



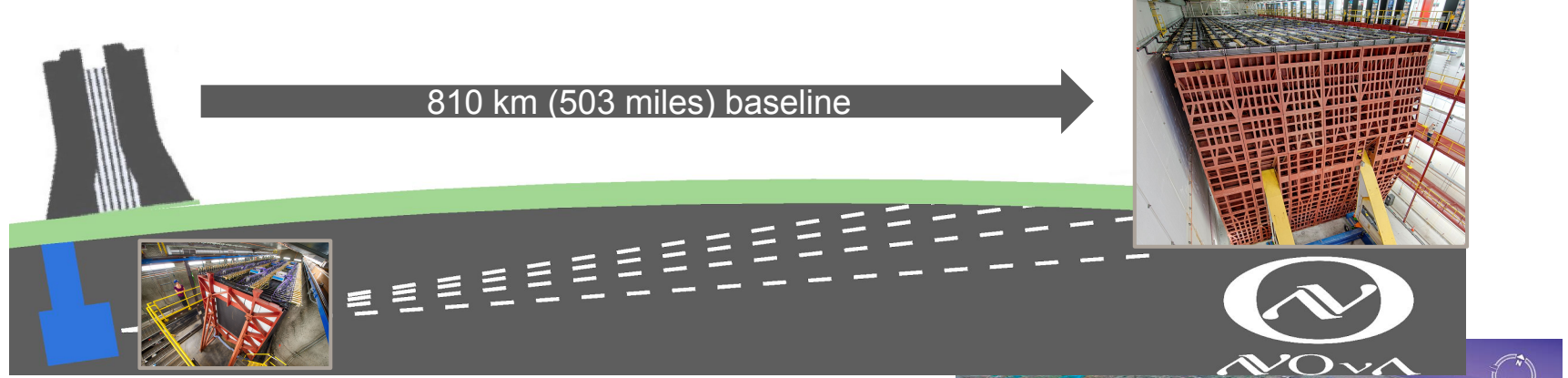
Ashley Back on behalf of the NOvA Collaboration

Three-flavour neutrino oscillations with NOvA

Rencontres du Vietnam Flavour Physics
Quy Nhon, Vietnam
August 18th, 2022

[Phys. Rev. D 106, 032004](#)





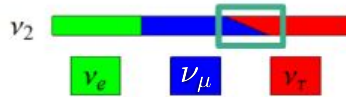
- Typical **long-baseline** neutrino oscillation experiment.
- **Near detector** (ND) ~100 m underground, at Fermilab.
- High target mass **far detector** (FD) on surface in northern Minnesota.
- Both positioned **off-axis** (from the beam center), giving a narrow energy spectrum peaked at ~2GeV.

The NOvA experiment

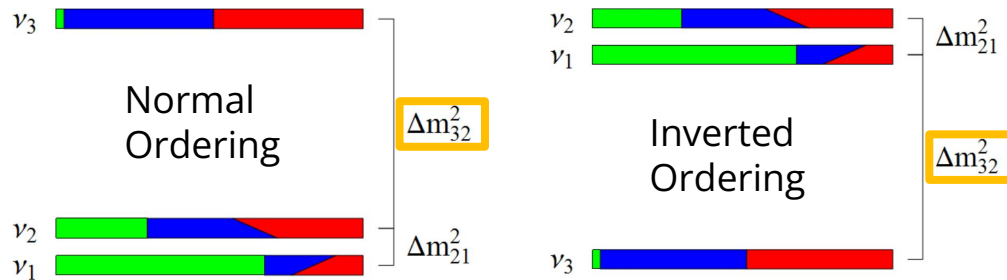


Key questions for NOvA

- Do ν_μ and ν_τ contribute equally to the mass states? Is θ_{23} **maximal**?



- Is electron flavor associated most with heavy or light mass states?

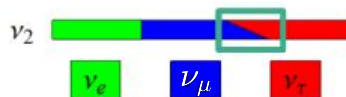


- Is there **CP violation** in the lepton sector? What is the value of δ_{CP} ?
- Is there physics beyond the **standard model/PMNS** matrix? Is the 3-flavor model complete?

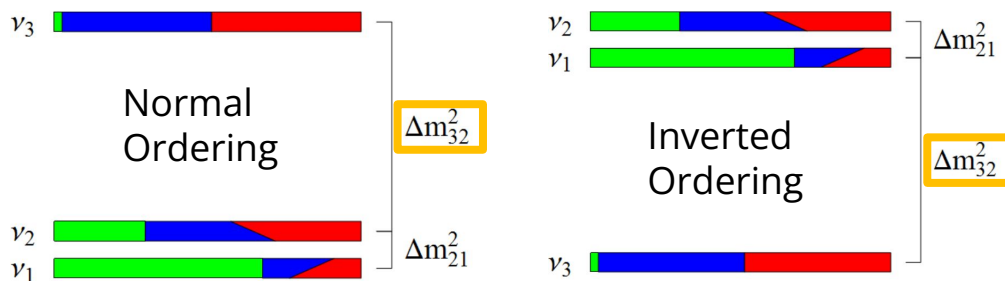
Key questions for NOvA

This talk

- Do ν_μ and ν_τ contribute equally to the mass states? Is θ_{23} **maximal**?

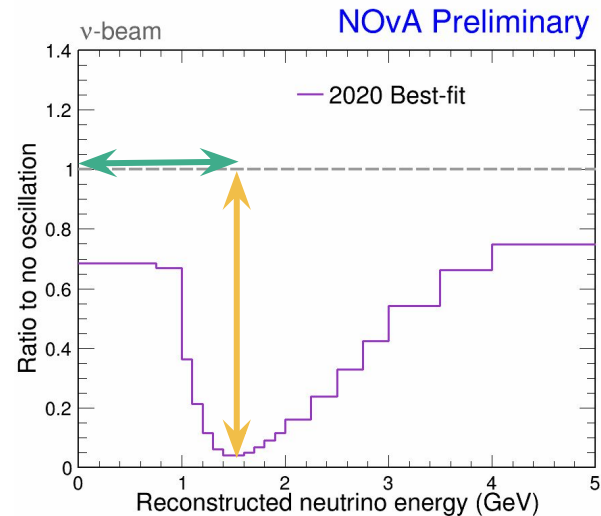
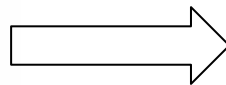
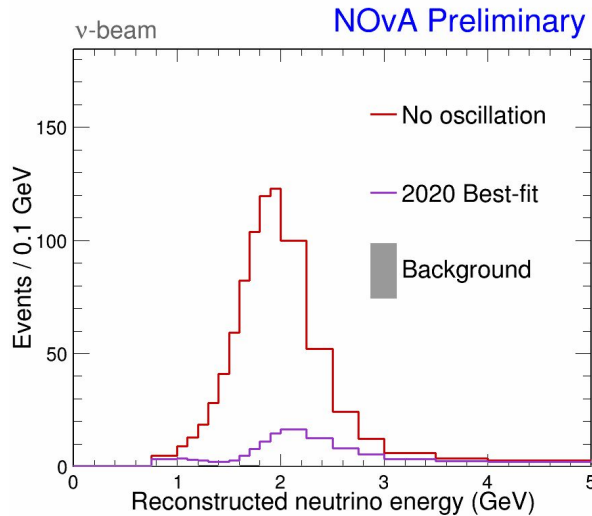


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- Is there **CP violation** in the lepton sector? What is the value of δ_{CP} ?
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ν_μ disappearance




The PMNS matrix gives a survival probability for ν_μ as:

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

Sensitivity to: $\sin^2(2\theta_{23})$ and Δm_{23}^2

Electron neutrino appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta_{CP} \mp \sin \Delta_{32} \sin \delta_{CP})$$


$$P_{\text{atm}} = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} (\Delta_{31})^2$$

$$\Delta_{ij} = (1.27 \Delta m_{ij}^2 L) / E$$

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

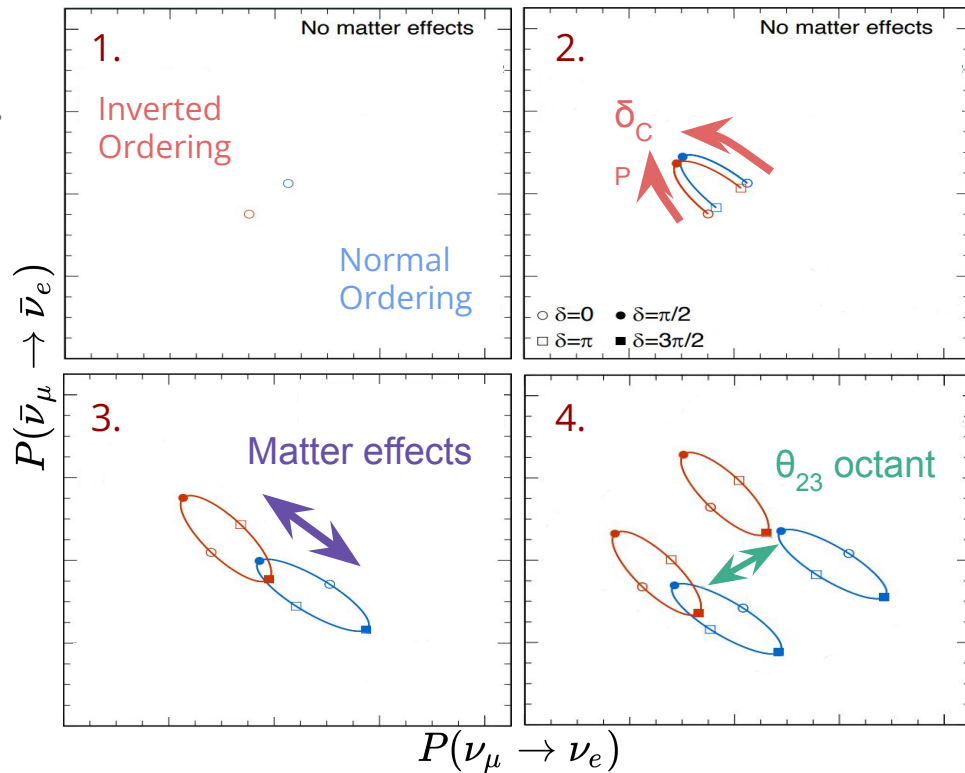
$$N_e = \text{Earth's electron density}$$

$$P_{\text{sol}} = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \frac{\sin^2(-aL)}{(-aL)^2} (\Delta_{21})^2$$

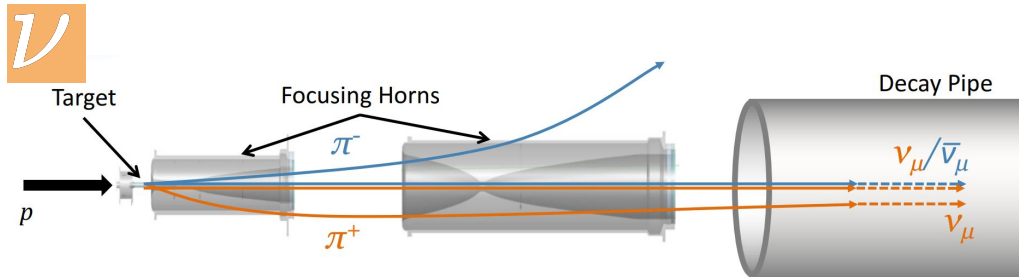
- Gives us access to every oscillation parameter
- Density of the Earth yields different effects for neutrinos and antineutrinos.

