First Oscillation Results Using Neutrinos and Antineutrinos from the NOvA Experiment

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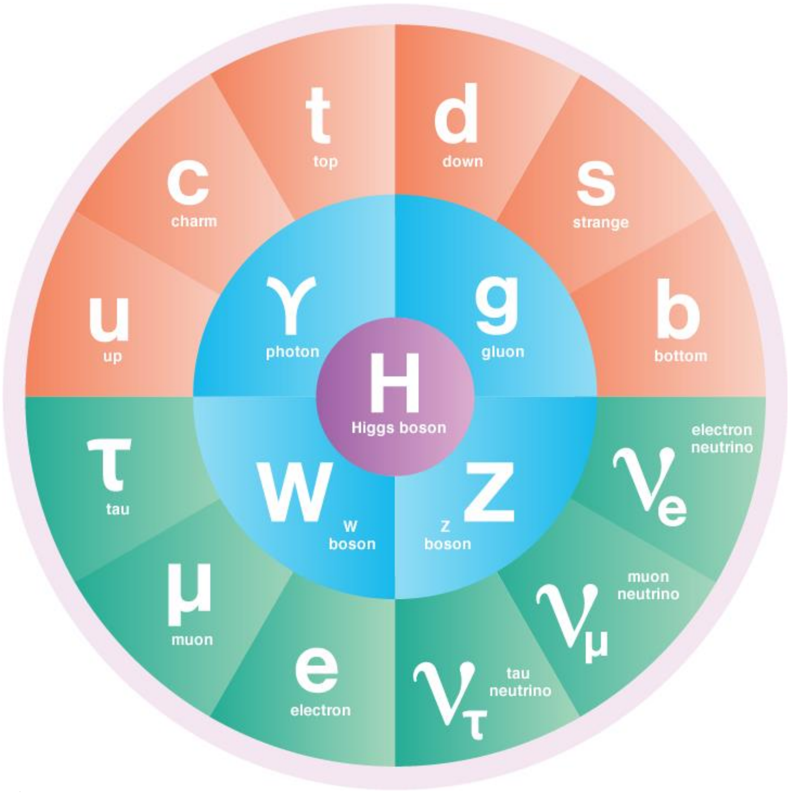
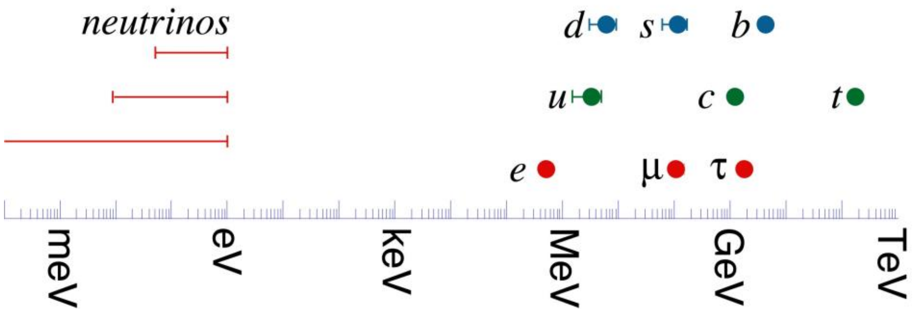
Neutrinos





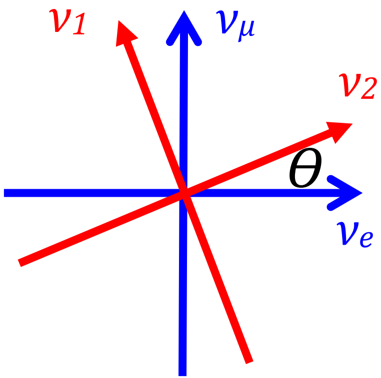
- What we don't know:
  - What the absolute neutrino mass is
  - What the mass hierarchy is
  - Why neutrino masses are so small
  - If they are CP violating
  - Why neutrino mixing looks so different from mixing in the quark sector

Neutrino Oscillations

- Created in one flavor but can be detected in another

- Each flavor is a superposition of mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



Three-Flavor Oscillations

- The mixing matrix can be written in terms of 3 angles and 1 phase. Usually factorized into components directly related to the experiments:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

- The (12) sector: Solar and Reactor, L/E 15,000 km/GeV
- The (23) sector: Atmospheric and Accelerator, L/E 500 km/GeV
- The (13) sector: Reactor and Accelerator, L/E 500 km/GeV

$$\sin^2\theta_{23} = 0.51 \pm 0.05 \quad \sin^2\theta_{13} = 0.0219 \pm 0.0012 \quad \sin^2\theta_{12} = 0.304 \pm 0.014$$

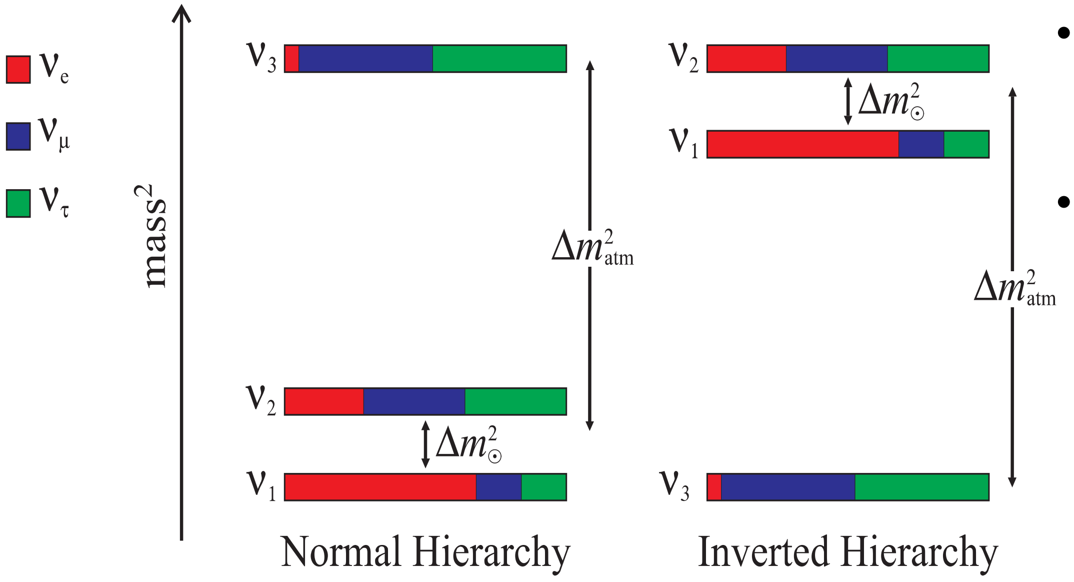
$$\delta_{CP} = ?$$

(from global averages)

Mass Squared Differences and Hierarchy

- Neutrino oscillation experiments can access the mass squared differences

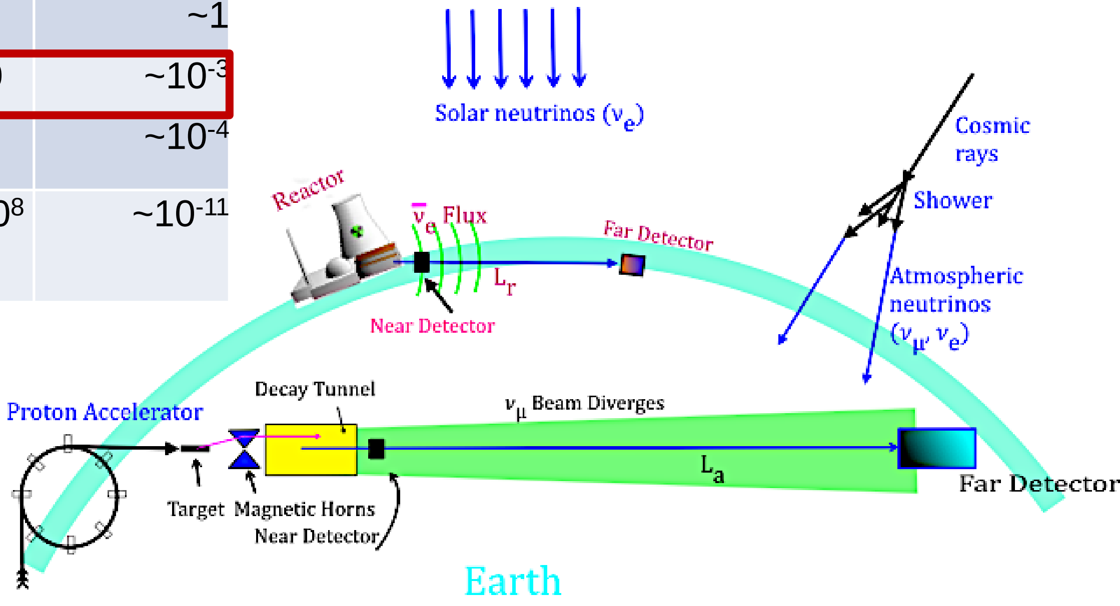
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$$



- By convention we denote the mass eigenstate with the largest fraction of ν_e as ν_1
- We haven't determined which mass eigenstate is the lightest → "hierarchy"
  - Normal: ν_1 is the lightest, just like the electron is the lightest charged lepton
  - Inverted: ν_3 is the lightest

Sources of ν's for Oscillation Studies

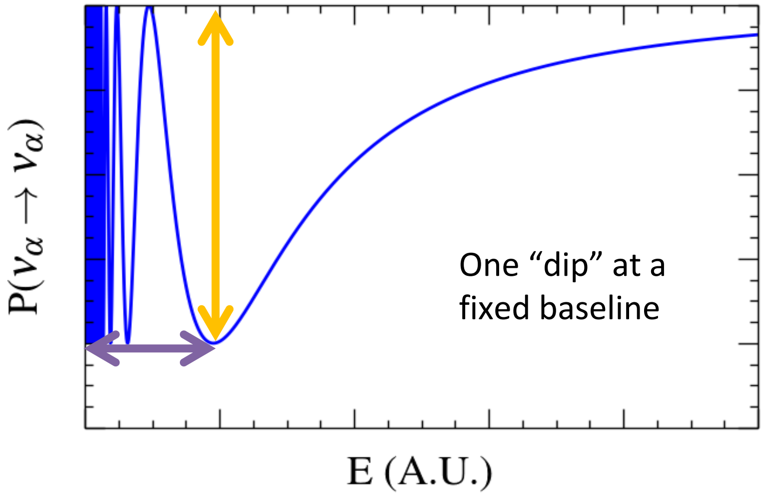
Source	Type of ν	E [MeV]	L [km]	$\min(\Delta m^2)$ [eV²]
Reactor	$\bar{\nu}_e$	~1	1	~10^{-3}
Reactor	$\bar{\nu}_e$	~1	100	~10^{-5}
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	~10^3	1	~1
Accelerator	$\nu_\mu, \bar{\nu}_\mu$	~10^3	1000	~10^{-3}
Atmospheric	$\nu_{\mu,e}, \bar{\nu}_{\mu,e}$	~10^3	10^4	~10^{-4}
Solar	ν_e	~1	1.5x10^8	~10^{-11}



$\nu_\mu \rightarrow \nu_\mu$ Oscillations

Probability of ν_μ survival in a ν_μ beam

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \boxed{\sin^2(2\theta_{23})} \right) \sin^2\left(\frac{\boxed{\Delta m^2} L}{4E} \right)$$



$\nu_\mu \rightarrow \nu_e$ Oscillations in Matter

Probability of ν_e appearance in a ν_μ beam

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

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

$$\Delta_{jk} \equiv \frac{\Delta m^2_{jk} L}{4E}$$

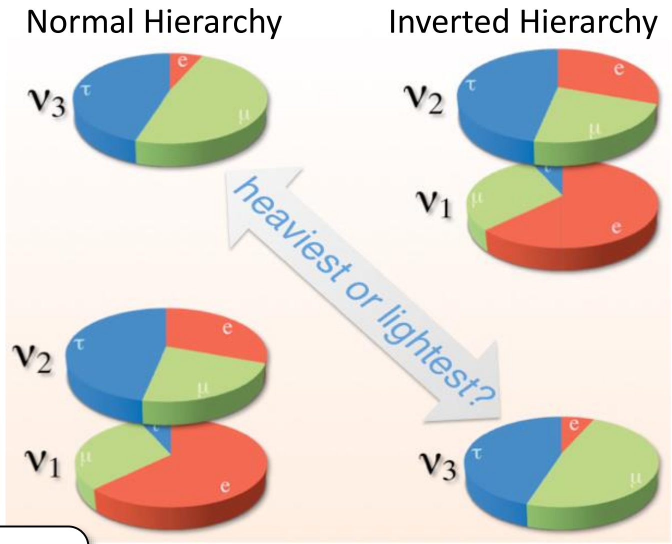
$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31} \qquad \sqrt{P_{\text{sol}}} = \cos\theta_{23}\sin(2\theta_{12})\frac{\sin(aL)}{aL}\Delta_{21}$$

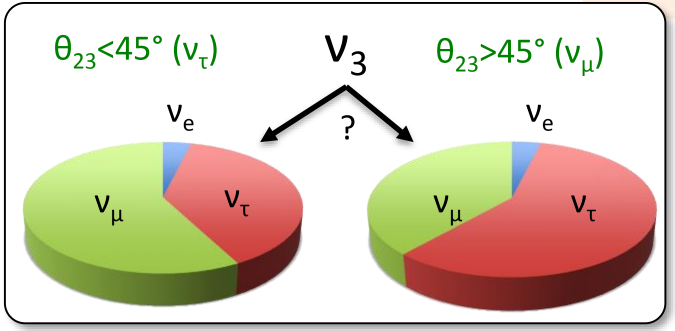
$$\boxed{a = \frac{G_F N_e}{\sqrt{2}}}$$

- $\nu_\mu \rightarrow \nu_e$ depends on:
  - *CP* phase: δ_{CP}
  - Mass hierarchy and matter effects
  - Atmospheric parameters: $\sin^2(\vartheta_{23})$, Δm^2_{32}
  - The smallest mixing angle: ϑ_{13}
  - Solar parameters: $\sin^2(\vartheta_{12})$, Δm^2_{12}

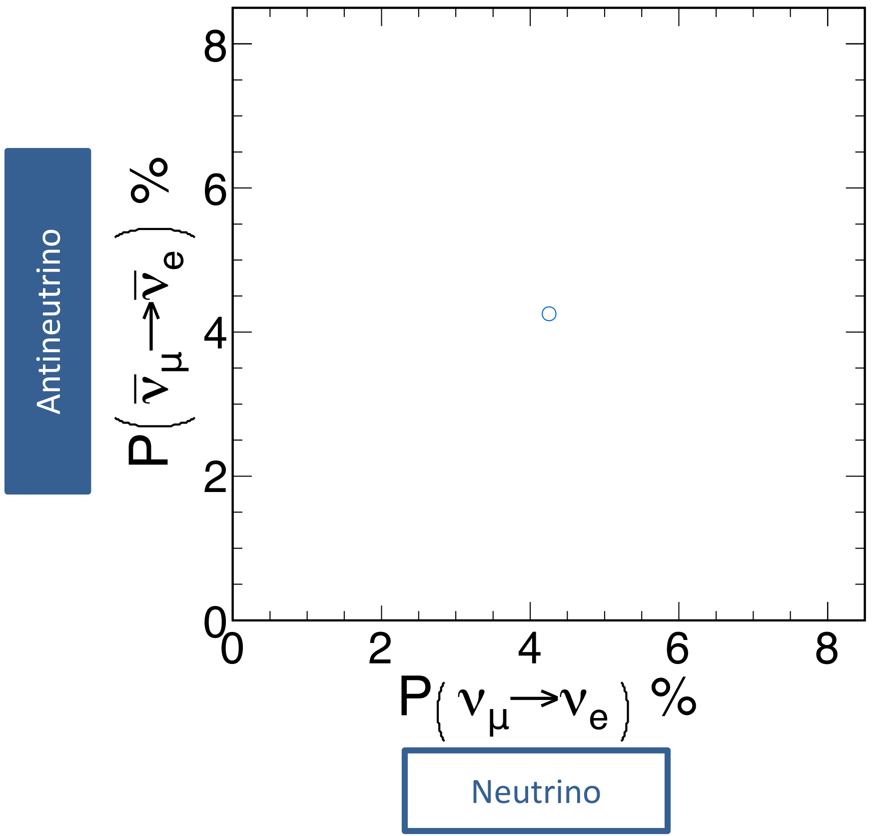
Open Questions in Neutrino Physics

- What is the mass hierarchy for atmospheric neutrinos?
- Is there a ν_μ-ν_τ symmetry?
  - Is the large mixing angle maximal, and if not, what is the octant?
- Is CP violated in the lepton sector?
- Are there other neutrinos beyond the three active flavors?



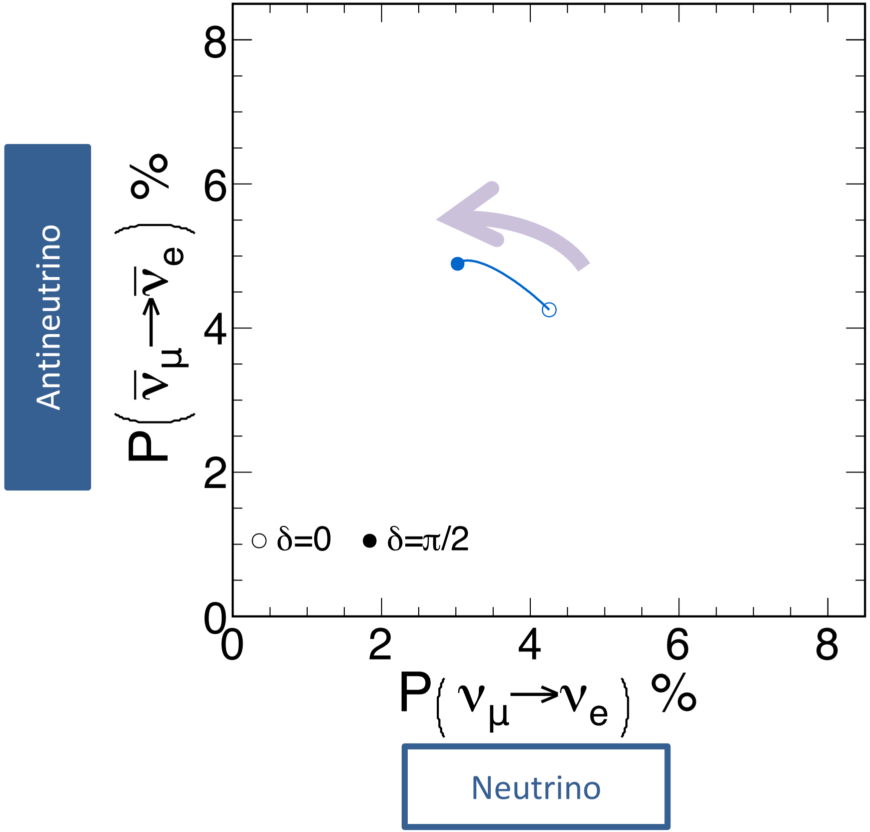


Electron Neutrino vs Antineutrino Appearance



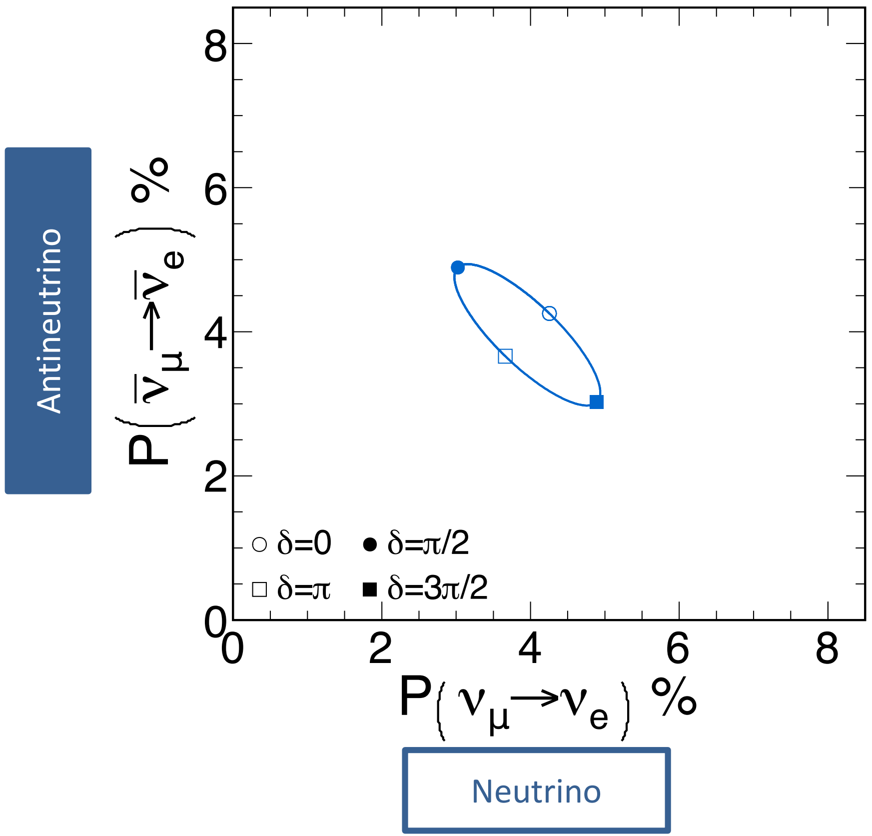
Vacuum and no CP violation: neutrinos and antineutrinos are the same

Electron Neutrino vs Antineutrino Appearance



CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Electron Neutrino vs Antineutrino Appearance



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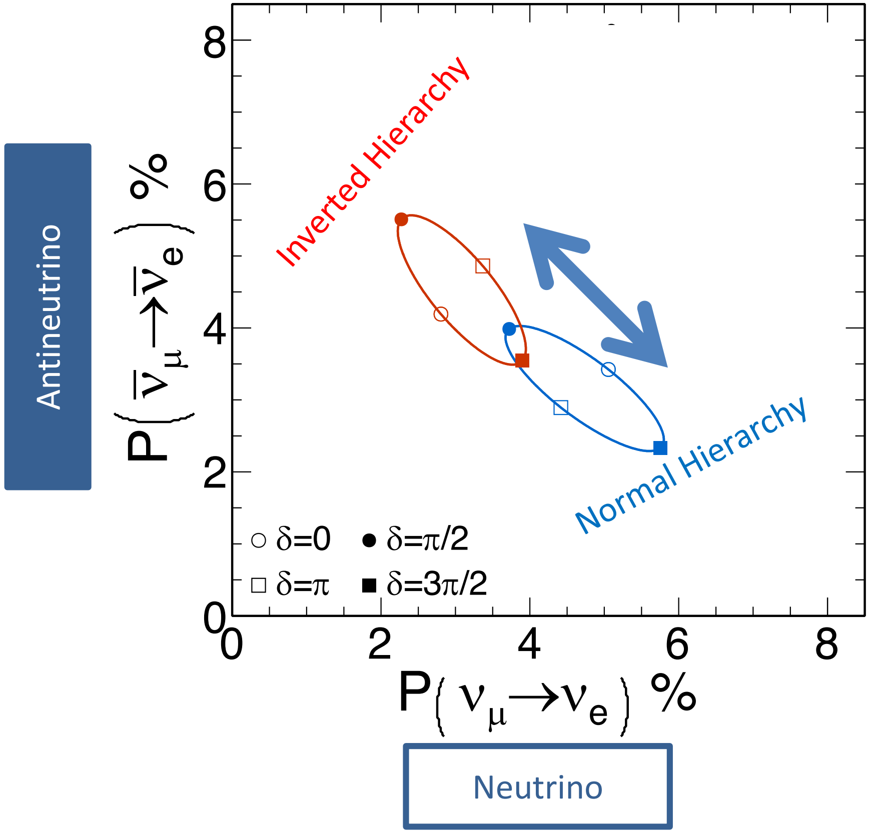
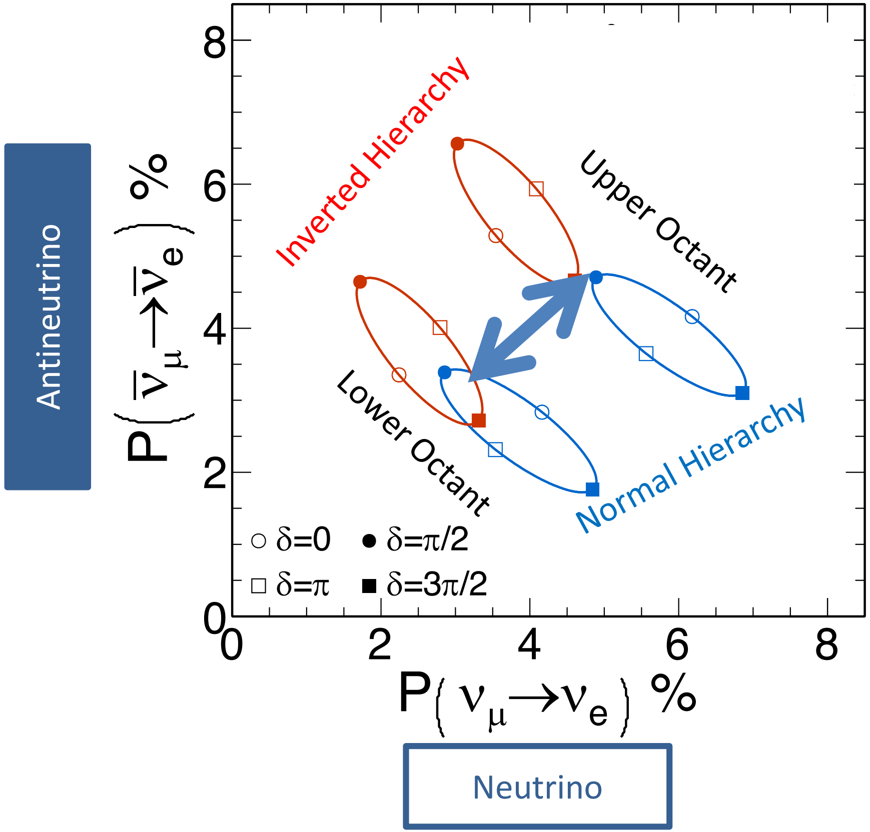
Electron Neutrino vs Antineutrino Appearance



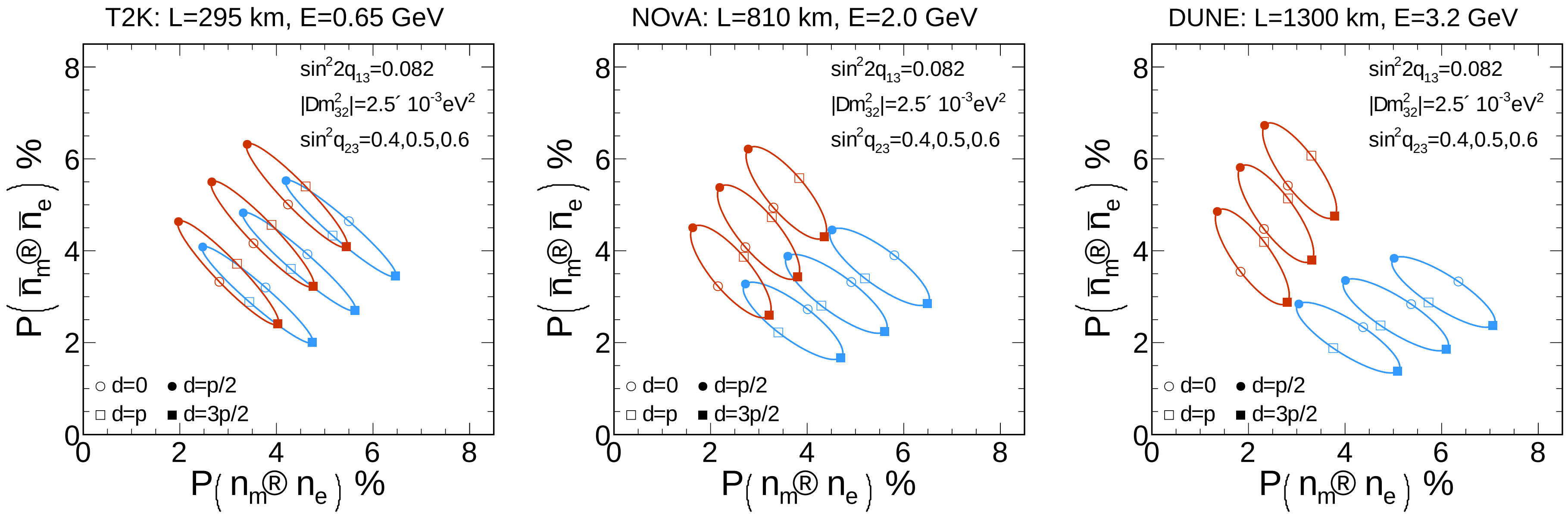
Matter effects also introduce opposite neutrino-antineutrino effects.

Electron Neutrino vs Antineutrino Appearance



The octant creates the same effect in neutrinos and antineutrinos.

