New Results from the NOvA Experiment

Jeff Hartnell

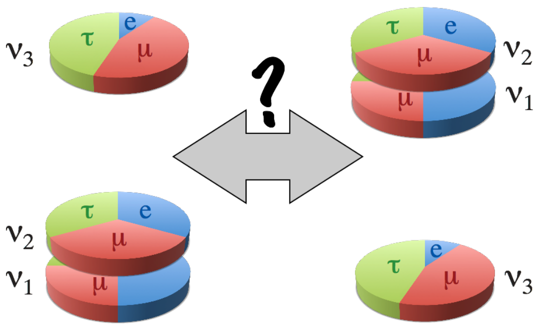
On behalf of the NOvA collaboration

Neutrino 2022, Virtual Seoul

1st June 2022

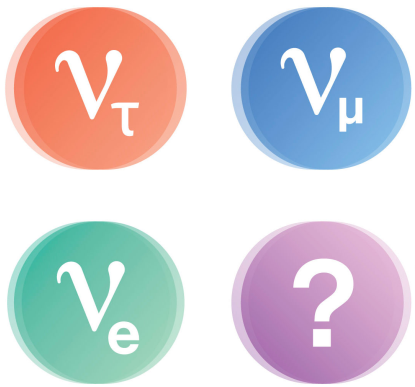
University of Sussex

Open Questions



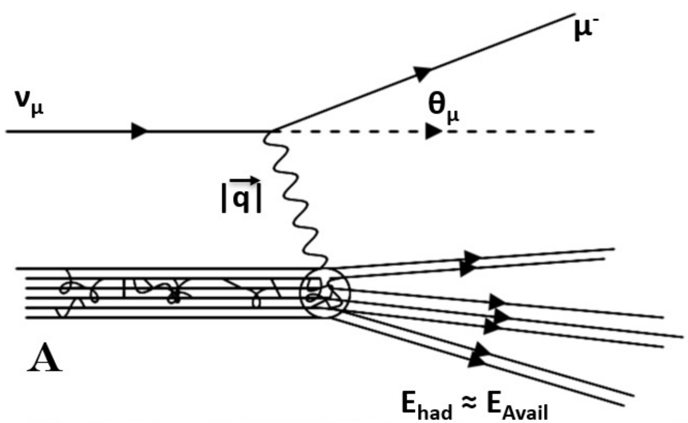
What is the neutrino mass ordering?

Do neutrinos violate CP symmetry?

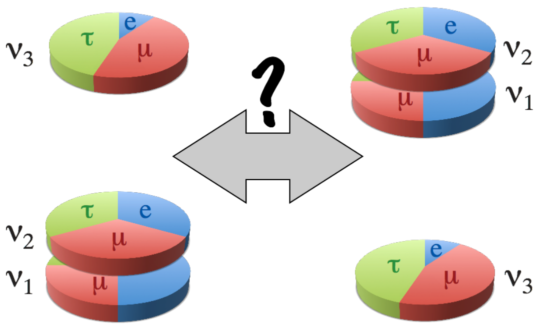


Are 3-flavour oscillations the full picture?

How are nuclear effects changing the interaction probability of neutrinos?

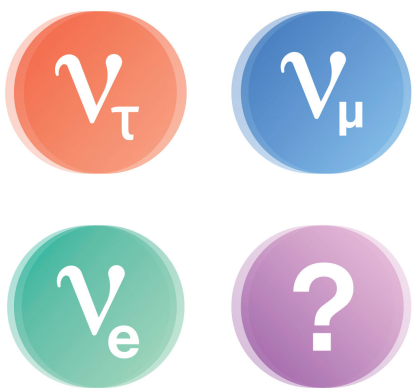


In this talk…



3-flavour oscillations

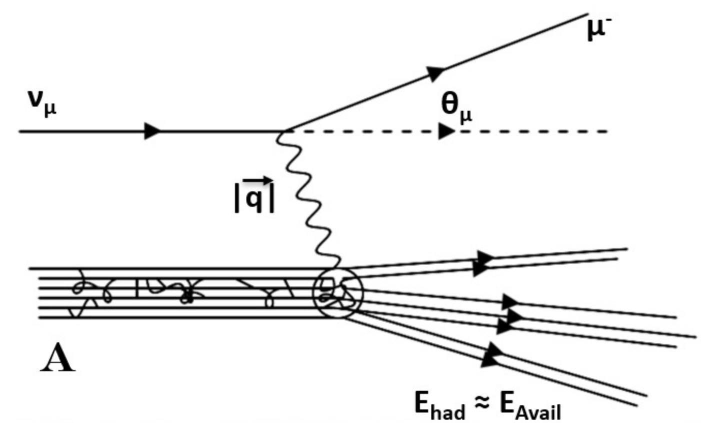
– New alternative statistical treatment



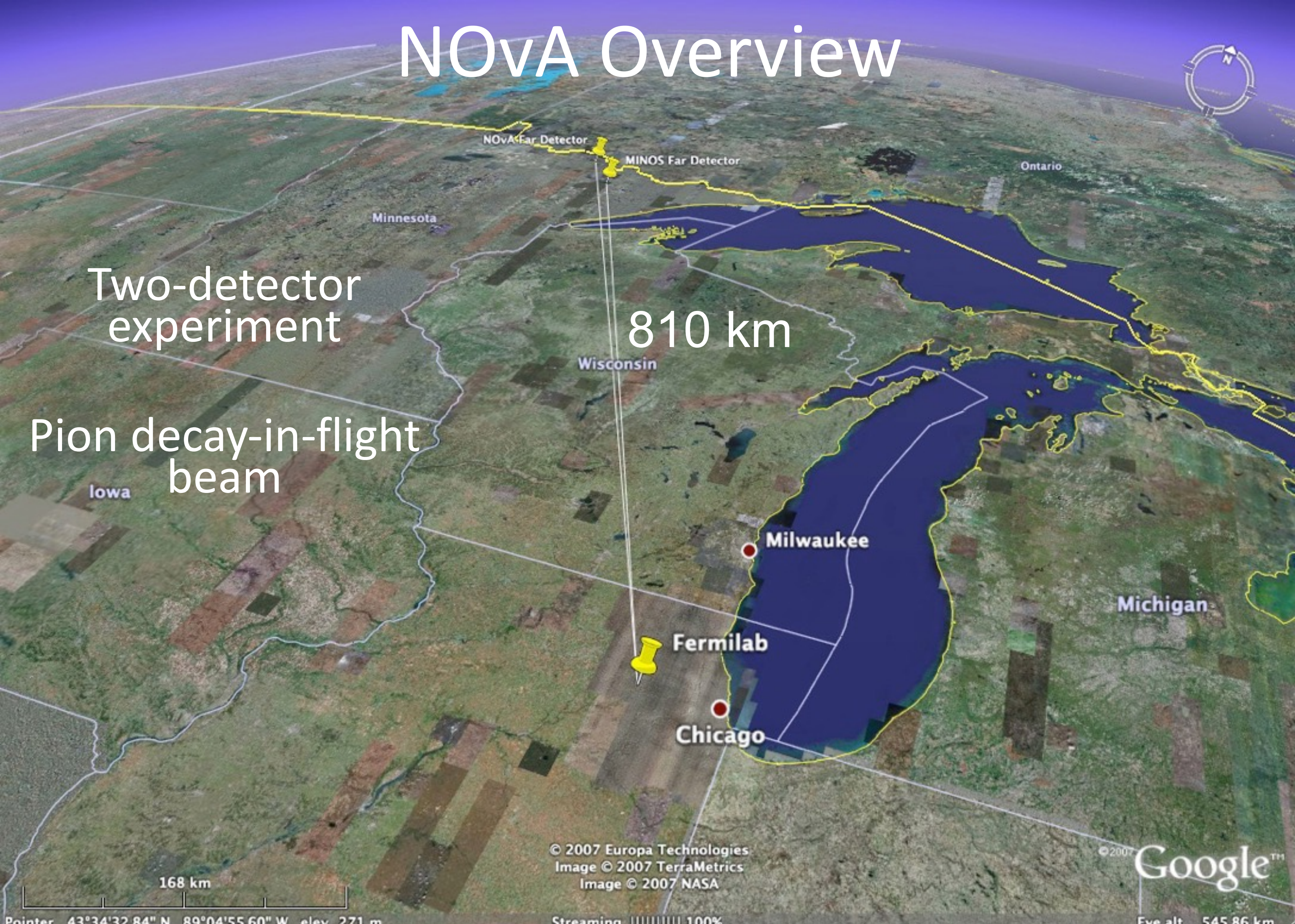
New two-detector sterile neutrino search

Two new ν_μ CC cross section measurements

– Focus on nuclear effects, e.g. 2p2h/MEC interactions



NOvA Overview

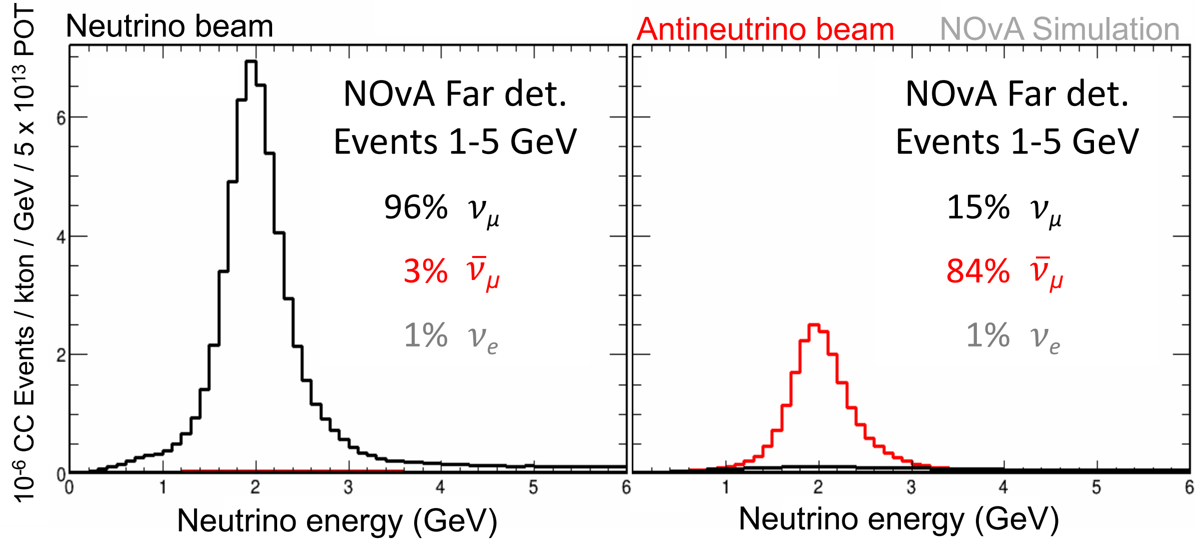


Two-detector experiment

Pion decay-in-flight beam

NuMI Off-Axis Narrow Band Beam

- Peak flux at ~2 GeV
- Neutrino or antineutrino mode
- High ν_μ ($\bar{\nu}_\mu$) purity
- Total protons-on-target: 37 x 10^{20}



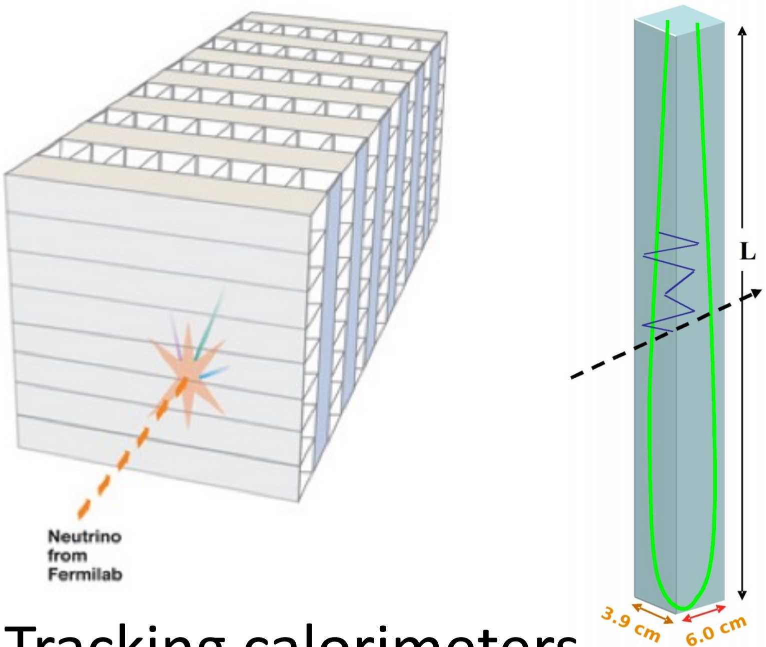
New beamline components installed →

New power record: 893 kW


MW-capable target


MW-capable horn

NOvA Detectors

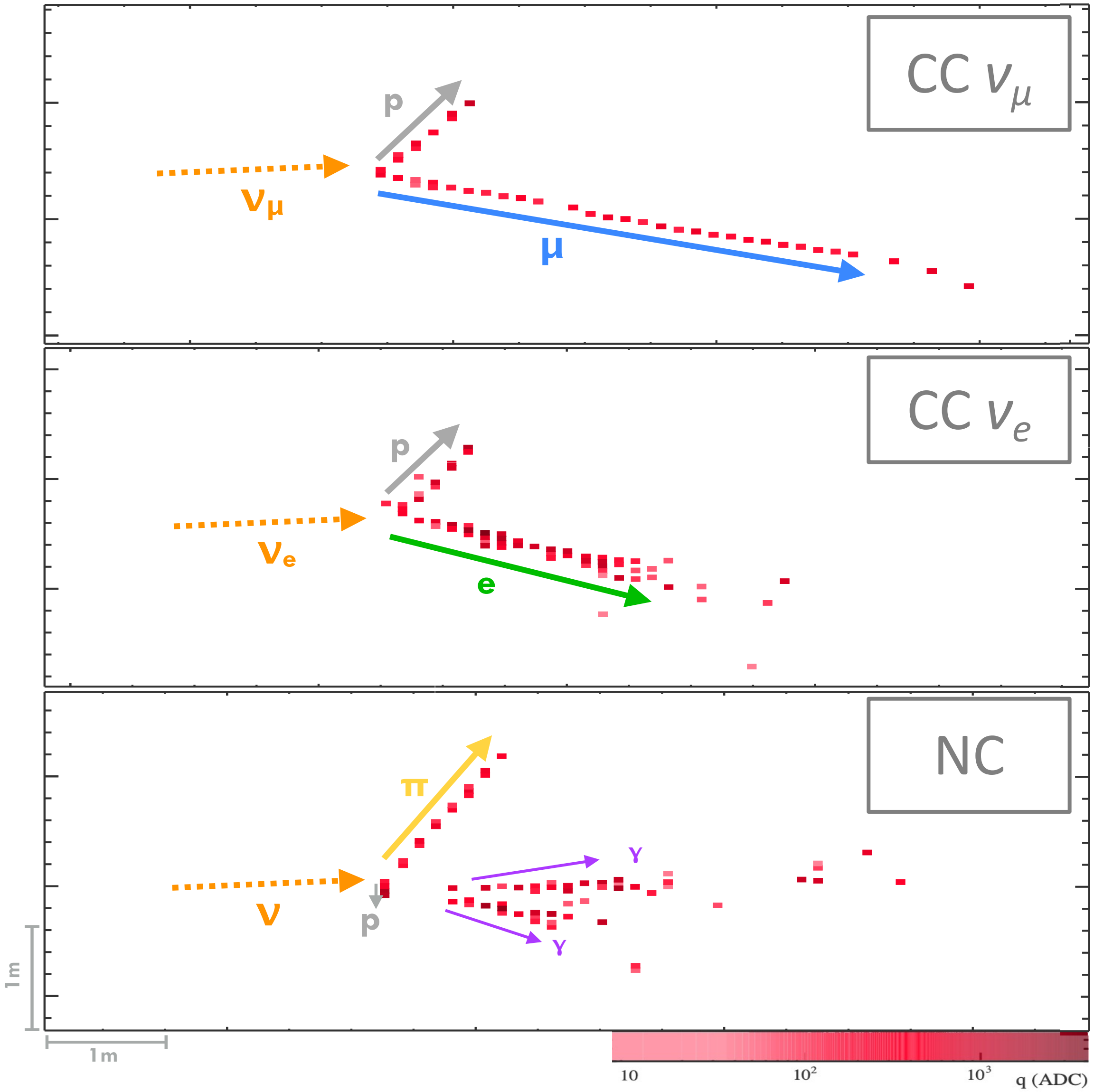


- Tracking calorimeters
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- Near Detector
  - 300 tons, 1 km from target
  - Huge statistics: >1M ν_μ CC selected events

14,000 Ton Far Detector

Detailed Event Images

Hermetic calorimeter that can image hadronic recoil system
~5 MeV/cell sensitivity, ~cm-scale tracking resolution



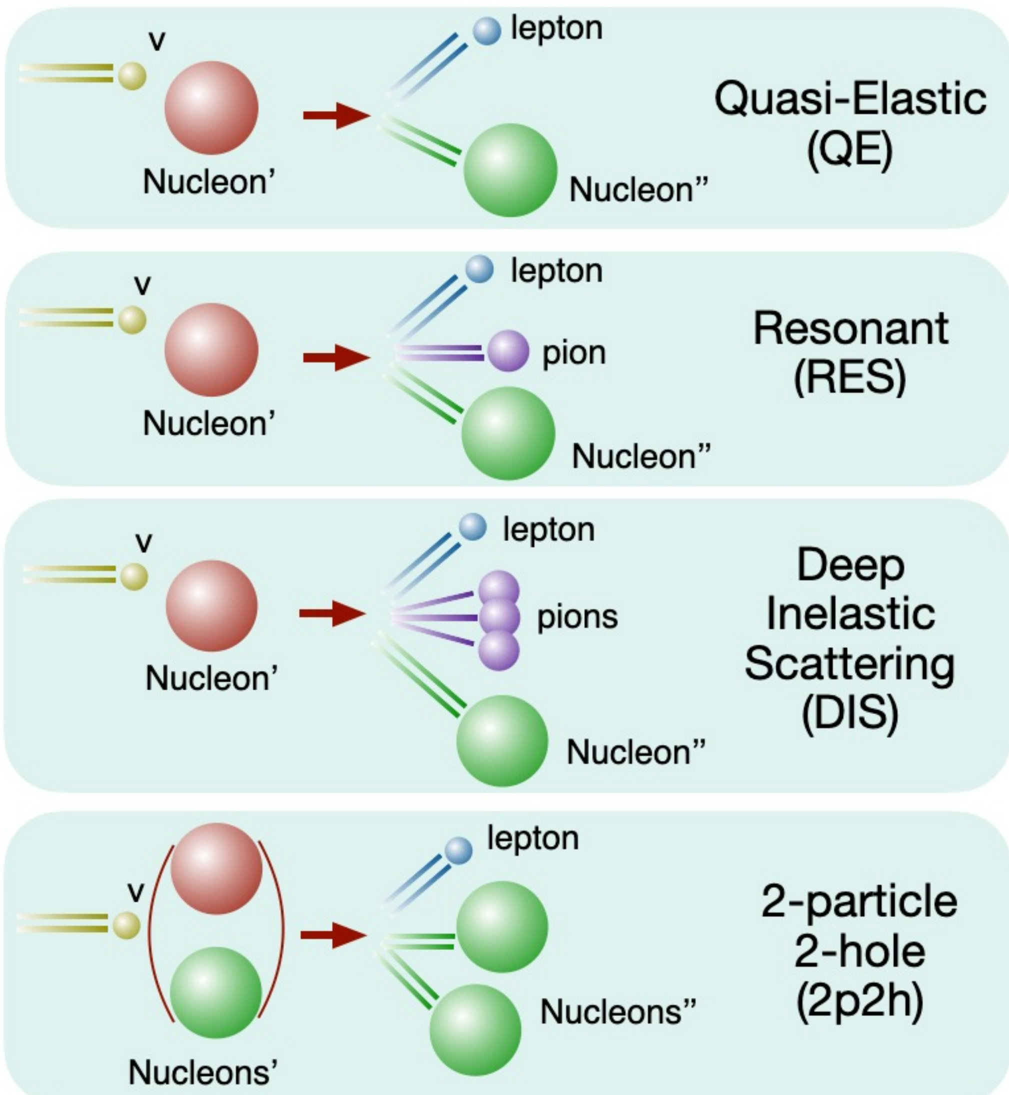
- Long, straight muon tracks a key feature for ν_μ CC
- Cross section analyses use machine learning to identify single particles
- Oscillation analyses use a convolutional neural net. to identify whole events
- Data-driven validation using control samples at Near and Far detectors
- Test beam run ongoing

