Recent Results from the NOvA experiment

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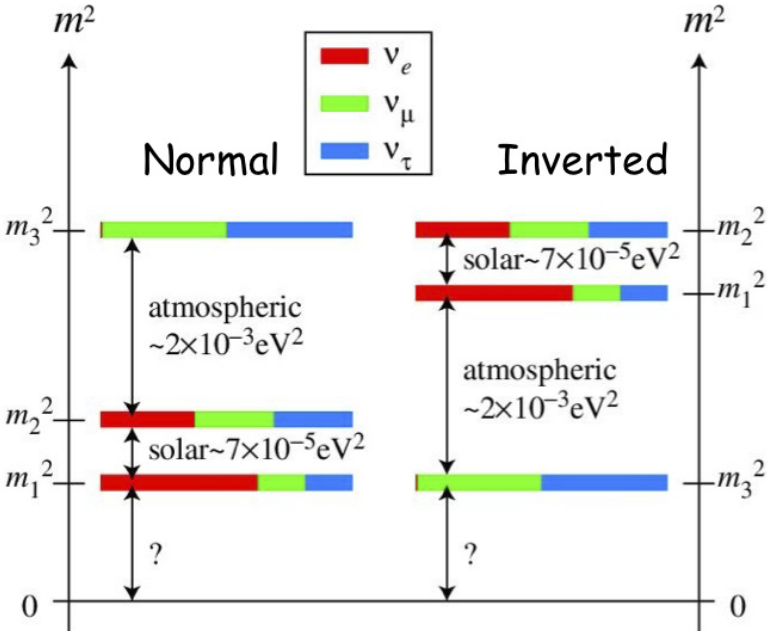
NOvA Physics Goals

- 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

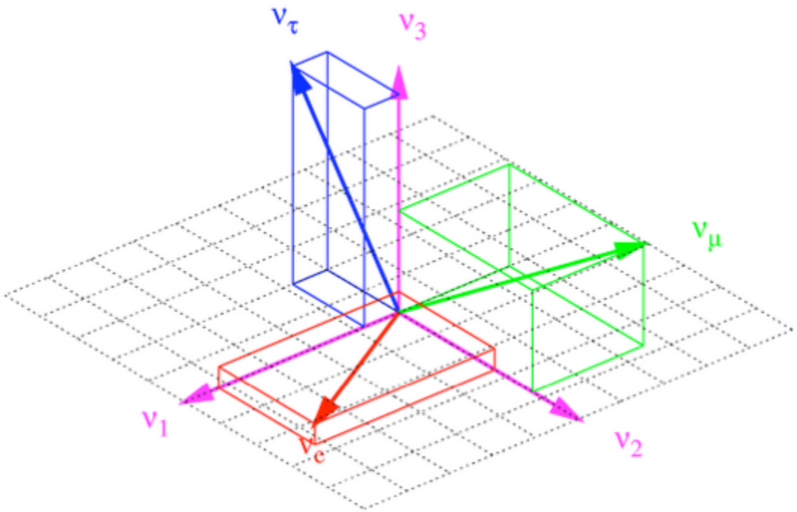
This talk: New ν_e and ν_μ oscillation results with NOvA's first antineutrino data



Neutrino Oscillation

- For the three-flavor case the PMNS matrix is most commonly parameterized by three real mixing angles θ_{12}, θ_{23} and θ_{13} and a single phase δ_{CP}

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



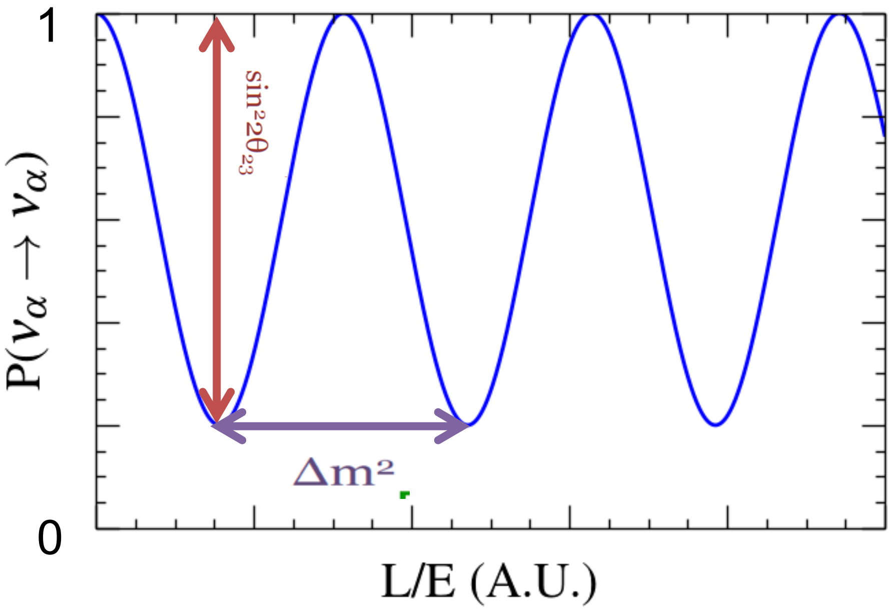
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

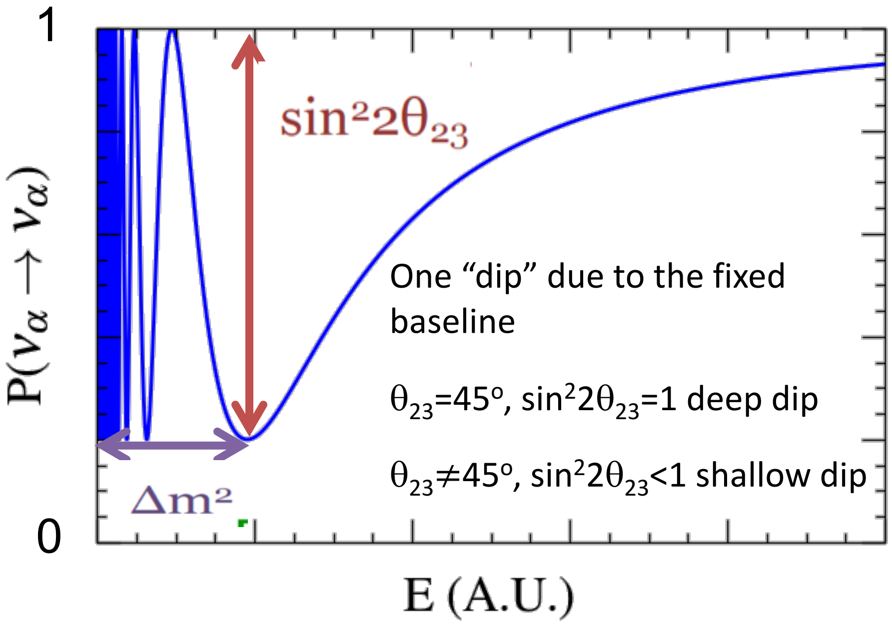
Including two independent squared mass differences $\Delta m^2{}_{21} = m^2{}_2 - m^2{}_1$ and $\Delta m^2{}_{32} = m^2{}_3 - m^2{}_2$, there are 6 free parameters that determine the neutrino oscillation.

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





One “dip” due to the fixed baseline

$\theta_{23}=45^\circ$, $\sin^2 2\theta_{23}=1$ deep dip

$\theta_{23}\neq 45^\circ$, $\sin^2 2\theta_{23}<1$ shallow dip

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

ν_μ disappearance

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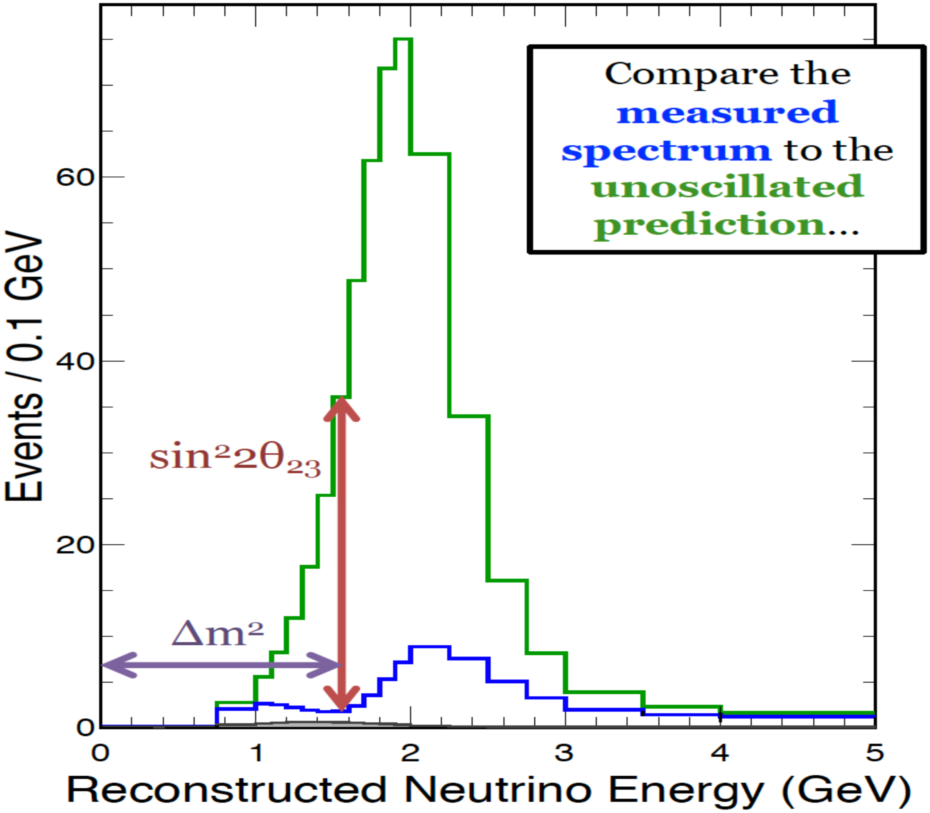
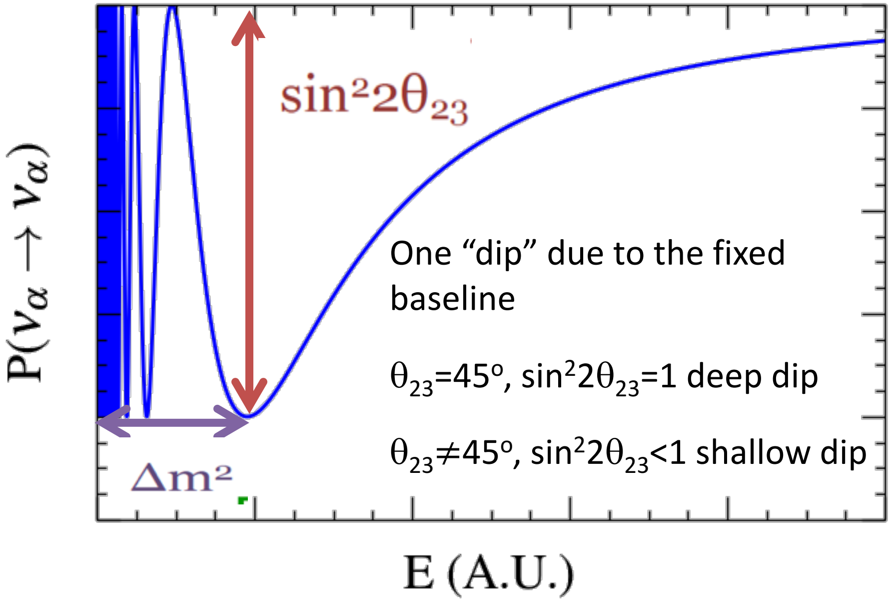


Compare the **measured spectrum** to the **unoscillated prediction…**



One “dip” due to the fixed baseline

θ_{23}=45°, $\sin^2 2\theta_{23}=1$ deep dip

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ν_e appearance

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

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

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

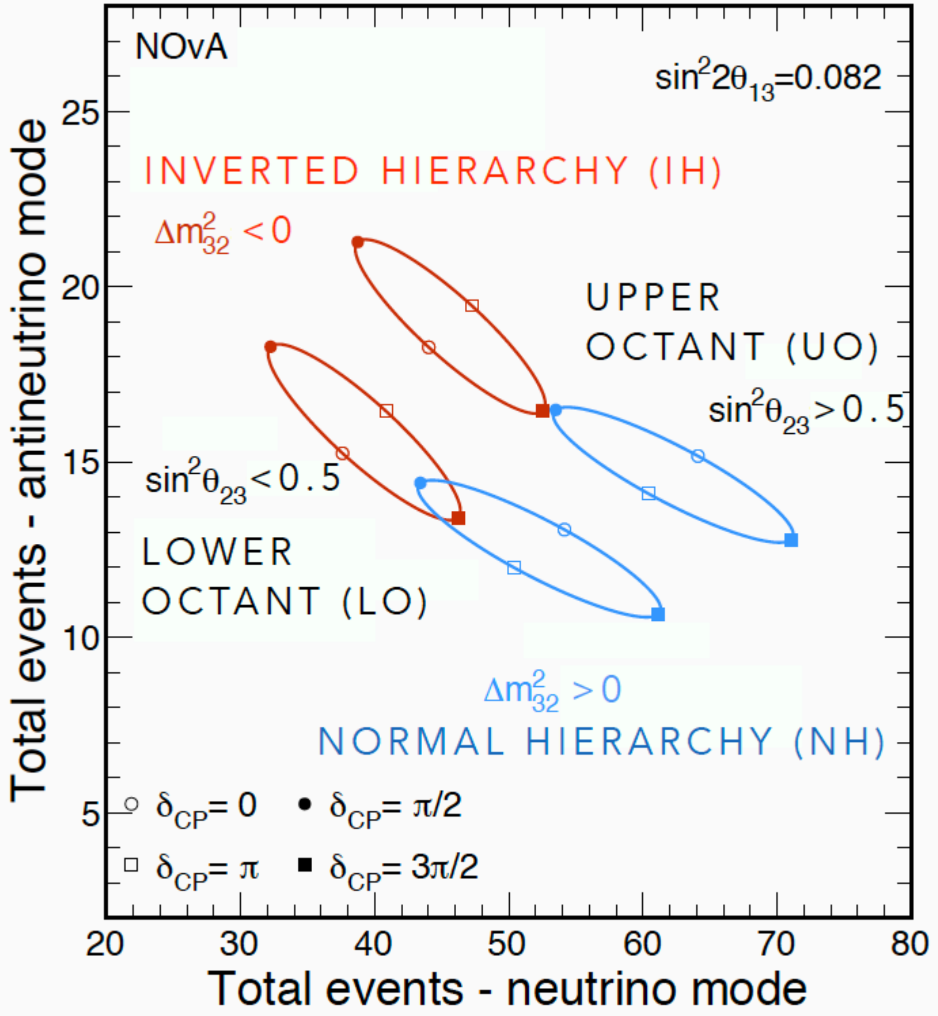
Matter effect

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- 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)

Appearance and Disappearance at NOvA

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

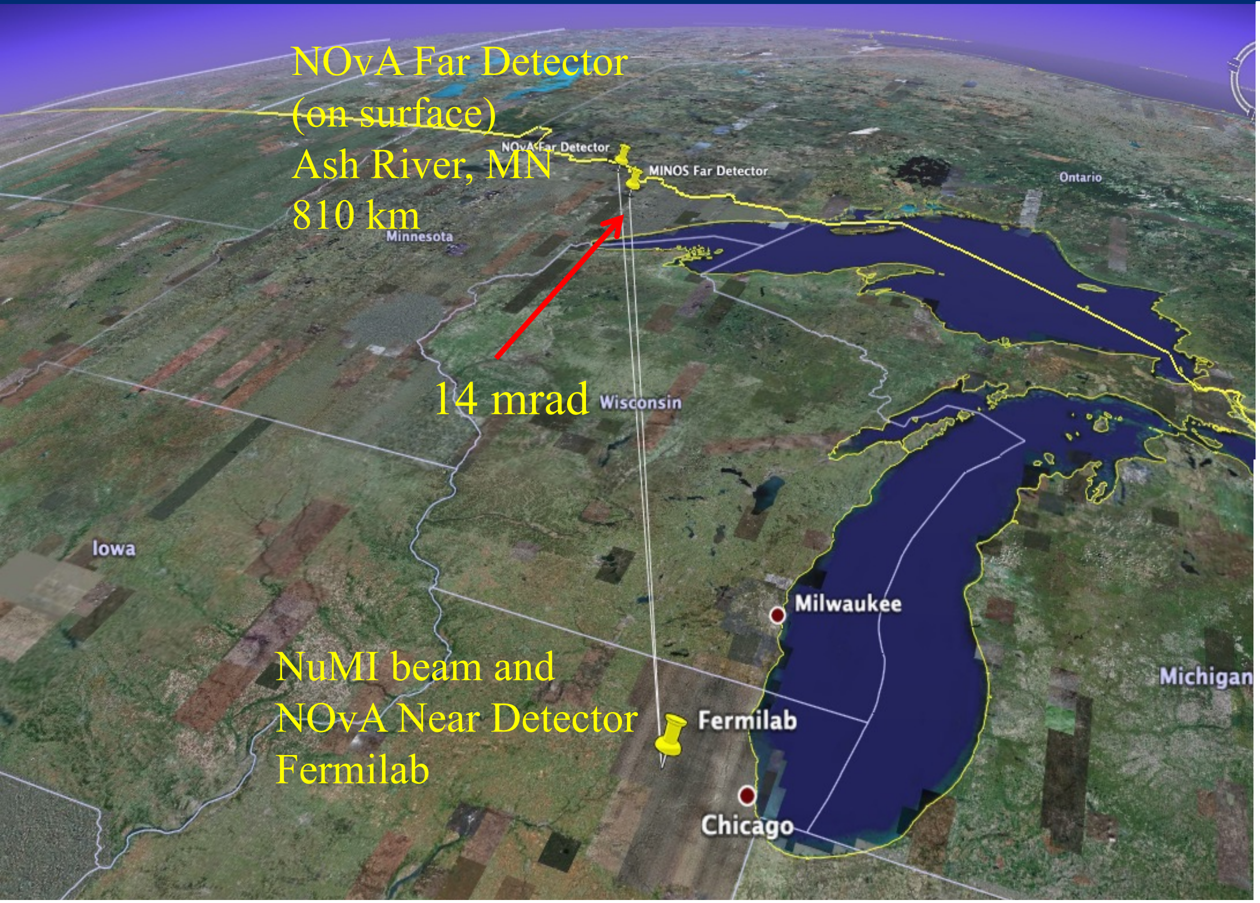


- Measuring ν_e and $\bar{\nu}_e$ appearance probabilities with ν_μ and $\bar{\nu}_\mu$ beam

