The NOvA Experiment and Neutrino Oscillations

Tomáš Nosek

Charles University, Institute of Particle and Nuclear Physics
(freshly National Centre for Nuclear Research)

April 29, 2022

Outline

I Everpresent motivation
II NOvA experimental setup and capabilities
III Concept and key features of the oscillation analysis
IV Results and their interpretation
V Future prospects with T2K

I won't discuss

- Lepton mixing
- Neutrino oscillation phenomenology
- Viability of 3ν-paradigm
- MSW and matter effects in neutrino oscillations

This shall be rather technical talk on the NOvA features

T2K

Same
Complementary
Comparable
Consistent
Concurrent

Everpresent motivation

Motivation

Neutrino masses and their SM integration

Dirac vs. Majorana neutrinos

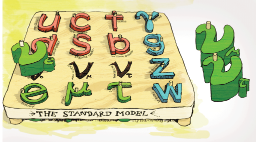
Fundamental parameters of lepton mixing

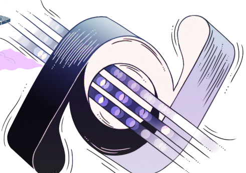
Neutrino mass ordering and theoretical limits on $0\nu\beta\beta$

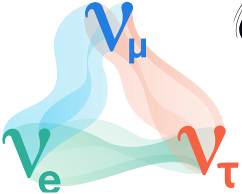
CP violation, matter-antimatter, Sacharov

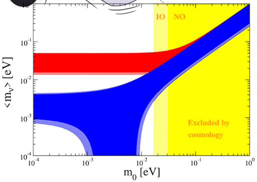
Sterile neutrinos, heavy neutrinos, dark matter and beyond

CMB anisotropy and consitency of cosmological models with direct measurements





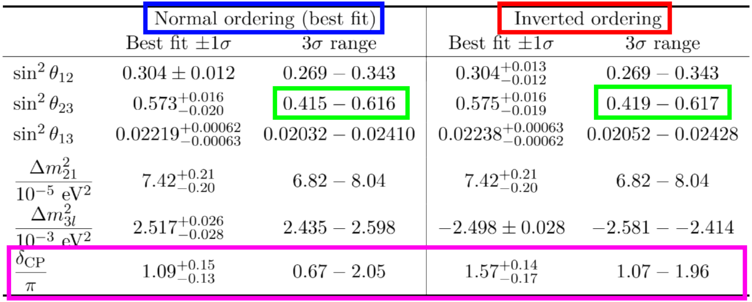




Parameters of the 3ν-paradigm neutrino oscillations

Neutrino oscillations = A neutrino created with a specific flavor can later be measured to have a different flavor, the probability of measuring a particular flavor has oscillatory patterns as a function of L/E.

NuFIT global analysis *JHEP 09, 178 (2020)*



	Normal ordering (best fit)		Inverted ordering	
	Best fit $\pm 1\sigma$	3σ range	Best fit $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.304 ± 0.012	$0.269 - 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 - 0.343$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 - 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 - 0.617$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 - 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 - 0.02428$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 - 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 - 8.04$
$\frac{\Delta m^2_{3l}}{10^{-3}\ \text{eV}^2}$	$2.517^{+0.026}_{-0.028}$	$2.435 - 2.598$	-2.498 ± 0.028	$-2.581 - -2.414$
$\frac{\delta_{\text{CP}}}{\pi}$	$1.09^{+0.15}_{-0.13}$	$0.67 - 2.05$	$1.57^{+0.14}_{-0.17}$	$1.07 - 1.96$

What is there to measure, anyway?

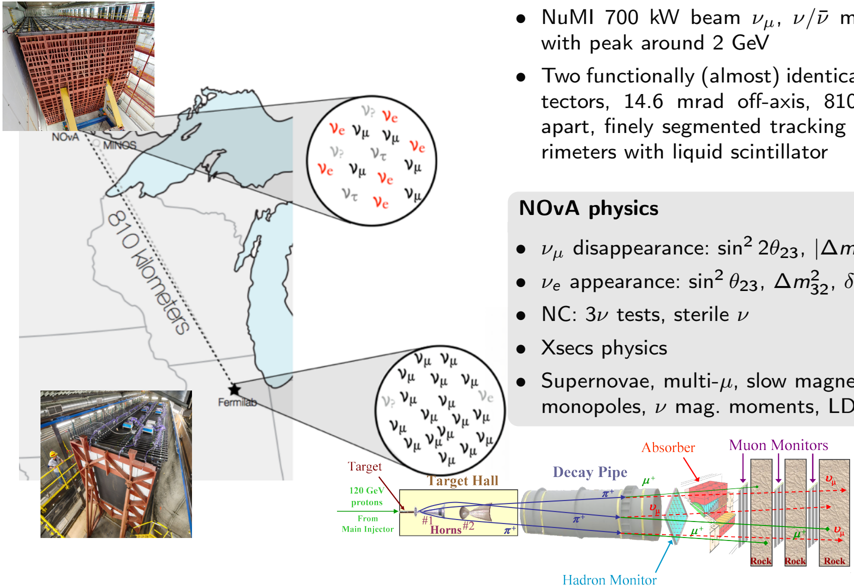
- Ordering of the mass states (mass ordering or hierarchy), is ν_3 the heaviest or the lightest: **NORMAL** vs. **INVERTED**?
- θ_{23} =, > (UO), < (LO) 45°? 23, $\mu\tau$ symmetry?
- CP violation in lepton sector, δ_{CP}?
- Tests of unitarity, 3ν-paradigm completeness, sterile ν etc.?

Long-baseline accelerator experiments (NOvA, T2K) $L/E \sim 10^{2-3}$ km/GeV are sensitive to

NO/IO, θ_{23} and δ_{CP}
(also θ_{13})

NOvA experimental setup and capabilities

The NOvA experiment



- NOvA is a long-baseline neutrino oscillation experiment (≈400 km/GeV)
- NuMI 700 kW beam ν_μ, $\nu/\bar{\nu}$ modes with peak around 2 GeV
- Two functionally (almost) identical detectors, 14.6 mrad off-axis, 810 km apart, finely segmented tracking calorimeters with liquid scintillator

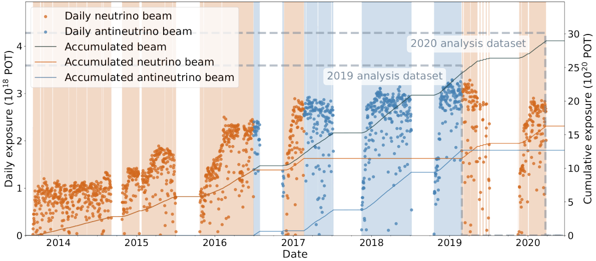
NOvA physics

- ν_μ disappearance: $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$
- ν_e appearance: $\sin^2 \theta_{23}$, Δm^2_{32}, δ_{CP}
- NC: 3ν tests, sterile ν
- Xsecs physics
- Supernovae, multi-μ, slow magnetic monopoles, ν mag. moments, LDM...

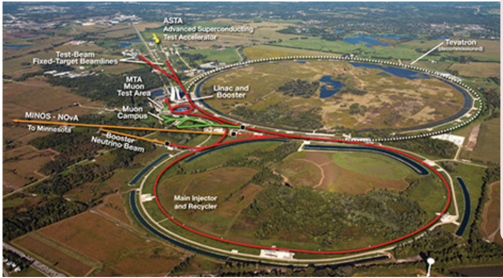
T2K

- Shorter 295 km baseline
- Larger off-axis angle, about 44 mrad → sharper E dist, but lower E and flux in comparison to on-axis
- E around 0.6 GeV, i.e. ≈ 490 km/GeV
- Lower total ν CC Xsec
- Lower $G_F n_e E$ matter effects distorting oscillation probability

The NuMI beam in Fermilab



Total exposure in 2020 analysis:
neutrino: 13.60×10^{20} POT 14 kt-equivalent
antineutrino: 12.50×10^{20} POT

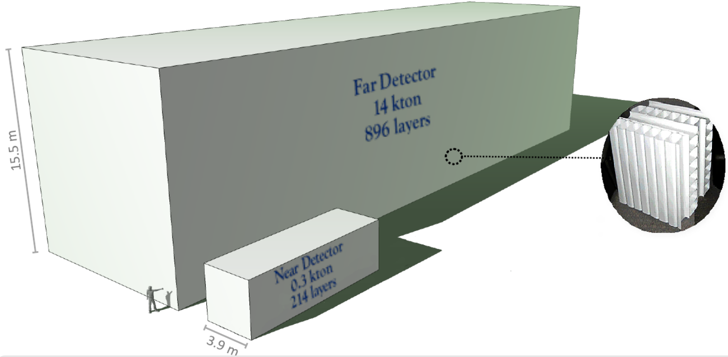


- Since Jan 2017 up to 700 kW ($> 18 \times 10^{18}$ protons/week)
- 120 GeV protons from Main Injector hit the graphite target in 10 μs spills
- Magnetic focusing optics allows for selecting either positively or negatively charged mesons (π, K) thus effectively create a ν or $\bar{\nu}$ dominated beam

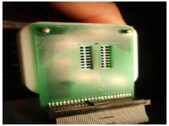
T2K

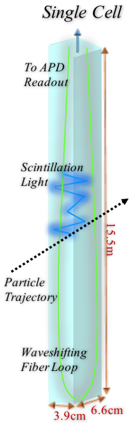
- Lower proton beam energy 30 GeV
- 3 focusing horns, not 2
- Beam power 500 kW
- Comparable exposure over 3×10^{21} POT (higher for T2K)
- Much higher total live-time and (+4 years of experience, +several years of SK experience)

NOvA detectors



- Two functionally similar detectors 810 km apart: **Near (ND)** and **Far (FD)** detector
- FD on the surface, ND about 100 m underground
- Consist of extruded plastic cells with alternating vertical and horizontal orientation for 3D reconstruction of neutrino interactions
- Filled with liquid scintillator, tracking calorimeter with 65% active mass (FD 14 kton, ND 0.3 kton)
- Each cell is connected to a pixel of an APD, i.e. more than 344 000 (FD) and 20 000 (ND) readout channels





T2K side

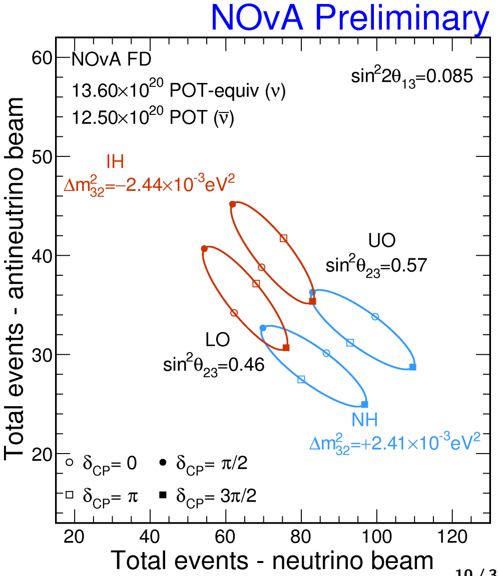
- Different ND280 and FD technology, sims etc.
- ND280 in a magnetic field, identification of wrong-sign components, better energy and momentum resolution, but won't capture specific FD response to the beam
- Both larger FD (SK) fiducial volume and mass, but worse energy resolution in the ν_μ osc. dip
- SK underground, better cosmics filtering
- NOvA's APDs have much higher quantum efficiency in comparison to conventional PMTs: dark currents vs. faint signals

