Latest 3-Flavor Neutrino Oscillation Results From T2K and NOvA

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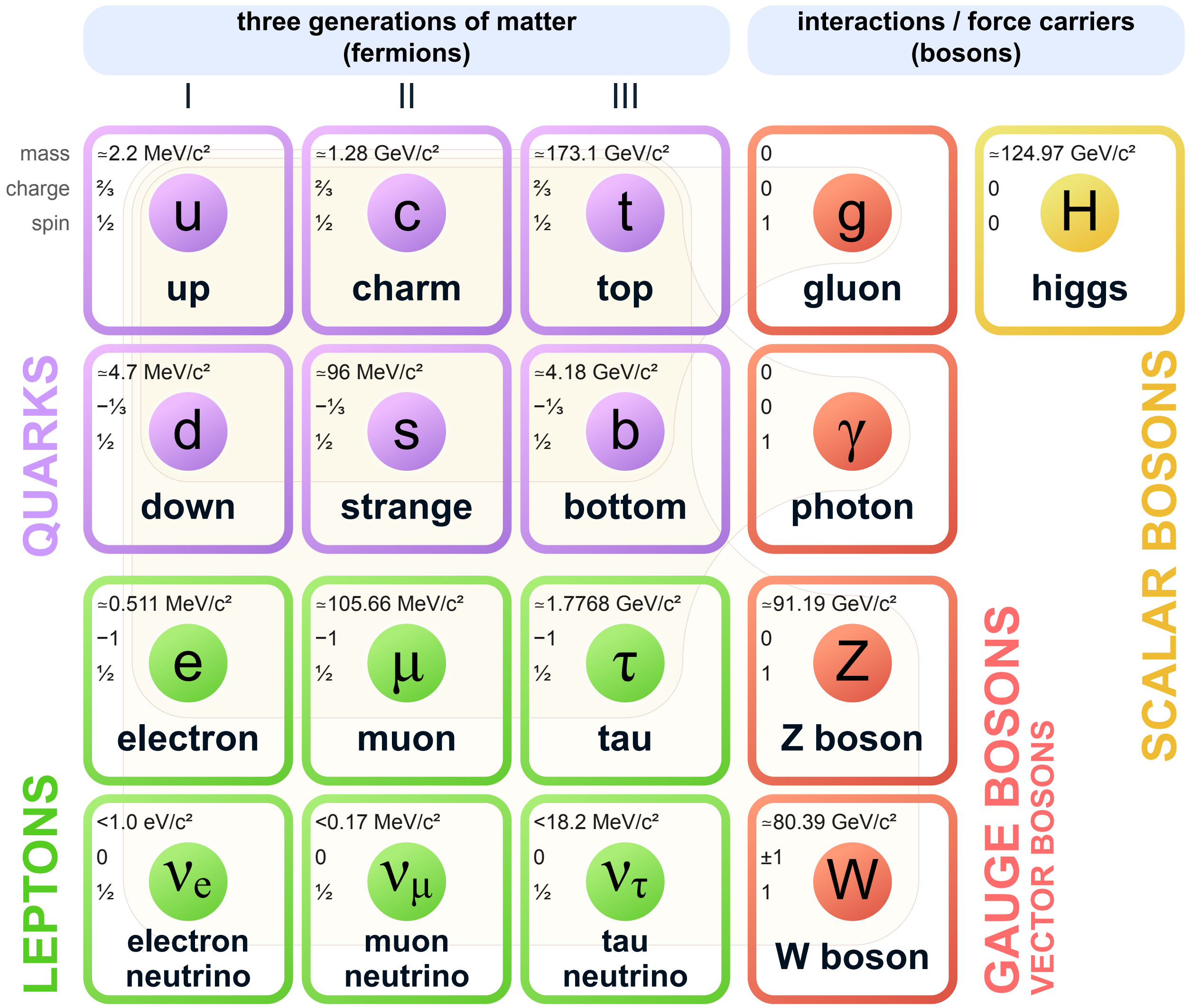
FPCP2021 (Shanghai, China)
June 7, 2021

Neutrinos and the Standard Model

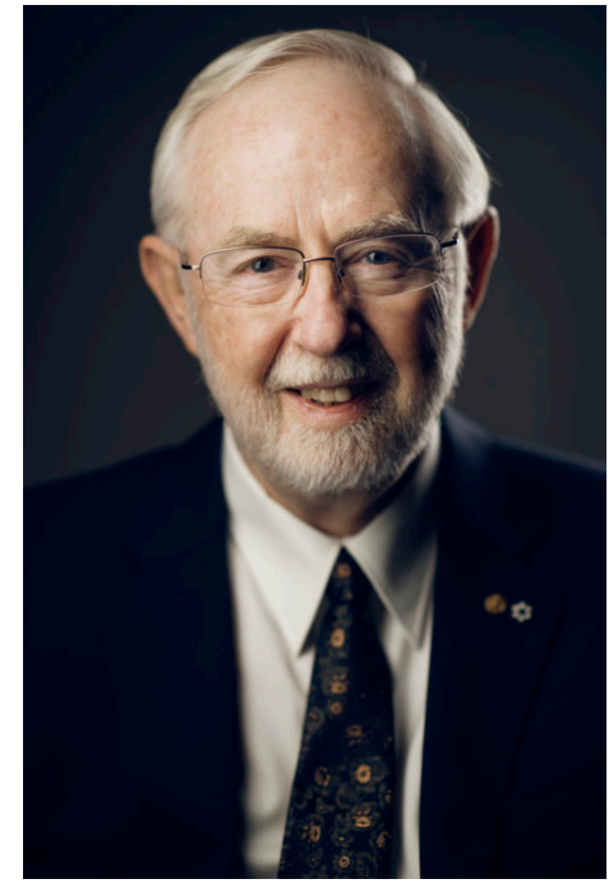
Standard Model of Elementary Particles



- Neutrinos in the standard model are massless
- Neutrino Oscillations
  - establish neutrinos have mass
  - physics beyond the standard model

The Nobel Prize in Physics 2015

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan



Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

3-Flavor Neutrino Oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} \exp\left[-i\frac{m_j^2 L}{2E_\nu}\right] U_{\alpha j} \right|^2$$

Transitions between the known neutrino flavors ν_e, ν_μ, ν_τ at distance ("baseline") L and neutrino energy E_ν

3-Flavor Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} \exp\left[-i\frac{m_j^2 L}{2E_\nu}\right] U_{\alpha j} \right|^2$$

Unitary PMNS matrix:

- Parameterizes mixing between flavor eigenstates ν_e, ν_μ, ν_τ and mass eigenstates ν_1, ν_2, ν_3
- 3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$
- CP violating phase δ_{CP}

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

Current strongest constraints:

- θ_{12} from solar exp.
- θ_{13} from reactor exp.
- θ_{23}, δ_{CP} from long baseline (LBL) accelerator exp.

3-Flavor Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} \exp\left[-i\frac{m_j^2 L}{2E_\nu}\right] U_{\alpha j} \right|^2$$

Oscillation probability also depend on mass eigenstate differences $\Delta m^2_{ij} = m_i^2 - m_j^2$

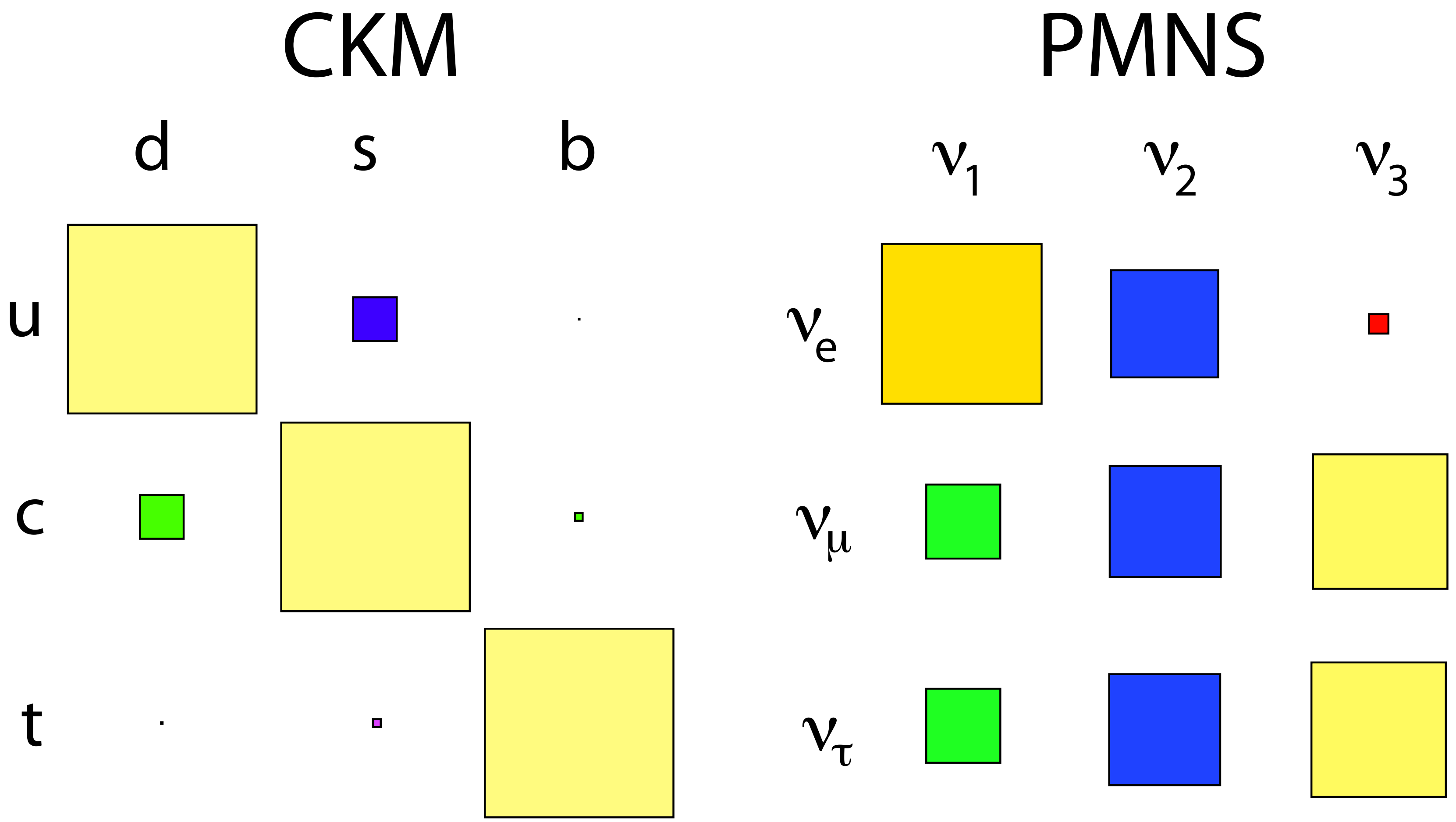
$\Delta m^2_{21} \simeq 8 \times 10^{-5}$ eV^2

- Strongest constraints from reactor exp.

$\left|\Delta m^2_{31}\right| \approx \left|\Delta m^2_{32}\right| \approx 2 \times 10^{-3}$ eV^2

- Strongest constraints from reactor and accelerator LBL exp.

Quark vs. Neutrino Mixing

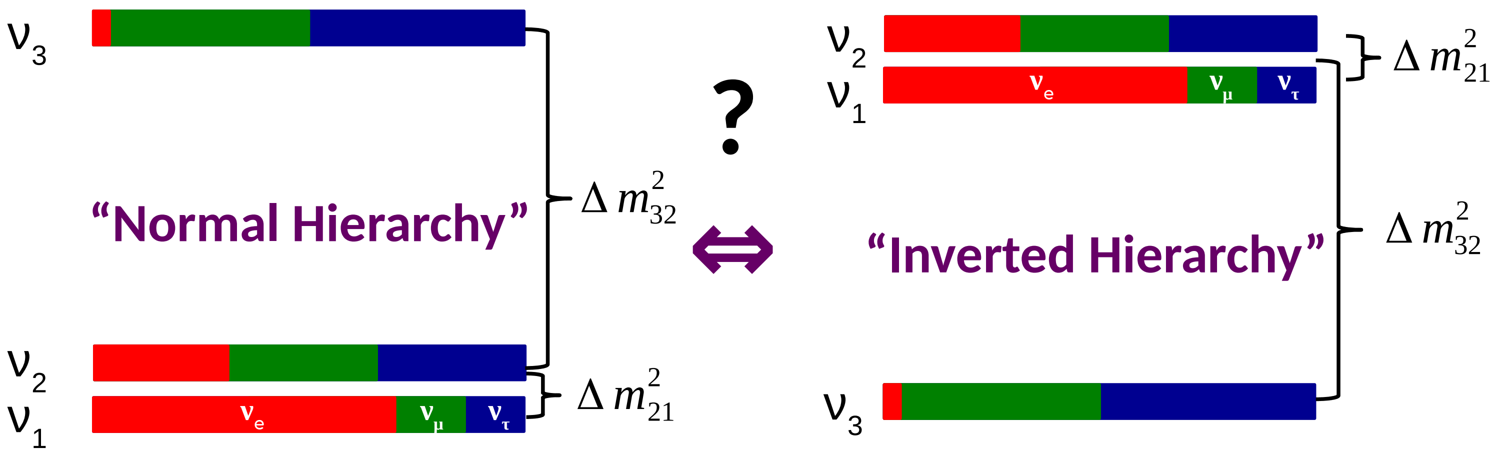


PoS(ICHEP2012)033

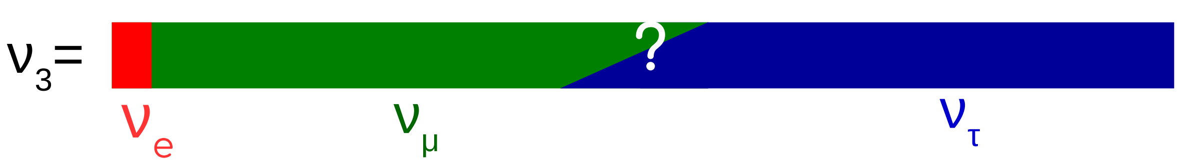
Area of squares represents square of matrix element

- Neutrino mixing stronger than quark mixing
- Jarlskog invariant could be $\mathcal{O}(10^3)$ larger for neutrinos than quarks:

$$J_{CP}^{CKM} \simeq 3 \times 10^{-5} \qquad J_{CP}^{PMNS} \lesssim 0.03$$



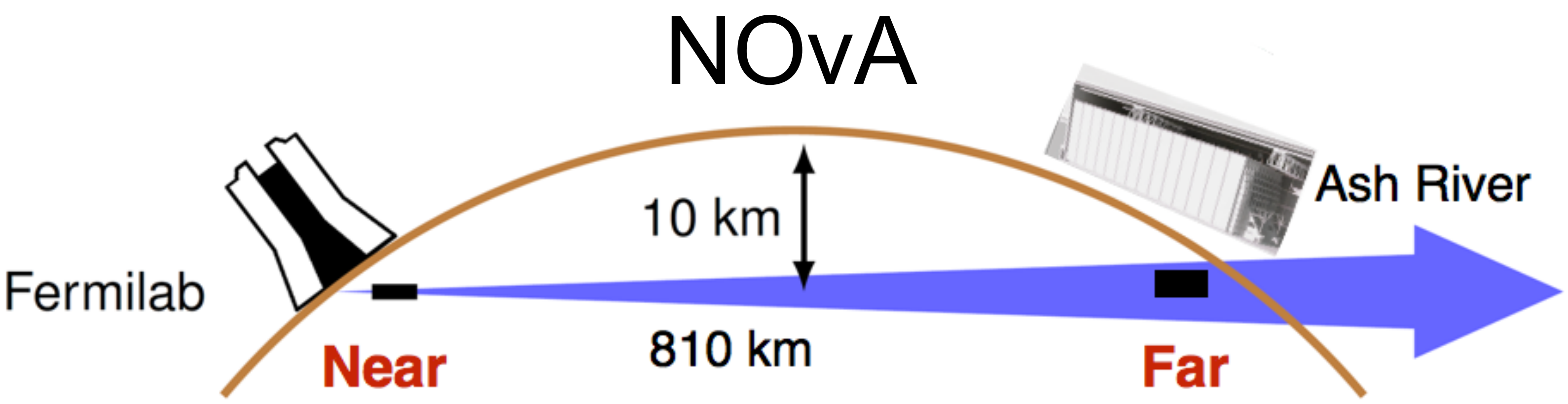
1) Is the neutrino mass hierarchy "Normal" or "Inverted"?
   - Symmetry governing order of neutrino and charged lepton masses?

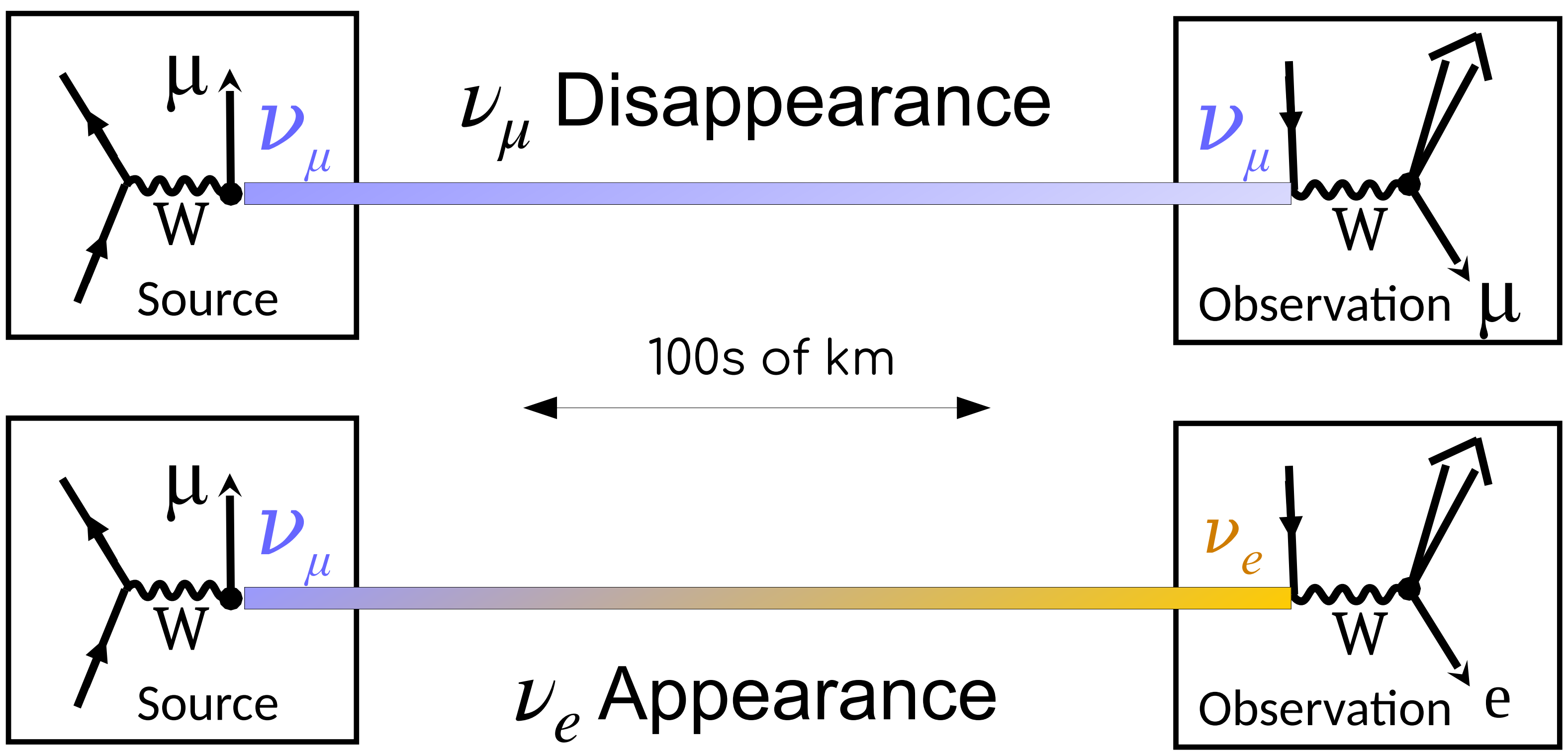


2) Maximal mixing of ν_μ, ν_τ with ν_2, ν_3?
   - $\theta_{23} = \pi/4$?
   - $\nu_\mu - \nu_\tau$ symmetry?

3) Do neutrinos violate CP?
   - δ_{CP}/π non-integral?
   - May help explain matter-antimatter asymmetry in universe

Long Baseline Accelerator ν Experiments





High-intensity ν_μ or $\overline{\nu}_\mu$ beam at E_ν ~ 1 to 10 GeV

Measure

- ν_μ and $\overline{\nu}_\mu$ disappearance
- ν_e and $\overline{\nu}_e$ appearance

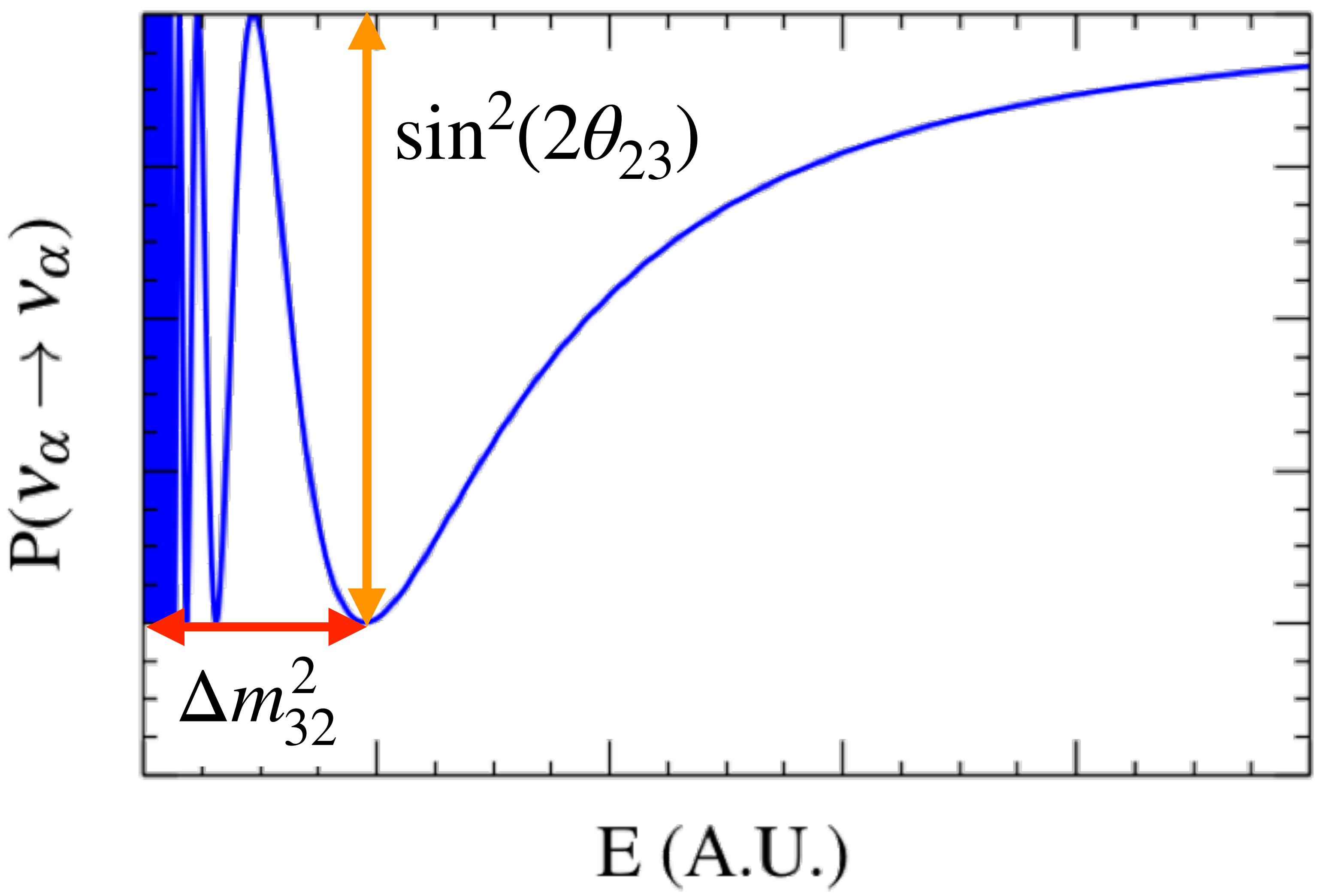
over baseline of 100s of km

Count charged current (CC) interactions (mostly νA)

- ν flavor determined from final state $\mu^\pm, e^\pm$
- E_ν measured from final state particles

ν_μ and $\bar{\nu}_\mu$ Disappearance

$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu\right) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right)$$



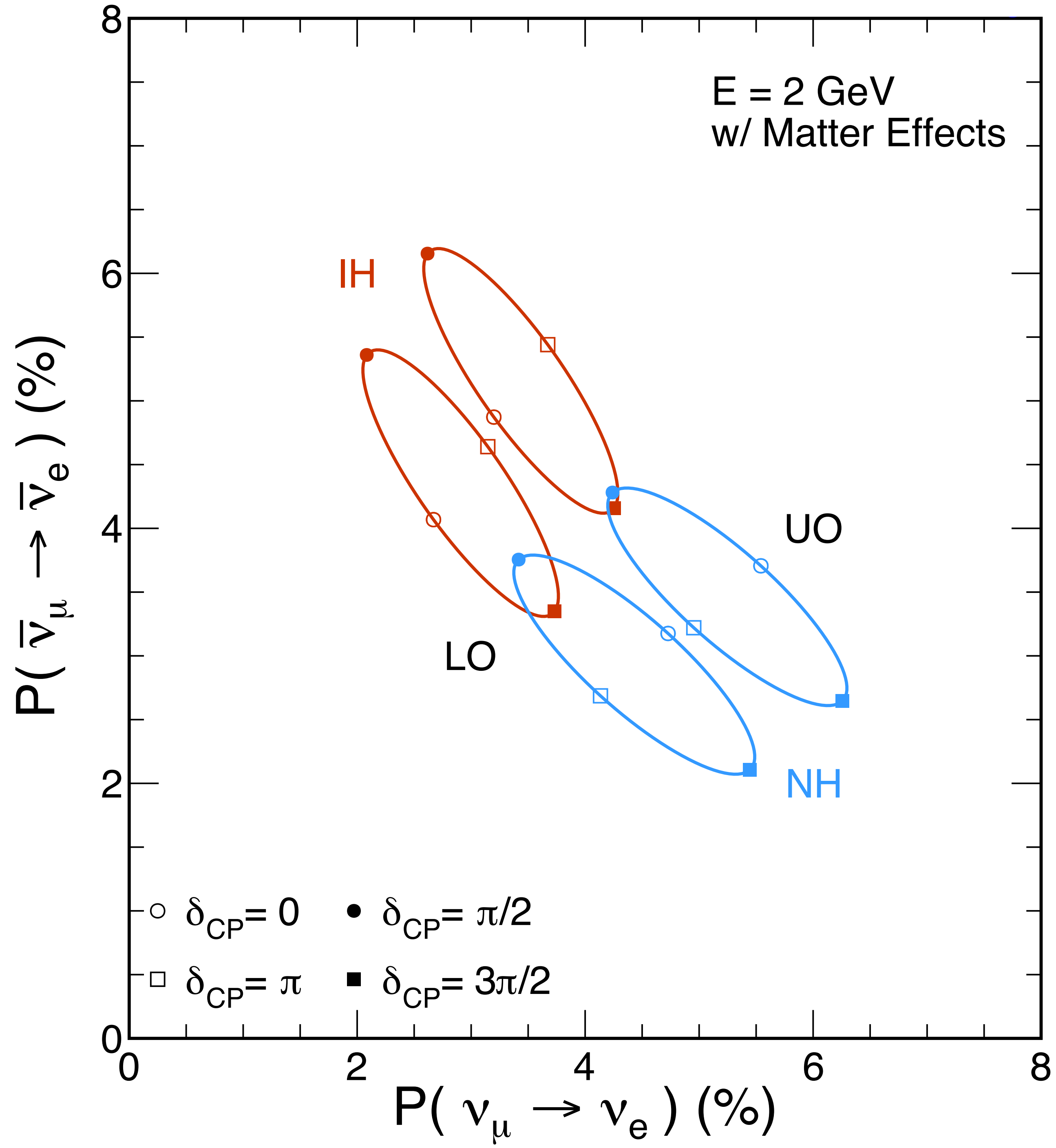
Oscillation “dip” in $\overset{(-)}{\nu}_\mu$ E_ν spectrum at far detector:

- Depth: $\sin^2(2\theta_{23})$
- Position: Δm^2_{32} and L (fixed)

ν_e and $\overline{\nu}_e$ Appearance

$P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

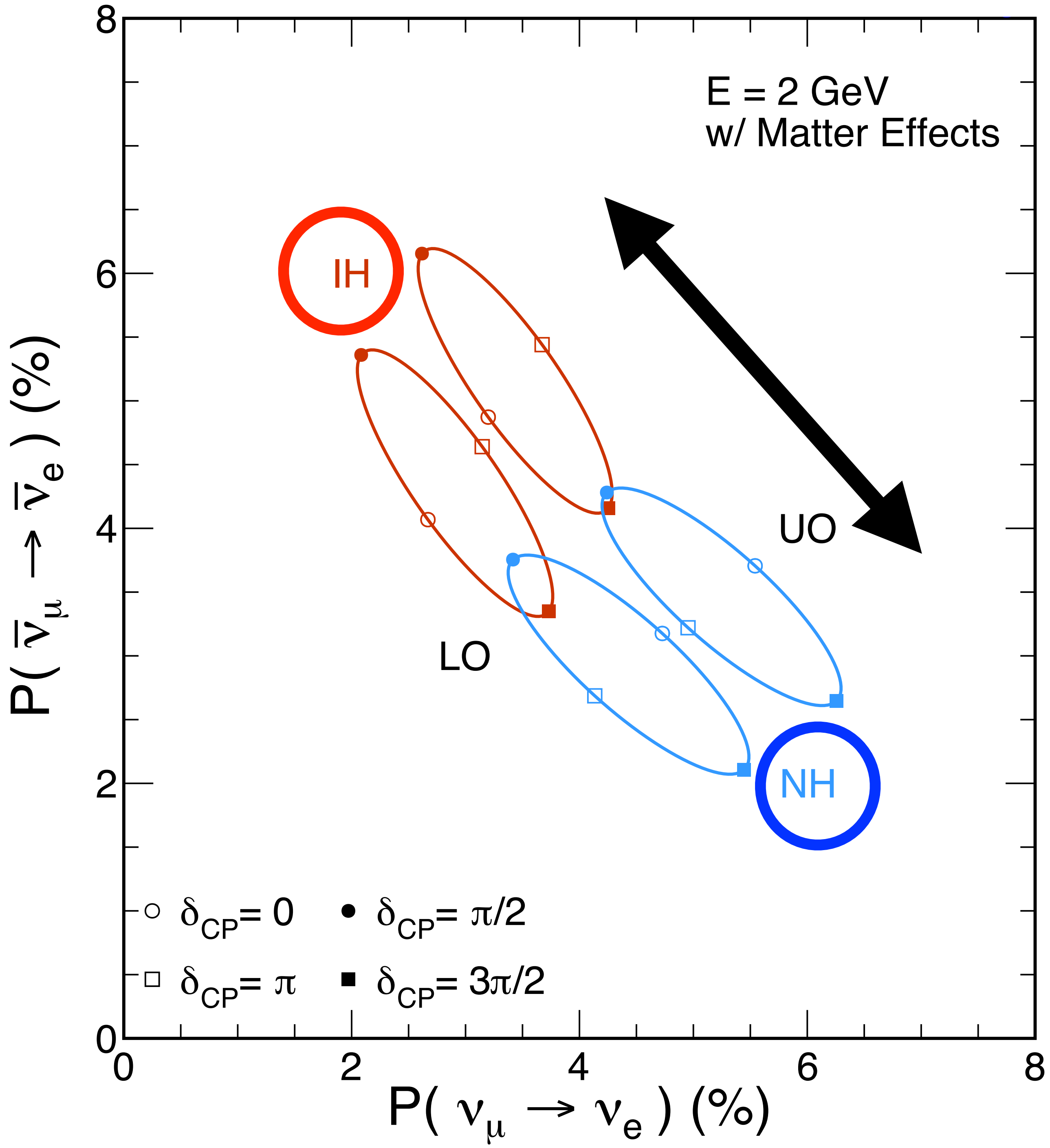
- Leading dependence on $\sin^2\theta_{23},\ \sin^2\theta_{13},\ |\Delta m^2_{32}|$
- Sub-leading dependence on δ_{CP} and mass hierarchy $(\pm\Delta m^2_{32})$



ν_e and $\overline{\nu}_e$ Appearance: Mass Hierarchy

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

- Leading dependence on $\sin^2\theta_{23},\ \sin^2\theta_{13},\ |\Delta m^2_{32}|$
- Sub-leading dependence on δ_{CP} and mass hierarchy $(\pm\Delta m^2_{32})$



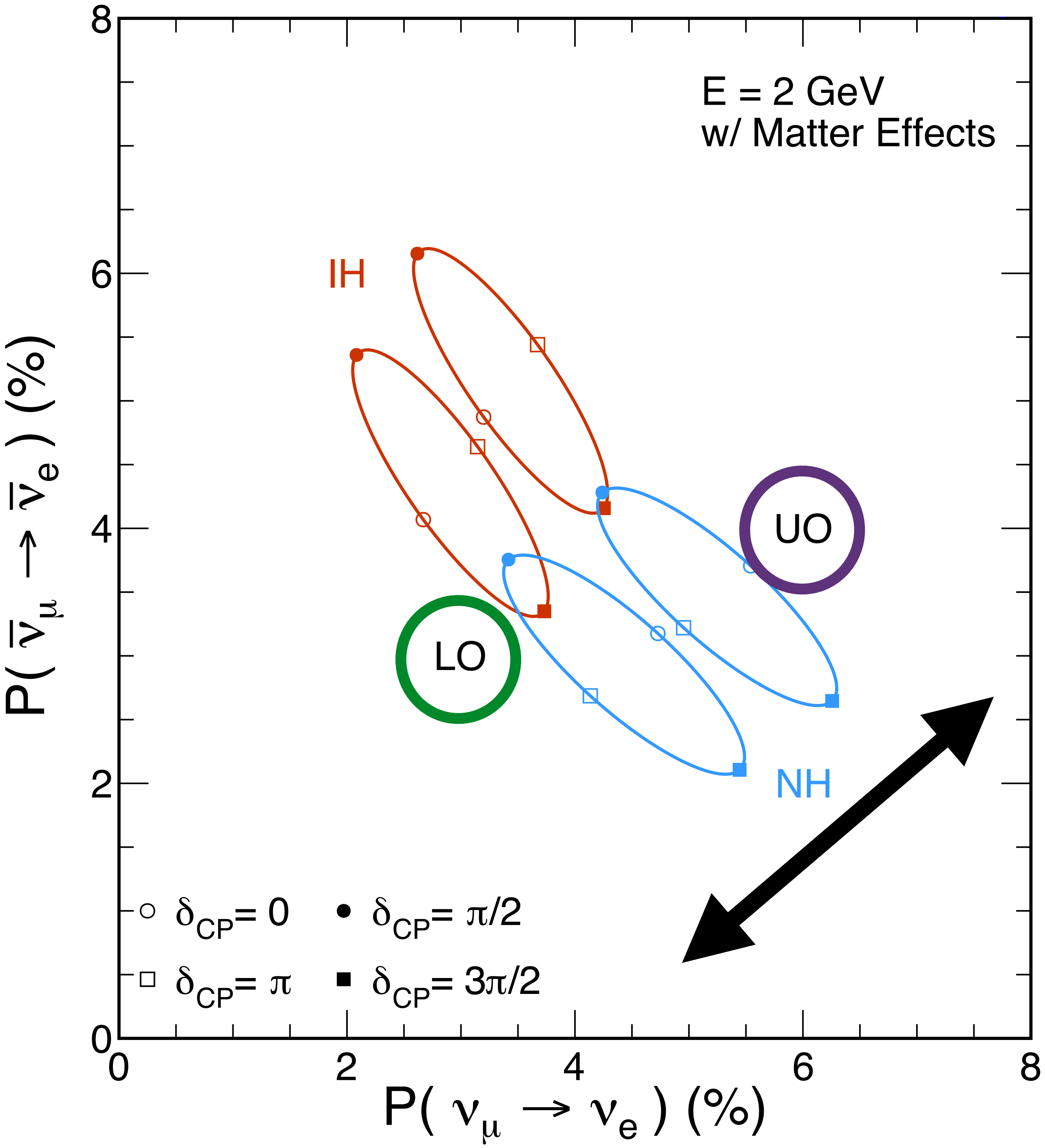
MSW ("Matter") Effect:

- ν_e, $\overline{\nu}_e$ forward scattering in matter changes effective masses of neutrinos
- Normal Hierarchy: $\Uparrow \nu_e$, $\Downarrow \overline{\nu}_e$ app.
- Inverted Hierarchy: $\Downarrow \nu_e$, $\Uparrow \overline{\nu}_e$ app.
- Size of effect is
  - ~10% for T2K (L = 296 km)
  - ~30% for Nova (L = 810 km)

ν_e and $\overline{\nu}_e$ Appearance: θ_{23} Octant

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

- Leading dependence on $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, $|\Delta m^2_{32}|$
- Sub-leading dependence on δ_{CP} and mass hierarchy ($\pm\Delta m^2_{32}$)



For non-maximal mixing:

- Lower Octant: $\theta_{23} < \pi/4$
- Upper Octant: $\theta_{23} > \pi/4$

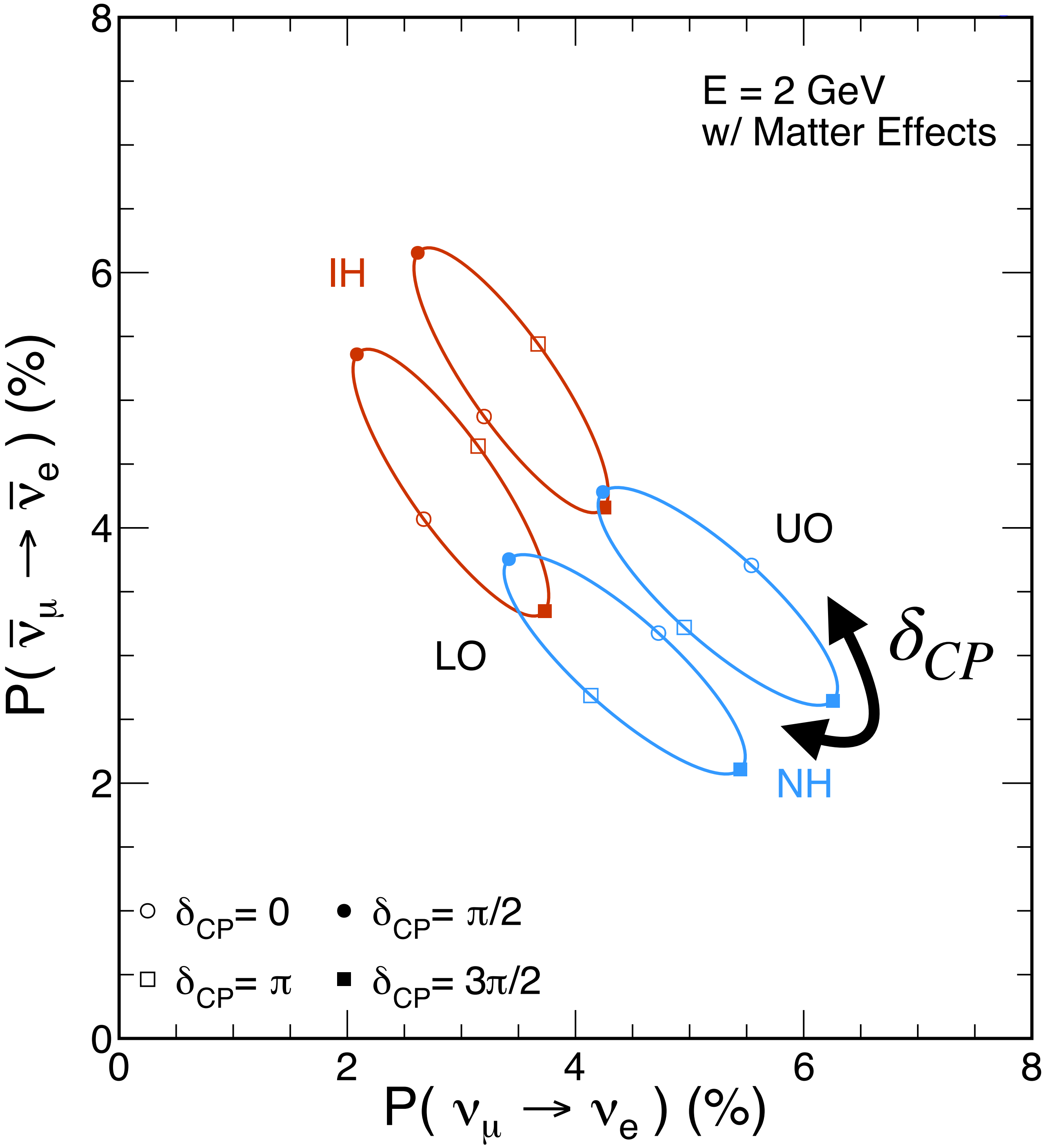
ν_e and $\overline{\nu}_e$ Appearance: δ_{CP}

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

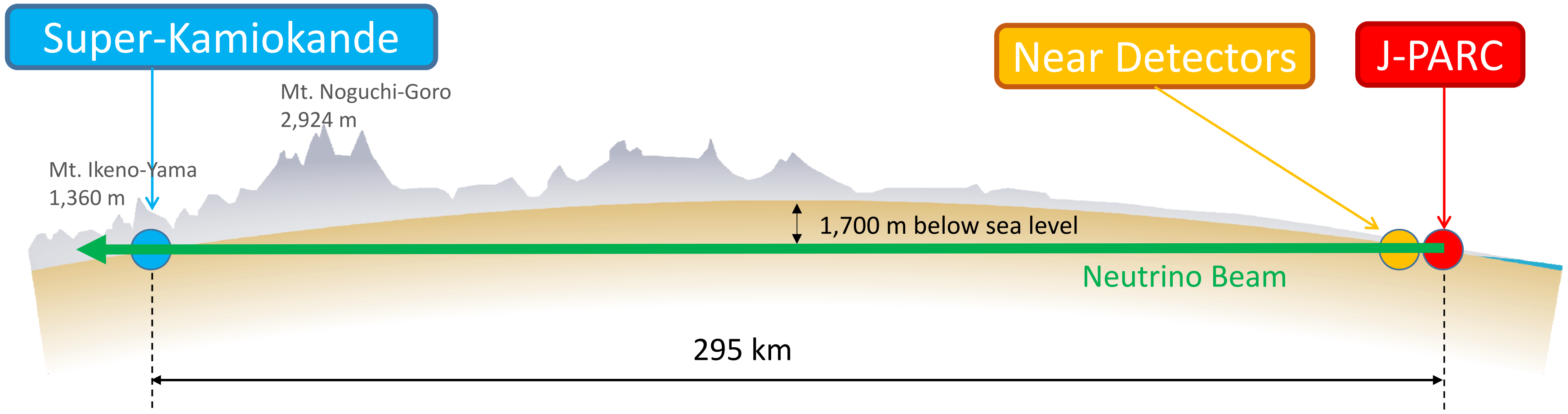
- Leading dependence on $\sin^2\theta_{23},\ \sin^2\theta_{13},\ |\Delta m^2_{32}|$
- Sub-leading dependence on δ_{CP} and mass hierarchy $(\pm\Delta m^2_{32})$

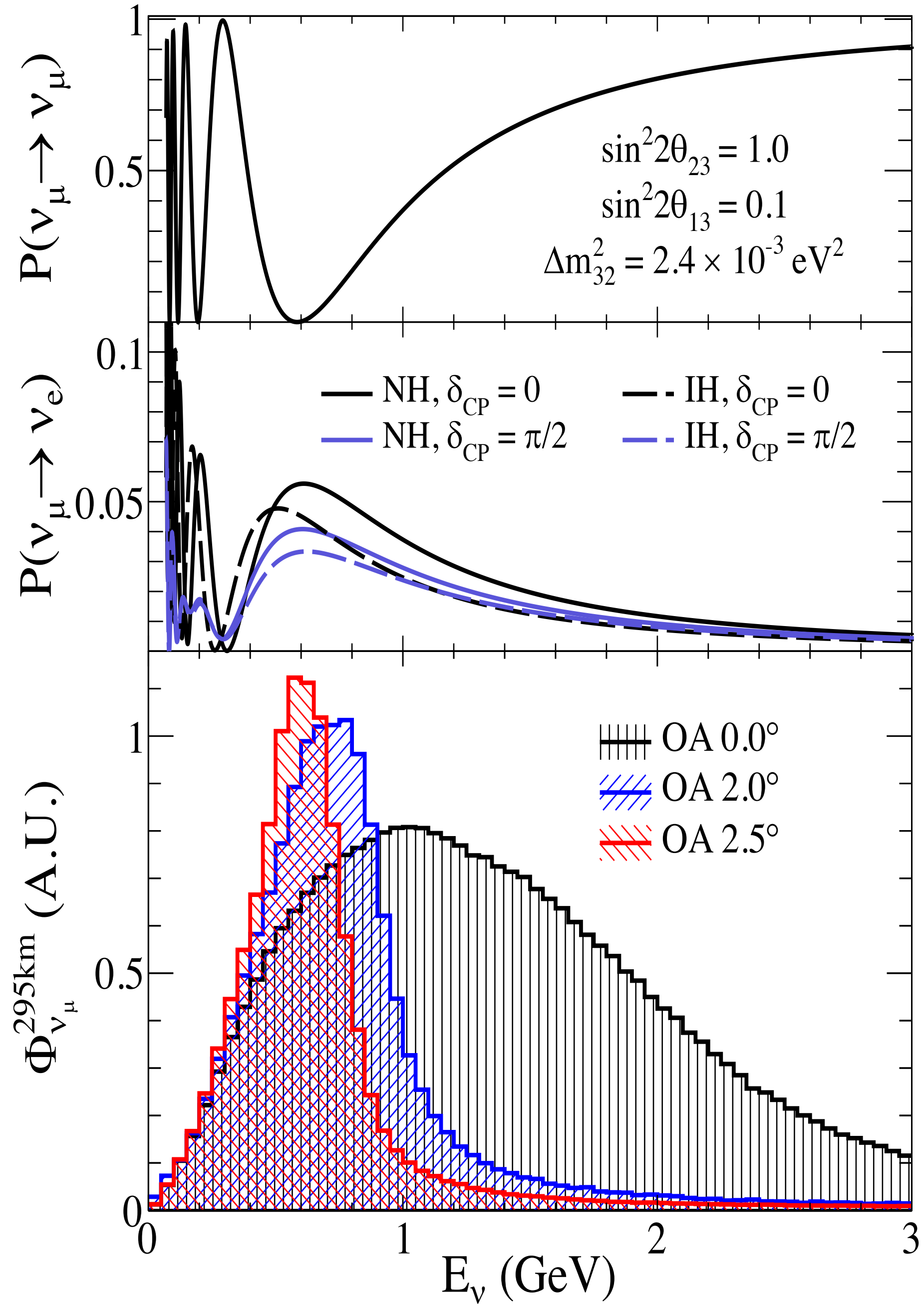
δ_{CP} can give an asymmetry between ν_e and $\overline{\nu}_e$ appearance:

- $\delta_{CP} = \pi/2$: $\Downarrow \nu_e$, $\Uparrow \overline{\nu}_e$ app.
- $\delta_{CP} = 3\pi/2$: $\Uparrow \nu_e$, $\Downarrow \overline{\nu}_e$ app.
- $\delta_{CP} = 0,\ \pi$: CP conserved



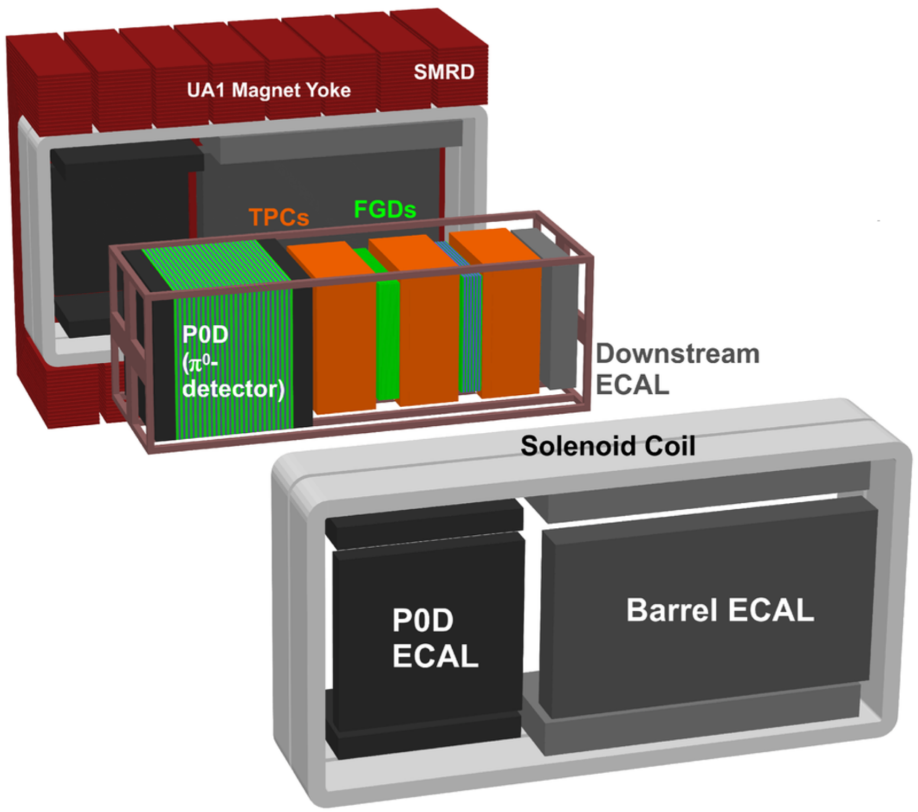
T2K Experiment





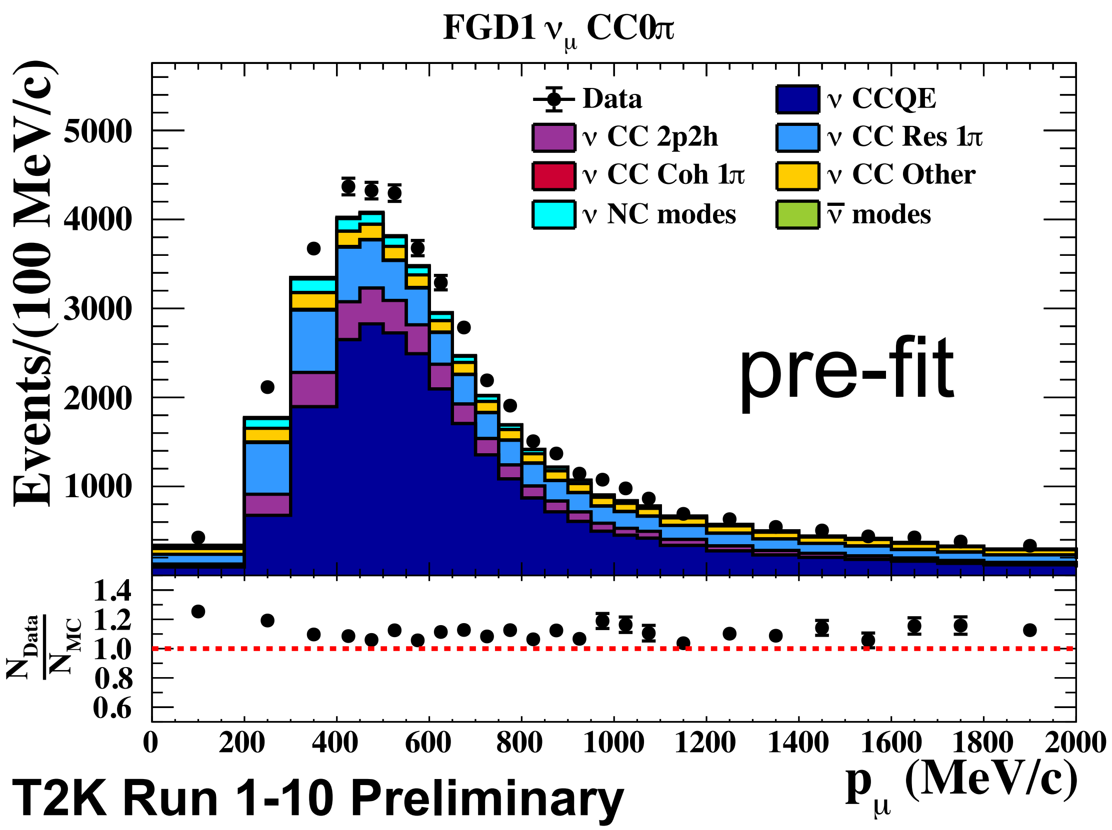
- ν_μ $(\bar{\nu}_\mu)$ beam generated at J-PARC
- Far detector (Super Kamiokande) at L = 295 km
- Narrow-band neutrino beam (red) peaked at E_ν = 0.6 GeV near oscillation maxima at L = 295 km

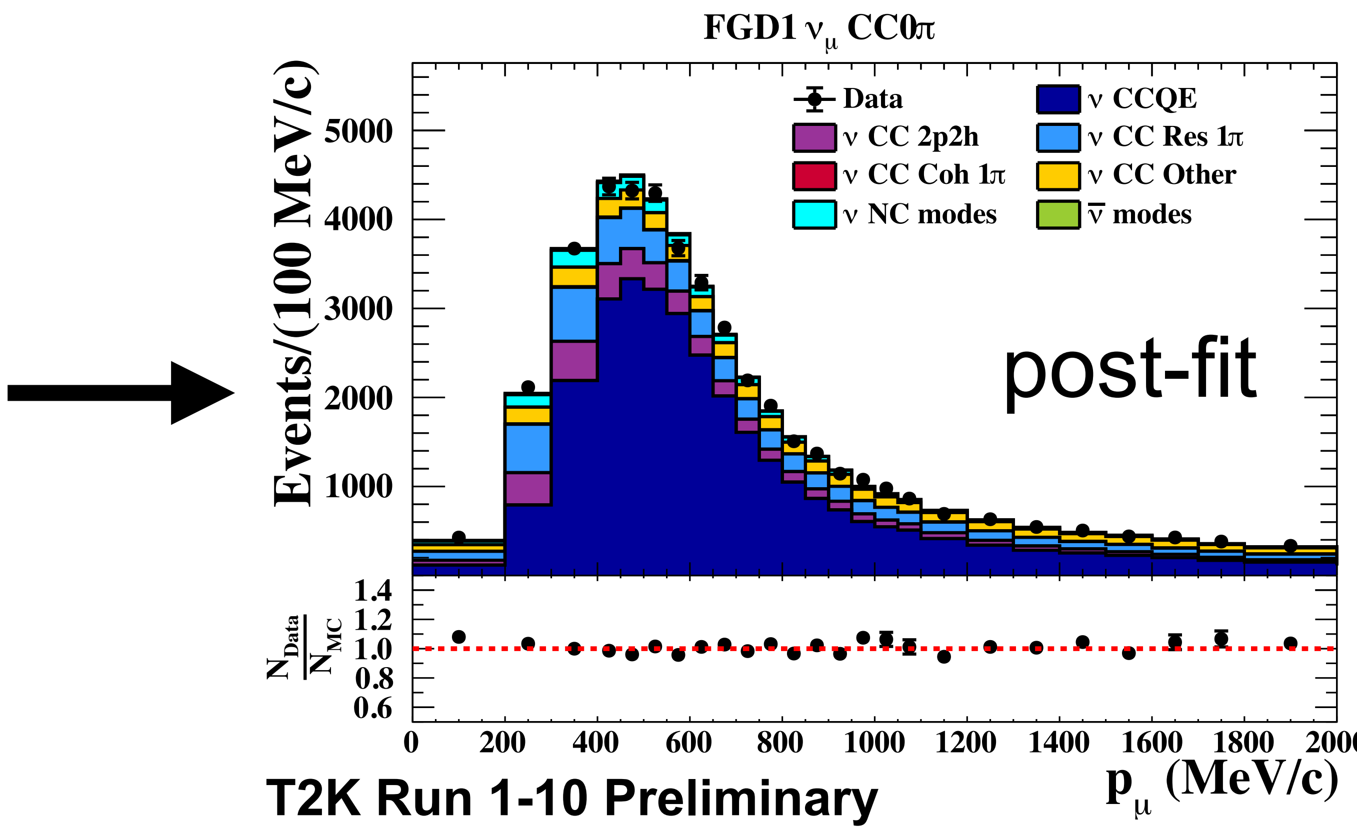
T2K Near Detector: ND280



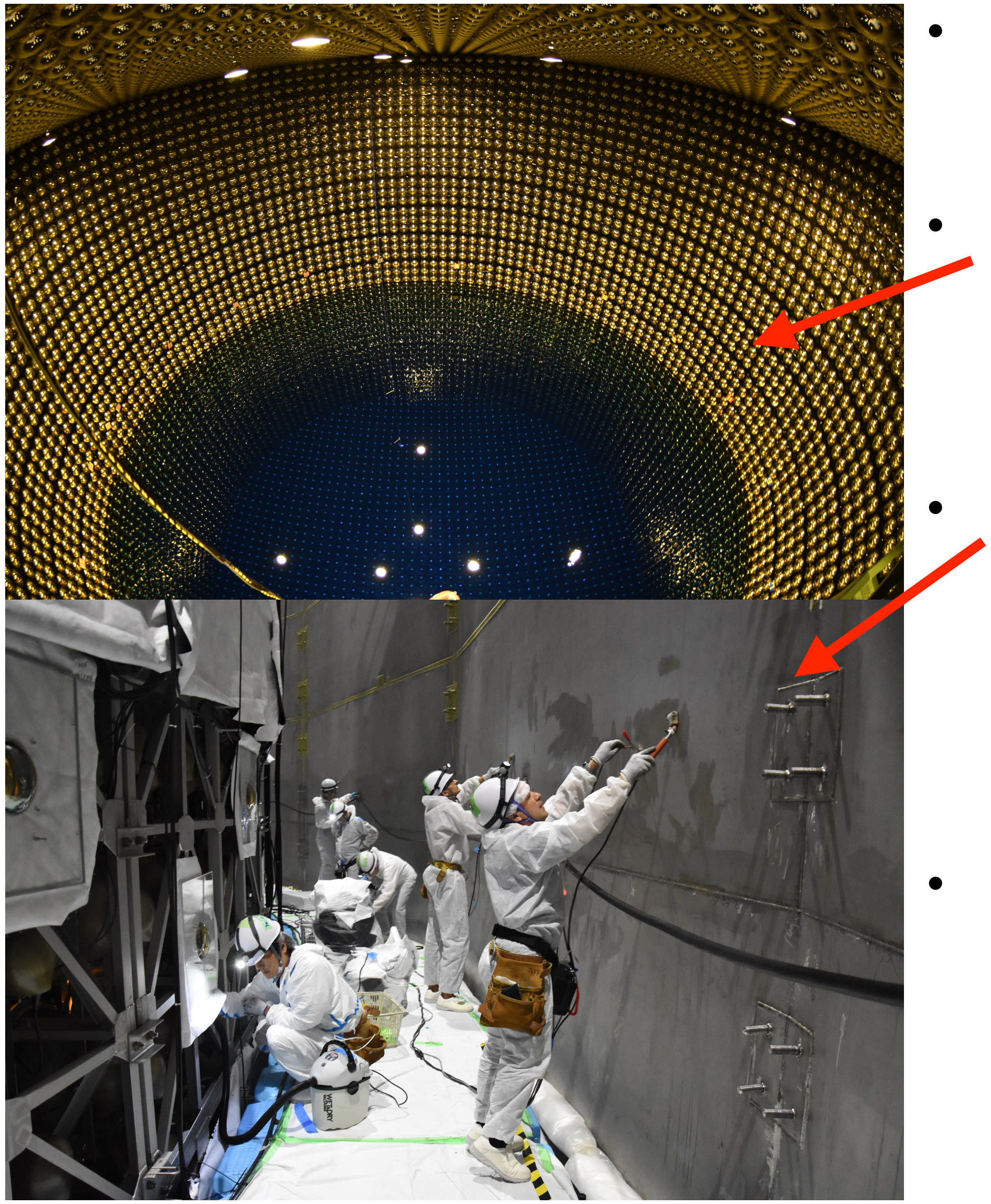
ND280

- CH and water targets (2000 kg)
- Magnetized tracker to measure momentum and charge
- Constrains neutrino interaction and flux models

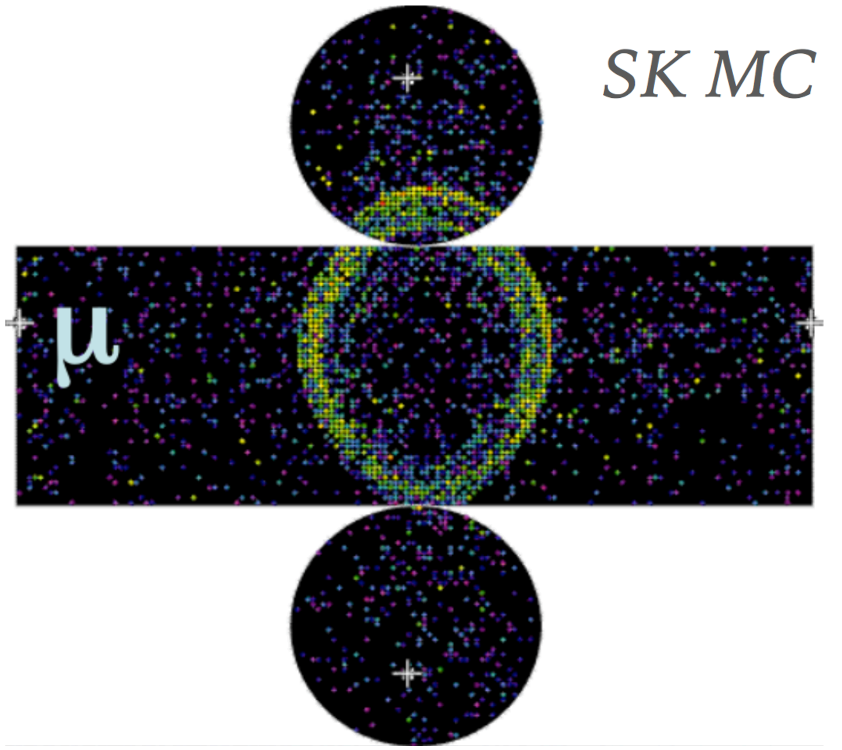


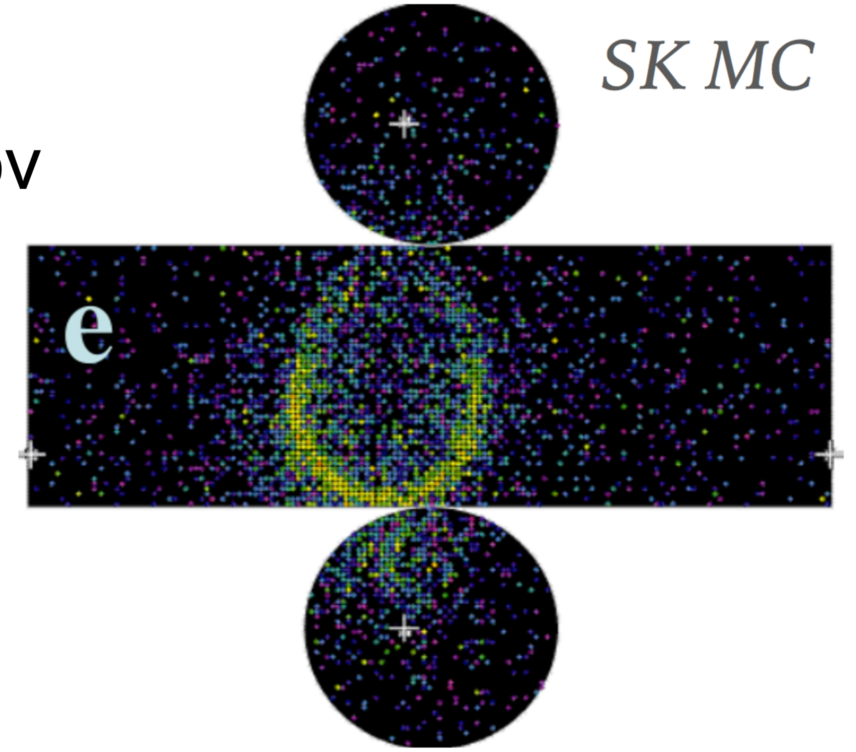


T2K Far Detector: Super Kamiokande

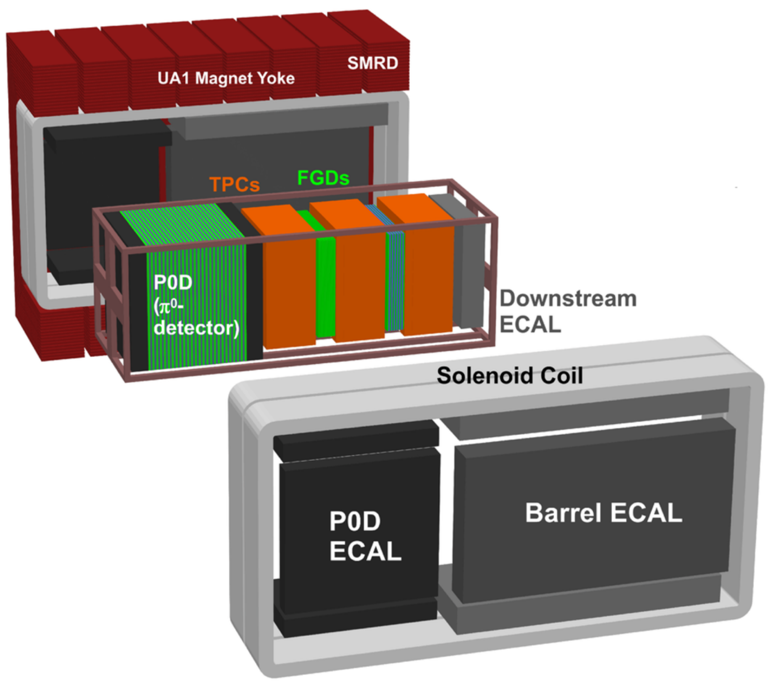


- 50 kt water-Cherenkov detector
- Inner detector
  - 11k 20” PMTs
  - 40% photo coverage
- Outer detector
  - 2k 8” PMTs
  - Cosmic veto and exiting particles
- Particle ID by Cherenkov ring pattern:
  - $\mu^{\pm}$ sharp rings
  - $e^{\pm}$ blurred rings due to showering

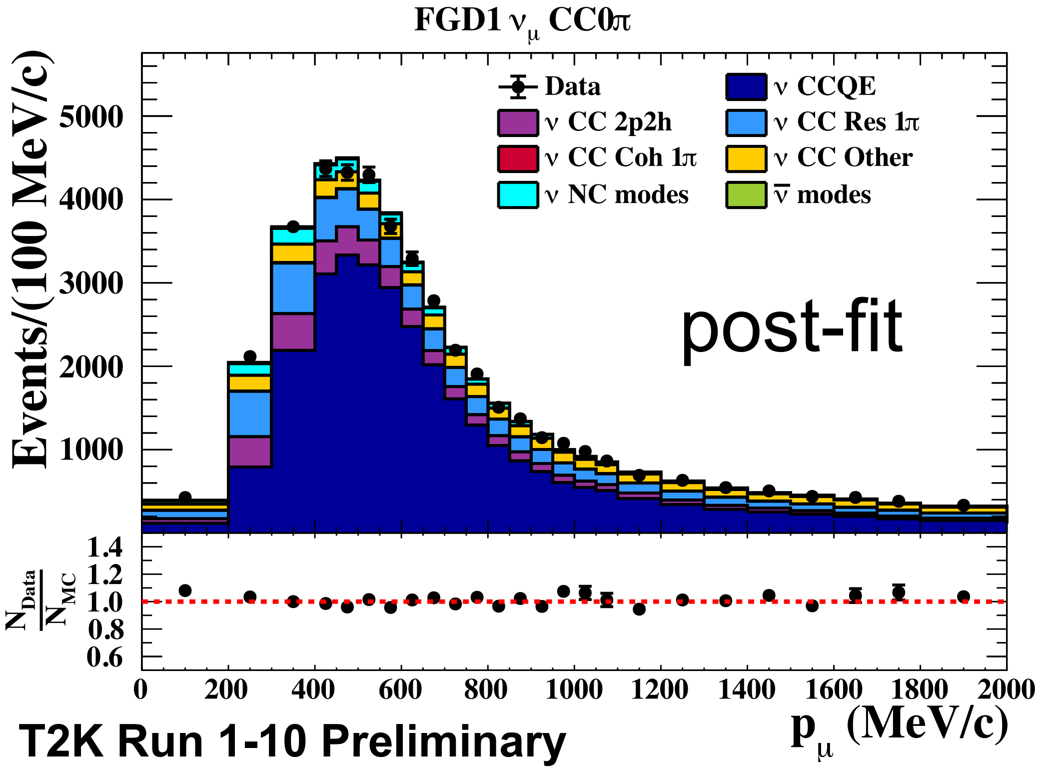




T2K Oscillation Analysis

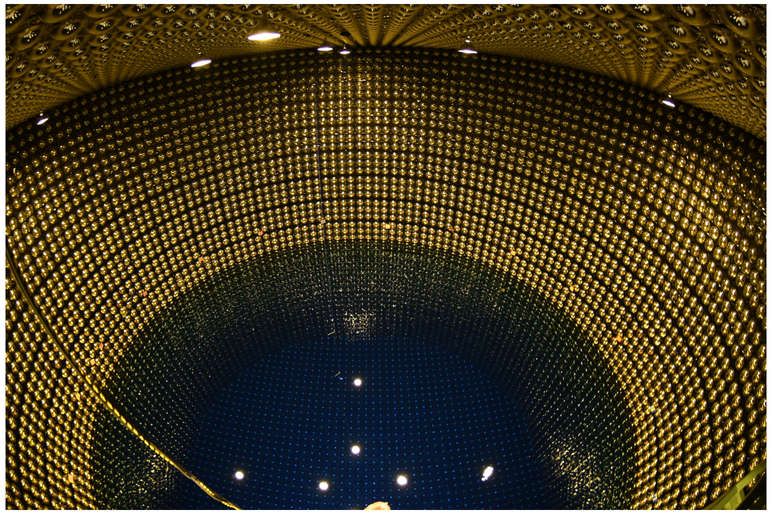


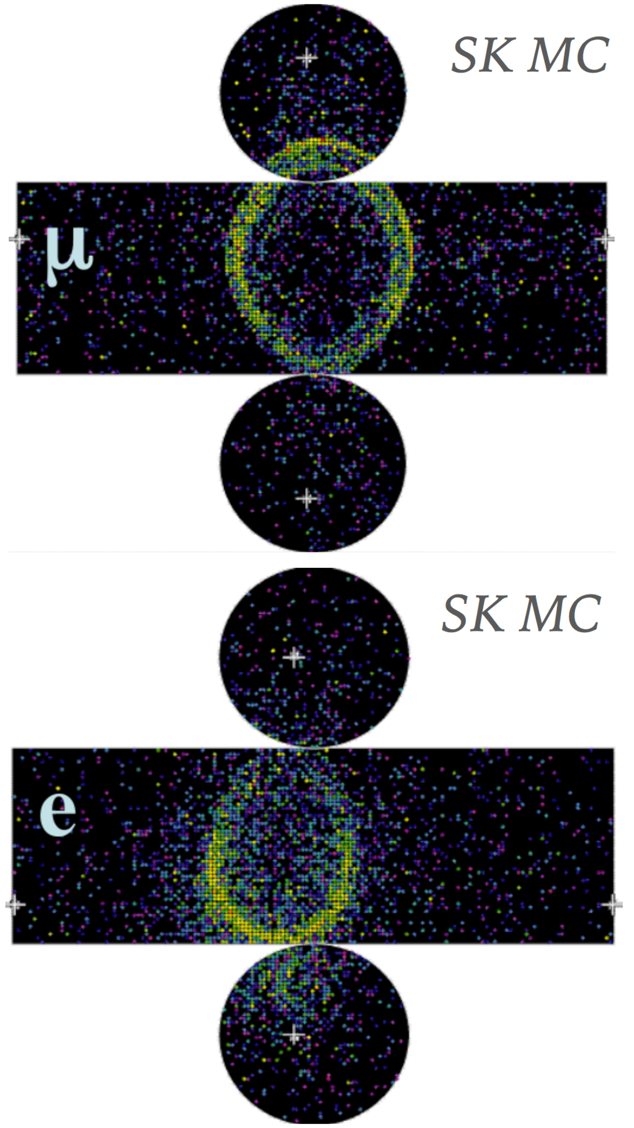
Near Detector: ND280



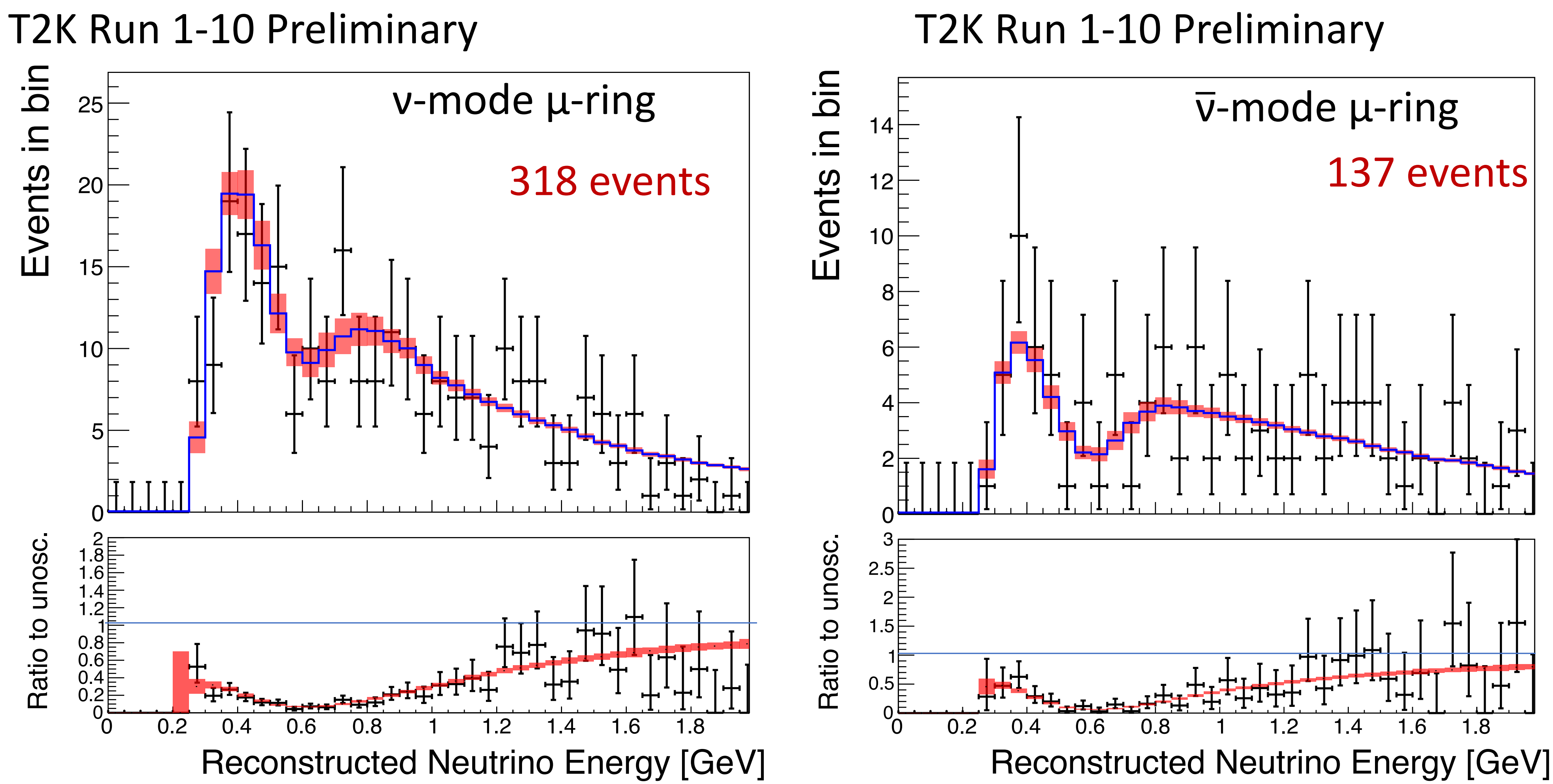
- Analysis strategy is to define a model and constrain with external and T2K data
- Perform different analyses to extract oscillation parameters and cross-check:
  - Sequential ND-FD vs. simultaneous fit
  - Frequentist vs. Bayesian statistics