- 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

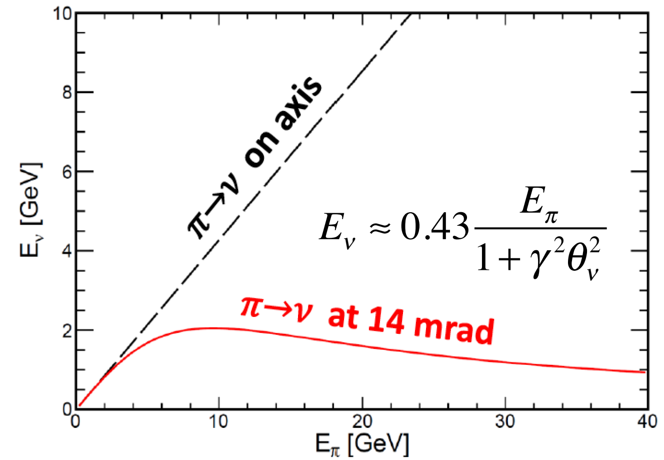
NuMI Off-Axis ν_e Appearance Experiment

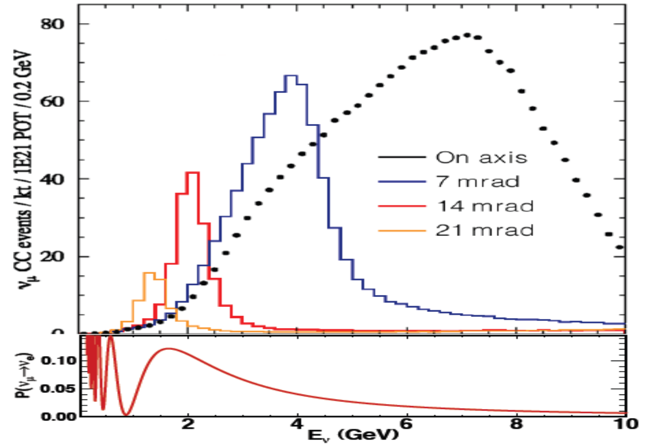


NOvA Far Detector
(on surface)
Ash River, MN
810 km

14 mrad

NuMI beam and
NOvA Near Detector
Fermilab

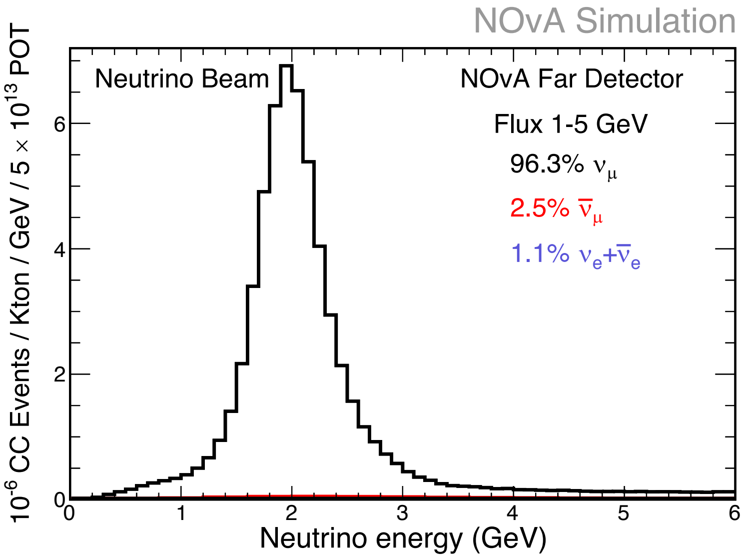




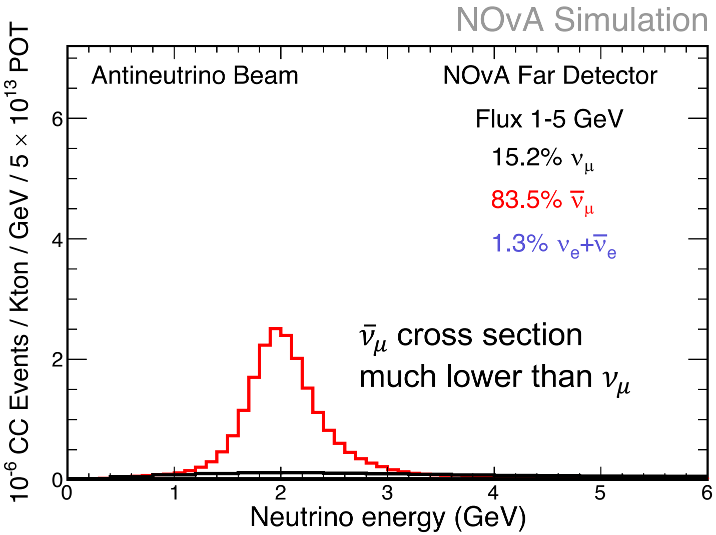
- Upgraded NuMI muon neutrino beam at Fermilab (700 kW design goal achieved)
- Longest baseline in operation (810 km), large matter effect (±30%), sensitive to mass hierarchy
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum, small wrong sign components

Beam Performance

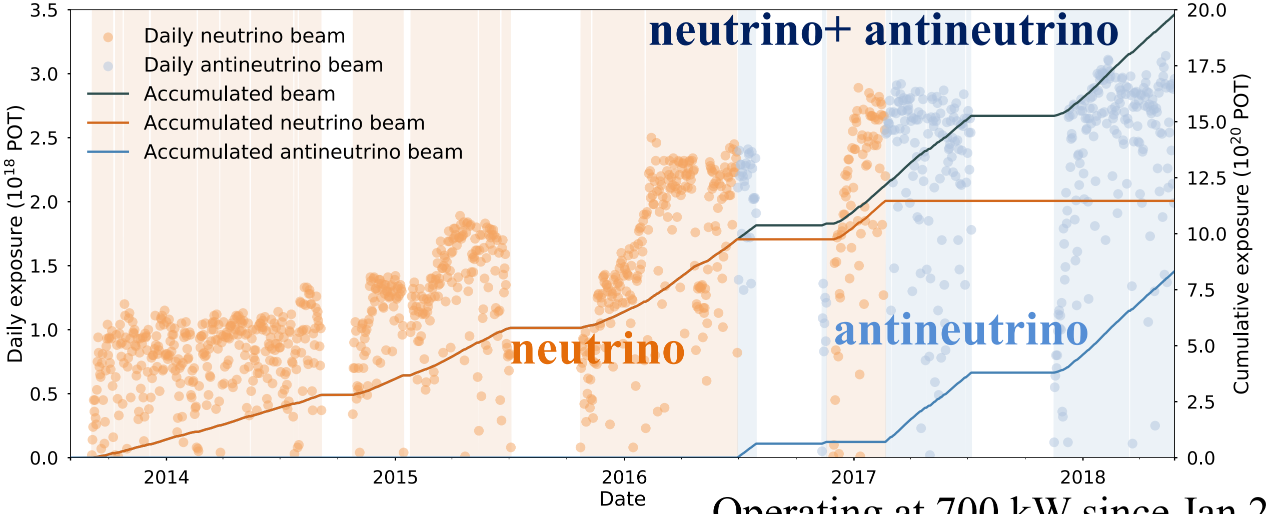
CC event rates at FD in neutrino beam



CC event rates at FD in antineutrino beam



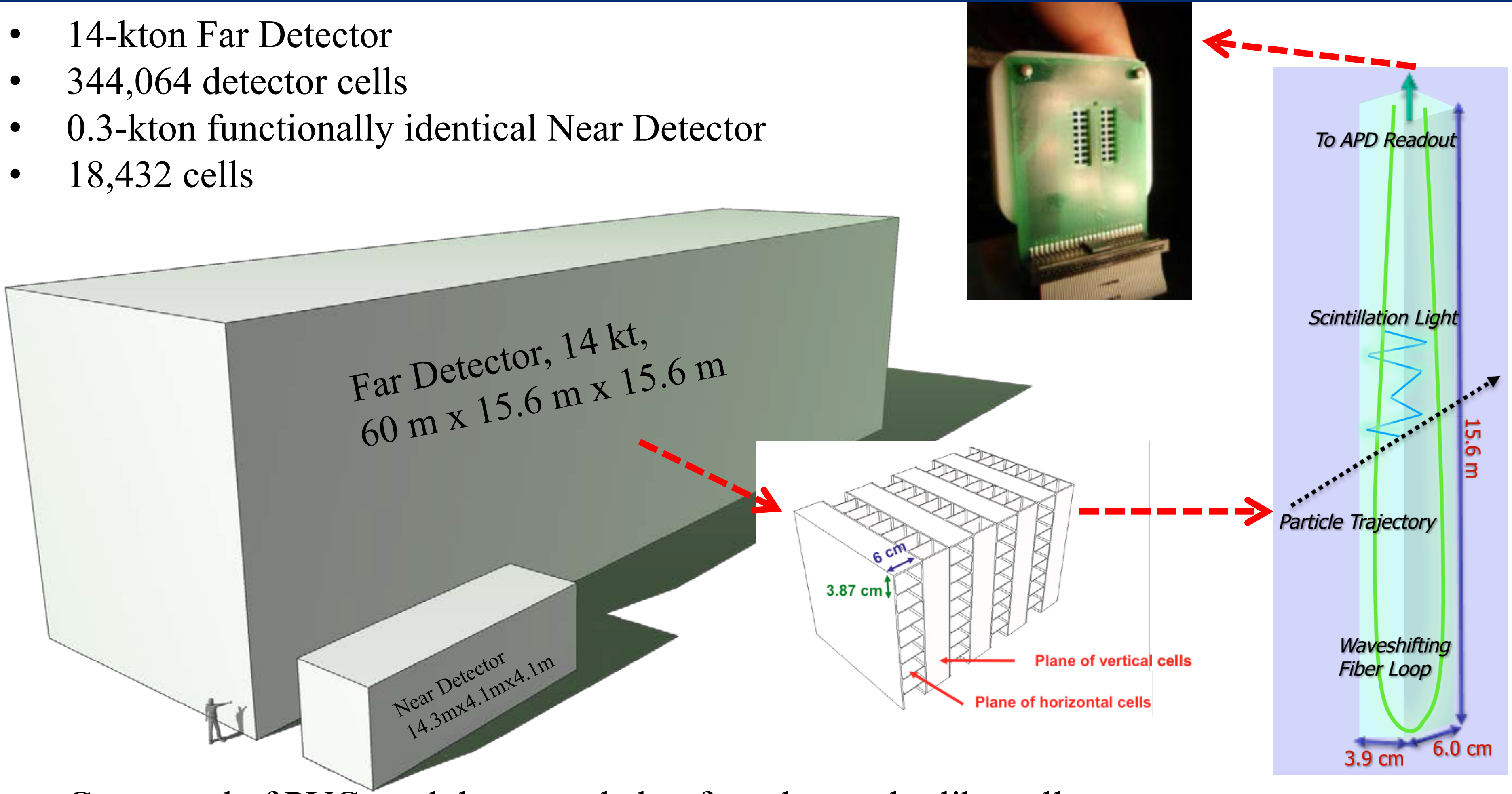
- **Neutrino beam** data: 8.85x10^{20} POT, taken Feb 2014 - Feb 2017
- First **antineutrino data**: 6.9 x 10^{20} POT, taken Feb 2017 - April 2018



Operating at 700 kW since Jan 2017

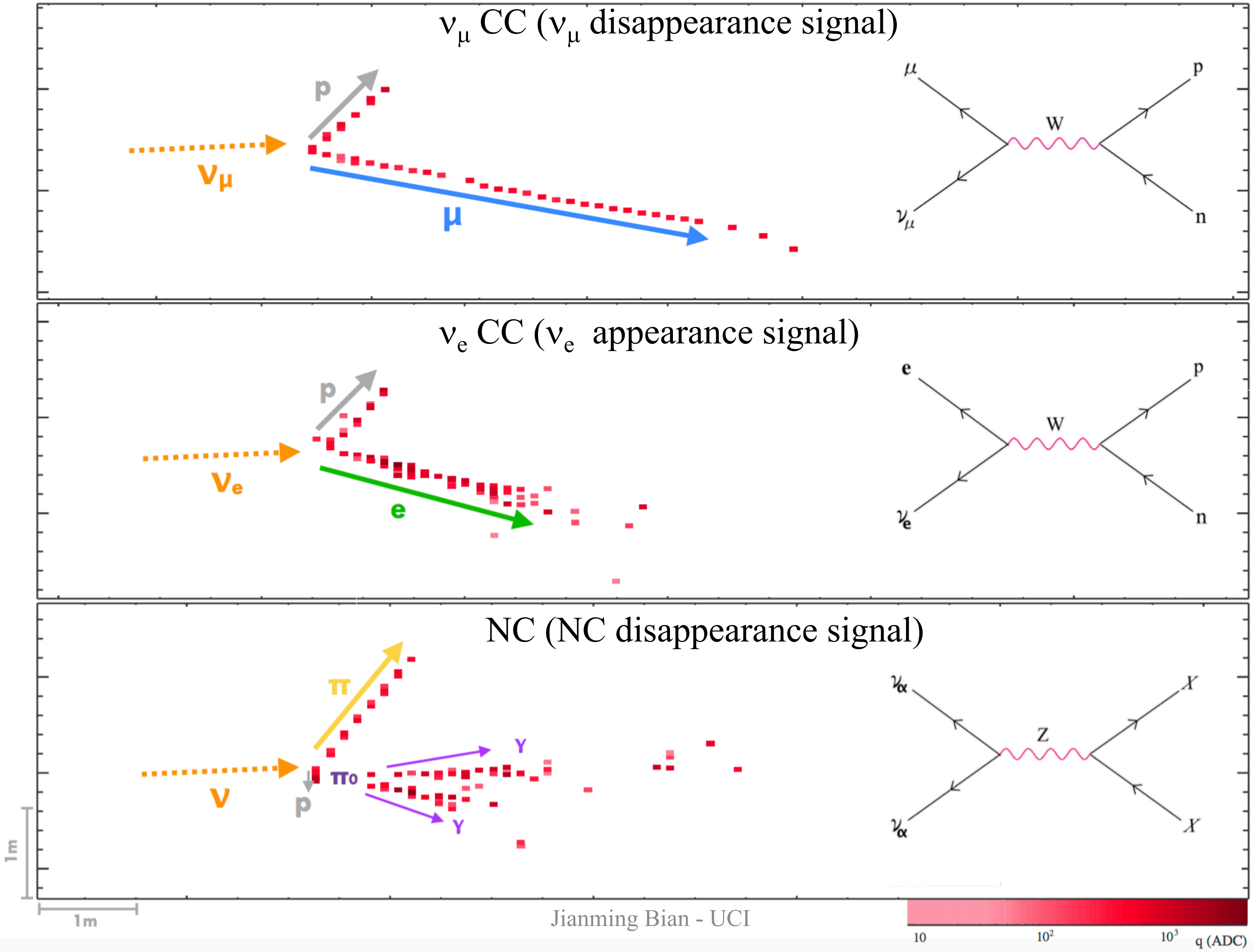
The NOνA Detectors

- 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



ν_μ CC (ν_μ disappearance signal)

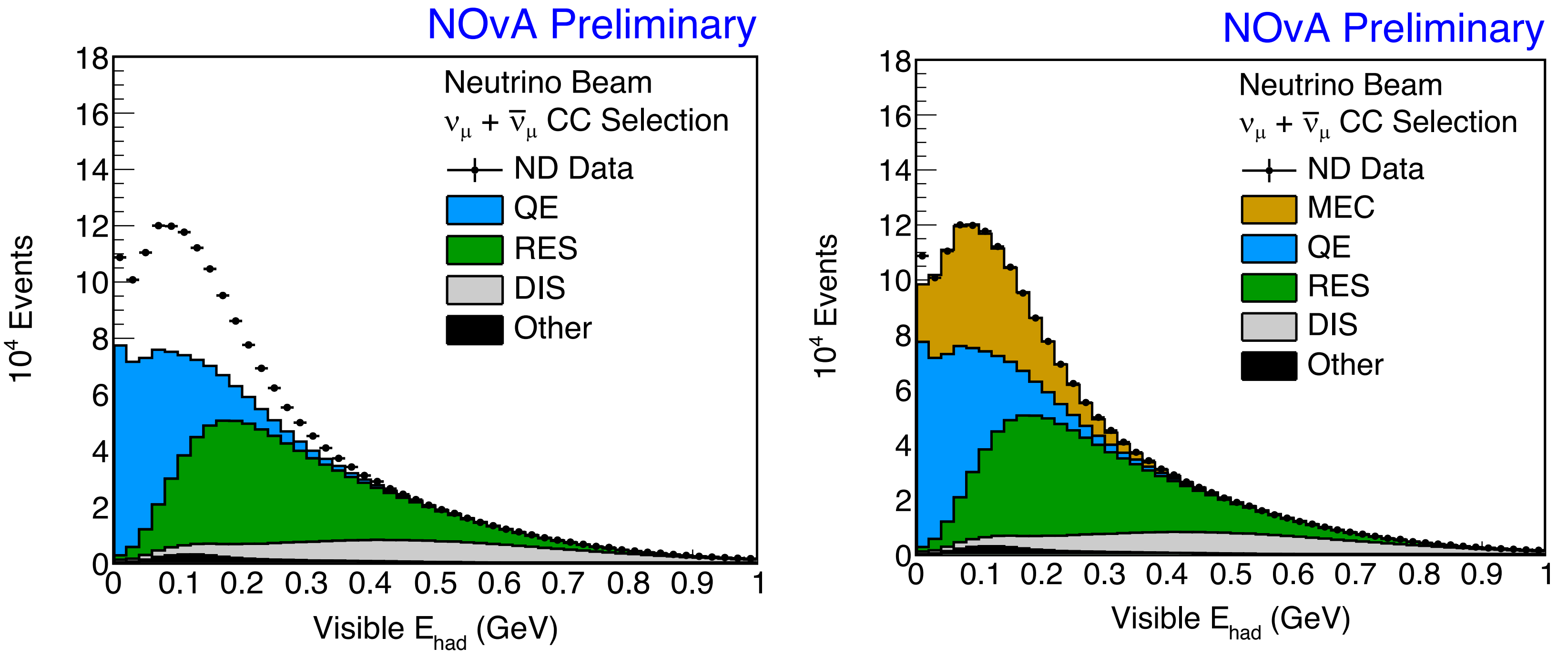
ν_e CC (ν_e appearance signal)

NC (NC disappearance signal)

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

(See Talk 134, Jeremy Wolcott, 08/17/2018)