Neutrinos vs antineutrinos: ν_e appearance

1. Inverted Ordering gives a **slight suppression** in both beam modes.
2. **CP violation** causes **opposite effects** in each ordering - tracing out ellipses.
3. **Matter effects** also produce **opposite effects** in neutrinos and antineutrinos.
4. The **octant of θ_{23}** causes either a **suppression** or **enhancement** in both beam modes.

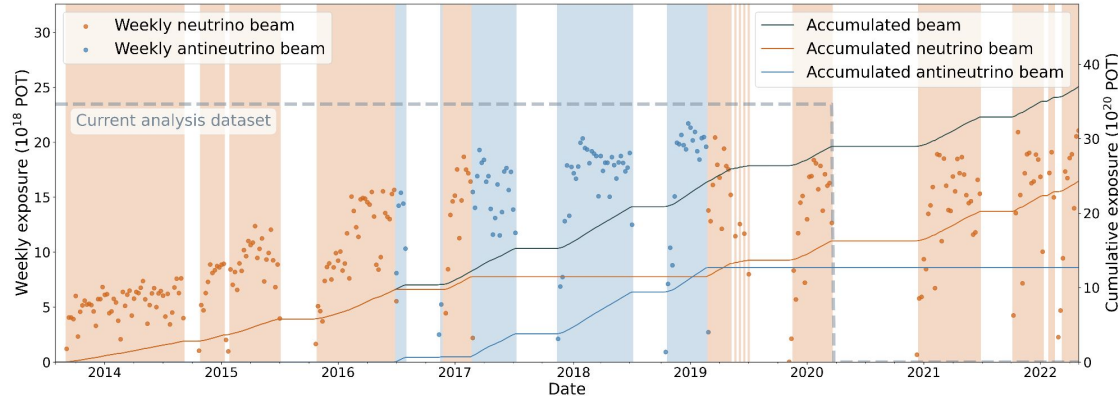


The NuMI beam

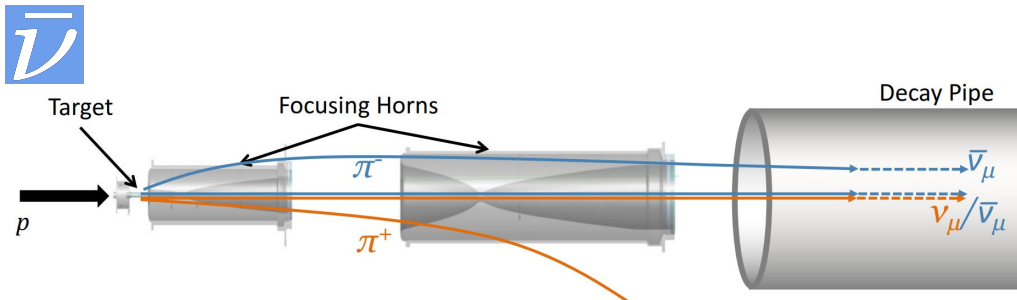


NuMI running at 700 kW design power since January 2017 and recently achieved a 1-hour average power record of **895 kW**!

- Charge select pions to get 96% (83%) pure neutrino (antineutrino) beam.
- Analysis based on 13.6×10^{20} protons on target (POT) in neutrino beam mode...

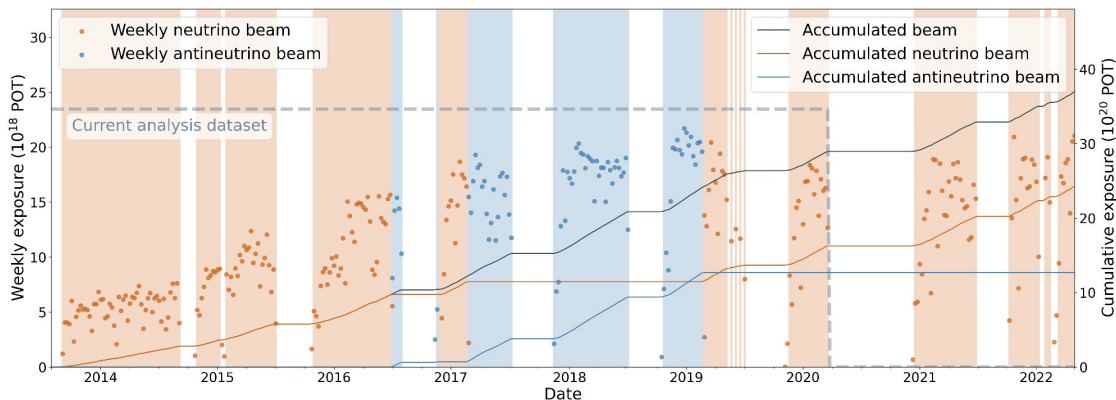


The NuMI beam



NuMI running at 700 kW design power since January 2017 and recently achieved a 1-hour average power record of **895 kW**!

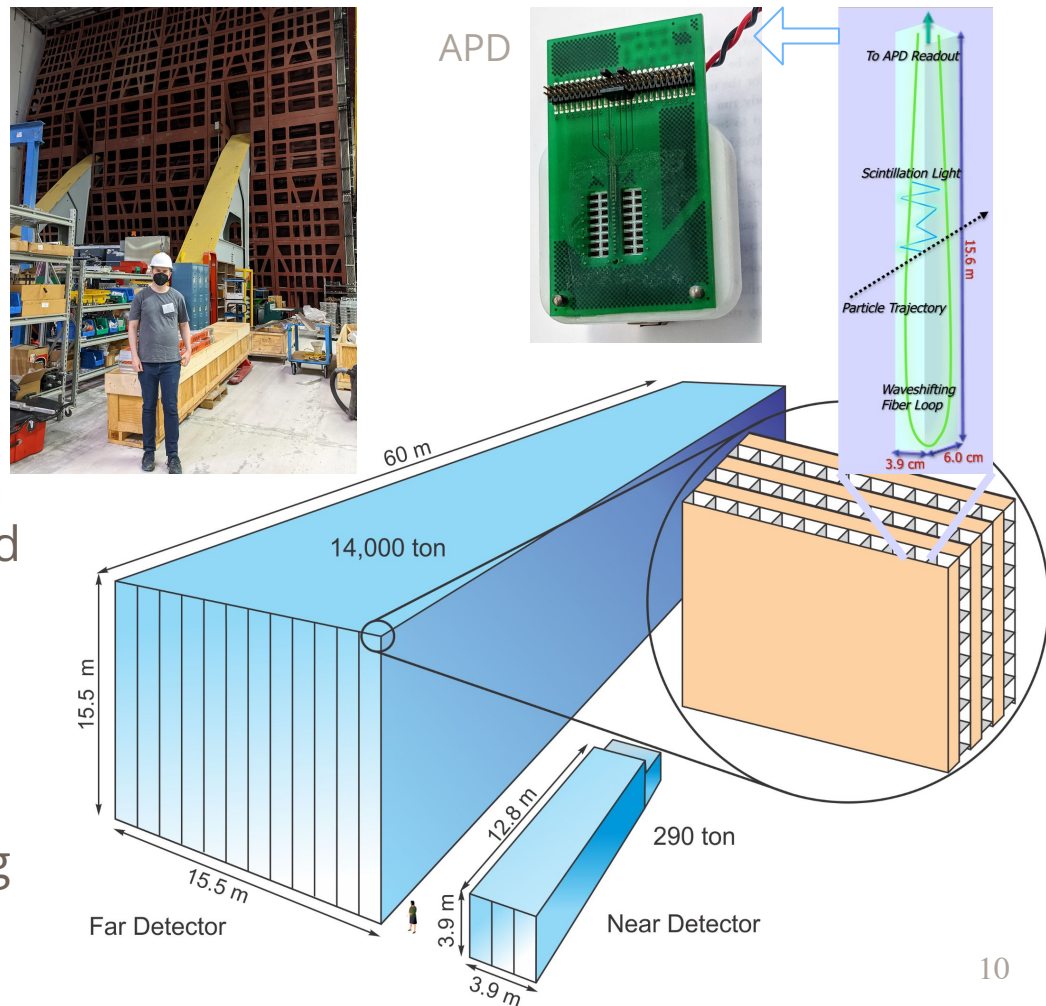
- Charge select pions to get 96% (83%) pure neutrino (antineutrino) beam.
- Analysis based on 13.6×10^{20} protons on target (POT) in neutrino beam mode... and 12.5×10^{20} POT in antineutrino mode.
- Both just under half the final exposure we expect.
- Close to doubling neutrino beam exposure already!



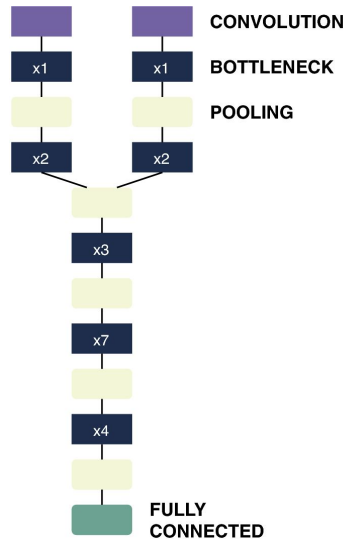
For scale, me standing in front of the Far Detector during our recent Collaboration Meeting visit.

NOvA detectors

- Highly granular **tracking calorimeters**, constructed with orthogonal layers PVC cells filled with **liquid scintillator**.
- Need a large target mass - 14 kton FD only detects ~100 neutrinos per year.
- Readout via wavelength-shifting fiber loop to **avalanche photodiodes (APDs)**.