Comparing Long Baseline Experiments

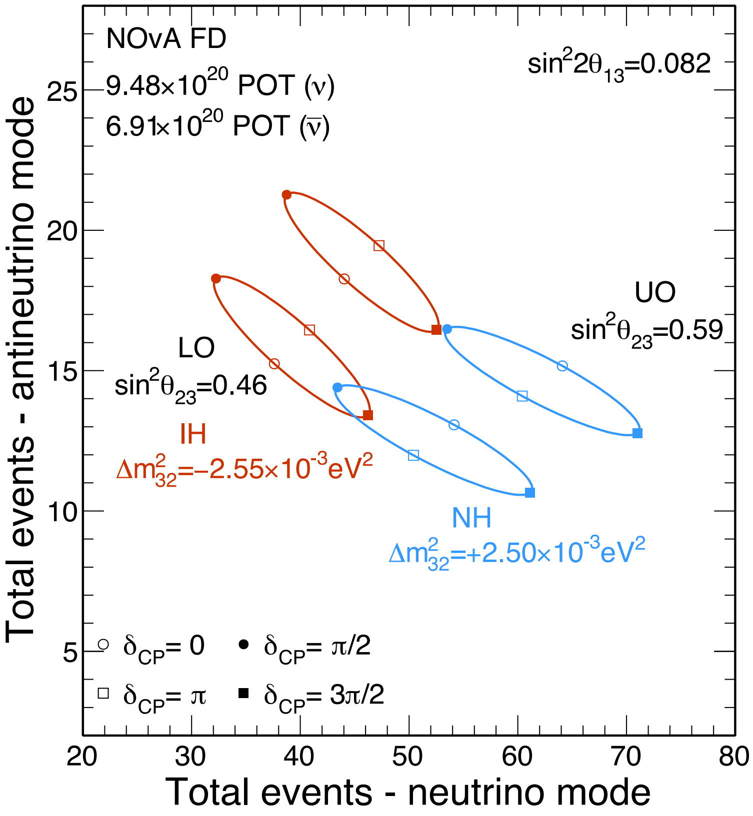


Physics Goals

- Is the mass hierarchy “normal” or “inverted”?
- Is there a ν_μ - ν_τ symmetry? I.e., is the large mixing angle maximal? If not, what is the octant?
- Is CP violated in the lepton sector?

In addition: Are there other neutrinos beyond the three known active flavors?

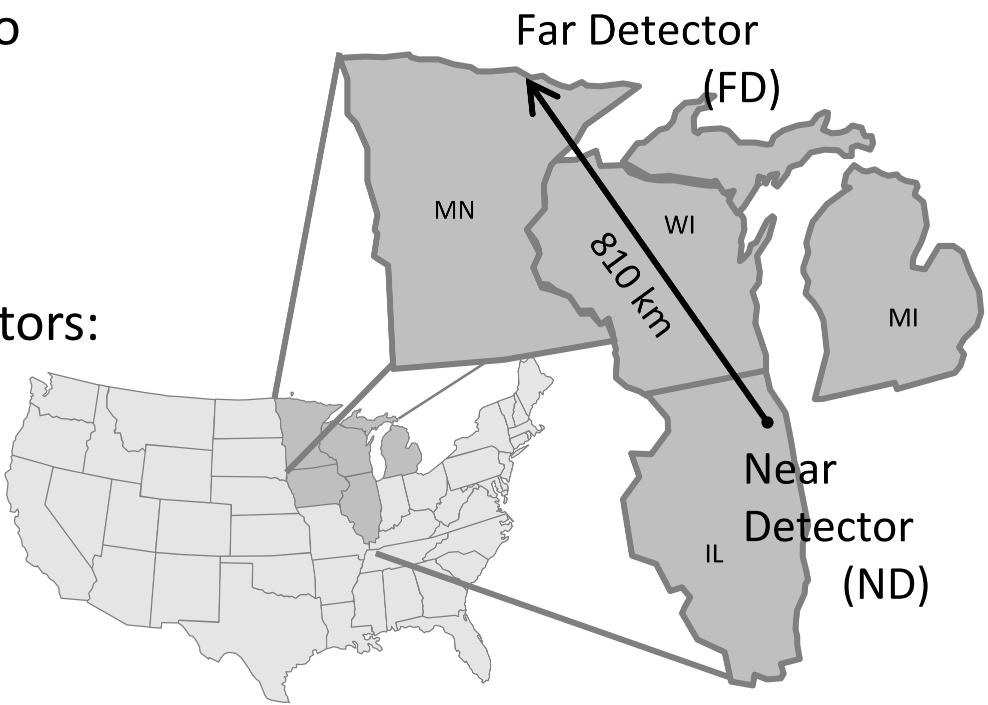
Plus: cross section analyses, searches for exotic phenomena and non-beam physics



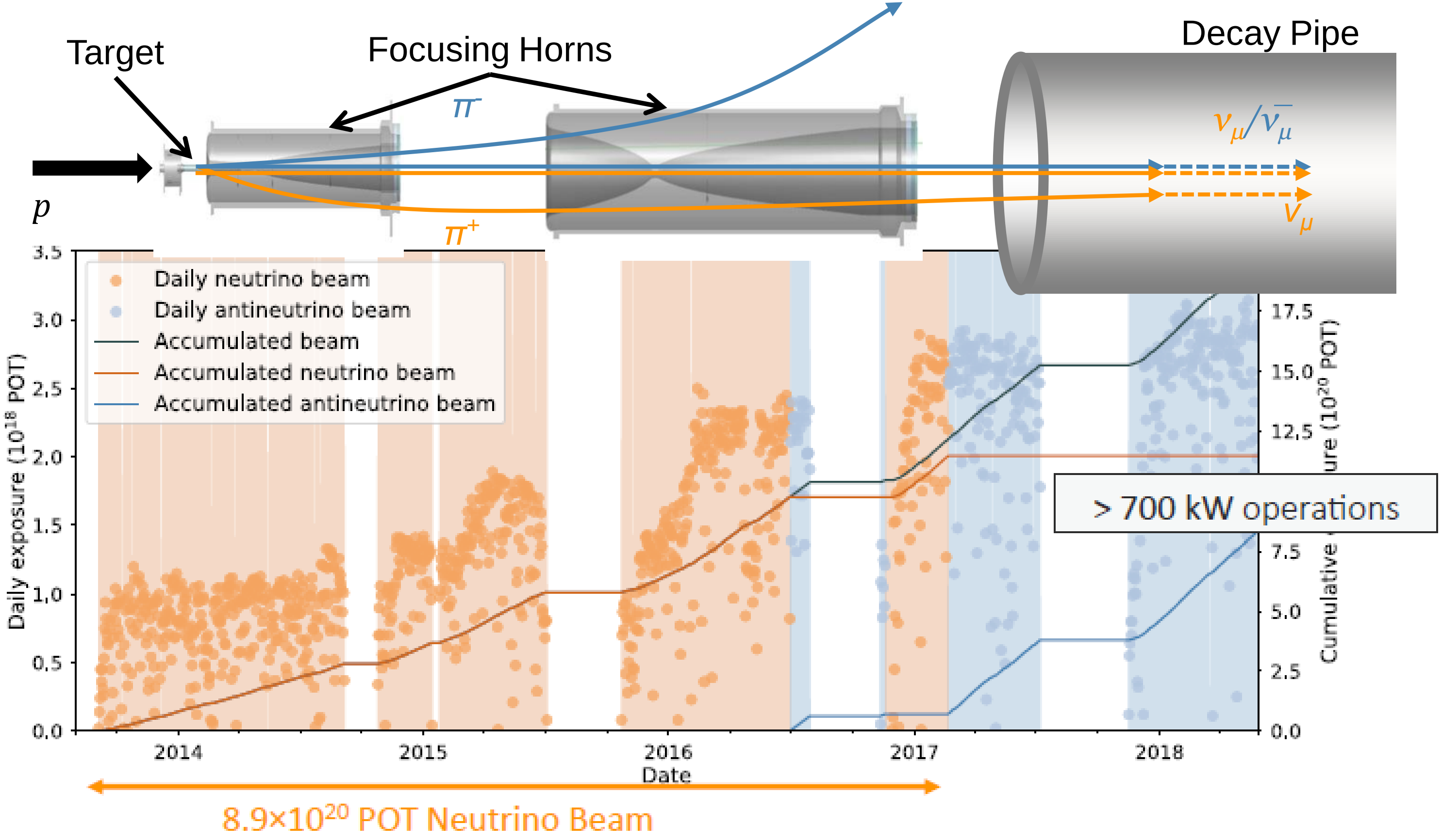
The NOvA Collaboration

NOvA

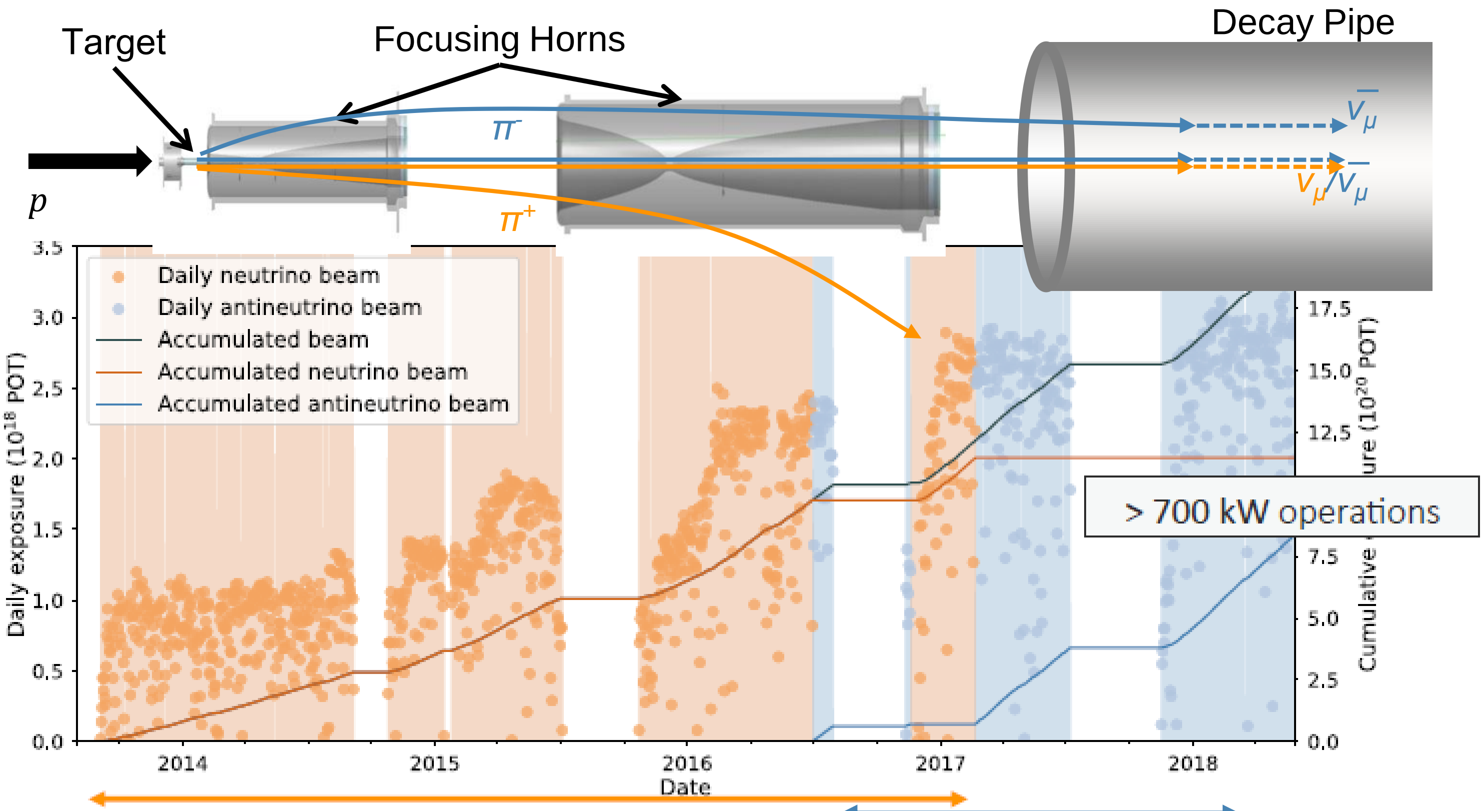
- NOvA is a long-baseline neutrino oscillation experiment
- Study neutrinos from the NuMI beam at Fermilab
- Two functionally identical detectors:
  - Far Detector (FD)
    14 kton; on the surface
  - Near Detector (ND)
    0.3 kton; underground



The NuMI Neutrino Beam

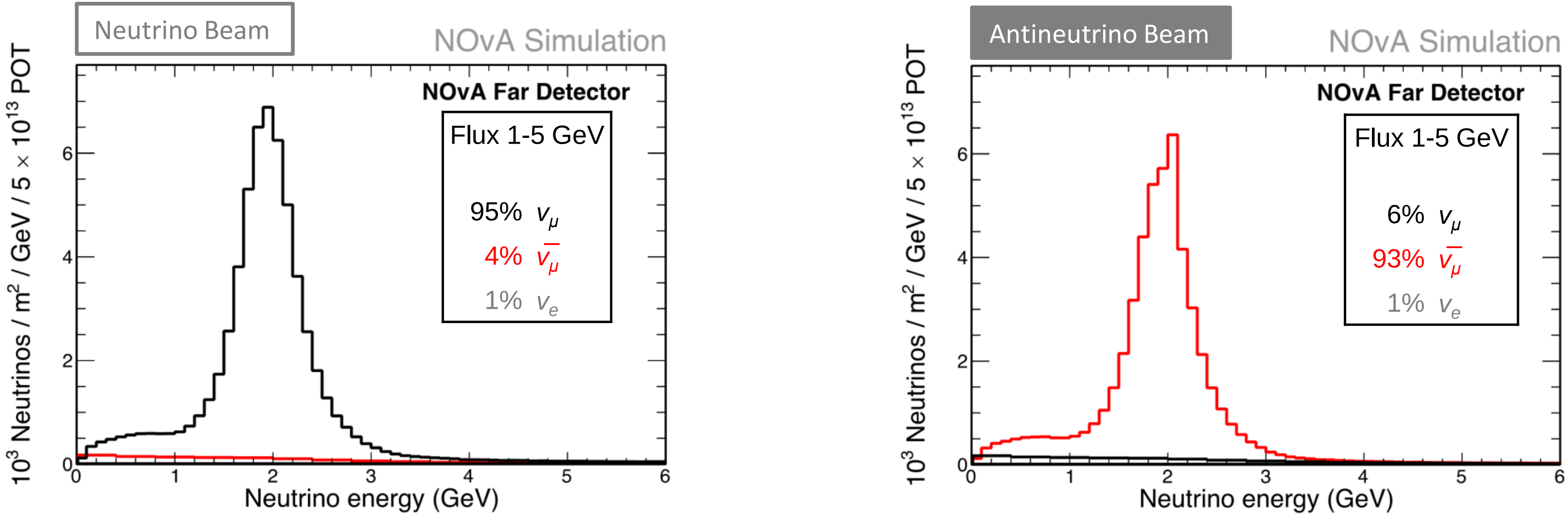


The NuMI Antineutrino beam

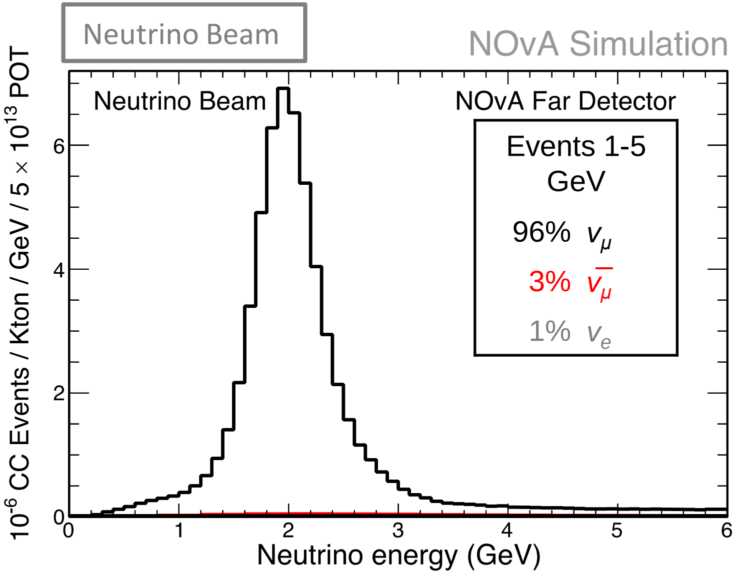


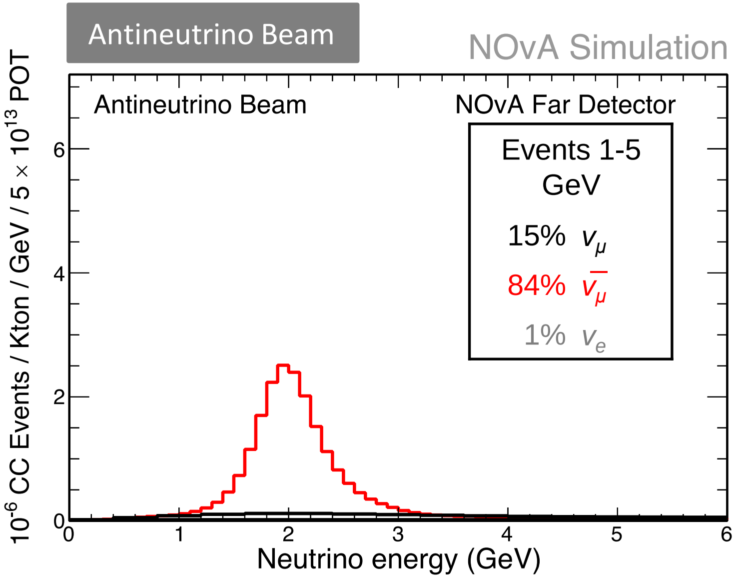
$8.9{\times}10^{20}$ POT Neutrino Beam

$6.9{\times}10^{20}$ POT Antineutrino Beam



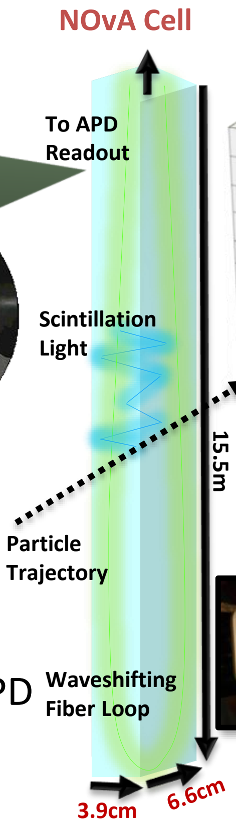
- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
  - p^+ colliding with p^+ and n^0 in the target
- Wrong-sign: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign
  - WS primarily would primarily come from the unfocused high-energy tail.

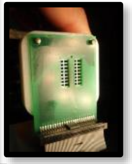


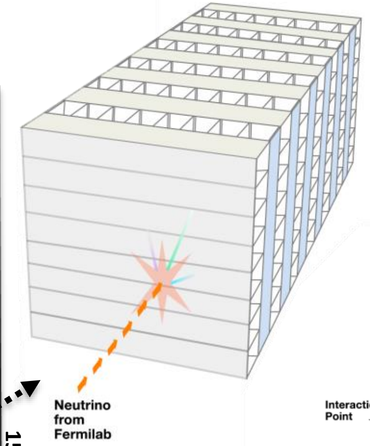


- The big difference is in the interaction: the cross section for antineutrinos is **~2.8 times lower** than for neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.
  - Lower kinematic *y*
  - More forward-going

NOvA Detectors

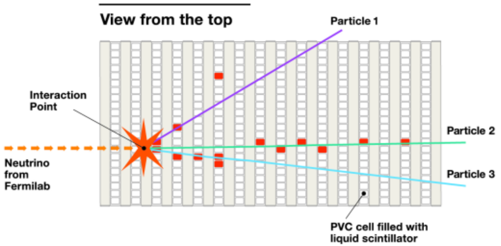


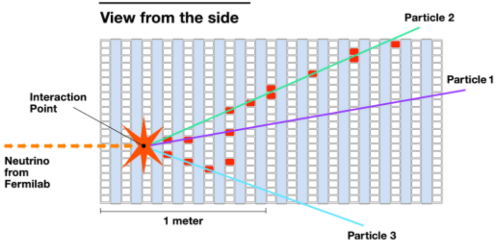




Detectors are fine-grained, low-*Z*, highly-active tracking calorimeters

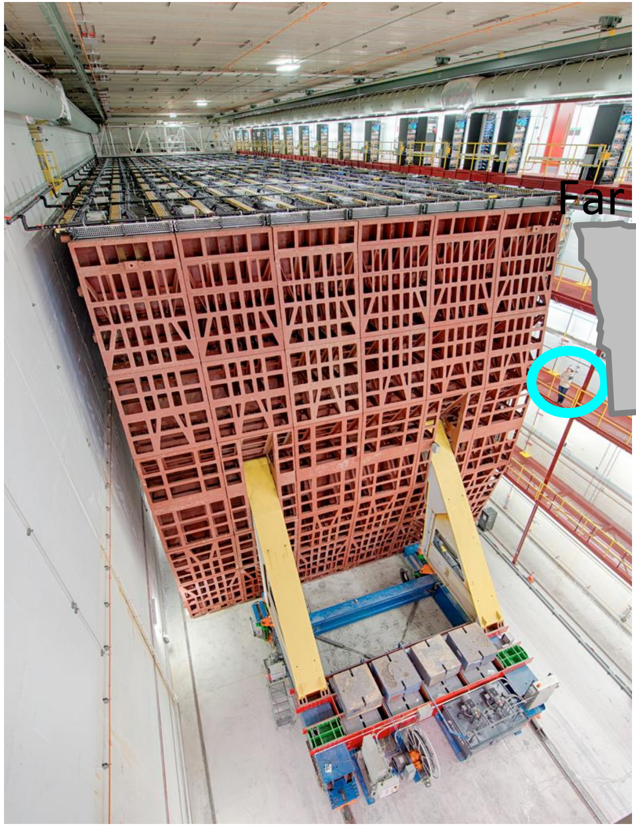
Orthogonal layers → top and side views for each event

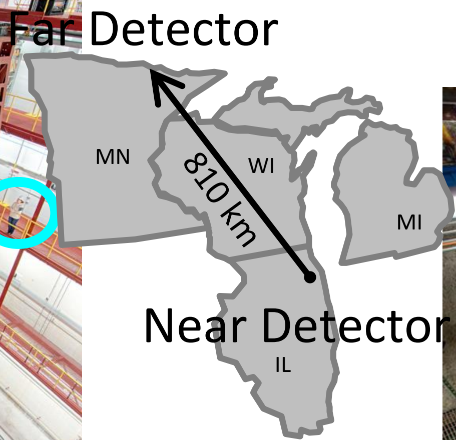


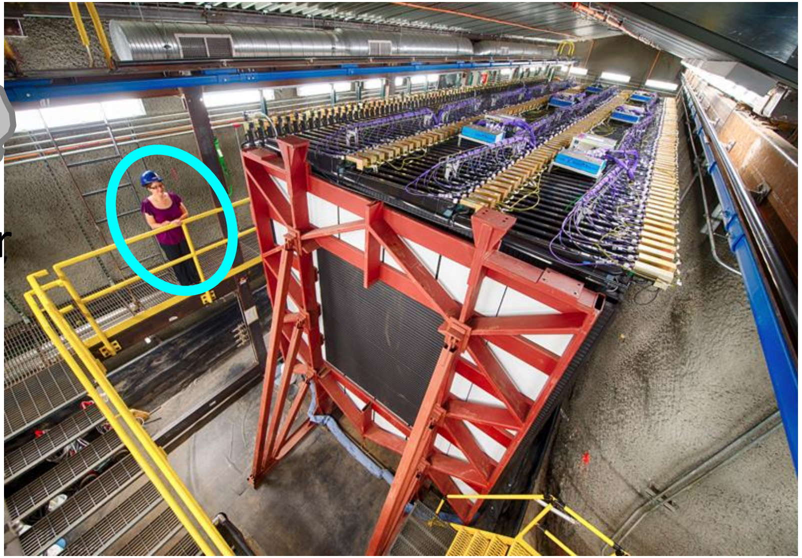


- PVC + Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via wavelength shifting fiber to APD
- Layered planes of orthogonal views

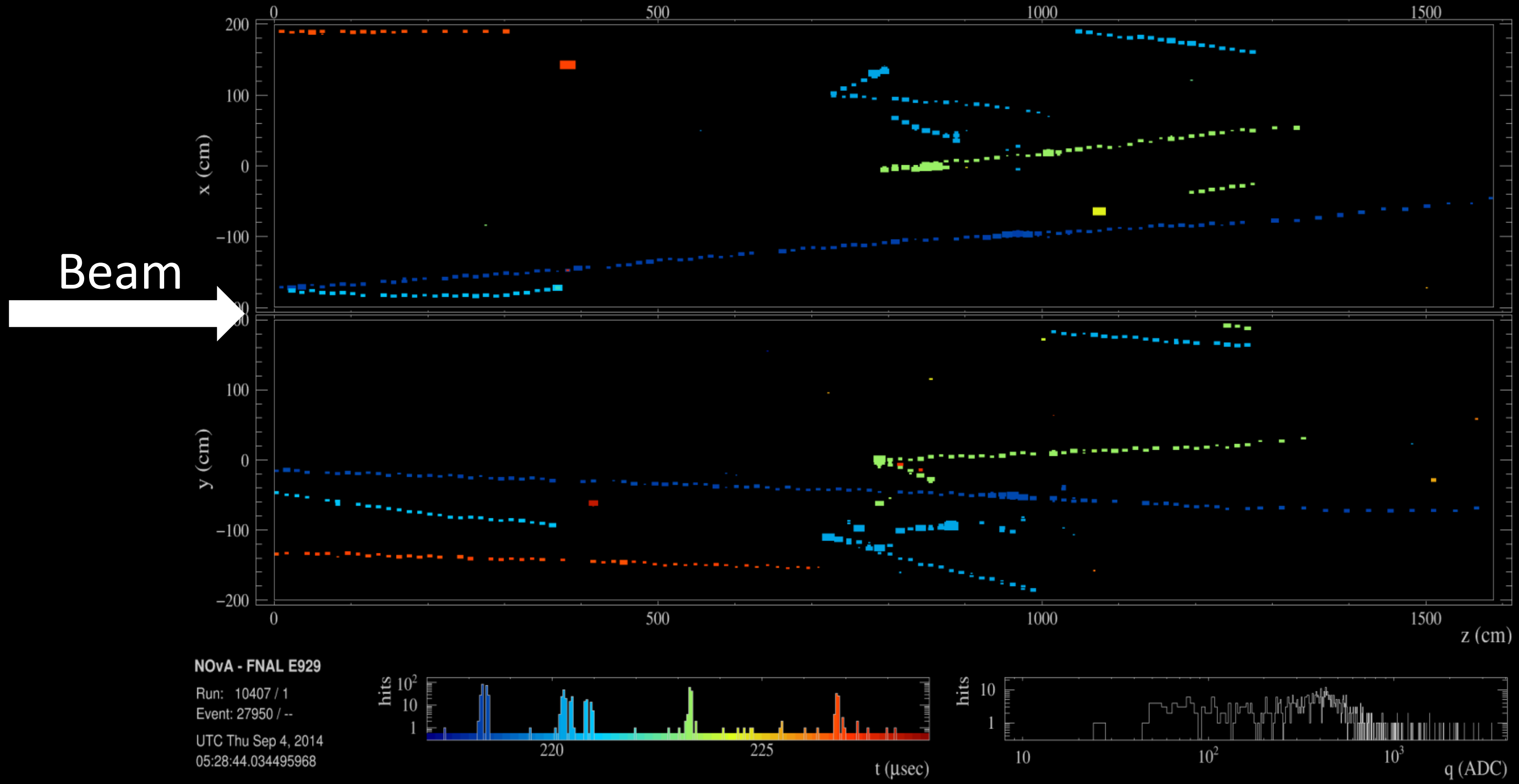
NOvA detectors







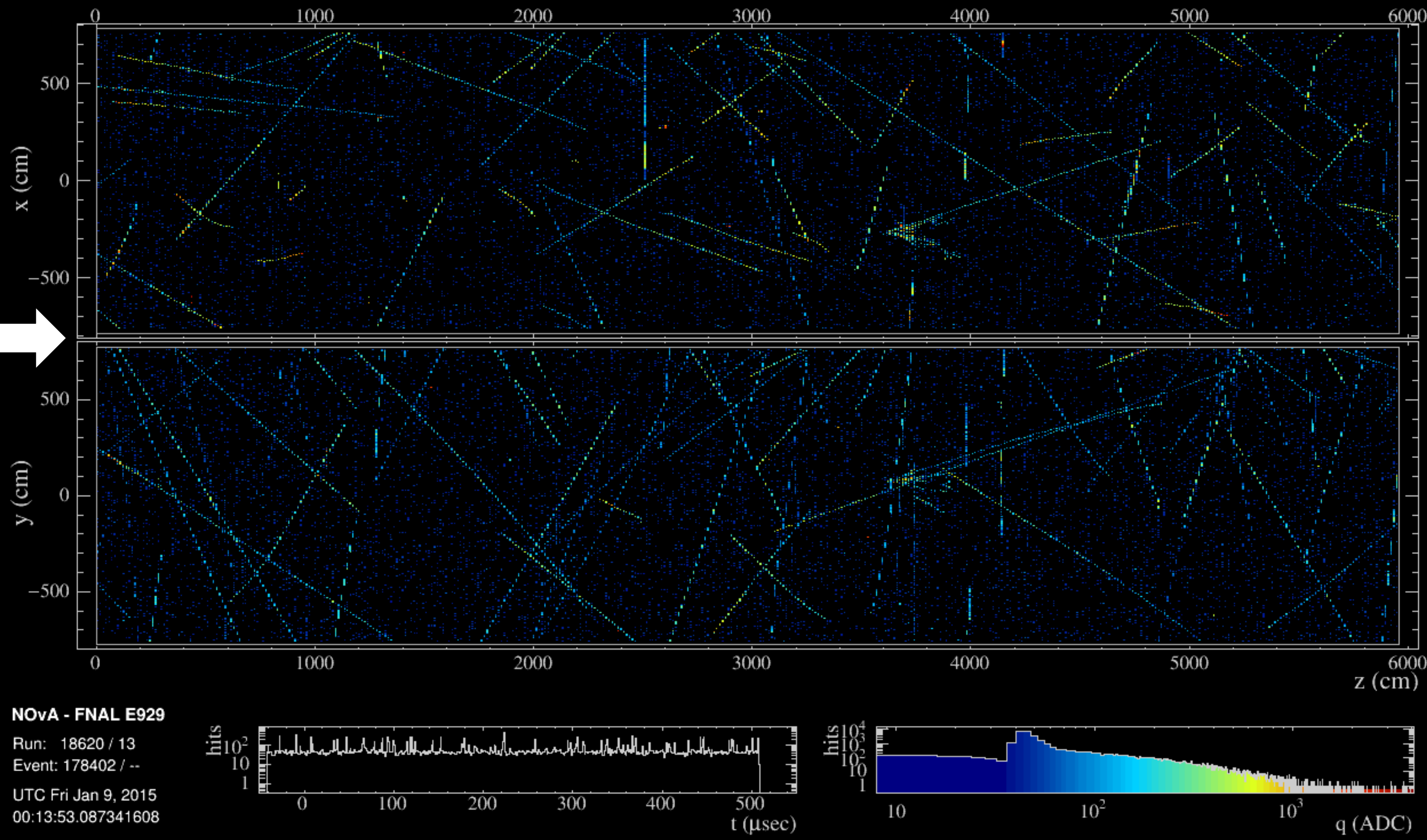
Near Detector Event Display



(colors show hit times)