Far Detector: Super Kamiokande



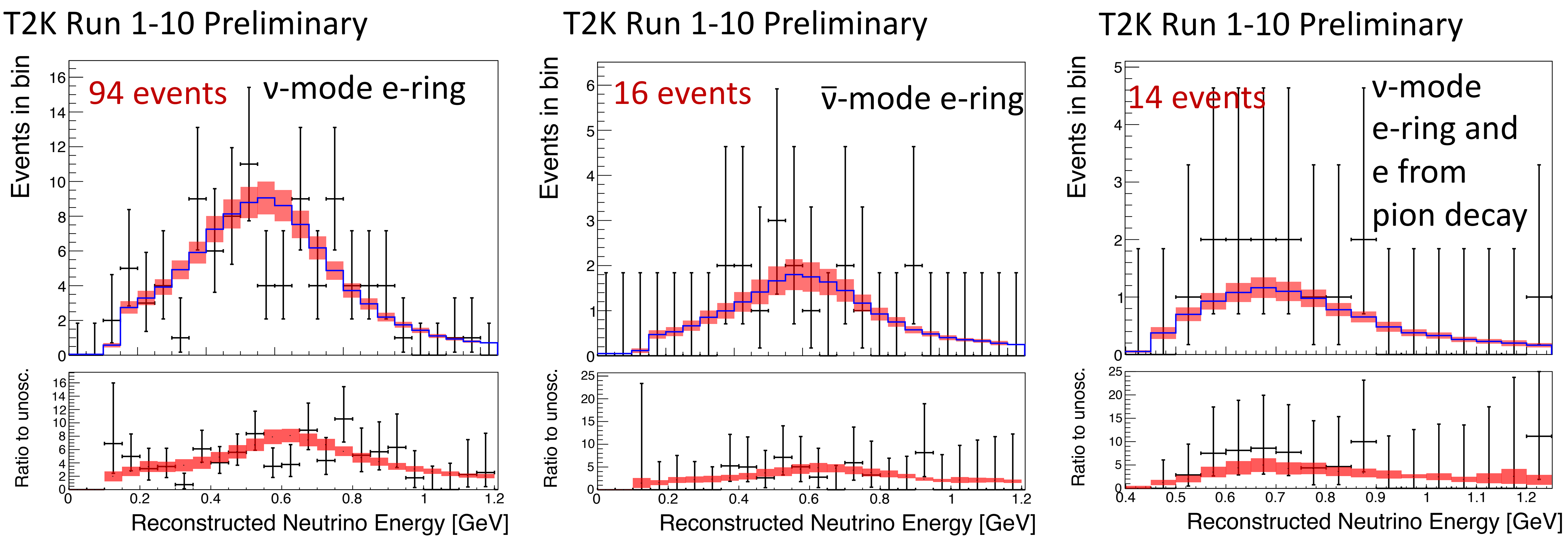


T2K ν_μ, $\bar{\nu}_\mu$ Data



- Two samples (1 ν-mode and 1-$\bar{\nu}$ mode) with μ-like rings
- Systematic uncertainty (red band) on best-fit is 3.0% (4.0%) in ν-mode ($\bar{\nu}$-mode)

T2K ν_e, $\bar{\nu}_e$ Data

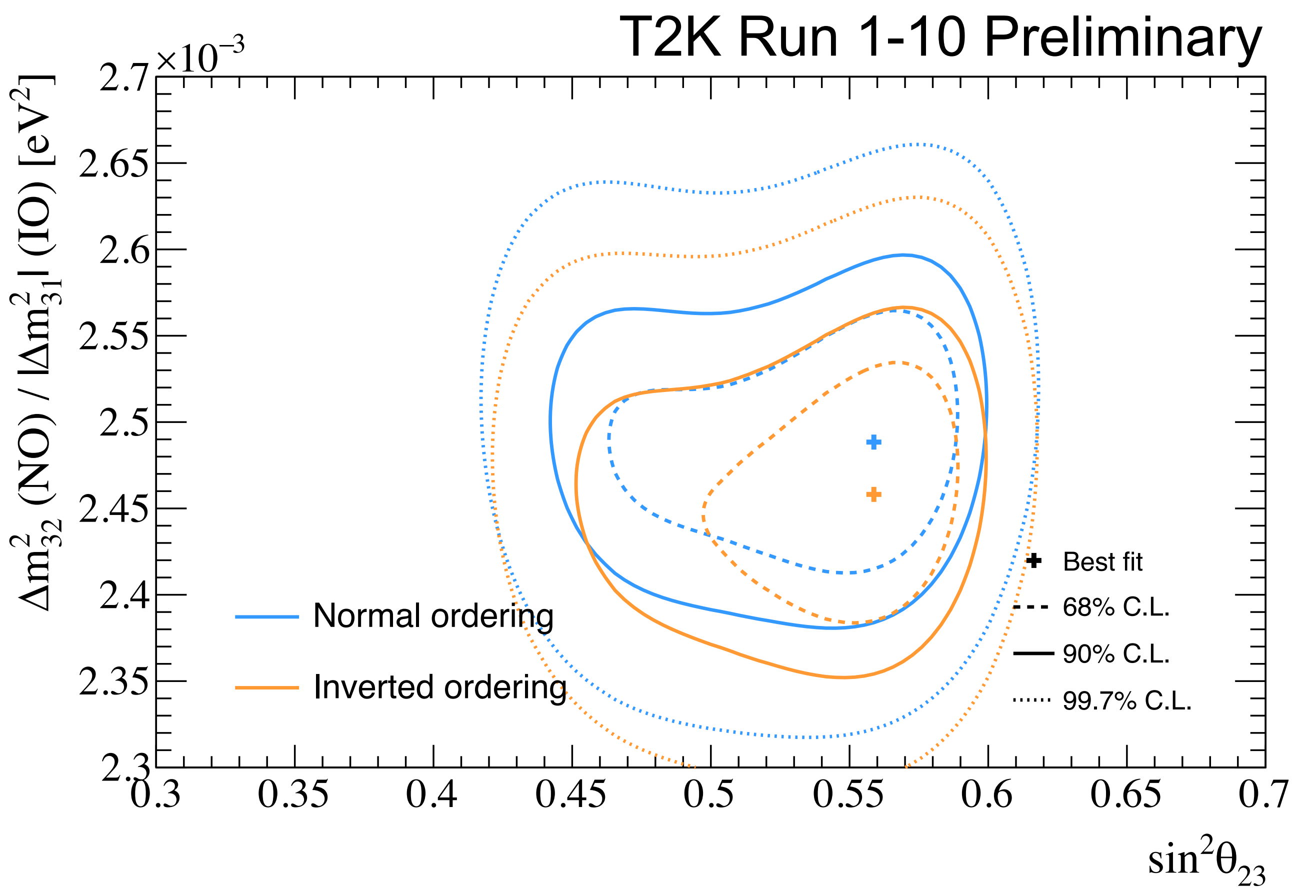


Three samples with electron-like Cherenkov rings

- Two (1 ν-mode and 1 $\bar{\nu}$-mode) with e-ring only targeting 0π events
- One in ν-mode with e-ring and e from π decay targeting 1π events

Systematic uncertainty (red band) on best-fit is 4.7-5.9% for 0π samples and 14.3% for 1π sample

T2K Results: Δm^2_{32}, θ_{23}



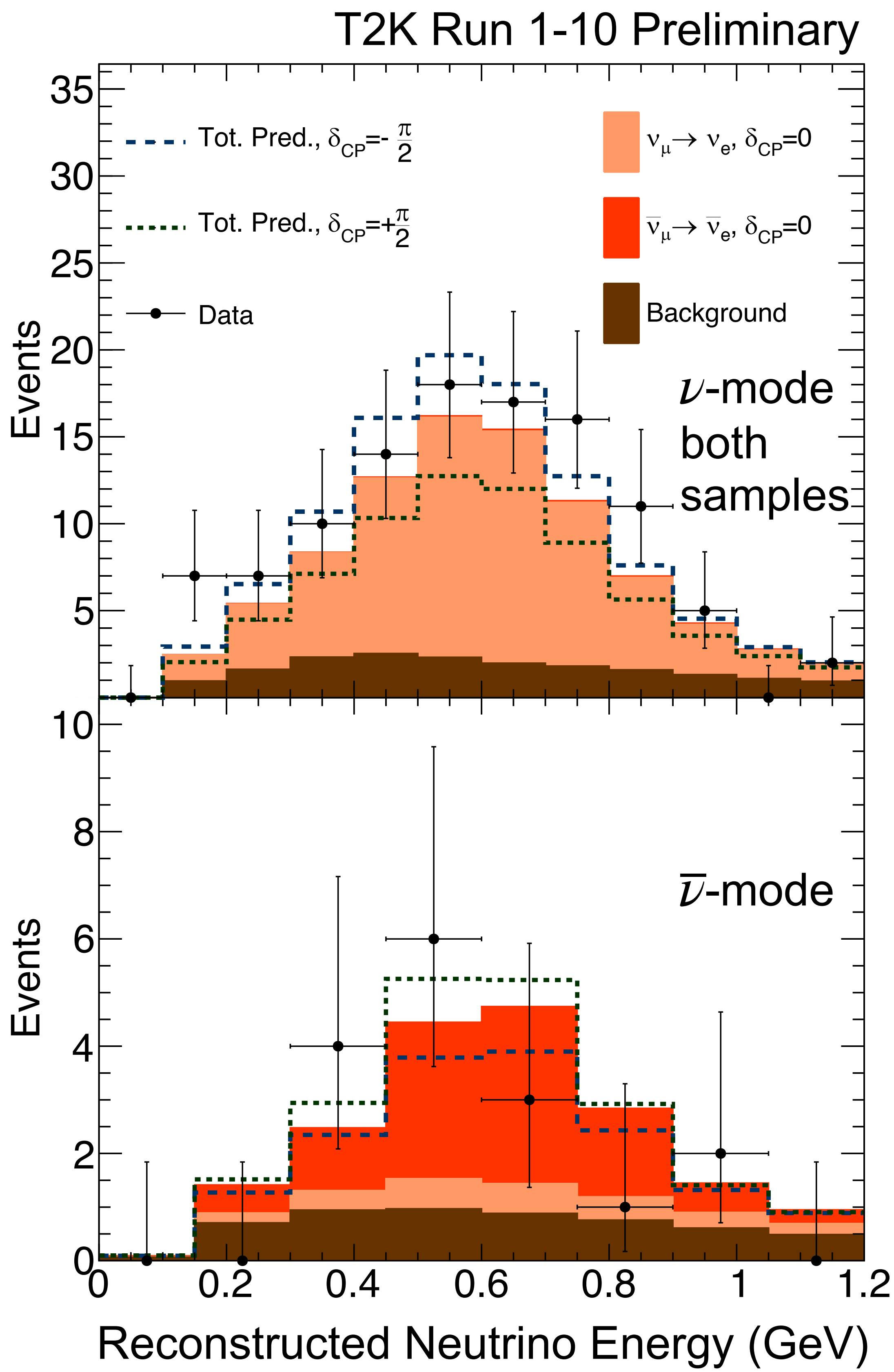
Posterior Probability

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})eV^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	−2.596 – −2.452 & 2.368 – 2.592

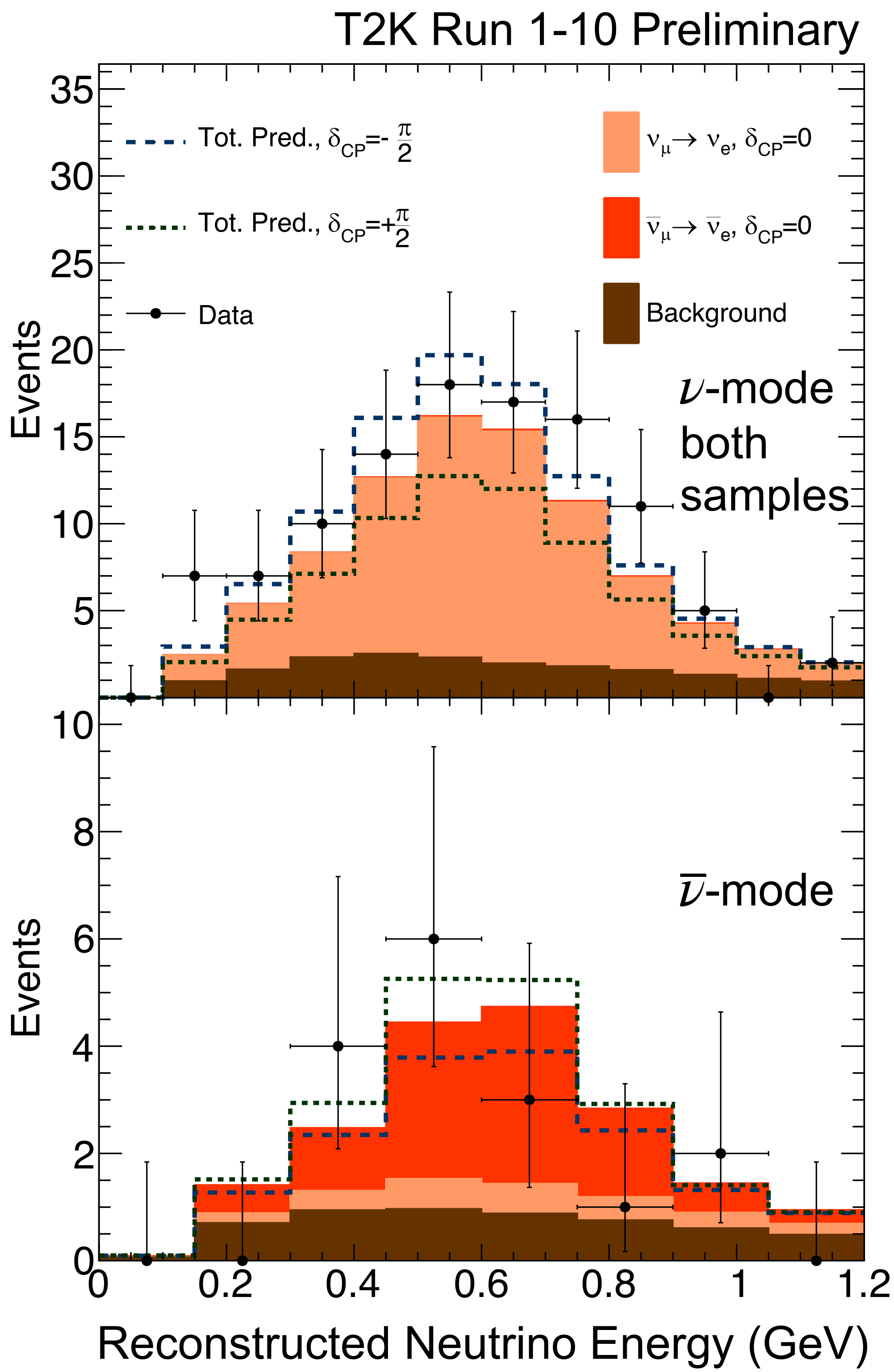
Preference for normal hierarchy and upper octant

T2K Results: ν_e, $\bar{\nu}_e$ Appearance



~45% difference in electron-like event rate between $\delta_{CP} = \pm\pi/2$

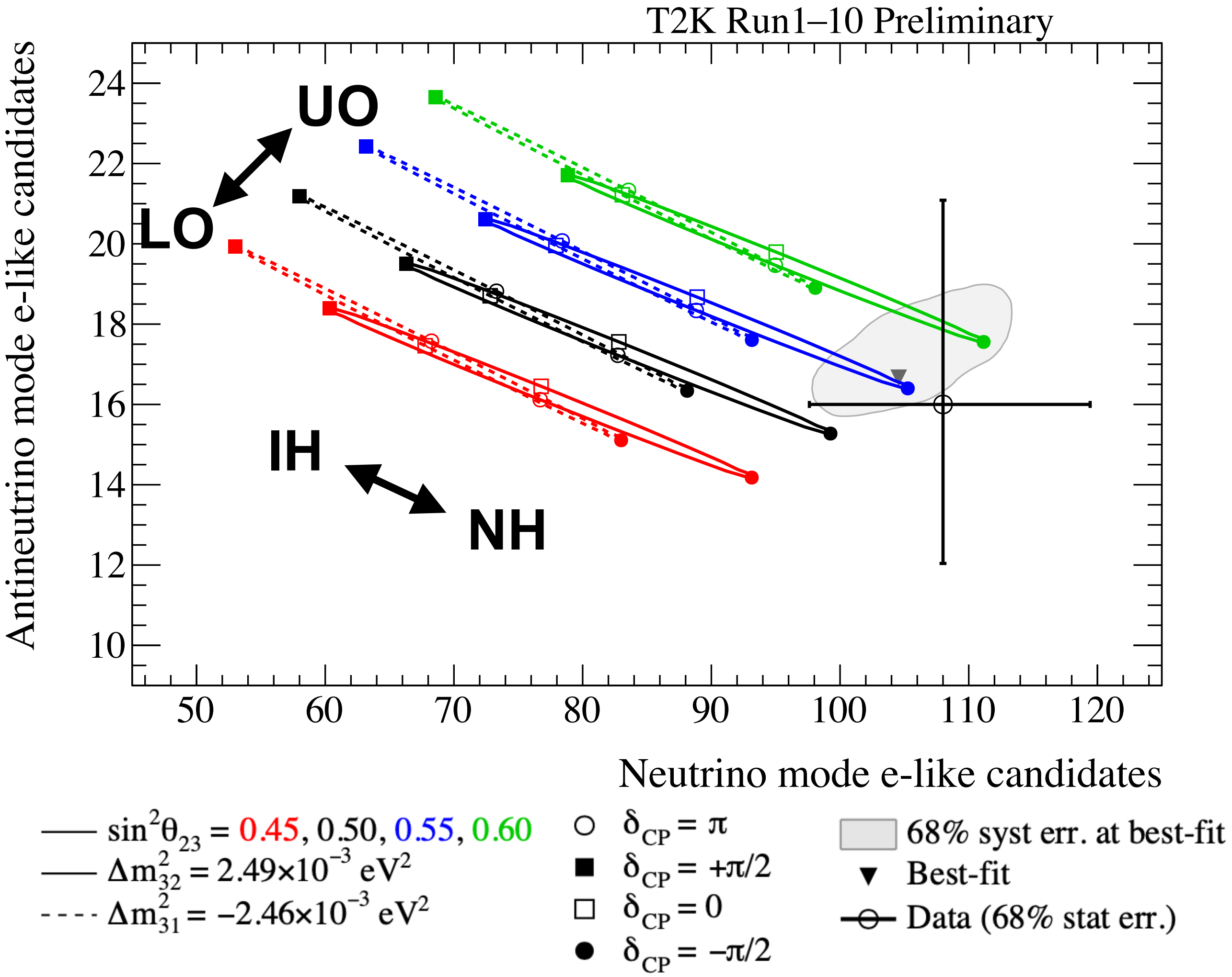
T2K Results: ν_e, $\bar{\nu}_e$ Appearance



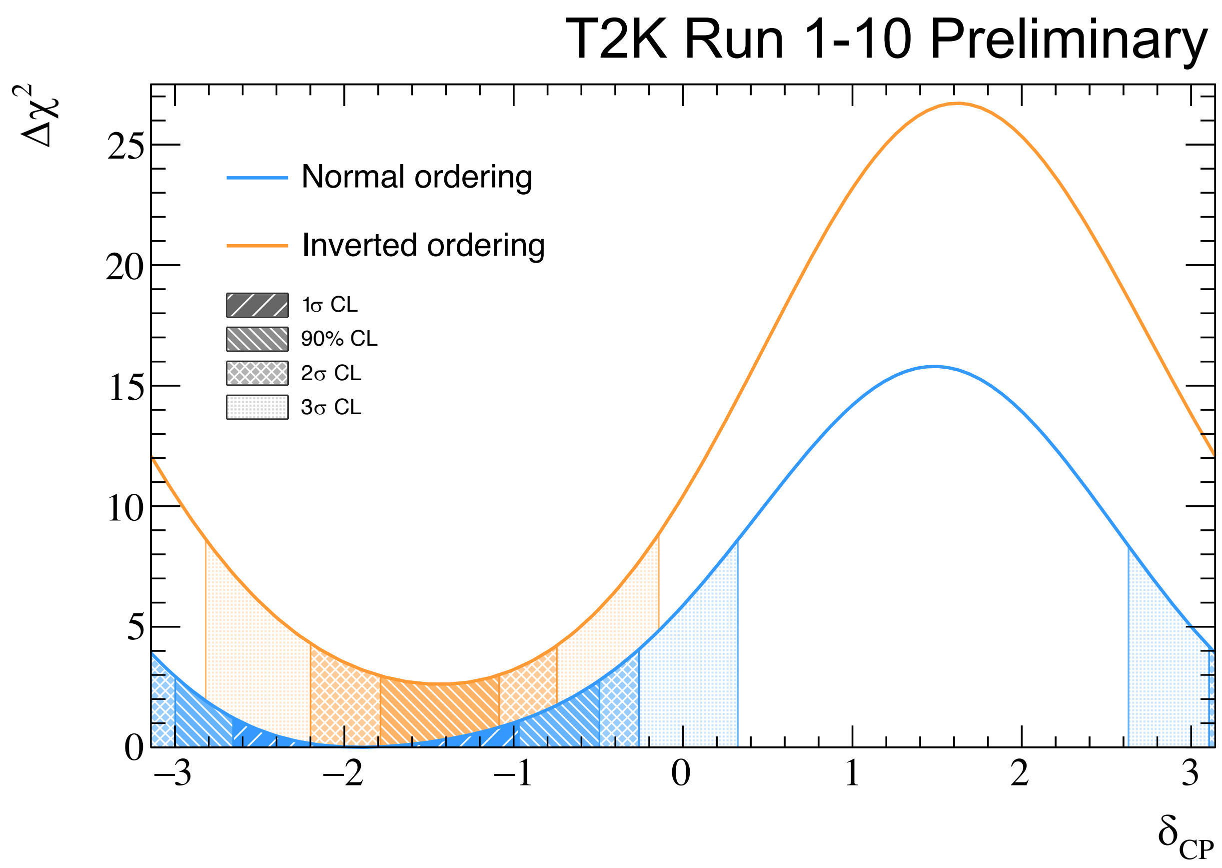
~45% difference in electron-like event rate between $\delta_{CP} = \pm\pi/2$

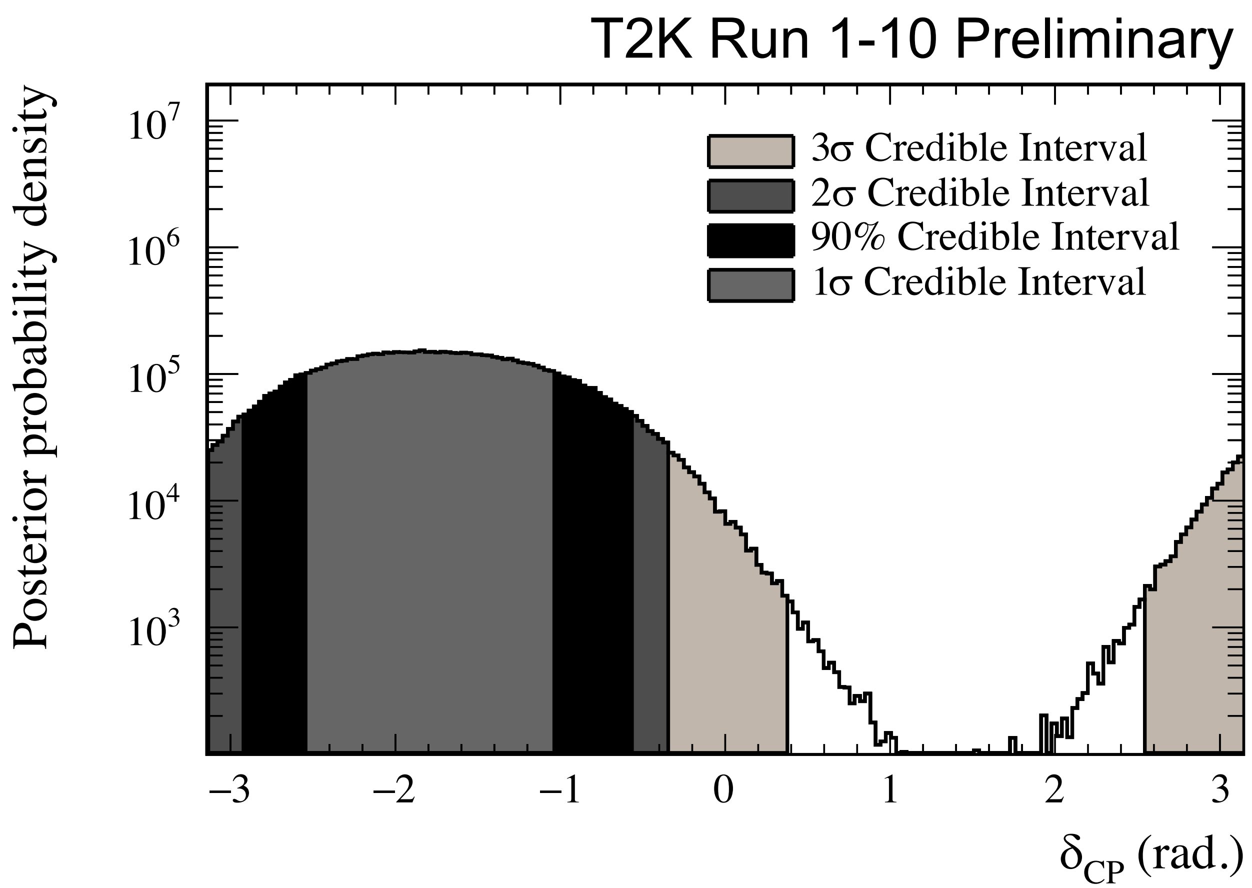
Preference for hierarchy-octant-δ_{CP} combination giving enhanced ν_e appearance

- Normal hierarchy, upper octant
- δ_{CP} near $-\pi/2$



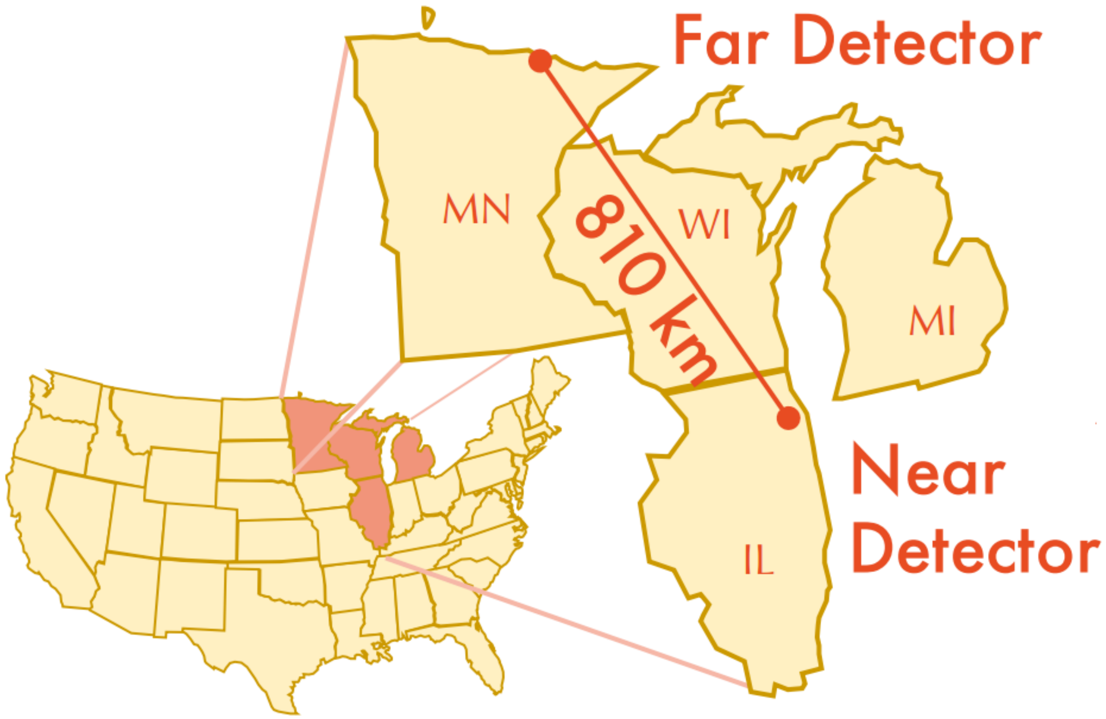
T2K Results: δ_{CP}



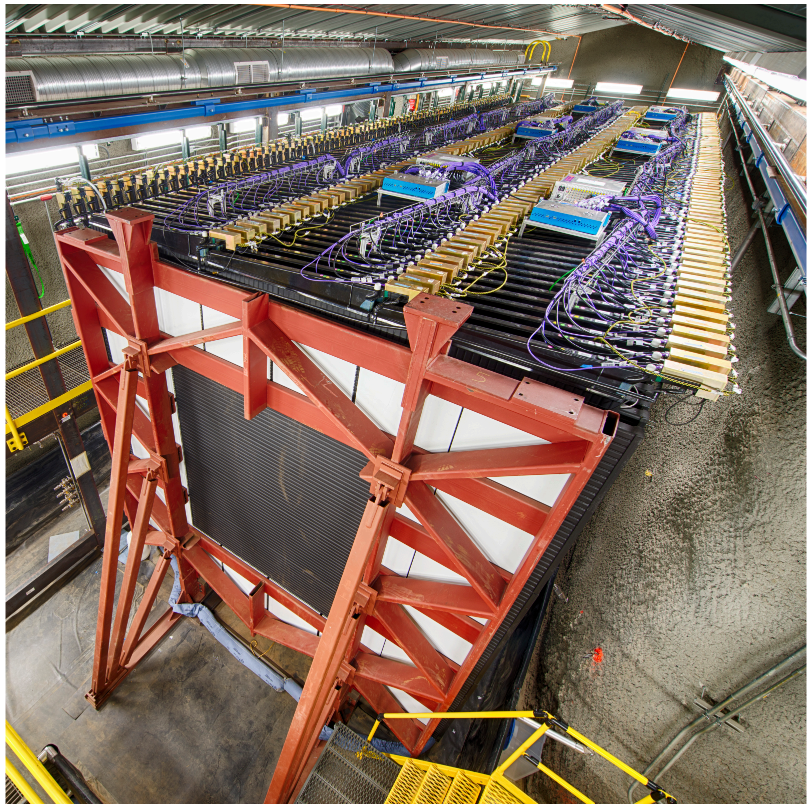


- 35% of δ_{CP} values excluded at 3σ marginalized over hierarchies
- CP conserving values ($\delta_{CP} = 0,\ \pi$) excluded at >90%

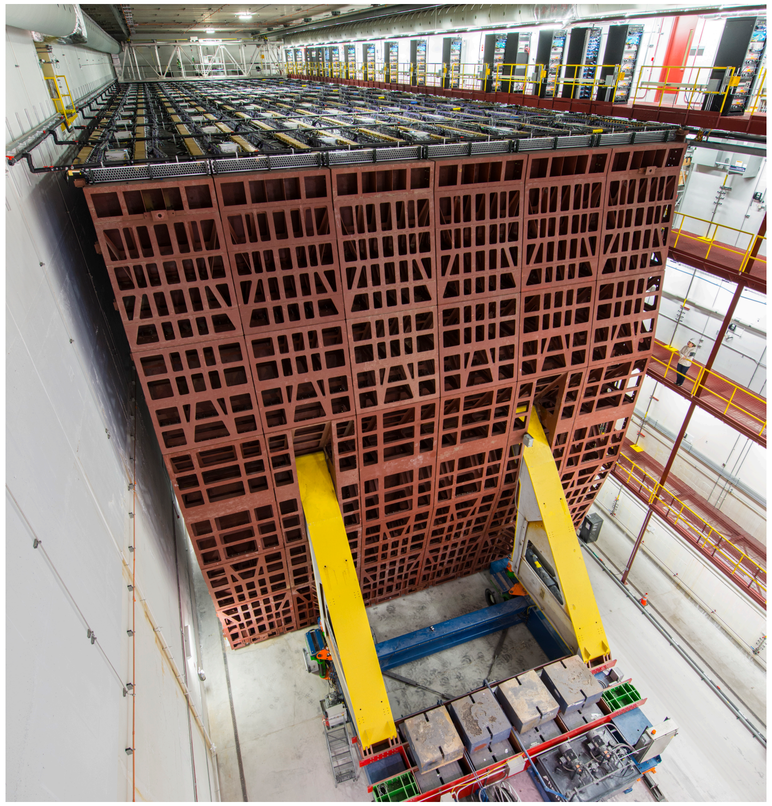
NOvA Experiment



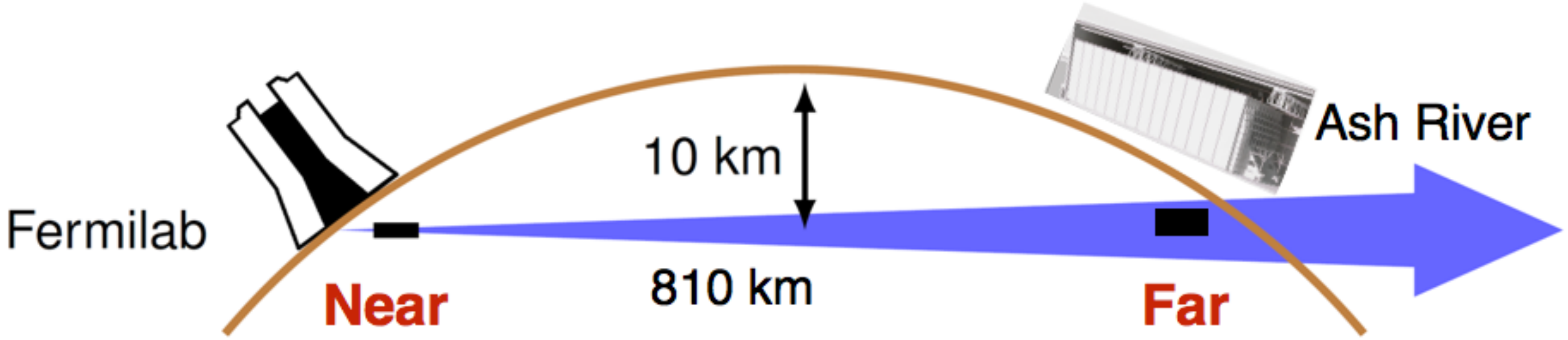
Near Detector (Fermilab)



