Latest Oscillation Results from the NOvA Experiment

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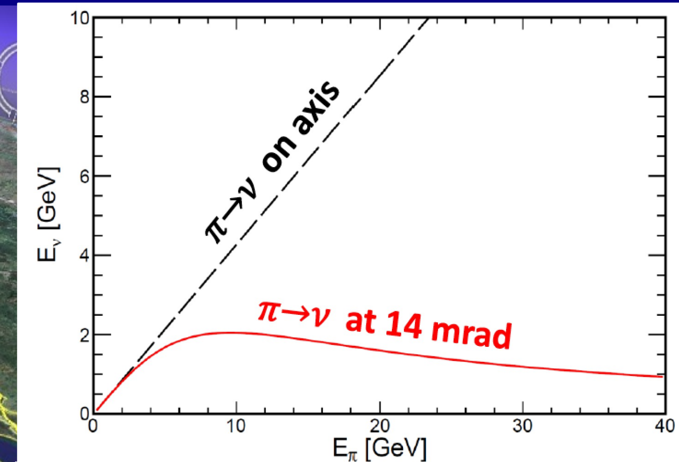
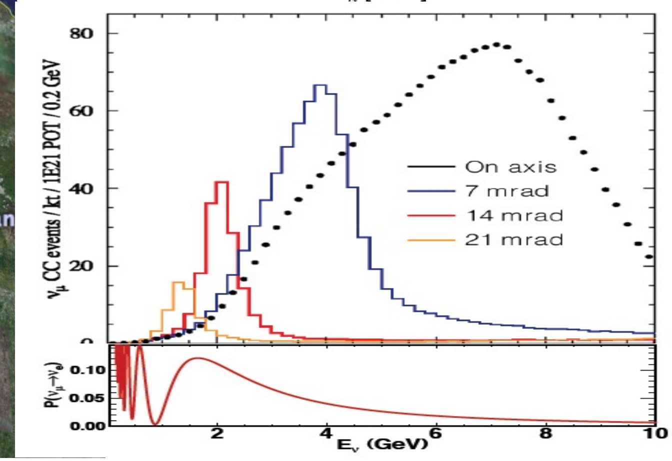
HQL 2021, University of Warwick, UK

NuMI Off-Axis ν_e Appearance Experiment (NOvA)

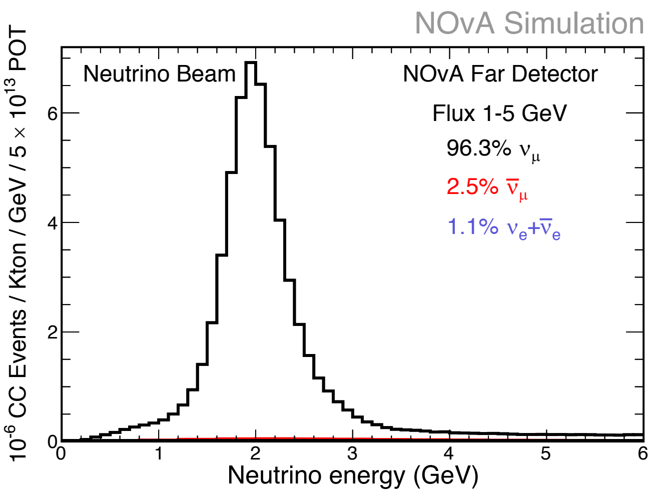




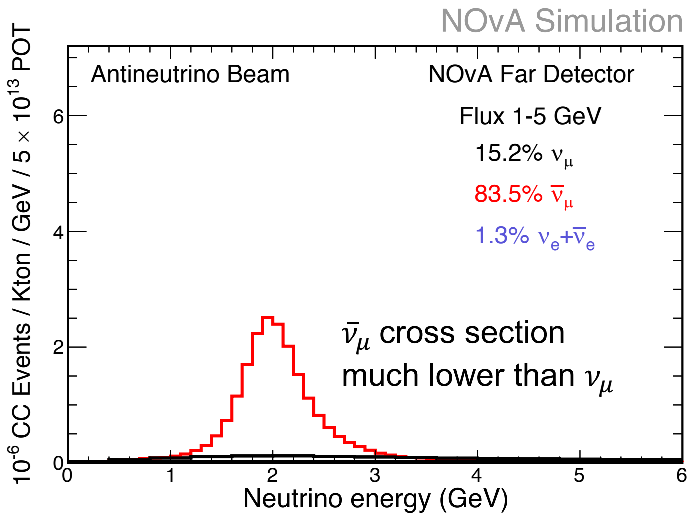
- Muon neutrino beam at Fermilab near Chicago
- Longest baseline in operation (810 km), large matter effect, sensitive to mass ordering
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum

Neutrino Beam Performance

ν_μ event rates at FD in neutrino beam

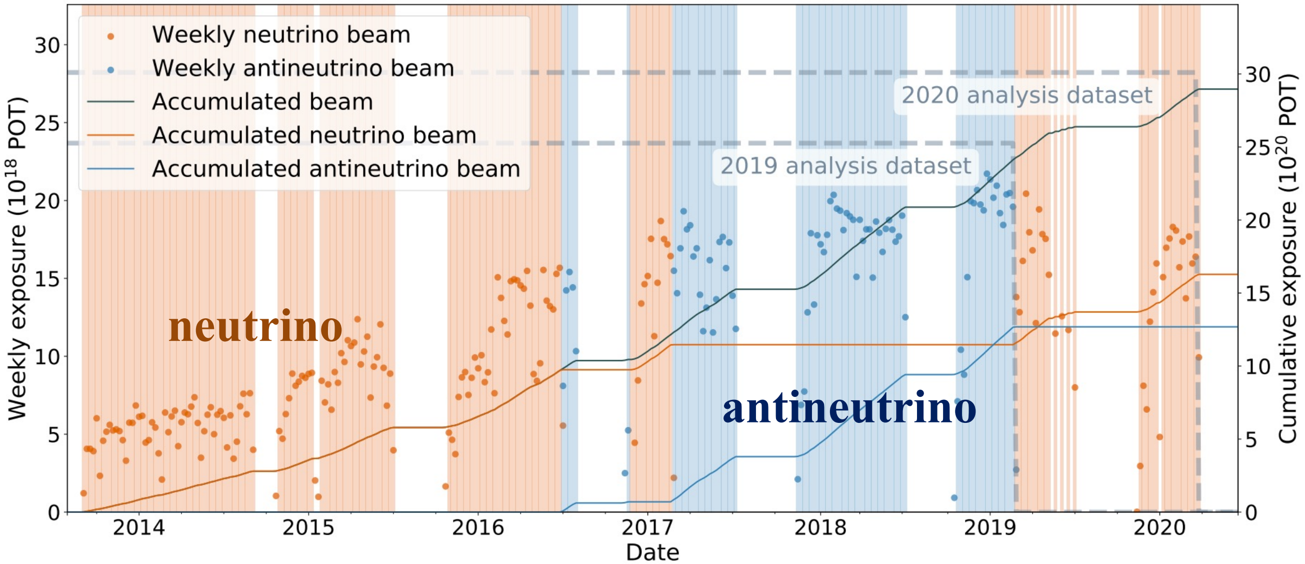


anti-ν_μ event rates at FD in antineutrino beam



Neutrino beam data: 13.6x10^{20} Protons on Target (POT), (+54% over 2019)

Antineutrino data: 12.5 x 10^{20} POT



Charge select pions to get 96% (83%) pure muon-neutrino, (anti-muon-neutrino) beam.

