Results and Prospects with NOvA

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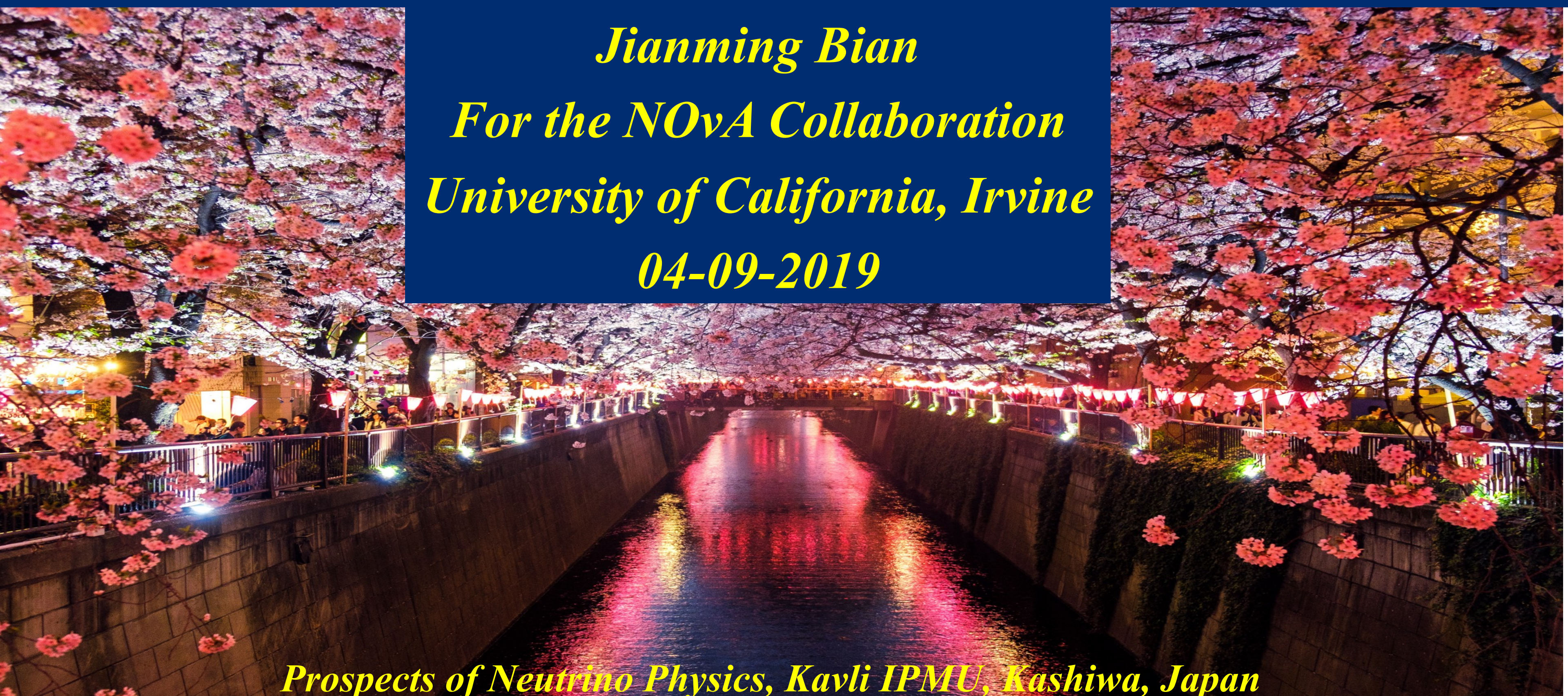


Prospects of Neutrino Physics, Kavli IPMU, Kashiwa, Japan

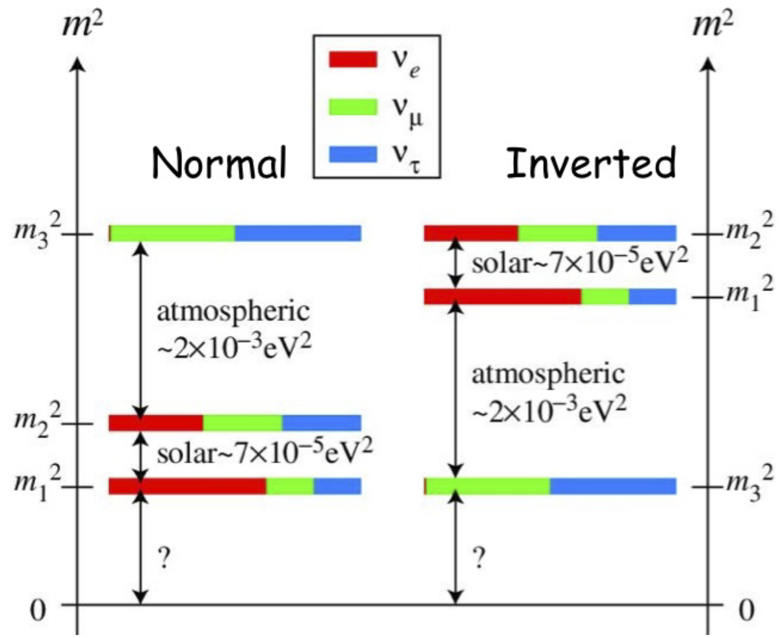
NOvA Physics Goals

- ν_e appearance + ν_μ disappearance
  - Mass hierarchy: $m_3>m_{1,2}$ or $m_{1,2}>m_3$? Implications for absolute neutrino masses, unified theories and neutrino-less double beta decay searches
  - CP phase δ_{CP}: whether neutrinos and antineutrinos behave the same way in oscillation? Implications for matter-antimatter asymmetry
  - Octant of θ_{23} : Is θ_{23} exactly 45°? Is ν_3 more strongly coupled to ν_τ or ν_μ?

- NC disappearance
  - Sterile neutrino search: are there other neutrinos beyond the three known active flavors?

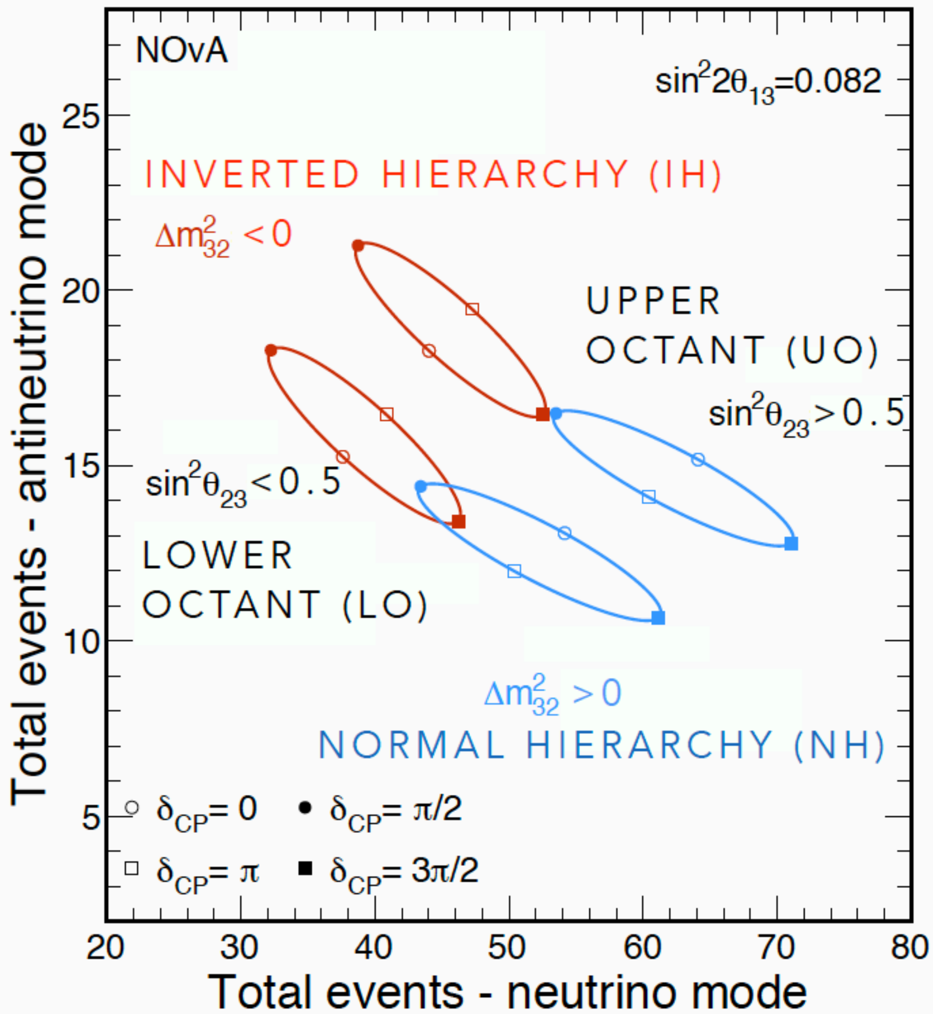
- Also, cross sections, exotic phenomena and non-beam physics

This talk: ν_e and ν_μ oscillation results with NOvA's first antineutrino data



Appearance and Disappearance at NOvA

$\nu_e/\bar{\nu}_e$ Appearance event counts

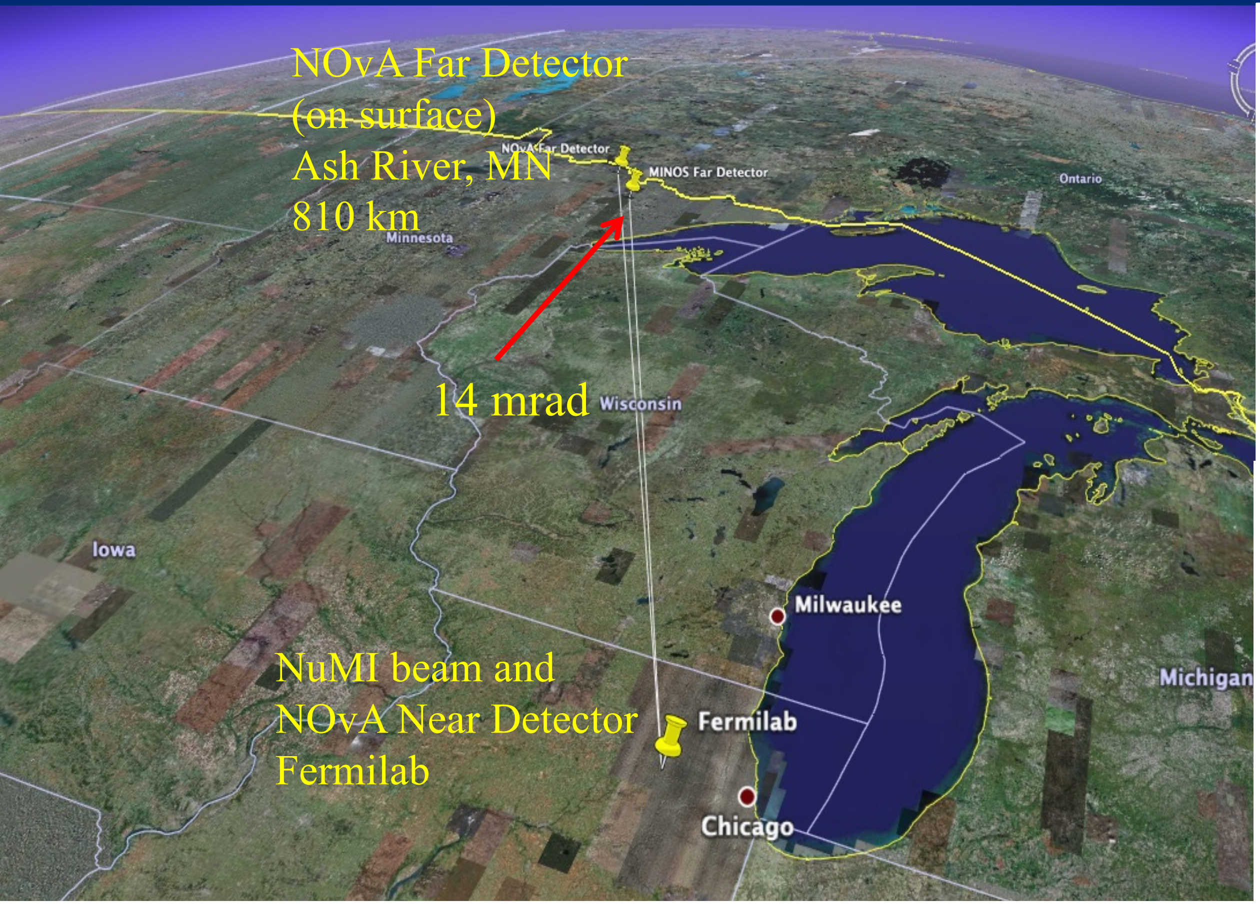


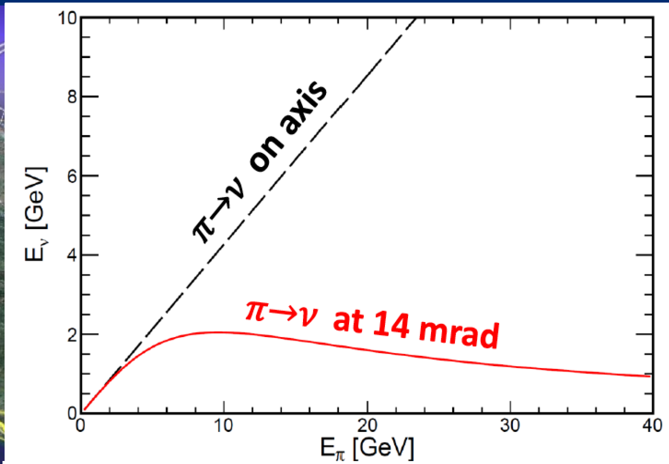
- Measuring ν_e and $\bar{\nu}_e$ appearance probabilities with ν_μ and $\bar{\nu}_\mu$ beam

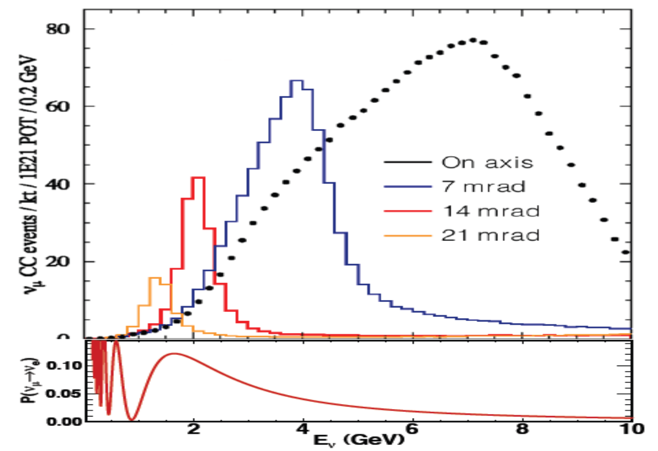
- When other parameters fixed, $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance probabilities depend on
  - sign of Δm^2_{32}
  - δ_{CP}
  - octant of θ_{23}

- ν_μ and $\bar{\nu}_\mu$ disappearance provides high precision Δm_{32} and $\sin^2 2\theta_{23}$, constrain θ_{23} octant

NuMI Off-Axis ν_e Appearance Experiment



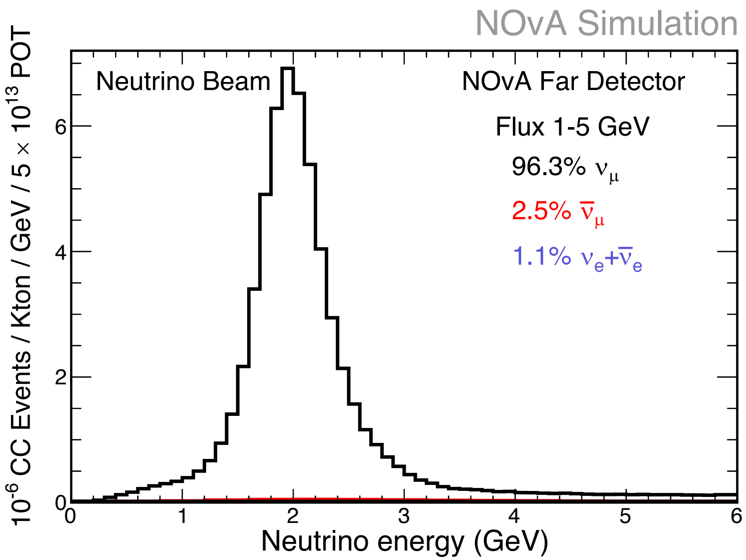




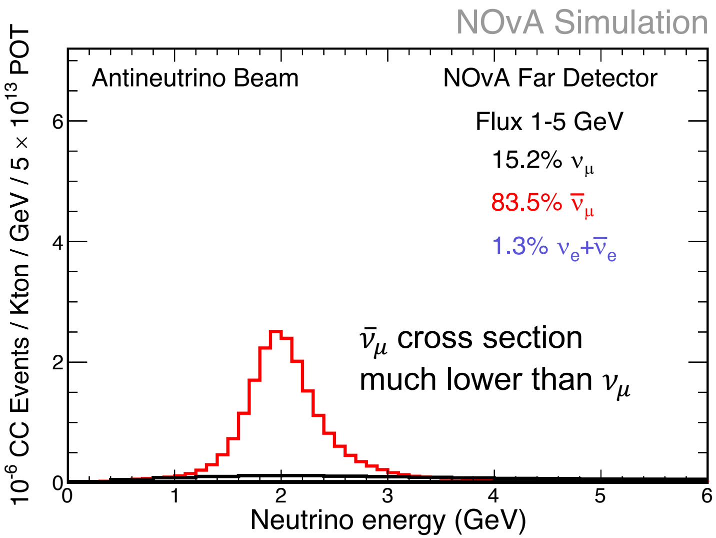
- Upgraded NuMI muon neutrino beam at Fermilab (700 kW design goal achieved)
- Longest baseline in operation (810 km), large matter effect (±30%), sensitive to mass hierarchy
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum, small wrong sign components ($\bar{\nu}$ in ν beam or ν in $\bar{\nu}$ beam)

Beam Performance

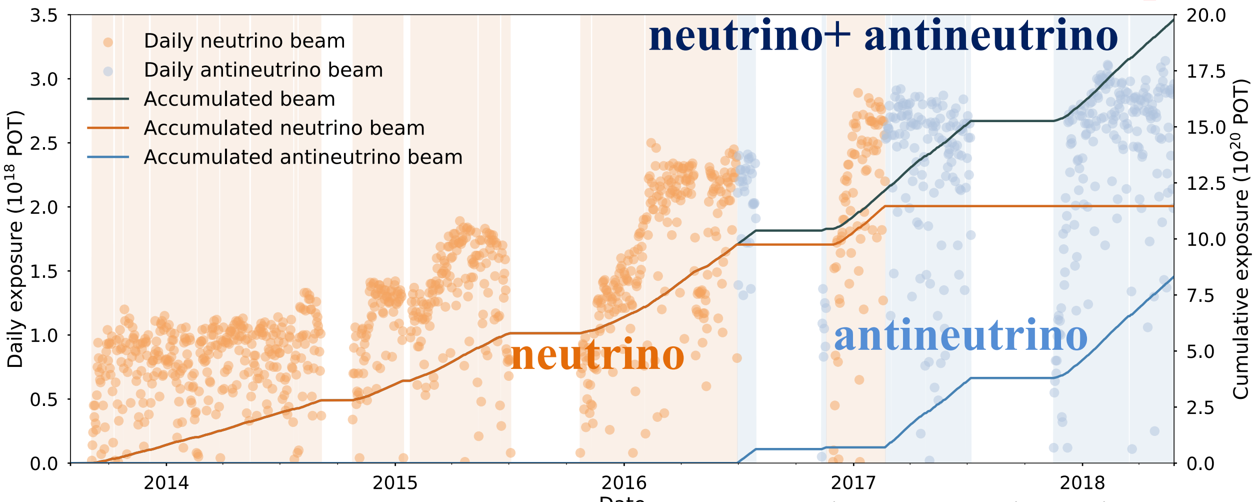
CC event rates at FD in neutrino beam



CC event rates at FD in antineutrino beam



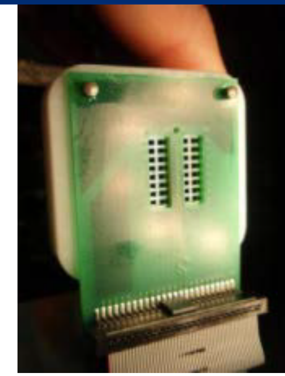
- **Neutrino beam** data: 8.85x10^{20} POT, taken Feb 2014 - Feb 2017
- First **antineutrino data**: 6.9 x 10^{20} POT, taken Feb 2017 - April 2018

