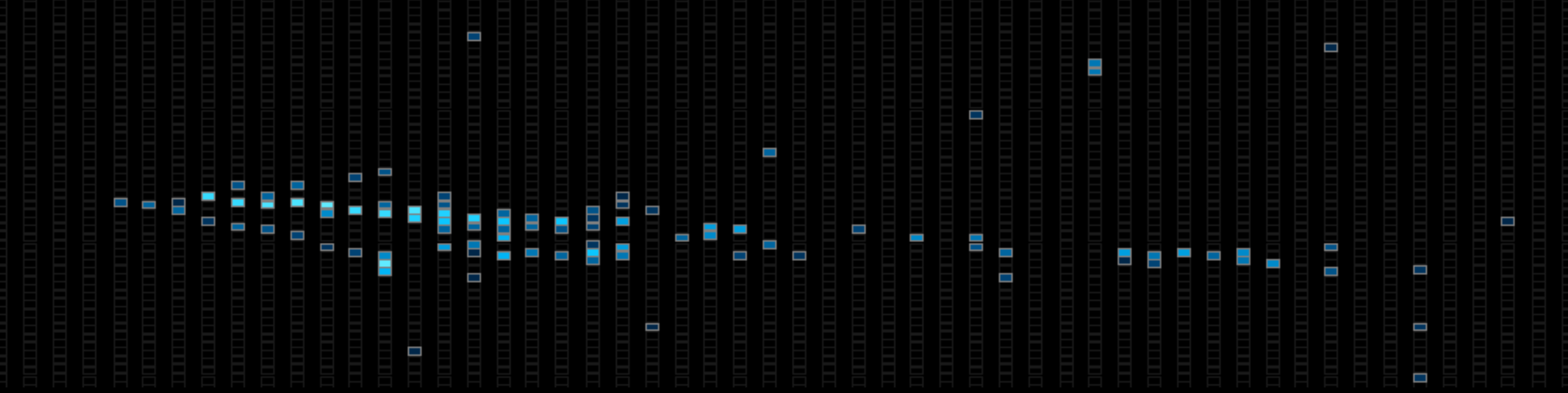


Report from the NOvA Experiment

Mark Messier
Indiana University

57th Annual Users Meeting: Inspirations from P5
Fermilab
11 July 2024

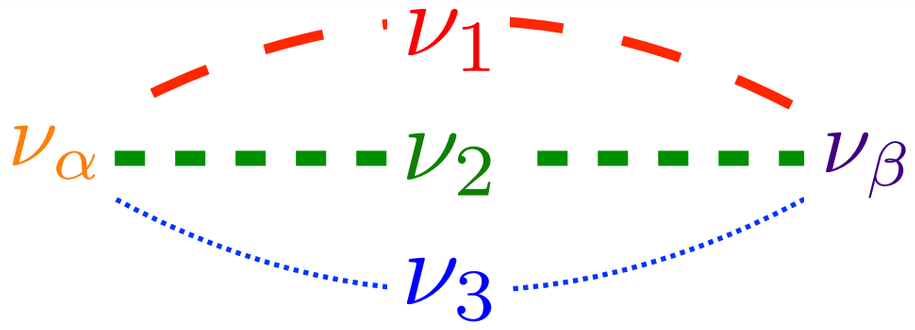
The NOvA Collaboration

211 members from 50 institutions in 8 countries

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

Neutrino mixing and oscillations



$$\left| \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right\rangle$$

$$P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2] \frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2|$
$\simeq 2 \times 10^{-3}\ \mathrm{eV}^2$

$\nu_\mu \longrightarrow \nu_\mu$
$\nu_\mu \longrightarrow \nu_\tau$

atmospheric and long baseline

$\Delta m^2_{31} \simeq \Delta m^2_{32}$

$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_e$

reactor and long baseline

$\Delta m^2_{21} \simeq 8 \times 10^{-5}\ \mathrm{eV}^2$

$\nu_e \longrightarrow \nu_e$
$\nu_e \longrightarrow \nu_\mu + \nu_\tau$

solar and reactor

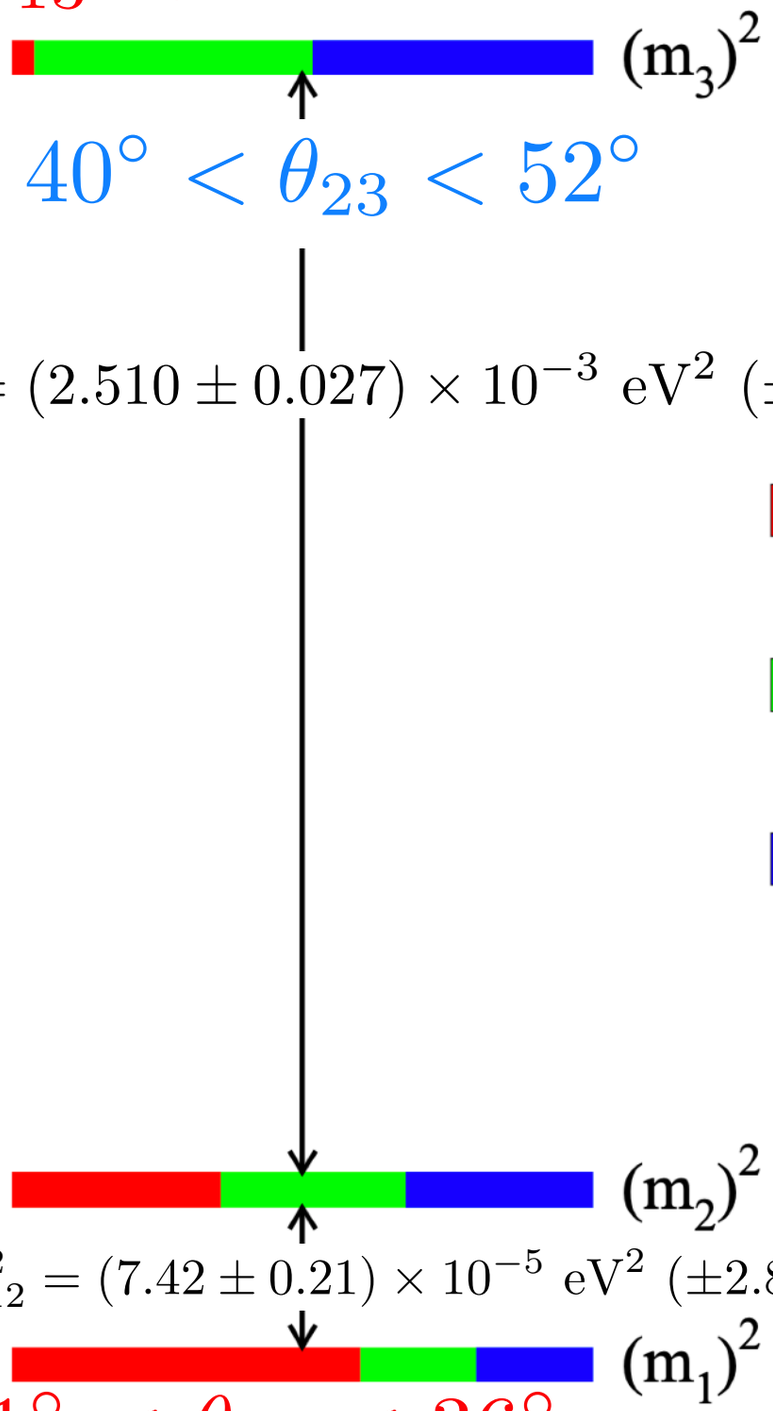
$8.2^\circ < \theta_{13} < 9.0^\circ$

$40^\circ < \theta_{23} < 52^\circ$

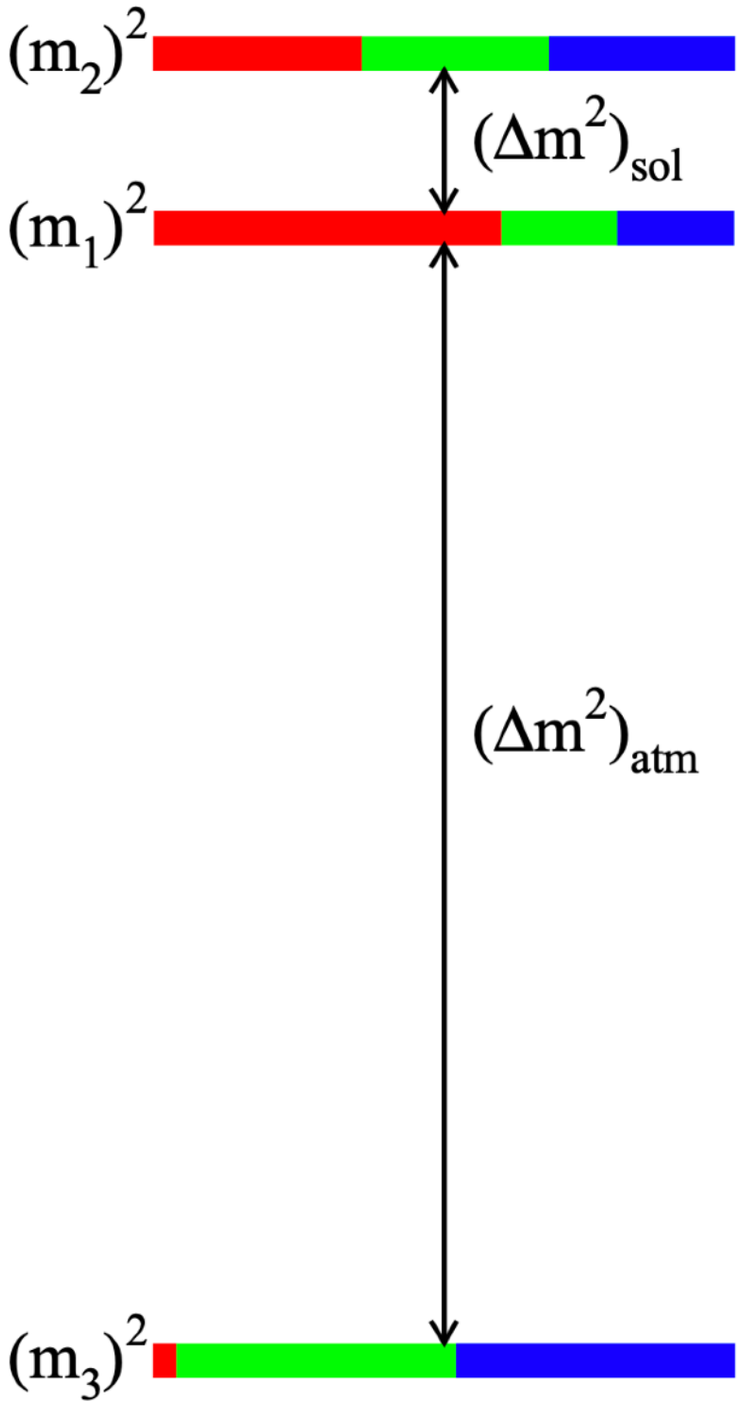
$\Delta m^2_{23} = (2.510 \pm 0.027) \times 10^{-3}\ \mathrm{eV}^2\ (\pm 1.1\%)$

$\Delta m^2_{12} = (7.42 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2\ (\pm 2.8\%)$

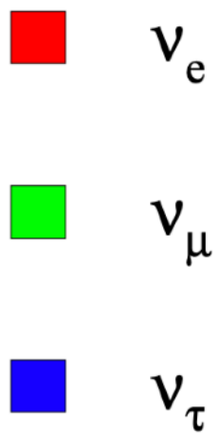
$31^\circ < \theta_{12} < 36^\circ$



normal ordering



inverted ordering



arXiv:2102.00594 NuFit, arXiv:2111.03086

Inspirations from P5

- Under the heading “Deciphering the Quantum Realm”, P5 calls for us to “Elucidate the Mysteries of Neutrinos”. NOvA addresses each of the main questions posed:
  - The ordering of the neutrino masses
  - Precision studies including exploration of muon-tau symmetry
  - Search for and measure CP violation
  - Searches for physics beyond the (ν) Standard Model
- **2008**: “Recommends a world-class neutrino program as a core of the US program”, “upgrade the neutrino source to 700 kW” and “rapid NOvA construction start”.
- **2014**: NOvA operations just beginning; P5 formulated what is now DUNE; first step is a recommended upgrade of the proton source to 1.2 MW.
- **2023**: Recommendation 1: “…support operations of ongoing experiments and research to enable maximum science” and reaffirms “major initiatives” including NOvA

https://science.osti.gov/-/media/hep/pdf/files/pdfs/p5_report_06022008.pdf
https://www.usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf
https://www.usparticlephysics.org/2023-p5-report/decipher-the-quantum-realm.html

