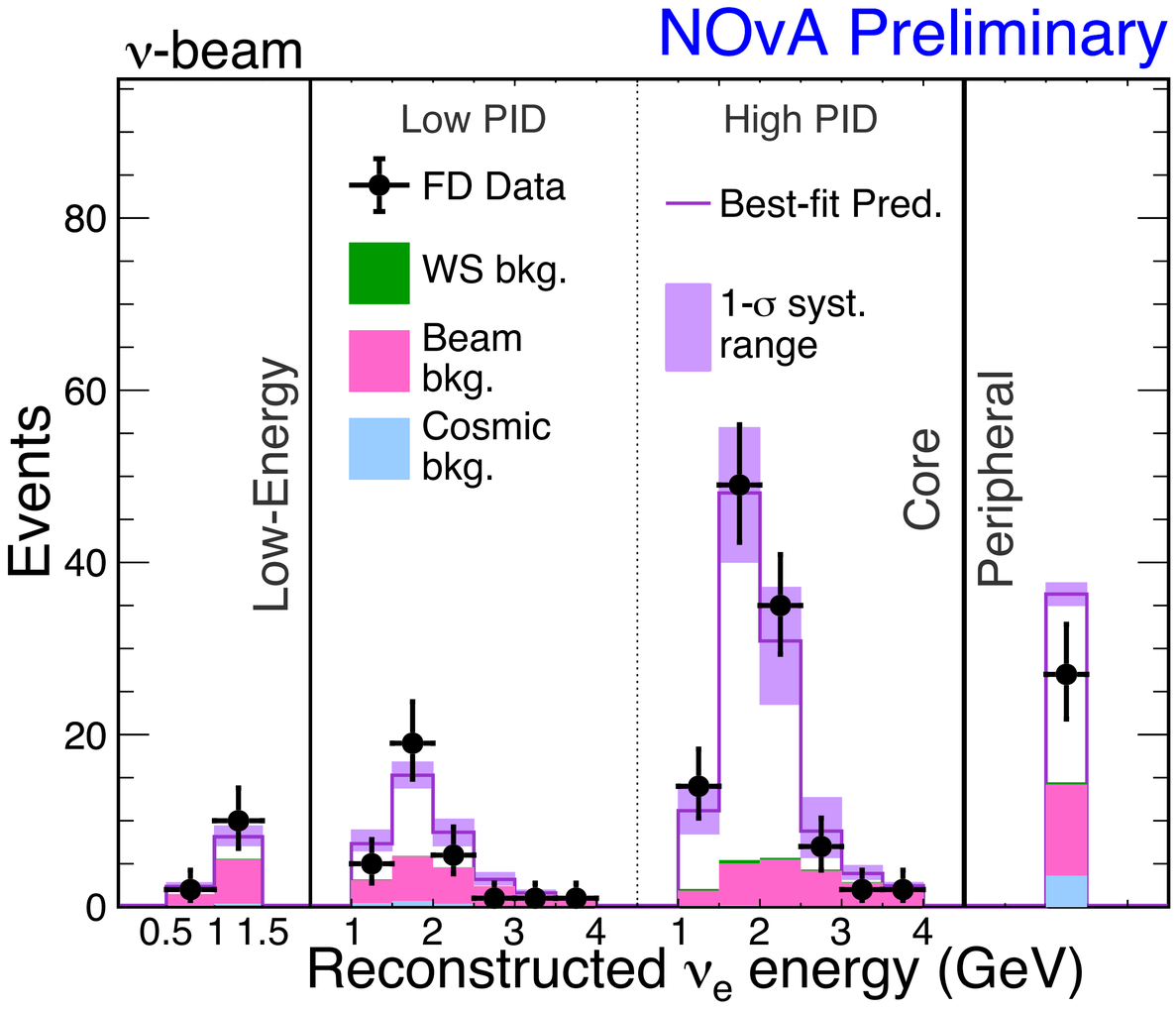


See 384 ν_μ signal events, expect 11.3 background events

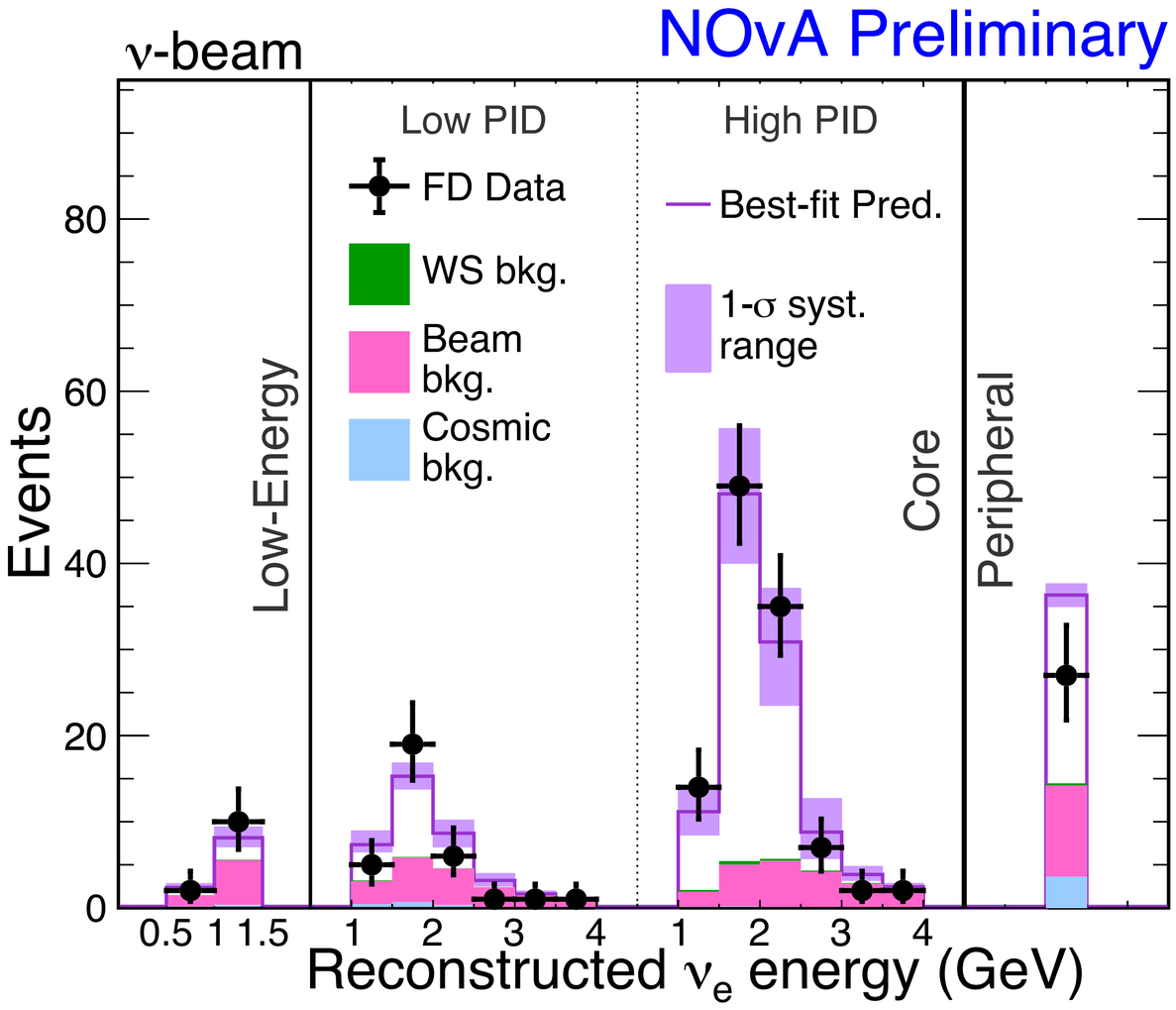
See 106 $\bar{\nu}_\mu$ signal events, expect 1.7 background events