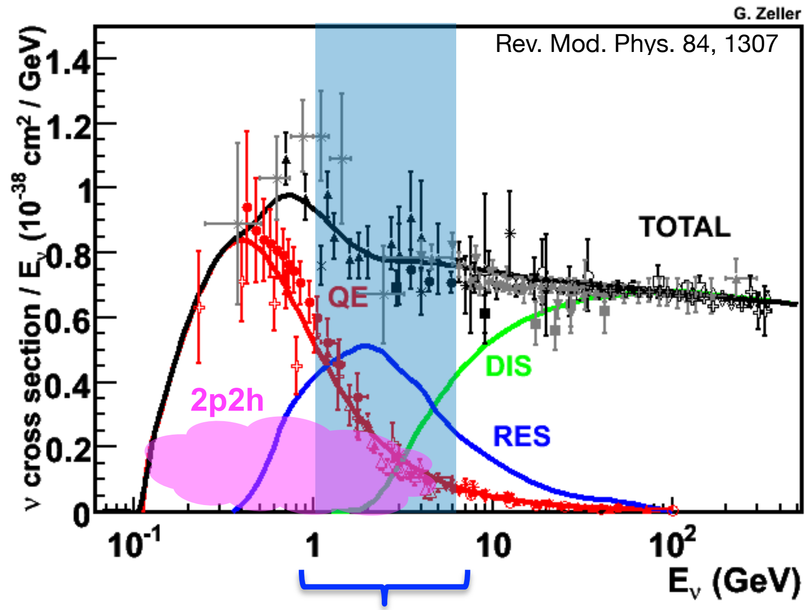
Poster 731
Dalton Myers

Poster 646
Anne Norrick,
Mike Wallbank

Poster 544
Róbert Králik

Neutrino Interaction Types



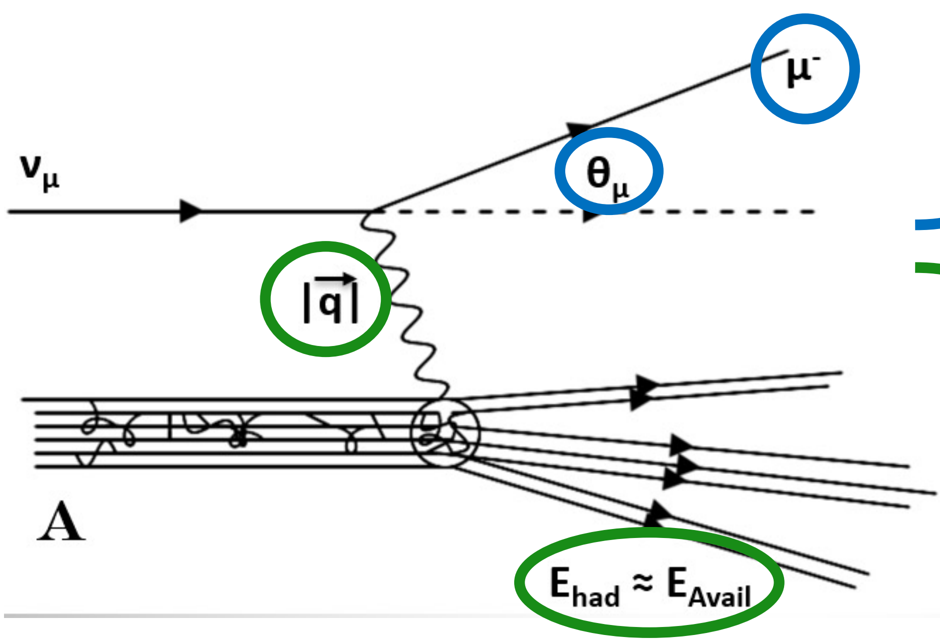


- NOvA can study all interaction types with huge statistics
- Nuclear effects are significant
  - Contribution of axial part of weak interaction can only be studied w/ neutrinos
- Better understanding important for reducing systematics on oscillation measurements

NOvA Data and Results

Two new ν_μ CC Cross Section Results

Both double differential

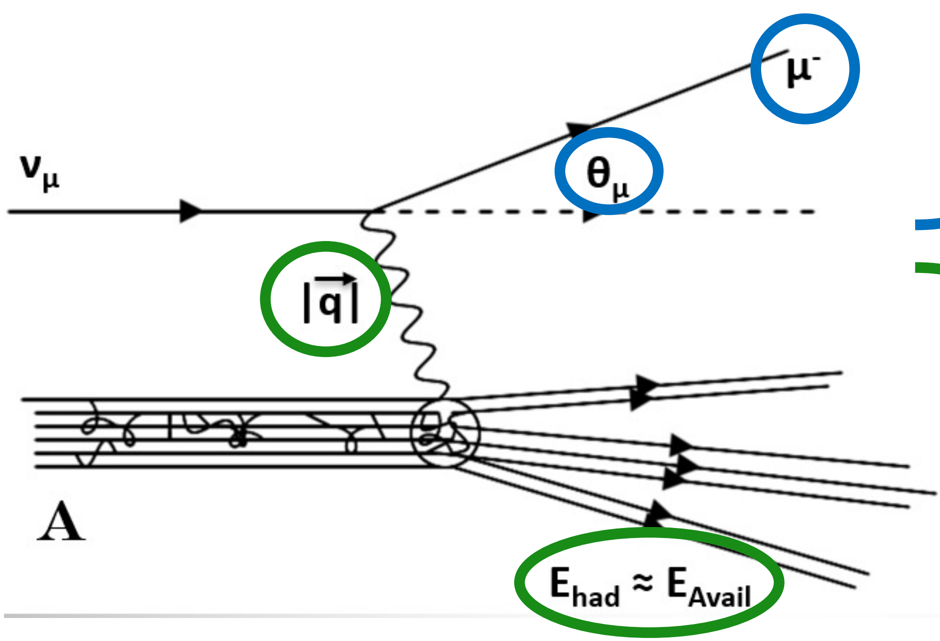


Muon System ⇨ Energy **vs** angle

Hadronic System ⇨ 3-momentum transfer $|\vec{q}|$ **vs** energy

Two new ν_μ CC Cross Section Results

Both focus on sensitivity to 2p2h / MEC events



Muon System

Exclusive
Select only events with low hadronic energy

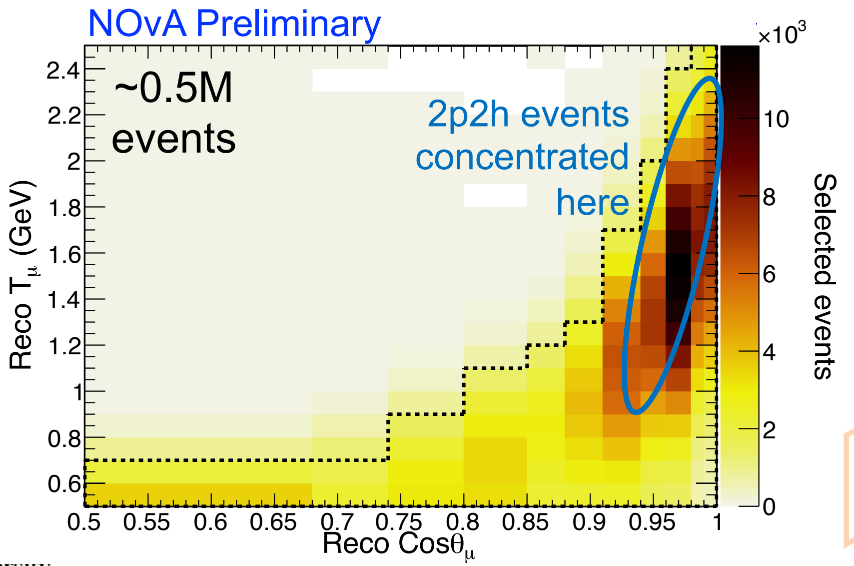
Hadronic System

Inclusive
Select all ν_μ CC events

Both build on previous ν_μ CC inclusive meas. (arXiv:2109.12220)

Muon System

- Events must have exactly one reconstructed track (low E_{had})
  - **Boosts 2p2h,** reduces DIS and RES
- Cross section reported at 115 kinematic points
  - 12-15% uncertainty typically
  - dominated by flux systematic

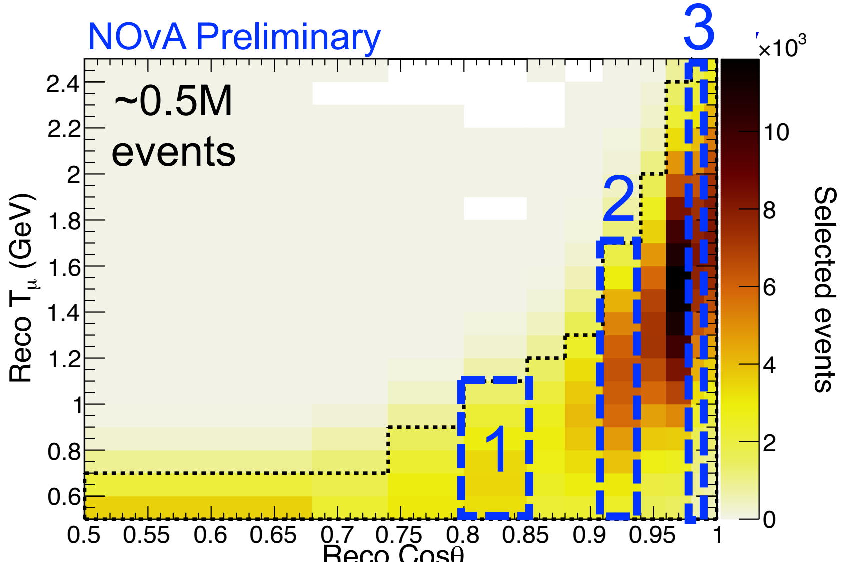


Poster 640
Leo Aliaga

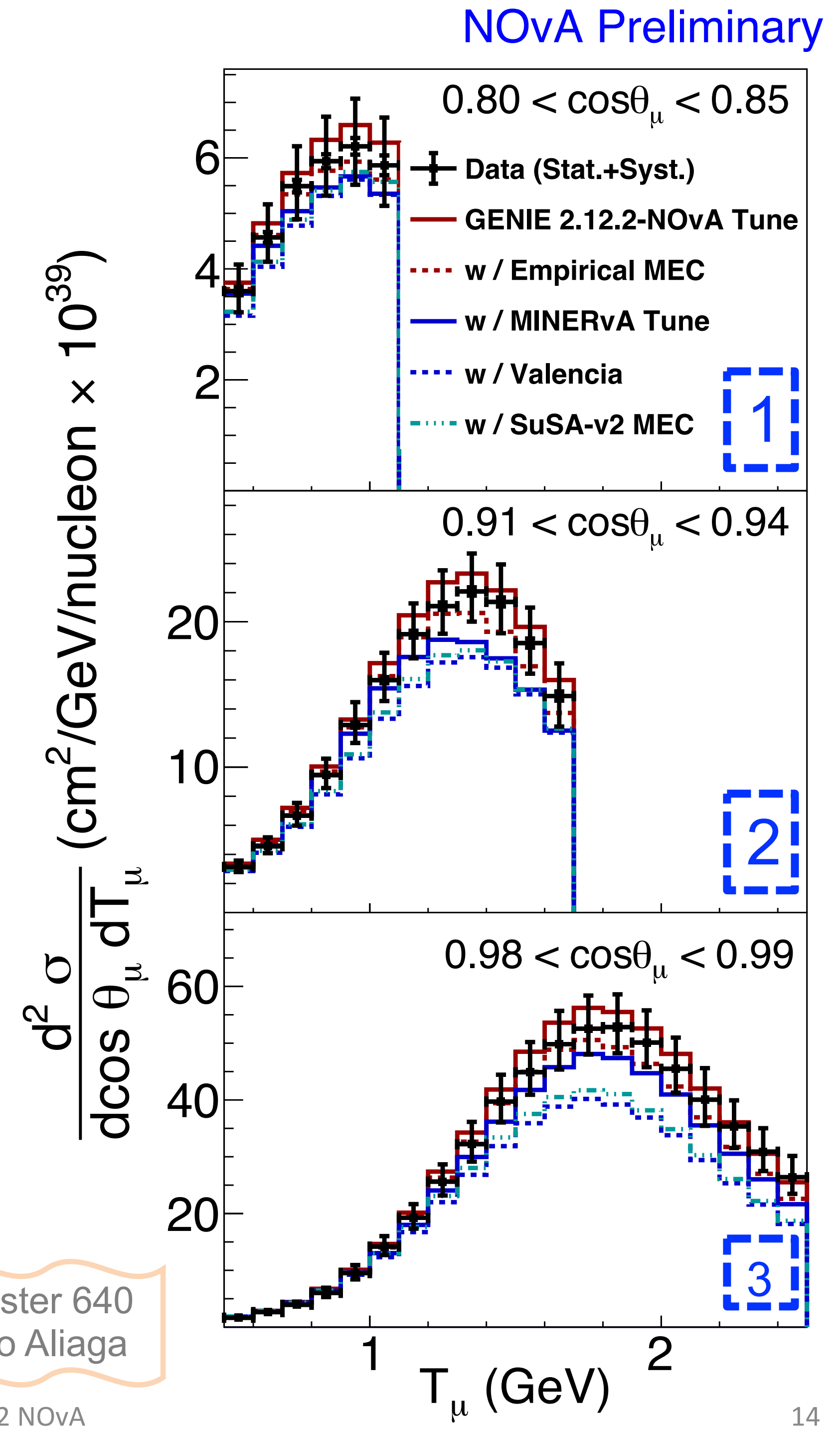
University of Sussex

Muon System

- Events must have exactly one reconstructed track (low E_{had})
  - **Boosts 2p2h,** reduces DIS and RES
- Cross section reported at 115 kinematic points
  - 12-15% uncertainty typically
  - dominated by flux systematic

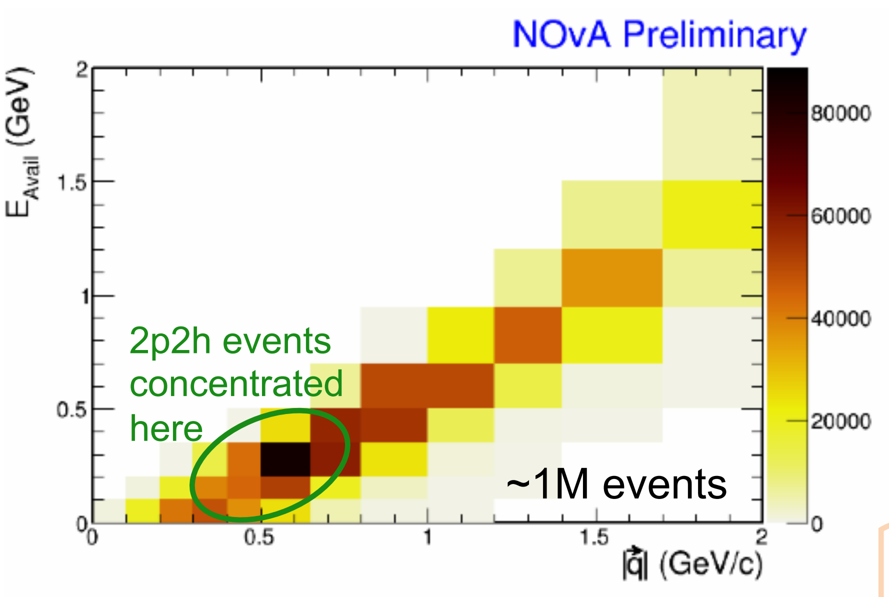


Poster 640
Leo Aliaga



Hadronic System

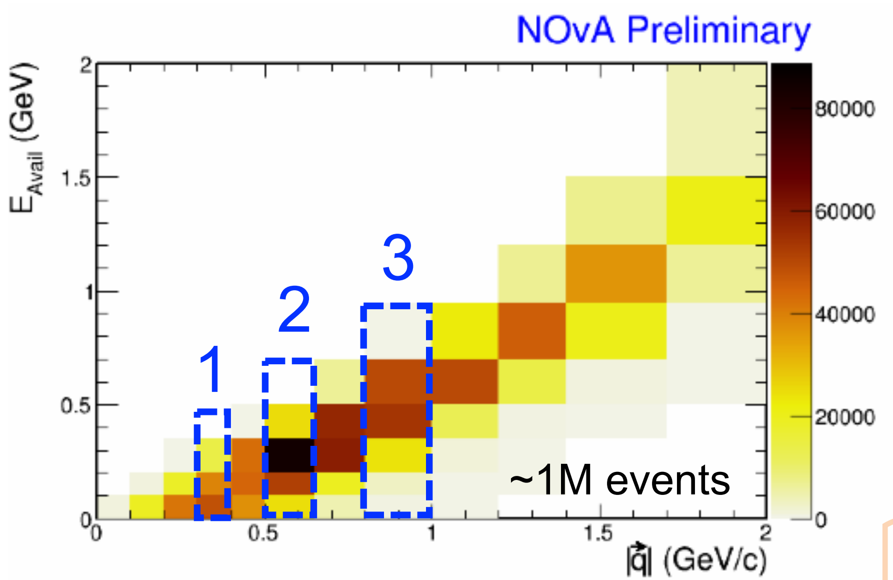
- NOvA's first measurement in $|\vec{q}|$ and E_{Avail}
  - **2p2h concentrated at low values**
- Cross section reported at 67 kinematic points
  - ~12% uncertainty typically
  - dominated by flux systematic



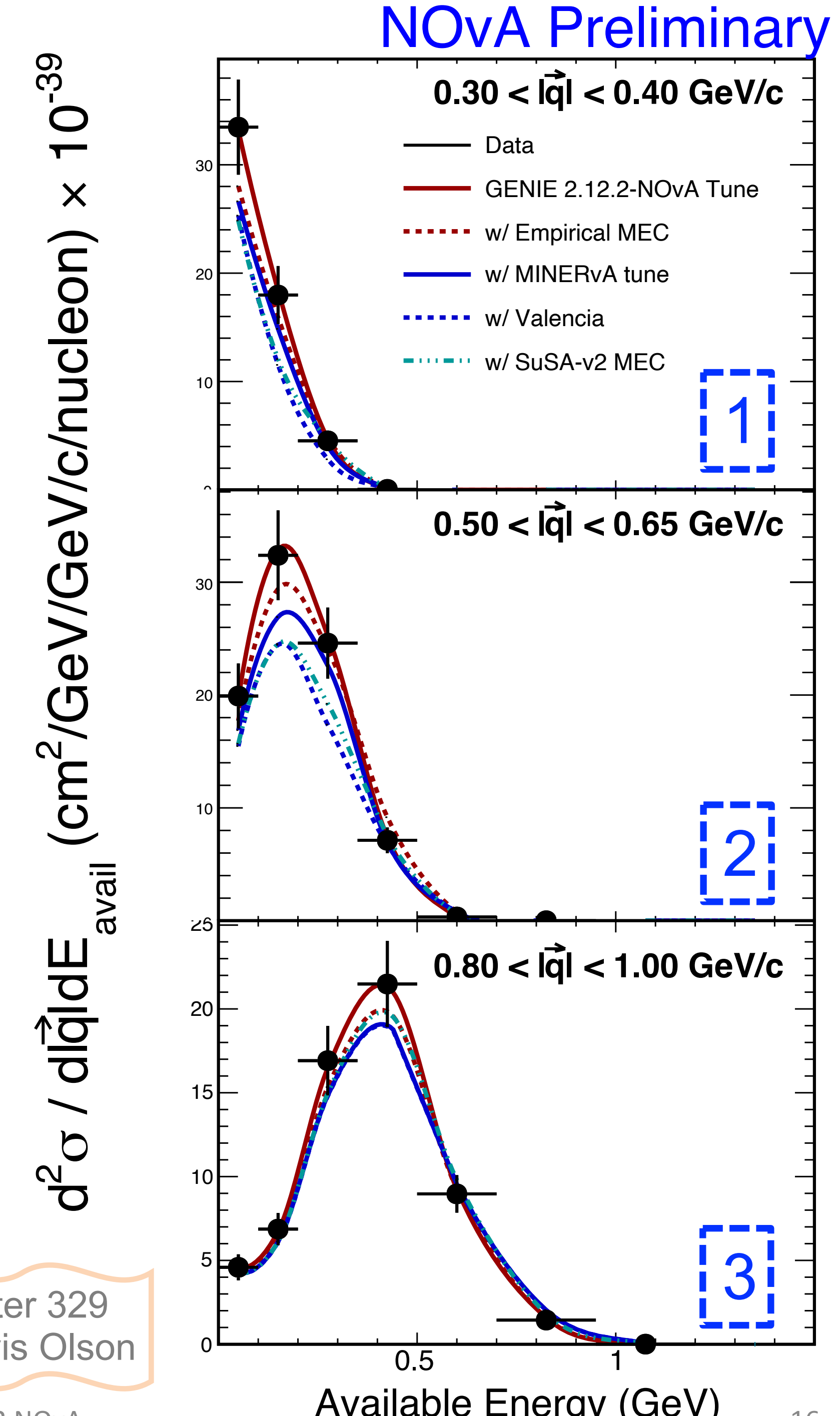
Poster 329
Travis Olson

Hadronic System

- NOvA's first measurement in $|\vec{q}|$ and E_{Avail}
  - **2p2h concentrated at low values**
- Cross section reported at 67 kinematic points
  - ~12% uncertainty typically
  - dominated by flux systematic