Exceed 700 kW design goal since Jan 2017

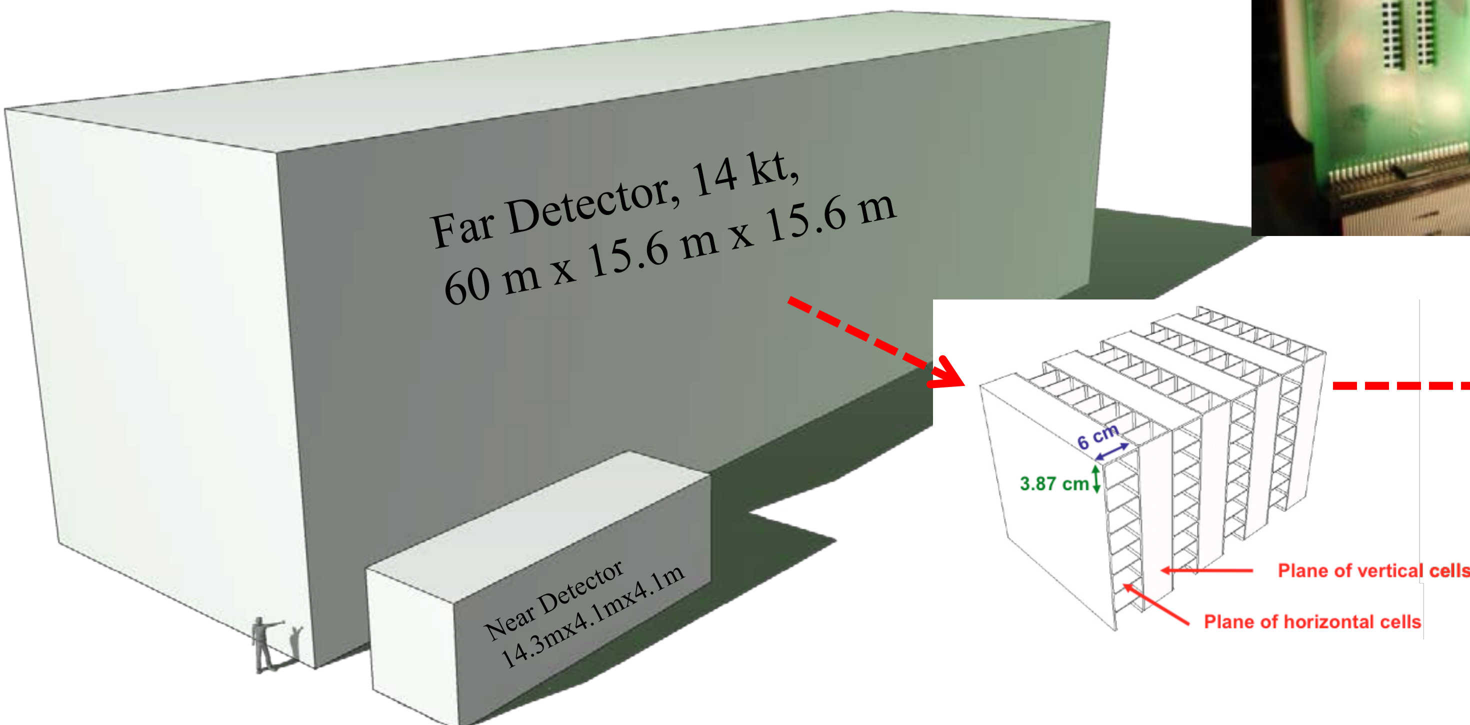
Upgrading beamline targets, horns and accelerator to achieve >=900 kW

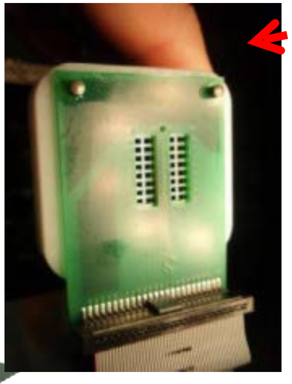
NOvA Detectors

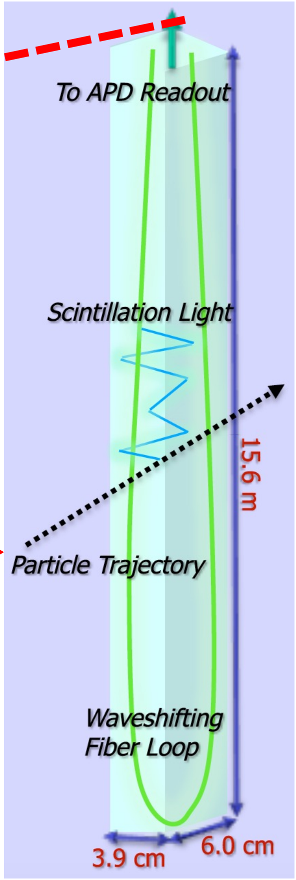
Far Detector (FD):

- 14-kton, fine-grained
- 344k detector cells

0.3-kton functionally identical Near Detector (ND), ~20k cells

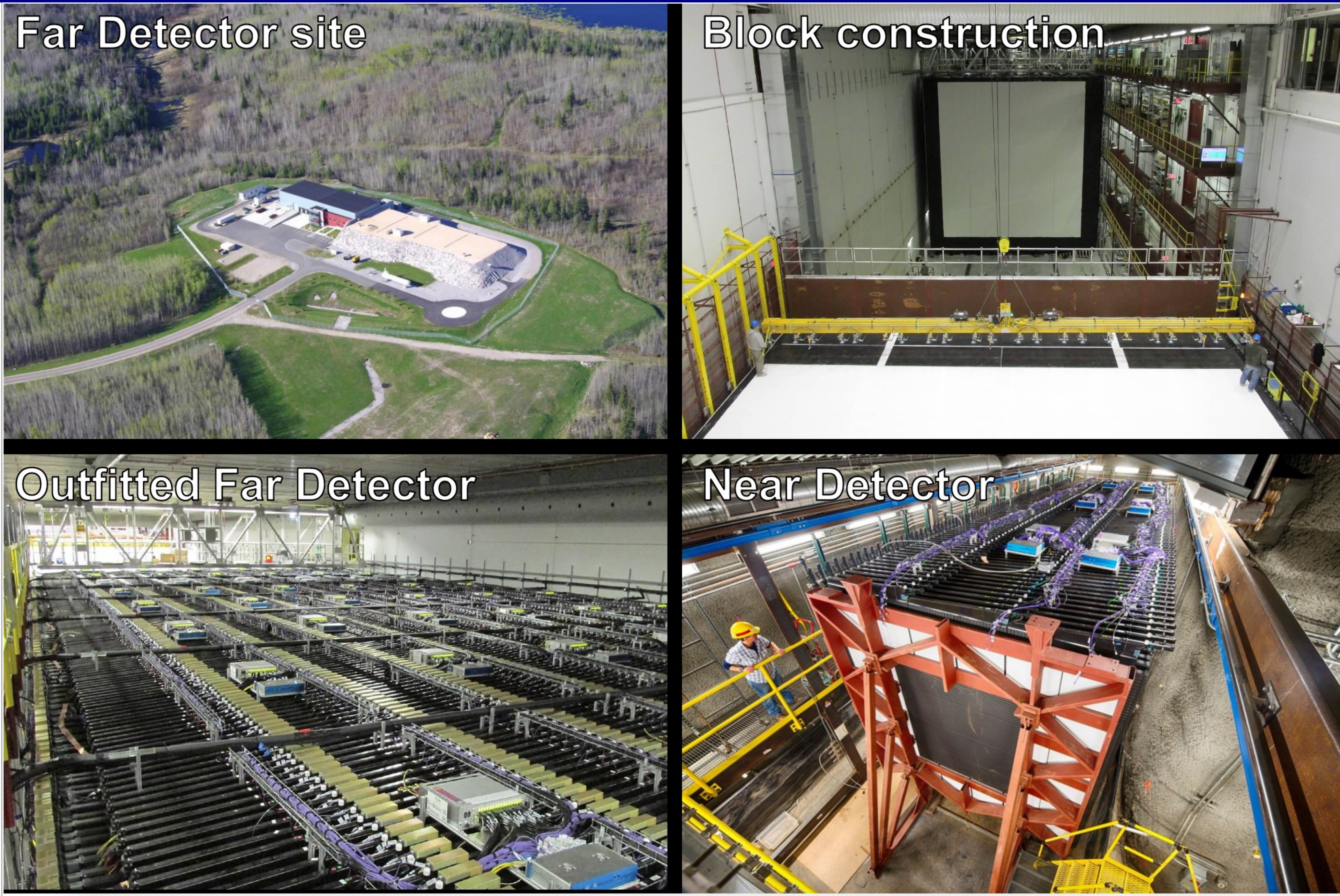






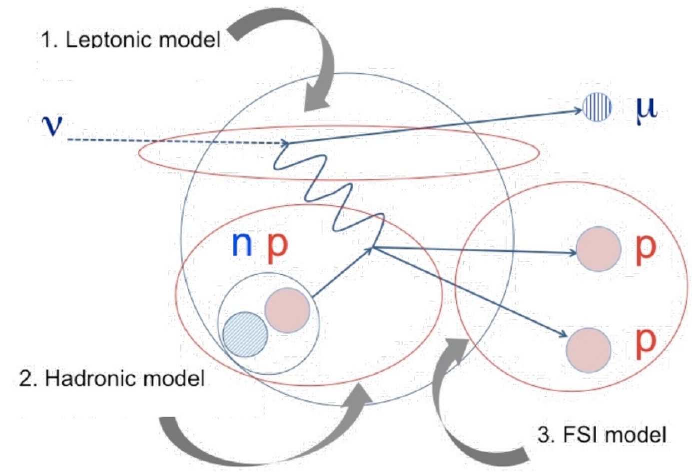
- Detectors are composed of PVC modules extruded to form long tube-like cells
- Each cell: filled with liquid scintillator, has wavelength-shifting fiber (WLS) routed to Avalanche Photodiode (APD)
- Cells arranged in planes, assembled in alternating vertical and horizontal directions → 3-D information of neutrino interactions

