Measurements of the Atmospheric Neutrino Oscillation Parameters (and others) with NOvA

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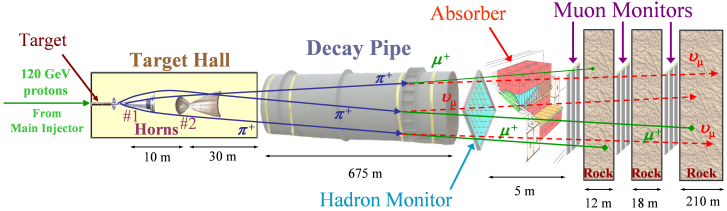
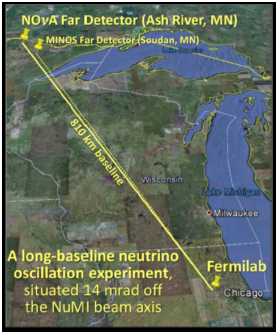
July 30, 2019

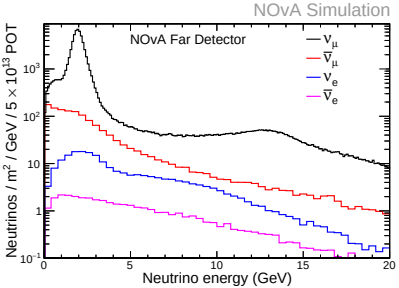
Design Overview

- Fermilab's NuMI beam
- Near detector
  - Measures unoscillated beam composition, energy spectrum
- Far detector
  - Observes oscillations from mixing parameters θ_{13}, θ_{23}, δ_{CP}, $|\Delta m^2_{32}|$, $\mathrm{sgn}(\Delta m^2_{32})$





- Off-axis → narrow spectrum at 2 GeV
- 1st oscillation maximum at 810 km

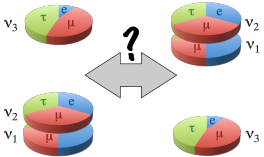


Physics Goals

- Observe:

$$\nu_\mu \to \nu_\mu \qquad \nu_\mu \to \nu_e$$
$$\bar{\nu}_\mu \to \bar{\nu}_\mu \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

- θ_{23} — is it maximal? (ν_3 has equal ν_μ, ν_τ)
- Octant of θ_{23} if not maximal (more ν_μ or ν_τ?)
- Sign of Δm^2_{32} — mass ordering (hierarchy)

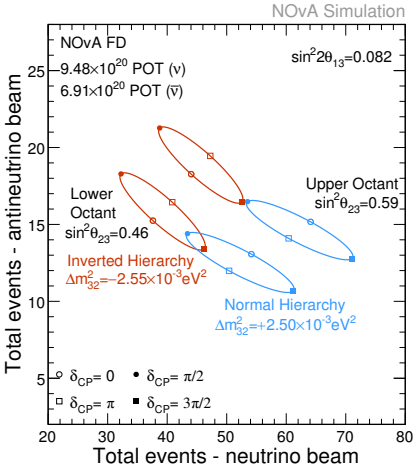


- Discover or constrain CP violation in neutrino sector

- Are there additional sterile neutrinos?

- Neutrino cross-sections

- Astrophysics

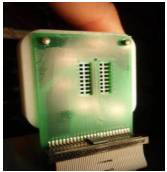


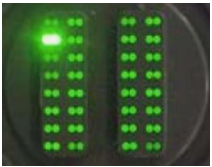
Matter effect enhances (suppresses) ν_e appearance for normal (inverted) ordering

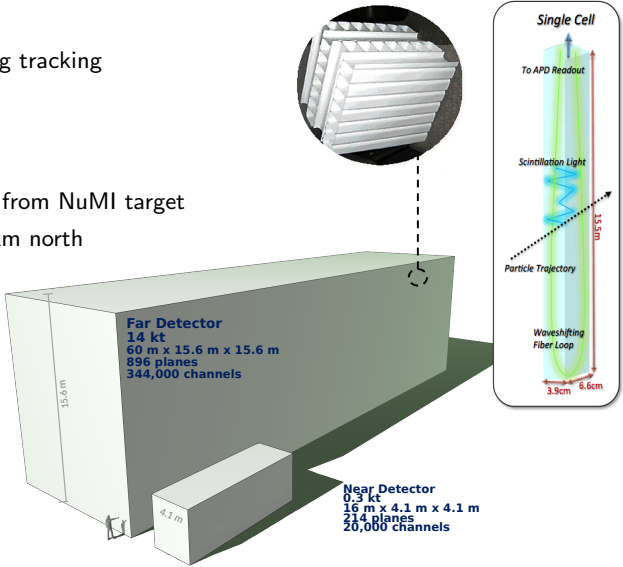
Detector Technology

- Two functionally identical detectors
- Segmented plastic and scintillator sampling tracking calorimeter
- 63% active
- APD readout
- Near detector is 300 t, underground, 1 km from NuMI target
- Far detector is 14 kt, on the *surface*, 810 km north