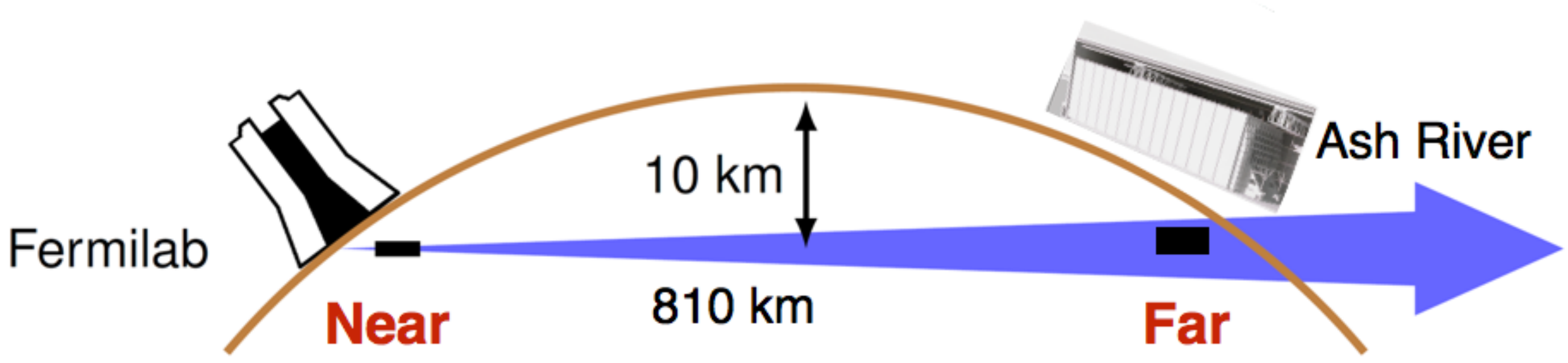
Far Detector (Ash River, MN)

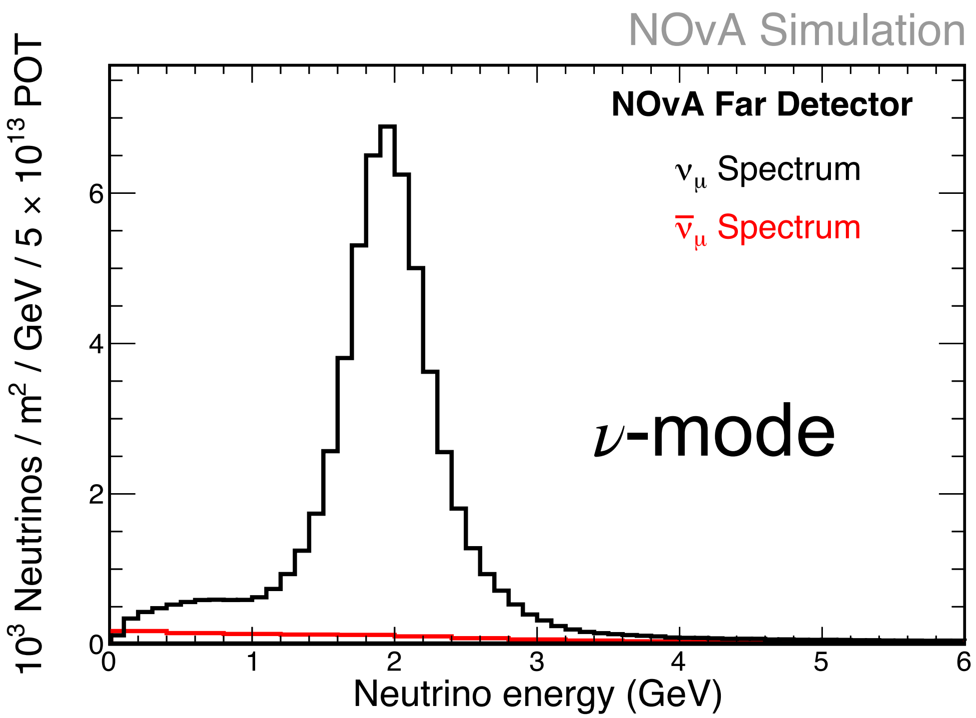


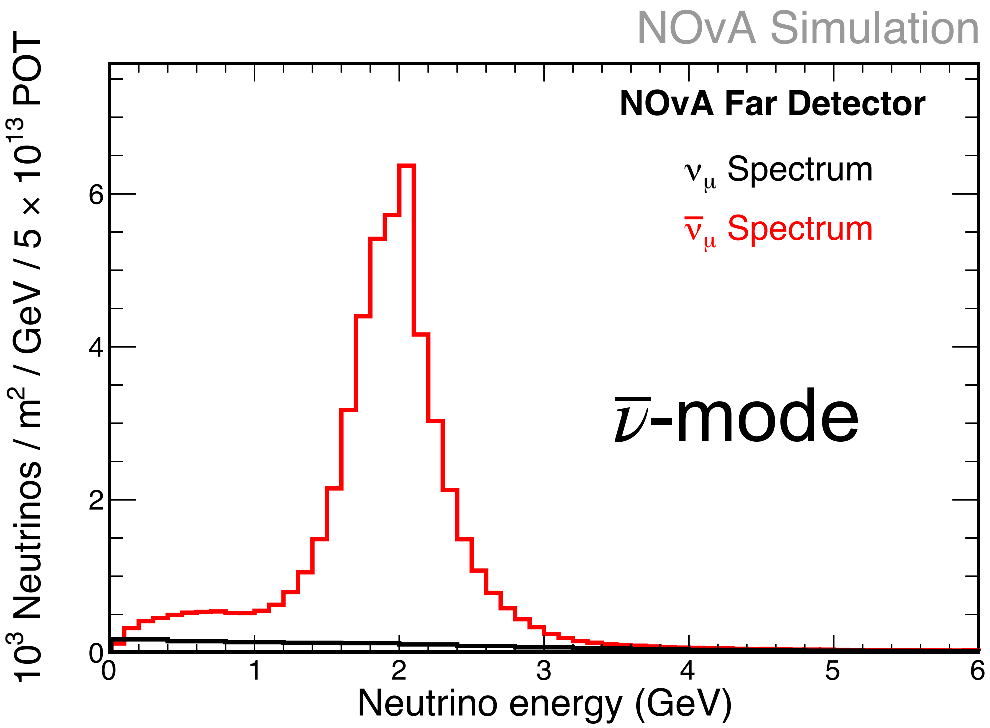
Long-baseline neutrino oscillation experiment in the NuMI neutrino beam at Fermilab



NOvA Neutrino Beam

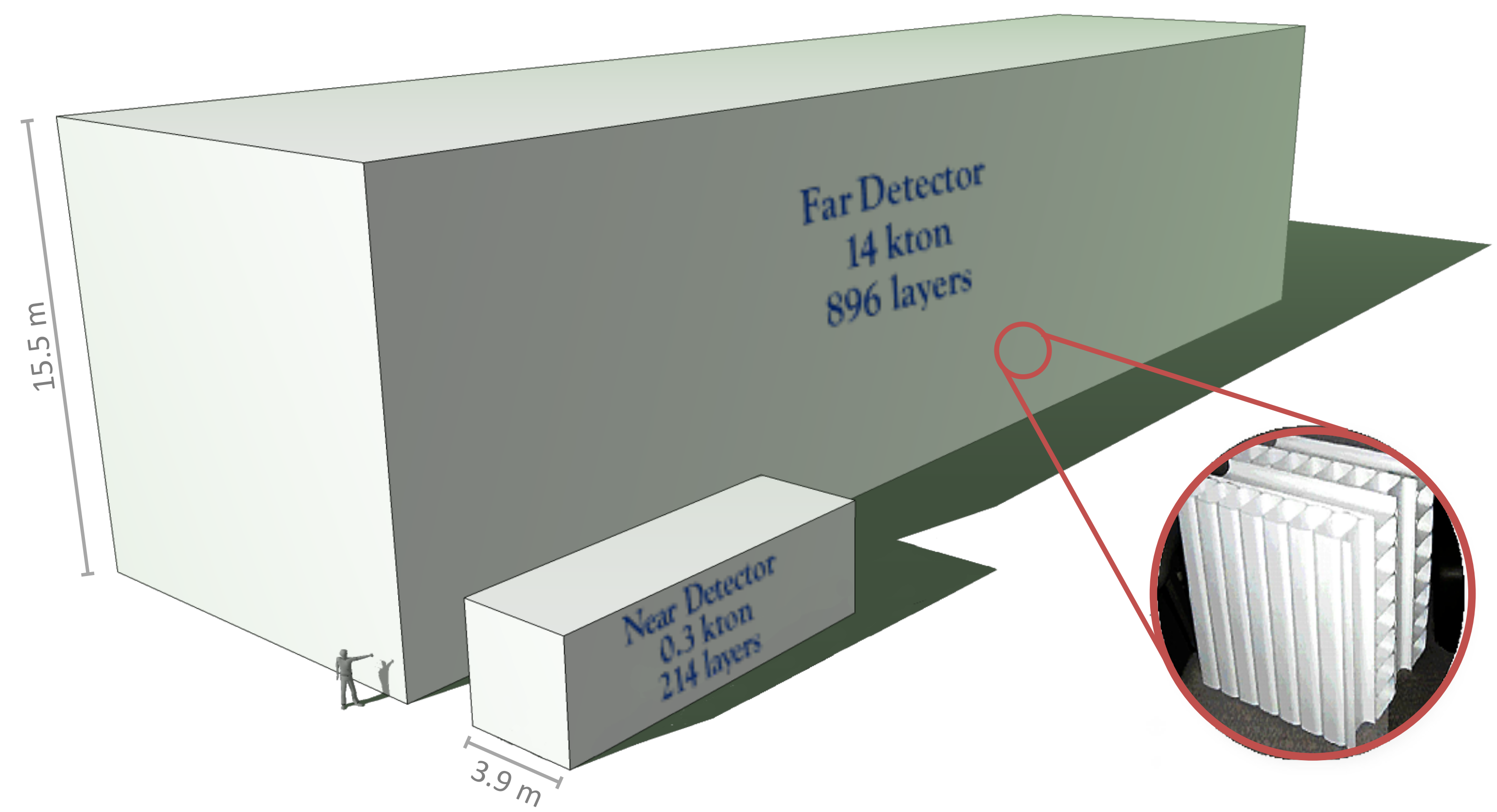


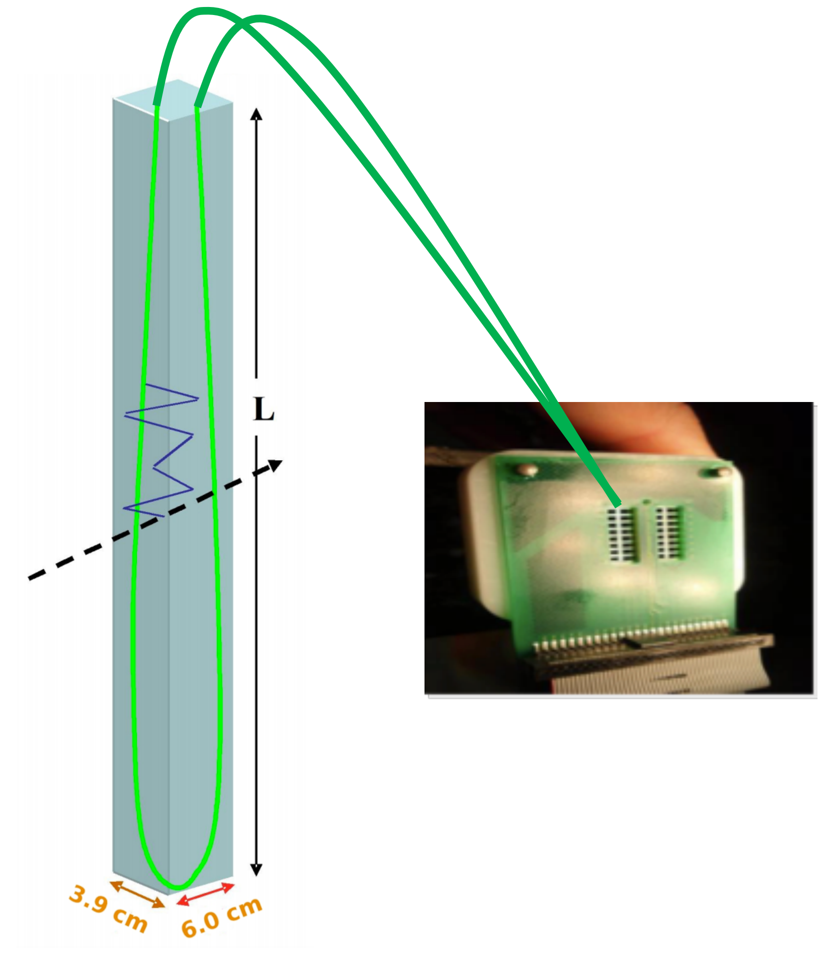




- NuMI beam peaks near E_ν = 2.0 GeV in the NOvA detectors
- Oscillation maxima near E_ν = 2.0 GeV at L = 810 km

NOvA Detectors





NOvA Near and Far Detectors

- Functionally equivalent tracking calorimeters
- Extruded PVC cells filled with liquid scintillator (mineral oil + 5% pseudocumene)
- WLS fiber collects and transports light to APD
- Optimized for electron ID: Low-Z, 62% active

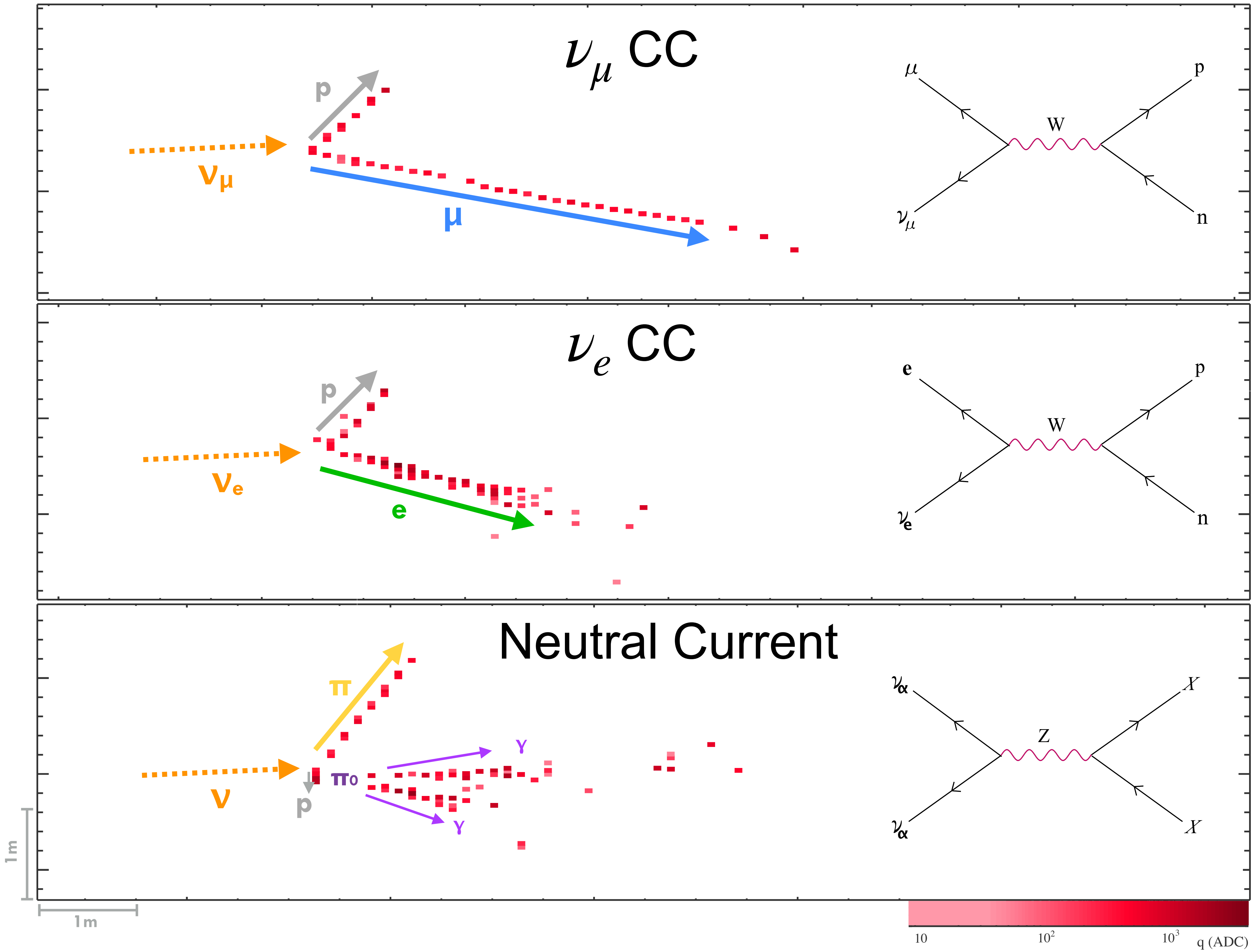
Far Detector

- 14 kton, 344k channels
- 810 km from source

Near Detector

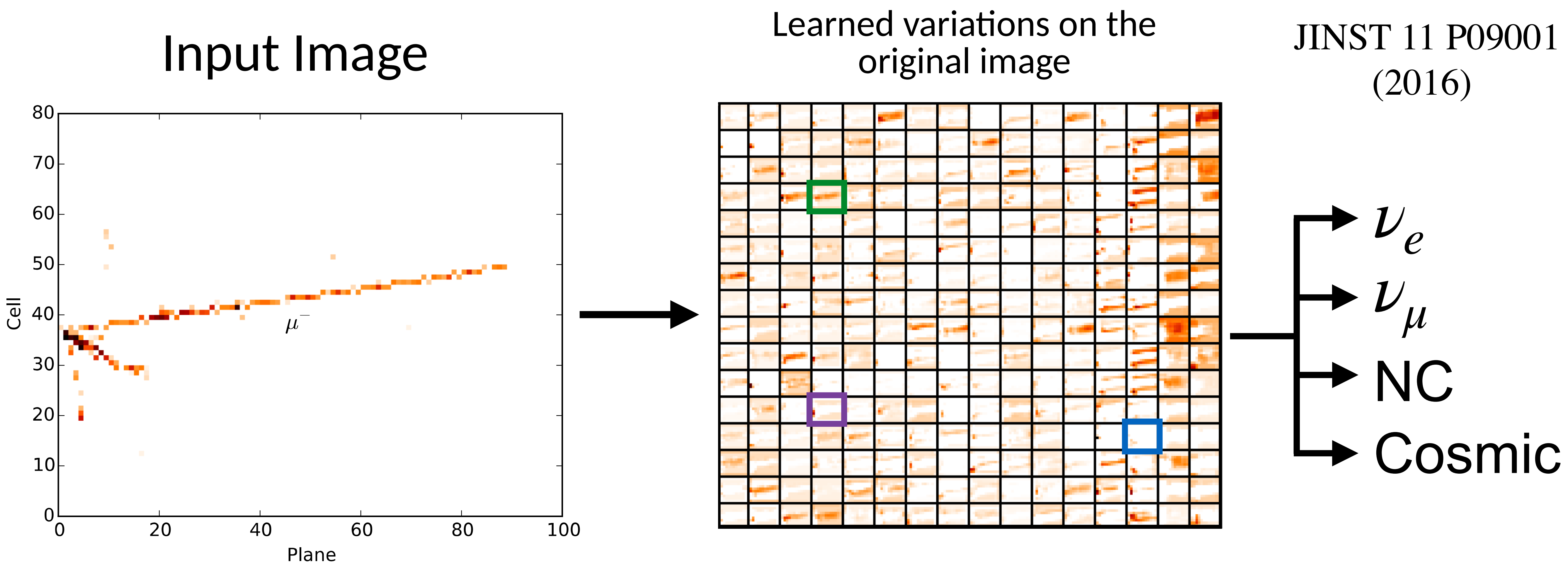
- 0.3 kton, 20k channels
- 1 km from source

NOvA Event Topologies



NOvA Event Classification

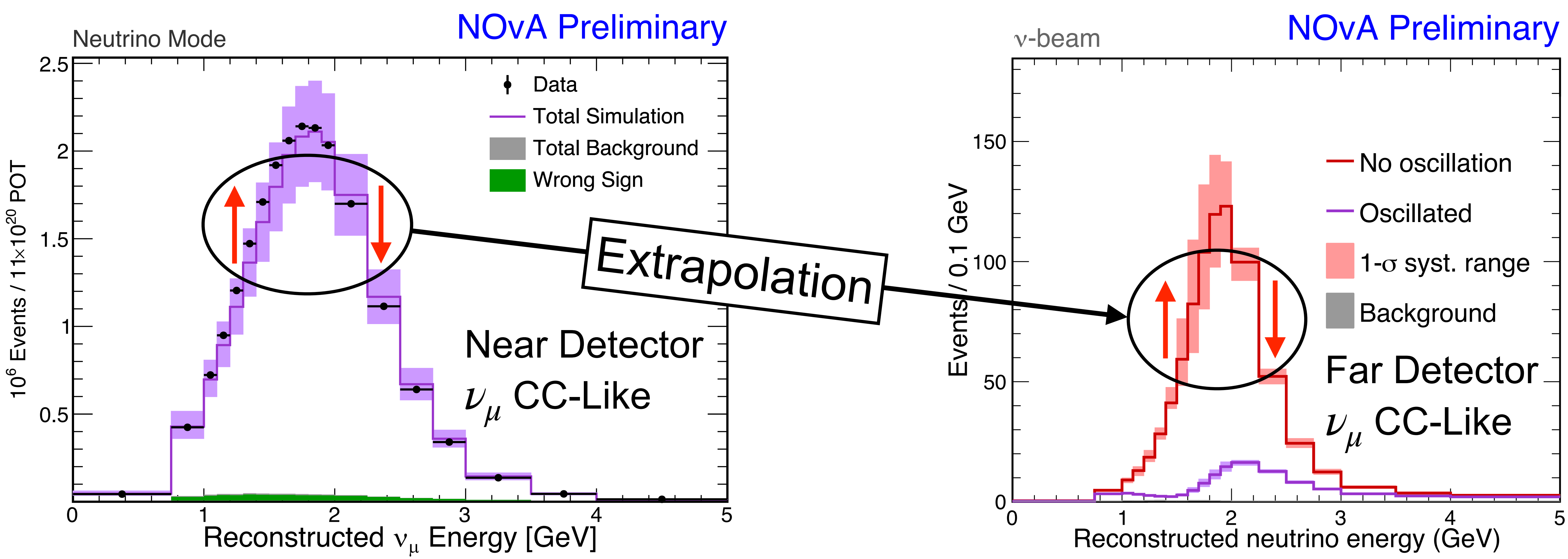
JINST 11 P09001 (2016)



Events classified by a Convolutional Neural Network (CNN)

- Computer vision technique
- Learns topological features
- Maps features to analysis event categories

NOvA Far Detector Predictions



Simulated ND spectra corrected to ND data and extrapolated to FD, accounting for

- Energy smearing
- Acceptance and selection efficiency
- Beam divergence
- Oscillations

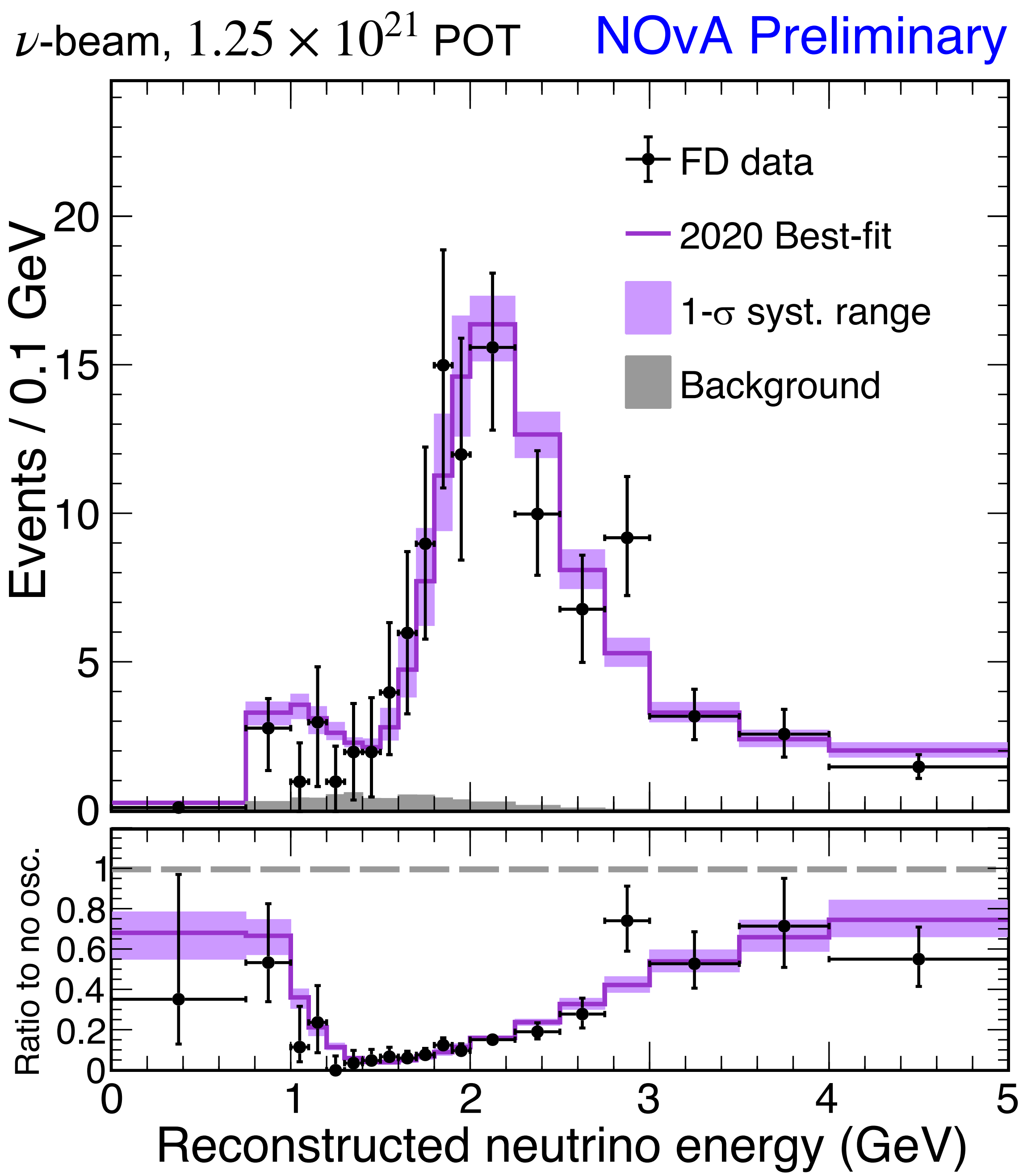
Data-driven FD predictions of

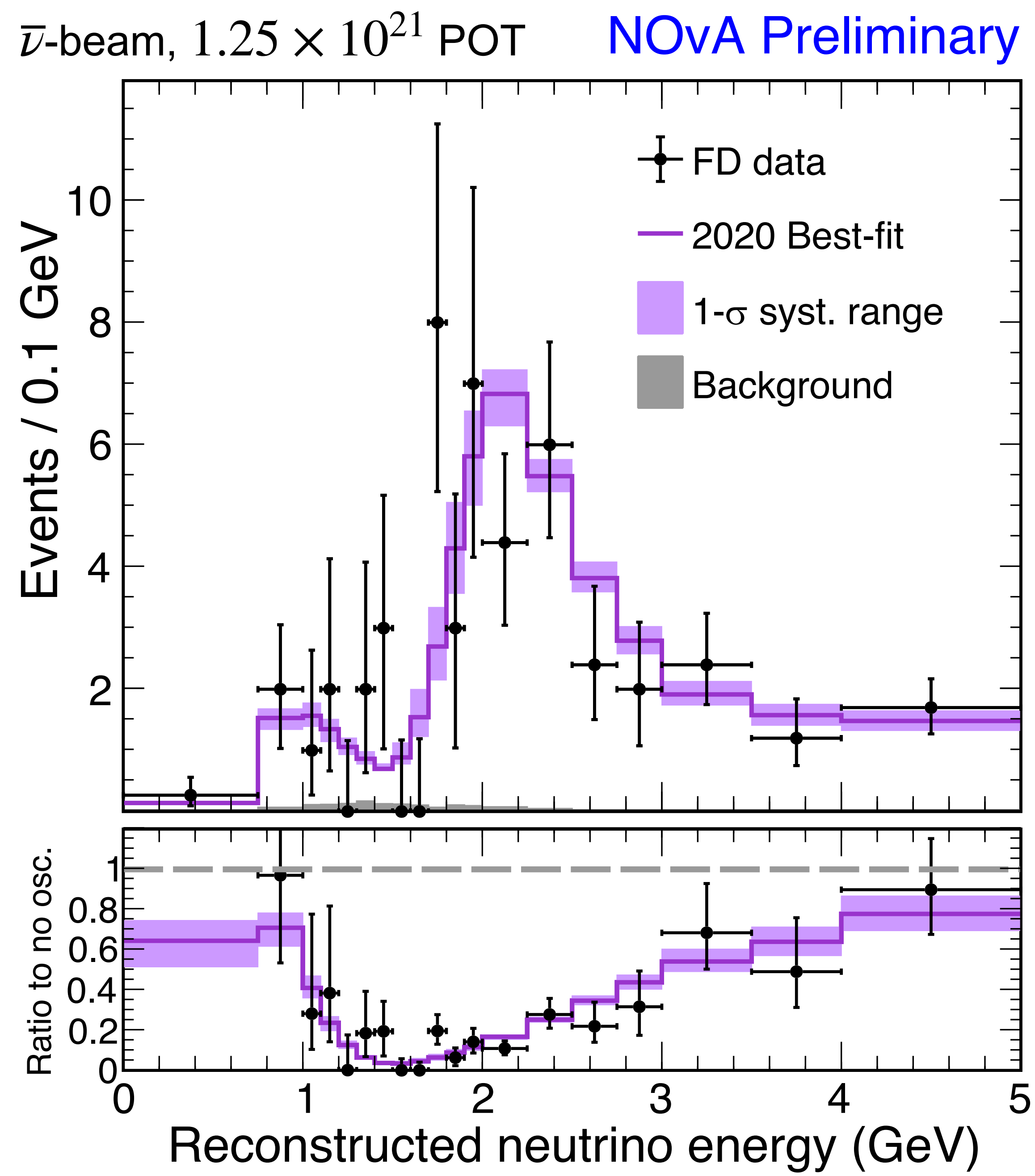
- ν_μ, $\bar{\nu}_\mu$ disappearance
- ν_e, $\bar{\nu}_e$ appearance
- Beam backgrounds

Uncertainties correlated between detectors significantly reduced:

- e.g. Flux: 7% → 0.3%

NOvA ν_μ, $\bar{\nu}_\mu$ Data

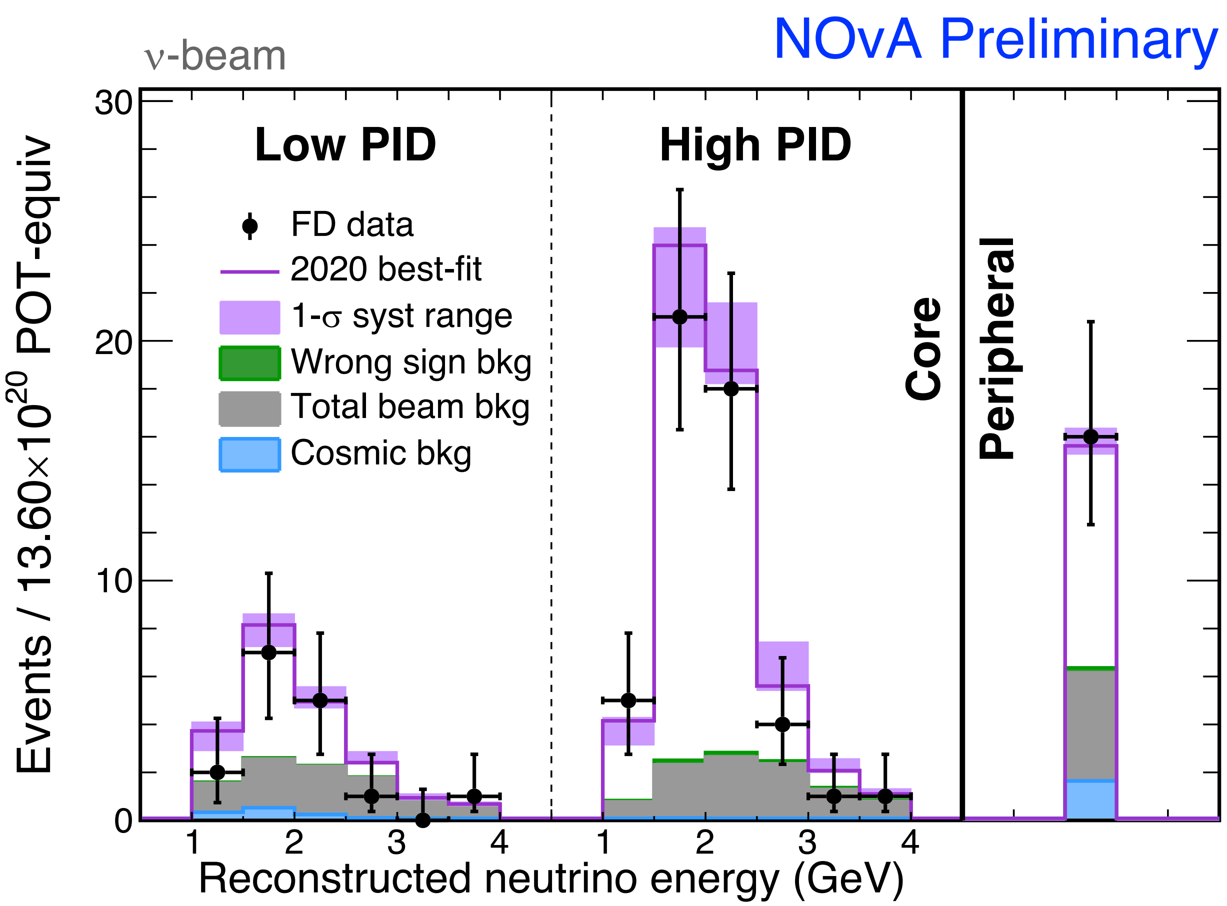


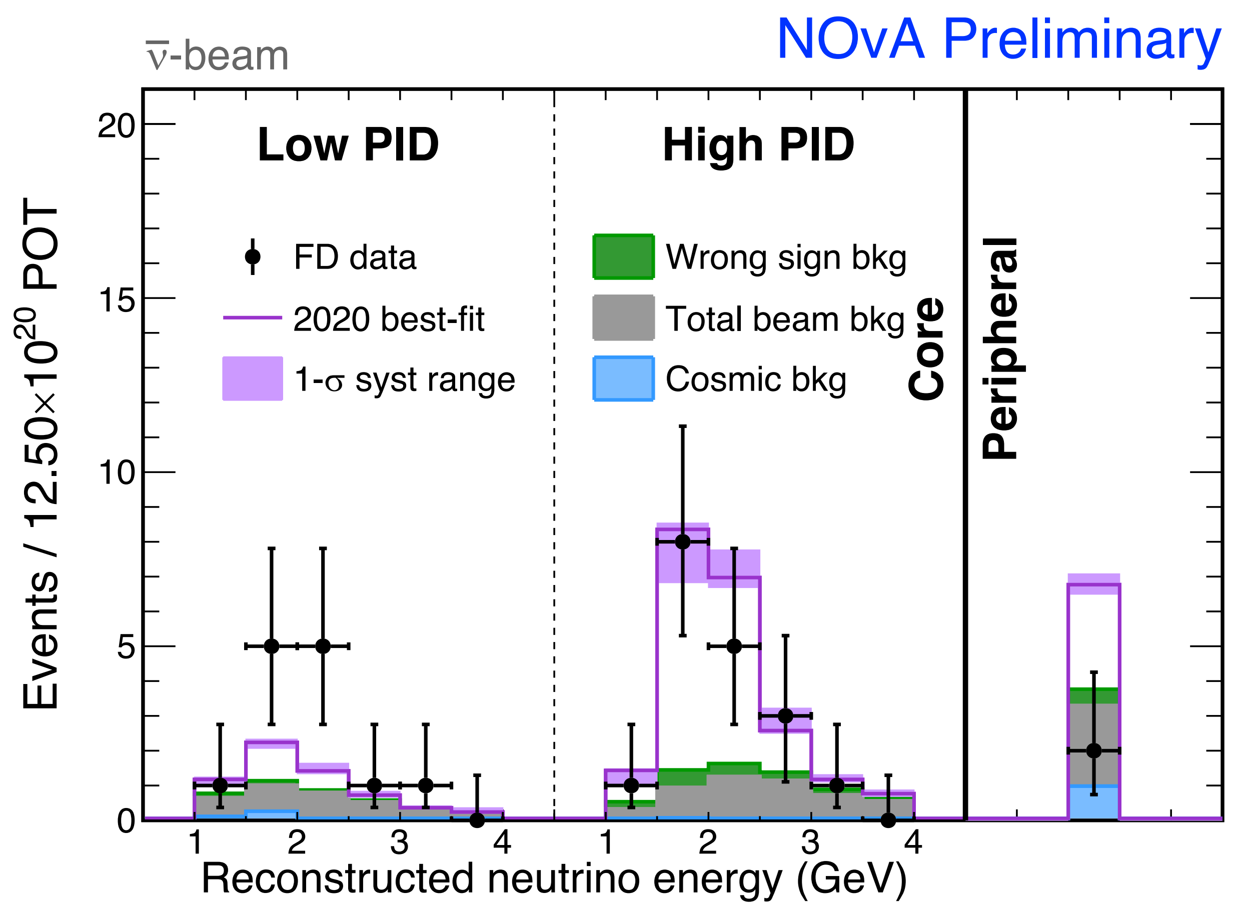


211 events
8.2 background

105 events
2.1 background

NOvA ν_e, $\bar{\nu}_e$ Data



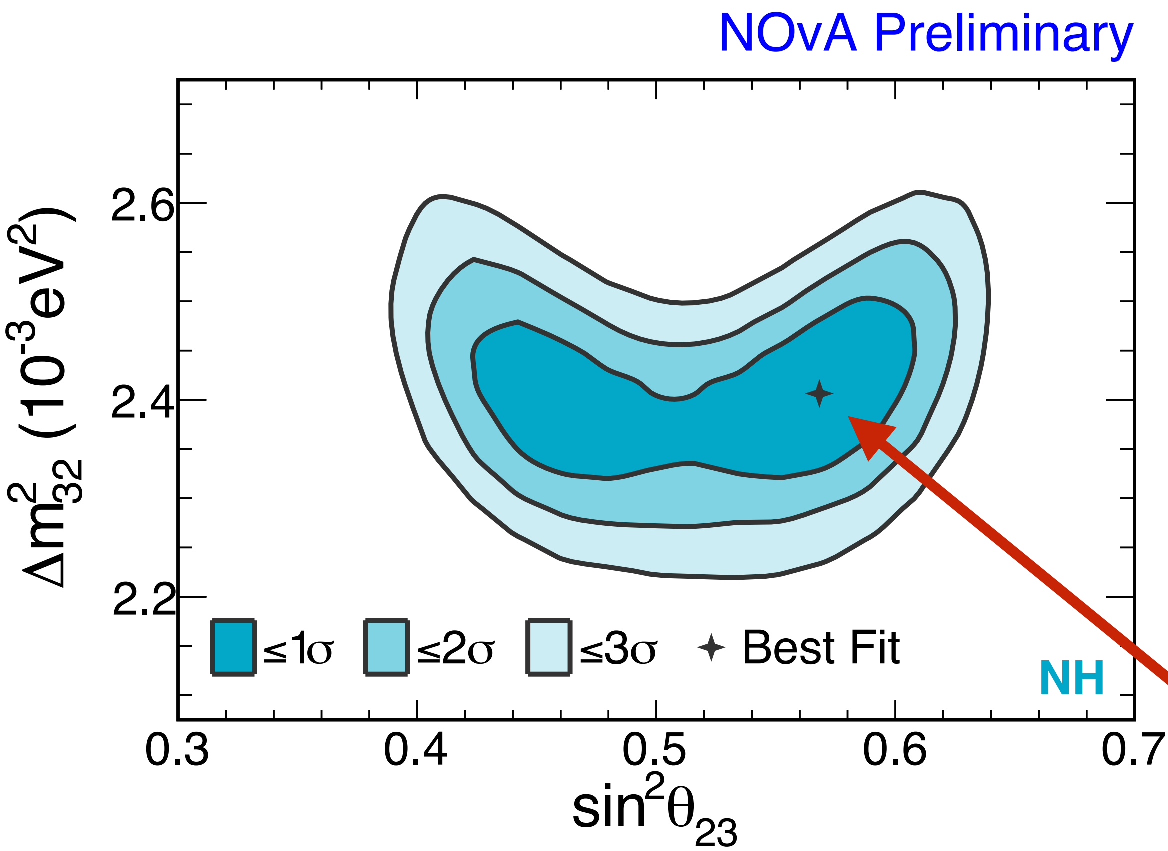


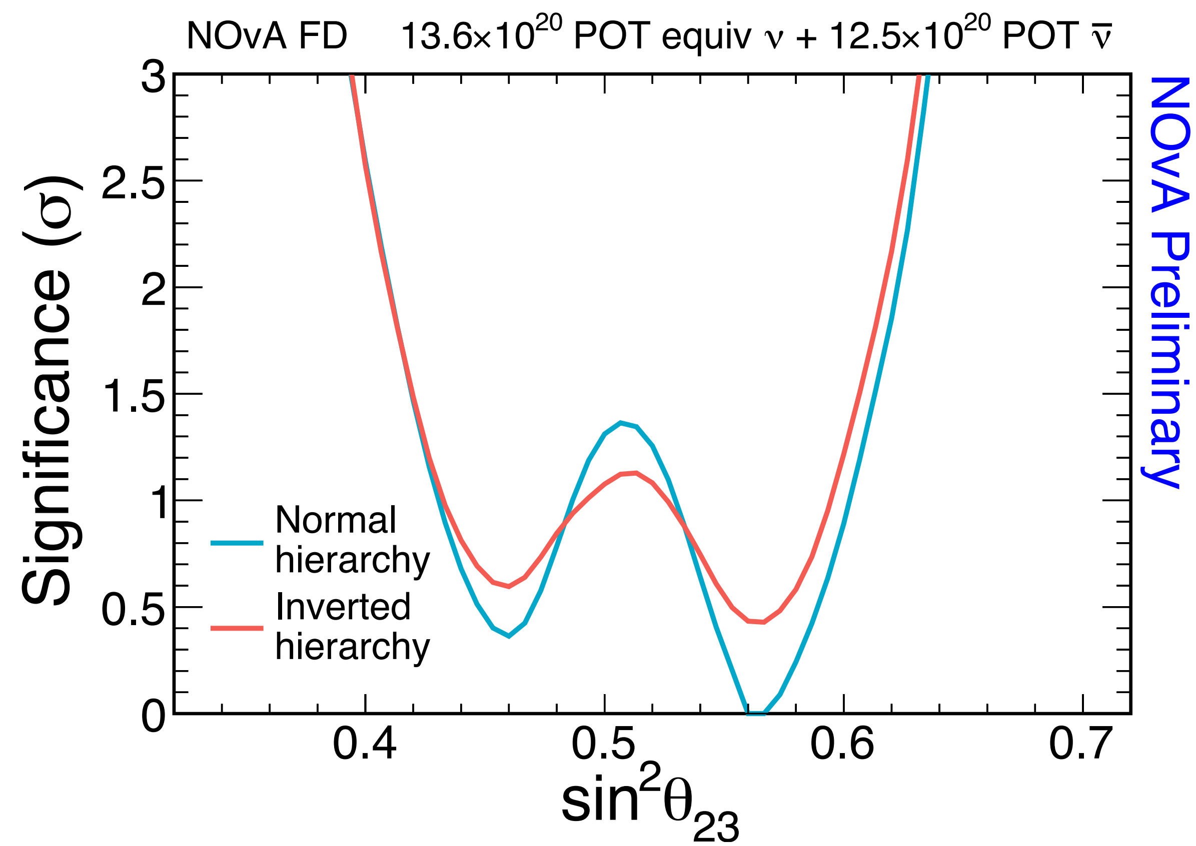
Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong Sign	1.0	
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd	26.8	26-28

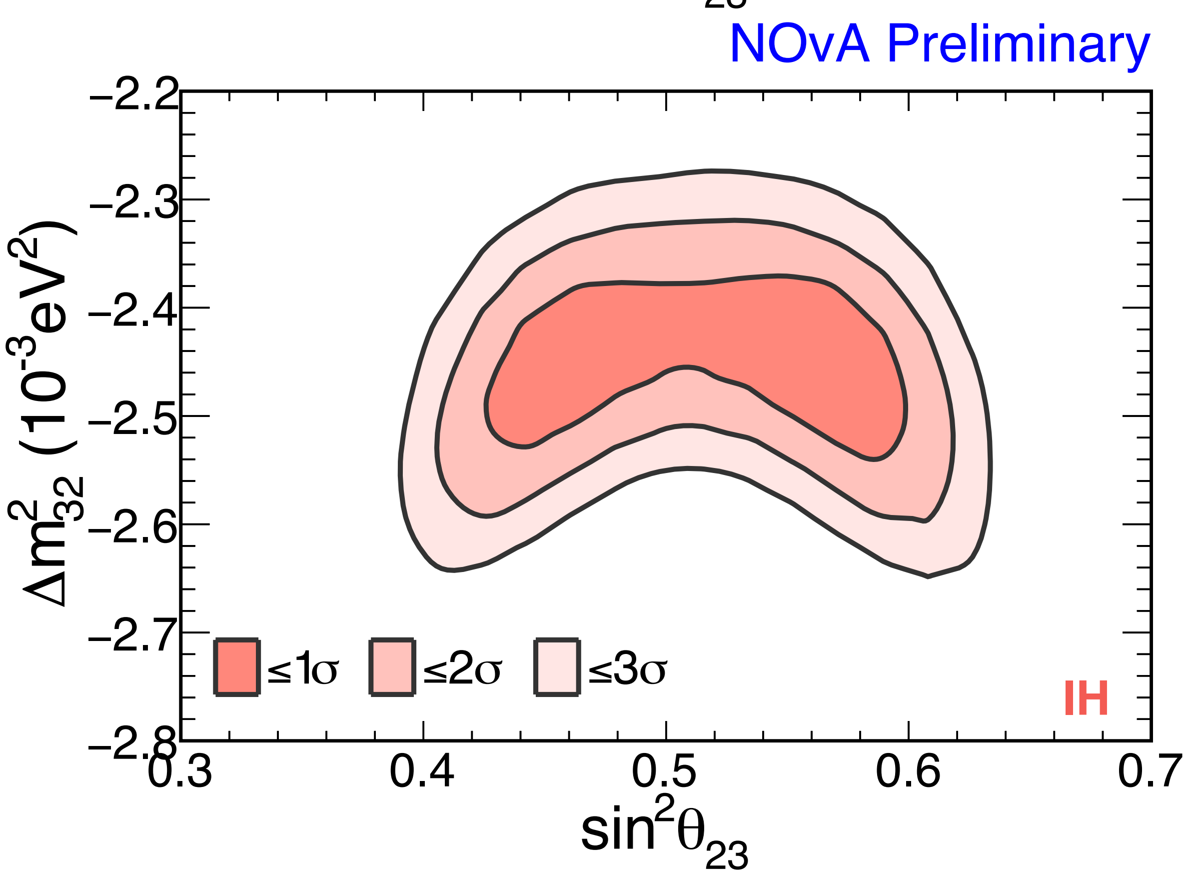
Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong Sign	2.3	
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd	14.0	13-15

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

NOvA Results: Δm^2_{32}, θ_{23}







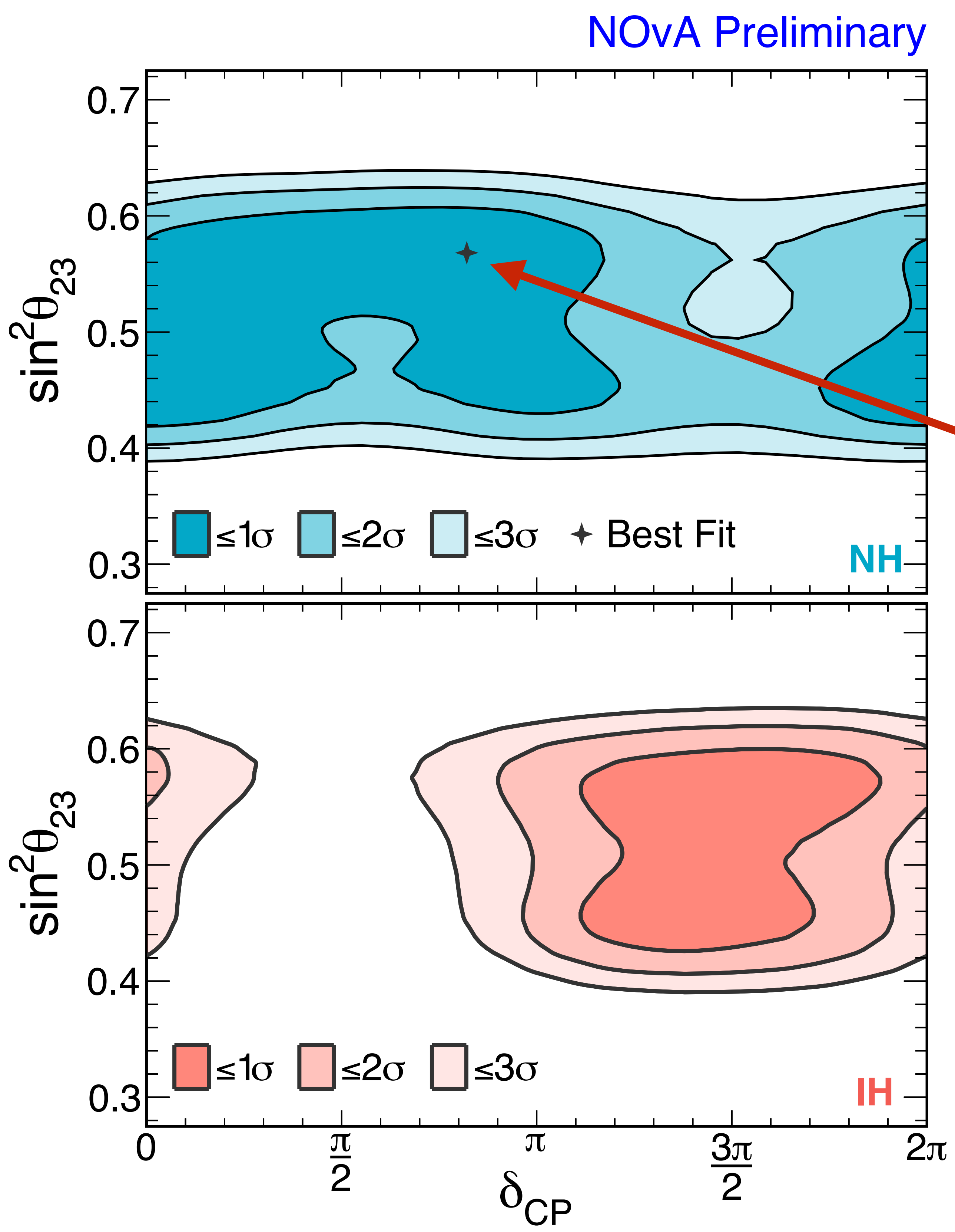
Best Fit:

- Normal Hierarchy, Upper Octant
- $\Delta m^2_{32} = +2.41 \pm 0.07\ (10^{-3}\ \text{eV}^2)$
- $\sin^2\theta_{23} = 0.57 + 0.03 / - 0.04$

Mild preferences for hierarchy, octant:

- Normal hierarchy favored at 1.0σ
- Upper Octant ($\sin^2\theta_{23} > 0.5$) favored at 1.2σ
- Max. Mixing ($\sin^2\theta_{23} = 0.5$) disfavored at 1.1σ

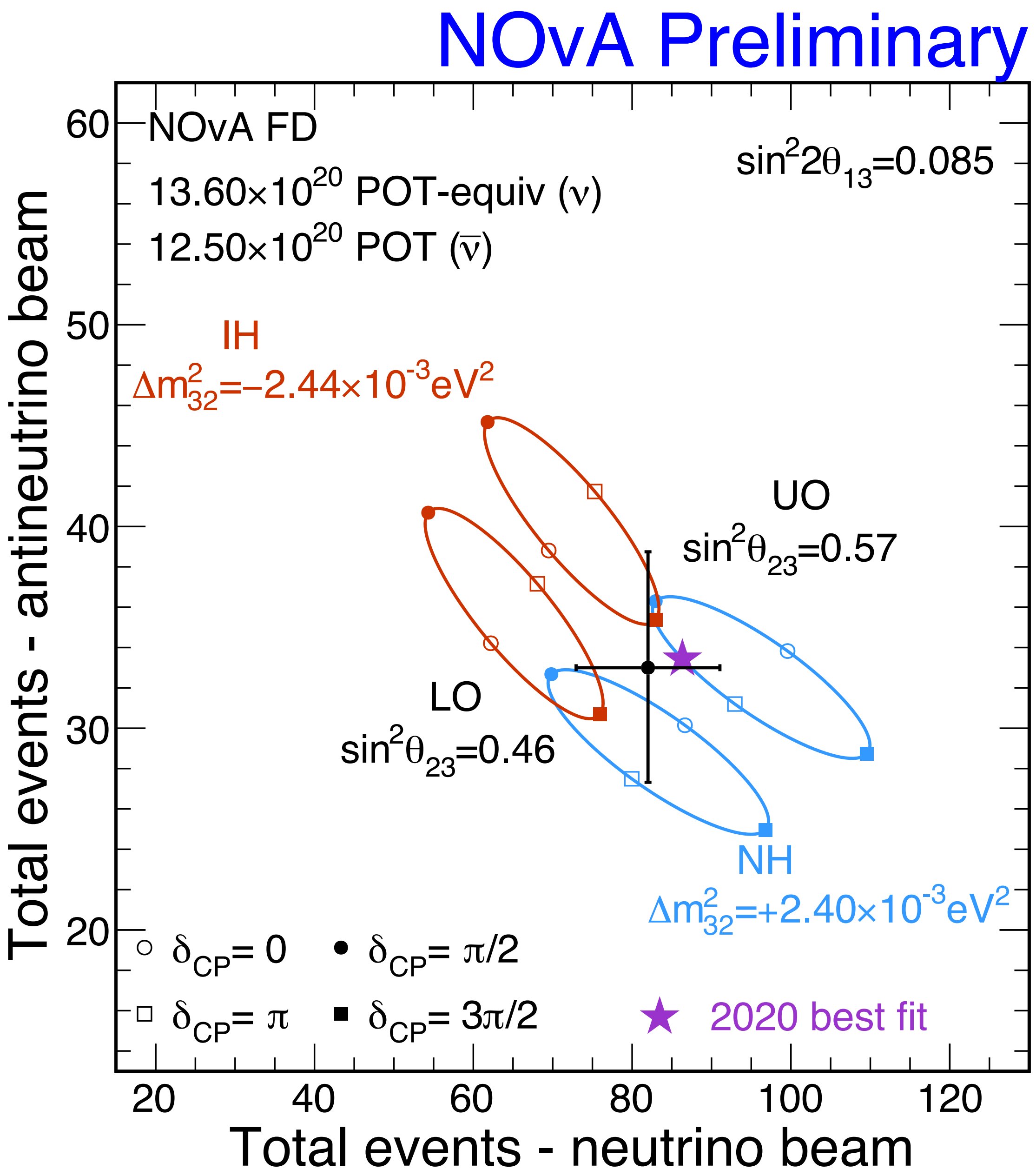
NOvA Results: θ_{23}, δ_{CP}

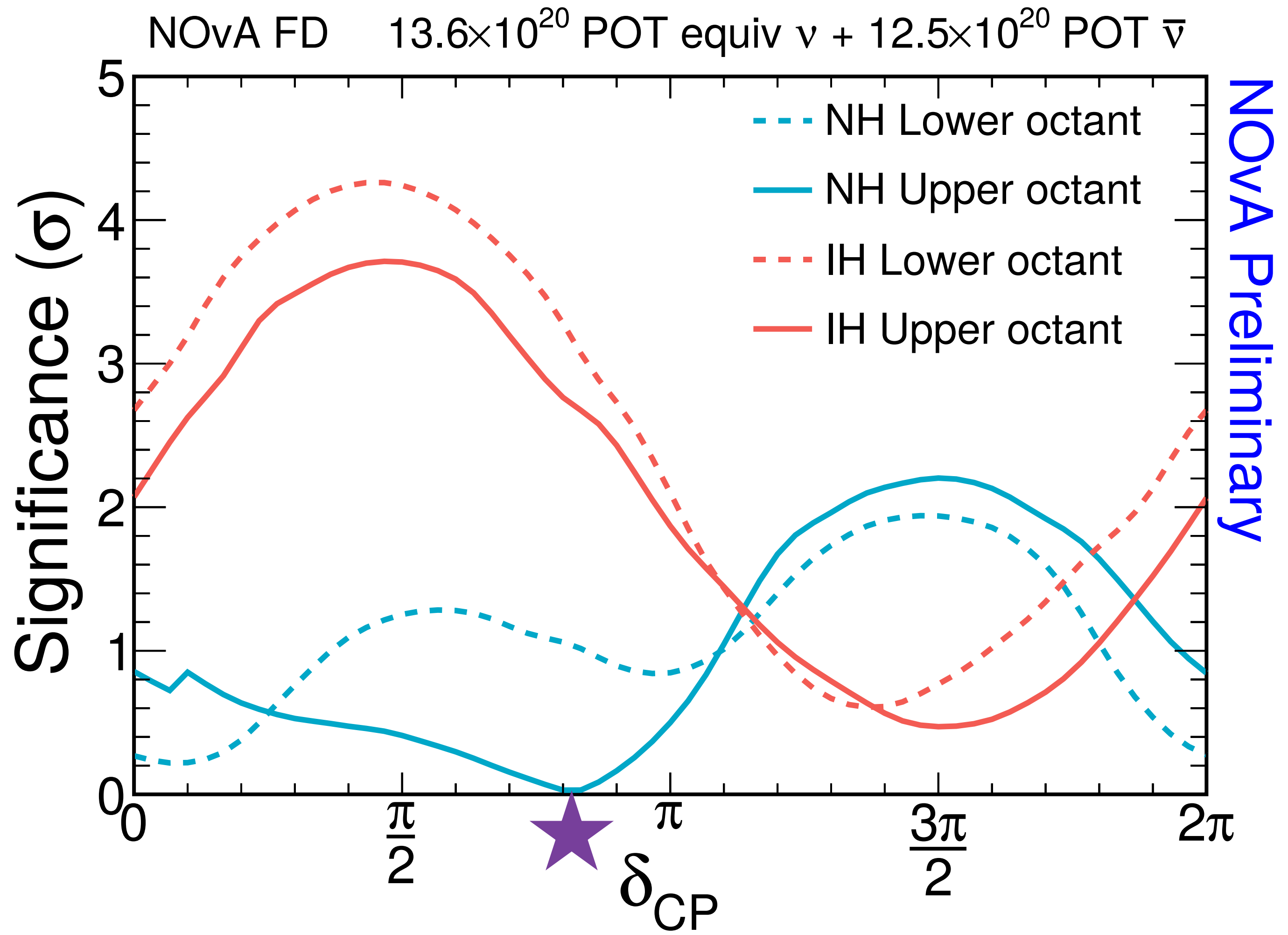


Best Fit:

- Normal Hierarchy, Upper Octant
- $\Delta m^2_{32} = +2.41 \pm 0.07\ (10^{-3}\ \text{eV}^2)$
- $\sin^2\theta_{23} = 0.57 + 0.03/-0.04$
- $\delta_{CP} = 0.82\pi$

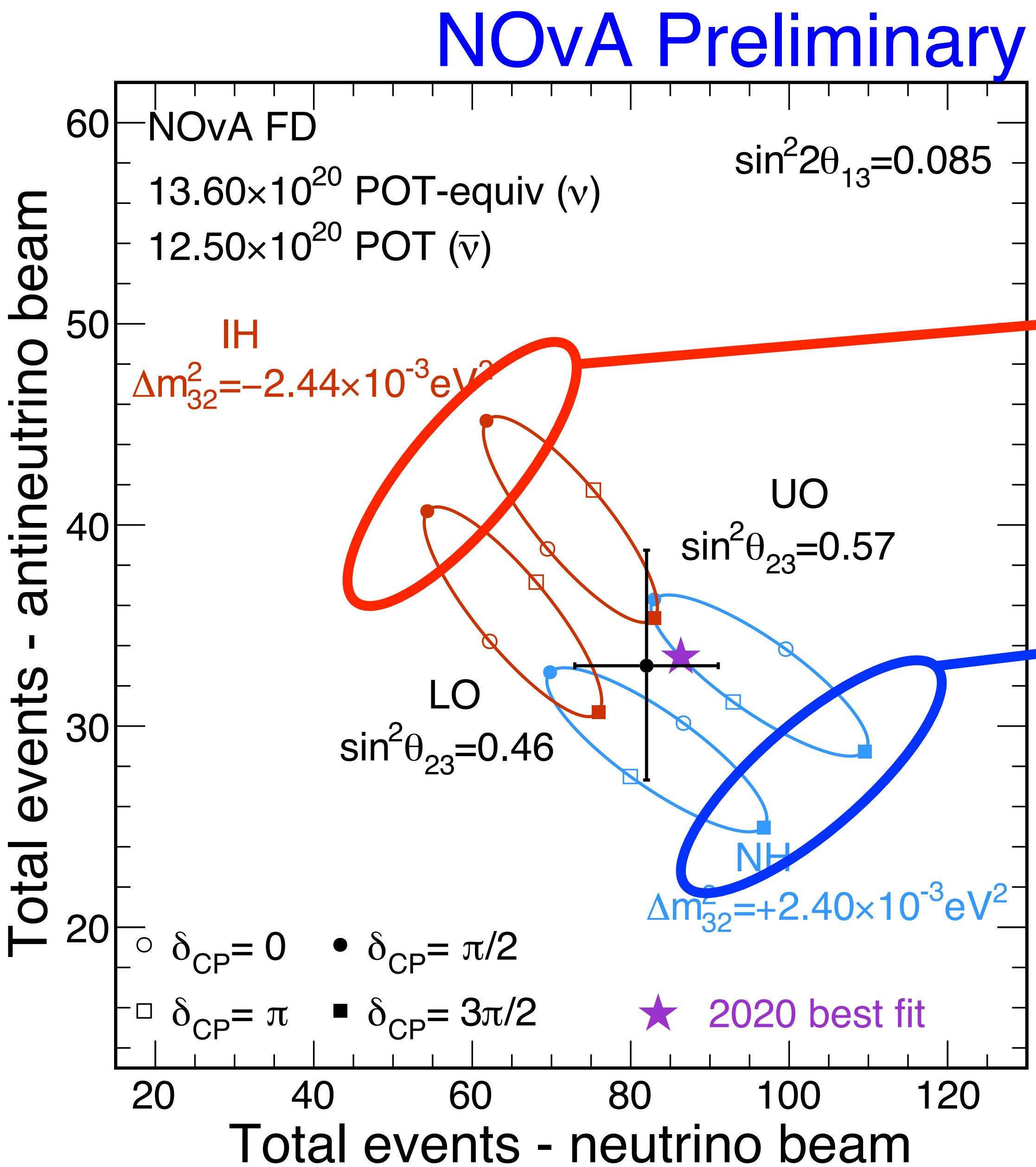
NOvA Results: $\nu_e/\overline{\nu}_e$ Appearance Asymmetry

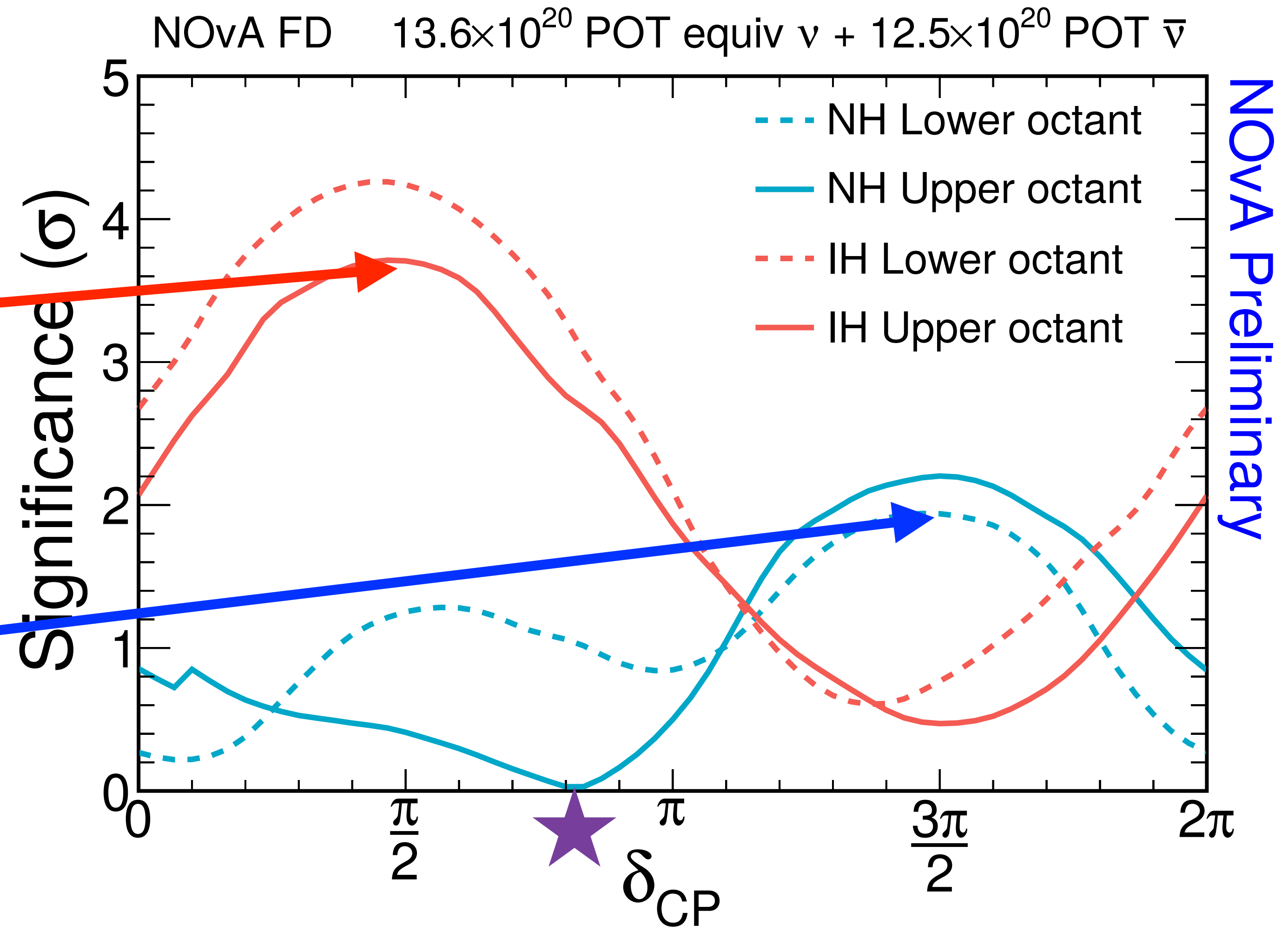




No strong asymmetry observed in ν_e and $\overline{\nu}_e$ appearance rates

NOvA Results: $\nu_e/\overline{\nu}_e$ Appearance Asymmetry



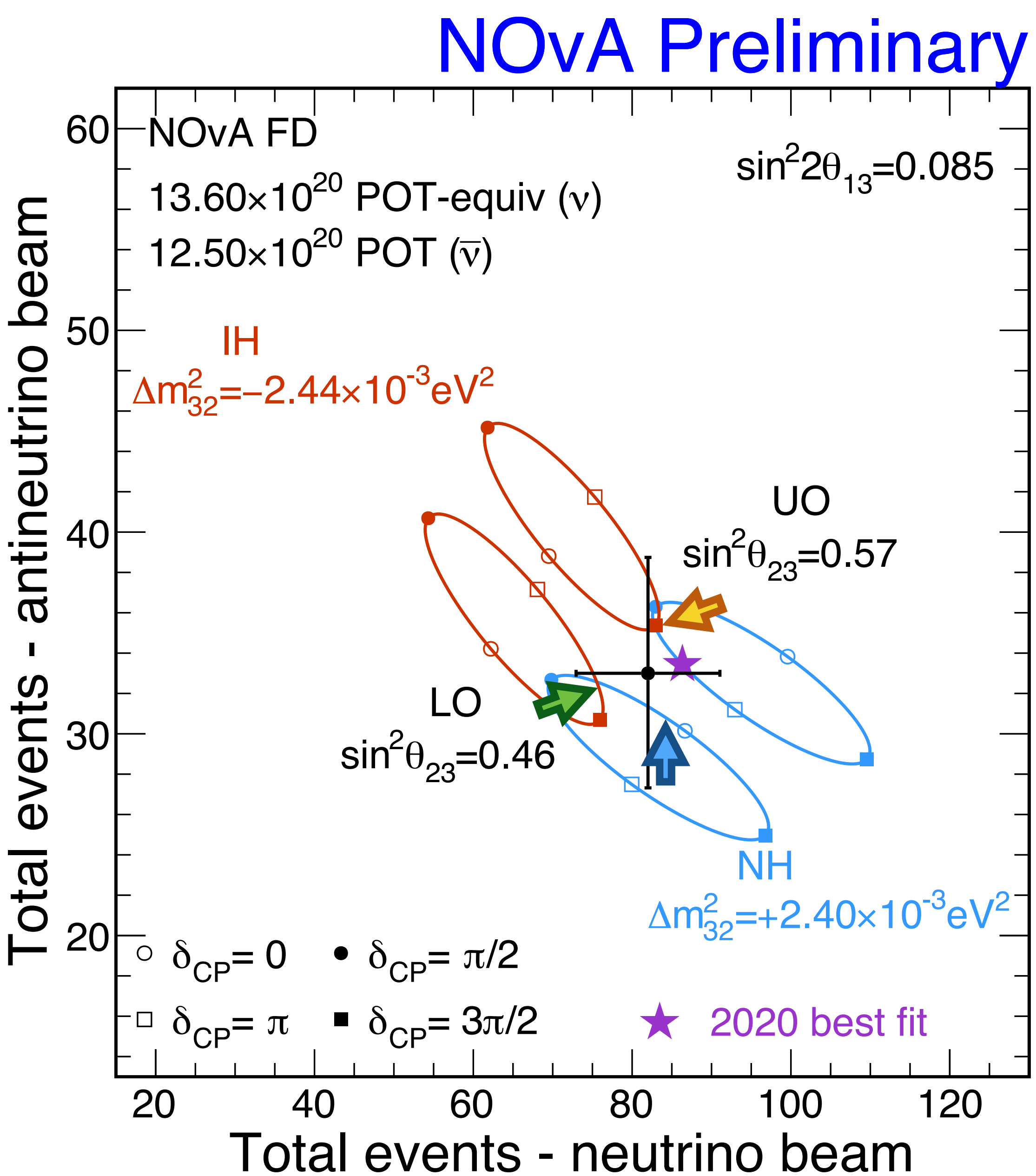


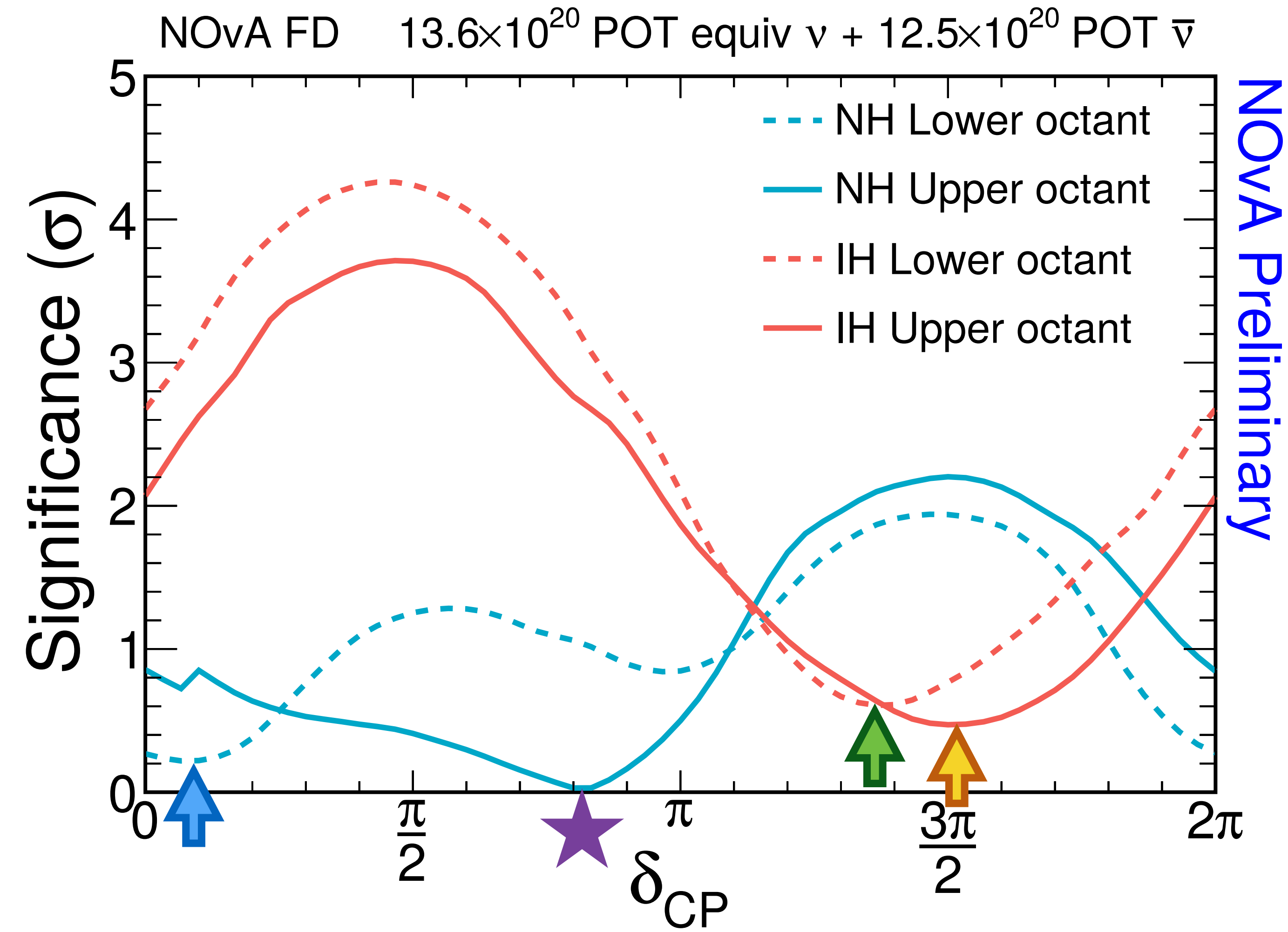
No strong asymmetry observed in ν_e and $\overline{\nu}_e$ appearance rates