Far Detector Event Display – 550 μs

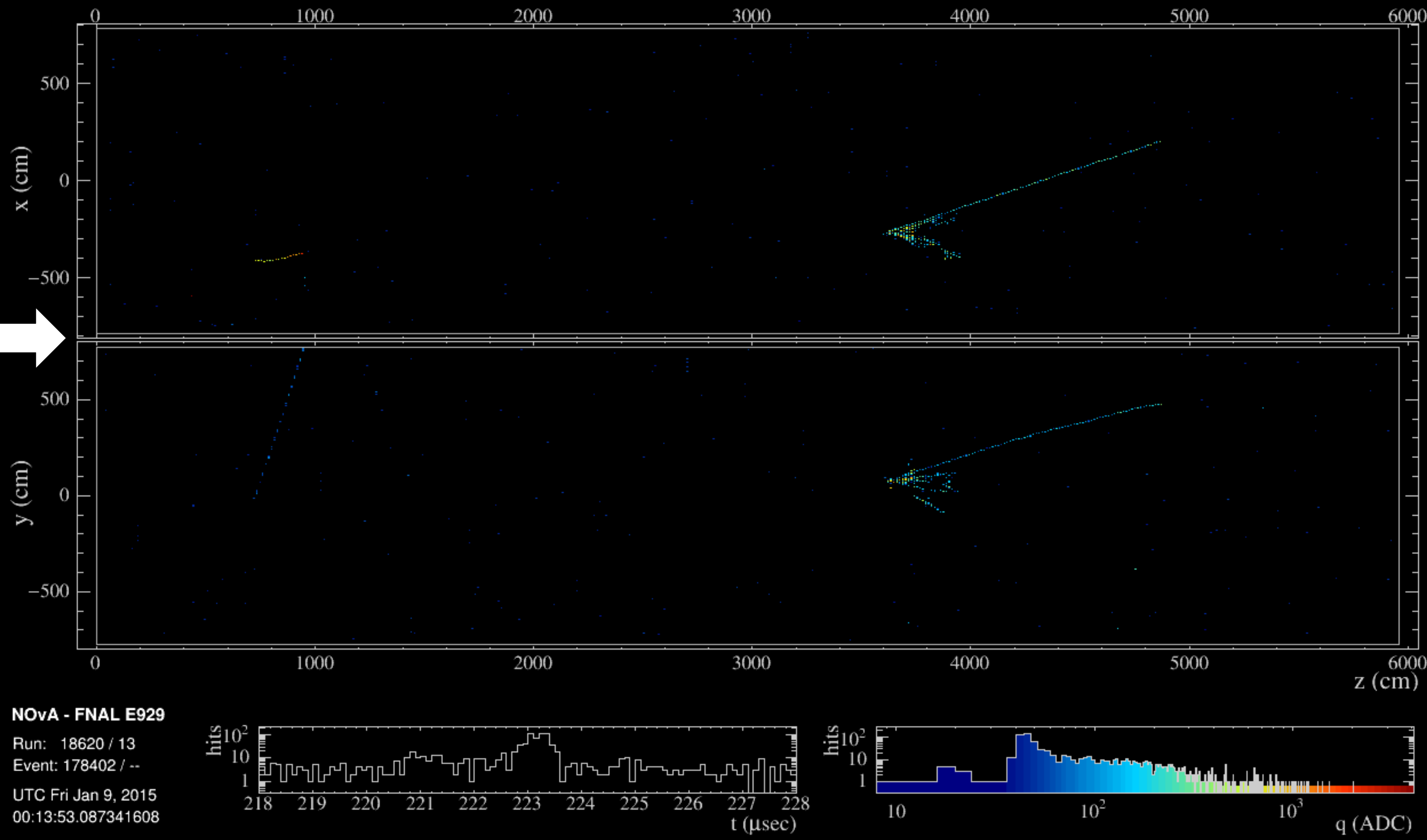
Beam



(colors show charge)

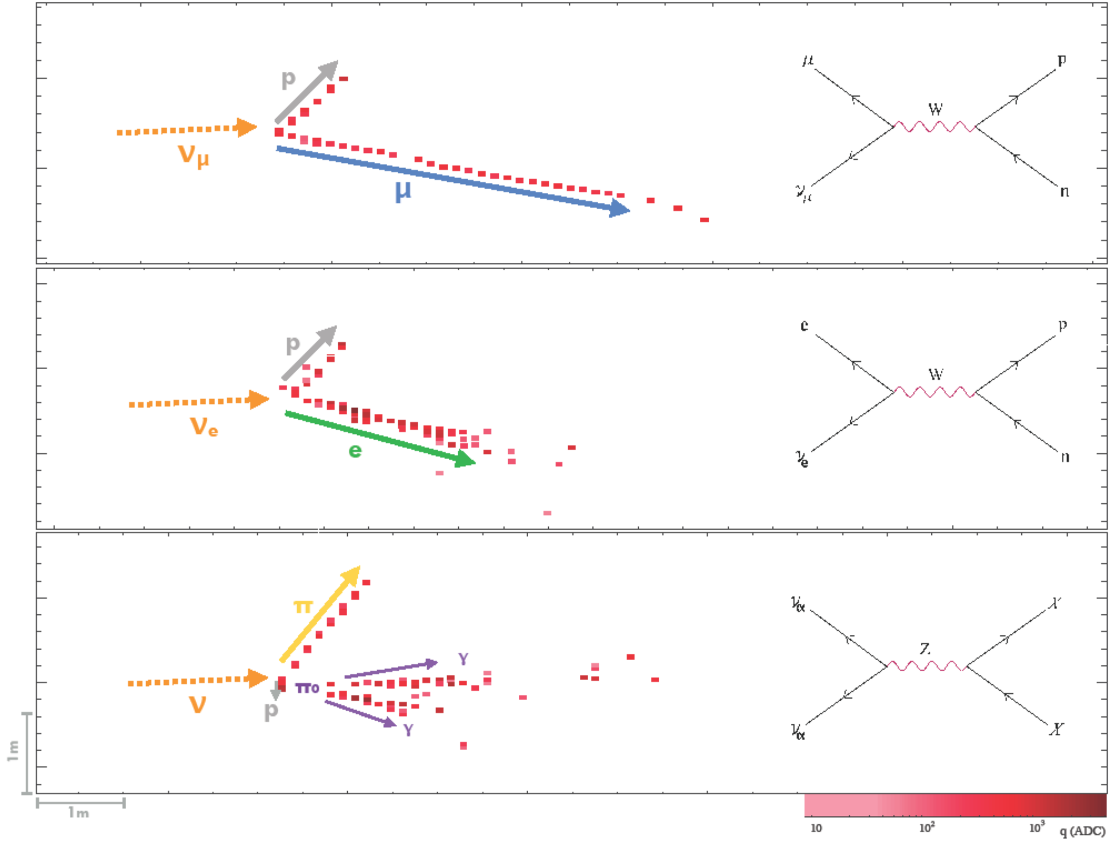
Far Detector Event Display – 10 μs

Beam



(colors show charge)

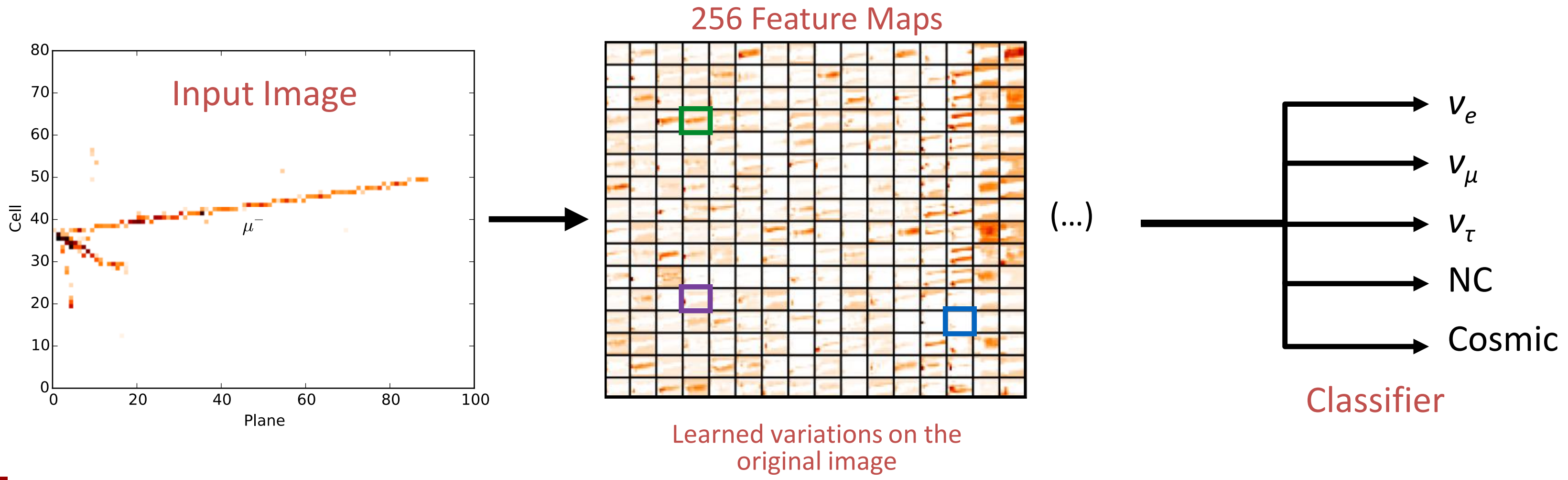
Selected Events from Near Detector Data



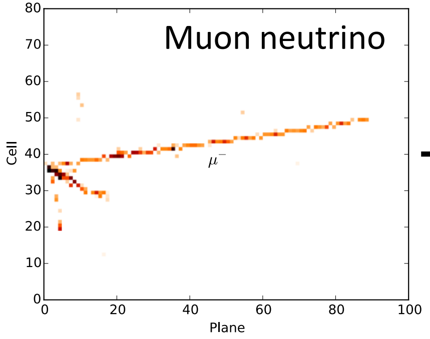
Joint Neutrino-Antineutrino Analysis

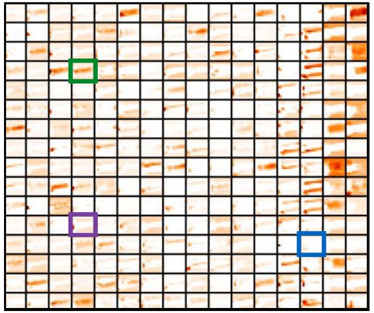
Event Identification

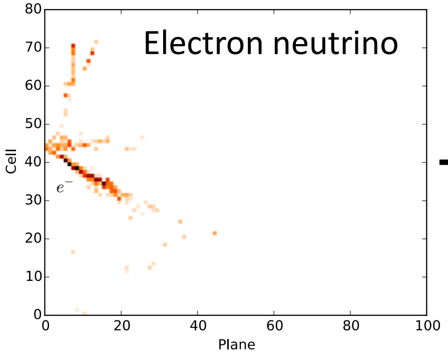
- We use a convolutional neural network.
- Successive layers of “feature maps”:
  - Create many variants on the original image which enhance different features.
  - Later layers apply variations to the feature maps from the previous layer.
- Ends with a “feed forward” neural network to create a multi-label classifier.

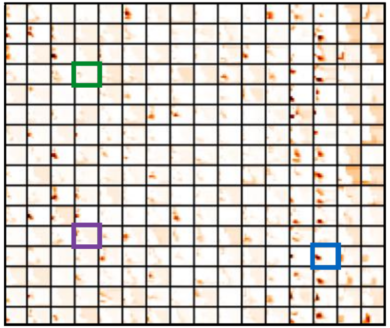


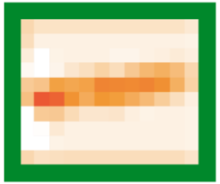
Event Identification







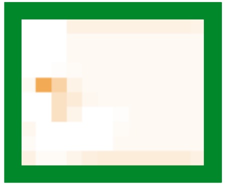




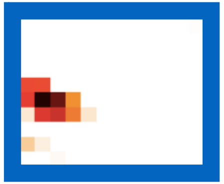
Responding to μ *tracks*

Responding to *e showers.*

Responding to *hadronic activity.*



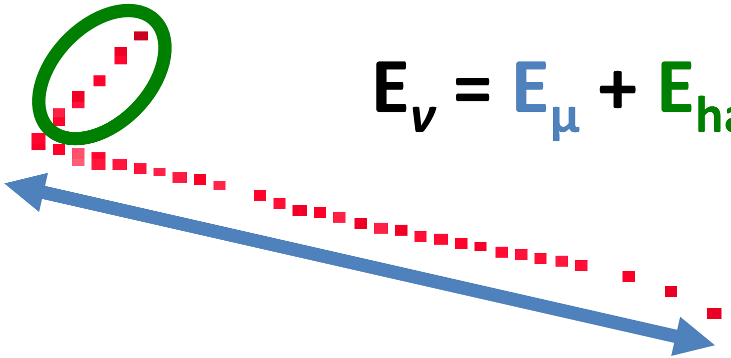
Responding to μ *tracks*



Responding to *e showers.*

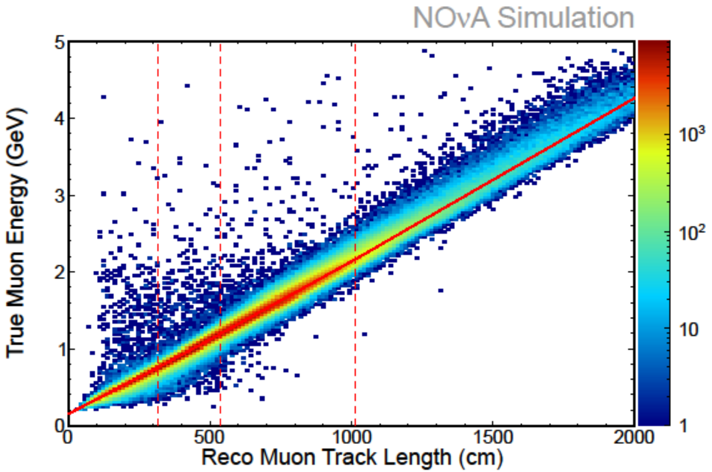
Responding to *hadronic activity.*

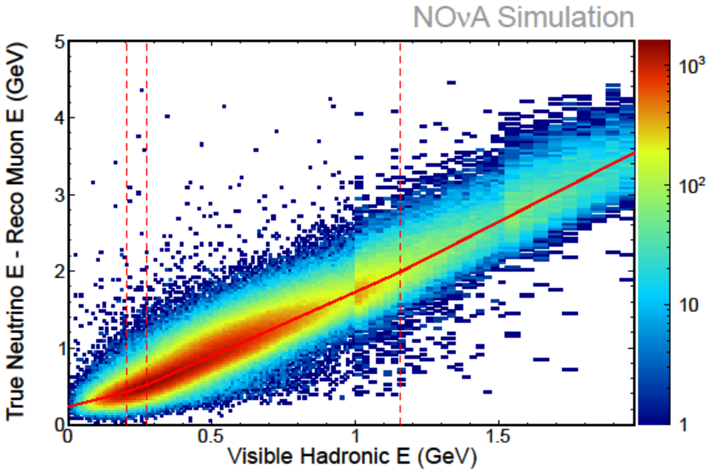
Muon Neutrino Energy



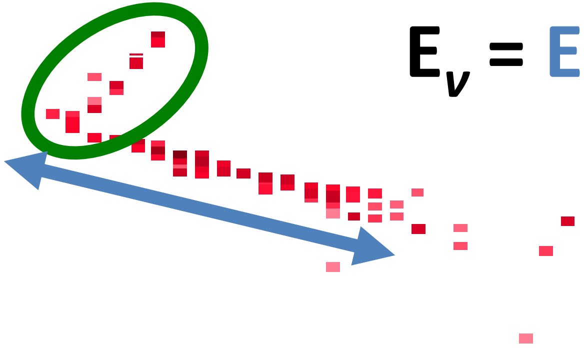
$$E_\nu = E_\mu + E_{had}$$

- Muon energy is calculated with a conversion from track length.
- Hadronic energy is the summed calorimetric energy of the non-muon hits, converted to true energy.
- Muon energy resolution (3%) is much better than hadronic energy resolution (30%).

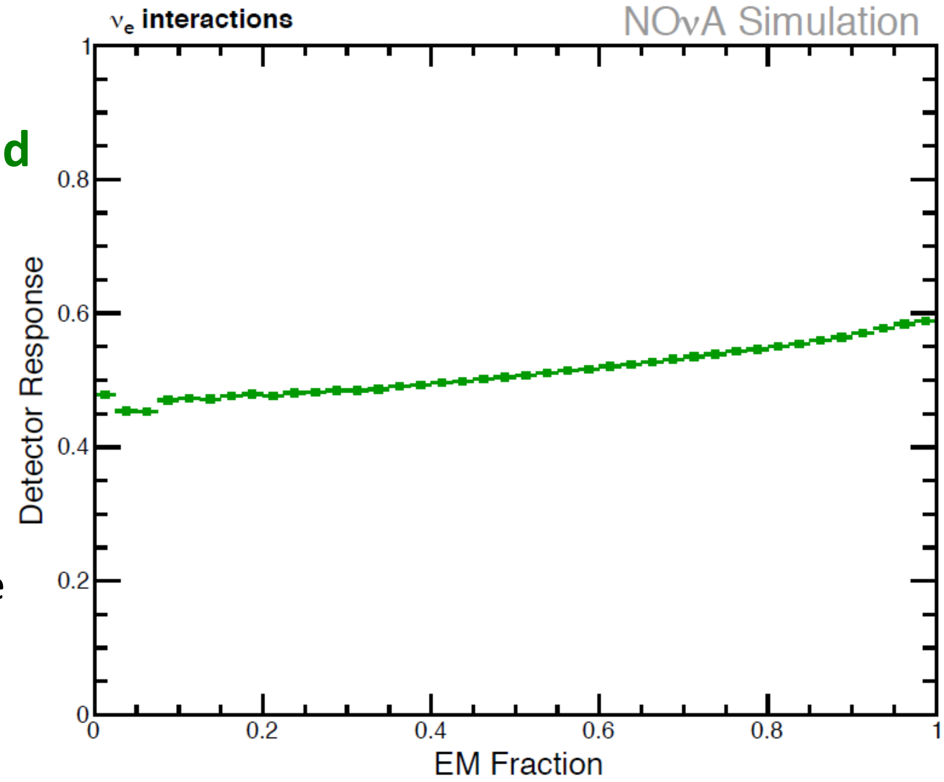




Electron Neutrino Energy



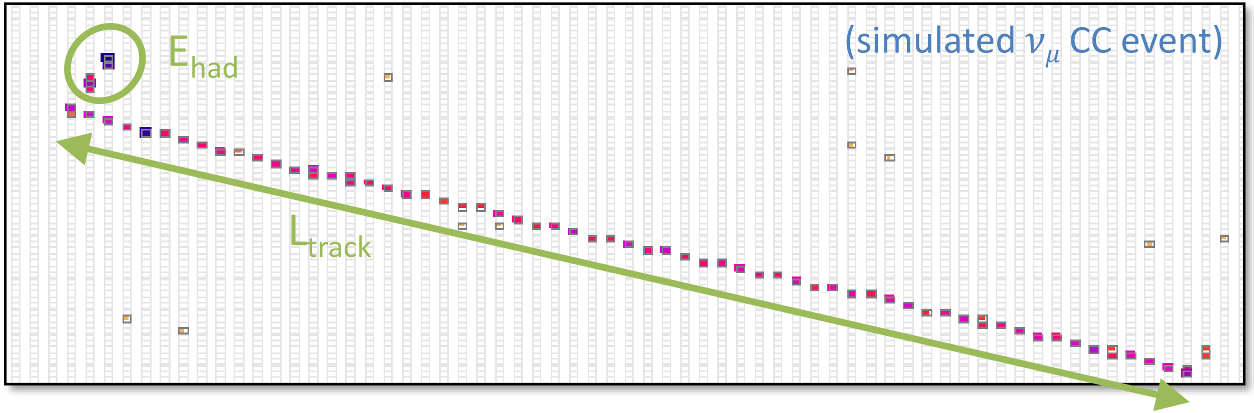
$$E_\nu = E_{EM} + E_{had}$$



- Detector response is different for EM energy and hadronic energy
- To take this into account we separate the EM and hadronic depositions with a CVN variant
- Energies reconstructed calorimetrically

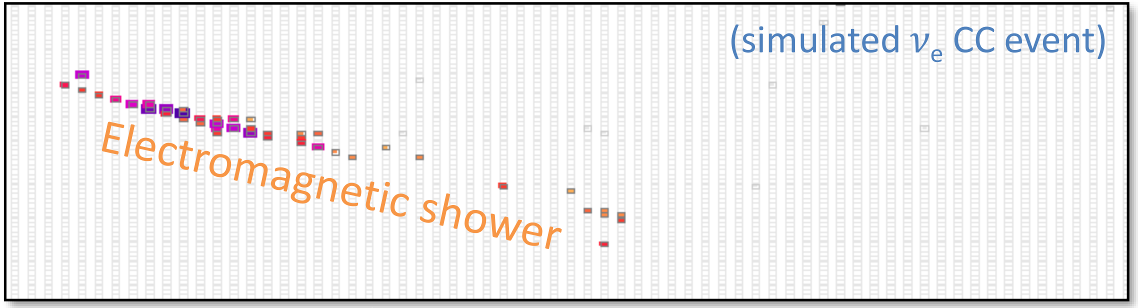
Muon neutrino analysis

1. Identify contained ν_μ CC events in each detector
2. Measure Near and Far energy spectra
3. Extract oscillation information from differences between both energy spectra



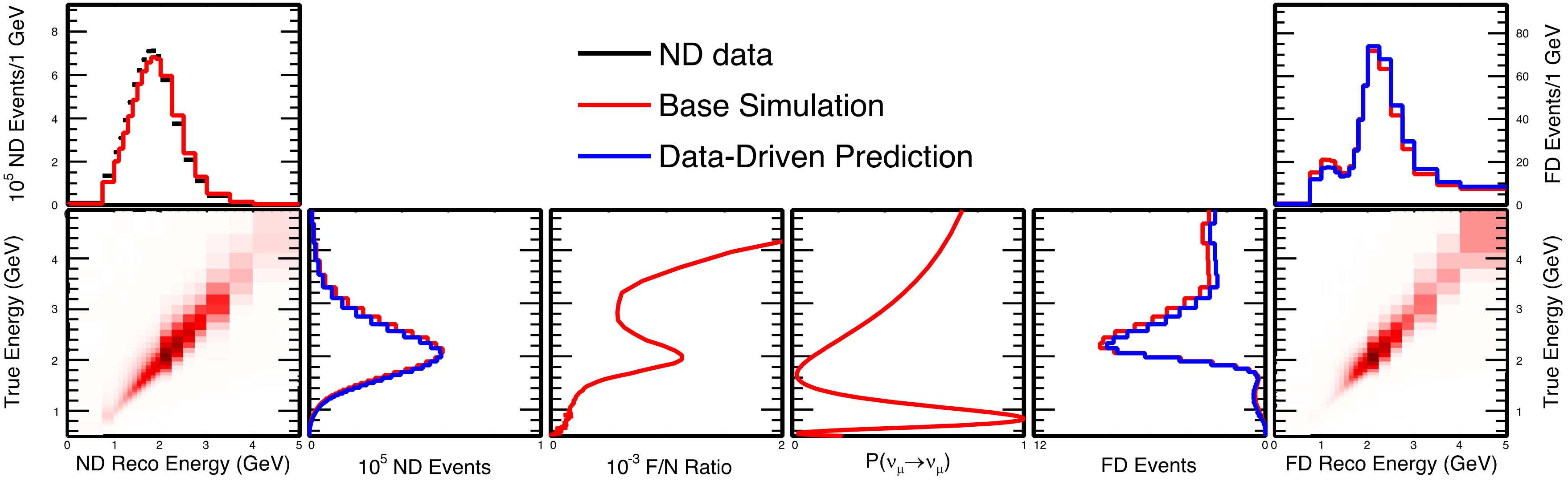
Electron neutrino analysis

1. Identify contained ν_e (ν_μ) CC candidates in each detector.
2. Use data to improve the prediction from the simulation:
   - ND ν_μ candidates → ν_e signal in the FD
   - ND ν_e candidates → FD beam backgrounds
   - FD data outside of the beam time window →FD cosmic ray background
3. Interpret any FD data excess over predicted backgrounds as ν_e appearance

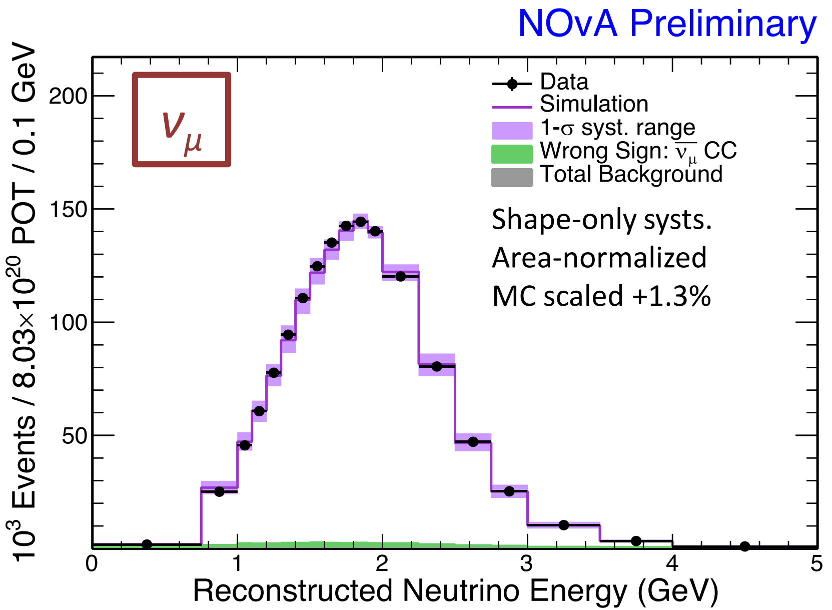


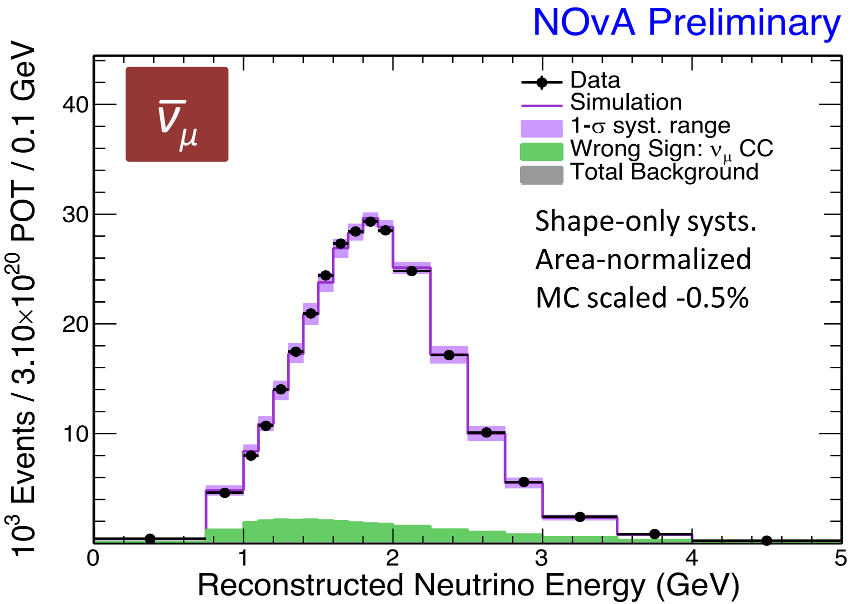
Constraints from ND Data

- Use reco-to-true migration for signal extrapolation
- ν_e backgrounds use the Far/Near ratio in bins of reconstructed energy
- Other (small) beam backgrounds are taken from simulation



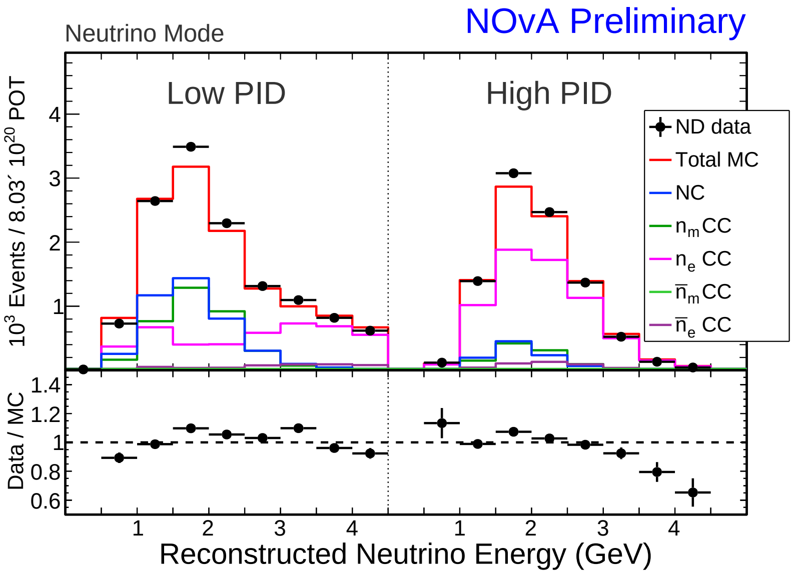
Muon Neutrinos at the ND

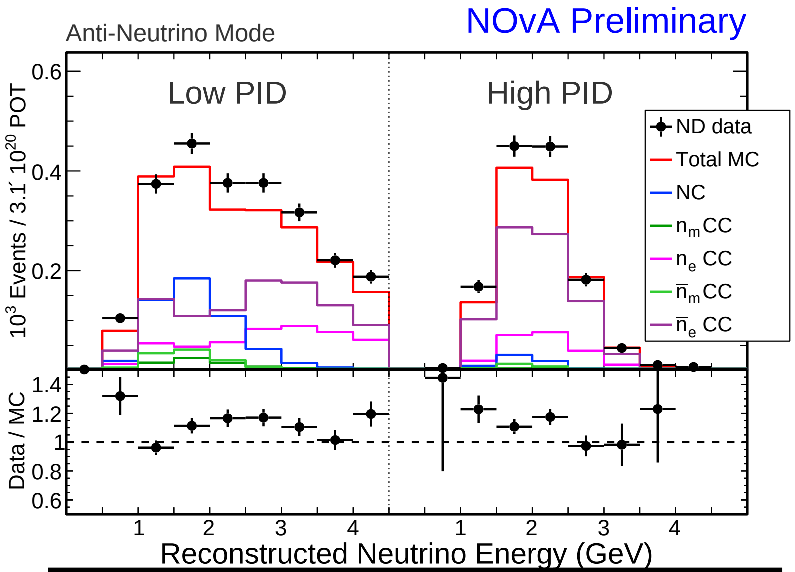




- Selected muon neutrino and antineutrino charged current interactions in ND.
- Used in the signal extrapolation
- Wrong sign contamination is estimated to be 3% (11%) for neutrino (antineutrino) beam.

