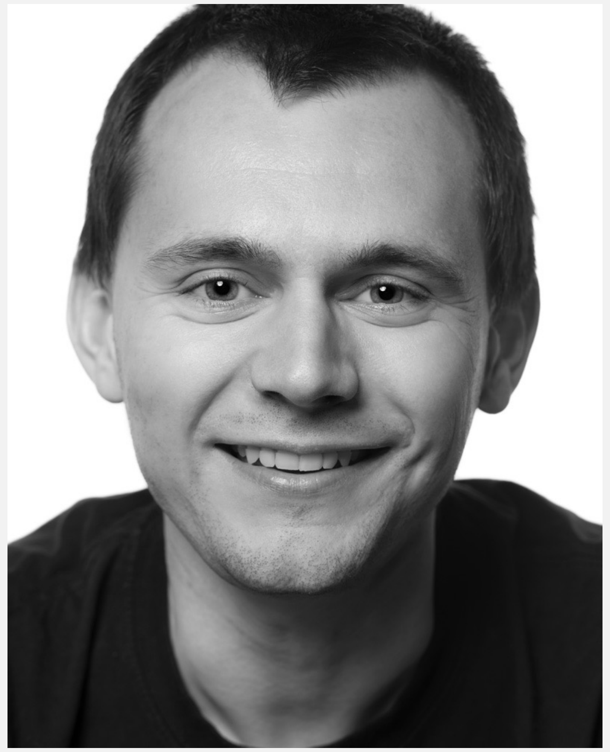


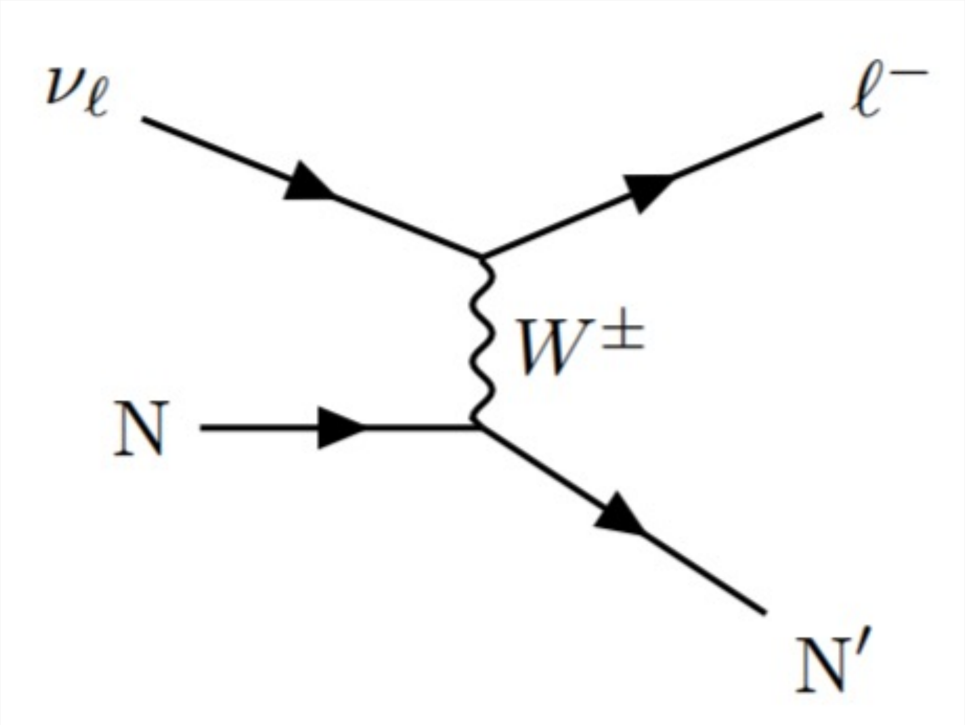
Latest Neutrino Oscillation Results From NOvA & T2K

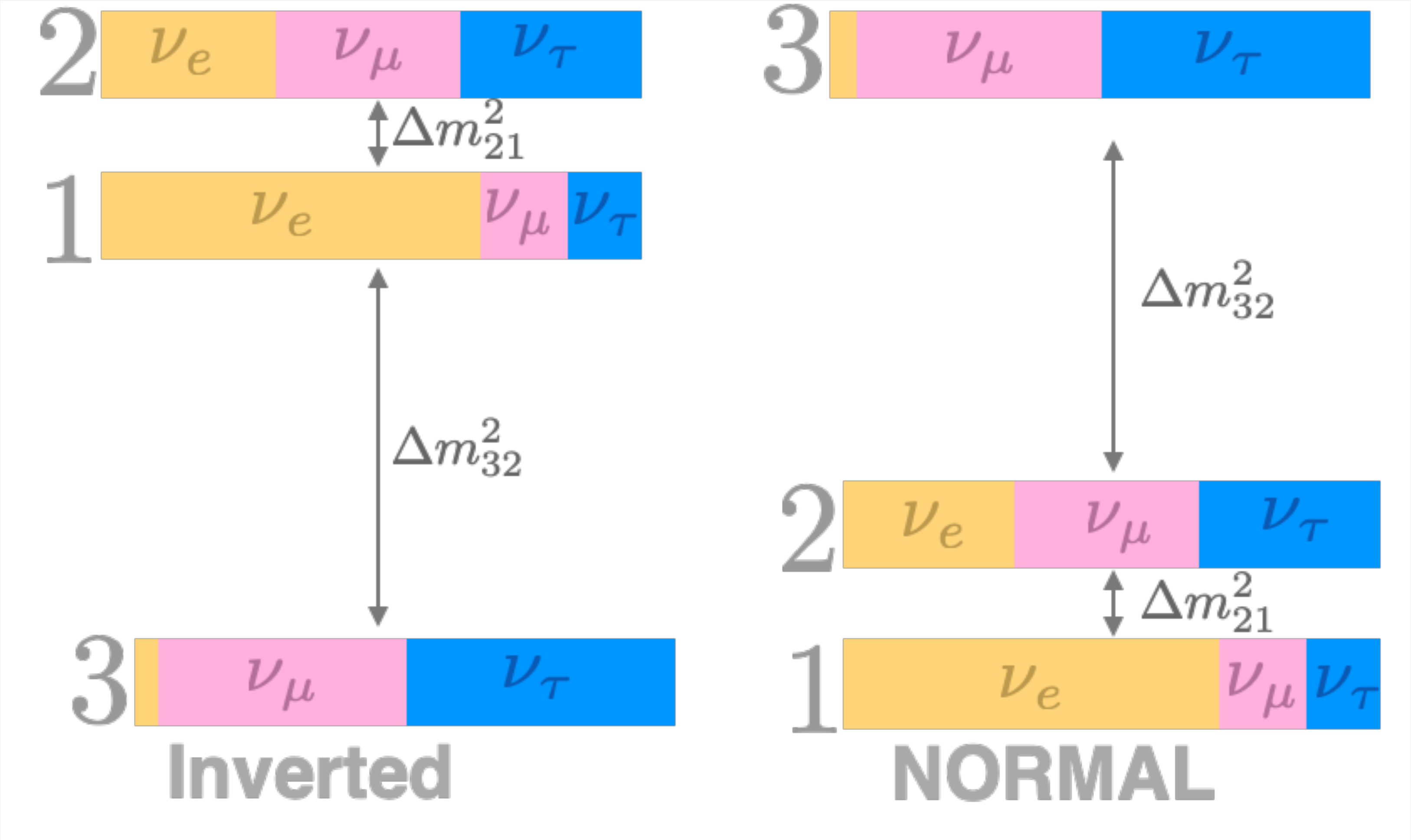
Karl Warburton

Iowa State University

11th May 2022

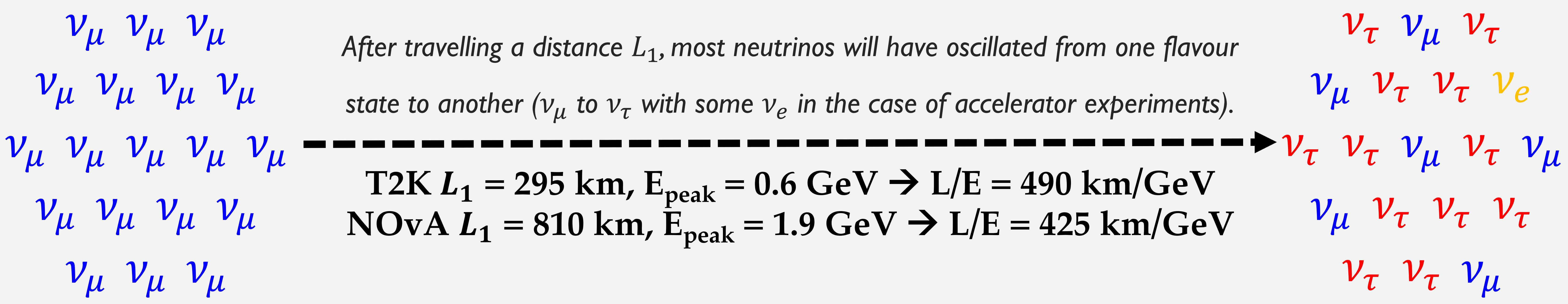
Motivation For Neutrino Oscillation Measurements





- Neutrino interactions are flavor conserving.
  - So, we want to measure the out-going lepton flavour.
- Oscillations occur as ν's propagate not as distinct flavor states but as superpositions of mass/energy eigenstates.
  - We have handles on the differences of these masses, but do not know how they ordered.
- Long-baseline neutrino oscillation experiments like NOvA and T2K measure oscillations using initially ν_μ beams.
  - ν_μ Disappearance ($\nu_\mu \rightarrow \nu_\mu$)
  - ν_e Appearance ($\nu_\mu \rightarrow \nu_e$)

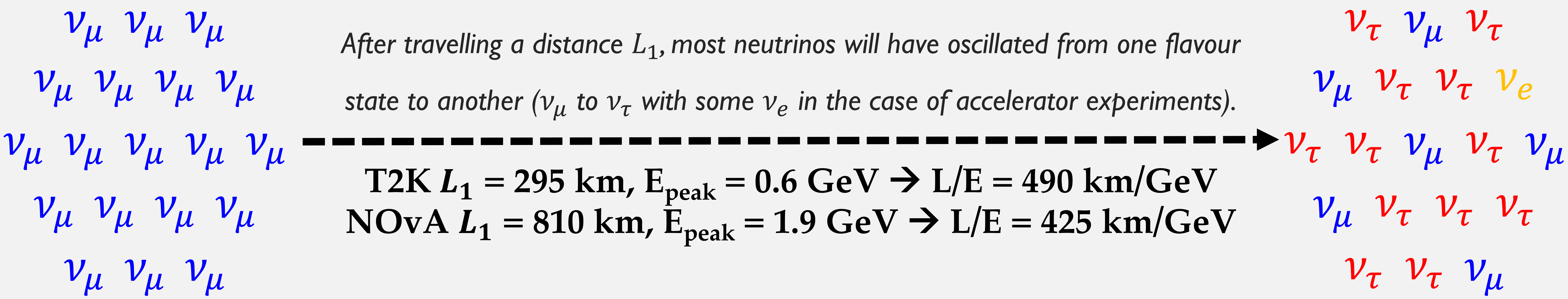
Measuring Long-baseline Neutrino Oscillations



After travelling a distance L_1, most neutrinos will have oscillated from one flavour state to another (ν_μ to ν_τ with some ν_e in the case of accelerator experiments).

T2K L_1 = 295 km, E_{peak} = 0.6 GeV → L/E = 490 km/GeV
NOvA L_1 = 810 km, E_{peak} = 1.9 GeV → L/E = 425 km/GeV

Measuring Long-baseline Neutrino Oscillations



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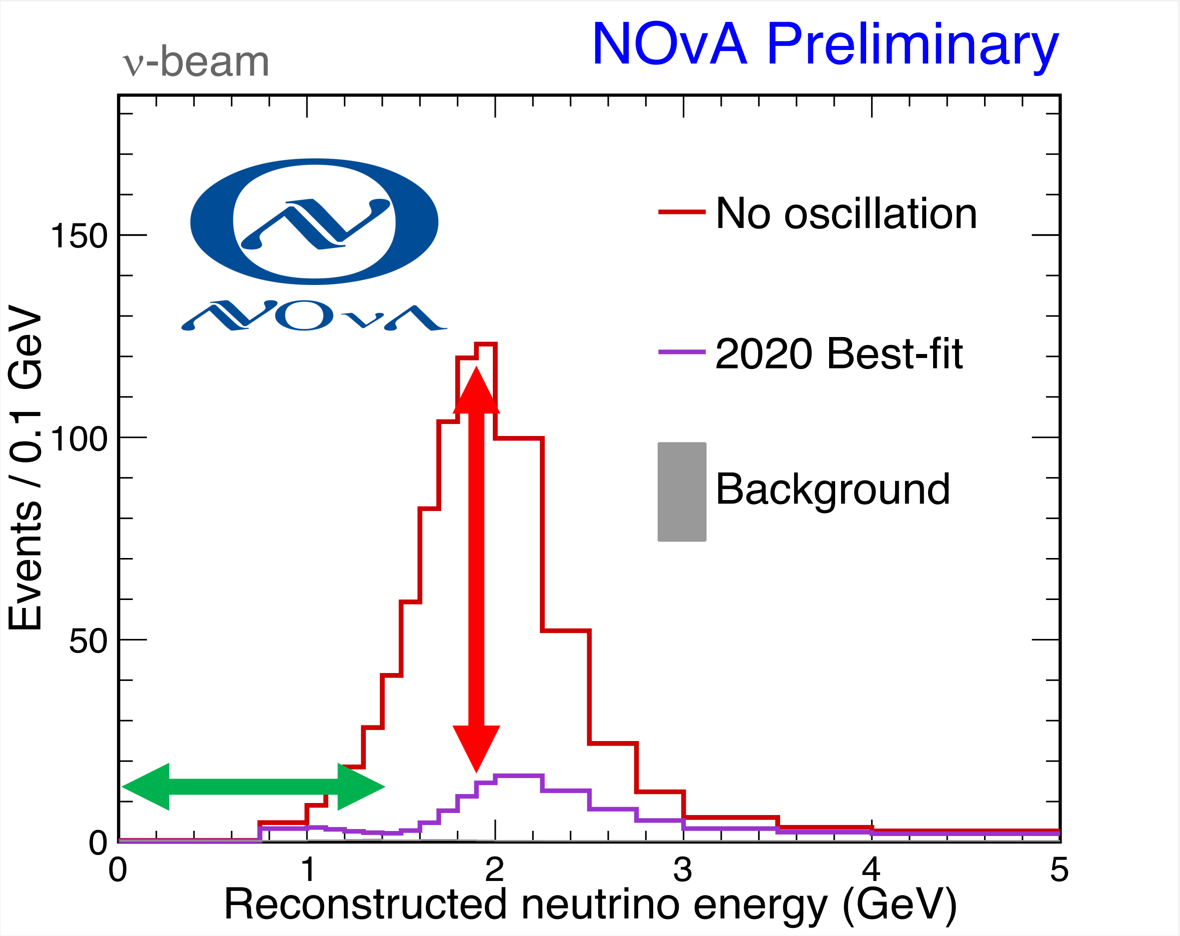

Oscillation rates are effectively a function of L/E in nature, so are energy dependent at a given distance. Mathematically they are described by 6 measurable parameters;

- *Charge-Parity-violating phase δ_{CP}.*
- *Mass-squared diffs $\Delta m^2_{21}, \Delta m^2_{32}$.*
  - *Determine where **maximal oscillation occurs**.*
- *Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$.*
  - *Determine the **magnitude of oscillations** at a given energy.*

How The Flux of Muon Neutrinos Changes in NOvA and T2K

- Both experiments are designed such that the neutrino flux is centred around the first oscillation maximum.
  - Most ν_μ's oscillate away.
  - Maximal appeared ν_e flux.
  - Neither experiment directly measures the ν_τ's which dominate the FD flux – only observe though neutral current interactions.

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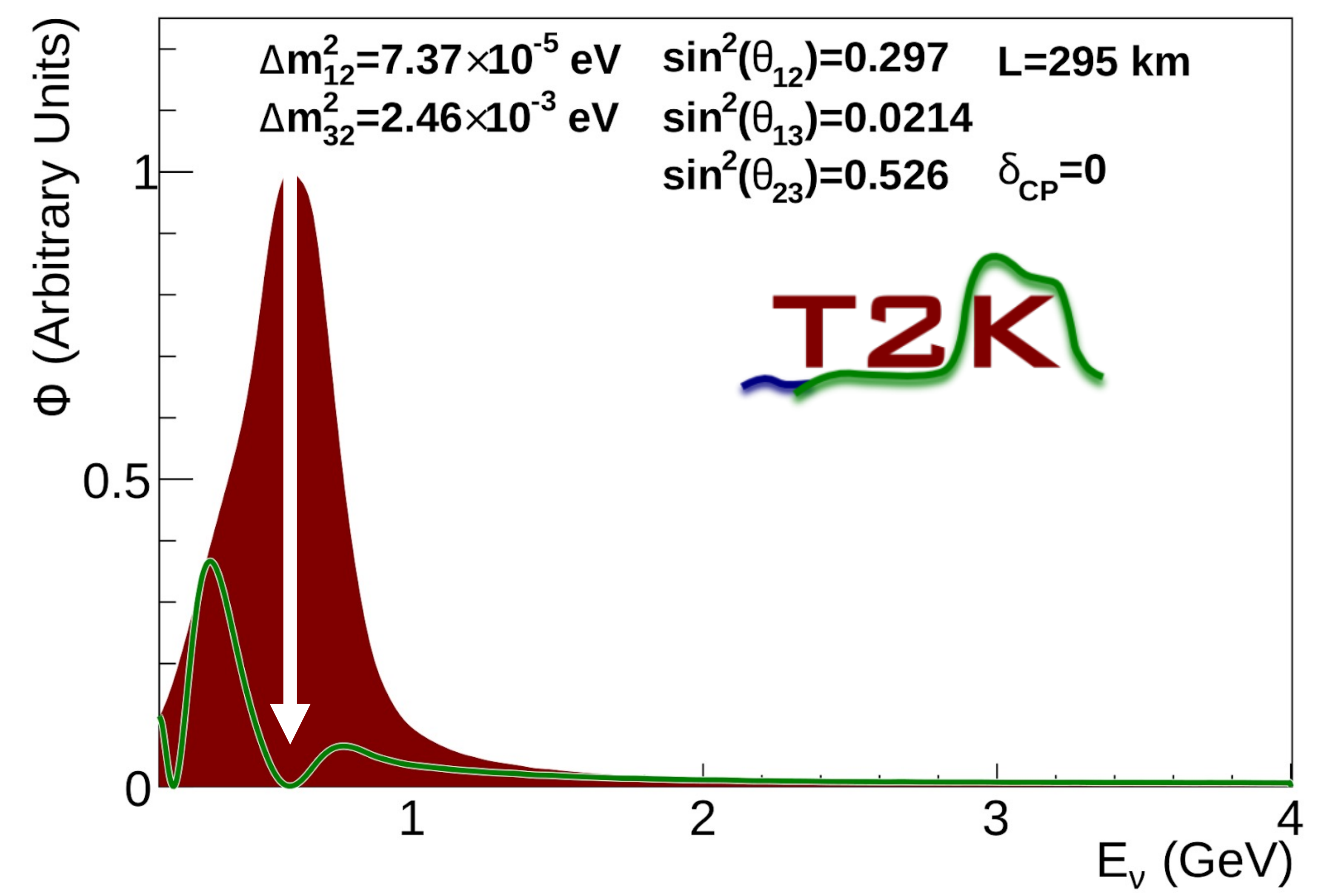
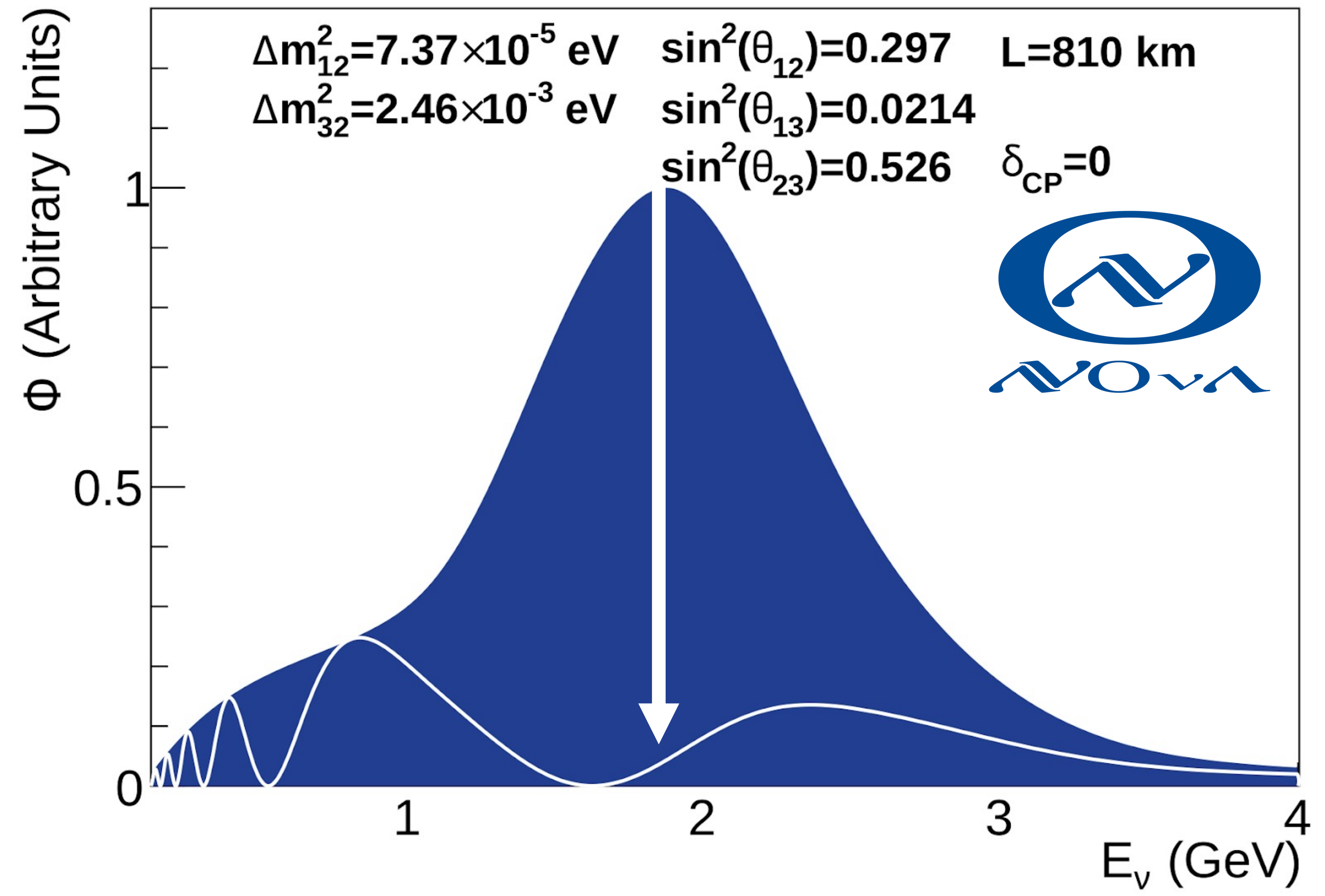
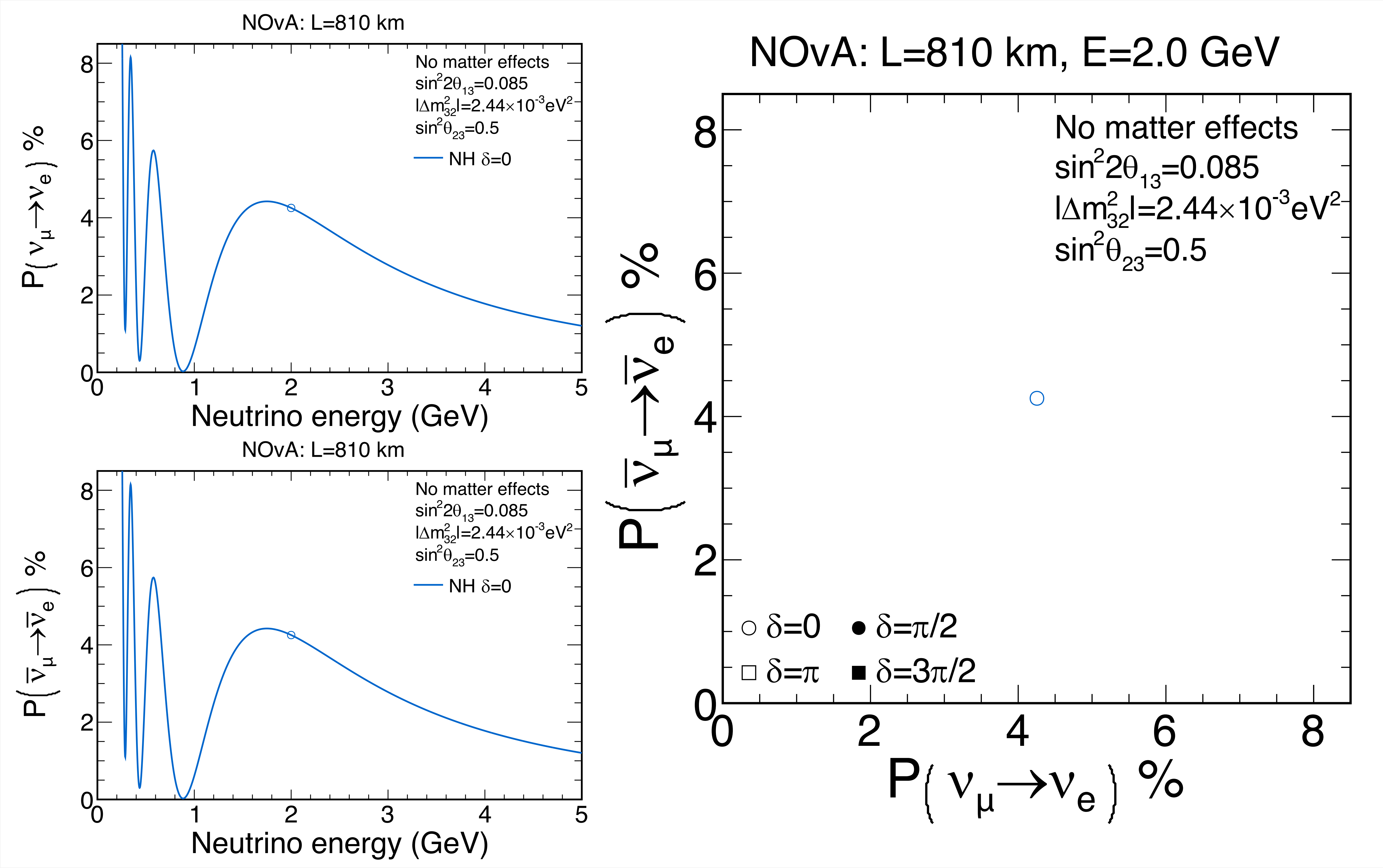