32 pixel APD sees
fiber pairs from 32 cells

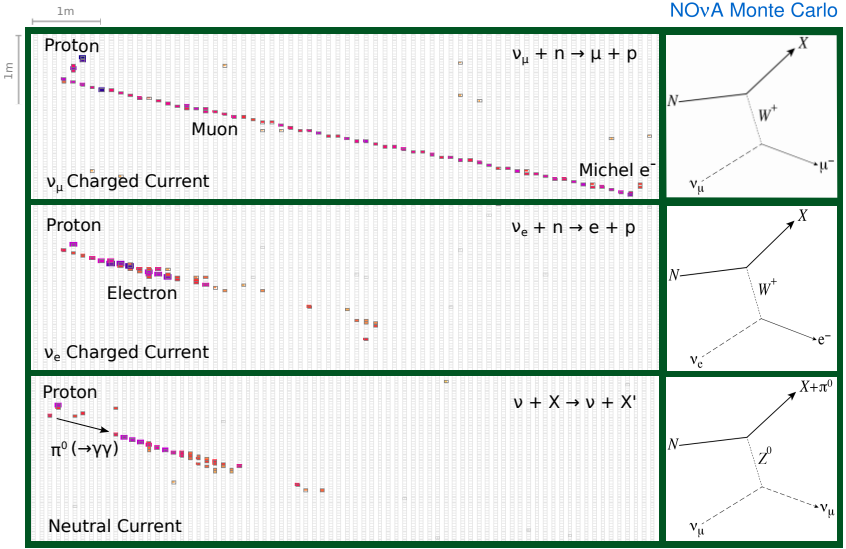




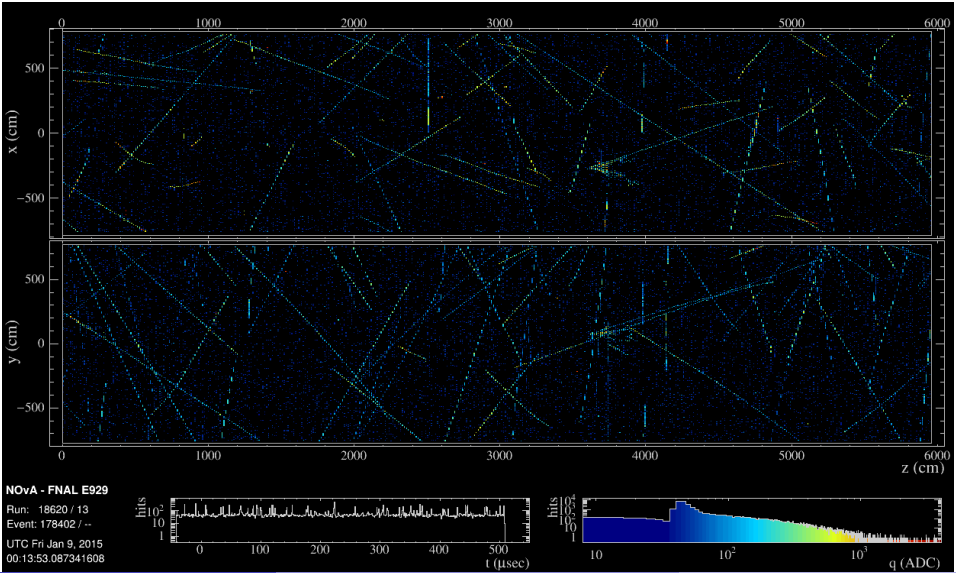


Event Topologies

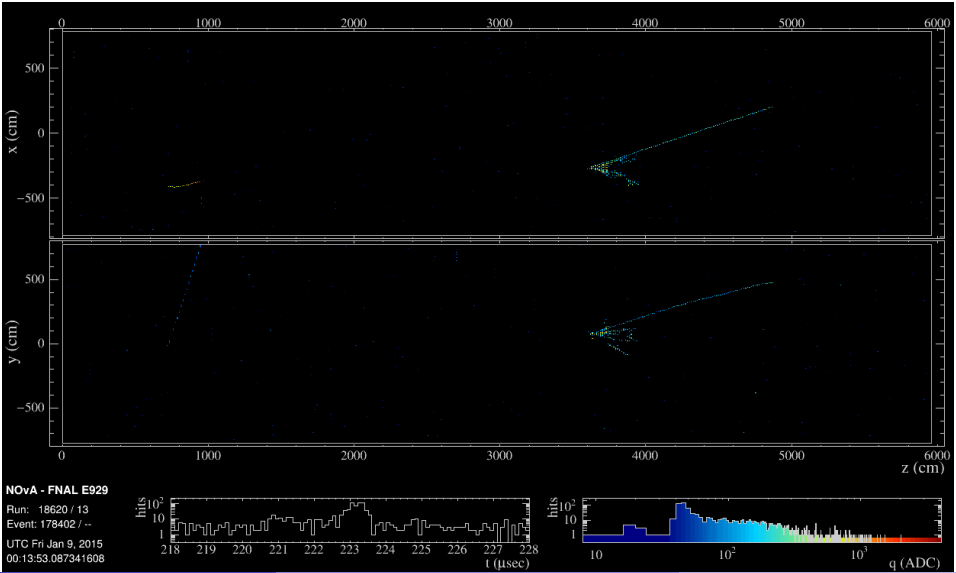
NOνA Monte Carlo



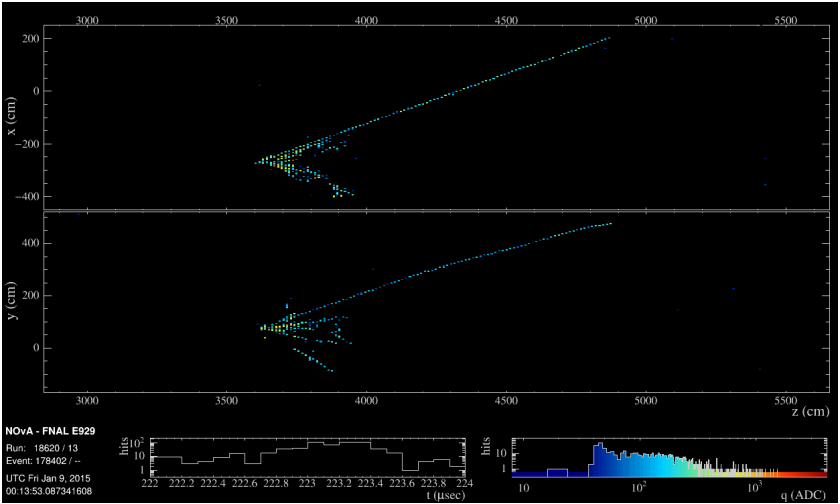
Cosmic Rejection — 550 μs exposure of the Far Detector — 150 kHz of cosmics



Cosmic Rejection — Zoomed into 10 μs NuMI beam pulse: 10^5 cosmic rejection



. . . and zoomed in spatially



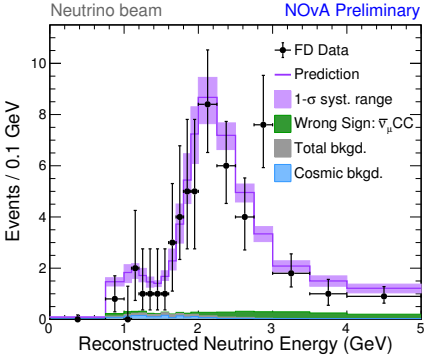
- Selection cuts and convolutional neural net classifier reduce background by a further 10^7

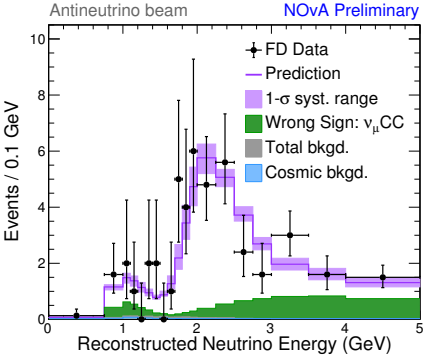