Electron Neutrinos at the ND

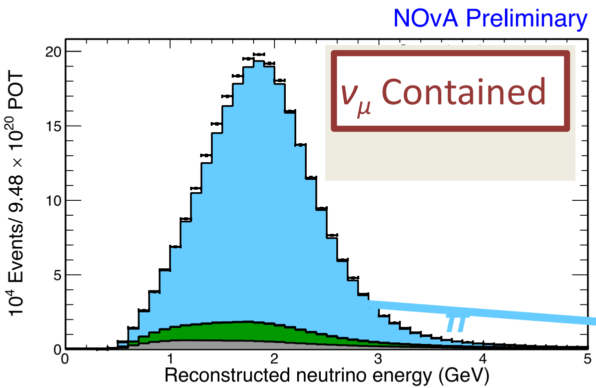


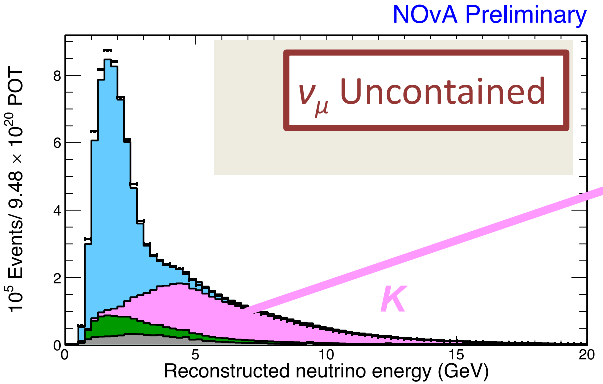


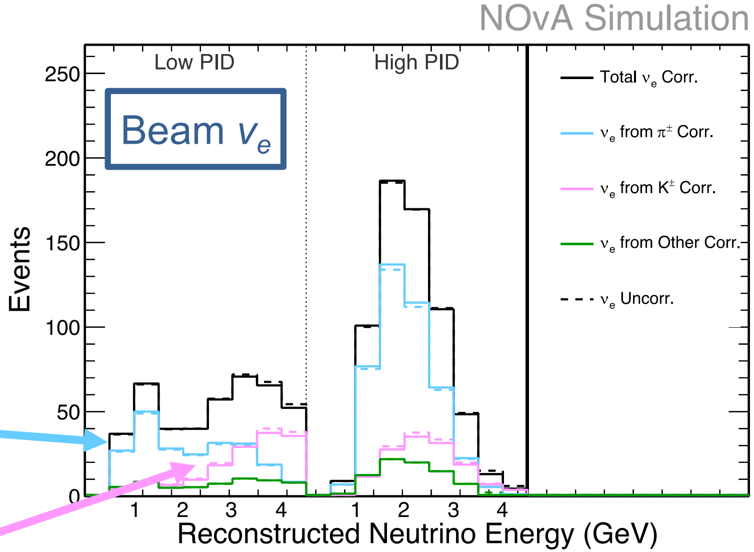
- ND ν_e-like sample has no appearance – all background
- To constrain backgrounds in the neutrino beam we use two data-driven technique
- For the antineutrino beam we scale all components proportionally

	Neutrino	Antineutrino
Beam $\nu_e/\bar{\nu}_e$	55%	76%
NC	24%	17%
CC $\nu_\mu/\bar{\nu}_\mu$	21%	7%

ν_e Decomposition





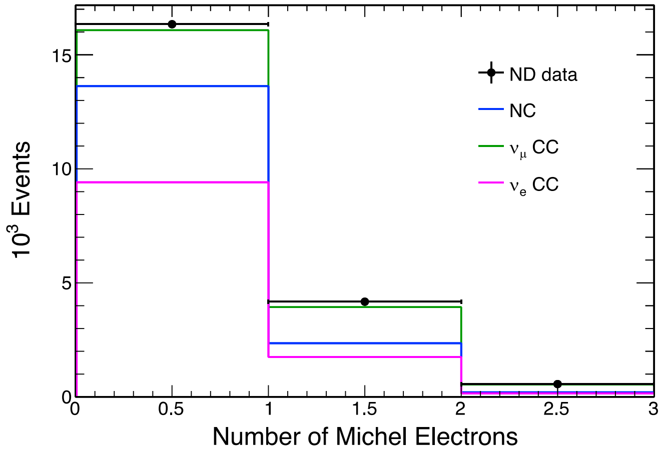


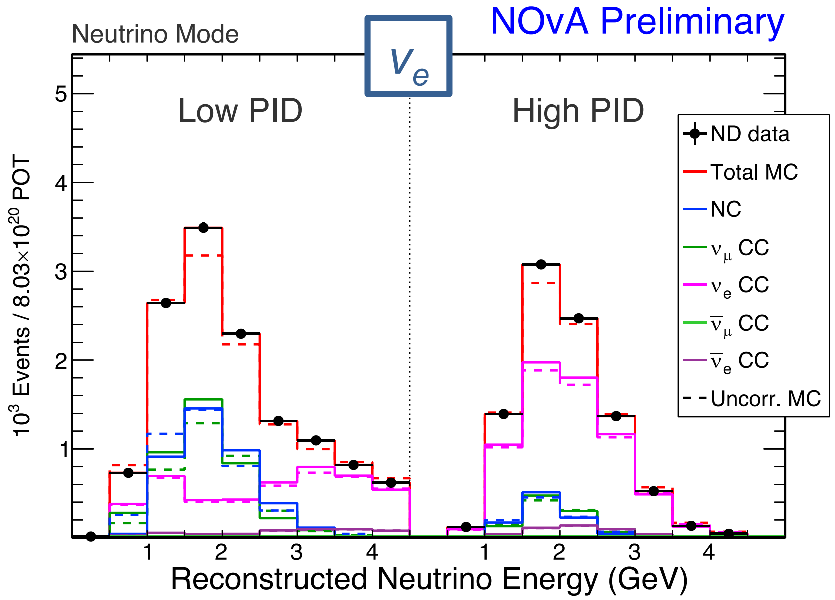
- ν_e and ν_μ events come from the same parents:
  - Lower energy neutrinos come primarily from π decay.
  - Higher energy neutrinos come primarily from K decay.
- Use contained ν_μ data to constrain the **π flux**
- Use higher energy uncontained events to constraint the **K flux**.

ν_e Decomposition

The CC/NC constrained using the number of observed Michel electrons.

- Determine the fraction of the two components in each analysis bin.

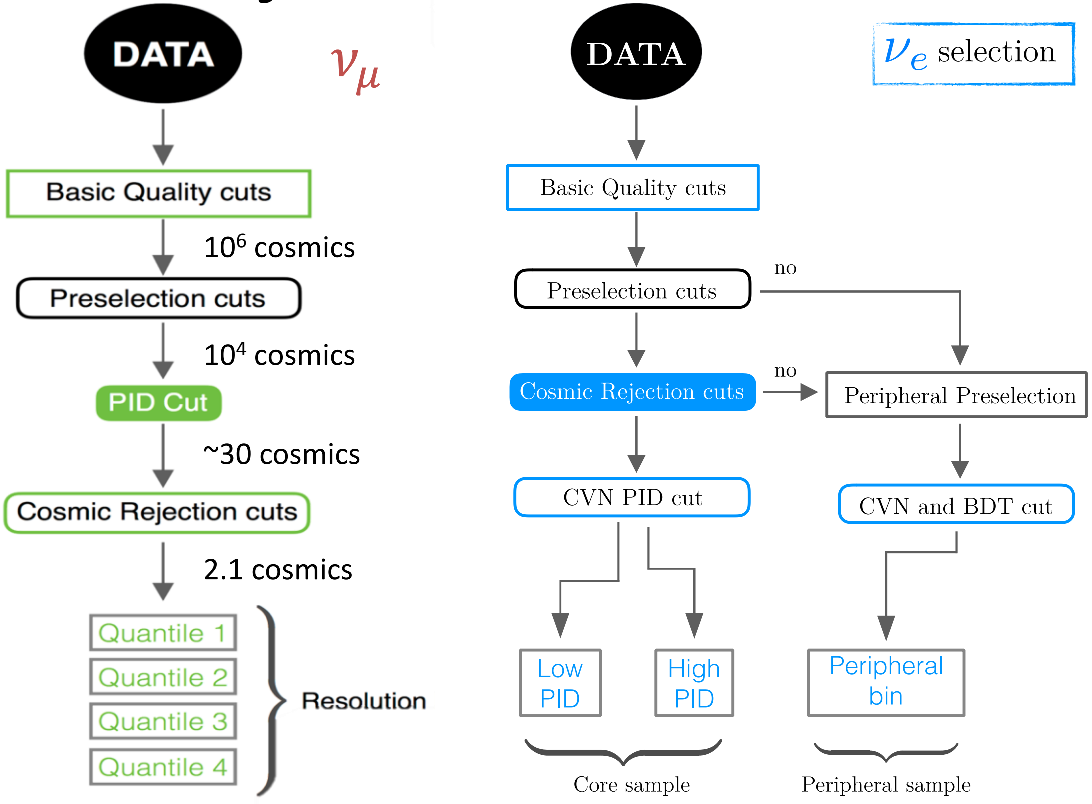




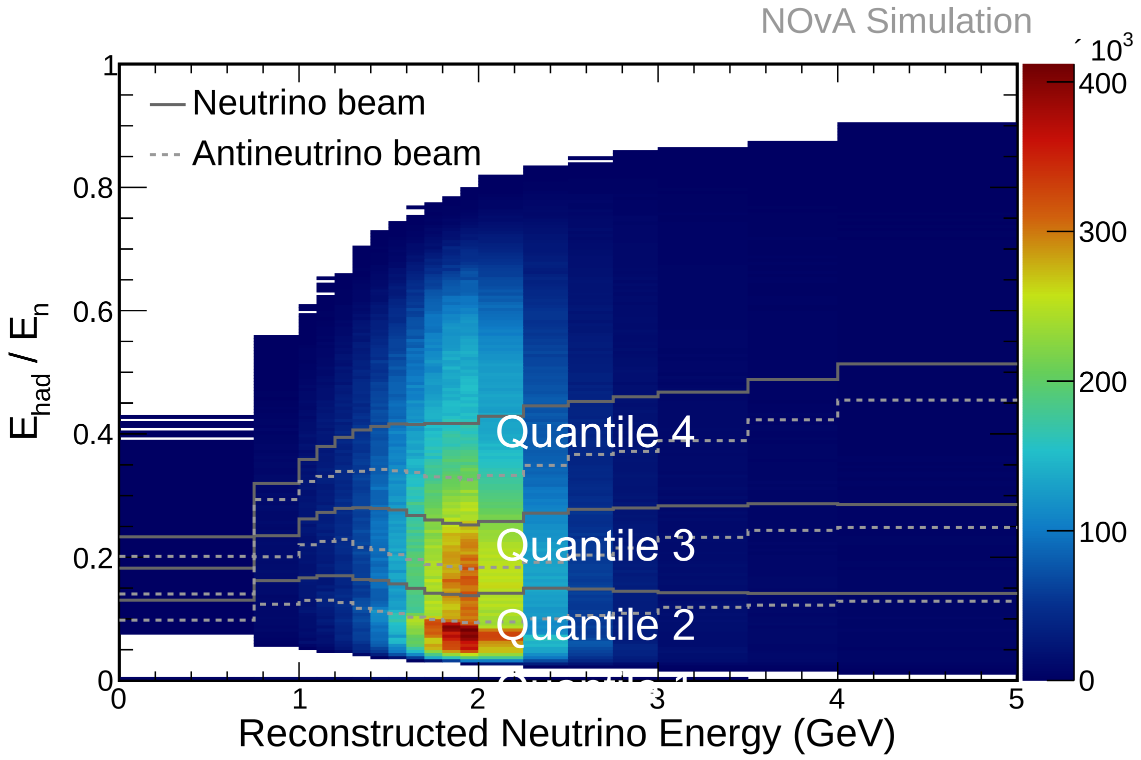
Change in Total	
ν_e CC	+3%
ν_μ CC	+7%
NC	-4%

FD selection and cosmic rejection

- Because the far detector sits on the surface, cosmic backgrounds are a significant issue.
- Even with a pulsed beam and excellent timing resolution, there is still a significant cosmic background.
- Selection steps are tuned to reduce cosmic backgrounds while maintaining sensitivity to oscillations

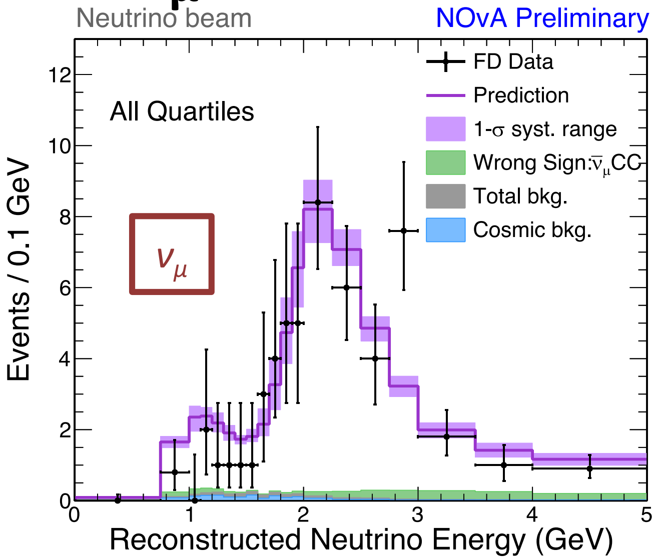


Binning for Sensitivity: ν_μ Events

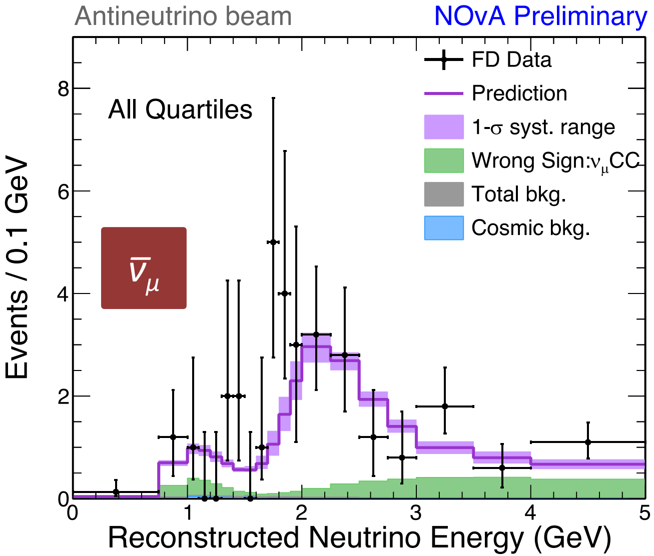


- Oscillation sensitivity depends on spectrum shape
- Improve sensitivity by separating high-resolution and low-resolution events.
- Split into 4 quantiles by hadronic energy fraction.
  - Muon energy resolution (3%) is much better than hadronic energy resolution (30%).

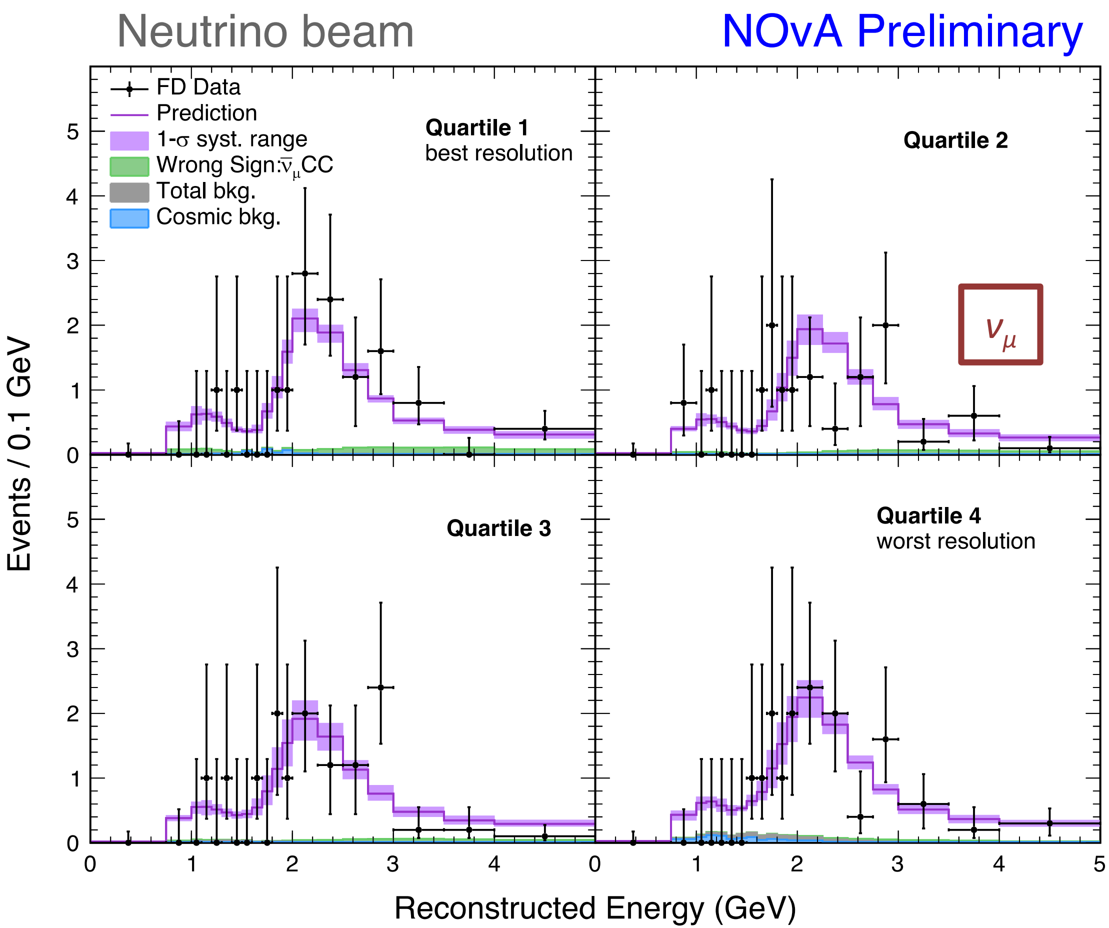
ν_μ and $\bar{\nu}_\mu$ data at the Far Detector

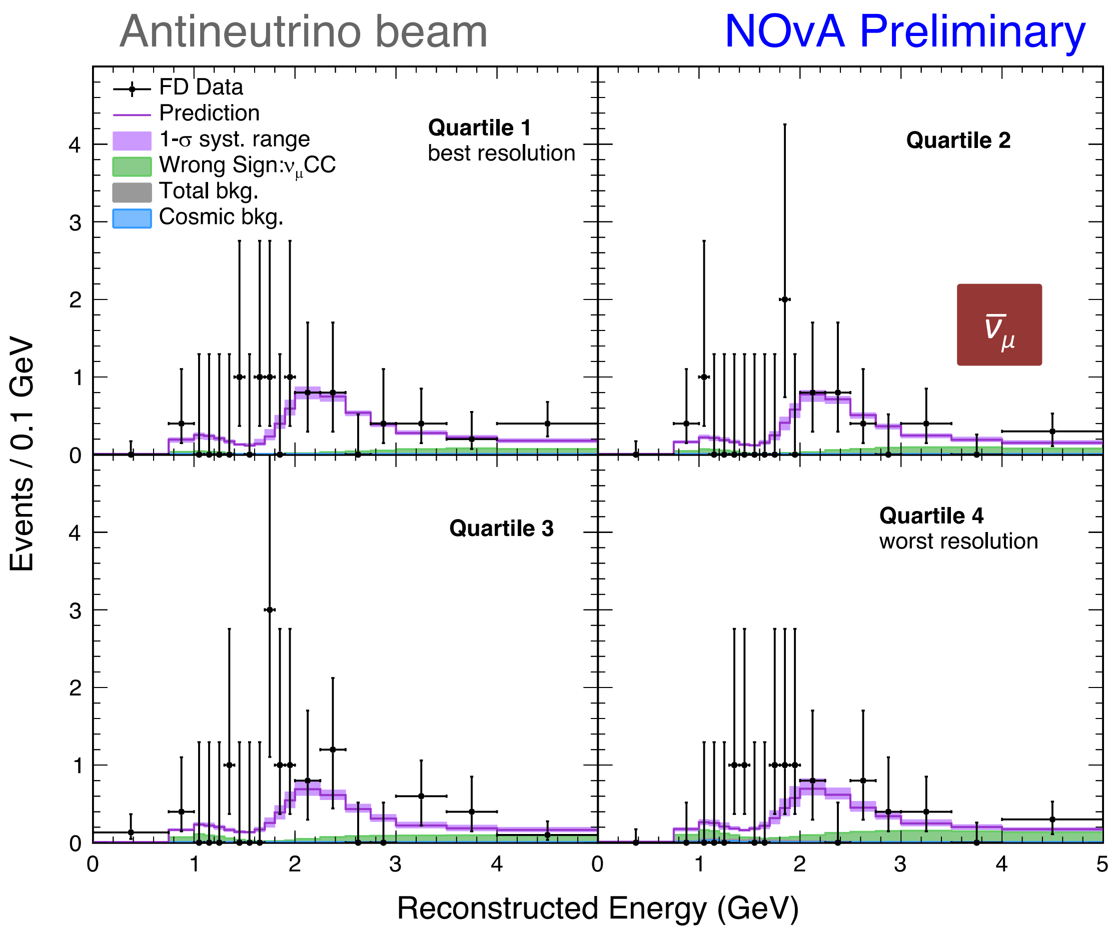


Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730



Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266


Neutrino beam
NOvA Preliminary
FD Data
Prediction
1-σ syst. range
Wrong Sign: $\bar{\nu}_\mu$CC
Total bkg.
Cosmic bkg.
Quartile 1
best resolution
Quartile 2
Quartile 3
Quartile 4
worst resolution
ν_μ
Events / 0.1 GeV
Reconstructed Energy (GeV)


Antineutrino beam
NOvA Preliminary
FD Data
Prediction
1-σ syst. range
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Total bkg.
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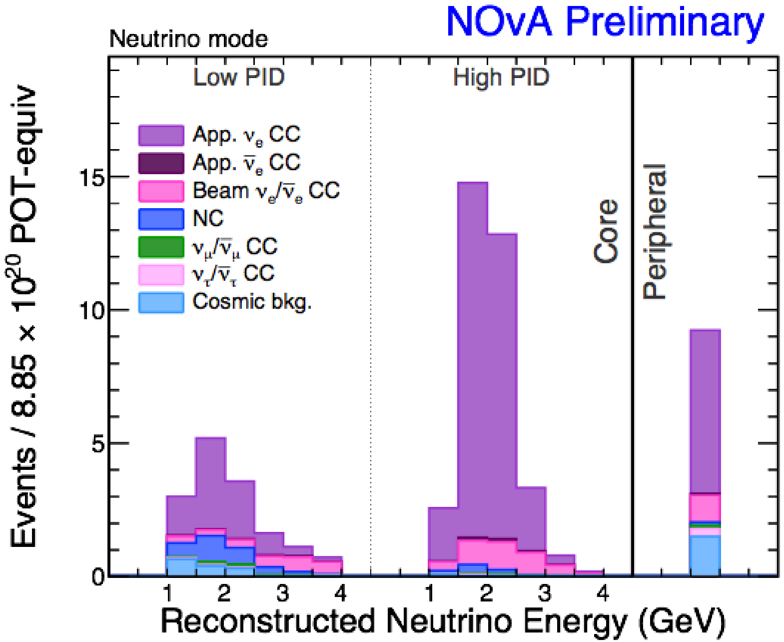
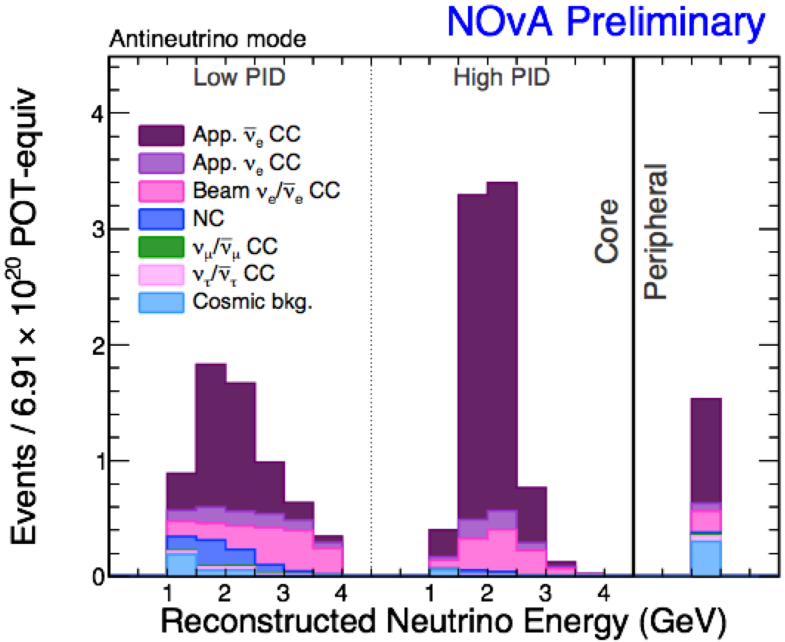
Events / 0.1 GeV
Reconstructed Energy (GeV)

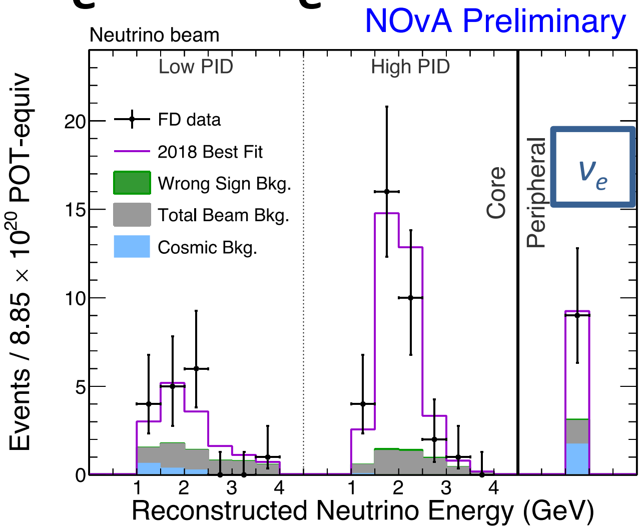
Binning for Sensitivity: ν_e Events

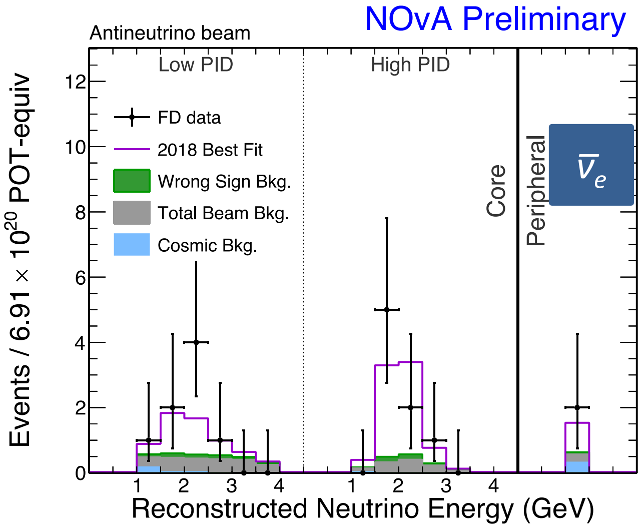




- Oscillation sensitivity depends on separating ν_e signal from background
- PID binning separates sample by purity
- Energy binning separates appeared ν_e from beam ν_e