How Oscillation Parameters Affect ν_e Appearance in NOvA

Neutrinos

Anti-Neutrinos



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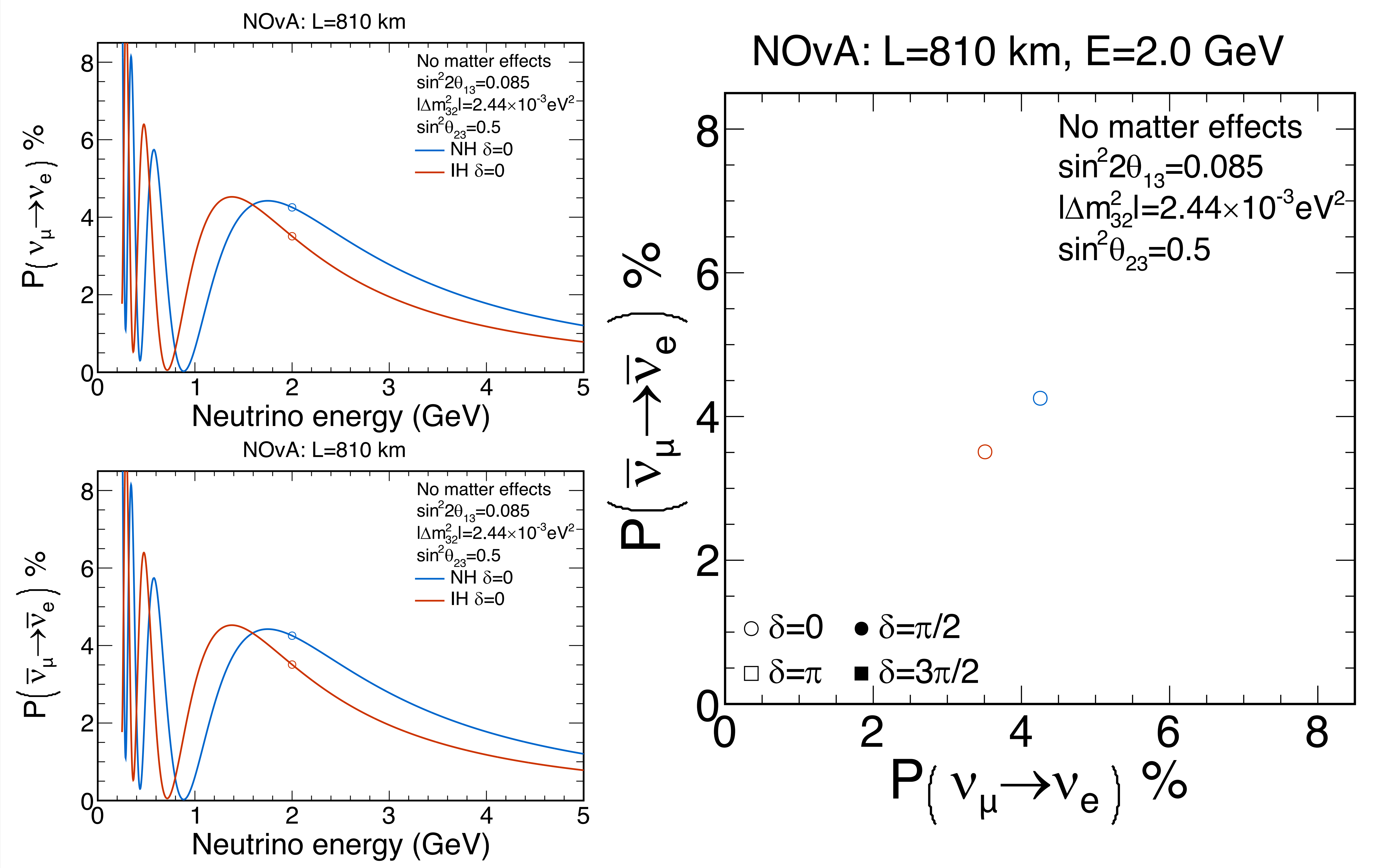

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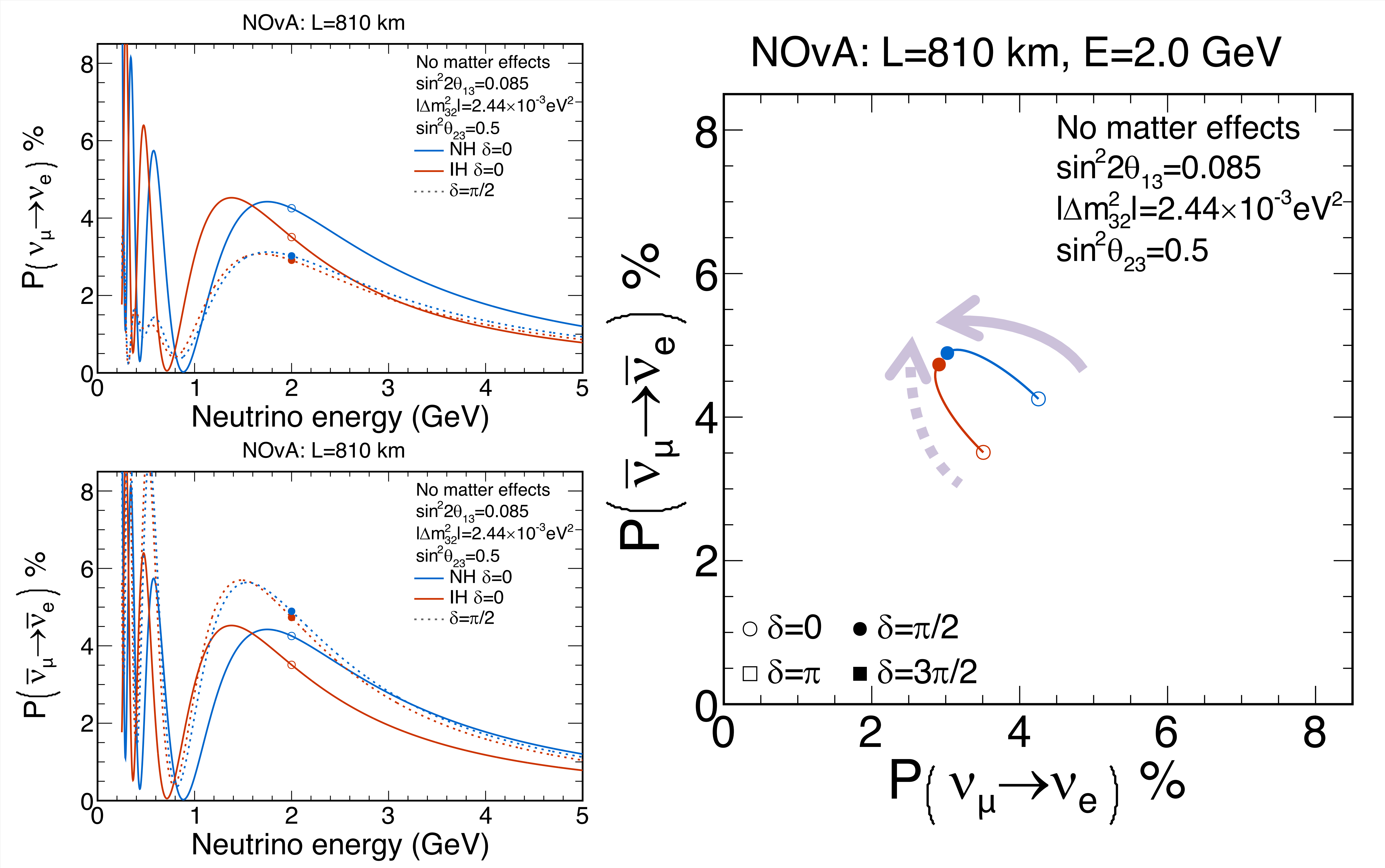

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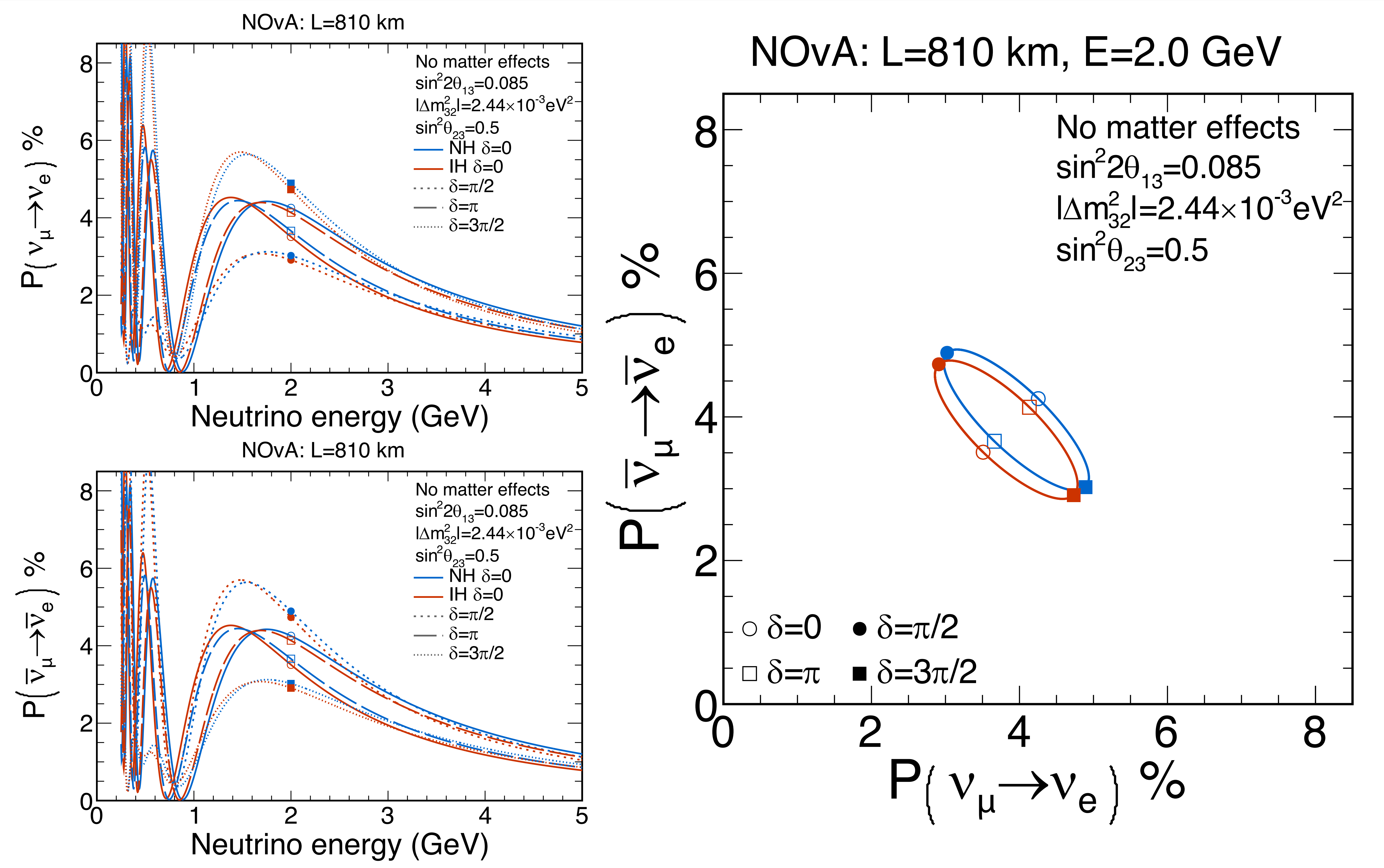

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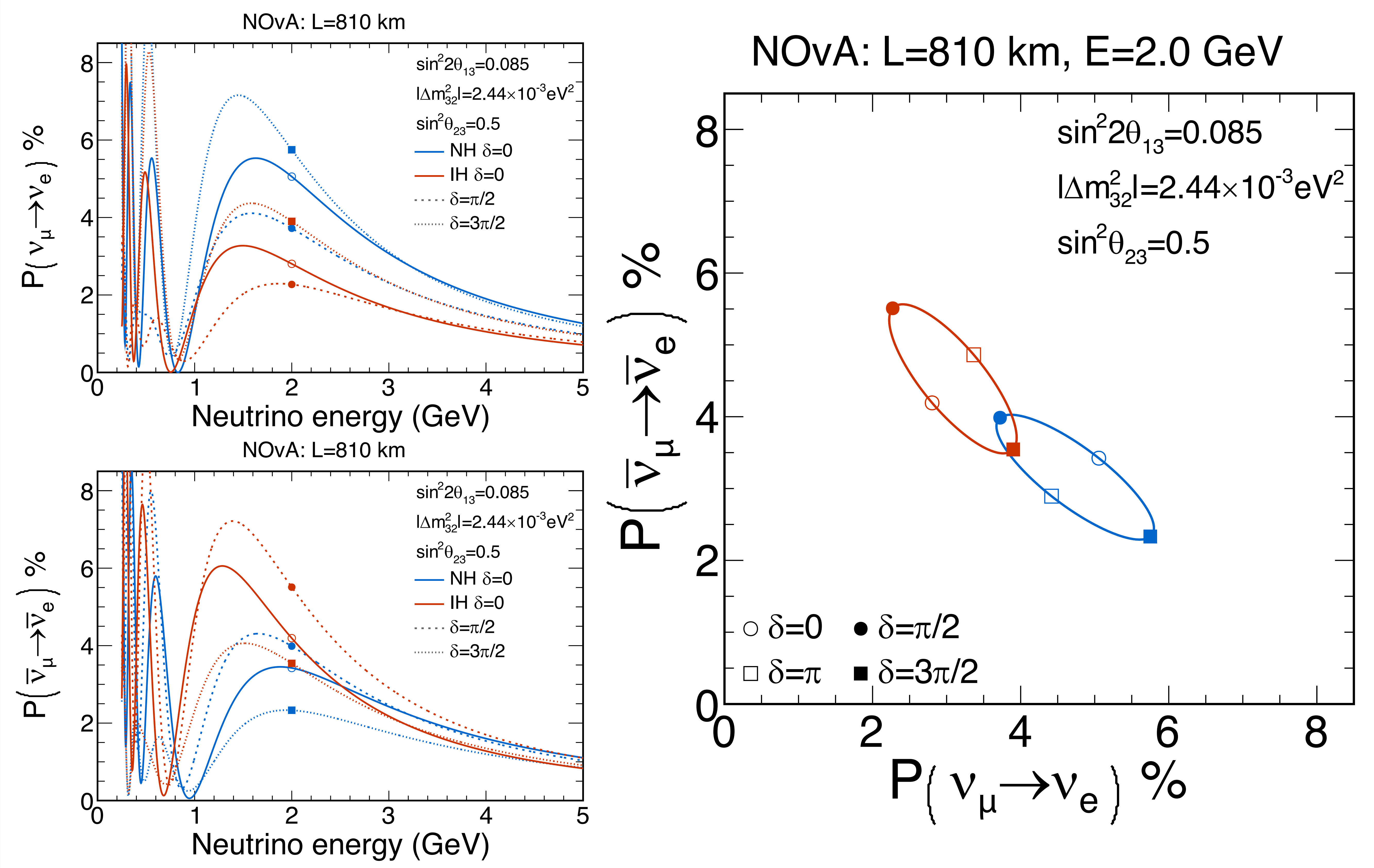

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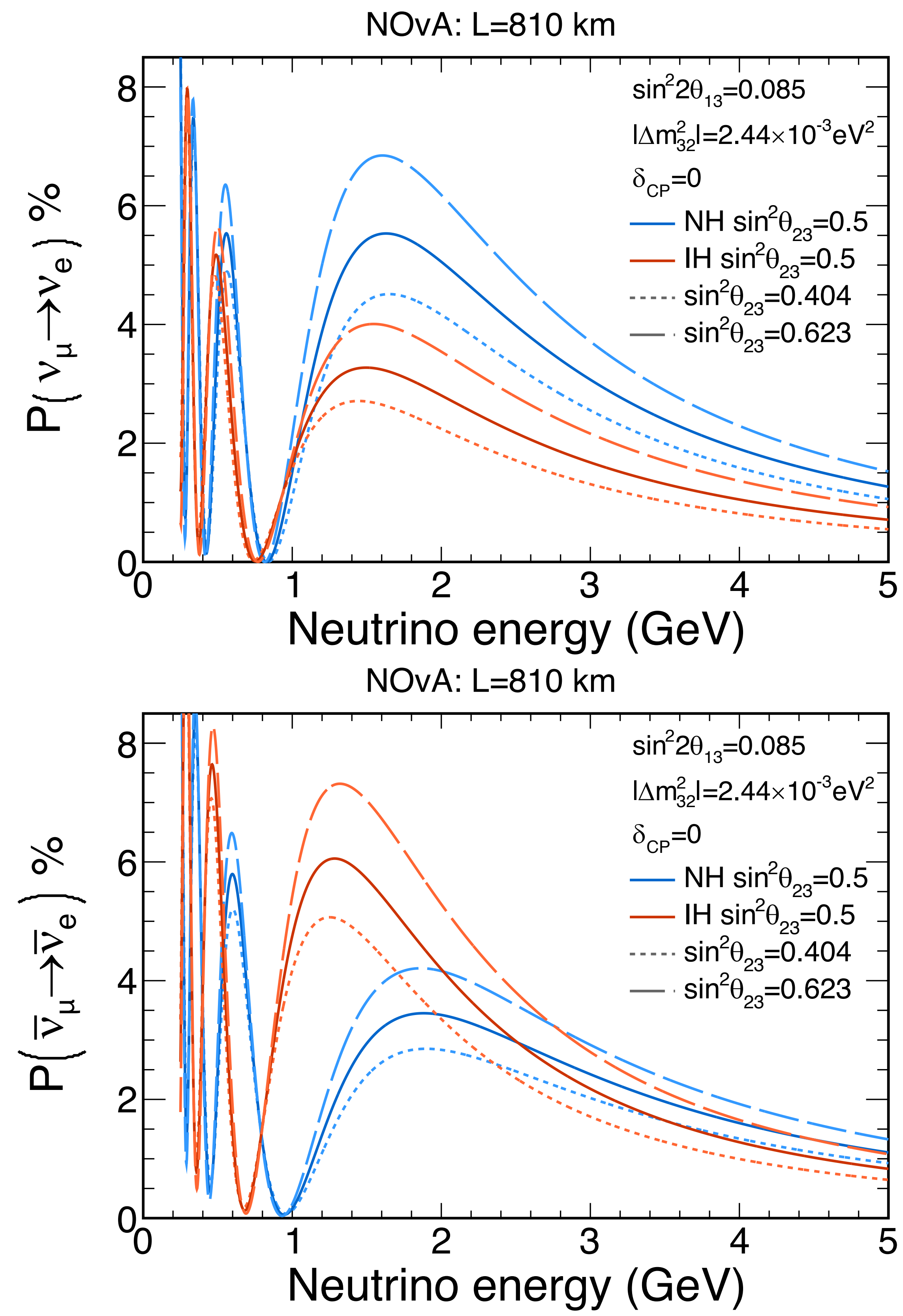
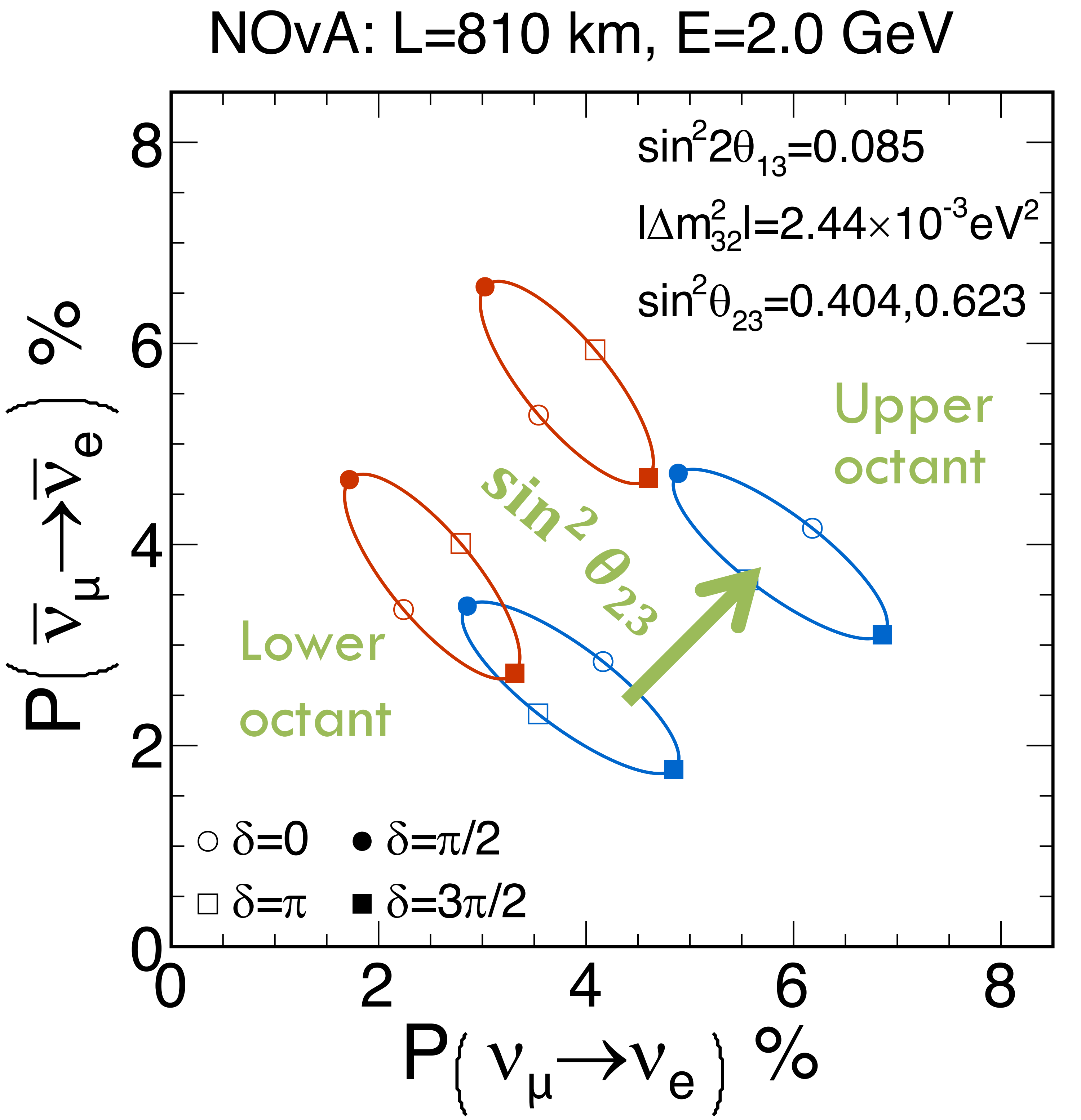




Performing A Neutrino Oscillation Analysis

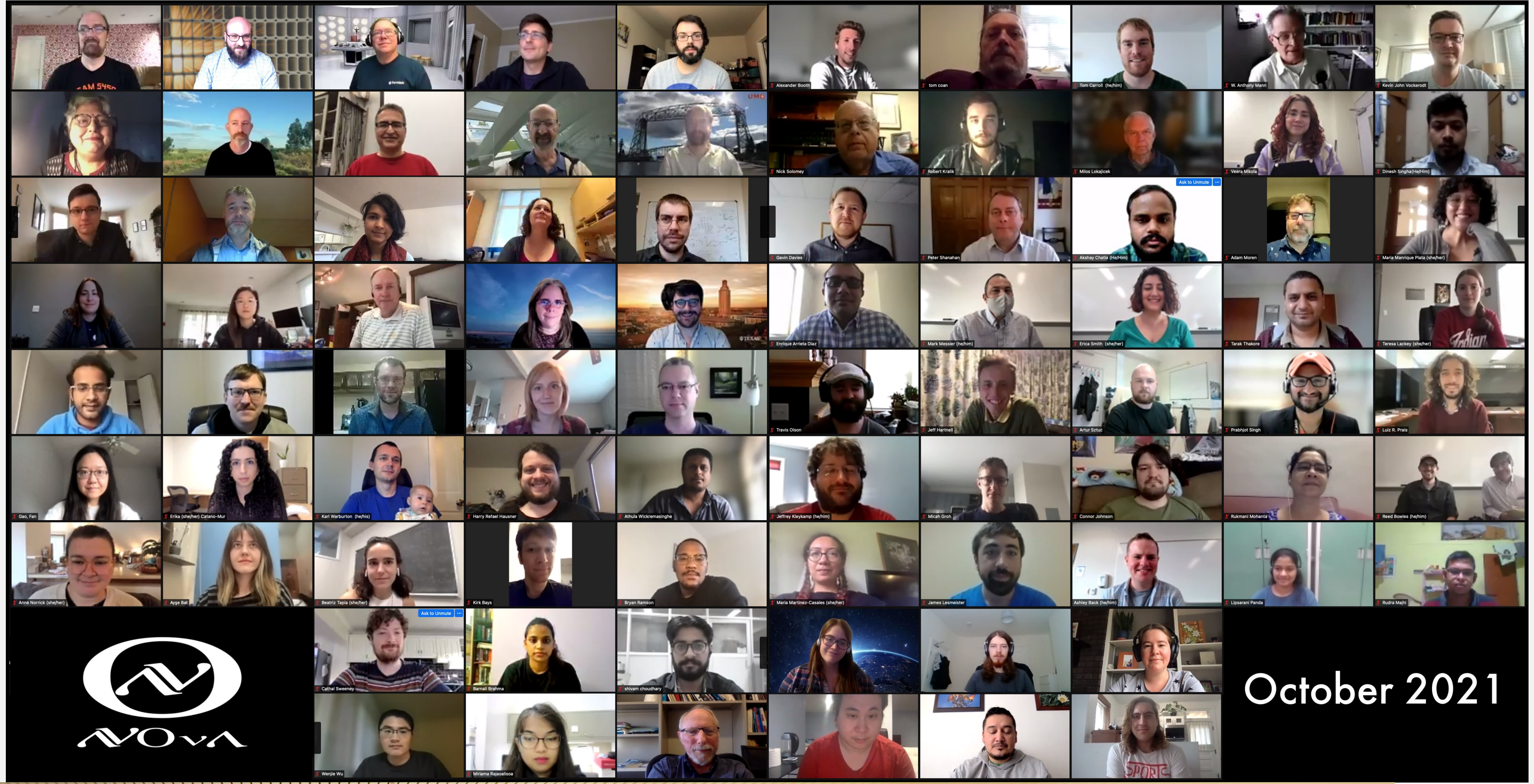
- Long-baseline neutrino oscillation experiments perform two sets of measurements;
  - Measure interactions before oscillations can occur at a Near Detector, using this data to study neutrino interactions.
  - Measure interactions after oscillations have occurred at a very large Far Detector, using this data to extract oscillation parameters.

- NOvA and T2K have a number of differences both in design and approach.
  - These differences make their results very complementary and allow for a thorough test of neutrino physics measurements.

Factor	***Invert for $\bar{\nu}$***	***Effect of NOvA***	***Effect on T2K***	***Explanation***
Mass Ordering	*Yes*	$\pm\mathbf{19}\%$	$\pm 10\%$	*Binary, NOvA has longer Baseline.*
CP Violation	*Yes*	$[-20\ldots+20]\%$	$[\mathbf{-30}\ldots\mathbf{+30}]\%$	*Continuous, T2K beam energy closer to 1st Osc. Max.*
θ_{23} *Octant*	*No*	$[-20\ldots+20]\%$	$[-20\ldots+20]\%$	*Continuous and unbounded effect on Osc. rate.*

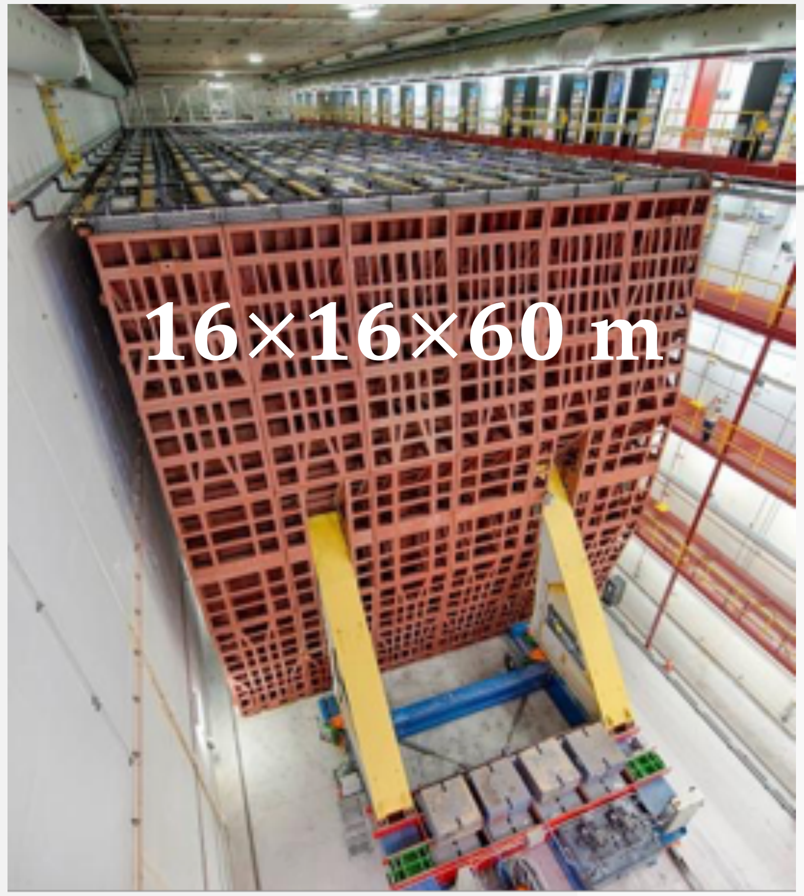
The Experiments

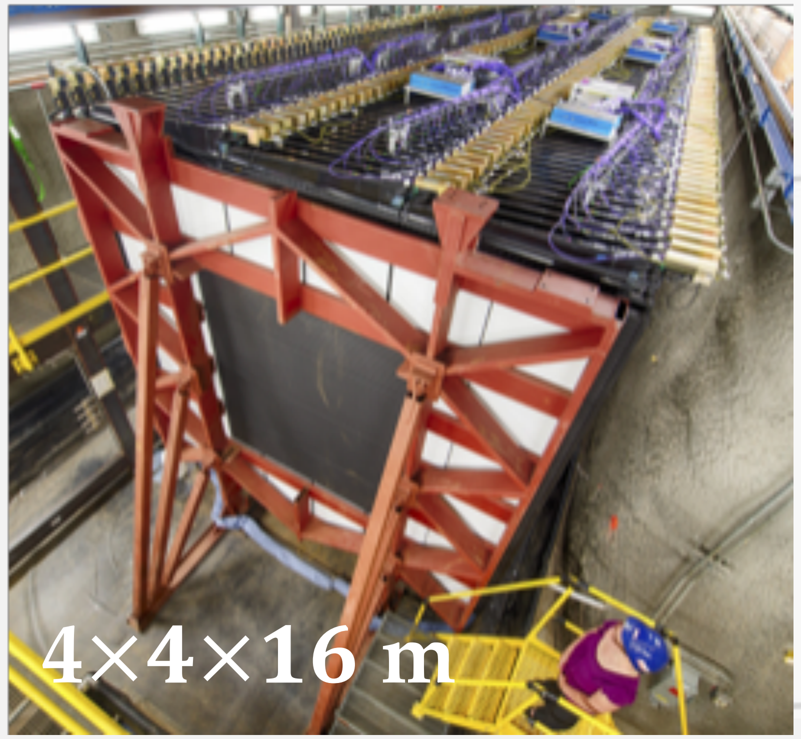
- Both large, international collaborations.
- Key physics goals are measuring neutrino oscillations, but also perform many other physics measurements.