Concept and key features of the oscillation analysis

Goal and $\nu_e + \bar{\nu}_e$ bi-event prediction

Measure disappearance $\nu_\mu \to \nu_\mu$ and appearance $\nu_\mu \to \nu_e$ in both ν_μ and $\bar{\nu}_\mu$ beam to extract θ_{23}, Δm^2_{32} and $\delta_{\rm CP}$ parameters

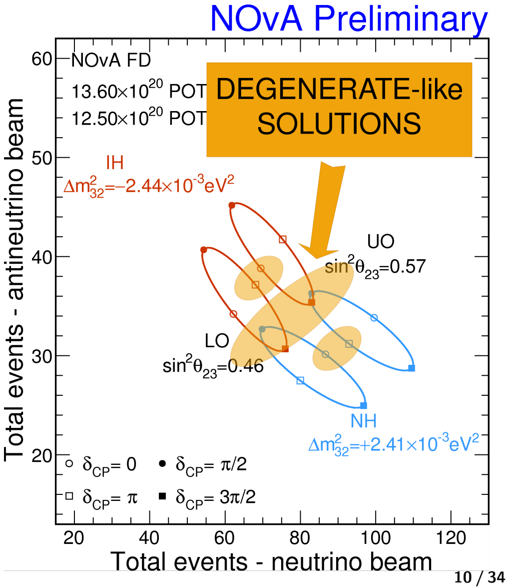
- $P(\nu_\mu \to \nu_\mu)$ depends mainly on $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$
- $P(\nu_\mu \to \nu_e)$ depends also on $\sin^2 \theta_{23}$, sign of Δm^2_{32}, and $\delta_{\rm CP}$!!
- Predicted event counts of ν_e and $\bar{\nu}_e$ vary due to oscillation parameters (possible CP violation, $\delta_{\rm CP}$) and matter effect, affecting ν_e and $\bar{\nu}_e$ differently
- NOvA has the longest baseline of experiments with artificial ν sources, consequent matter effect has an impact of up to about $\pm$30% of ν_e CC events (w.r.t. vacuum expectation)
- Ellipses are drawn in a plane of expected ν_e vs. $\bar{\nu}_e$ as a function of $\delta_{\rm CP}$ for normal (NH) and inverted (IH) neutrino mass hierarchy (ordering) and for upper (UO) and lower (LO) octant of θ_{23}



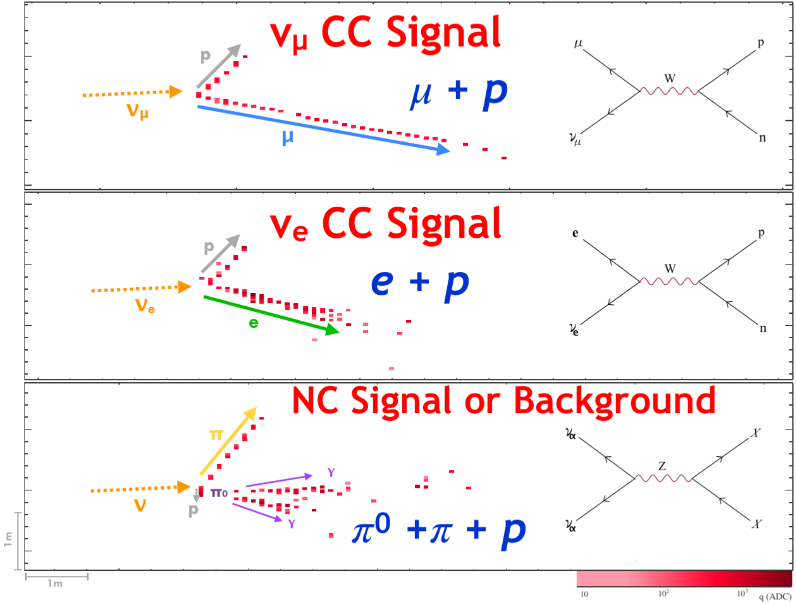
Goal and $\nu_e + \bar{\nu}_e$ bi-event prediction

Measure disappearance $\nu_\mu \rightarrow \nu_\mu$ and appearance $\nu_\mu \rightarrow \nu_e$ in both ν_μ and $\bar{\nu}_\mu$ beam to extract θ_{23}, Δm^2_{32} and δ_{CP} parameters

- $P(\nu_\mu \rightarrow \nu_\mu)$ depends mainly on $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$
- $P(\nu_\mu \rightarrow \nu_e)$ depends also on $\sin^2 \theta_{23}$, sign of Δm^2_{32}, and δ_{CP} !!
- Predicted event counts of ν_e and $\bar{\nu}_e$ vary due to oscillation parameters (possible CP violation, δ_{CP}) and matter effect, affecting ν_e and $\bar{\nu}_e$ differently
- NOvA has the longest baseline of experiments with artificial ν sources, consequent matter effect has an impact of up to about $\pm$30% of ν_e CC events (w.r.t. vacuum expectation)
- Ellipses are drawn in a plane of expected ν_e vs. $\bar{\nu}_e$ as a function of δ_{CP} for normal (NH) and inverted (IH) neutrino mass hierarchy (ordering) and for upper (UO) and lower (LO) octant of θ_{23}



Standard topology of NOvA ν interactions



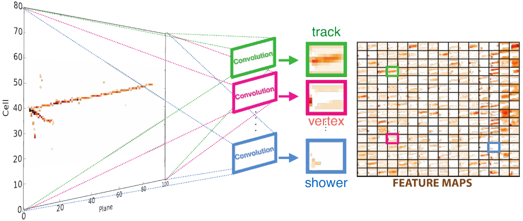
T2K

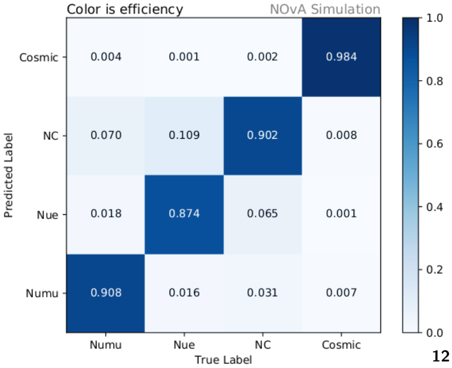
- SK has Cherenkov rings and indirect information on the interaction topology supplemented by the model tune from ND280
- Different detector "output" requires different neutrino energy estimation, different reconstruction and classification methods which are differently efficient in different parts of phase space etc.

Classification of ν interactions and final states

CVN: classify event ν_μ, ν_e, NC, cosmics
pCVN: classify interaction products, i.e. single-particle representations (“prongs”)

- Two neural networks (Convolutional Visual Networks) working with the topological visualization of the reconstructed data (to recognize topological dominants)
- Architecture based on MobileNetV2
- **INPUT:** event calibrated pixelmaps
- **OUTPUT:** normalized PID score for eligible classification hypotheses (interaction – CVN, or particle – pCVN)
- Trained and validated on cosmic data and simulated interactions (5+5 milllion interactions), separately for ν and $\bar{\nu}$
- CVN efficiency >87%, purity >82%
- pCVN efficiency >80%, purity >78%
- Several supporting PIDs (BDT, μ identification etc.)

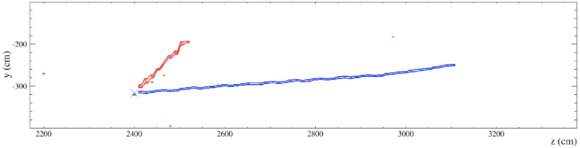




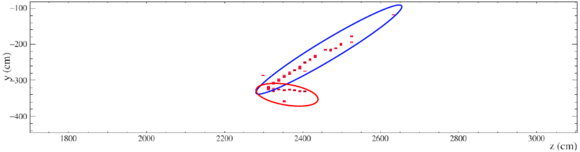
Predicted Label \ True Label	Numu	Nue	NC	Cosmic
Cosmic	0.004	0.001	0.002	0.984
NC	0.070	0.109	0.902	0.008
Nue	0.018	0.874	0.065	0.001
Numu	0.908	0.016	0.031	0.007

Energy reconstruction

ν_μ energy



ν_e energy



$$E_{\nu_\mu} = E_\mu + E_{\mathrm{had}}$$

- ν_μ energy is a sum of μ energy and hadronic part energy
- μ energy is estimated from the track length
- Hadronic energy calorimetric reconstruction
- Hadronic part is identified as everything that was not assigned to the μ track

$$E_{\nu_e} = \text{quadratic function of } E_{\mathrm{EM}} \text{ and } E_{\mathrm{had}}$$

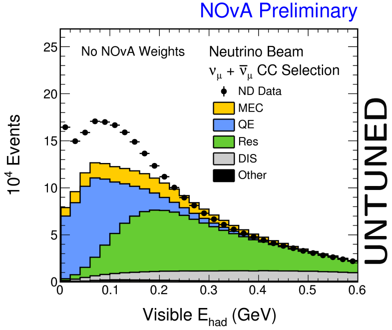
- Both are from calorimetric reconstruction
- EM shower (EM "prong") is identified with a pCVN if e and γ PID scores are dominant
- Remaining activity is accounted for hadronic energy

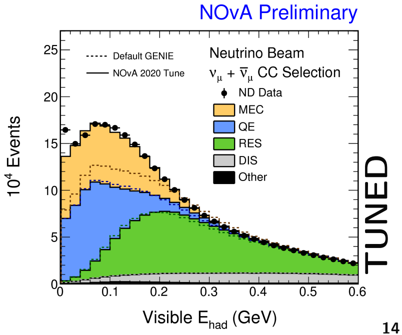
- Both estimators are optimized separately for ν and $\bar{\nu}$ beam FD MC, E_{ν_μ} also for ND

Interaction model and its ND tuning

- Using GENIE v3.0.6
- Custom-Model-Configuration (CMC) from the available collections
- NOvA's nominal interaction model comes from theory driven models with tunes to external scattering data
- Internal NOvA tune of the MEC interaction as a double gaussian fit in the exchanged energy (q_0) and momentum ($|\vec{q}|$)

	Phenomena	Model
Cross section	CCQE	Valencia, Nieves et al., *Phys.Rev.C70, 055503 (2004)*
	NCEL	Ahrens et al., *Phys.Rev.D35, 785 (1987)* (GENIE default)
	DIS	Bodek-Yang, *arXiv:hep-ex/0308007* (GENIE default)
	RES	Berger-Sehgal, *Phys.Rev.D76, 113004 (2007)*
	MEC	Valencia MEC, *Phys.Rev.D88, 113007 (2013)* + NOvA ND data tune
	COH	Rein-Sehgal + PCAC formula, *Phys.Lett.B657:207-209 (2007)* (GENIE default)
Hadr.	Low-W	Empirical AGKY with KNO scaling, *Nucl.Phys.B40, 317 (1972)*
	High-W	PYTHIA/JETSET, *JHEP2006, 026–026 (2006)*
	FSI	INTRANUKE hN, *Acta Phys.Polon. B40, 2445 (2009)* + $\pi^+ - {}^{12}C$ data tune
	Nucleus	Bodek-Ritchie, *Phys.Rev.D24, 1400 (1981)*





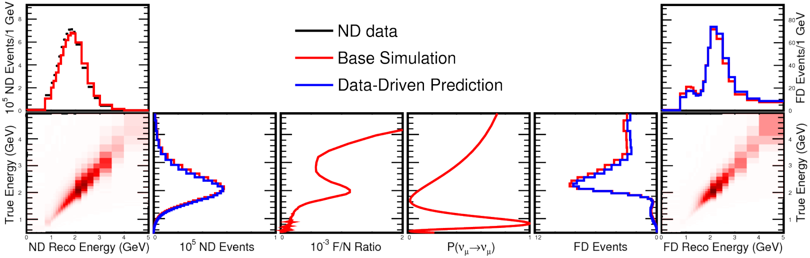
F/N extrapolation method

- ND sees the neutrino spectrum as a combination of **neutrino *flux*** from NuMI, **CC *cross sections***, ***detector acceptance*** and ***selection efficiency***
- The ND measured spectra are used to correct FD MC oscillated predictions using the **Far/Near (F/N)** extrapolation technique, i.e. to assemble analysis predictions

$$\textbf{FD prediction} = \frac{\textbf{ND data corrected MC}}{\textbf{ND MC uncorrected}} \times \textbf{FD MC}$$

- Due to functional similarity of both detectors, this procedure largely cancels detector correlated uncertainties (ν flux and cross sections)

ND $\nu_\mu \longrightarrow$ FD ν_μ signal
ND $\nu_\mu \longrightarrow$ FD ν_e signal + WS $\bar{\nu}_e$ bkg.
ND ν_e-like $\longrightarrow$ FD ν_e beam bkg.