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



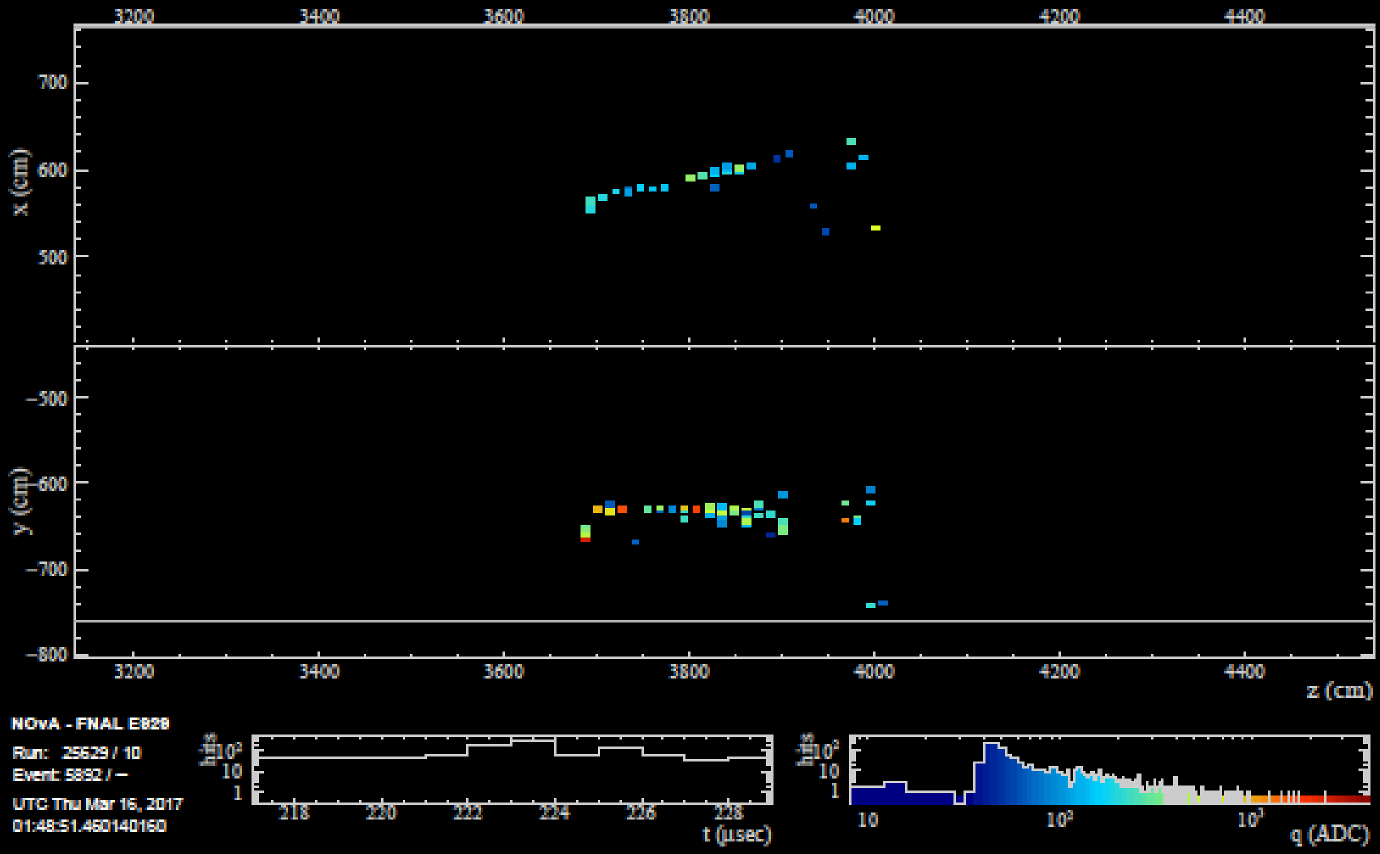


Strong (>4σ) evidence of $\bar{\nu}_e$ appearance

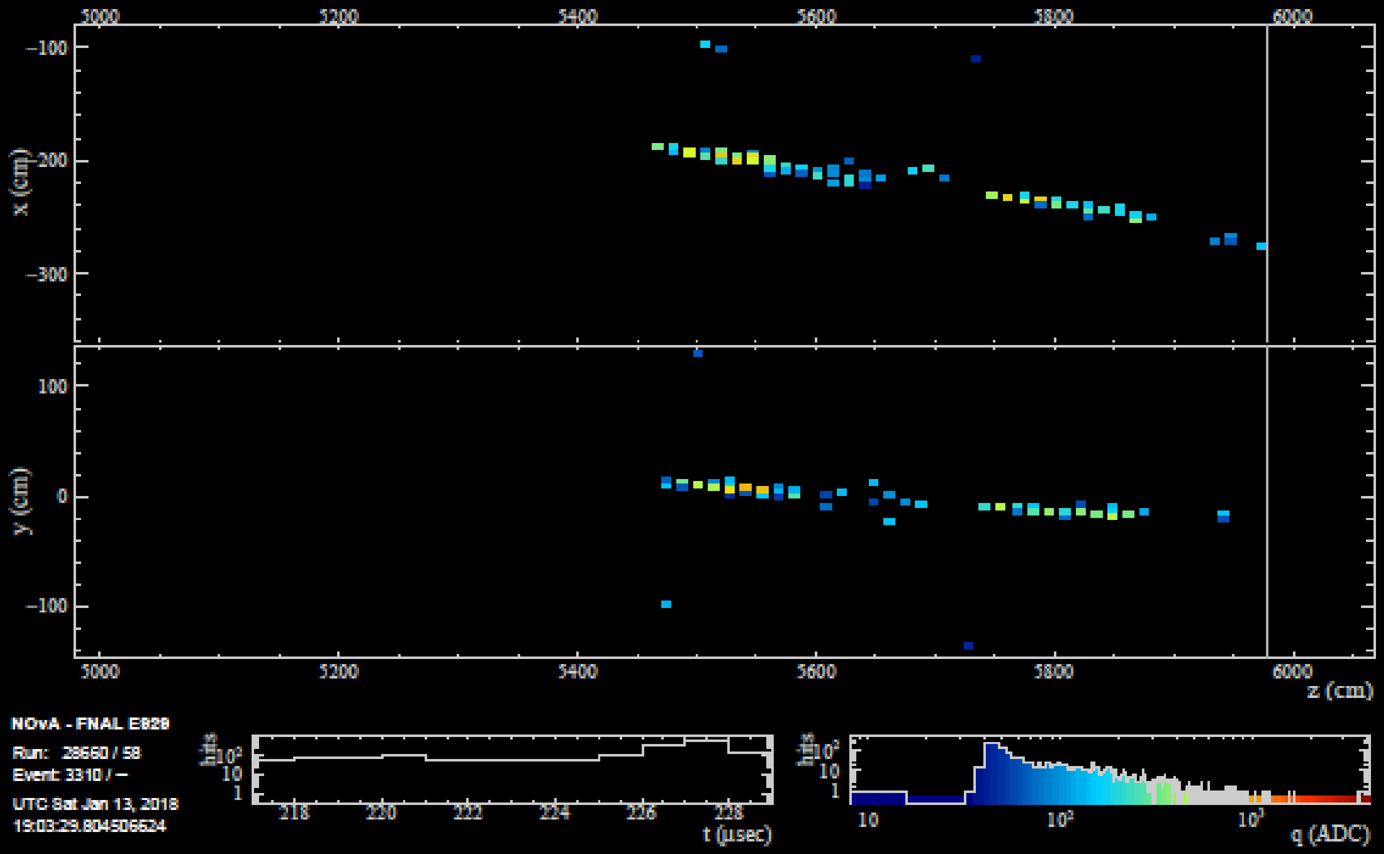
Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

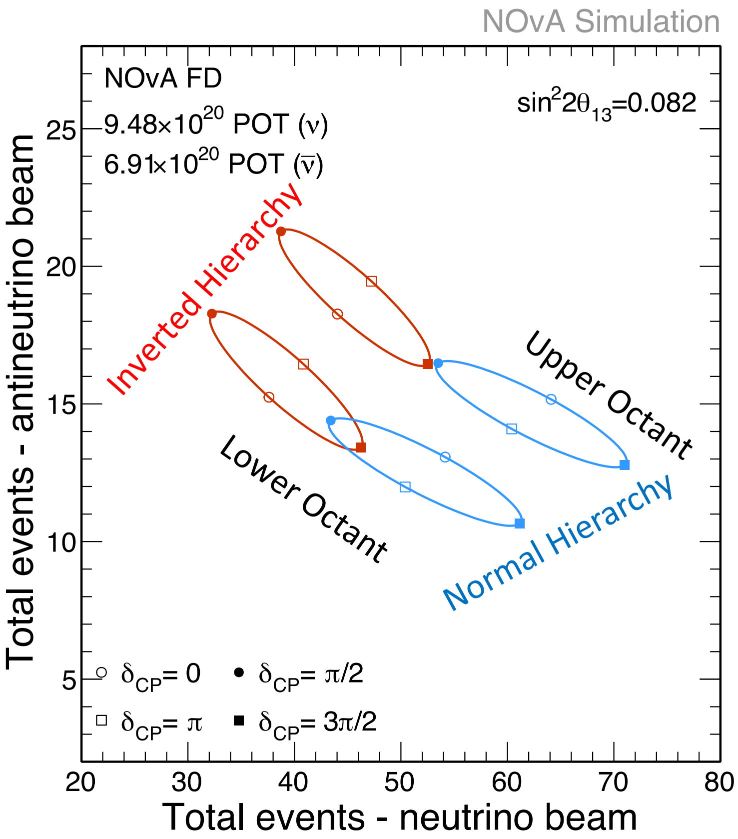
Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

Core Event – High CVN Bin



Peripheral Event

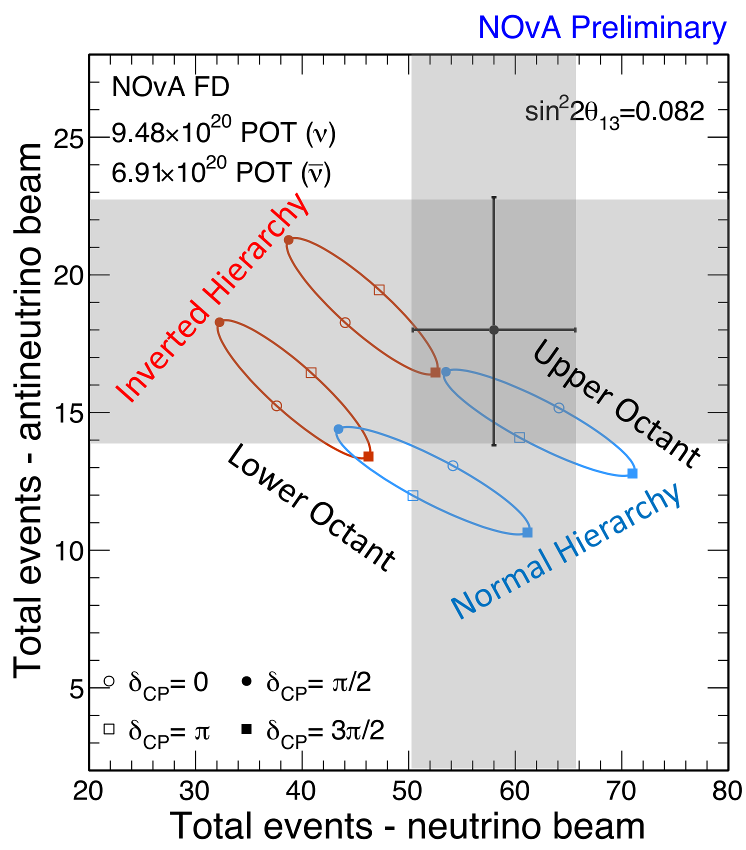




10-22 Expected for $\overline{\nu}_e$

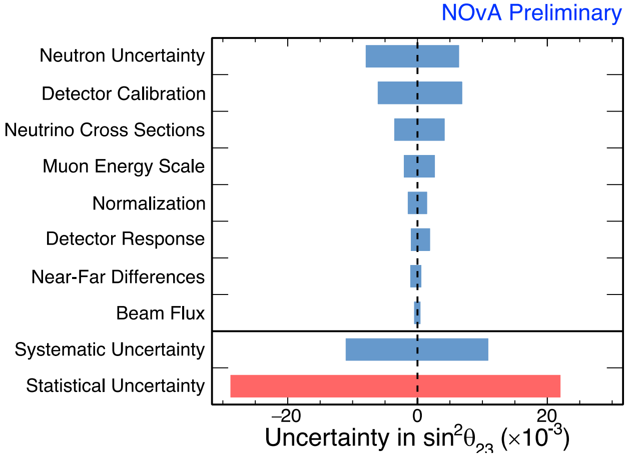
30-75 Expected for ν_e

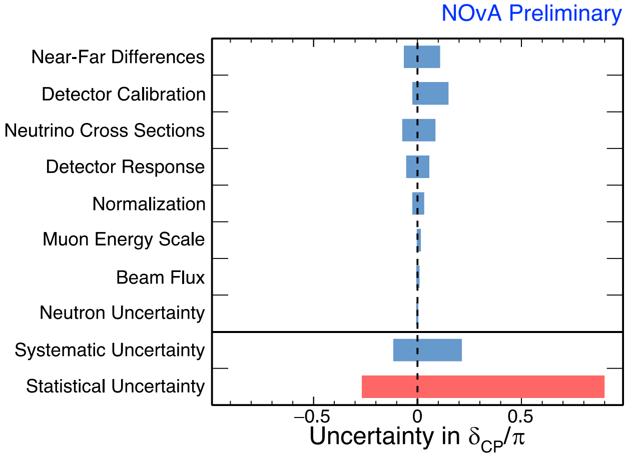
18 observed $\bar{\nu}_e$

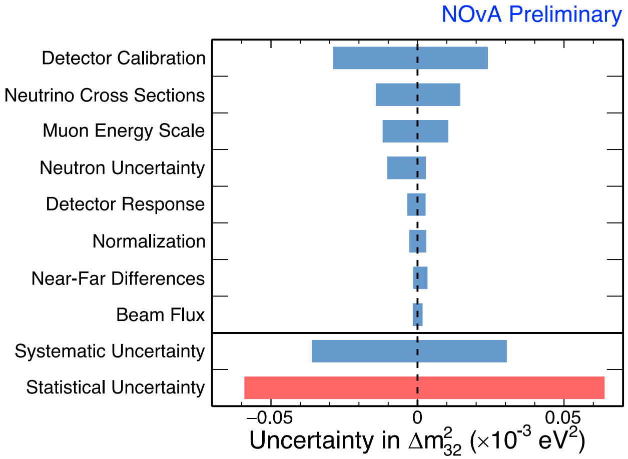


58 observed ν_e

Systematic Uncertainties

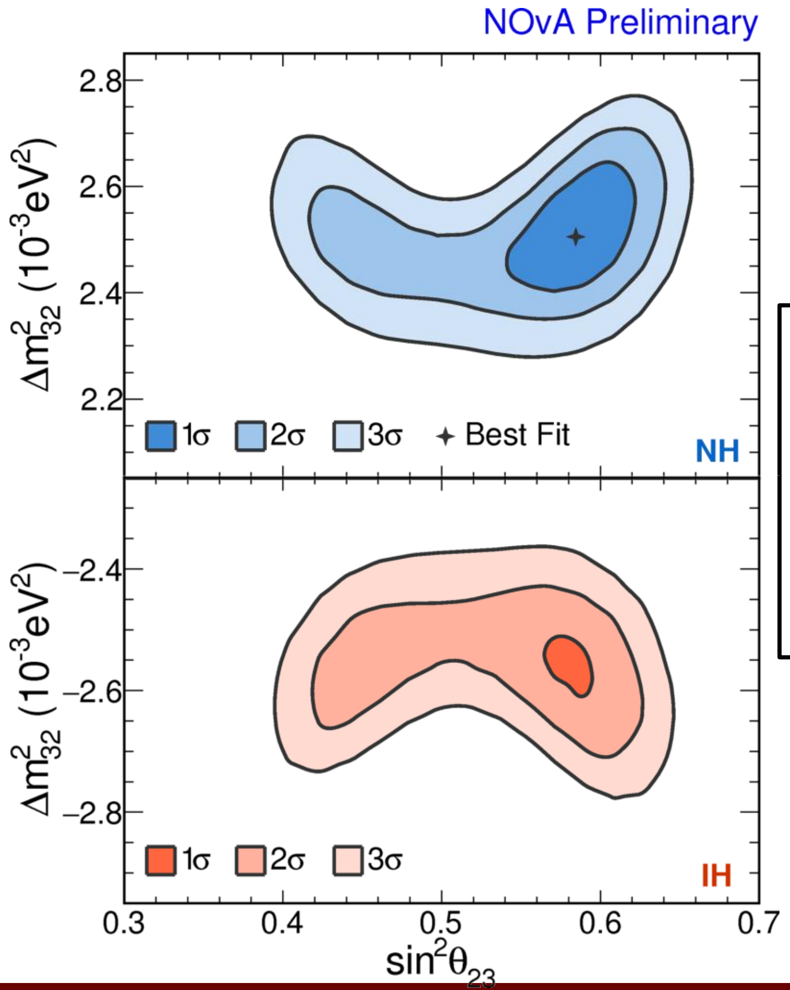






Most important systematics:

- Detector Calibration - Will be improved by the test beam program
- Neutrino cross sections - Particularly nuclear effects (RPA, MEC)
- Muon energy scale
- Neutron uncertainty – **new** with $\bar{\nu}$'s



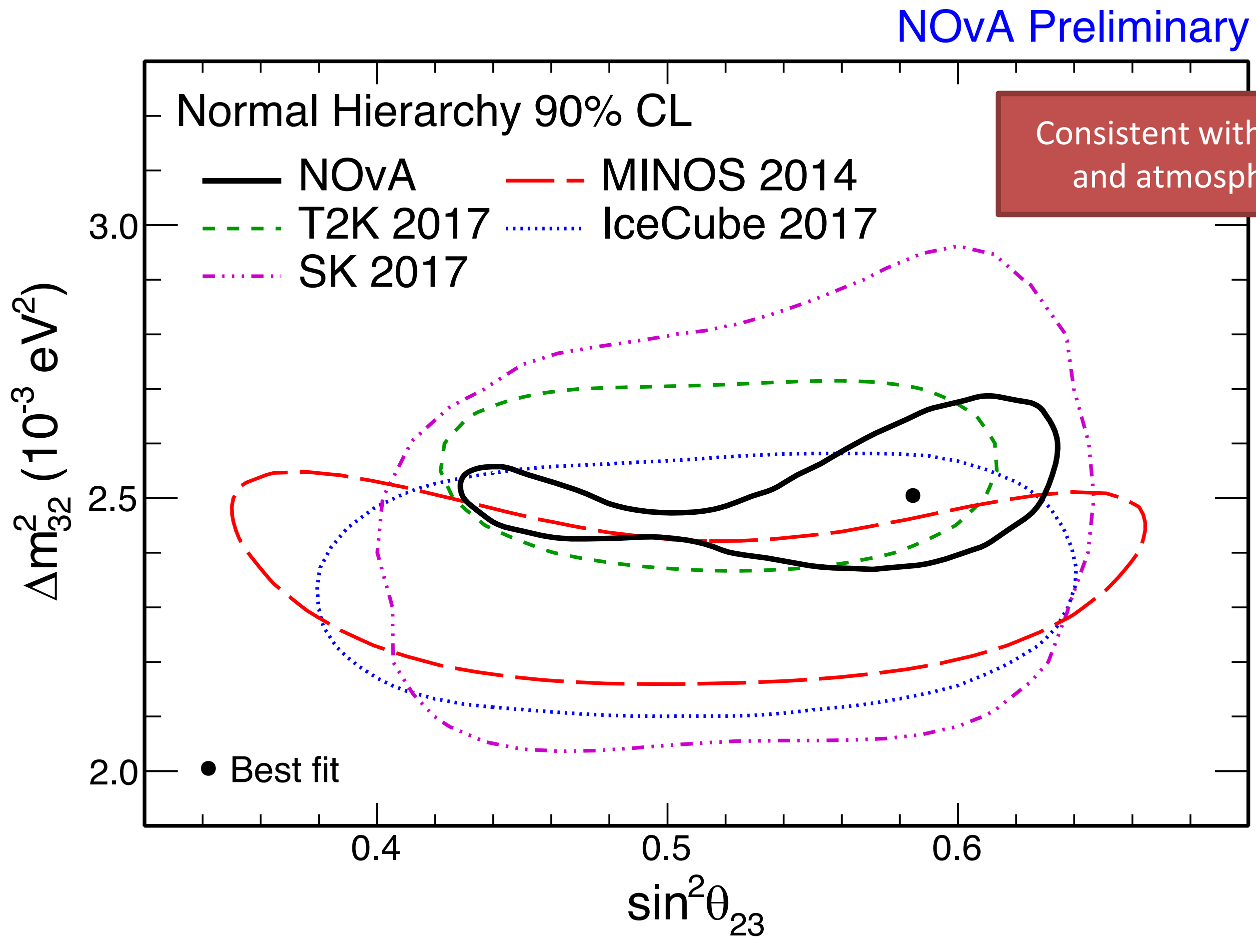
Best Fit

Normal hierarchy

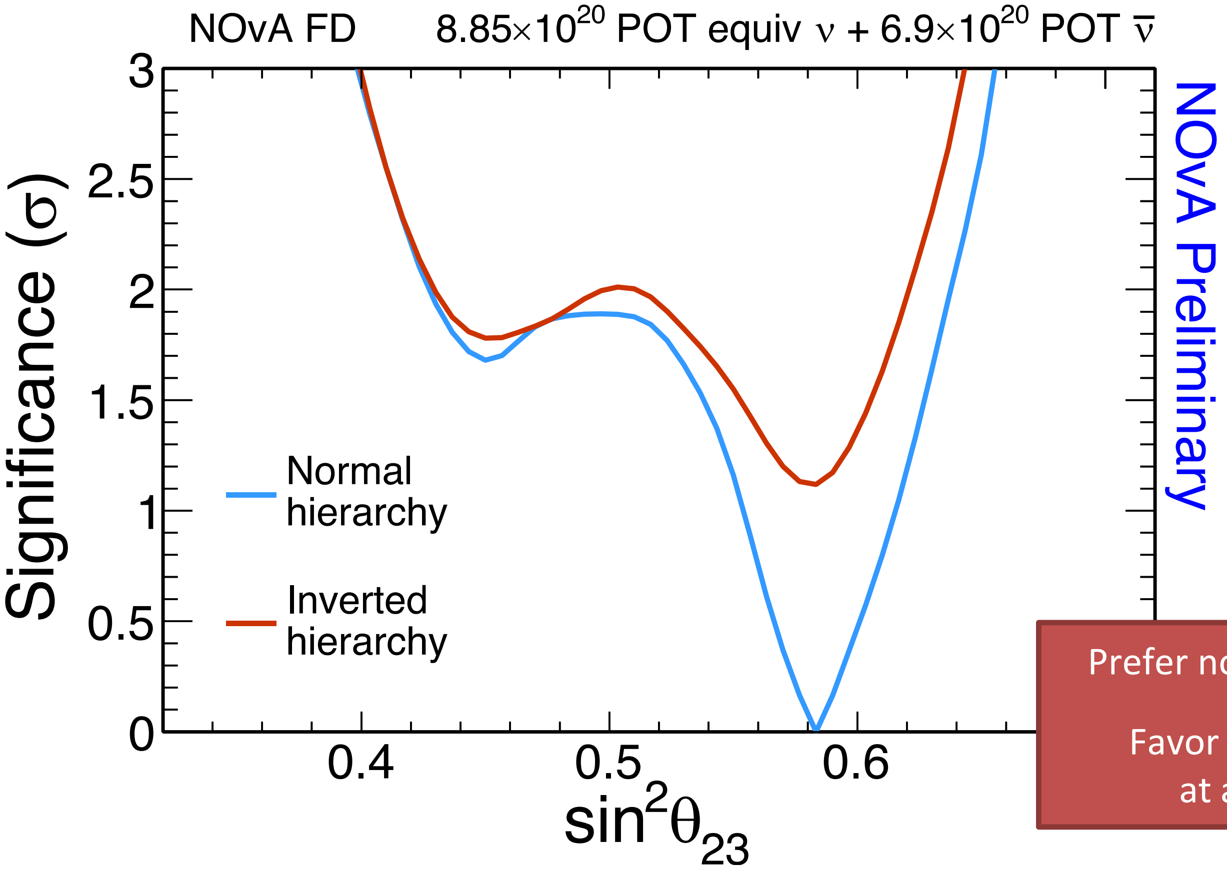
Upper Octant

$\Delta m^2 = (2.51^{+0.12}_{-0.08})\times10^{-3}$ eV^2

$\sin^2\vartheta_{23} = 0.58 \pm 0.03$



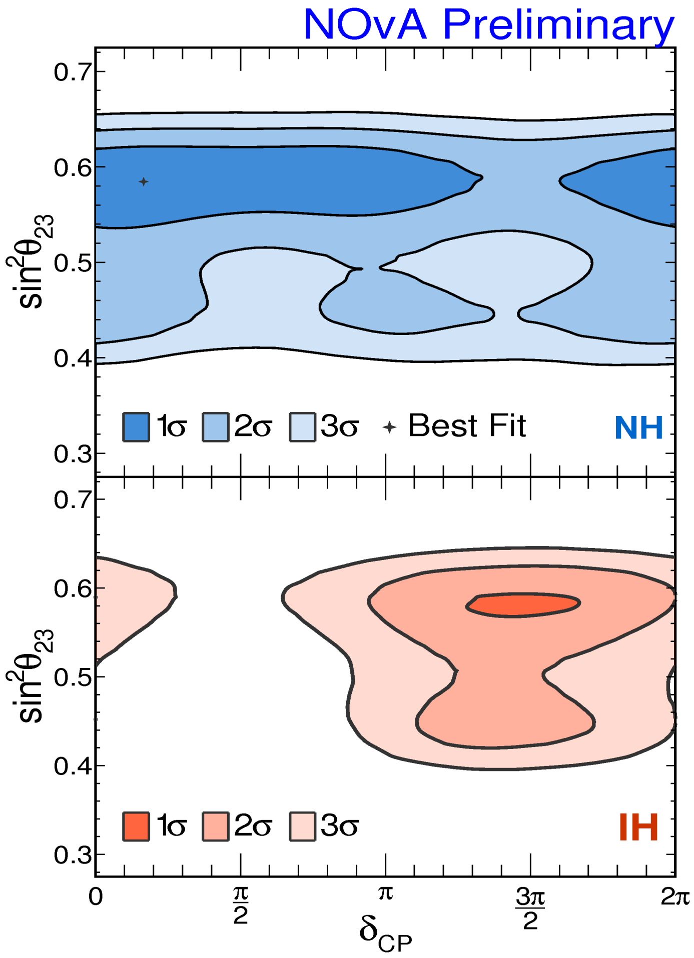
Consistent with other long-baseline and atmospheric experiments.



Prefer non-maximal at **1.8σ**.

Favor the upper octant at a similar level.

Exclude IH, $\delta=\pi/2$ at > 3σ



Best Fit

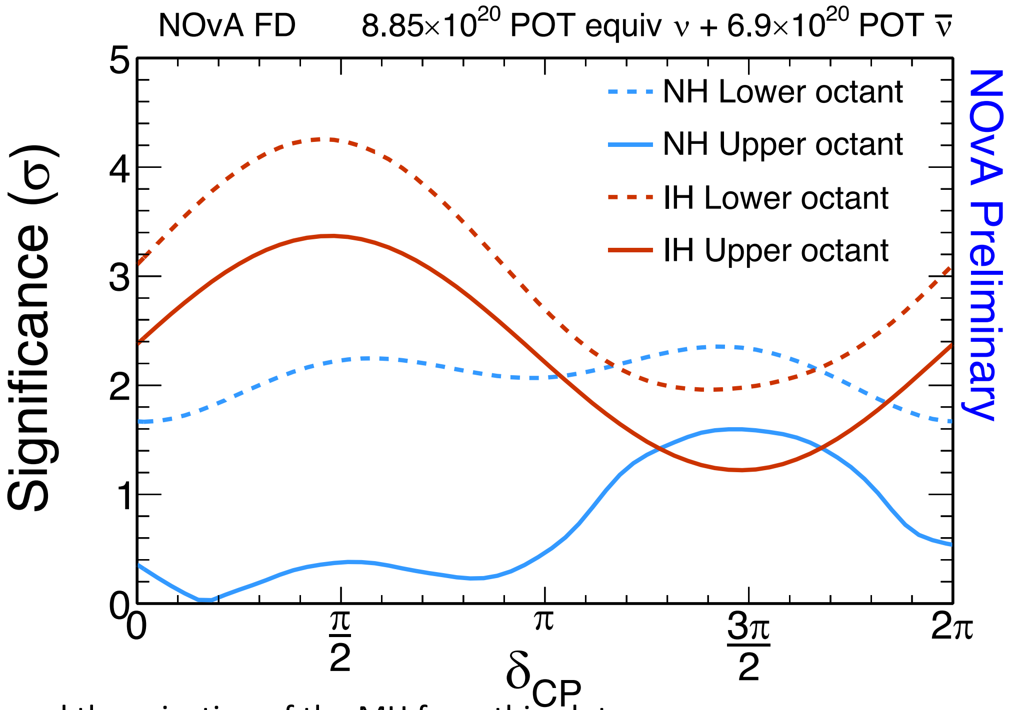
Normal hierarchy

Upper Octant

$\Delta m^2 = (2.51^{+0.12}_{-0.08})\times10^{-3}\ \mathrm{eV}^2$

$\sin^2\vartheta_{23} = 0.58 \pm 0.03$

$\delta = 0.17\pi$

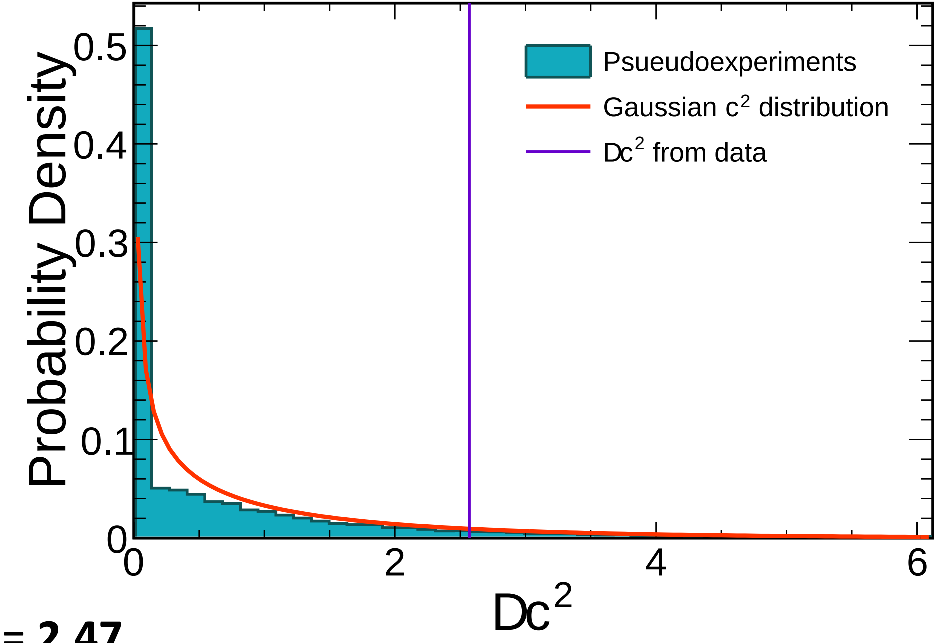


Consistent with all δ_{CP} values in NH at < 1.6σ.