Poster 329
Travis Olson



Comparison of 2p2h Models to Data

- Large χ^2 values seen for all 2p2h models/tunes
- Tuned models match data better than Valencia/SuSA-v2

Muon System

2p2h Model	χ^2 (115 d.o.f.)	
GENIE v2-12.2 NOvA Tune	**200**	Tuned models
Empirical MEC	**190**	
Valencia w/ MINERvA Tune	**340**	
Valencia	**630**	Theoretical models
SuSA - v2	**620**	

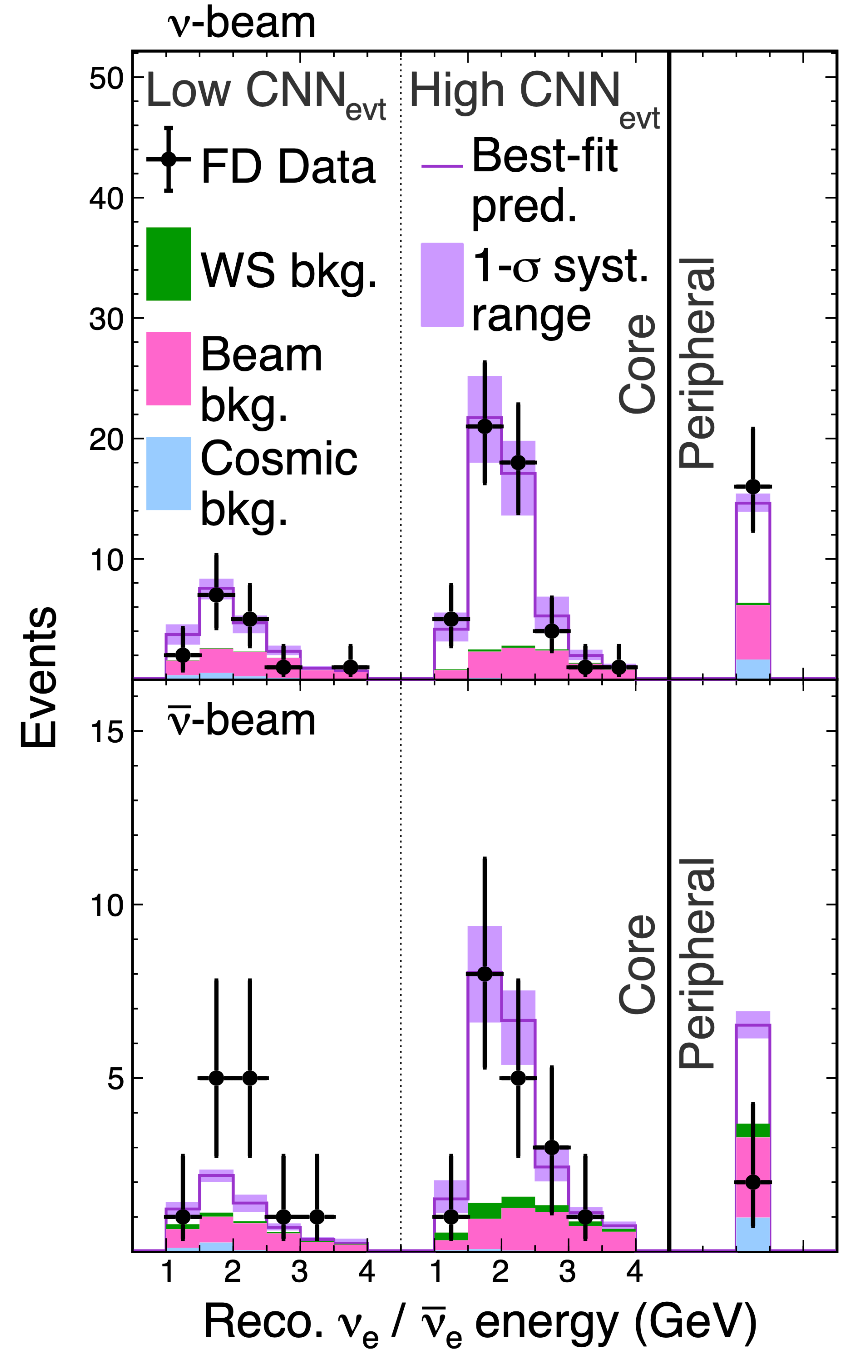
- Hadronic System analysis suggests similar conclusions
- χ^2 calculated for data vs. simulation with the various 2p2h models using full covariance matrix
- Correlations between bins are dominant contribution to χ^2
- Data release for these high-statistics analyses coming soon
  - Can explore many aspects of generator models beyond 2p2h with this data

Oscillation Results

2020 data set: https://arxiv.org/abs/2108.08219

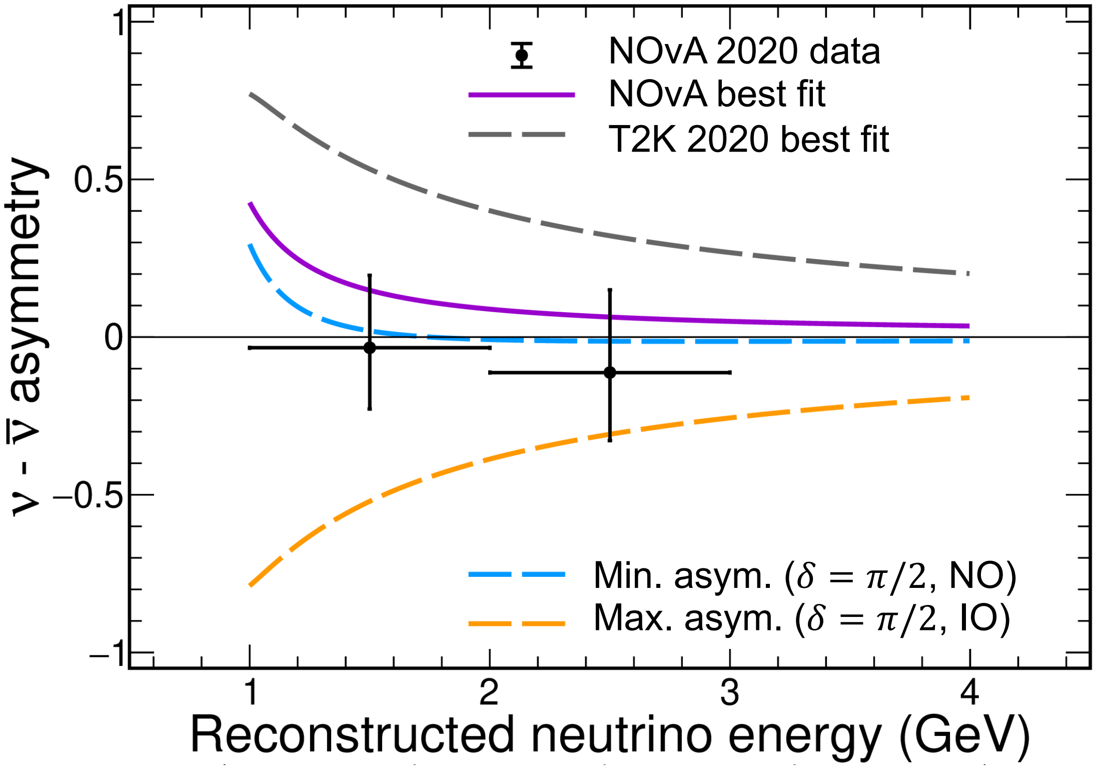
Far Detector 2020 ν_e and $\bar{\nu}_e$ spectra

- Observe
  - 82 ν_e candidates (27 bkg)
  - 33 $\bar{\nu}_e$ candidates (14 bkg)



University of Sussex

Appearance Asymmetry: $P(\nu_e) - P(\bar{\nu}_e) \,/\, P(\nu_e) + P(\bar{\nu}_e)$

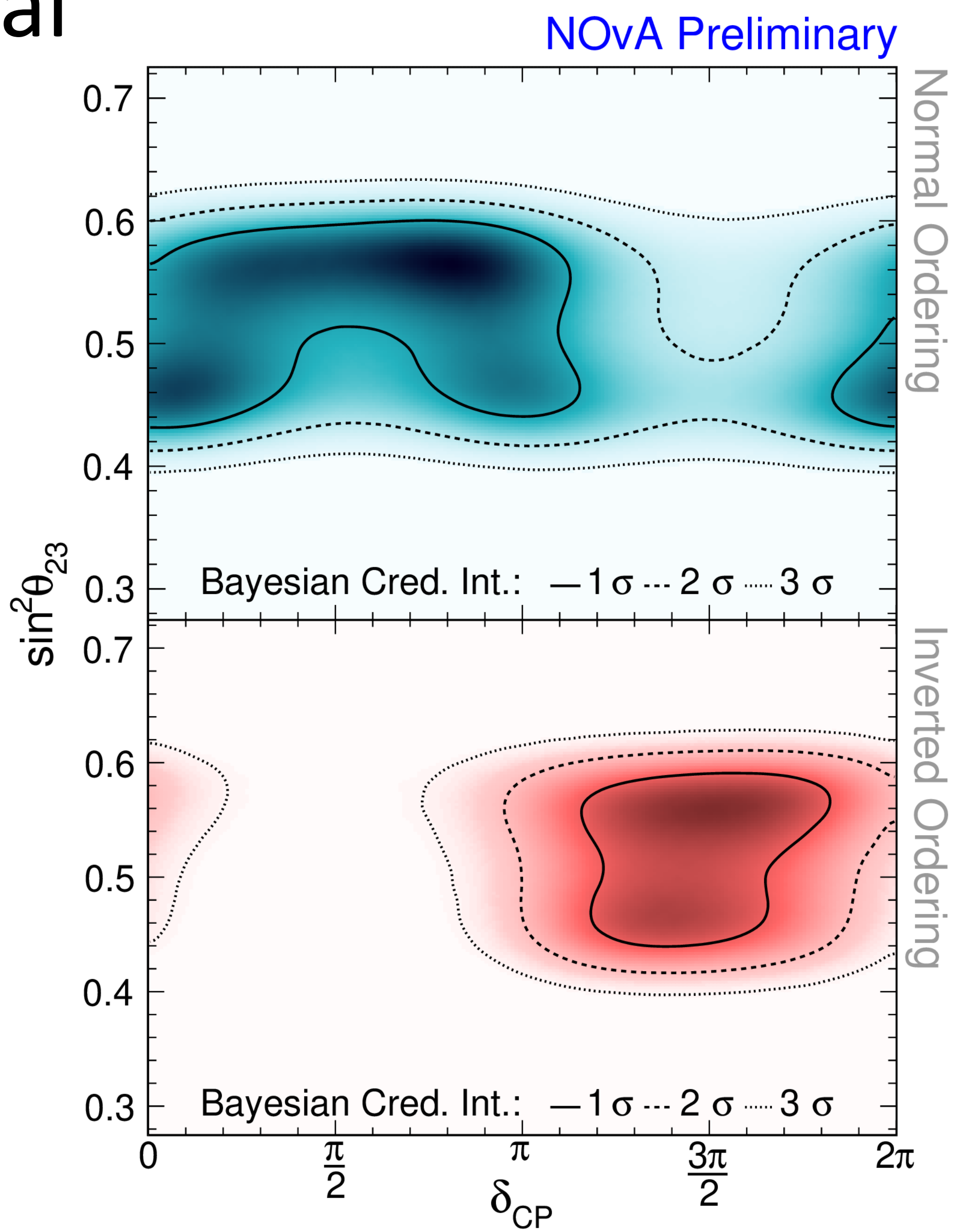


- Asymmetry consistent with zero to 25% precision
- Disfavour mass ordering-δ_{CP} combinations with large asymmetry

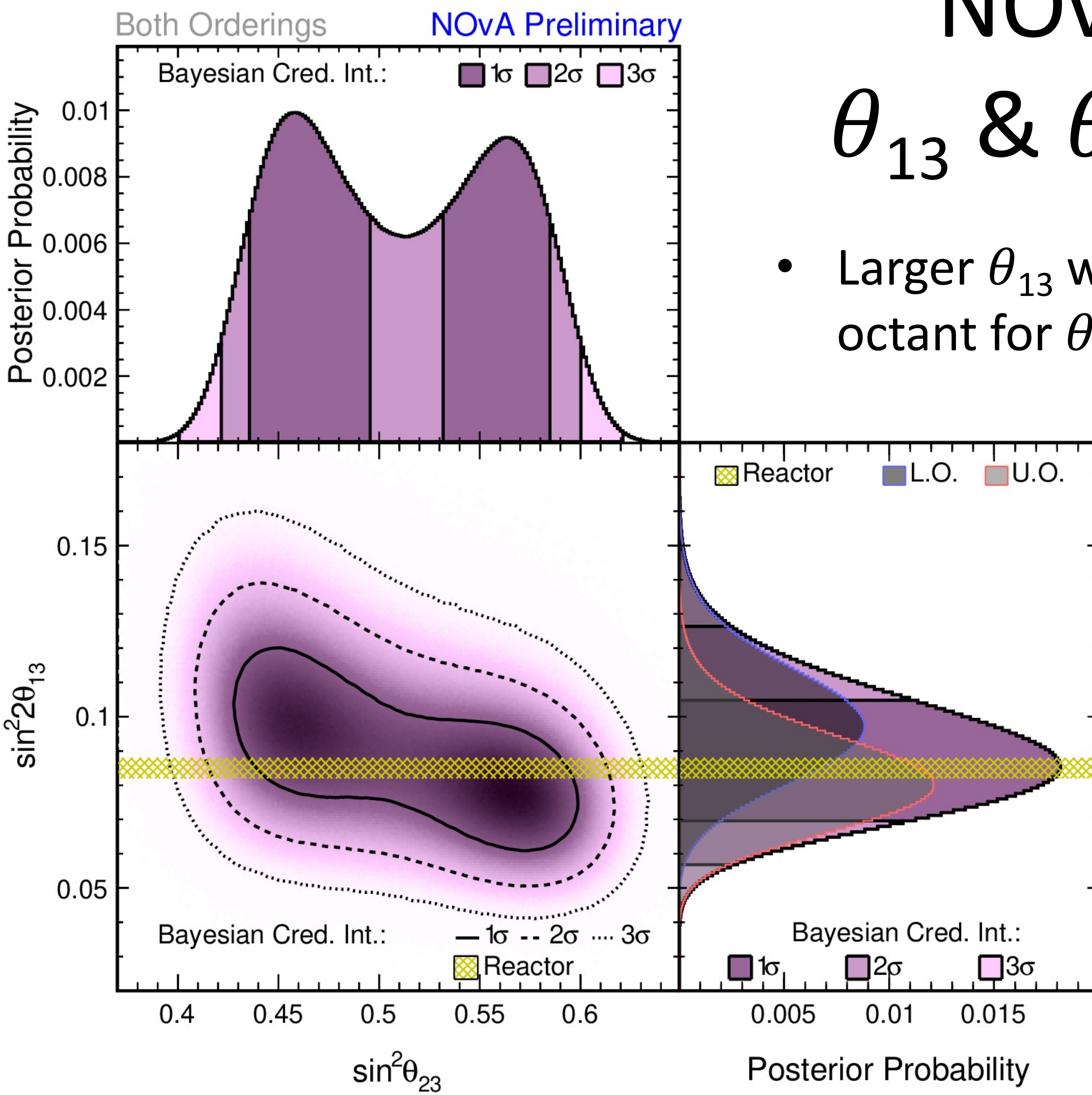
Alternative Statistical Treatment

- Markov Chain MC Bayesian analysis
- Allows results to be examined in new ways
- Conclusions the same as frequentist results
- Exclude IO, $\delta = \pi/2$ at $> 3\sigma$

Poster 332
Pierre Lasorak
Artur Sztuc
Jeremy Wolcott



NOvA-only θ_{13} & θ_{23} results



- Larger θ_{13} would favour lower octant for θ_{23} and vice versa

- Normally use reactor θ_{13} constraint in fit
- Here θ_{13} is measured by NOvA
- $\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$
- Consistent with reactor experiments

2020 3-Flavour Frequentist Result

Best Fit

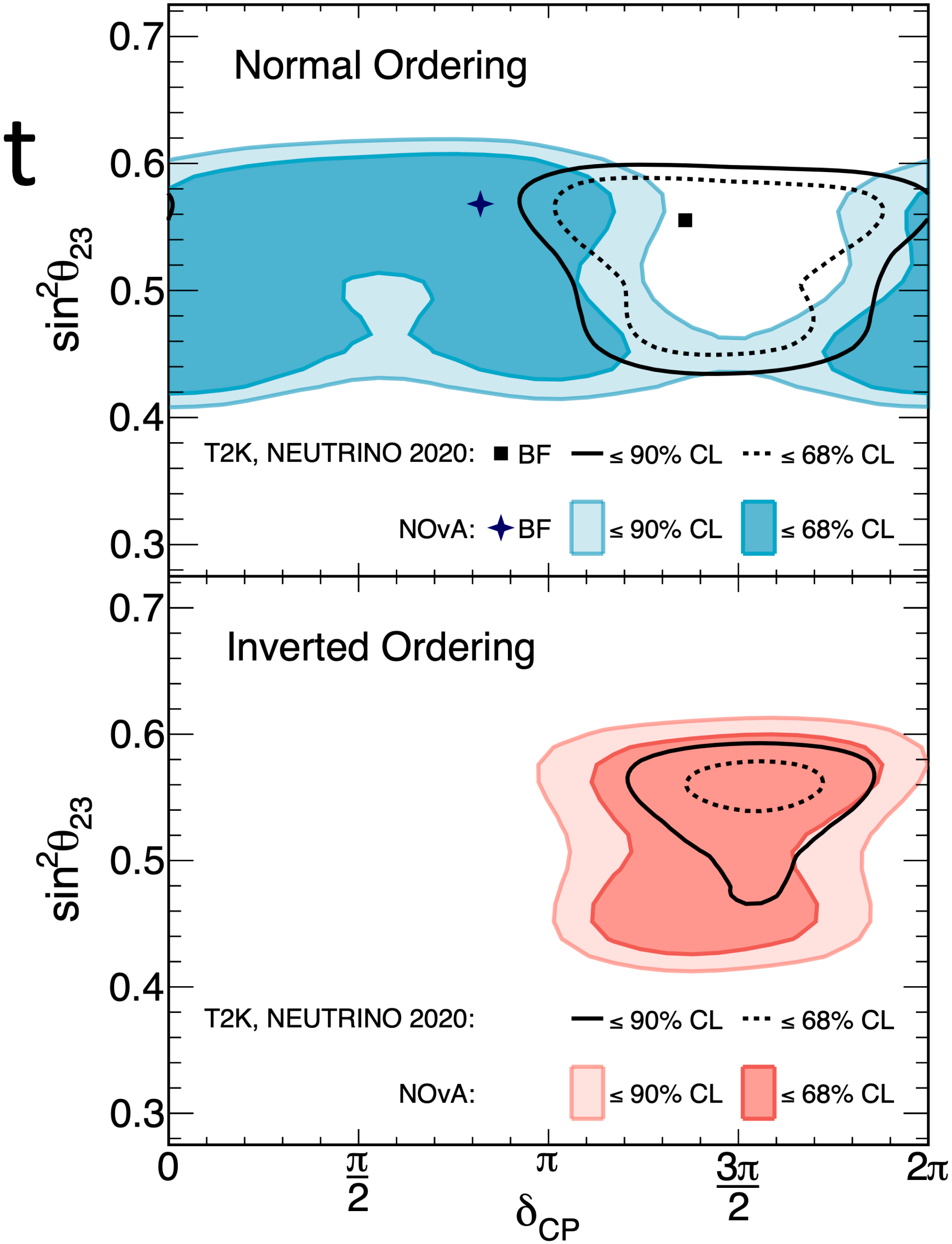
Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$

Poster 318
Liudmila Kolupaeva
Andrew Sutton



- Significant progress on joint fit with T2K
  - coming this year

Beyond 3-Flavour Oscillations

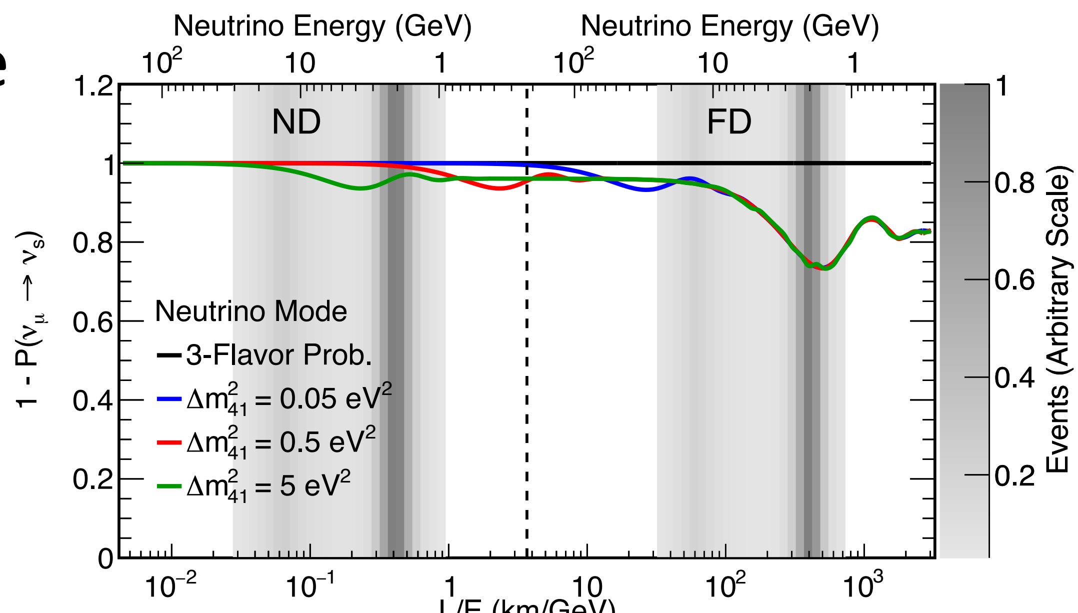
Sterile Neutrino Search

- Are 3-flavour oscillations the full picture?
  – Is there a 4th, sterile, neutrino?