Fermilab

Batavia, IL

NOvA Far Detector Laboratory

Ash River, MN

April 2012

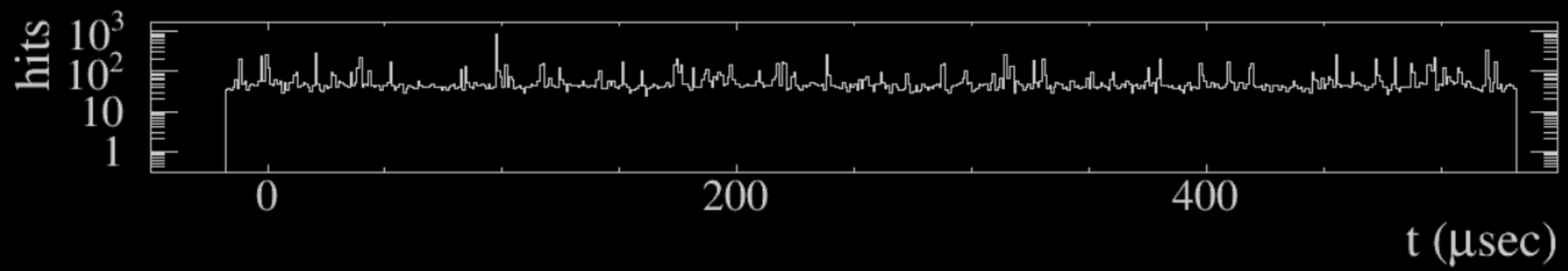
60 m

15.5 m

NOvA - FNAL E929

Run: 18605 / 0
Event: 161 / PerCal

UTC Tue Jan 6, 2015
23:25:55.172218000



Daily neutrino beam
Daily antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam
2024 analysis dataset
2020 analysis dataset
Daily exposure (10^{18} POT)
Cumulative exposure (10^{20} POT)
Date

27×10^{20} POT

NOvA Simulation

NOvA Far Detector

ν_μ Spectrum

$\bar{\nu}_\mu$ Spectrum

ν_μ	95%
$\bar{\nu}_\mu$	4%
$\nu_e + \bar{\nu}_e$	1%

Flux 1-5 GeV

10^3 Neutrinos / m^2 / GeV / 5 × 10^{13} POT

Neutrino energy (GeV)

13×10^{20} POT

NOvA Simulation

NOvA Far Detector

ν_μ Spectrum

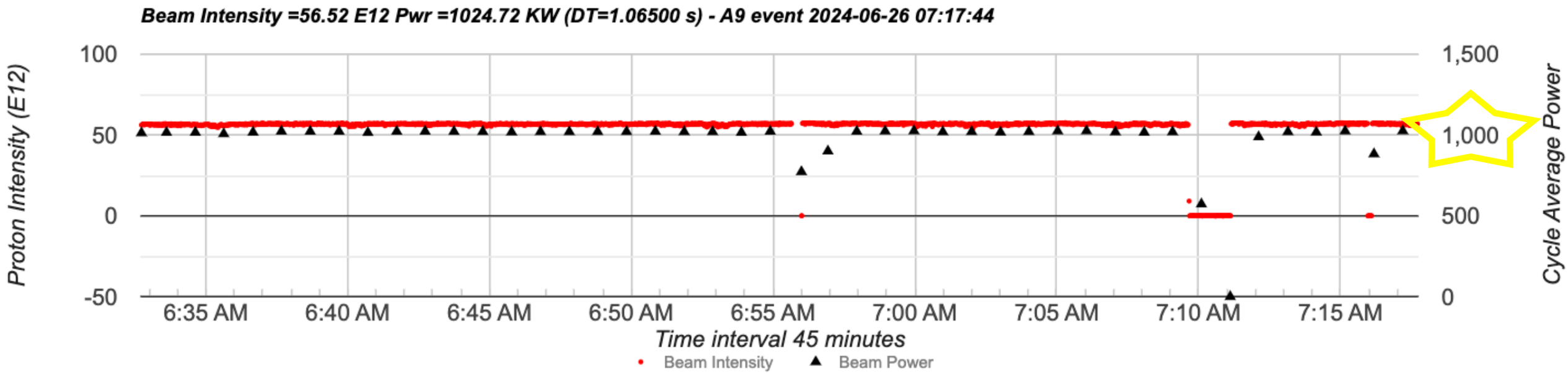
$\bar{\nu}_\mu$ Spectrum

$\bar{\nu}_\mu$	93%
ν_μ	6%
$\nu_e + \bar{\nu}_e$	1%

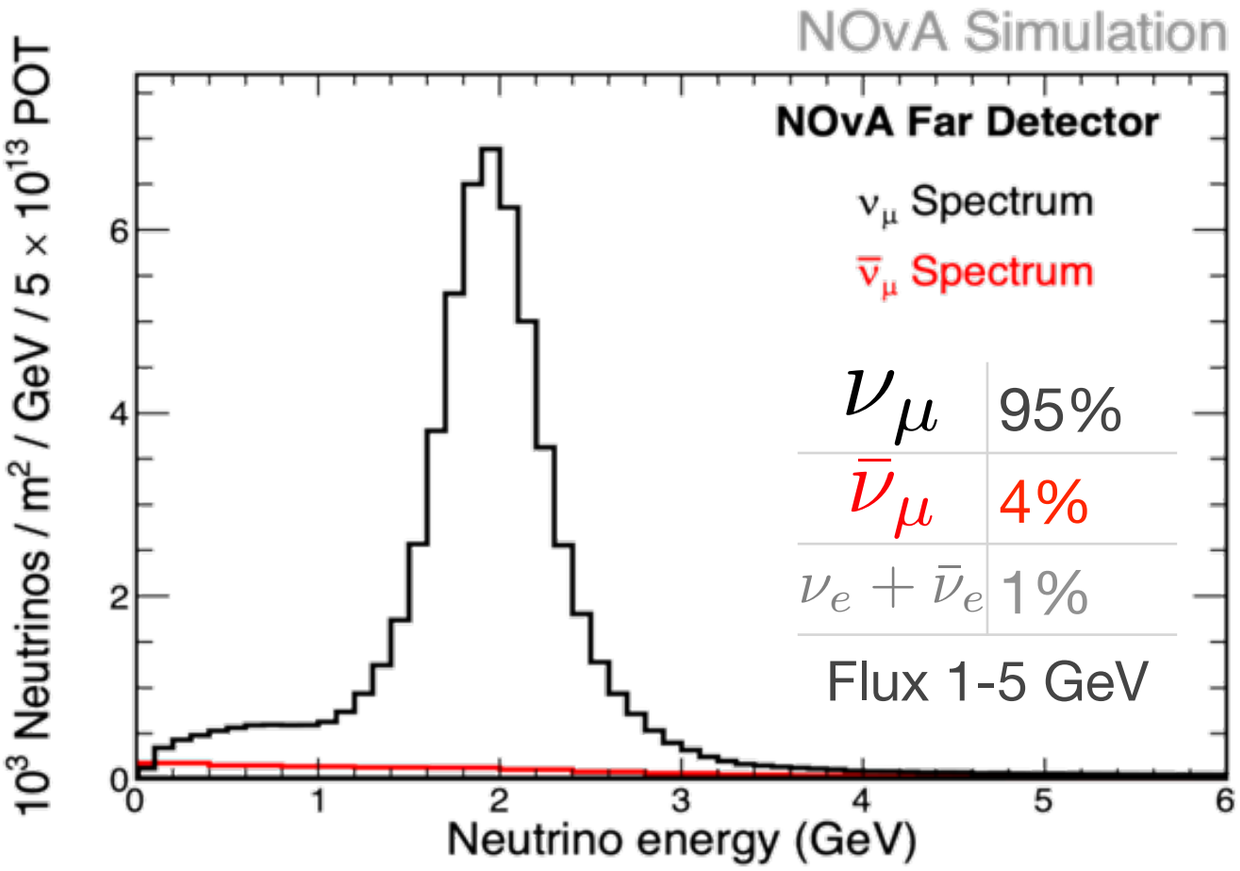
Flux 1-5 GeV

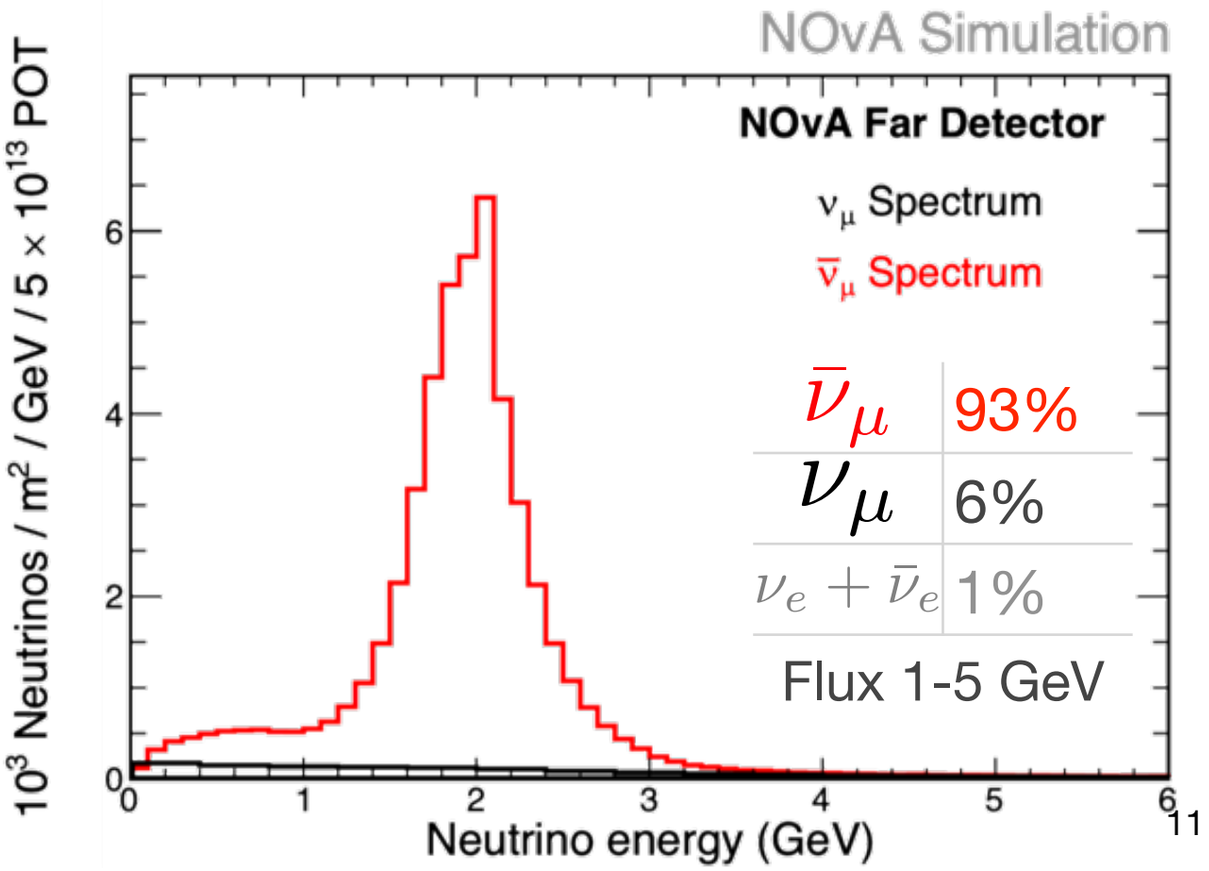
10^3 Neutrinos / m^2 / GeV / 5 × 10^{13} POT

Neutrino energy (GeV)



New NuMI power record: 1.018 MW





Fermilab JETP Seminars From NOvA

28 June 2024	New 3-flavor neutrino oscillation results from NOvA	Erika Catano-Mur (William & Mary)
22 March 2024	Measurement of the Triple-Differential Muon-Antineutrino Charged-Current Inclusive Cross Section in the NOvA Near Detector	Prabhjot Singh (Queen Mary University London)
09 February 2024	Results from a joint analysis of data from NOvA and T2K	Zoya Vallari (Caltech)
02 February 2024	Exploring signatures in muon-neutrino charged-current measurements at NOvA	Leonidas Aliaga Soplin (UT Arlington) & Travis Olson (University of Houston)