NOvA Detectors

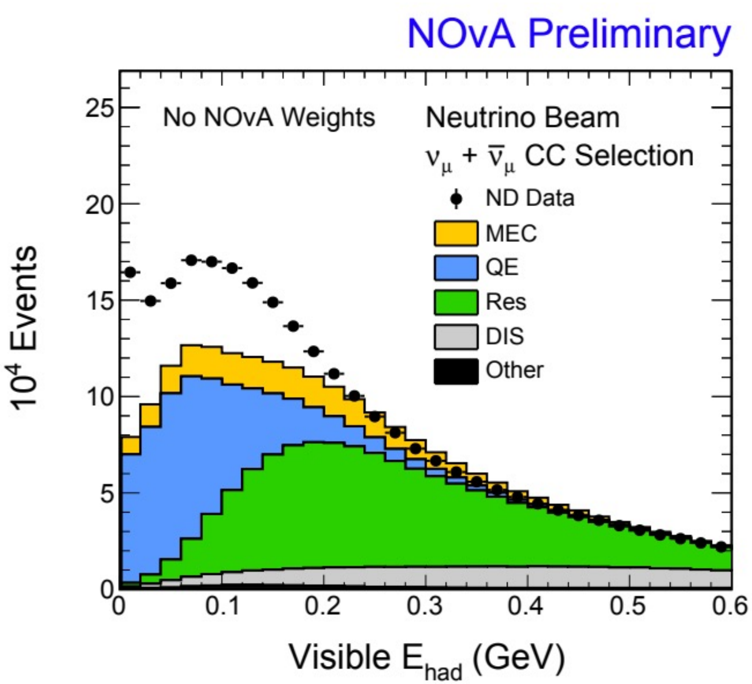


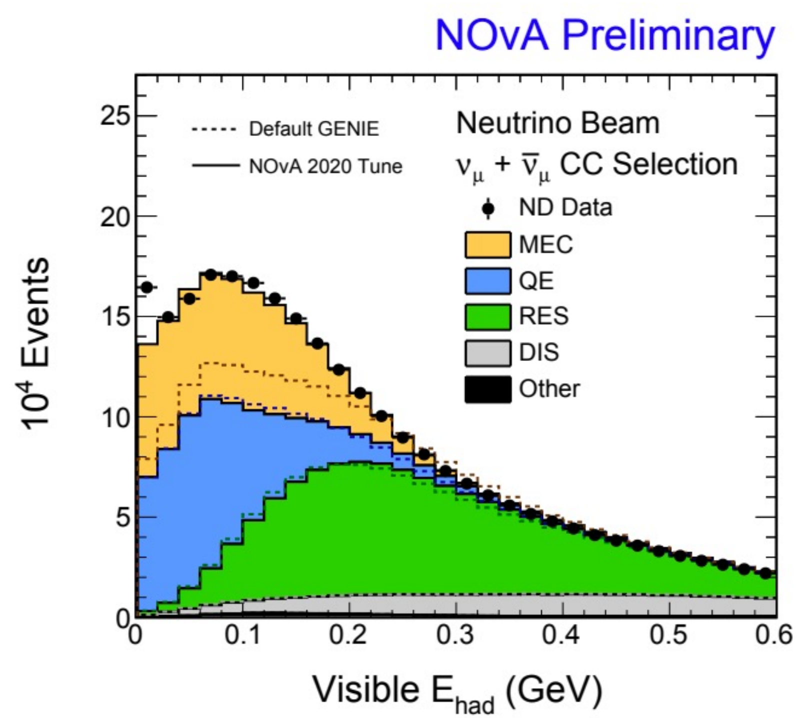
Neutrino Interaction Tuning

- Upgrade to GENIE 3.0.6 in 2020 (more models)
- Chose the most "theory-driven" available set of models along with GENIE's re-tune of some parameters
- Custom tuning for both central values and systematics:
  - Final State Interactions: external π-scattering data
  - Meson Exchange Current (MEC, Multi-nucleon interaction, 2p2h): amount tuned in 2D space to match NOvA ND data ($q_0 = E_\nu - E_\mu$, $|q| = |p_\nu - p_\mu|$)



T. Katori, AIP Conf. Proc. 1663, 030001 (2015)]

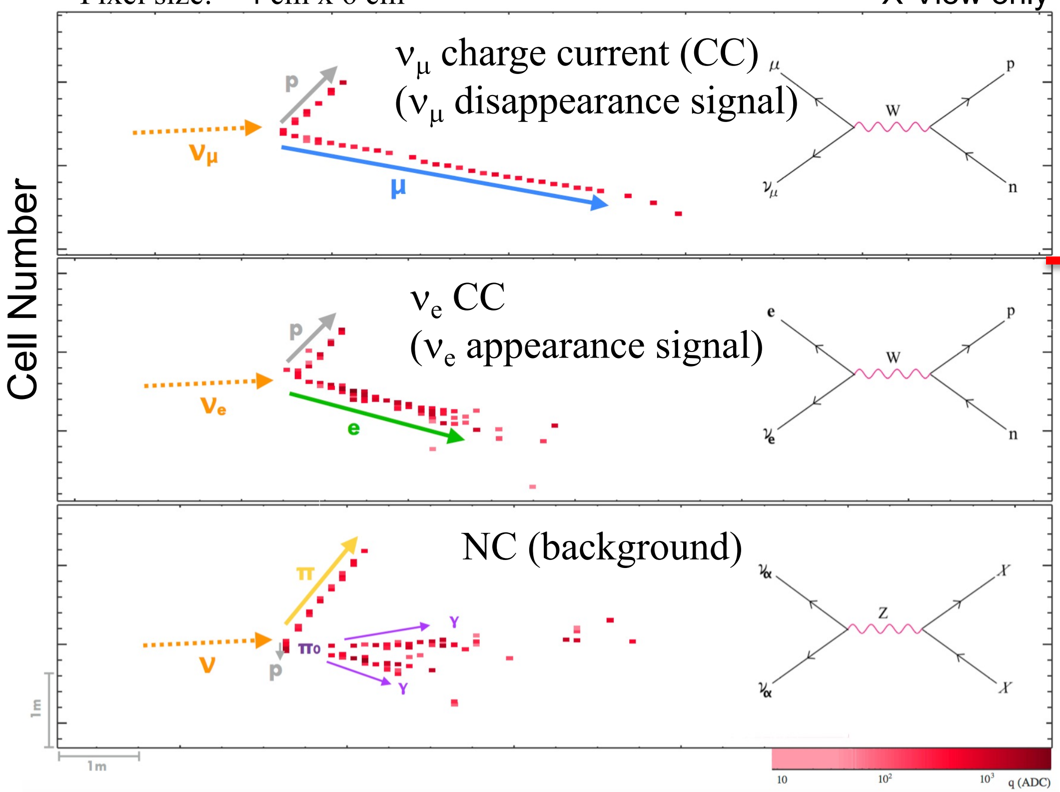




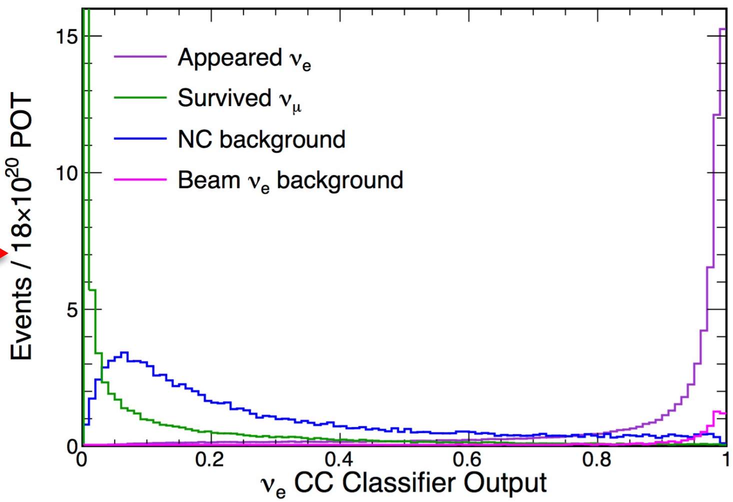
Deep-Learning based neutrino classifier (PID)

- CVN: a convolutional neural network (CNN), based on modern image recognition technology
- Extract features directly from pixel maps
- Statistical power equivalent to 30% more exposure than previous neutrino classifiers

Pixel size: ~ 4 cm x 6 cm



CVN output in the far detector MC

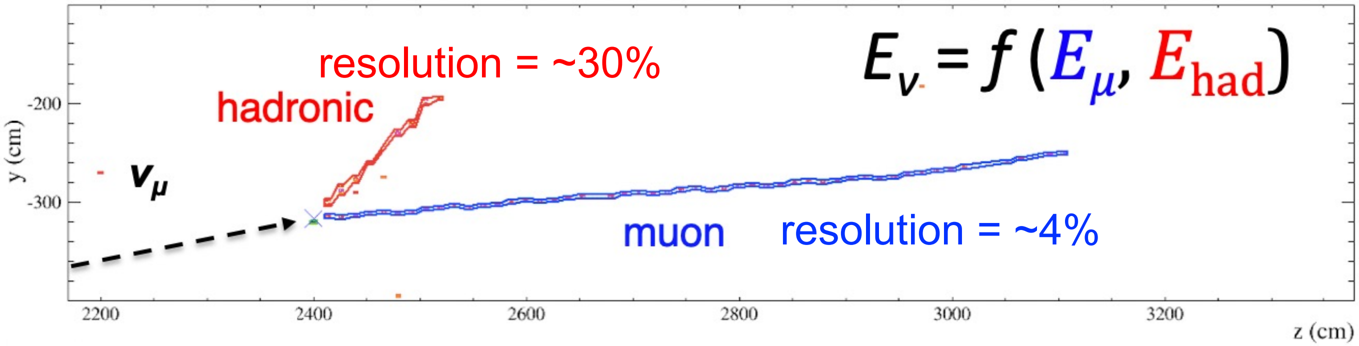


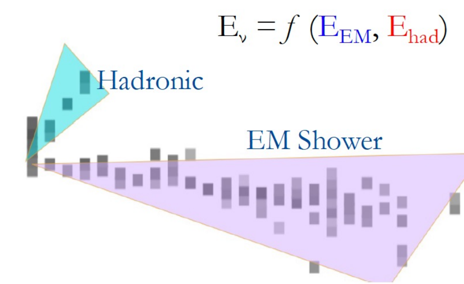
A. Aurisano et. al, JINST 11, P09001 (2016)