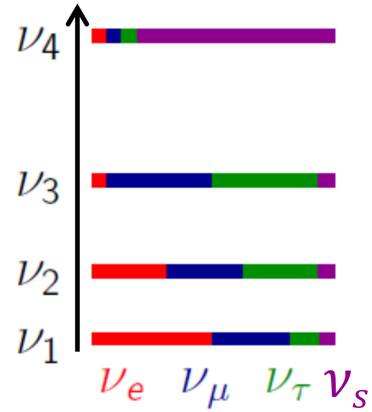
Phys.Rev.Lett. 127 (2021) 20, 201801
Phys.Rev.D 96 (2017) 7, 072006

- **New sterile ν search using neutrino beam data**
  – Include new neutrino interaction type
    - neutral current + ν_μ **charged current**
  – Covariance matrix fit to 3+1 sterile ν model
  – Expanded Δm^2_{41} range
    - oscillations allowed in both detectors simultaneously
    - new dedicated systematics for this analysis

Poster 591
v Hewes
David Dueñas



Sterile ν oscillations at NOvA



3+1 model

Add 4th mass eigenstate

ν_μ CC disappearance

$$
\begin{aligned}
P(\nu_\mu \to \nu_\mu) \approx 1 &- \sin^2 2\theta_{23} \sin^2 \Delta_{31} \\
&+ 2 \sin^2 2\theta_{23} \underline{\sin^2 \theta_{24}} \sin^2 \Delta_{31} \\
&- \underline{\sin^2 2\theta_{24}} \sin^2 \Delta_{41}
\end{aligned}
$$

Far detector only

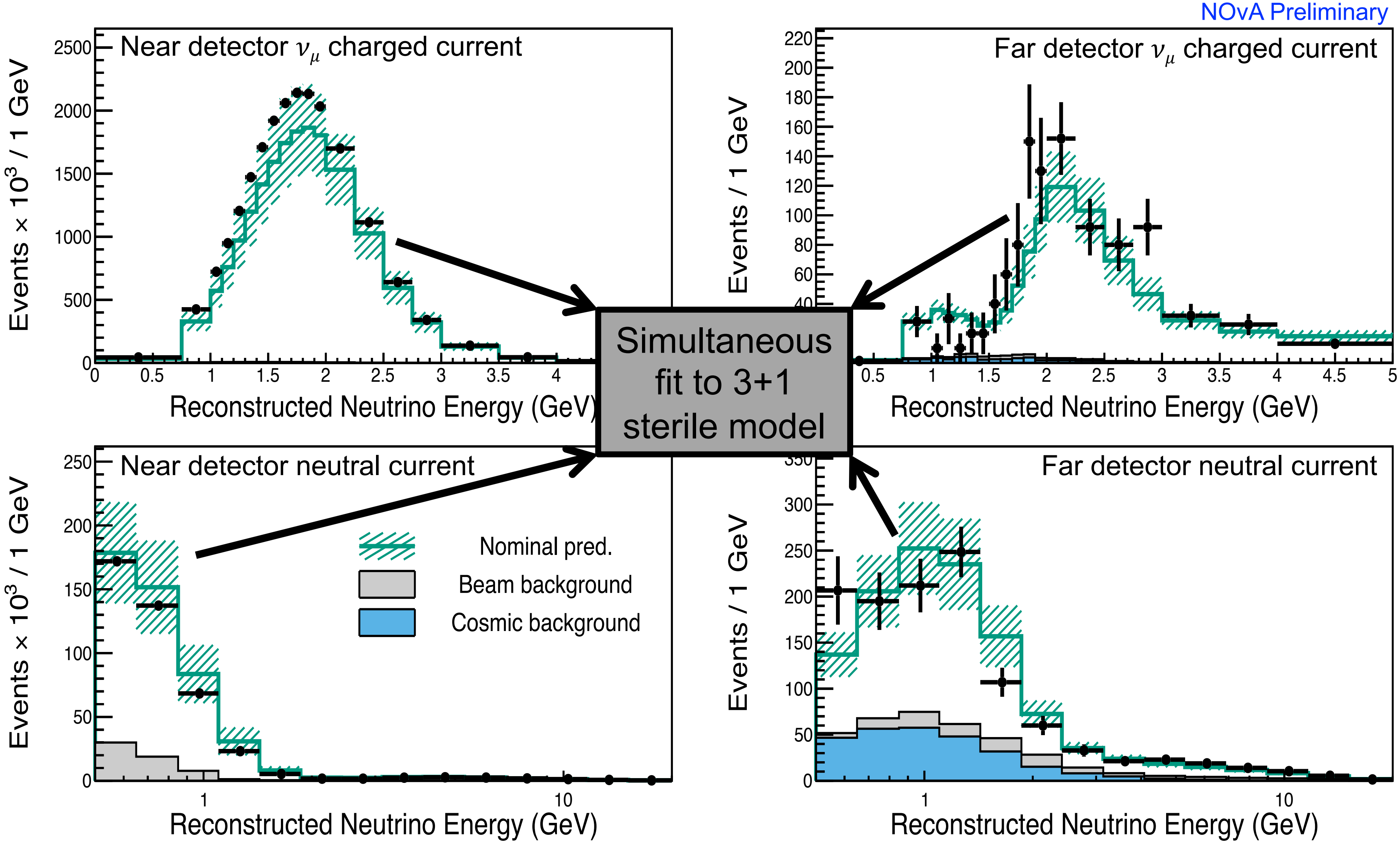
NC disappearance

$$
\begin{aligned}
1 - P(\nu_\mu \to \nu_s) \approx 1 &- \cos^4 \theta_{14} \underline{\cos^2 \theta_{34} \sin^2 2\theta_{24}} \sin^2 \Delta_{41} \\
&- \underline{\sin^2 \theta_{34}} \sin^2 2\theta_{23} \sin^2 \Delta_{31} \\
&+ \frac{1}{2} \sin \delta_{24} \underline{\sin \theta_{24}} \sin 2\theta_{23} \sin \Delta_{31}
\end{aligned}
$$

Far detector only

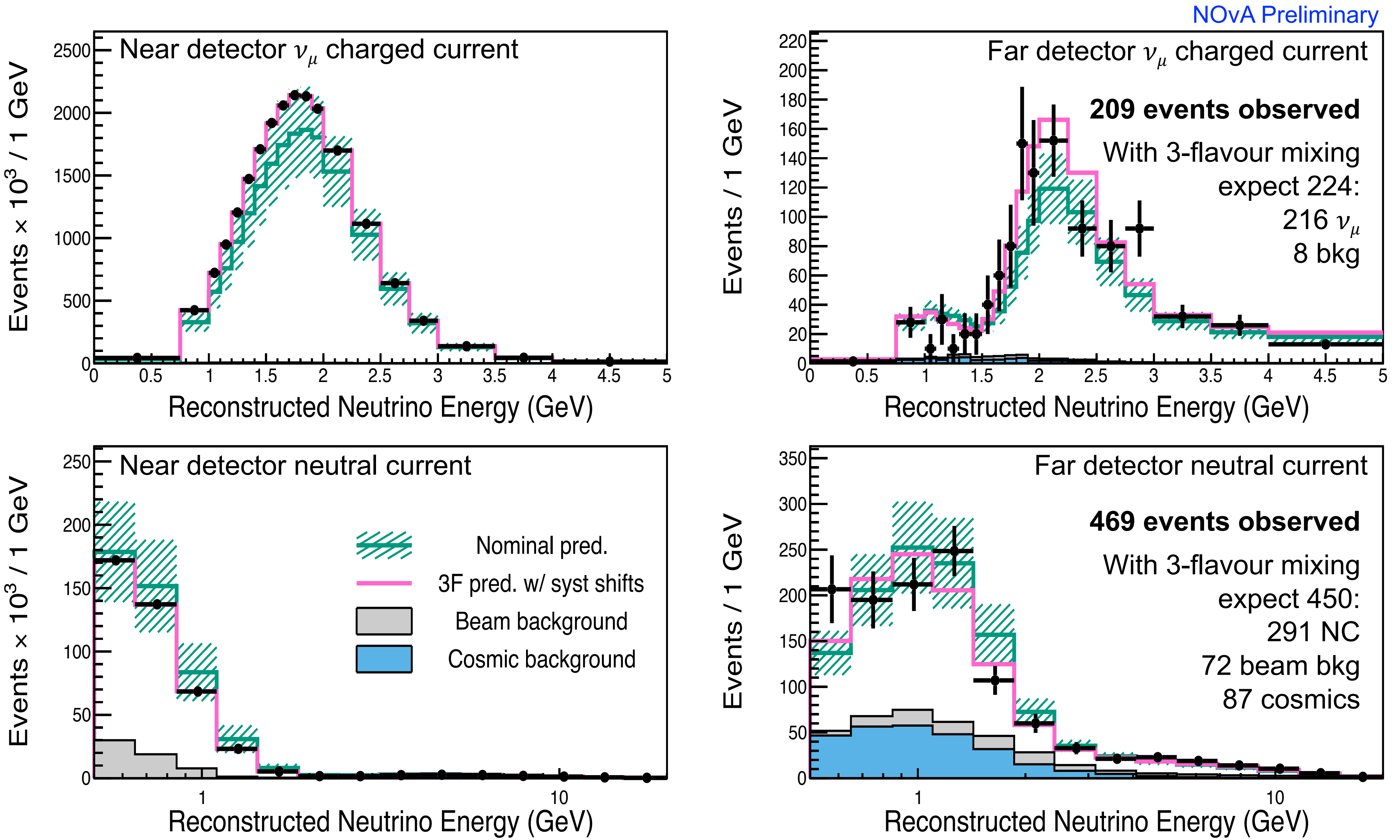
[Note: analysis uses full formalism with matter effects]

Spectra used in Sterile ν Search



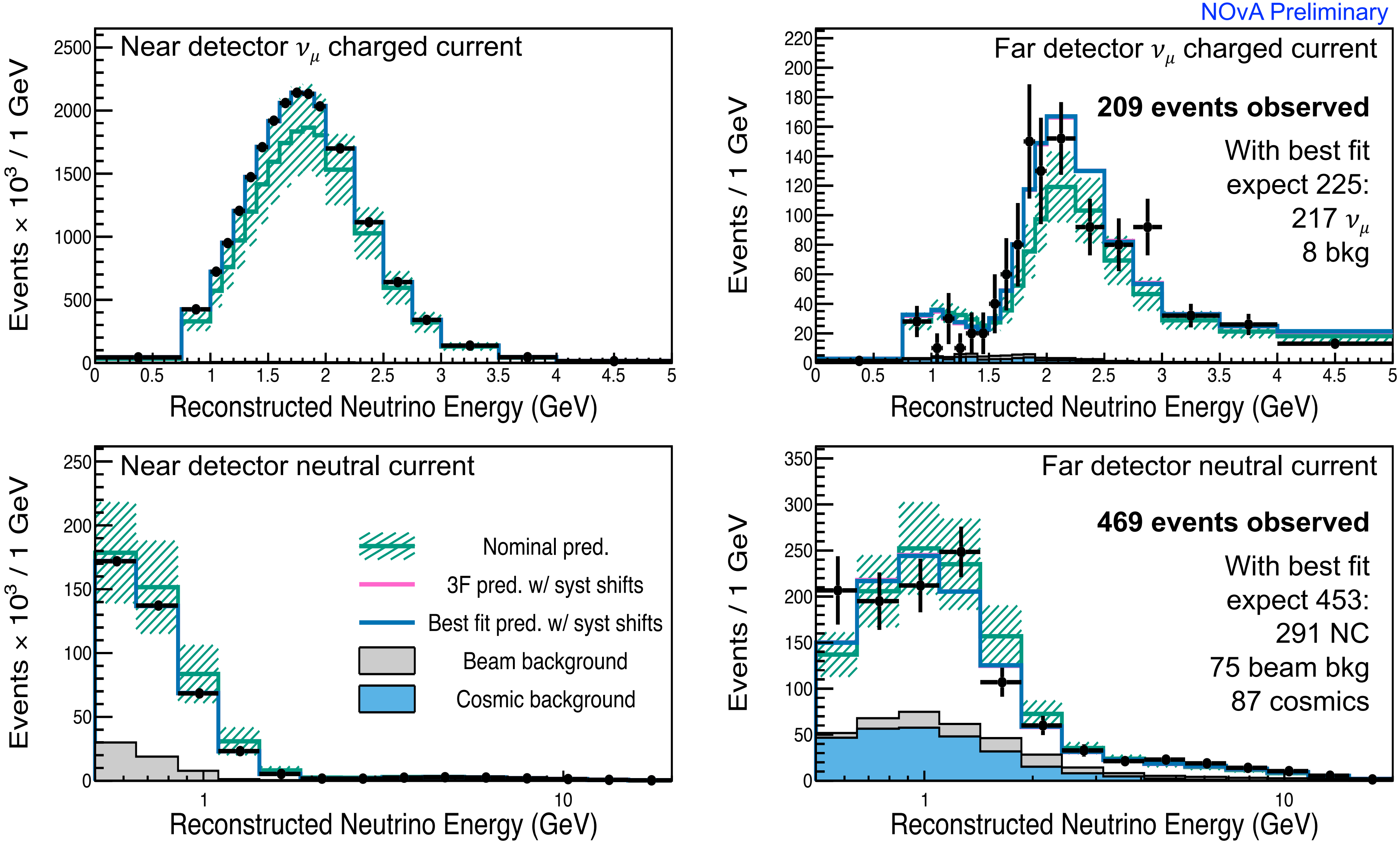
Pre-fit MC distributions (data-driven 2p2h tune not included in this analysis)

Spectra used in Sterile ν Search



3-Flavor hypothesis with systematic pulls included here

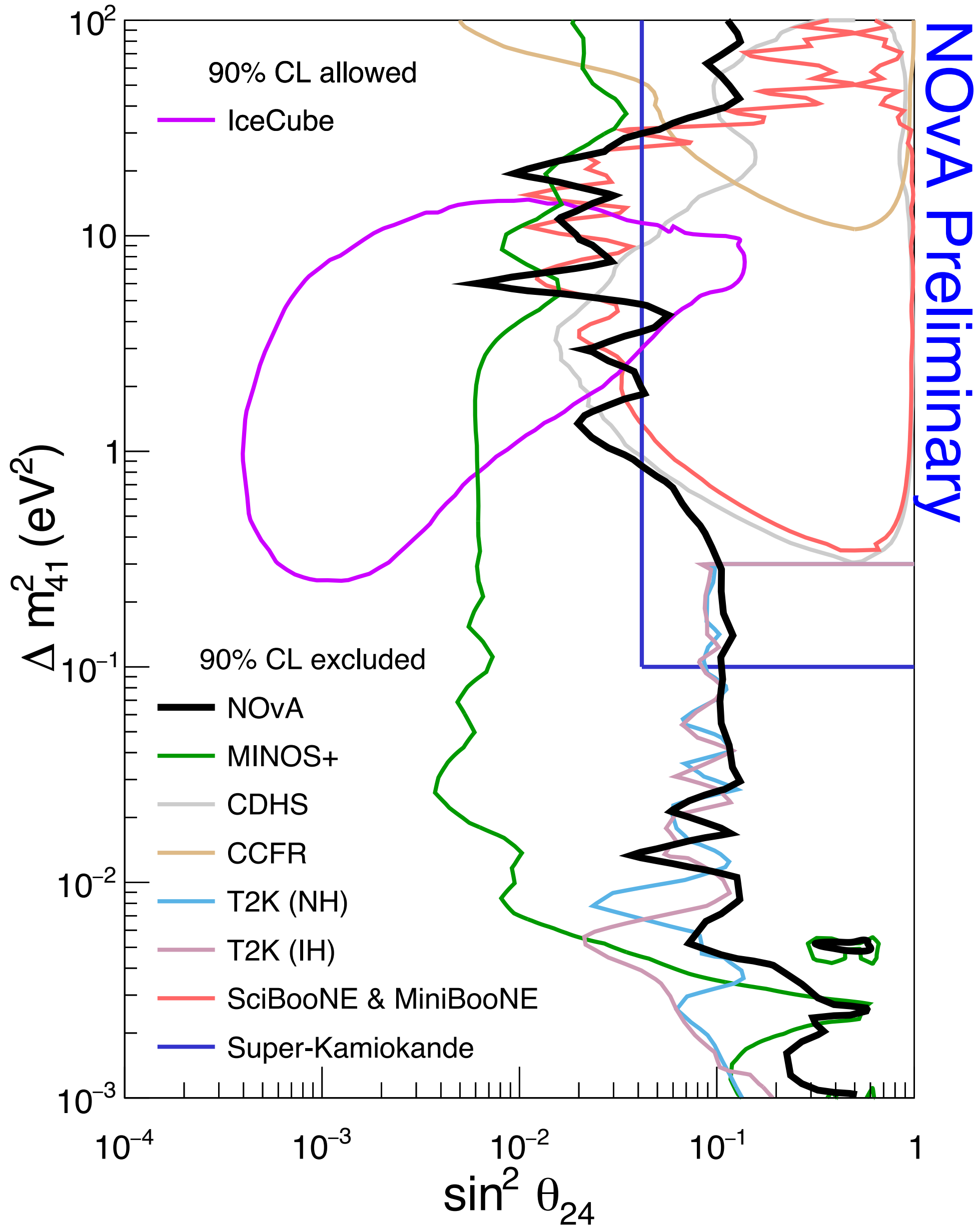
Spectra used in Sterile ν Search



Full best-fit for sterile neutrinos included here

Sterile Neutrino Search Results

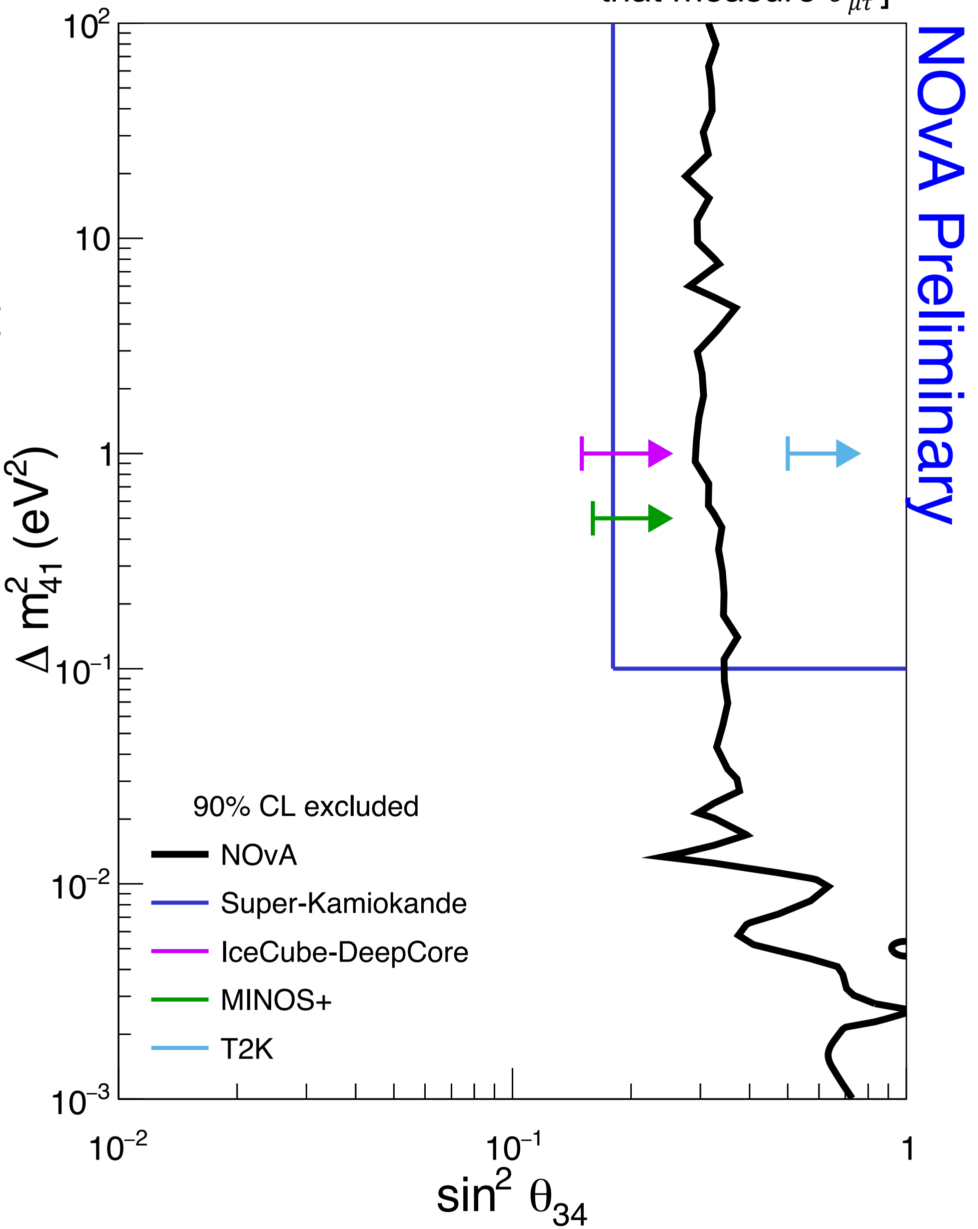
- Data shows no evidence for sterile neutrinos
  - Best fit at small θ_{24} and θ_{34} with low significance
- Competitive limits on θ_{24} for Δm^2_{41} = ~10 eV^2
- Goodness of fit:
  - χ^2/d.o.f. = 56.4/66
- Analysis systematics limited at large Δm^2_{41} (Near det.) but less so for small Δm^2_{41} (Far det.)