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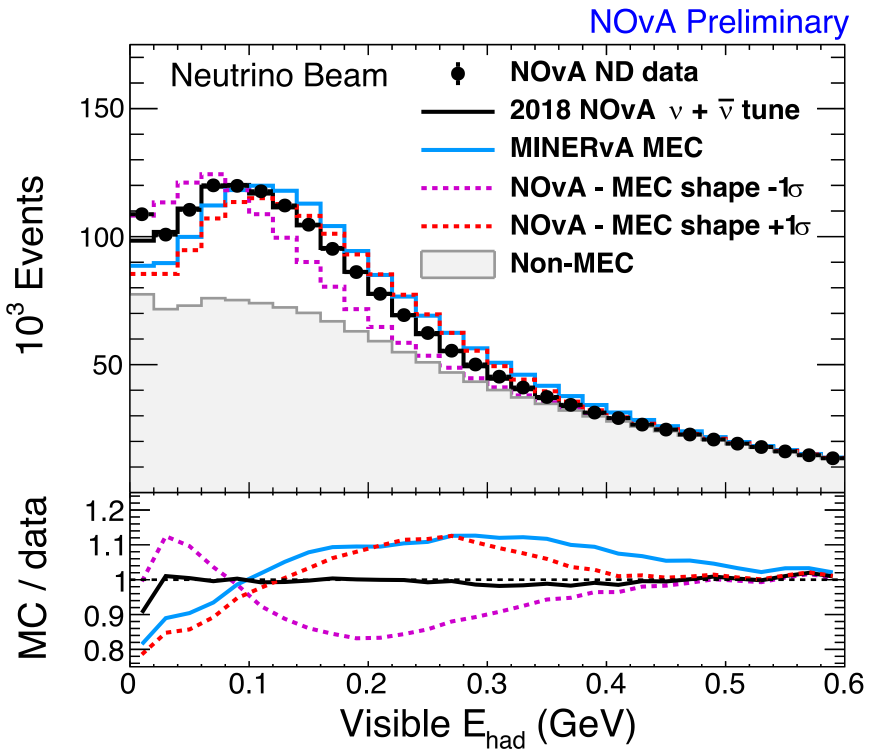
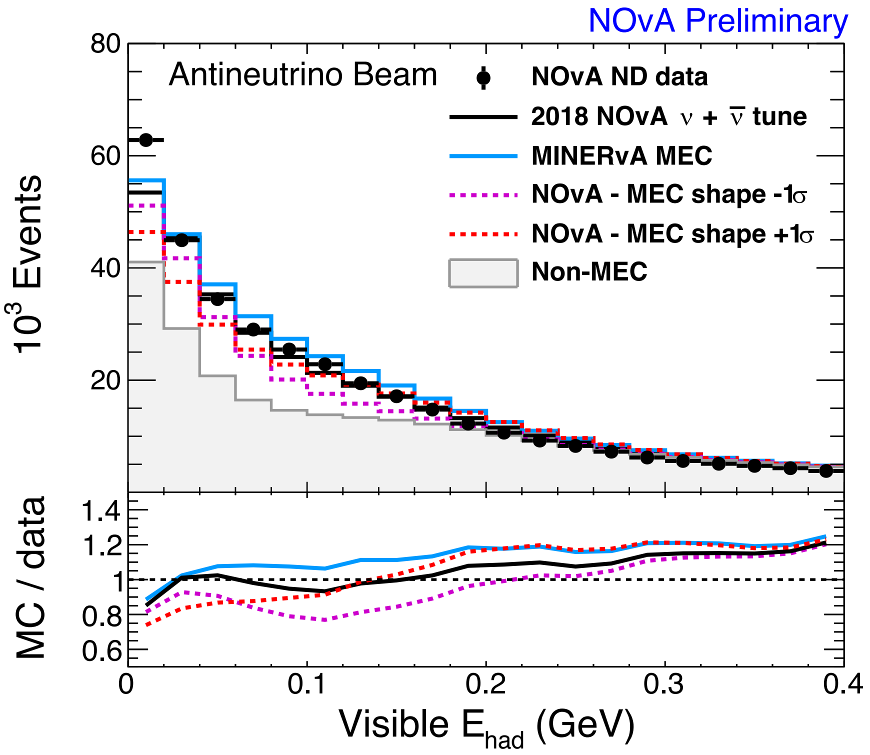
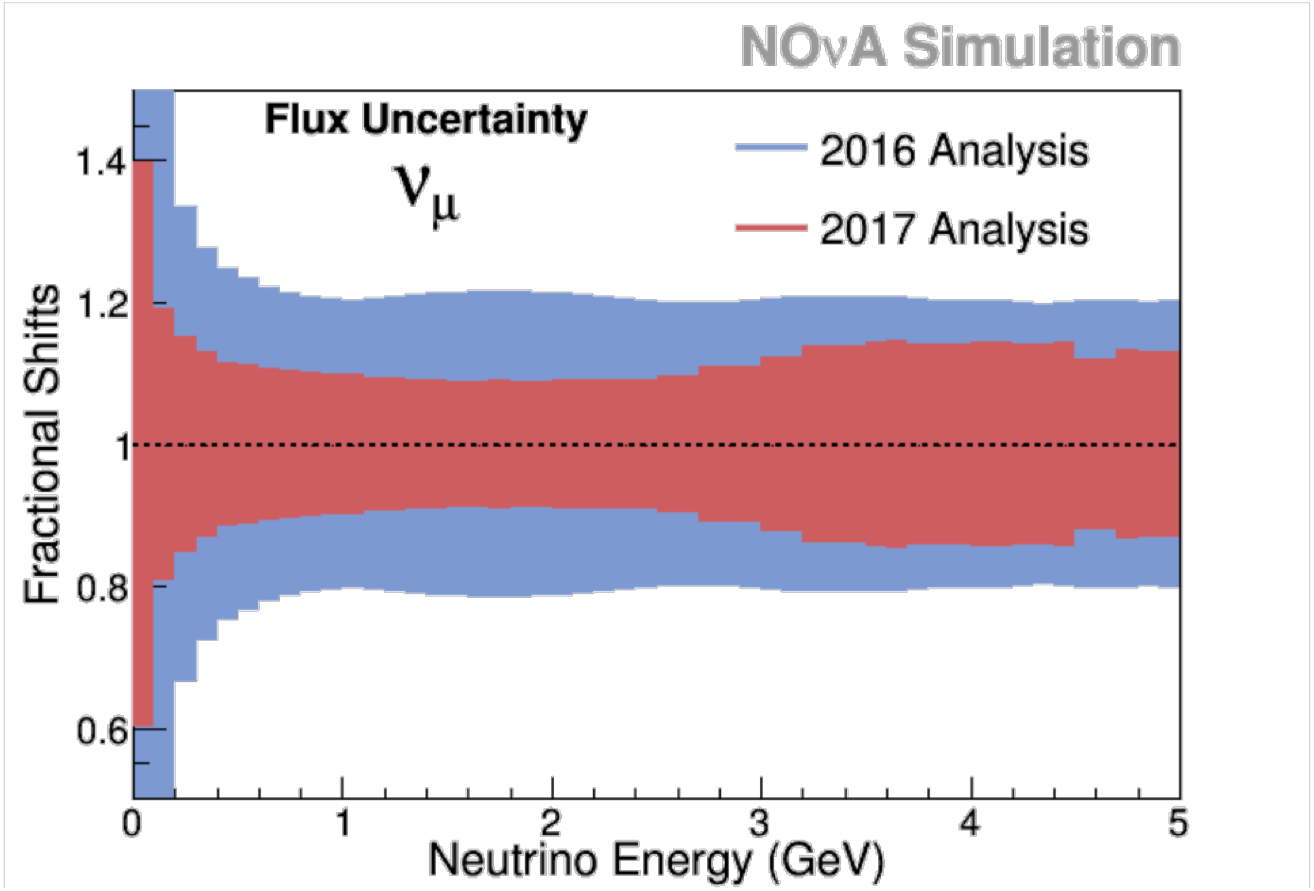
- MEC shape systematic estimated by re-fitting using models with QE and RES related systematic shifts





Improved Flux Model

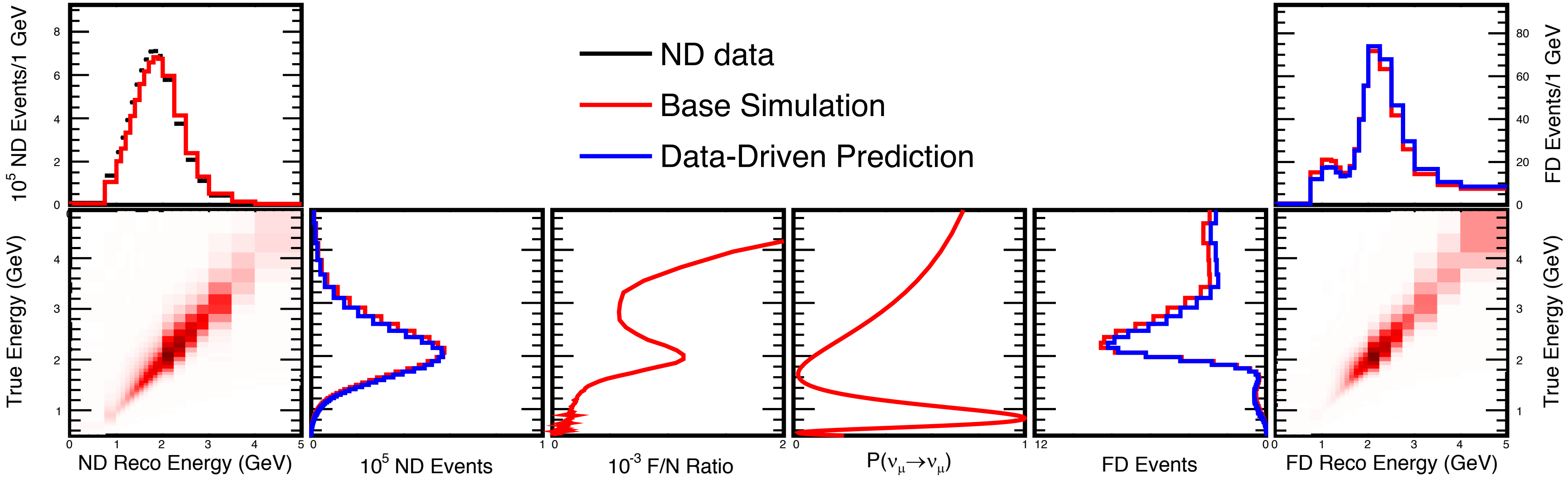


- Package to Predict the Flux (PPFX) from MINERvA (Phys. Rev. D 94, 092005. 2016).
  - Based on thin target hadron production data from NA49 and MIPP.
- Significantly reduced systematic uncertainties.
  - Central values also changed within prior systematics, but not shown here.

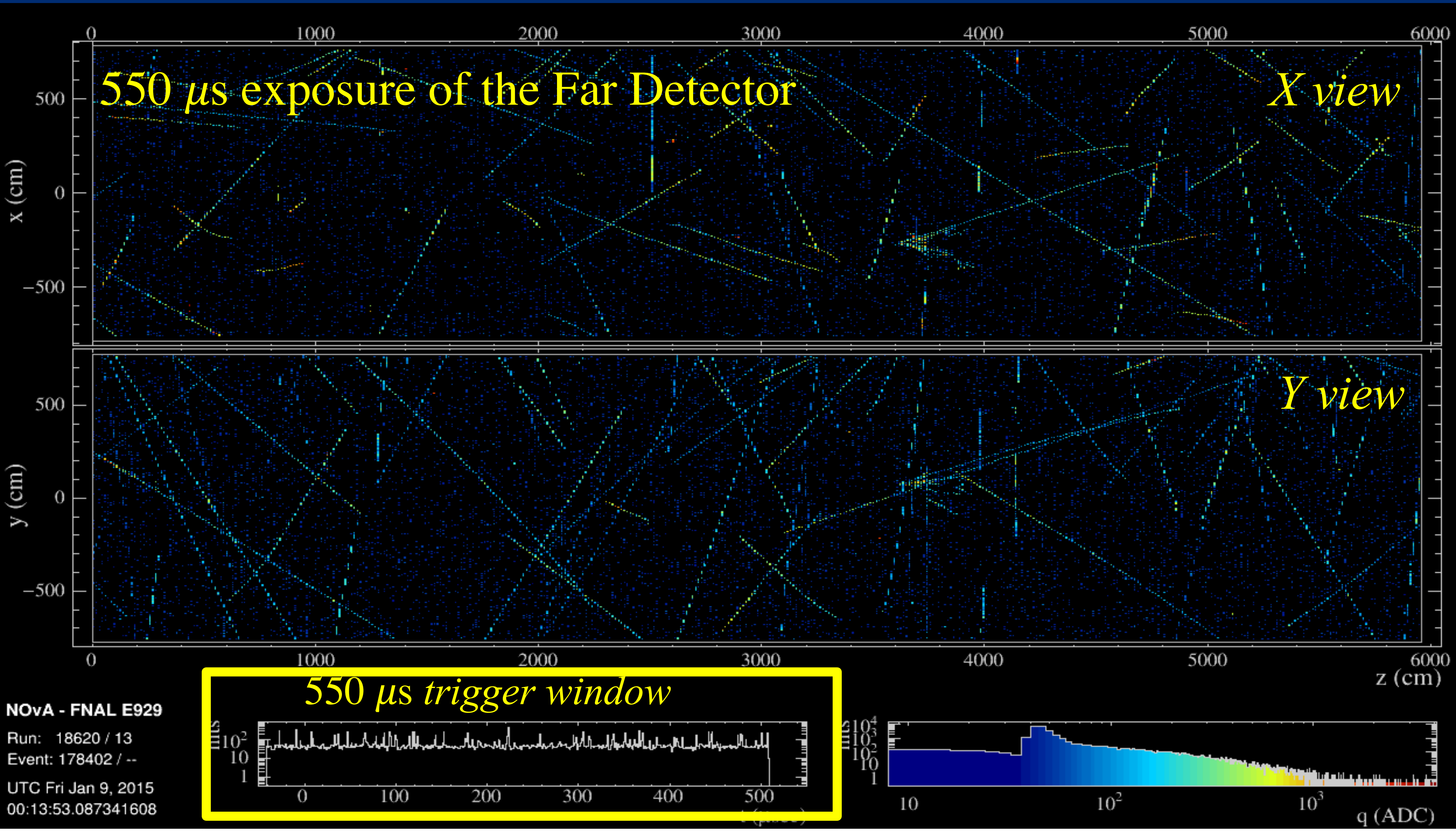
Analysis Strategy

- 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



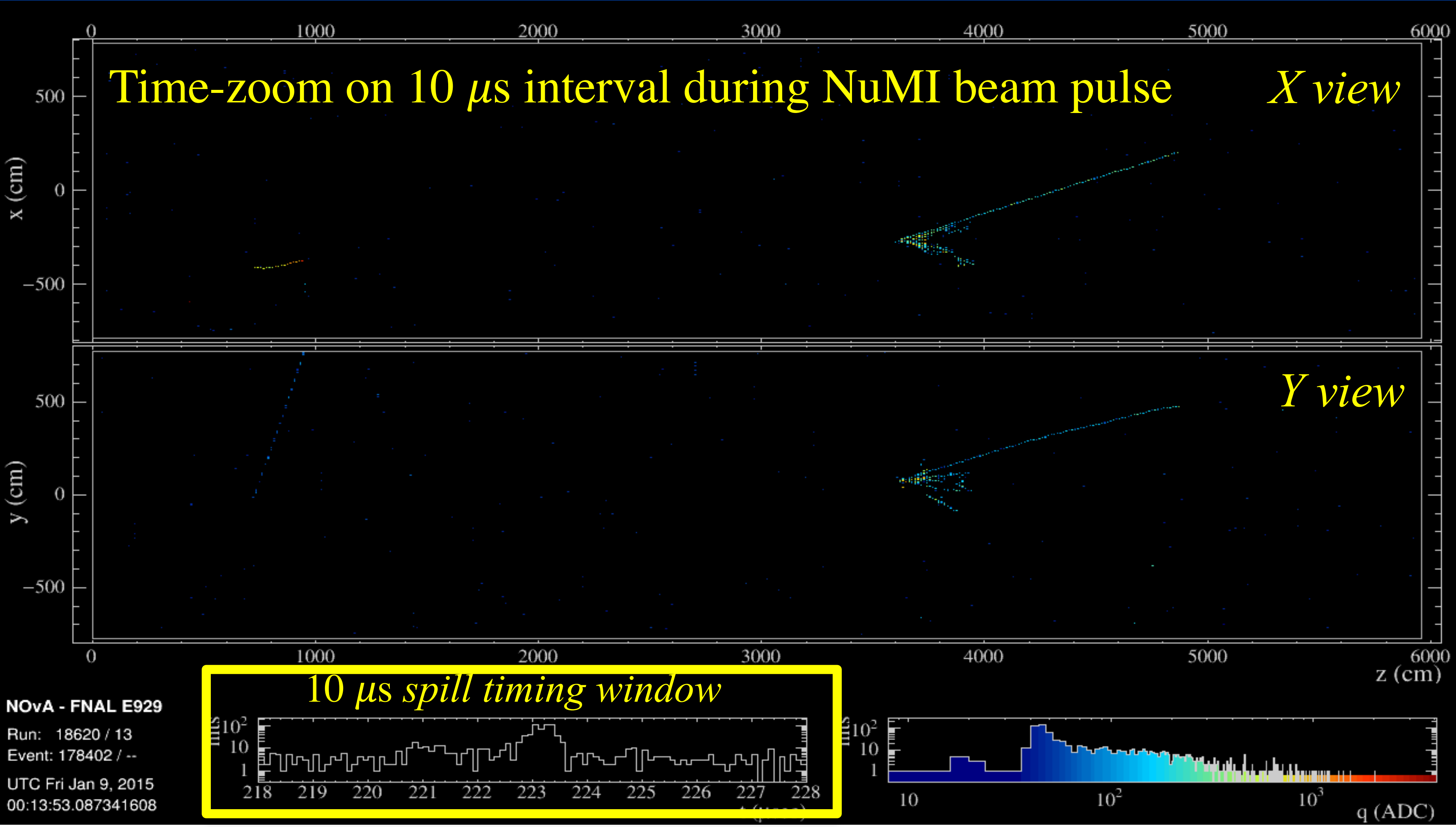
Event clustering


550 μs exposure of the Far Detector

550 μs trigger window

- 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

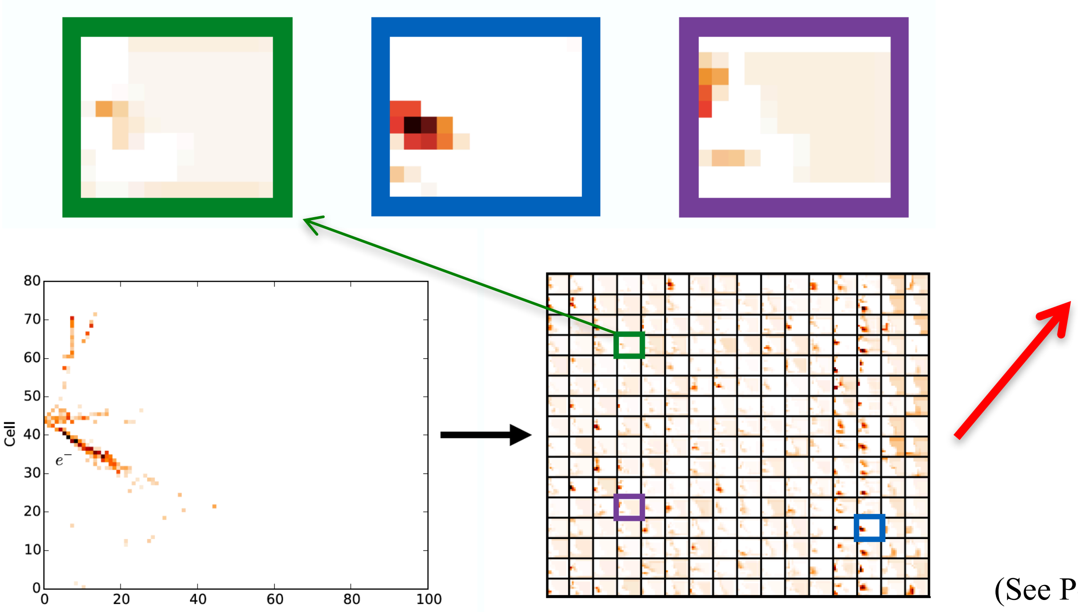


Event clusters that contain neutrino interactions can be correctly selected in the neutrino spill timing window

Deep-Learning based PID for ν_e and ν_μ Analyses

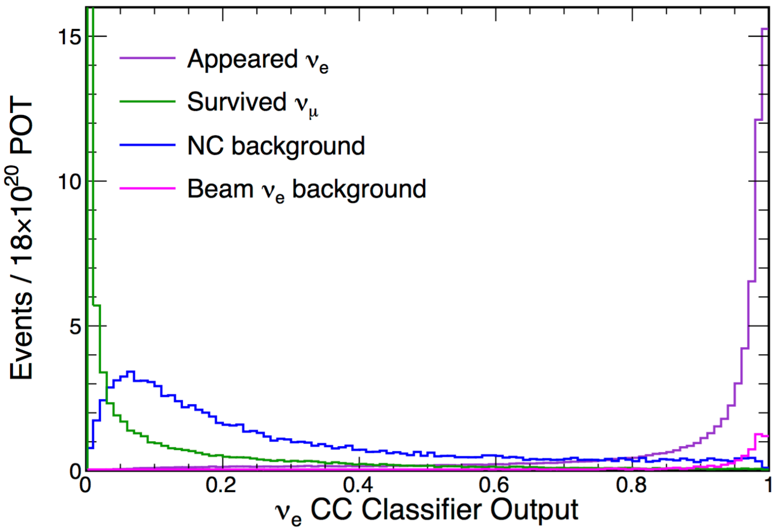
- CVN: a convolutional neural network (CNN), based on modern image recognition technology
- Introduce convolution filters to extract features from the hit map for the training of the neural net
- Statistical power equivalent to 30% more exposure than previous ν_e PIDs
- ν_e , ν_μ and NC analyses all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