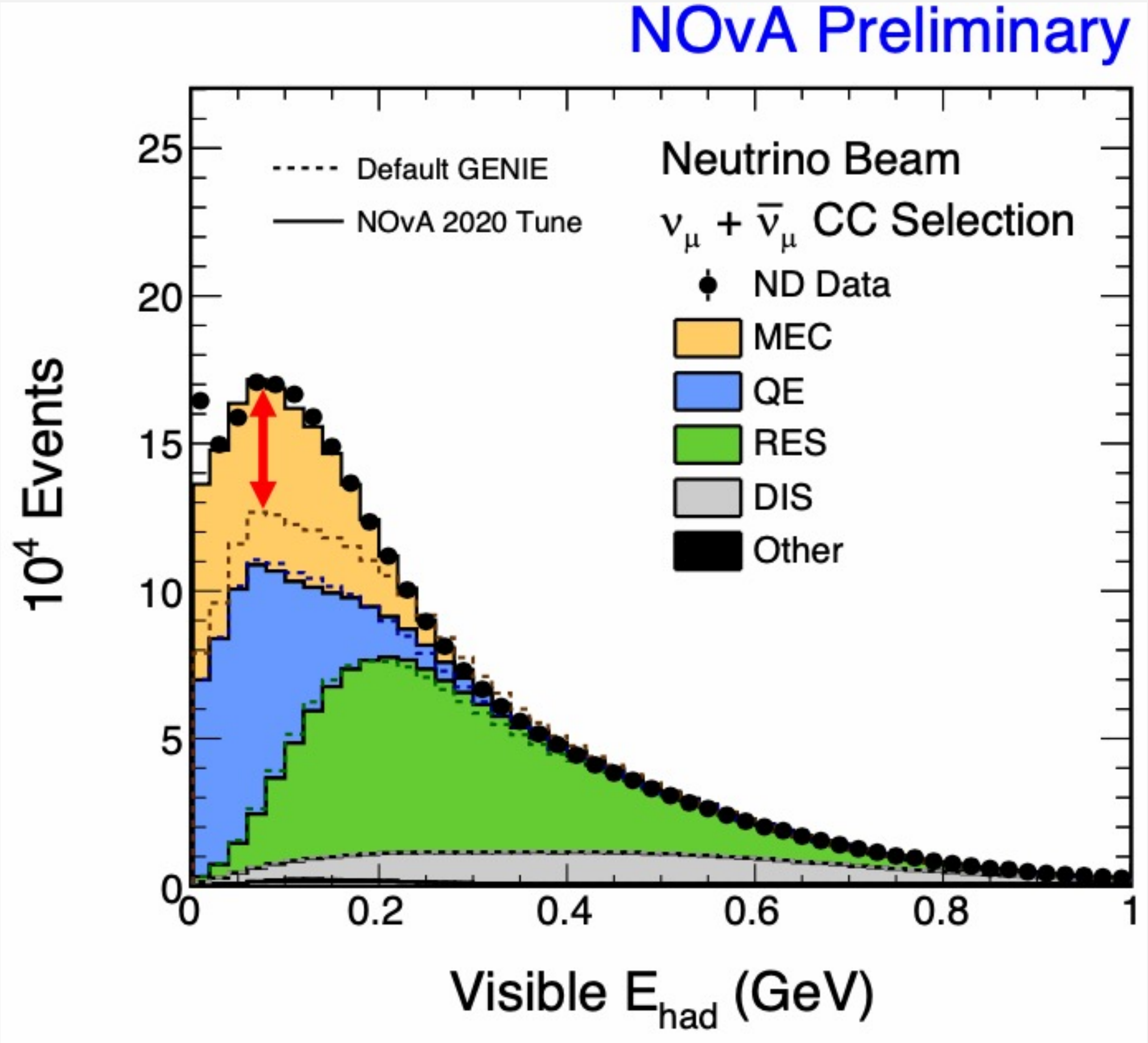
The NuMI Off-Axis ν_e Appearance (NOvA) Experiment

- Uses the Neutrinos at the Main Injector (NuMI) beamline at Fermilab, IL.
- Consists of two functionally identical sampling calorimeters which are 810 km apart.
- Detectors are constructed out of alternating planes of plastic scintillator to achieve 3D reconstruction.
- Has excellent timing resolution allowing for the rejection of the high cosmic ray flux at the FD.



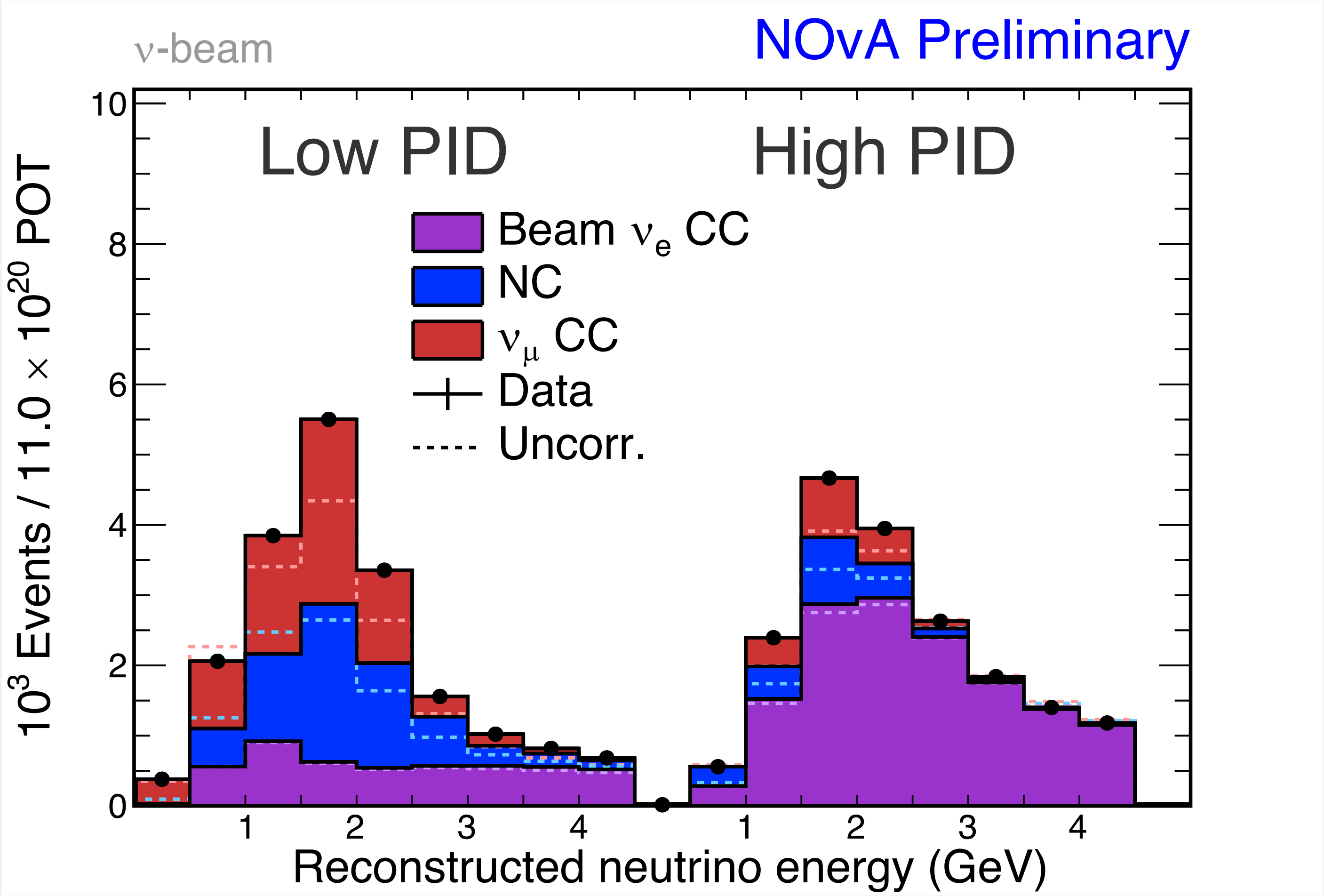


Using the NOvA Near Detector

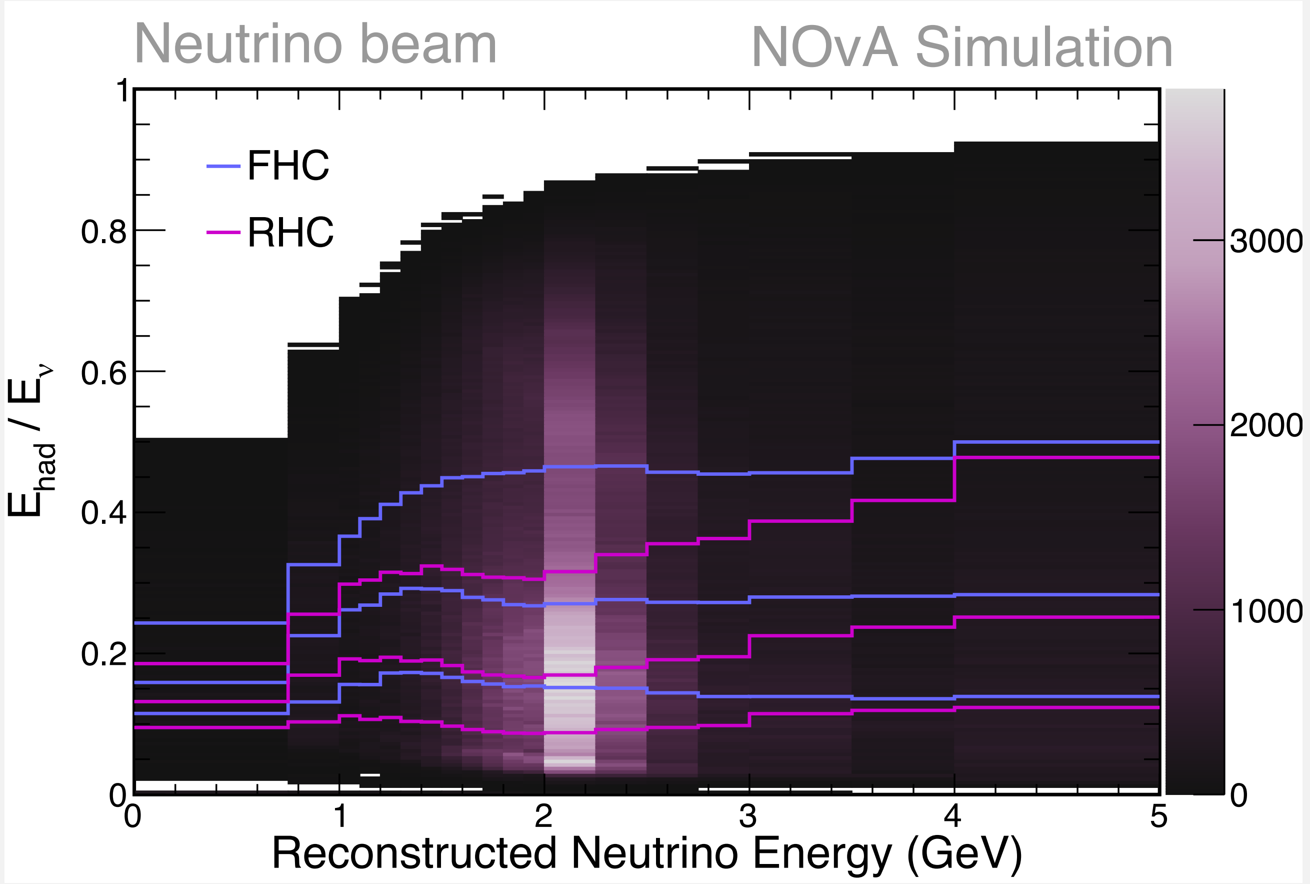


- Raw simulation significantly under-predicts near detector data.
  - Tuning is performed, taking external pion-scattering data as additional input.
  - Large changes are required to the 2p2h (MEC) model.
- By design, the post-tune Monte Carlo almost exactly matches ND data.
- Tuning is performed separately for neutrino and anti-neutrino modes.

- The ND is also used to measure beam ν_e's, the largest background to the ν_e appearance measurement in the FD.
  - Pion and kaon weights are scaled to ensure data/simulation agreement.

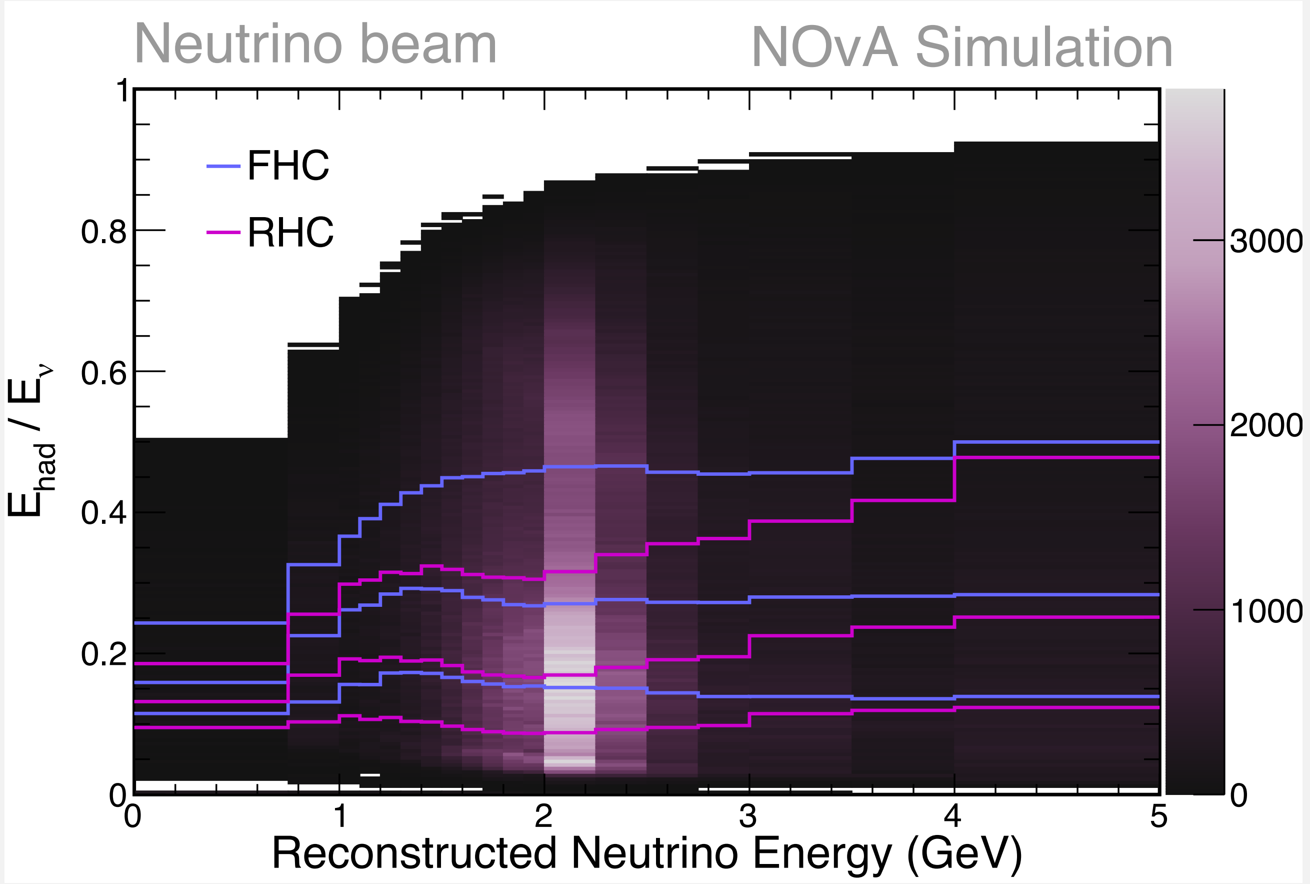


Separating Neutrino Samples



- Increased sensitivity by separating selected events into sub-samples.
  - By energy resolution (hadronic energy fraction) for ν_μ events.
  - By purity ("low" and "high" PID bins) for ν_e events.
  - The ν_e sample also includes an uncontained, high-PID sample.

Separating Neutrino Samples



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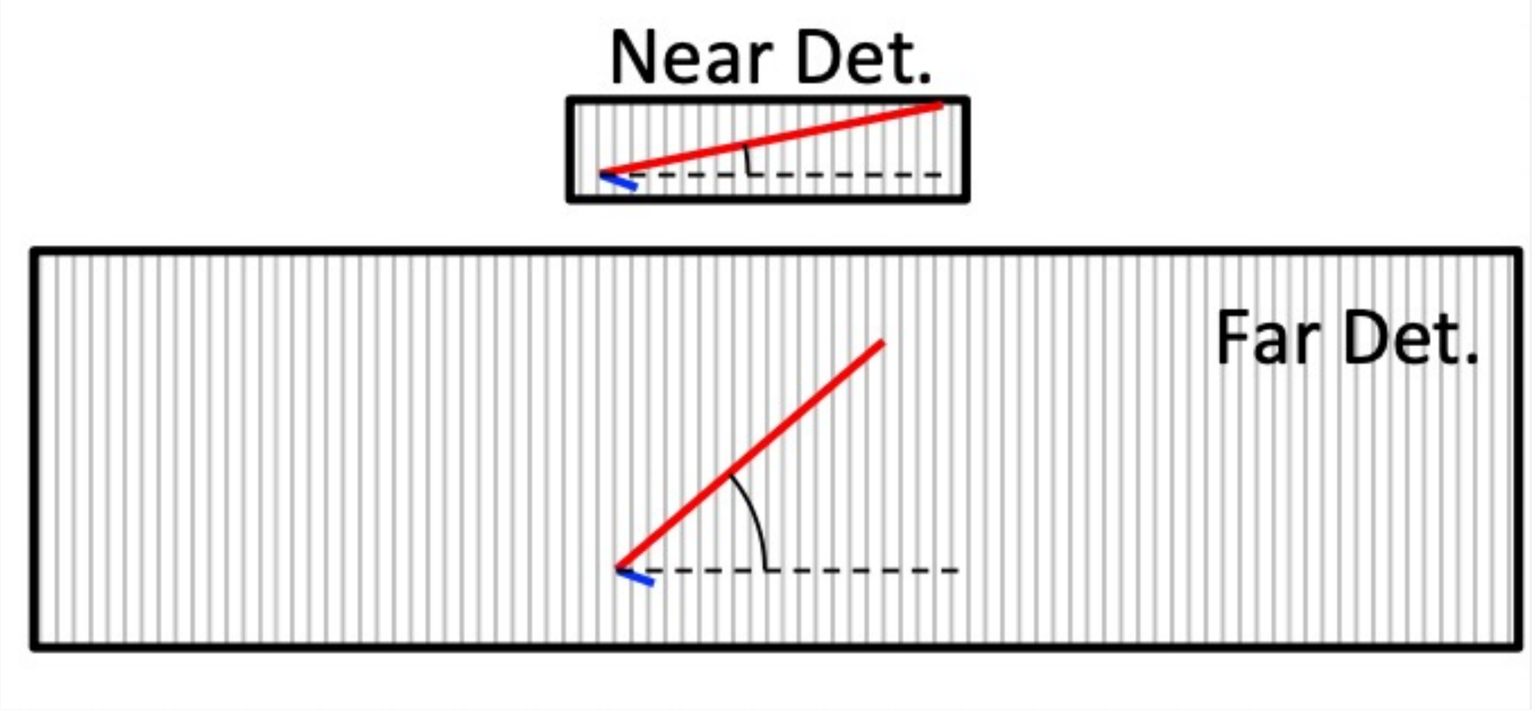
  - The ν_e sample also includes an uncontained, high-PID sample.

- NOvA also extrapolates in bins of lepton trans. mom. (p_t).
  - The ND and FD have very different lepton angle acceptances.
  - Allows NOvA to rebalance the kinematics between the detectors.
  - These bins are then recombined for fitting.



In predicting the Far Detector event count, NOvA also takes advantage of the fact that the two detectors are functionally identical, and so many uncertainties cancel out.

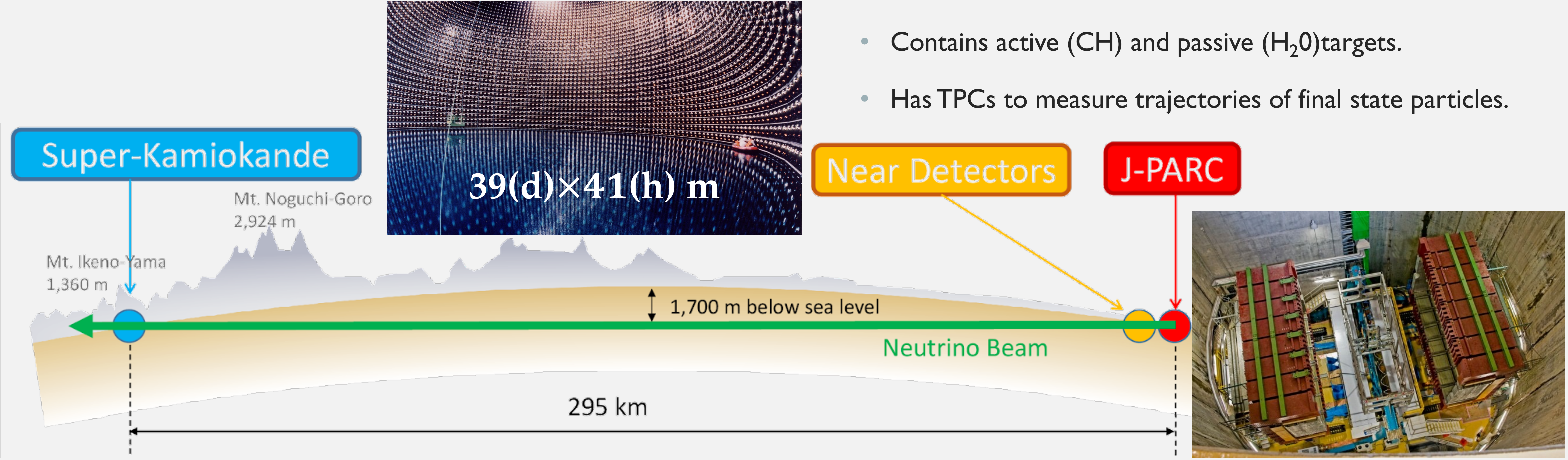
The Tokai To Kamioka (T2K) Experiment

- Uses the neutrino beam from the J-PARC Neutrino Facility in Tokai, Japan.

- The Far Detector in Kamioka is 295 away from the multi-component Near Detector system in Tokai.

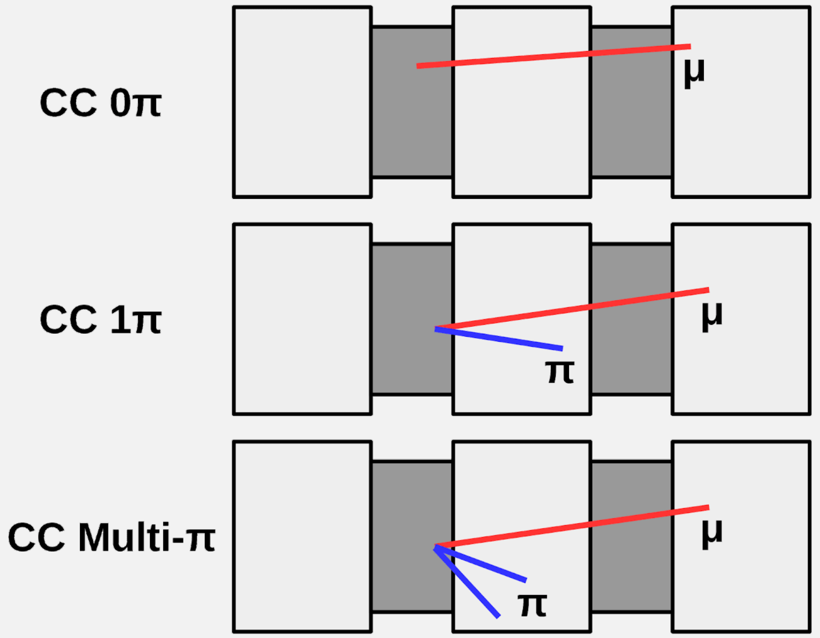
- Utilises 11k 20" PMTs in the FD (40% coverage).

- The multi-component ND is designed such that it;
    - Is magnetized to measure charge and momentum.
    - Is able to constrain the wrong sign backgrounds.
    - Contains active (CH) and passive (H_20)targets.
    - Has TPCs to measure trajectories of final state particles.