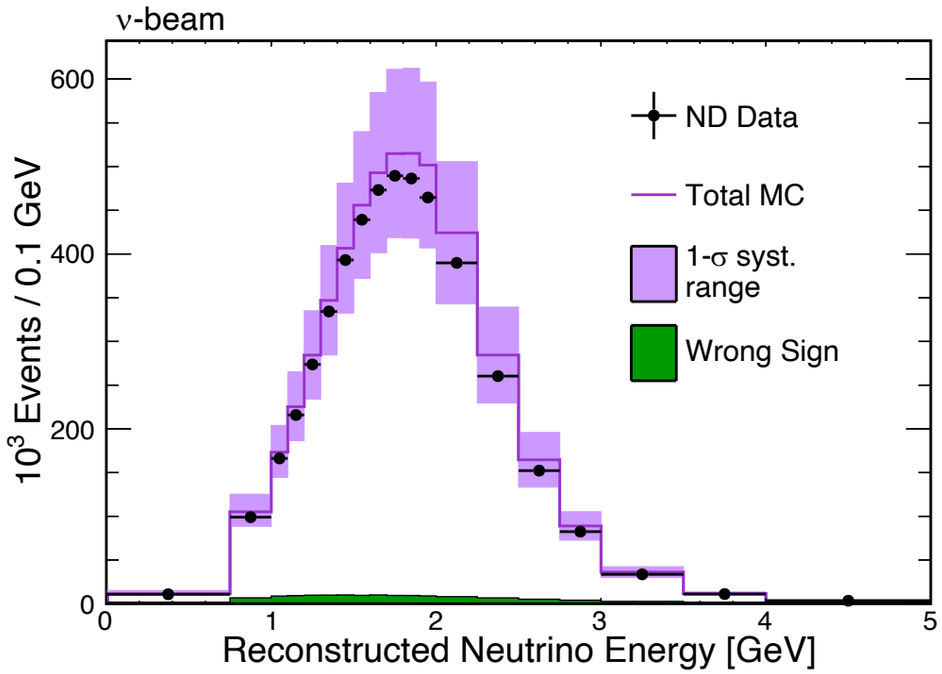
NOvA PHDs July 2023 - July 2024

(1)	7/2023	Constraining neutrino oscillation and interaction parameters with the NOvA Near Detector and Far Detector data using Markov Chain Monte Carlo	**Michael Dolce**, Tufts University
(2)	7/2023	A measurement of muon neutrino charged-current interactions with a charged pion in the final state using the NOvA near detector	**Paul Rojas**, Colorado State University
(3)	7/2023	Measurement of the Total Cross-Section of Muon Neutrino Charged-Current Coherent Pion Production in NOvA Near Detector	**Kuruppumullage Don Chatura Dilshan Kuruppu**, University of South Carolina
(4)	8/2023	Constraining neutrino interaction uncertainties for oscillation measurements in the NOvA experiment using Near Detector data	**Maria Martinez-Casales**, Iowa State University
(5)	8/2023	Measurement of the muon neutrino charged-current single charged pion production cross-section in the NOvA Near Detector	**Cathal Sweeney**, University College London, UK
(6)	9/2023	Study of neutron detector response and related systematic uncertainties in the NOvA oscillation analysis	**Miranda Rabelhofer**, Iowa State University
(7)	10/2023	Improving the NOvA 3-Flavour Neutrino Oscillation Analysis	**Veera Mikola**, University College London, UK
(8)	1/2024	Analysis of neutrino interactions for the search of supernova signals	**Andrey Sheshukov**, Joint Insitute of Nuclear Research
(9)	4/2024	BSM Studies Using Long-baseline Neutrino Experiment	**Barnali Brahma**, Indian Institute of Technology Hyderabad
(10)	5/2024	Classification of particles with a convolutional neural network for neutrino and antineutrino events in the NOvA experiment	**Akshay Chatla**, University of Hyderabad

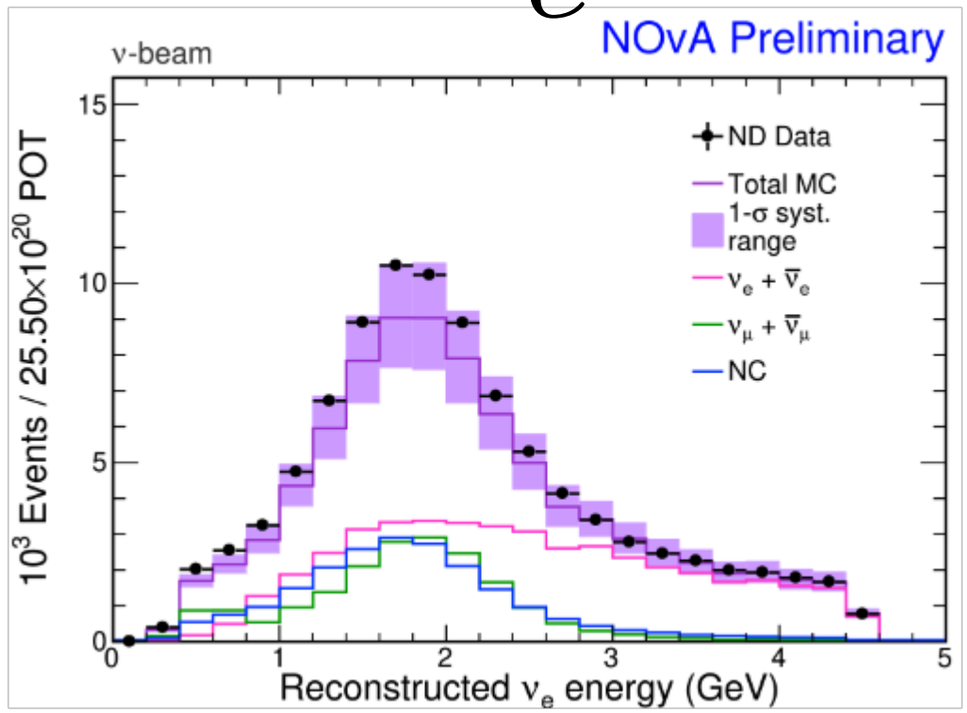
ν

6.5M Events

ν_μ

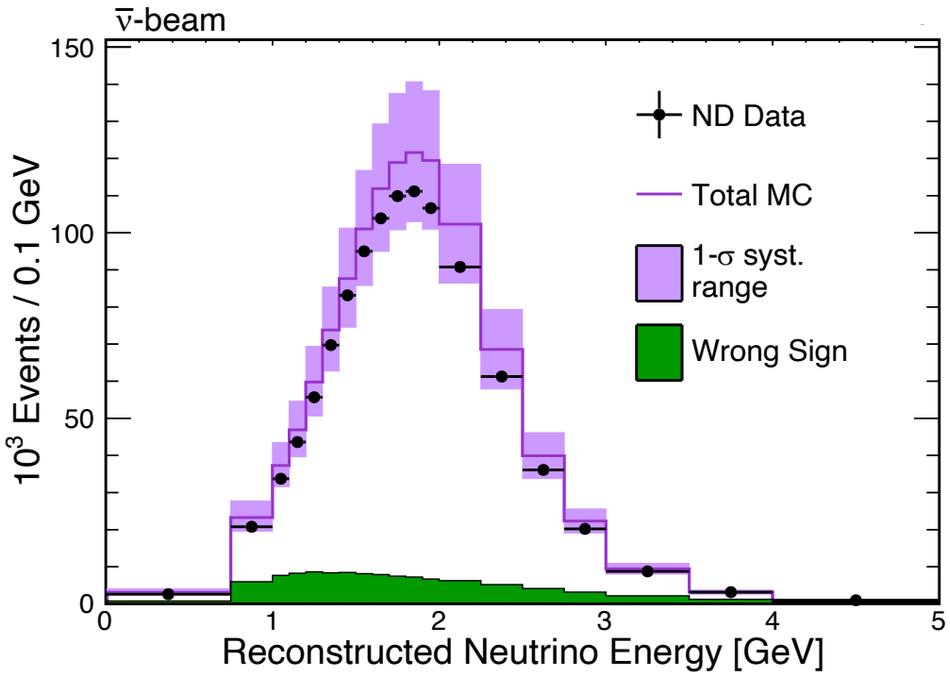


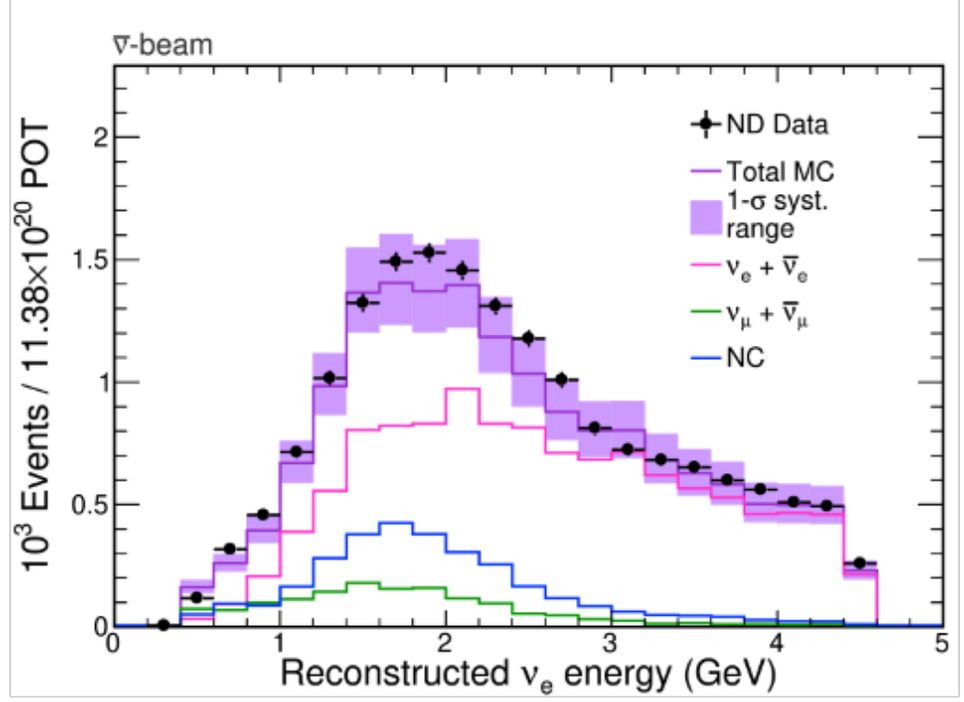
ν_e



$\bar{\nu}$

1.5M Events

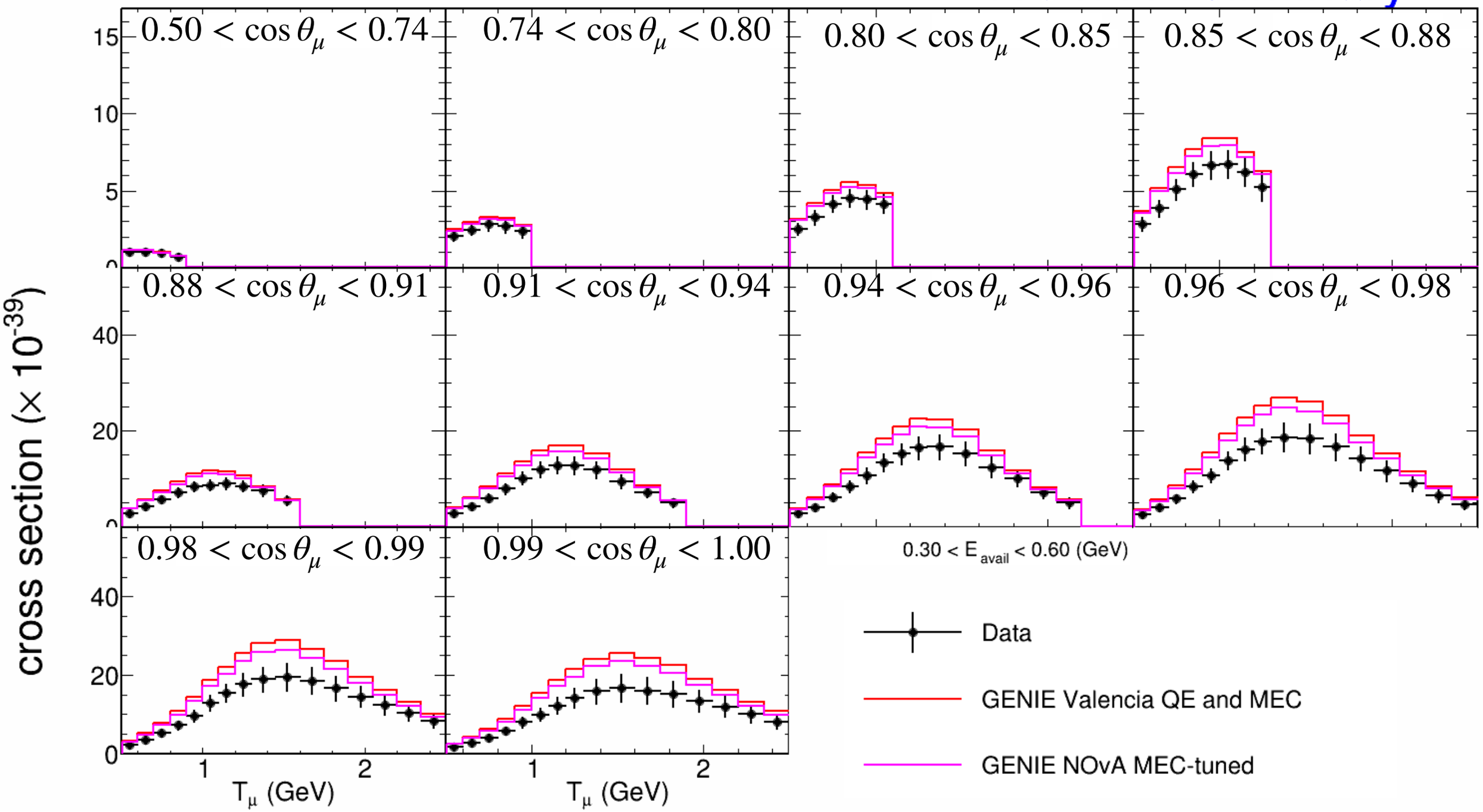




Near detector measurements

High statistics measurements at near detector provide reliable extrapolation to far detector and opportunities for cross-section measurements.