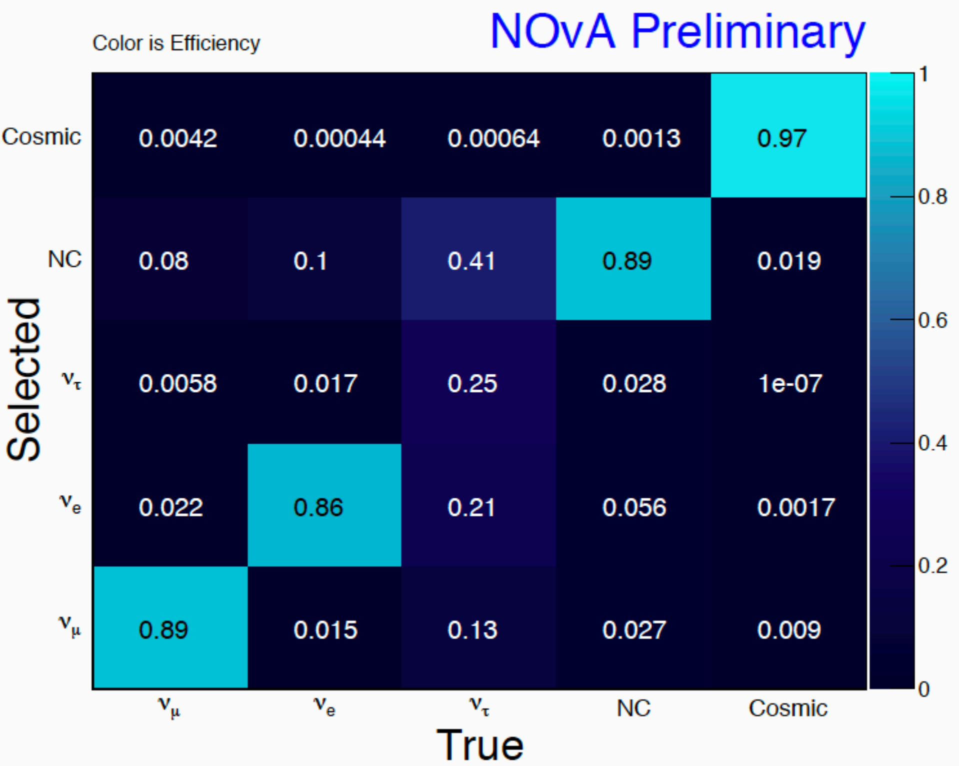


(See Poster 206, Fernanda Psihas)

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

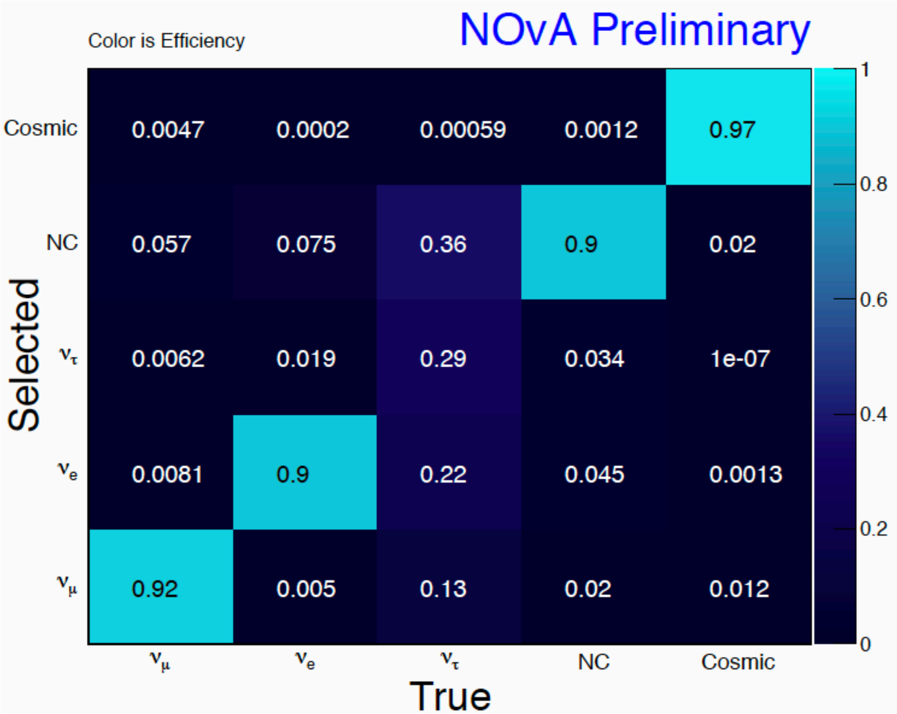
PID efficiencies

Neutrino



Selected \ True	ν_μ	ν_e	ν_τ	NC	Cosmic
Cosmic	0.0042	0.00044	0.00064	0.0013	0.97
NC	0.08	0.1	0.41	0.89	0.019
ν_τ	0.0058	0.017	0.25	0.028	1e-07
ν_e	0.022	0.86	0.21	0.056	0.0017
ν_μ	0.89	0.015	0.13	0.027	0.009

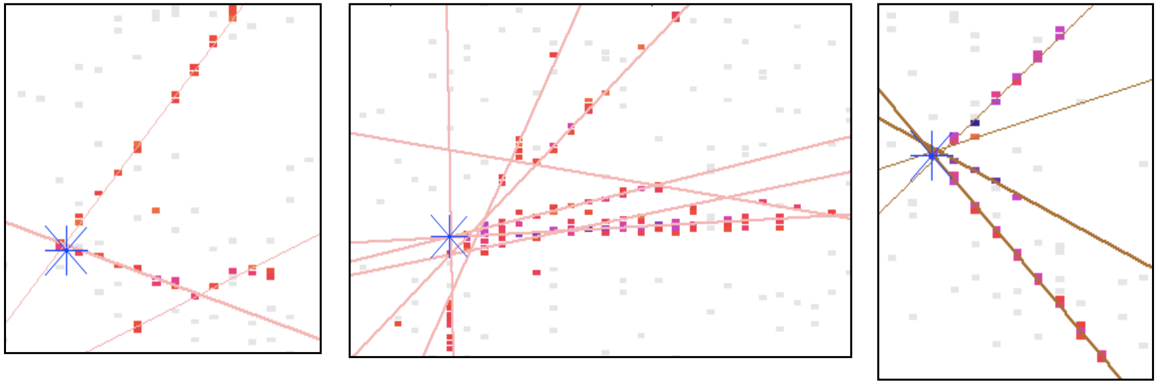
Anti-Neutrino



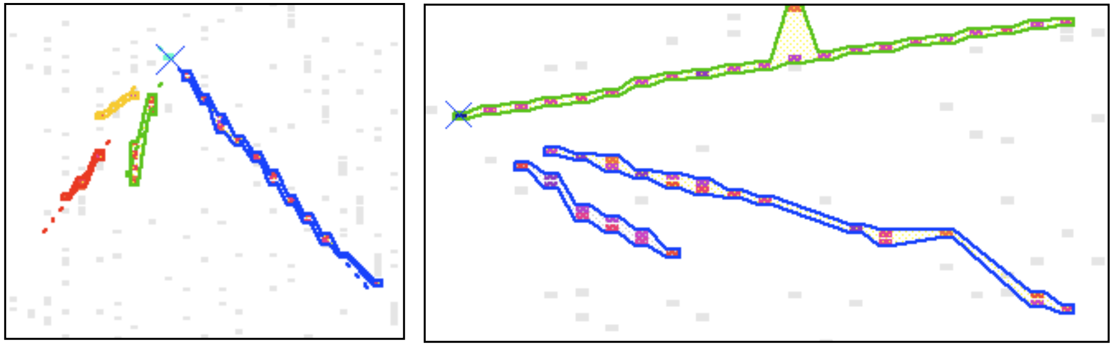
Selected \ True	ν_μ	ν_e	ν_τ	NC	Cosmic
Cosmic	0.0047	0.0002	0.00059	0.0012	0.97
NC	0.057	0.075	0.36	0.9	0.02
ν_τ	0.0062	0.019	0.29	0.034	1e-07
ν_e	0.0081	0.9	0.22	0.045	0.0013
ν_μ	0.92	0.005	0.13	0.02	0.012

Prong/track Reconstruction

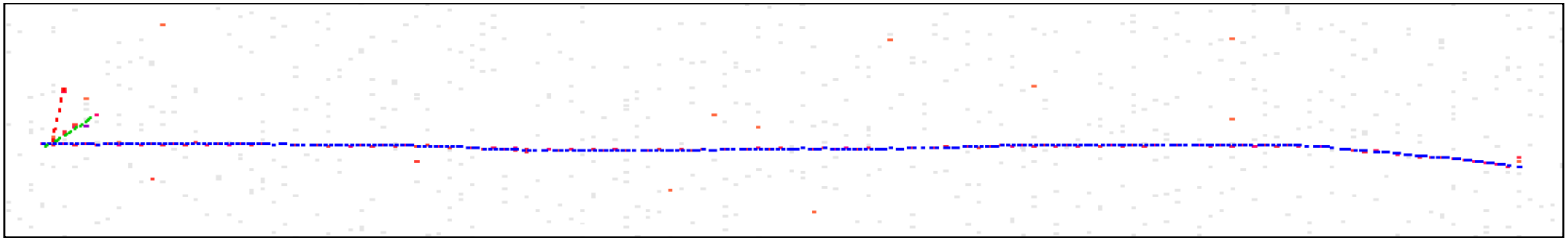
Vertexing: Find lines of energy depositions with Hough transform. Then determine the vertex that all lines converge to



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

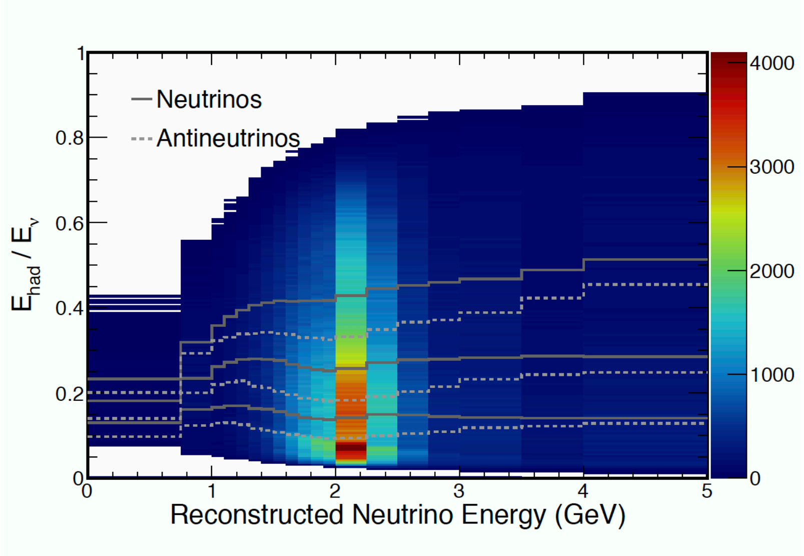


Tracking: Trace particle trajectories with **Kalman filter** tracker (below).
Also have a **cosmic ray tracker** that reconstructs cosmic tracks with high speed.

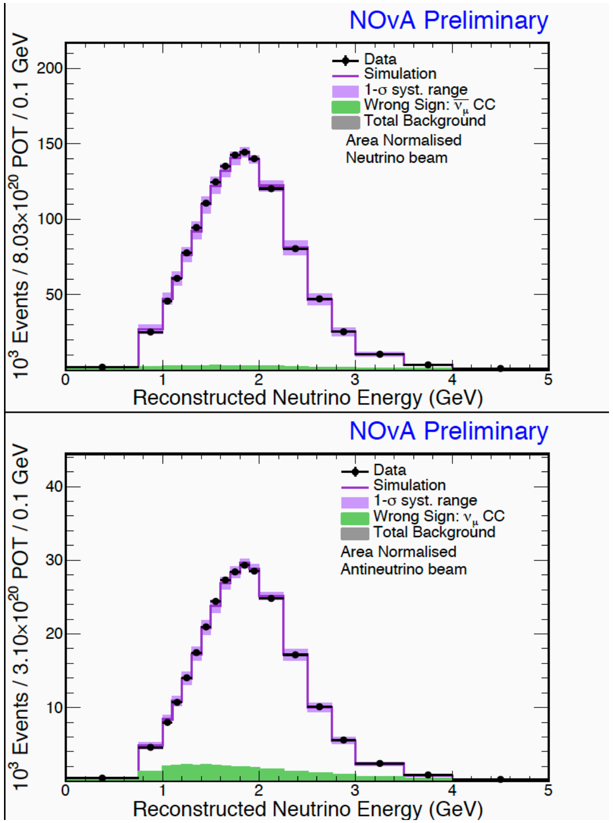


Near Detector Spectrum (ν_μ disappearance)

- Select ν_μ ($\bar{\nu}_\mu$) CC in ND from neutrino (antineutrino) beam, wrong sign contamination 3% (11%)
- $E_\nu = E_\mu + E_{had}$, data split in 4 equal energy quantiles 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

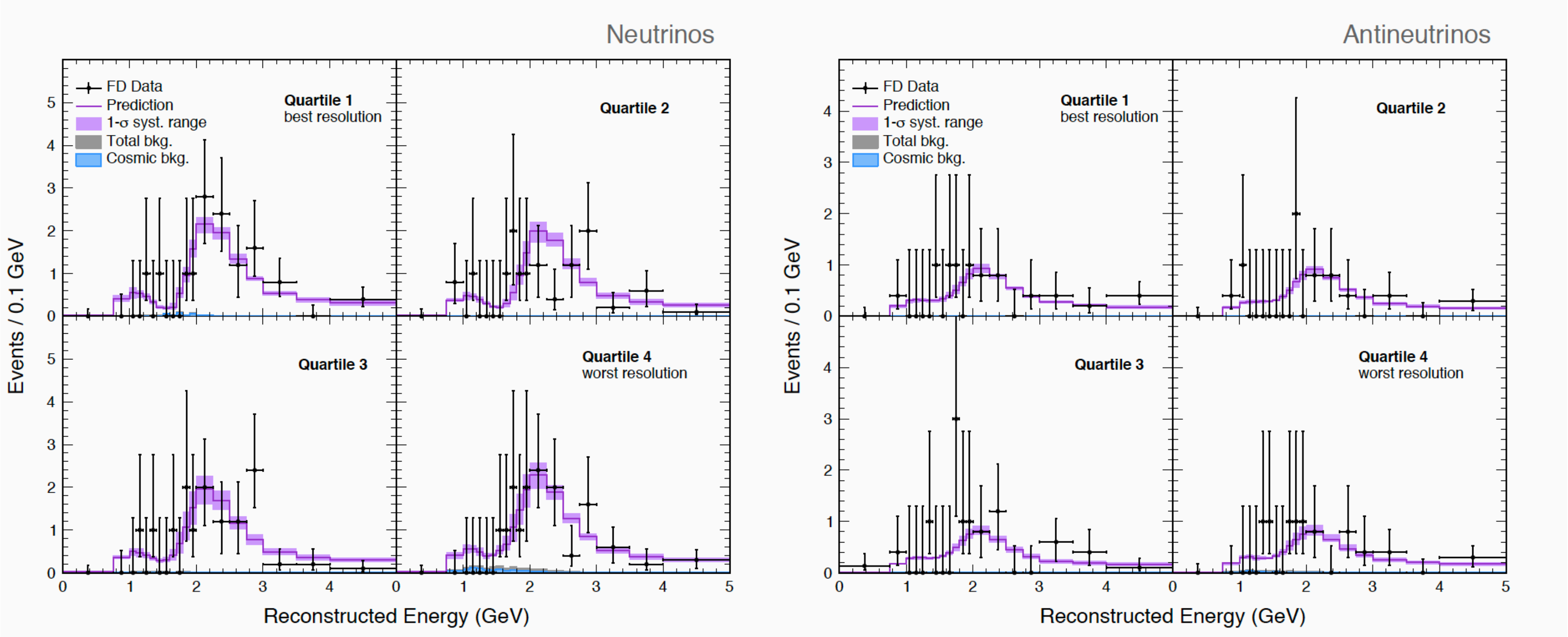
Data/MC normalization difference:

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

ν_μ Data at Far Detector

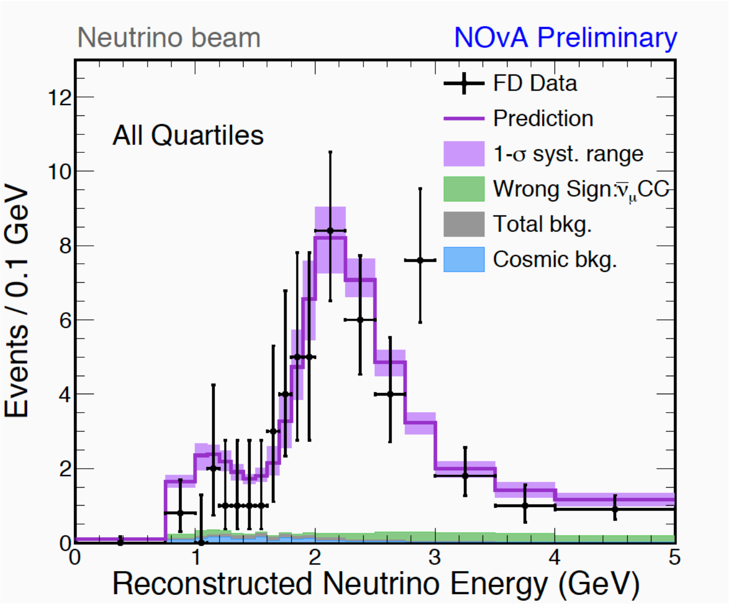
- FD selection:
  - Additional BDT to reduce cosmic backgrounds
  - Estimate cosmic background rate from timing sidebands of the NuMI beam triggers and cosmic trigger data

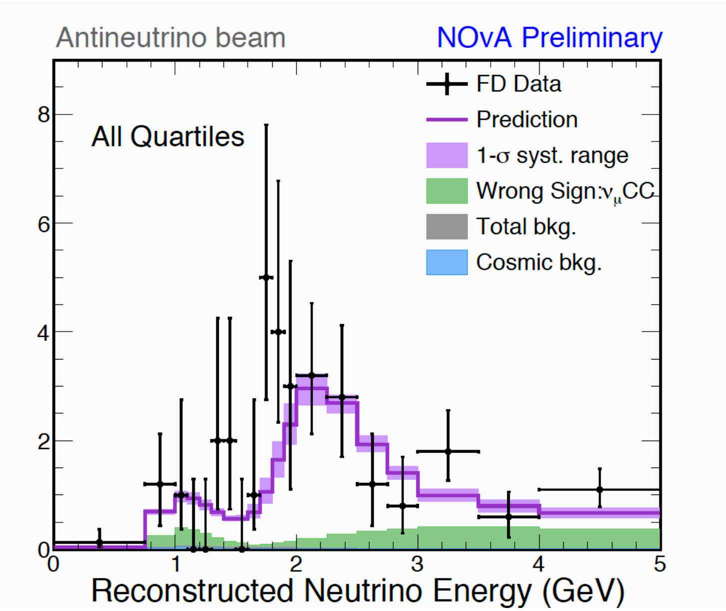
ν_μ events in 4 quartiles, each quartile extrapolated independently



ν_μ Data at Far Detector

- FD selection:
    - Additional BDT to reduce cosmic backgrounds
    - Estimate cosmic background rate from timing sidebands of the NuMI beam triggers and cosmic trigger data
- Neutrino beam:
    - Observe 113 events
    - Expect 730 +38/-49(syst.) w/o oscillations
- Antineutrino beam:
    - Observe 65 events
    - Expect 266 +12/-14(syst.) w/o oscillations

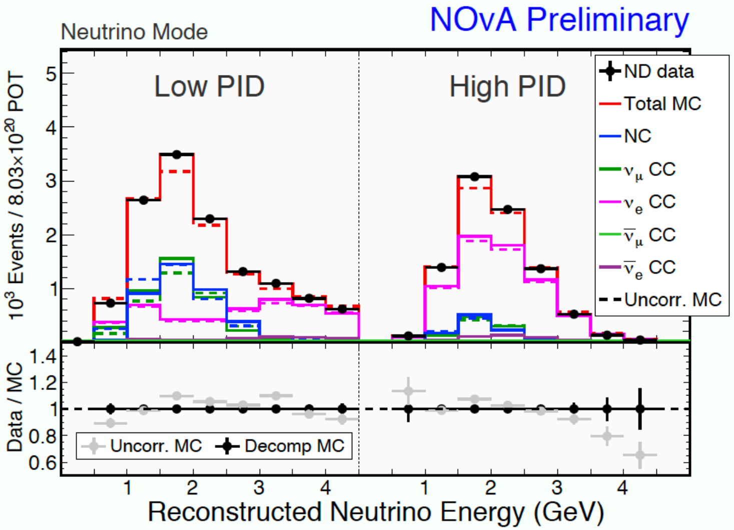


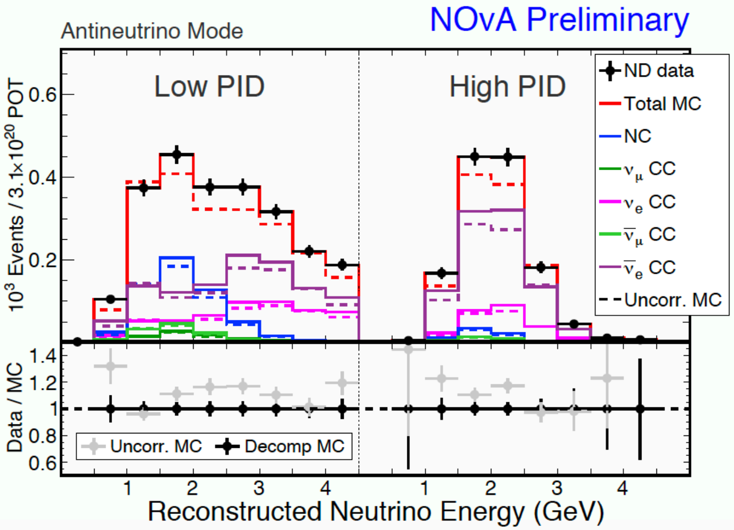


4 quartiles combined

Near Detector Spectrum (ν_e appearance)