T2K

- T2K approach employs fit to ND data, where either frequentist analysis is used to extract parameters (interaction+flux) to construct FD analysis predictions to later extract osc. parameters, or Bayesian MCMC joint ND+FD fit marginalized over nuisance parameters to constrain osc. parameters, i.e. **"tuning"** the model
- NOvA's extrapolation is a direct **"correction"** to the MC mismodeling which is based on the functional-modeling similarity of the detectors

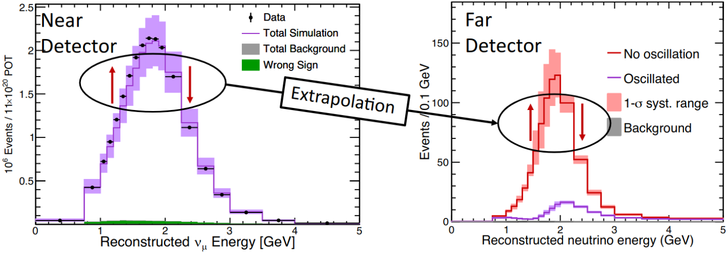
F/N extrapolation method

- ND sees the neutrino spectrum as a combination of **neutrino *flux*** from NuMI, **CC *cross sections***, ***detector acceptance*** and ***selection efficiency***
- The ND measured spectra are used to correct FD MC oscillated predictions using the **Far/Near (F/N)** extrapolation technique, i.e. to assemble analysis predictions

$$\mathbf{FD\ prediction} = \frac{\mathbf{ND\ data\ corrected\ MC}}{\mathbf{ND\ MC\ uncorrected}} \times \mathbf{FD\ MC}$$

- Due to functional similarity of both detectors, this procedure largely cancels detector correlated uncertainties (ν flux and cross sections)

$$\text{ND } \nu_\mu \longrightarrow \text{FD } \nu_\mu \text{ signal}$$
$$\text{ND } \nu_\mu \longrightarrow \text{FD } \nu_e \text{ signal} + \text{WS } \bar{\nu}_e \text{ bkg.}$$
$$\text{ND } \nu_e\text{-like} \longrightarrow \text{FD } \nu_e \text{ beam bkg.}$$

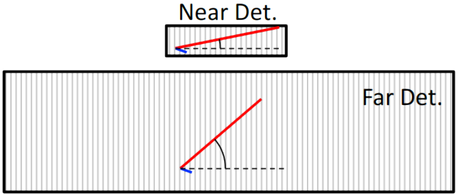


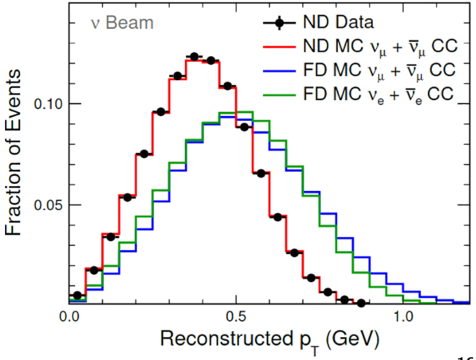
T2K

- T2K approach employs fit to ND data, where either frequentist analysis is used to extract parameters (interaction+flux) to construct FD analysis predictions to later extract osc. parameters, or Bayesian MCMC joint ND+FD fit marginalized over nuisance parameters to constrain osc. parameters, i.e. **"tuning"** the model
- NOvA's extrapolation is a direct **"correction"** to the MC mismodeling which is based on the functional-modeling similarity of the detectors

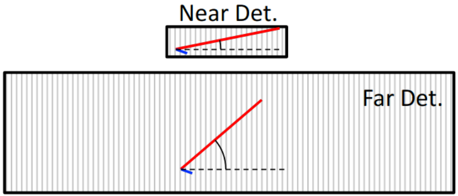
Extrapolating kinematics

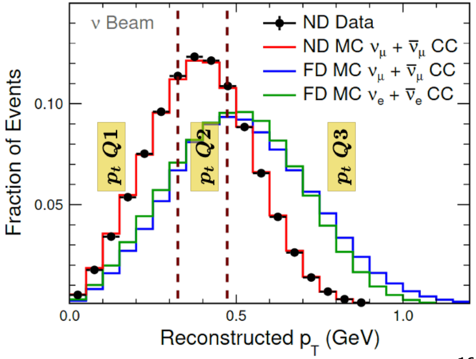
- Motivated by different kinematic acceptance of the detectors the recent analysis introduces extrapolation of kinematic subsamples
- ND data/MC are divided into **3 quantiles based on the primary lepton reconstructed $\boldsymbol{p_t}$**, quantiles are constructed in the ND MC and applied on the FD MC predictions
- p_t extrapolation significantly enhances the robustness of the F/N technique and effectively "rebalances" the kinematics to match between the detectors to further mitigate the actual ND/FD differences
- The p_t samples (bins) are summed after the extrapolation to form the final analysis predictions entering the fit





Extrapolating kinematics

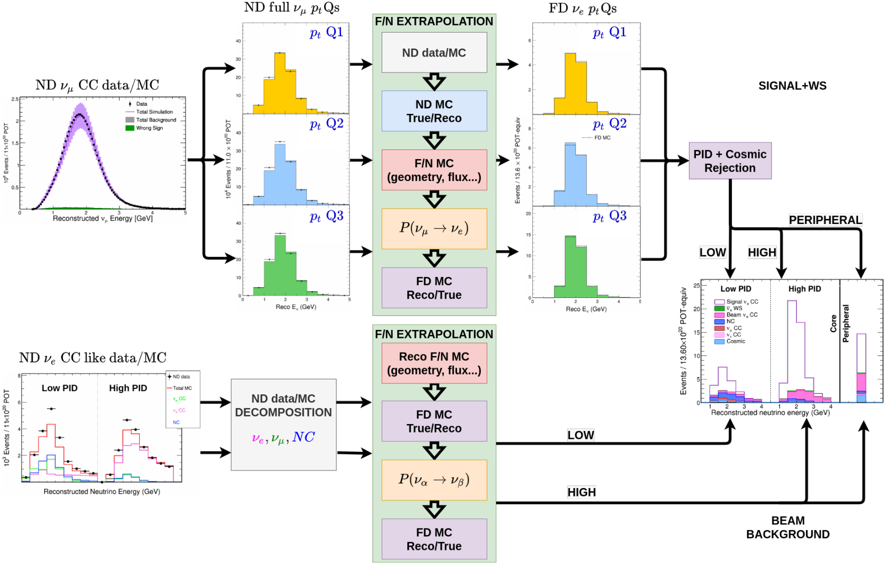




- Motivated by different kinematic acceptance of the detectors the recent analysis introduces extrapolation of kinematic subsamples
- ND data/MC are divided into **3 quantiles based on the primary lepton reconstructed $\boldsymbol{p_t}$**, quantiles are constructed in the ND MC and applied on the FD MC predictions
- p_t extrapolation significantly enhances the robustness of the F/N technique and effectively "rebalances" the kinematics to match between the detectors to further mitigate the actual ND/FD differences
- The p_t samples (bins) are summed after the extrapolation to form the final analysis predictions entering the fit

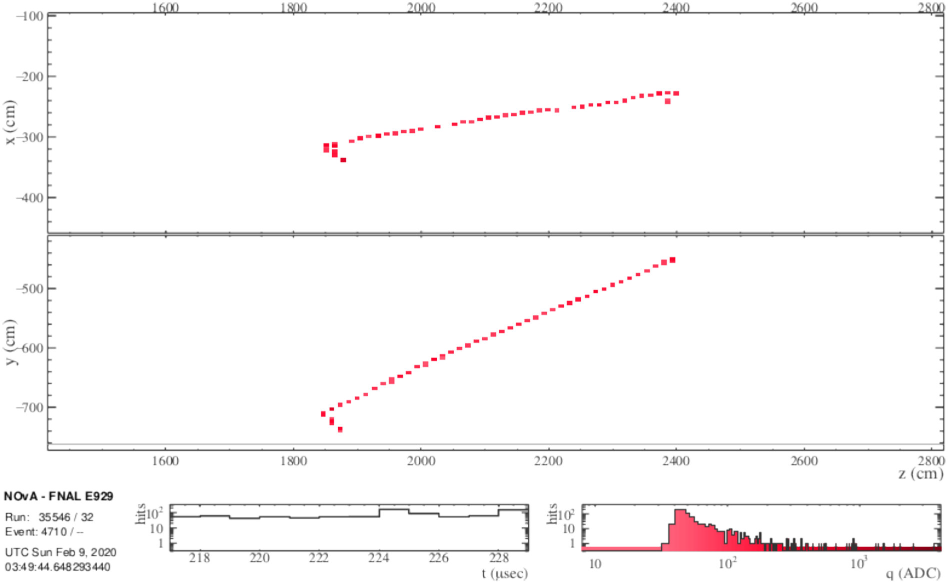
Extrapolating $\nu_\mu \rightarrow \nu_e$

- ν_e analysis is performed in 3 samples based on the event PID and special containment criteria (events on the periphery) because of the principally different background in the samples
- ν_μ analysis is performed in 4 quartiles based on the fraction of hadronic energy E_{had} (not μ) in the ν_μ event, lower E_{had} fractions correspond to better energy resolution (Q1–4: 6, 8, 10, 12%)