- Note: you cannot read the rejection of the MH from this plot.
  - This is an FC-corrected plot of significance for rejecting particular sets of values (δ, octant, hierarchy).
  - It is *not* a likelihood surface, so it cannot be profiled to remove δ and the octant.
- Additionally, the MH itself is highly non-Gaussian so we need to use FC.
  - A binary choice with degenerate, unknown parameters.

Mass Hierarchy Preference

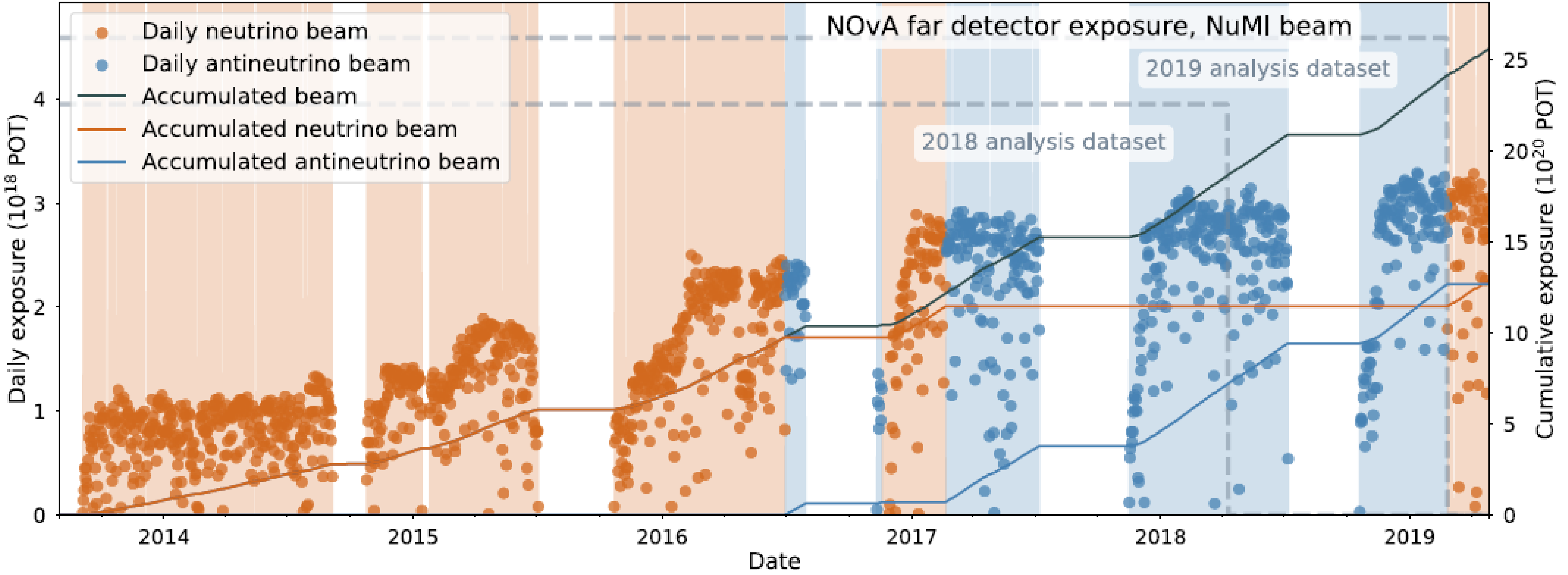
NOvA Preliminary



- χ^2(IH) - χ^2(NH)= **2.47**
- giving a *p*-value of **0.076** from the FC empirical χ^2.
- or equivalently **1.8σ**

The Future

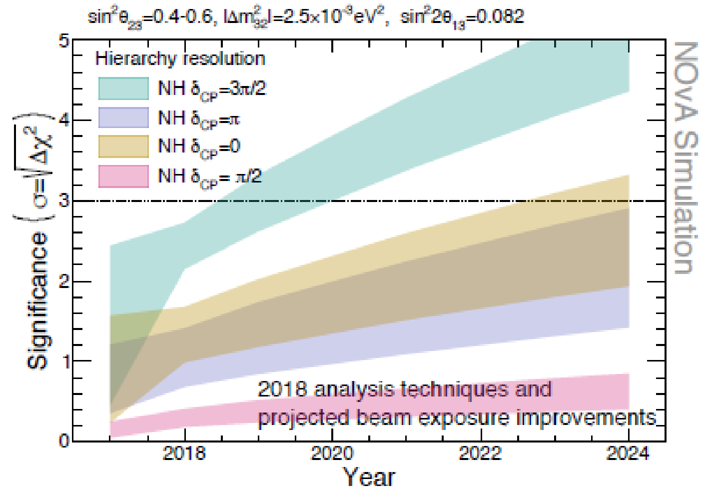
NOvA prospects - 2019

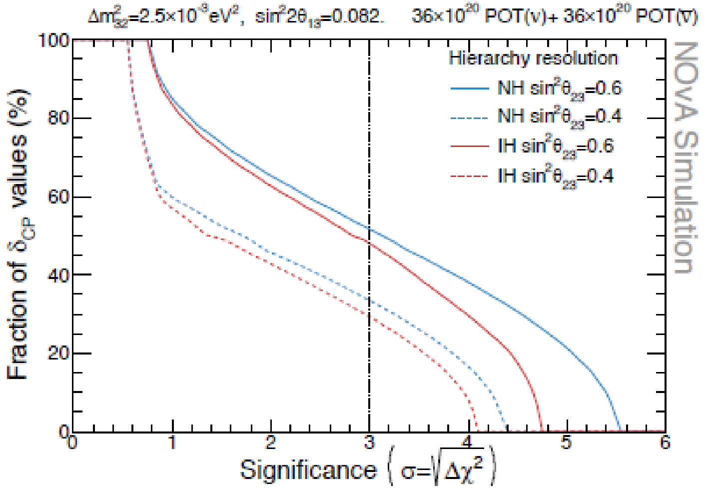


Update with ~80% more antineutrino data right around the corner!

NOvA prospects

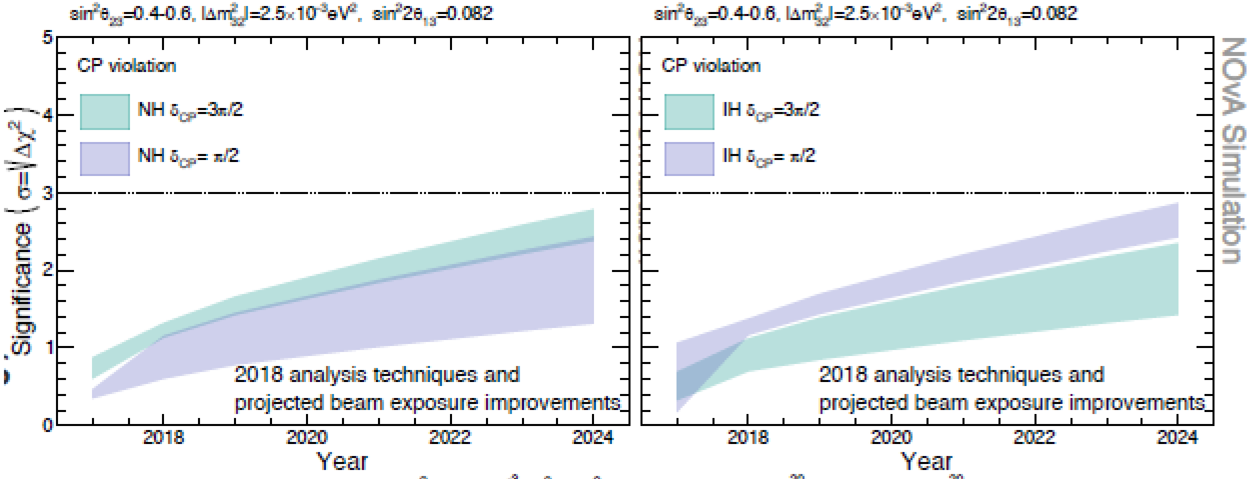
- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach.
- 3 σ sensitivity to hierarchy (if NH and $\delta_{CP}=3\pi/2$) for allowed range of θ_{23} by 2020. 3 σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.

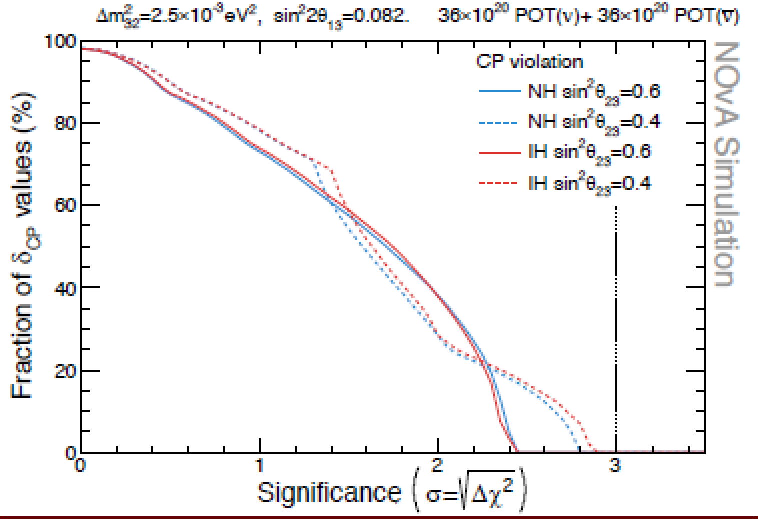




NOvA prospects

- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach.
- 2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024.



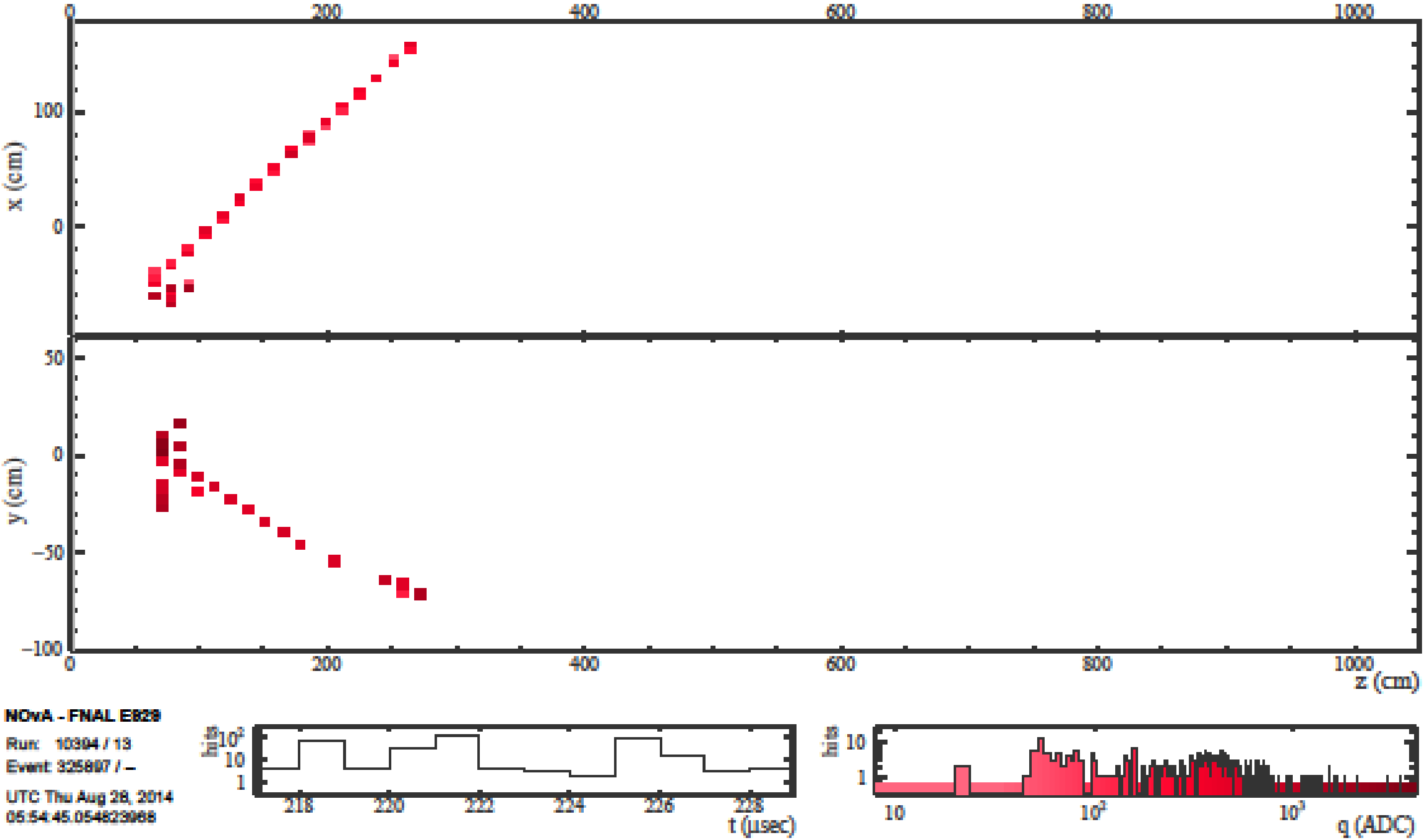


Summary and Outlook

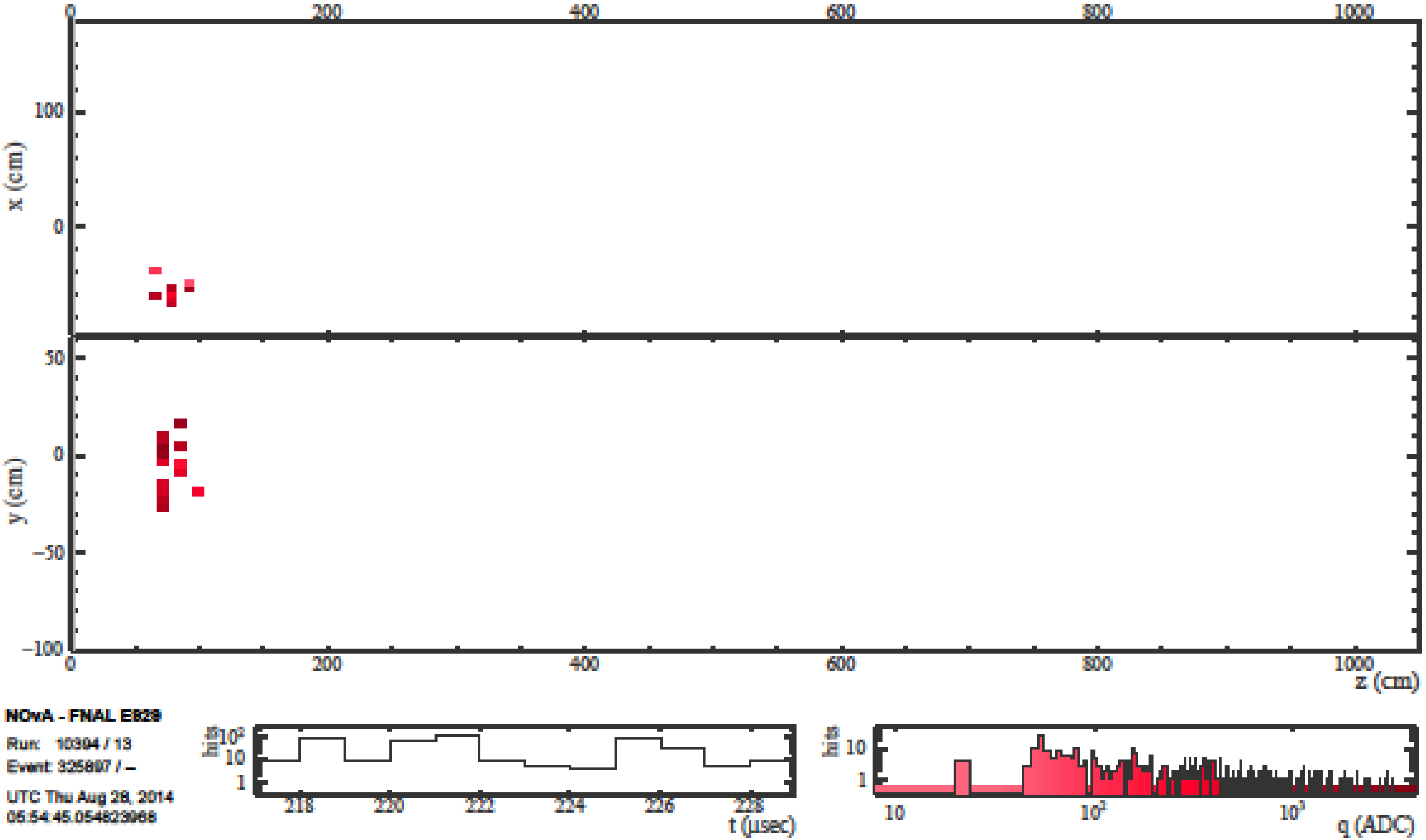
- First NOvA anti-neutrino data (6.9e20 POT) has been analyzed together with 8.85e20 POT of neutrino data
  - Update with 80% more antineutrino data coming soon!
- We observe >4 σ evidence of electron anti-neutrino appearance
  - Achieved in our **first** antineutrino result thanks to outstanding beam performance and support from Fermilab
- A joint appearance and disappearance analysis for these data:
  - Prefers Normal Hierarchy at 1.8 σ and excludes at $\delta_{CP} = \pi/2$ at > 3 σ
  - Disfavors maximal mixing at 1.8 σ and the lower octant at a similar level
- Future NOvA running can reach 3 σ sensitivity for the mass hierarchy by 2020 and covers significant CP range by 2024.
  - Thanks to extended running, accelerator improvements, and analysis improvements thanks to the test beam.