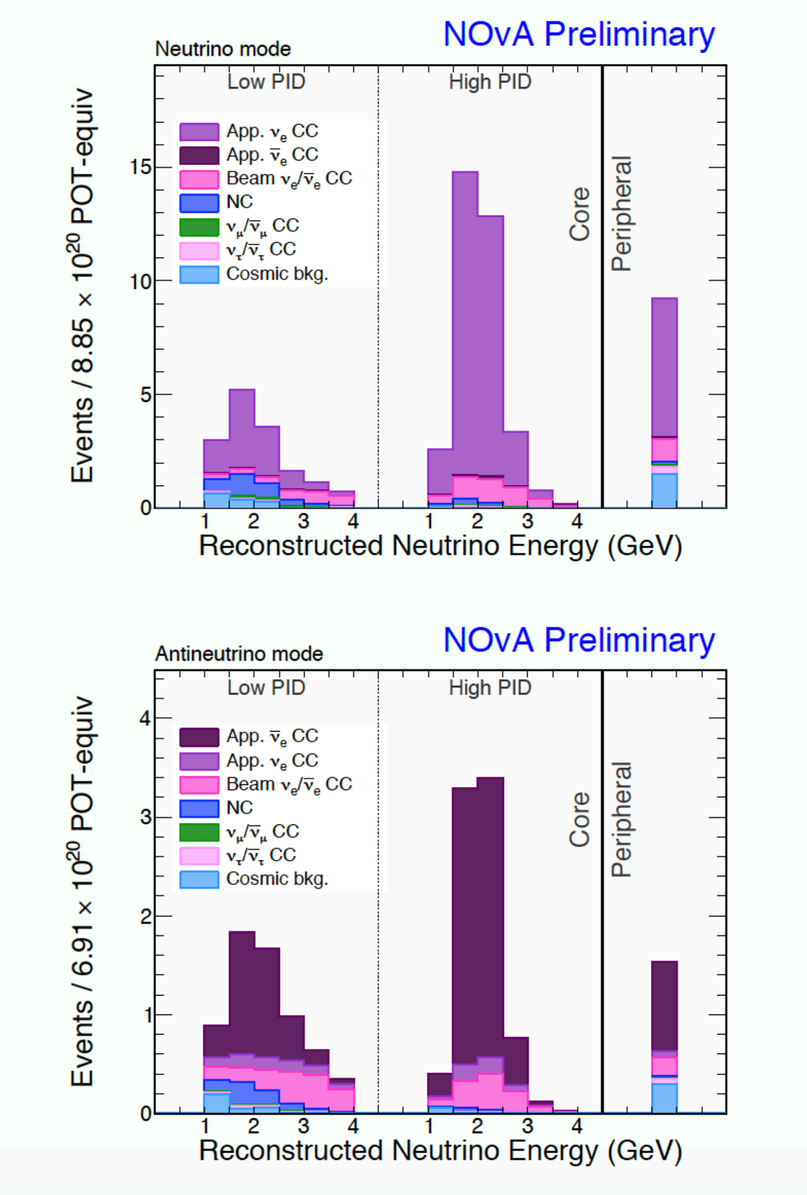
- Select ν_e ($\bar{\nu}_e$) CC in ND from neutrino (antineutrino) beam
- $E_\nu = f(E_e, E_{had})$, data split into low and high particle ID (purity) range
- For neutrino beam:
  - Contained and uncontained ν_μ events constrain the π/K contributions to the beam ν_e's.
  - Michel electrons constrains 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





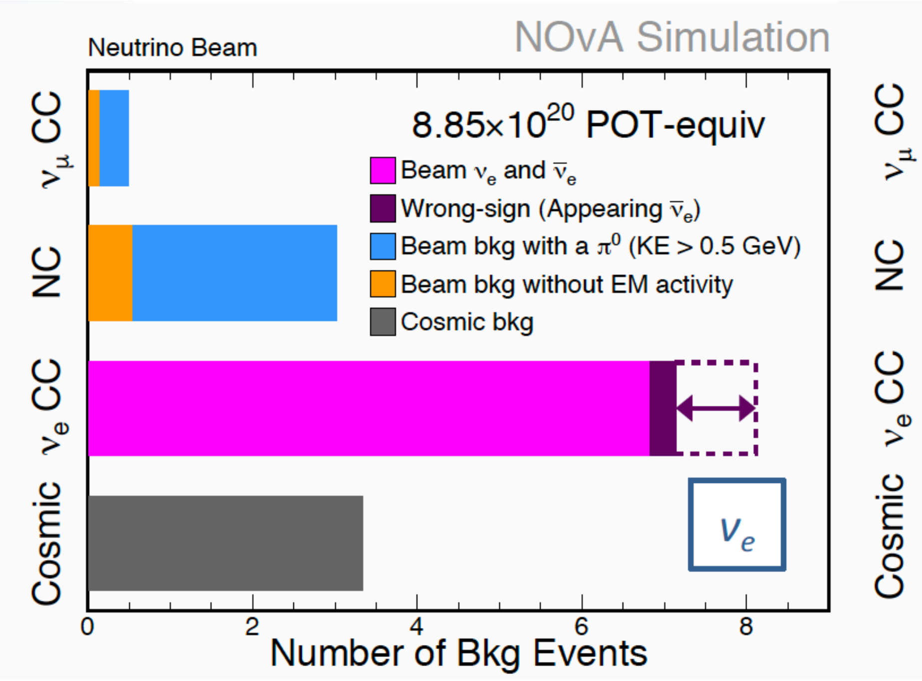
ν_e Far Detector Prediction

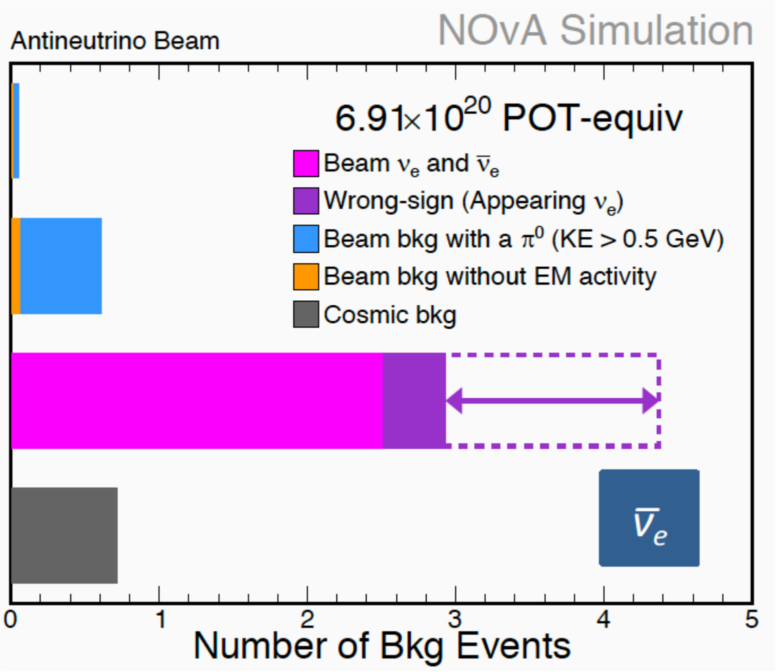
- FD selection:
  - Add a one-bin peripheral with less stringent containment selection to include more signal
  - Use location dependent BDT and tight PID cuts to recover signal events in this peripheral bin
- ND→FD extrapolation: Each component propagated independently in energy and PID bins
- Neutrino beam:
  - Background: 11 beam, 3 cosmic and < 1 wrong sign
- Antineutrino beam:
  - Background events : 3.5 beam, <1 cosmic and 1 wrong sign



ν_e Far Detector Backgrounds

- Neutrino beam:
  - Background: 11 beam, 3 cosmic and < 1 wrong sign
- Antineutrino beam:
  - Background events : 3.5 beam, <1 cosmic and 1 wrong sign

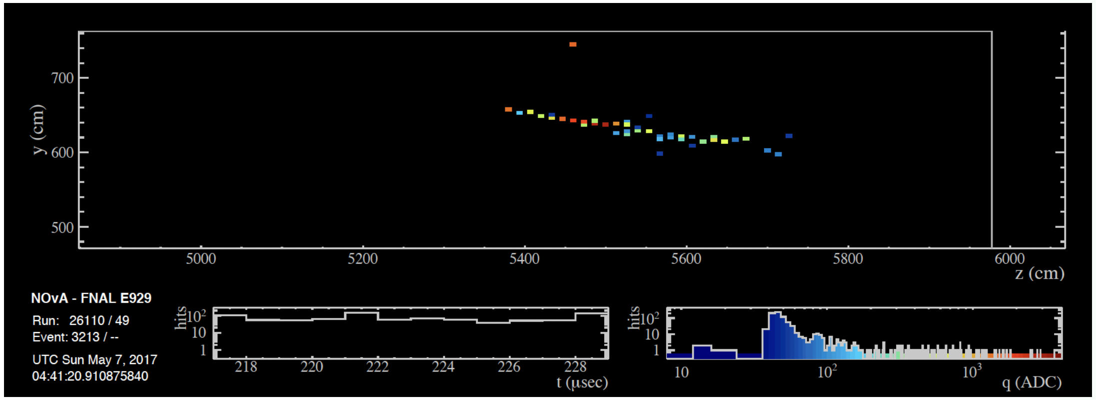


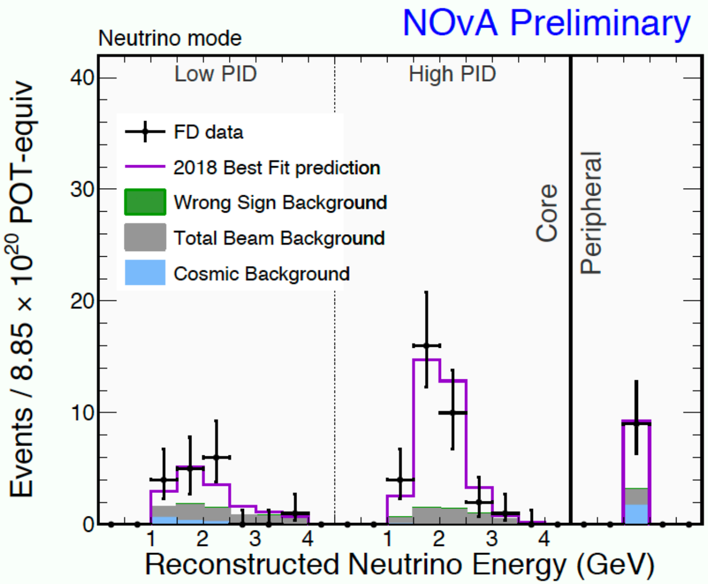


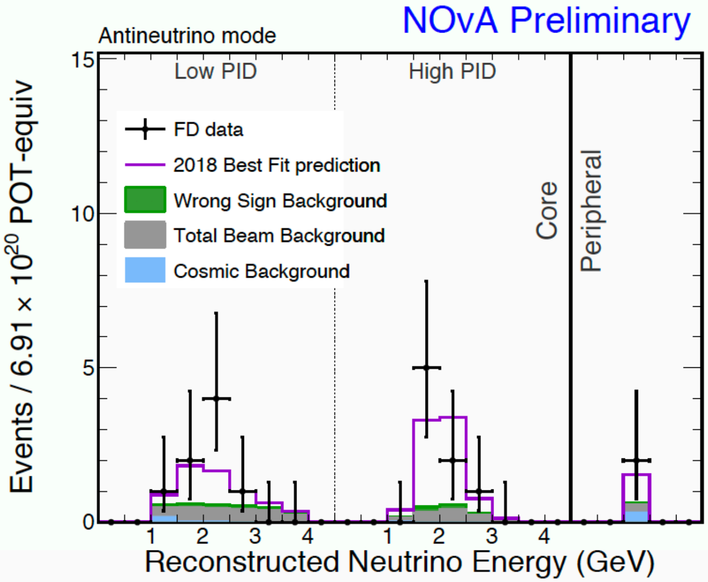
- Major backgrounds from beam ν_e
- Wrong sign background depends on oscillation

ν_e Data at Far Detector

Selected ν_e candidate in FD Data



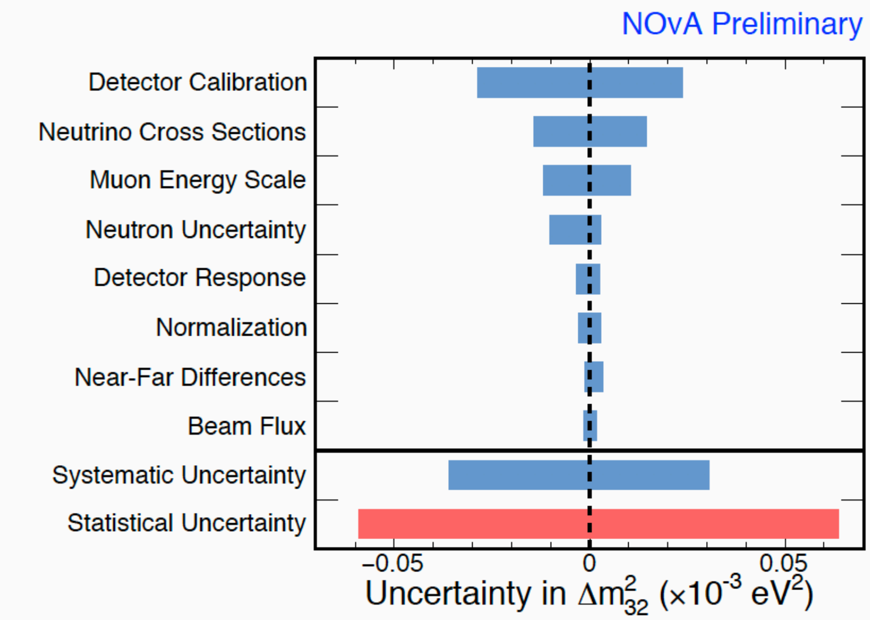


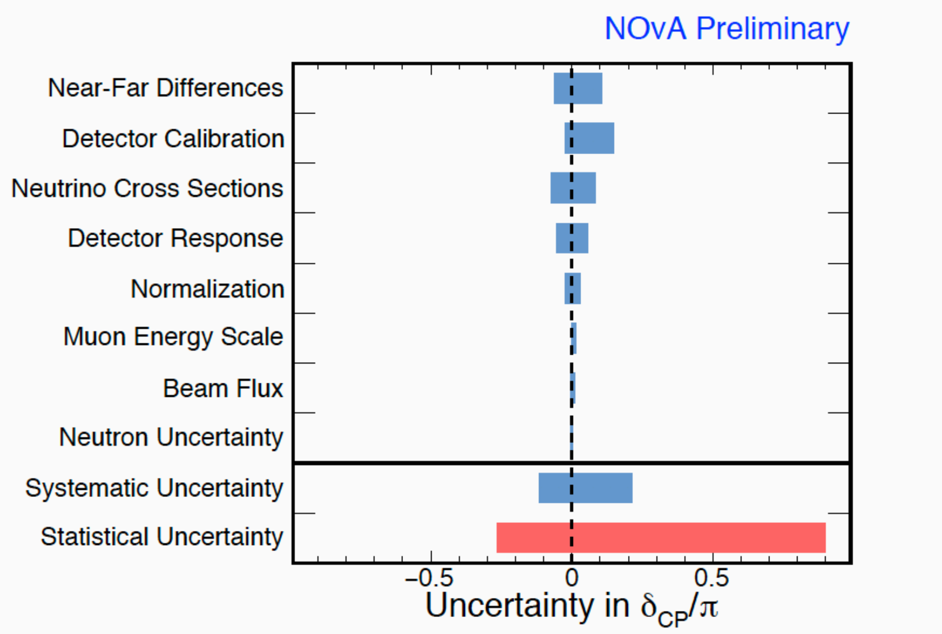


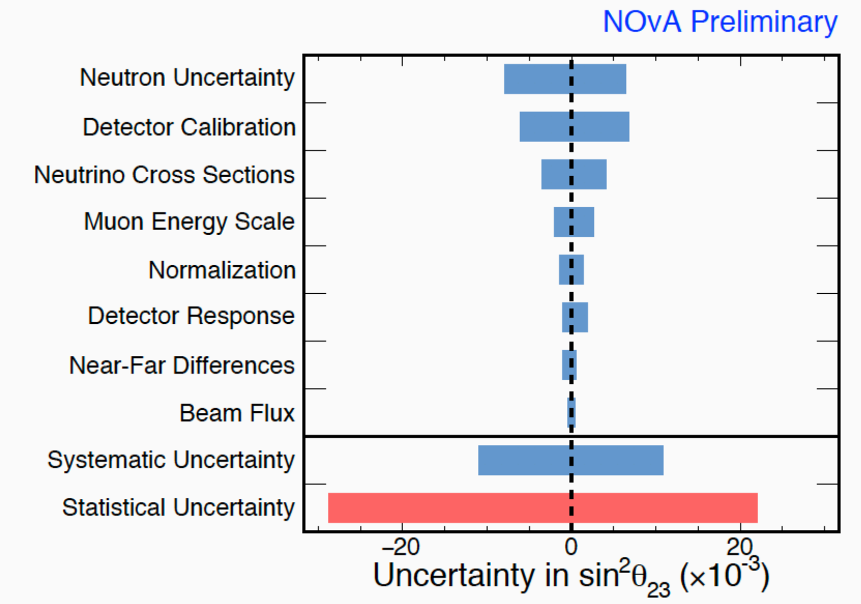
- Neutrino beam:
  - Observe 58 events, expect 15 background events
- Antineutrino beam:
  - Observe 18 events, expect 5.3 background events

- $> 4\sigma$ $\bar{\nu}_e$ appearance

Systematic Uncertainties (Joint fit)

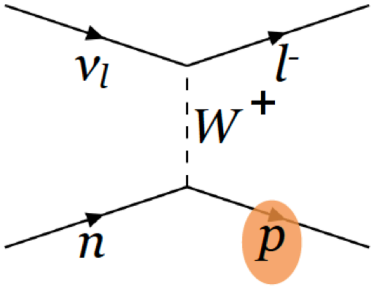


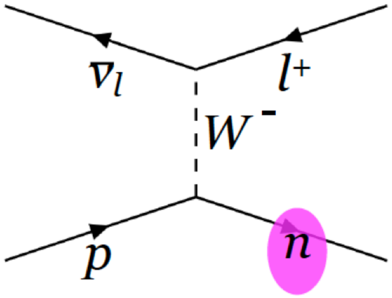




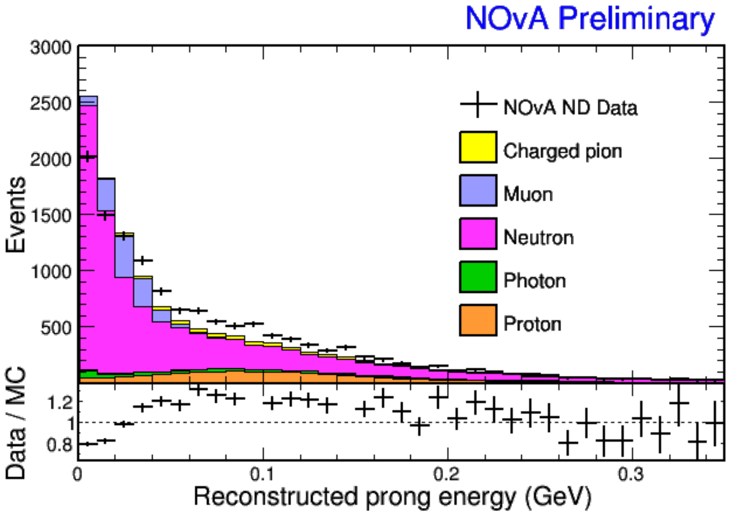
- Largest systematics for ν_μ and ν_e are **calibration** and **cross-sections**.
- Both analyses are statistically limited.
- Upcoming NOvA test beam program will address calibration and detector response uncertainties
- Neutron uncertainty – new with $\bar{\nu}$’s

Neutron Response Systematic for $\bar{\nu}$





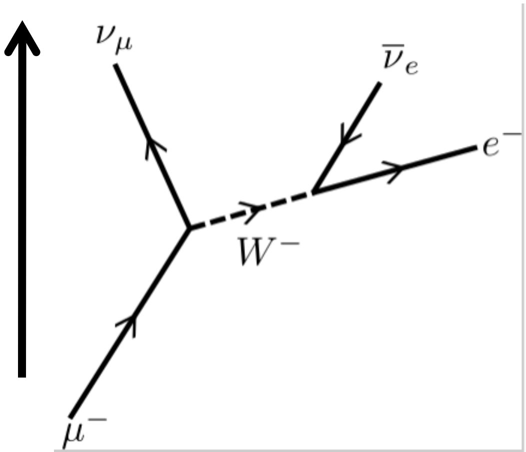
- $\bar{\nu}$'s have neutrons where ν's have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of some neutrons to cover the low-energy discrepancy.
- Shifts the mean ν_μ energy by 1% in the antineutrino beam and 0.5% in the neutrino beam.
  - Negligible impact was seen on selection efficiencies.