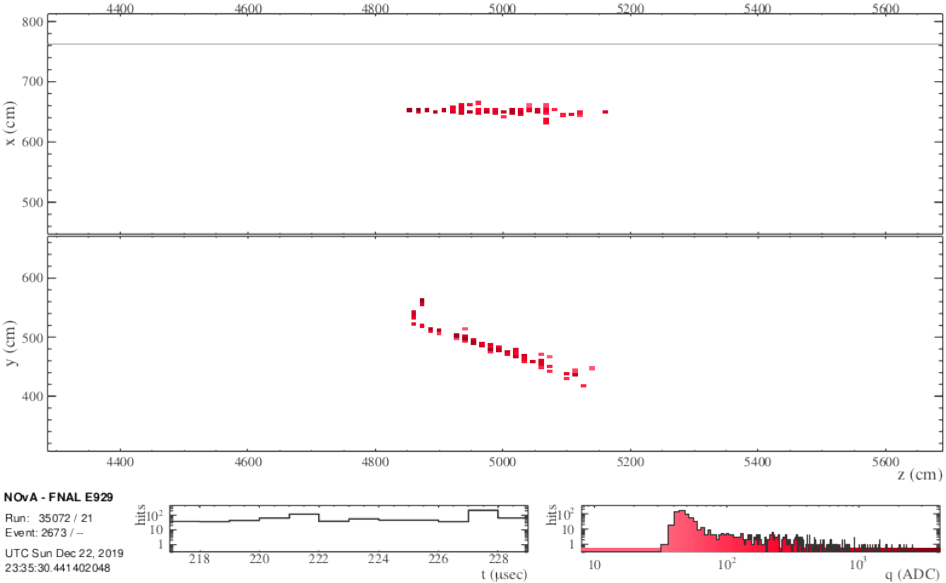


Results and their interpretation

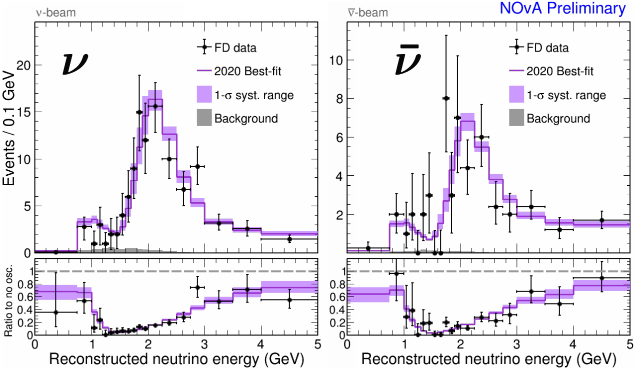
FD data ν_μ CC



FD data ν_e CC



Far detector $\nu_\mu \to \nu_\mu$ disappearance data



211 ν_μ CC candidates observed			
$\nu_\mu \to \nu_\mu$ 201.1		$\bar{\nu}_\mu \to \bar{\nu}_\mu$ 12.6	
NC	cosmic	other	**total**
2.6	5.0	1.0	**$222.3^{+16.3}_{-15.7}$**

105 $\bar{\nu}_\mu$ CC candidates observed			
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ 77.2		$\nu_\mu \to \nu_\mu$ 26.0	
NC	cosmic	other	**total**
0.8	0.9	0.4	**$105.4^{+7.8}_{-7.7}$**

- Further divided into 4 quartiles based on the fraction of hadronic energy E_{had} (not μ) in the ν_μ event
- Selection efficiency over 31% (depends on the beam mode and osc. parameters), better purity in Q with lower E_{had} fraction 92–99% – combined 96% (98%) for ν ($\bar{\nu}$)
- Energy resolution in Q1–4: 7.8% (8.5%), 9.2% (8.9%), 10.4% (9.7%), 11.5% (10.2%) for ν ($\bar{\nu}$)
- Cosmic background is estimated from the NuMI trigger cosmic windows around the beam spills
- Other predictions from the best-fit oscillation parameter estimates

Far detector $\nu_\mu \to \nu_e$ appearance data

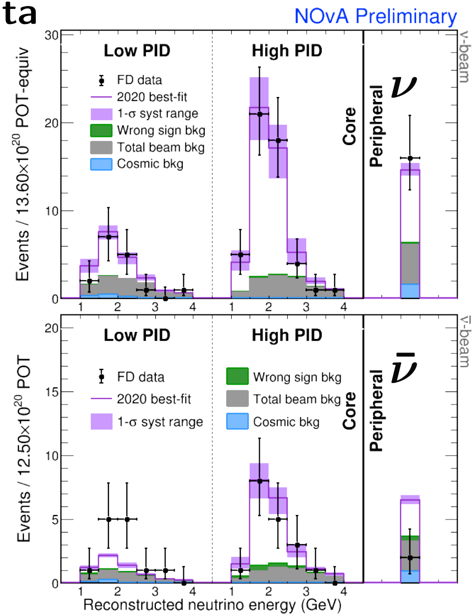
82 ν_e CC candidates observed

Signal $\nu_\mu \to \nu_e$			**59.0**		
$\bar{\nu}_e$	beam ν_e	ν_μ	NC	cos.	other
1.0	14.1	1.7	6.3	3.1	0.5
total 85.8$^{+4.1}_{-4.2}$ (background 26.8)					

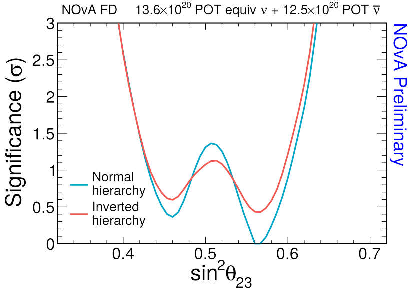
33 $\bar{\nu}_e$ CC candidates observed

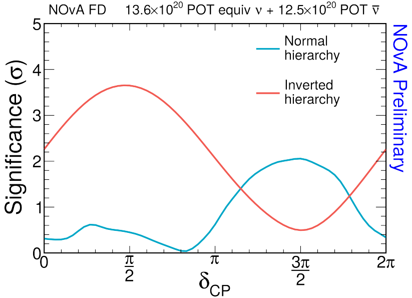
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$			**19.2**		
ν_e	beam ν_e	ν_μ	NC	cos.	other
2.3	7.3	0.4	2.2	1.6	0.3
total 33.2$^{+1.5}_{-1.7}$ (background 14.0)					

- Selection efficiency 63% (75%) for ν ($\bar{\nu}$), w/o peripheral bin 54% (64%)
- Energy resolution about 14% (9%) for Low (High) PID
- >4σ for appearing $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam



Oscillation parameters estimates





- Osc. parameters estimates are fitted jointly for all analysis samples ($\nu_\mu + \nu_e + \bar{\nu}_\mu + \bar{\nu}_e$) by minimizing a standard log-likelihood ratio for independent bins with Poisson distribution (frequentist)
- 3ν-paradigm is tested, while $\sin^2 2\theta_{12} = 0.851$, $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2 and $\rho = 2.84$ g/cm^3 (N_e) are fixed, $\sin^2\theta_{13} = 0.085 \pm 0.003$
- Fit is performed independently in 4 hyperplanes of parametric space: NO/IO, $\theta_{23} \gtrless 45^\circ$
- Rejection significance and confidence levels (regions) are corrected by Feldman-Cousins "unified approach" (*Phys.Rev.D57, 3873 (1998)*)
- Inverted ordering and lower $\theta_{23} < 45^\circ$ octant are disfavored at about 1σ level

Best fit (*p*-value 0.705)

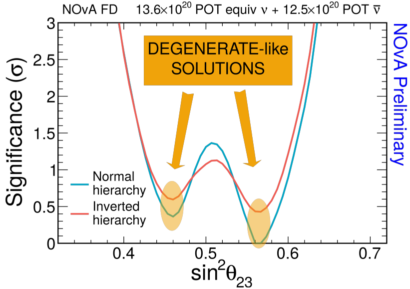
Normal ordering, upper 23 octant

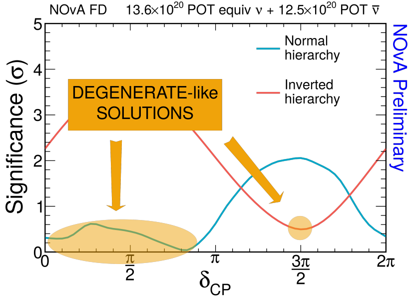
$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

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

$$\delta_{\text{CP}} = 0.82\pi$$

Oscillation parameters estimates





- Osc. parameters estimates are fitted jointly for all analysis samples $(\nu_\mu + \nu_e + \bar{\nu}_\mu + \bar{\nu}_e)$ by minimizing a standard log-likelihood ratio for independent bins with Poisson distribution (frequentist)
- 3ν-paradigm is tested, while $\sin^2 2\theta_{12} = 0.851$, $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2 and $\rho = 2.84$ g/cm^3 (N_e) are fixed, $\sin^2\theta_{13} = 0.085 \pm 0.003$
- Fit is performed independently in 4 hyperplanes of parametric space: NO/IO, $\theta_{23} \gtrless 45^\circ$
- Rejection significance and confidence levels (regions) are corrected by Feldman-Cousins "unified approach" (*Phys.Rev.D57, 3873 (1998)*)
- Inverted ordering and lower $\theta_{23} < 45^\circ$ octant are disfavored at about 1σ level

Best fit (*p*-value 0.705)