Backups

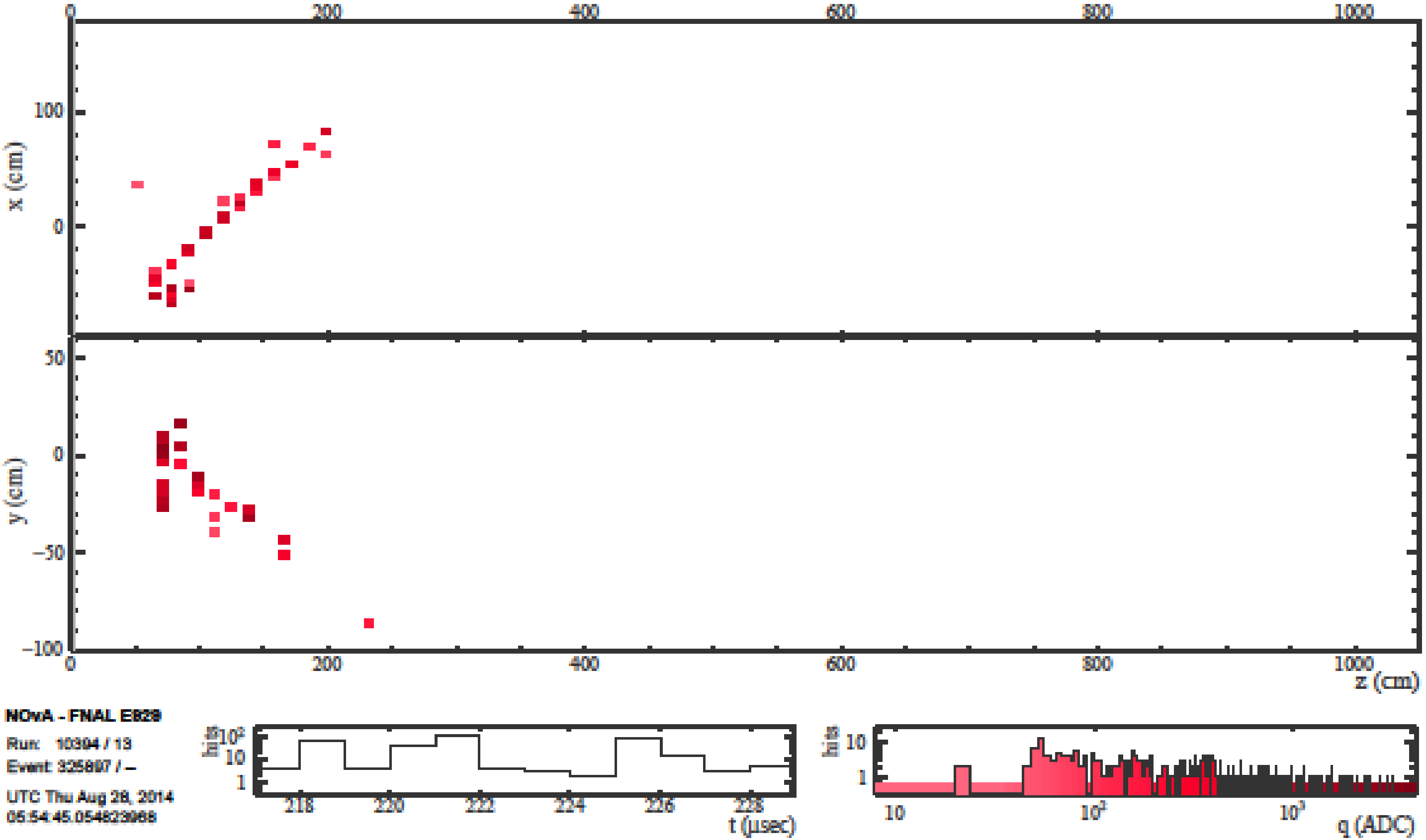
Cross-check: Muon Removed Events



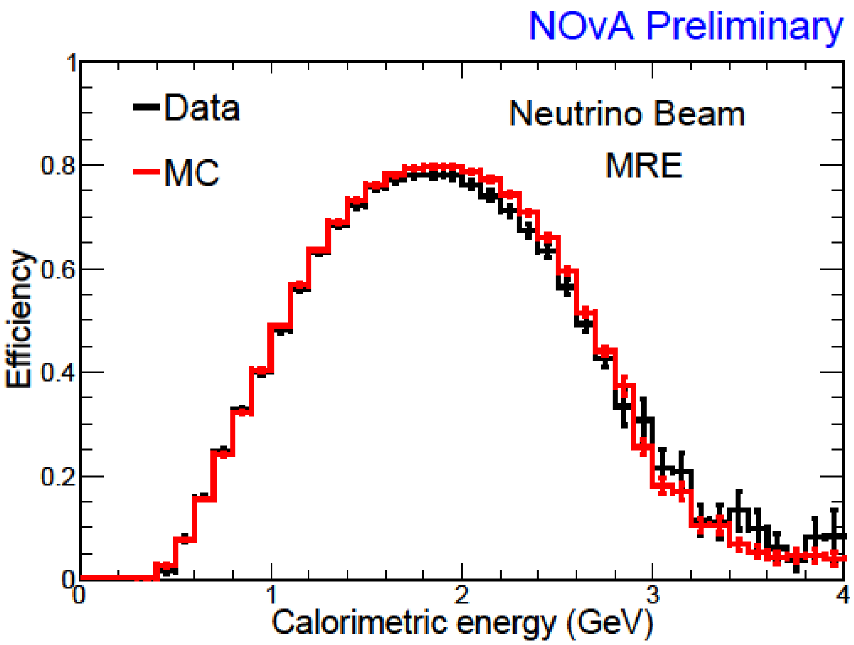
Cross-check: Muon Removed Events

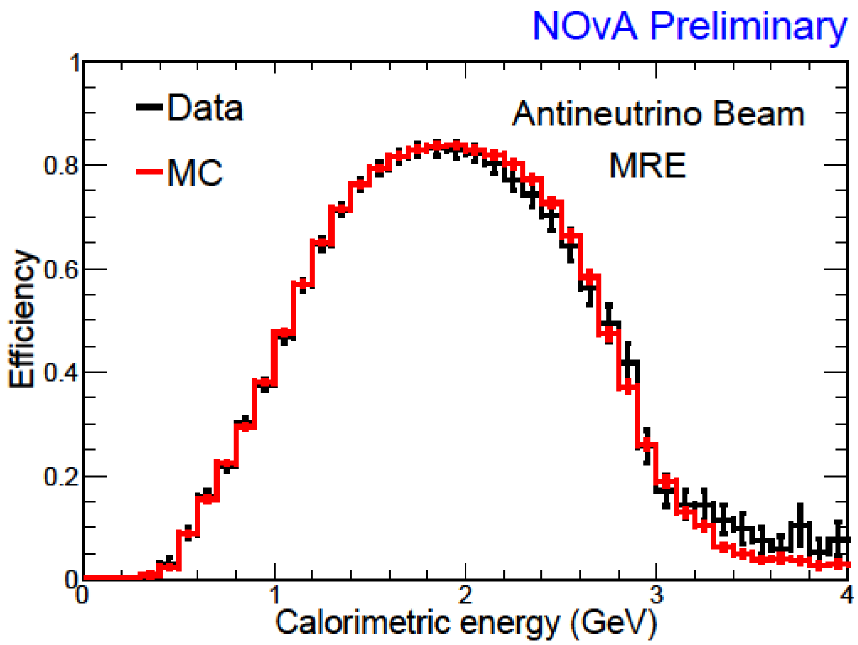


Cross-check: Muon Removed Events

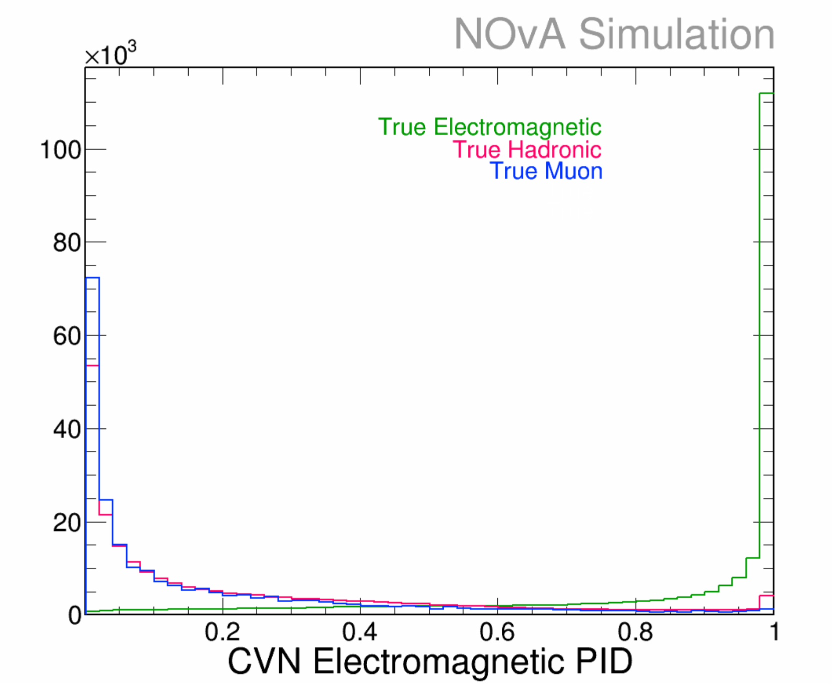


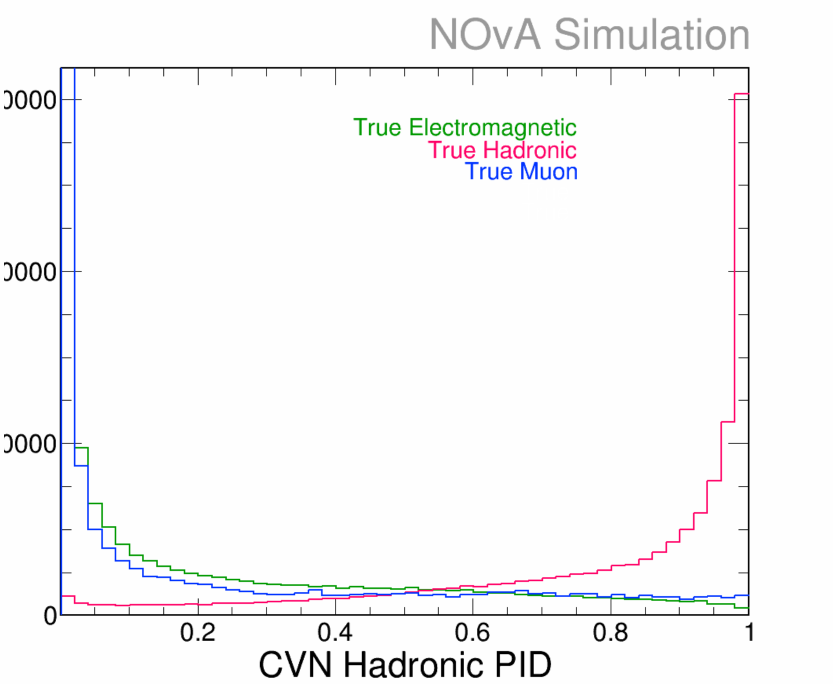
Cross-check: Muon Removed Events





Particle Identification

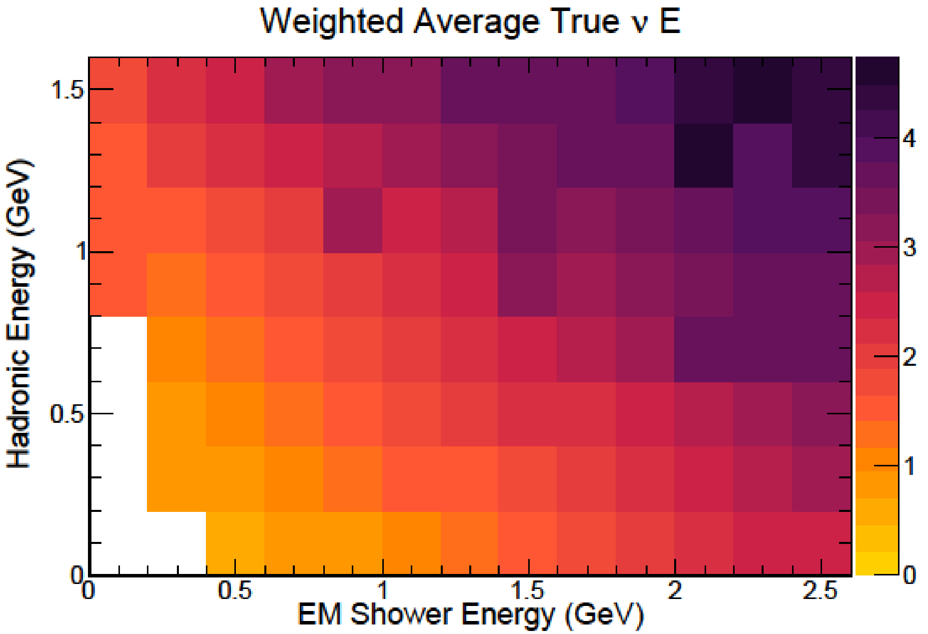




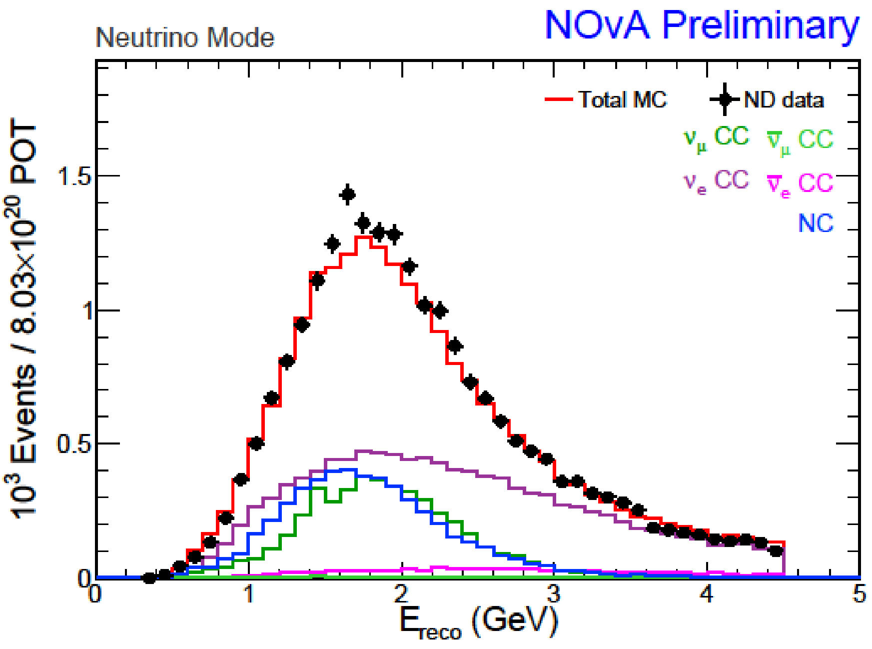
Energy Estimation - ν_e

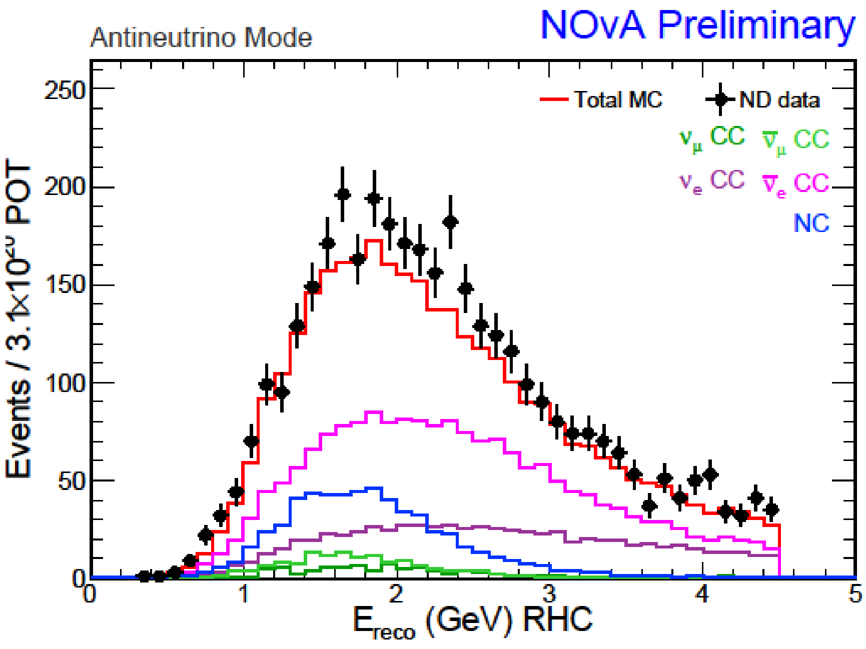
- Electromagnetic energy is the summed calorimetric energy for CVN-selected showers.
- Hadronic energy is the total calorimetric energy minus EM shower energy.
- Neutrino energy is calculated as the following:

$$E_{\nu e} = A*E_{EM} + B*E_{HAD} + C*E_{EM}^2 + D*E_{HAD}^2$$

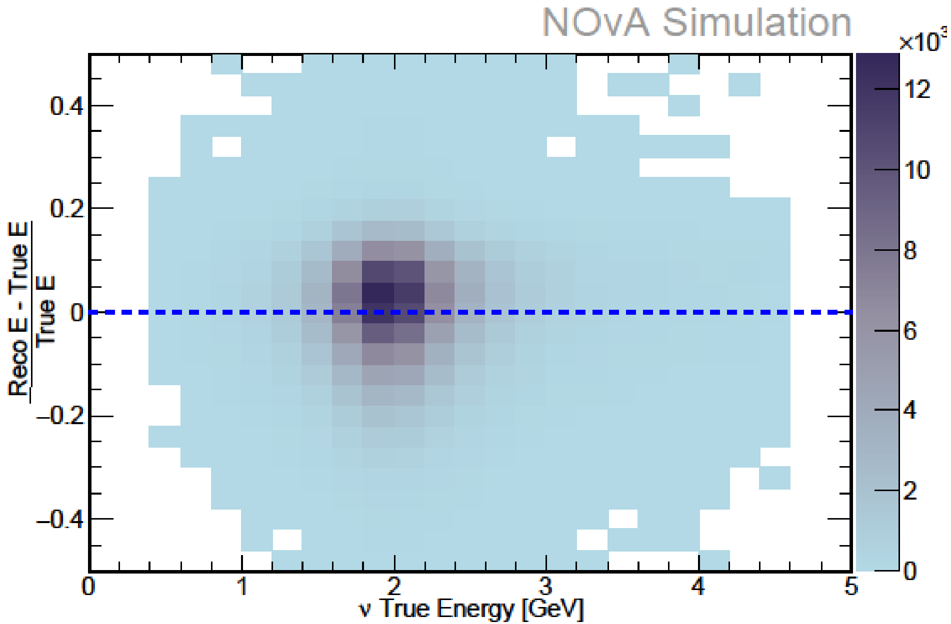


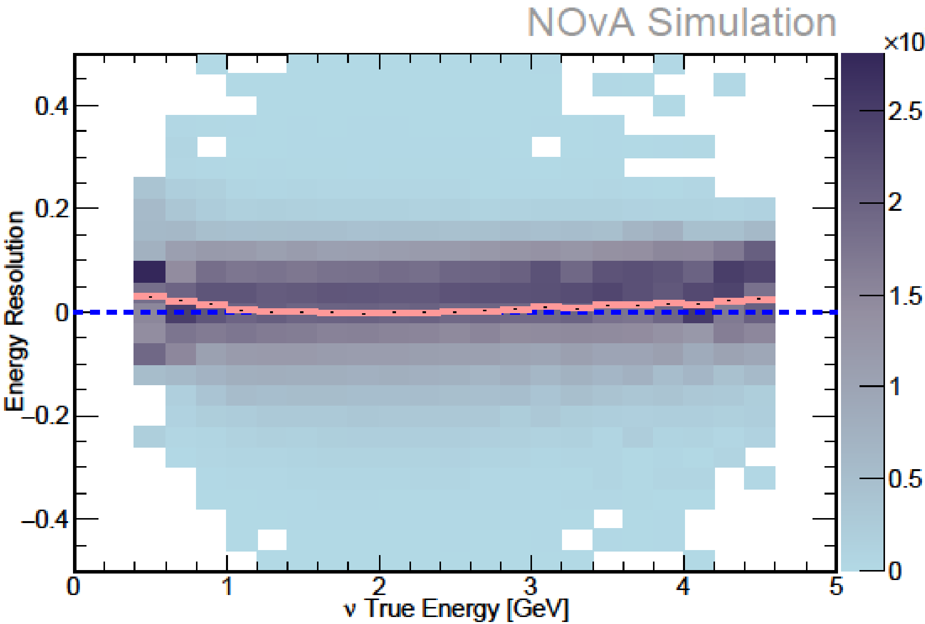
Near Detector ν_e Energy





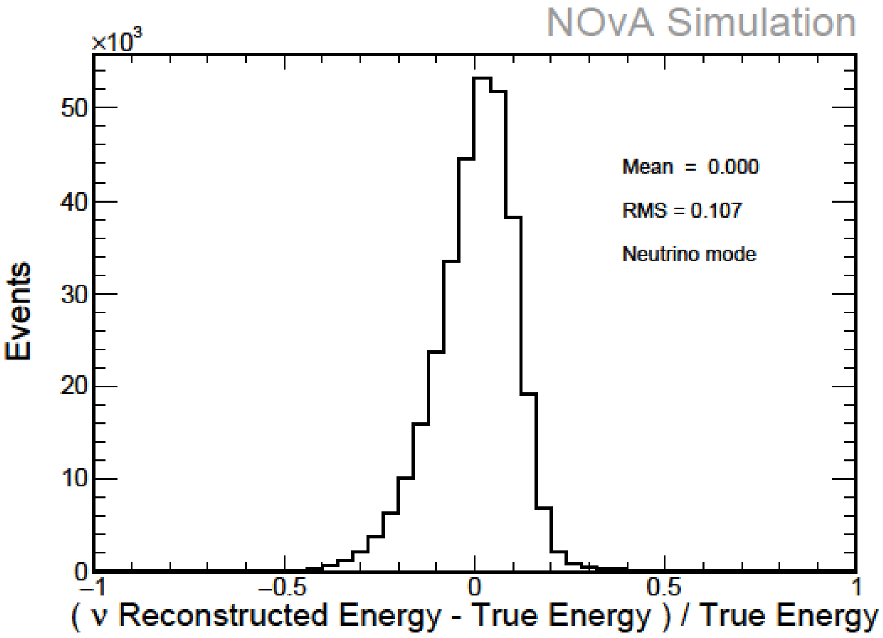
Energy Resolution - ν_e

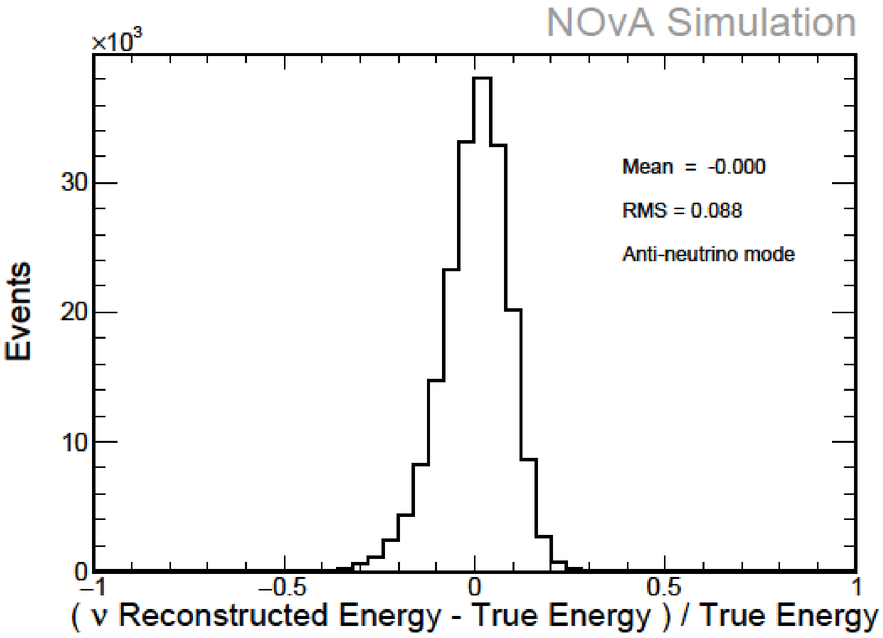




- events are weighted by a function that flattens the true energy spectrum implicit in the simulation
- this minimizes bias between 1-4 GeV

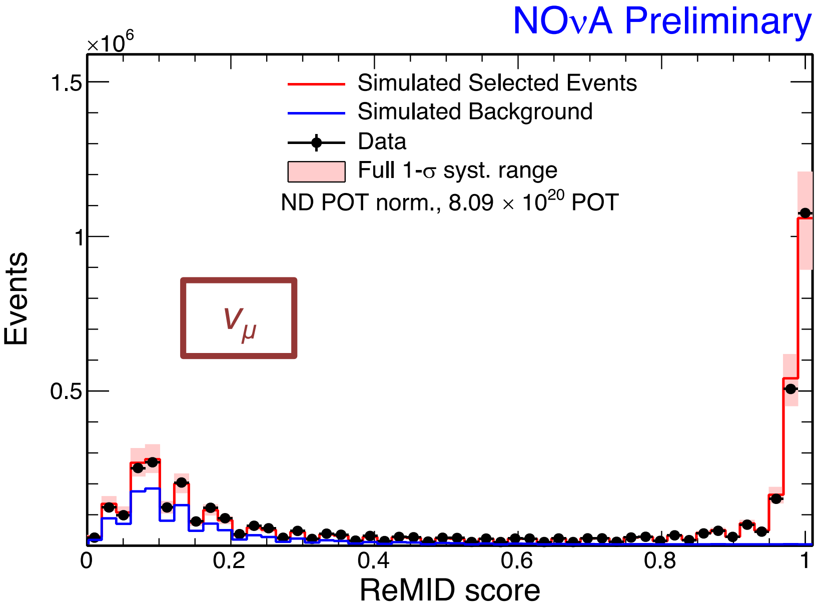
Energy Resolution - ν_e





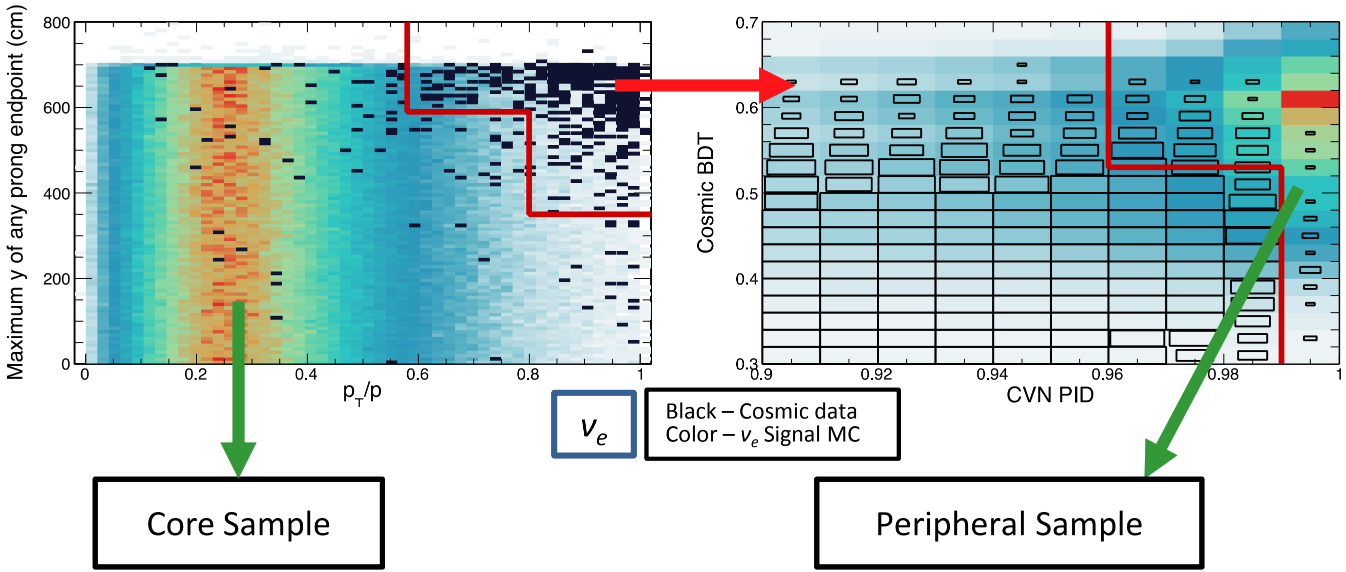
Other Selections

- Some basic additional cuts:
  - Contained, fiducial events, well-reconstructed, reasonable energy range
- An additional ν_μ **requirement**: **a track identified as a muon**.
  - CVN identifies events with a muon, but it does not identify the muon track.
  - Identify muons in reconstructed tracks using a kNN
    - Track length, dE/dx, scattering, fraction of track-only planes



- Additional cosmic rejection needed at the Far Detector.
  - 11 billion cosmic rays/day in the Far Detector on the surface.
  - 10^7 rejection power required *after* timing cuts are applied.
- The ν_μ **sample** uses a BDT based on:
  - Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.

- Cosmic rejection for the ν_e **sample** is in 2 stages:
  - **Core sample**: require contained events, beam-directed events, away from the detector top
  - **Peripheral sample**: events failing the core selection can pass a BDT cut plus a tight CVN cut.
    - Different BDT from ν_μ based on the same containment variables used for cuts in the core sample.



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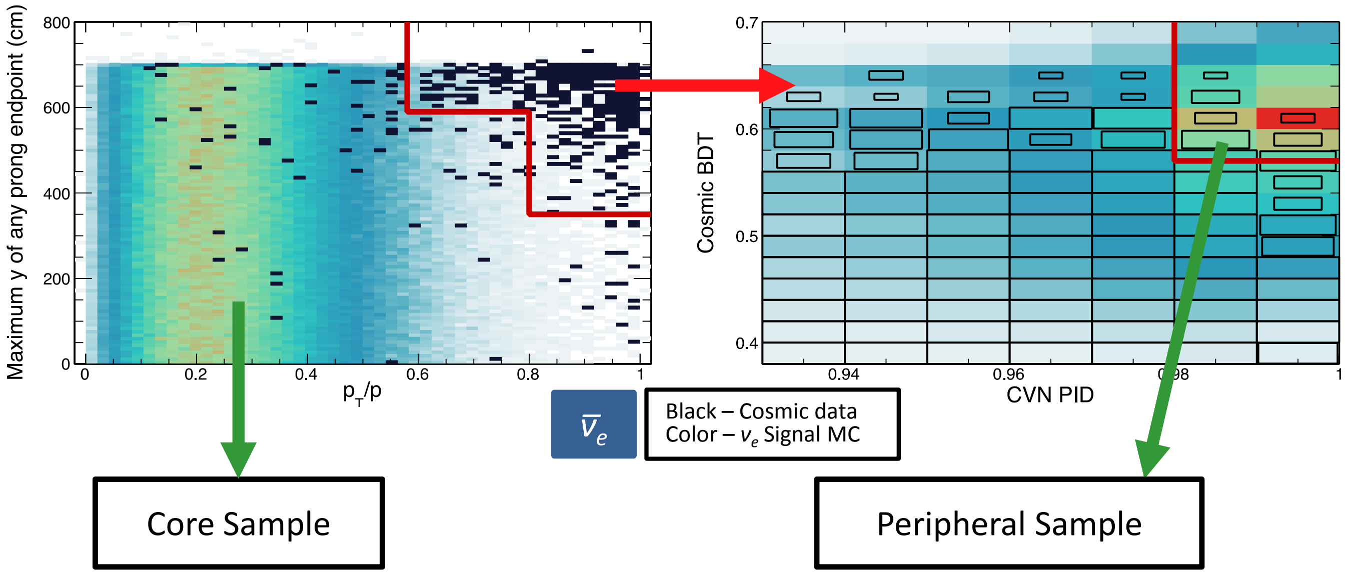
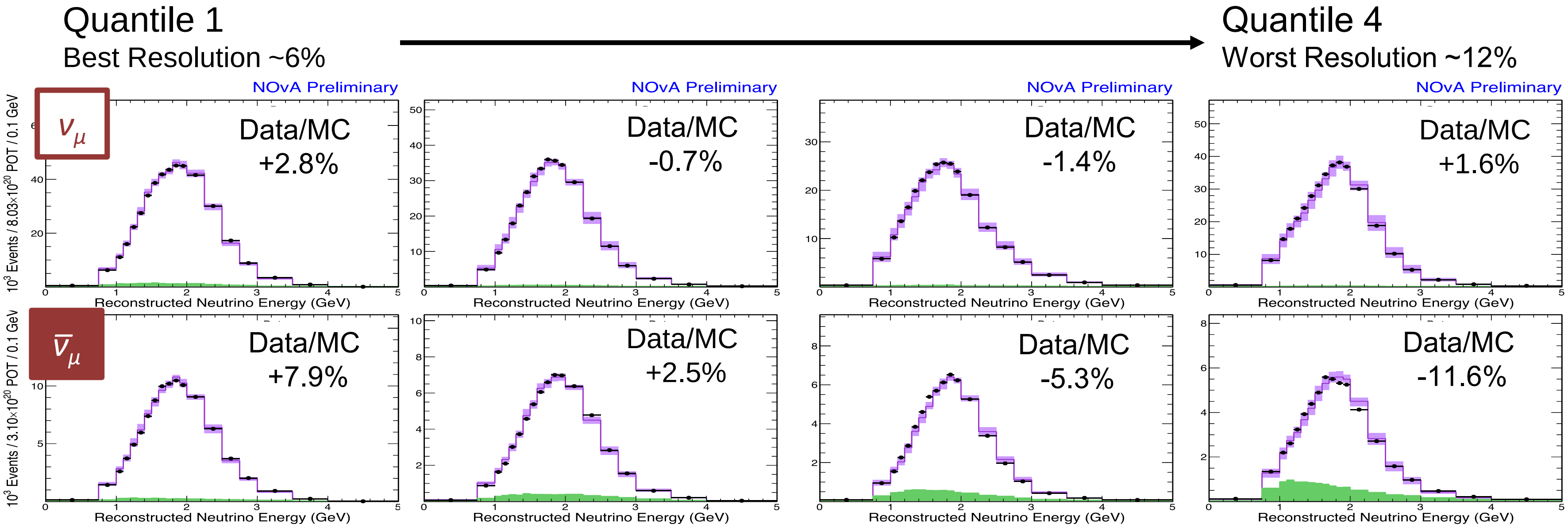


Binning for Sensitivity: ν_μ Events

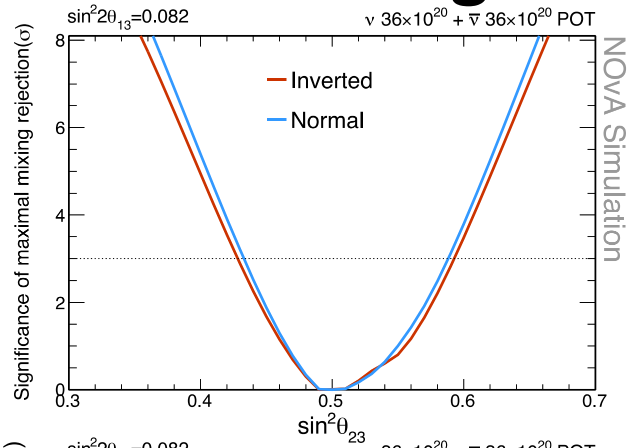
Data
Area-normalized MC
Shape-only systematics
Wrong-sign

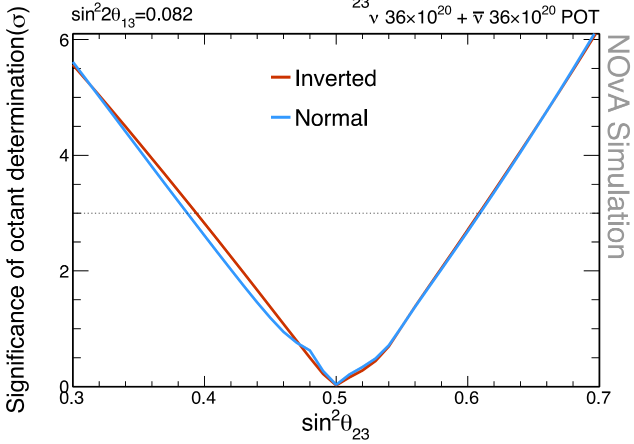


- Data-MC shape agreement good within each quantile.
- By extrapolating each separately, we transport kinematic differences between data and simulation to the FD.
  - Can see this in the different normalizations applied to each quantile.

Future Sensitivity: Octant and Maximal Mixing

- Above 3 σ sensitivity to θ_{23} maximal mixing outside of the 0.42-0.58 range by 2024.
- Above 3 σ sensitivity for octant determination outside of 0.4-0.6 range by 2024.