NOvA Preliminary



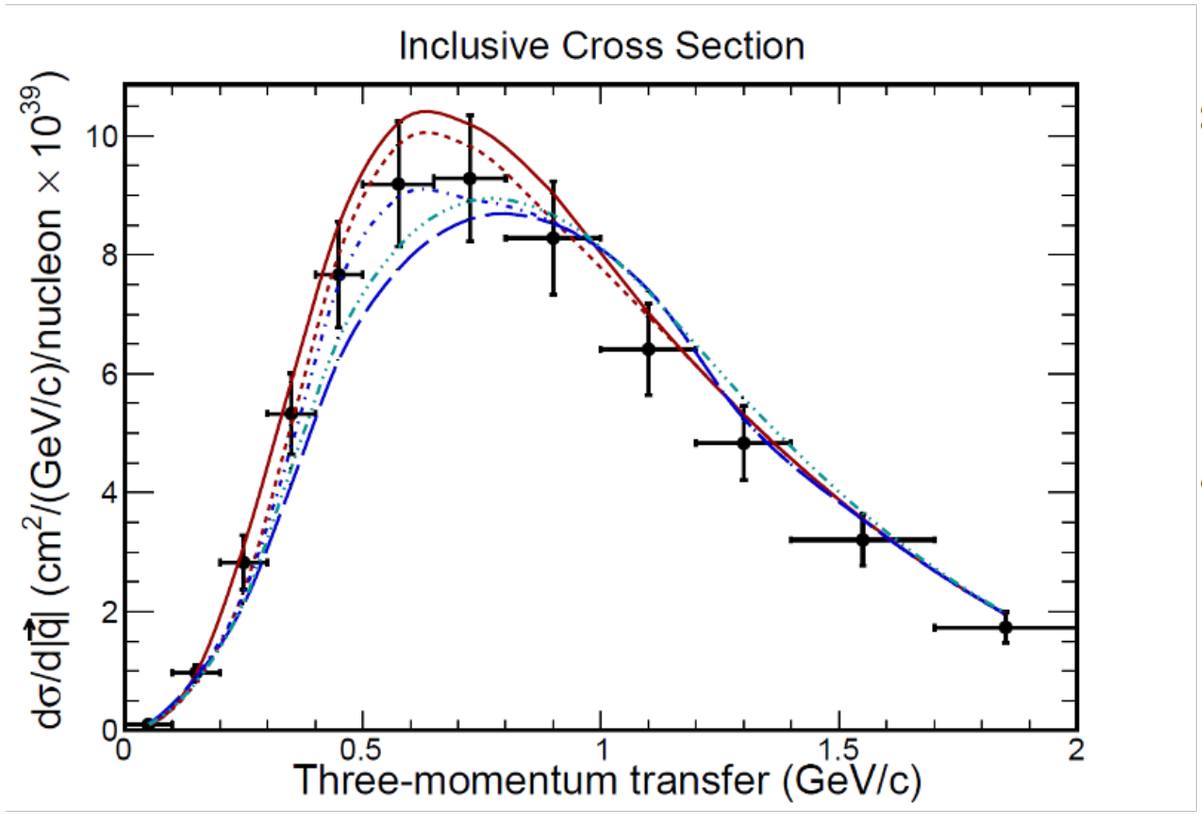
14% of data sample with E_{avail} between 300 and 600 MeV

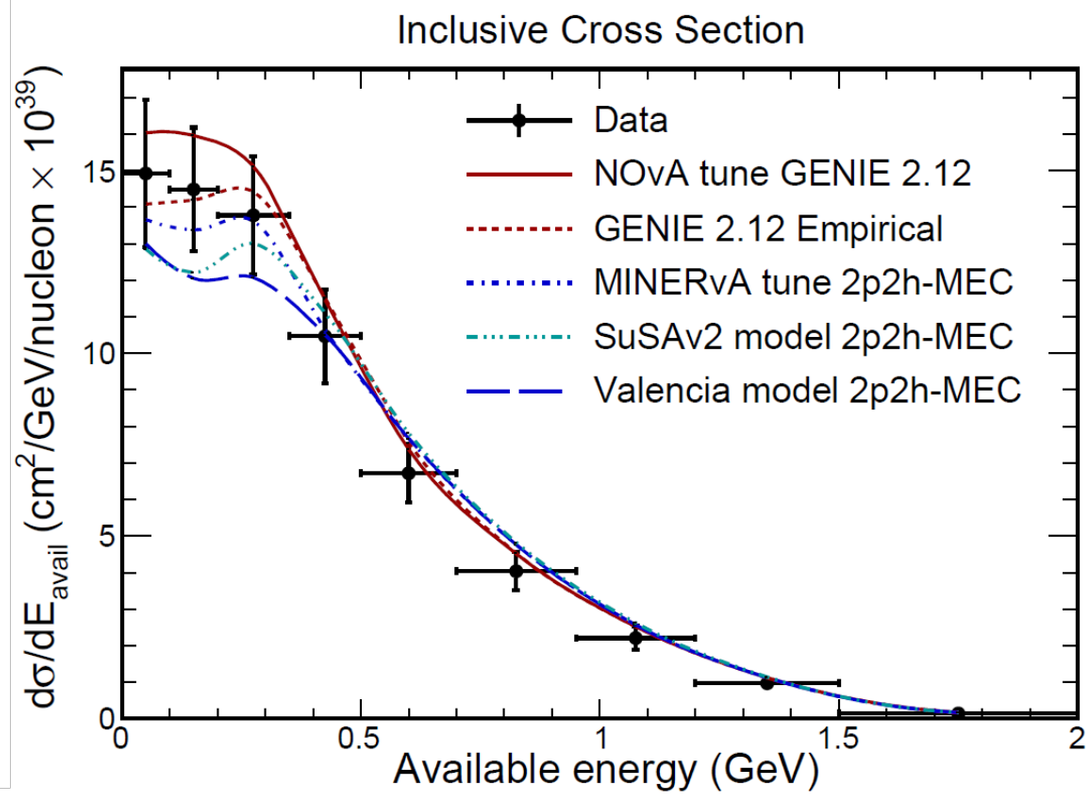
Interaction category

quasi-elastic	meson exchange	resonant production	deep-inelastic	Other
4%	1%	68%	22%	5%

From, "Measurement of the Triple-Differential Muon-Antineutrino Charged-Current Inclusive Cross Section in the NOvA", JETP 22 March 2024

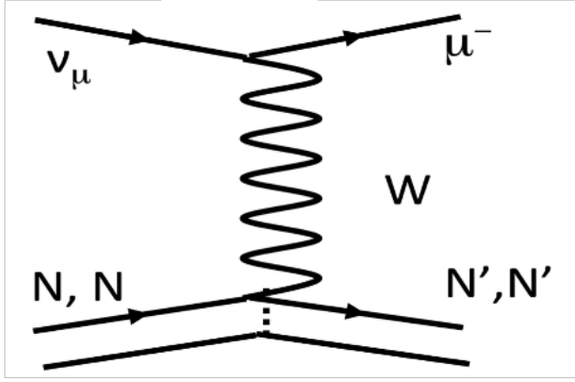
Measurement of total inclusive cross-section





Theoretical treatments of 2p2h-meson exchange currents systematically underestimate the total cross-section.

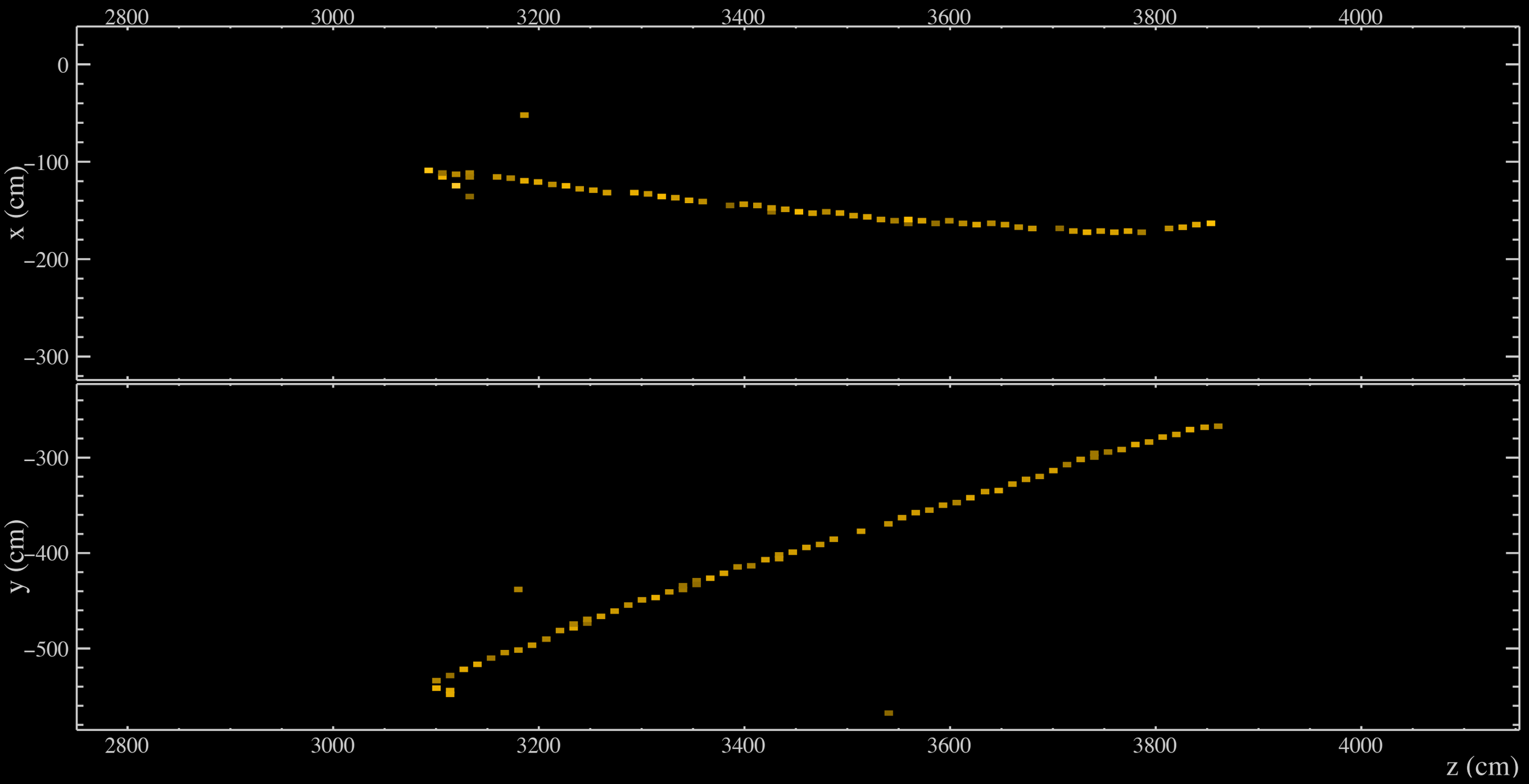
Empirical treatments (GENIE tuned by NOvA, eg.) are better matches to the data.