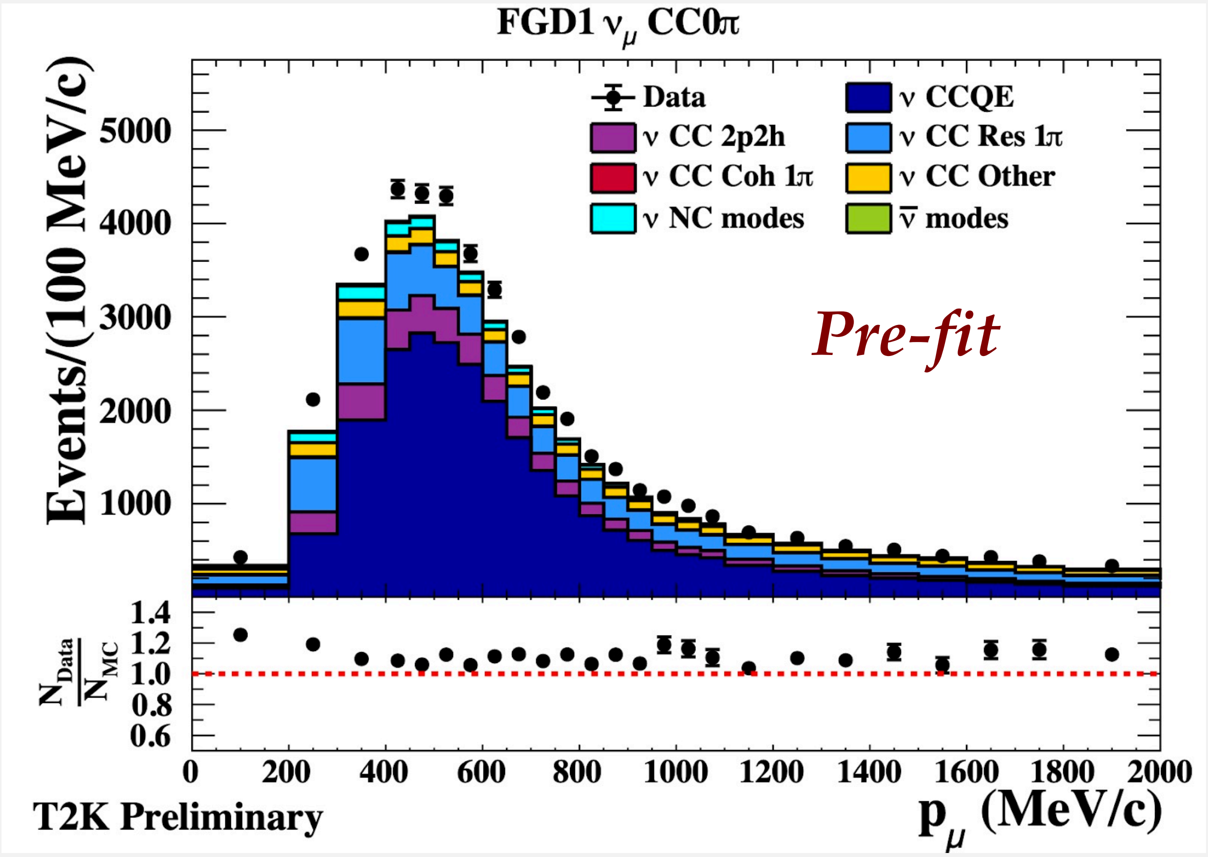


Using The T2K Near Detector

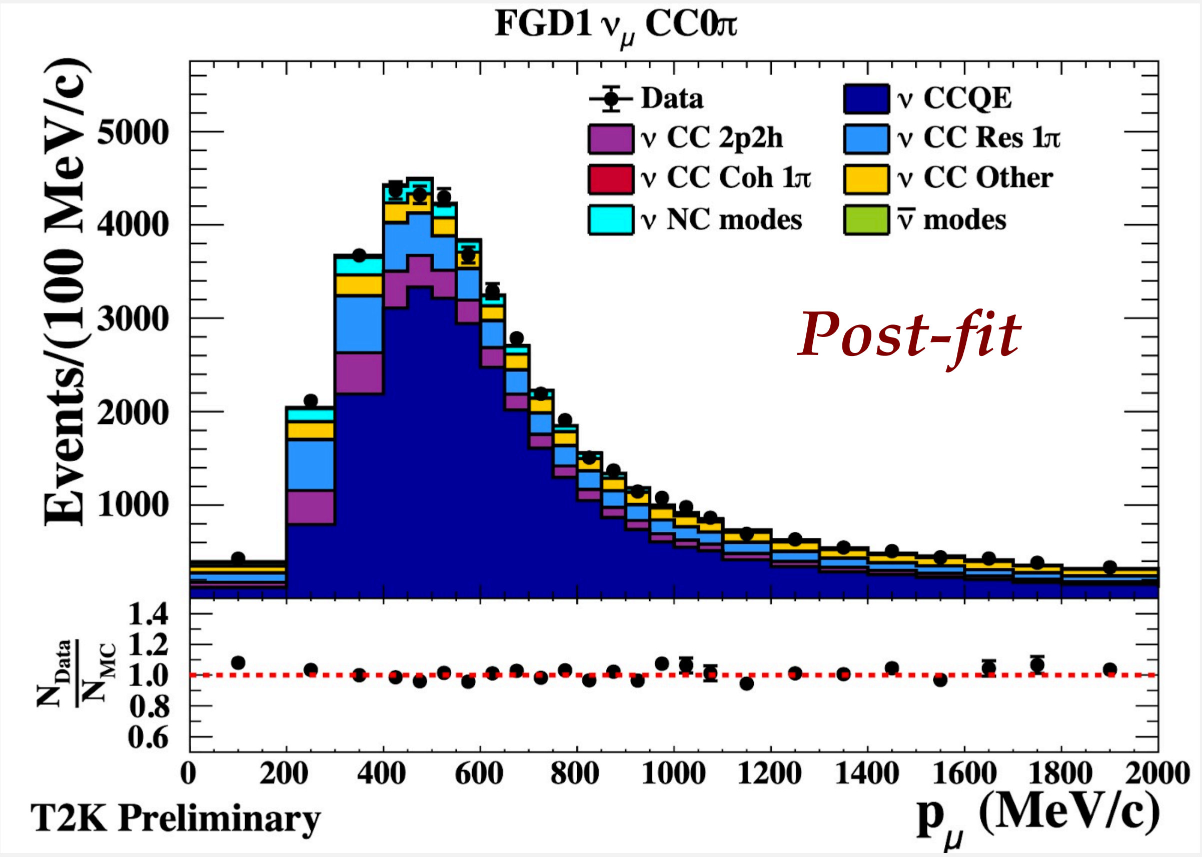
The T2K Near and Far Detectors are very different, so it pursues a very different approach to NOvA.



- INGRID is used to ensure beam alignment.
- Samples in ND280 are separated by interaction topology and location;
  - Split by pion multiplicity (shown left).
  - Split by target material – FGD 1 (CH) and FGD 2 (CH+$H_2$0).
  - Separate samples for neutrino and anti-neutrino mode.

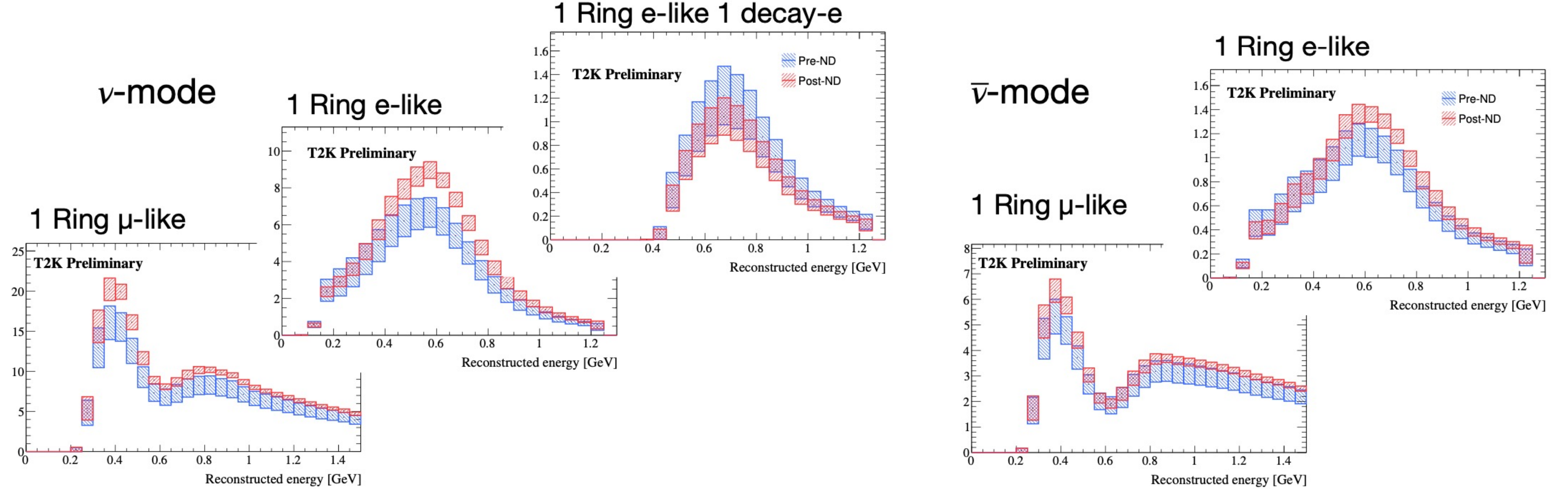


A covariance matrix fit is then performed to each sample individually in order to constrain the detector, flux and cross-section uncertainties.



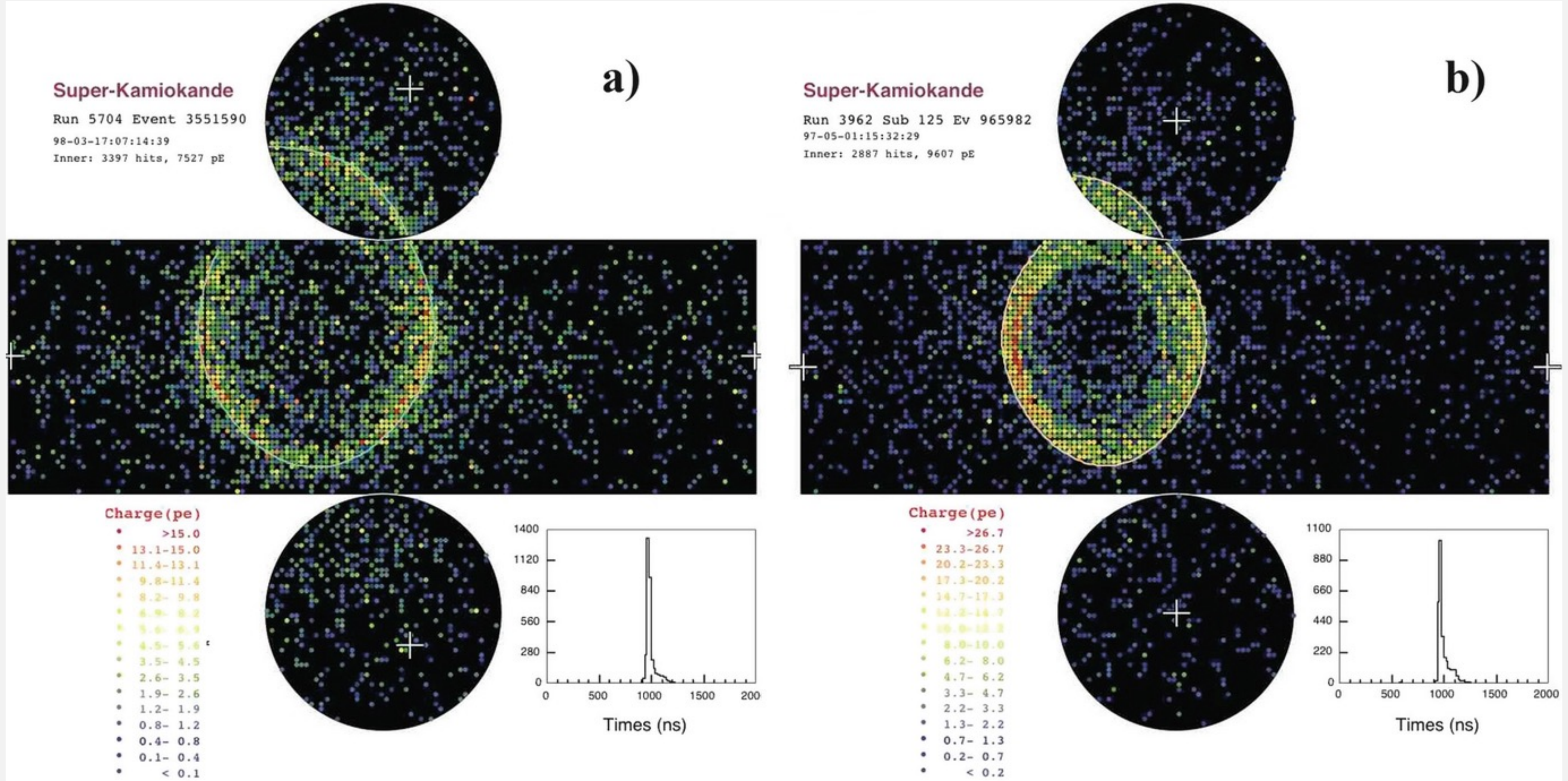
Predicting The T2K Far Detector Spectra

The tuned model reduces uncertainties associated with the predicted the flux at the Far Detector.



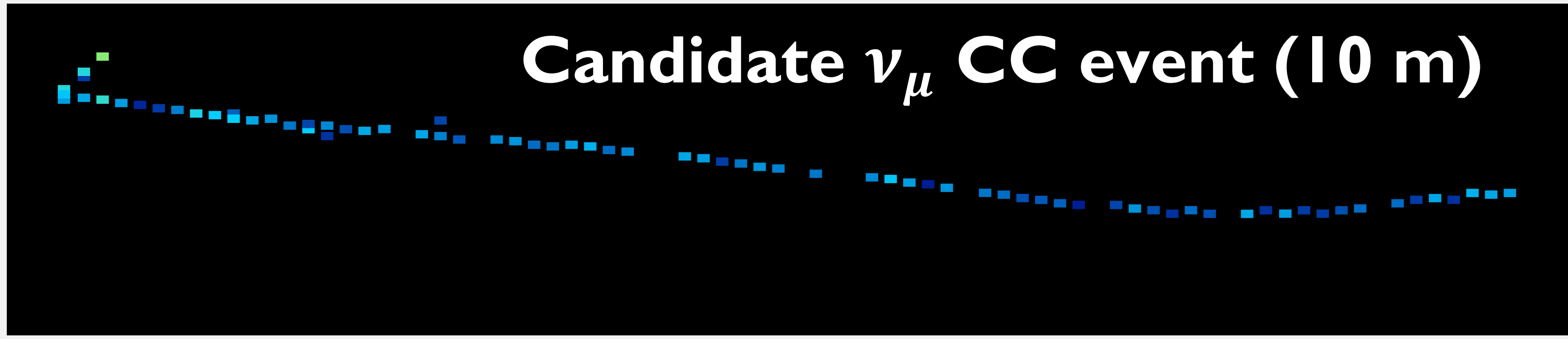
Systematic uncertainties					
Beam mode	**Neutrino**			**Antineutrino**	
SK sample	**1 Ring μ-like**	**1 Ring e-like**	**1 Ring e-like 1de**	**1 Ring μ-like**	**1 Ring e-like**
Before ND280 fit	11.1%	13.0%	18.7%	11.3%	12.1%
After ND280 fit	3.0%	4.7%	14.3%	4.0%	5.9%

Example Far Detector Neutrino Interactions



- Ring characteristics to identify neutrino flavour.
  - Electrons produce "fuzzy" rings.
  - Muons product "sharp" rings.
- Hadronic activity (protons) are below the Cherenkov threshold, and so aren't identifiable.

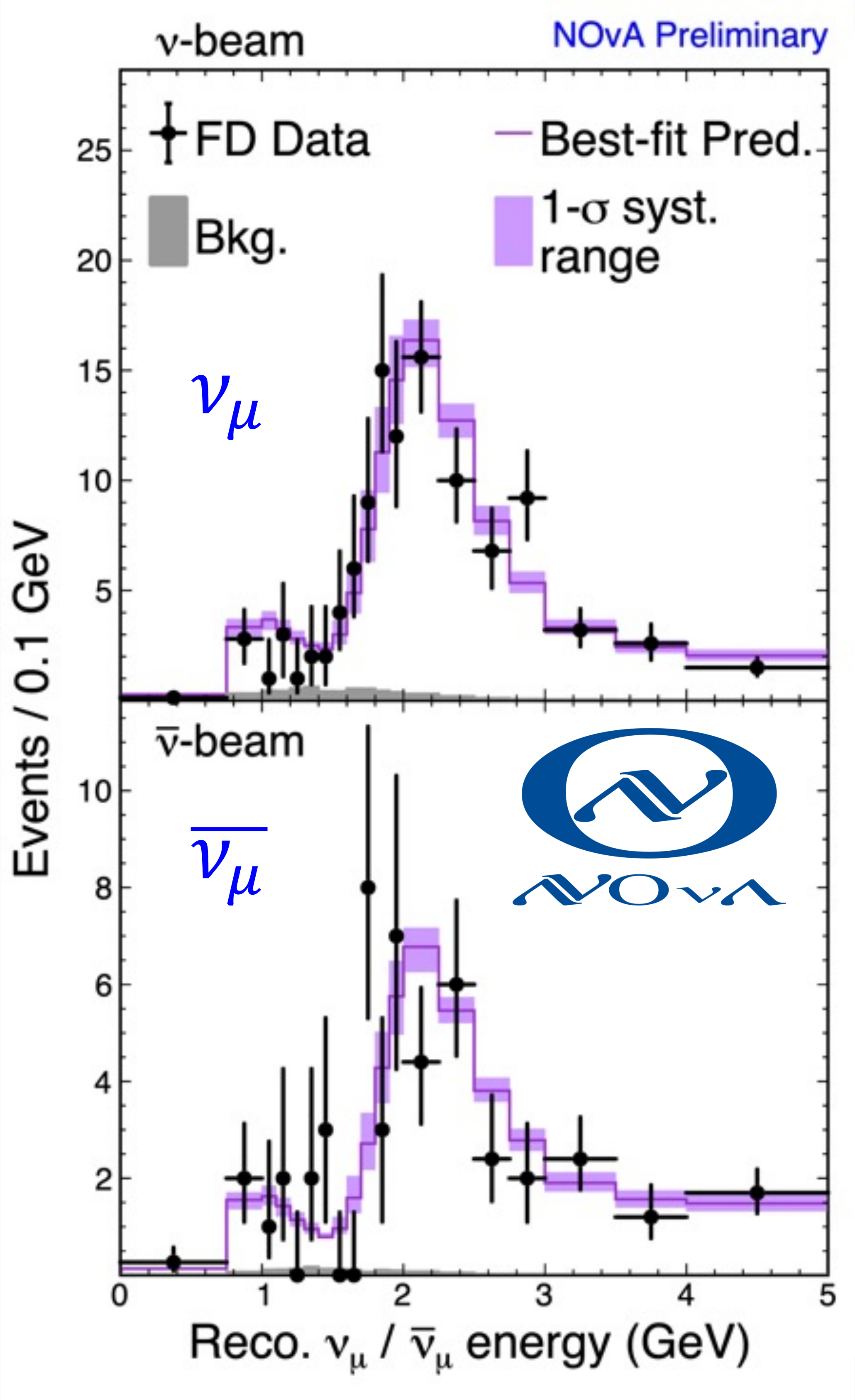
- Outgoing charged lepton cluster to identify neutrino flavour.
  - Muons produce long, straight tracks.
  - Electrons create shorted, shower-like clusters of hits.
- It is possible to identify hits from hadronic activity.
  - Improves E_{res} and minimises cross-section and FSI uncertainties.

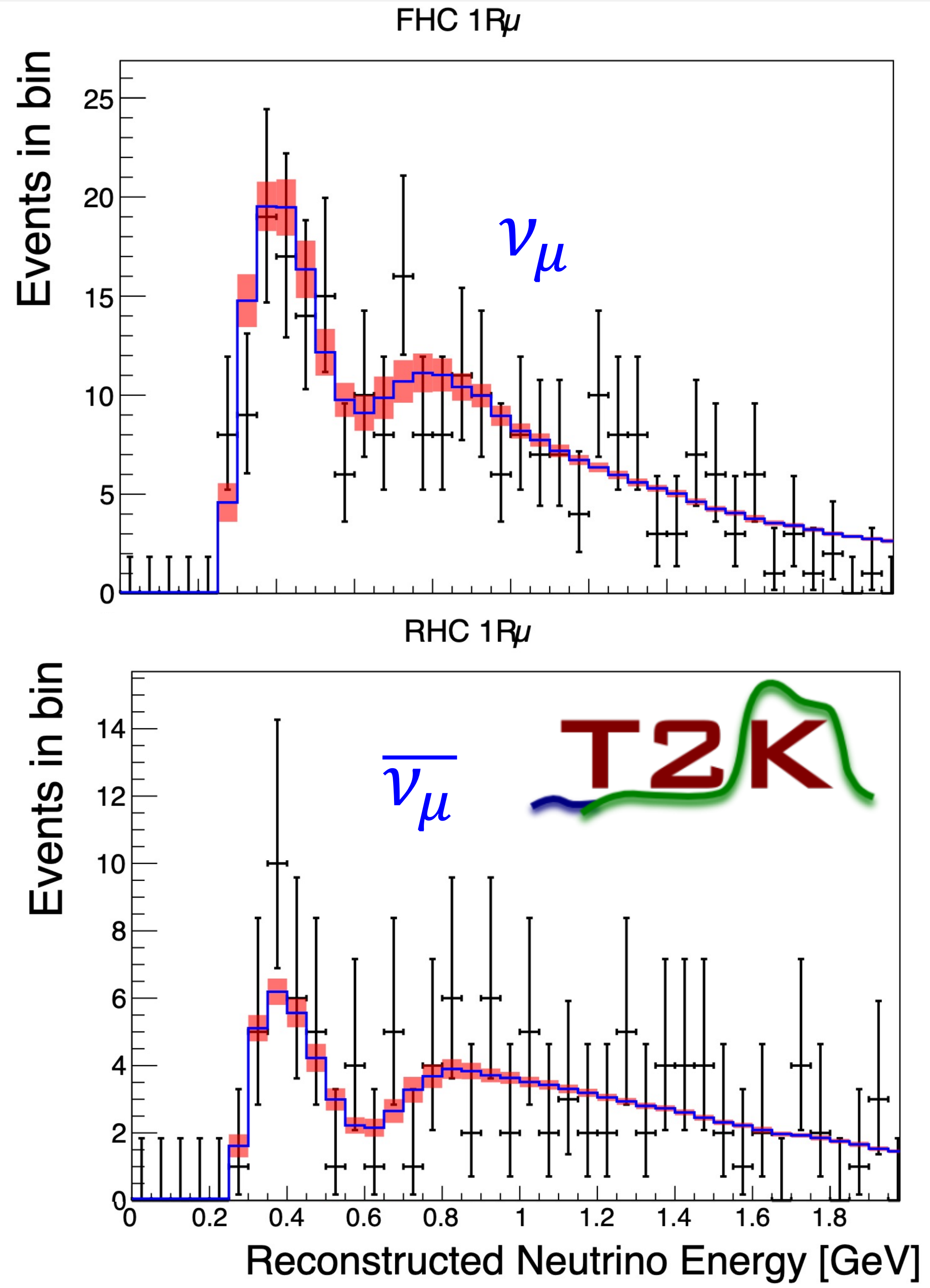


Candidate ν_μ CC event (10 m)

Candidate $\overline{\nu_e}$ CC event (4 m)

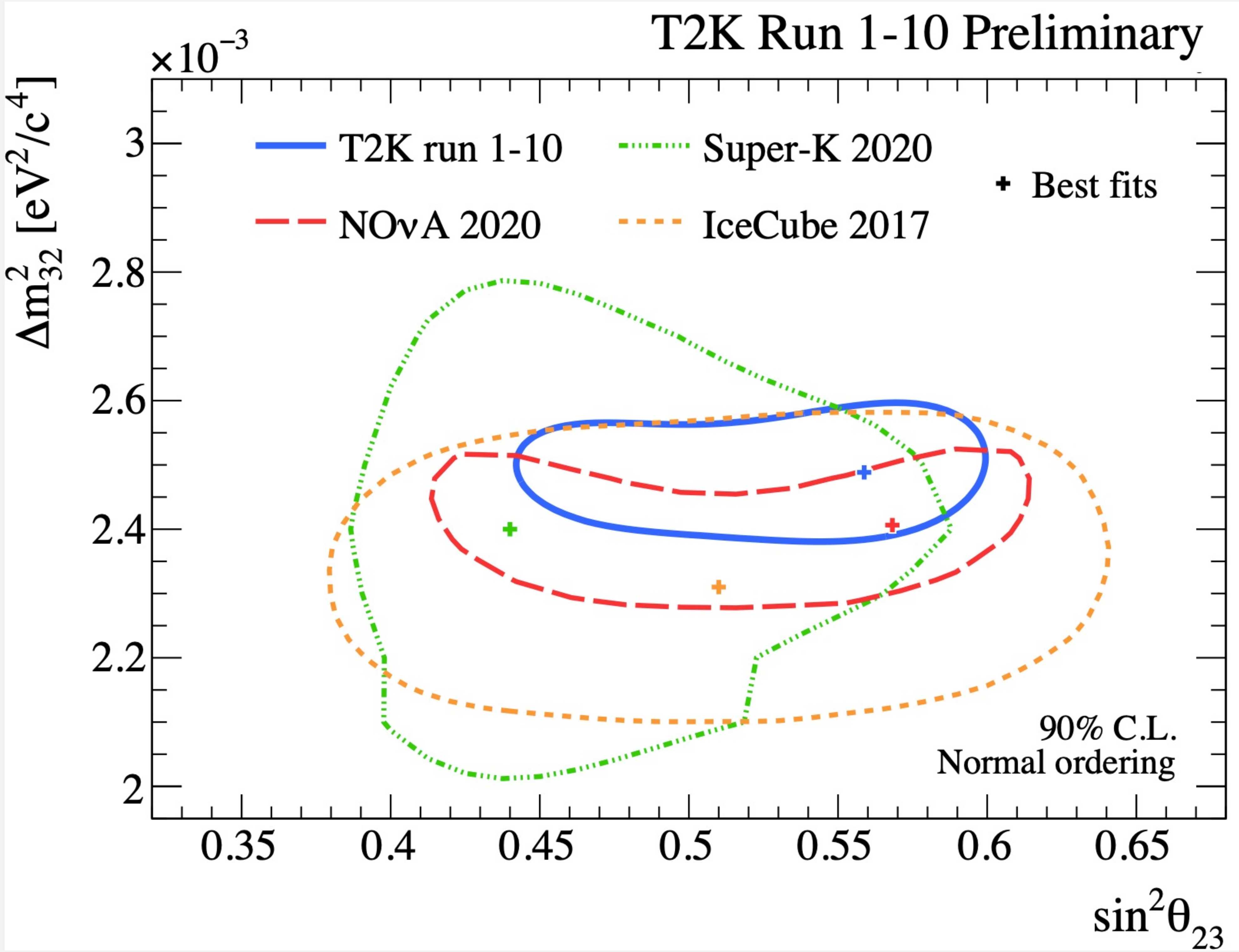
Performing The ν_μ Disappearance Analysis





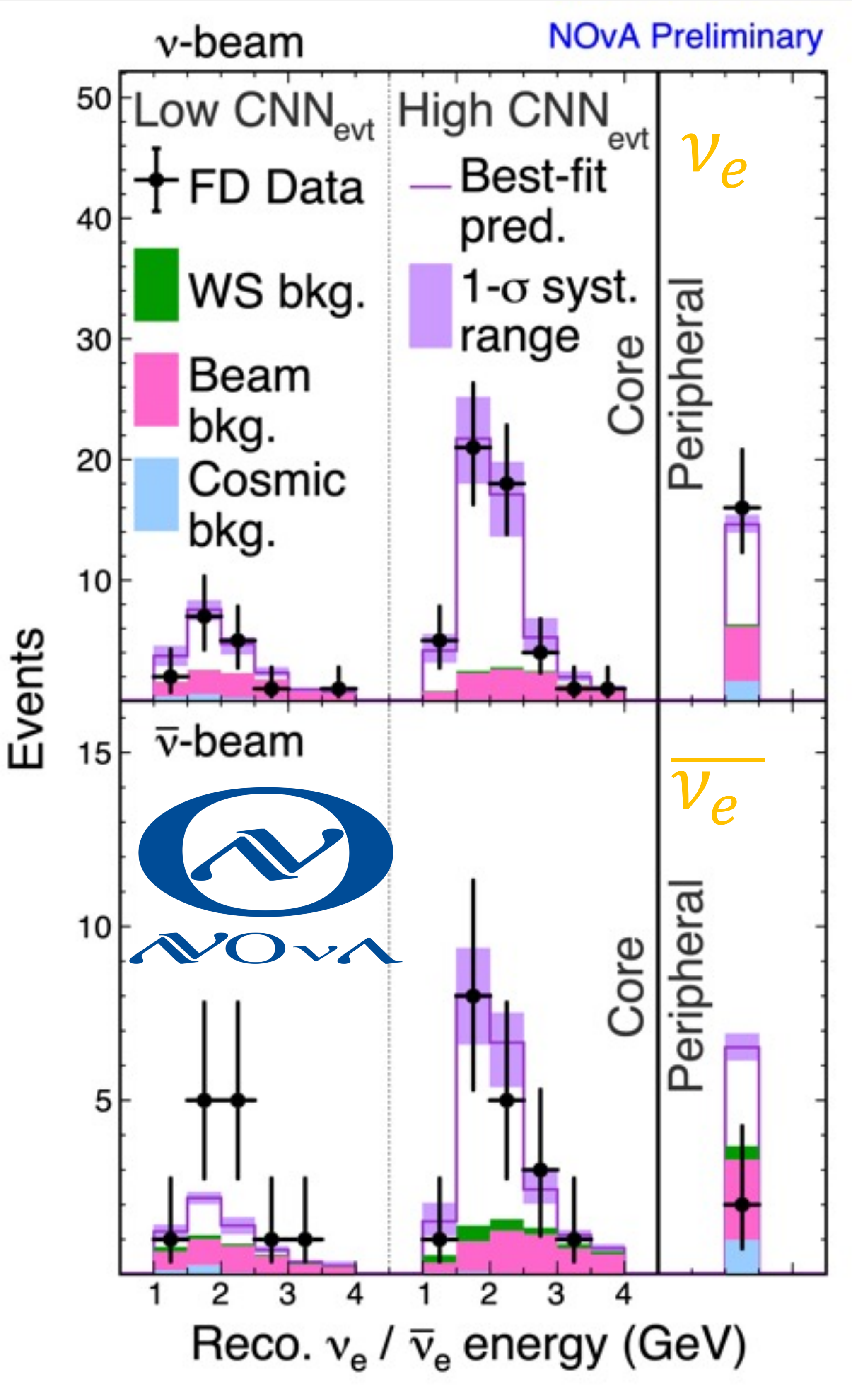
- Measure ν_μ interactions in ν & $\bar{\nu}$ modes.
- Both experiments see clear disappearance signal in both samples.
  - The no oscillation prediction would be approaching >1k events for each experiment.
- Despite their different design choices achieve complementary sensitivity.