2024 ν_e events

2024 ν_e events

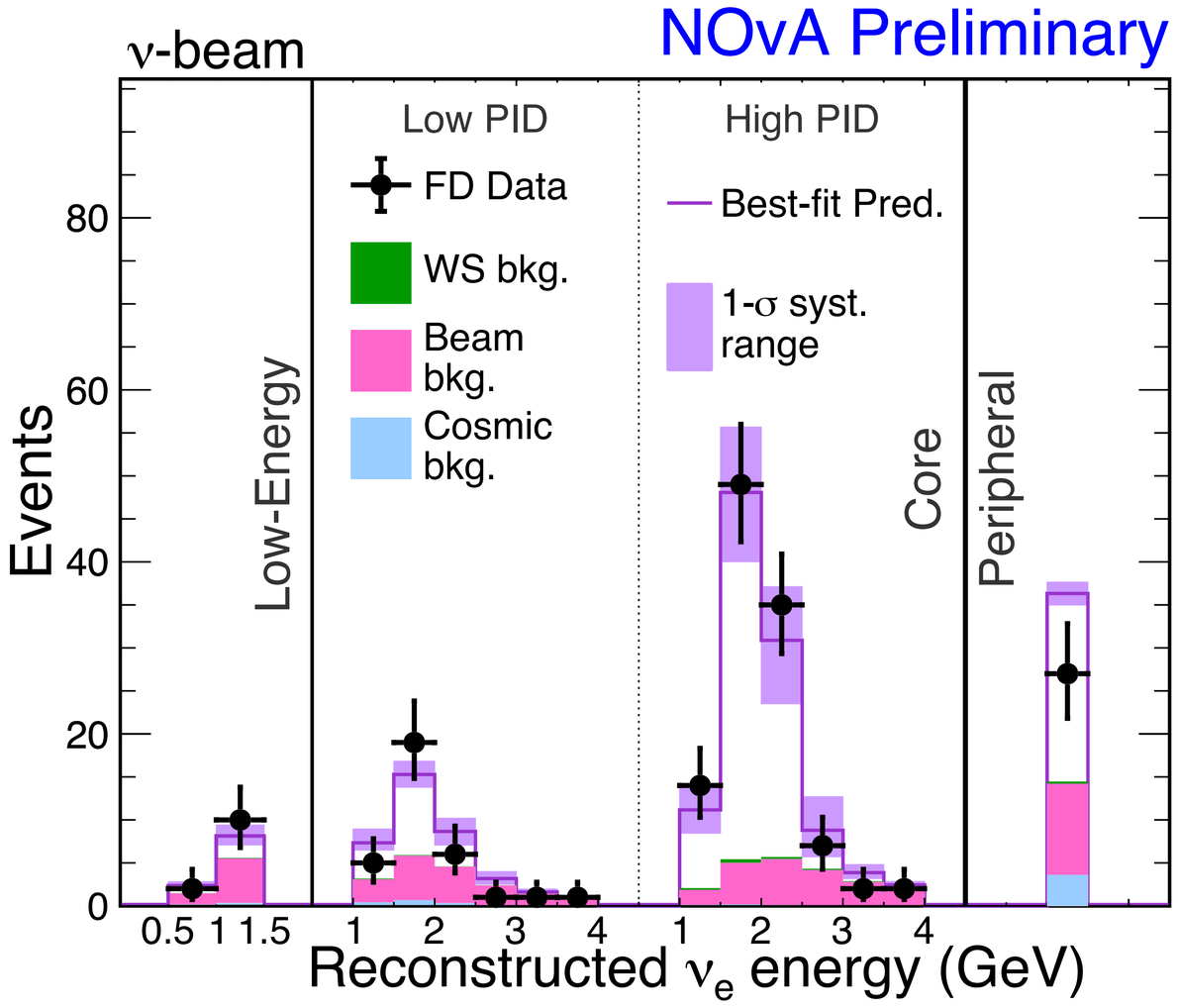


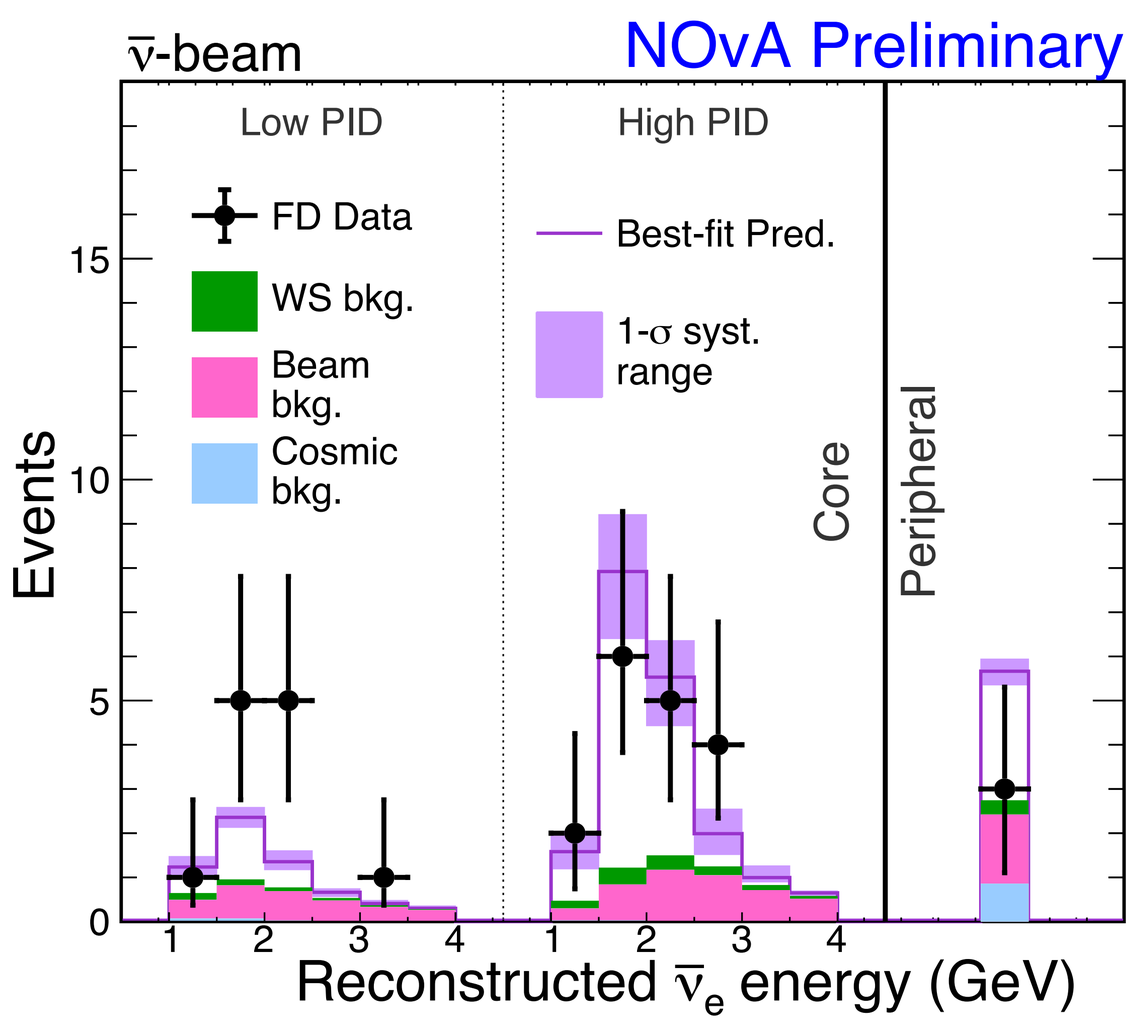
2024 ν_e events



See 169 ν_e signal events, expect 54.9 background events

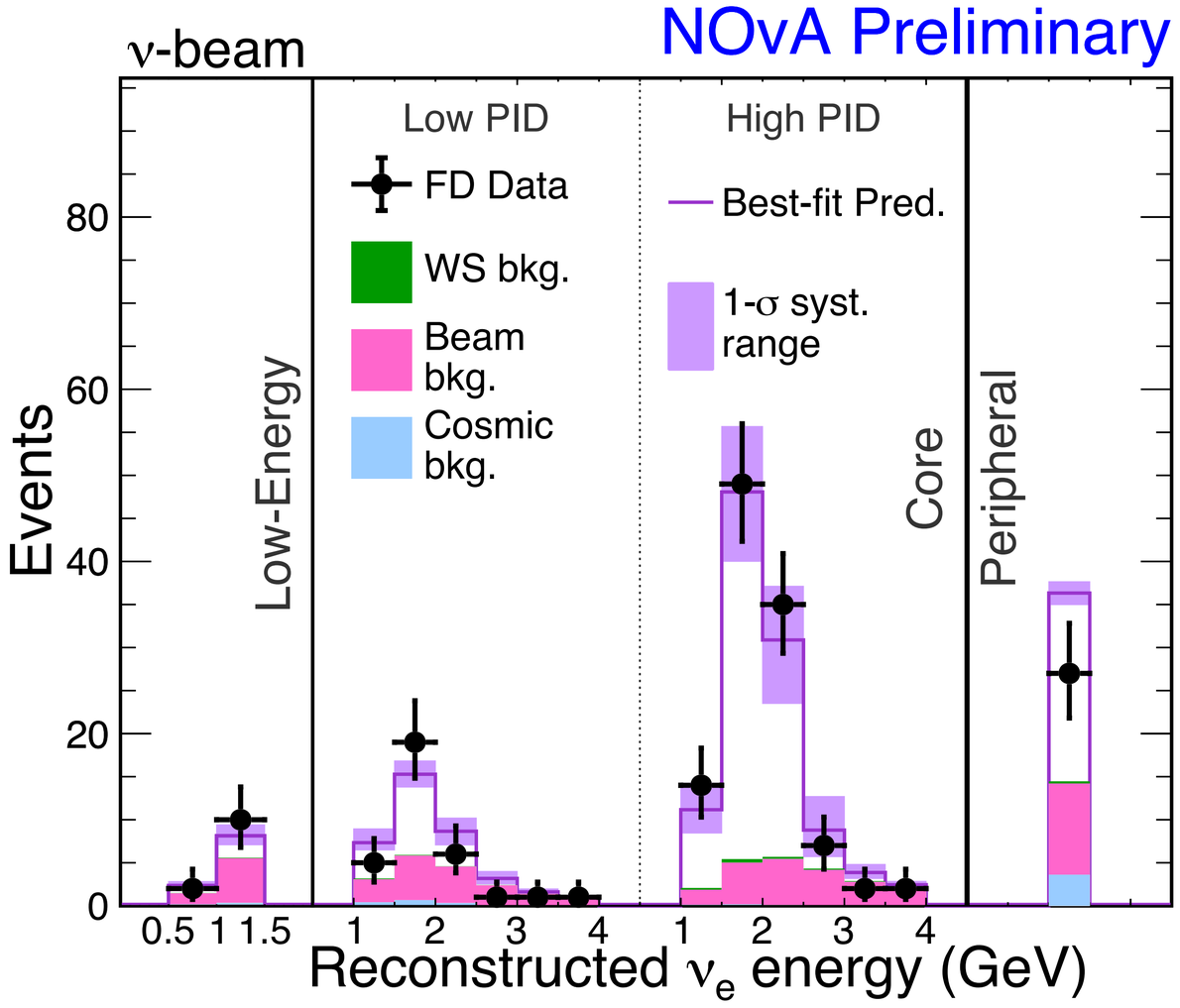
2024 ν_e events

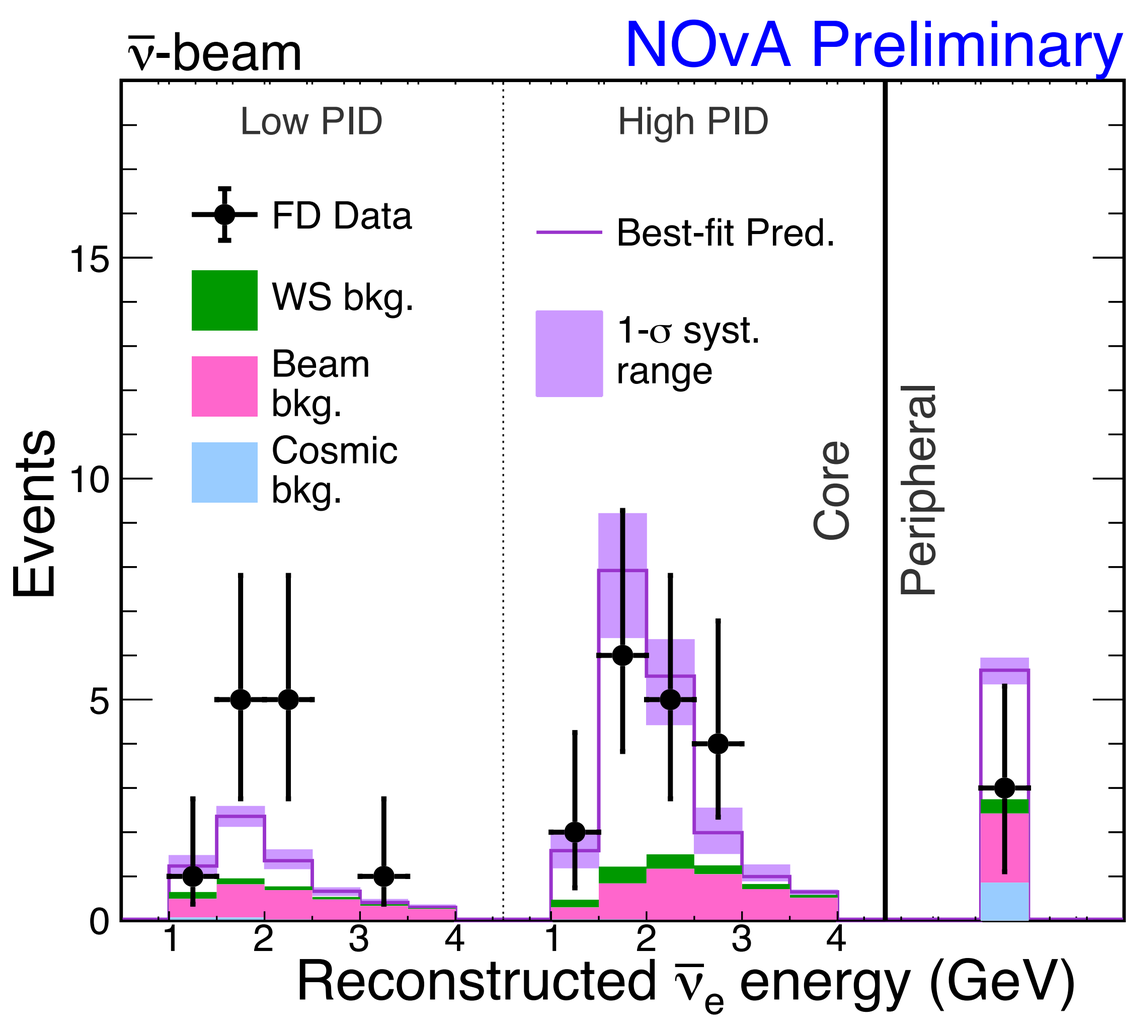




See 169 ν_e signal events, expect 54.9 background events

2024 ν_e events

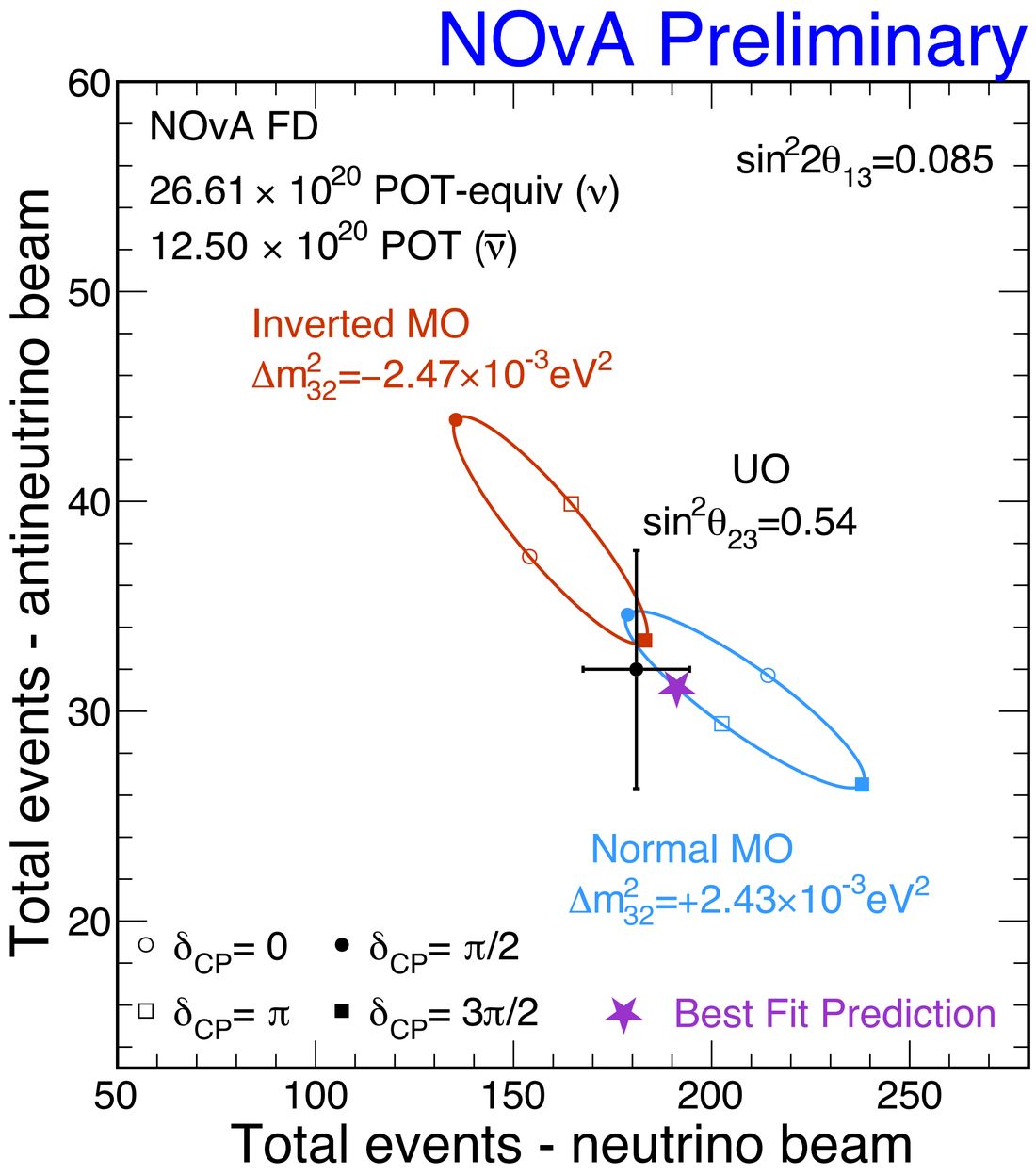




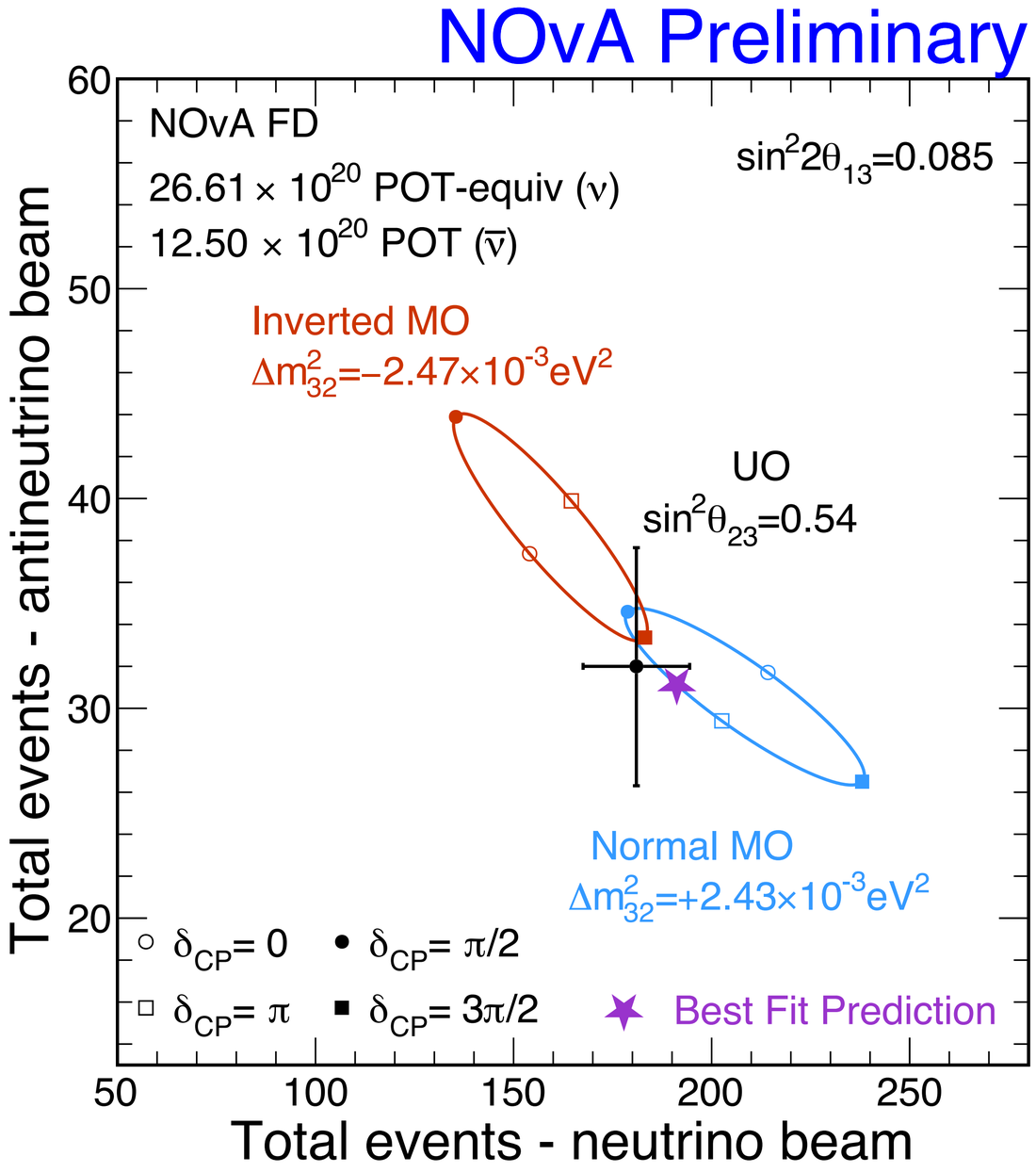
See 169 ν_e signal events, expect 54.9 background events