"2p2h" scattering

From, "Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA", JETP 2 February 2024

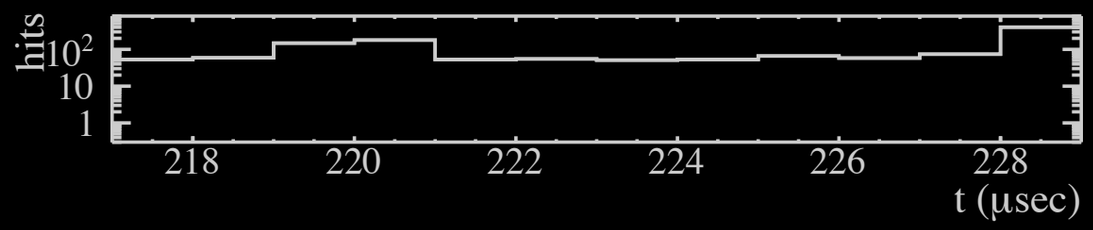
E = 2.1 GeV

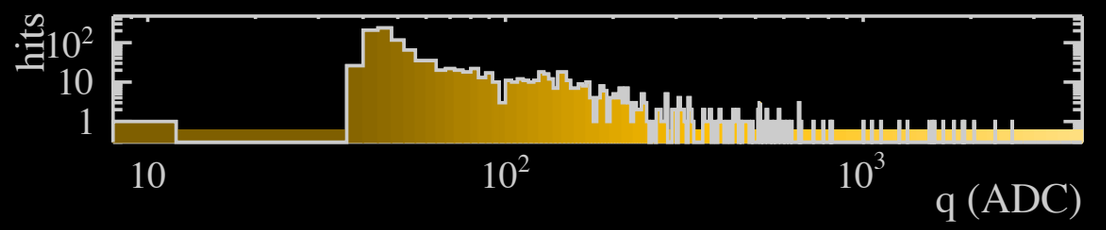


NOvA - FNAL E929

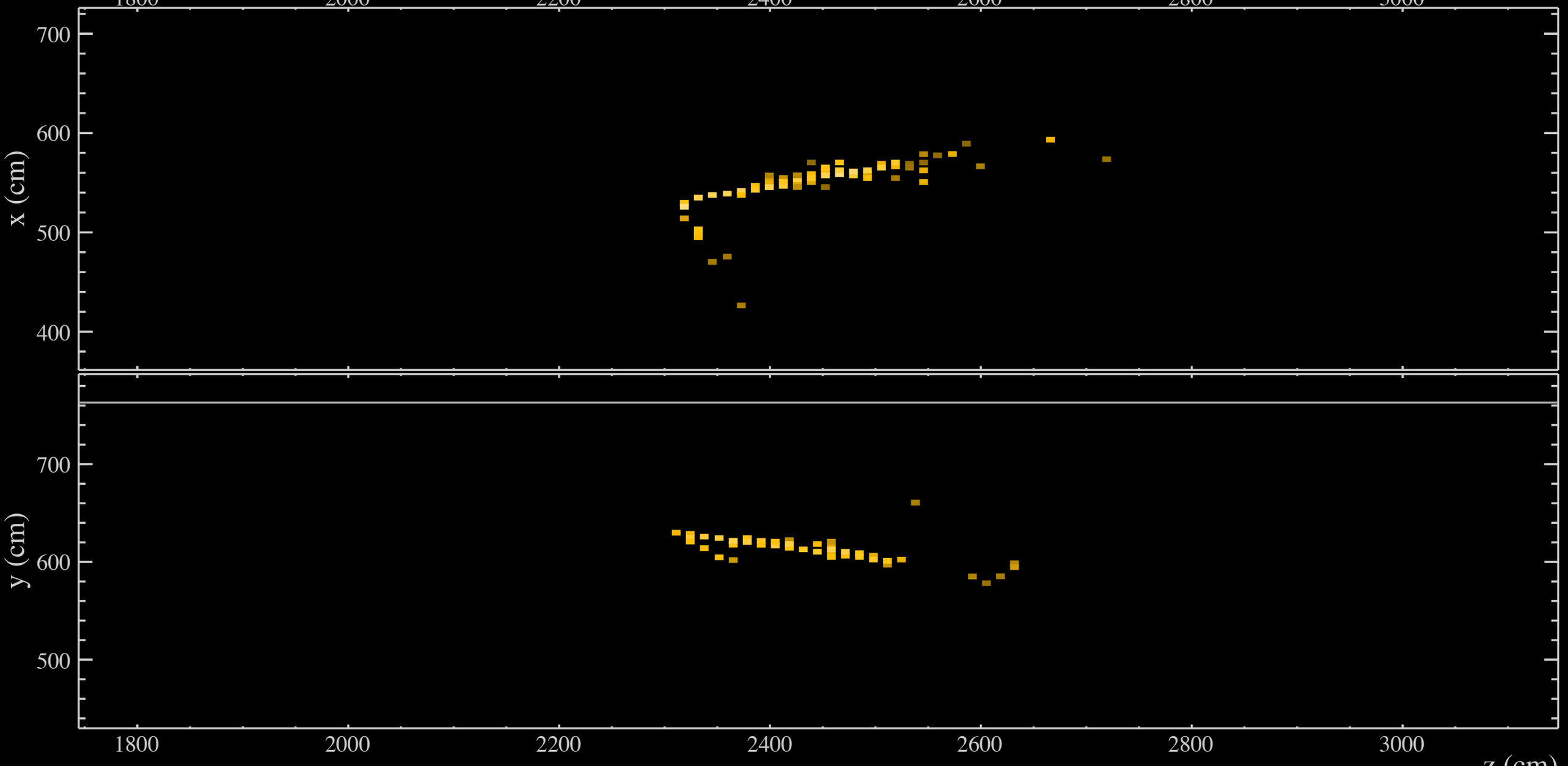
Run: 46405 / 15
Event: 7393 / NuMI

UTC Fri May 5, 2023
15:32:3.216403056





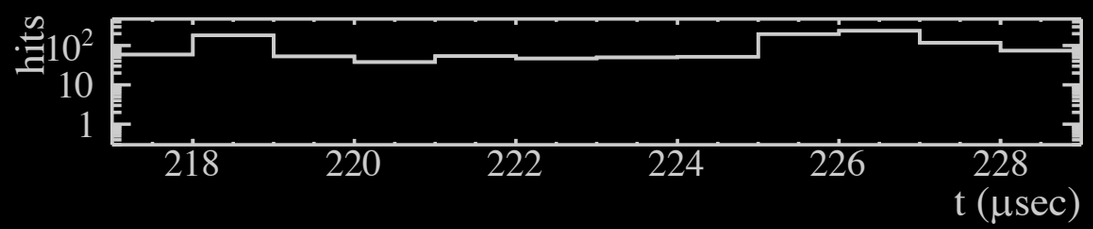
E = 2.0 GeV

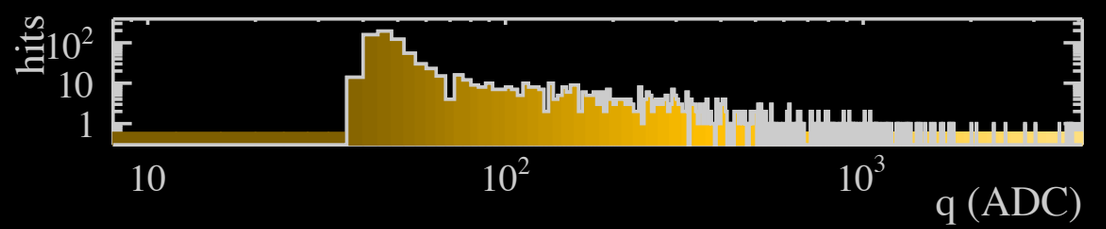