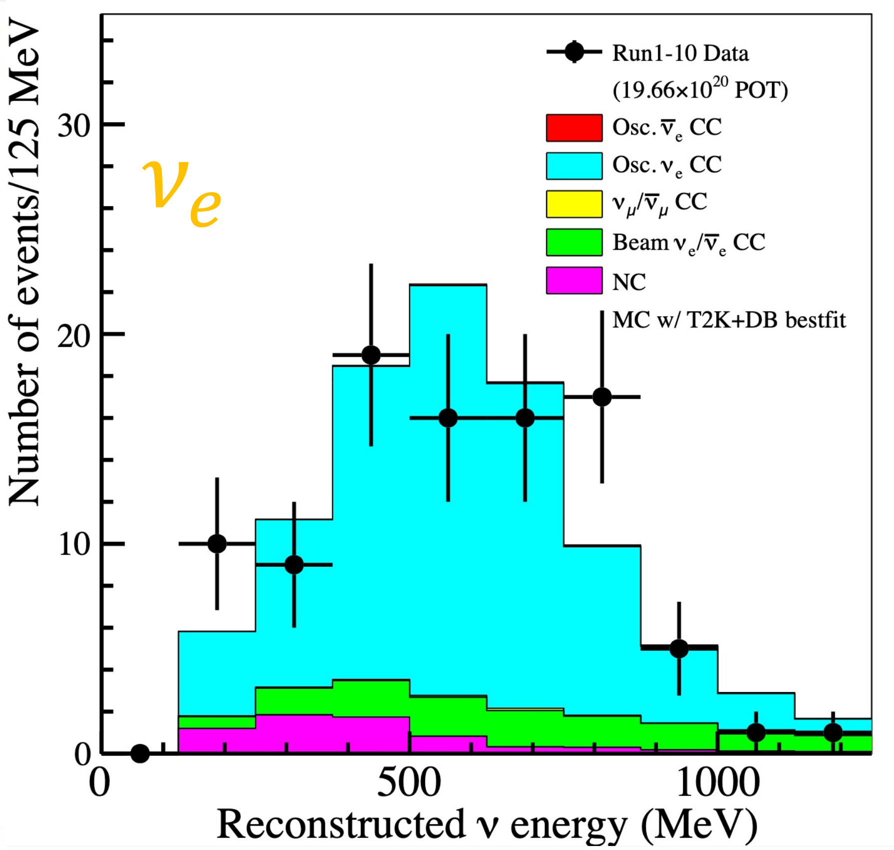
The ν_μ Disappearance Constraints

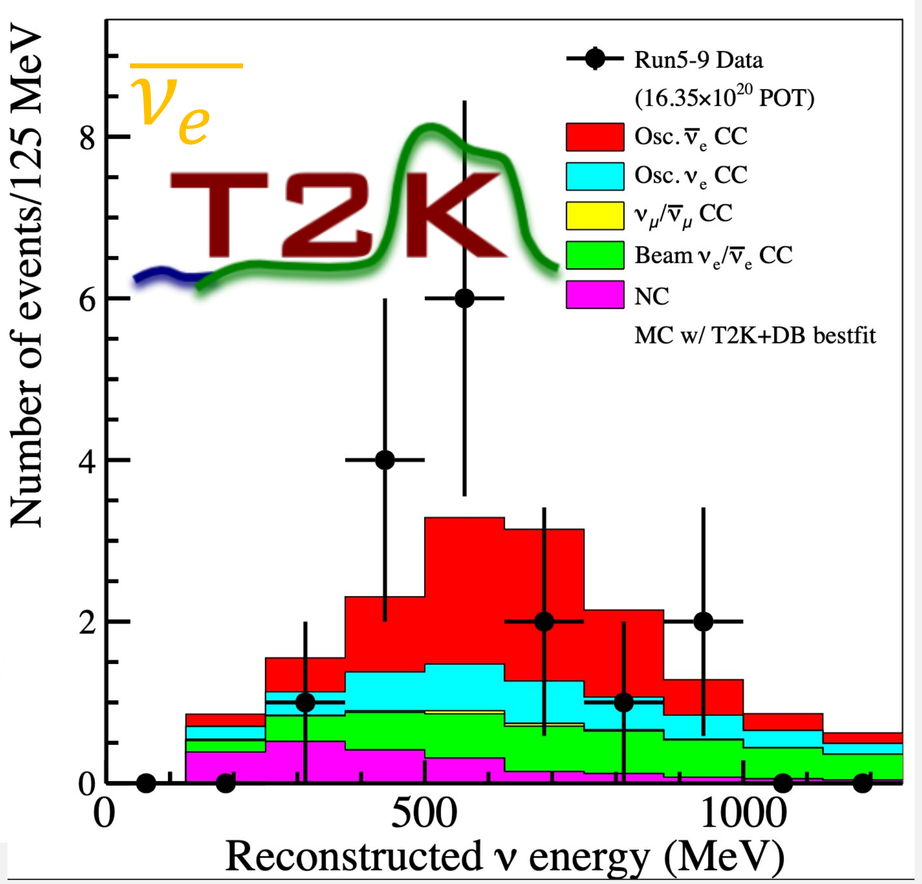


- Largely consistent phase spaces.
  - Neither exclude maximal mixing, though both have a best fit point in the upper octant.
  - Global average precision on $|\Delta m^2_{32}|$ is 1.1% for a given mass ordering.
- NOvA provides a slightly tighter constraint on the mass-squared splitting.
- T2K provides a slightly tighter constraint on the mixing angle.

Performing The ν_e Appearance Analysis

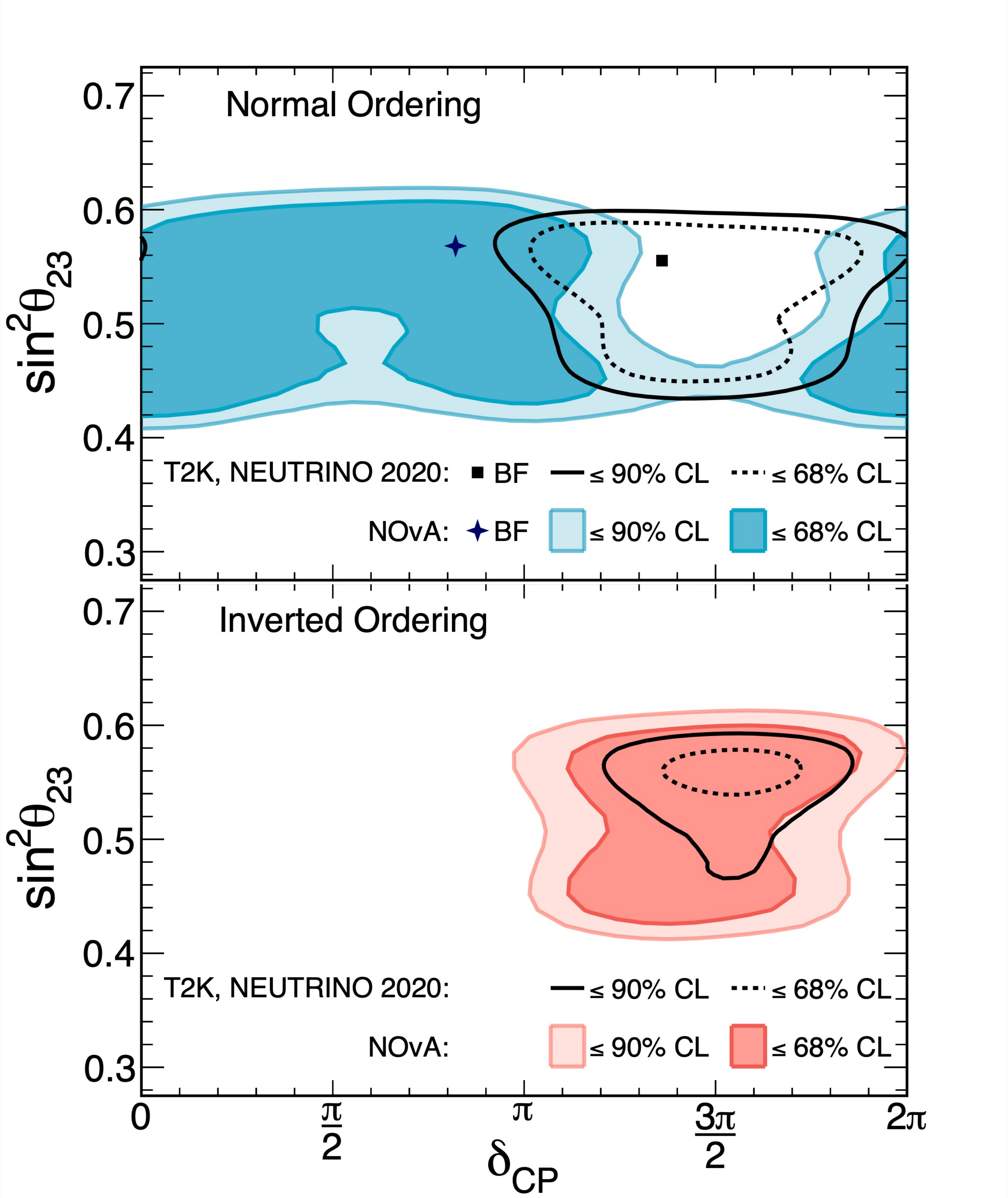






- Measure ν_e interactions in ν & $\bar{\nu}$ modes.
- Both experiments see clear appearance signal.
  - NOvA sees $> 4\sigma$ evidence of $\overline{\nu_e}$ appearance.
  - T2K also has a $1e1\pi$ sample in neutrino mode, where they tag the Michel electron from pion decay.
- Use appearance measurements to extract the value of δ_{CP} and the neutrino mass ordering.
  - NOvA generally has good sensitivity to νMO, but it can be difficult to ascertain for certain δ_{CP} values.

The ν_e Appearance Constraints



- Both analyses include a constraint on θ_{13} from reactor expts.
- Both experiments favour the normal hierarchy.
  - Consistent ranges of θ_{23}.
  - Very different δ_{CP} regions.
- In the disfavoured inverted hierarchy, they have better agreement for δ_{CP}.

NOvA Best Fit Point

Normal Hierarchy

$$\Delta m^2_{32} = (2.41 \pm 0.07)\times 10^{-3}\ eV^2$$
$$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$$
$$\delta_{CP} = 0.82\pi$$

T2K Best Fit Point

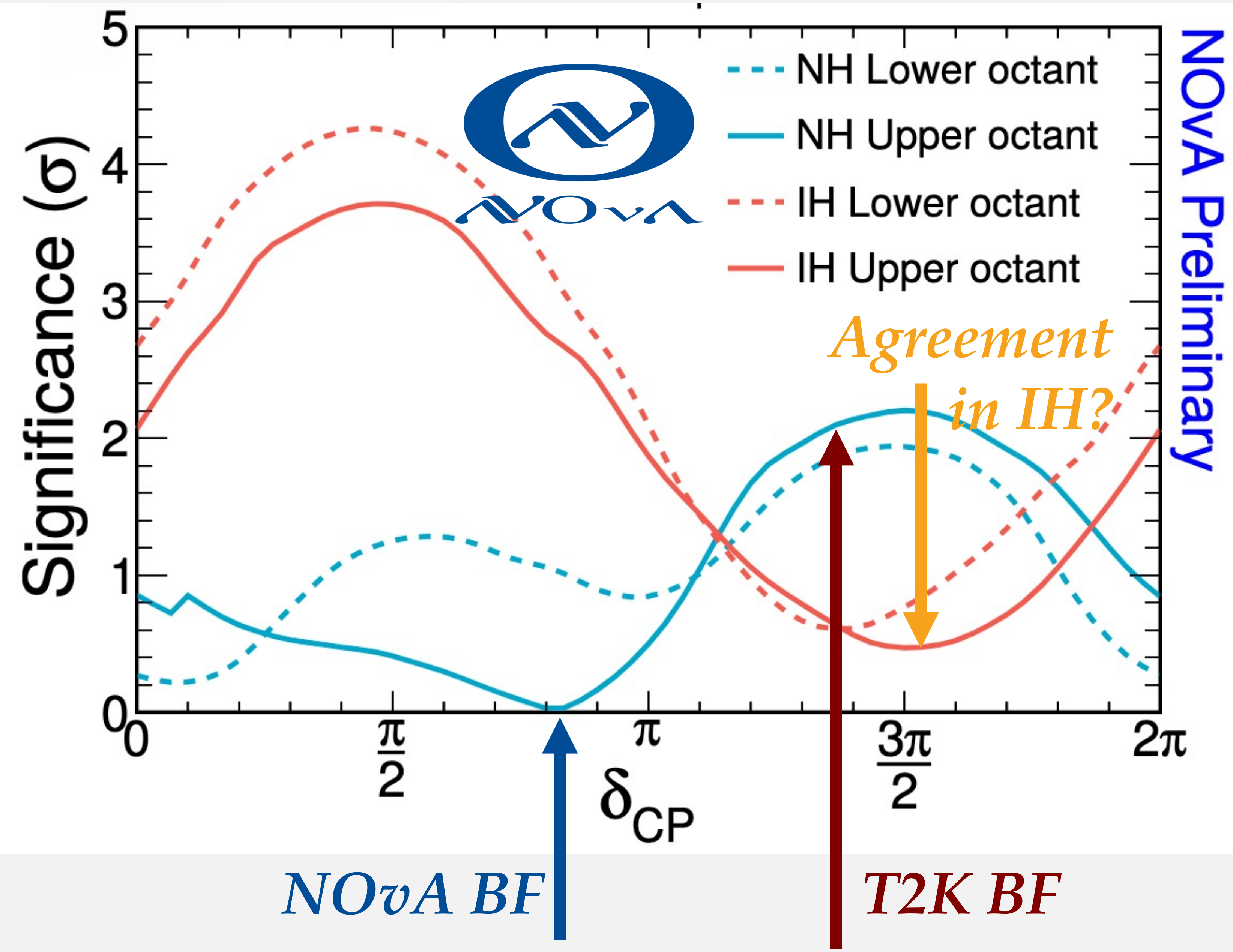
Normal Hierarchy

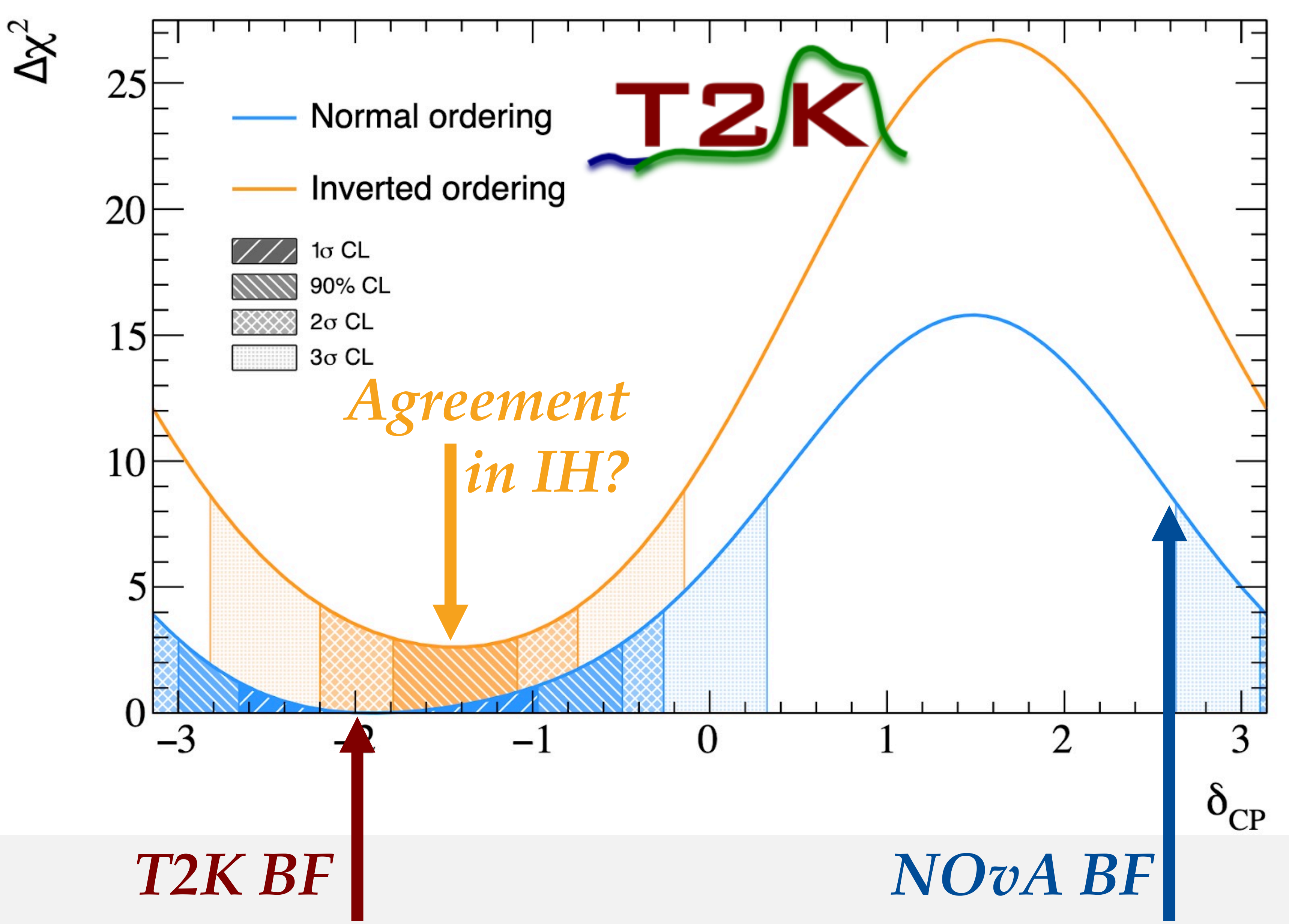
$$\Delta m^2_{32} = (2.49^{+0.06}_{-0.08})\times 10^{-3}\ eV^2$$
$$\sin^2\theta_{23} = 0.546^{+0.024}_{-0.046}$$
$$\delta_{CP} = 1.37\pi$$

1-D Constraints on δ_{CP}

Note the different axis ranges, so hard to compare quickly.
The respective Best Fit Points are marked on each plot.

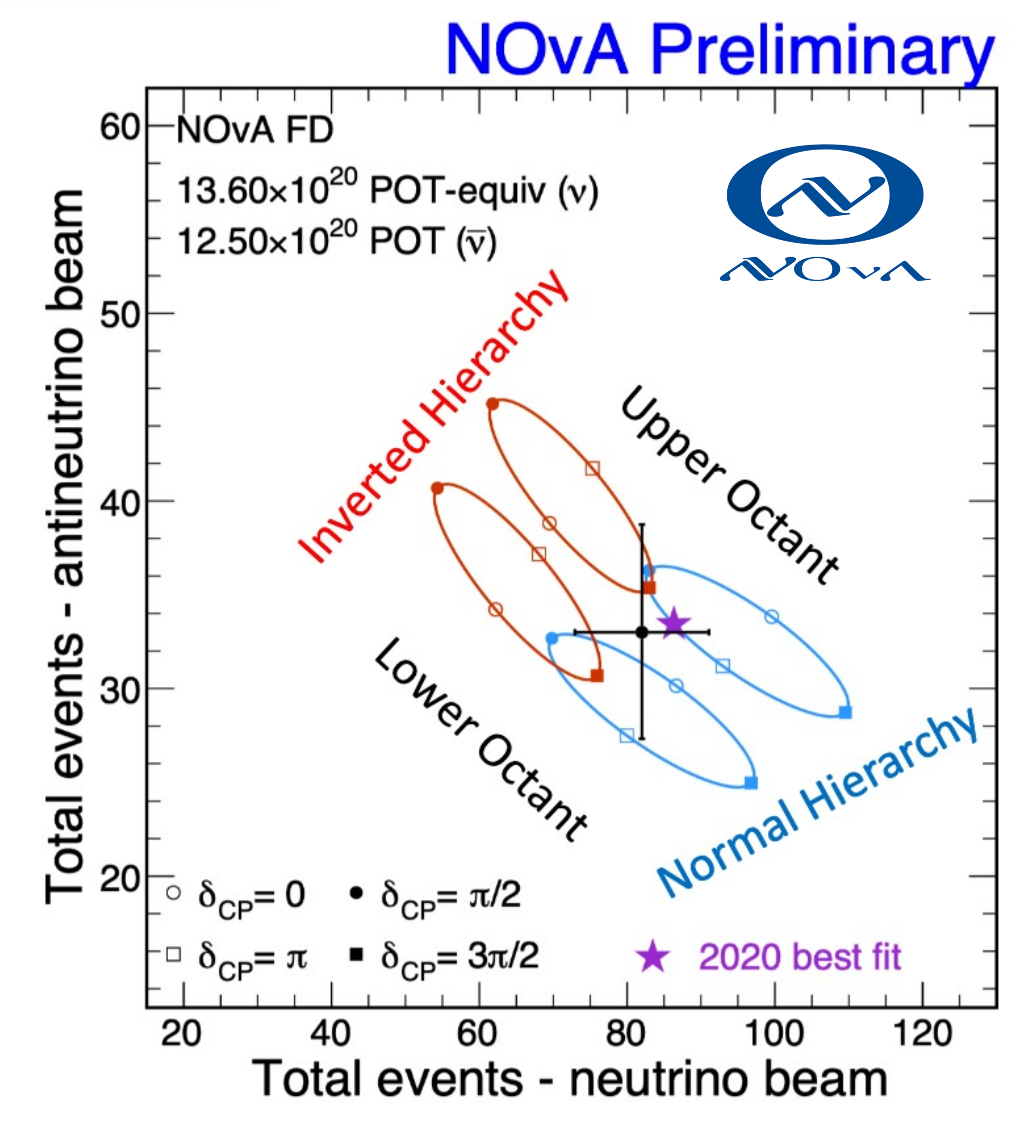
Can see that each experiment disfavours the others best fit quite strongly.
Can also see that the parameter space in the Inverted Ordering is more consistent.

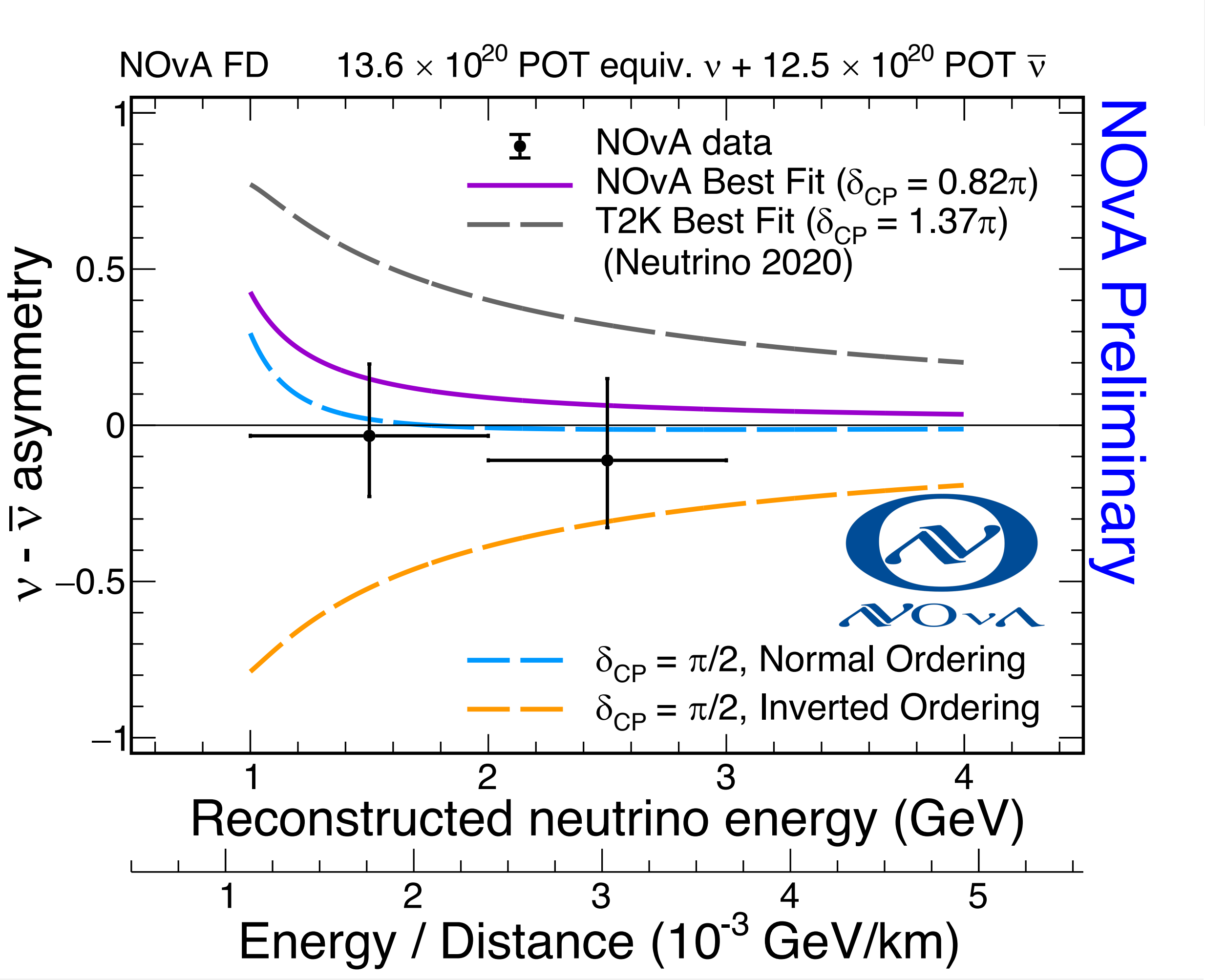




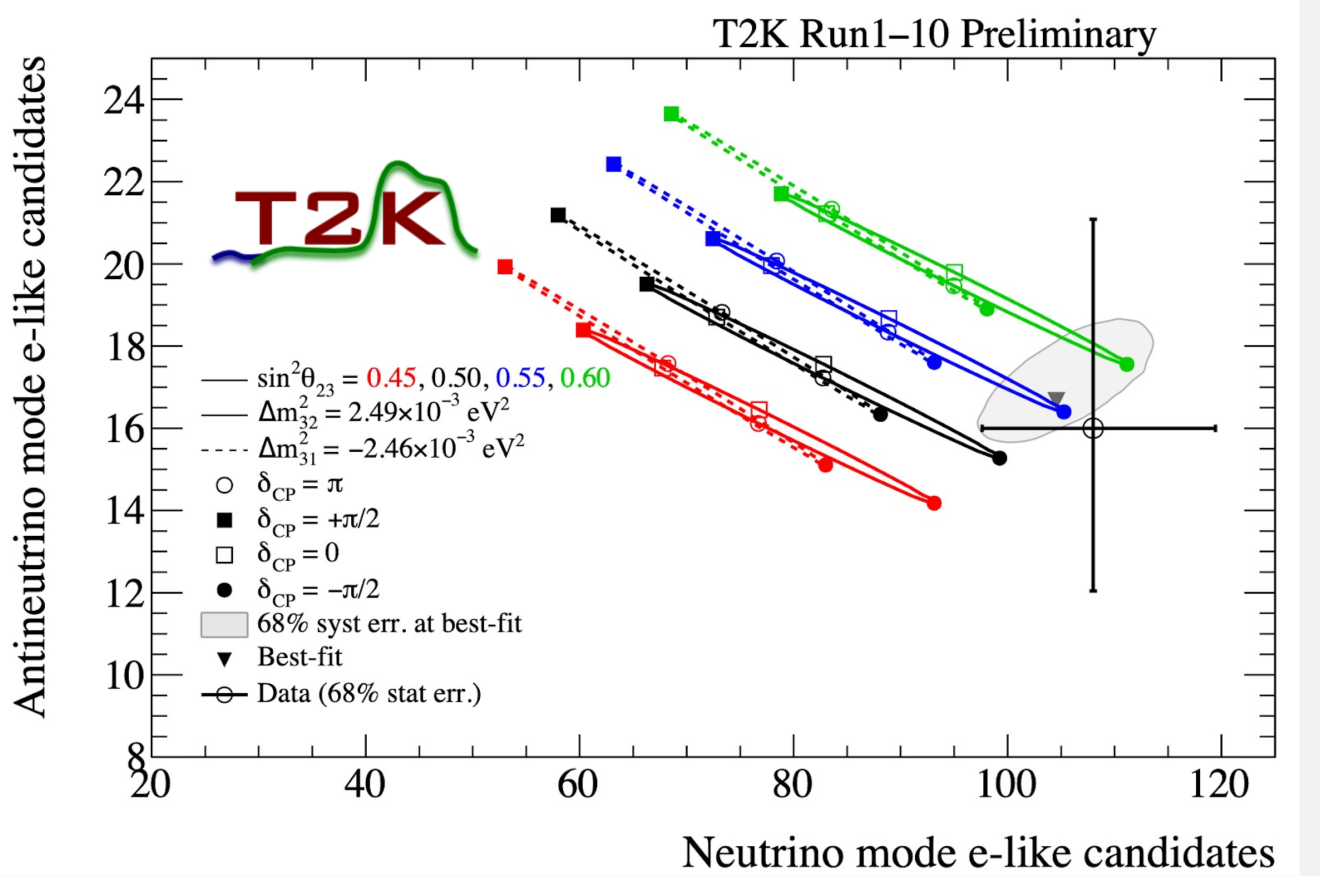
A Joint Oscillation Fit In The Near Future

- A joint fit allows us to fully explore the complementarity of the two experiments.
    - Full statistical treatment of the combined datasets and correlation of important systematic parameters between datasets is possible.
    - A potential future analysis would also seek to use a shared neutrino interaction model.
- The first joint analysis is making great progress, and the collaborations aim to release this result later in 2022.