θ_{34} Results

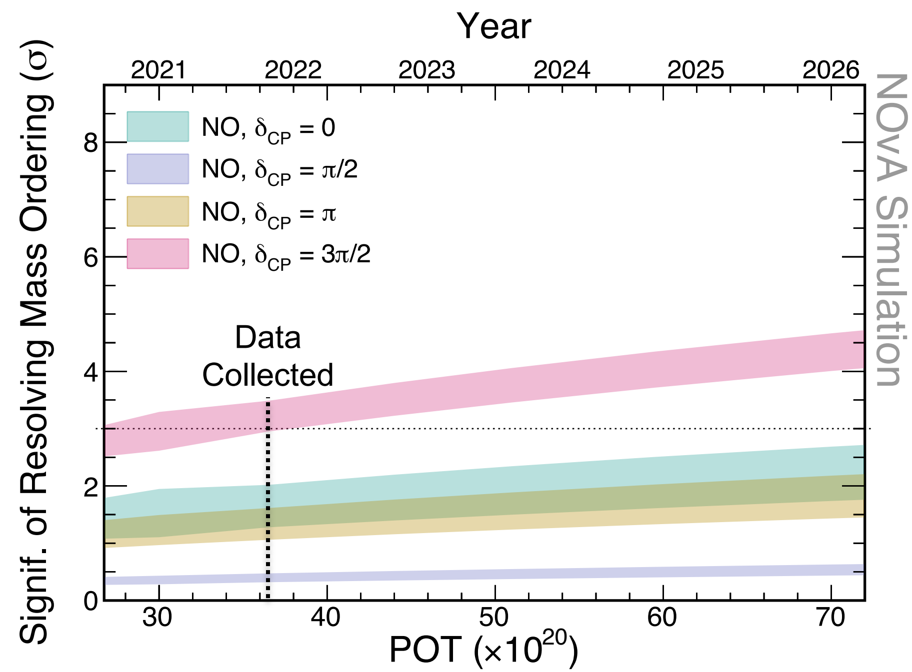
- A measure of mixing between ν_τ and a sterile ν
  - Historically studied via ν_τ appearance searches at short baselines as $\theta_{\mu\tau}$
- NOvA's sensitivity comes from **neutral current** events
  - enhanced by constraints on θ_{24} from ν_μ charged current events
- Long-baseline providing sensitivity at small Δm^2_{41}
- New constraints on θ_{34}

[Not displayed: constraints from τ appearance searches that measure $\theta_{\mu\tau}$]



Future Prospects

- Increasing sensitivity to mass ordering to come
  - Will more than double data set in both beams
  - $>3\sigma$ mass ordering sensitivity for 30-40% of δ-values
  - By run end, statistical errors still significantly larger than current systematics on ν_e appearance



Poster 559: $\bar{\nu}_\mu$
Connor Johnson
Prahbjot Singh

Poster 407: NSI
Jeffrey Kleykamp
Luiz Prais et al.

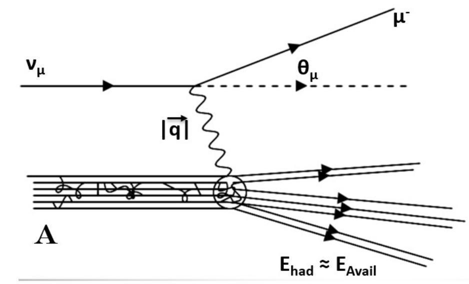
Poster 354: $\bar{\nu}_\mu \pi^0$
Fan Gao

Poster 323: $\bar{\nu}_e$
Derek Doyle
Ayse Bat

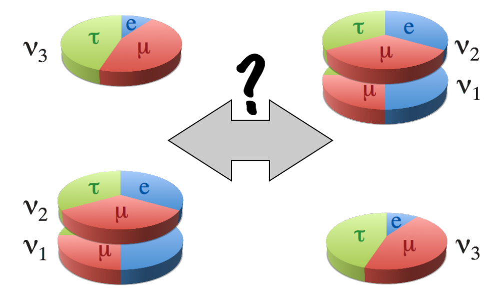
- Watch this space for:
  - NOvA-T2K joint fit
  - Further tests of alternative models (e.g. NSI)
  - Antineutrino beam cross section measurements

Conclusions

- Observe discrepancies w/ 2p2h models

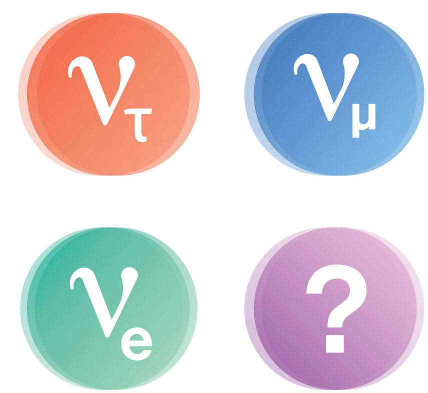


- Asymmetry in $\nu_e - \bar{\nu}_e$ appearance consistent with zero to 25% precision



- Measure: $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$
  – consistent with reactor experiments

- Data shows no evidence of a sterile ν



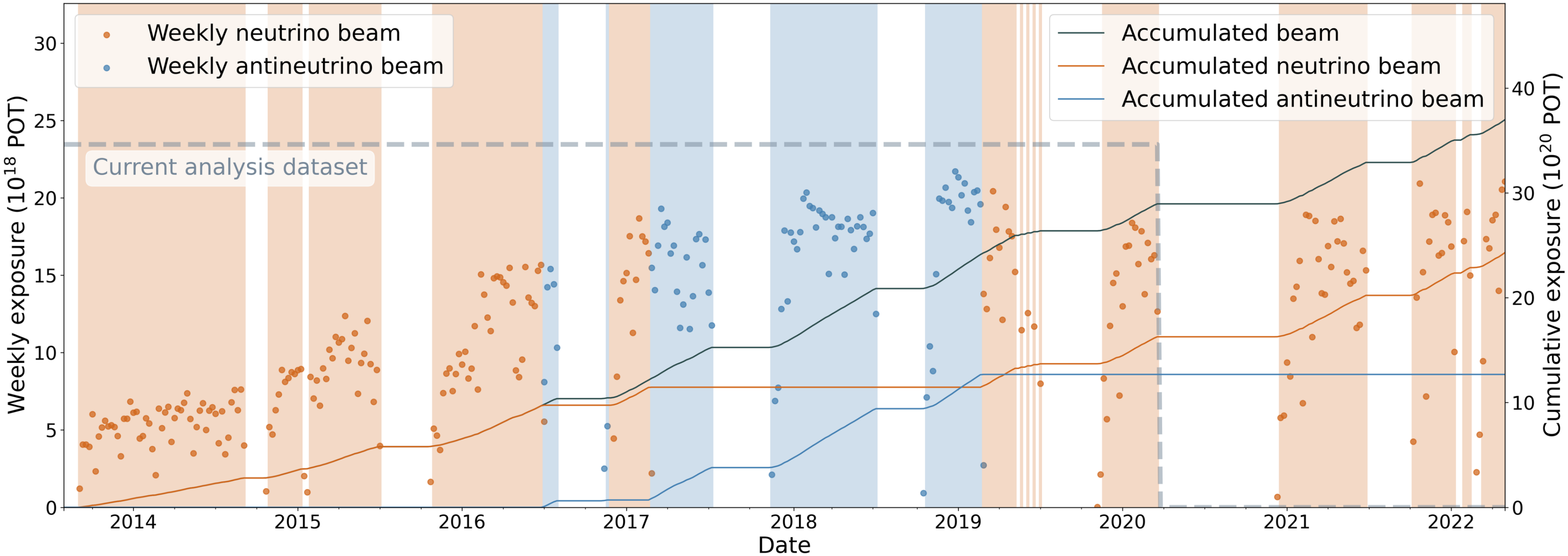
- Much new data & results to come…

The NOvA Collaboration

Thanks!

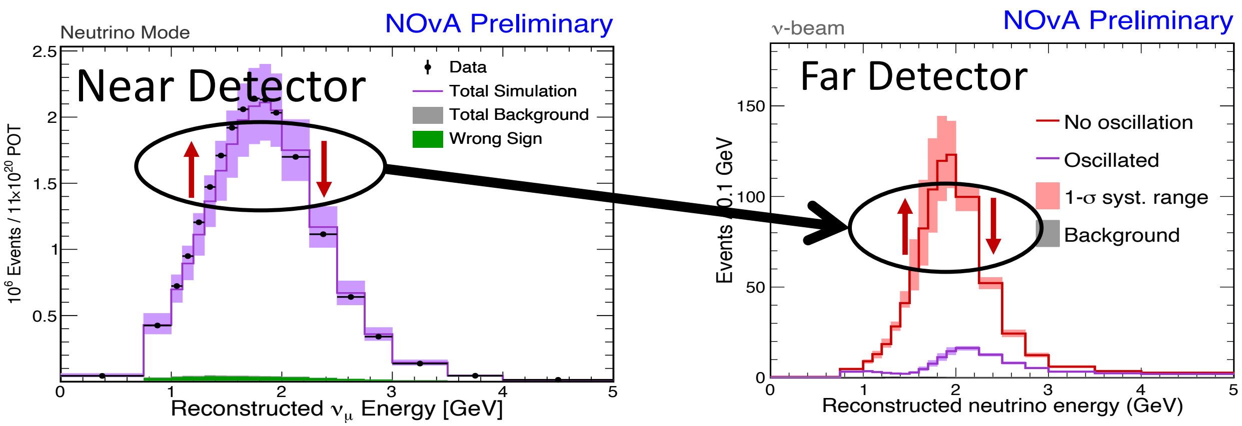
Backup Slides

NOvA NuMI Beam Exposure



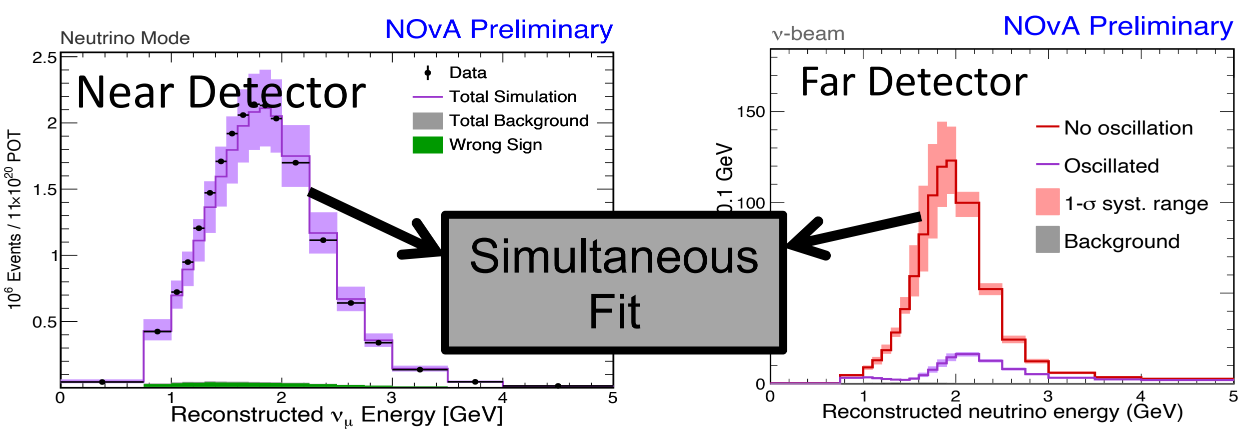
Different Two-Detector Methodologies

- Extrapolation:



- Use in 3-Flavour analysis
- Bin-by-bin corrections transferred to Far detector
- Constrains otherwise large systematic uncertainties from flux and cross section

- Simultaneous two-detector fit:



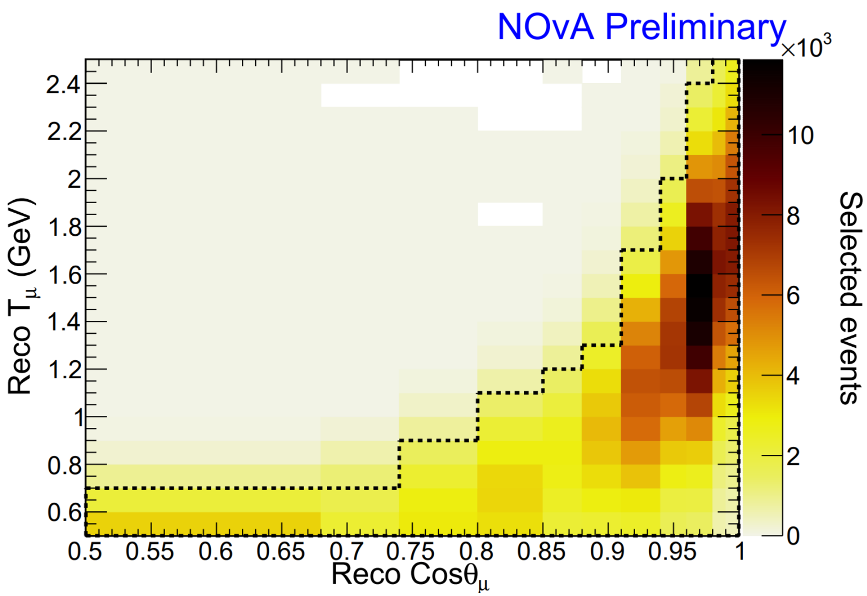
- Sterile search requires a simultaneous fit to both detectors
  - signal can exist in both detectors for large Δm^2_{41}
  - still allows constraint of systematics due to differing potential signal compared to the Far detector

Muon System Analysis (Low E_{had})

Numu CC Low Had – Analysis

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \frac{\sum_j U_{ijk}(N^{\mathrm{sel}}(\cos\theta_\mu, T_\mu, E_{Avail})_j P(\cos\theta_\mu, T_\mu, E_{Avail})_j)}{\epsilon(\cos\theta_\mu, T_\mu, E_{Avail})_{ik}(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i N_{\mathrm{target}}\phi}$$

- Analysis is done in 3D and then projected down to 2D
  - Muon Kinematics and available energy
- Simulation used is GENIE v2.12.2 with NOvA ND tune applied
  - Analysis built to be insensitive to the tune



Signal Definition:

ν_μCC interactions

- T_p^{max} = 250 MeV
- T_π^{max} = 175 MeV

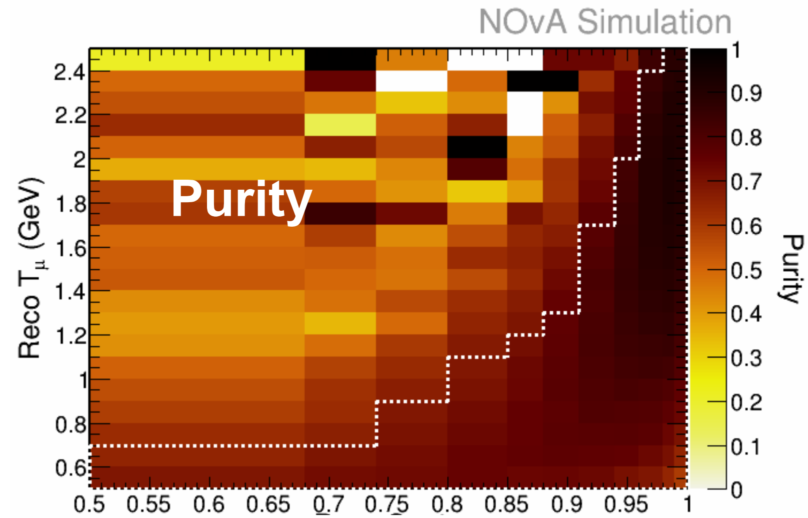
Numu CC Low Had – Selection

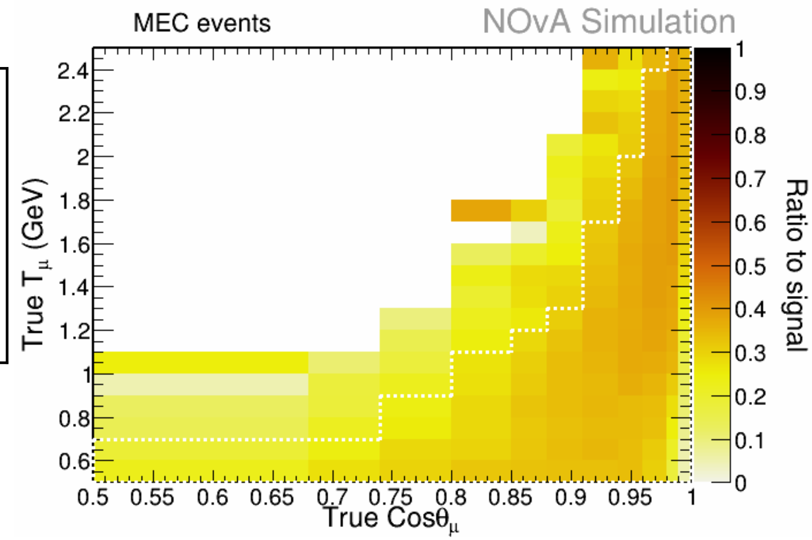
- Require 1 and only 1 reconstructed track
  → Associated with the muon
- Greatly reduce ν_μCC RES and DIS from the selected sample
- Selected sample has high purity (>90% in most of the bins).