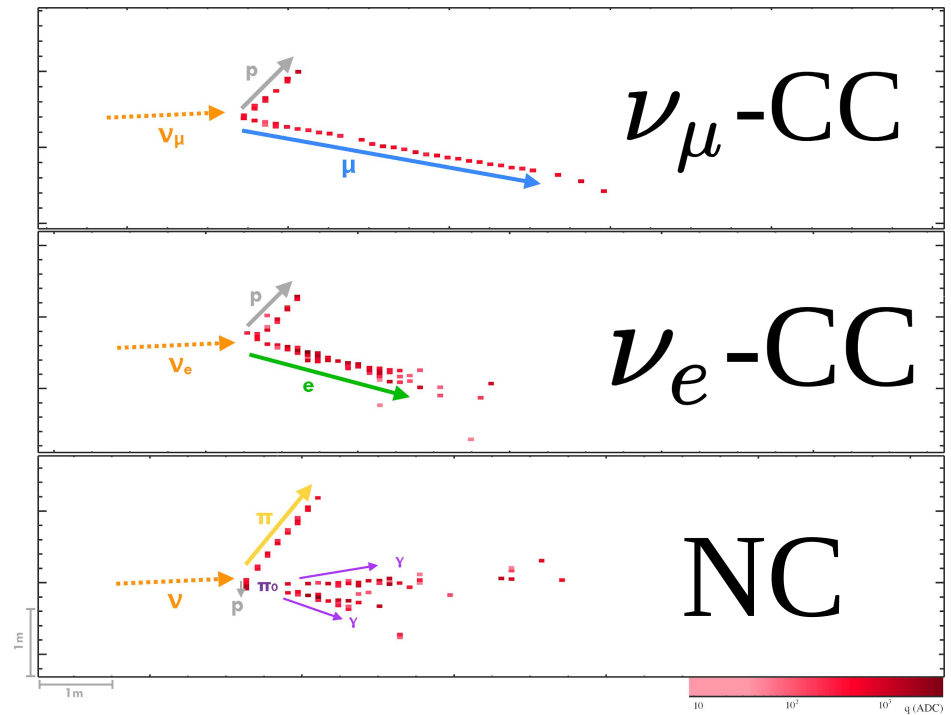


Event selection

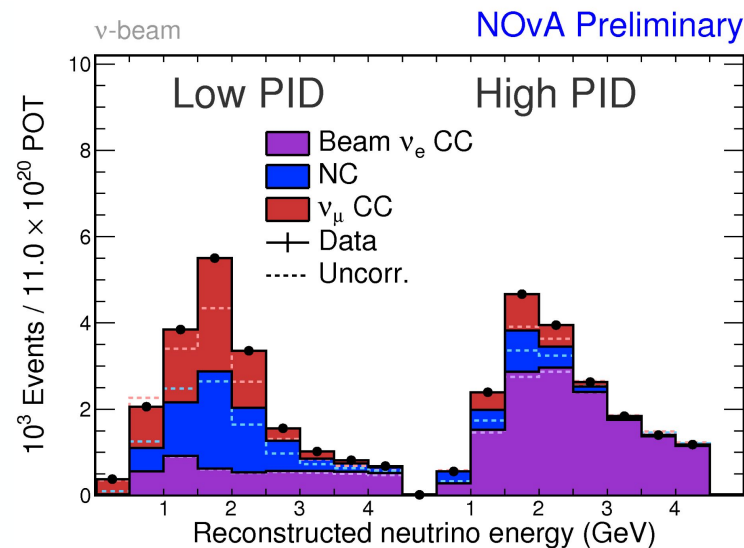
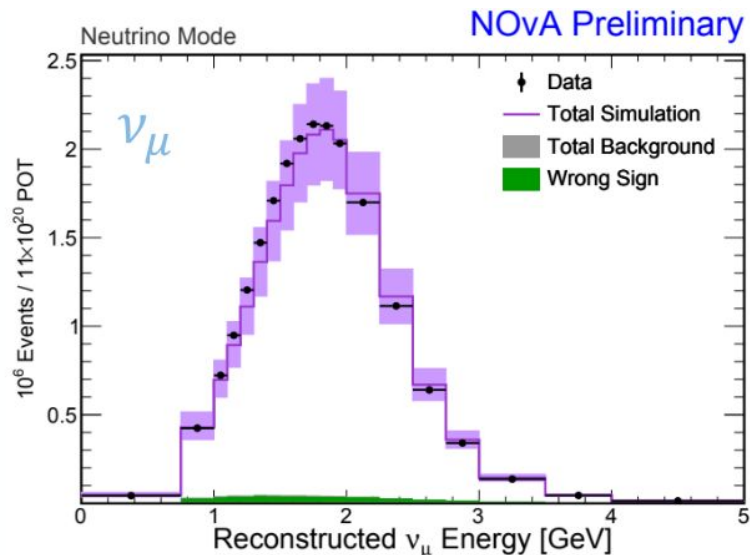


[Phys.Rev. D 100 \(2019\) no.7, 073005](#)

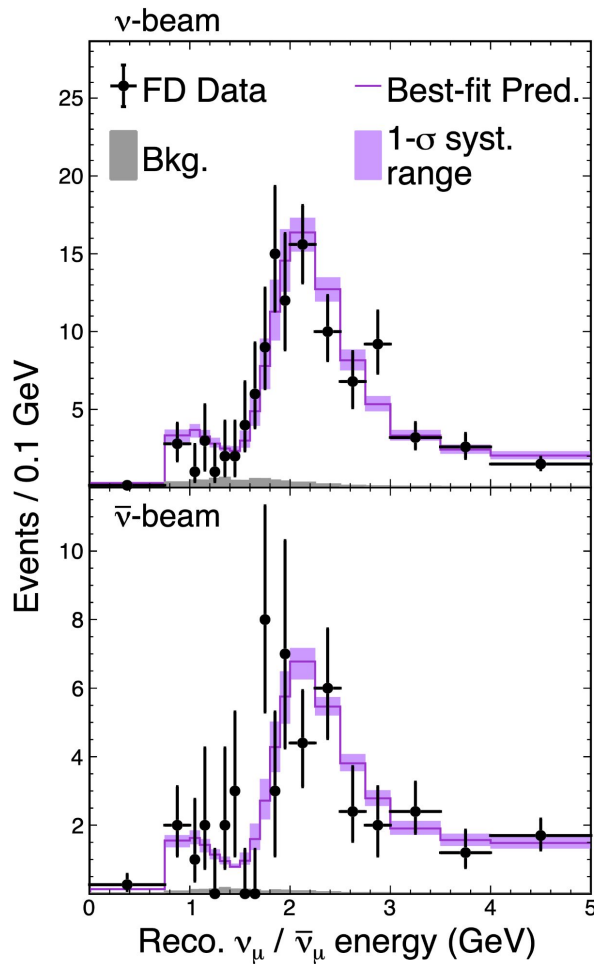
- NOvA uses a **convolutional neural network (CNN)** to classify events
 - a deep-learning technique inspired by image recognition.
- We also use basic quality and containment, precise beam timing and a cosmic rejection boosted decision tree to select neutrino candidates.



Constraints using ND data



- We scale simulation to ND data to constrain signal and background rates in the FD prediction, with bin-by-bin corrections.
 - We adjust the ν_μ CC, ν_e CC and NC components separately in the ND ν_e data.
- The ν_μ ND data constrains the FD **signal** while ND ν_e data constrains the prediction for beam **backgrounds**.



- Observed **211** events on a background prediction of **8.2**
 - Integral of total best-fit prediction is 222.3 events.

Selected ν_{μ} CC candidates



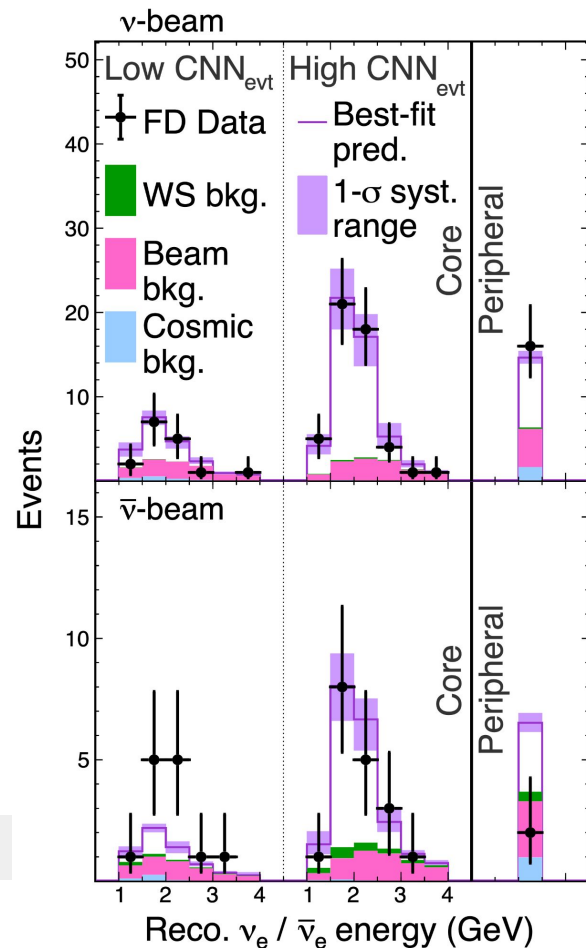
- Observed **105** events on a background prediction of **2.1**
 - Integral of total best-fit prediction is 105.4 events.

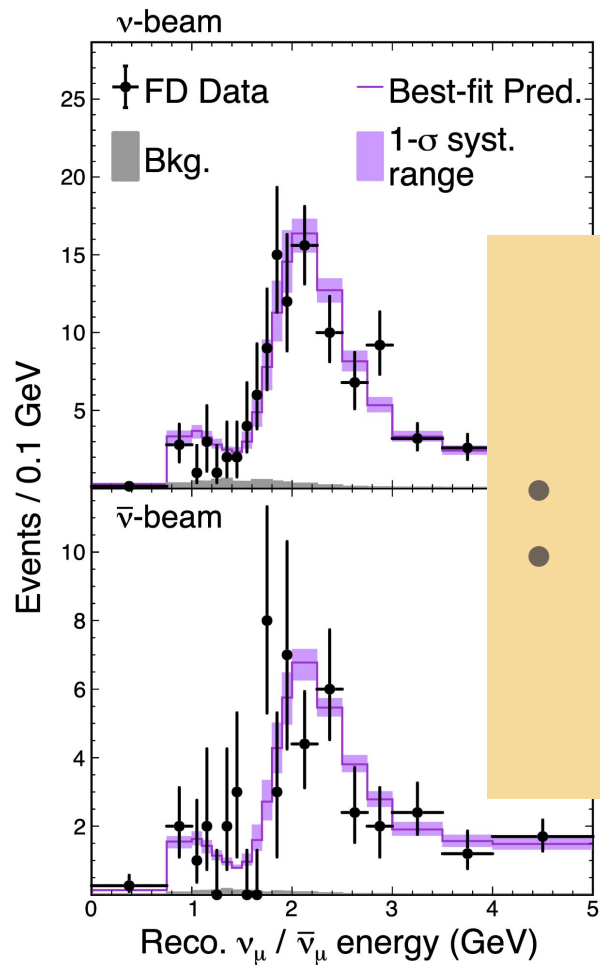
- Observed **82** events on a background prediction of **26.8**
 - Integral of total best-fit prediction is 85.8 events.