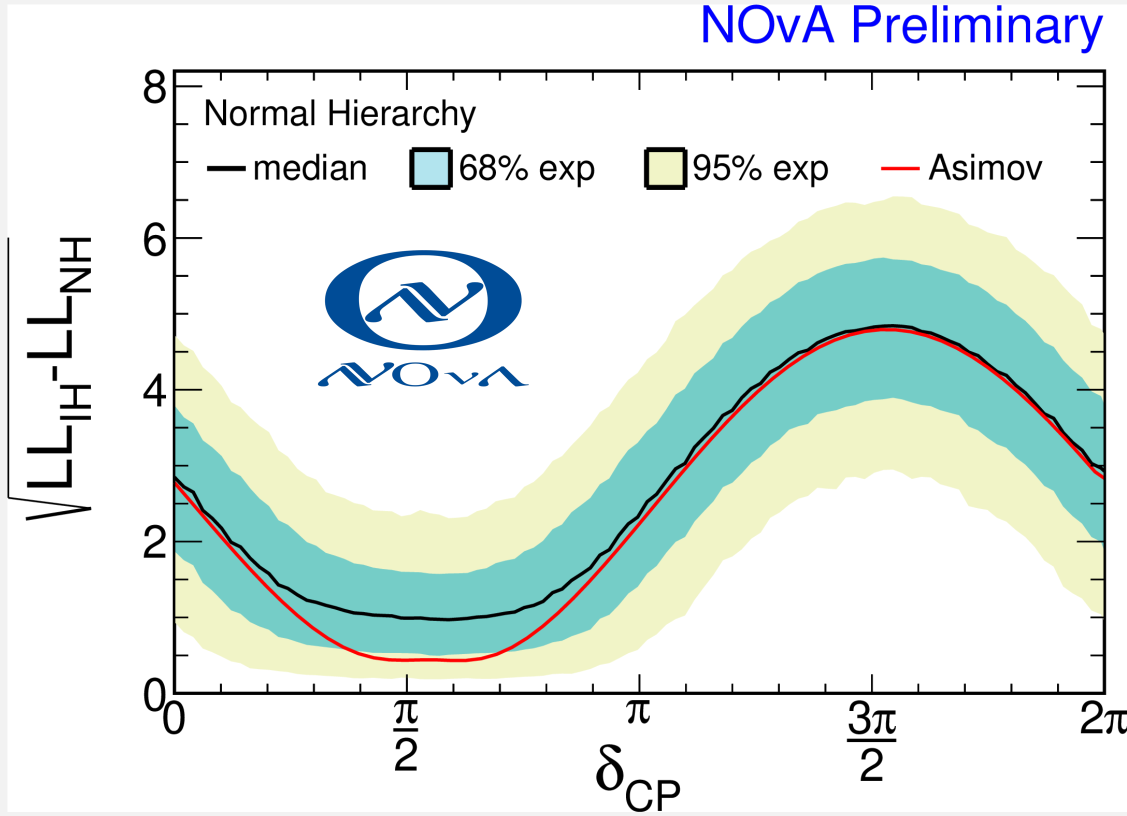


The measured neutrino/anti-neutrino asymmetry as measured by NOvA.

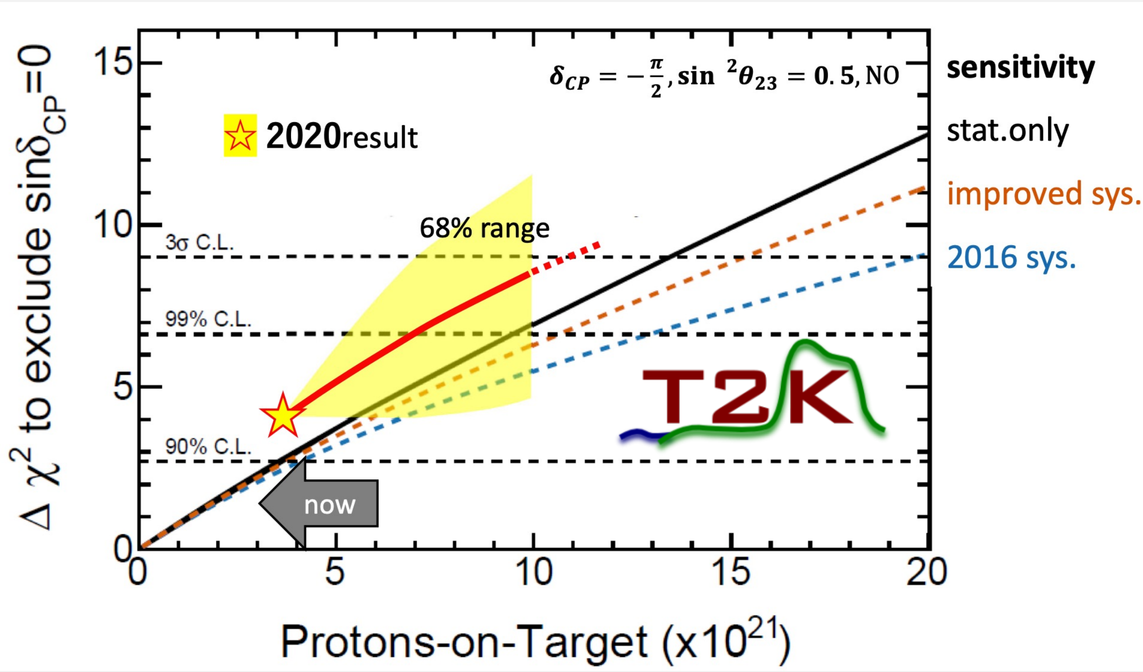


Some Final Thoughts

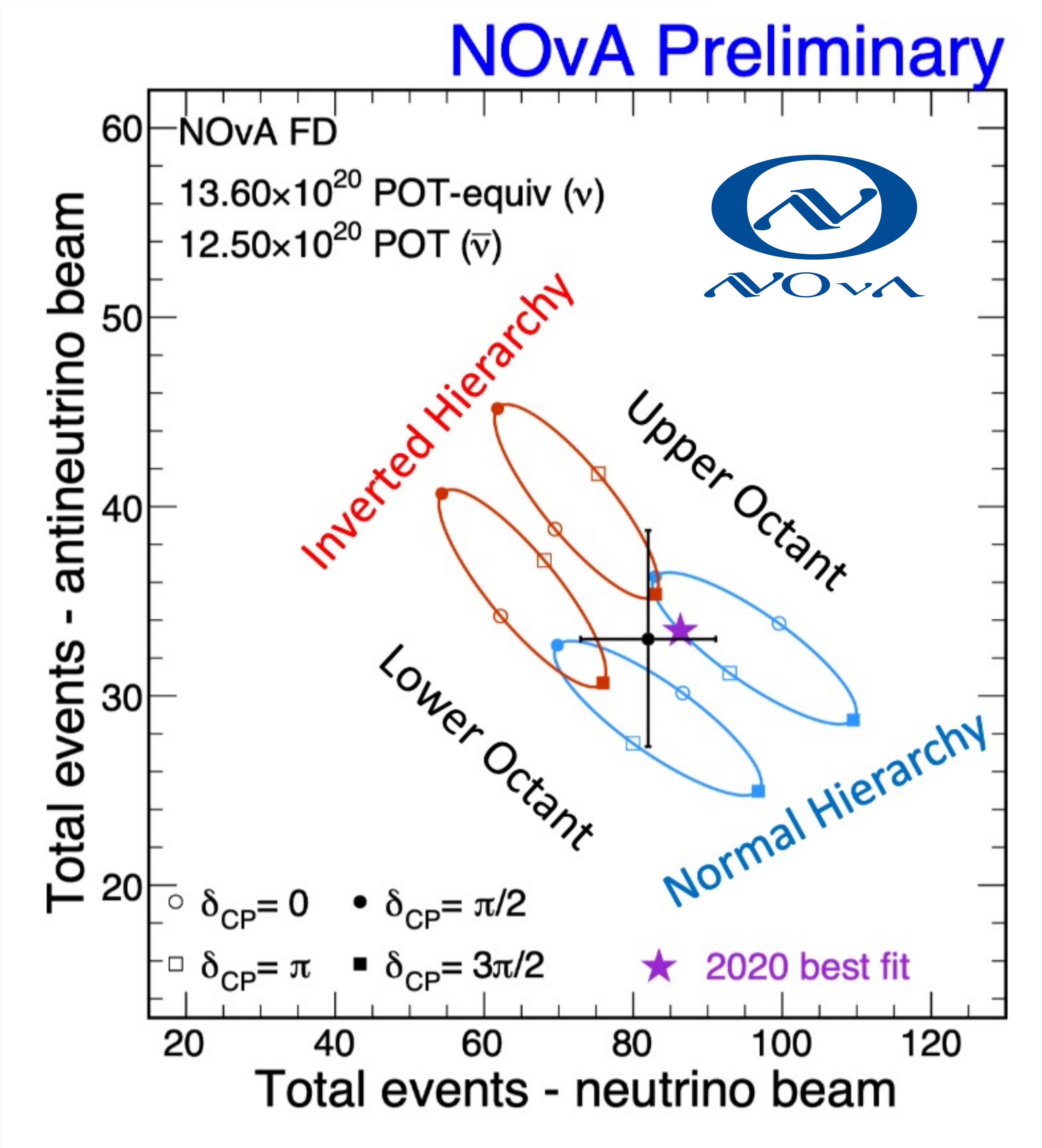
- NOvA and T2K perform World leading measurements of neutrino oscillations.
  - Interesting tension in their current results, which a future joint fit hopes to address.
  - Each experiment will roughly triple their current exposures by 2027, offering fantastic opportunities for future discovery, both individually and jointly.
- The era of precision measurements of three-flavour neutrino oscillations is here.
  - NOvA and T2K will inform the physics programs of DUNE and T2HK.
- NOvA and T2K don't just perform three-flavour oscillation measurements.
  - NOvA has published 2 sterile nu, 2 cross-section, 4 DL and 6 "exotic physics" papers.
  - T2K has published 1 sterile nu, 24 cross-section and 6 "exotic physics" papers.
  - Both will have new and updated results at NEUTRINO 2022, in just 3 weeks!

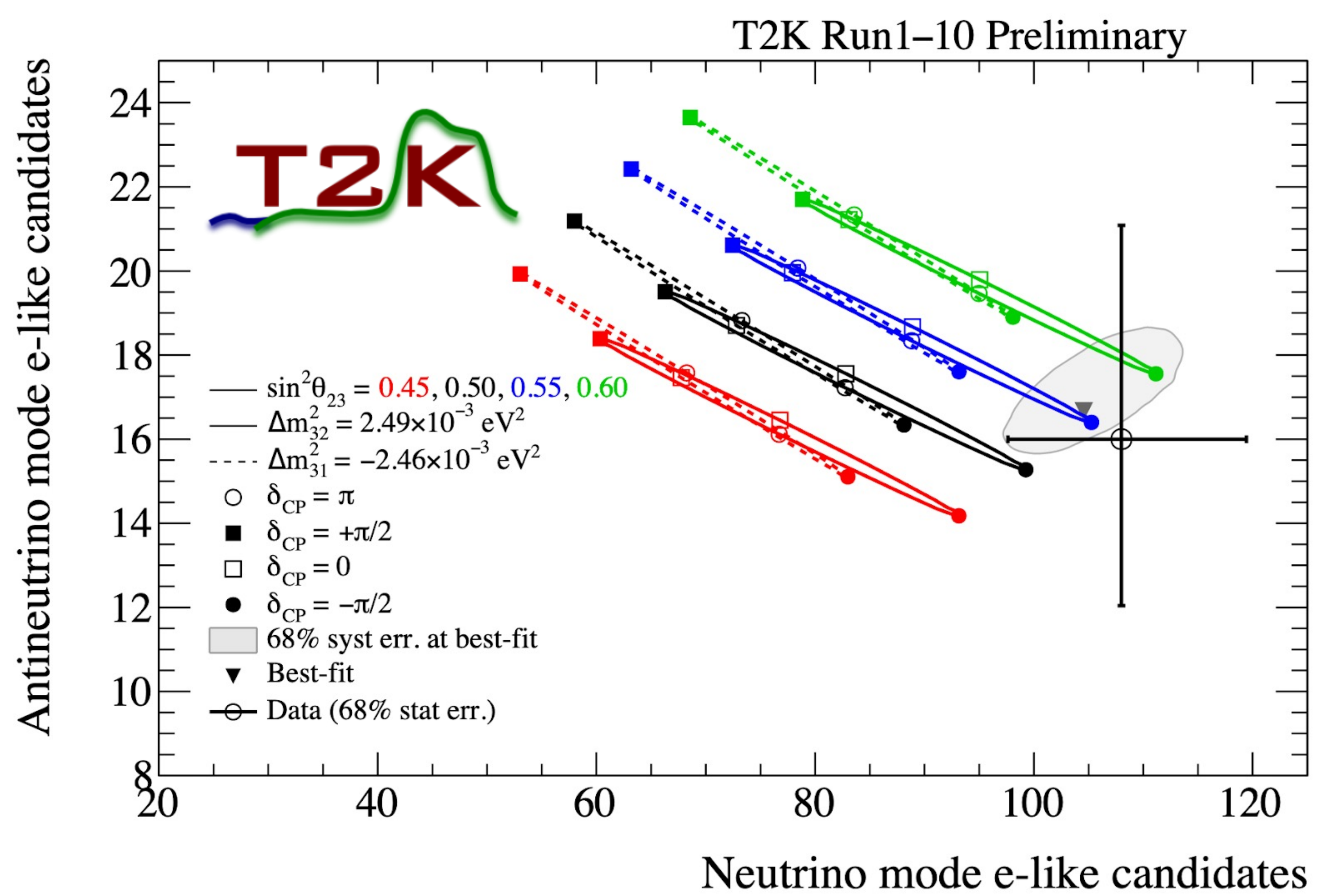


Top - NOvA MH Rejection.
Bottom - T2K δ_{CP} sensitivity.



Bi-Probability Plots

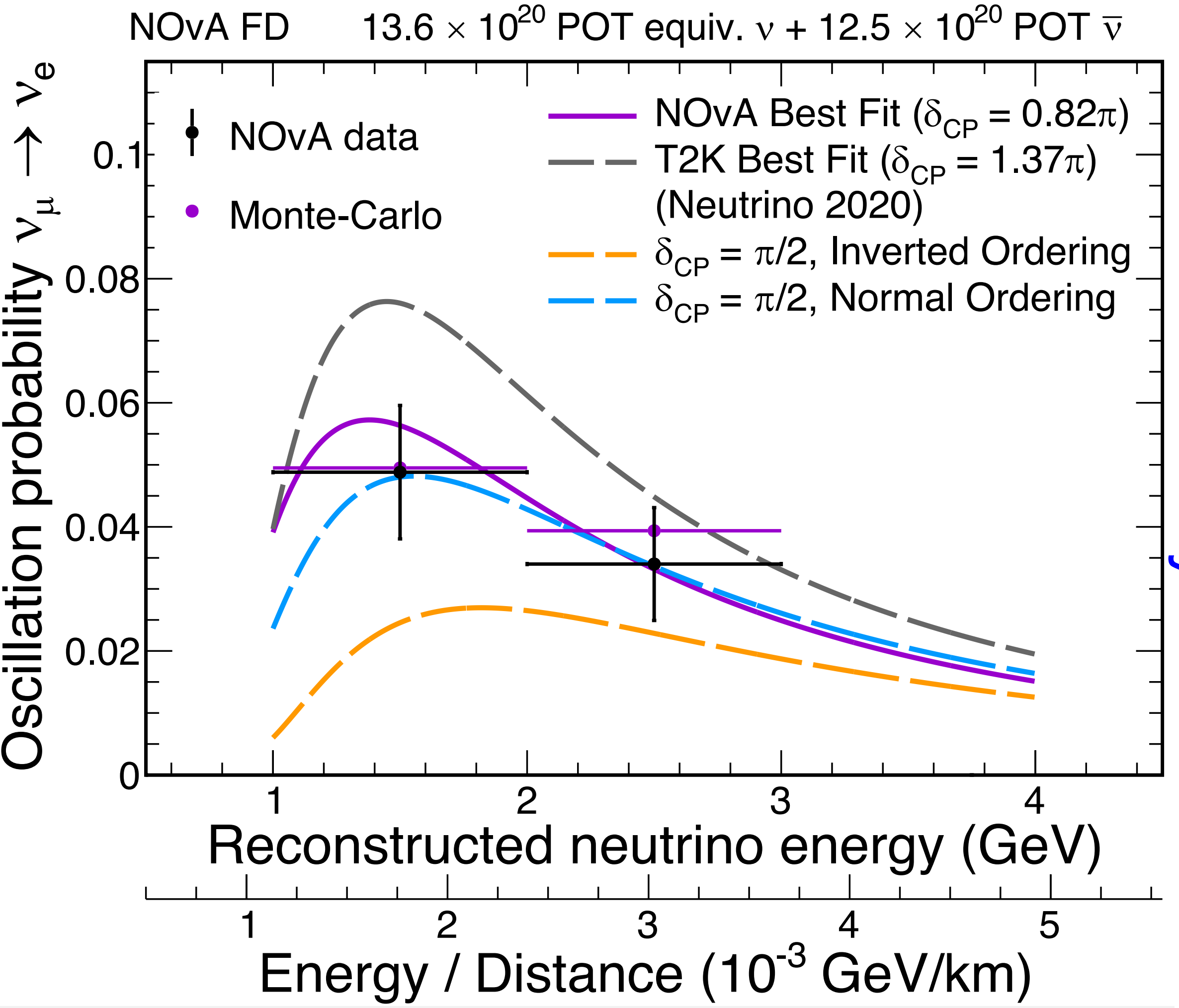




By plotting the raw $\nu_e/\bar{\nu}_e$ event counts for the two experiments one can make some interesting observations;

- *Both favor the Normal Hierarchy.*
- *Both prefer Upper Octant, though only mildly.*
- *There is some tension in the value of δ_{CP}*

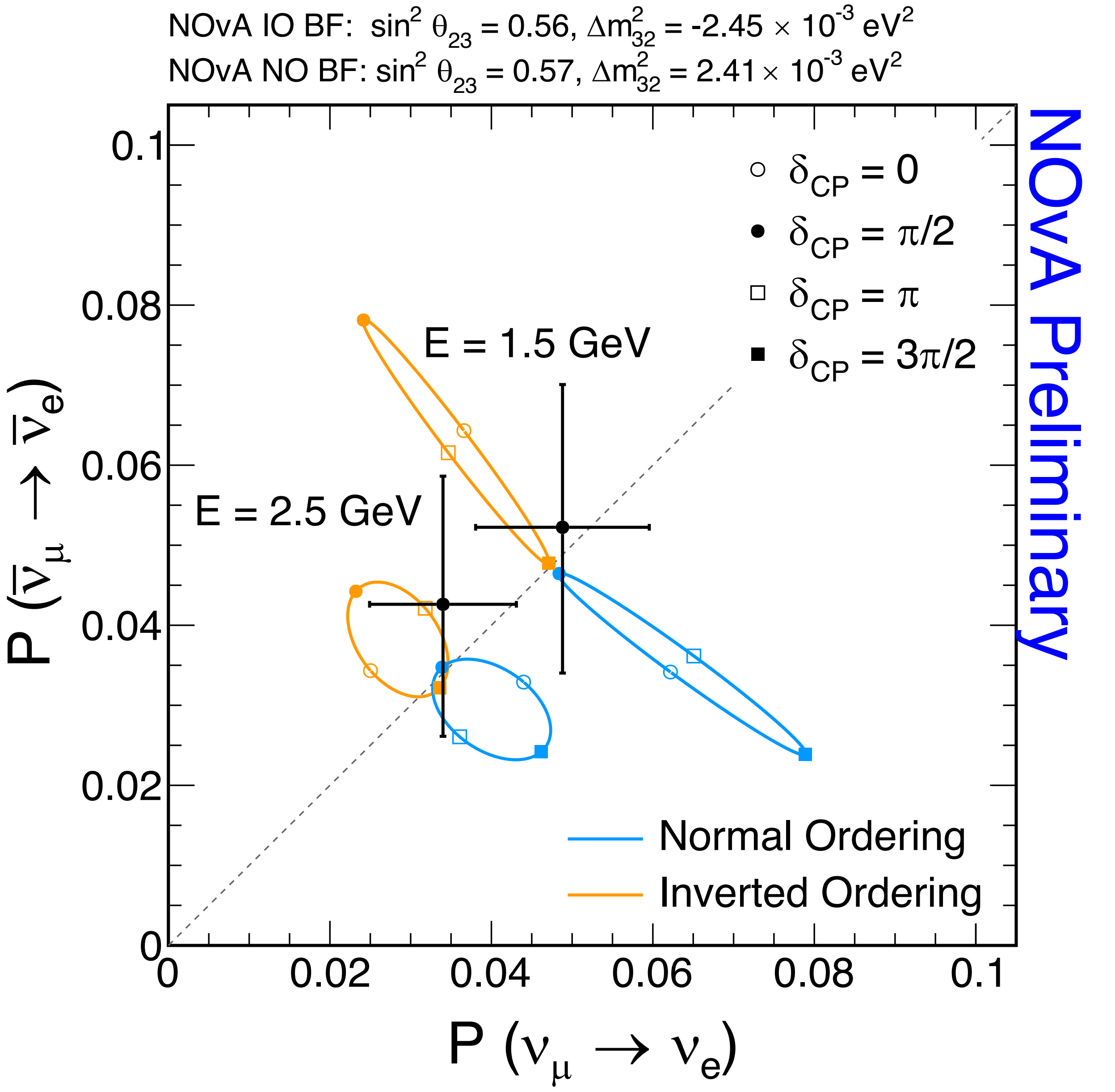
NOvA Asymmetry Measurement



Left – Neutrino Osc Prob

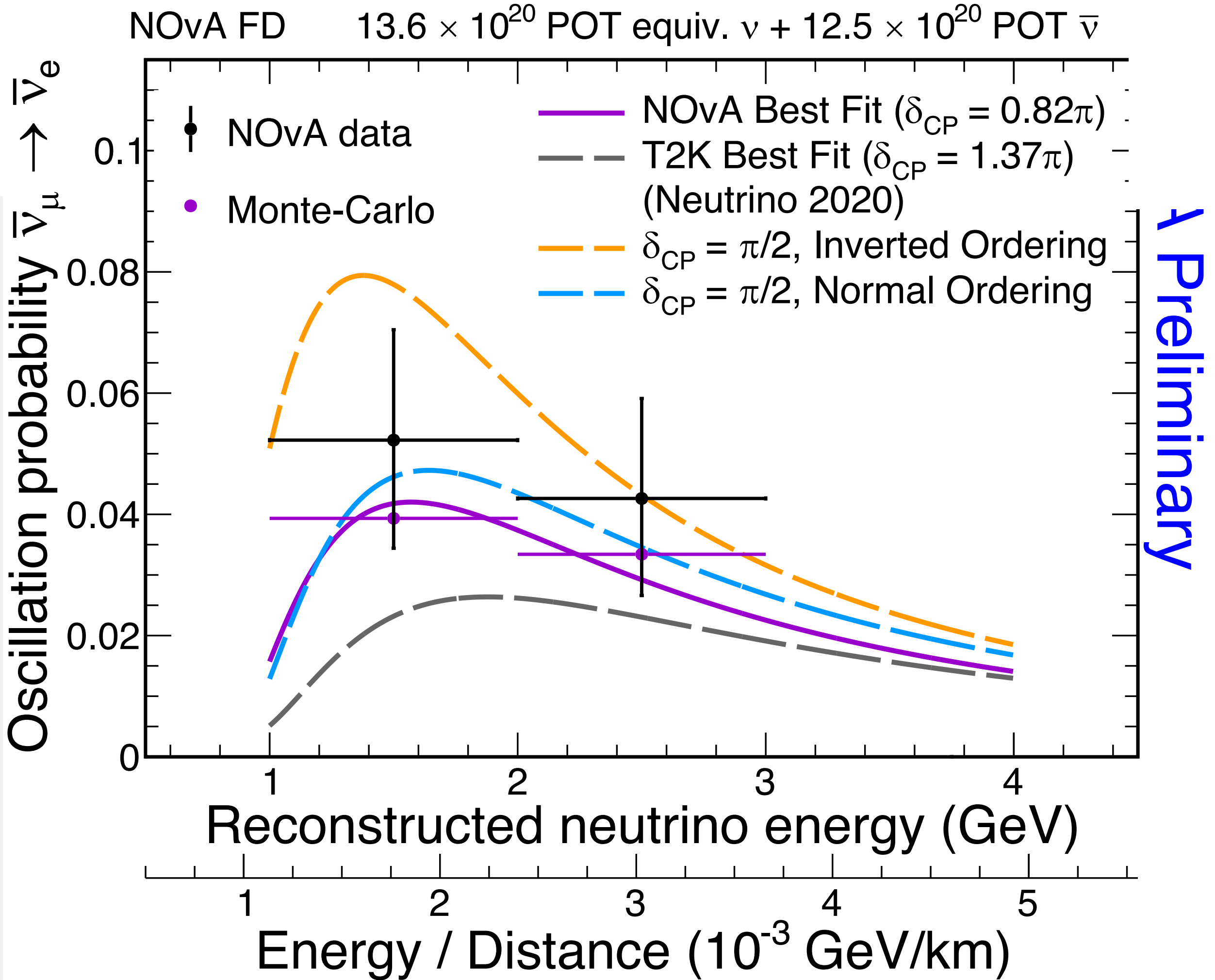
Bottom – Anti-Nu Osc Prob

Right – Bi-Event Plot



Measured oscillation probabilities

Errors from Poisson fluctuations, covering 68% of mock experiments.



Combined fit result.

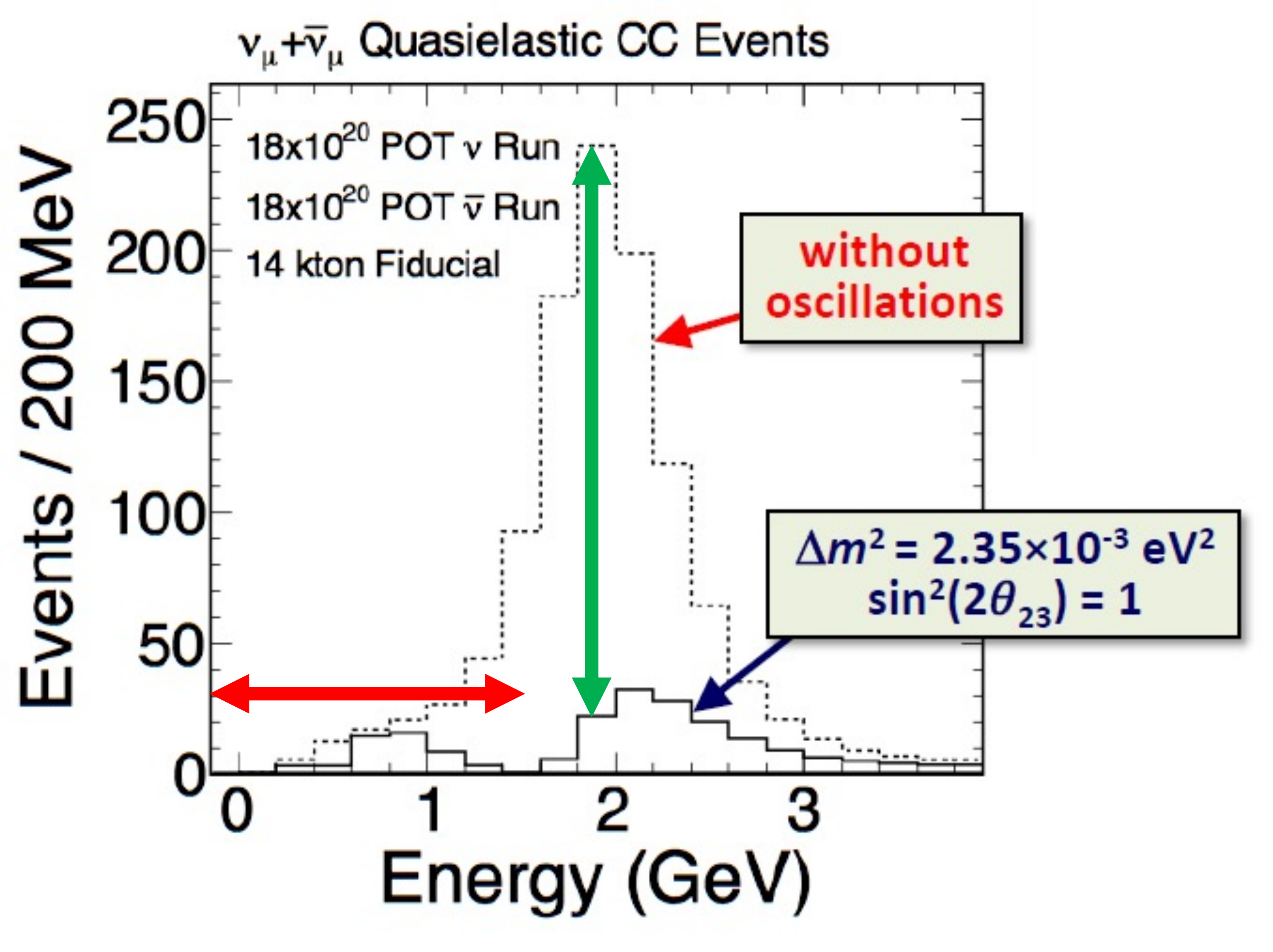
E bins are 1-2 GeV and 2-3 GeV.