See 32 $\bar{\nu}_e$ signal events, expect 12.2 background events

δ_{cp} and mass ordering

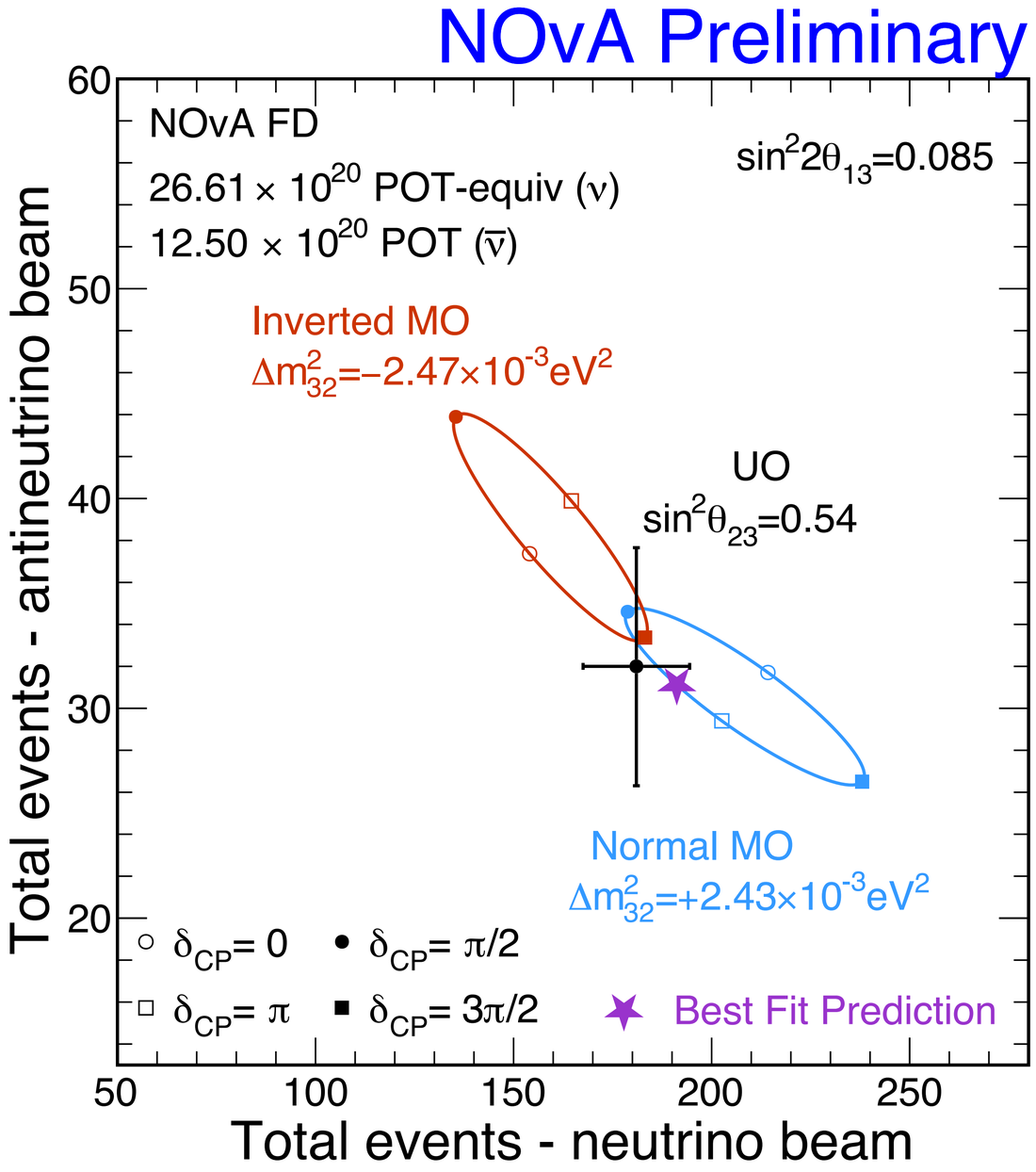


δ_{cp} and mass ordering



Both δ_{CP} and the mass ordering affect the amount of asymmetry between ν_e and $\bar{\nu}_e$

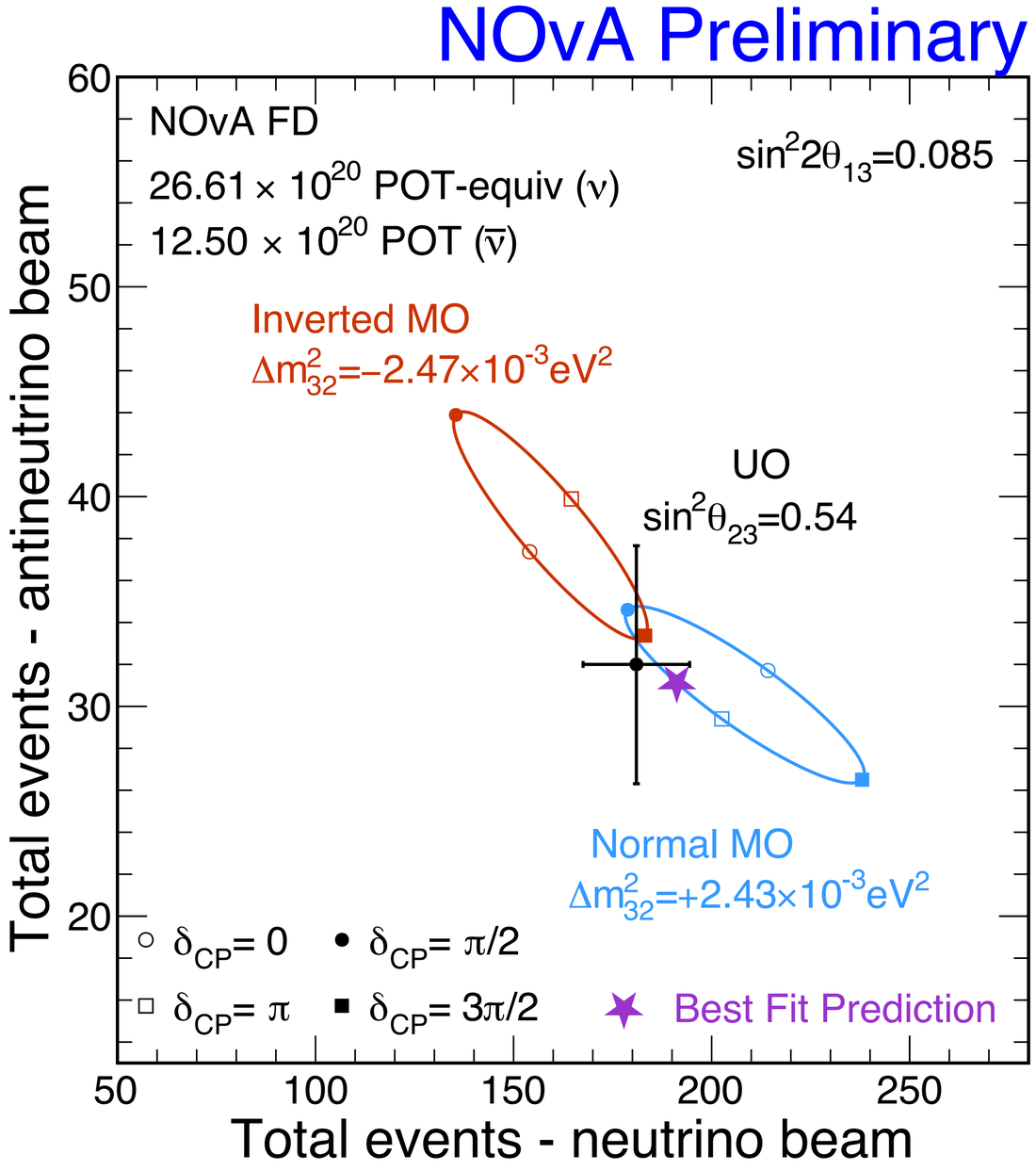
δ_{cp} and mass ordering



Both δ_{CP} and the mass ordering affect the amount of asymmetry between ν_e and $\bar{\nu}_e$

NOvA's data point lies in region where effects are degenerate

δ_{cp} and mass ordering

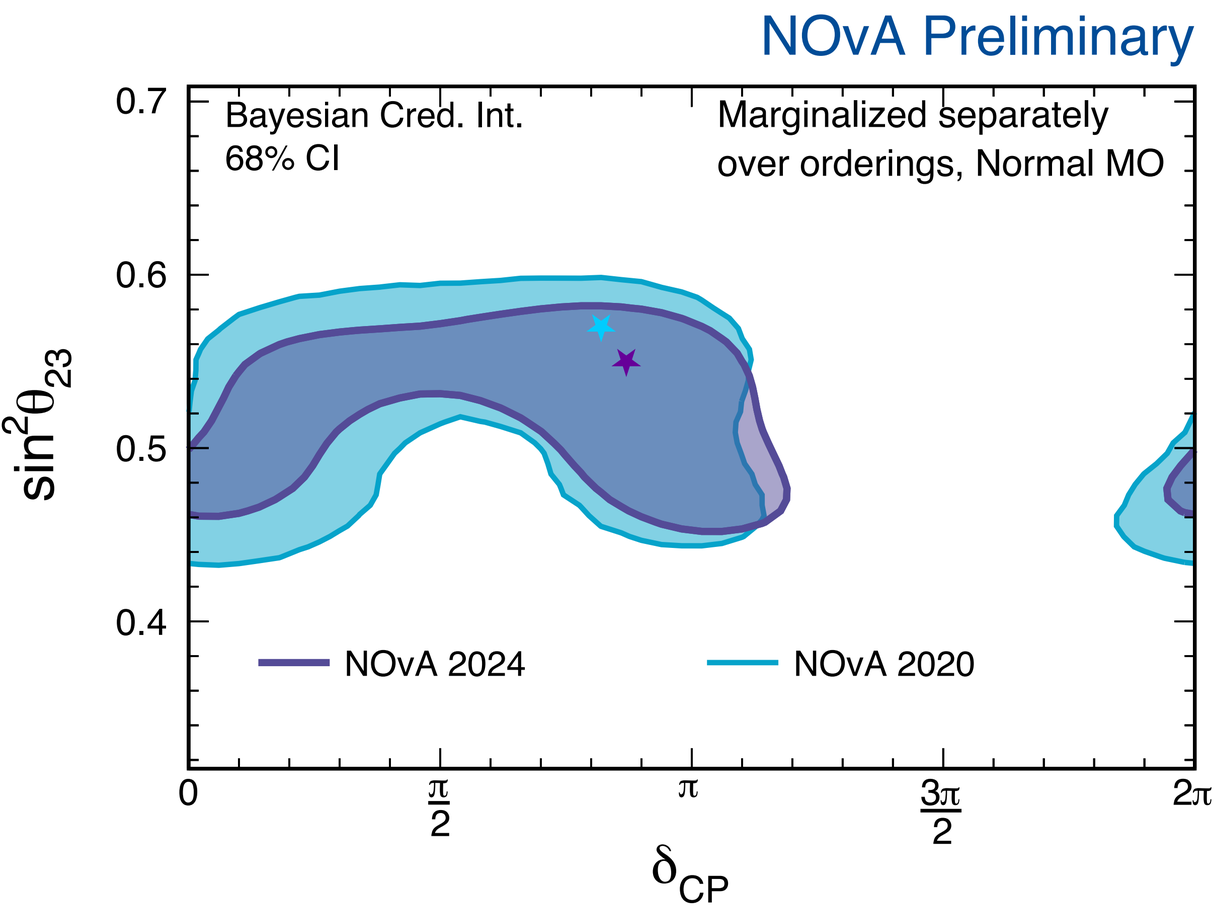


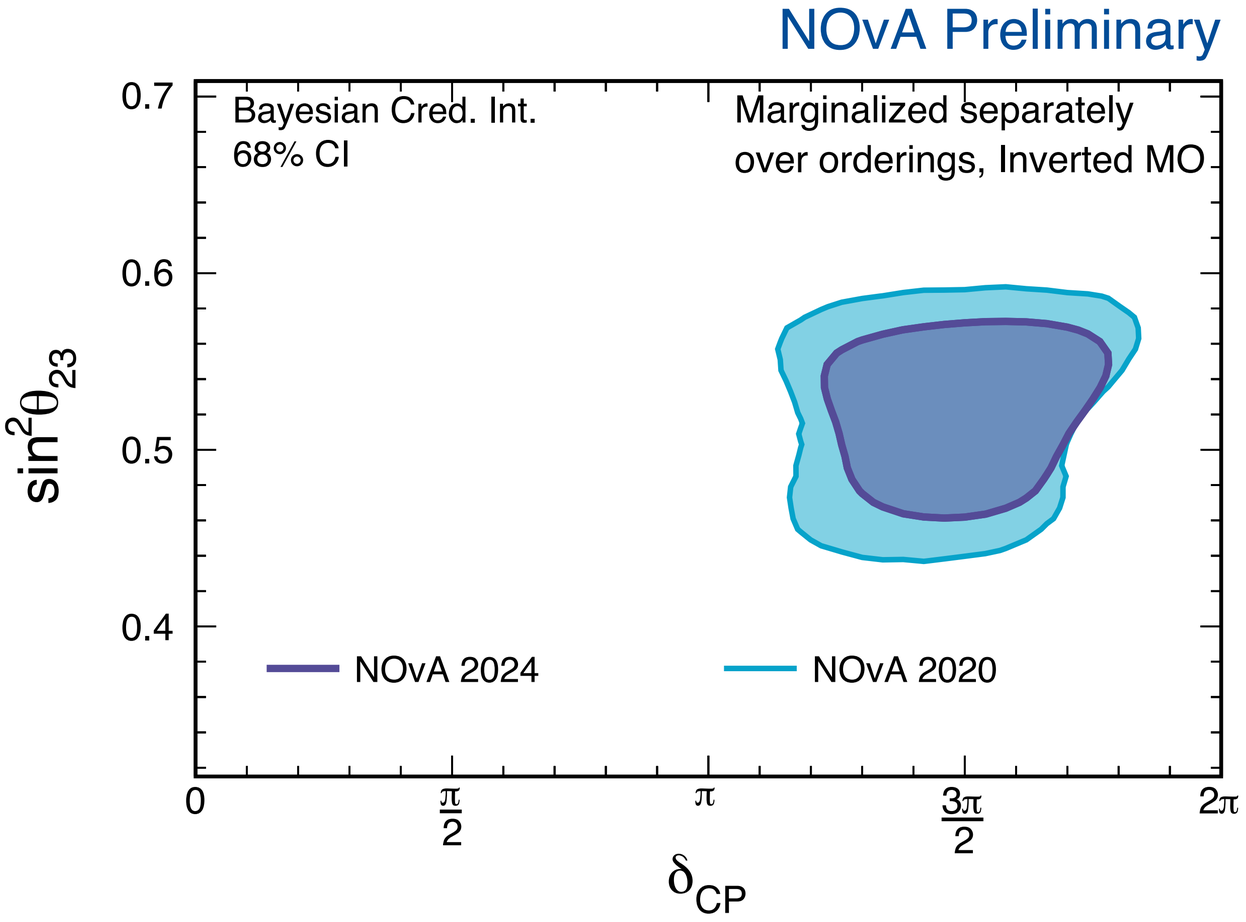
Both δ_{CP} and the mass ordering affect the amount of asymmetry between ν_e and $\bar{\nu}_e$