New, faster CVN trained for 2020 analysis

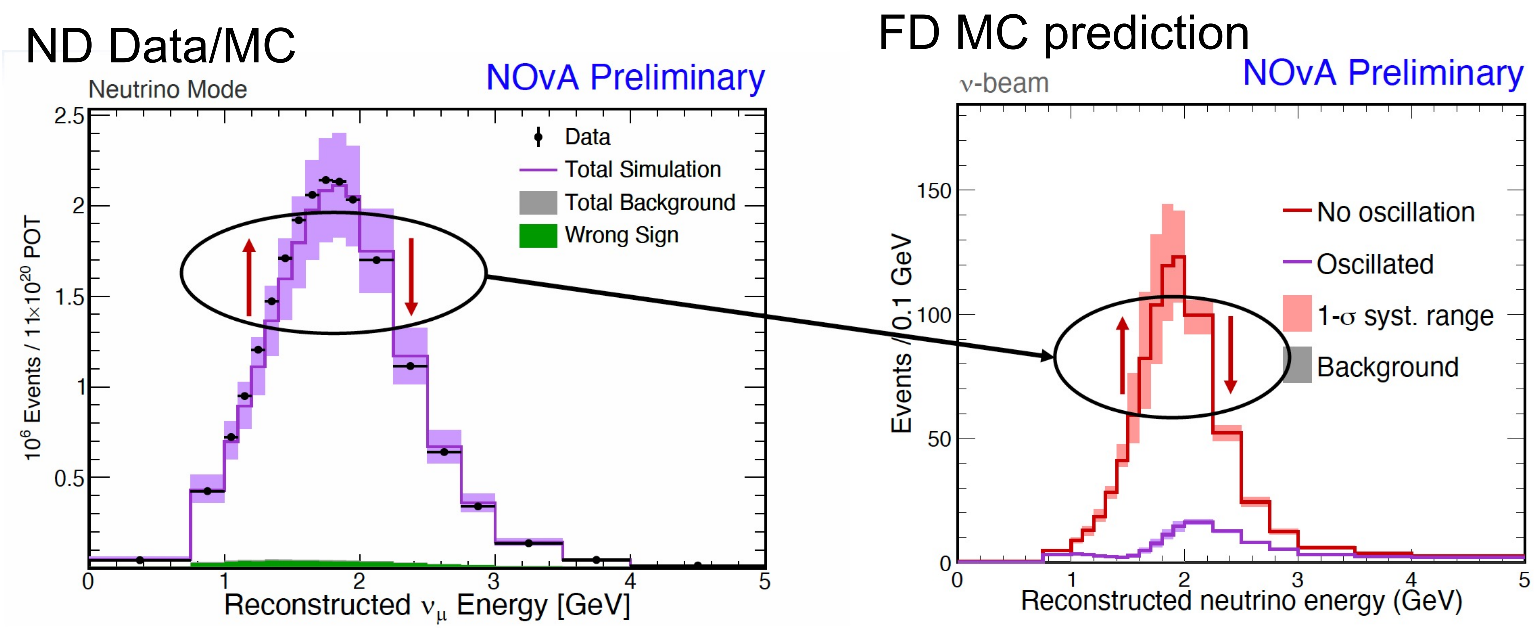
Select ν_μ ($\bar{\nu}_\mu$) CC and ν_e ($\bar{\nu}_e$) CC candidates from neutrino (antineutrino) beam with CVN in Near Detector (ND) and Far Detector (FD)

Energy Reconstruction and Extrapolation



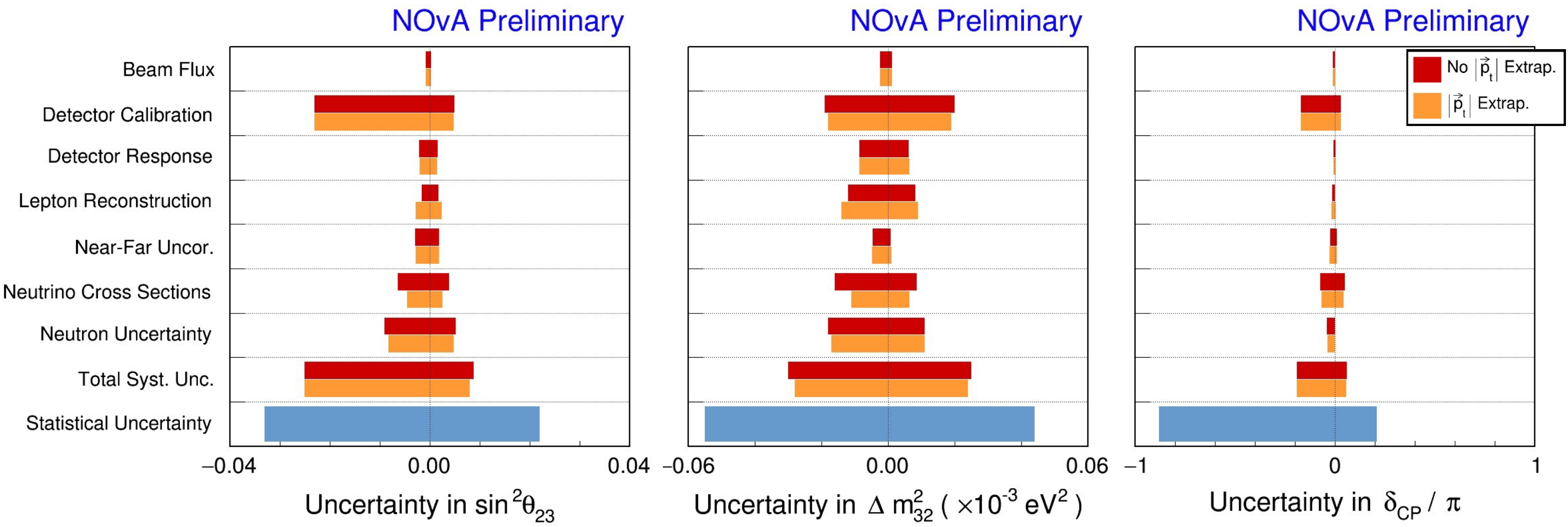


Overall Resolution:~11%



- Signal neutrino energy is the sum of muon/electron and hadronic energy.
- Observe data-MC differences in neutrino energy spectrum at the ND, extrapolate them to modify the FD MC prediction (significantly reduce systematics)
- Systematic uncertainties determined in ND also extrapolated to FD

Energy Reconstruction and Extrapolation



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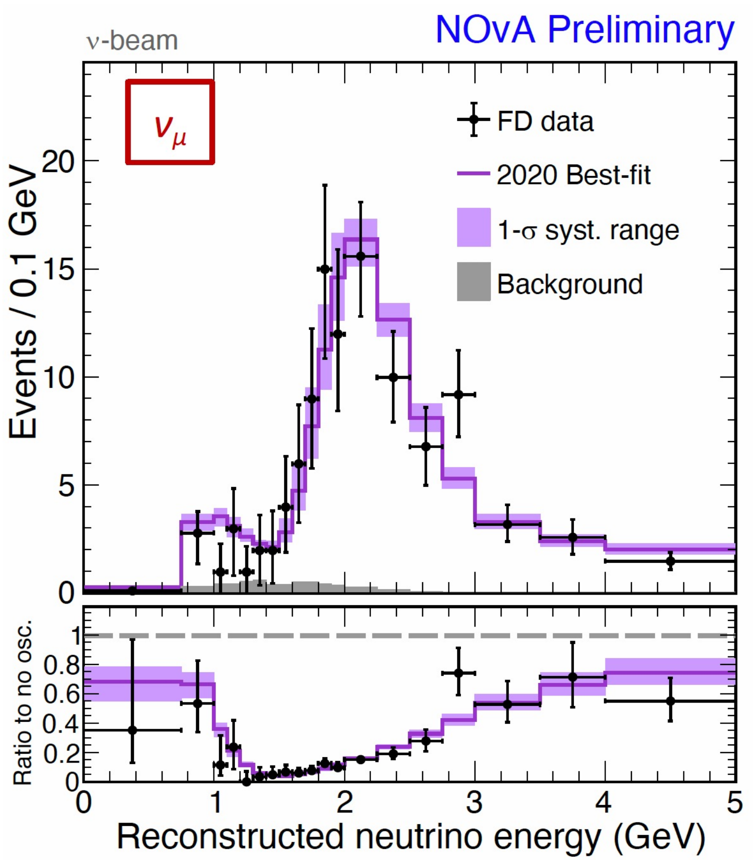
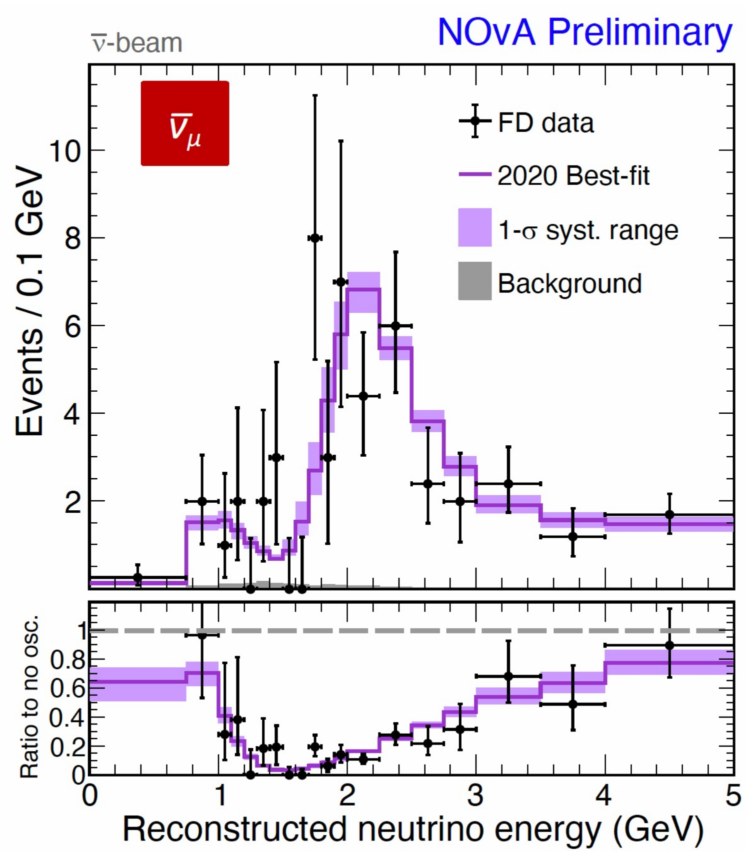
ν_μ and $\bar{\nu}_\mu$ Data at Far Detector