Selected sample is >500k events

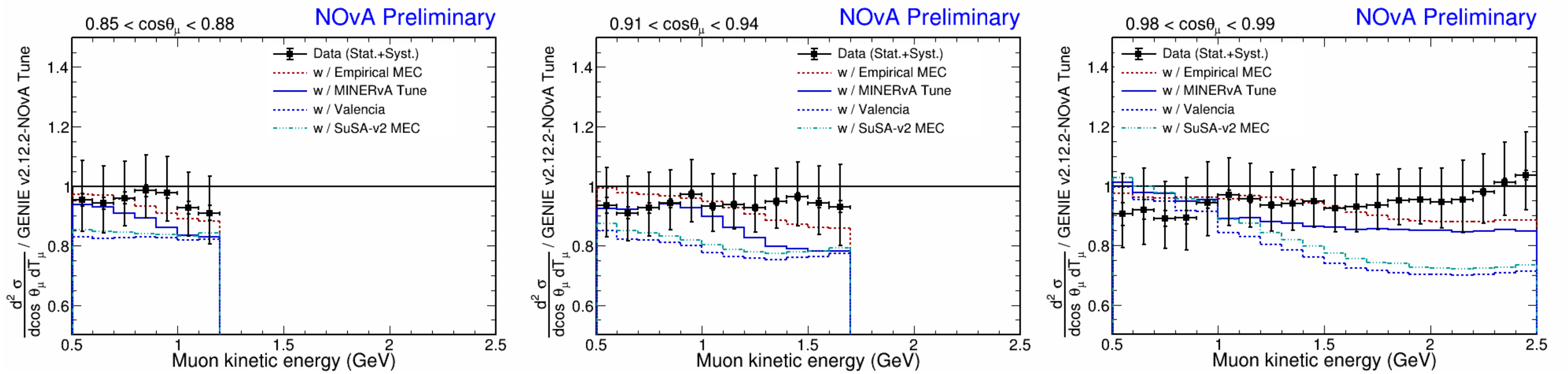
39.7%	**33.7%**	**23.0%**	**2.5%**	**1.1%**

Expected MEC fraction is ~40% for many bins



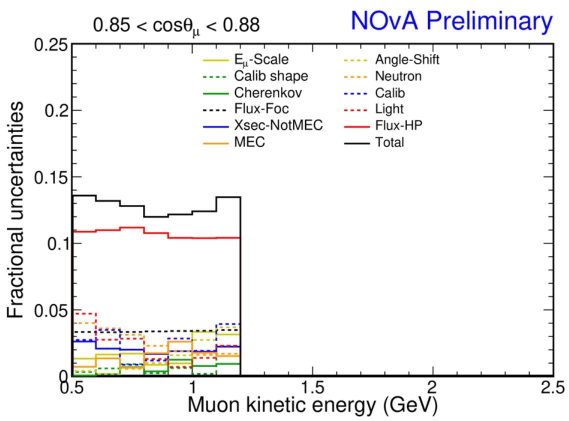


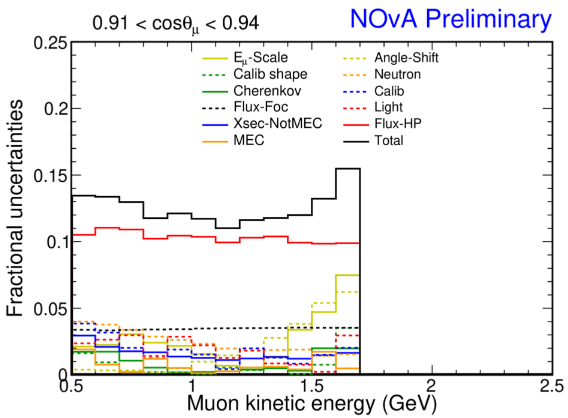
Numu CC Low Had – Ratio w.r.t. the NOvA Tune

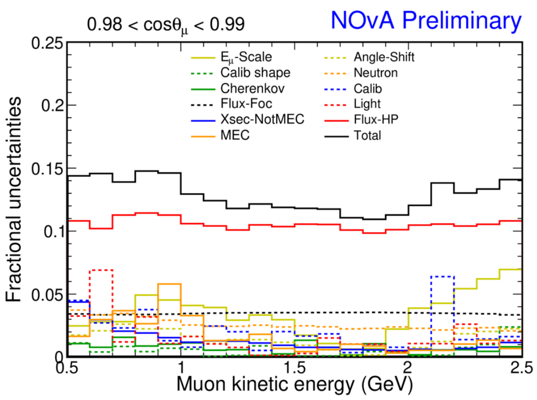


- Ratios highlight differences of models w.r.t. our data.

Numu CC Low Had – Uncertainties







- 12-15% uncertainty typically
  - dominated by flux systematics
  - muon kinematic reconstruction uncertainties rise at the edges

NOvA Numu CC Low Hadronic activity - all slices

- Require only 1 reconstructed track
  → Associated with the muon
- Greatly reduce ν_μCC RES and DIS from the selected sample

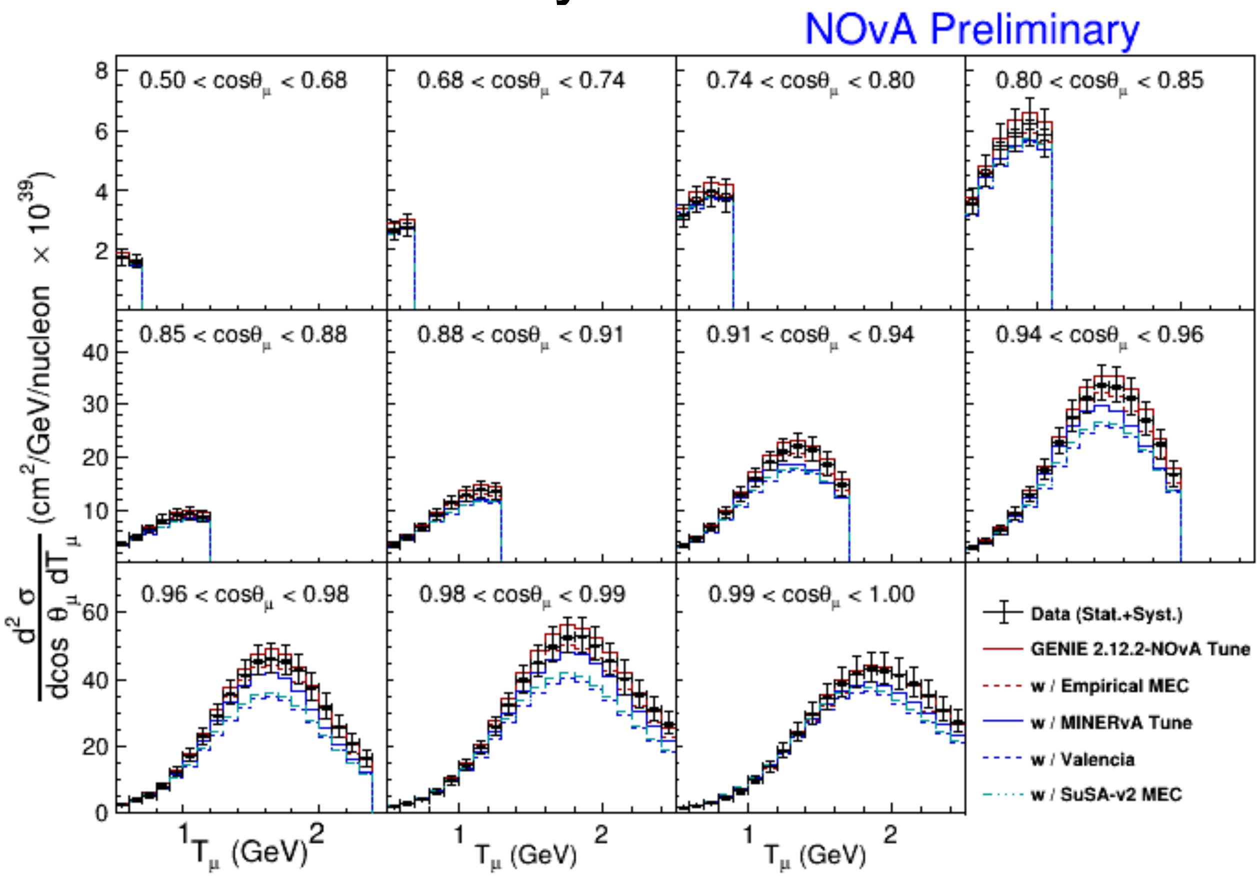
Signal Definition:

ν_μCC interactions

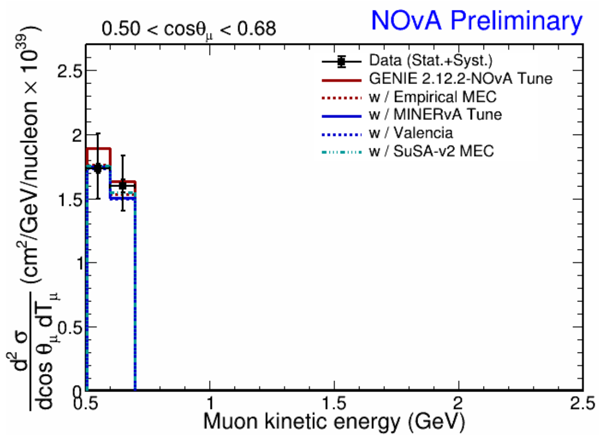
- T_p^{max} = 250 MeV
- T_π^{max} = 175 MeV

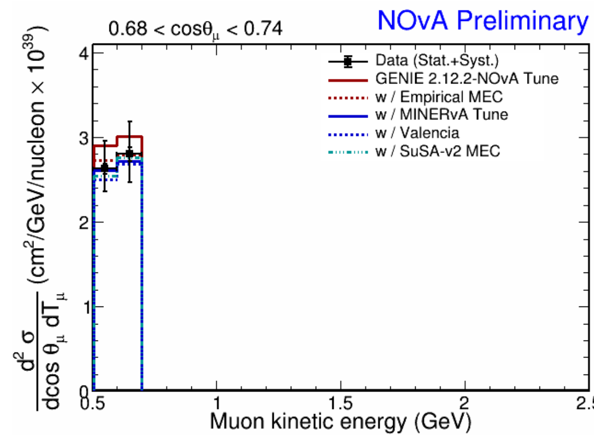
- Cross sections reported in 115 kinematic points

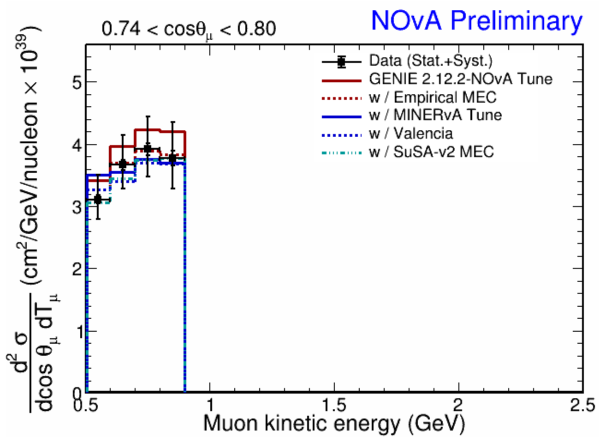
- **12-15% uncertainty typically**
  → dominated by flux systematic

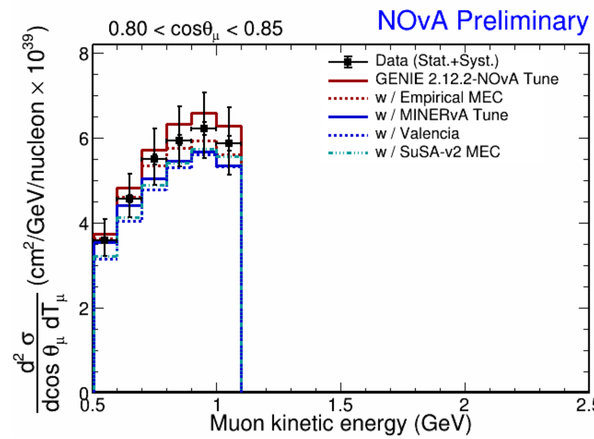


Numu CC Low Had – Remaining Results

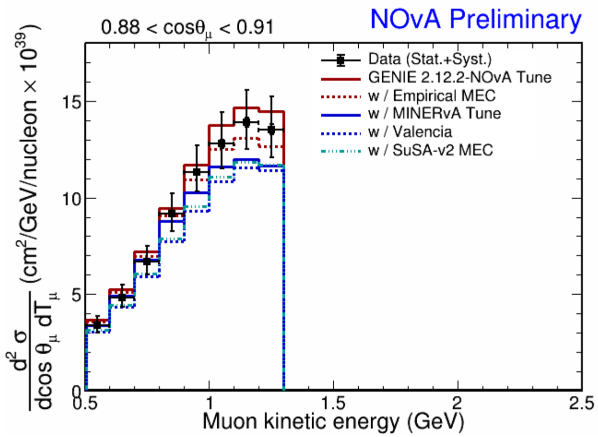


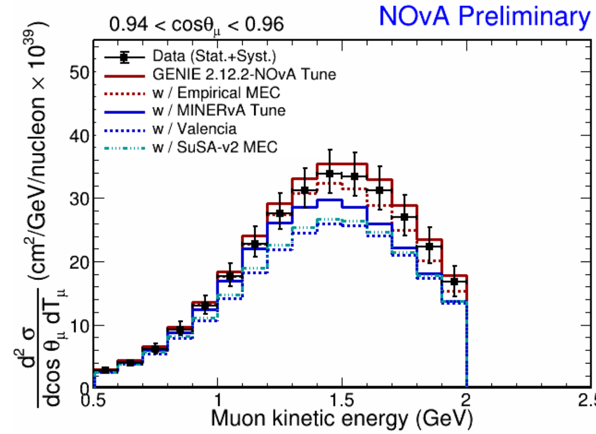


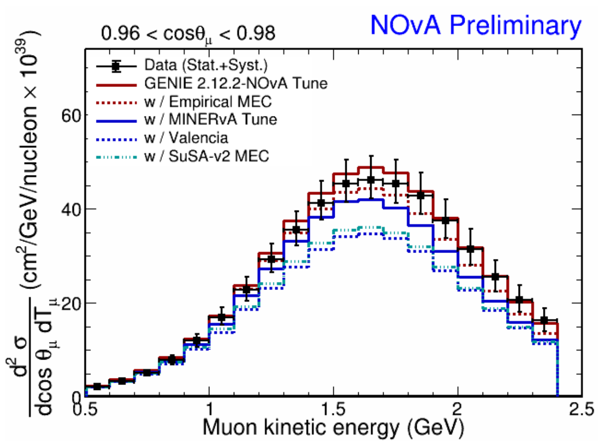


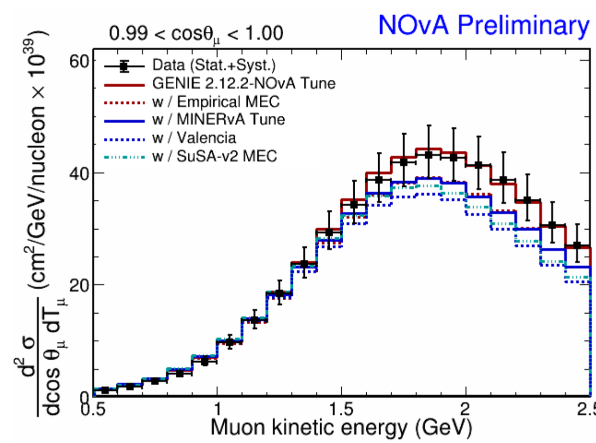


Numu CC Low Had – Remaining Results









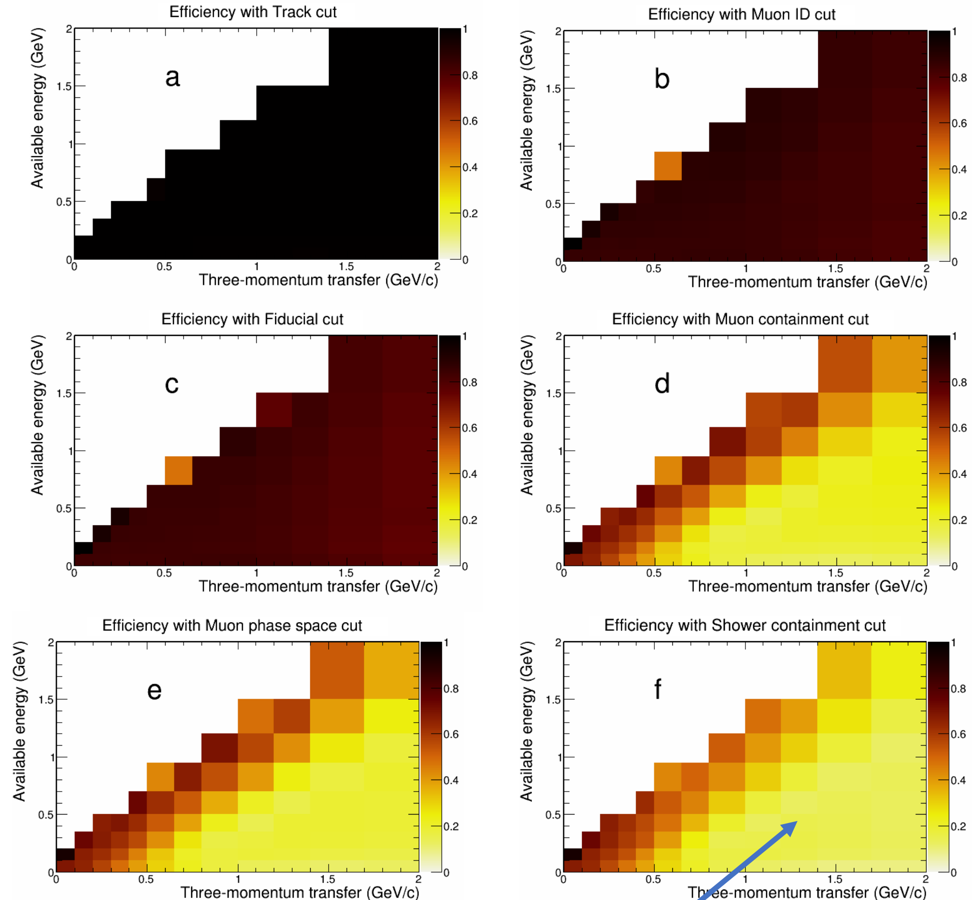
Hadronic System Analysis

- $|\vec{q}| \leq 2$ GeV/c
- $E_{Avail} \leq 2$ GeV

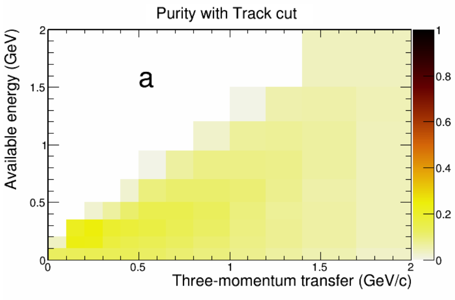
Hadronic variables
Efficiency versus selections:

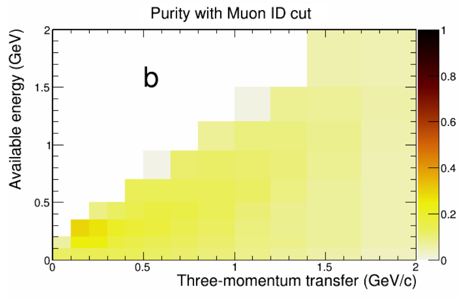
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta} U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\boldsymbol{\varepsilon_{ij}}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

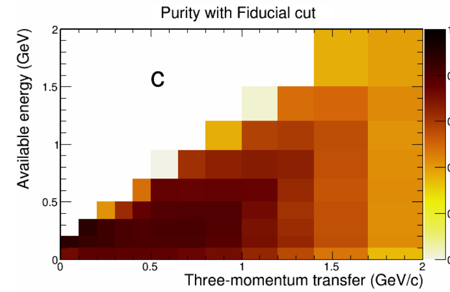
Selection cut	Selected signal events	Efficiency
All true signal	1,956,000	100%
Quality	1,952,000	99.9%
Track reconstruction	1,951,000	99.8%
Muon identification	1,667,000	85.3%
Vertex fiducial	1,609,000	82.3%
Muon containment	482,600	24.7%
Muon phase space	432,200	22.1%
Shower containment	365,300	18.7%

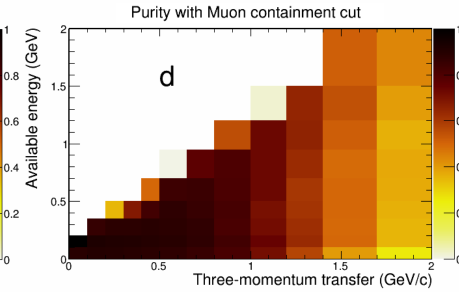


Hadronic variables Purity versus selections:

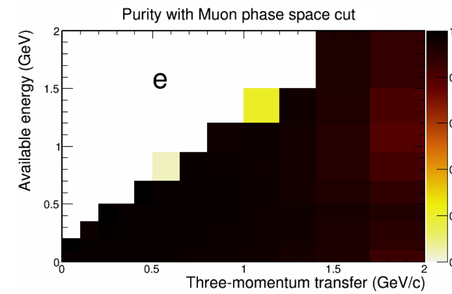


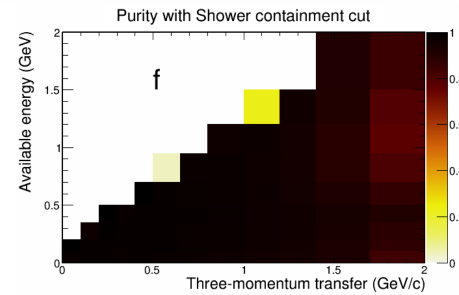






Selection cut	Background	Total events	Purity
Quality	34,868,000	36,671,000	5.41%
Track reconstruction	34,011,000	35,994,000	5.51%
Muon identification	25,733,000	27,428,000	6.18%
Vertex fiducial	2,572,000	4,207,000	38.86%
Muon containment	1,055,000	1,546,000	46.54%
Muon phase space	39,000	479,000	91.86%
Shower containment	33,000	405,000	91.85%