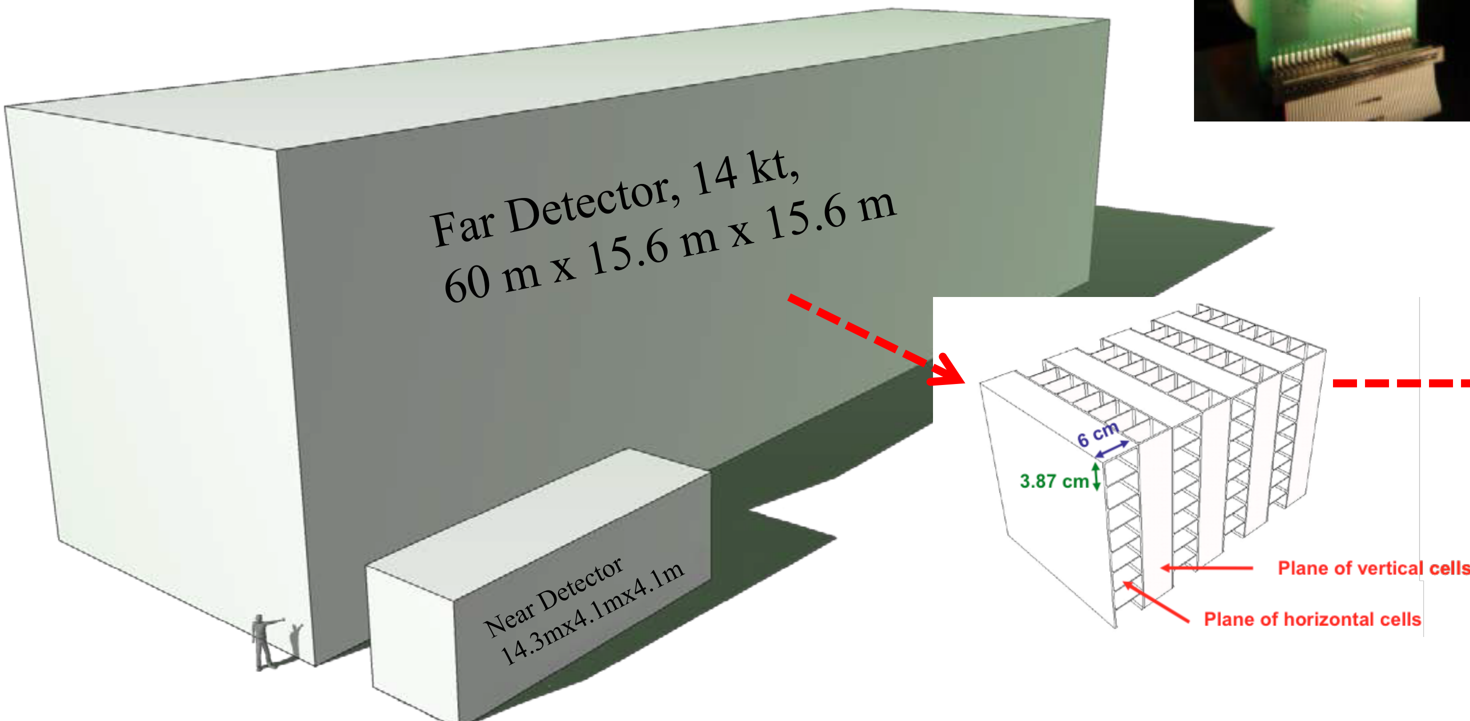


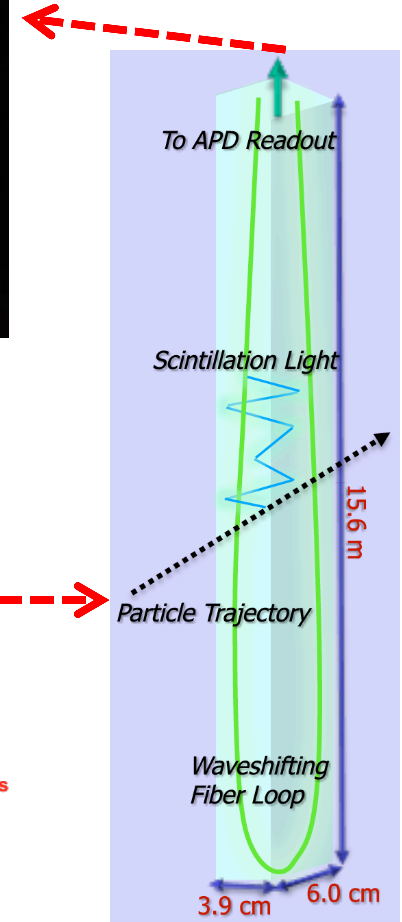
Operating at 700 kW since Jan 2017

The NOνA Detectors

- 14-kton Far Detector
- 344,064 detector cells
- 0.3-kton functionally identical Near Detector
- 18,432 cells

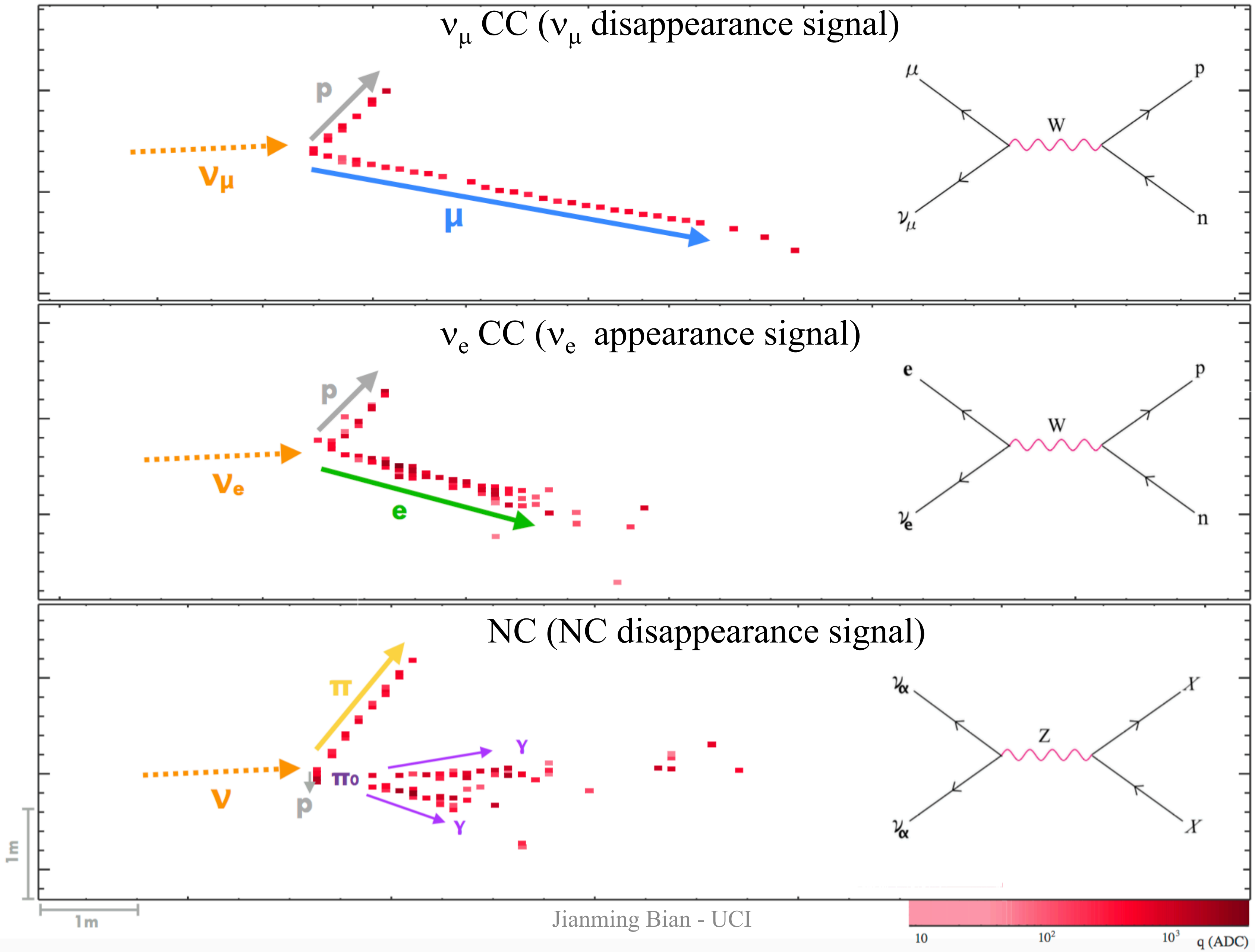






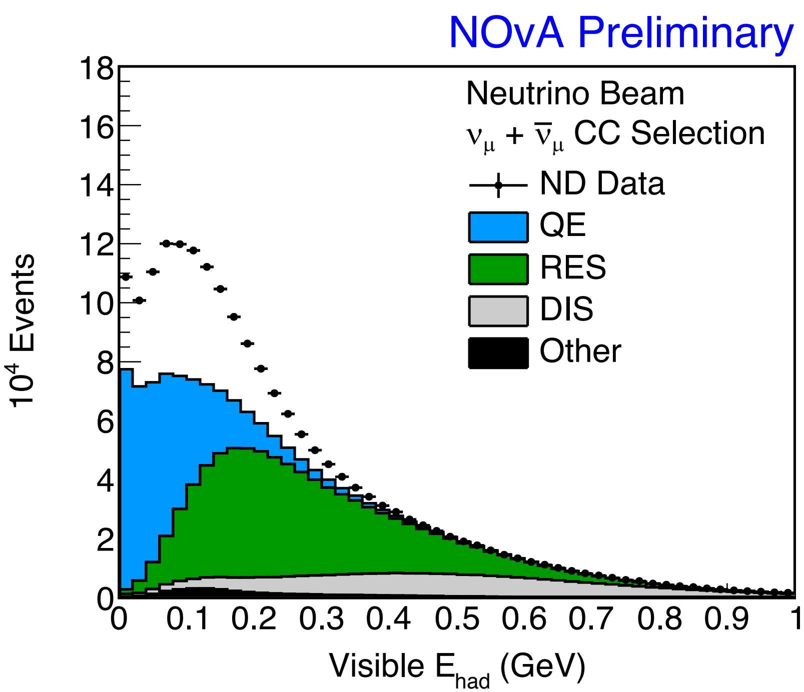
- Composed of PVC modules extruded to form long tube-like cells
- Each cell: filled with liquid scintillator, has wavelength-shifting fiber (WLS) routed to Avalanche Photodiode (APD)
- Cells arranged in planes, assembled in alternating vertical and horizontal directions
- Low-Z and low-density, each plane just 0.15 X_0, great for e^- vs π^0 separation

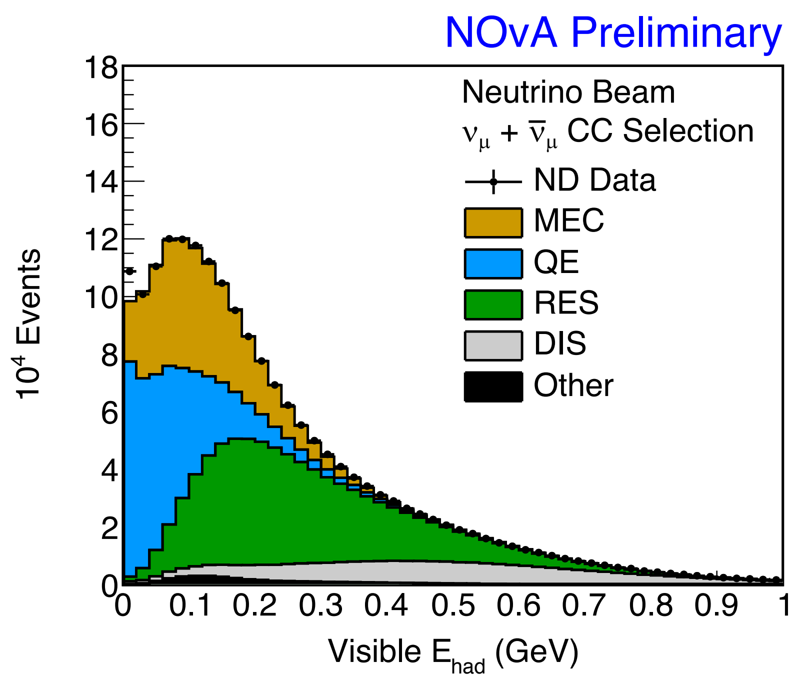
NOvA Event Topologies



Neutrino Interaction Tuning

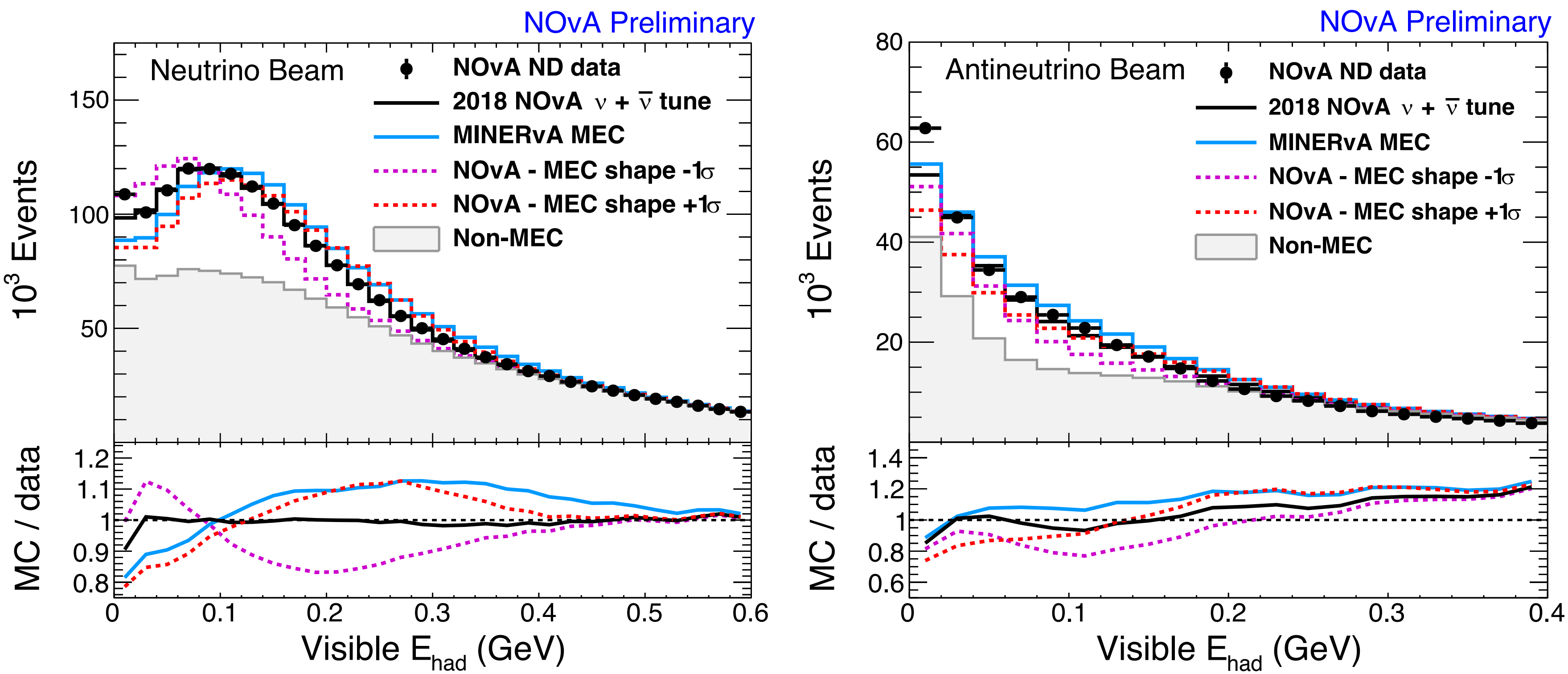
- QE, RES tuned to consider long-range nuclear correlations using València model via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
- DIS at high invariant mass ($W>1.7$ GeV/c^2) weighted up 10% based on NOvA data
- Empirical MEC (Meson Exchange Current) model for Multi-nucleon ejection (2p2h) [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)], amount tuned in 2D 3-momentum and energy transfers ($q_0 = E_\nu - E_\mu$, $|q| = |p_\nu - p_\mu|$) space to match ND data



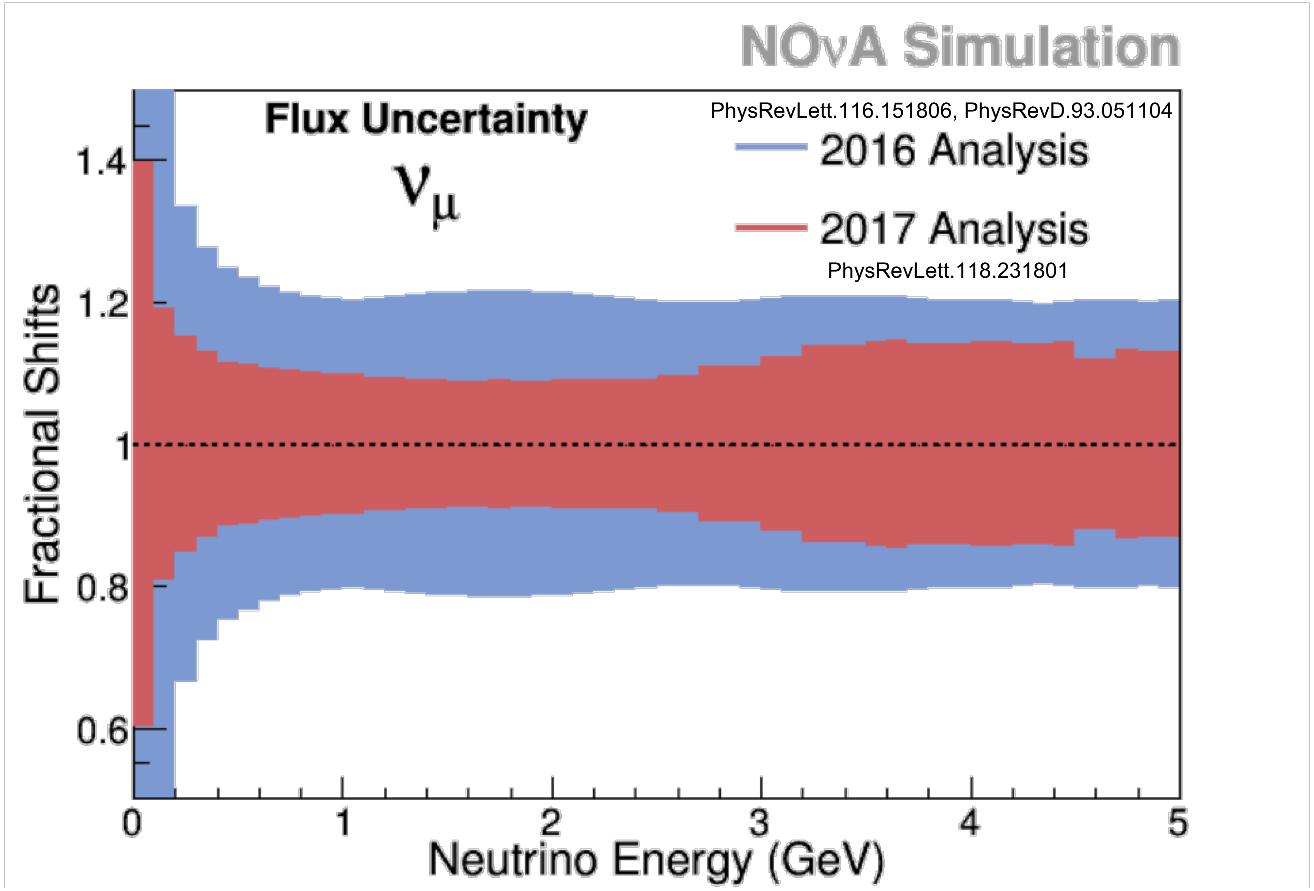


Neutrino Interaction Tuning

- MEC shape systematic estimated by re-fitting using models with QE and RES related systematic shifts



Improved Flux Model

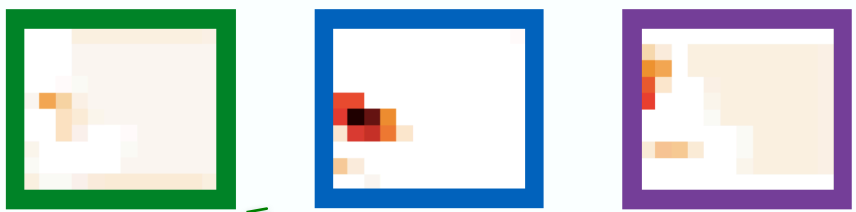


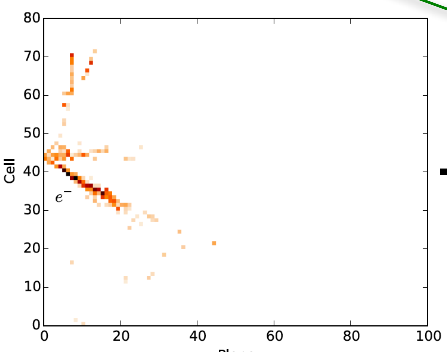
- Package to Predict the Flux (PPFX) from MINERvA (Phys. Rev. D 94, 092005. 2016).
  - Based on thin target hadron production data from NA49 and MIPP.
- Significantly reduced systematic uncertainties.
  - Central values also changed within prior systematics, but not shown here.