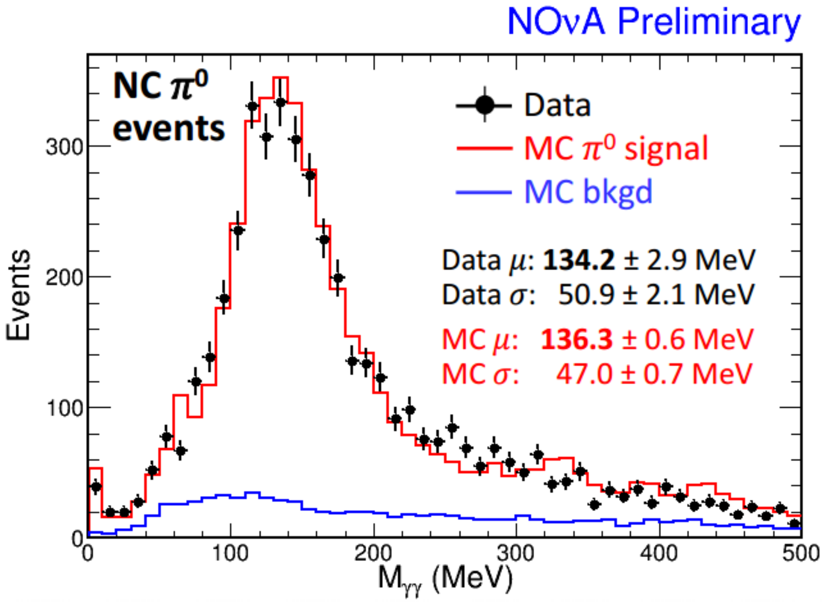
Systematic Error in Calibration

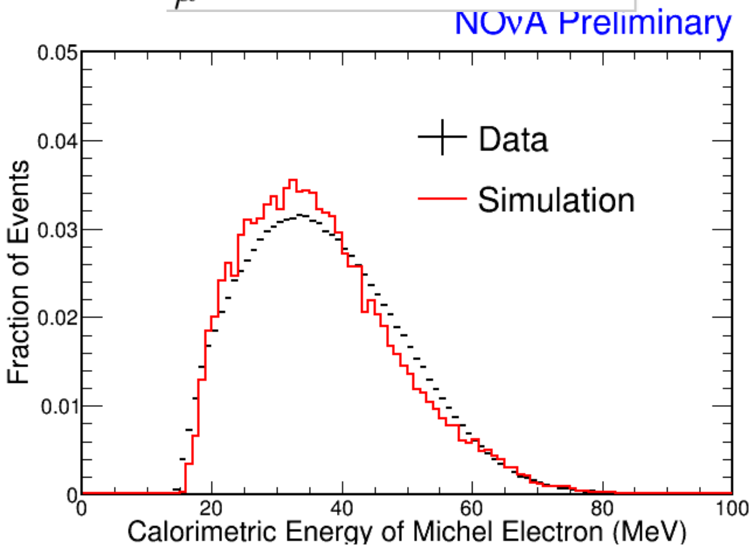
- Our calibration is built on dE/dx from stopping cosmic muons.
- Control samples for calibration uncertainty
  - π^0 mass peak in ND
  - Michel electrons in ND and FD

Michel electrons from muon decays

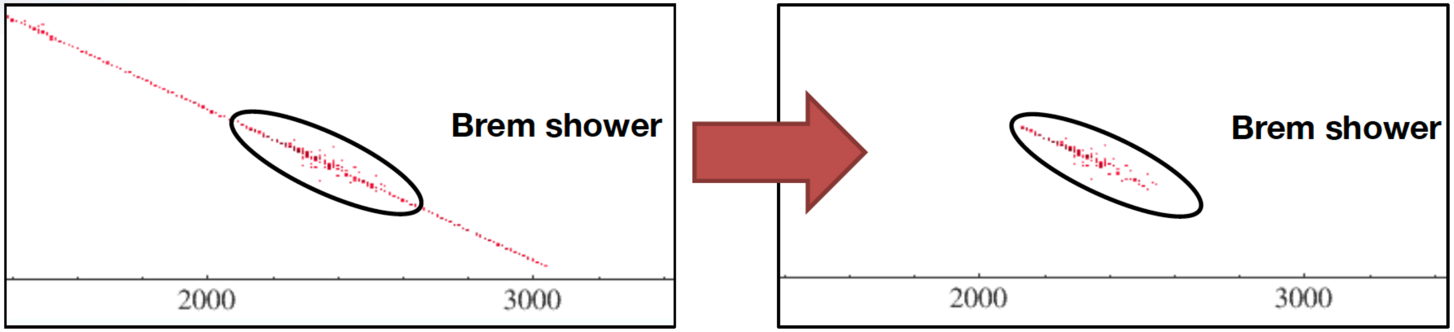


$$m^2_{\pi^0}=2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{12})$$

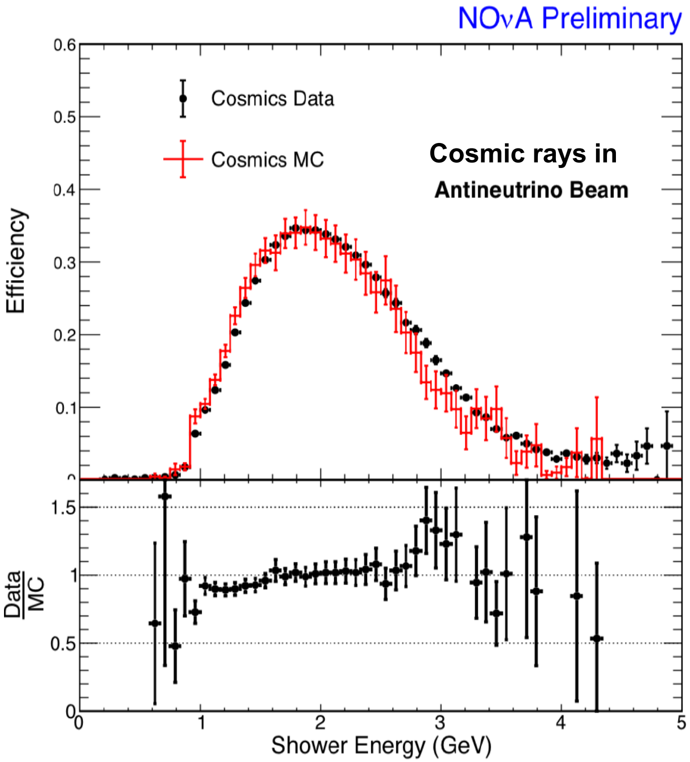




Cross-checks: Muon-removed from bremsstrahlung

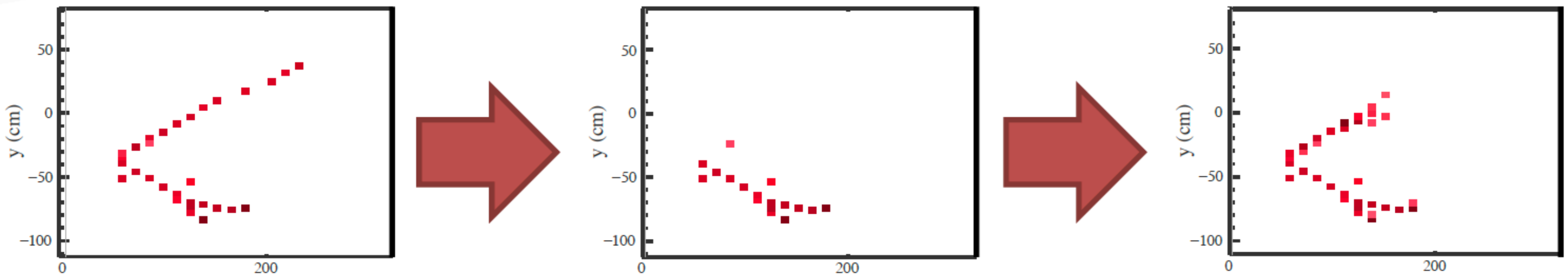


- Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector.
- Efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.

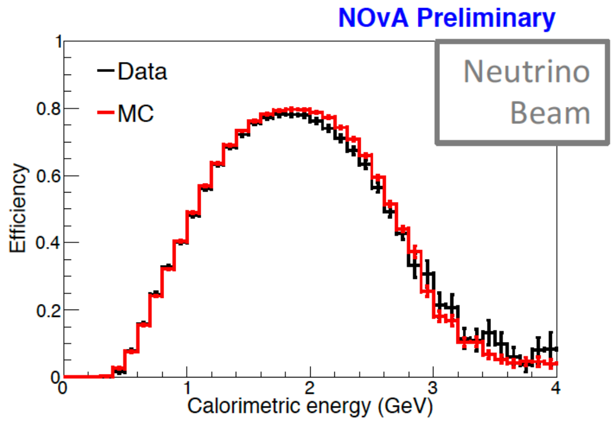

NOνA Preliminary

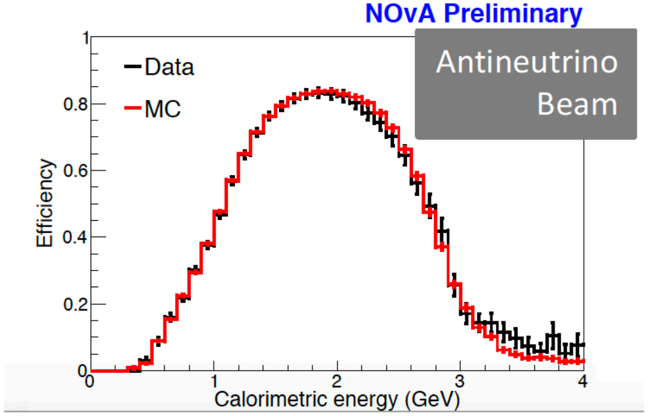
Cosmic rays in Antineutrino Beam

Cross-checks: Muon-removed, Electron-added

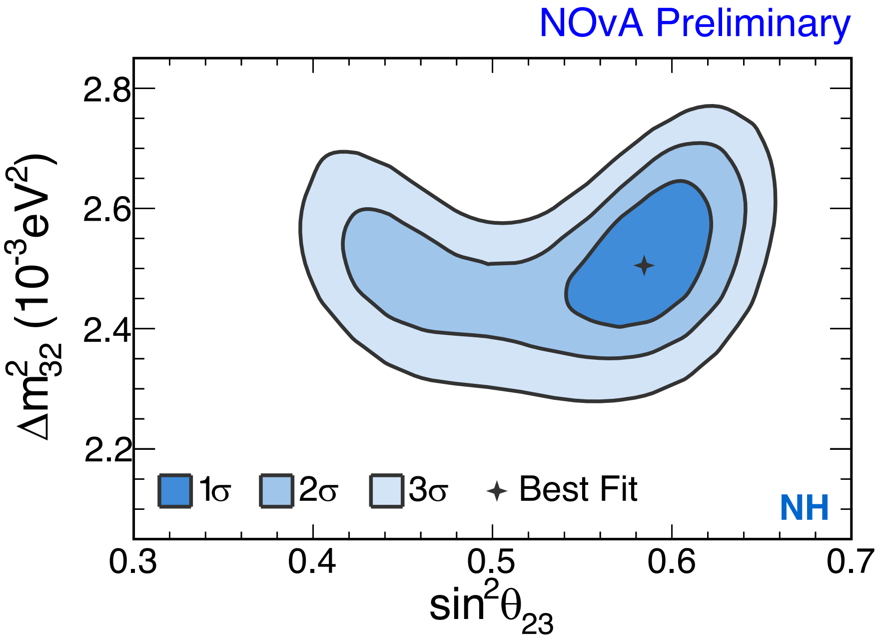


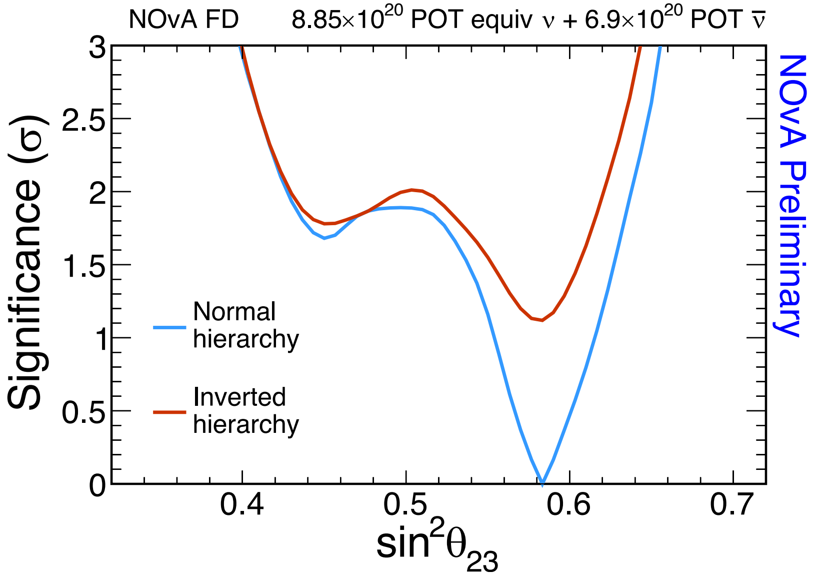
- We can create a control sample of “electron neutrino” events by removing the muon and replacing it with a simulated electron.
- Compare the efficiency between MRE events with real and simulated hadronic showers.
  - Allows us to focus on the effect of the hadronic shower on efficiency.
- Efficiency agrees between data and MC at the 2% level for both neutrino and antineutrino beams.

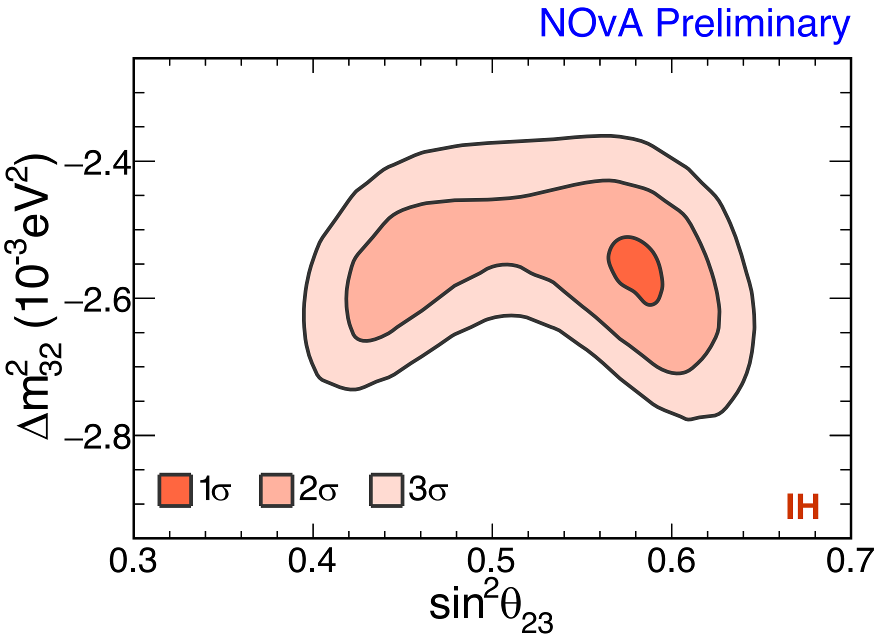




Joint Appearance and Disappearance



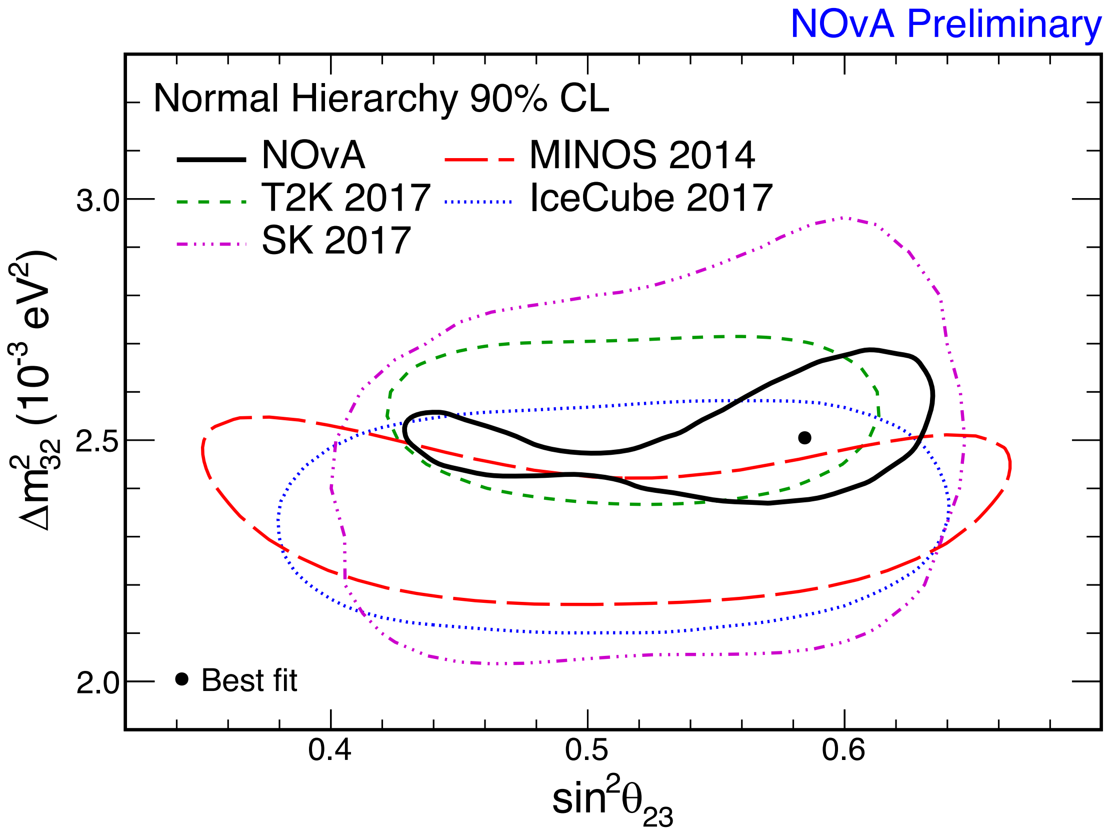




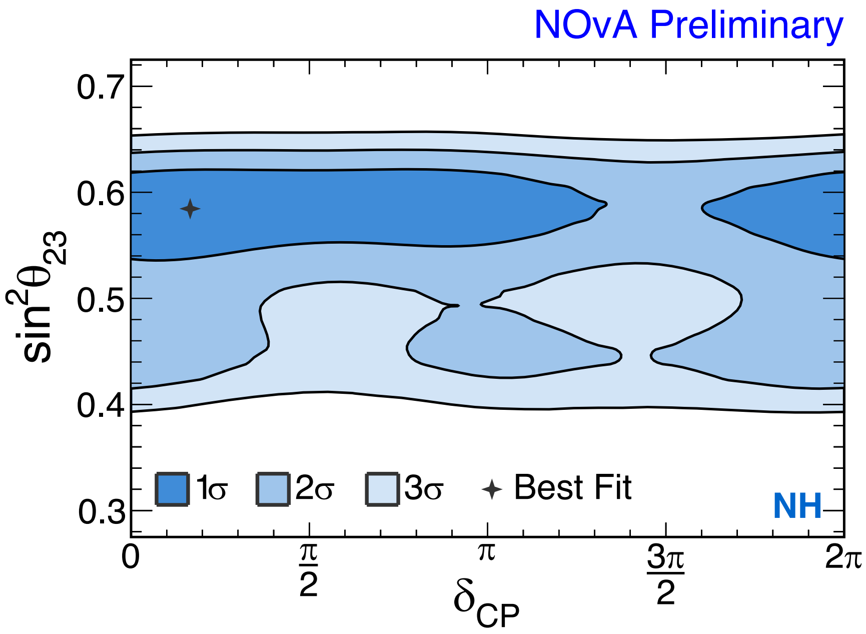
- Statistically limited, largest systematics for ν_μ and ν_e are calibration and cross-sections.
- Best fit:
  - Normal Hierarchy
  - $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
  - $\Delta m^2_{32} = (2.51+0.12-0.08)*10^{-3}$ eV^2
- Prefer non-maximal at 1.8σ, favor upper octant at similar level