The NOvA IH and NH best-fit points are used to produce elipses.

Measuring Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m_{32}{}^2 L}{E}\right)$$

$$\Delta m_{ij}{}^2 \equiv m_i{}^2 - m_j{}^2$$



- The value of θ_{23} affects the magnitude of the oscillation dip.
- The value of $\Delta m_{32}{}^2$ affects the energy at which energy the oscillation dip occurs.

Measuring Electron Neutrino Appearance

$$P(\nu_\mu \to \nu_e) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}[\cos \Delta m_{32} \cos\delta \mp \sin \Delta m_{32} \sin\delta]$$

$$P_{atm} \equiv \sin^2(\theta_{23})\sin^2(2\theta_{13})\frac{\sin^2(\Delta m_{31} \mp aL)}{(\Delta m_{31} \mp aL)^2}(\Delta m_{31})^2$$

$$P_{atm} \equiv \cos^2(\theta_{23})\sin^2(2\theta_{12})\frac{\sin^2(\mp aL)}{(\mp aL)^2}(\Delta m_{31})^2$$

$“-” = neutrinos$

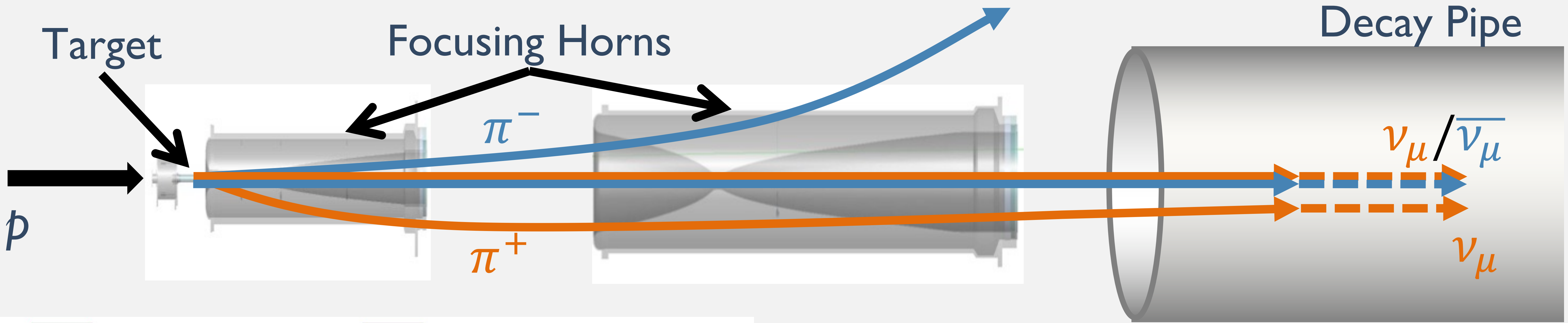
$“+” = anti-neutrinos$

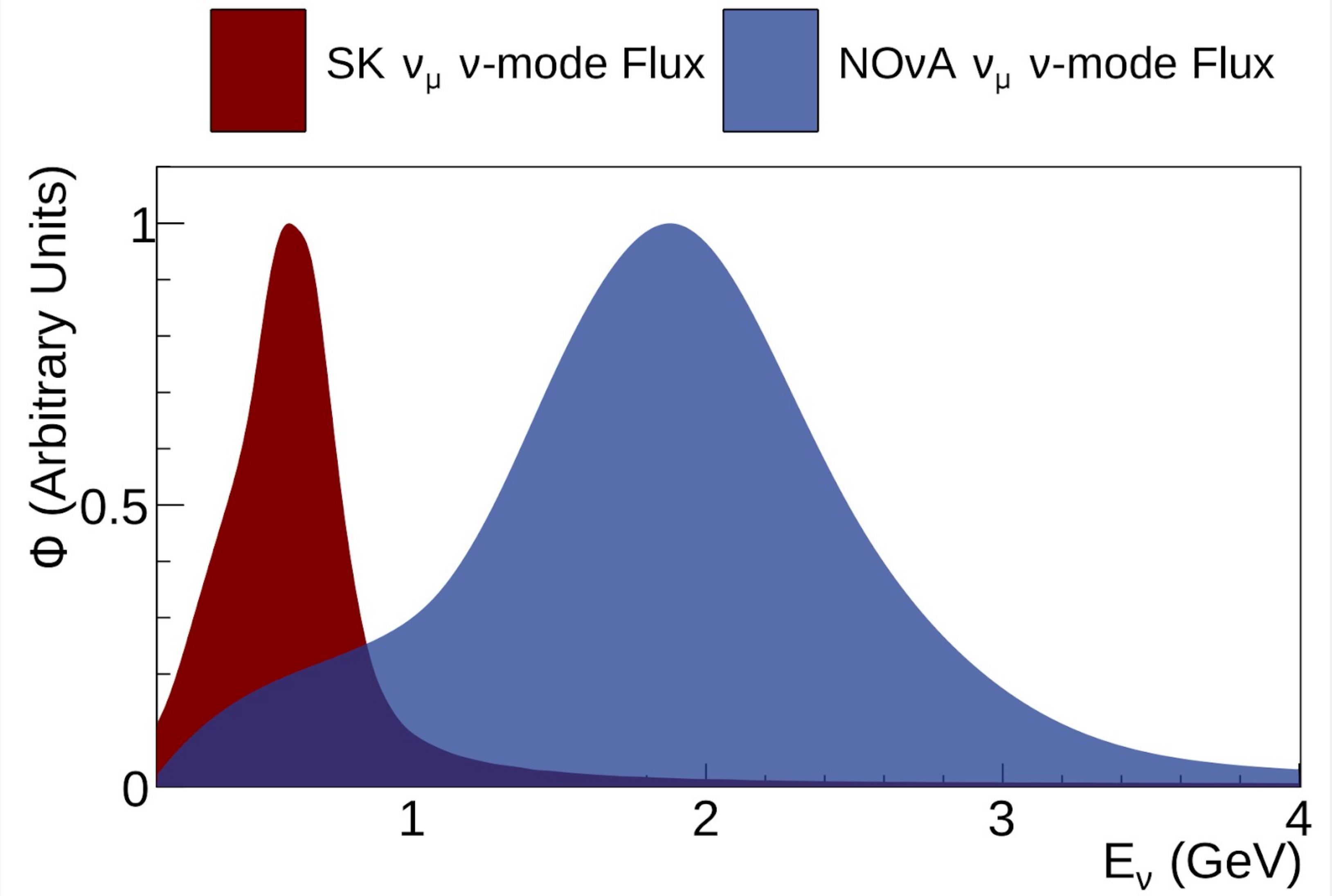
$a \equiv G_F N_e/\sqrt{2}$

$N_e = electron\ density$

Octant of θ_{23}	Neutrino mass hierarchy	Matter effects	CP violating phase
Is the mixing angle more than or less than 45 degrees?	Is the ν_3 mass state the lightest or heaviest mass state?	Increases with distance travelled through media. Caused by ν_e scattering off electrons.	Do neutrinos and anti-neutrinos behave differently?

The Neutrino Beamlines





- By preferentially selecting π^+/ π^- the experiments can measure neutrino or anti-neutrino oscillations.
- Oscillation rate is a function of L/E, so the differing baselines mean that neutrino energies must be different.

Data Taken For These Results

Both experiments continue to take data

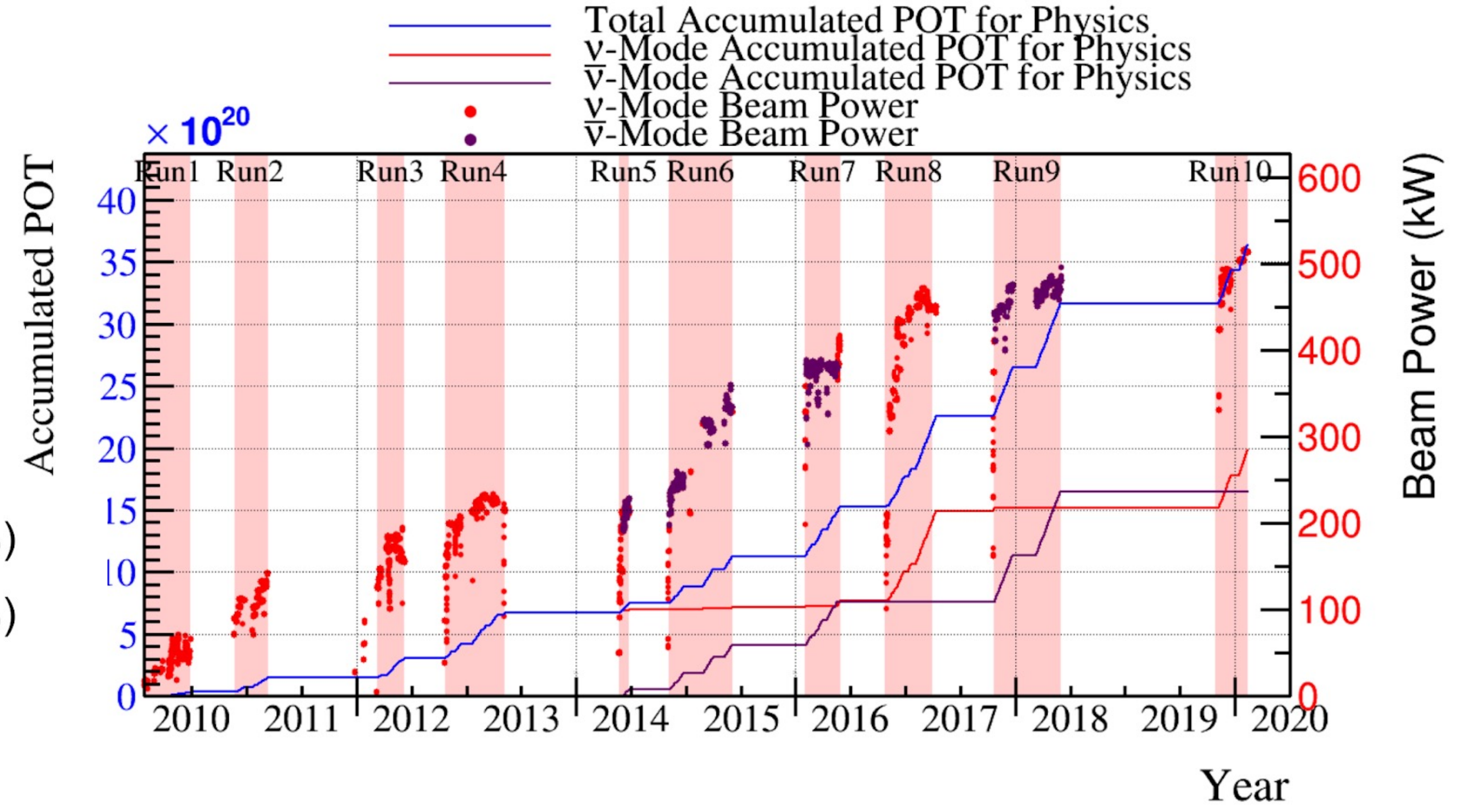
T2K

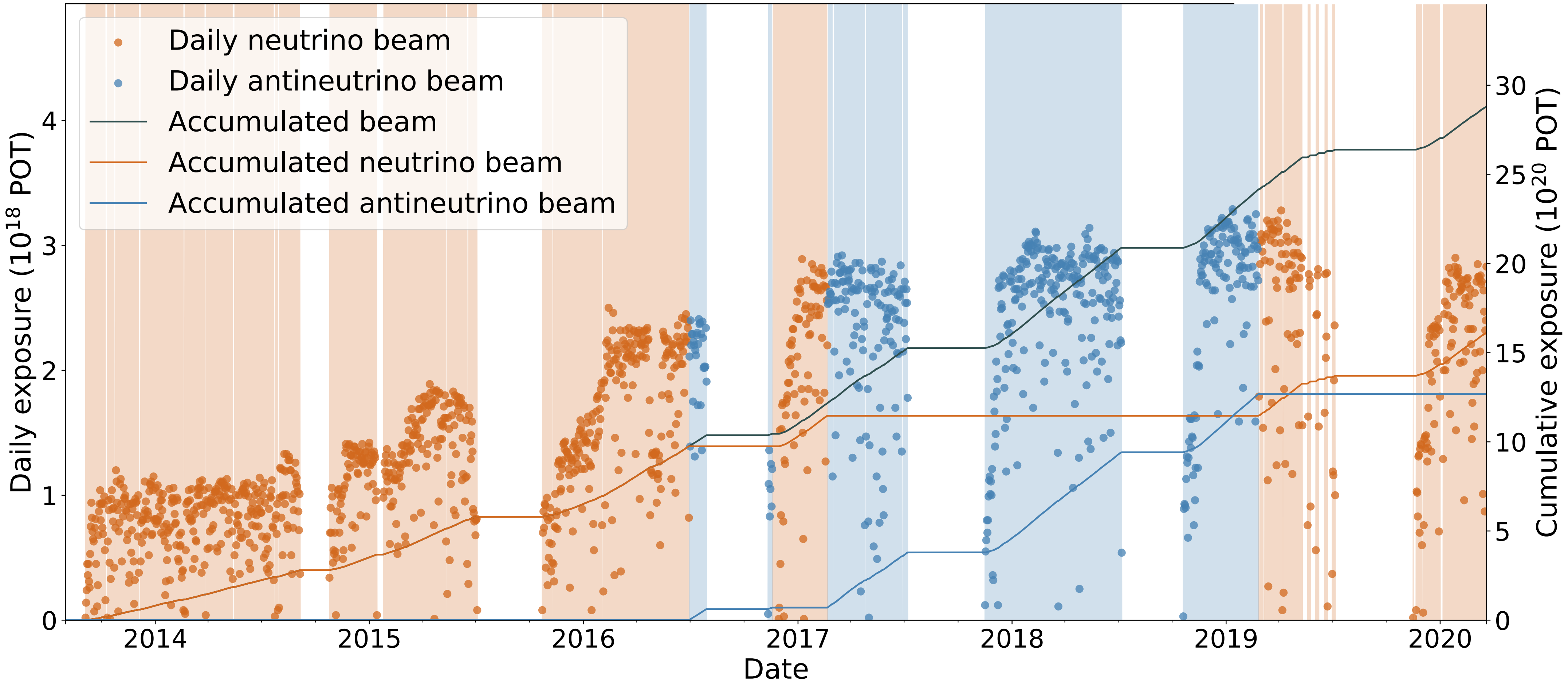
23 Jan 2010 - 12 Feb 2020

POT Total : 3.64059×10^{21}
(maximum power 522.627 kW)

ν mode : 1.99006×10^{21} (54.7%)

$\bar{\nu}$ mode : 1.65053×10^{21} (45.3%)



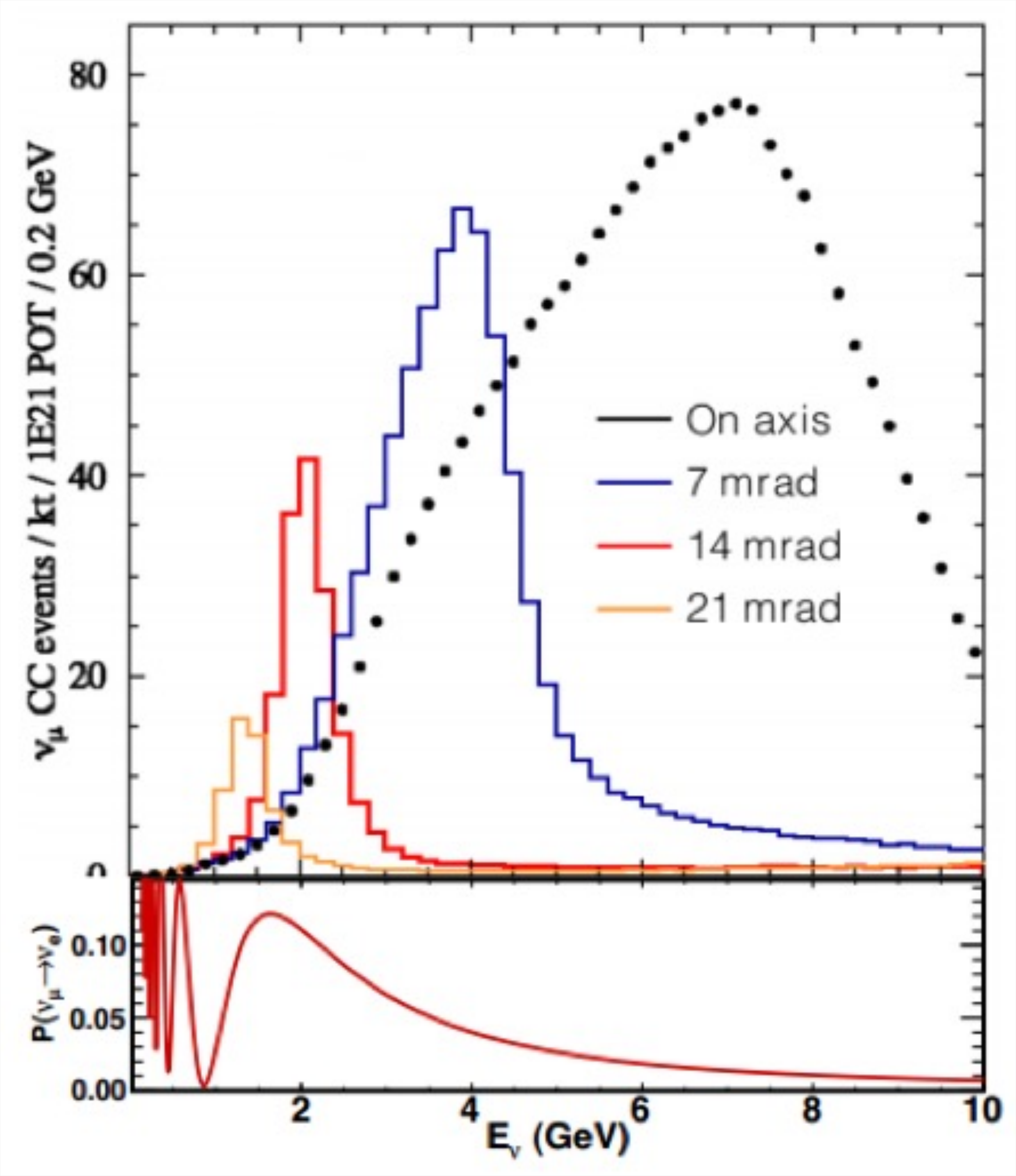


NOvA

13.60×10^{20} POT-equiv (ν)
12.50×10^{20} POT ($\bar{\nu}$)

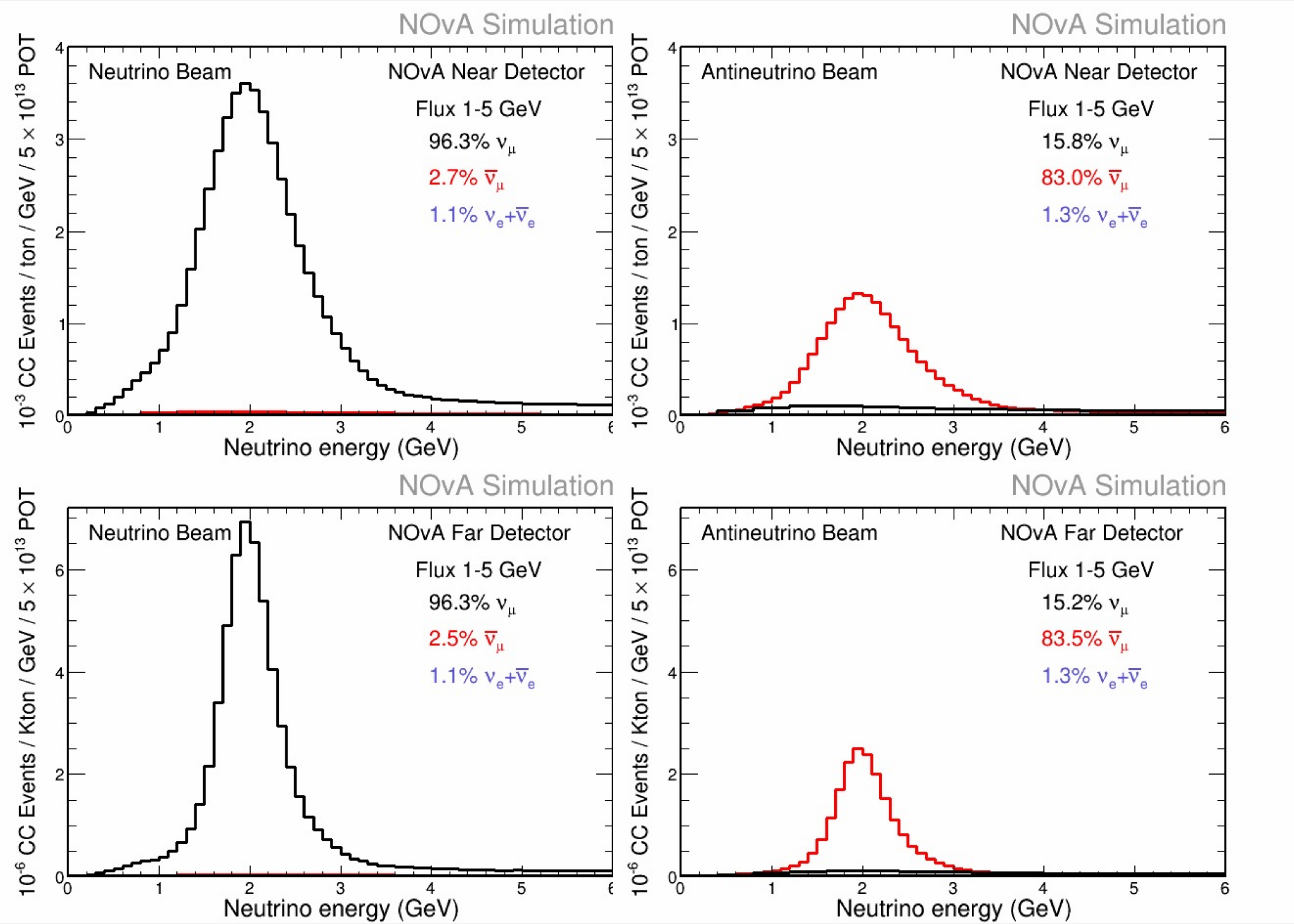
Recent Beam Power Record of 893 kW!
Actually ran at ~900 kW for most of the hour.

Strategically Positioned detectors



- By positioning the detector off-axis the energy spectrum of neutrinos changes significantly.
  - This is due to decay kinematics.
- At NOvA's 810 km baseline, the first appearance oscillation peak is around 1.8 GeV.
- Choosing an off-axis angle of 14 mrad is a compromise between having the largest possible neutrino flux, and the mean neutrino energy being close to the oscillation peak.
  - By largely removing the high energy tail, background rejection is also made easier.
- For T2K this occurs at 2.5° off-axis.

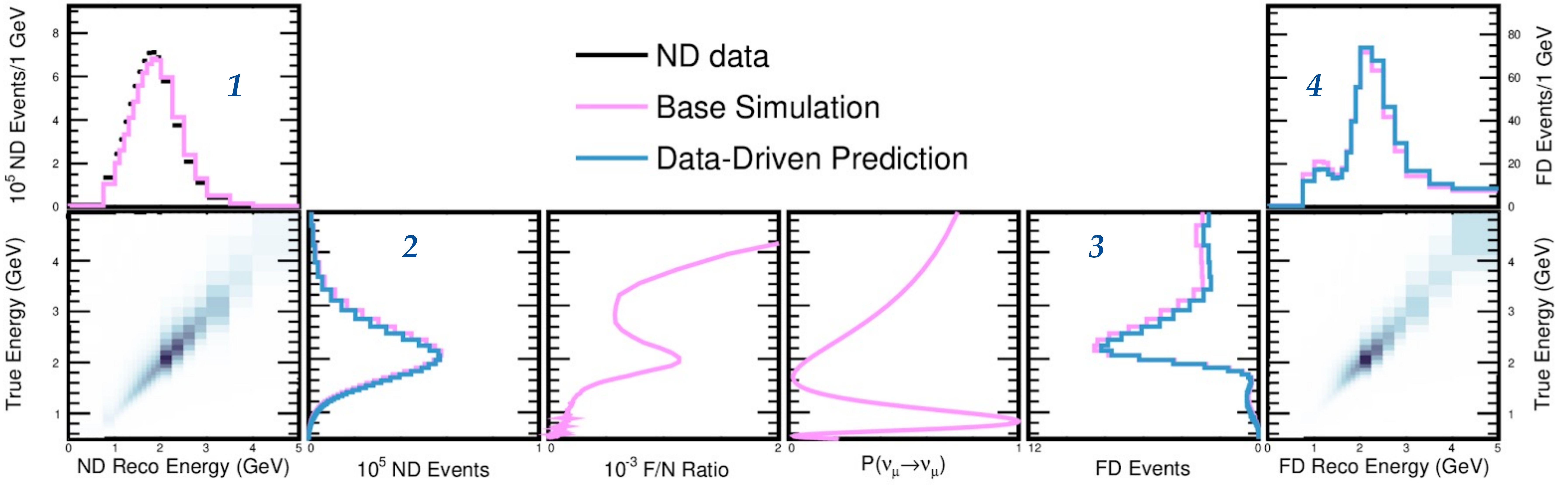
Rates For (Anti)Neutrino Mode in the Near/Far Detectors



- Can see that the event rates are much higher in neutrino mode (left) than anti-neutrino mode (right).
- Can see that contamination by wrong-sign neutrinos is much larger in anti-neutrino mode (15.8%) than in neutrino mode (2.7%).
- Can see the effect of off-axis detector, with the Far Detector spectrum being much narrower than the Near Detector.