ν_μ Far Detector Data

Data from 2013 to 2019

- Neutrino mode: 8.85×10^{20} protons-on-target
- 113 events selected
- Background: 4.2 events, half cosmic, half beam

- Anti-neutrino mode: 12.33×10^{20} protons-on-target
- 102 events selected
- Background: 2.2 events: 0.8 cosmic, 1.4 beam

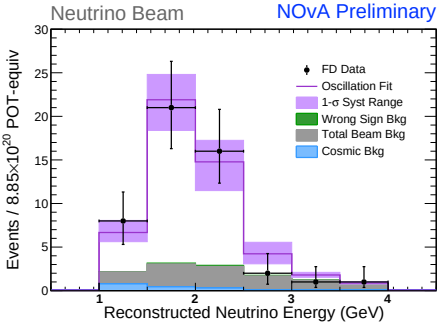


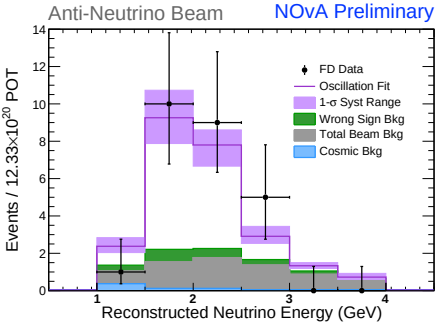


Selected Events — ν_e

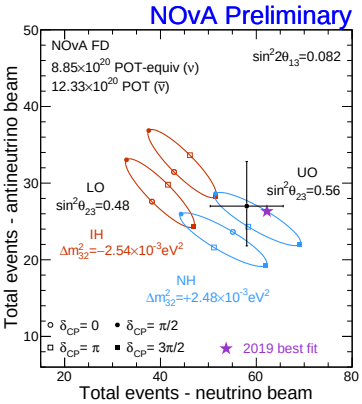
- Selected 58 events in FD in ν mode
- Background: 14.7 events
  - 11 beam (intrinsic ν_e, ν_μ, ν_τ, neutral current)
  - 0.7 wrong-sign (appearing $\bar{\nu}_e$)
  - 3 cosmic