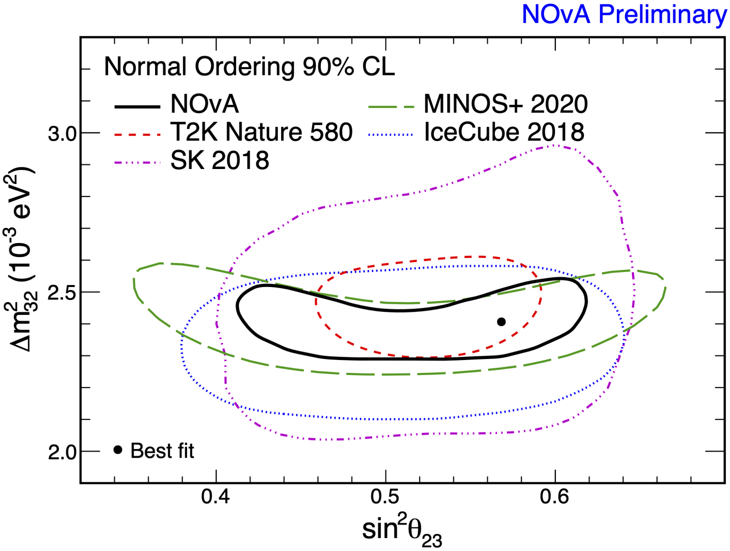
Normal ordering, upper 23 octant

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

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

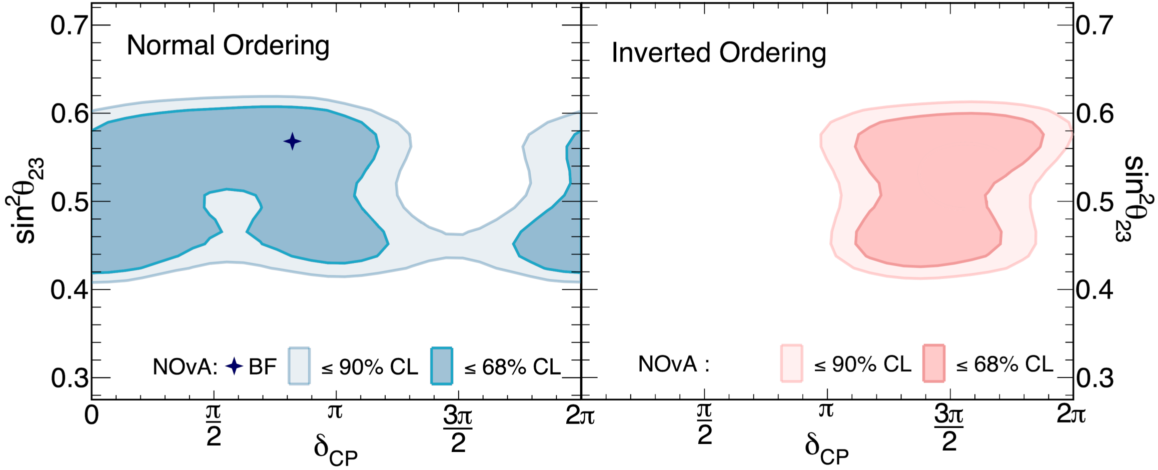
$$\delta_{\rm CP} = 0.82\pi$$

Parameters constraints Δm^2_{32} vs. $\sin^2\theta_{23}$



One of the most precise measurements of $|\Delta m^2_{32}|$ and θ_{23}

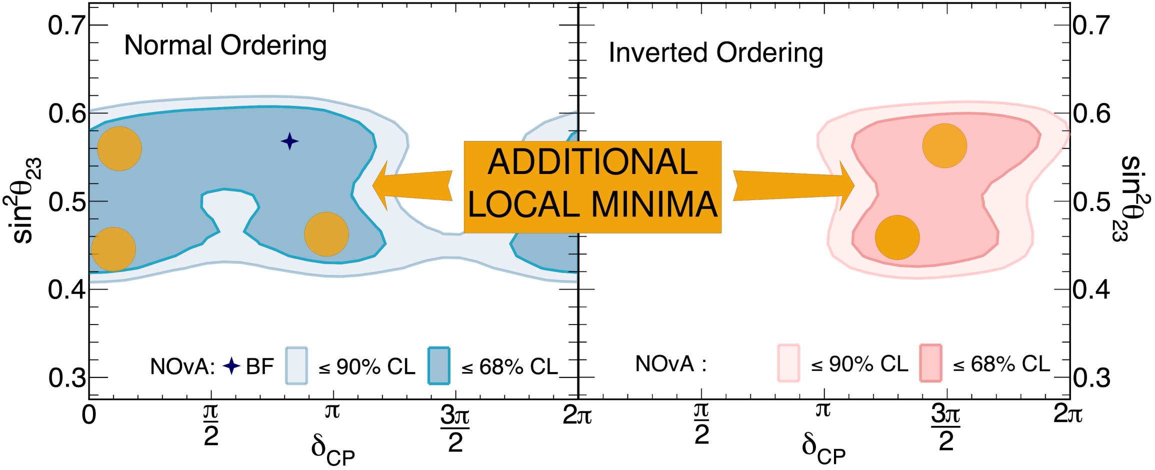
Oscillation parameters estimates, δ_{CP} vs. $\sin^2\theta_{23}$



IO with δ_{CP} around $\pi/2$ rejected over 3σ

IO and LO ($\theta_{23} < 45°$) disfavored at cca 1σ, any value of δ_{CP} within 2σ ☹

Oscillation parameters estimates, δ_{CP} vs. $\sin^2\theta_{23}$


ADDITIONAL LOCAL MINIMA

IO with δ_{CP} around $\pi/2$ rejected over 3σ

IO and LO ($\theta_{23} < 45^\circ$) disfavored at cca 1σ, any value of δ_{CP} within 2σ ☹

Oscillation parameters estimates, summary

arXiv:2108.08219 [hep-ex]

Best fit (p-value 0.705)

Normal ordering, upper 23 octant

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

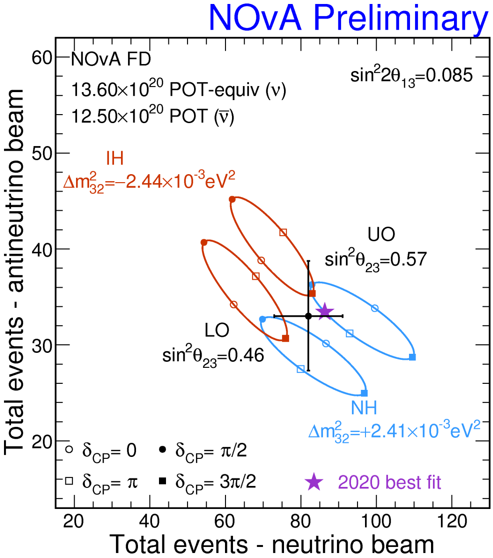
$$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

$$\delta_{\mathrm{CP}} = 0.82\pi$$

- 3ν in accordance with the observed data:

  82 ν_e CC, 33 $\bar{\nu}_e$ CC

- Total exposure 13.60×10^{20} POT-14kt detector equivalent for ν-beam and 12.50×10^{20} POT for $\bar{\nu}$-beam (more than 40% of the total expected exposure for NOvA)
- NOvA alone cannot reject the wrong mass ordering or 23 octant or measure δ_{CP} with reasonable significance due to degenerate solutions (rejection significances about 1σ), nevertheless the data point to preferred regions of parametric space



Future prospects with T2K (?)

NOvA and T2K complementarity

- The basic concept of the neutrino oscillation measurement is believed to be the same at the fundamental level (**accelerator long-baseline neutrino oscillation experiments**)

- Different neutrino beams, different neutrino energy, different baseline, different detection technology

$$\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow$$

- Different detector modeling, different reconstruction methods, different analysis features, different systematics

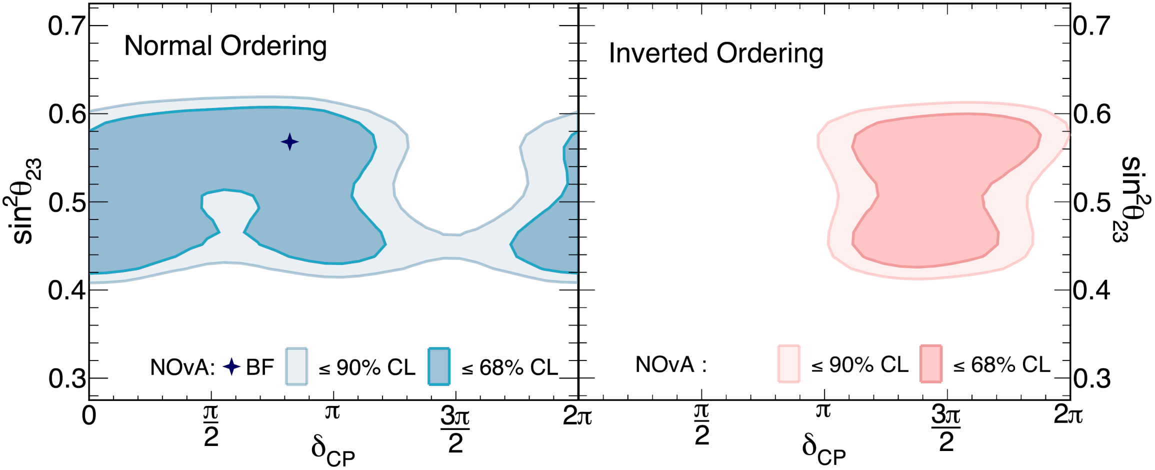
$$\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow$$

- Sensitivity to different aspects of the non-oscillation phenomena in action:
  0.6 GeV interactions of CCQE+MEC vs 2 GeV with substantial portions of RES and DIS
  Matter effects affecting the propagation and oscillation of neutrinos (larger at NOvA)
- Sensitivity to different regions of the neutrino oscillation parametric space: δ_{CP} at T2K, θ_{23} and mass ordering at NOvA

$$\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow\Downarrow$$

- **Complementary results that make more sense combined than on their own**

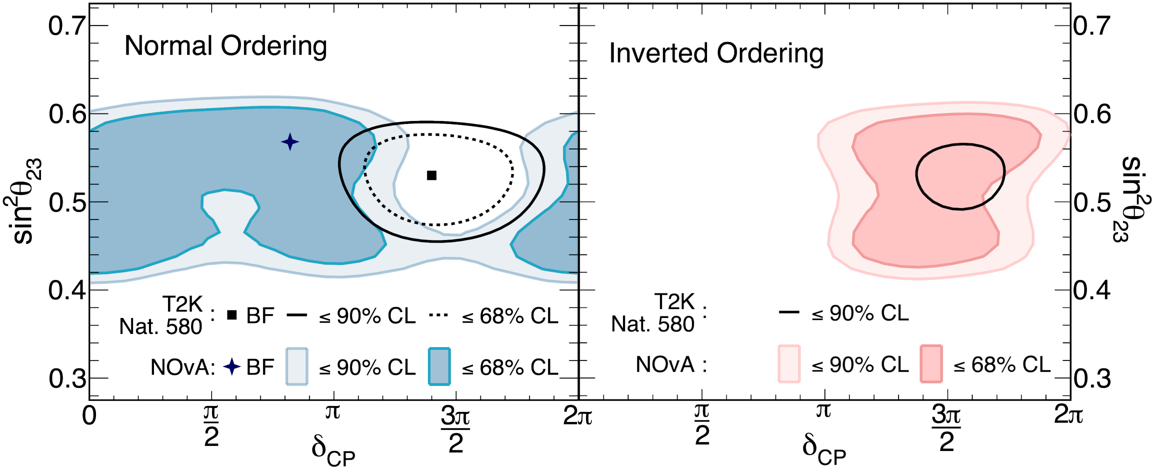
Parameters constraints θ_{23} vs. δ_{CP} vs. T2K



Is this inconsistent?

Seems rather **complementary** (consistent at 2σ, anyway)!

Parameters constraints θ_{23} vs. δ_{CP} vs. T2K

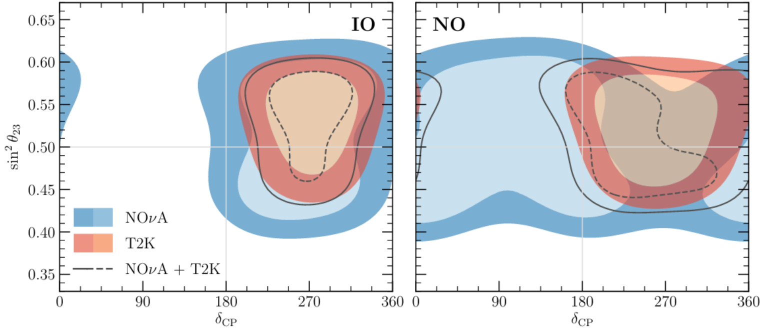


Is this inconsistent?

Seems rather **complementary** (consistent at 2σ, anyway)!

NOvA + T2K?