NOvA's data point lies in region where effects are degenerate

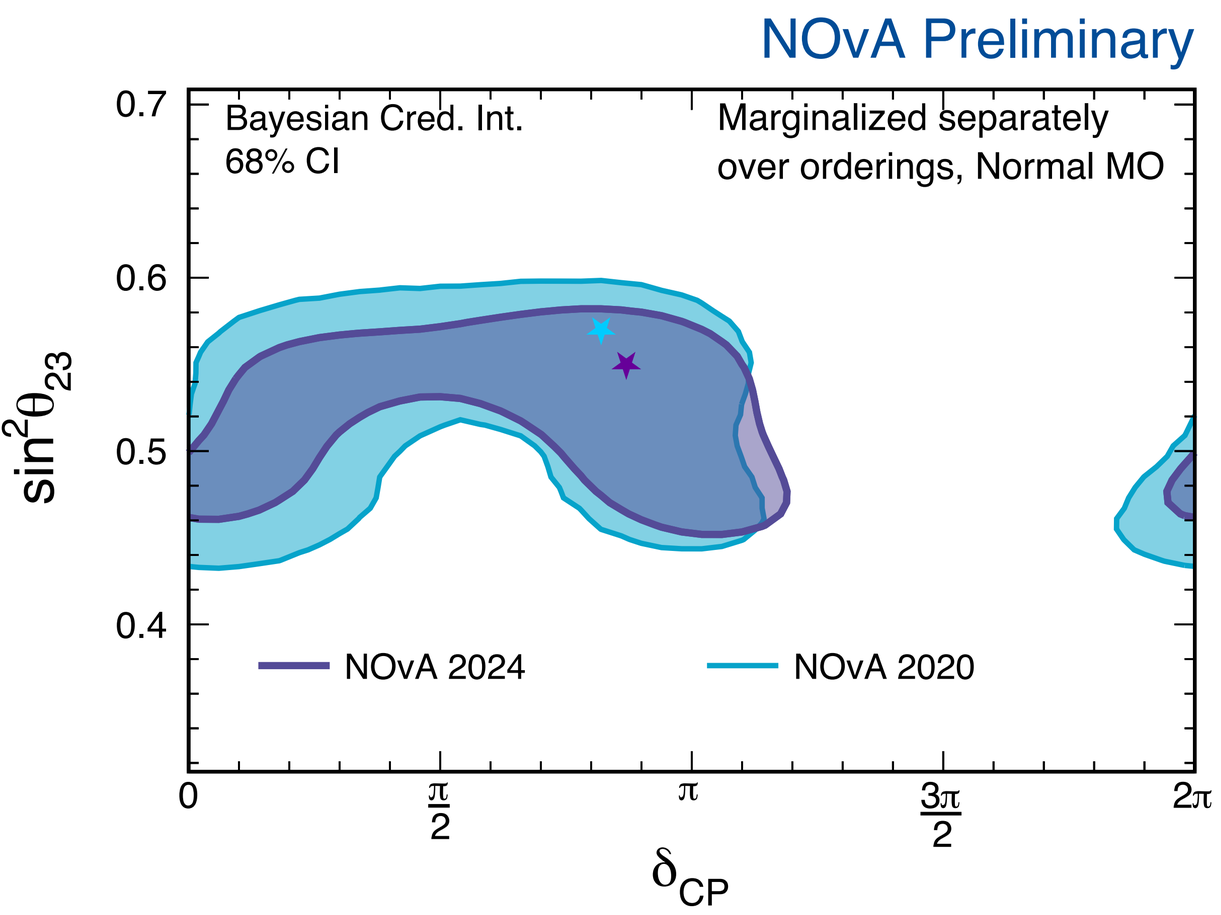
Need more antineutrino data to disentangle these effects!

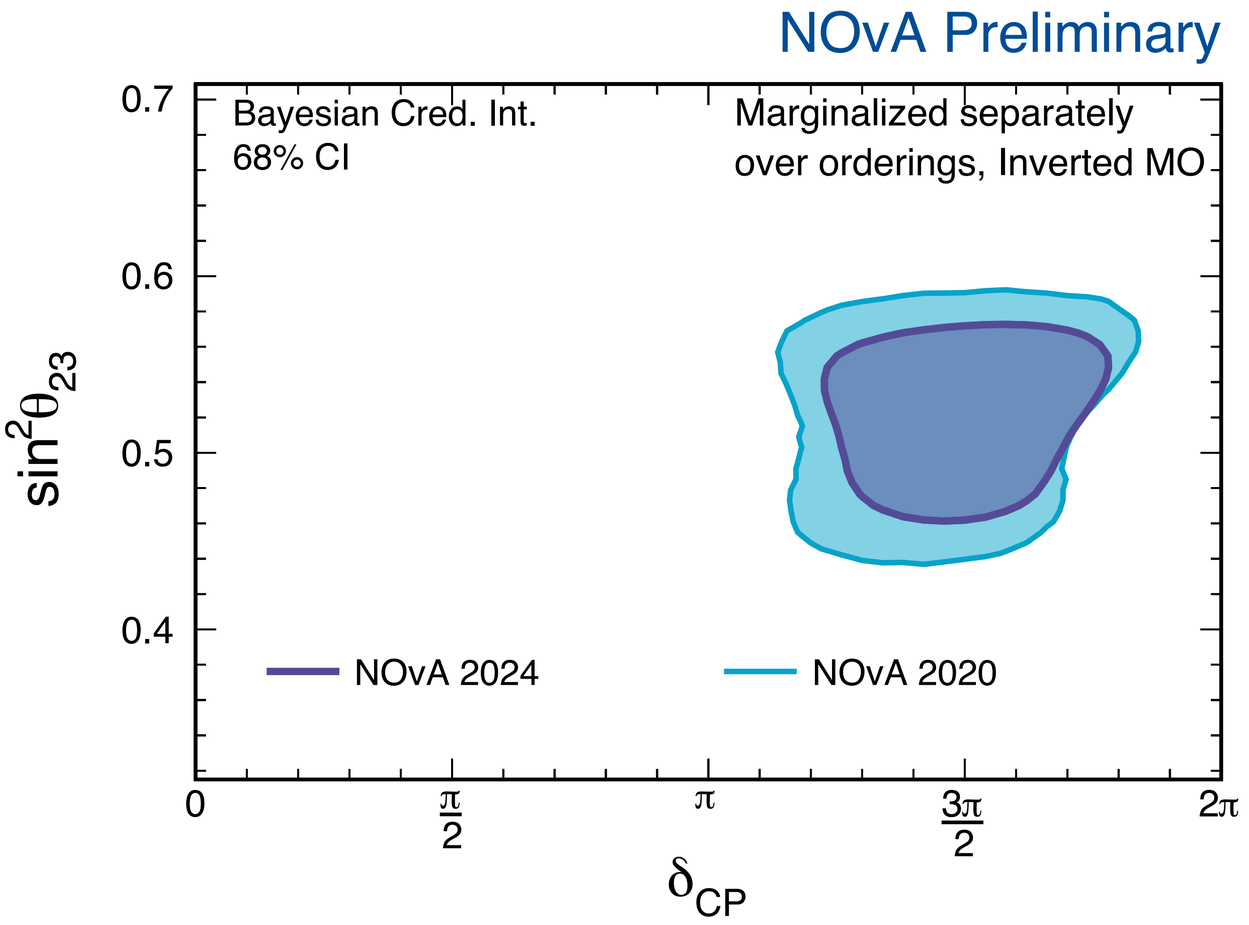
δ_{cp} and mass ordering





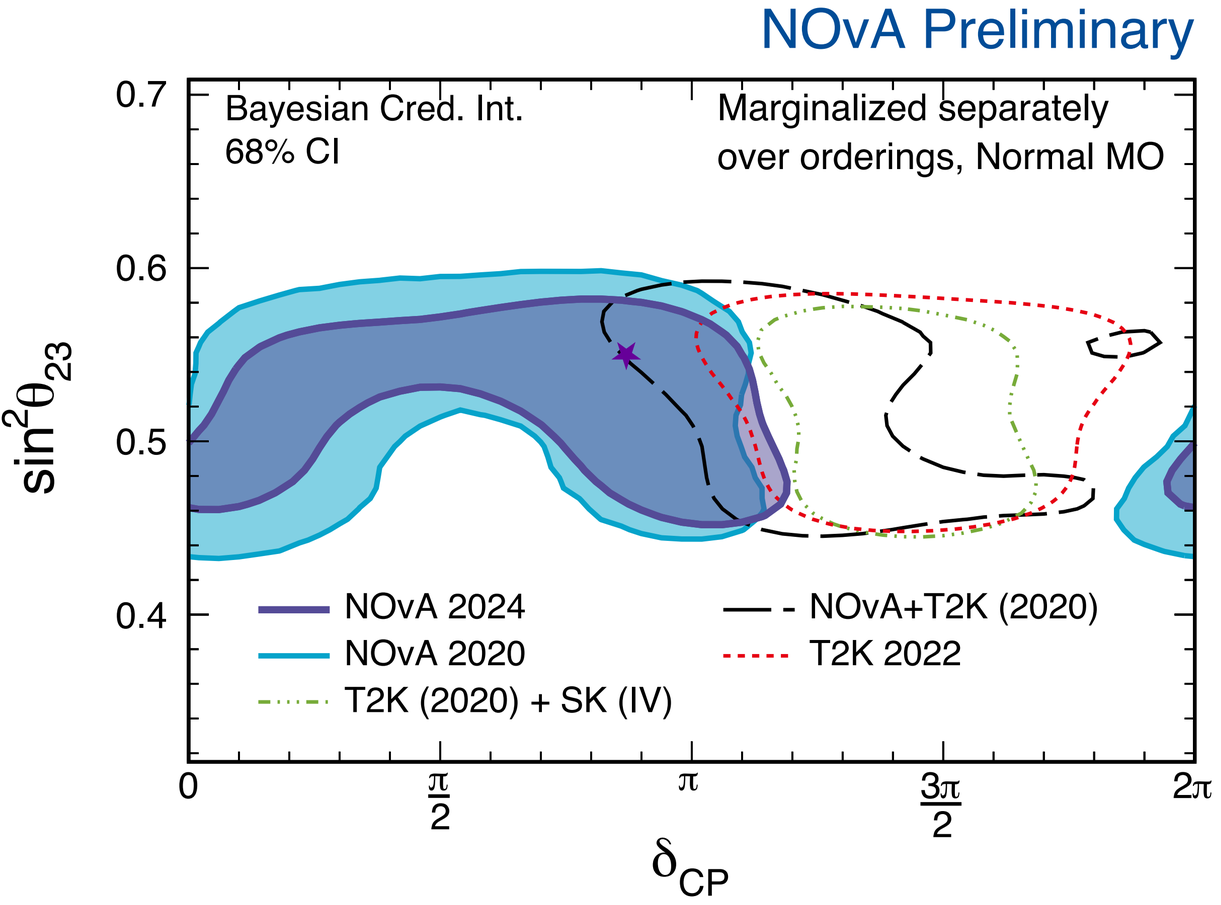
δ_{cp} and mass ordering

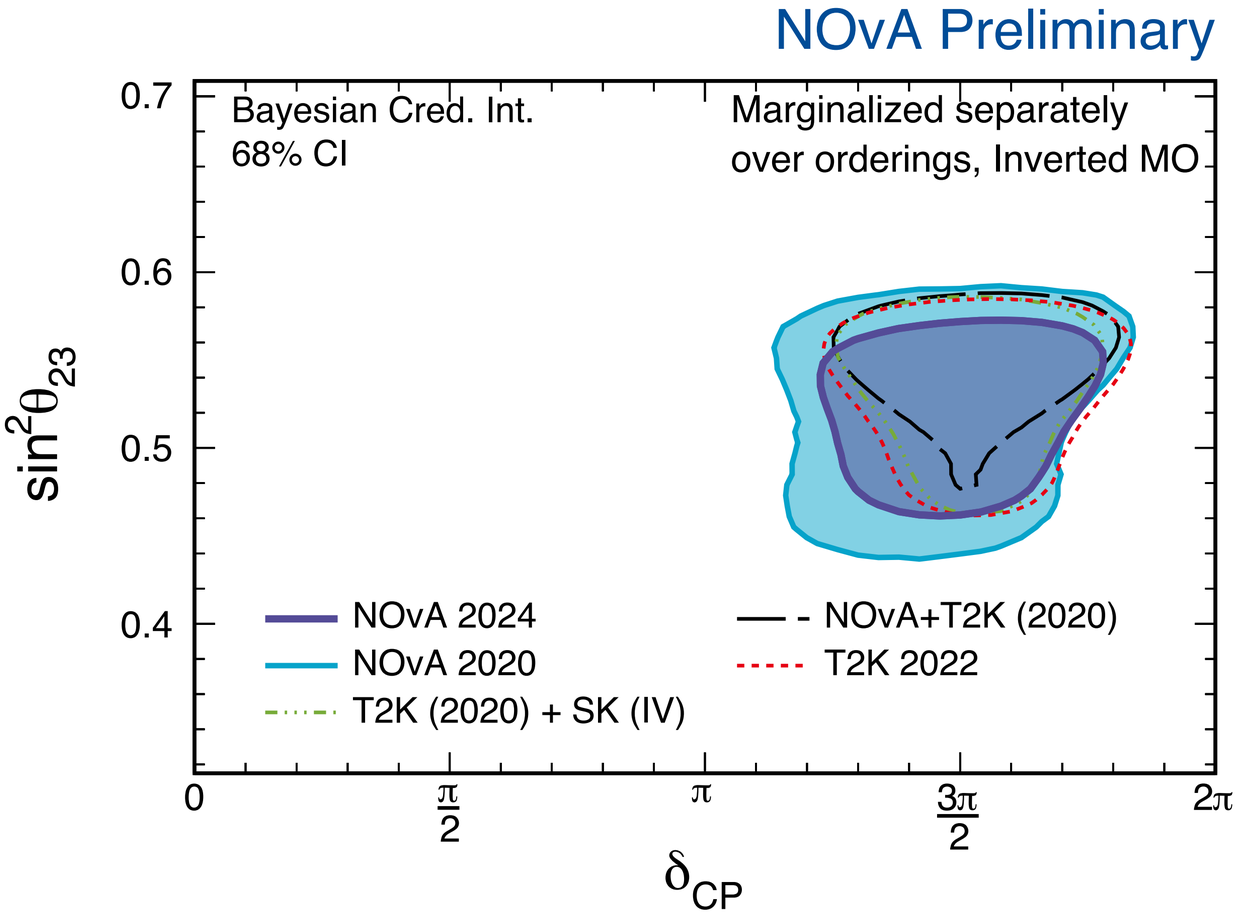




Best fit point lies near CP conserving value of δ_{CP} in normal ordering, but overall have no strong preference

δ_{cp} and mass ordering





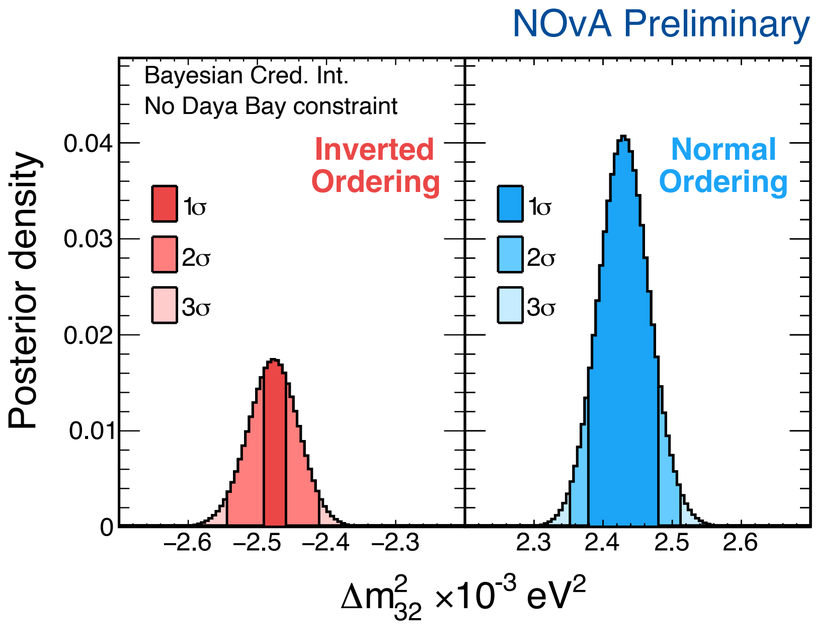
Best fit point lies near CP conserving value of δ_{CP} in normal ordering, but overall have no strong preference

Agree with preferred areas of other experiments for inverted ordering but not for normal ordering.