- FD selection:
  - Additional Boosted Decision Tree (BDT) to reduce cosmic backgrounds





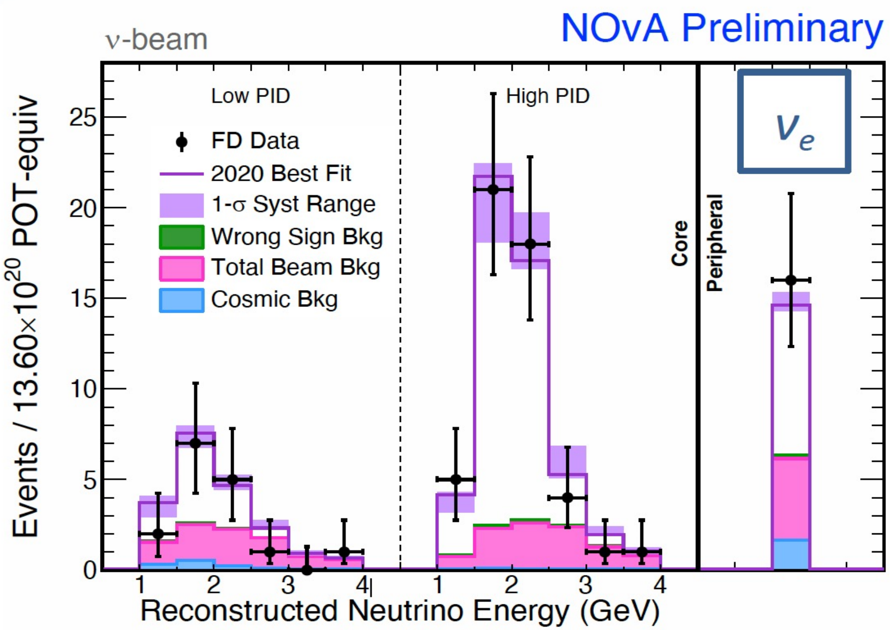
Neutrino beam:

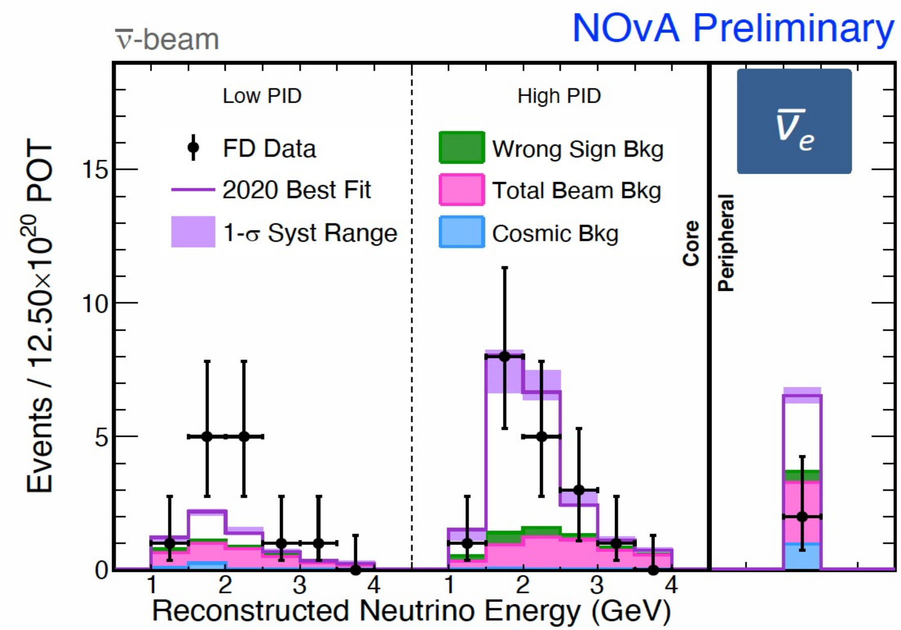
- Observe 211 events
- Total bkg prediction: 9.3 events

Anti-Neutrino beam:

- Observe 105 events
- Total bkg prediction: 2.8 events

ν_e and $\bar{\nu}_e$ Data at Far Detector





- ND data split into low and high PID ranges and extrapolate to FD
- FD selection: Add a region close to detector top with tighter cosmic ray cuts to count more signal events

Neutrino beam:

- Observe 82 ν_e like events
- Total bkg prediction: 26.8:1.0 wrong sign, 22.7 beam bkg, 3.1 cosmic

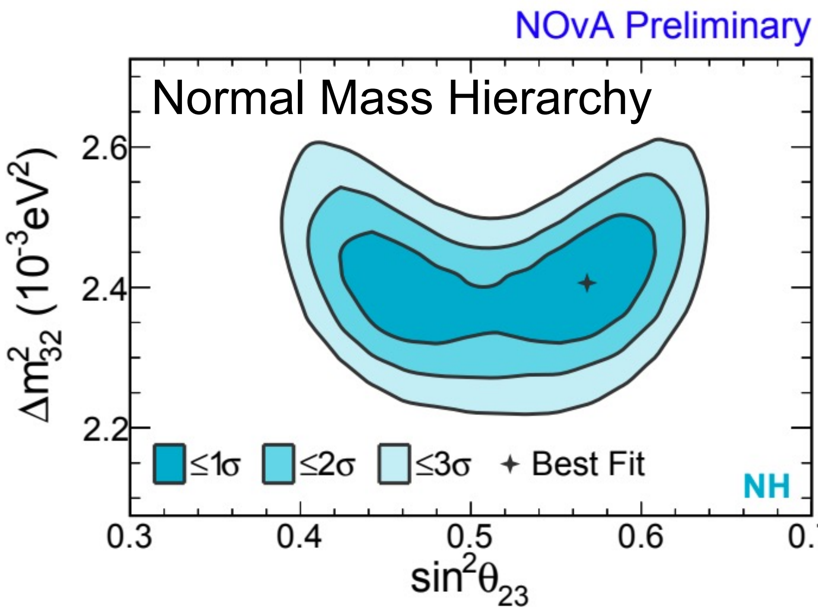
Anti-Neutrino beam:

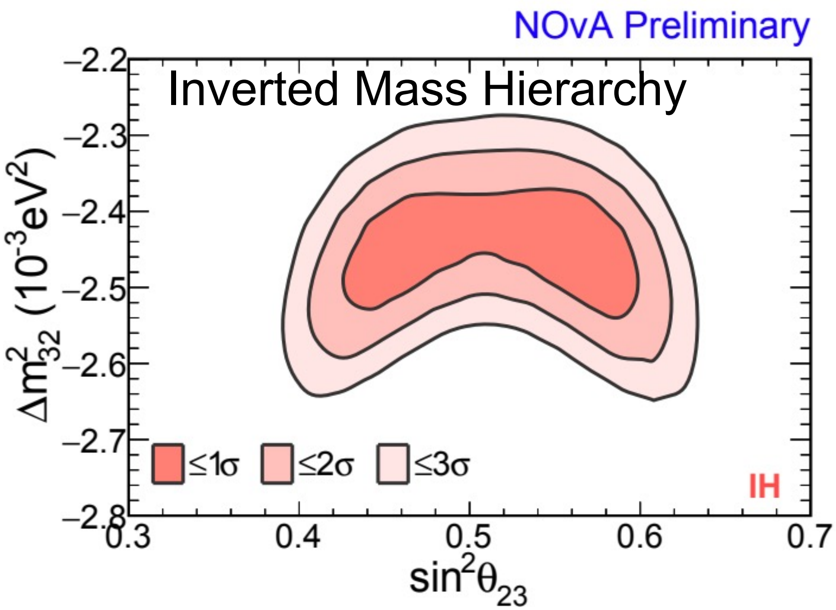
- Observe 33 $\bar{\nu}_e$ like events
- Total bkg prediction: 14.0: 2.3 wrong sign, 10.2 beam bkg, 1.6 cosmic