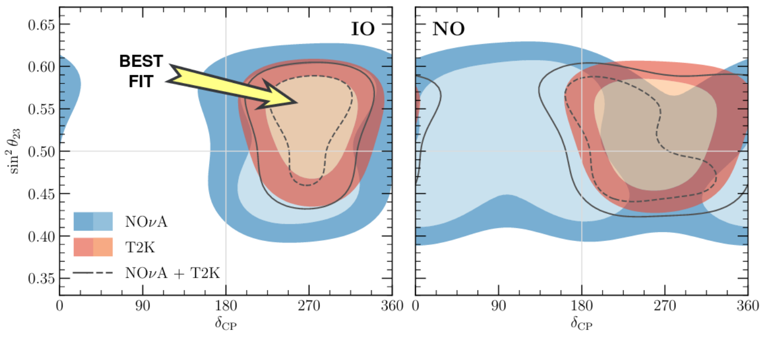
NuFIT: *JHEP 09, 178 (2020)*

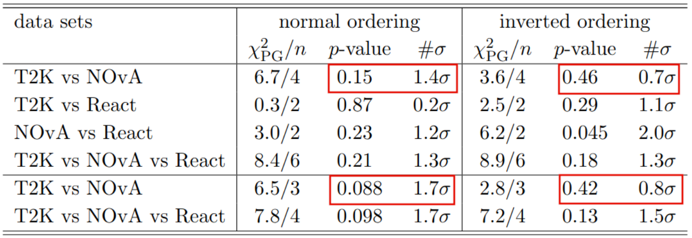


data sets	normal ordering			inverted ordering		
	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$
T2K vs NOvA	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs React	0.3/2	0.87	0.2σ	2.5/2	0.29	1.1σ
NOvA vs React	3.0/2	0.23	1.2σ	6.2/2	0.045	2.0σ
T2K vs NOvA vs React	8.4/6	0.21	1.3σ	8.9/6	0.18	1.3σ
T2K vs NOvA	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ
T2K vs NOvA vs React	7.8/4	0.098	1.7σ	7.2/4	0.13	1.5σ

NOvA + T2K?

NuFIT: *JHEP 09, 178 (2020)*





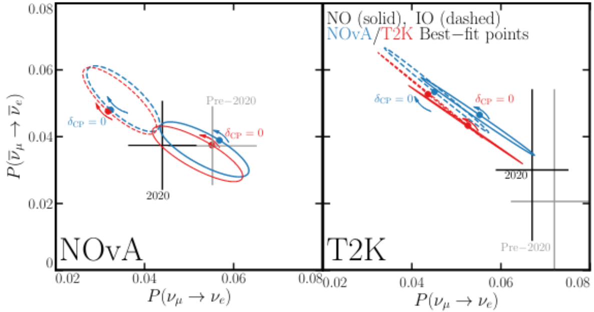
data sets	normal ordering			inverted ordering		
	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$
T2K vs NOvA	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs React	0.3/2	0.87	0.2σ	2.5/2	0.29	1.1σ
NOvA vs React	3.0/2	0.23	1.2σ	6.2/2	0.045	2.0σ
T2K vs NOvA vs React	8.4/6	0.21	1.3σ	8.9/6	0.18	1.3σ
T2K vs NOvA	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ
T2K vs NOvA vs React	7.8/4	0.098	1.7σ	7.2/4	0.13	1.5σ

θ_{13} free

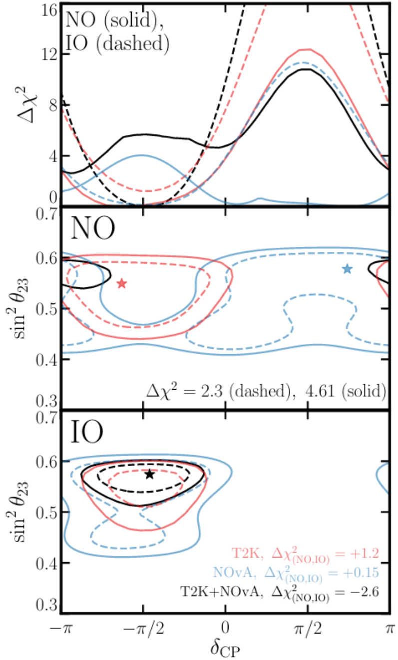
$\sin^2\theta_{13} = 0.0224$

NOvA + T2K?

Phys.Rev.D 103, 013004 (2021)

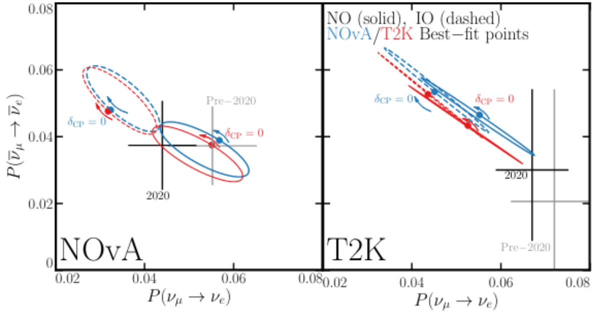


- Simplistic toy simulations of both the experiments based on the available published info
- Gaussian approximation
- The T2K+NOvA combined results prefer INVERTED ordering at 2.6σ CL and rejects more than 75% of $\delta_{\rm CP}$ values for NO at more than 2σ CL

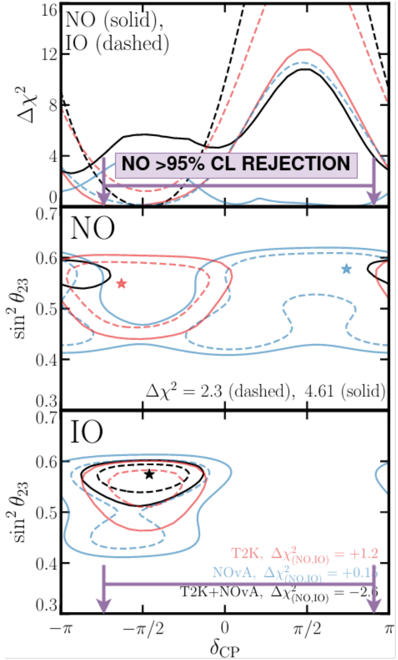


NOvA + T2K?

Phys.Rev.D 103, 013004 (2021)

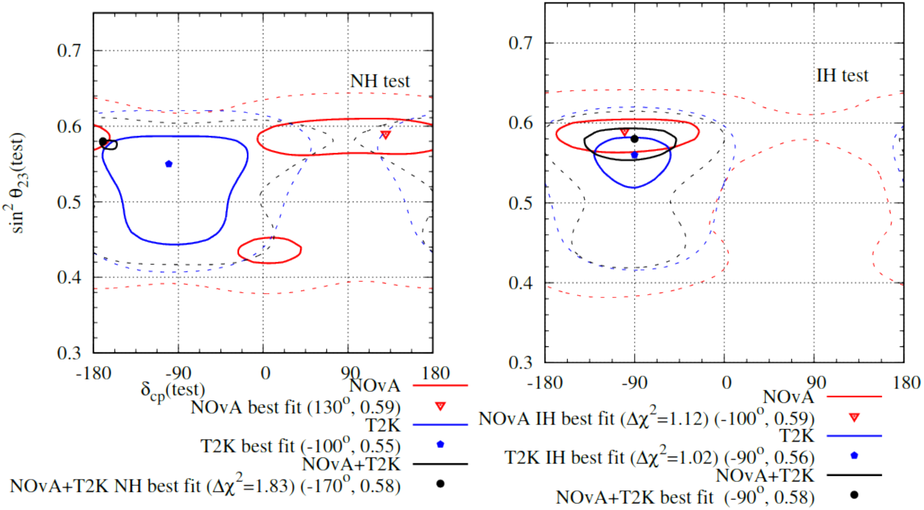


- Simplistic toy simulations of both the experiments based on the available published info
- Gaussian approximation
- The T2K+NOvA combined results prefer INVERTED ordering at 2.6σ CL and rejects more than 75% of δ_{CP} values for NO at more than 2σ CL



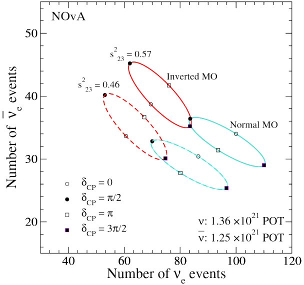
NOvA + T2K?

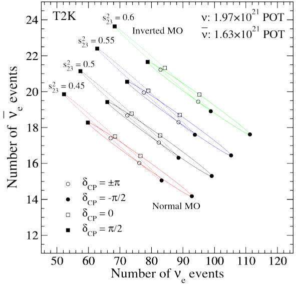
Universe 2022, 8, 109



NOvA + T2K conclusion

Sci Rep 12, 5393 (2022)





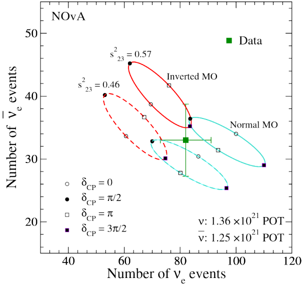
- Both experiments are limited either statistically or by the presence of the degenerate-like solutions (significantly better or more precise results with more statistics are not expected), **don't forget they independently measure also $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ in $\nu_\mu \to \nu_\mu$ when interpreting the plots on the left**
- 2020 results and several studies indicate that though both NOvA and T2K disfavor IO of neutrino masses at about 1σ, the joint analysis fit might converge on IO
- Joint NOvA+T2K analysis could bring much more interesting results even before the dawn of JUNO, HyperK and DUNE
- Leverage statistics and break the parametric space degeneracies
- NOvA+T2K analysis collaboration was established in 2019 and has been working towards the analyses unification
- First preliminary results are expected during 2022

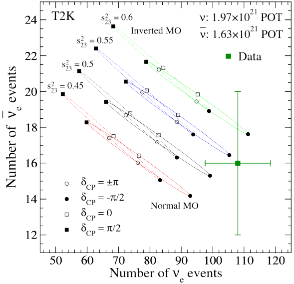
NOvA+T2K joint fit

- As of yet, joining the fitters (don't forget about different interaction models and different ways of producing analysis predictions, different unknown unknowns)
- Joint fit based on MCMC Bayesian inference (MaCh3 in case of T2K, new framework for NOvA was developed during 2021)

NOvA + T2K conclusion

Sci Rep 12, 5393 (2022)





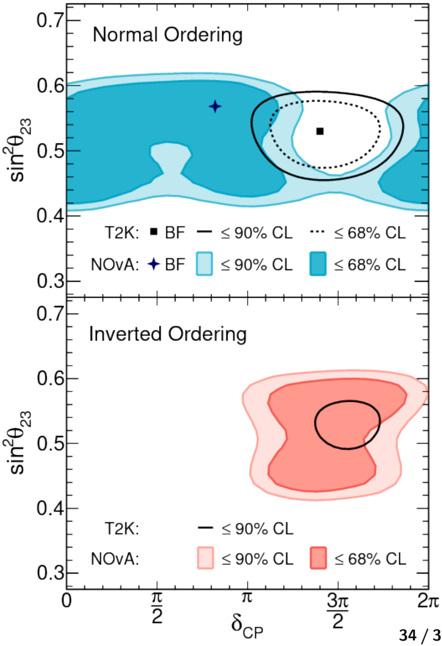
- Both experiments are limited either statistically or by the presence of the degenerate-like solutions (significantly better or more precise results with more statistics are not expected), **don't forget they independently measure also $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ in $\nu_\mu \to \nu_\mu$ when interpreting the plots on the left**
- 2020 results and several studies indicate that though both NOvA and T2K disfavor IO of neutrino masses at about 1σ, the joint analysis fit might converge on IO
- Joint NOvA+T2K analysis could bring much more interesting results even before the dawn of JUNO, HyperK and DUNE
- Leverage statistics and break the parametric space degeneracies
- NOvA+T2K analysis collaboration was established in 2019 and has been working towards the analyses unification
- First preliminary results are expected during 2022