Mass Ordering

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

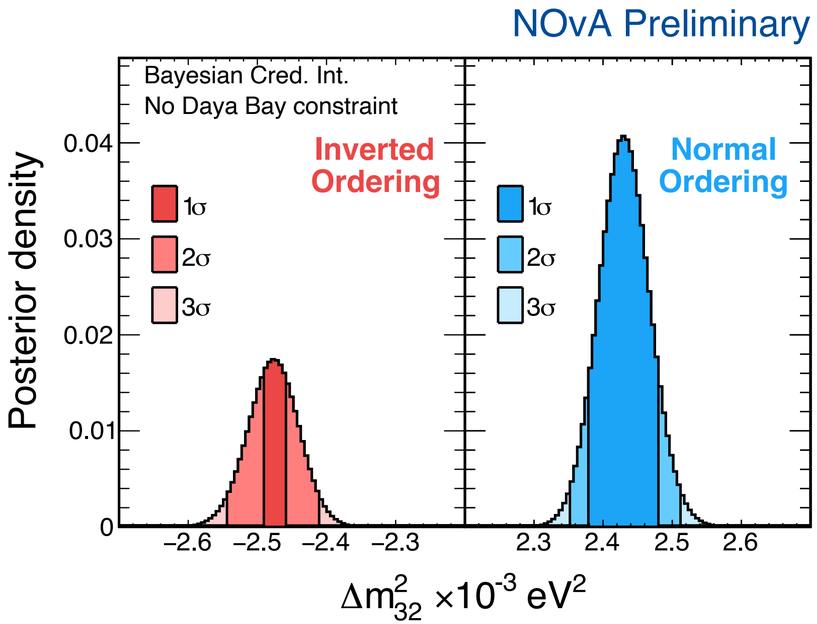
Mass Ordering



	No constraint	
	Probability	Bayes Factor
Normal MO preference	**69%**	2.2

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

Mass Ordering

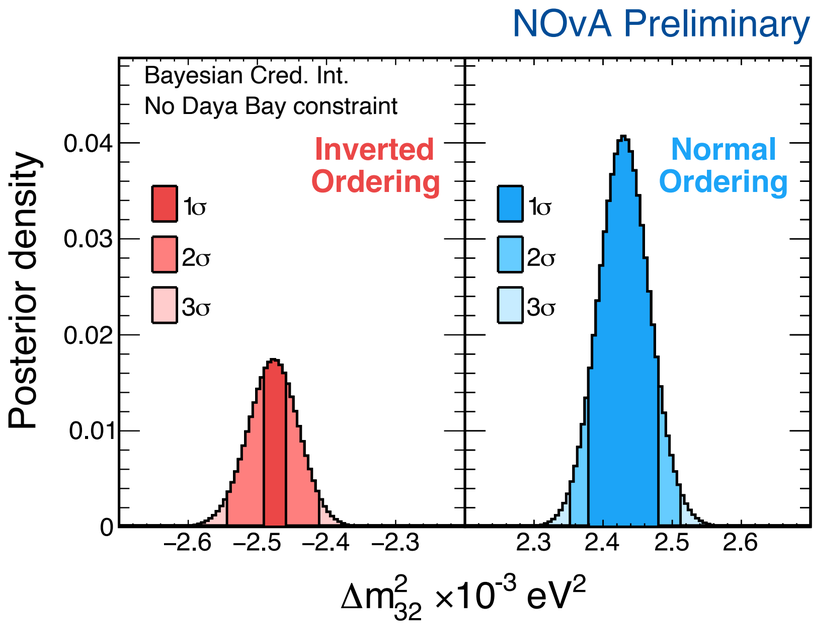


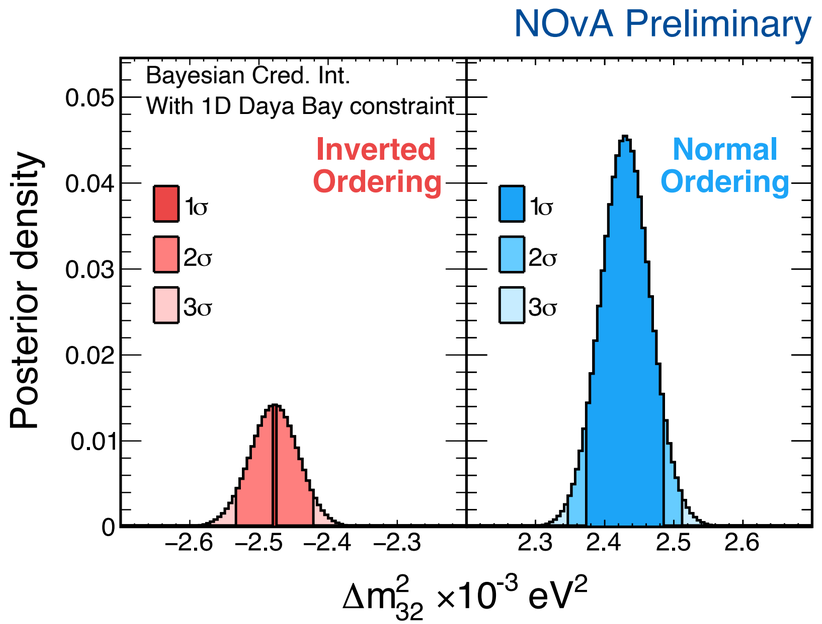
Can use precise measurement of θ_{13} from Daya Bay experiment to constrain our value

	No constraint	
	Probability	Bayes Factor
Normal MO preference	**69%**	2.2

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

Mass Ordering



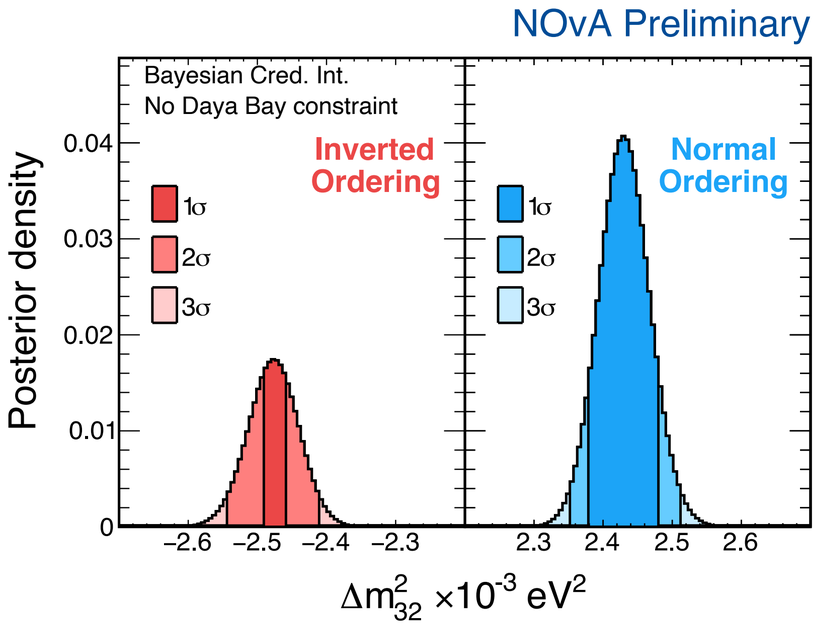


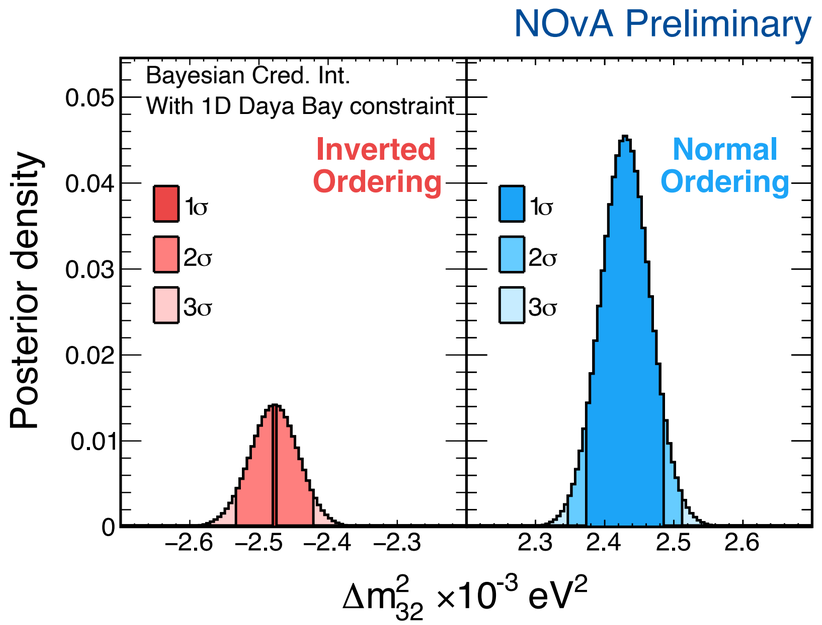
Can use precise measurement of θ_{13} from Daya Bay experiment to constrain our value

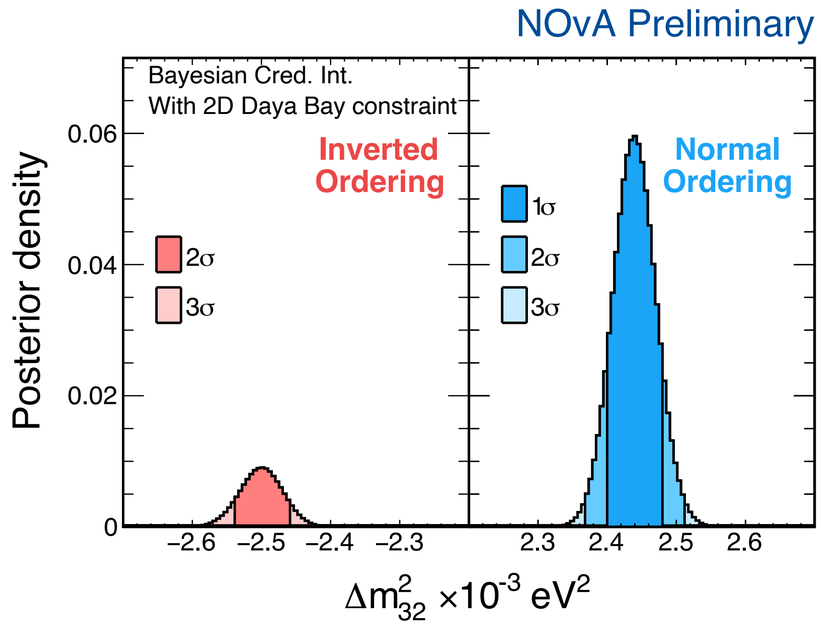
	No constraint		Daya Bay 2023 1D $\sin^2 2\theta_{13}$	
	Probability	Bayes Factor	Probability	Bayes Factor
Normal MO preference	**69%**	2.2	**76%**	3.2

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

Mass Ordering





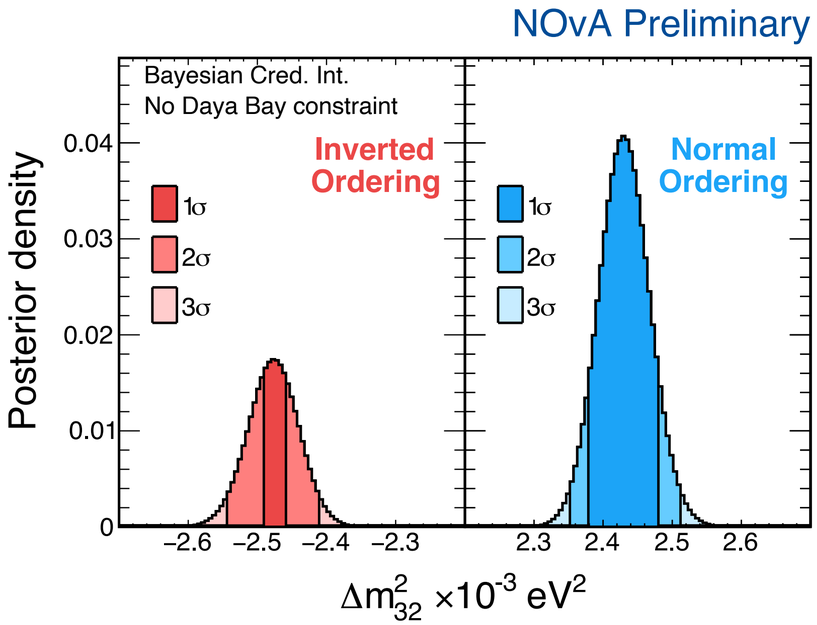


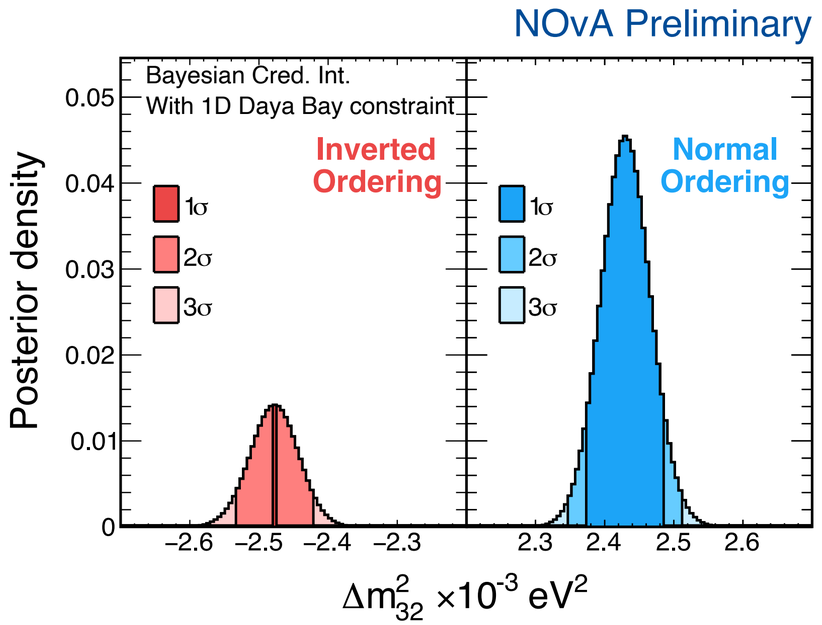
Can use precise measurement of θ_{13} from Daya Bay experiment to constrain our value