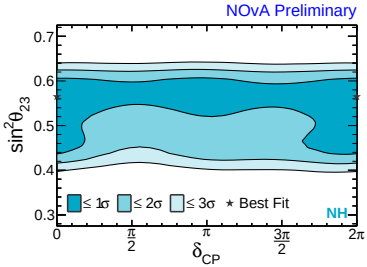
- Selected 27 in $\bar{\nu}$ mode
- Background: 10.3 events
  - 7.0 beam
  - 2.2 wrong-sign
  - 1.1 cosmic
- 4.4σ electron anti-neutrino appearance
  - Only world observation of ν_e appearance

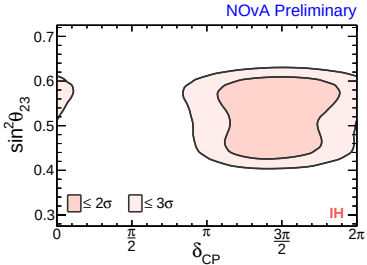


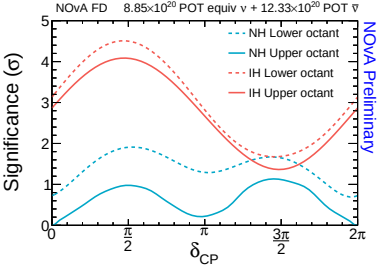


Combined Appearance/Disappearance Results — Mass ordering, θ_{23}, δ_{CP}



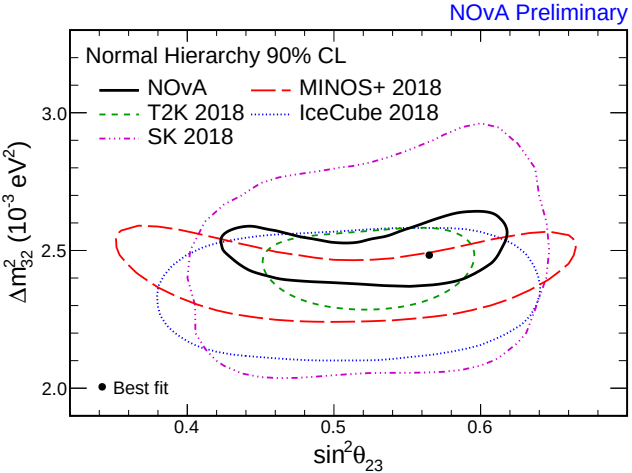




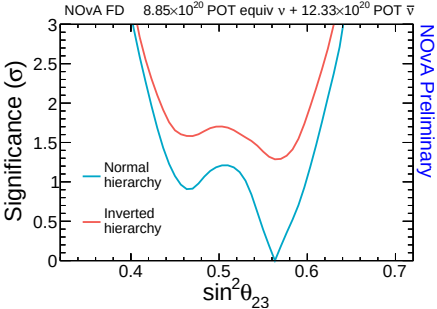


- Prefer normal hierarchy by 1.9σ
- Prefer **upper octant** by 1.6σ
- Exclude $\delta = \pi/2$ in IH at $> 3\sigma$

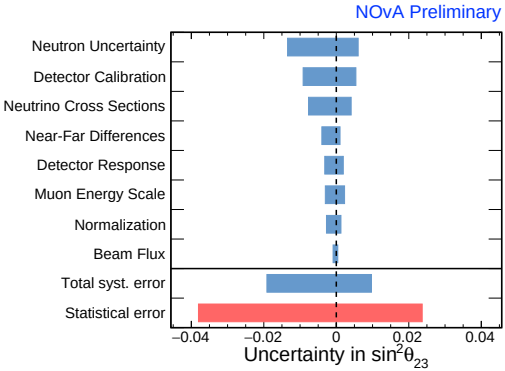
Combined Appearance/Disappearance Results — θ_{23}, Δm^2_{32}



- $\Delta m^2_{32} = (2.48^{+0.10}_{-0.06}) \times 10^{-3}\,\mathrm{eV}^2$ (NH)
- $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$ (upper octant)



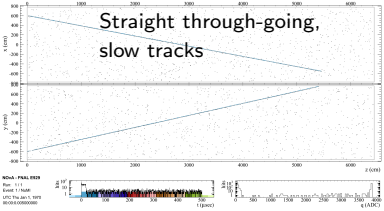
Systematics



- Statistics dominated
- But systematic uncertainties are important
- Working to reduce all major systematics:
  - Neutron response uncertainty — important for $\bar{\nu}$
  - Calibration — to be improved by 2019 test beam
  - Neutrino cross sections