Selected ν_e CC candidates

- Observed **33** events on a background prediction of **14.0**
 - Integral of total best-fit prediction is 33.2 events.

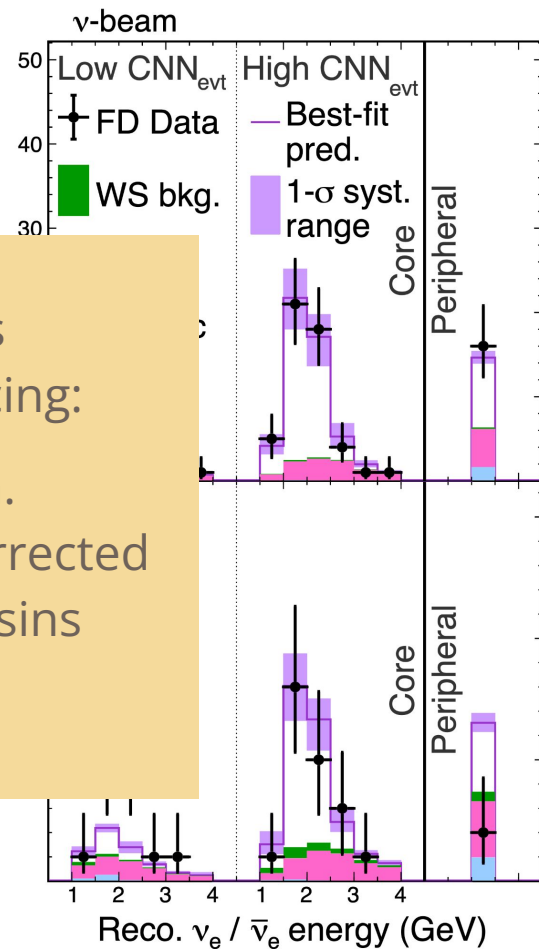
>4 σ evidence of electron antineutrino appearance





Fit the four datasets simultaneously, producing:

- Bayesian interpretation.
- Frequentist method corrected using the Feldman-Cousins unified approach.



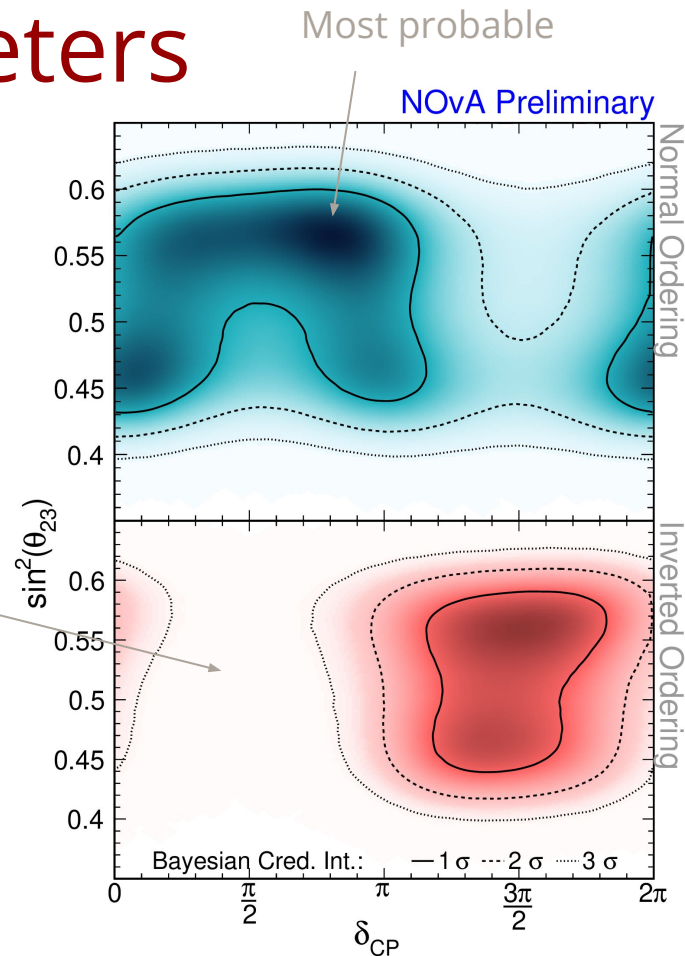
Fit to oscillation parameters

Bayesian interpretation has similar conclusions to our frequentist results.

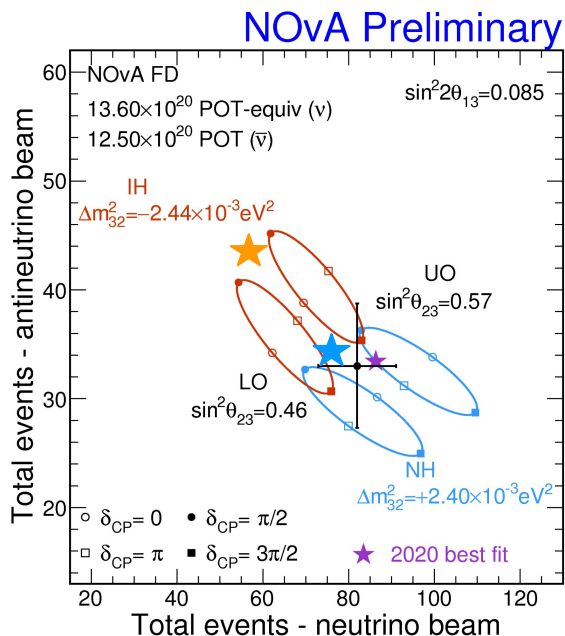
- Rule out IO, $\delta = \pi/2$ region at $>3\sigma$.
- Weak preference for Normal Ordering, Upper Octant of θ_{23} .

Excluded

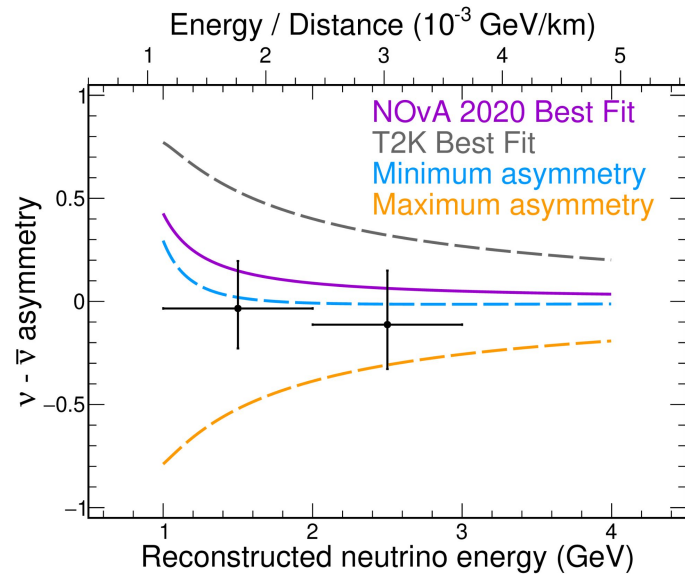
Posterior probability density, marginalized over both mass orderings, showing 1, 2, and 3 σ credible regions.



Asymmetry



$$\frac{P(\nu) - P(\bar{\nu})}{P(\nu) + P(\bar{\nu})}$$

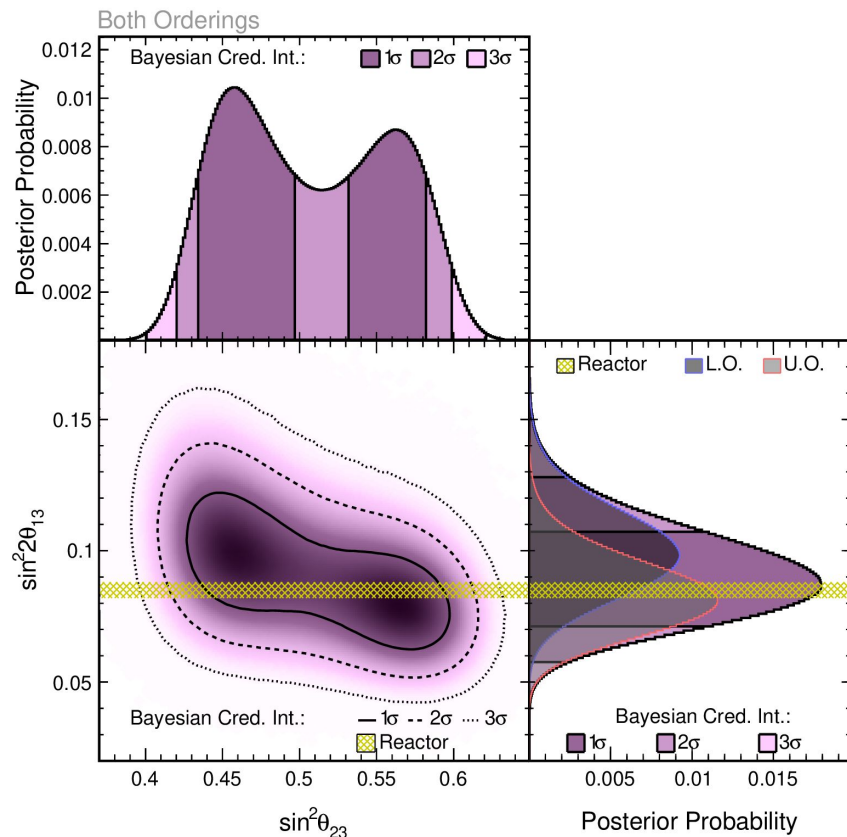


Plotting number of candidates in neutrino vs antineutrino beam mode, puts observed result in the highly degenerate central region.

We see **no strong asymmetry** in the appearance rates \rightarrow consistent with both slightly negative and slightly positive asymmetries, but disfavoring more extreme asymmetries.