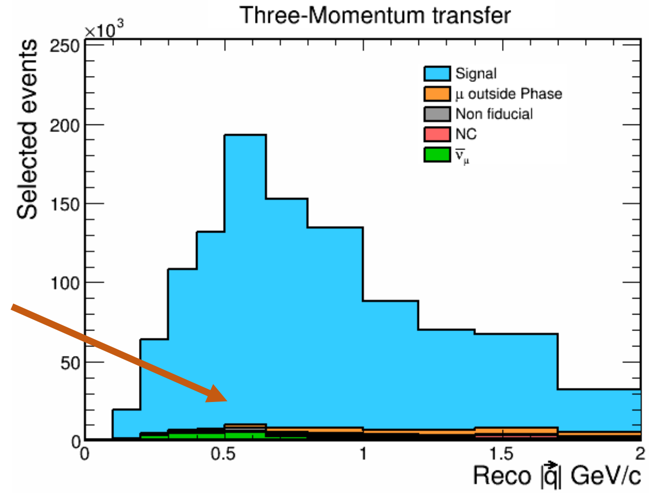


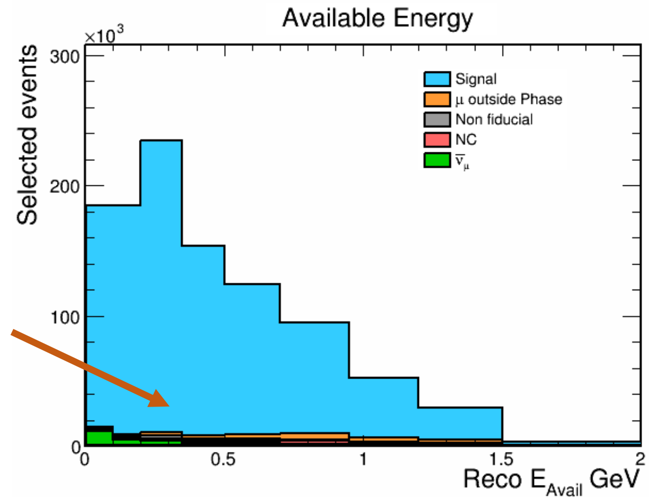


Hadronic variables
Background events in sample:

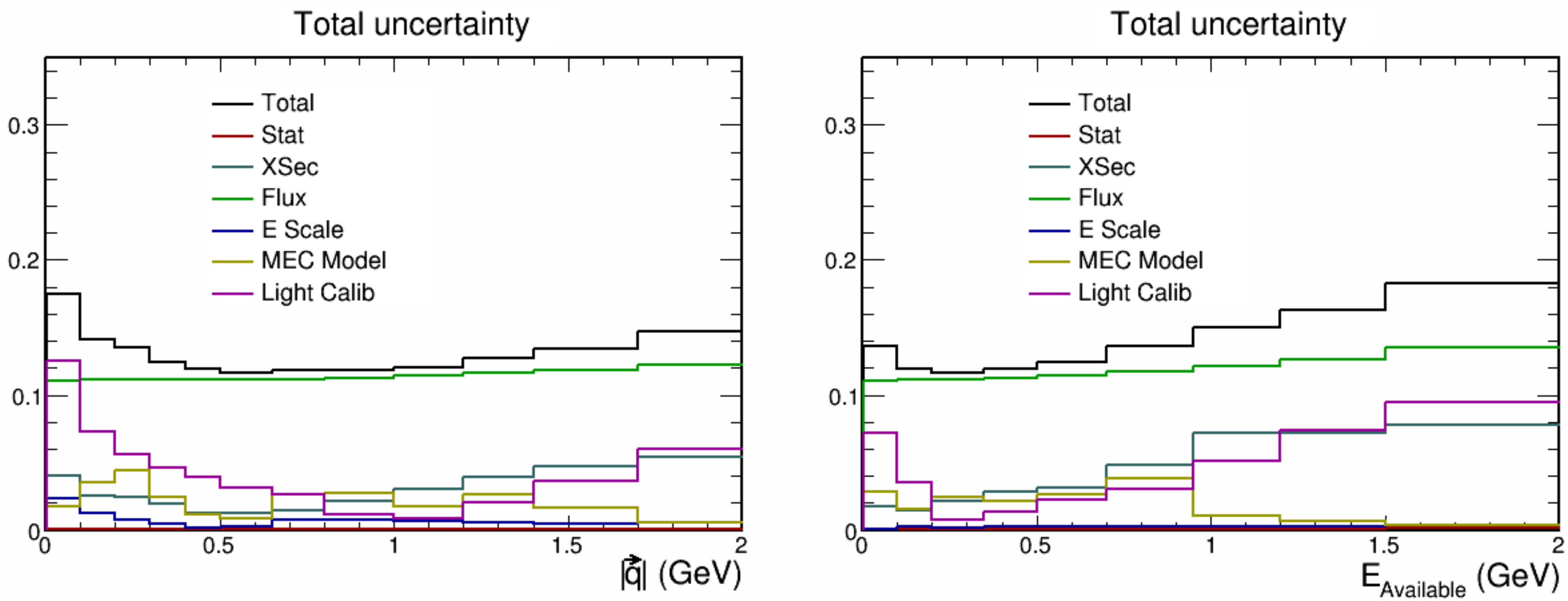
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta} U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - \boldsymbol{N_{\alpha\beta}^{Bkgd}}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

Process	Selected events	Event fraction
Signal	372,000	91.85%
Total background	33,000	8.15%
Outside phase space	15,000	3.70%
Non-fiducial	7,600	1.78%
CC Anti-neutrino	6,000	1.48%
Neutral current	4,200	1.04%
Electron neutrino	160	0.04%

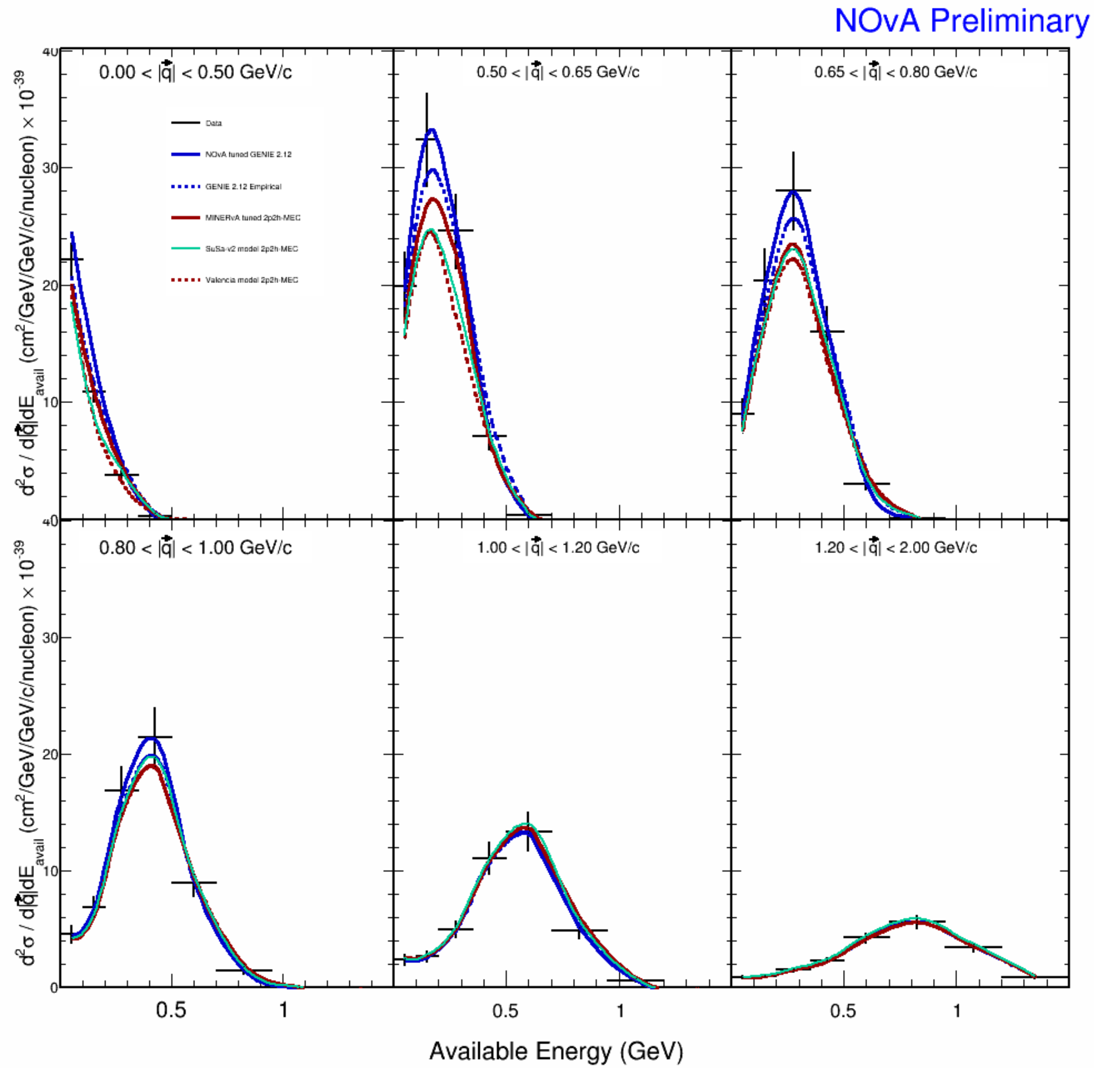




Hadronic variables-Summary of uncertainties



Hadronic variables
Results all slices



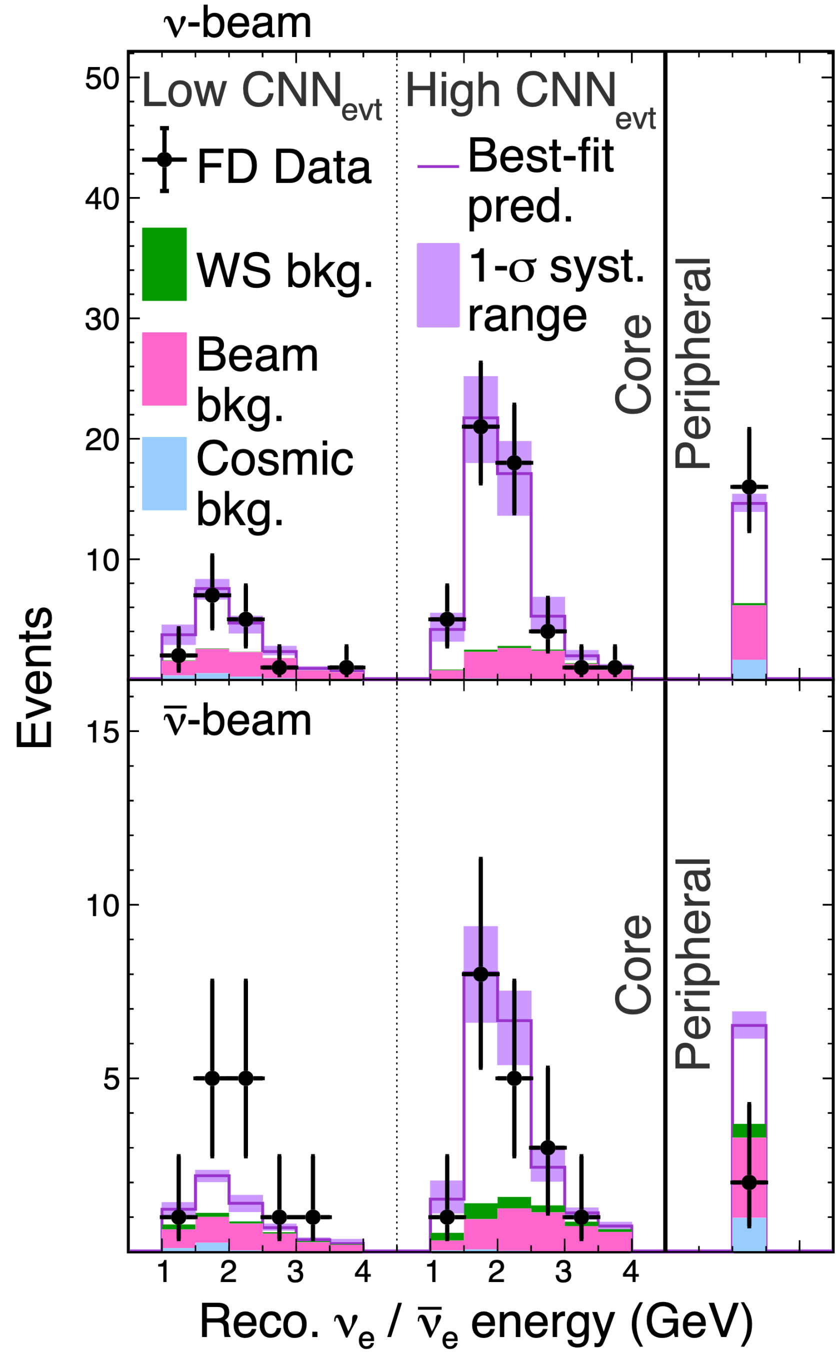
Far Detector
ν_e and $\bar{\nu}_e$ spectra

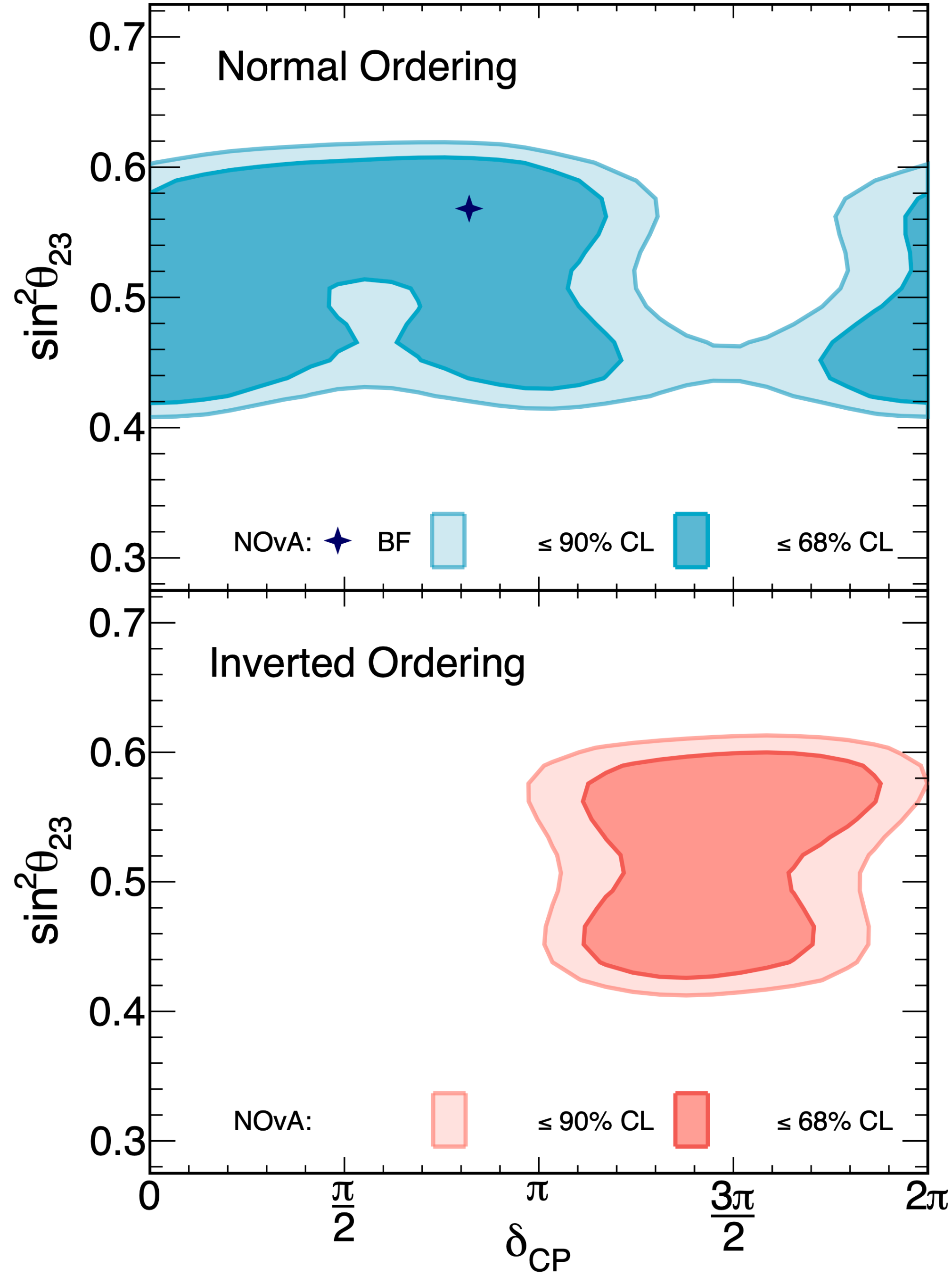
2020 data set: https://arxiv.org/abs/2108.08219

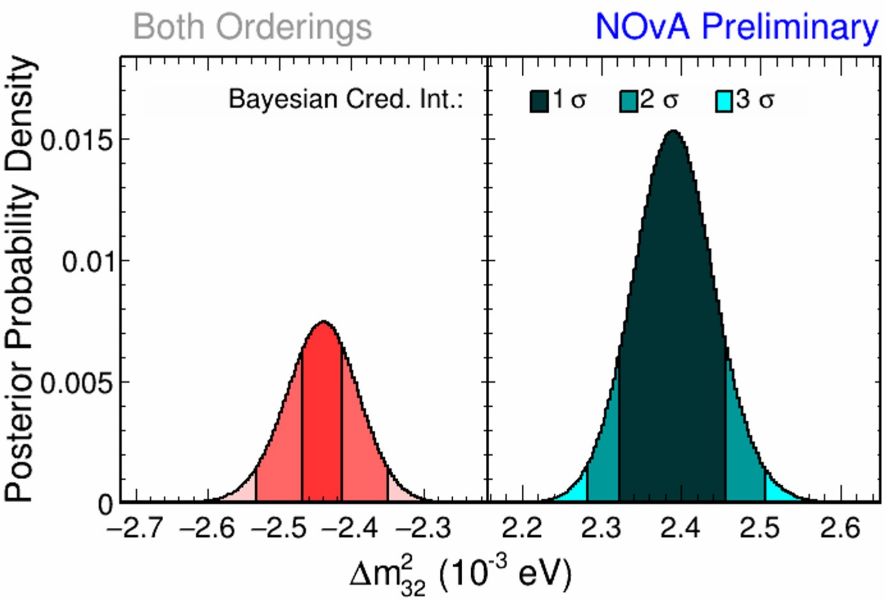
Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