>4 σ $\bar{\nu}_e$ appearance

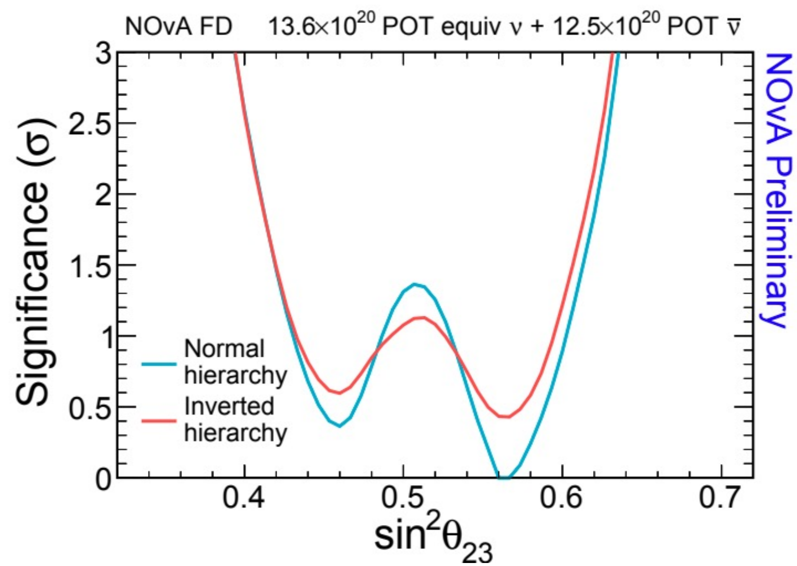
Extract oscillation parameters by fitting oscillation-weighted FD MC to FD data

Joint Appearance and Disappearance



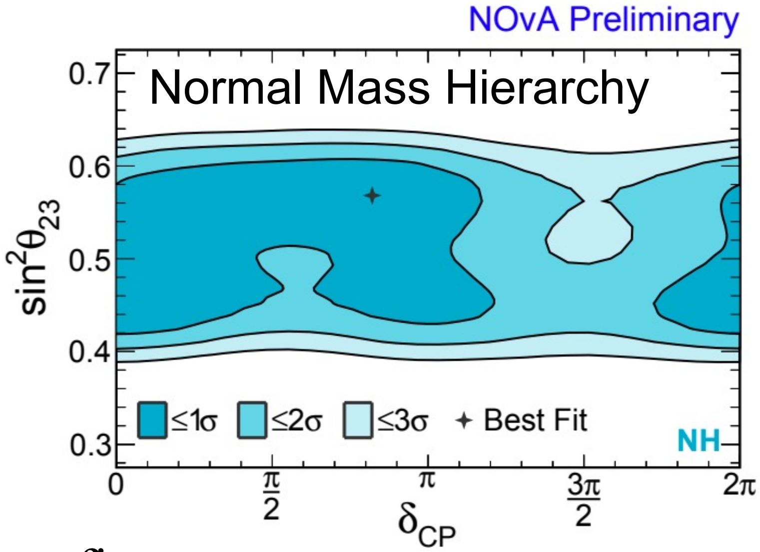


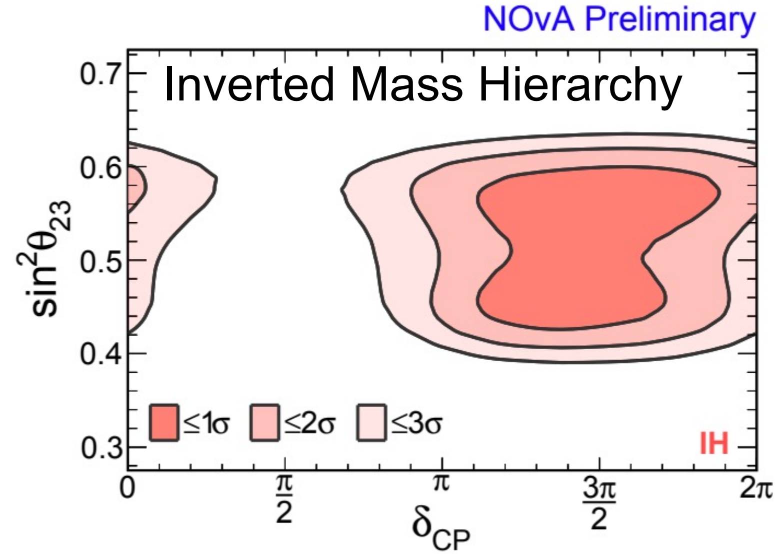
- Use frequentist analysis Feldman-Cousins method to infer oscillation parameters
- $\sin^2\theta_{13}$ = 0.085+-0.003 constrained from PDG avg. of reactor data



- Best fit:
  - Normal Mass Hierarchy
  - $\sin^2\theta_{23} = 0.57+0.03-0.04$ (UO)
  - $\Delta m^2_{32} = (2.41+0.07-0.07)*10^{-3}\ eV^2$
- Disfavor maximal mixing ($\theta_{23}=45^o$) at 1.1 σ
- Disfavor lower octant ($\theta_{23}<45^o$) at 1.2 σ

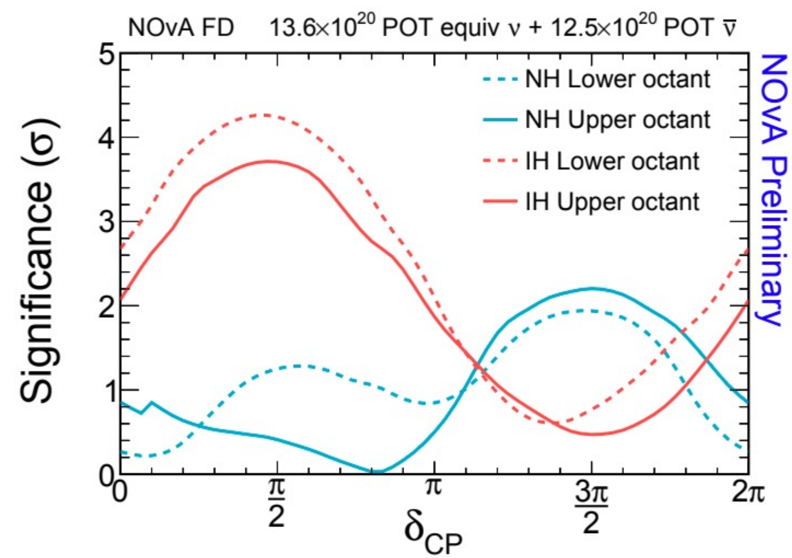
Joint Appearance and Disappearance





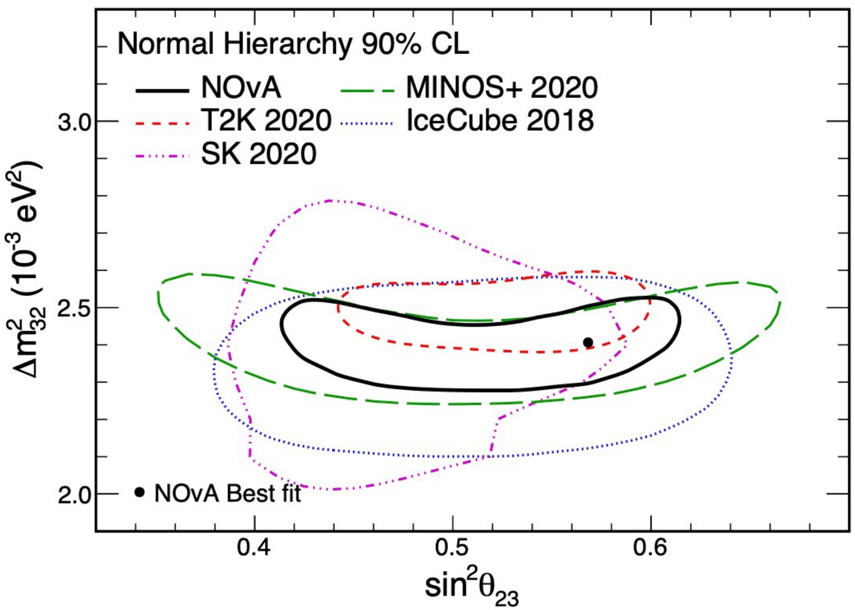
- Best fit:
  - Normal Mass Hierarchy ($m_3 > m_{1,2}$)
  - δ_{CP}= 0.82 π
  - $\sin^2\theta_{23}$ = 0.57+0.03−0.04 (UO)
  - Δm^2_{32} = (2.41+0.07-0.07)*10^{-3} eV^2