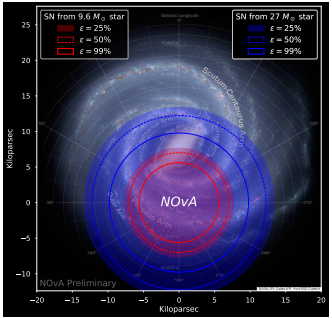
Astrophysics with NOvA

- Large fine-grained detectors support a variety of astrophysical analyses
- Far Detector sensitive to slow, intermediate-mass magnetic monopoles

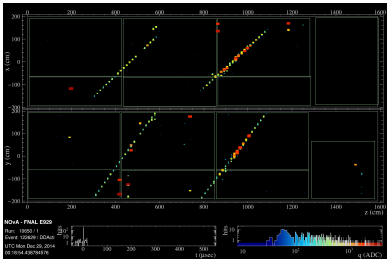


Galactic core-collapse supernovae

- 2200 inverse beta decay events at 10 kpc
- Burst of 2–4 hit clusters



- Seasonal dependence of multi-muon cosmics in Near Detector
- Phys. Rev. D99, 122004 (2019), arXiv:1904.12975



Plus multi-messenger astrophysics with gravitational waves, dark matter searches, $n\bar{n}$ oscillation, and more...

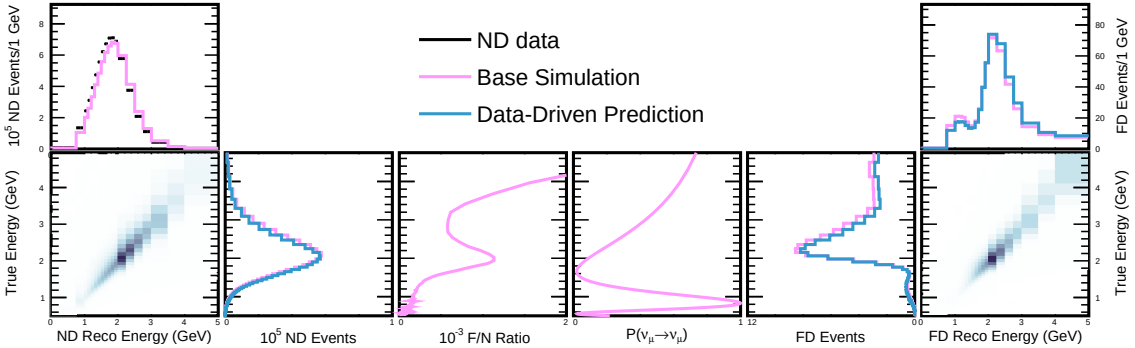
Conclusions

- Observed appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam at 4.4σ
- Favor normal hierarchy at 1.9σ
- Inverted and δ around $\pi/2$ excluded at 3σ

- Plan to run until 2025
  - Potential 3σ reach for mass ordering
  - Potential 2σ sensitivity to CP violation
- Astrophysics! — poster PS3-219 today & tomorrow
  - And posters PS1-131, PS1-103 in session 1

Predicting the Far Detector Spectrum

- Near Detector data used to predict Far Detector data given any oscillation parameters

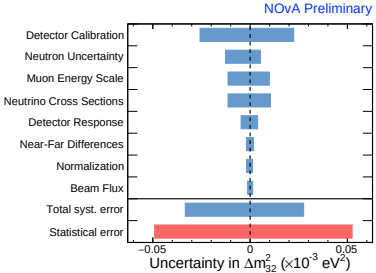


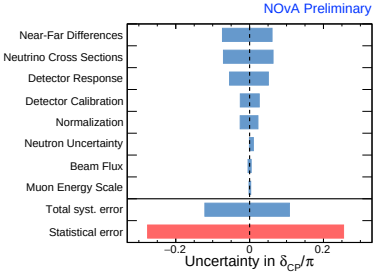
- Uncertainties in flux, cross section and efficiency largely cancel: similar detectors in same beam
- But at second order rely on simulation for reco-to-true matrices, Far/Near flux ratio, etc.