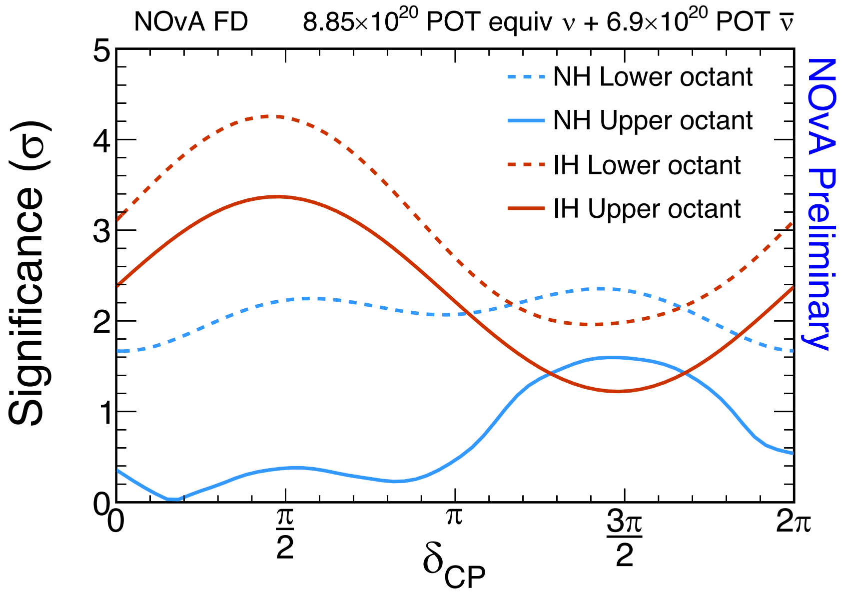
Joint Appearance and Disappearance

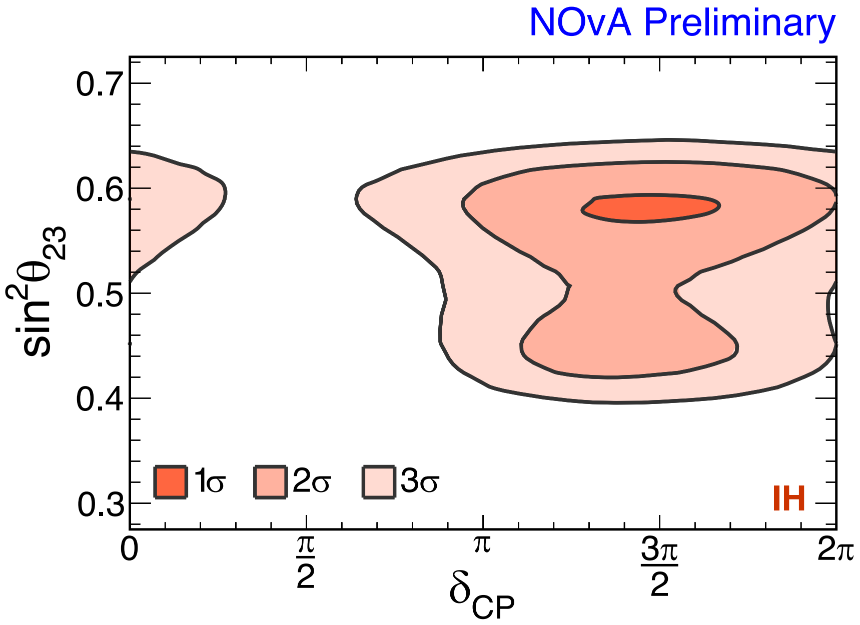
NOvA’s allowed 90% C.L. regions are compatible to other experiments



Joint Appearance and Disappearance



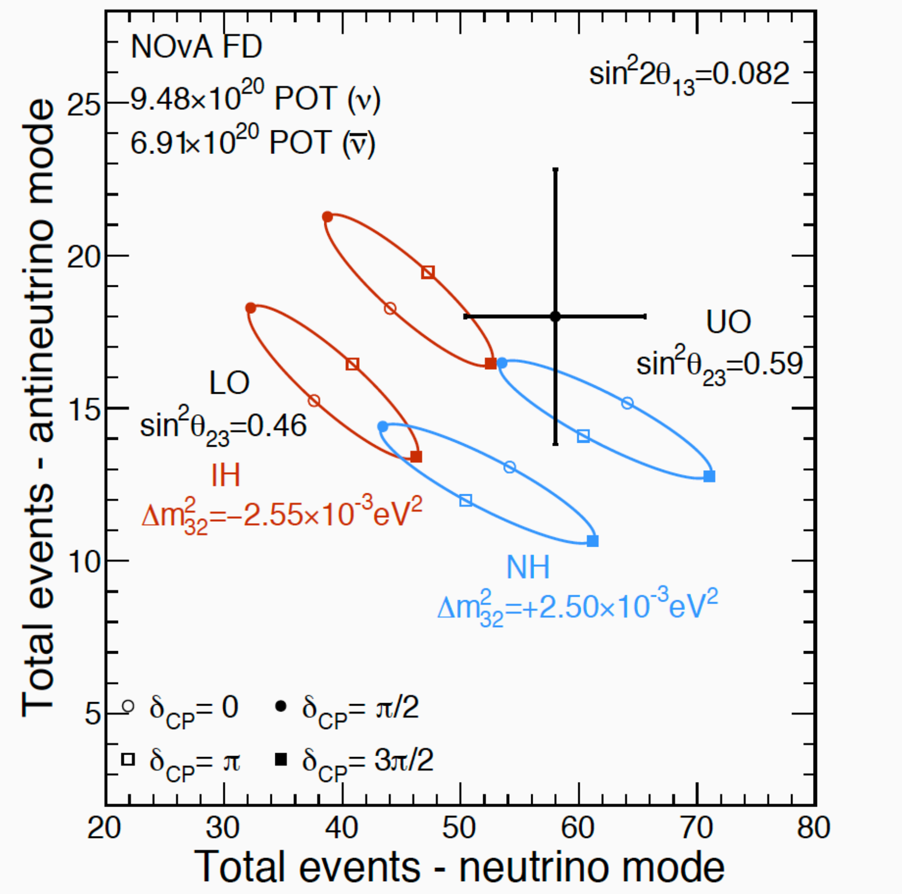




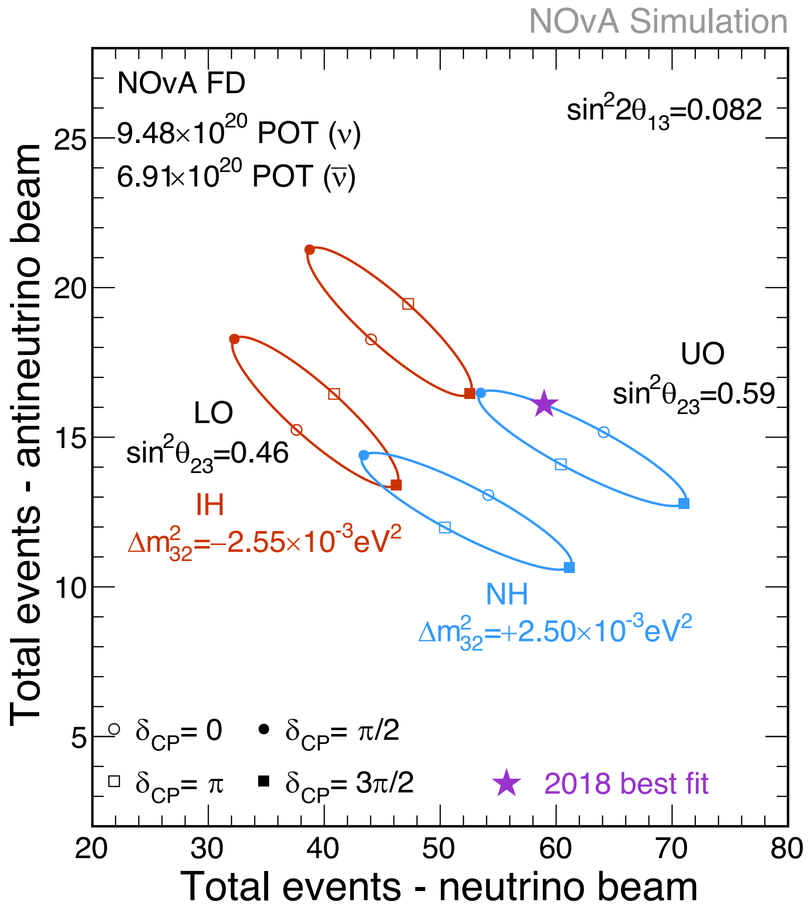
- Statistically limited, largest systematics for ν_μ and ν_e are calibration and cross-sections
- Best fit:
  - Normal Hierarchy
  - δCP= 0.17π
  - $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
  - $\Delta m^2_{32} = (2.51{+}0.12{-}0.08)*10^{-3}$ eV^2
- Consistent with all δCP values in NH at < 1.6σ
- Exclude δ=π/2 in IH at > 3σ
- 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

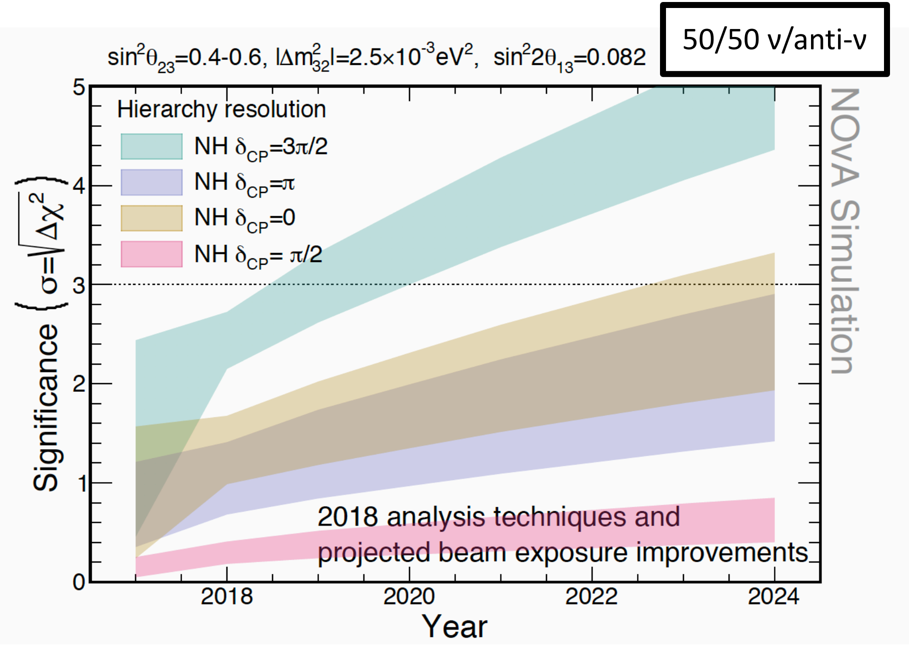
- Prefer non-maximal at 1.8σ, favor upper octant
  Consistent with all δCP values in NH at < 1.6σ
- Exclude δ=π/2 in IH at > 3σ
- Prefer NH at 1.8σ

Looking Forward

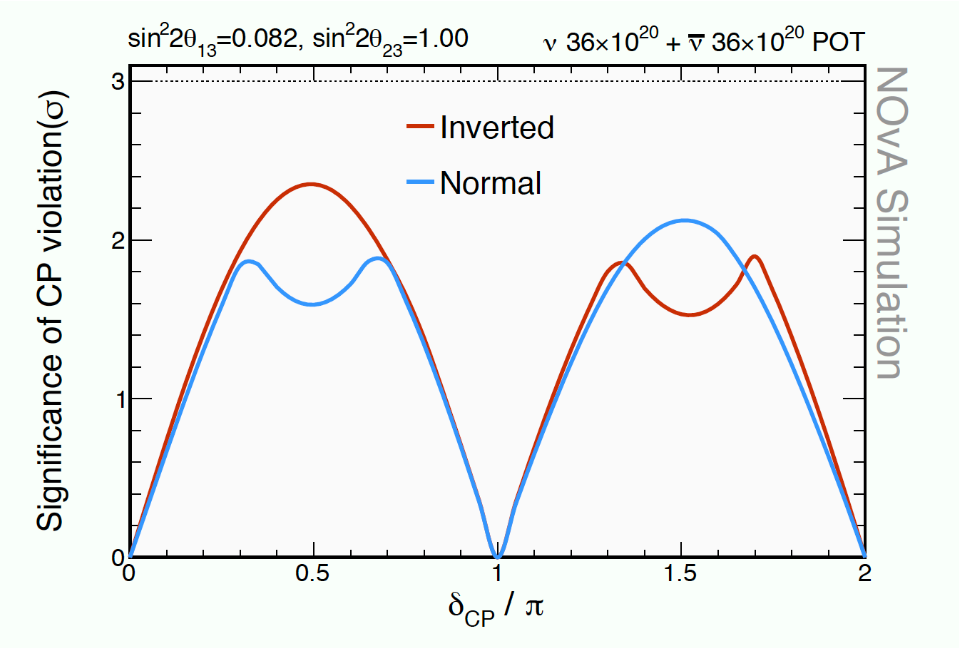
- Taking antineutrino data since 2017, switch back to neutrinos in 2019, run 50% neutrino, 50% anti-neutrino
- Extended running through 2024, test beam program and potential accelerator improvement to enhance ultimate reach

- If δCP=3π/2, 3 σ sensitivity to MH by 2020, ~5 σ by 2024
- 3 σ to MH for 30-50% (depending on octant) of δCP range by 2024
- 2+ σ to CP at δCP=3π/2 or δCP=π/2 by 2024

Thank you!



50/50 ν/anti-ν

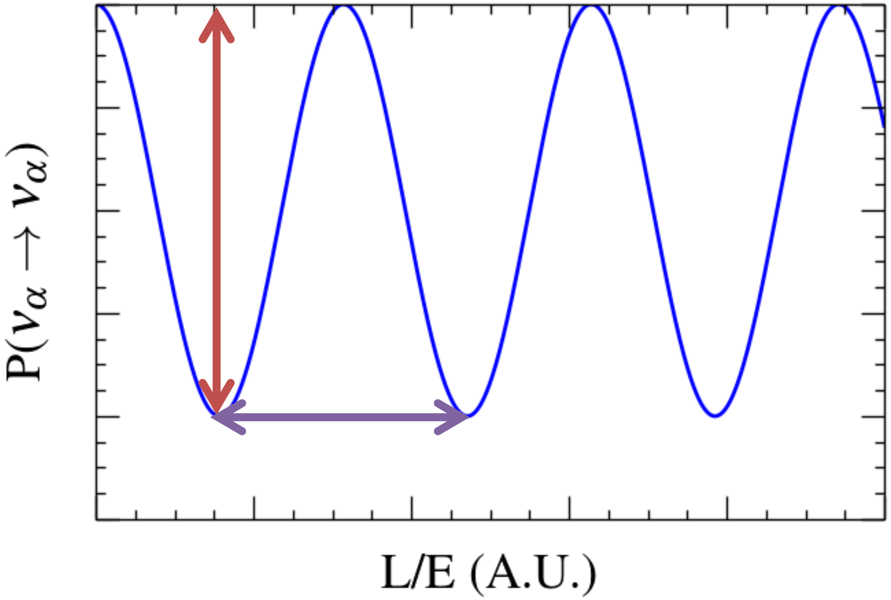


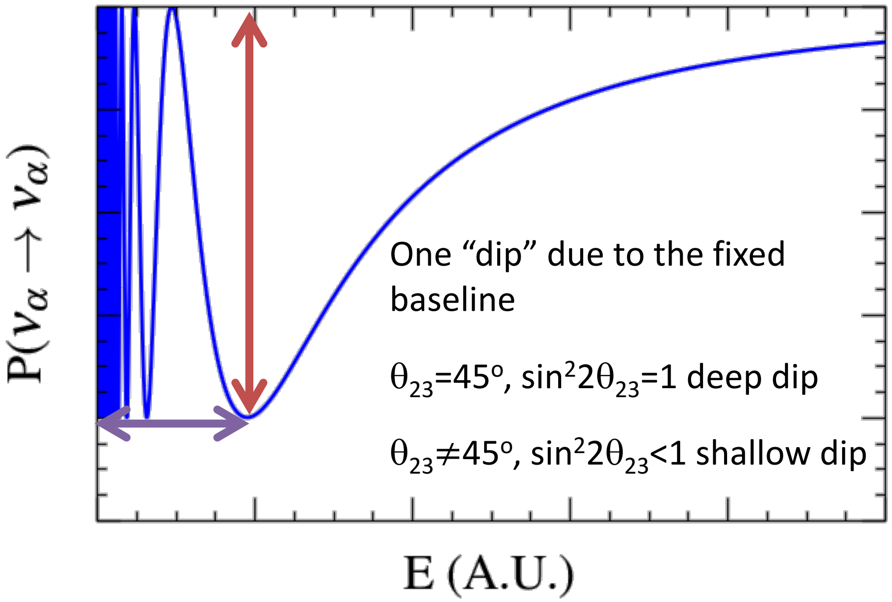
Backup

ν_μ disappearance

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

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





One “dip” due to the fixed baseline

θ_{23}=45°, $\sin^2 2\theta_{23}$=1 deep dip

$\theta_{23} \neq$45°, $\sin^2 2\theta_{23}$<1 shallow dip

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

ν_e appearance

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

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

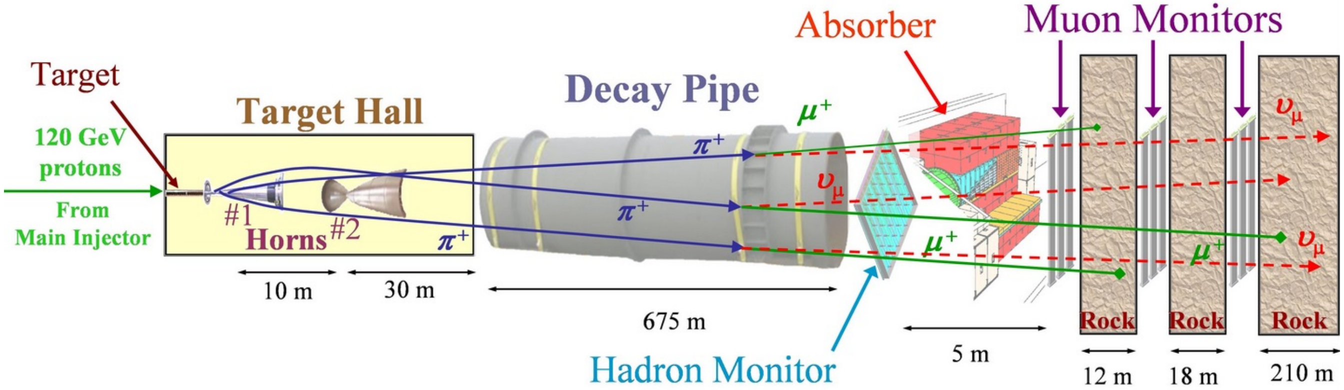
$$-\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