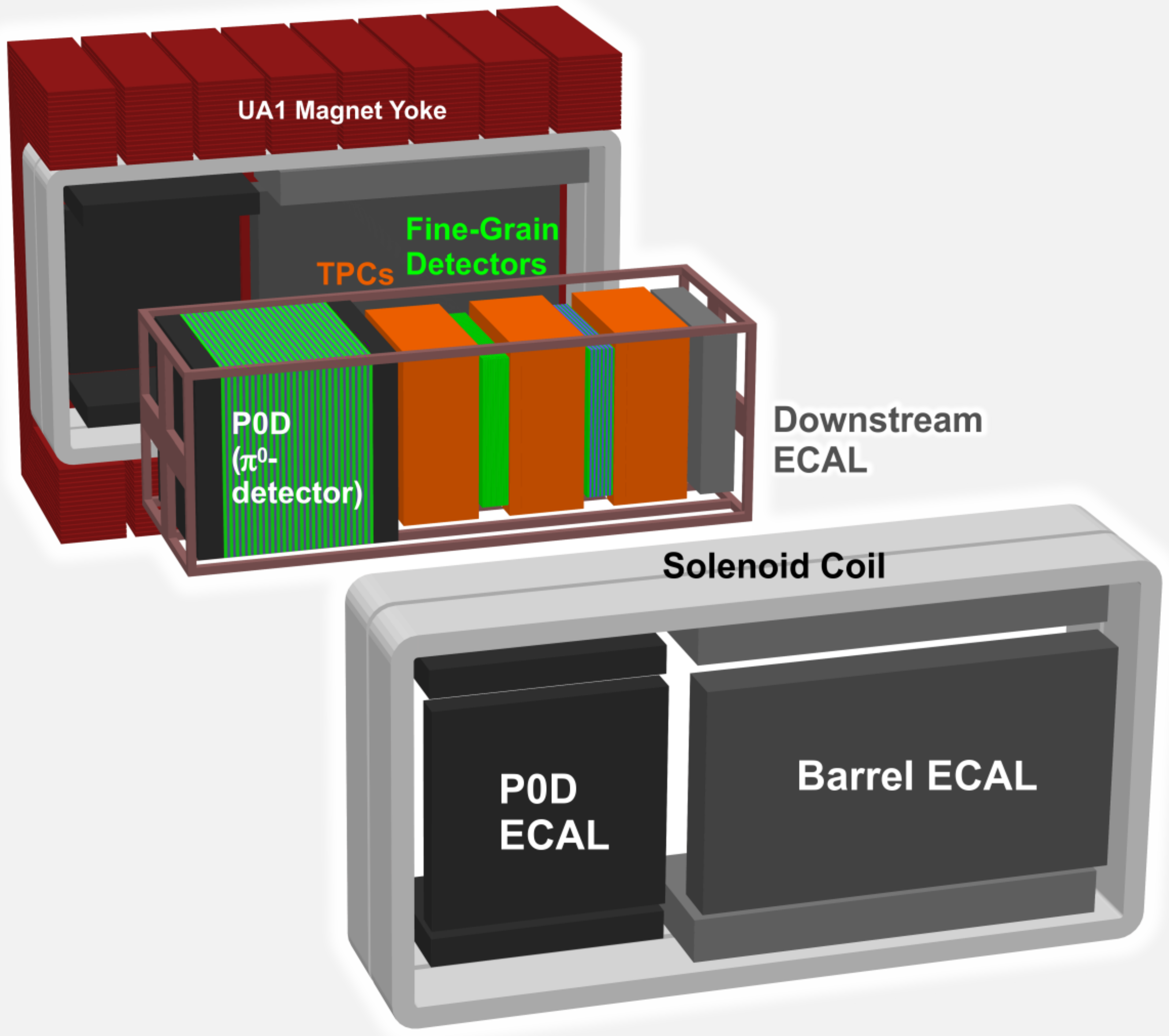
Predicting The NOvA Far Detector Spectra

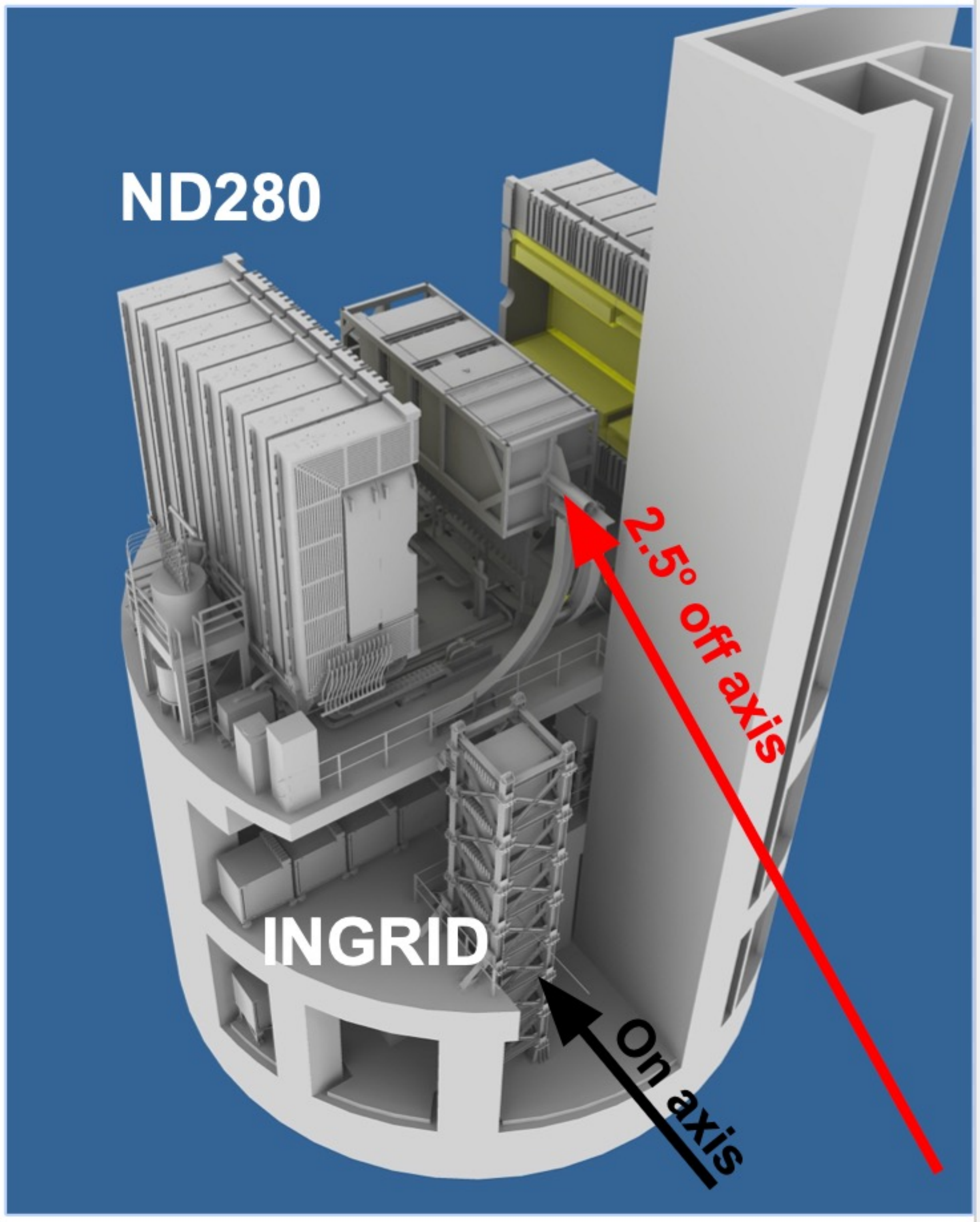
The NOvA Near and Far Detectors are functionally identical, so many uncertainties cancel out.



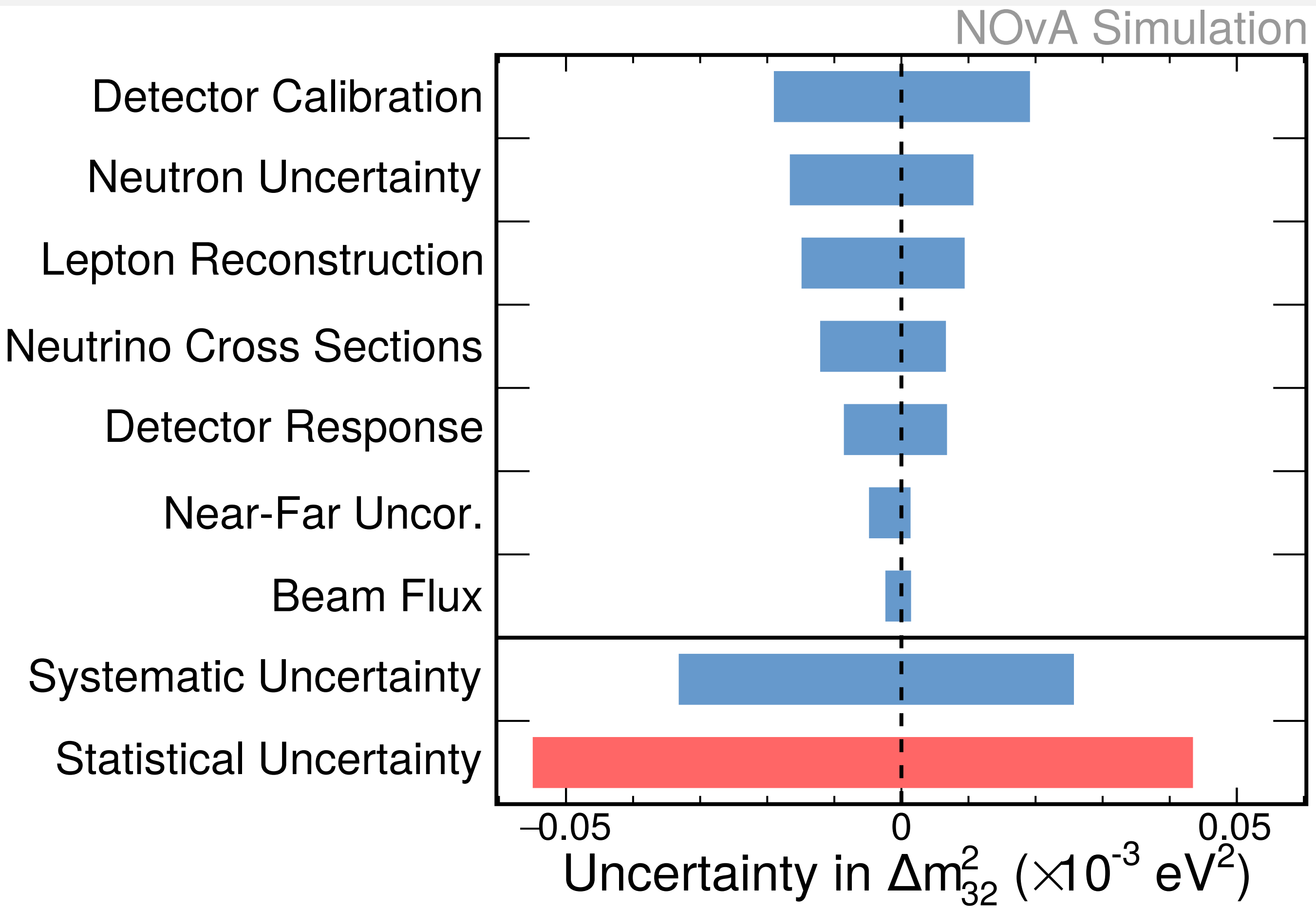
1. Sample events in the Near Detector
2. Estimate true neutrino energy spectrum by using the tuned interaction model.
3. Account for Near/Far detector differences and apply oscillation probs.
4. Predict the observed Far Detector event rates after oscillation.

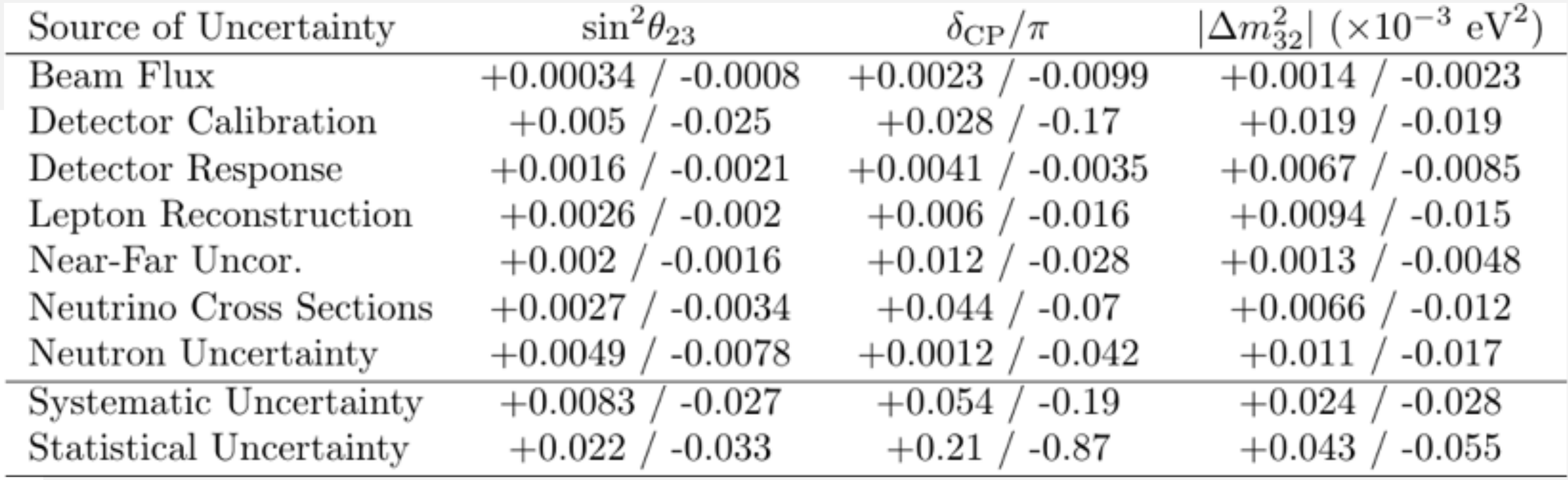
The T2K Near Detector Complex





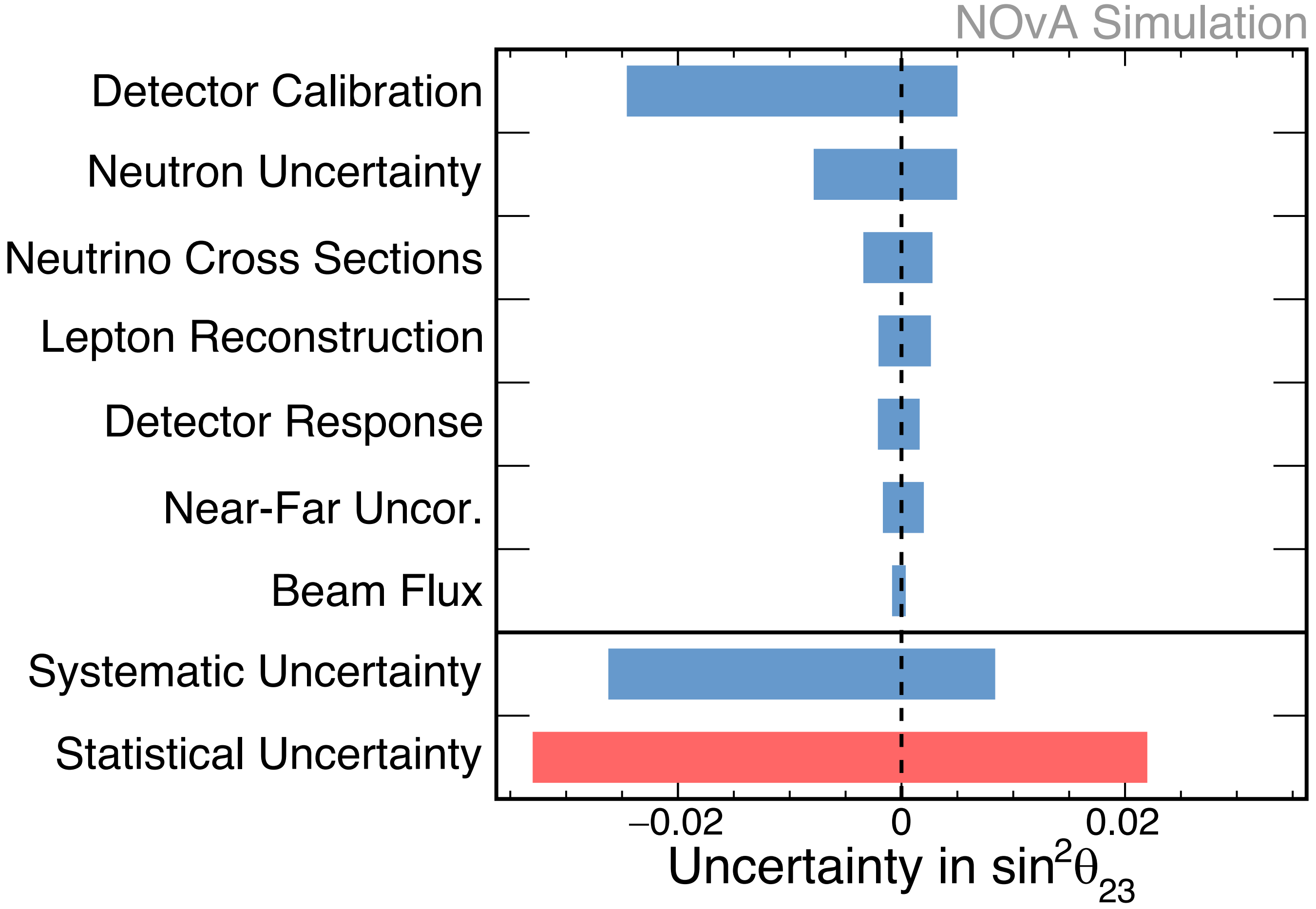
Uncertainties – NOvA

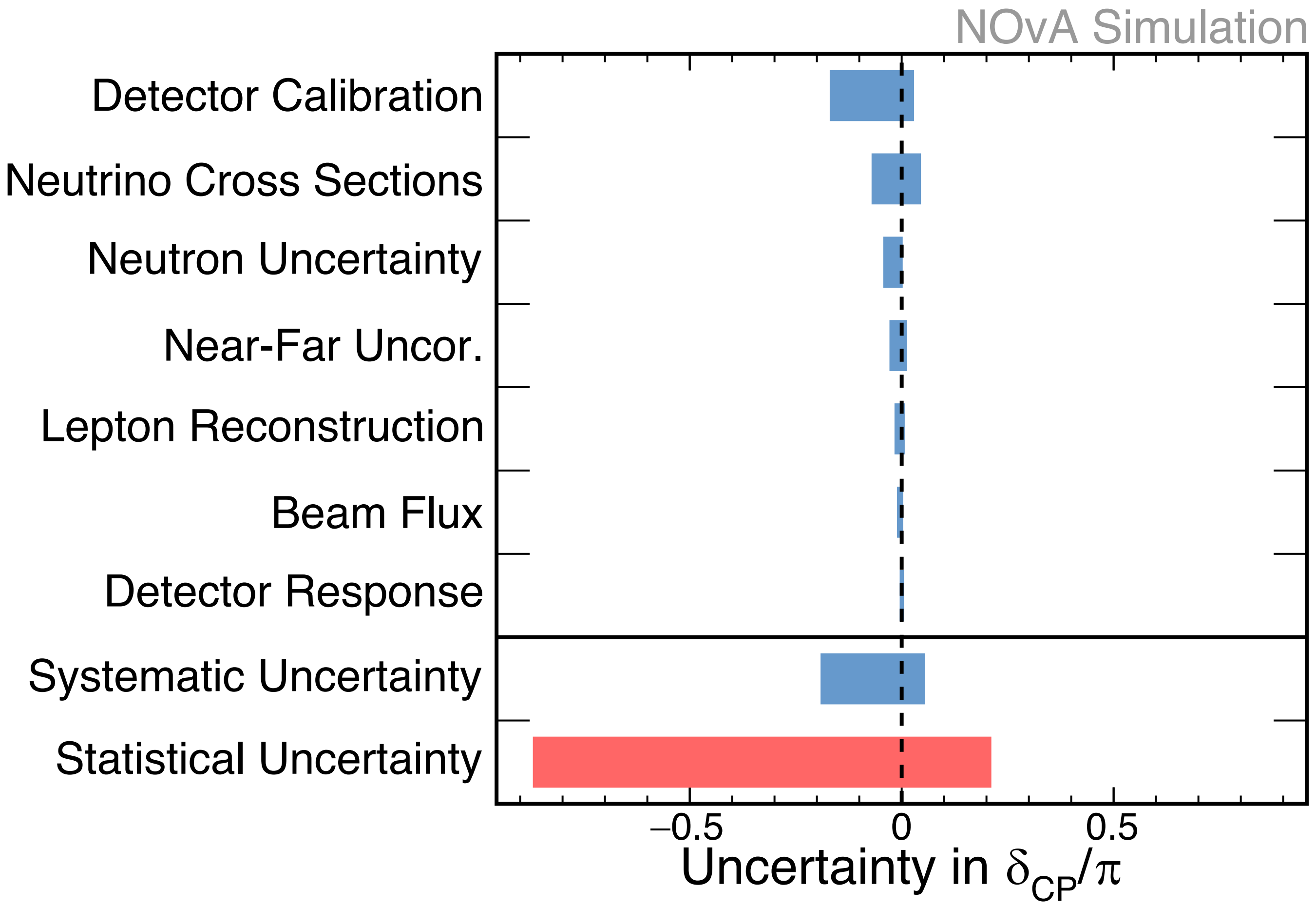




Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ ($\times10^{-3}$ eV^2)
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -0.0085
Lepton Reconstruction	+0.0026 / -0.002	+0.006 / -0.016	+0.0094 / -0.015
Near-Far Uncor.	+0.002 / -0.0016	+0.012 / -0.028	+0.0013 / -0.0048
Neutrino Cross Sections	+0.0027 / -0.0034	+0.044 / -0.07	+0.0066 / -0.012
Neutron Uncertainty	+0.0049 / -0.0078	+0.0012 / -0.042	+0.011 / -0.017
Systematic Uncertainty	+0.0083 / -0.027	+0.054 / -0.19	+0.024 / -0.028
Statistical Uncertainty	+0.022 / -0.033	+0.21 / -0.87	+0.043 / -0.055

NOvA requires more than twice the 2027 projected POT to become Stats-limited for Hierarchy determination.





Systematic Limits – T2K

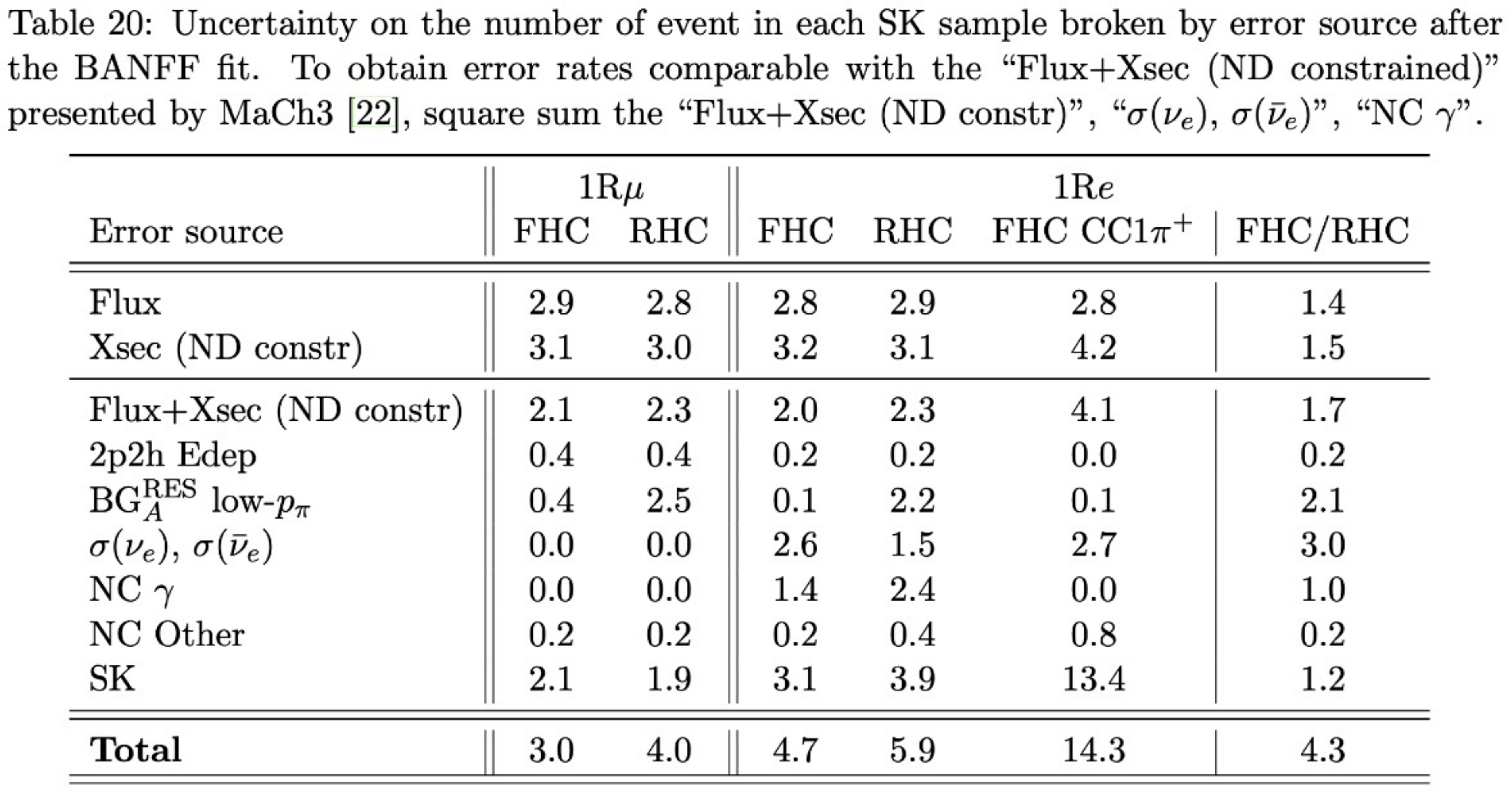
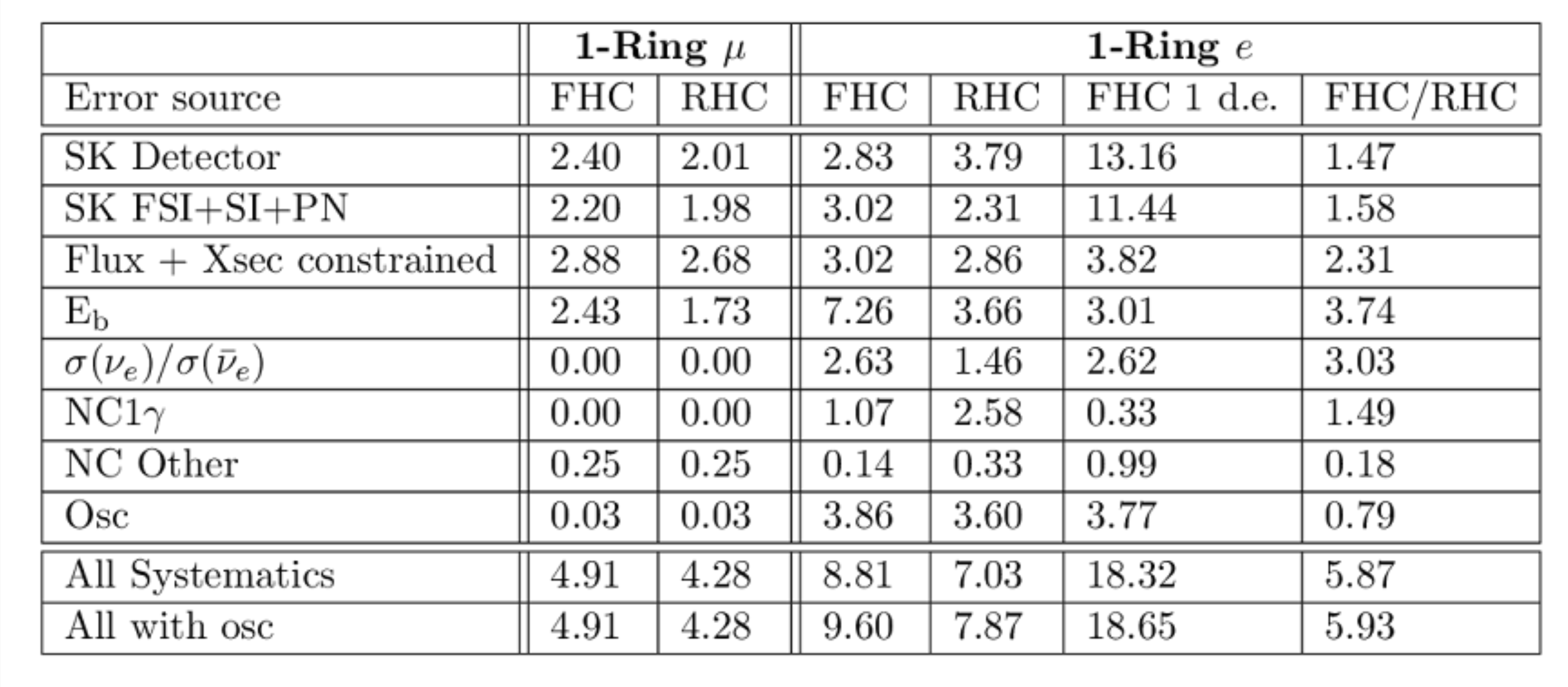


Table 20: Uncertainty on the number of event in each SK sample broken by error source after the BANFF fit. To obtain error rates comparable with the "Flux+Xsec (ND constrained)" presented by MaCh3 [22], square sum the "Flux+Xsec (ND constr)", "$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$", "NC γ".

	1Rμ		1Re			
Error source	FHC	RHC	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3



	1-Ring μ		**1-Ring e**			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93