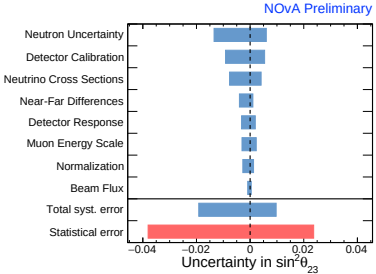
Backup

Backups

Systematics



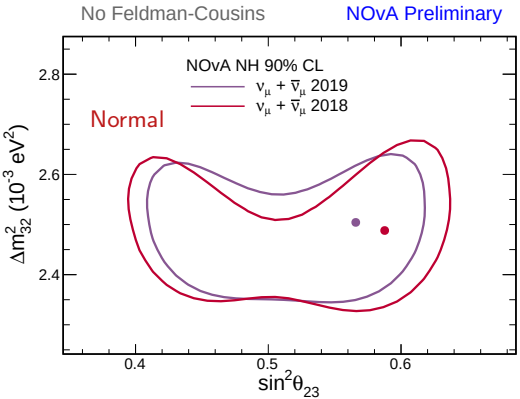


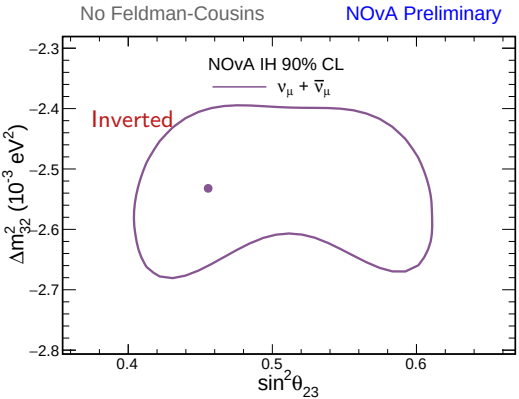


- Statistics dominated
- But systematic uncertainties are important. Leading:
  - Calibration — to be improved by 2019 test beam program
  - Neutrino cross sections
  - Neutron response uncertainty — important for $\bar{\nu}$

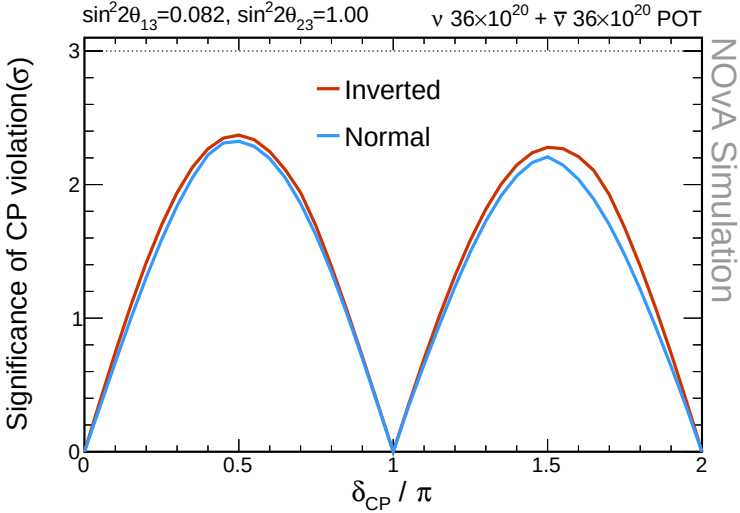
Results — ν_μ Only

- Neutrinos and anti-neutrinos are fit together assuming CPT

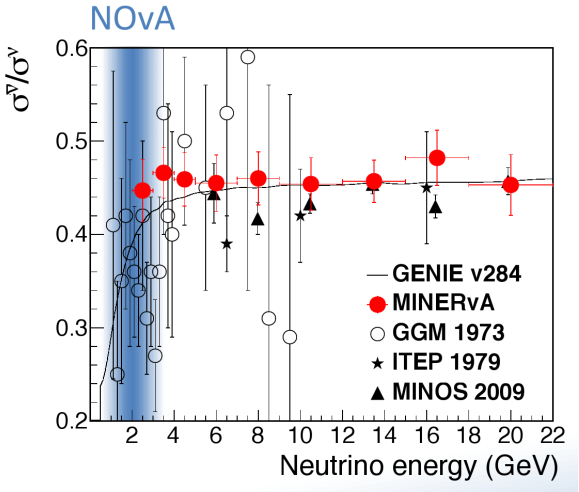




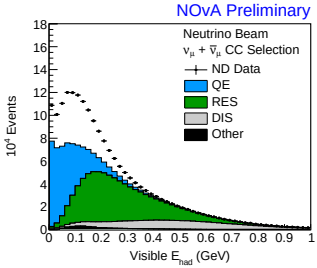
Delta sensitivity

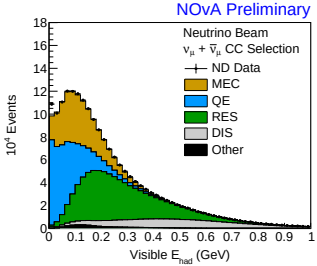


Wrong-sign cross section

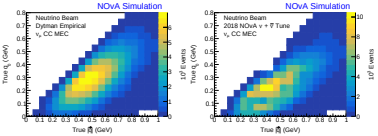


MEC Tuning





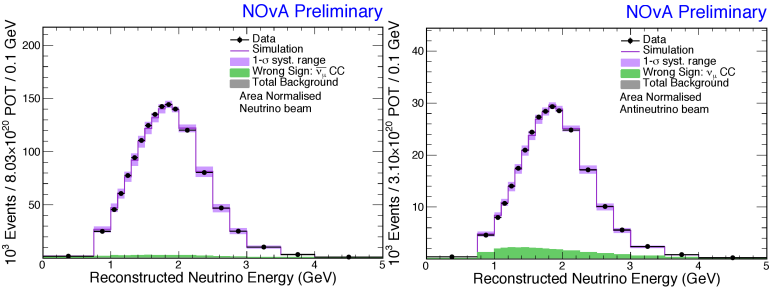
- We enable GENIE's empirical "meson exchange current" (MEC) model
- Accounts for interactions on correlated nucleon pairs leading to multi-nucleon knockout (two particle, two hole: 2p2h)
- All remaining ν_μ excess in data is used to scale MEC in 2D bins of $(q_0, |\vec{q}|)$