Hierarchy-Octant-δ_{CP} combinations producing strong asymmetry disfavored

- IH, $\delta_{CP} = \pi/2$ excluded at >3σ
- NH, $\delta_{CP} = 3\pi/2$ disfavored at ~2σ

NOvA Results: $\nu_e/\overline{\nu}_e$ Appearance Asymmetry



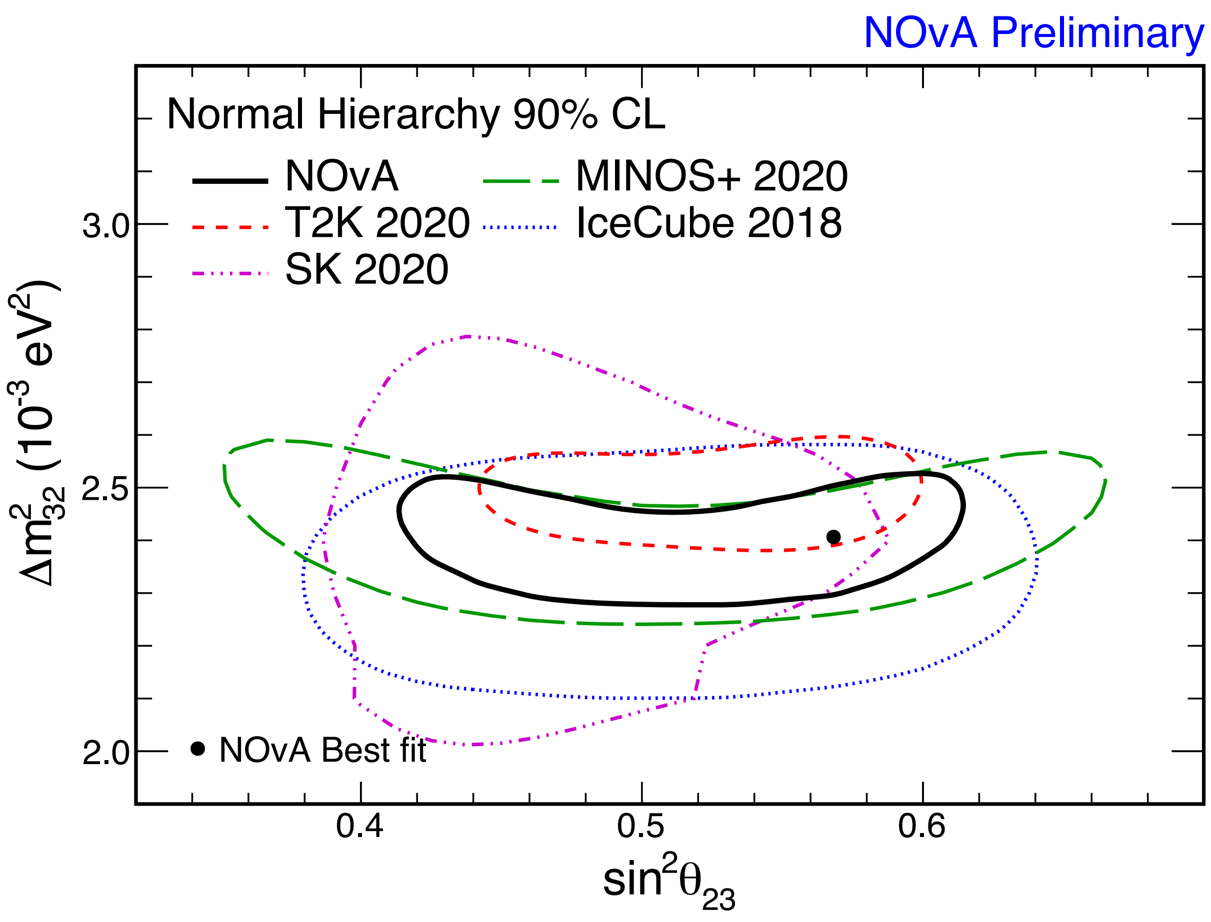


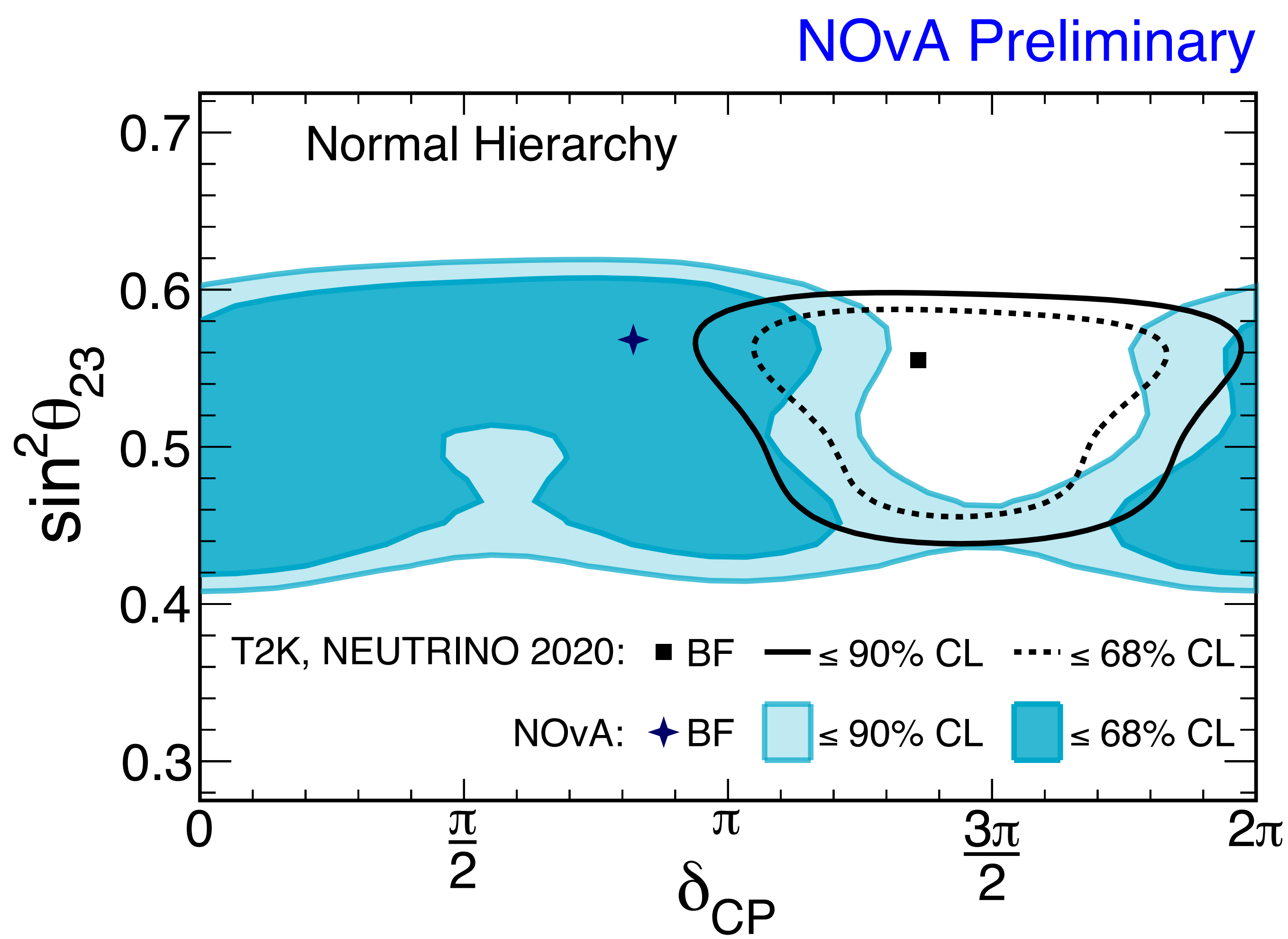
No strong asymmetry observed in ν_e and $\overline{\nu}_e$ appearance rates

No strong preferences for hierarchy, octant:

- Normal hierarchy preferred at 1.0σ
- Upper octant preferred at 1.2σ

Consistent with hierarchy-octant-δ_{CP} combinations giving "cancellation" of asymmetry

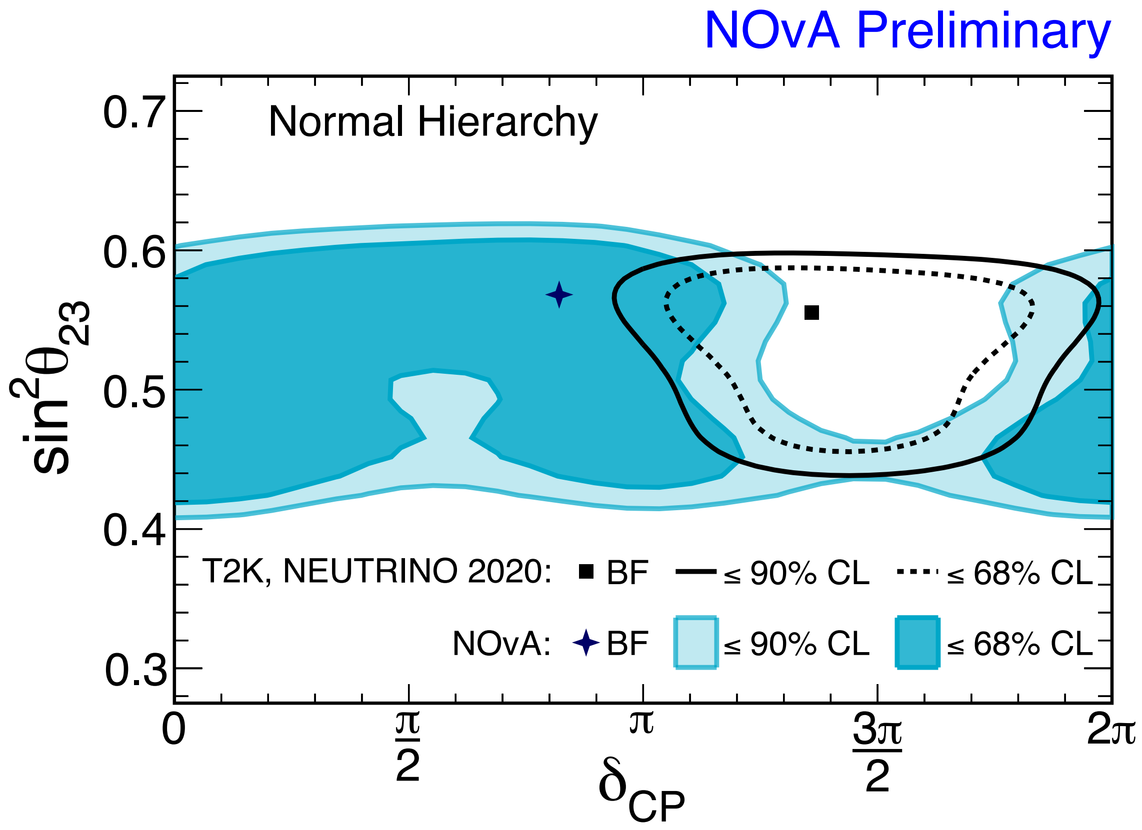




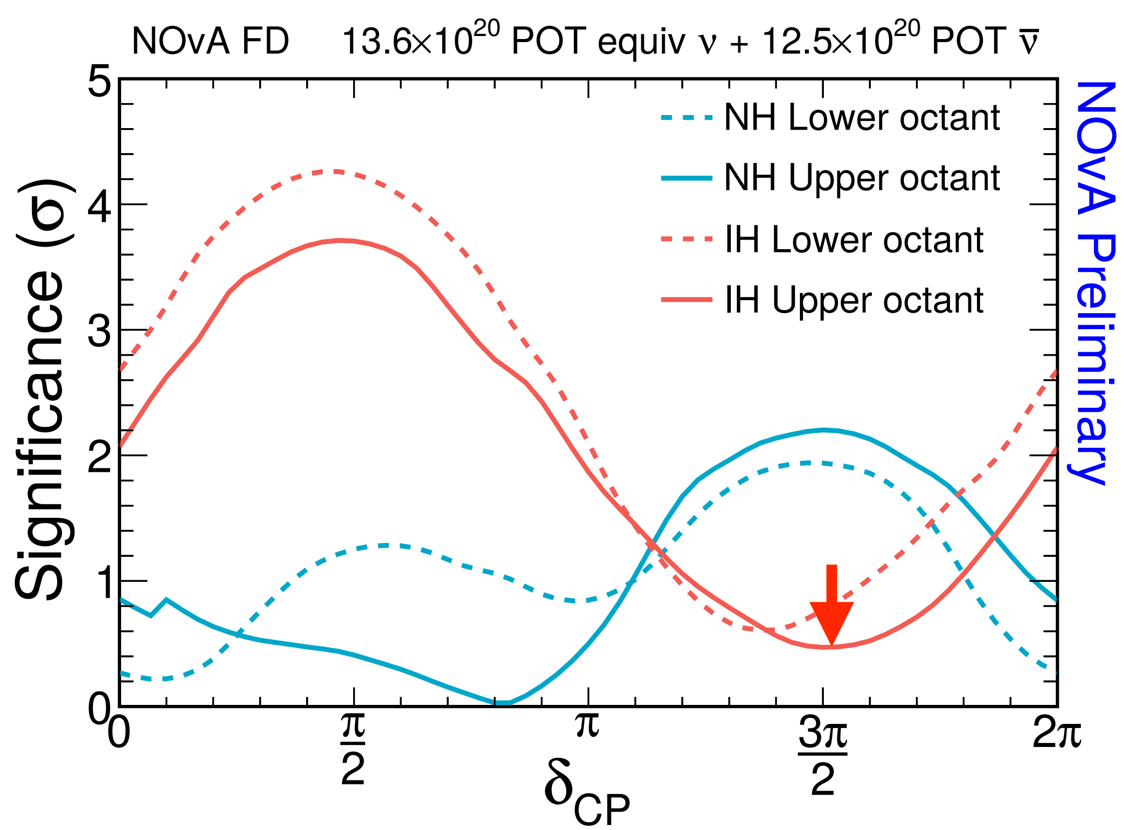
Consistency amongst precision measurements of $\sin^2\theta_{23}$ and Δm^2_{32}

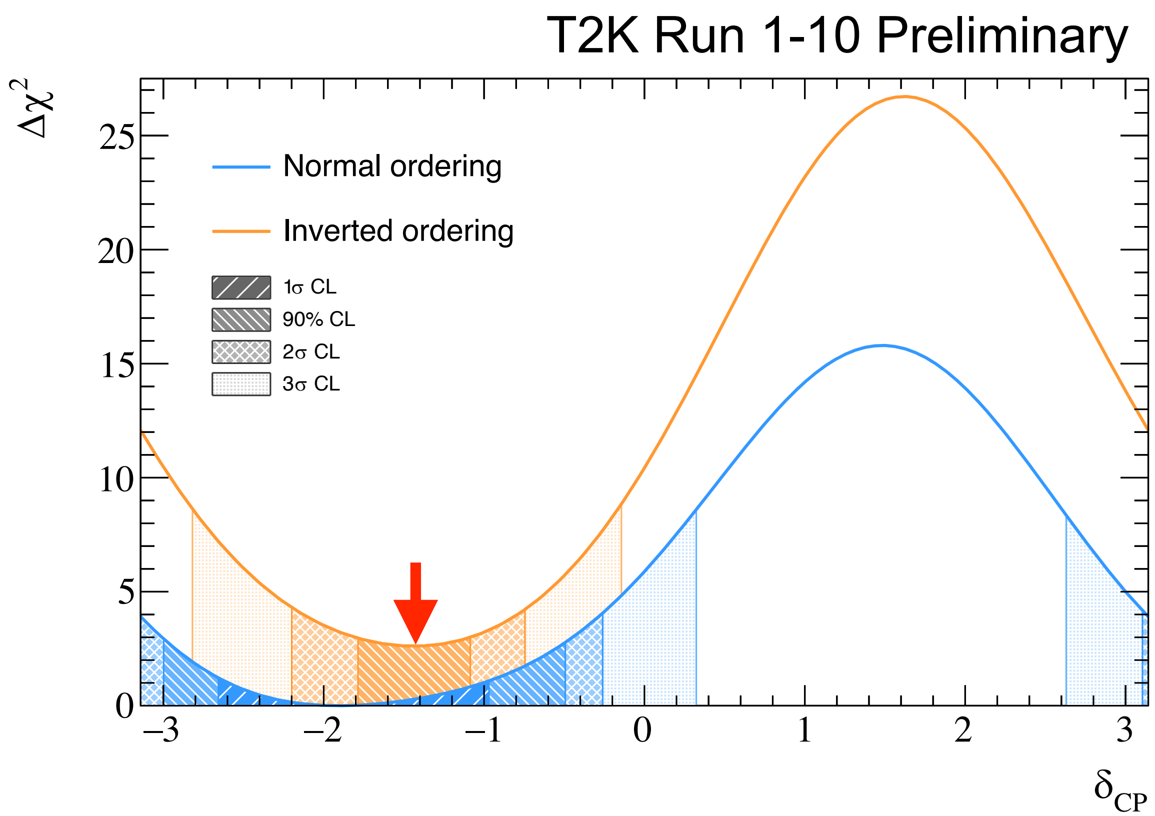
- NOvA and T2K are narrowing allowed regions in δ_{CP}
- Quantifying consistency requires joint analysis of NOvA and T2K data

T2K and NOvA: MH and δ_{CP}

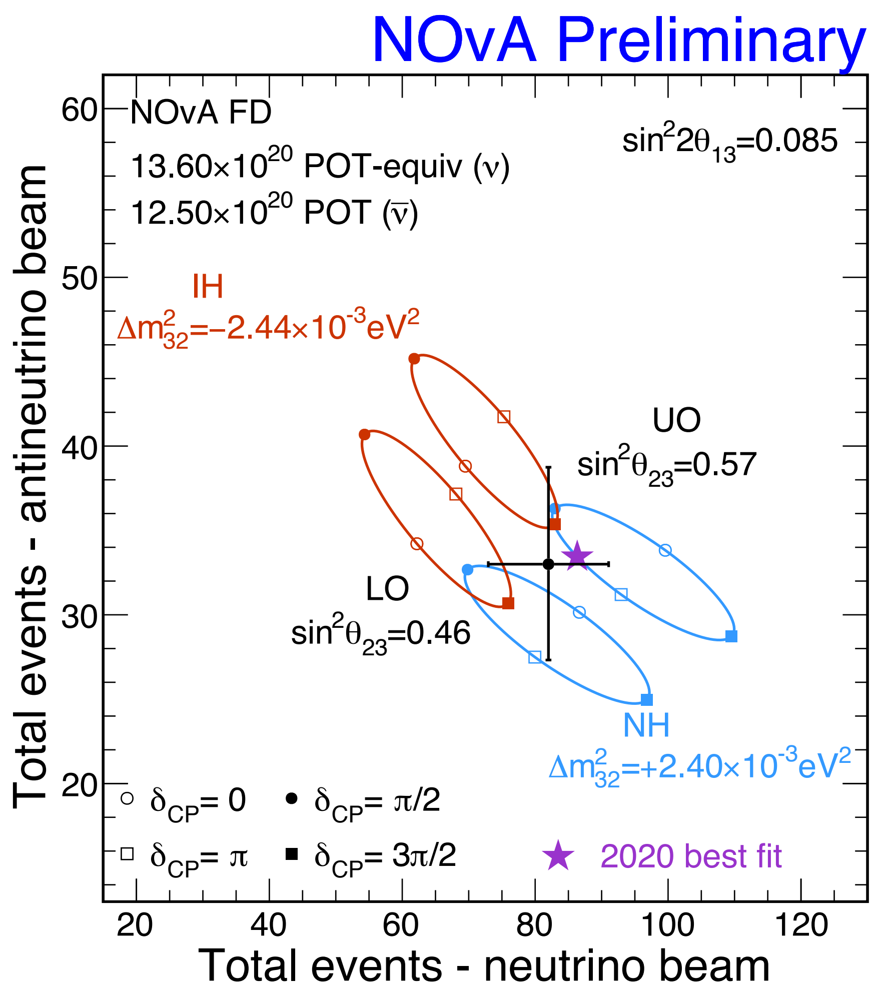


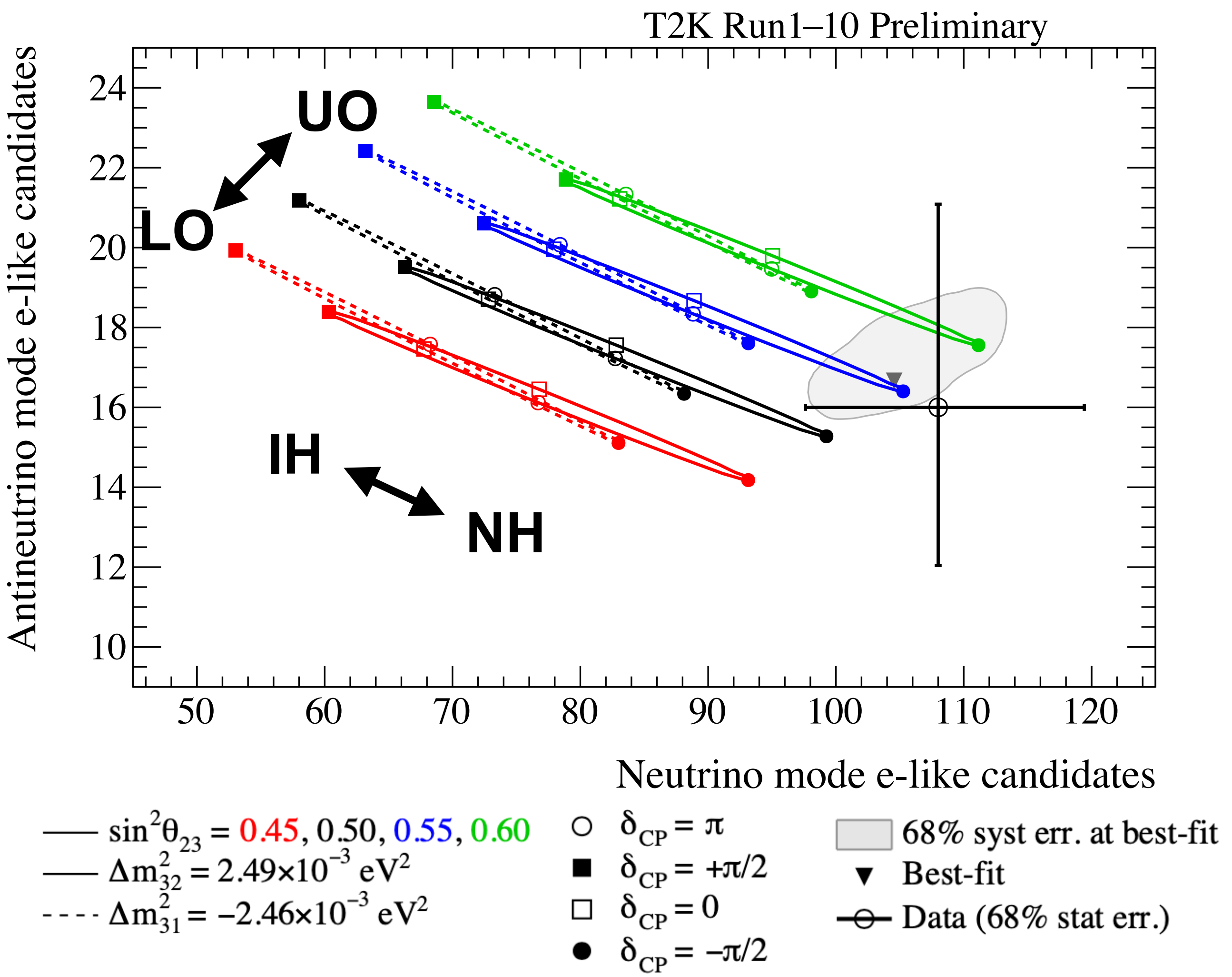
- Nova and T2K each have mild preference for the NH
- In the IH, NOvA and T2K each have preference for δ_{CP} near $3\pi/2$
- A NOvA-T2K joint fit could converge on the IH [Phys. Rev. D 103, 013004]





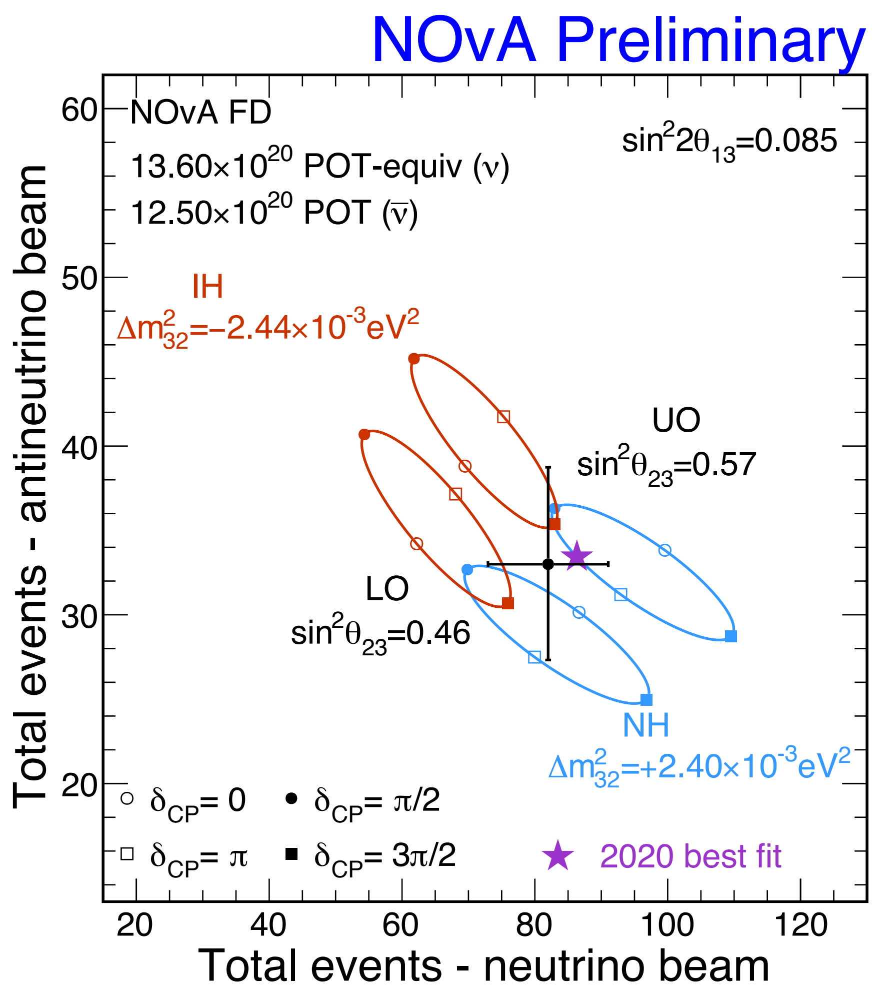
NOvA-T2K Joint Analysis

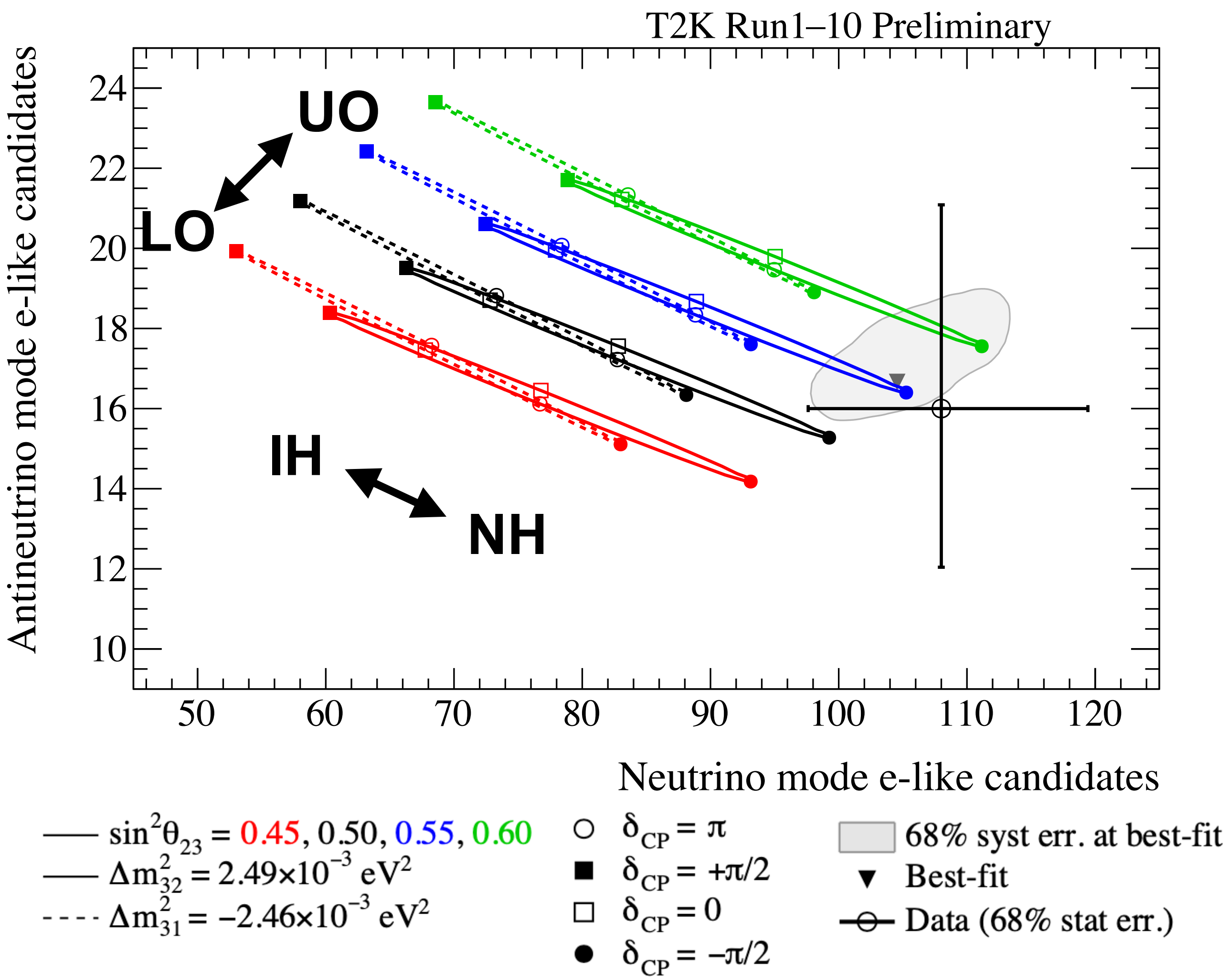




- NOvA and T2K have different energies, baselines, and degeneracies
- Collaboration formed to perform joint analysis of NOvA and T2K data
- Leverage statistics and break degeneracies
- Aiming for initial results in 2022

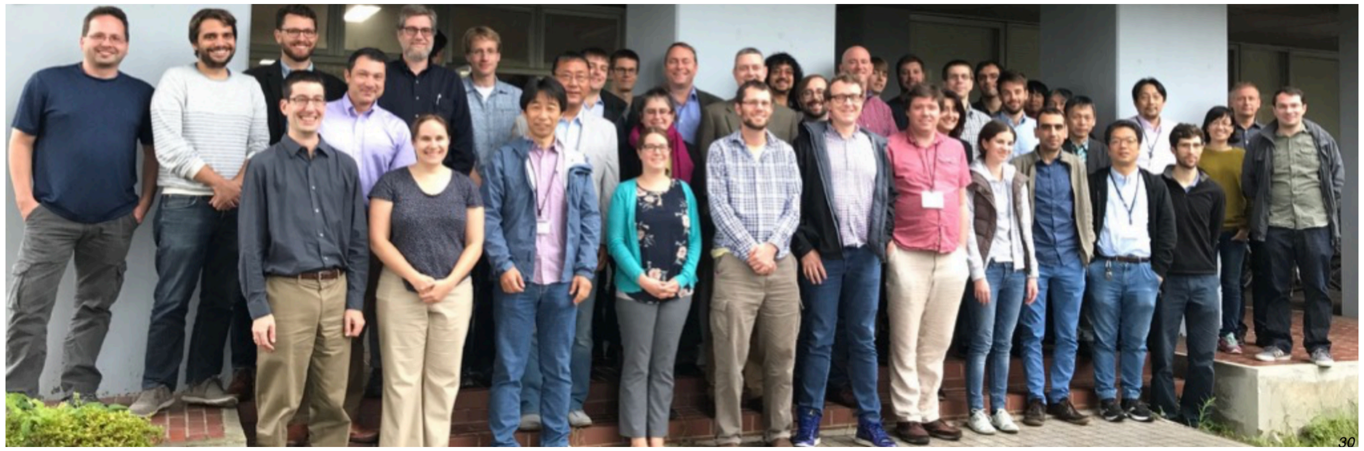
NOvA-T2K Joint Analysis





NOvA-T2K, Fermilab

NOvA-T2K, J-PARC



Summary

- Latest 3-flavor ν oscillation results from NOvA and T2K prefer
  - normal mass hierarchy
  - θ_{23} upper octant
- T2K observes stronger ν_e, $\bar{\nu}_e$ appearance asymmetry than NOvA
- NOvA and T2K are narrowing allowed regions in δ_{CP}
- Joint analysis of NOvA and T2K data underway

T2K Systematic Uncertainties

After ND Fit

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".

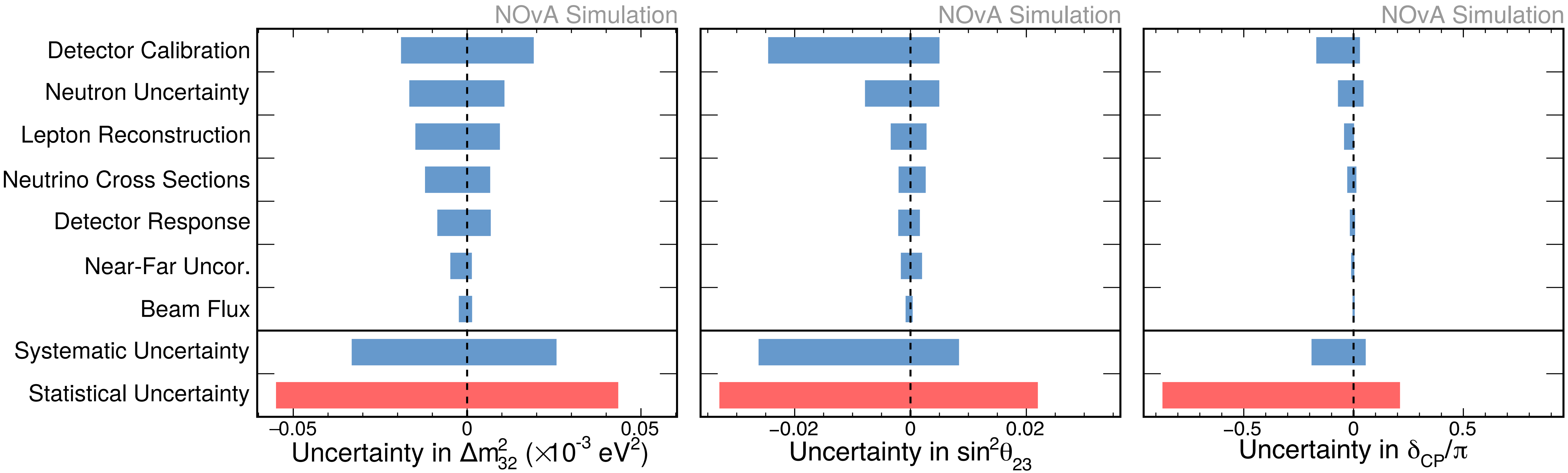
	1Rμ		1Re			
Error source	FHC	RHC	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	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

Before ND Fit

Table 21: Uncertainty on the number of event in each SK sample broken by error source before the BANFF fit.