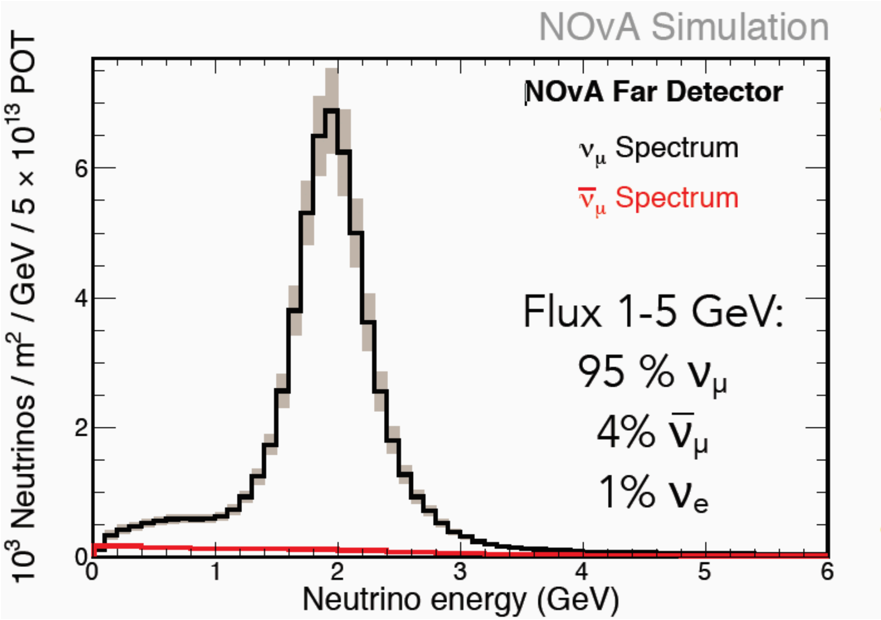
Matter effect

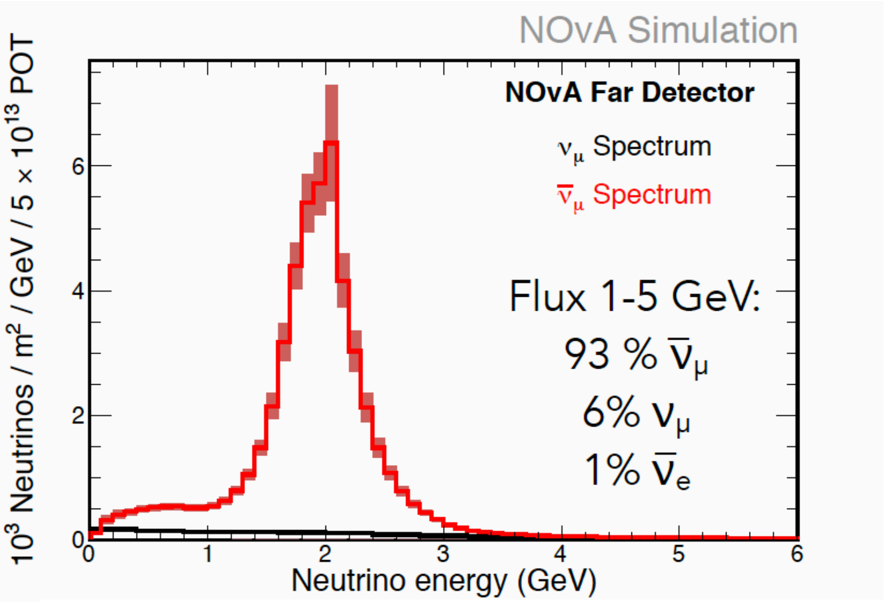
$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \qquad \Delta = \frac{\Delta \mathrm{m}_{31}^2 L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- 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

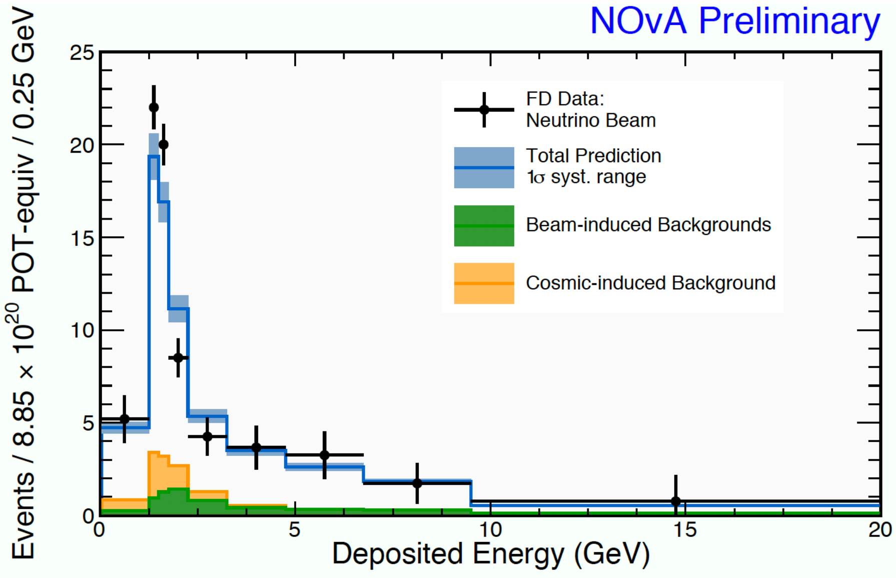


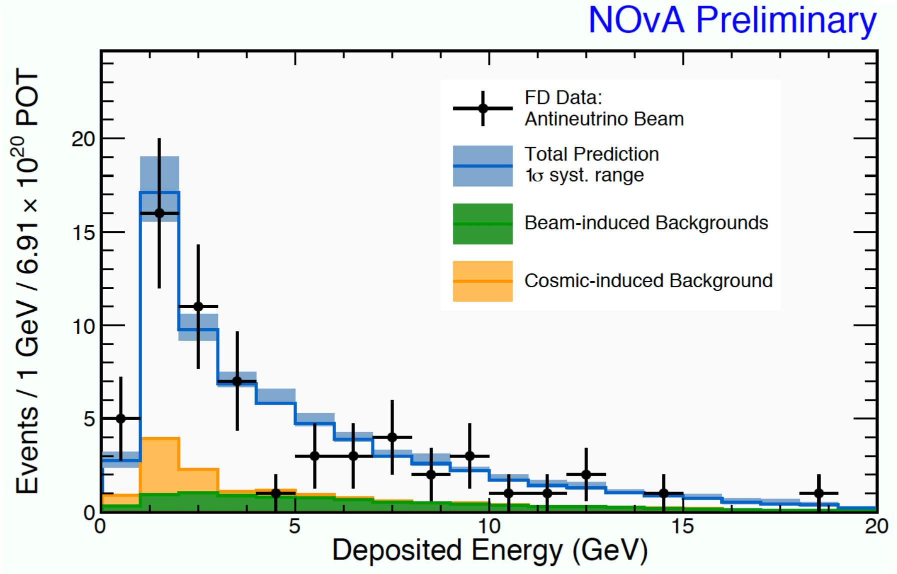




Observed NC events in Far Detector

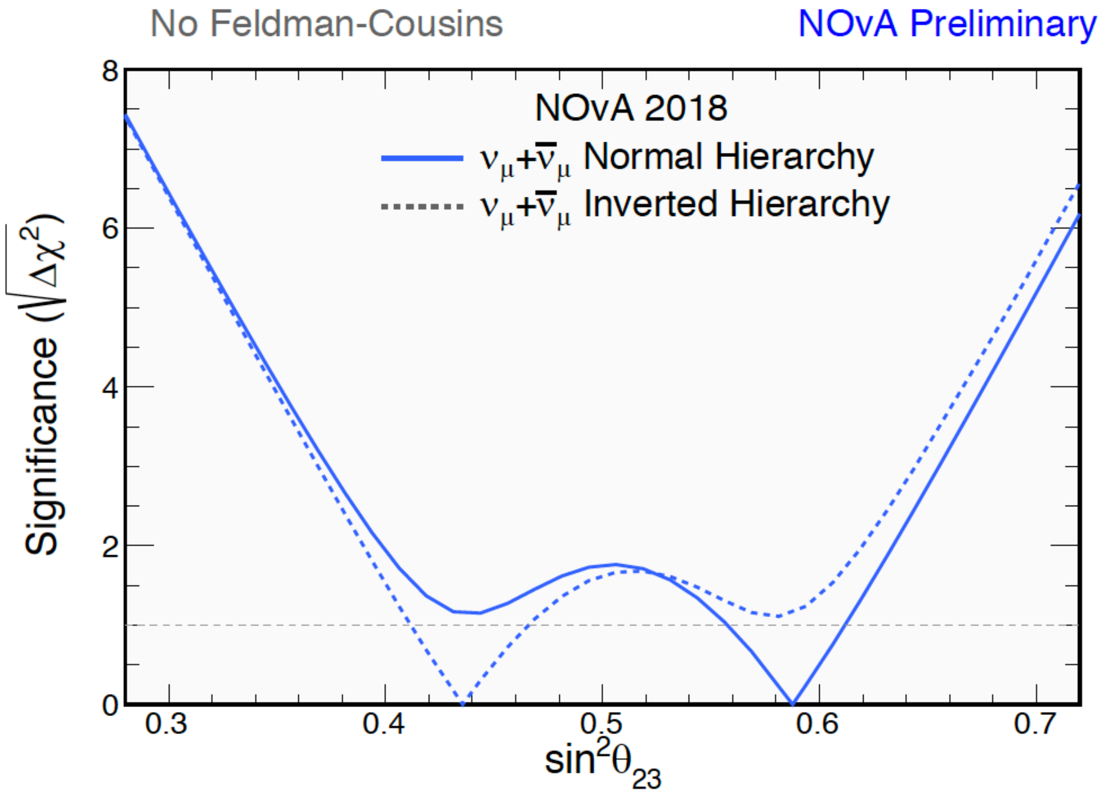
- FD selection:
  - NC CVN selection applied
  - Additional Deep-learning based cosmic rejection
- Neutrino beam:
  - Observe 201 events, predict 188 ± 13 (syst.) events (38 bkg.)
- Antineutrino beam:
  - Observe 61 events, predict 69 ± 8 (syst.) events (16 bkg.)
- No significant suppression for NC observed,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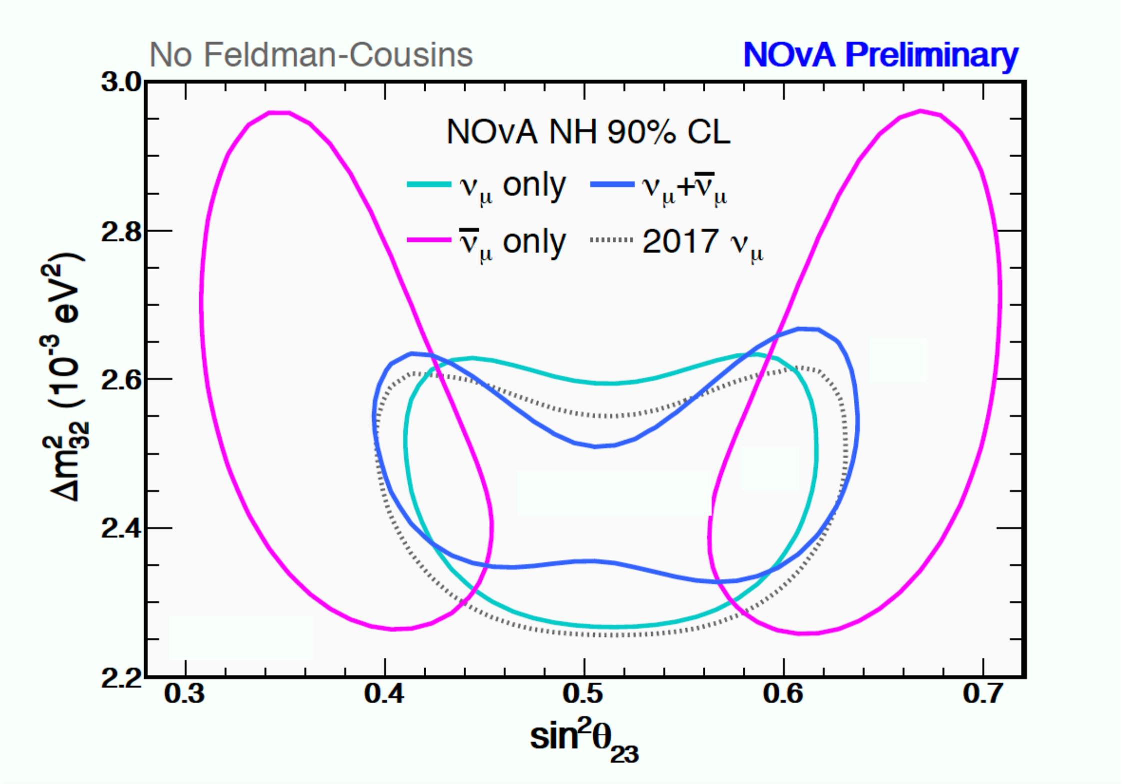
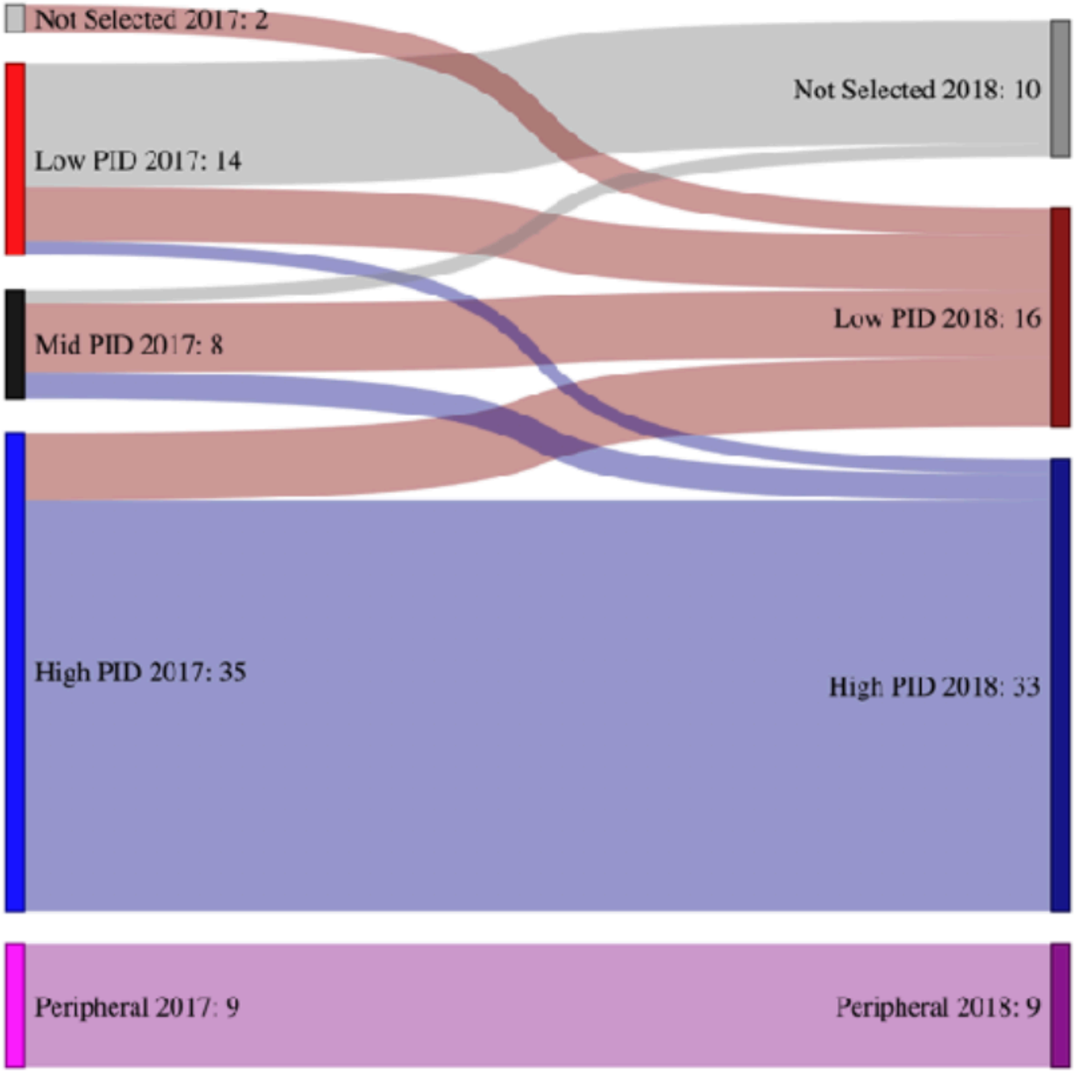


2017/2018 RHC ν_e FD Data

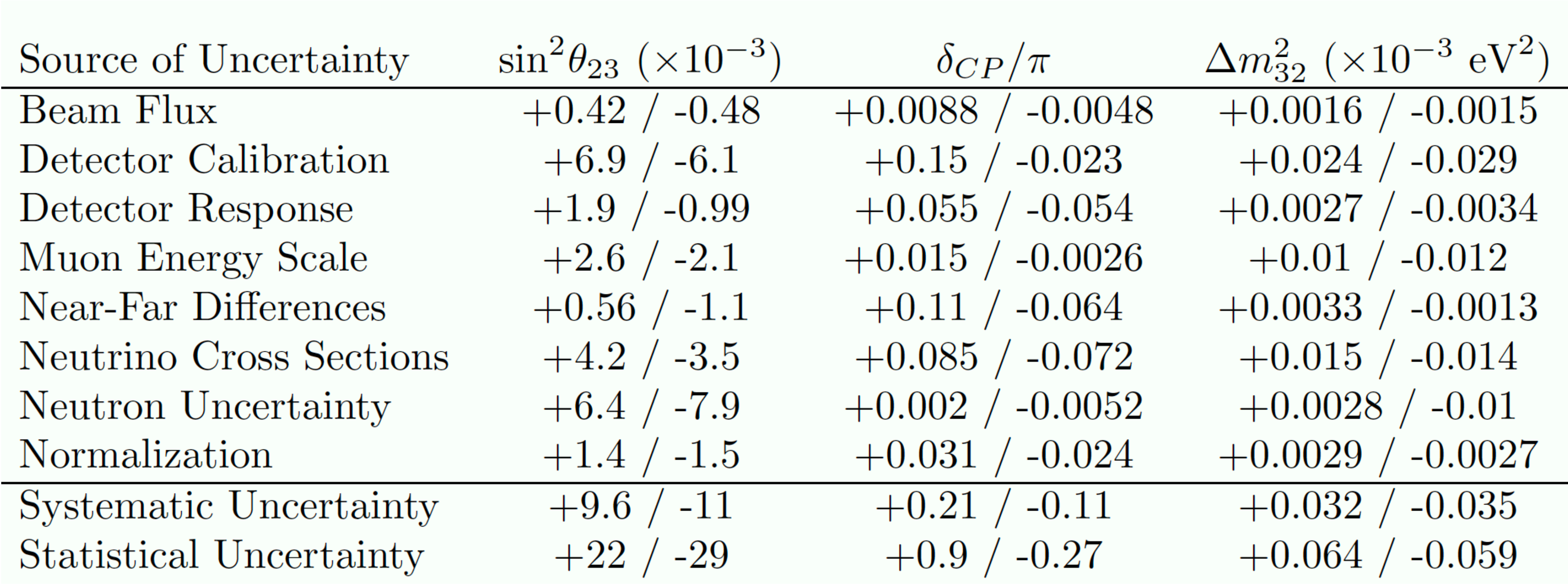
66 FD data events in 2017 analysis



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