17

Measurement of θ_{13}



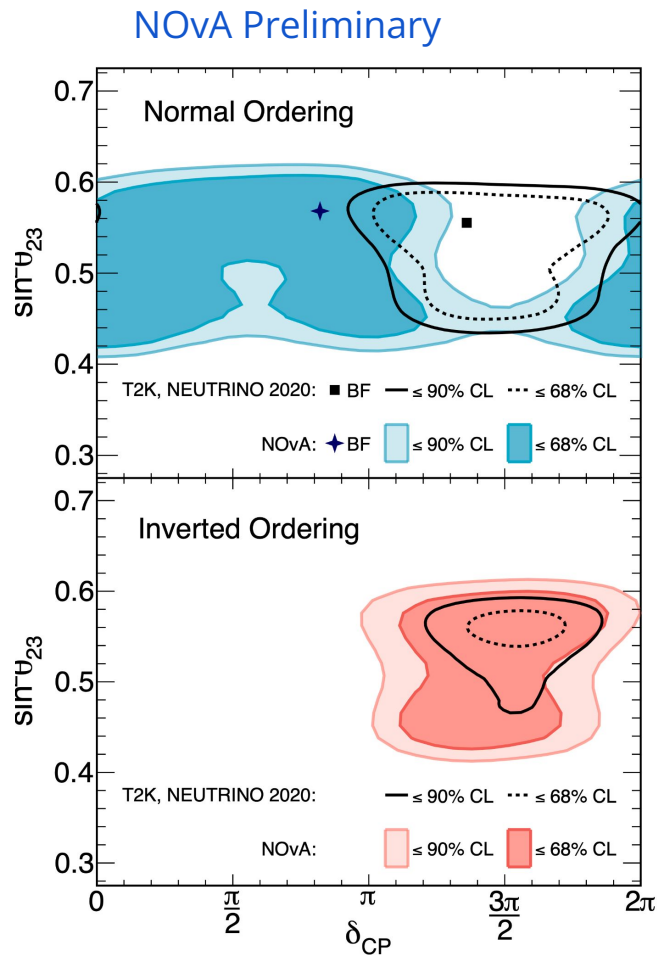
- The results so far all use a constraint on θ_{13} from reactor experiments.
- The Bayesian interpretation of our data allows us to drop this constraint and make a NOvA measurement of θ_{13} .

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

- Consistent with the measurements from reactor experiments.
- Good test of PMNS consistency \rightarrow NOvA measurement uses a very different strategy to reactor experiments.

Comparison with T2K

- Frequentist contours.
- Some tension between preferred regions for the Normal Ordering.
 - Agree on the preferred region in the Inverted Ordering.
- A joint fit of the data from the two experiments is needed to properly quantify consistency.
 - Significant progress made on a joint-fit → coming this year!



Future of NOvA

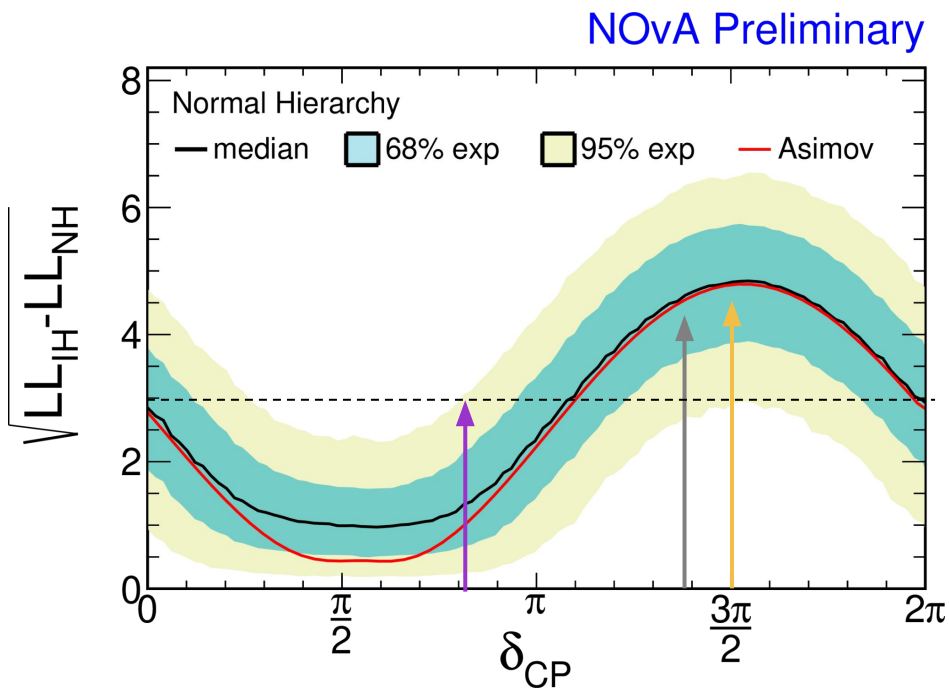
NOvA will continue taking data until 2026.

- equal exposure in both beam modes.
- >2x current POT.

Sensitivity to mass ordering depends on the value of δ_{CP} .

- **NOvA best-fit** ($\delta_{CP}=0.82\pi$) has $\sim 2.5\%$ chance of 3σ .
- **Most favourable parameters**/T2K best-fit ($\delta_{CP}=1.37\pi$) have $\sim 50\%$ chance of 4σ .

NOvA's successful Test Beam program will help reduce detector systematics.



Outlook

NOvA is well suited to investigating key questions in Neutrino Physics.

With our latest 3-flavor oscillation analysis, NOvA sees:

- $>4\sigma$ evidence of electron antineutrino appearance.
- No strong asymmetry in ν_e appearance rates between beam modes.
- First comprehensive NOvA measurement of θ_{13} , consistent with measurements from reactor experiments.

Thank you!



<http://novaexperiment.fnal.gov>

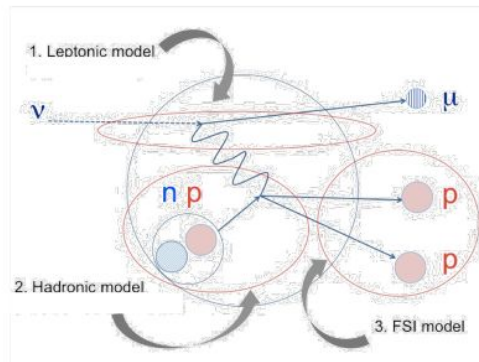


Extra slides

Neutrino interaction model

Slide from A Himmel,
Neutrino 2020.

- Constantly evolving understanding of ν interactions.
- Upgrade to GENIE 3.0.6 \rightarrow freedom to choose models
- Chose the most “theory-driven” set of models plus GENIE’s re-tune of some parameters*.
- Some **custom tuning** is still required.
 - Substantially less than was needed with GENIE 2.12.2, which required tweaks to most models.



Process	Model	Reference
Quasielastic	Valencia 1p1h	J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C 70 (2004) 055503
Form Factor	Z-expansion	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
Multi-nucleon	Valencia 2p2h	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D 88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D 76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Int.	hN semi-classical cascade	S. Dytman, Acta Physica Polonica B 40 (2009)

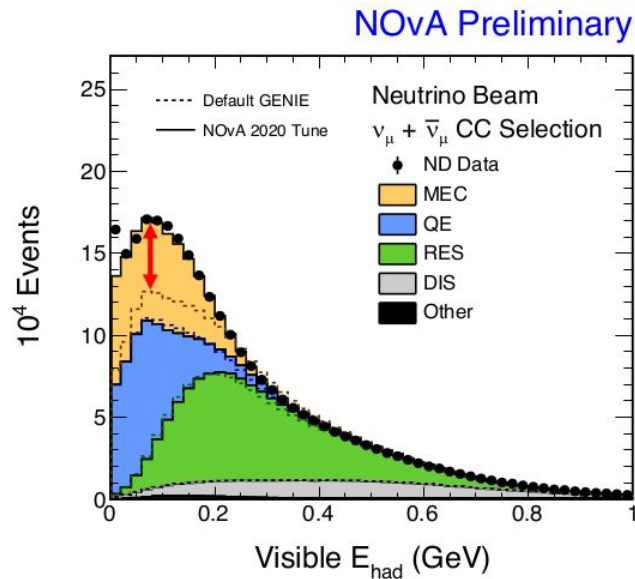
* We call our tune N1810j_0211a, and it is built by starting with G1810b_0211a and substituting the Z-expansion form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.

Fig: Teppei Katori, “Meson Exchange Current (MEC) Models in Neutrino Interaction Generators” AIP Conf.Proc. 1663 (2015) 030001

Neutrino interaction model

Slide from A Himmel,
Neutrino 2020.

- 2p2h or Meson Exchange Current or Multi-nucleon Interactions:
 - Disagreement of models with multiple experiments well-known
 - Tuned to **NOvA ND data** with two 2D gaussians in q_0 - $|\vec{q}|$ space.
 - Generous systematics covering normalization and kinematic shape
- Final State Interactions
 - Used **external π -scattering data** primarily to set uncertainties
 - Required adjusting central value, change in overall xsec was small.