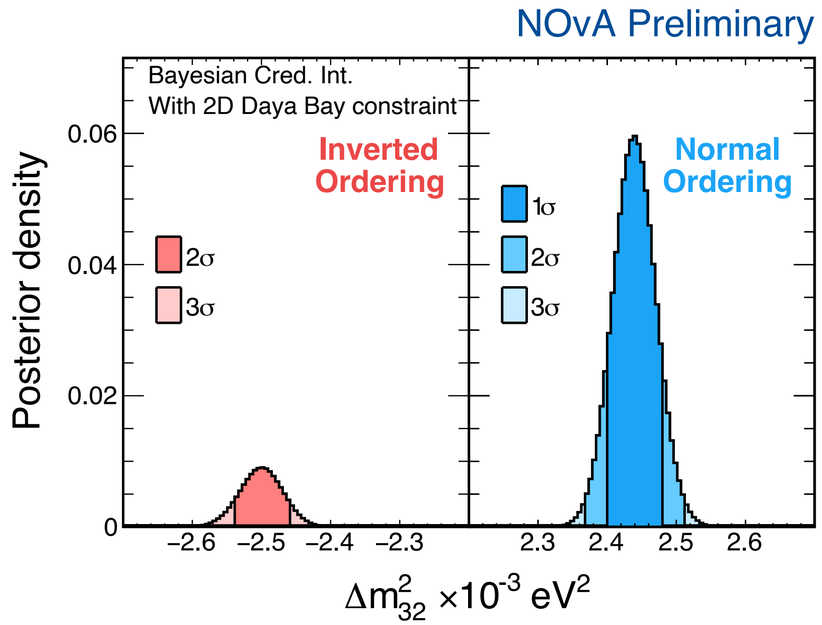
	No constraint		Daya Bay 2023 1D $\sin^2 2\theta_{13}$		Daya Bay 2023 2D ($\sin^2 2\theta_{13}$, Δm^2_{32})	
	Probability	Bayes Factor	Probability	Bayes Factor	Probability	Bayes Factor
Normal MO preference	**69%**	2.2	**76%**	3.2	**87%**	6.8

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

Mass Ordering







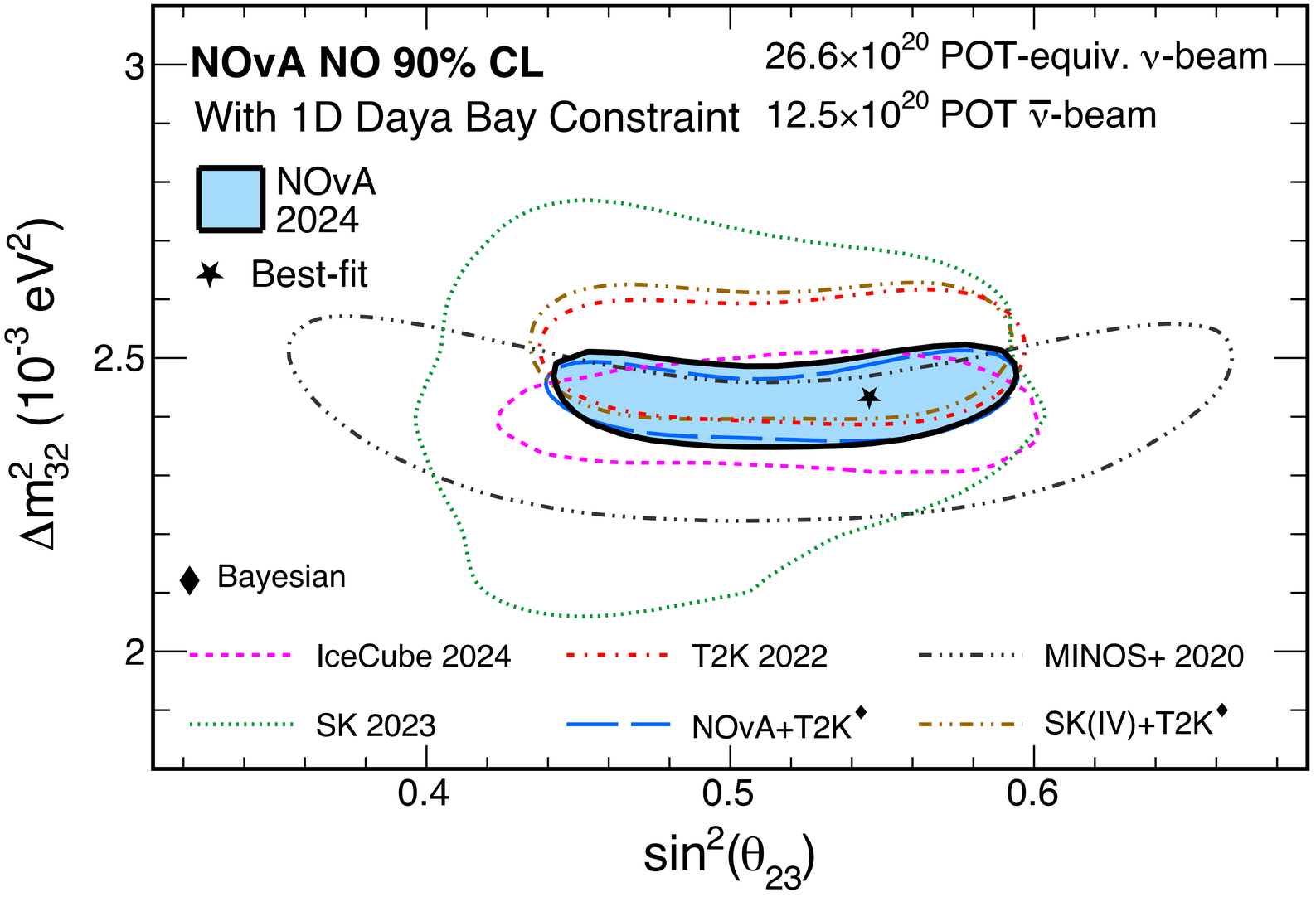
Can use precise measurement of θ_{13} from Daya Bay experiment to constrain our value

	No constraint		Daya Bay 2023 1D $\sin^2 2\theta_{13}$		Daya Bay 2023 2D ($\sin^2 2\theta_{13}$, Δm^2_{32})	
	Probability	Bayes Factor	Probability	Bayes Factor	Probability	Bayes Factor
Normal MO preference	**69%**	2.2	**76%**	3.2	**87%**	6.8

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

$\nu_2 - \nu_3$ sector results

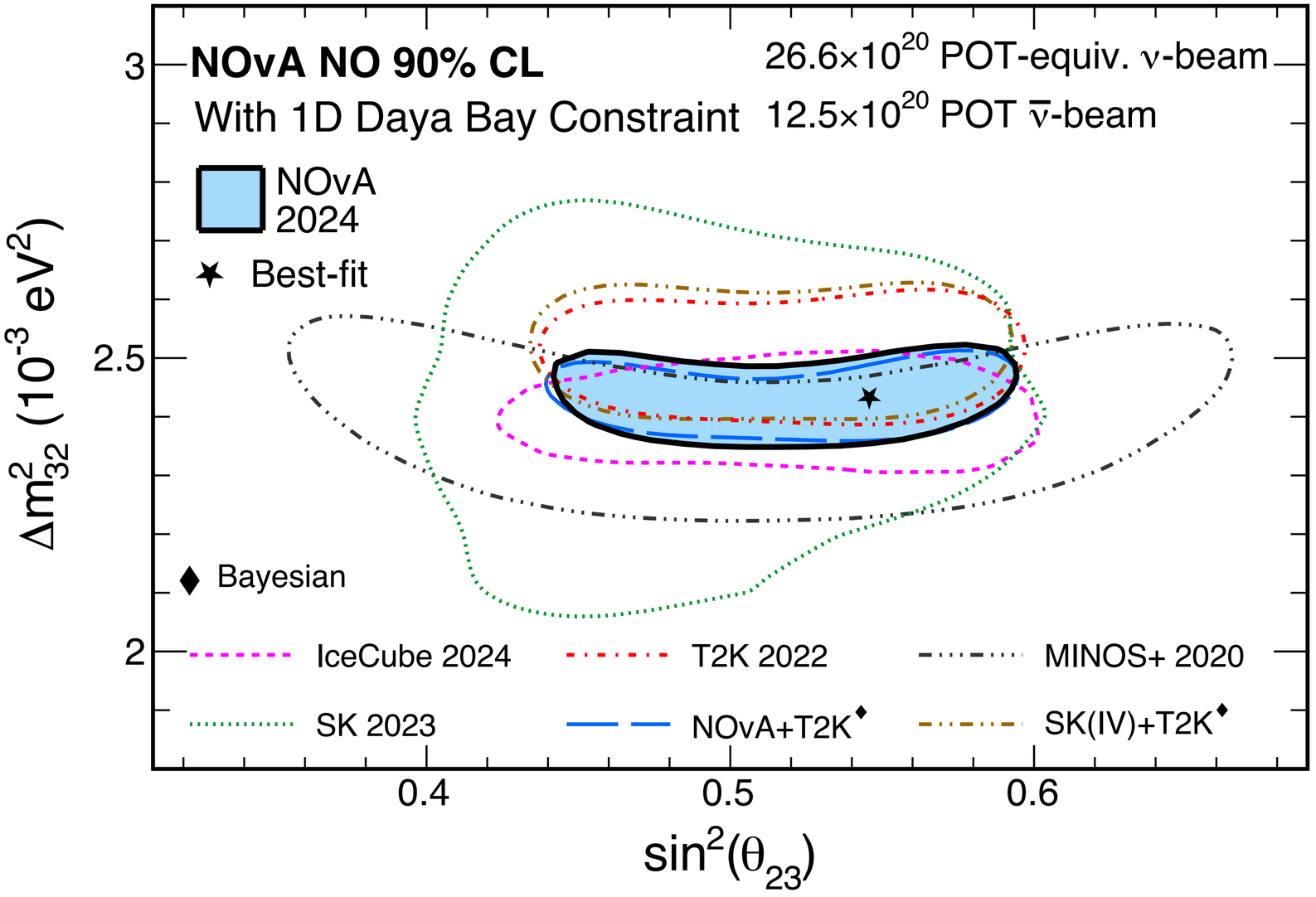
NOvA Preliminary



$\sin^2\theta_{23}$	Both mass orderings	Normal mass ordering	Inverted mass ordering
Unconstrained	0.48	0.55	0.47
1D reactor constraint	0.55	0.55	0.55
2D reactor constraint	0.55	0.55	0.55

$\nu_2 - \nu_3$ sector results

NOvA Preliminary

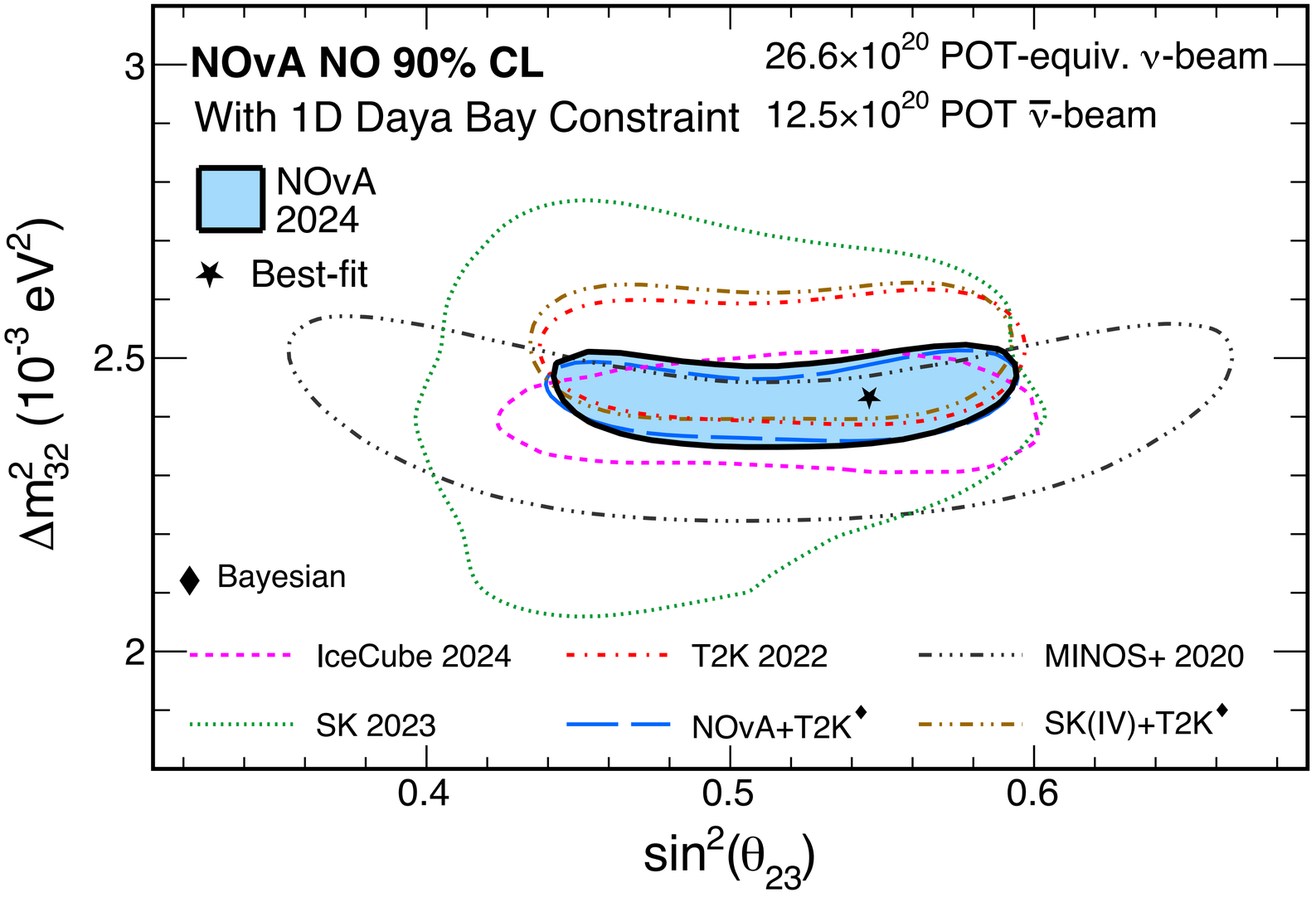


Prefer upper octant

$\sin^2\theta_{23}$	Both mass orderings	Normal mass ordering	Inverted mass ordering
Unconstrained	0.48	0.55	0.47
1D reactor constraint	0.55	0.55	0.55
2D reactor constraint	0.55	0.55	0.55