Deep-Learning based PID for ν_e and ν_μ Analyses

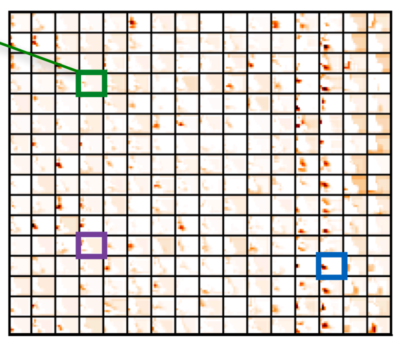
- CVN: a convolutional neural network (CNN), based on modern image recognition technology
- Introduce convolution filters to extract features from the hit map for the training of the neural net
- Statistical power equivalent to 30% more exposure than previous ν_e PIDs
- ν_e , ν_μ and NC analyses all use CVN as event selector

Outputs of convolutional filters (features)

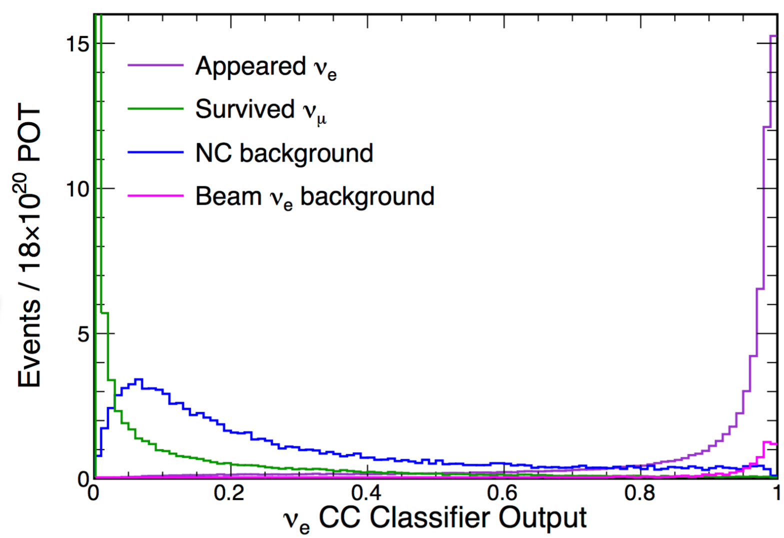




Hit map of a ν_e CC event



CVN output in the far detector MC



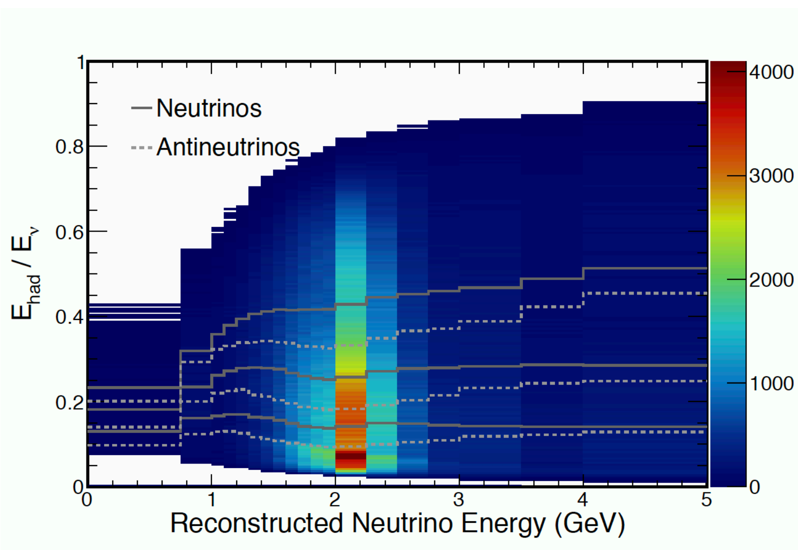
A. Aurisano, A. Radovic and D. Rocco et. al, JINST 11, P09001 (2016)

At NOvA, CVN has been extended to single particle ID, energy reconstruction (for future analyses), etc

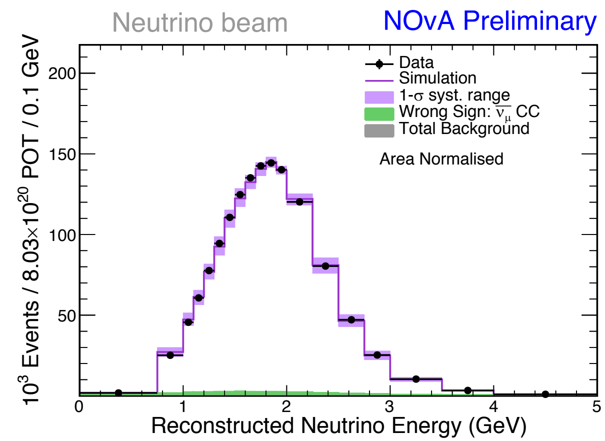
P.Baldi, J.Bian, L.Hertel and L.Li, Phys.Rev.D 99, 012011 (2019)

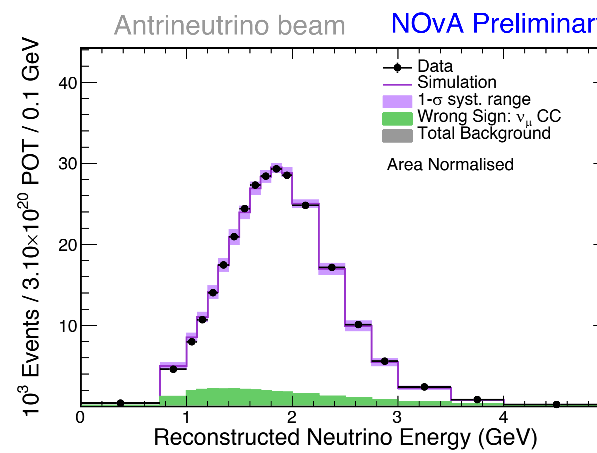
Near Detector Spectrum (ν_μ disappearance)

- Select ν_μ ($\bar{\nu}_\mu$) CC in ND from neutrino (antineutrino) beam, wrong sign contamination 3% (11%)
- E_ν = E_μ + E_{had}, data split in 4 equal energy quartiles based on E_{had}/E_ν, resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.
- Normalize ND MC to data in each E_ν bin, then extrapolate the 4 quantiles to FD



Reco ν_μ ($\bar{\nu}_\mu$) energy, all Quartiles



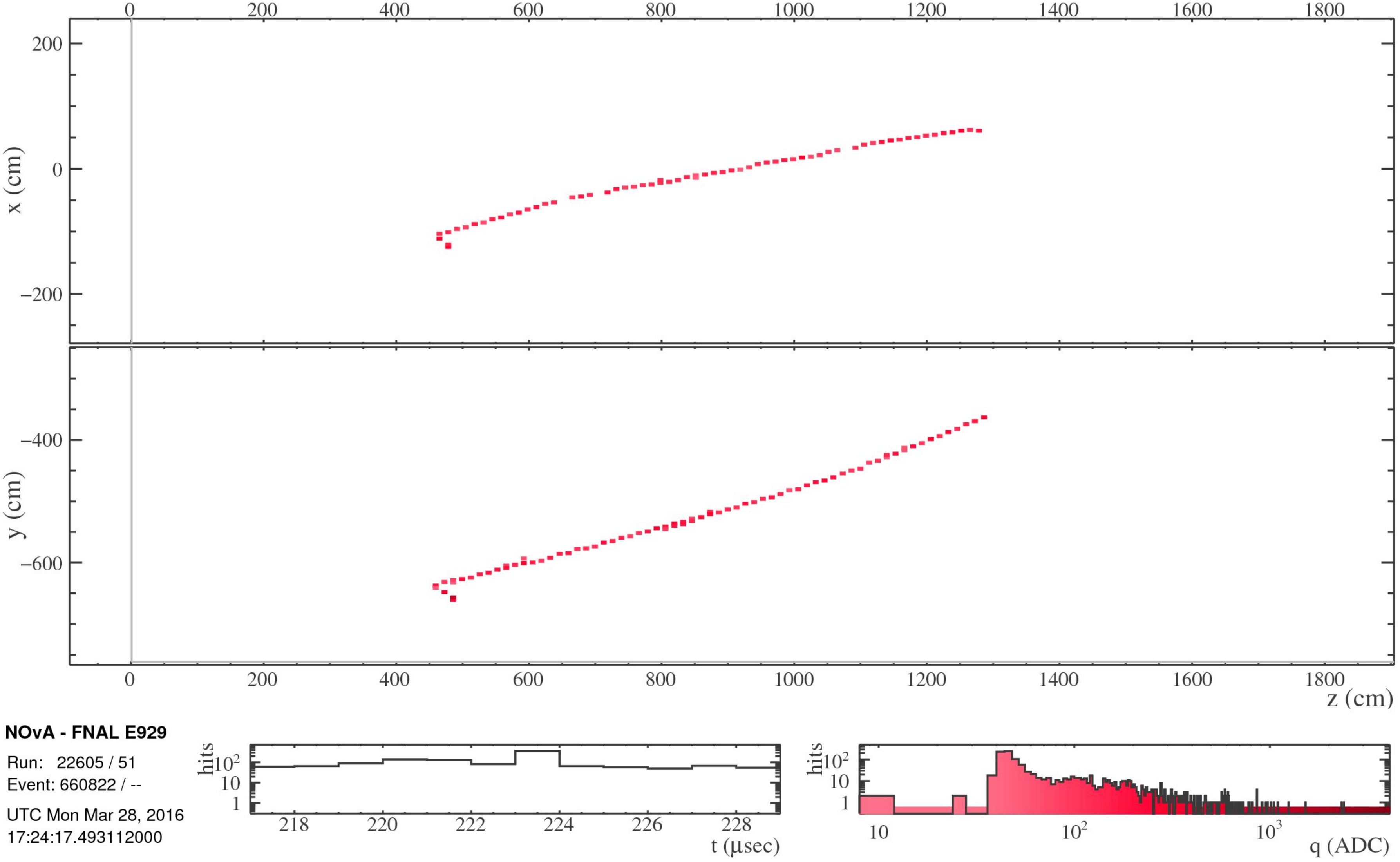


Area-normalized, shape-only systematics

Data/MC normalization difference:

1.3% and 0.5% for ν_μ and $\bar{\nu}_\mu$

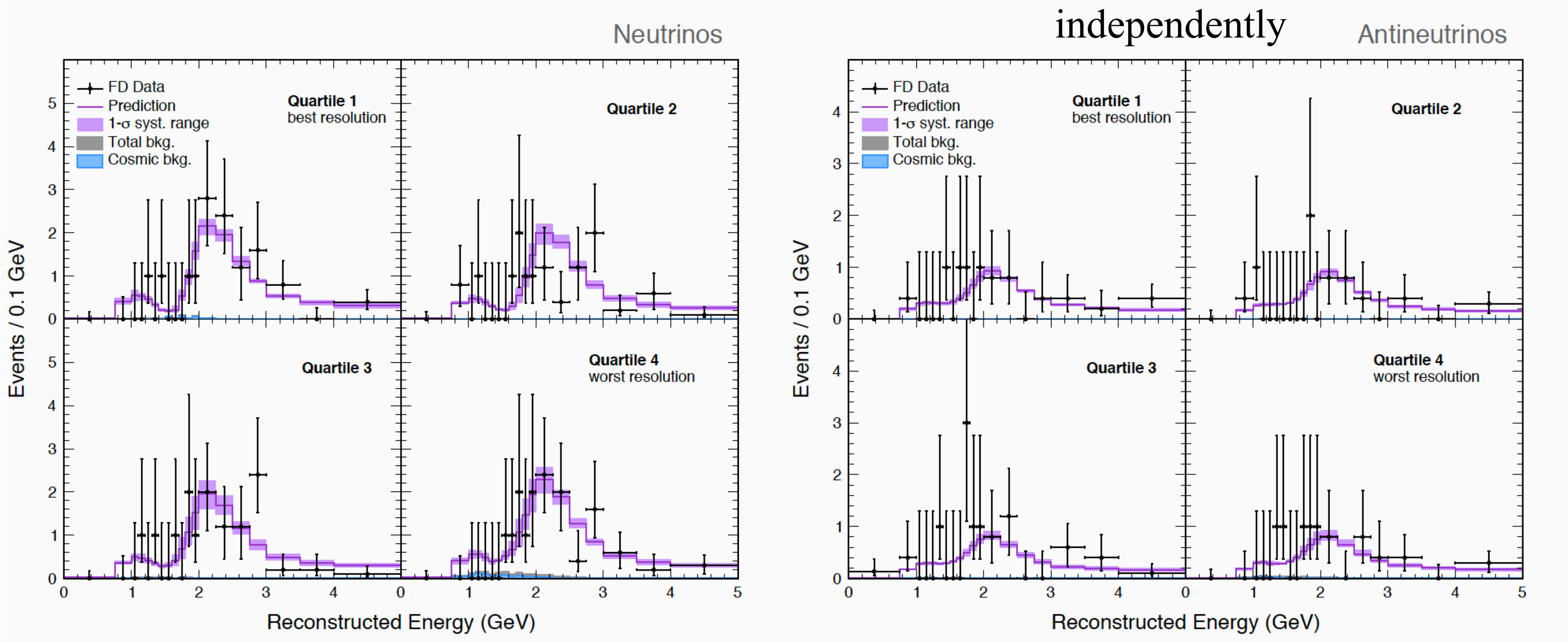
ν_μ Data at Far Detector



ν_μ Data at Far Detector

- FD selection:
  - Additional Boost Decision Tree (BDT) to reduce cosmic backgrounds
  - Estimate cosmic background rate from timing sidebands of the NuMI beam triggers and cosmic trigger data

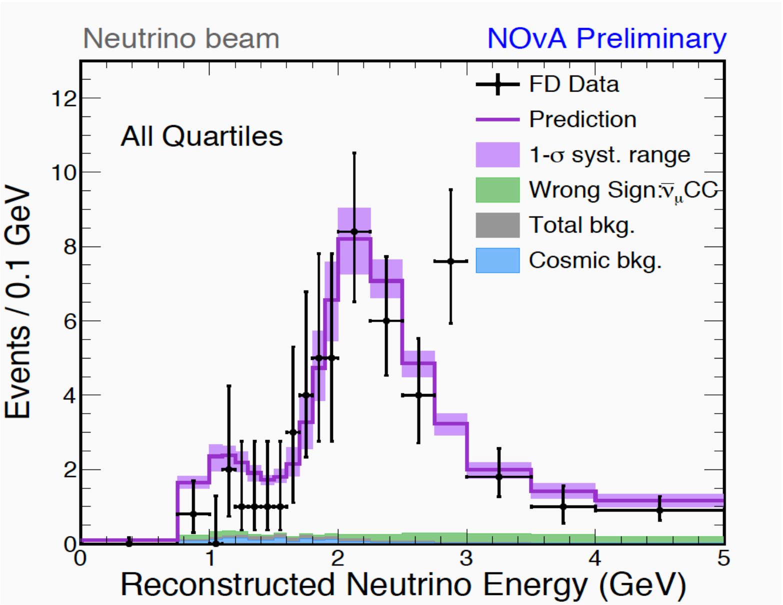
ν_μ events in 4 quartiles, each quartile extrapolated independently



ν_μ Data at Far Detector

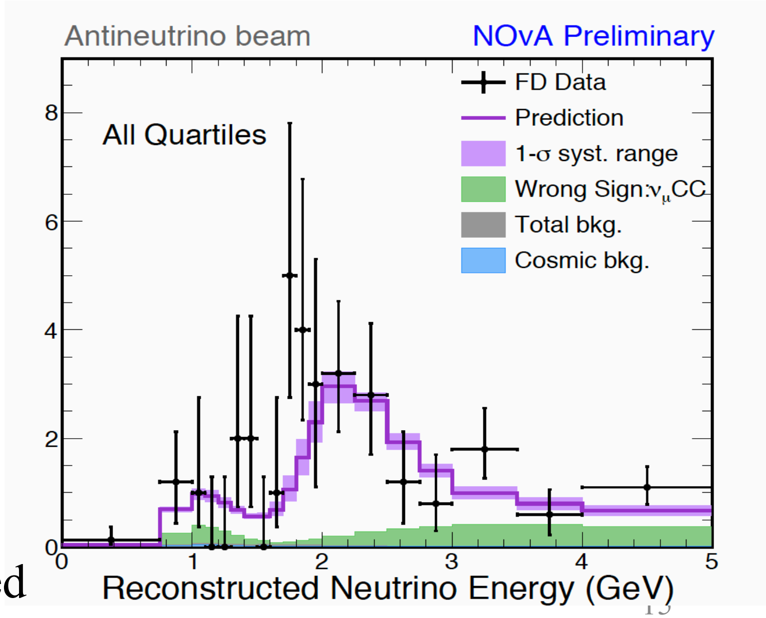
Neutrino beam:

- Observe 113 events
- Prediction at best fit: 121
- Cosmic background: 2.1
- Beam background: 1.2
- Expect 730 +38/-49(syst.) w/o oscillations



Anti-Neutrino beam:

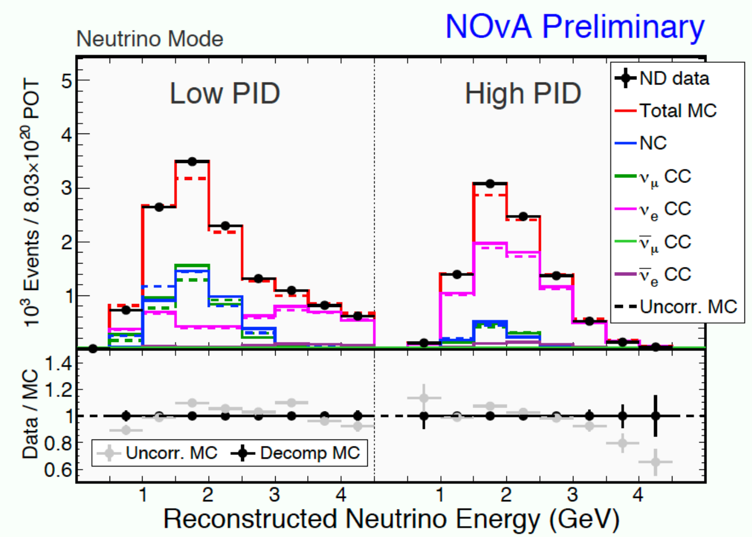
- Observe 65 events
- Prediction at best fit 50
- Cosmic background 0.5
- Beam background 0.6
- Expect 266 +12/-14(syst.) w/o oscillations

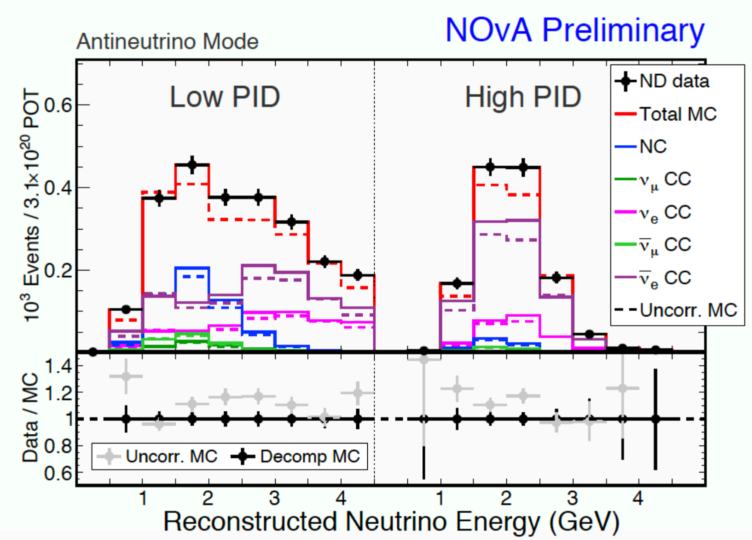


4 quartiles combined

Near Detector Spectrum (ν_e appearance)

- Select ν_e ($\bar{\nu}_e$) CC in ND from neutrino (antineutrino) beam
- $E_\nu = f(E_e, E_{had})$, data split into low and high particle ID (purity) range
- For neutrino beam:
  - Contained and uncontained ν_μ events constrain the π/K contributions to the beam ν_e's.
  - Michel electrons constrain NC/ν_μ CC balance in each E_ν bin
- For antineutrino beam, scale all components evenly to match data
- ND→FD extrapolation: Each component propagated independently in energy and PID bins

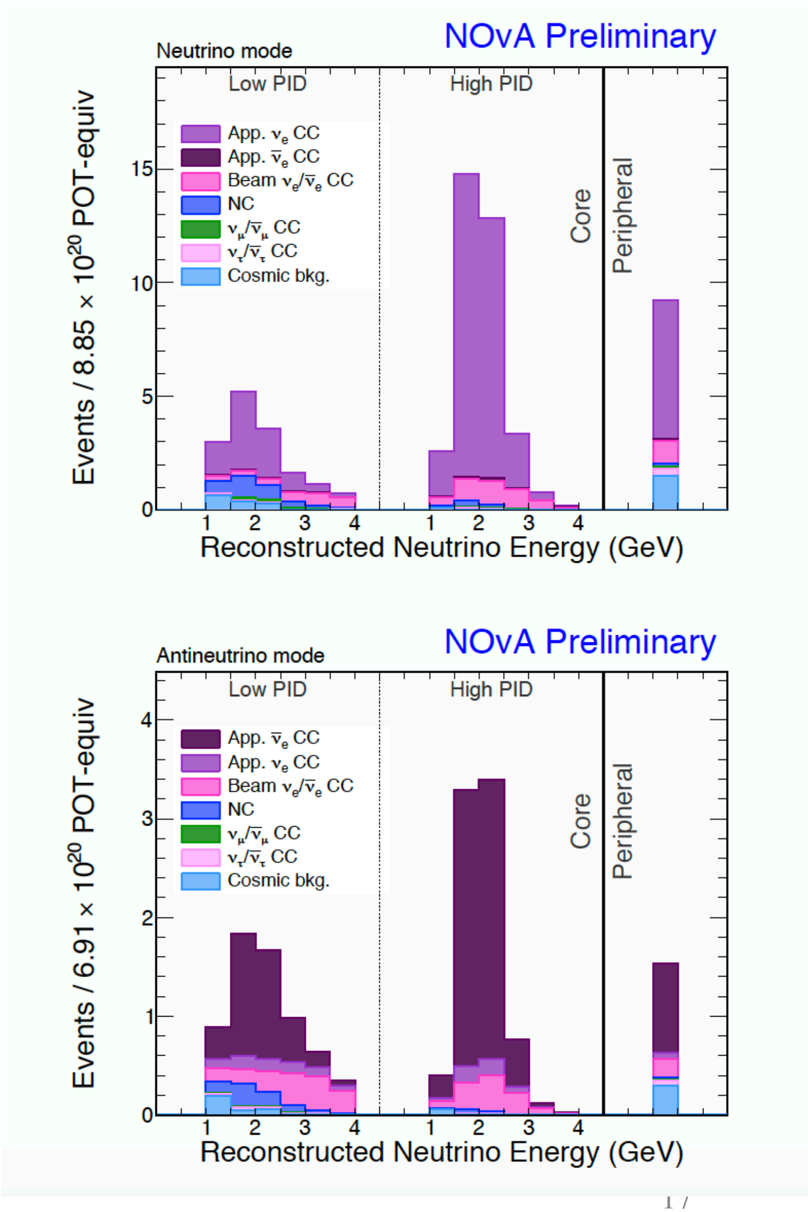




ν_e Far Detector Prediction

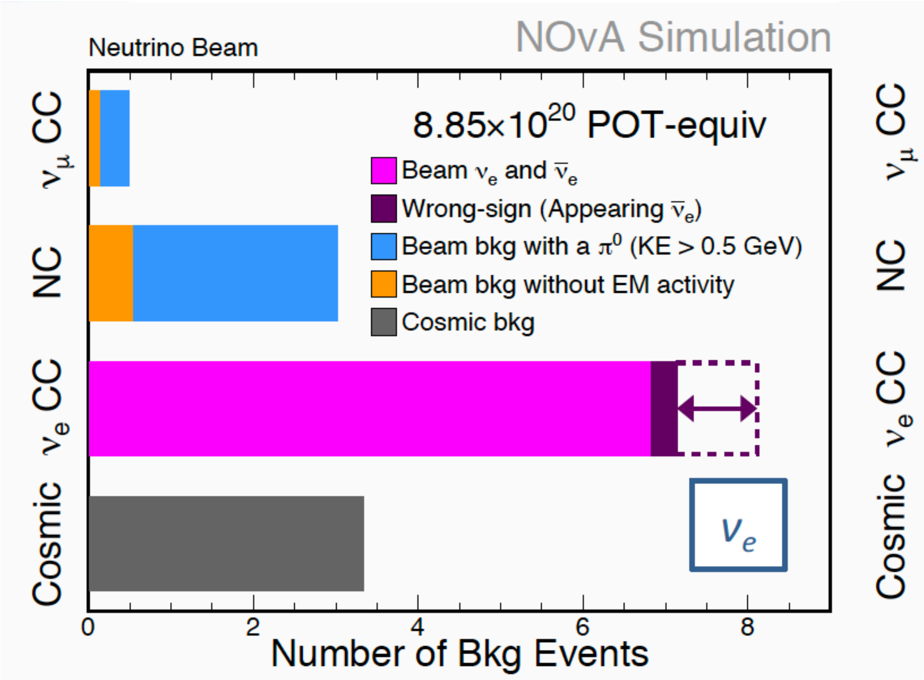
- FD selection:
  - Add a one-bin peripheral with less stringent containment selection to include more signal
  - Use location dependent BDT and tight PID cuts to recover signal events in this peripheral bin

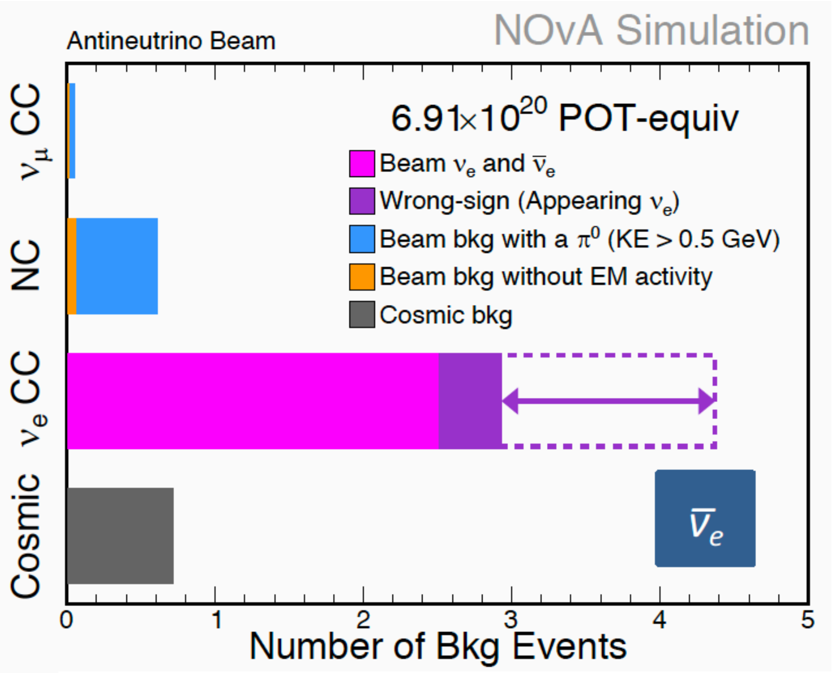
- ND→FD extrapolation: Each component propagated independently in energy and PID bins
  - ND ν_μ sample to predict FD ν_μ background and appearance ν_e (signal+wrong-sign)
  - ND ν_e-like sample to predict FD beam ν_e backgrounds



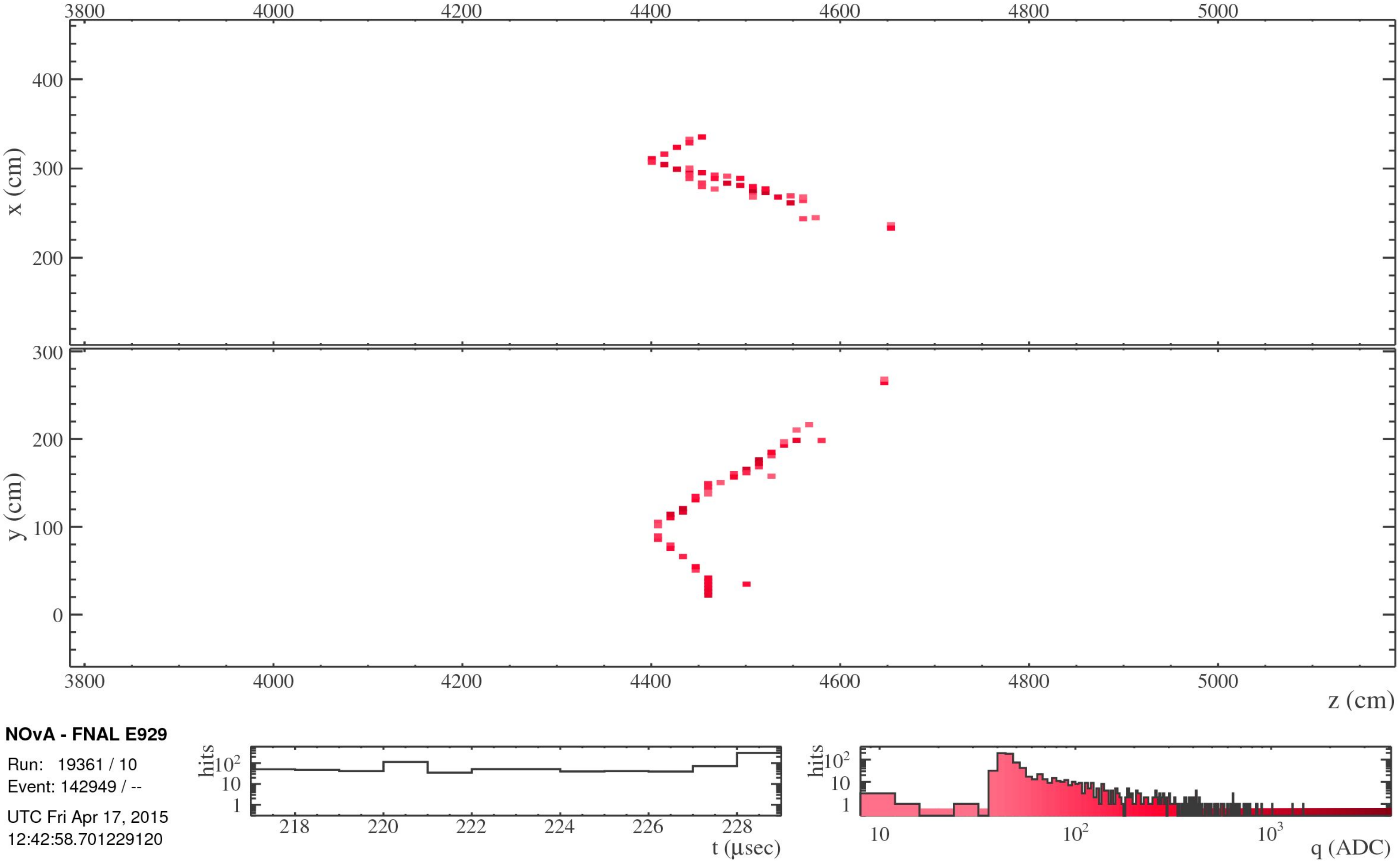
ν_e Far Detector Backgrounds

- Major backgrounds from beam ν_e
- Wrong sign background depends on oscillation





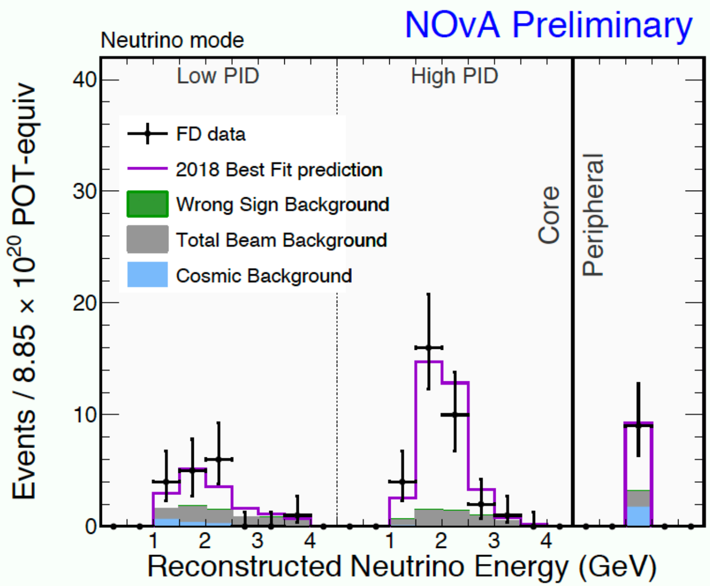
ν_e Data at Far Detector



ν_e Data at Far Detector

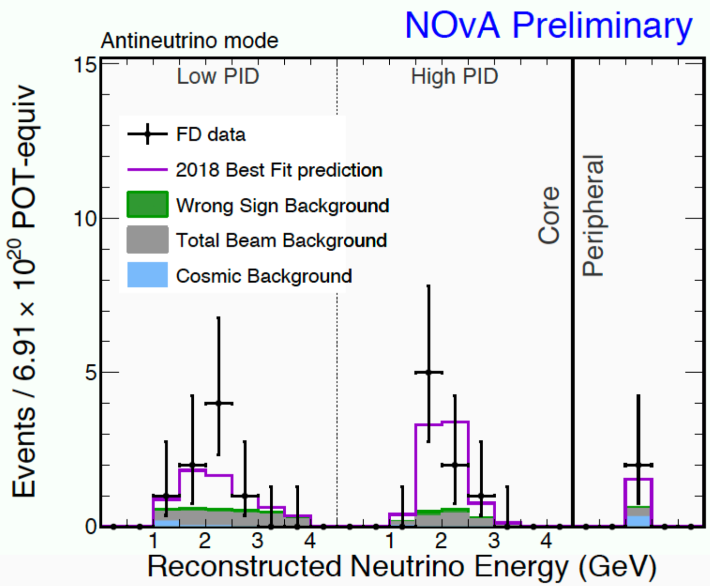
Neutrino beam:

- Observe 58 events
- Prediction at best fit 59.0
- Appearance ν_e (signal) 43.9
- Total background 15.1
  - Appearance $\bar{\nu}_e$ (wrong-sign) 0.7
  - Beam $\nu_e + \bar{\nu}_e$ 6.8
  - Cosmic background 3.3



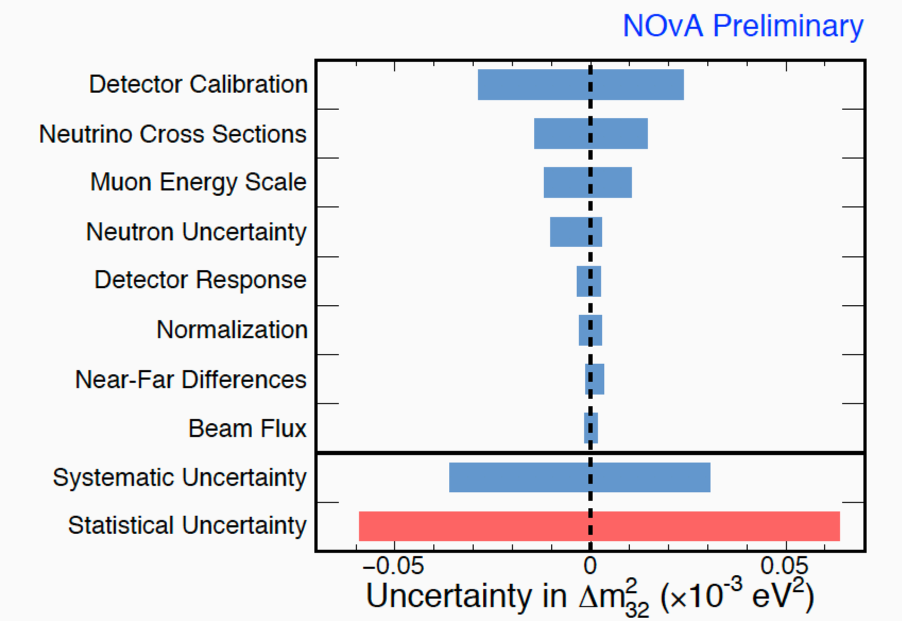
Anti-Neutrino beam:

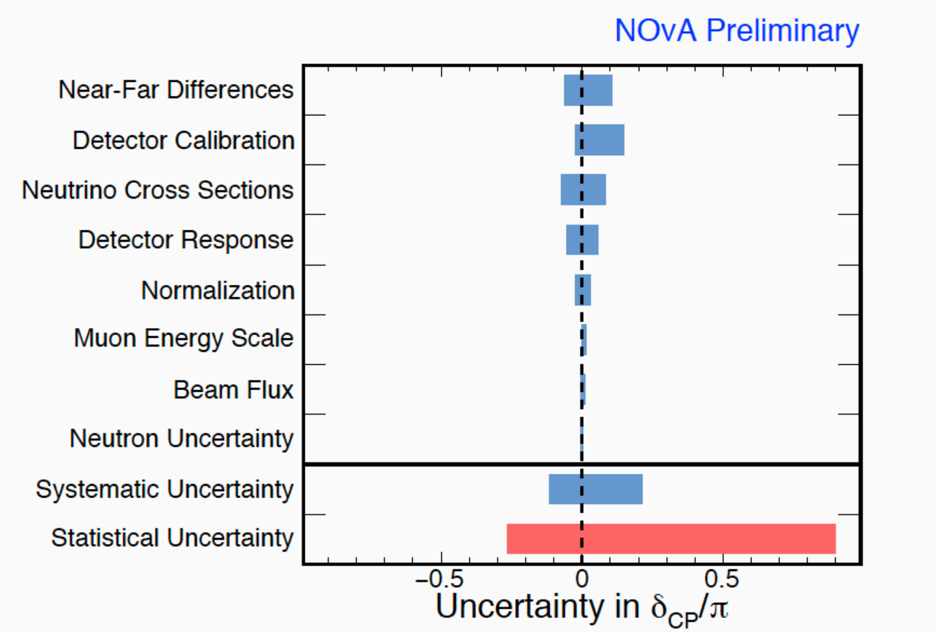
- Observe 18 events
- Prediction at best fit 16.1
- Appearance $\bar{\nu}_e$ (signal) 10.6
- Total background 5.5
  - Appearance ν_e (wrong-sign) 1.1
  - Beam $\nu_e + \bar{\nu}_e$ 2.8
  - Cosmic background 0.7

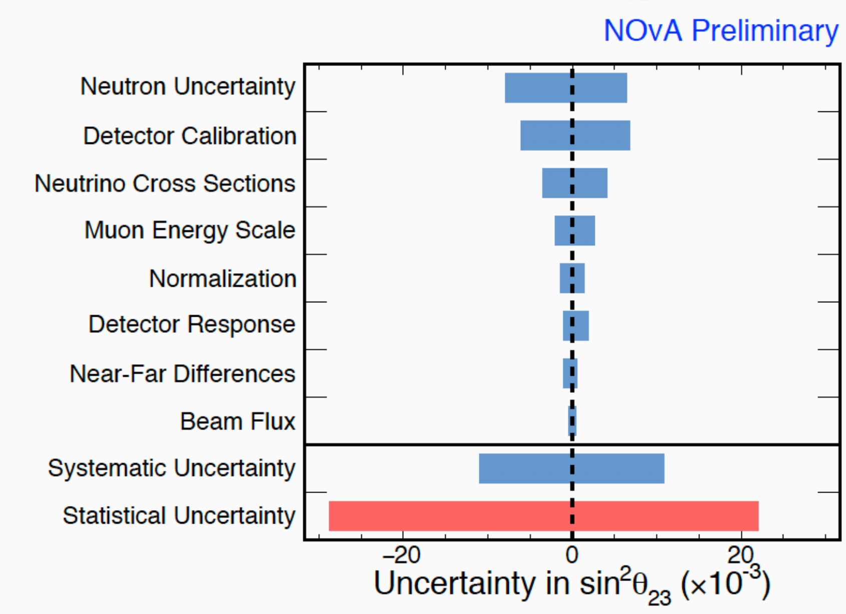


> 4σ $\bar{\nu}_e$ appearance

Systematic Uncertainties (Joint fit)

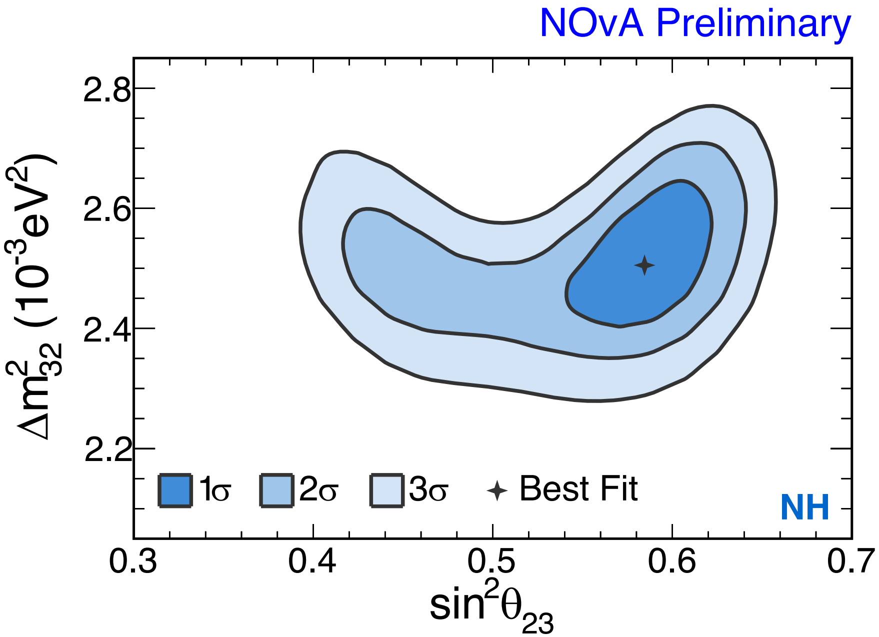


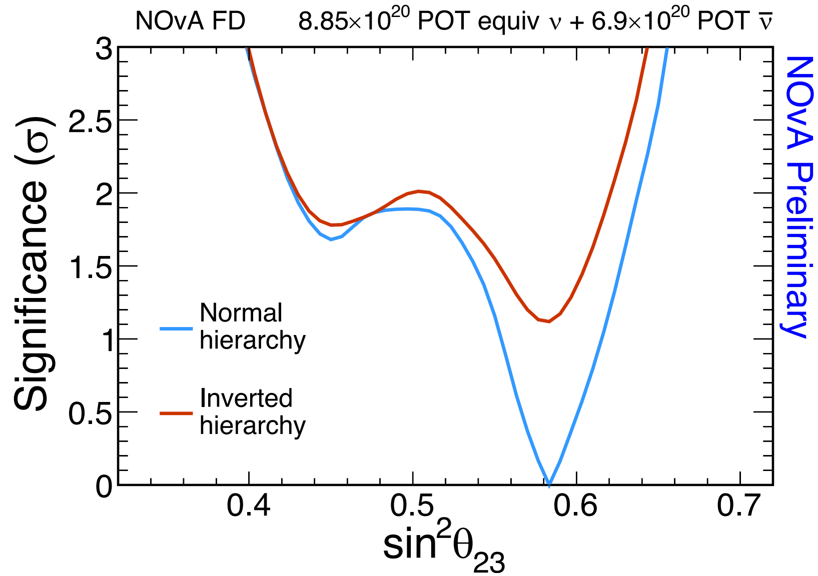


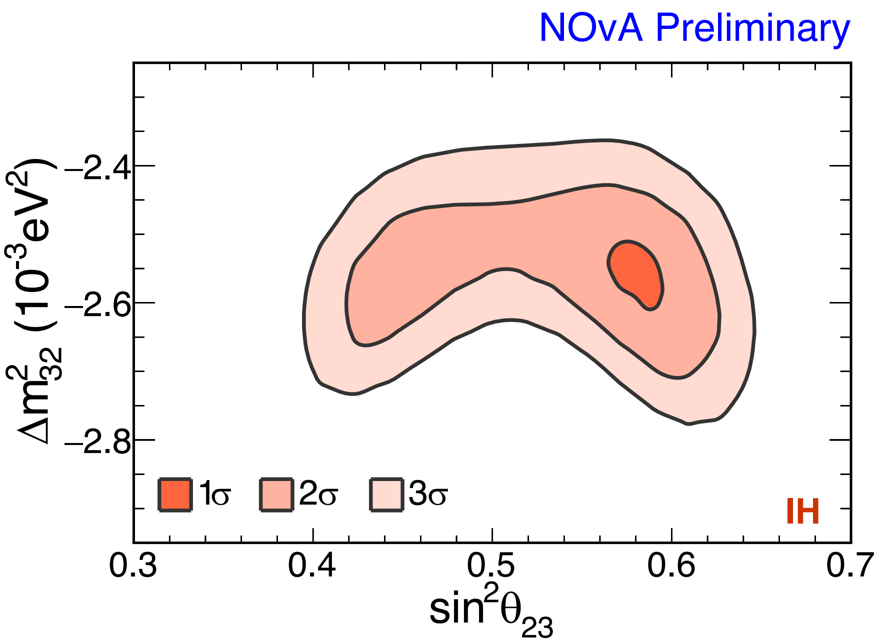


- Largest systematics for ν_μ and ν_e are **calibration, muon energy scale** and **cross-sections**.
- **Neutron uncertainty** – new with $\bar{\nu}$'s
- Upcoming NOvA test beam program will address calibration and detector response uncertainties

Joint Appearance and Disappearance



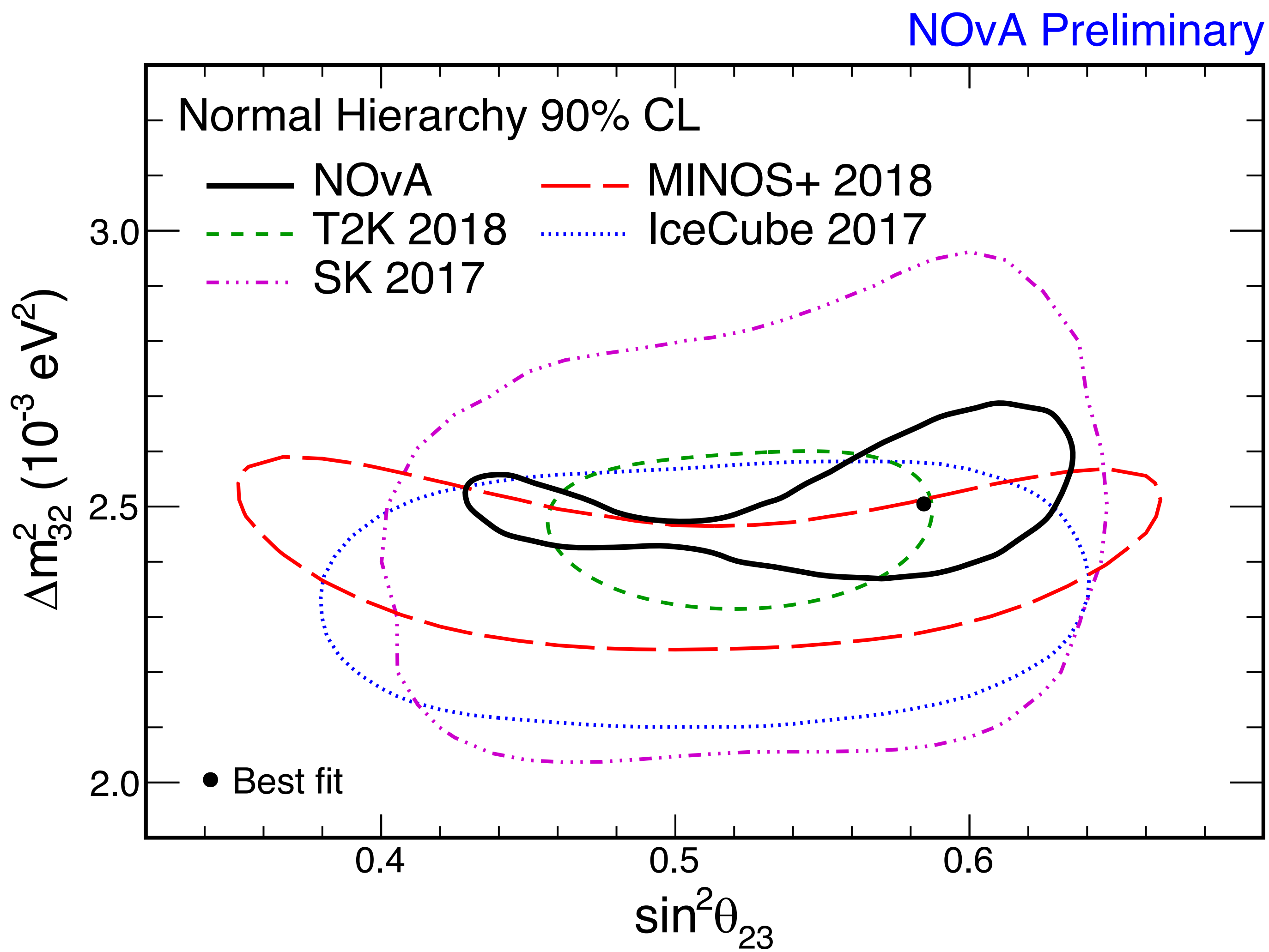




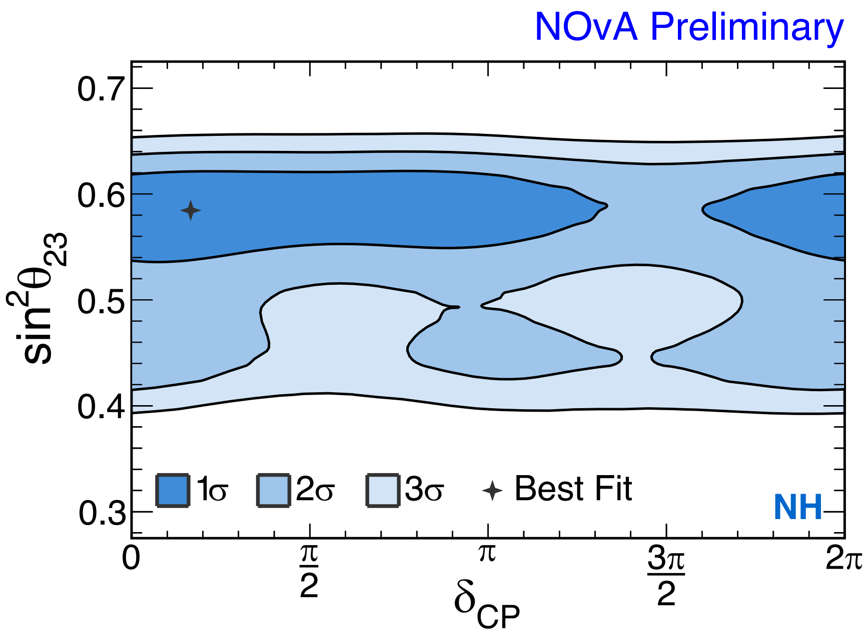
- Statistically limited, largest systematics for ν_μ and ν_e are calibration and cross-sections.
- Best fit:
  - Normal Hierarchy
  - $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
  - $\Delta m^2_{32} = (2.51+0.12-0.08)*10^{-3}$ eV^2
- Prefer non-maximal at 1.8σ, favor upper octant at similar level

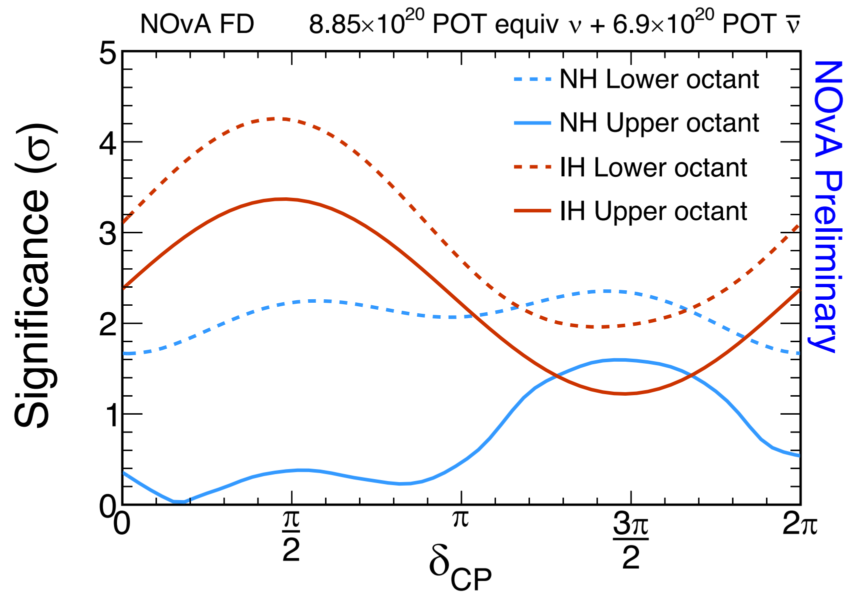
Joint Appearance and Disappearance

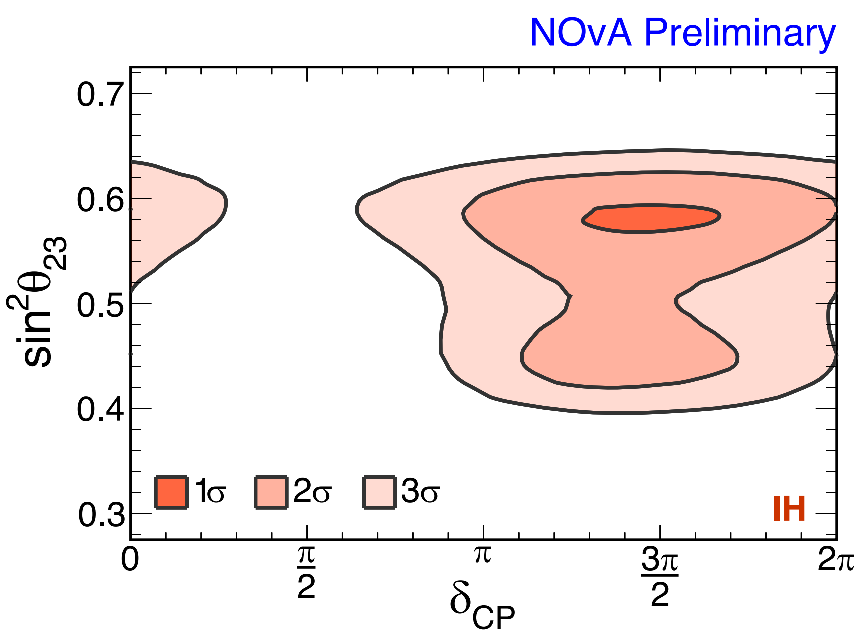
NOvA's allowed 90% C.L. regions are compatible to other experiments



Joint Appearance and Disappearance

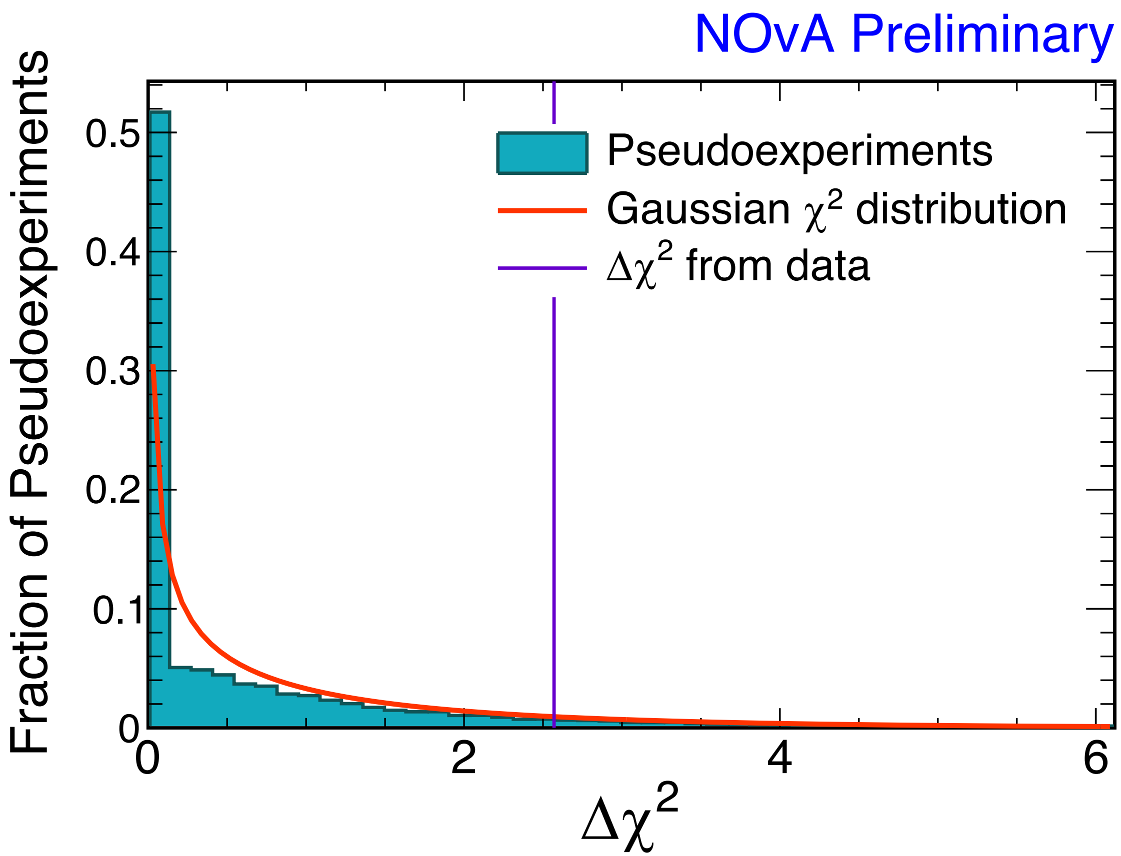






- Statistically limited, largest systematics for ν_μ and ν_e are calibration and cross-sections
- Best fit:
  - Normal Hierarchy
  - $\delta_{CP} = 0.17\pi$
  - $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  - $\Delta m^2_{32} = (2.51{+}0.12{-}0.08) * 10^{-3}\ \mathrm{eV}^2$
- Consistent with all δCP values in NH at $< 1.6\sigma$
- Exclude $\delta = \pi/2$ in IH at $> 3\sigma$