Posters

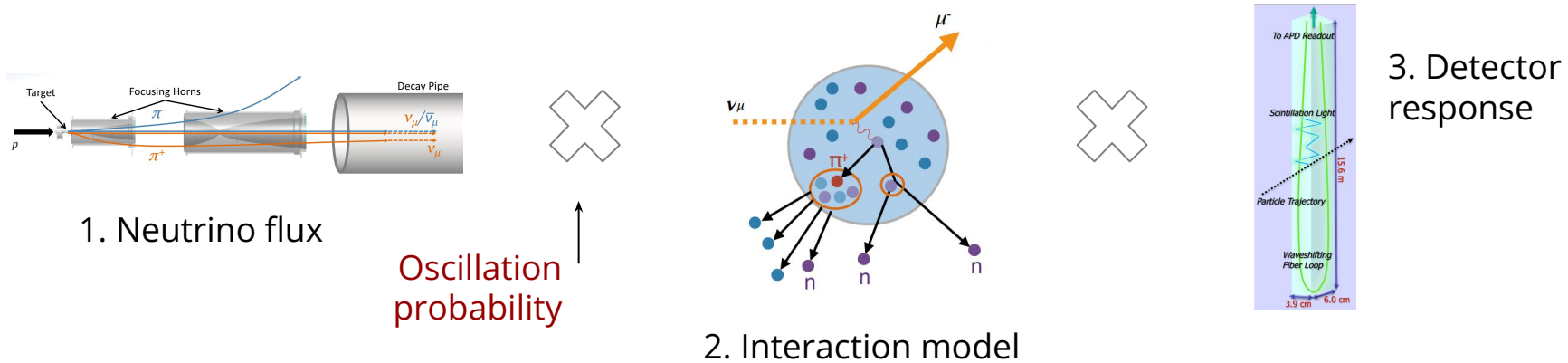
67. Cross section adjustments for 2p2h

– Maria Martinez Casales

352. Central value tuning and uncertainties for the hN FSI model in GENIE 3

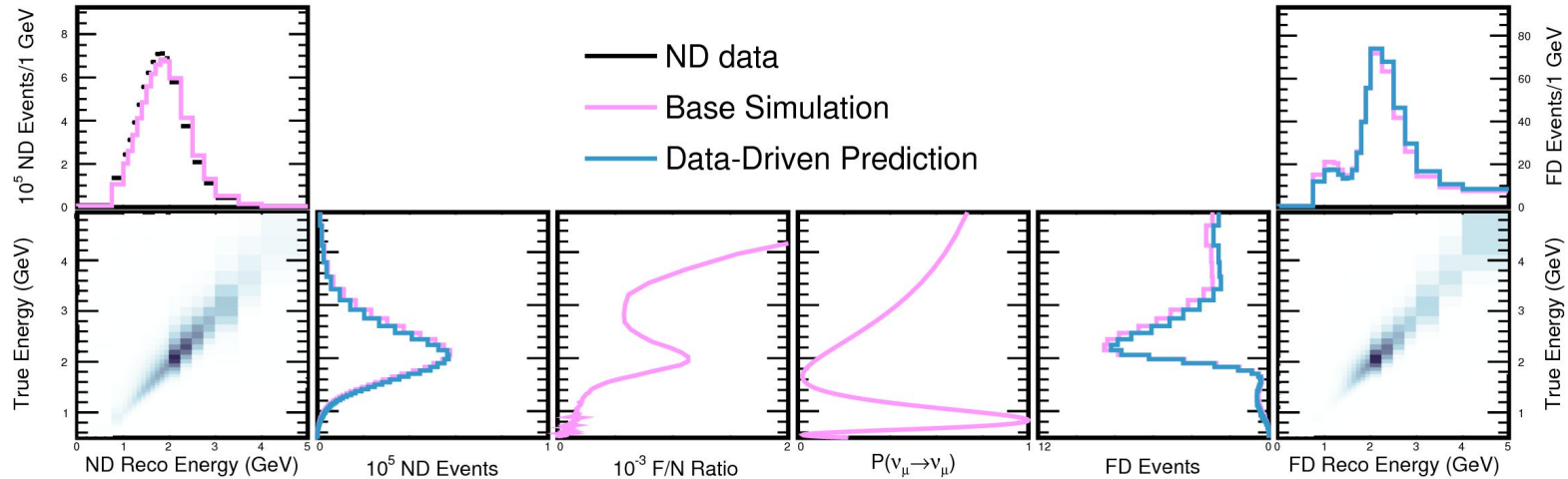
– Michael Dolce, Jeremy Wolcott, Hugh Gallagher

Building a far detector prediction



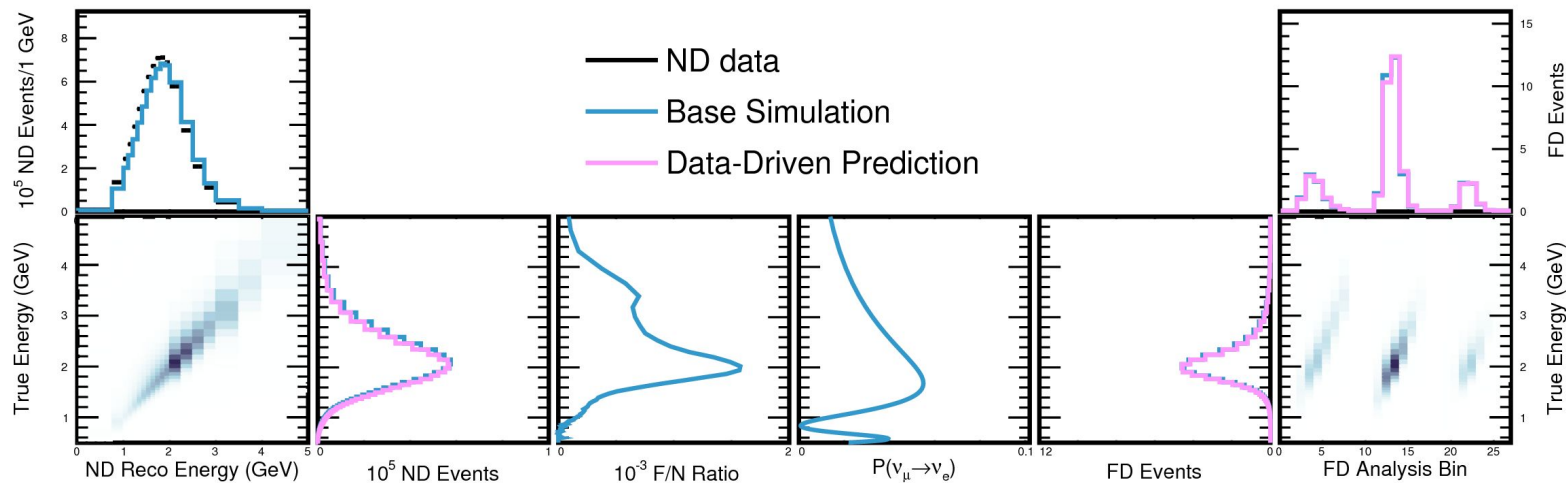
1. GEANT 4 simulation of neutrino flux, re-weighted using external NuMI beam measurements.
2. Interactions simulated using GENIE 3.0.6 with custom configuration, tuned on external and NOvA ND data → updated for this analysis.
3. Simulation of final state particles propagated through light readout and front-end electronics using GEANT 4 → also updated for this analysis.

To evaluate the effect of a systematic shifts on our FD prediction, we propagate our nominal MC and each shift through the extrapolation procedure using our corrected ND MC .



- Selected ν_μ ND events (**4 quartiles**) \rightarrow FD ν_μ signal prediction.

To evaluate the effect of a systematic shifts on our FD prediction, we propagate our nominal MC and each shift through the extrapolation procedure using our corrected ND MC .



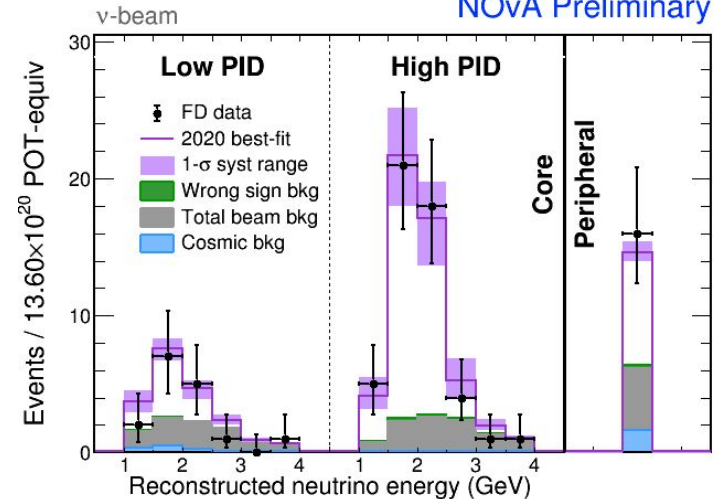
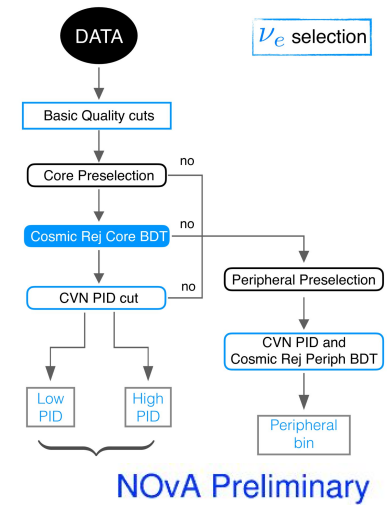
- Selected ν_μ ND events (**4 quartiles**) \rightarrow FD ν_μ signal prediction.
- Selected ν_μ ND events \rightarrow FD ν_e signal prediction.
- Selected $\nu_e/\nu_\mu/\text{NC}$ ND events \rightarrow FD ν_e background prediction.

Enhancing sensitivity: ν_e

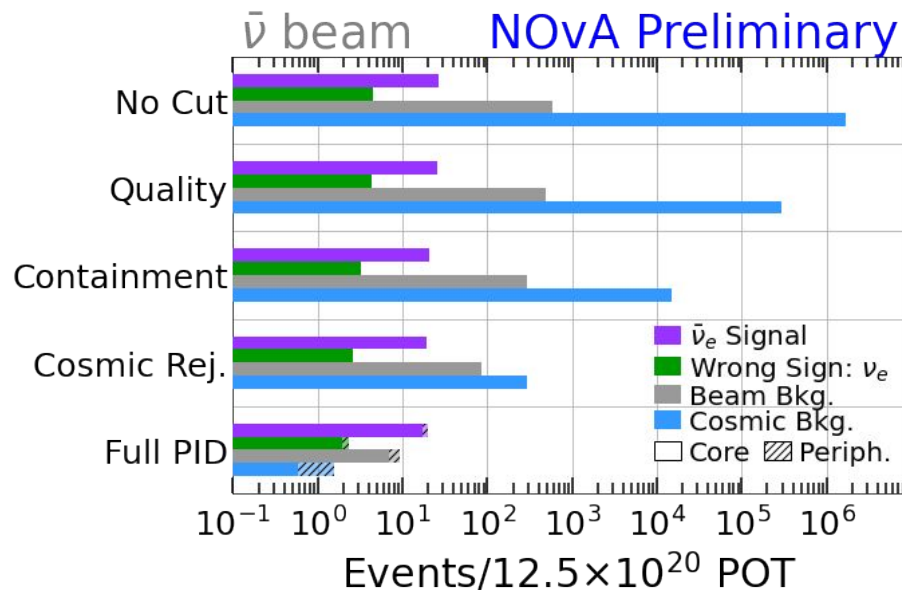
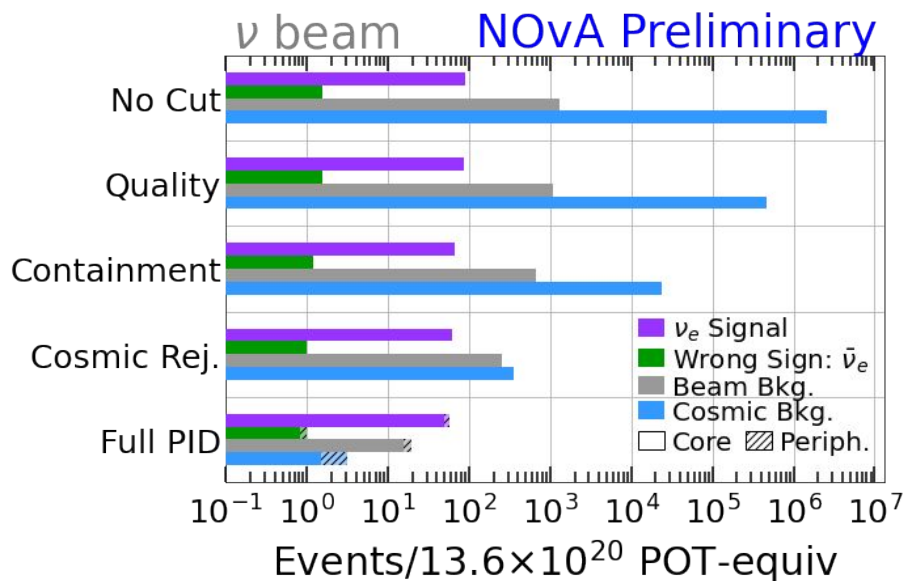
Sensitivity comes mainly from signal and background separation.