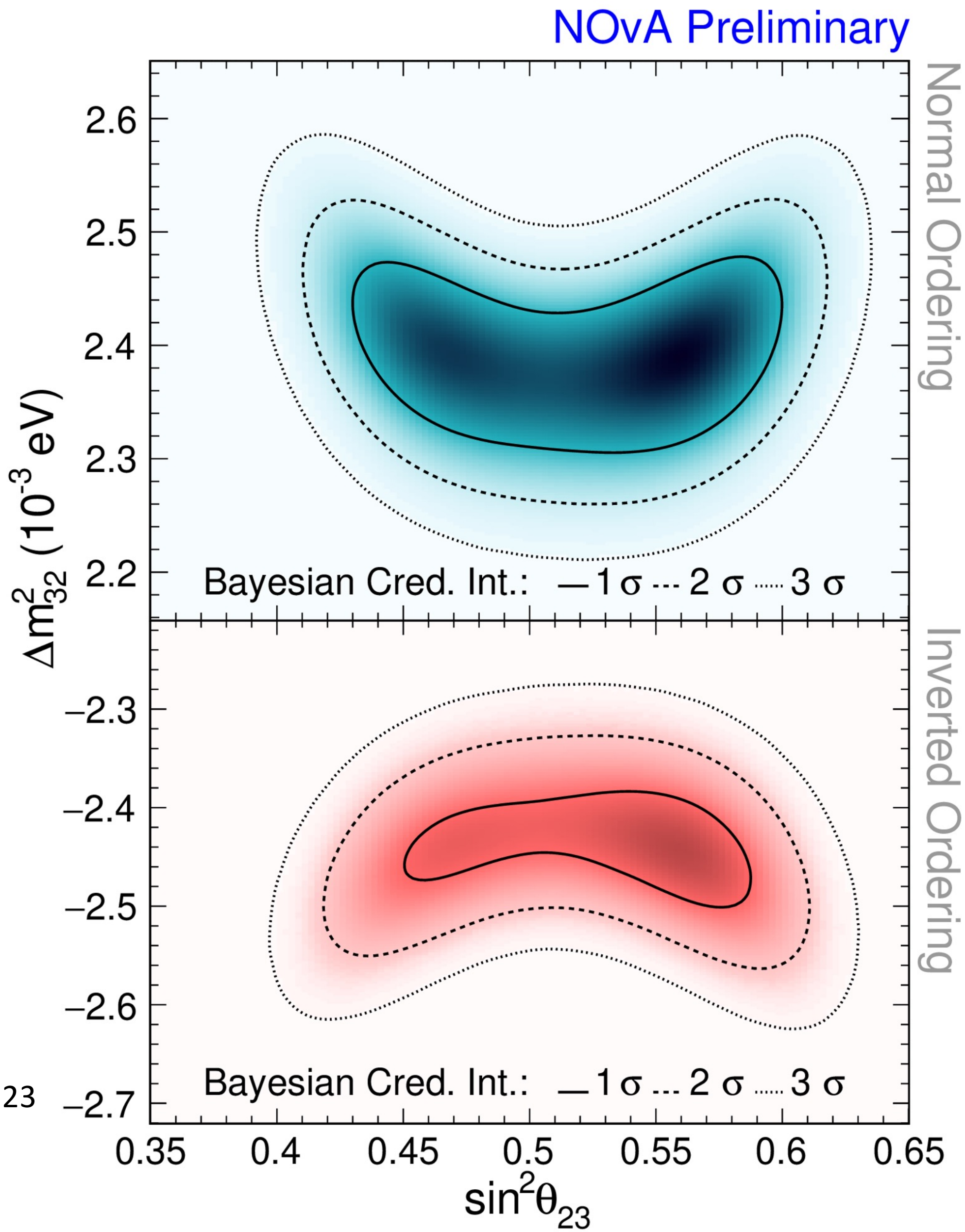
>4σ evidence of $\bar{\nu}_e$ appearance



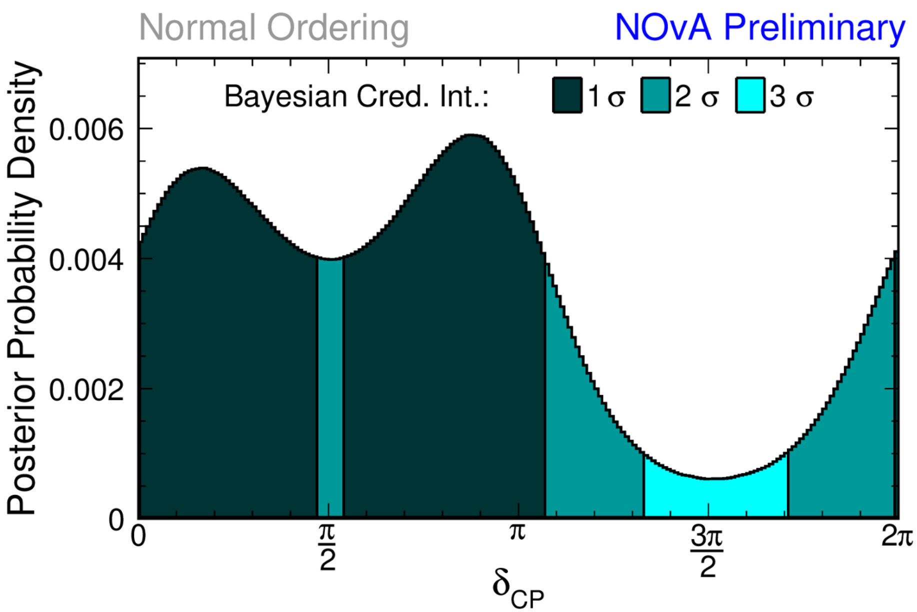

Normal Ordering
Inverted Ordering
$\sin^2\theta_{23}$
0.7
0.6
0.5
0.4
0.3
NOvA: BF
≤ 90% CL
≤ 68% CL
NOvA:
≤ 90% CL
≤ 68% CL
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
δ_{CP}

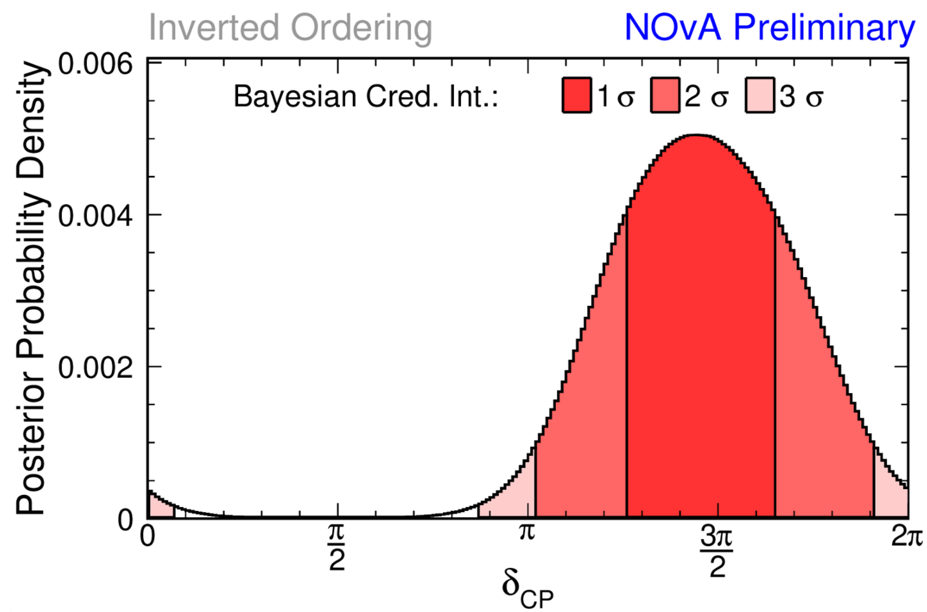


Posterior Probability	Lower Octant	Upper Octant	Sum
Normal Ordering	0.26	0.42	0.68
Inverted Ordering	0.11	0.21	0.32
Sum	0.37	0.63	1.00

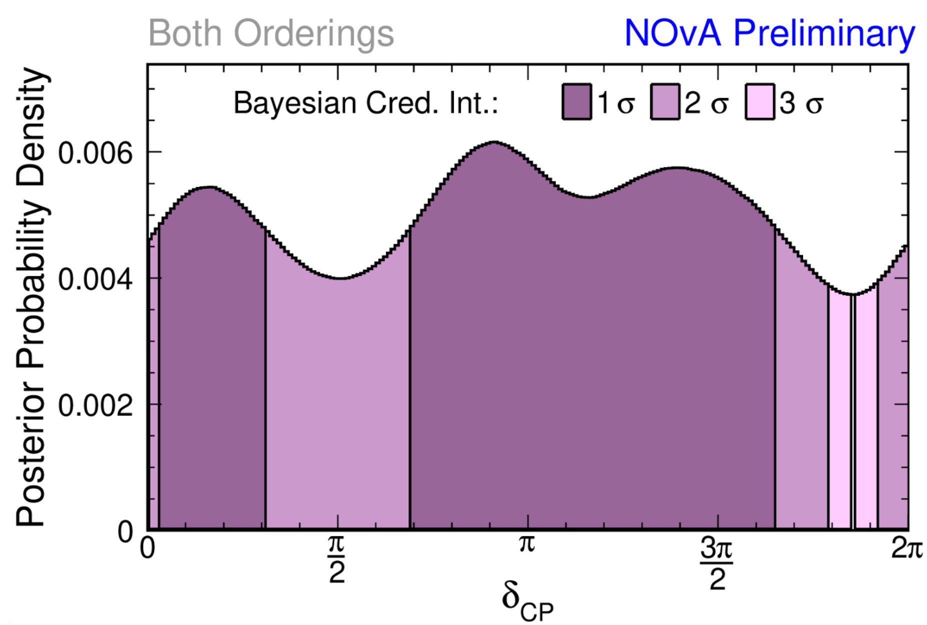


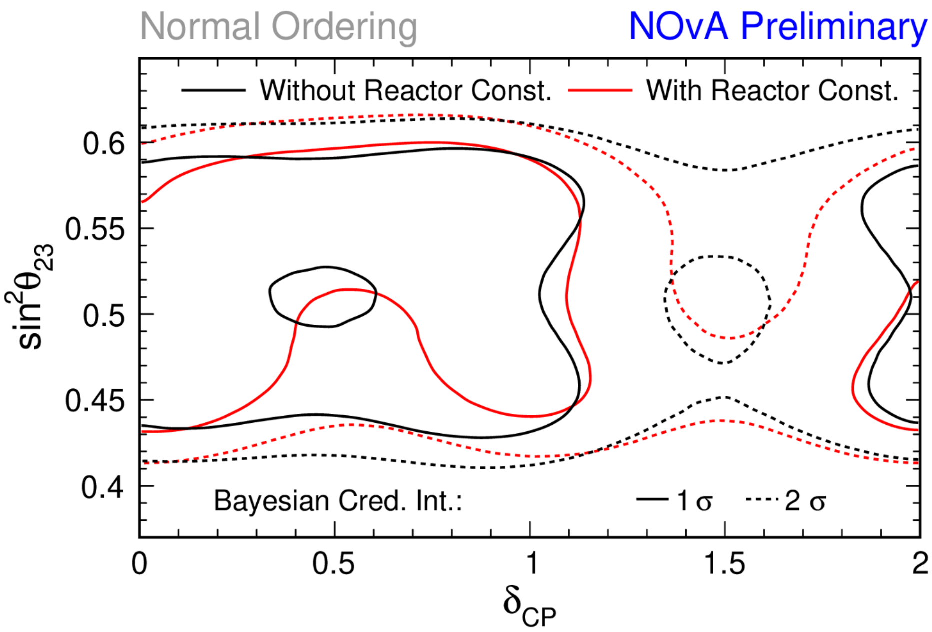
- Weak preference for upper octant of θ_{23} and Normal Mass Ordering.

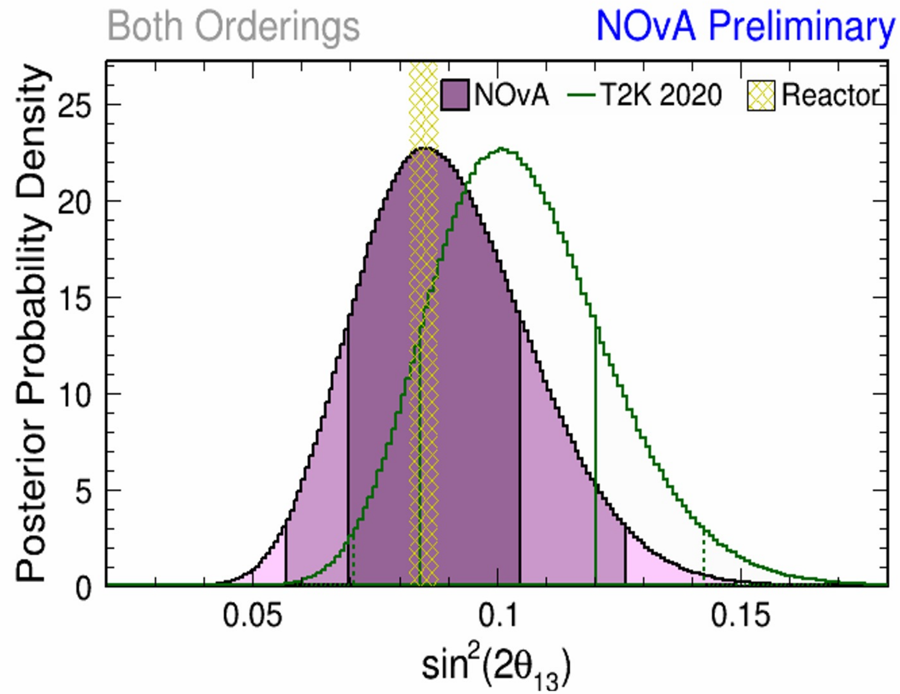


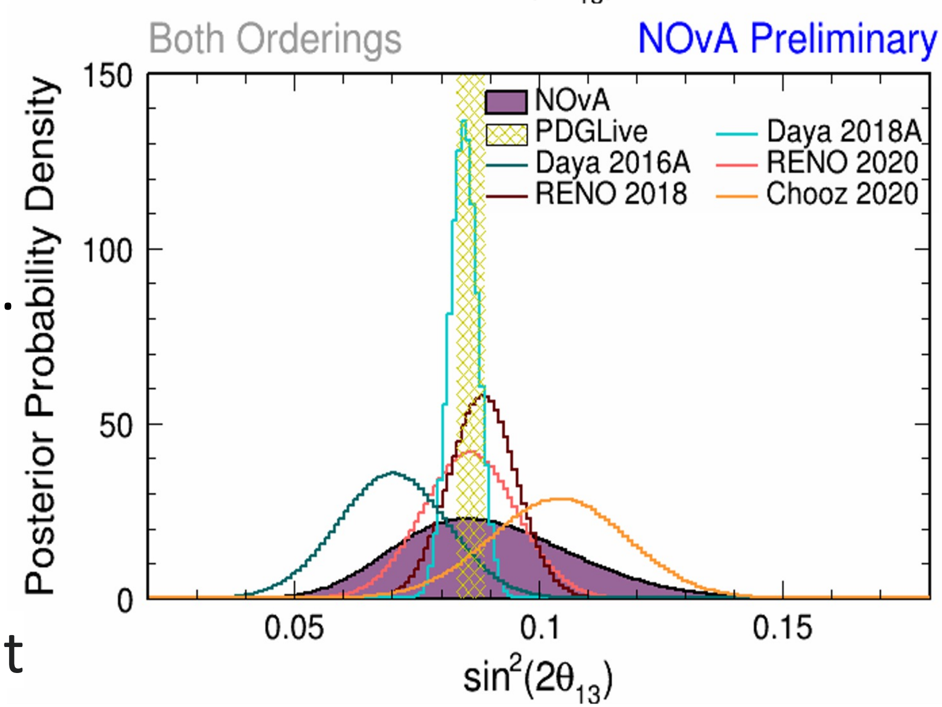


- CP violation more probable in the Inverted Mass Ordering.
- $3\pi/2$ disfavoured in the Normal Ordering at more than 2σ Credible Interval.
- When both orderings taken into the account, no strong preference for δ.





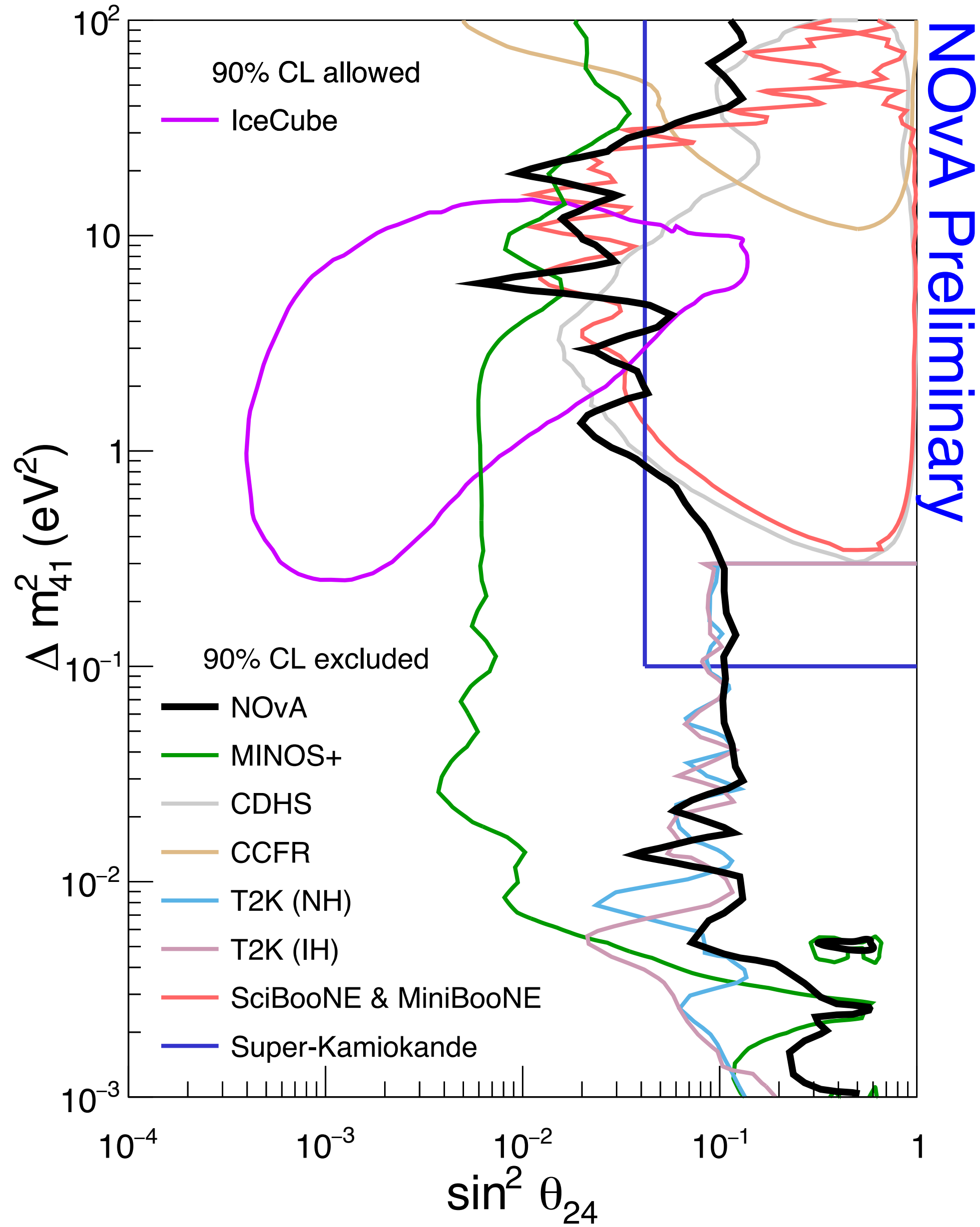




- No tension between T2K and NOvA for θ_{13}.
- No tension between accelerator and reactor neutrino experiments.
- Long-distance $\nu_\mu \to \nu_e$ agree with short-distance $\bar{\nu}_e \to \bar{\nu}_e$.
- Higher preference for the Upper Octant with the Reactor Constraint

Sterile Neutrino Search Results

- Citations:
  - SK: K. Abe et al. (Super-Kamiokande), Phys. Rev. D 91, 052019 (2015)
  - CDHS: F. Dydak et al. (CDHSW), Phys. Lett. B 134, 281 (1984)
  - CCFR: I.E. Stockdale et al. (CCFR), Phys. Rev. Lett. 52, 1384 (1984)
  - SciBooNE: K. B. M. Mahn et al. (SciBooNE, MiniBooNE), Phys. Rev. D 85, 032007 (2012)
  - MINOS+: P. Adamson et al. (MINOS+) Phys. Rev. Lett. 122, 091803 (2019)
  - T2K: K. Abe et al. (T2K) Phys. Rev. D 99, 071103(R) (2019)
  - IceCube: M. G. Aartsen et al. (IceCube), Phys. Rev. Lett. 125, 141801 (2020)



Papers

- Recent NOvA Papers
  - "Adjusting neutrino interaction models and evaluating uncertainties using NOvA near detector data", Eur.Phys.J.C 80 (2020) 12, 1119
  - "Measurement of Neutrino-Induced Neutral-Current Coherent π0 Production in the NOvA Near Detector", Phys.Rev.D 102 (2020) 1, 012004
  - Search for Slow Magnetic Monopoles with the NOvA Detector on the Surface", Phys.Rev.D 103 (2021) 1, 012007
  - "Seasonal Variation of Multiple-Muon Cosmic Ray Air Showers Observed in the NOvA Detector on the Surface", Phys.Rev.D 104 (2021) 1, 012014
  - "Extended search for supernova-like neutrinos in NOvA coincident with LIGO/Virgo detections", Phys.Rev.D 104 (2021) 6, 063024
  - "Search for active-sterile antineutrino mixing using neutral-current interactions with the NOvA experiment", Phys.Rev.Lett. 127 (2021) 20, 201801
  - "An Improved Measurement of Neutrino Oscillation Parameters by the NOvA Experiment",
  - "Measurement of the Double-Differential Muon-neutrino Charged-Current Inclusive Cross Section in the NOvA Near Detector"