Mass Hierarchy Preference

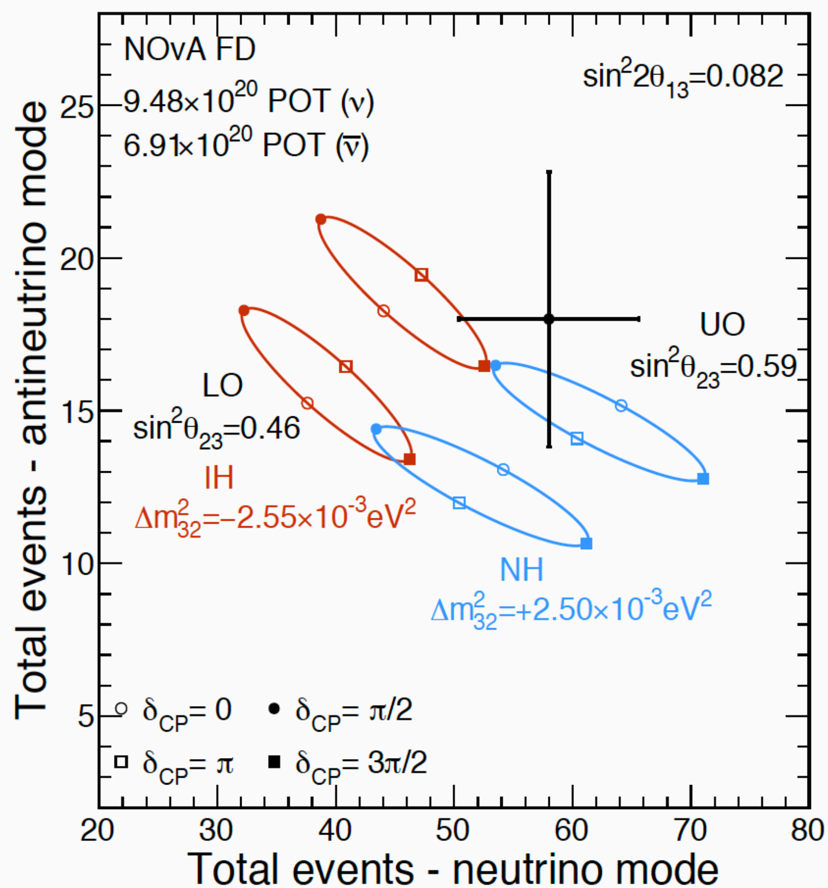


Feldman-Cousins pseudo-experiments: assume IH, set other oscillation parameters to best fit values in data under IH hypothesis
Fit: allow CP, octant and other parameters to float

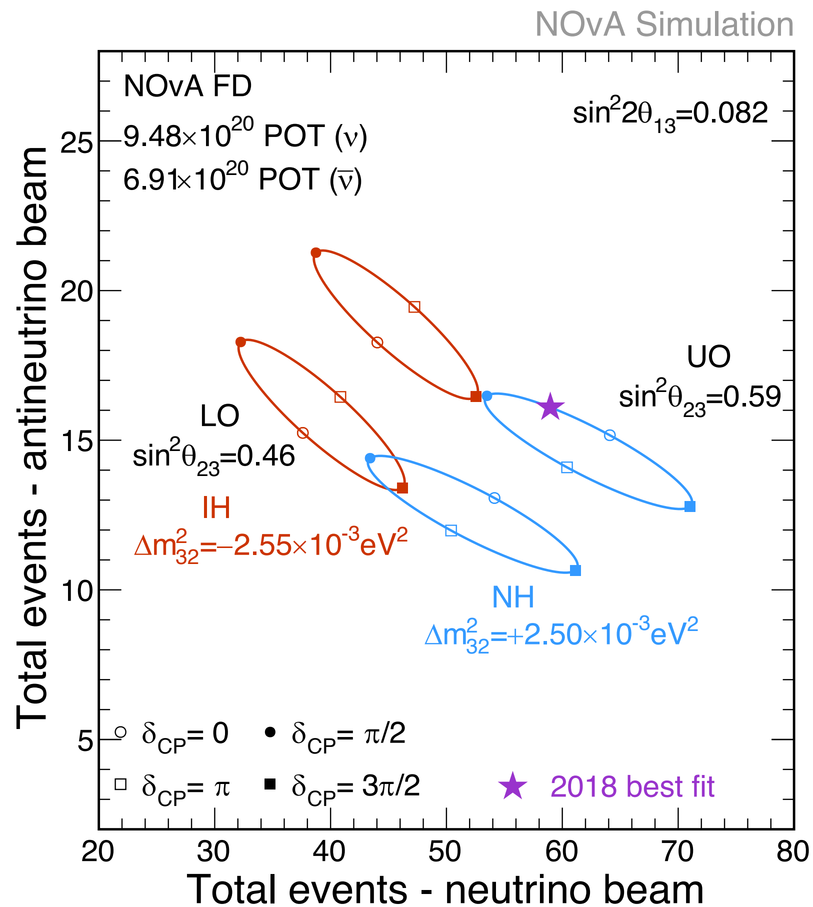
From data $\Delta\chi^2 = \chi^2(IH) - \chi^2(NH) = 2.47$
p-value is 0.076 → Prefer NH at 1.8σ

Joint Appearance and Disappearance

$\nu_e/\bar{\nu}_e$ appearance event counts



Best fit from $\nu_e/\bar{\nu}_e + \nu_\mu/\bar{\nu}_\mu$ combined analysis

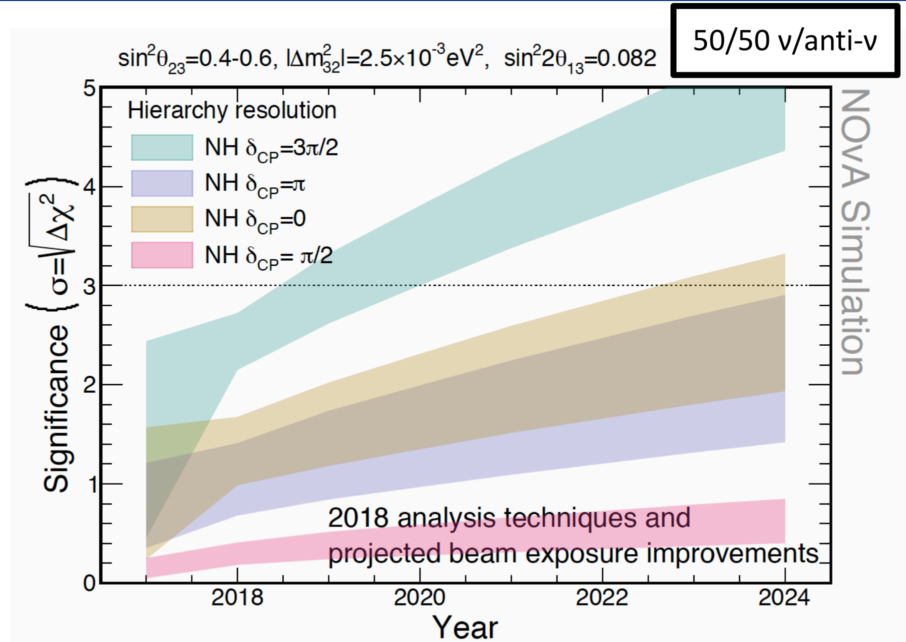


Error bars represent counting uncertainty of $\nu_e/\bar{\nu}_e$ appearance, full power from joint fit to $\nu_e/\bar{\nu}_e$+$\nu_\mu/\bar{\nu}_\mu$ energy/PID spectra

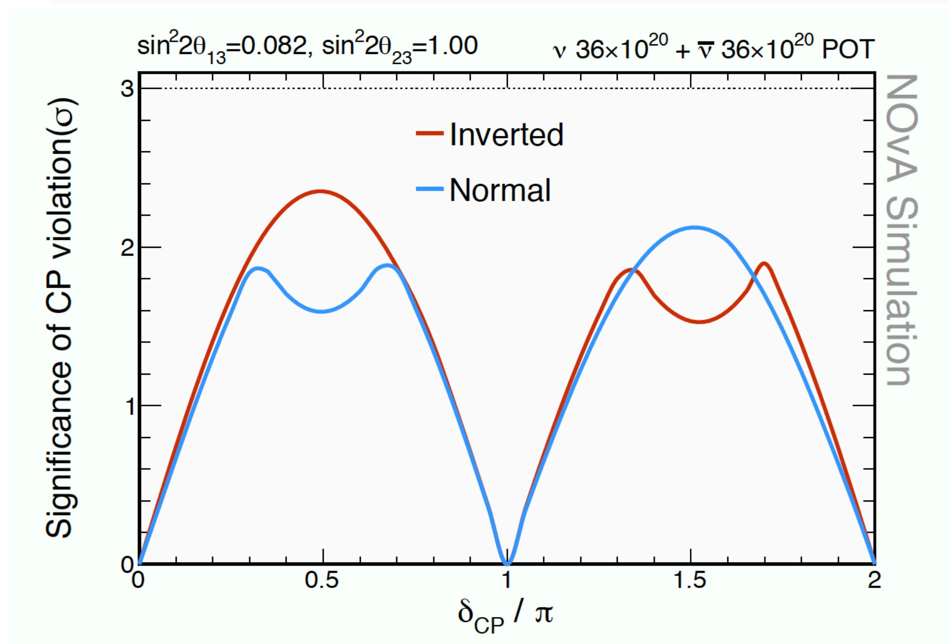
- Prefer non-maximal at 1.8σ, favor upper octant
  Consistent with all δ_{CP} values in NH at < 1.6σ
- Exclude δ=π/2 in IH at > 3σ
- Prefer NH at 1.8σ

Looking Forward

- Taking antineutrino data since 2017-2018, switched back to neutrinos in Feb 2019, run 50% neutrino, 50% anti-neutrino
- Extended running through 2025, test beam program and potential accelerator improvement to enhance ultimate reach



- If $\delta_{CP}=3\pi/2$, 3 σ sensitivity to MH by 2020, ~5 σ by 2024
- 3 σ to MH for 30-50% (depending on octant) of δ_{CP} range by 2024
- 2+ σ to CP at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ by 2024



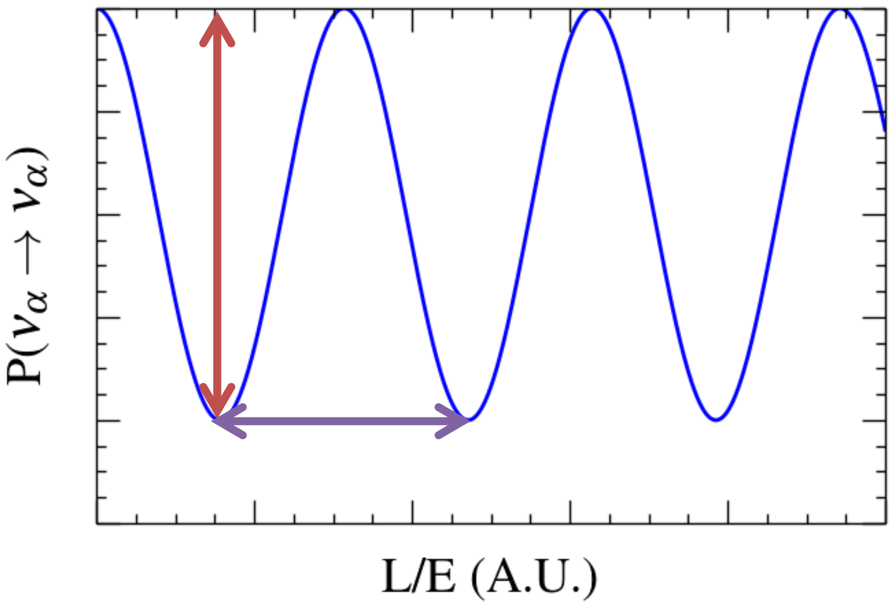
Thank you!

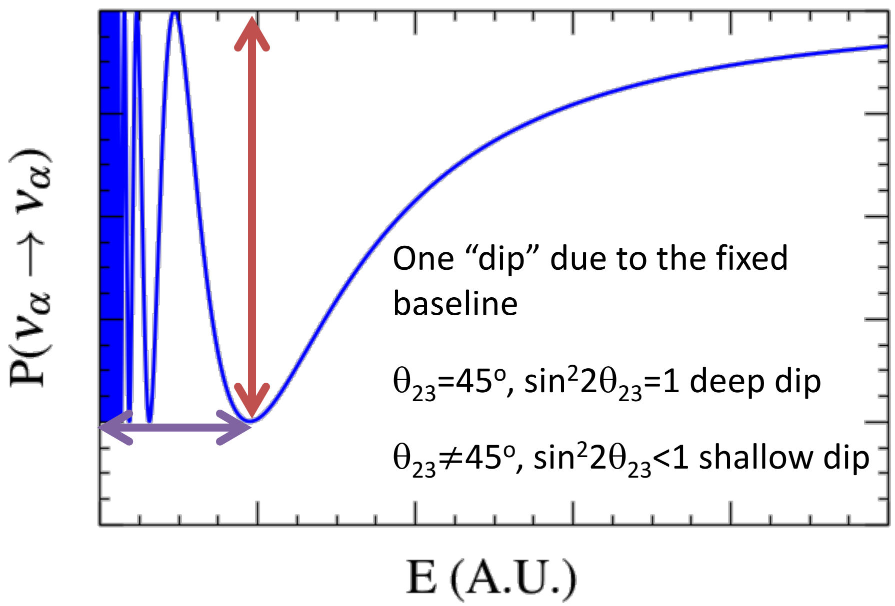
Backup

ν_μ disappearance

$$P(\mu\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

ν_μ disappearance: High precision Δm_{32} and $\sin^2 2\theta_{23}$, constrain octant





Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

$$+ \; 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \; 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

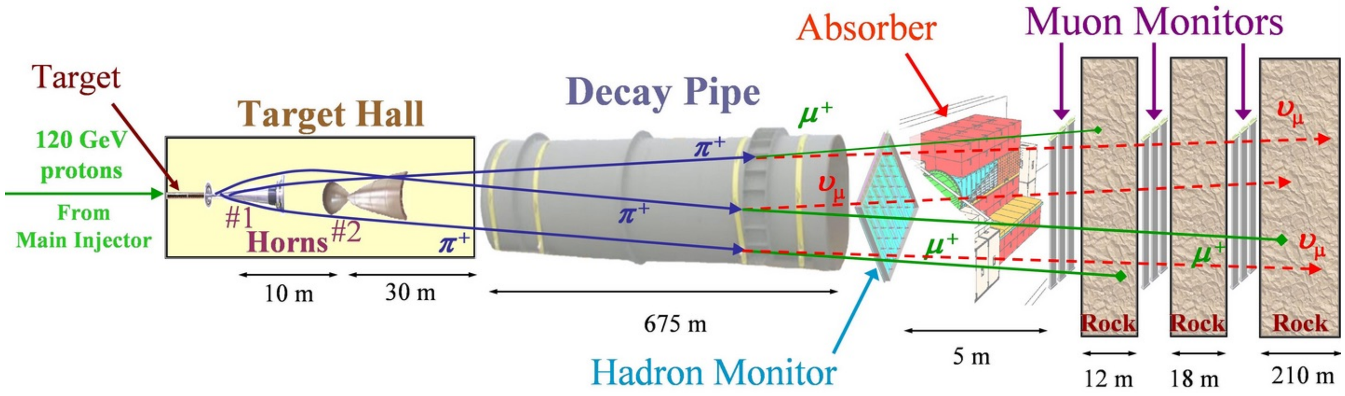
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E}$$

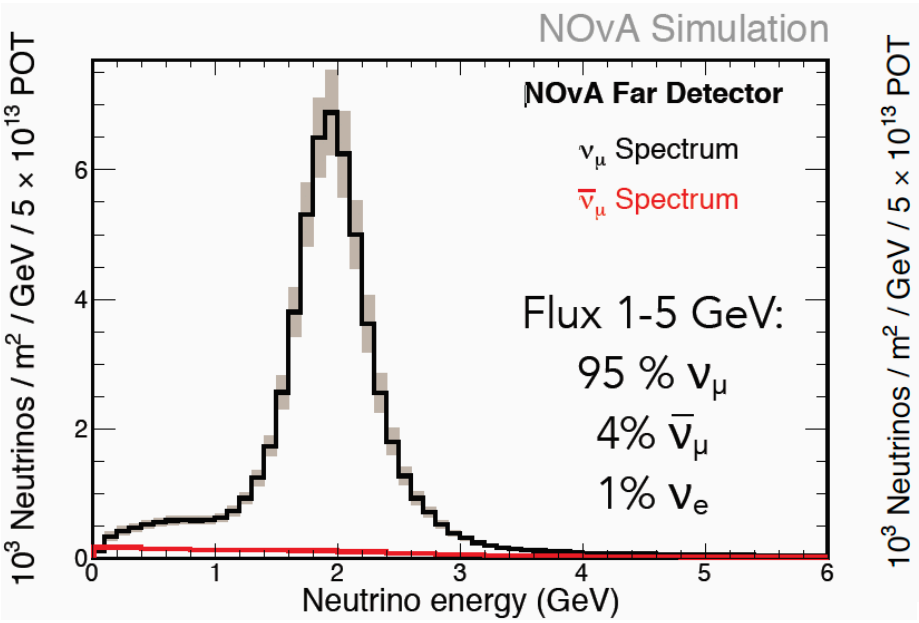
Matter effect

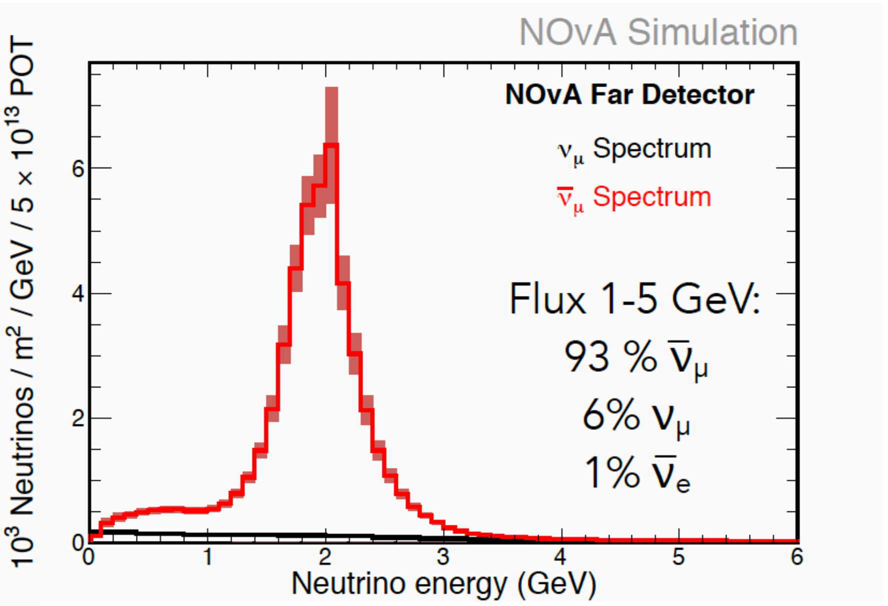
$$\mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- Measuring mass hierarchy (sign of Δ value), δ_{CP} and octant of θ_{23} with ν_e appearance,
- $P(\nu_\mu \longrightarrow \nu_e)$ difference between $\Delta > 0$ and $\Delta < 0$ enlarged by matter effect A ($\propto L$ when fix L/E to oscillation maximum)