We split into three samples:

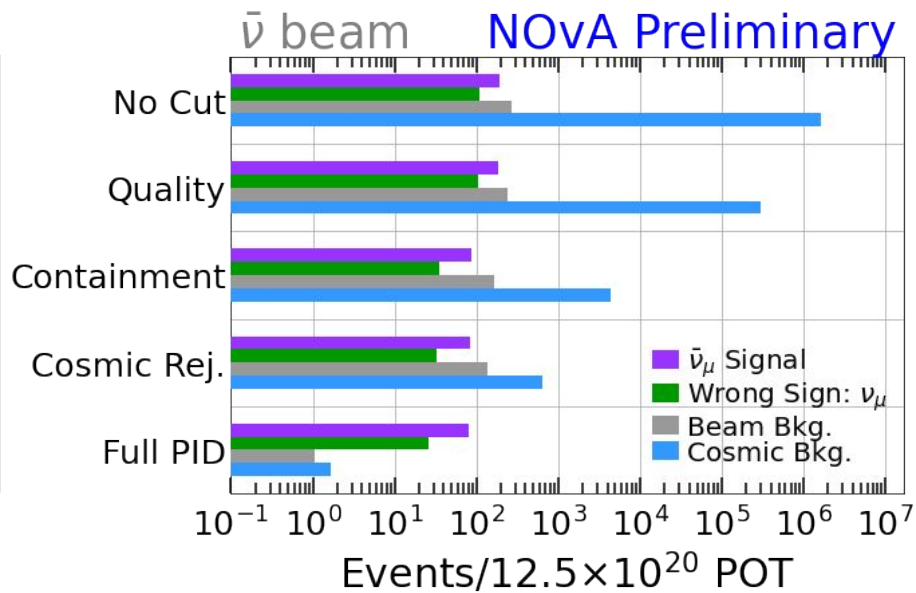
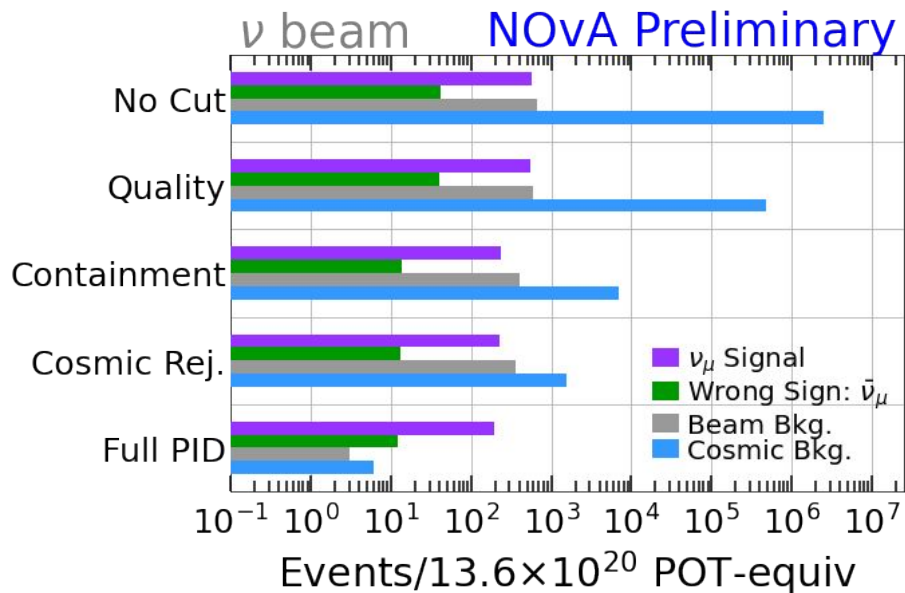
- High and low purity core samples.
- Peripheral sample.
 - Captures highly ν_e -like events (high PID score) that fail initial containment and cosmic rejection cuts.
 - No energy binning.



Nue selection: cut-flow



Numu selection: cut-flow

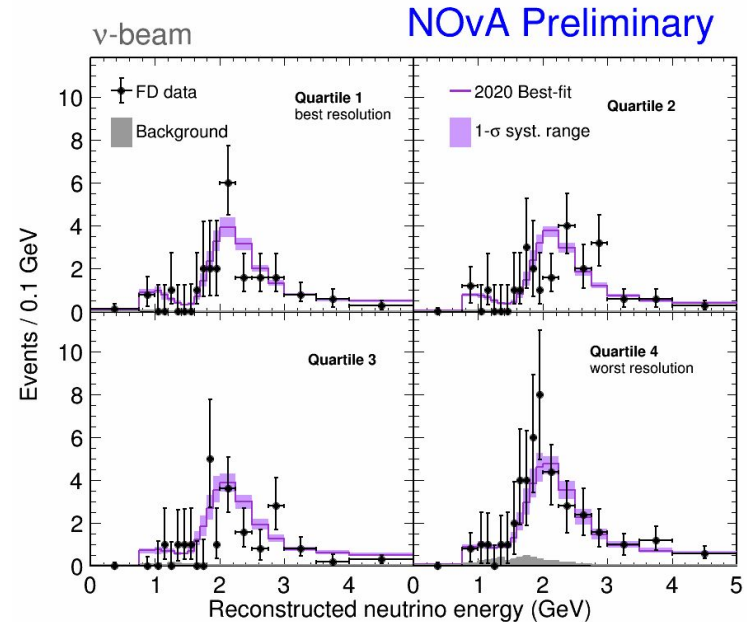


Enhancing sensitivity: ν_μ

Sensitivity comes mainly from the shape of the energy spectrum - particularly in the dip region.

We split into four samples by energy resolution \rightarrow binning by fraction of hadronic energy.

Resolution varies from $\sim 6\%$ in Quartile 1 to $\sim 12\%$ in Quartile 4.

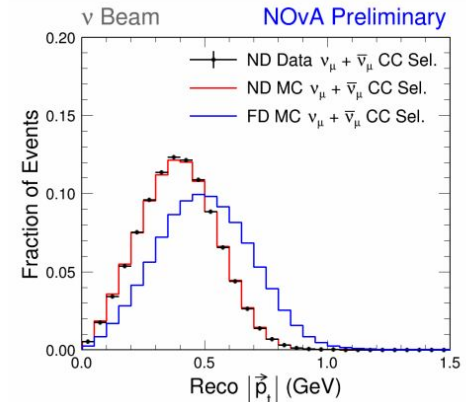
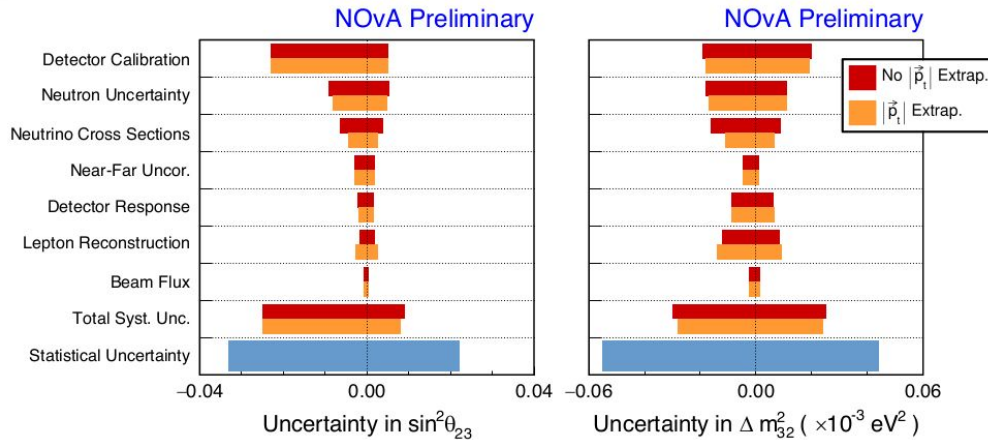
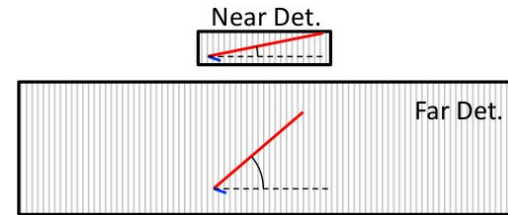


Enhancing sensitivity: ν_μ

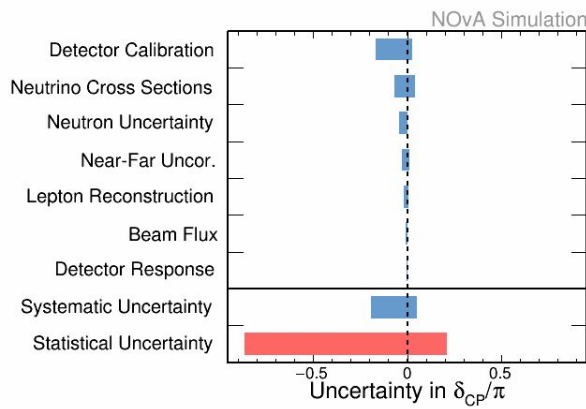
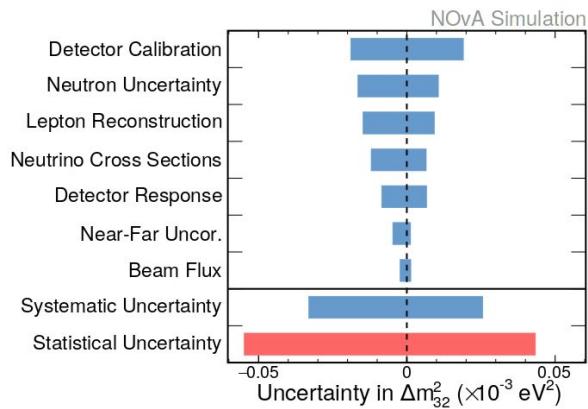
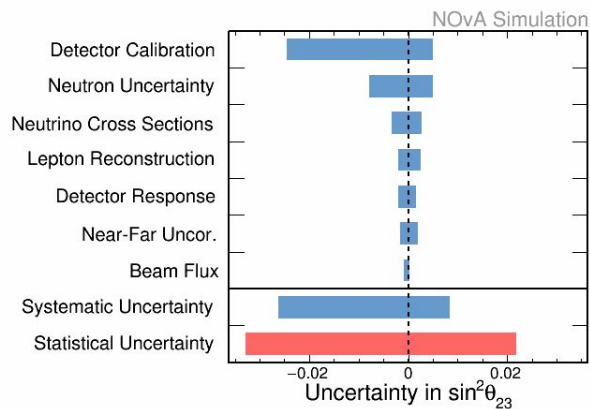
Containment in ND limits range of lepton angles more than in FD.