NOvA+T2K joint fit

- As of yet, joining the fitters (don't forget about different interaction models and different ways of producing analysis predictions, different unknown unknowns)
- Joint fit based on MCMC Bayesian inference (MaCh3 in case of T2K, new framework for NOvA was developed during 2021)

Conclusions

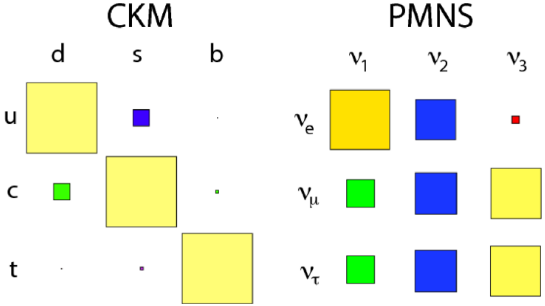
- NOvA continues in its endeavor to provide precise measurements of θ_{23}, Δm^2_{32} and δ_{CP}
- Incorporating new methods to enhance the analysis robustness and reliability, test beam program to reduce calibration and detector response systematics
- Approved beam upgrades and operation until 2025 promise more than double the accumulated exposure
- T2K and NOvA 2020 results have induced quite an excitement, we are looking forward to seeing new results on Neutrino 2022 conference
- We are looking forward even more to seeing joint T2K+NOvA results which promise a more detailed insight to the questions of CP violation and neutrino mass hierarchy with significance comparable to the next generation neutrino oscillation experiments
- T2K+NOvA collaborative efforts started in 2019, a joint fitter is underway, hoping to see some news at Neutrino 2022



BACK UP

3ν-paradigm mixing

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



$\nu_{e/\mu/\tau}$ – weak interaction eigenstates
ν_i – mass eigenstates with m_i
$U_{\alpha i}$ – elements of PMNS mixing matrix

- Leptonic mixing: 9 parameters
  $m_1, m_2, m_3, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, a, b$
- Neutrino oscillations: 6 parameters
  $\Delta m^2_{21}, \Delta m^2_{32}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

Conditions of 3ν-paradigm viability

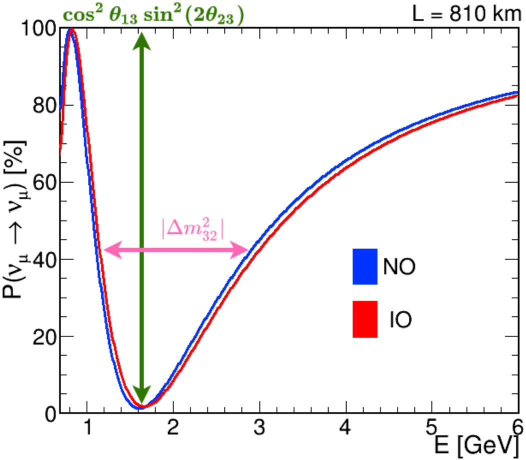
- 3 Dirac neutrinos with tiny masses (one ν_R for each ν_L)
- 3 "pure" Majorana neutrinos (SM would lose renormalizability or gauge invariance without extra physical objects)
- 3 light weakly active neutrinos and several heavy sterile neutrinos (See-Saw), U does not need to be unitary
- Similarly, 3 active neutrinos + neutrinos at different mass scales are effectively described in 3ν-paradigm with "small" unitarity violation

Oscillation probability (NOvA)

Small parameters $\varepsilon \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx 0.03$ and $\sin^2\theta_{13} \approx 0.02$

Disappearance channel $\nu_\mu \to \nu_\mu$

$$P(\nu_\mu \to \nu_\mu; L, E) \quad \approx \; 1 - \cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32} L}{4E} + \\ + \mathcal{O}(\varepsilon, \sin^2\theta_{13})$$



Oscillation probability (NOvA)

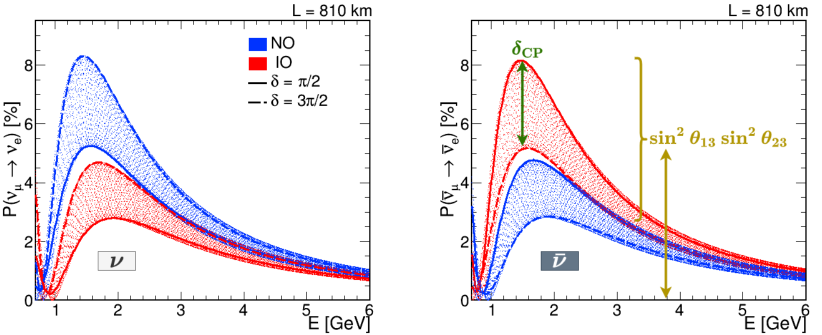
Appearance channel $\nu_\mu \to \nu_e$

$+\nu_e$ coherent forward scattering on pseudo-free e (matter effect), N_e density of e

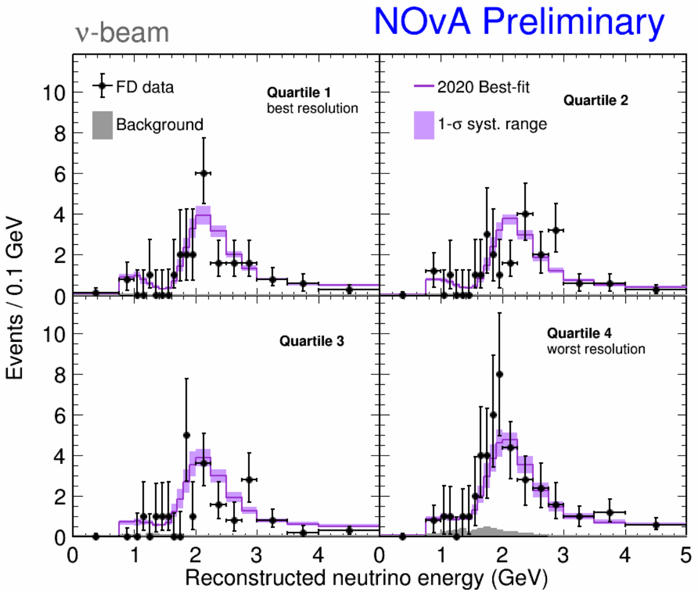
$$P(\nu_\mu \to \nu_e; L, E, A) \approx 4 s_{13}^2 s_{23}^2 \frac{\sin^2 \Delta}{(1-A)^2} + \varepsilon^2 \sin^2 2\theta_{12} c_{23}^2 \frac{\sin^2 A\Delta}{A^2} +$$

$$+ 8\, \varepsilon\, c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \cos(\Delta + \delta_{\mathrm{CP}}) \frac{\sin A\Delta}{A} \frac{\sin \Delta(1-A)}{1-A}$$

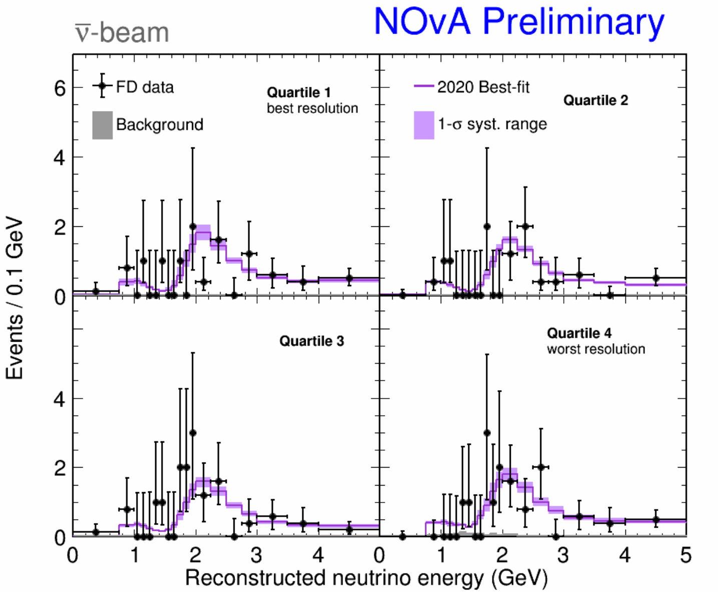
$$\Delta \equiv \frac{\Delta m_{31}^2 L}{4E} \qquad A \equiv \sqrt{2} G_{\mathrm{F}} N_e \frac{2E}{\Delta m_{31}^2}$$



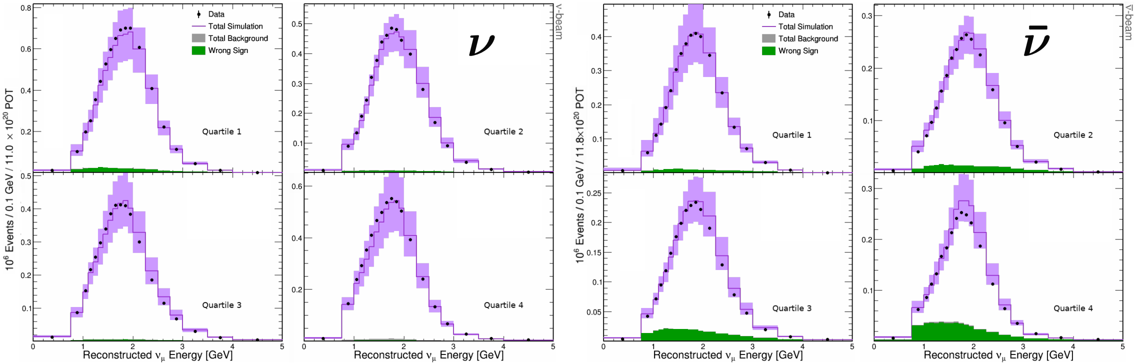
FD ν_μ data by Q, ν beam



FD $\bar{\nu}_\mu$ data by Q, $\bar{\nu}$ beam



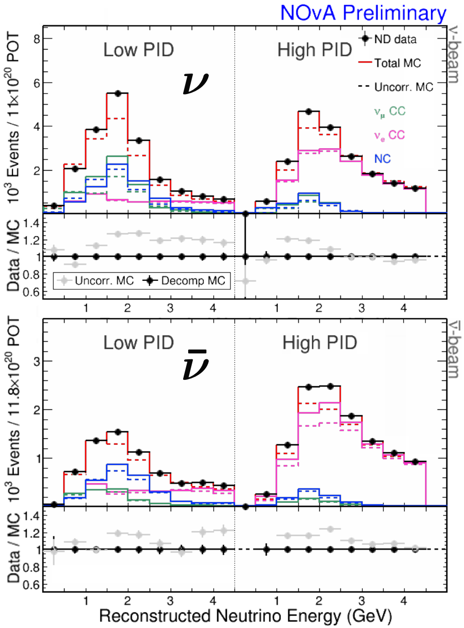
ND ν_μ CC selection



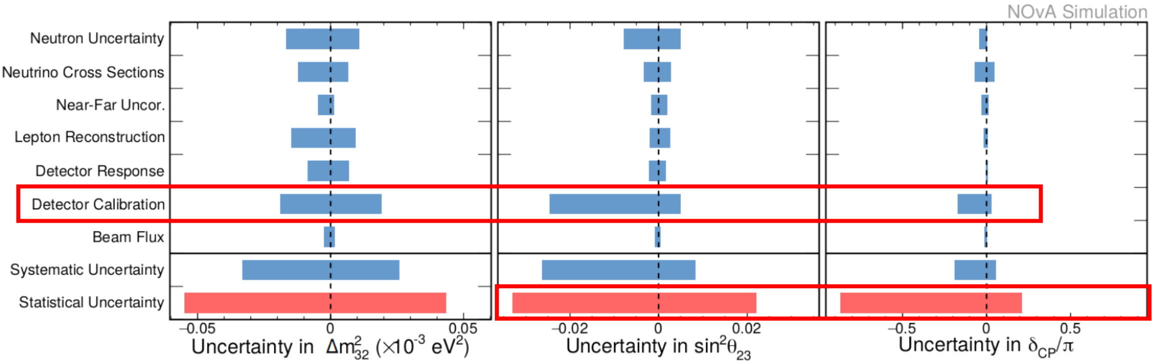
- This selection is used to predict all signal channels $\nu_\mu \rightarrow \nu_\mu, \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu, \nu_\mu \rightarrow \nu_e$ and wrong-signed background $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in ν beam (adequately $\bar{\nu}$)
- Large systematic uncertainties are rooted in uncertainties on beam ν_μ flux and cross-sections
- MC is corrected by data/MC proportionally in each bin for ν_μ and $\bar{\nu}_\mu$, other background is neglected