NuMI Off-Axis ν_e Appearance Experiment

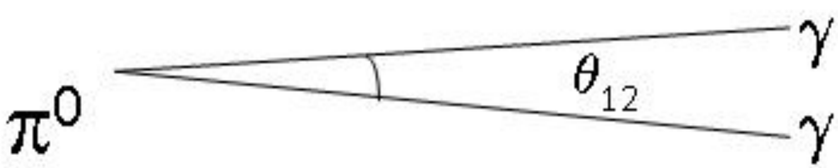




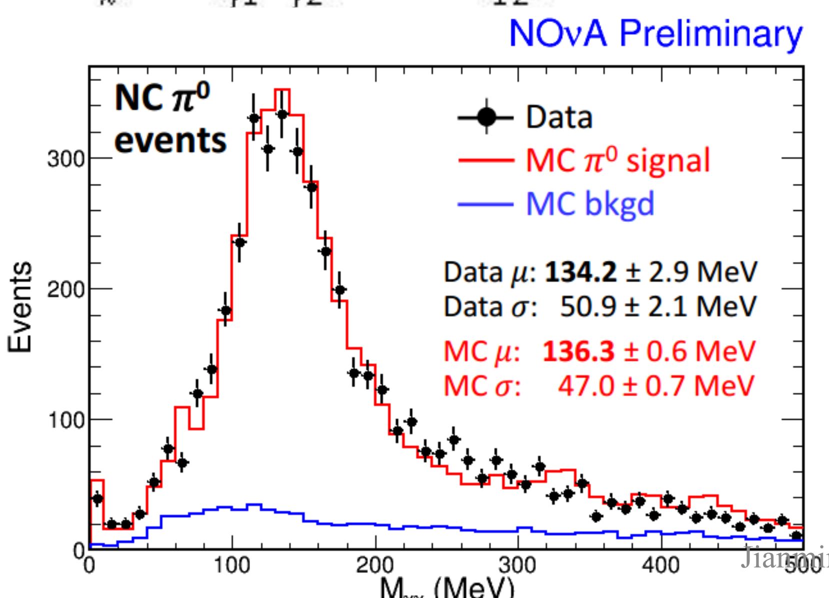


Systematic Error in Calibration

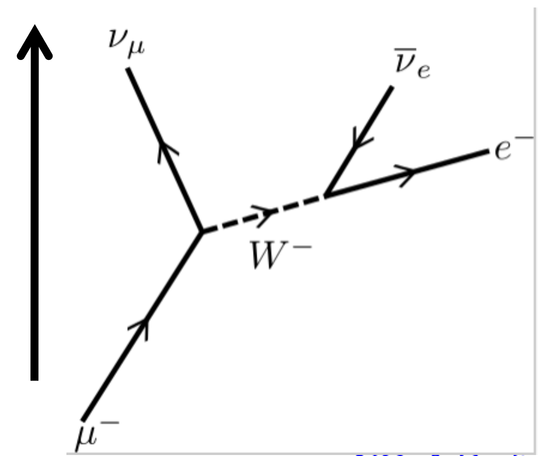
- Our calibration is built on dE/dx from stopping cosmic muons.
- Control samples for calibration uncertainty
  - π^0 mass peak in ND
  - Michel electrons in ND and FD

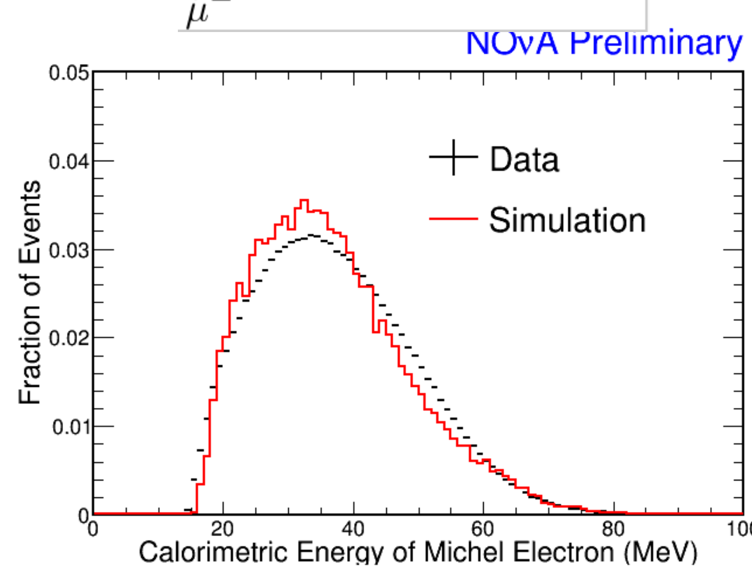


$$m^2_{\pi^0}=2E_{\gamma1}E_{\gamma2}(1-\cos\theta_{12})$$

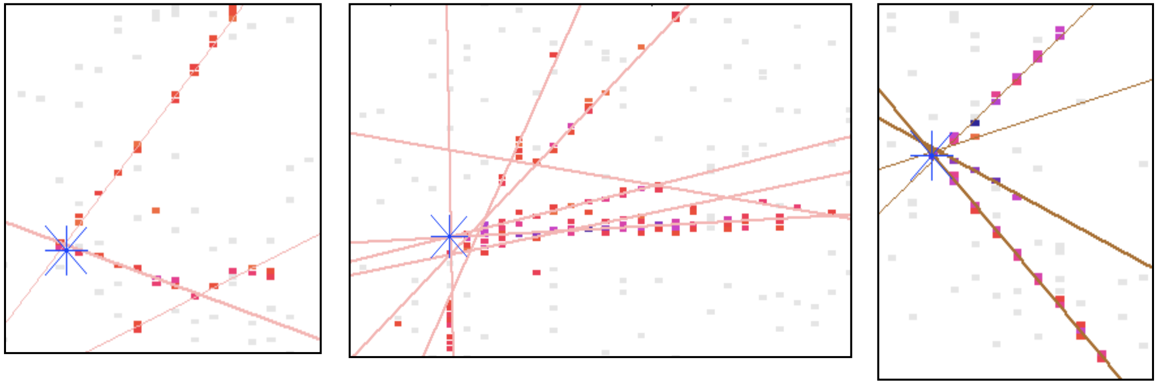


Michel electrons from muon decays

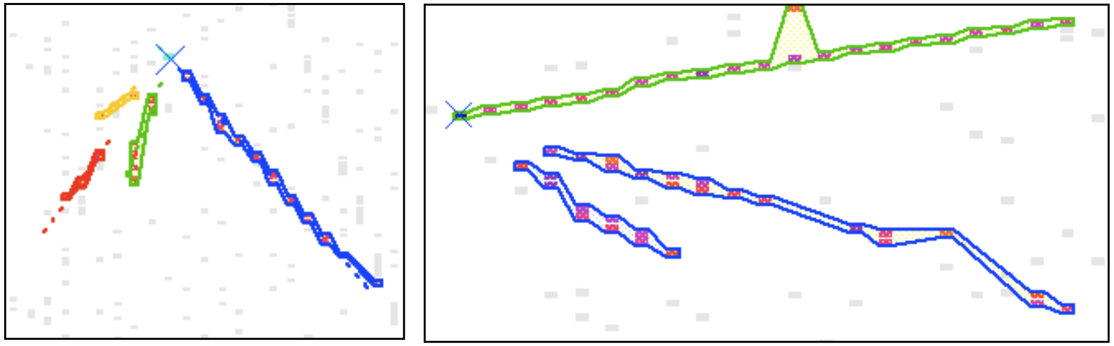




Prong/track Reconstruction

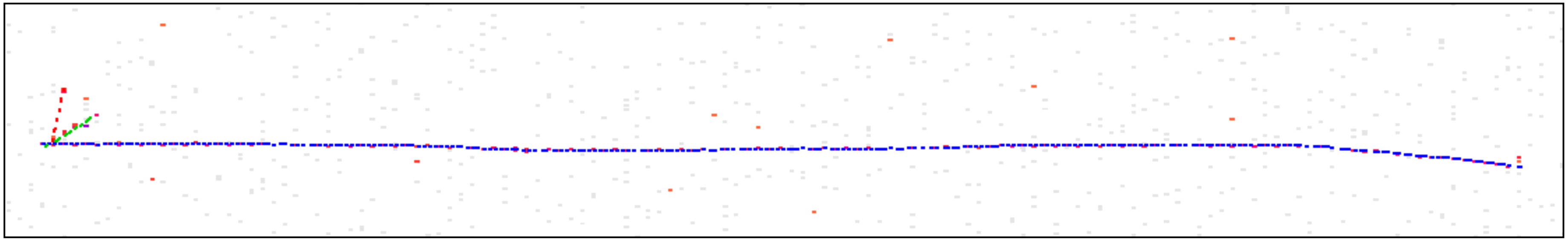


Vertexing: Find lines of energy depositions with Hough transform. Then determine the vertex that all lines converge to

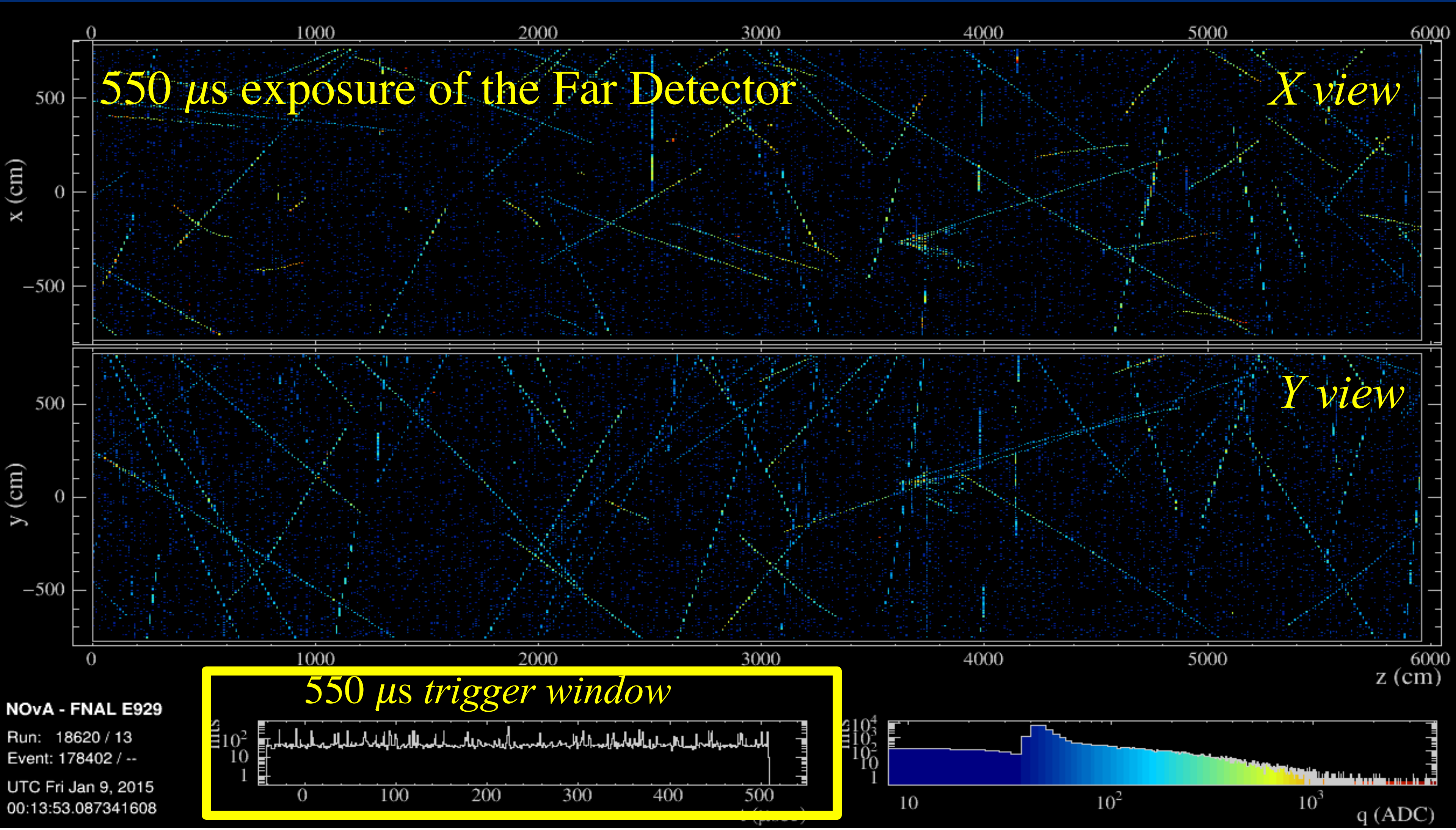


Shower Clustering: Based on the vertex and the lines, showers are reconstructed by angular clustering

Tracking: Trace particle trajectories with **Kalman filter** tracker (below). Also have a **cosmic ray tracker** that reconstructs cosmic tracks with high speed.

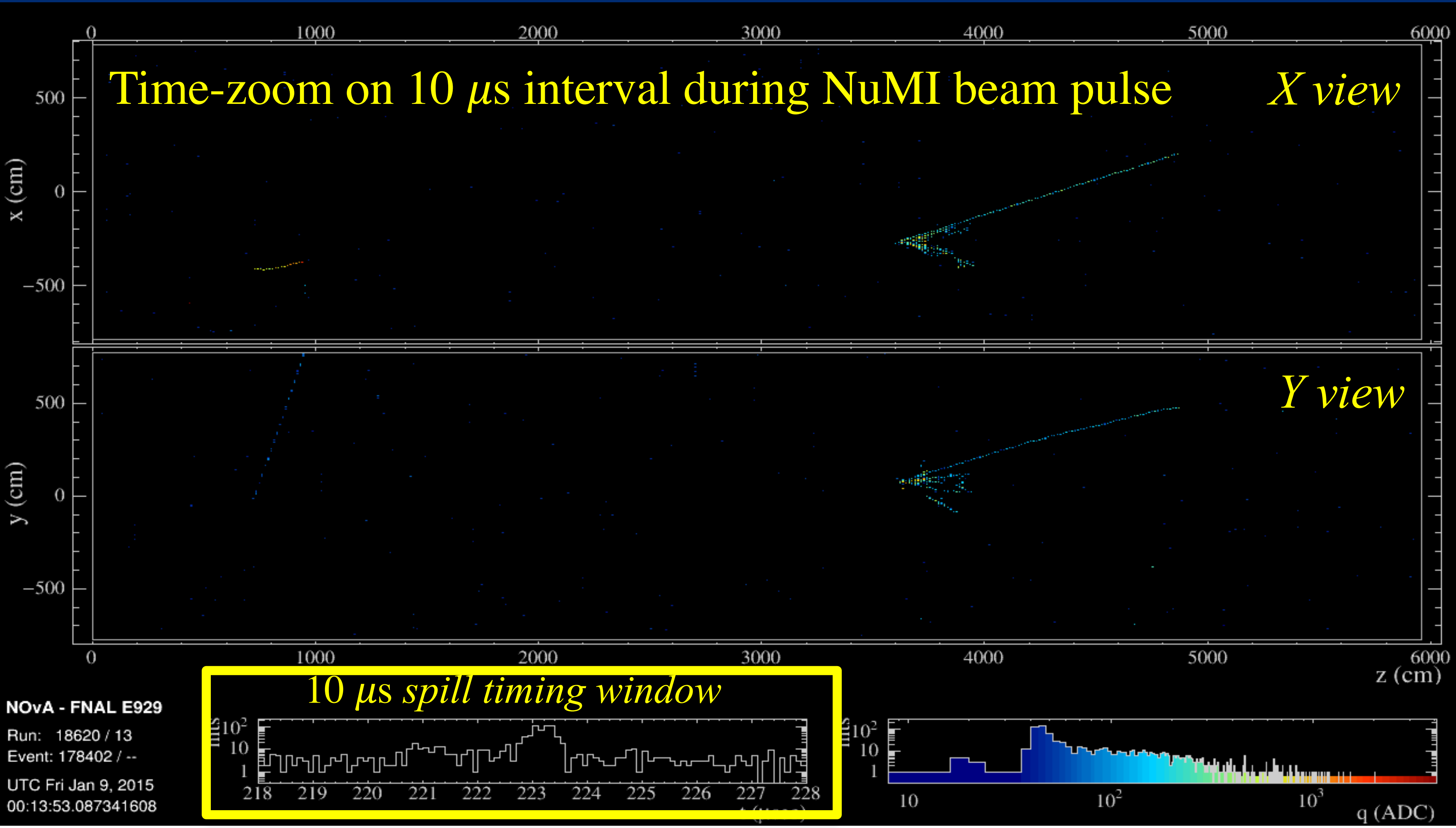


Event clustering



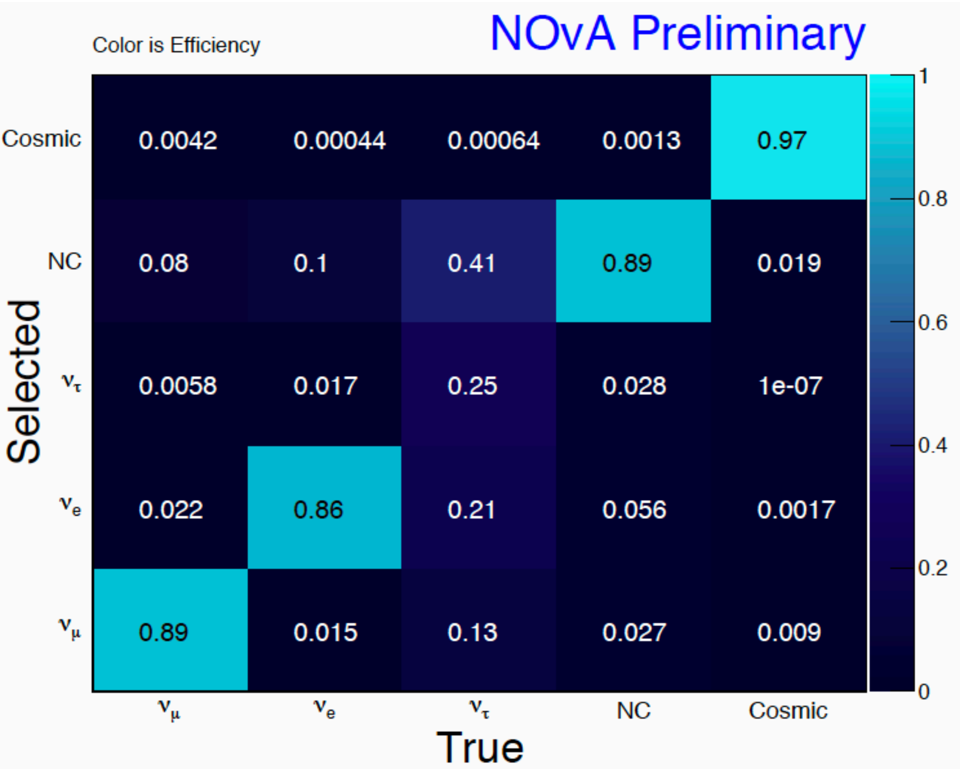
- Because NOvA is on surface, hits in a trigger window are a combination of cosmic and beam events.
- First step in reconstruction is to cluster hits by space-time coincidence to separate neutrino hits and cosmic hits.