	1Rμ		1Re			
Error source	FHC	RHC	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	5.1%	4.7%	4.8%	4.7%	4.9%	2.7%
Cross-section (all)	10.1%	10.1%	11.9%	10.3%	12.0%	10.4%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%	1.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%	10.7%

NOvA Systematic Uncertainties



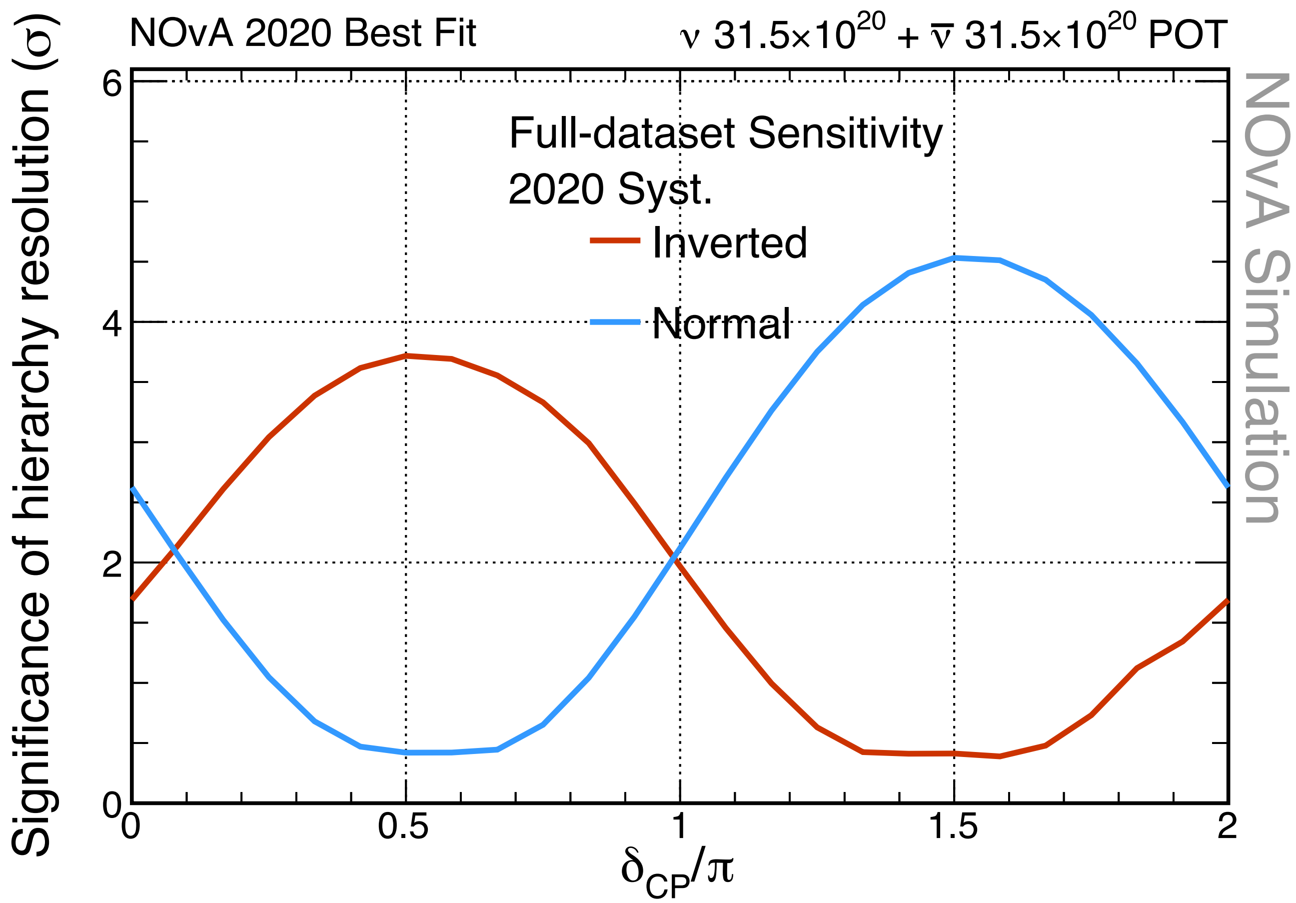
Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -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

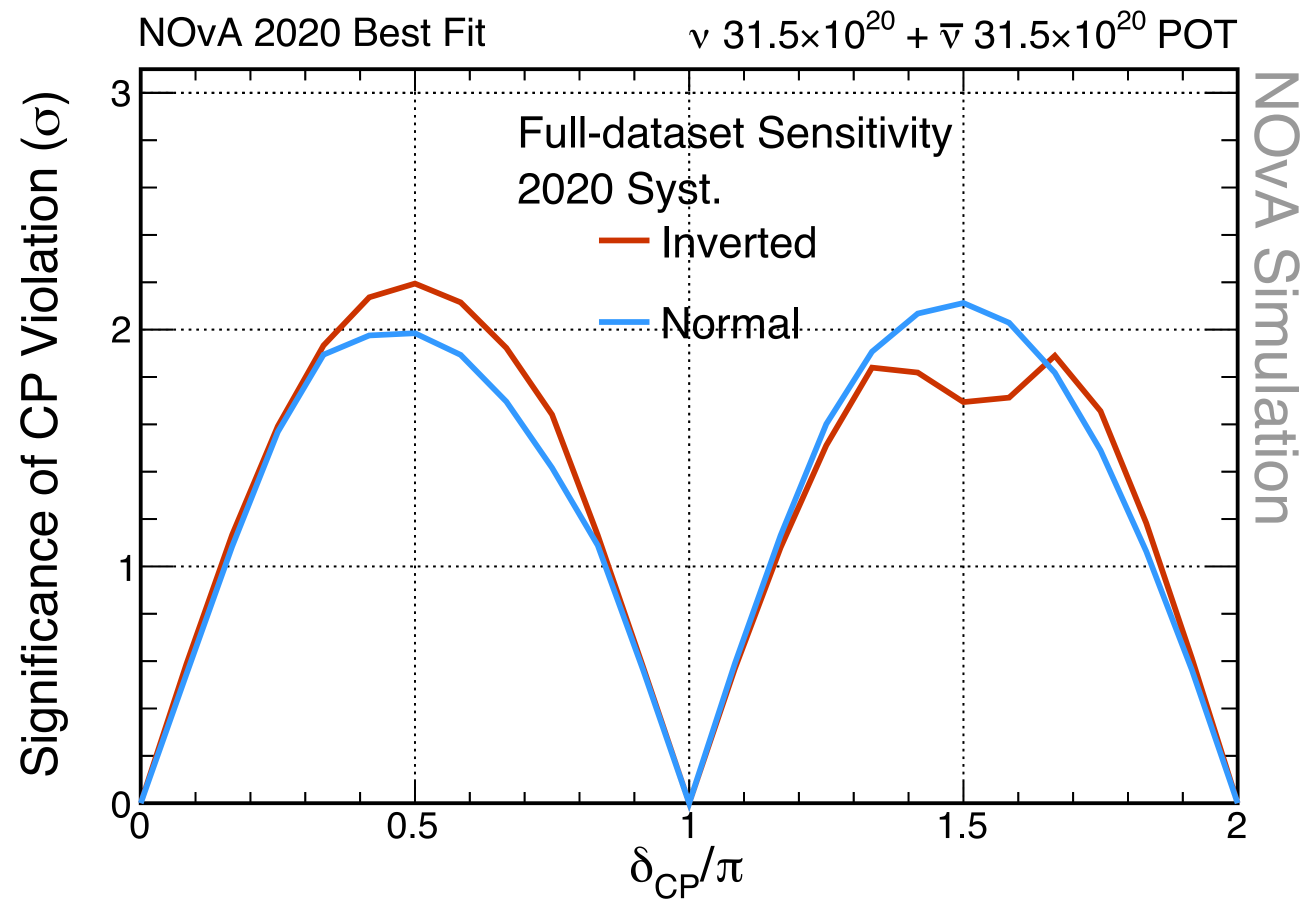
NOvA FD Event Counts

	Neutrino beam		Antineutrino beam	
	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
$\nu_\mu \to \nu_\mu$	201.1	1.7	26.0	0.2
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	12.6	0.0	77.2	0.2
$\nu_\mu \to \nu_e$	0.1	59.0	0.0	2.3
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.0	1.0	0.0	19.2
Beam $\nu_e + \bar{\nu}_e$	0.0	14.1	0.0	7.3
NC	2.6	6.3	0.8	2.2
Cosmic	5.0	3.1	0.9	1.6
Others	0.9	0.5	0.4	0.3
Signal	$214.1^{+14.4}_{-14.0}$	$59.0^{+2.5}_{-2.5}$	$103.4^{+7.1}_{-7.0}$	$19.2^{+0.6}_{-0.7}$
Background	$8.2^{+1.9}_{-1.7}$	$26.8^{+1.6}_{-1.7}$	$2.1^{+0.7}_{-0.7}$	$14.0^{+0.9}_{-1.0}$
Best fit	222.3	85.8	105.4	33.2
Observed	211	82	105	33

Event counts at the FD, both observed and predicted at the best-fit point

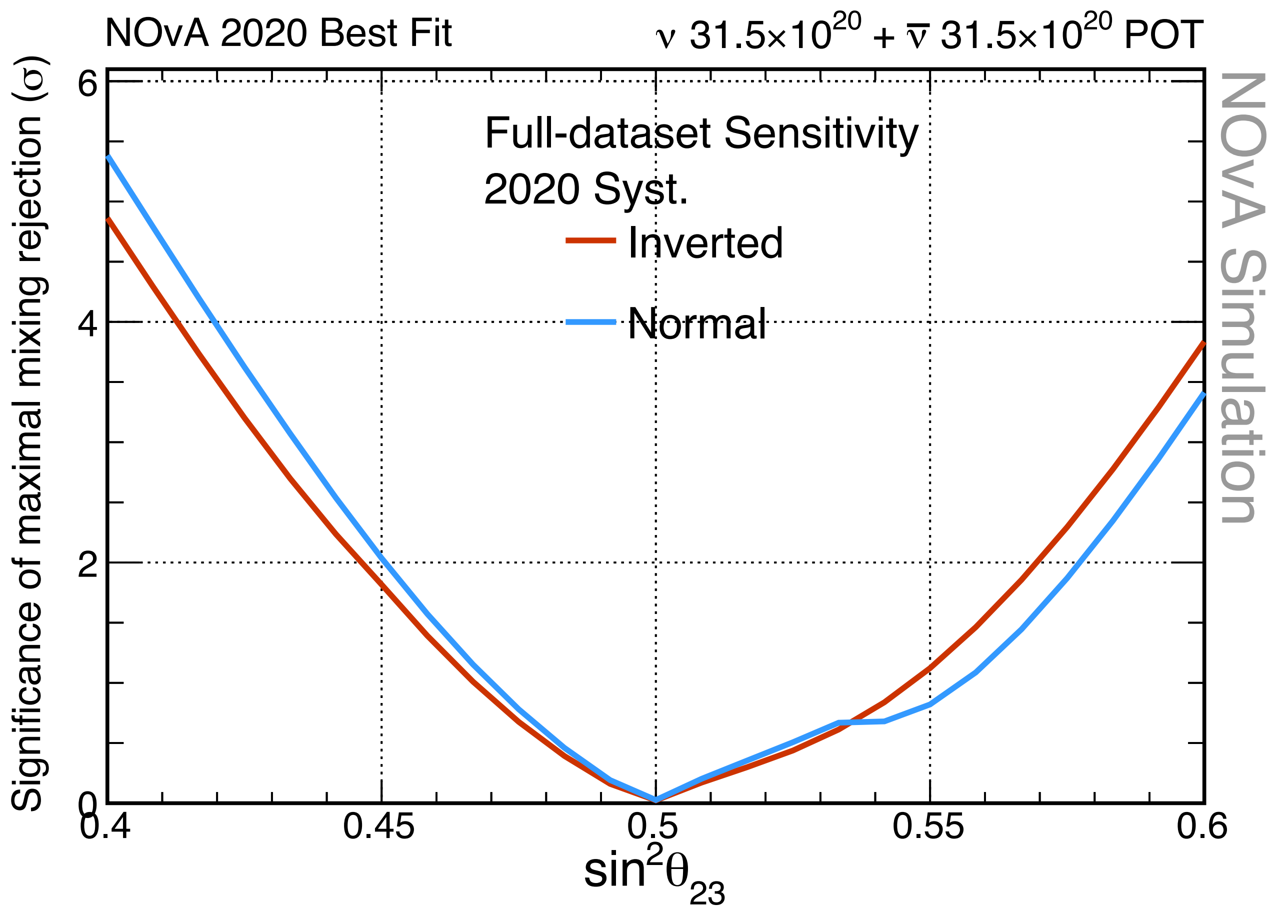
NOvA Future Sensitivities

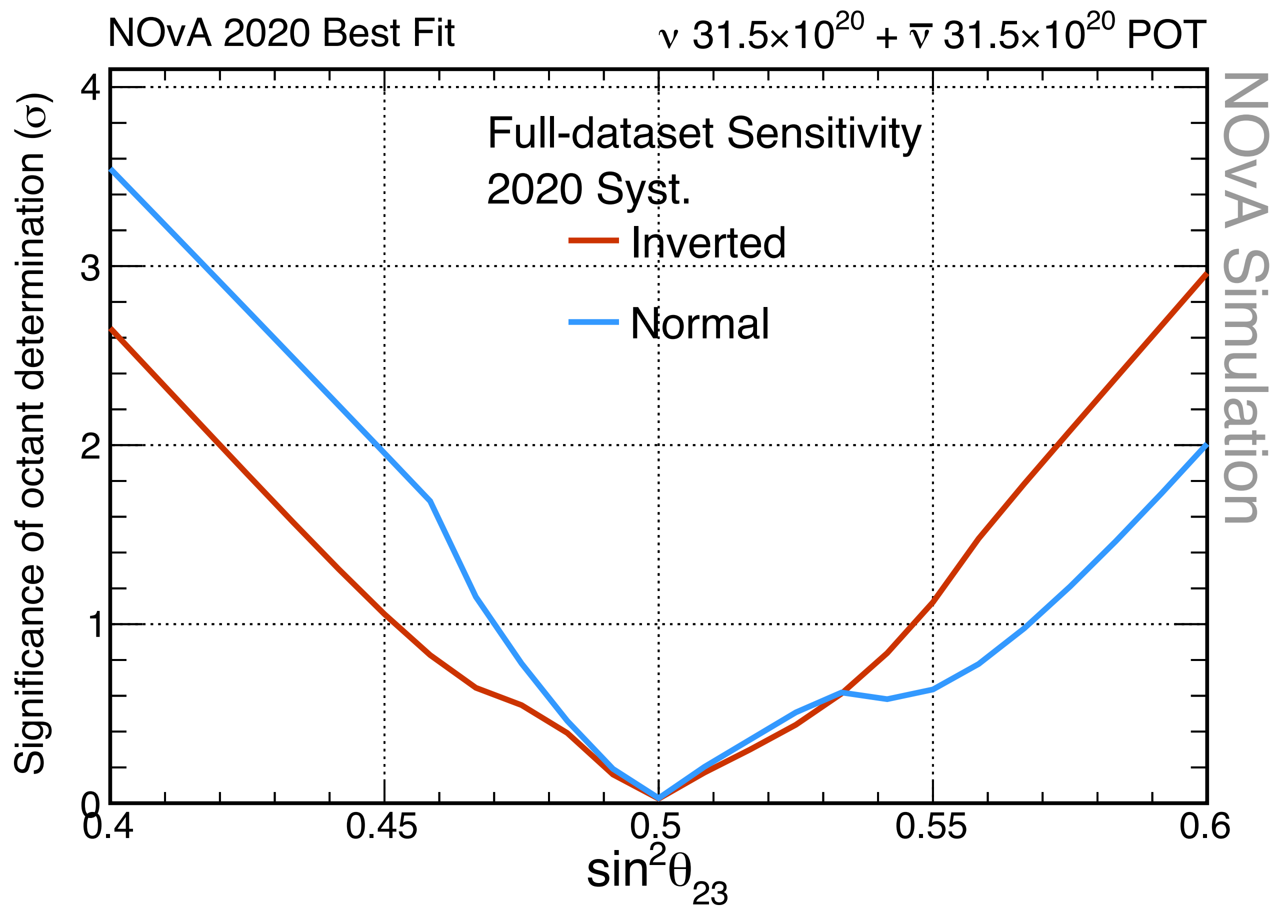




~2.5X increase in ν and $\overline{\nu}$ exposure

NOvA Future Sensitivities



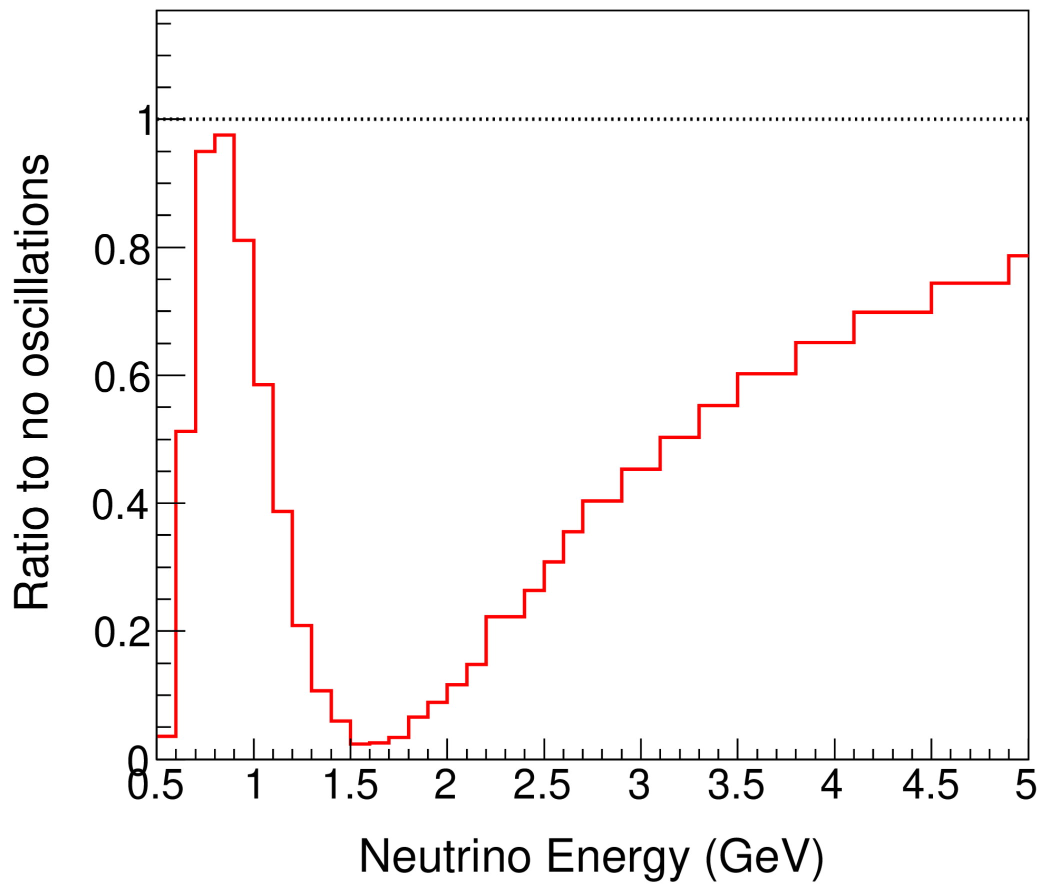


~2.5X increase in ν and $\overline{\nu}$ exposure

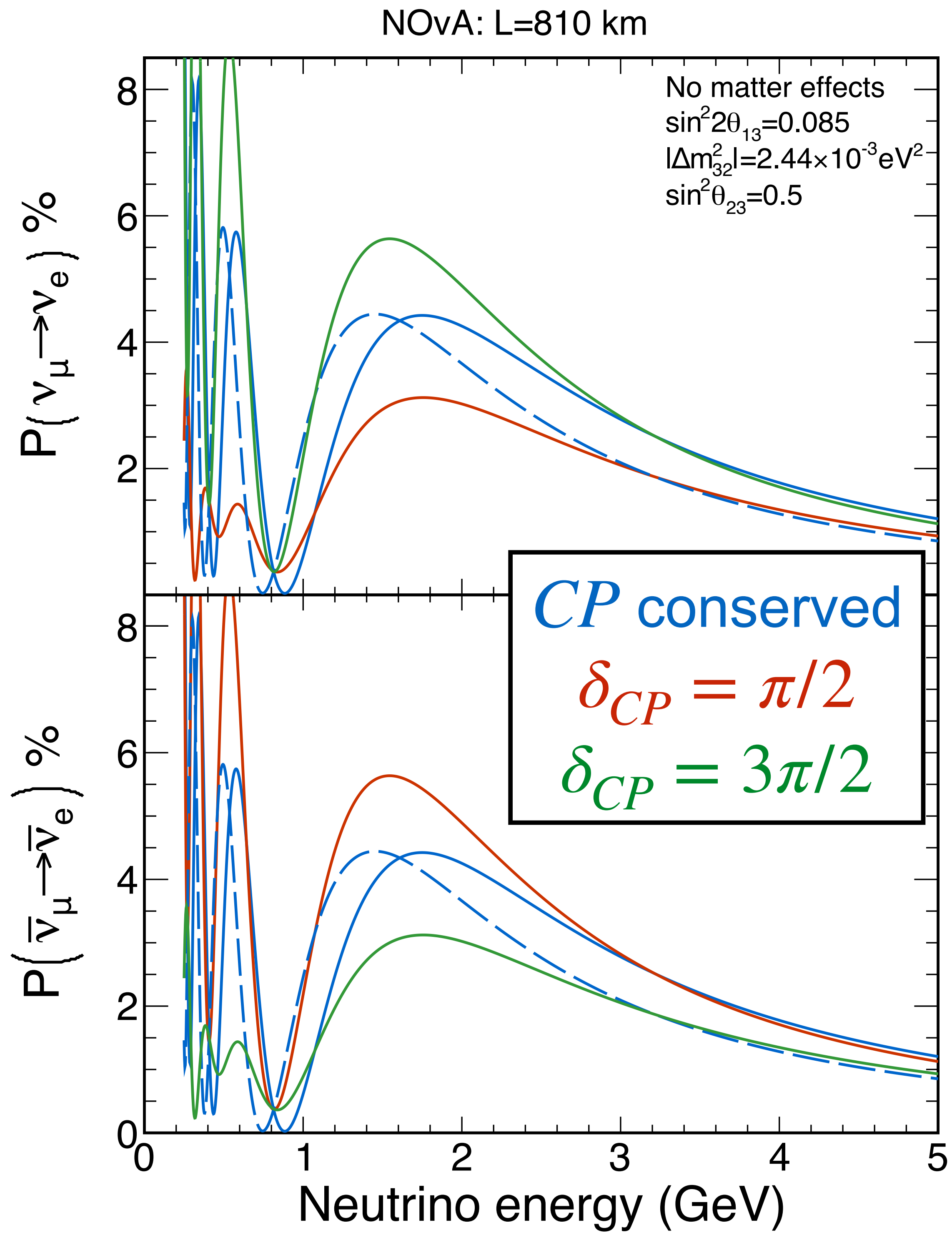
NOvA Oscillation Probabilities

$\nu_\mu, \bar{\nu}_\mu$ Disappearance

L = 810 km

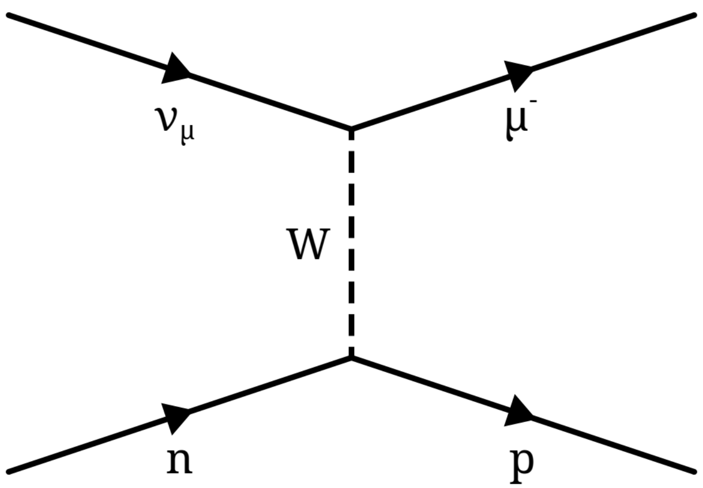


$\nu_e, \bar{\nu}_e$ Appearance

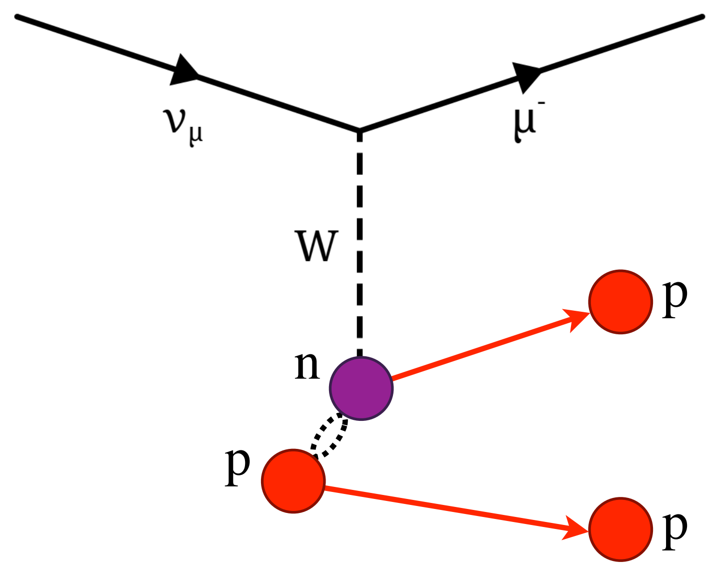


T2K E_ν Reconstruction

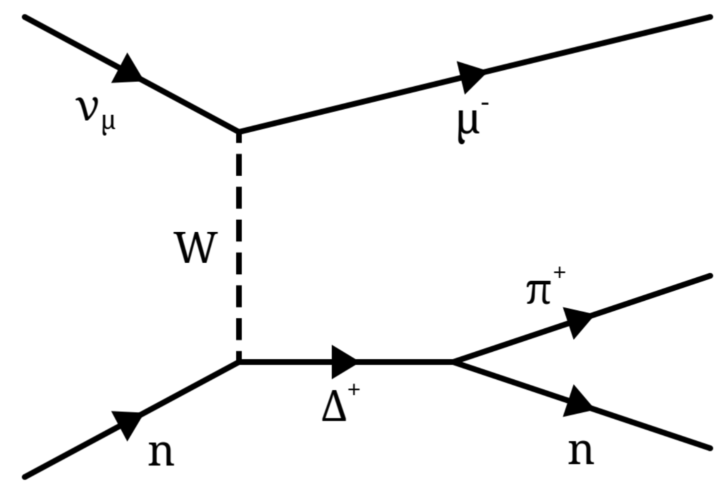
Quasi-Elastic (QE)

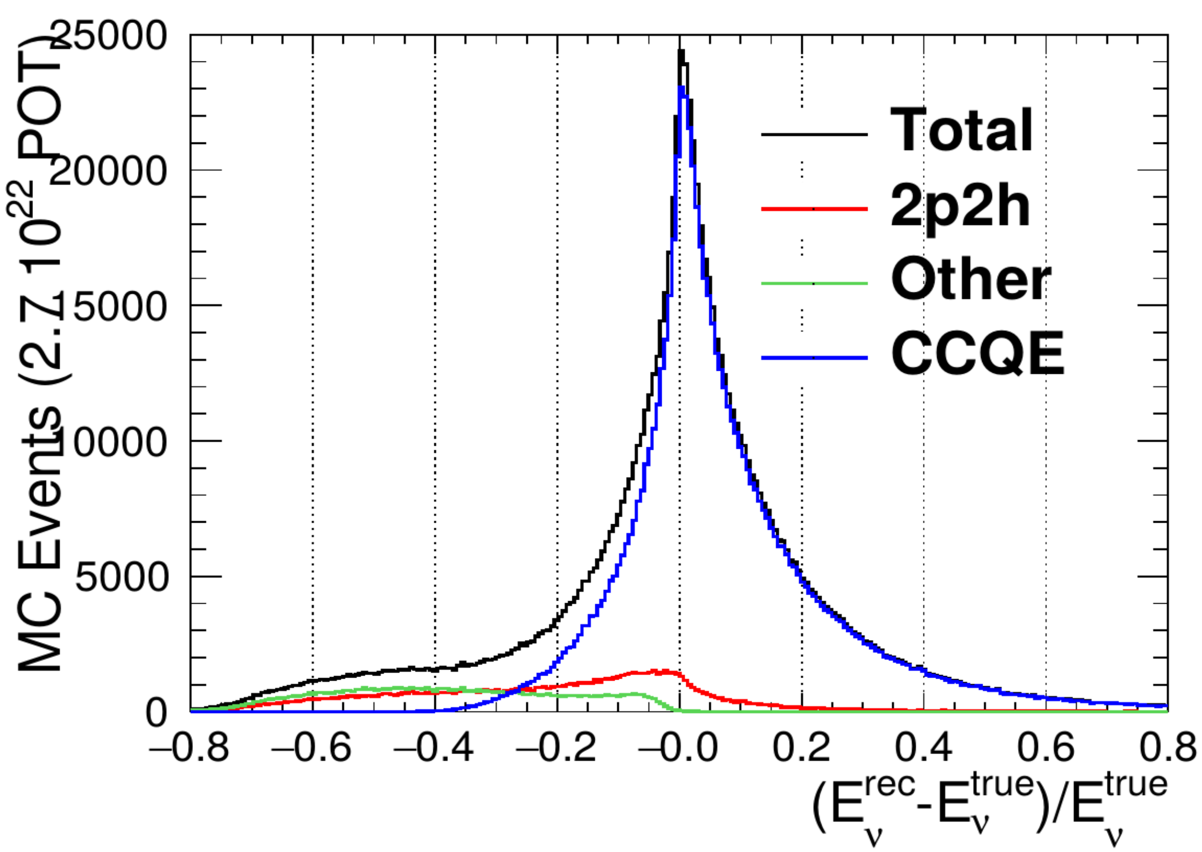


2 Particle 2 Hole (2p2h)



Resonance Production

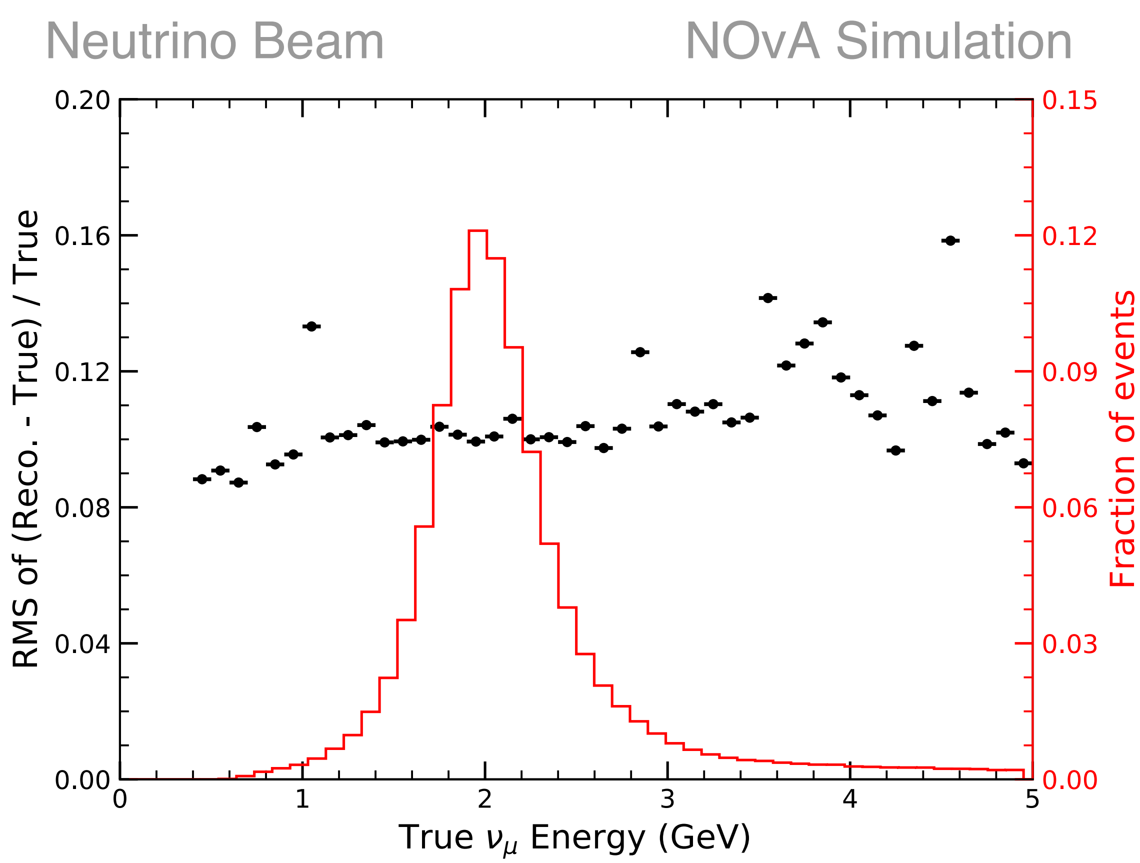


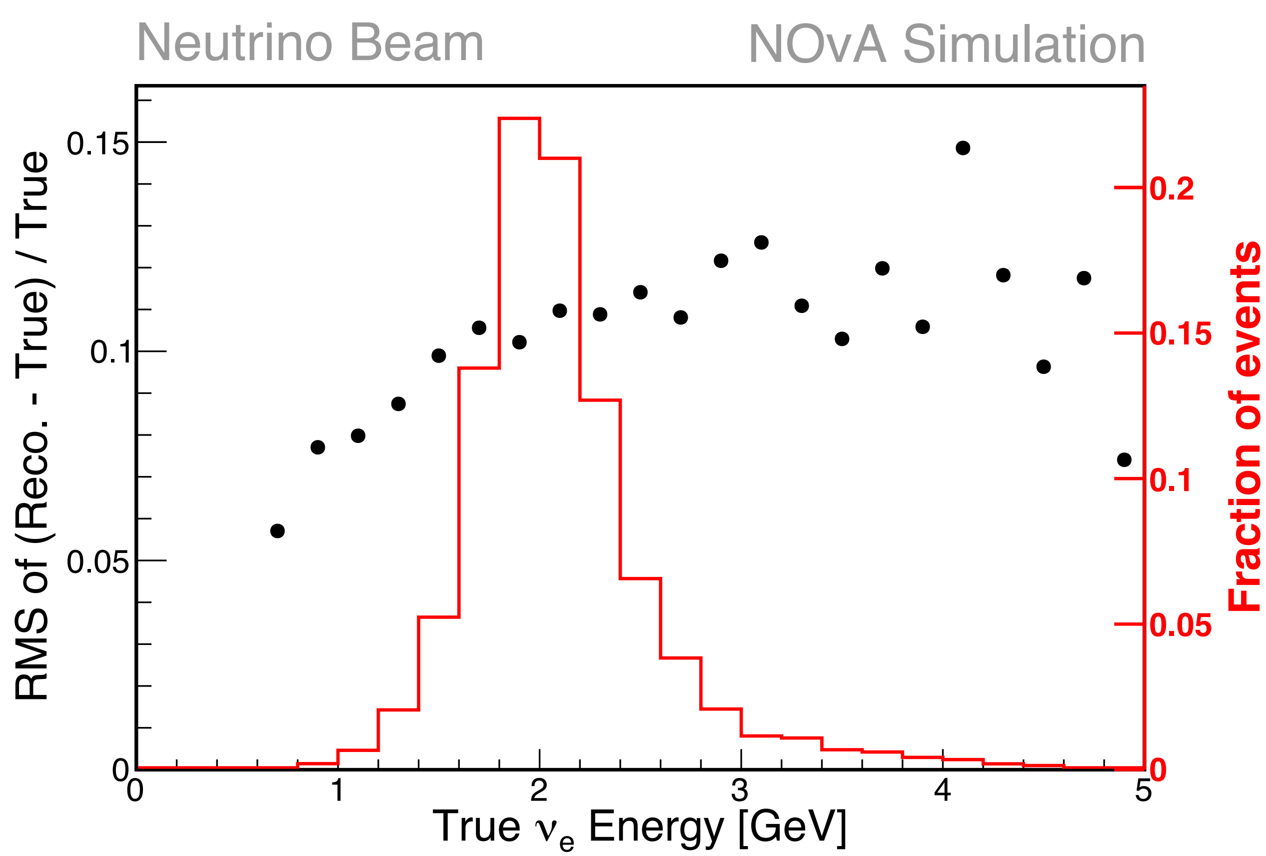


$$E_{\mathrm{QE}}^{\mathrm{Rec}}\left(p_\ell,\theta_\ell\right)=\frac{2M_{N,i}E_\ell-M_\ell^2+M_{N,f}^2-M_{N,i}^2}{2\left(M_{N,i}-E_\ell+p_\ell\cos\theta_\ell\right)}$$