Mitigate by splitting ND data into 3 samples of transverse lepton momentum and extrapolate to FD.

Increases robustness and reduces cross-section systematics by ~30 % (overall reduction in systematics (5-10 %)).



Key systematic uncertainties



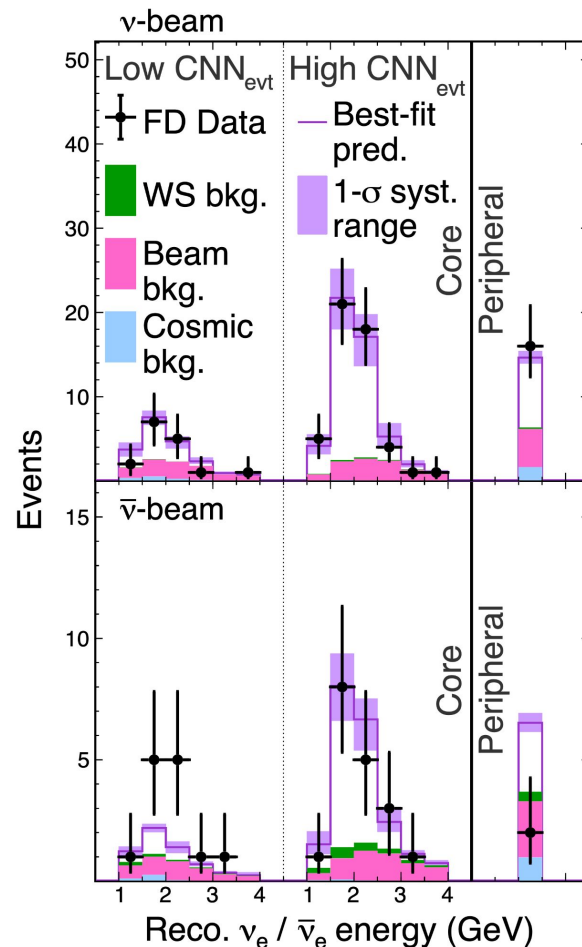
- Measurements are still statistics limited.
- Key systematic uncertainties from detector calibration, neutrino cross-sections and neutrons.

Total observed	82
Integral at best fit	85.8
Electron antineutrino	1.0
Total beam background	22.7
Cosmic background	3.1

Total observed	33
Integral at best fit	33.2
Electron neutrino	2.3
Total beam background	10.2
Cosmic background	1.6

>4 σ evidence of electron antineutrino appearance

Selected ν_e CC candidates



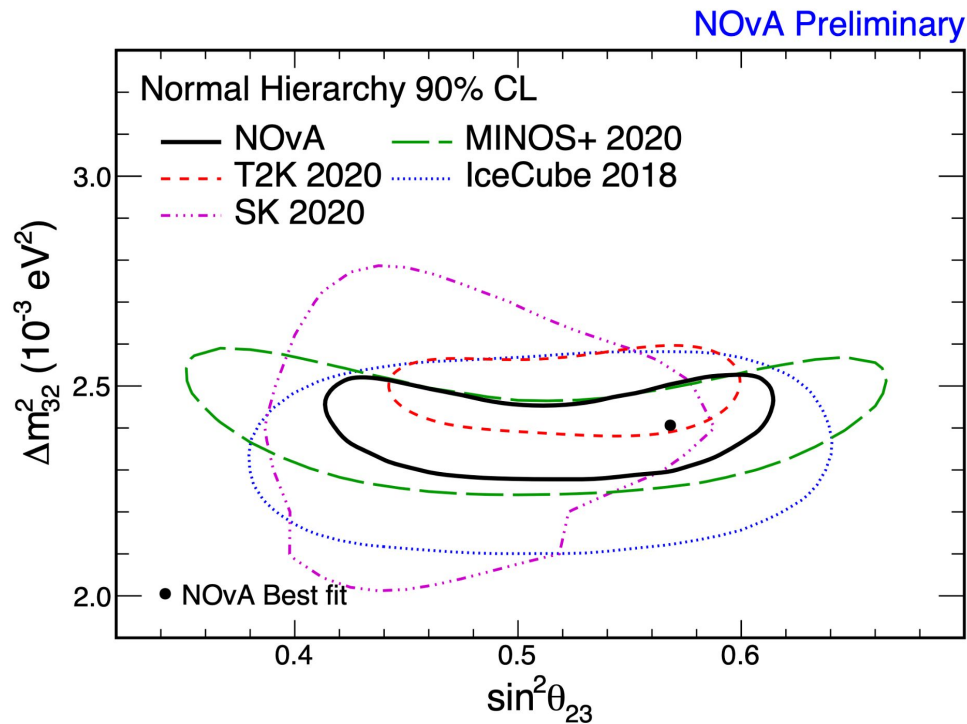
Fit to oscillation parameters

Best fit:

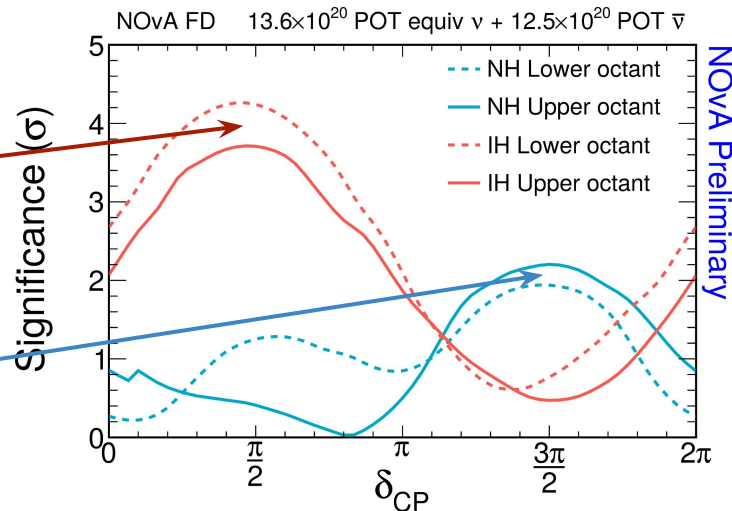
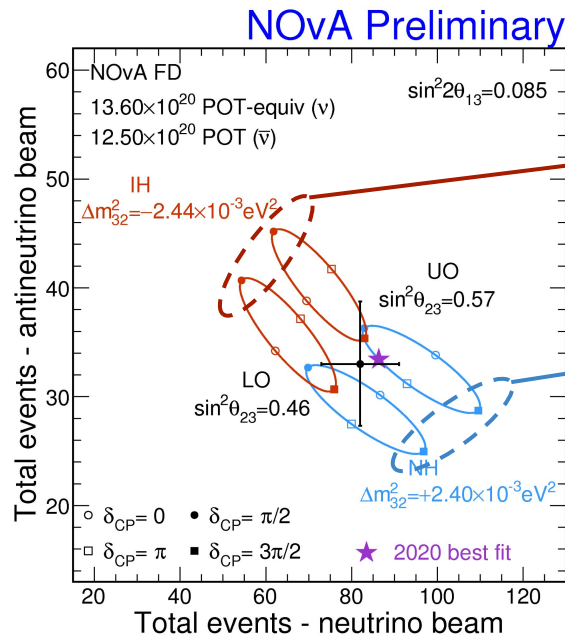
$$\Delta m_{23}^2 = (2.41 \pm 0.07) \times 10^{-3} \text{eV}^2$$

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

1.1 σ preference for
non-maximal mixing



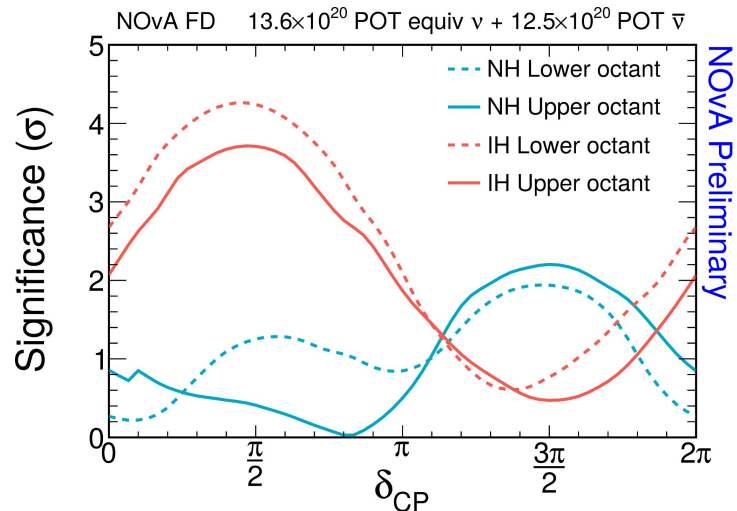
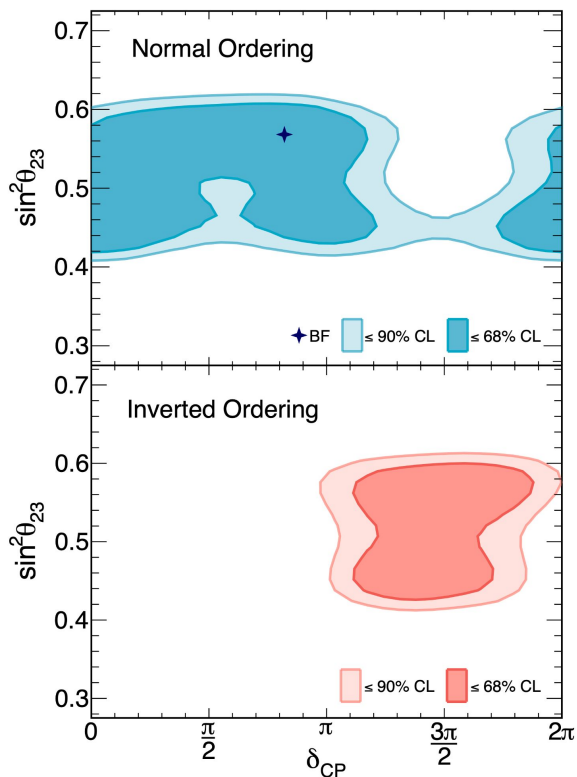
Fit to oscillation parameters - Frequentist



Exclude IH $\delta = \pi/2$ at $>3\sigma$
 Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer:
 Normal Hierarchy at 1.0σ
 Upper Octant at 1.2σ

Fit to oscillation parameters - Frequentist



Exclude IH $\delta = \pi/2$ at $>3\sigma$
 Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer:
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NOvA & T2K bi-event plots