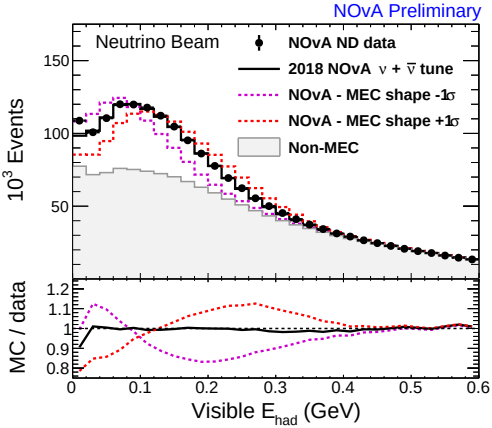
- By construction, tuned MC closely matches the data

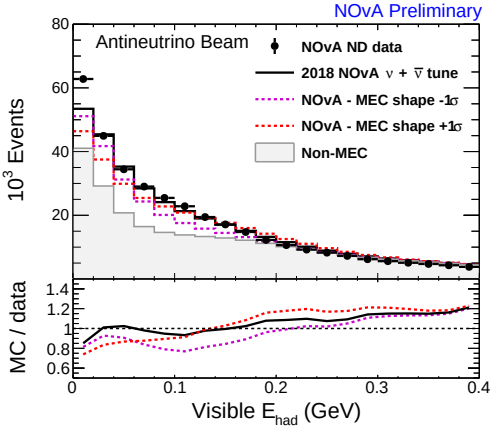
Near Detector Data/MC Agreement After Tune

- After tune, data & MC agree up to 1.3% normalization difference for ν beam (0.5% for $\bar{\nu}$ beam)
- Shapes shown here — normalization difference removed for display



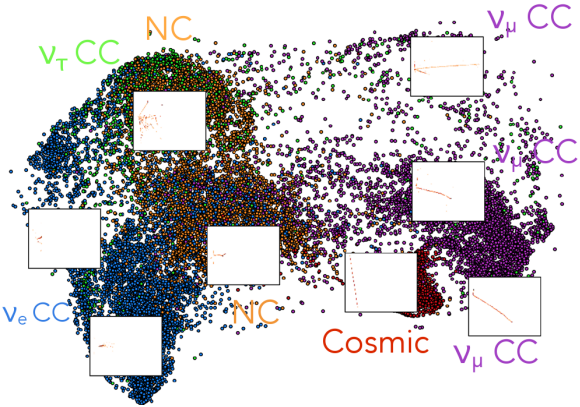
MEC Uncertainty





- Shift quasielastic and resonant events within their (correlated) errors and retune 2p2h to produce MEC error band

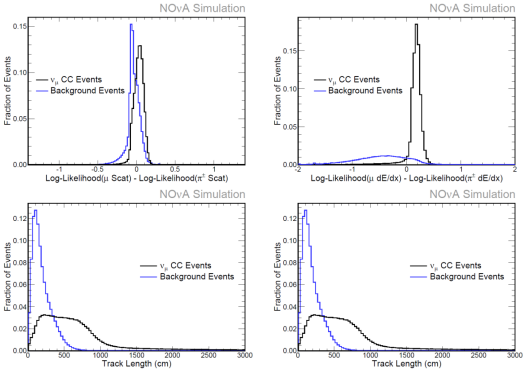
Updated Classifier for 2018



- Updated with improved tuning
- Optimized separately for neutrino and anti-neutrino beams
- Cosmic data included in training

Selection — ν_μ

- In selected ν_μ CC events, muon is selected using conventional kNN based on muon track length, scattering, fraction of planes with hadronic energy, $\mathrm{d}E/\mathrm{d}x$
- Events without a sufficiently muon-like track are rejected