Due to Cherenkov thresholds, E_ν reconstructed from only final state lepton energy & angle assuming quasi-elastic kinematics

NOvA E_ν Resolution

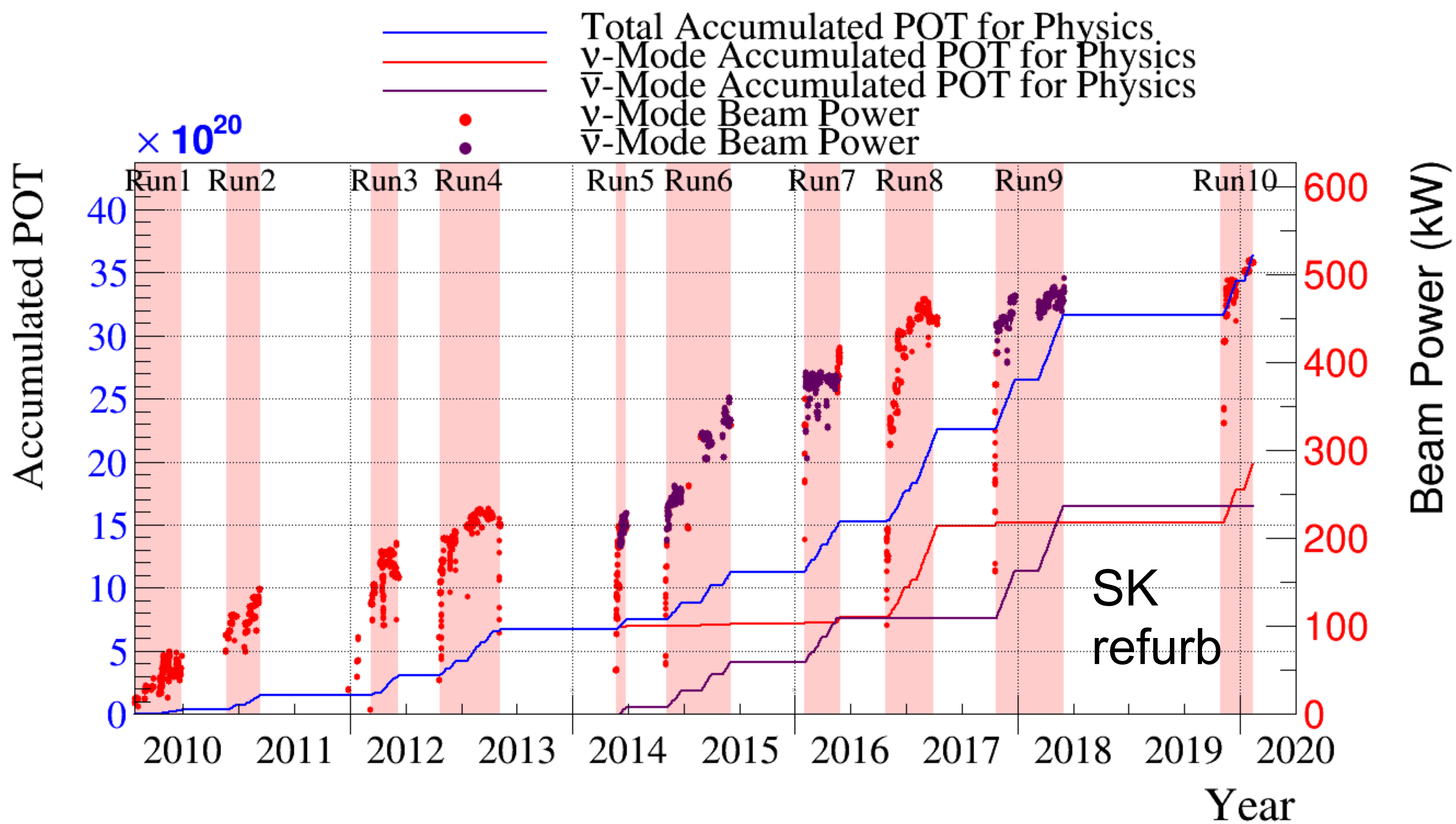




ν_μ CC E_ν reconstructed from μ track length and hadronic calorimetric energy

ν_e CC E_ν reconstructed from e shower and hadronic calorimetric energies

T2K Beam Exposure

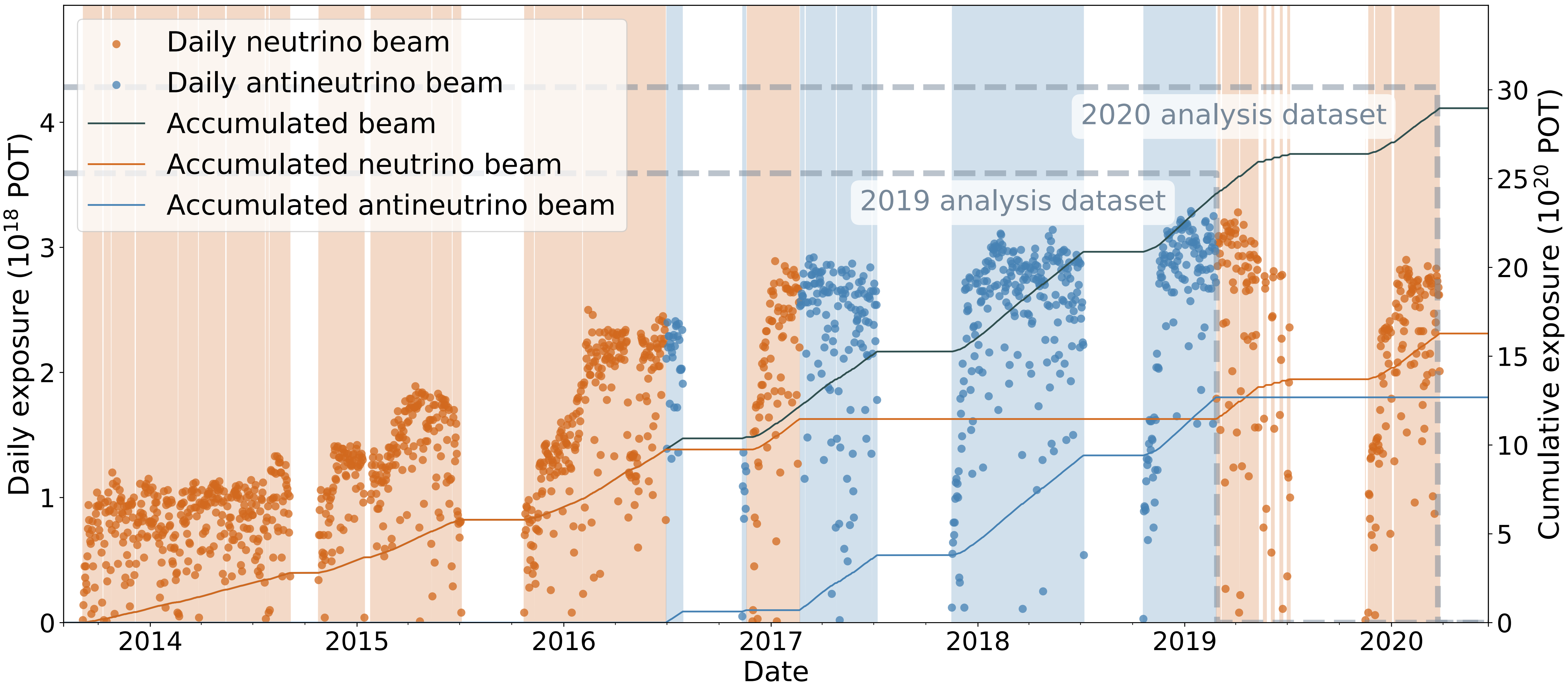


Accumulated protons on target (POT) for these results

- ν-mode: 1.97×10^{21} POT
- $\bar{\nu}$-mode: 1.63×10^{21} POT

33% increase in ν-mode exposure (Run 10) for these results

NOvA Beam Exposure

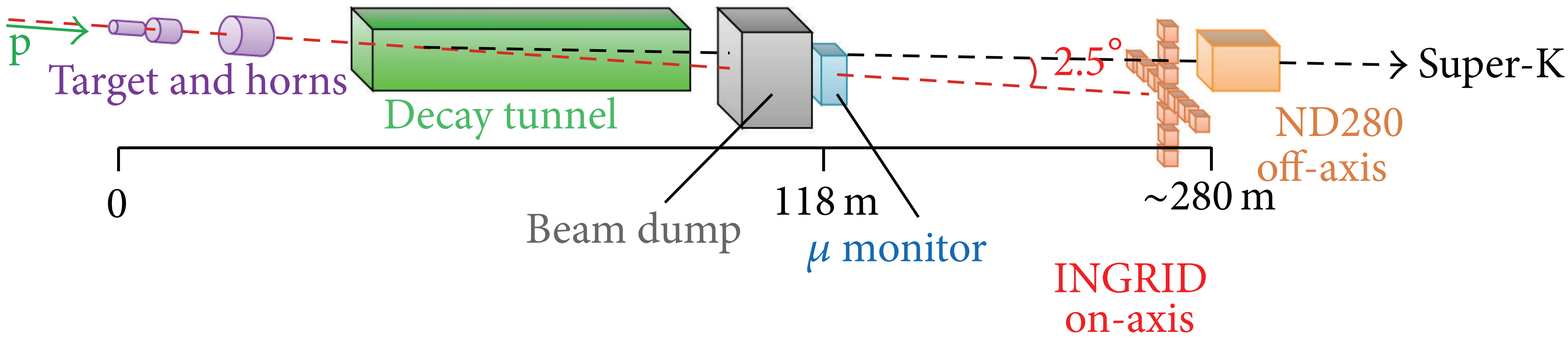


Accumulated protons on target (POT) for these results (2020 analysis)

- ν-mode: 1.36×10^{21} POT
- $\bar{\nu}$-mode: 1.25×10^{21} POT

54% increase in ν-mode exposure over 2019 analysis

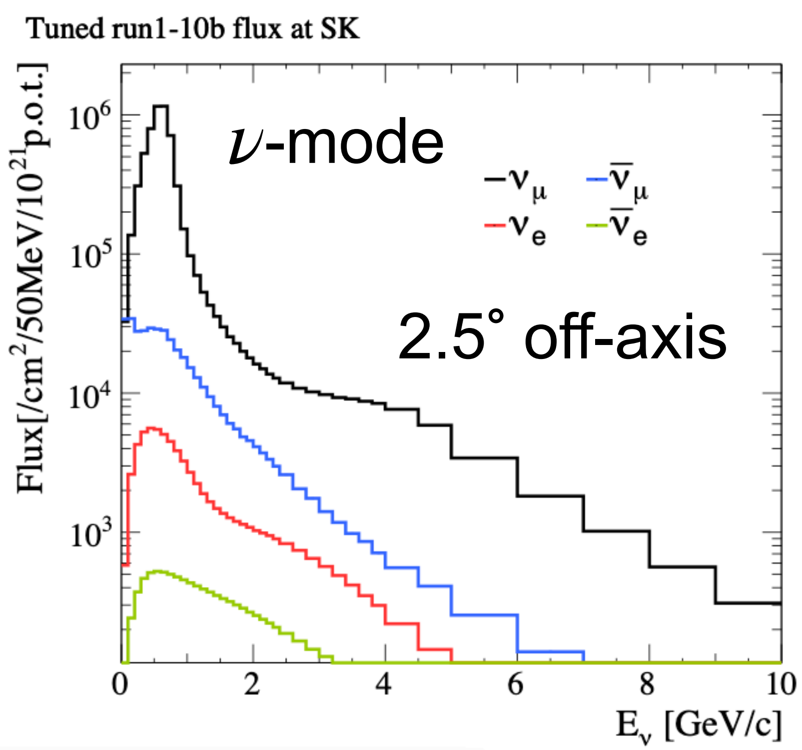
T2K Neutrino Beam

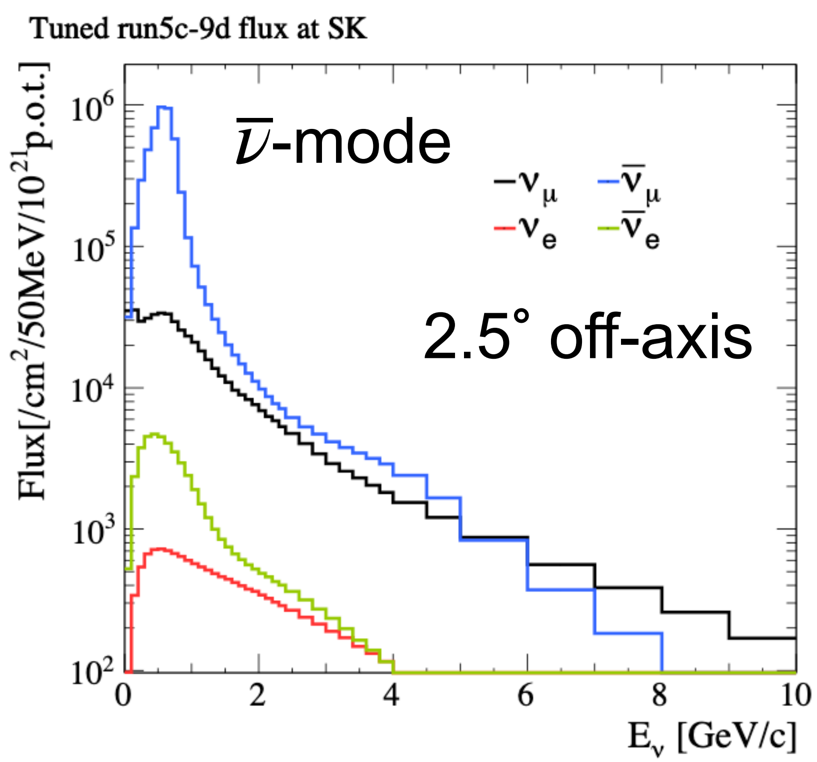


30 GeV protons from J-PARC Main Ring on graphite target

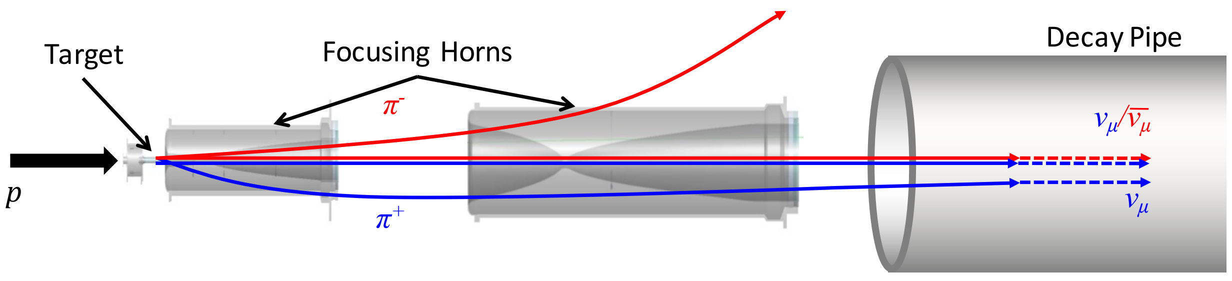
Magnetic horns focus produced $\pi^{\pm}, K^{\pm}$ down decay tunnel

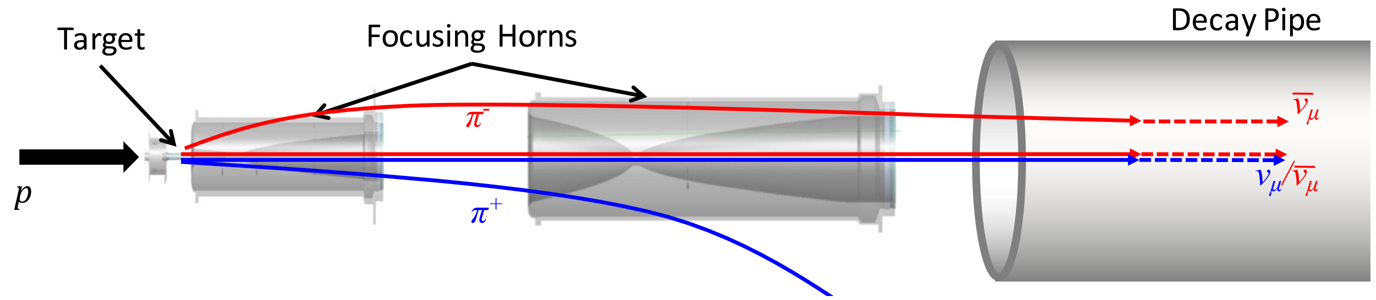
Horn polarity gives ν_μ or $\overline{\nu}_\mu$ enhanced beam

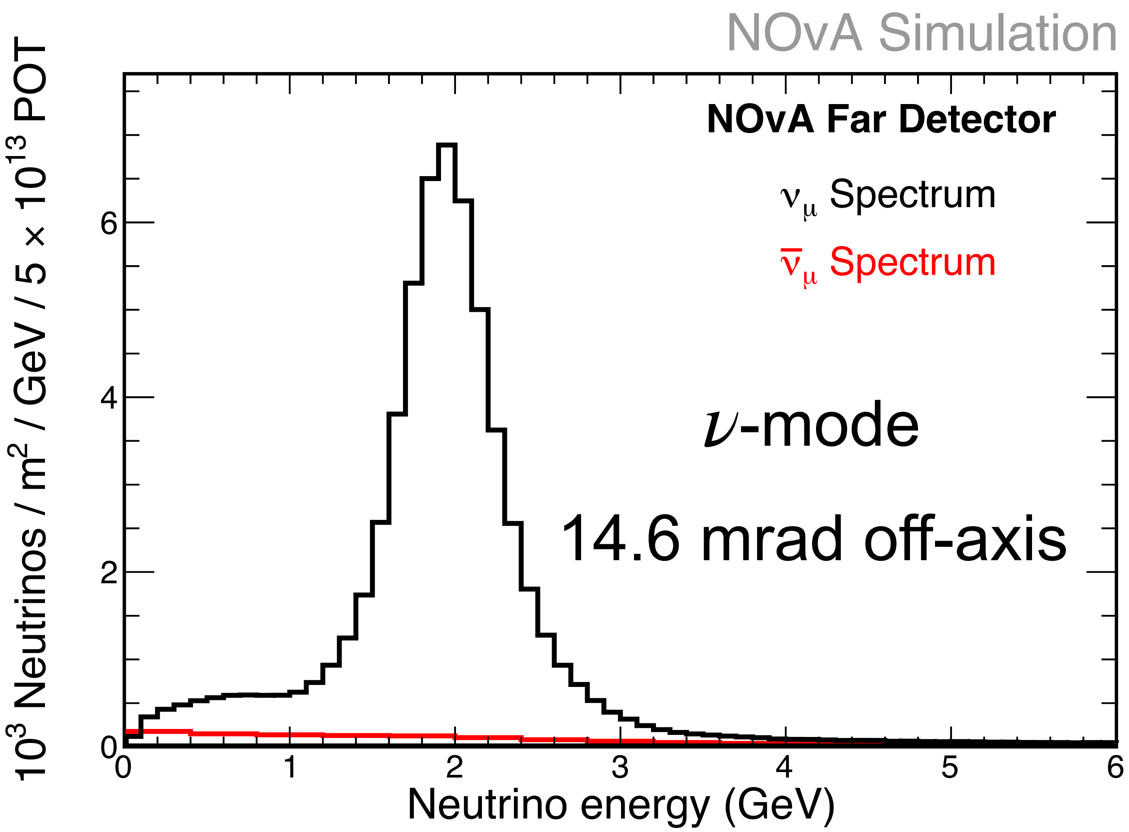


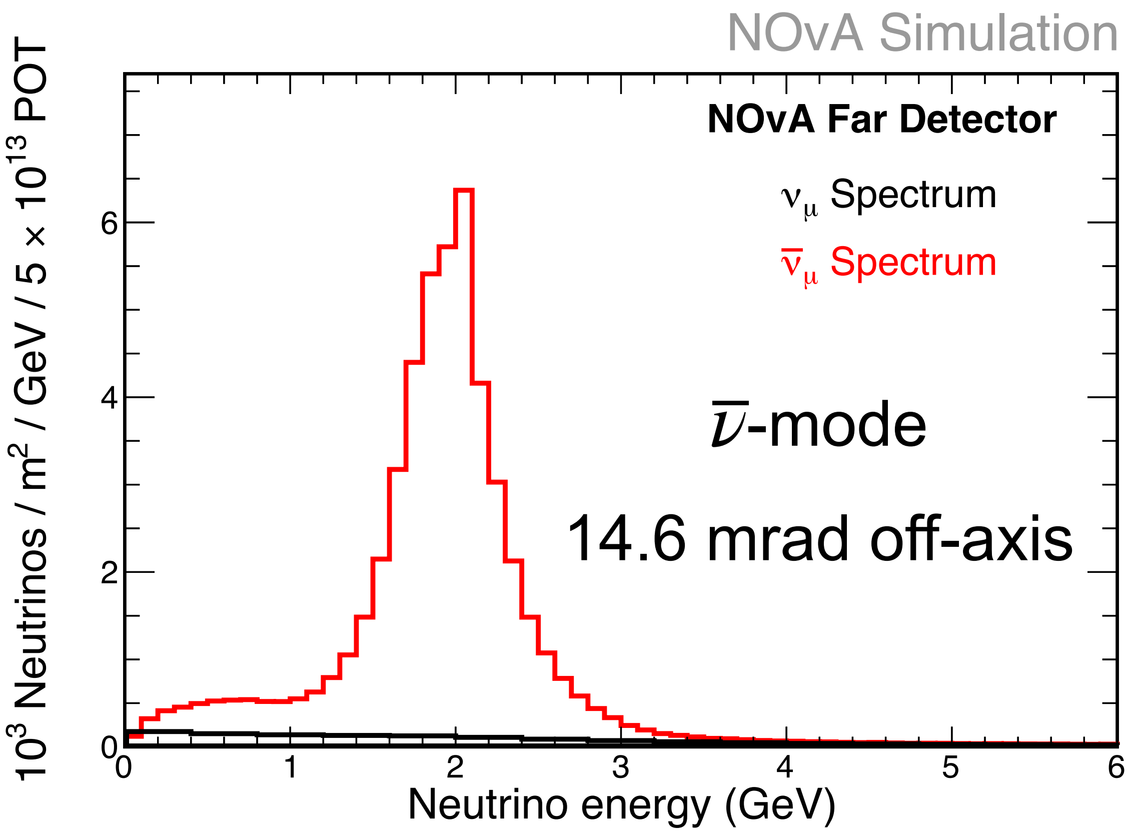


NOvA Neutrino Beam









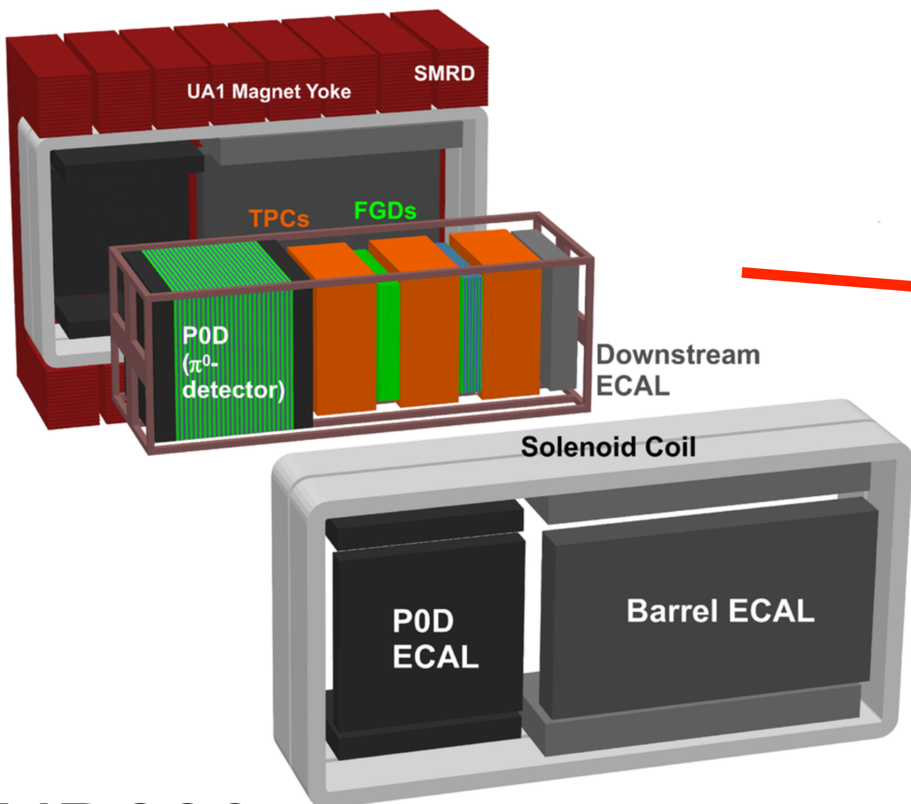
120 GeV protons from Fermilab Main Injector on graphite target

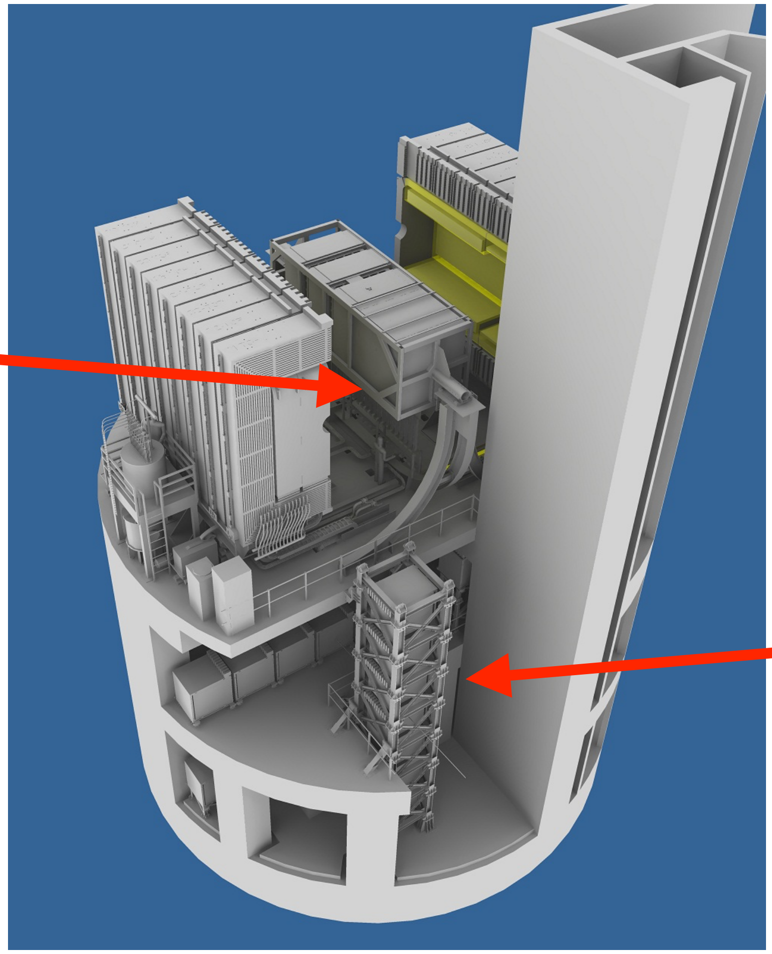
Magnetic horns focus produced $\pi^{\pm}, K^{\pm}$ down decay tunnel

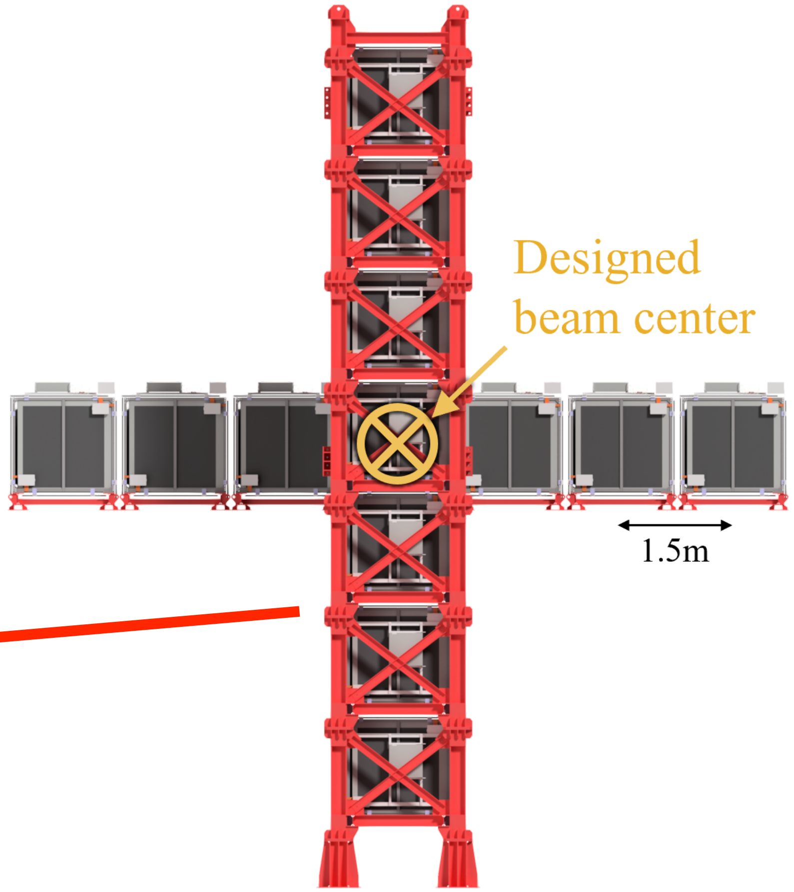
Horn polarity gives ν_μ or $\overline{\nu}_\mu$ enhanced beam

Near and Far detectors 14.6 mrad off-axis giving narrow band beam peaked near 2 GeV

T2K Near Detectors







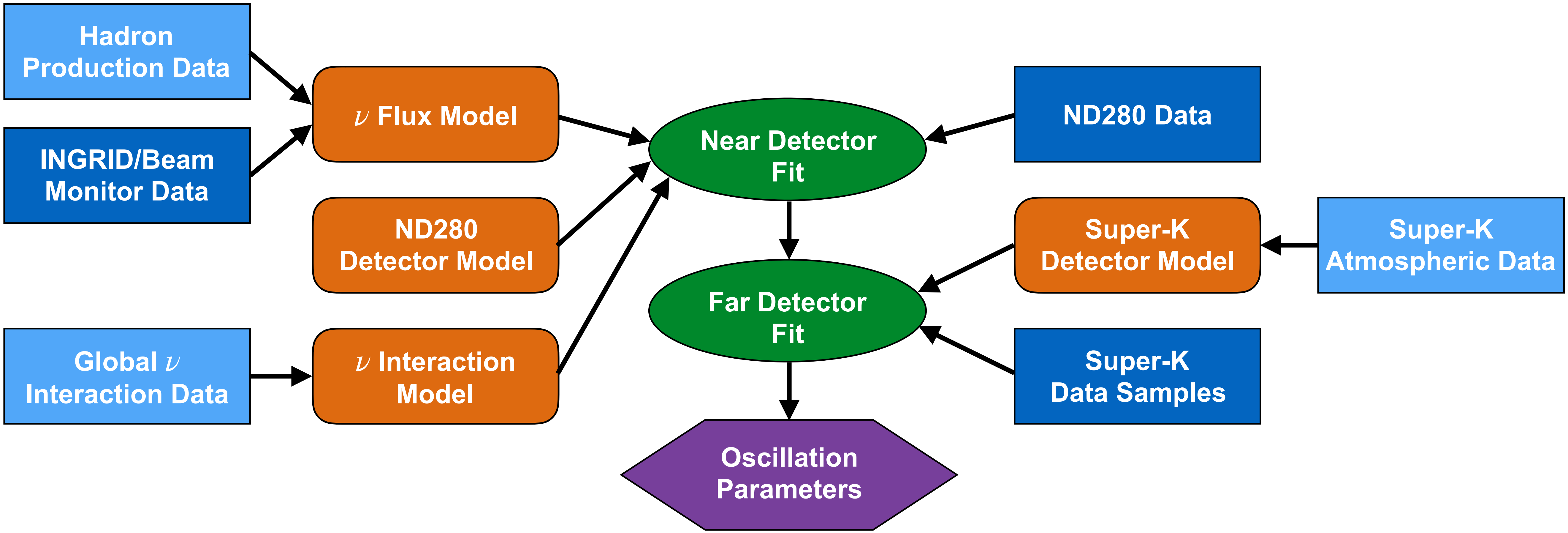
ND280

- 2.5° off-axis (same as Super-K)
- CH and water targets (2000 kg)
- Magnetized tracker to measure momentum and charge
- Constrains neutrino interaction and flux models

INGRID

- On-axis detector
- Monitors beam direction and stability

T2K Oscillation Analysis

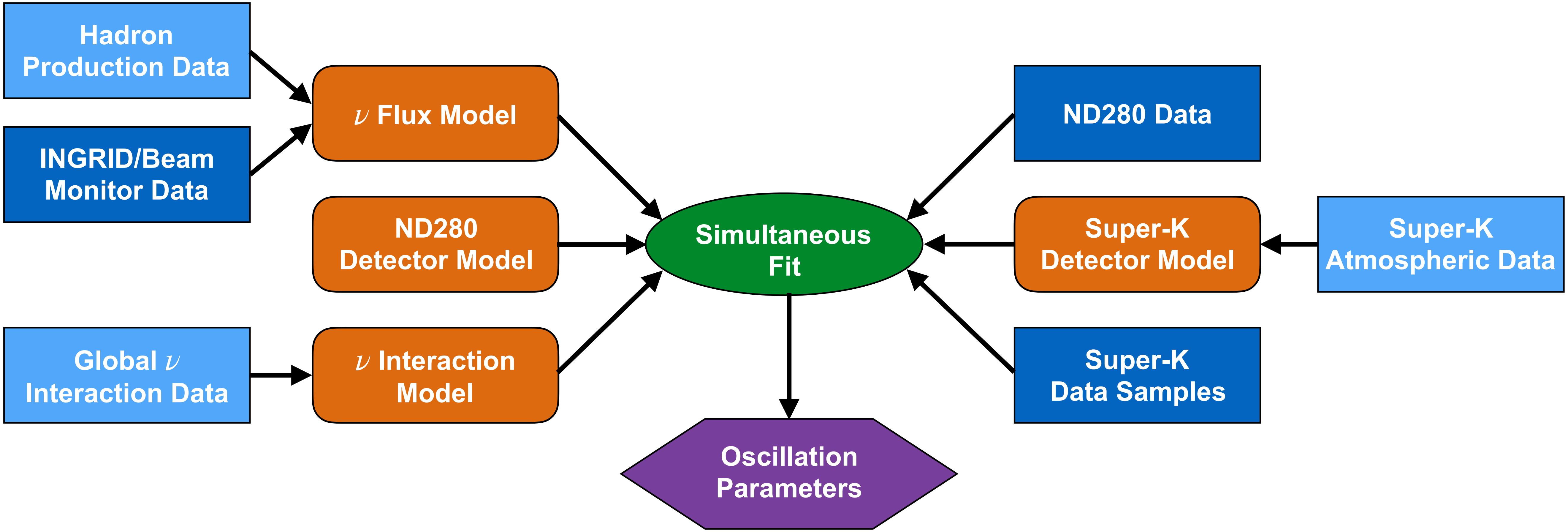


- Analysis strategy is to define a model and constrain with data
- Perform different analyses and cross-check:
  - Sequential ND-FD vs. simultaneous fit
  - Bayesian vs. Frequentist

Joint fit of

- $\nu_\mu, \bar{\nu}_\mu$ disappearance
- $\nu_e, \bar{\nu}_e$ appearance

T2K Oscillation Analysis



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