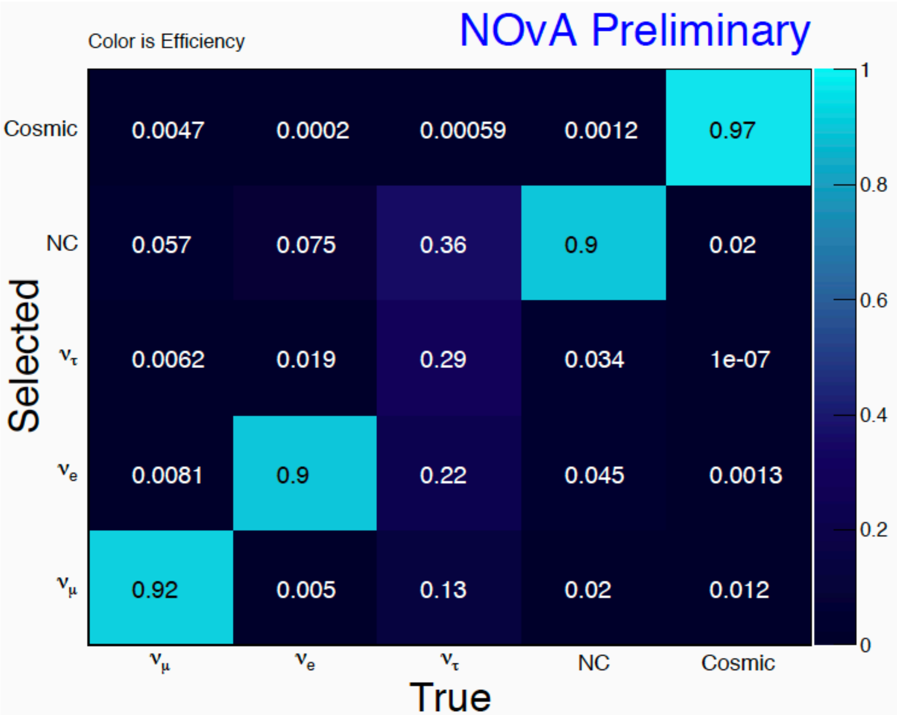
Event clustering



Event clusters that contain neutrino interactions can be correctly selected in the neutrino spill timing window

PID efficiencies

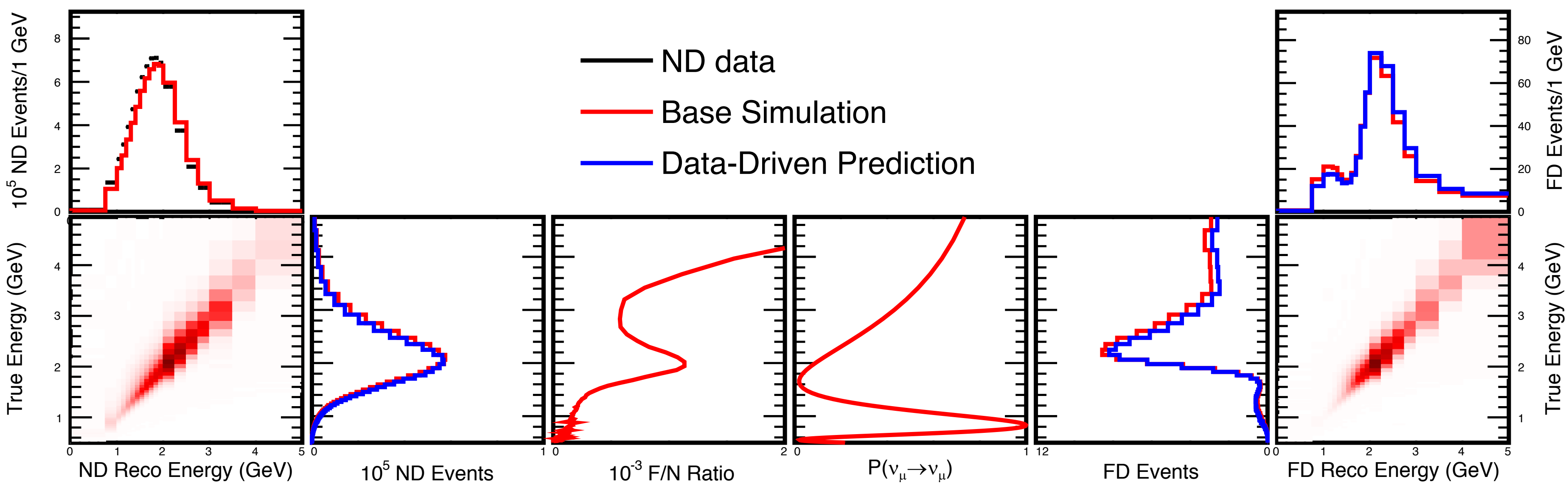




Analysis Strategy

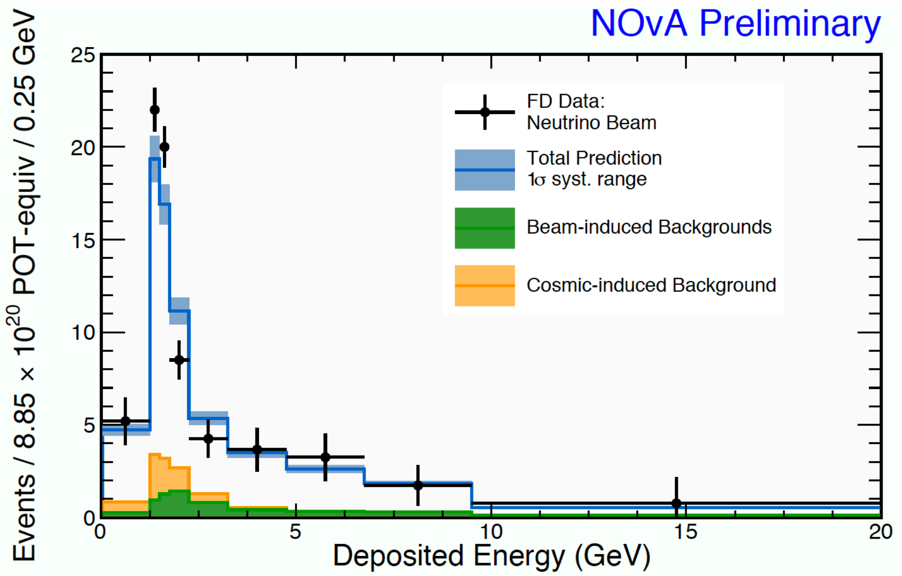
- Separate ν_μ/ν_e /NC signal from beam backgrounds
- Extrapolate observed ND spectrum to FD, reject cosmic rays in FD, make FD unoscillated prediction
- Measure shapes and yields of signal events in energy/PID bins in FD to determine oscillation parameters

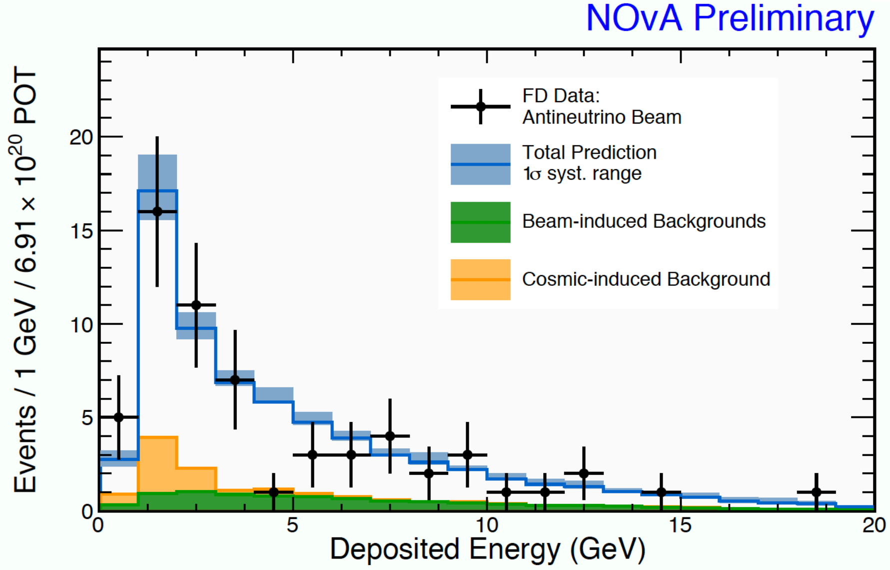
ND→FD extrapolation for ν_μ disappearance



Observed NC events in Far Detector

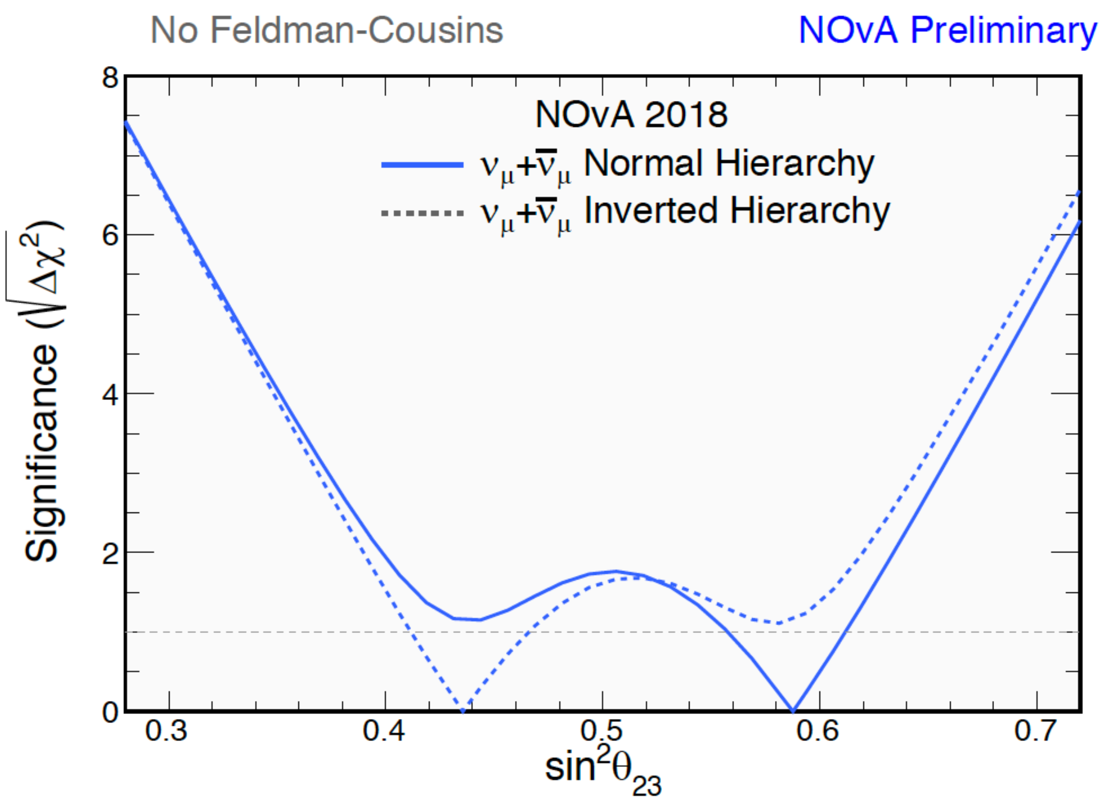
- FD selection:
  - NC CVN selection applied
  - Additional Deep-learning based cosmic rejection
- Neutrino beam:
  - Observe 201 events, predict 188 ± 13 (syst.) events (38 bkg.)
- Antineutrino beam:
  - Observe 61 events, predict 69 ± 8 (syst.) events (16 bkg.)
- No significant suppression for NC observed, consistent with 3-flavor oscillation





ν_μ appearance fit

- Combined data of neutrino and antineutrino beams fitted assuming CPT invariance
- If fit separately, $\bar{\nu}_\mu$ data prefers non-maximal while ν_μ prefers maximal
- χ^2s consistent with combined fit oscillation parameters with $p > 4\%$
- Matter effects introduce small asymmetry in the point of maximal disappearance, ~1σ prefers Upper (Lower) Octant in NH (IH)



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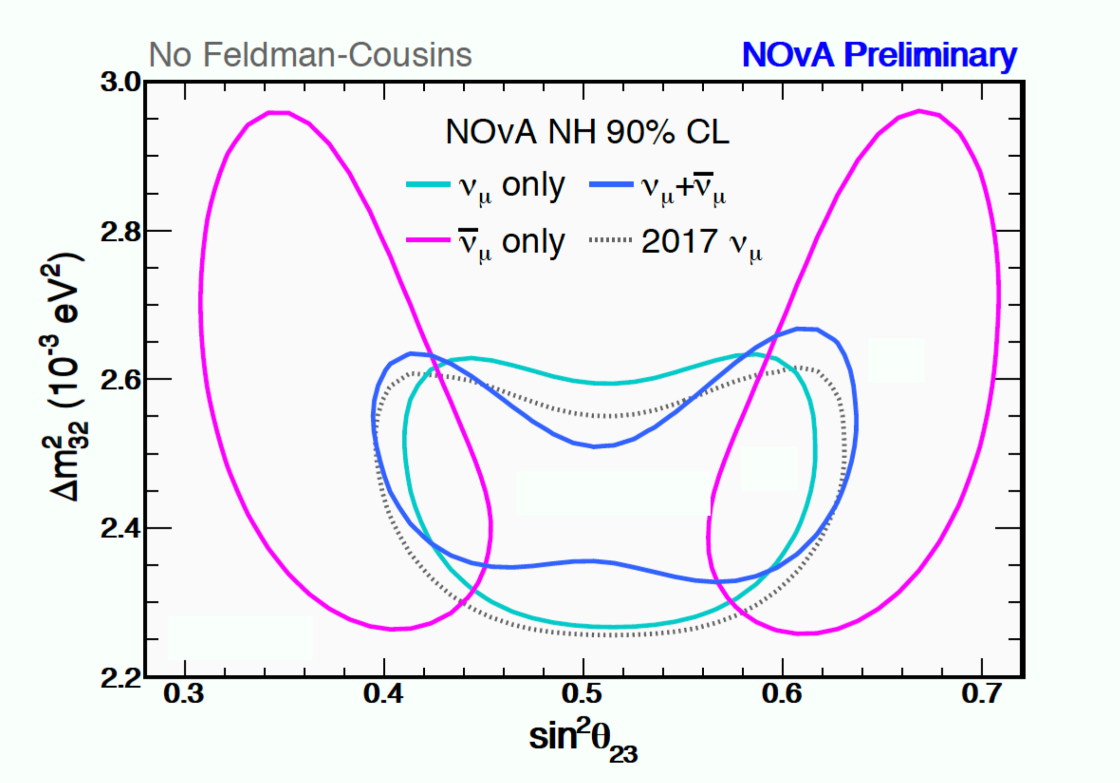
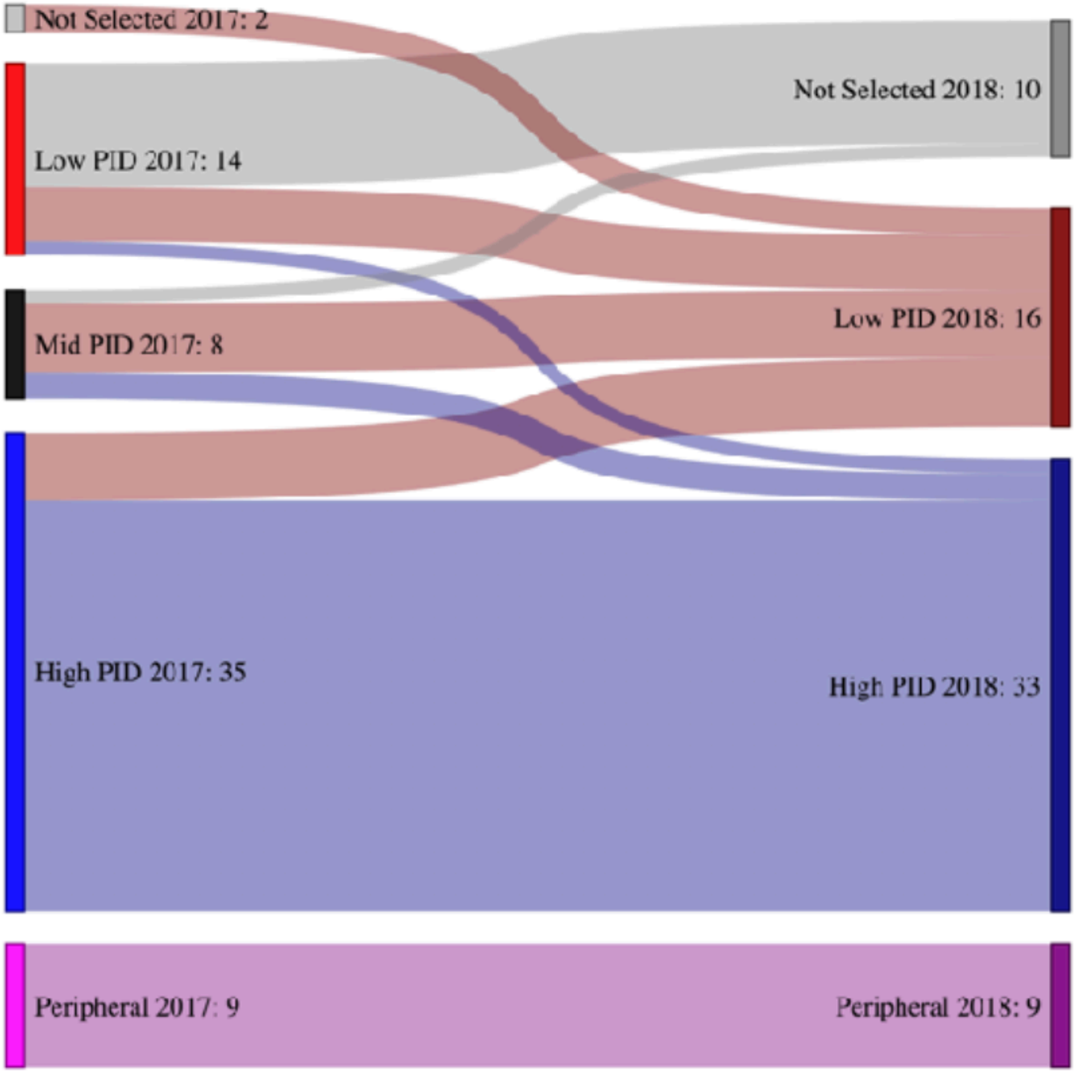


2017/2018 RHC ν_e FD Data

66 FD data events in 2017 analysis



58 FD data events in 2017 analysis

Change in data events after retraining of PID, new training improved bkg rejection

Systematic Uncertainties (Joint Fit)

Source of Uncertainty	$\sin^2\theta_{23}$ ($\times 10^{-3}$)	δ_{CP}/π	Δm^2_{32} ($\times 10^{-3}$ eV^2)
Beam Flux	+0.42 / -0.48	+0.0088 / -0.0048	+0.0016 / -0.0015
Detector Calibration	+6.9 / -6.1	+0.15 / -0.023	+0.024 / -0.029
Detector Response	+1.9 / -0.99	+0.055 / -0.054	+0.0027 / -0.0034
Muon Energy Scale	+2.6 / -2.1	+0.015 / -0.0026	+0.01 / -0.012
Near-Far Differences	+0.56 / -1.1	+0.11 / -0.064	+0.0033 / -0.0013
Neutrino Cross Sections	+4.2 / -3.5	+0.085 / -0.072	+0.015 / -0.014
Neutron Uncertainty	+6.4 / -7.9	+0.002 / -0.0052	+0.0028 / -0.01
Normalization	+1.4 / -1.5	+0.031 / -0.024	+0.0029 / -0.0027
Systematic Uncertainty	+9.6 / -11	+0.21 / -0.11	+0.032 / -0.035
Statistical Uncertainty	+22 / -29	+0.9 / -0.27	+0.064 / -0.059