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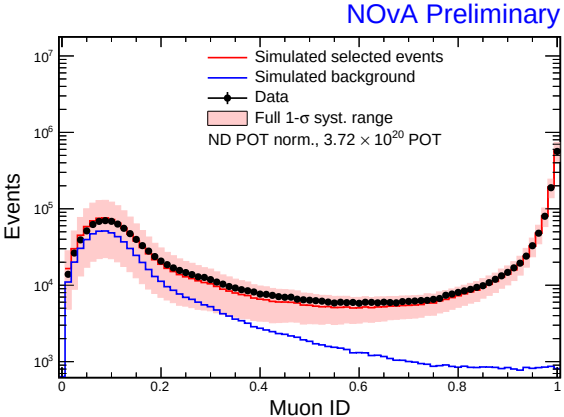
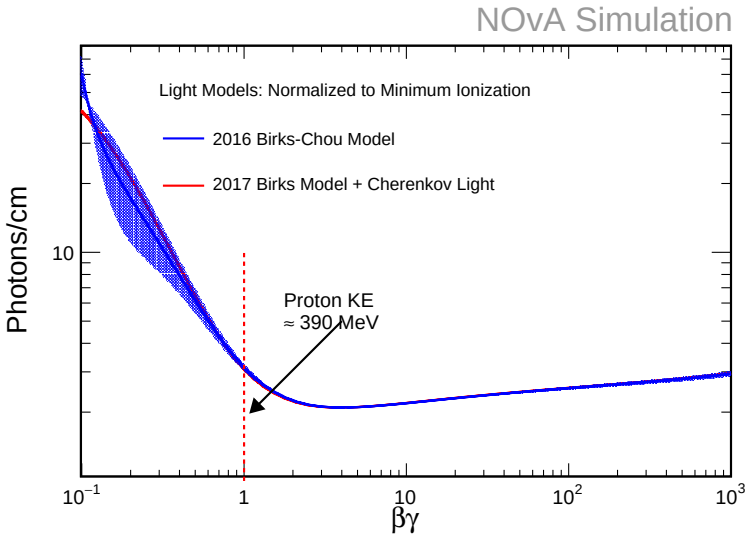


Birks, Cherenkov changes



Backup

ν_e Appearance

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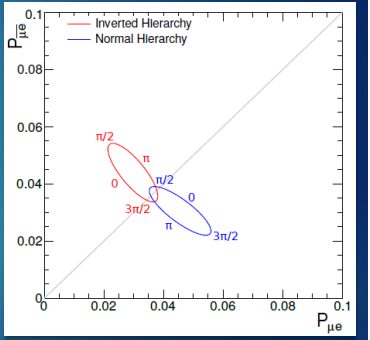
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$$\Delta_{ij} \equiv \frac{1.27\Delta m_{ij}^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}$$
$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$

- Depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, $\mathrm{sign}(\Delta m^2_{31})$
- $\sin^2 2\theta_{13}$=0.095 → most ν_μ go to ν_τ
- Look for deviations due to hierarchy (matter effects) and CP-violation

- NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2GeV, different dependence on $sign(\Delta m^2_{32})$ and δ_{CP}



Backup

ν_e Appearance

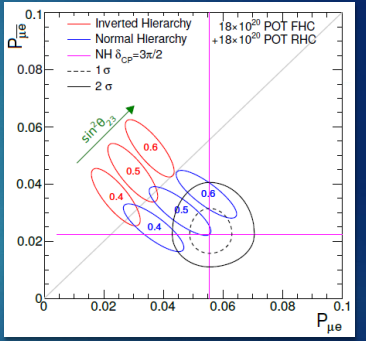
16

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$$\Delta_{ij} \equiv \frac{1.27\Delta m_{ij}^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}$$
$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$

- Depends simultaneously on θ_{13}, θ_{23}, δ_{CP}, $\mathrm{sign}(\Delta m^2_{31})$
- $\sin^2 2\theta_{13}$=0.095 → most ν_μ go to ν_τ
- Look for deviations due to hierarchy (matter effects) and CP-violation

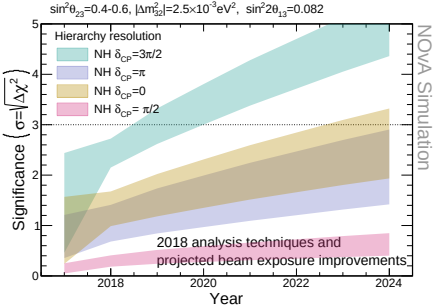
- NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2GeV, different dependence on $sign(\Delta m^2_{32})$ and δ_{CP}
- $P \propto \sin^2\theta_{23}$
- Constrain a space region

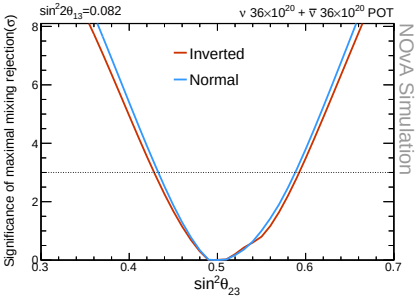


Outlook

Sensitivity assuming:

- 50% neutrino mode, 50% antineutrino mode; anti-neutrino for rest of 2018
- 36×10^{20} POT of each by 2024 given projected accelerator improvements
- Current analysis techniques (conservative), but modestly improved systematics





- For normal hierarchy, 3σ for $> 30\%$ of true δ values by 2024
- 3σ rejection of maximal mixing if true $\sin^2\theta_{23} < 0.43$ or > 0.59