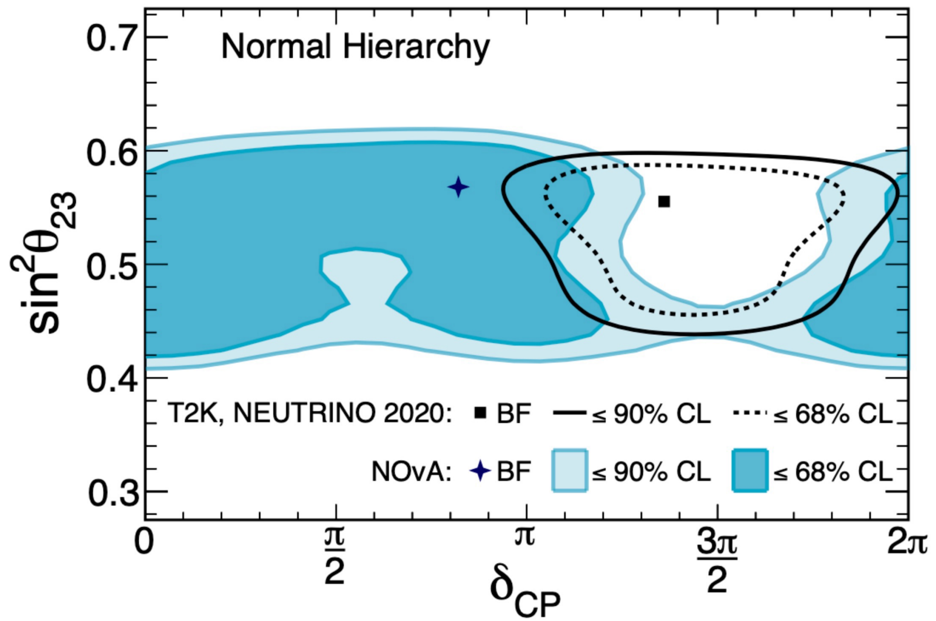
- Exclude $\delta_{CP}=\pi/2$ in IH at > 3σ
- Disfavor (NH, $\delta_{CP}=3\pi/2$) at ~2σ
- Disfavor Inverted Mass Ordering at 1.0σ



Compare with Other Experiments

NOvA's allowed 90% C.L. regions are compatible to other experiments



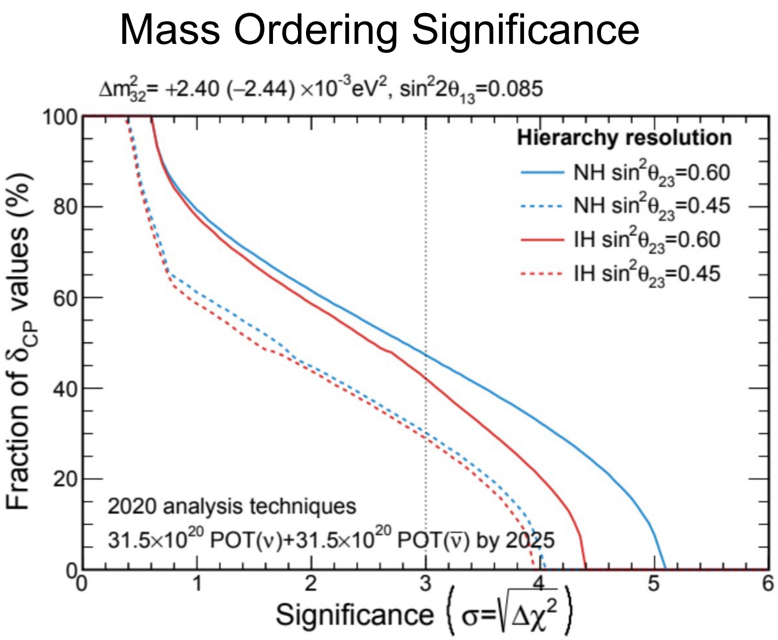


Agreement across many precision measurements about values of "atmospheric" parameters

- Apparent tension in allowed values of δ_{CP}
- NOvA & T2K are working on a fully self-consistent joint fit (including systs)

Summary and Prospect

- NOvA new results
  - Precisely measured $\sin^2\theta_{23} = 0.57{+}0.03{-}0.04$ and $\Delta m_{23}^2 = (2.41{+}0.07{-}0.07)*10^{-3}\ eV^2$
  - Exclude $\delta_{CP}=\pi/2$ in IH at > 3σ
  - Disfavor (NH, $\delta_{CP}=3\pi/2$) at $\sim 2\sigma$



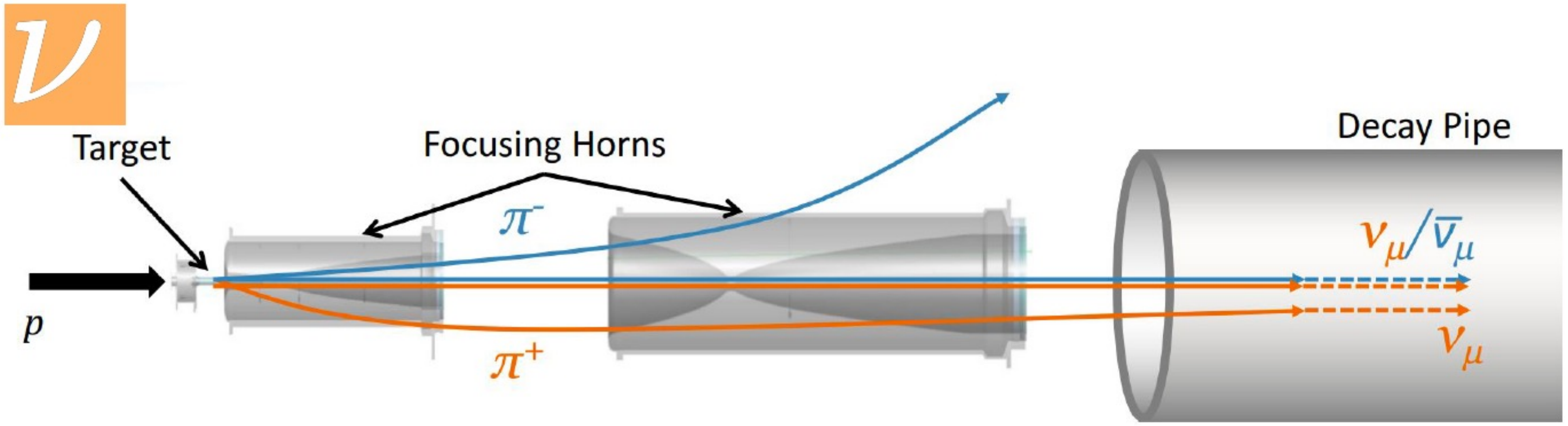
- NOvA is running through 2026, test beam program and potential accelerator improvement to enhance ultimate reach
- Optimistically, if $\delta_{CP}=3\pi/2$, 4-5 σ sensitivity to Mass Ordering
- >=3σ sensitivity to Mass Ordering for 30-50% of δ_{CP} values (depends on θ_{23} and true ordering)

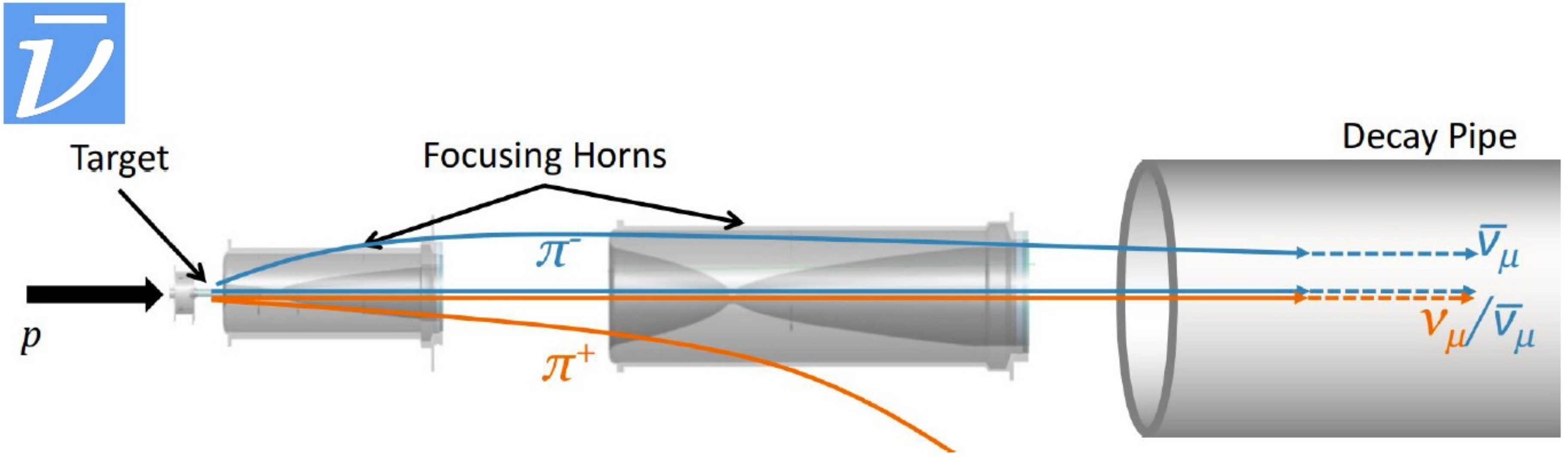
Thank you!