$\nu_2 - \nu_3$ sector results

NOvA Preliminary

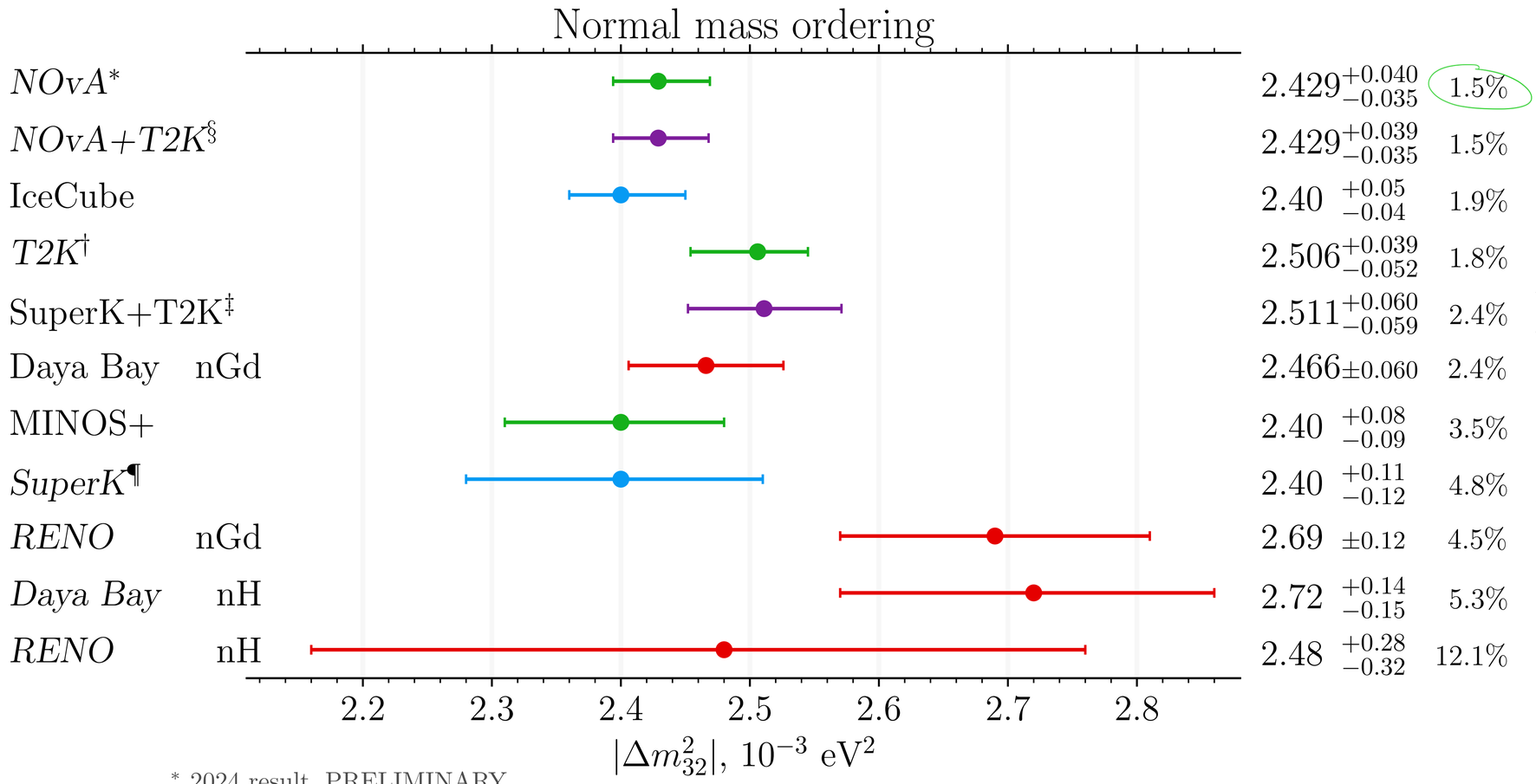


Prefer upper octant

Agreement with previous results + other experiments

$\sin^2\theta_{23}$	Both mass orderings	Normal mass ordering	Inverted mass ordering
Unconstrained	0.48	0.55	0.47
1D reactor constraint	0.55	0.55	0.55
2D reactor constraint	0.55	0.55	0.55

$\nu_2 - \nu_3$ sector results

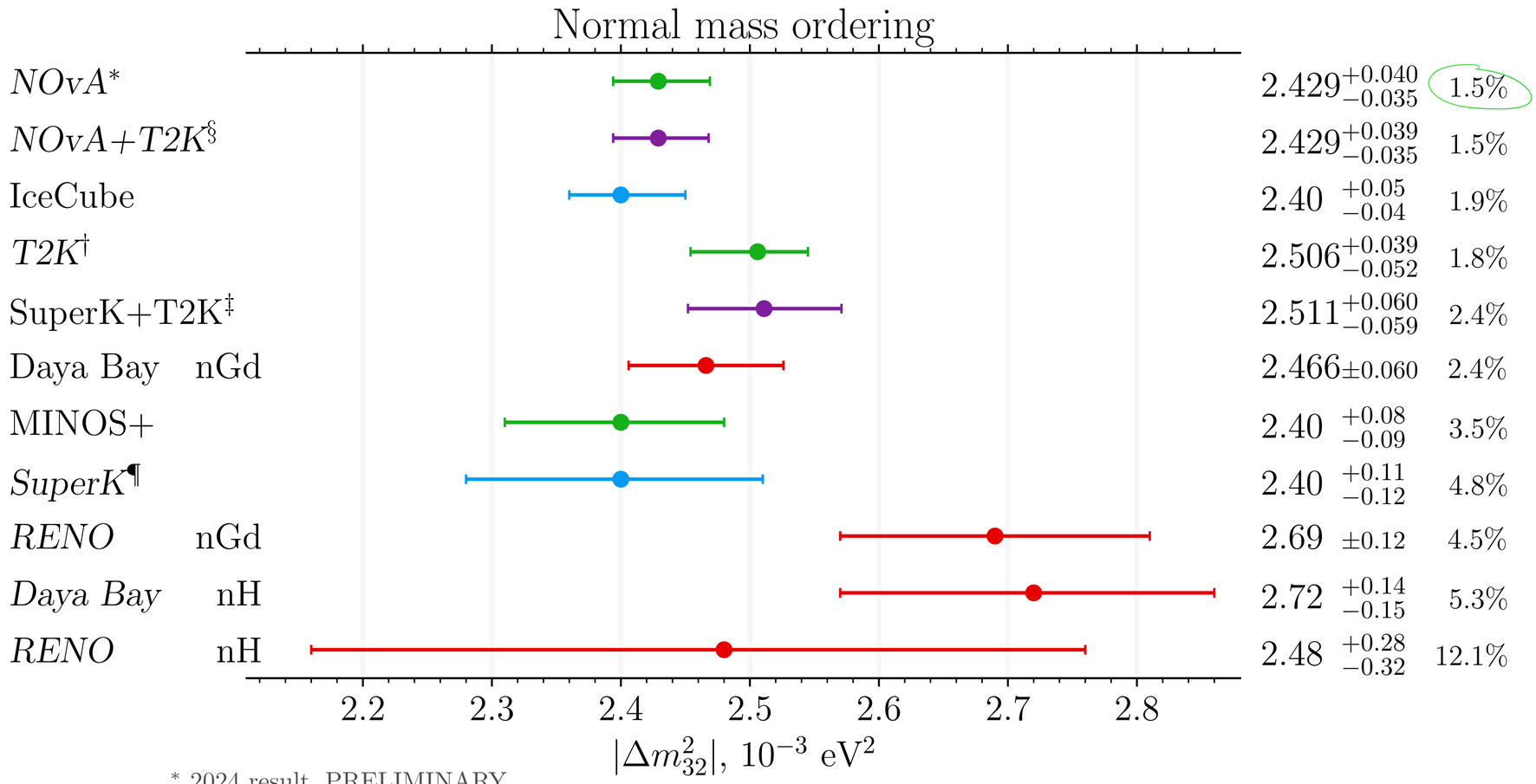


* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488

Preliminary
Published

$\nu_2 - \nu_3$ sector results



* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

Preliminary
Published

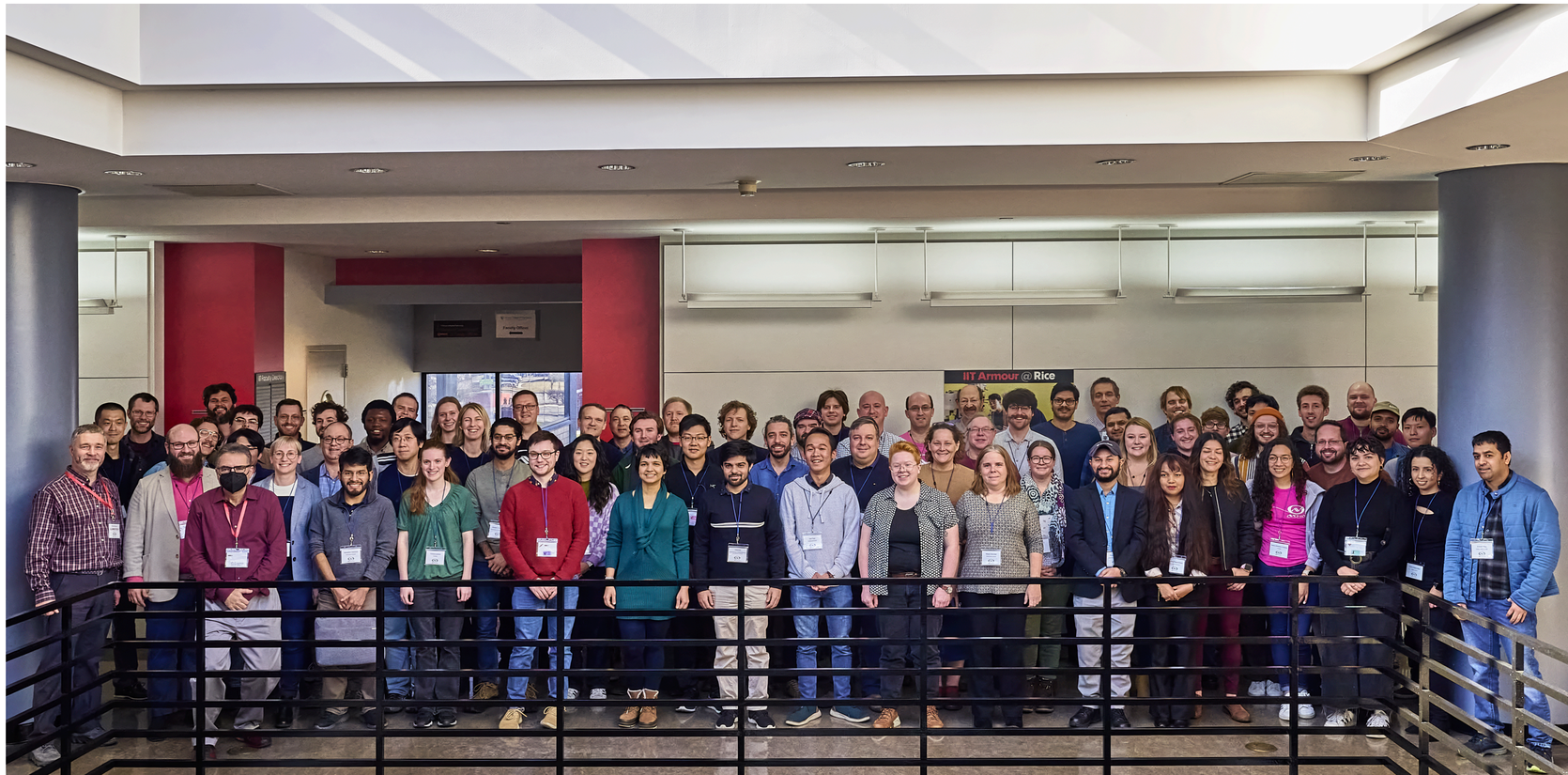
¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488

NOvA-only Δm^2_{32} result has world leading precision for single experiment measurement

Summary

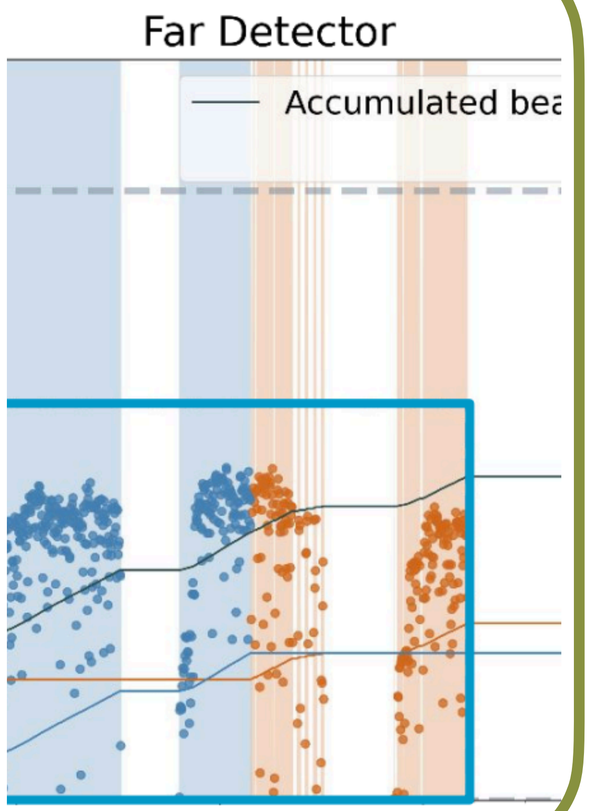
- New NOvA results with almost 2x neutrino data and analysis improvements
- Most precise single experiment measurement of Δm^2_{32}
- Strong preference for normal ordering when 2D reactor constraint is applied to θ_{13} and Δm^2_{32}
- Goal to double antineutrino data before end of running

Thank you!



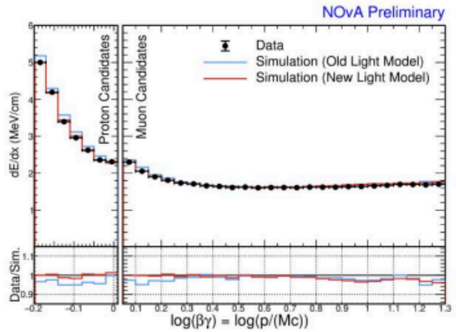
Backups

New for 2024

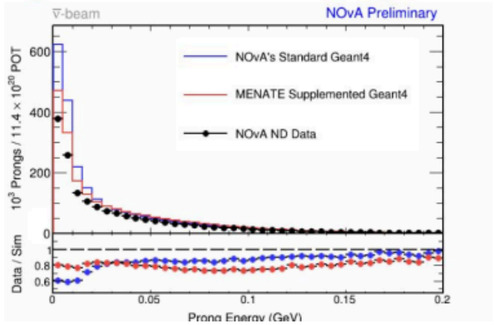


More data!