NOvA - FNAL E929

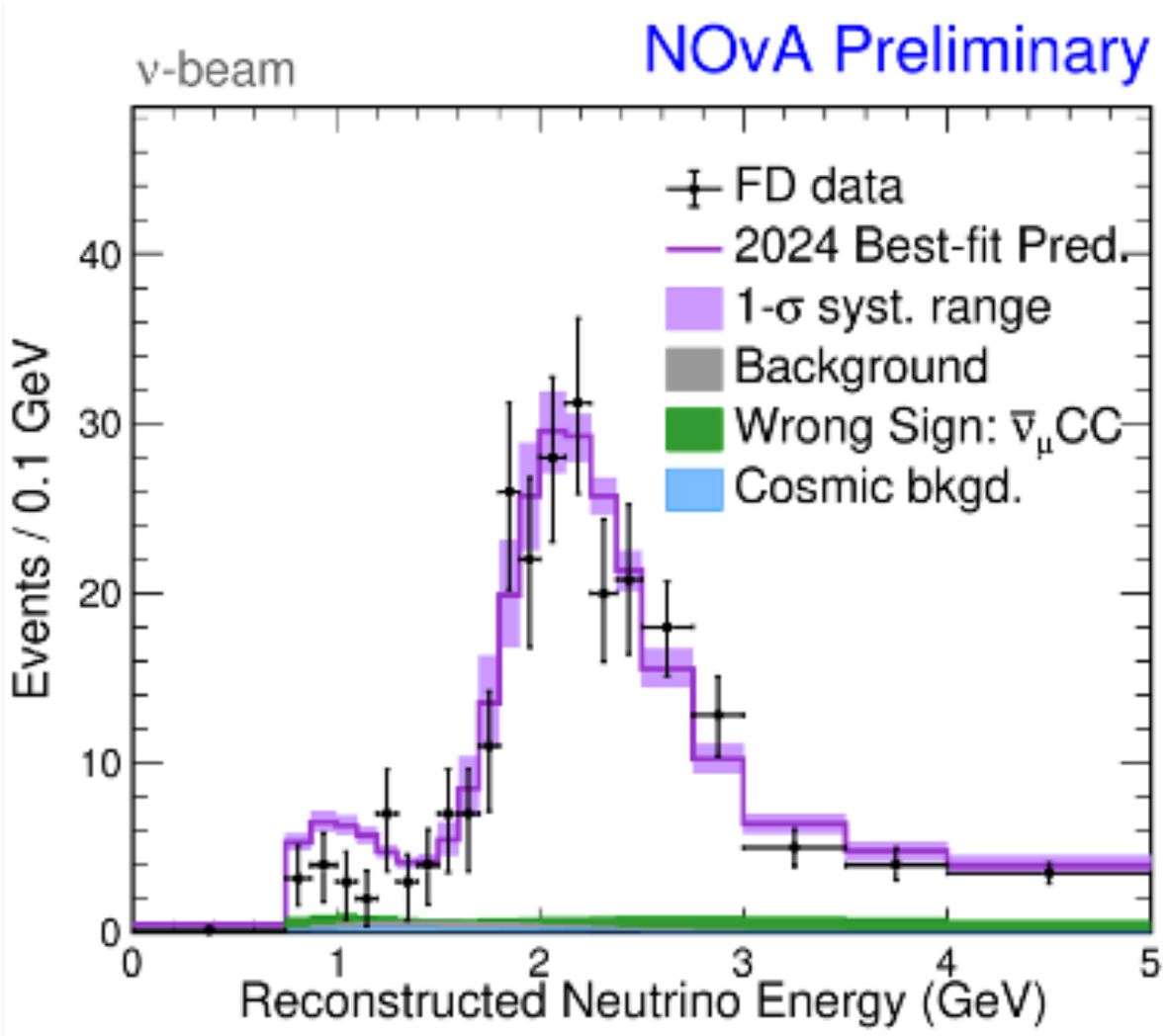
Run: 41554 / 26
Event: 1810 / NuMI

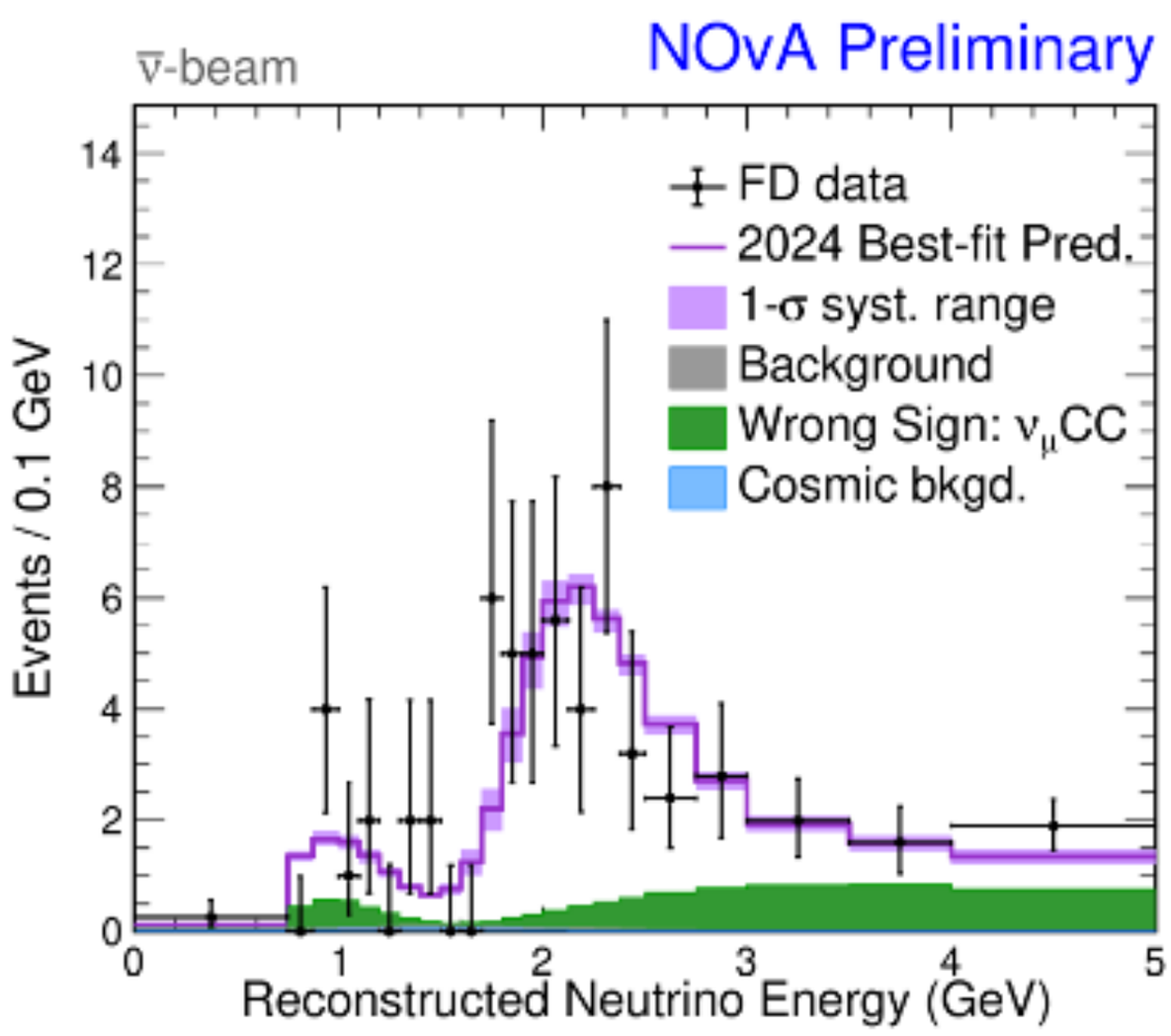
UTC Tue Nov 16, 2021
06:36:34.854617280





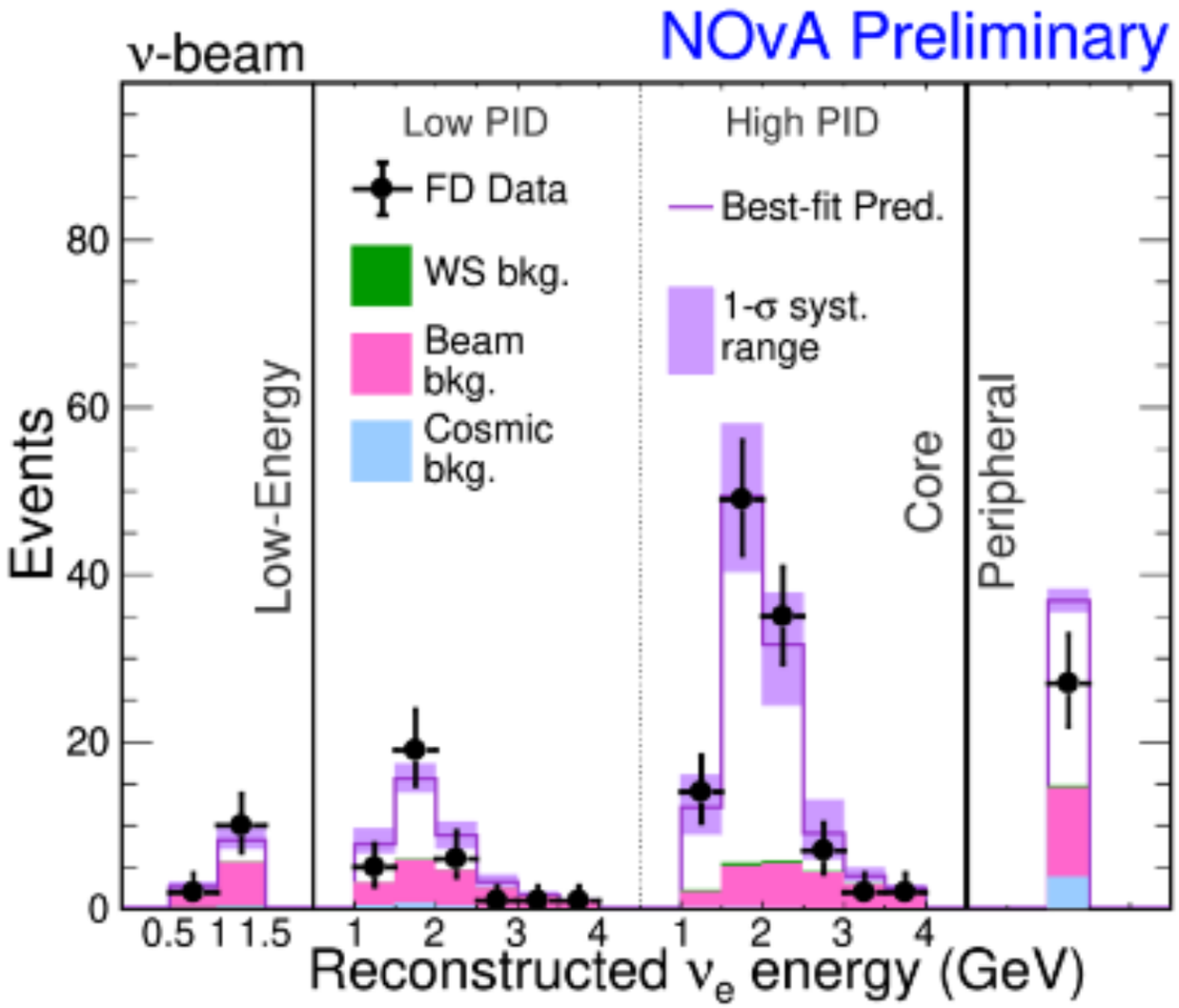
$\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$



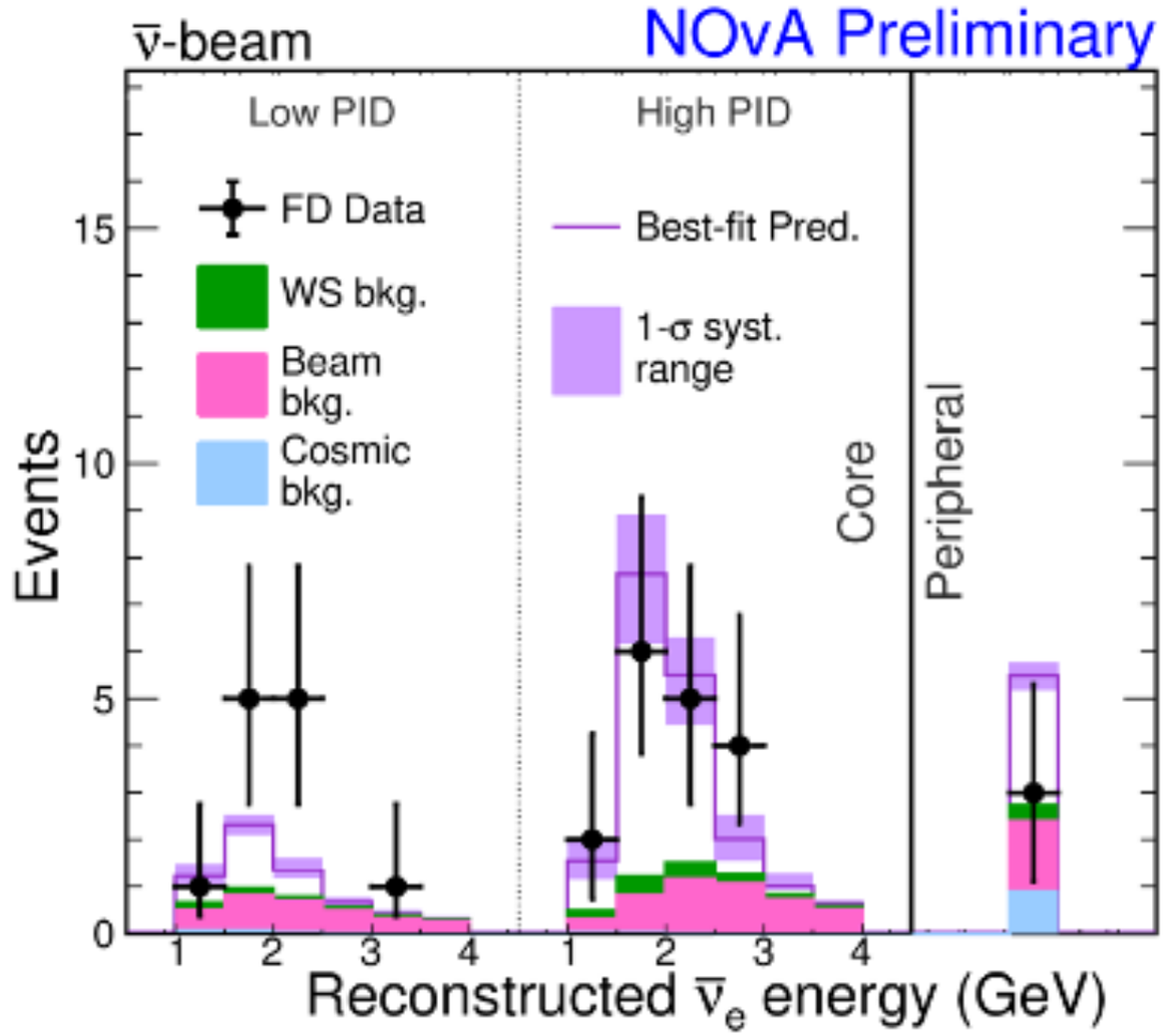


	$\nu_\mu \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
Observed	384	106
Predicted background	11	2