Backup

NuMI Off-Axis Beam

Charge select pions to get 96% (83%) pure muon-neutrino, (anti-muon-neutrino) beam.





Oscillation Analysis Process

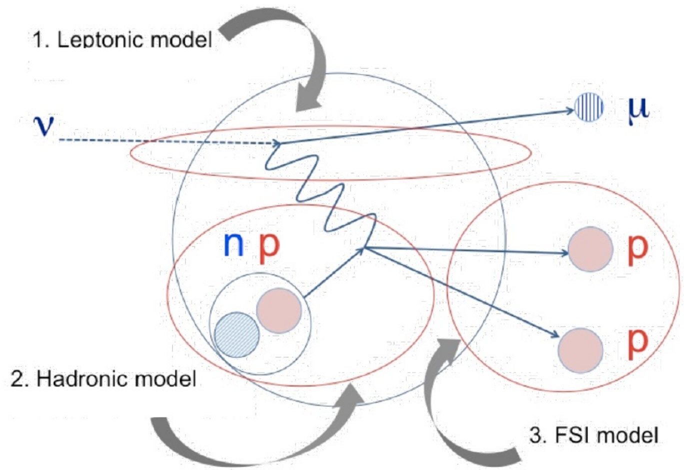
Measure neutrino flavor change vs. energy over a long travel distance to determine oscillation parameters:

- Identify ν_e and ν_μ charge current events from cosmic rays and beam backgrounds (PID)
- Reconstruct neutrino energy and other kinematic variables
- Observe differences between data and MC simulation at Near Detector (ND), extrapolate them to Far Detector (FD) to correct FD MC
- Infer oscillation parameters by fitting oscillation-weighted FD MC to FD data

+ Tune interaction models based on ND data and external data, mitigating uncertainties on neutrino flux, cross sections, and detector response

Neutrino Interaction Tuning

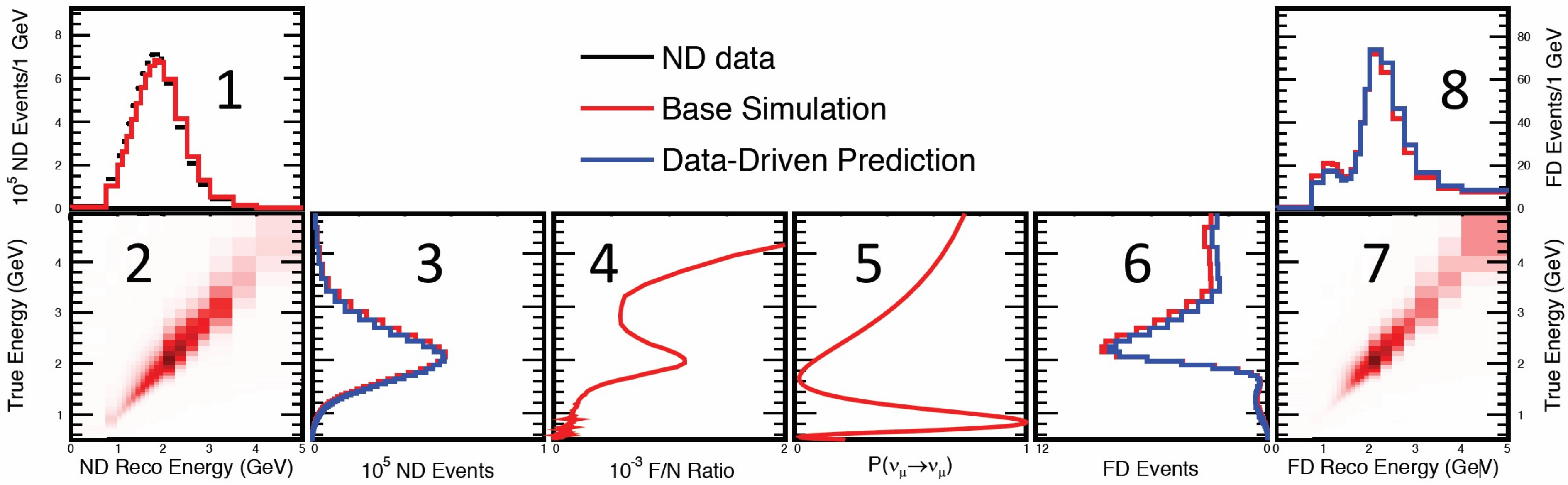
- Upgrade to GENIE 3.0.6 in 2020 (more models)
- Chose the most "theory-driven" available set of models along with GENIE's re-tune of some parameters
- Custom tuning for both central values and systematics:
  - Final State Interactions: external π-scattering data
  - Meson Exchange Current (MEC, Multi-nucleon interaction, 2p2h): amount tuned in 2D space to match NOvA ND data ($q_0 = E_\nu - E_\mu$, $|q| = |p_\nu - p_\mu|$)



T. Katori, AIP Conf. Proc. 1663, 030001 (2015)]

Process	Model	Reference
Quasielastic	Valencia plus Z-expansion form factor	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
MEC	Valencia w/ custom tune	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Interactions	hN w/ custom tune	S. Dytman, Acta Physica Polonica B 40 (2009)

Energy reconstruction and Extrapolation

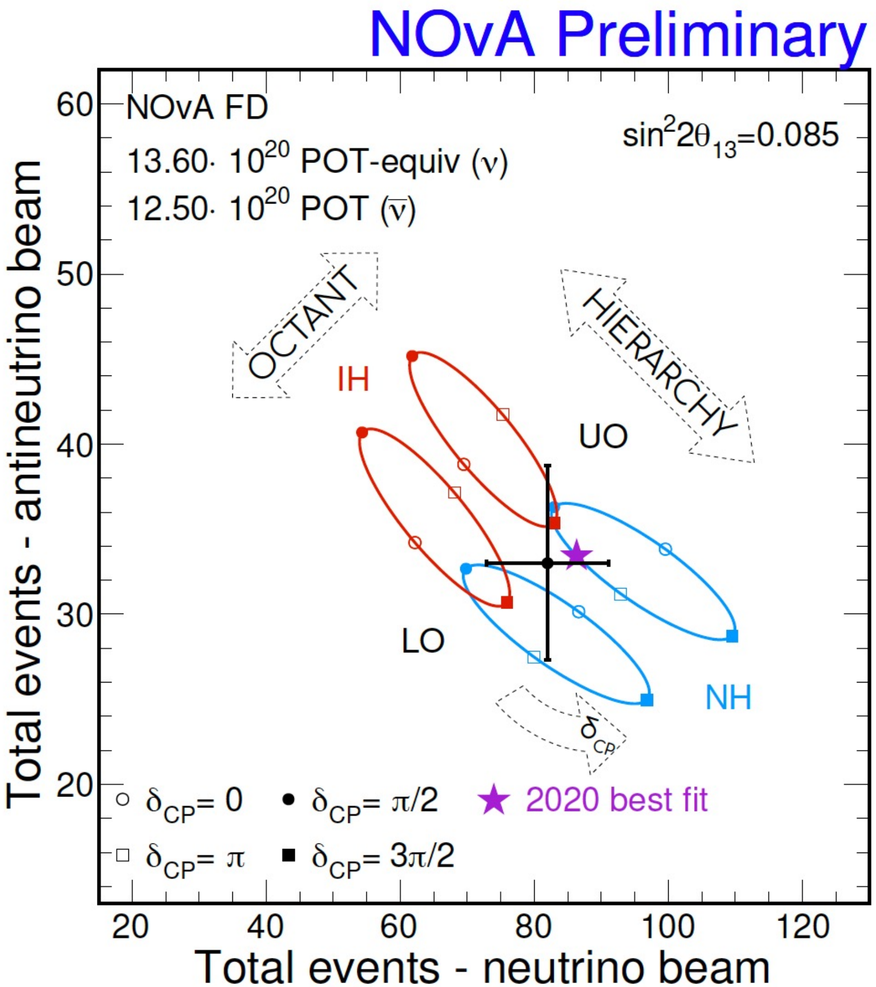


1. ND Data Reco E_ν 2. ND Reco-to-True E_ν Weighting 3. ND True E_ν 4. Far / Near Ratio 5. Oscillations Probability 6. FD True Eν 7. FD True-to-Reco E_ν Weighting 8. Predicted FD Reco E_ν

- The extrapolation for ν_μ disappearance is divided into 4 bins in hadronic energy fraction called quartiles, each bin
- For ν_e appearance the ND ν_μ CC data and intrinsic beam ν_e background are extrapolated separately

Joint Appearance and Disappearance

$\nu_e/\bar{\nu}_e$ appearance event counts and best fit from $\nu_e/\bar{\nu}_e + \nu_\mu/\bar{\nu}_\mu$ combined analysis



- Disfavor maximal mixing (θ_{23}=45°) at 1.1 σ
- Disfavor lower octant (θ_{23}<45°) at 1.2 σ
- Consistent with all δ_{CP} values in NH at < 1.1σ
- Exclude $\delta_{CP}=\pi/2$ in IH at > 3σ
- Disfavor (NH, $\delta_{CP}=3\pi/2$) at ~2σ
- Disfavor inverted mass ordering at 1.0σ

Mass Ordering Significance vs. Year