ND ν_e CC selection

- ND ν_e CC selection is a sample of beam neutrinos "resembling" the ν_e CC, it is used to predict $\nu_\mu \rightarrow \nu_e$ channel background
- To properly account for the oscillations when generating the FD predictions, the spectra need to be "decomposed" into particular components
- The yield of secondary π and K are corrected from special contained and uncontained ND samples of ν_μ from which the beam ν_e originate (BEN)
- From distributions of Michel e from μ decays, the relative numbers of ν_μ and NC interactions are estimated
- Unfortunately, the methods cannot be used for $\bar{\nu}$ beam and the components are estimated proportionally to ND data/MC

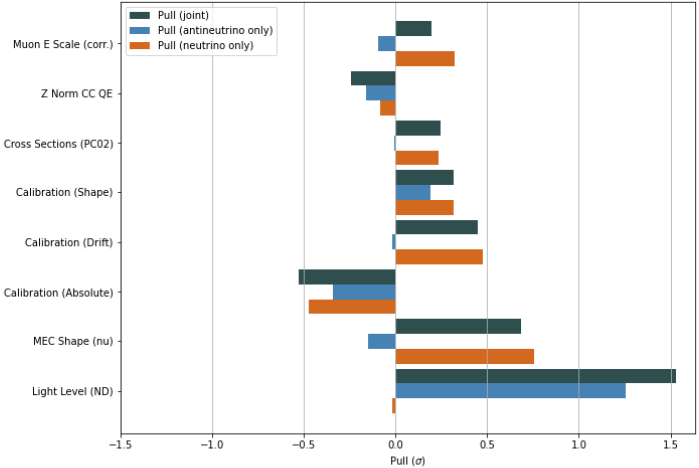


Systematic uncertainties



- Better calibration (ND/FD relative uncertainties) is vital for precise measurement of θ_{23}
- With more than twice the exposure until 2025, the statistical uncertainties on Δm^2_{32} and $\sin^2\theta_{23}$ might reach the systematic limits, to this end, further reduction of systematic uncertainties is one of the most straightforward ways of analysis improvement
- Statistical uncertainties dominate due to the degenerate-like solutions of the oscillation problem: δ_{CP}, θ_{23} and mass ordering

Systematic uncertainties, pulls



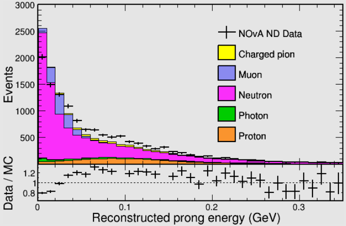
- The largest pulls correspond to known most important systematics: calibration, meson exchange current XSec, light level modelling

Systematics, summary

There are more than 100 systematic effects estimated for the NOvA analysis,
67 independent systematic uncertainties were implemented in the end (pull-terms)

Significant uncertainties

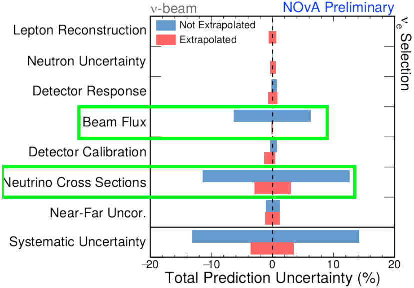
- **Calibration:** data/MC discrepancy of dE/dx
- **ν interactions:** from model parameters
- ***n* uncert.:** mismodeled *n* response (1% $E_{\bar{\nu}}$)



Other uncertainties

- **Response:** light yield, Čer./scin., aging
- **Lepton reco.:** μ track, angle reconstruction
- **F/N:** acceptance, exposure, mass etc.
- **Beam:** hadron production, focusation

- **Shifted predictions ($\pm1\sigma, \pm2\sigma$) created by:**
  1. Reweighting MC by event type
  2. Adjusting simulated variables
  3. Adjusting MC parameters and resimulating
- Systematics are evaluated by repeating the F/N extrapolation and **generating shifted predictions** (osc. par. during the fit)
- Uncerts on flux and interactions are additionally treated with **PCA in N and F/N basis** to reduce the number of nuisance parameters



Novelties and upgrades 2020

Primary

- About 50% more ν POT exposure
- Upgrade to GENIE v3.0.6 + NOvA ND tune + ν interaction model configuration
- Upgrade to Geant4 v10.4 + improved detector light model
- New clustering algorithm (better pile-up stability, up to +7% effective exposure)
- F/N extrapolation in reconstructed p_t of primary leptons

Secondary

- Retrained PID algorithms (NNs, BDTs)
- Reoptimalized energy estimators
- Reoptimalized selections
- Reevaluated systematic uncertainties

Expected effect for BF

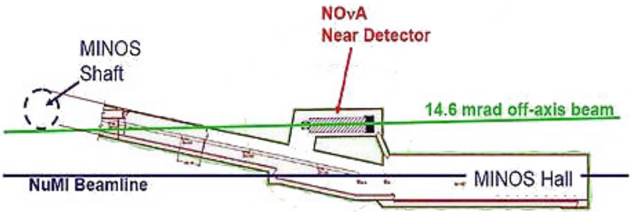
ν-beam: +60% ν_μ CC, +60% ν_e CC

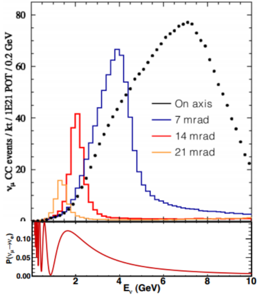
$\bar{\nu}$-beam: –2% $\bar{\nu}_\mu$ CC, +20 % $\bar{\nu}_e$ CC

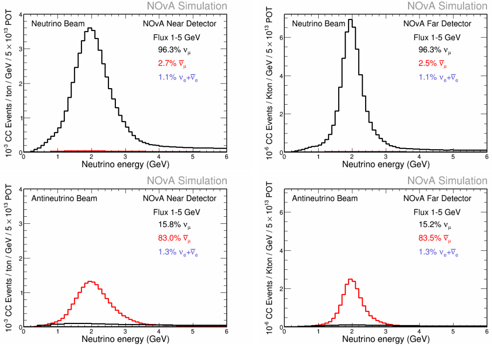
2019: 113 ν_μ, 58 ν_e, 102 $\bar{\nu}_\mu$, 27 $\bar{\nu}_e$

	Phenomena	Model
Cross section	CCQE	Valencia, Nieves et al., *Phys.Rev.C70, 055503 (2004)*
	NCEL	Ahrens et al., *Phys.Rev.D35, 785 (1987)* (GENIE default)
	DIS	Bodek-Yang, *arXiv:hep-ex/0308007* (GENIE default)
	RES	Berger-Sehgal, *Phys.Rev.D76, 113004 (2007)*
	MEC	Valencia MEC, *Phys.Rev.D88, 113007 (2013)* + NOvA ND data tune
	COH	Rein-Sehgal + PCAC formula, *Phys.Lett.B657:207-209 (2007)* (GENIE default)
Hadr.	Low-W	Empirical AGKY with KNO scaling, *Nucl.Phys.B40, 317 (1972)*
	High-W	PYTHIA/JETSET, *JHEP2006, 026–026 (2006)*
	FSI	INTRANUKE hN, *Acta Phys.Polon. B40, 2445 (2009)* + $\pi^+ - {}^{12}C$ data tune
	Nucleus	Bodek-Ritchie, *Phys.Rev.D24, 1400 (1981)*

Off the beam axis

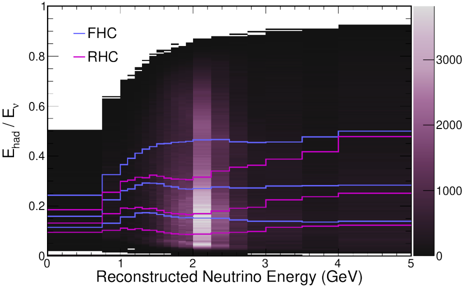






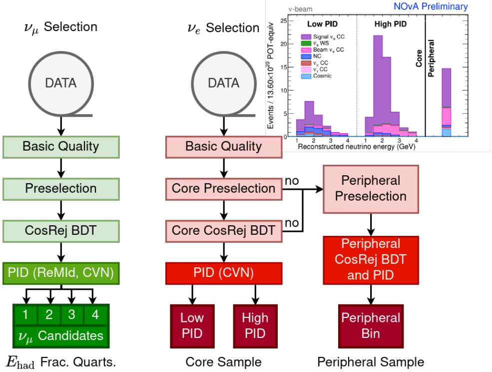
- Detectors about 14.6 mrad off the beam axis
- Sharp neutrino energy spectrum ($\sim$2 GeV)
- Reducing backgrounds with broad energy distributions
- Reducing wrong-sign neutrino contamination, i.e. $\bar{\nu}$ in ν beam
- $\bar{\nu}_\mu$ CC total XSec about 2.3× lower than for ν_μ CC at 2 GeV

Selection and analysis samples



ν_μ CC E_{had} quartiles

- ν (FHC) and $\bar{\nu}$ (RHC) data are divided into 4 samples by the fraction of hadronic energy in the total E_{ν_μ}
- Constructed as quartiles in unoscillated FD MC
- Worse energy resolution for higher E_{had} fraction would lead to worse sensitivity to $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Special binning reduces the computing requirements of the fit



ν_e CC PID samples

- **Low PID:** bkg. dominated by NC and ν_μ CC
- **High PID:** "pure" ν_e CC, bkg. dominated by beam $\nu_e + \bar{\nu}_e$
- **Peripheral:** not fully contained events without E reconstruction but with very high PID score

Validating classification cross-checks

- Testing the ν_e CC selection efficiency relative to preselection criteria
- **Muon Removed Electron added** (MRE): removing reconstructed μ track to insert a simulated electron in ν_μ CC candidate events to be identified (mix of EM and hadronic showers)
- **Muon Removed Decayed in Flight** (MRDiF): removing reconstructed μ track from FD cosmic in-flight-decayed μ to identify the EM shower
- Both cross-checks OK