$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



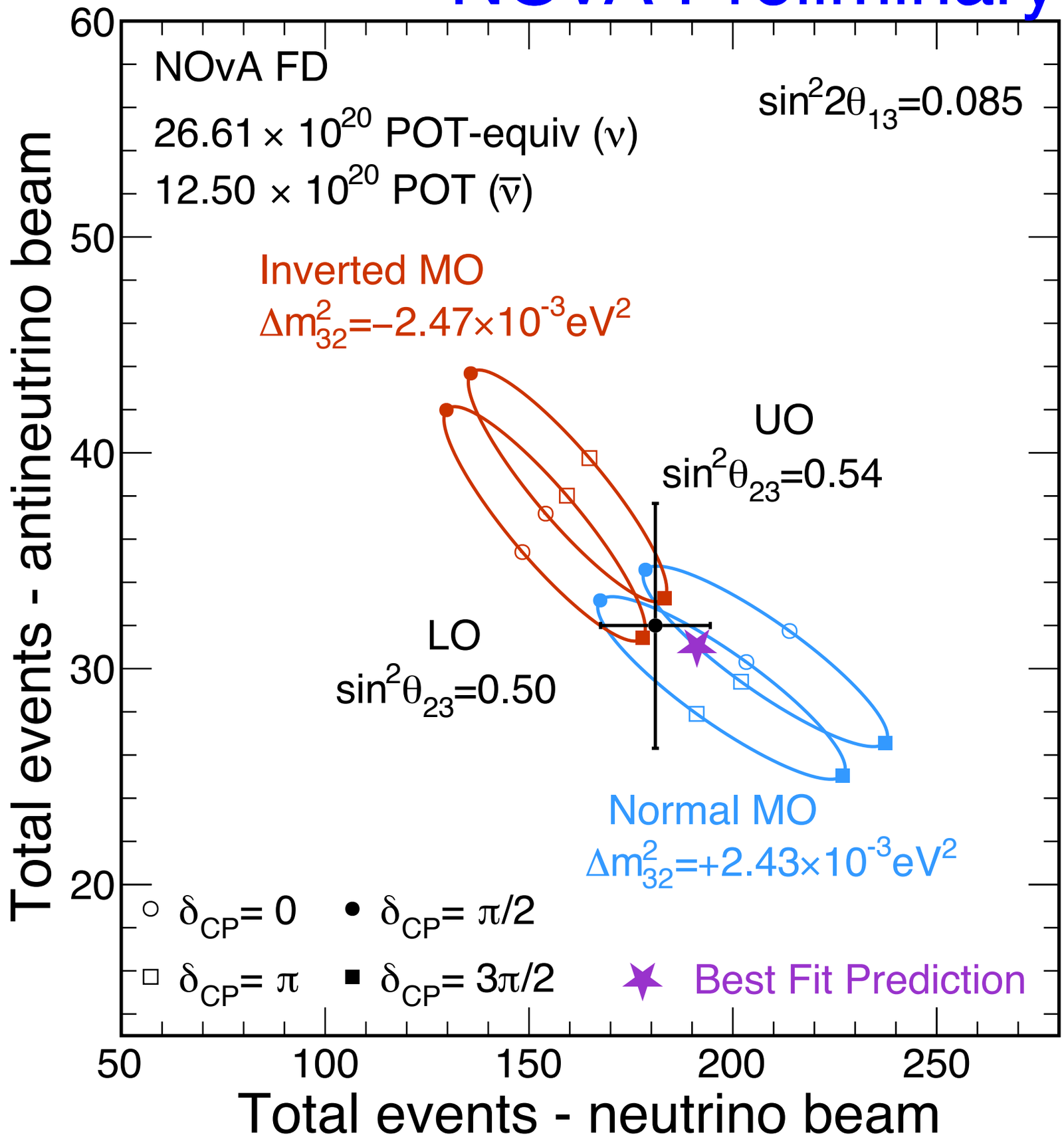
$\nu_\mu \rightarrow \nu_e$



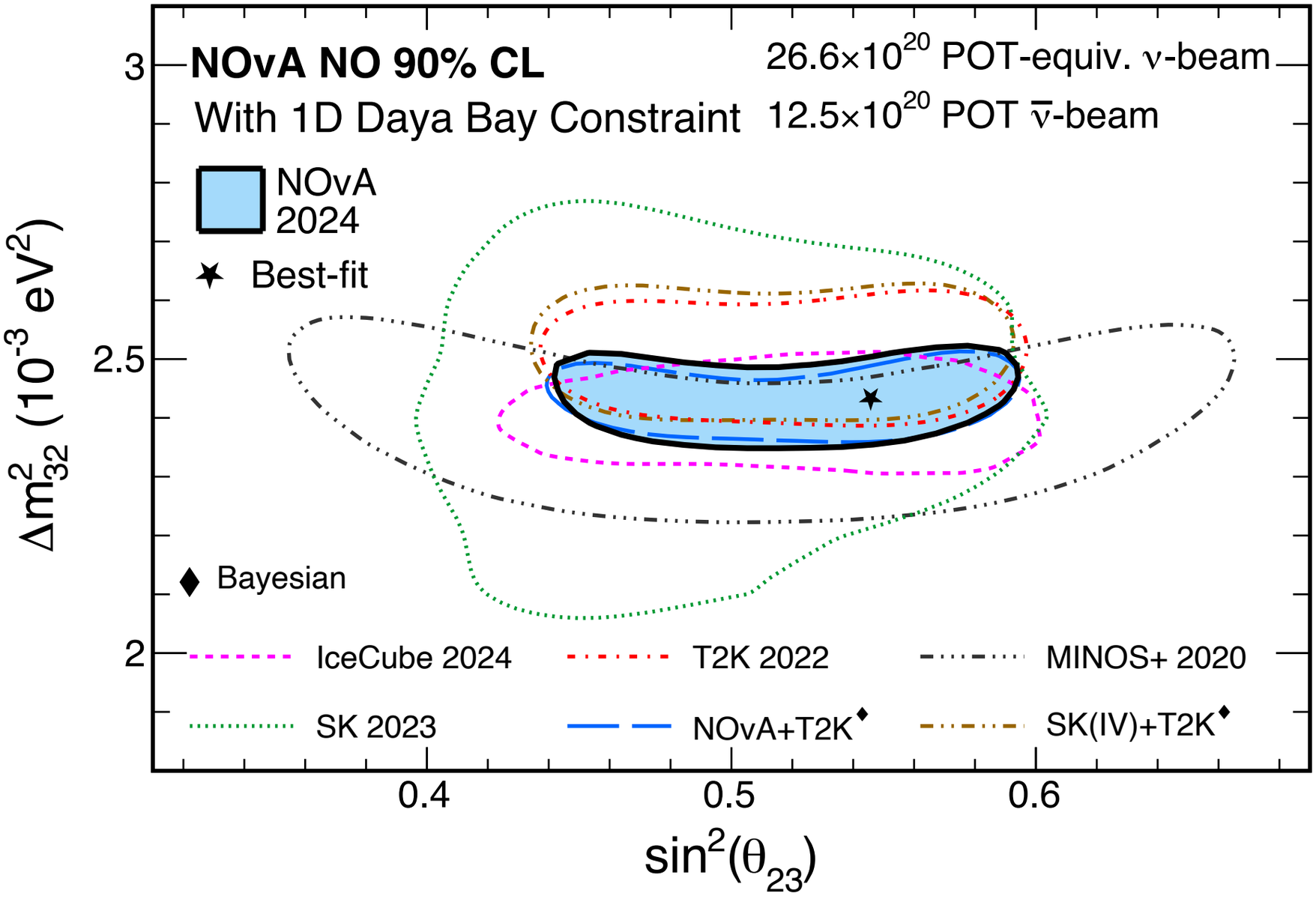
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

	low energy		
Observed	169	12	32
Predicted background	55	7	12

NOvA Preliminary



NOvA Preliminary

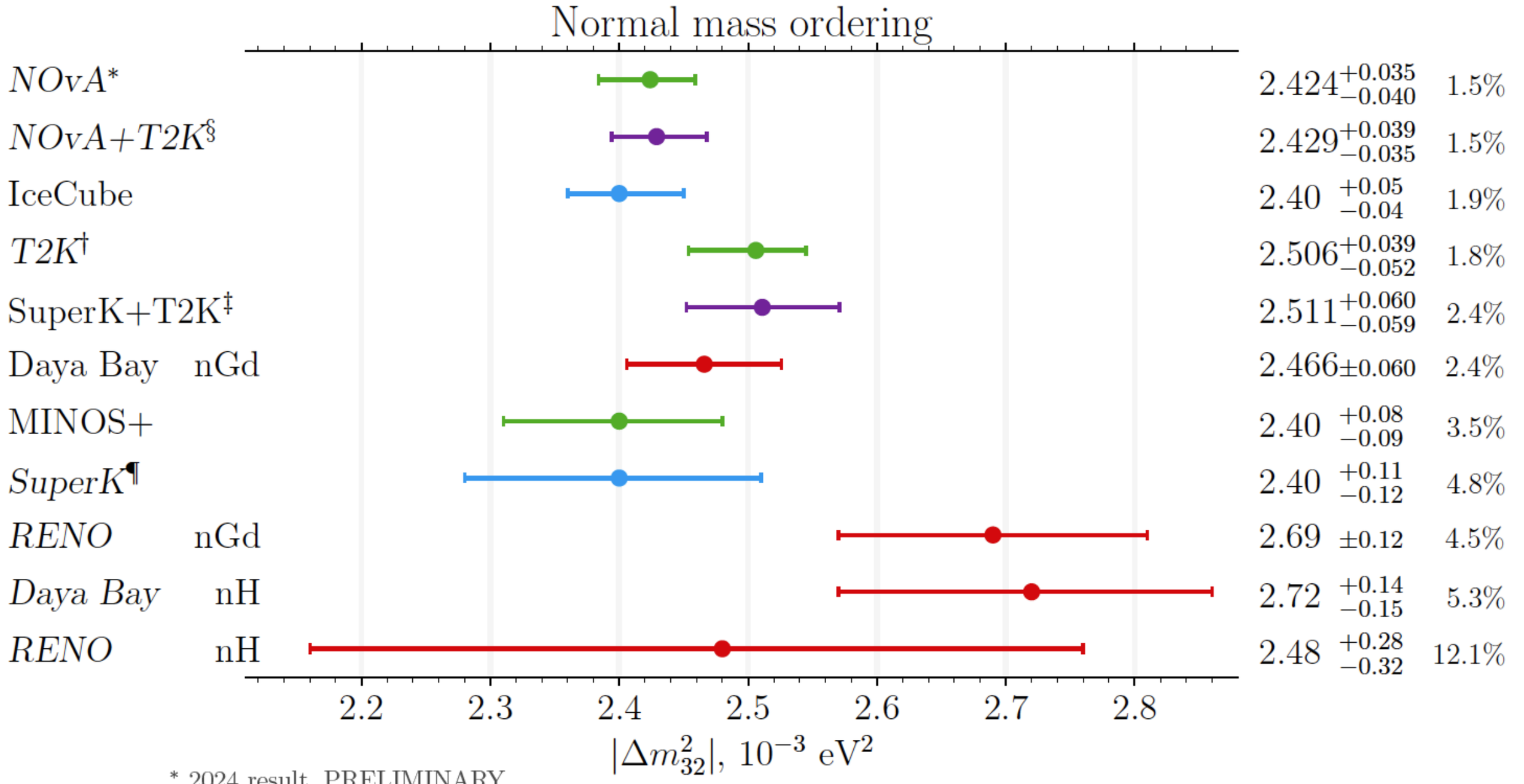


IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

Mass Ordering

	Normal	Inverted
$\Delta m^2_{32}/10^{-3}$ eV^2	$+2.433^{+0.035}_{-0.036}$	$-2.473^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	$0.546^{+0.032}_{-0.075}$	$0.539^{+0.028}_{-0075}$
$\delta_{\rm CP}$	0.9π	1.5π

$\leftarrow$ Maximal mixing ($\sin^2\theta_{23} = 0.5$) allowed within 1 σ.

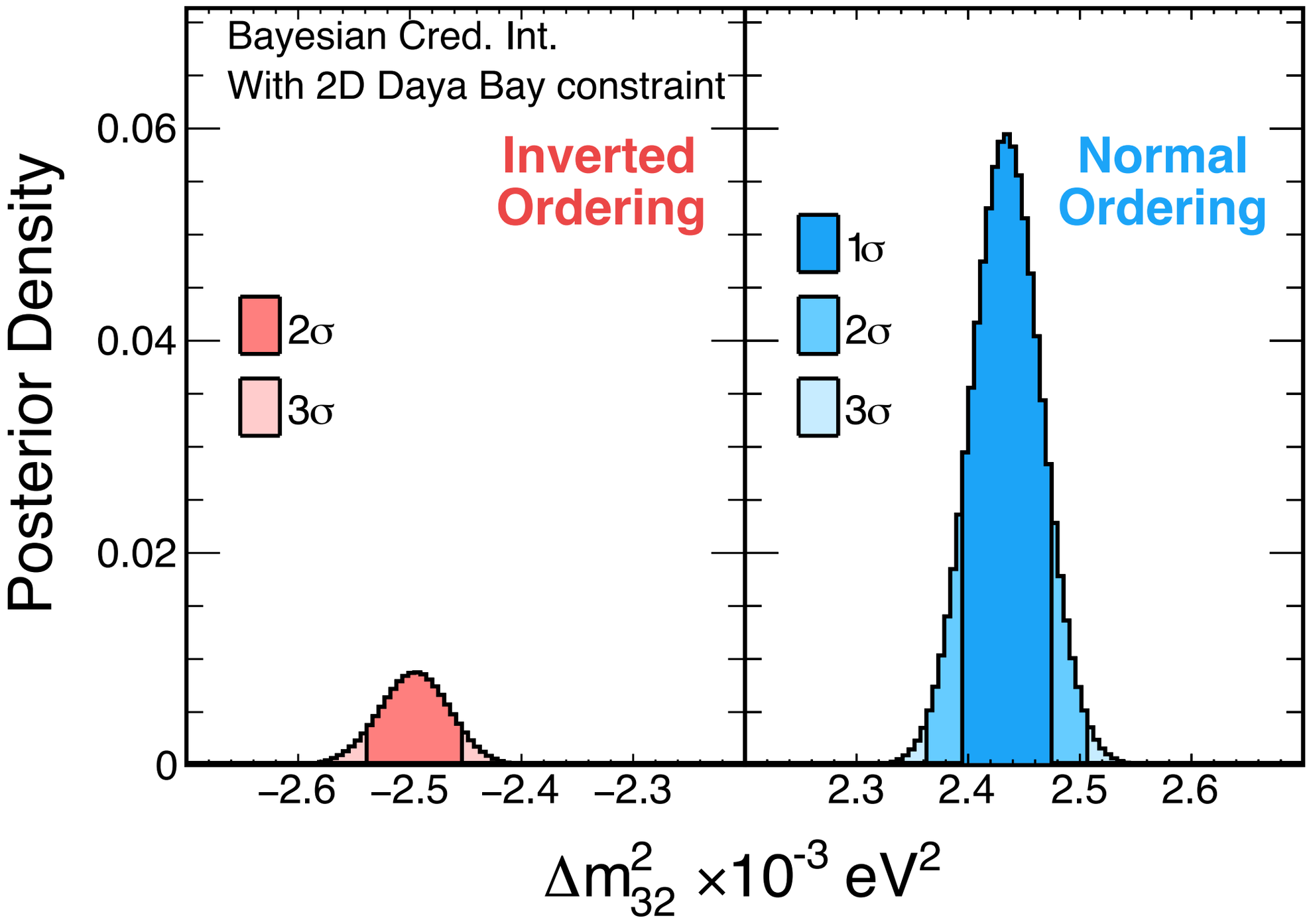


* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result
¶ SKI-V result, arXiv:2311.05105
‡ based on SKI-IV and T2K 2020, arXiv:2405.12488