Improved Light Production Model

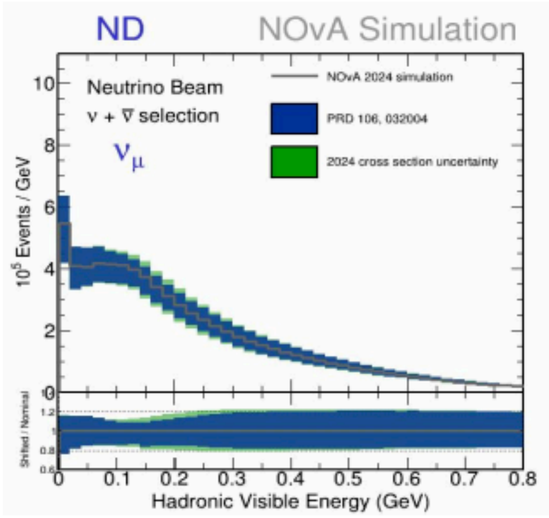


Improved n-C Scattering Model

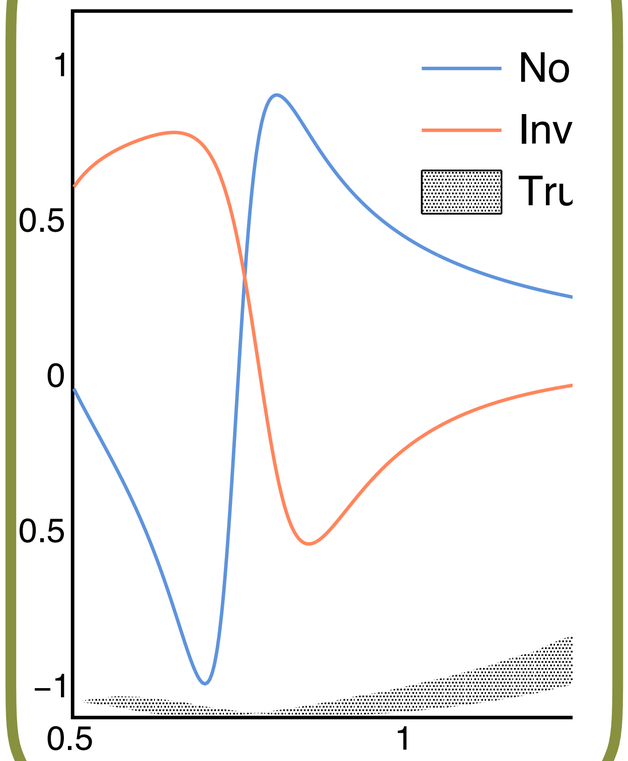


Improved detector simulations

Additional Systematic Uncertainties for Pion Production

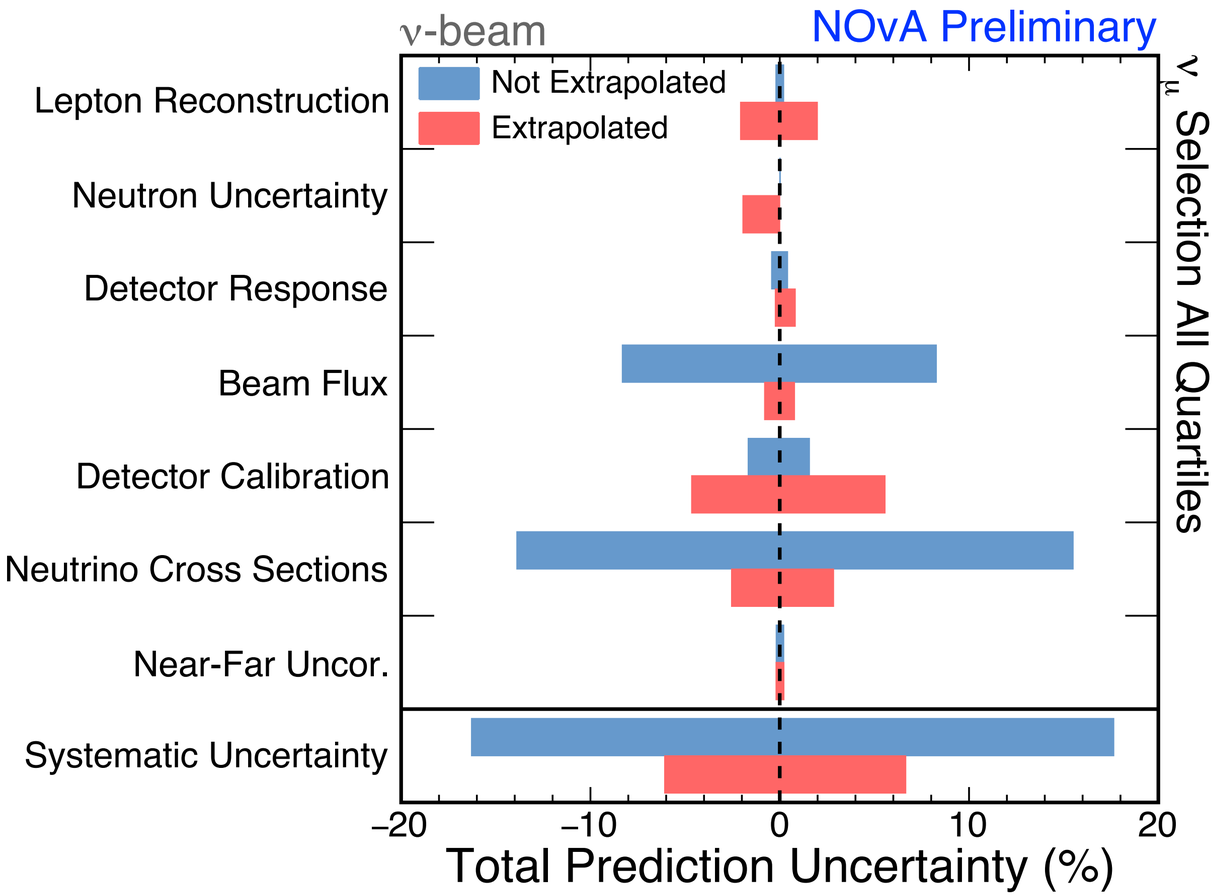


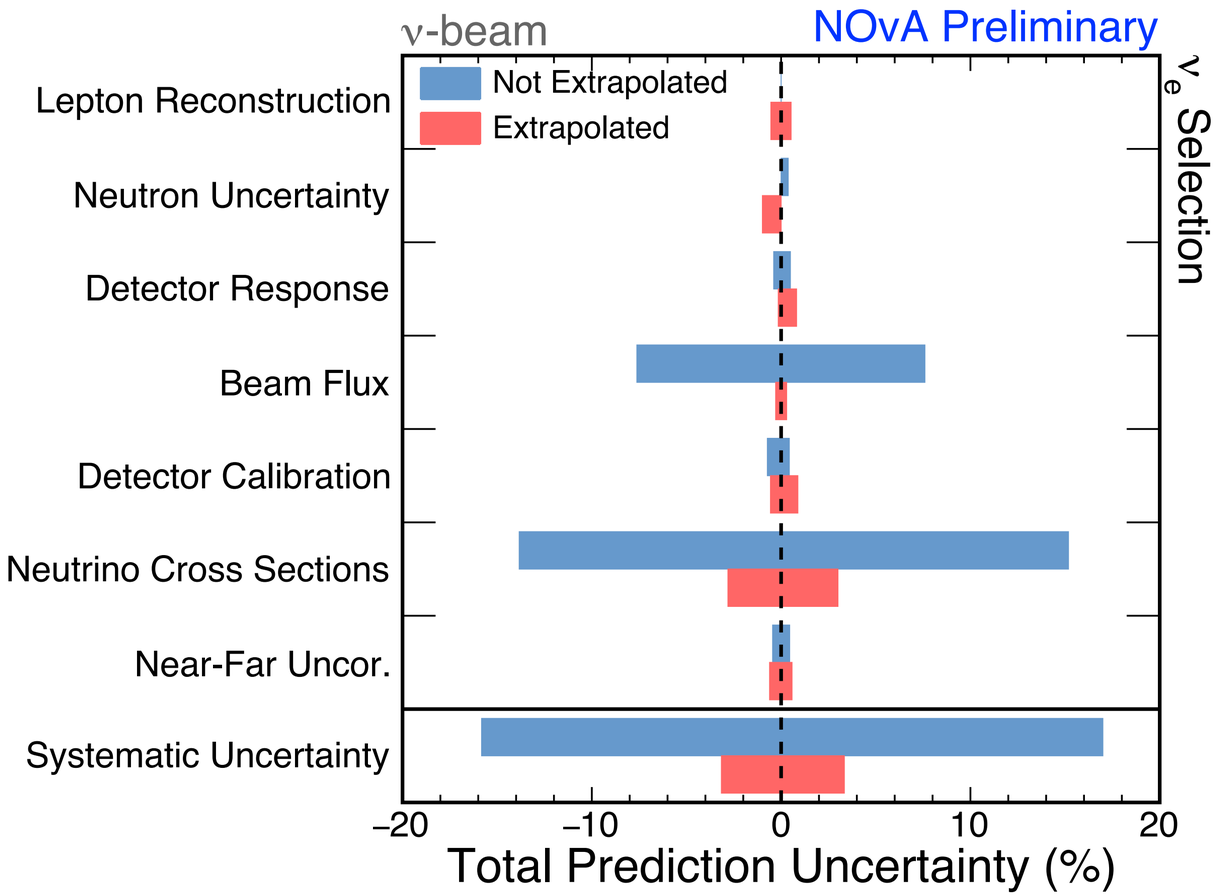
Improved uncertainty predictions



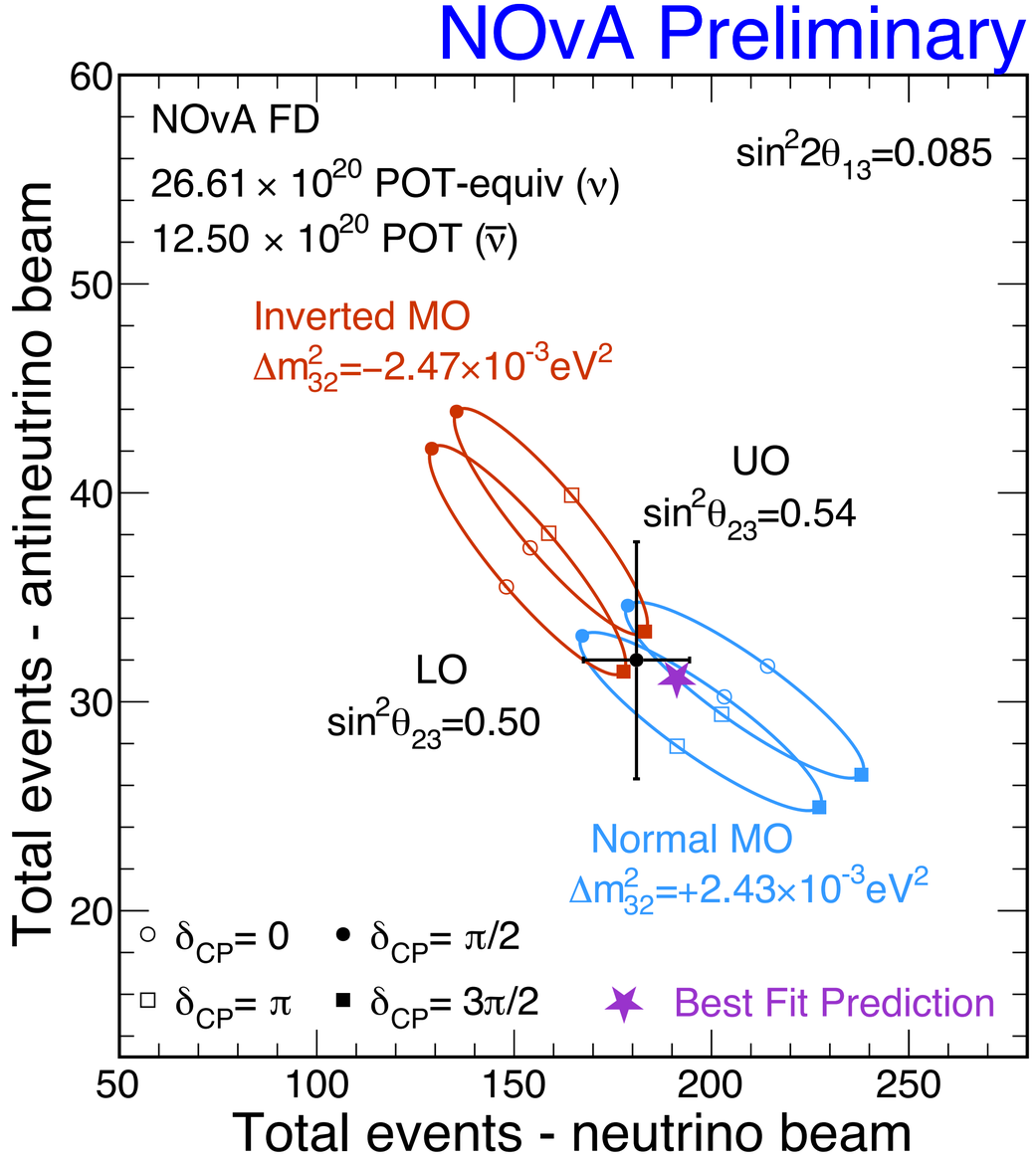
New Selection

Systematics

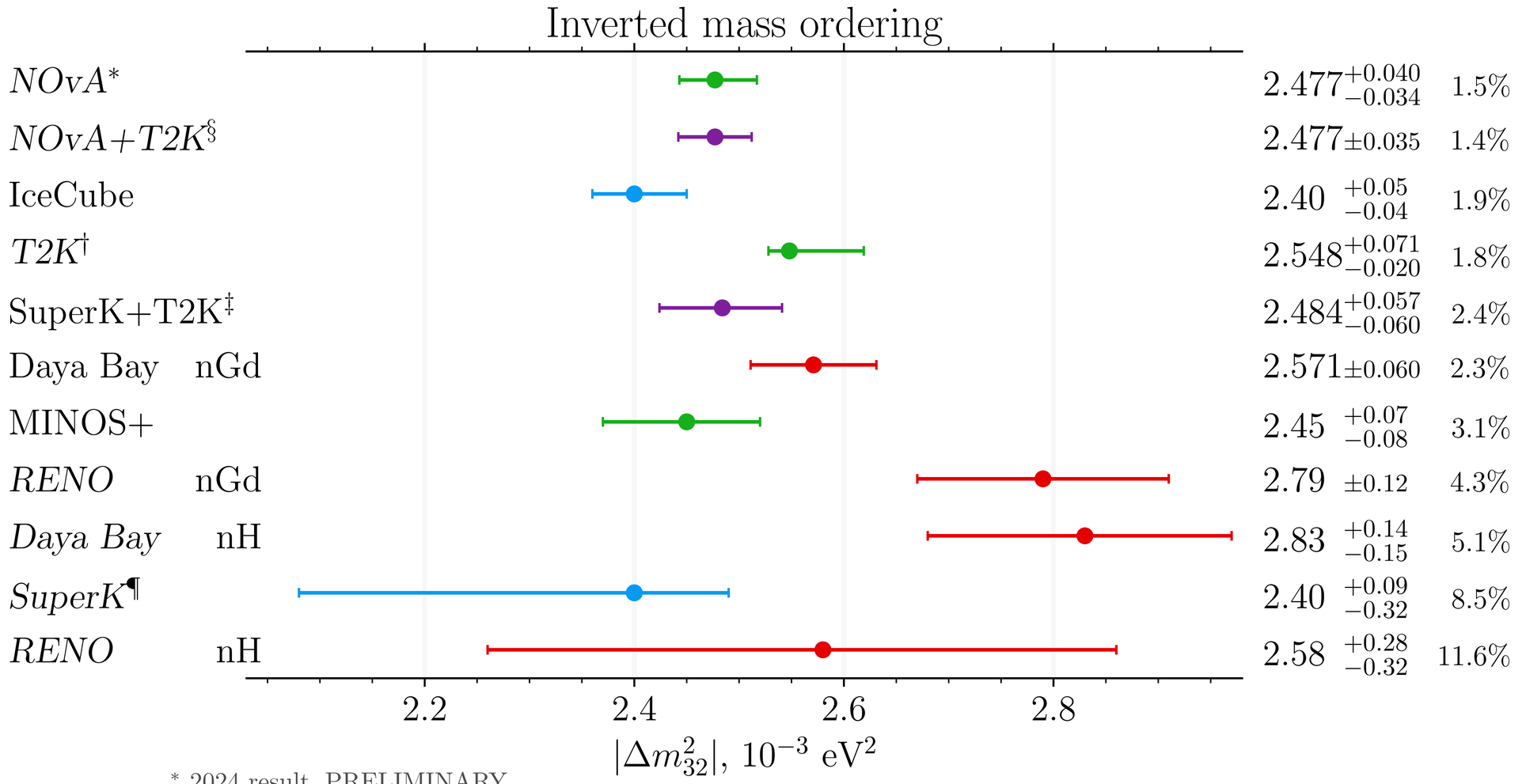




Octant and δ_{CP}



Δm^2_{32} precision IO



v11 2024.10: git.jinr.ru/nu/osc

* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488

Preliminary
Published