Preliminary
Published

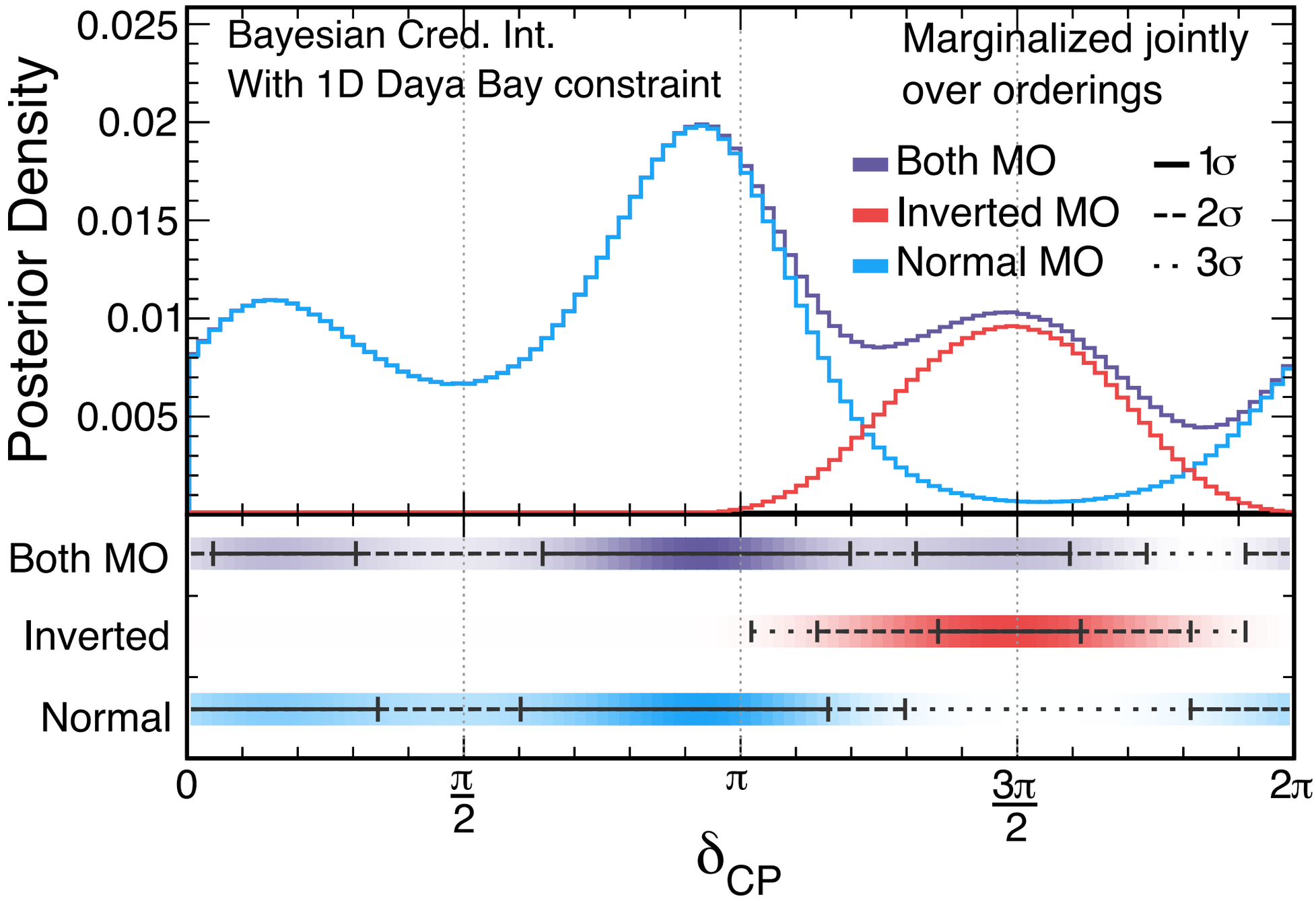
NOvA's is the best single-experiment measurement.

NOvA Preliminary



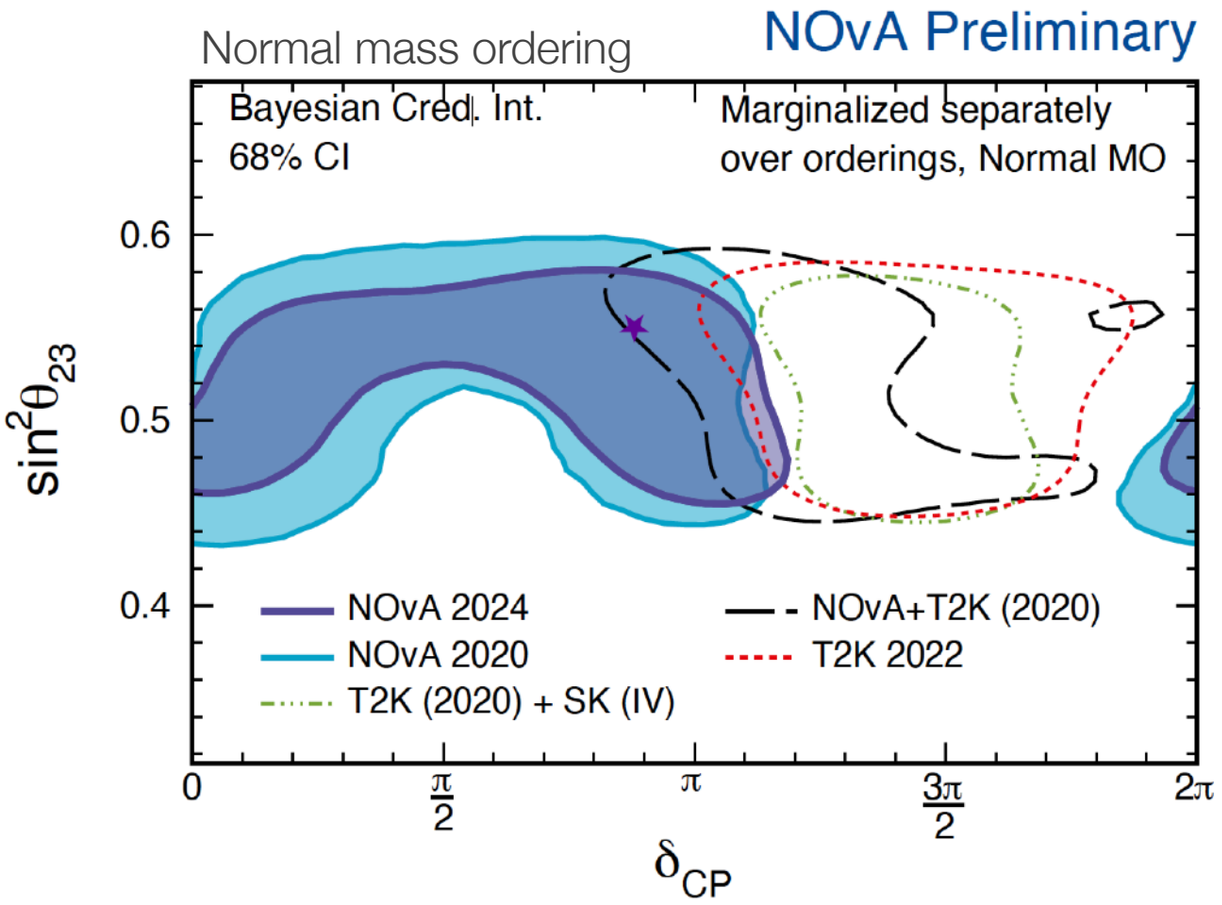
NOvA data, combined with reactor measurements, prefer normal ordering with a Bayes factor of 6.8

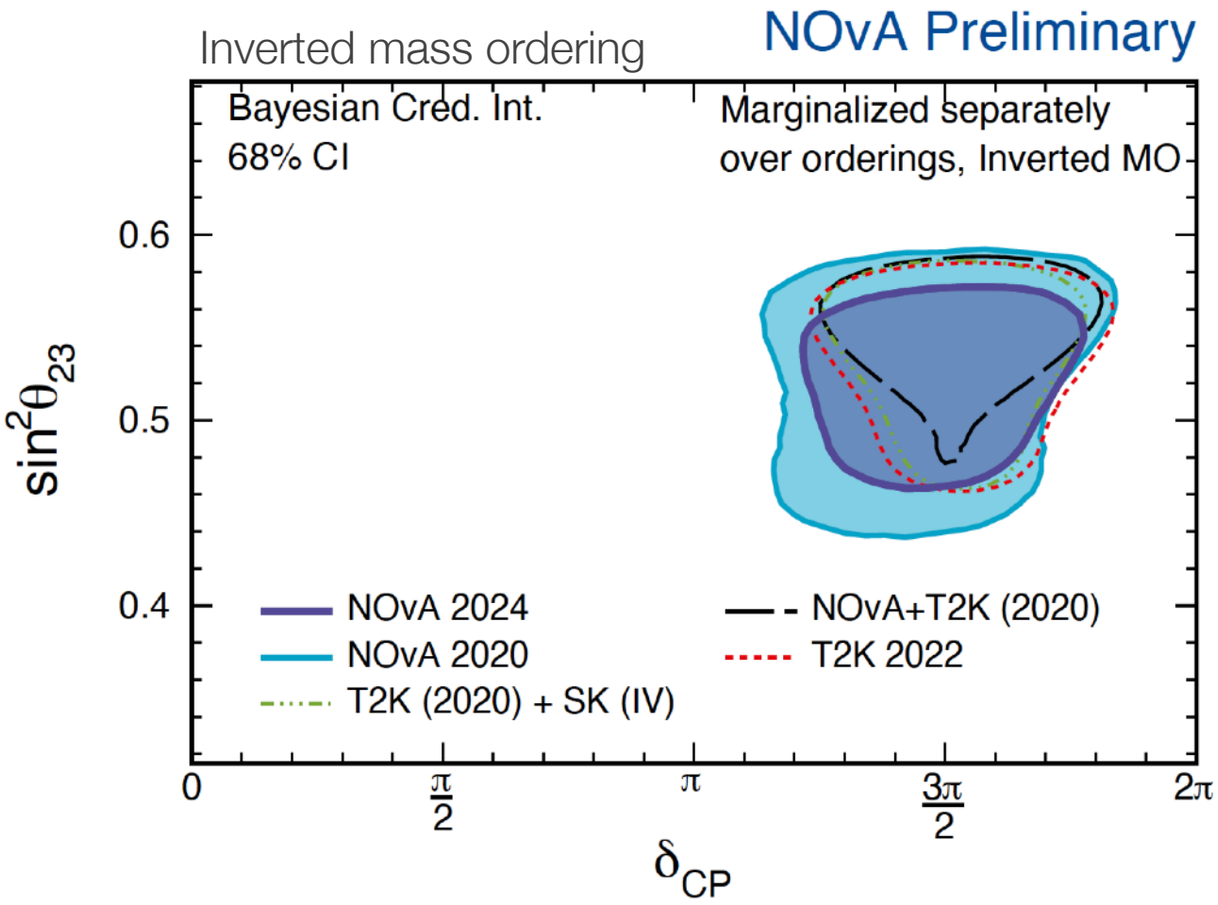
NOvA Preliminary



- NOvA data prefer regions where the effects of matter and CP phase cancel.
- Regions where these add (NO, 3π/2) & (IO, π/2) are largely ruled out.
- If the ordering is inverted, CP conserving values of δ (0, π, 2π) are ruled out at 3σ.

NOvA - T2K Joint Fit





- Individual experiments (T2K in red and NOvA in blue) favor normal ordering, but fit together (**black, dashed**) there is no preference normal ordering vs. inverted ordering
- $\delta_{CP} = \pi/2$ excluded at 3σ
- δ_{CP} unconstrained in NO, $\delta_{CP}=0$, π excluded at 3σ in IO
- This joint fit uses 2020 data sets. Future joint-fits will be a topic of a workshop later this year.

Summary and conclusions

- **This year NOvA released new data, doubling its neutrino data set and NuMI set beam power record of 1 MW**
  - Best single experiment measurement of Δm^2_{32} (1.5%)
  - Slight preference for θ_{23} in upper octant, maximal (μ/τ-symmetric) θ_{23} is a very good fit
  - Data prefer oscillation parameters to be in region where effects of matter an CP phase cancel.
  - Interpretation of CP violation strongly coupled to mass ordering resolution
- **NuMI will continue operations through end of CY2026**
  - Our goal is to double antineutrino data set.
  - Will either show that the oscillation parameters are in the degenerate region or resolve the mass ordering at ~2σ.