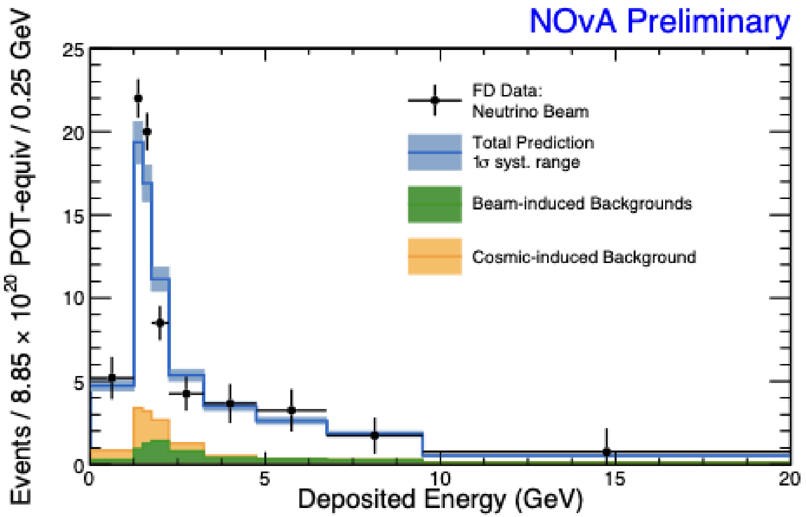


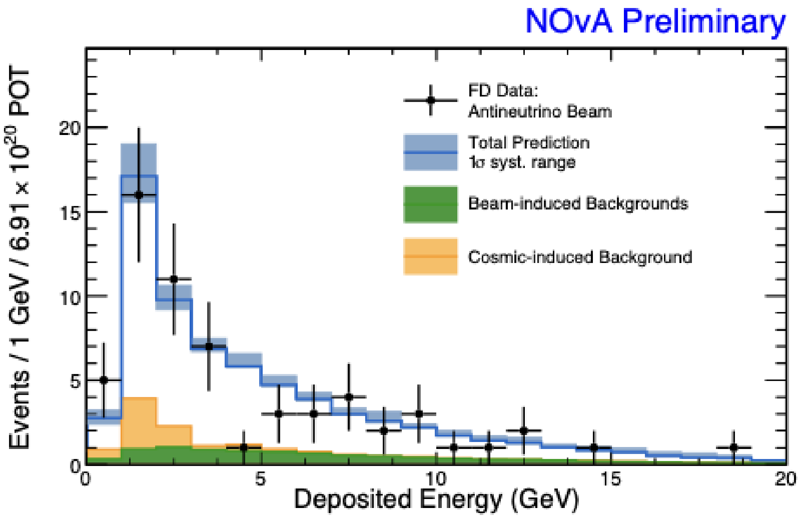


Test Beam Program

- The test beam program is how we will realize those analysis improvements.
  - Reduced systematics
  - Additional validation of ML techniques
  - Simulation improvements
- Installation and commissioning efforts are ongoing
- Full data taking this fall

Neutral current disappearance

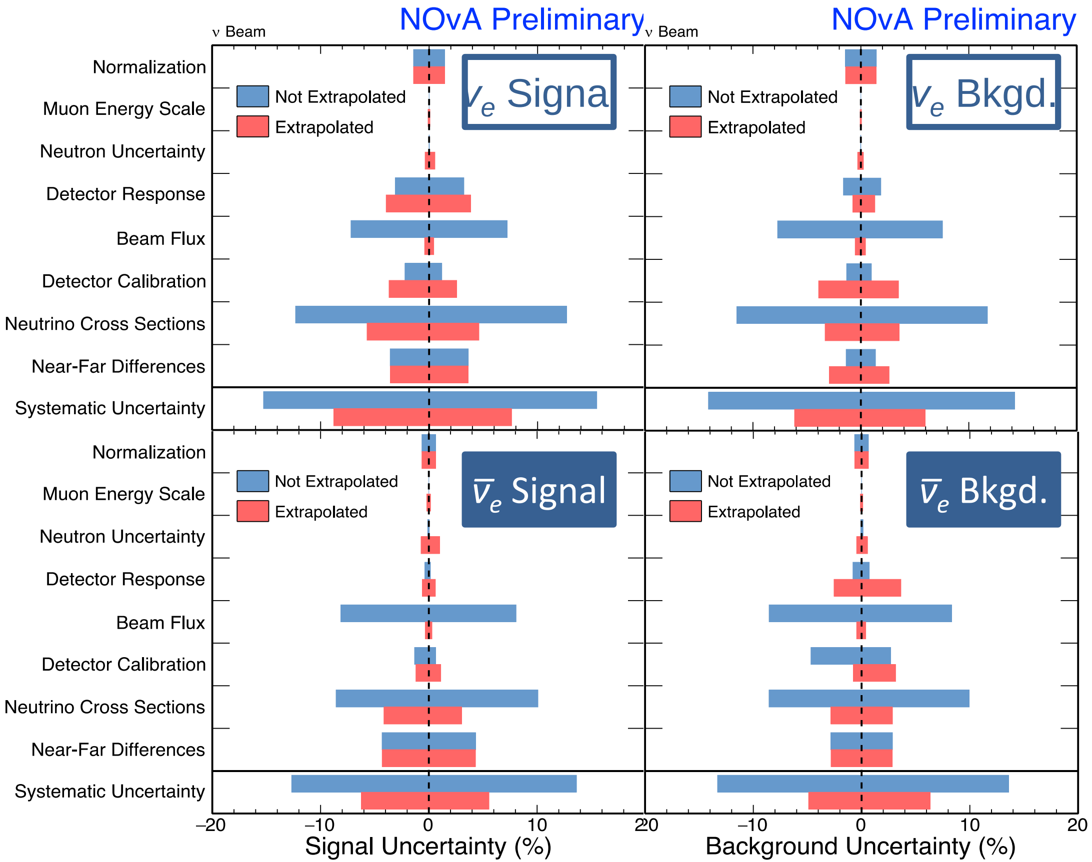




Neutrino beam sample: predict 188 ± 13 (syst.) interactions (38 bkg.), observe 201.
Antineutrino beam sample we predict 69 ± 8 (syst.) interactions (16 bkg.), observe 61.

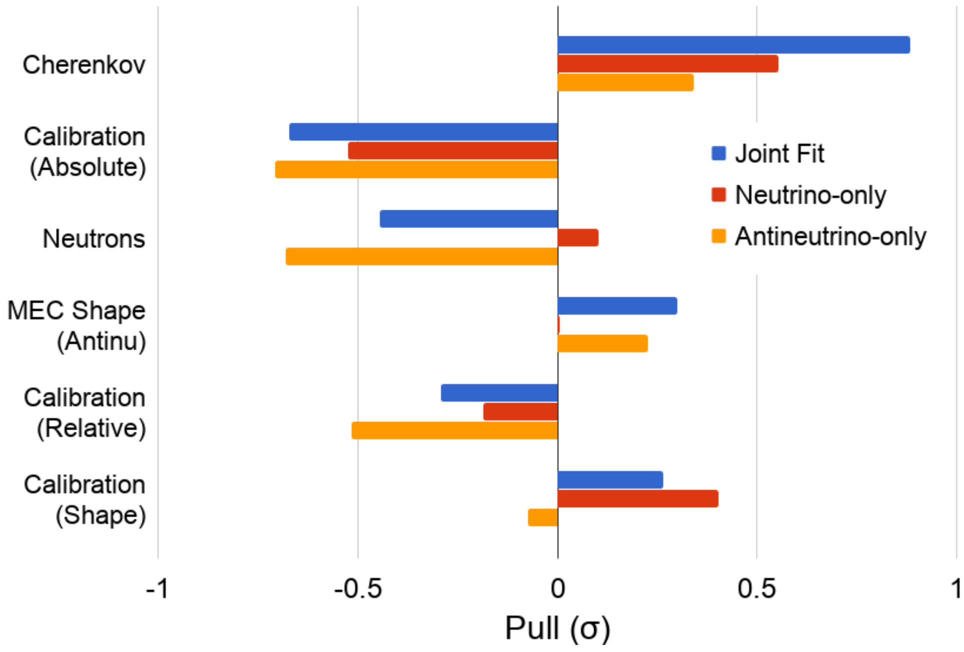
No significant suppression of neutral current interactions observed for neutrinos or antineutrinos

Systematics Reduced with Extrapolation

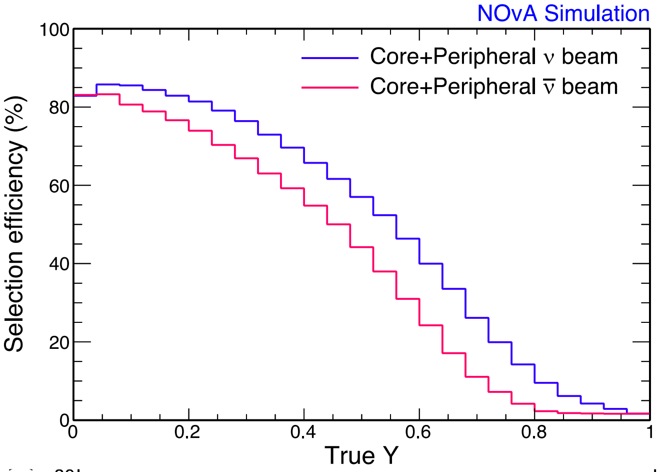


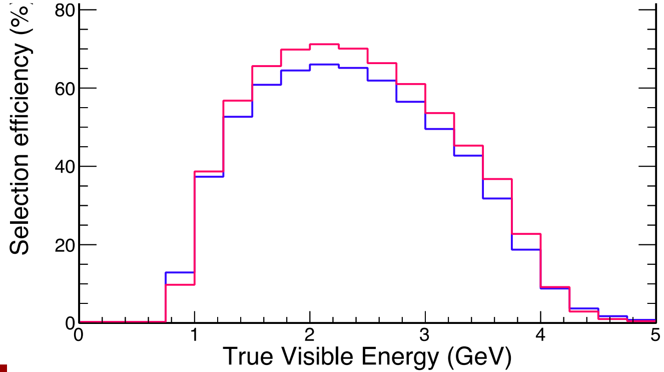
Pulls in the Fit

- A total of 49 systematic parameters were included in the fit.
- Largest pulls mostly correspond to the systematics already called out as most important.
    - Exception: Cherenkov is a part of "Detector Response"
- For systematics affecting both neutrinos and antineutrinos, we see consistent pulls from from both parts of the data.

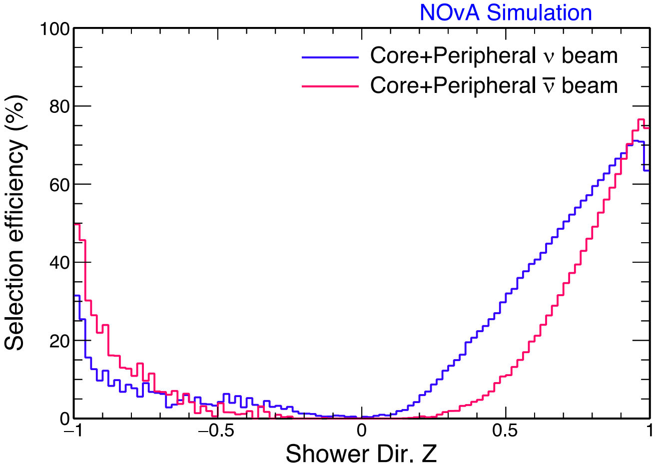


Efficiency for Neutrinos vs. Antineutrinos

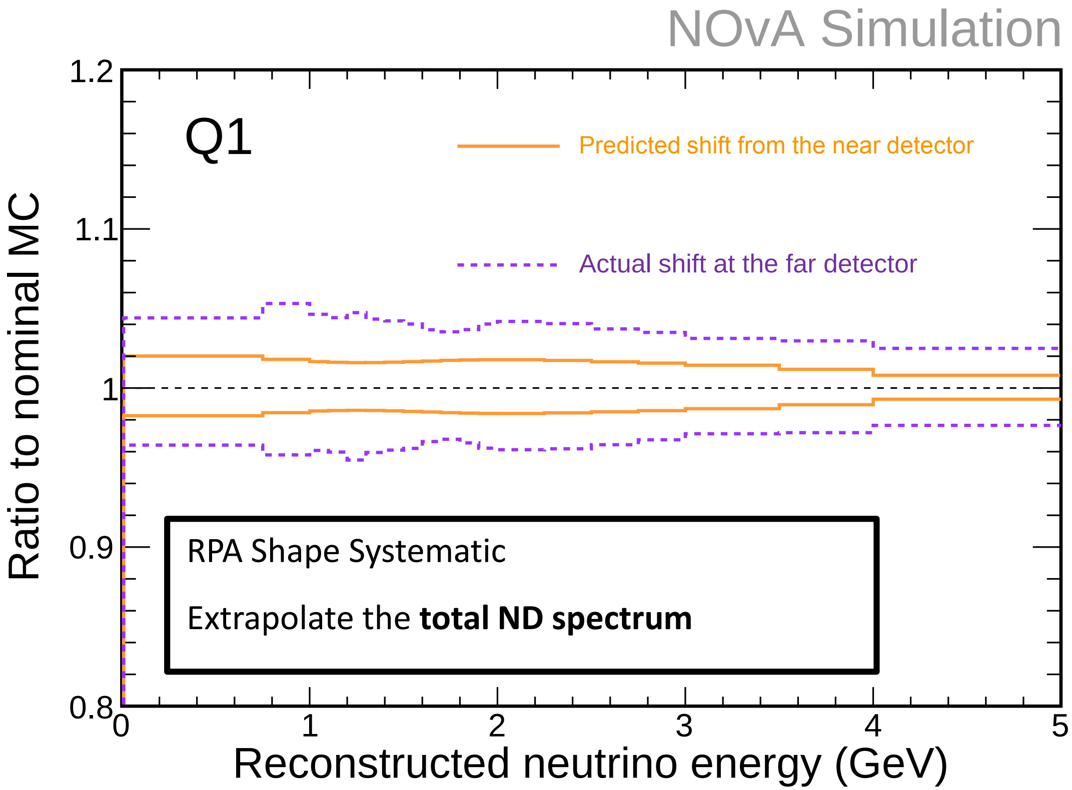




$\bar{\nu}$ Efficiency improvement with $\bar{\nu}$-trained network		
$\bar{\nu}_e$ CC	$\bar{\nu}_\mu$ CC	NC
+14%	+6%	+10%



Extrapolation with Resolution Bins



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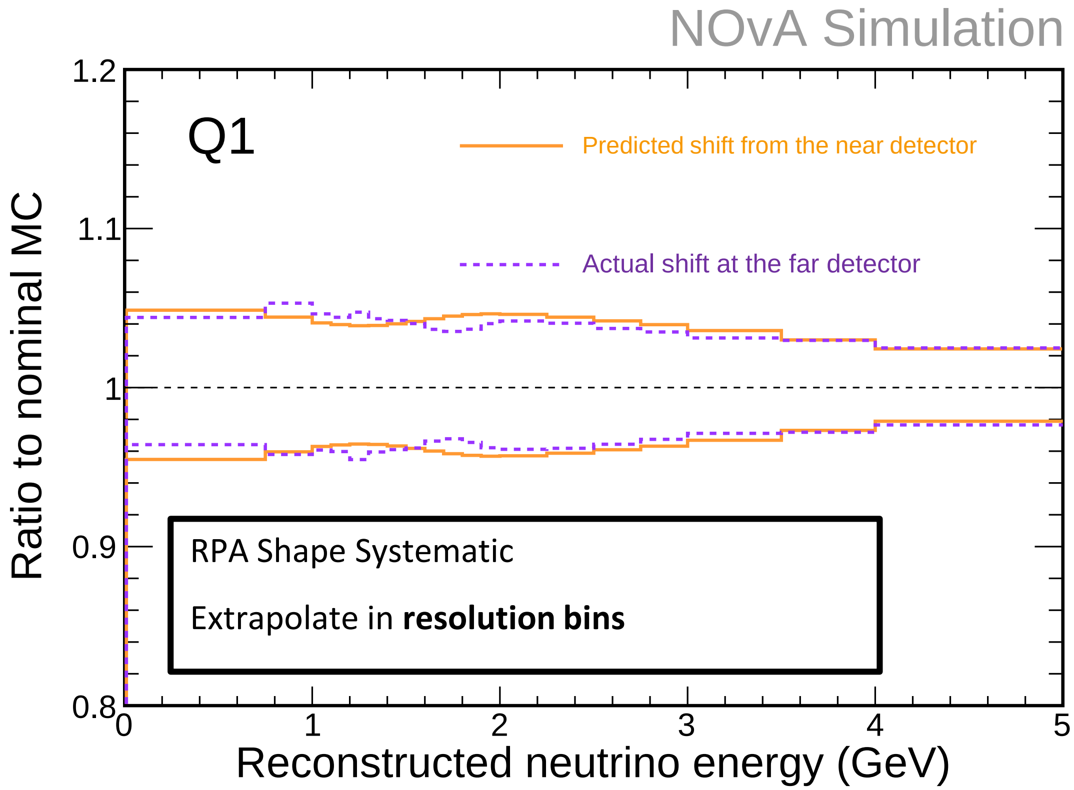
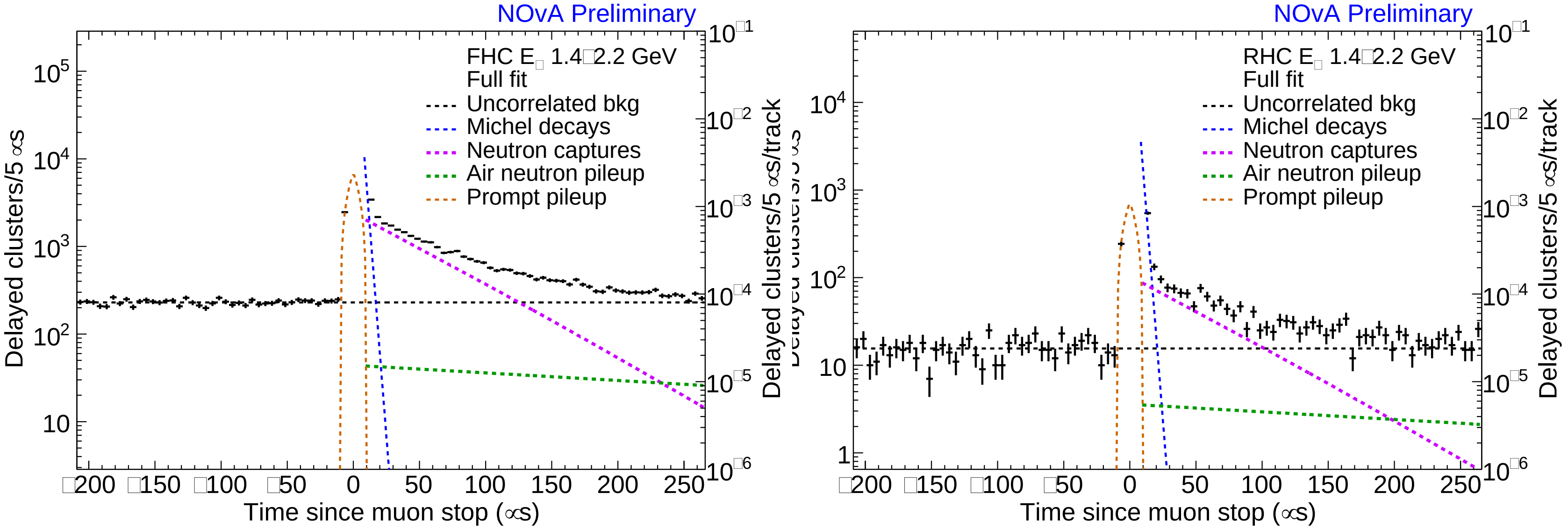
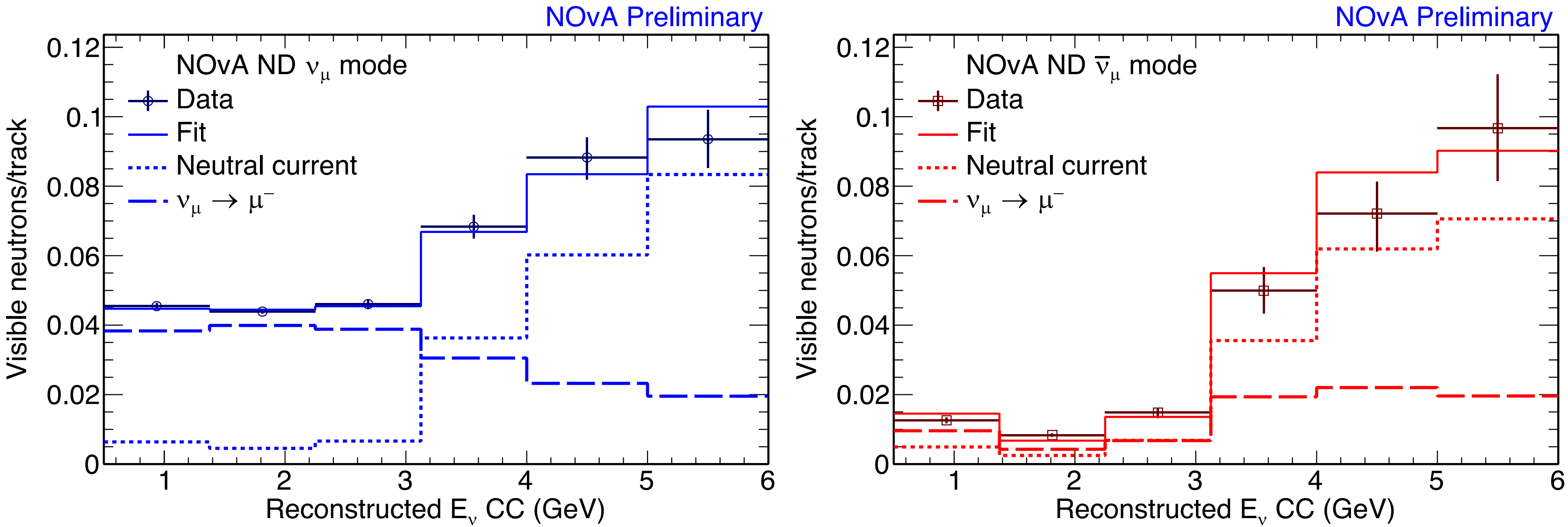


Wrong-sign Constraint with Neutron Capture



- Look for delayed clusters of hits following stopping muons.
- Fit the various time components to measure the rate of neutron captures in bins of neutrino energy.
- Then fit the neutron captures vs. reconstructed energy to extract the number of ν_μ CC and NC events in the neutrino and antineutrino beams.

Wrong-sign Constraint with Neutron Capture



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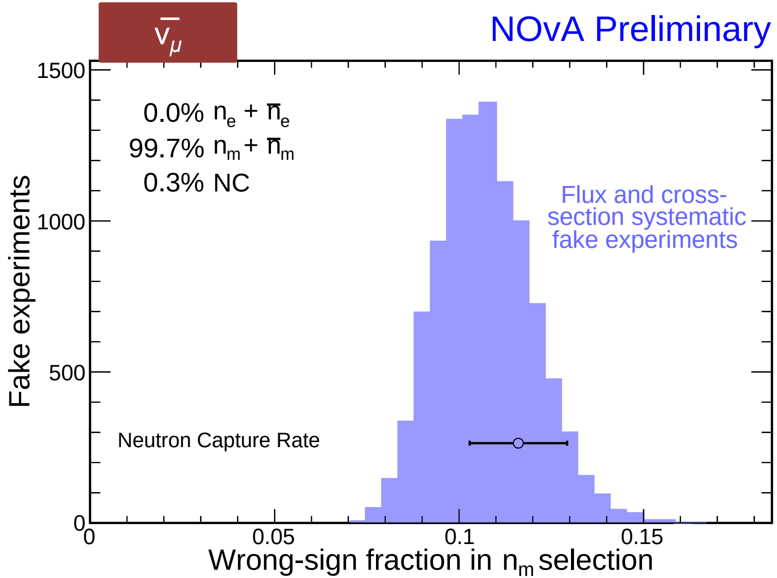
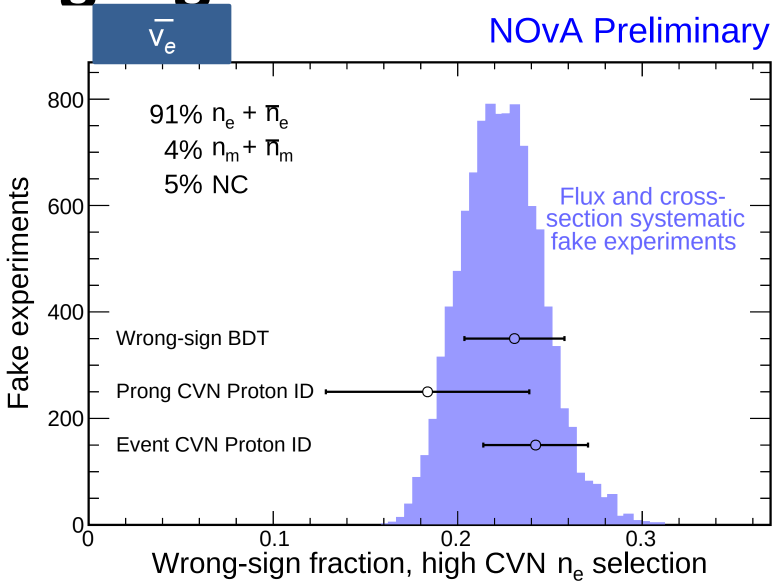
What's new with $\bar{\nu}$'s? Wrong-sign contamination

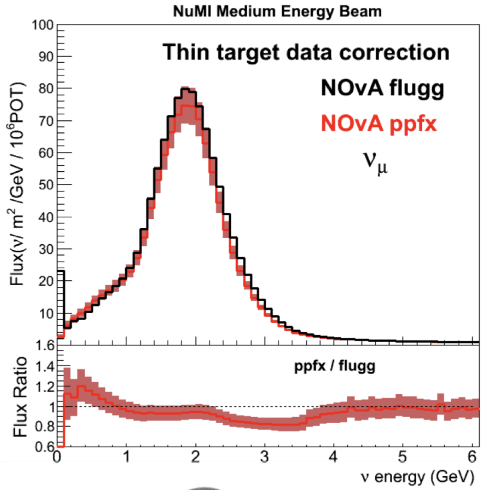




- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirm using data-driven cross-checks
  - 11% WS in the ν_μ sample checked using neutron captures.
  - 22% WS in beam ν_e checked using identified protons and event kinematics.

Simulation Tuning

- We tune our simulation to get a better central value *and* to set systematic uncertainties.
- Beam flux is tuned using the **Package to Predict the FluX** using external data.
    - **Minerva**, Phys. Rev. D 94, 092005 (2016)
- We tune our cross-section model primarily to account for **nuclear effects**.
    - Backstory: disagreements are seen in cross sections as measured on a single nucleons vs. in more complex nuclei.
    - Nuclear effects are a likely solution, but the theory for them remains incomplete.
    - So, we tune using a combination of **external theory** inputs and our own **ND data**.



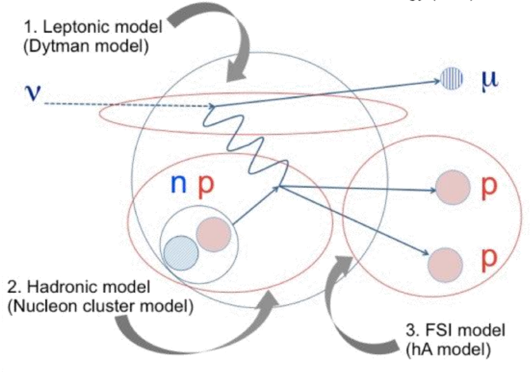


Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

Tuning the Neutrino Interaction Model

From **external theory**:

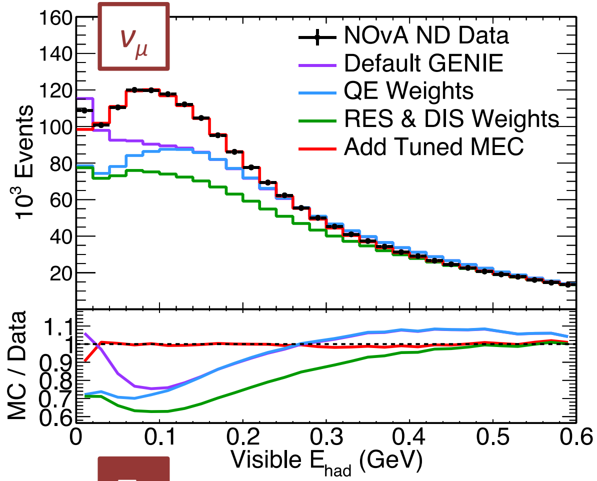
- Valencia RPA model† of nuclear charge screening applied to QE.
- Same model applied to resonance.

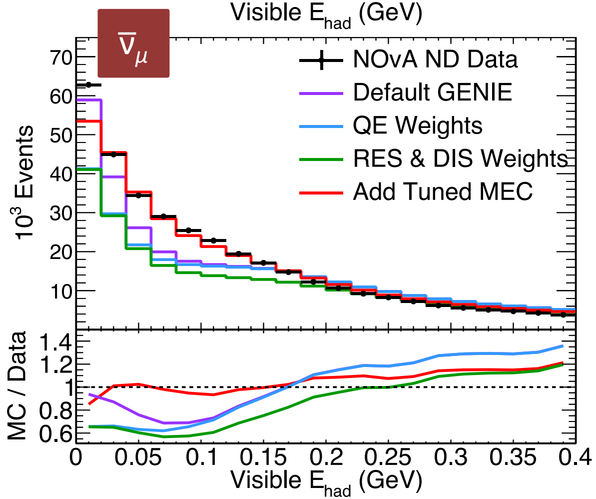
From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.
- Add MEC interactions
  - Start from Empirical MEC*
  - Retune in $(q_0, |\boldsymbol{q}|)$ to match ND data
  - Tune separately for $\nu / \bar{\nu}$

† "Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014



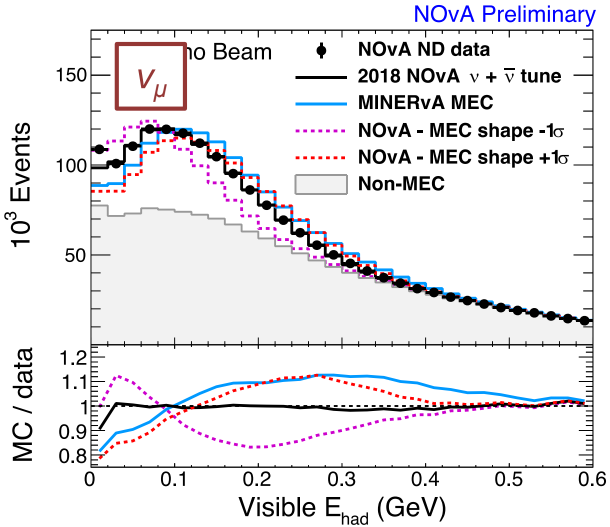


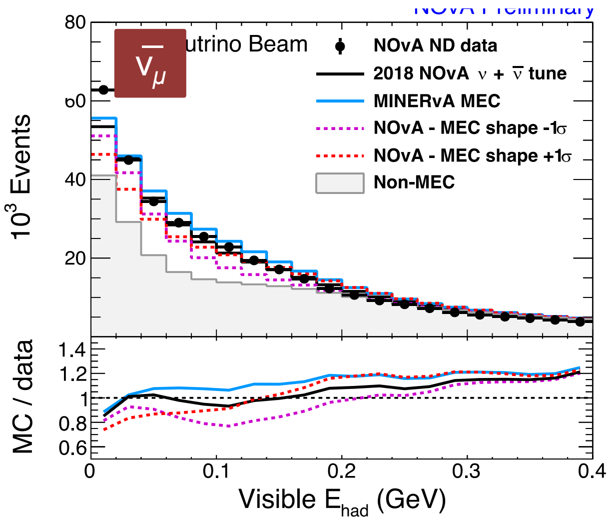
MEC Uncertainties

- We also determine uncertainties on the MEC component we introduce.
  - Both on shape and total rate.
- Repeat the tuning procedure with shifts in the Genie model.
  - Turn Genie systematic knobs coherently to push the non-MEC
    x-sec more QE-like or more RES-like.
- Independently, **Minerva*** has also tuned a multi-nucleon component to their data.
- The resulting tune is ~1σ away from the NOvA tune.

*Minerva, Phys. Rev. Lett. 116, 071802 (2016)

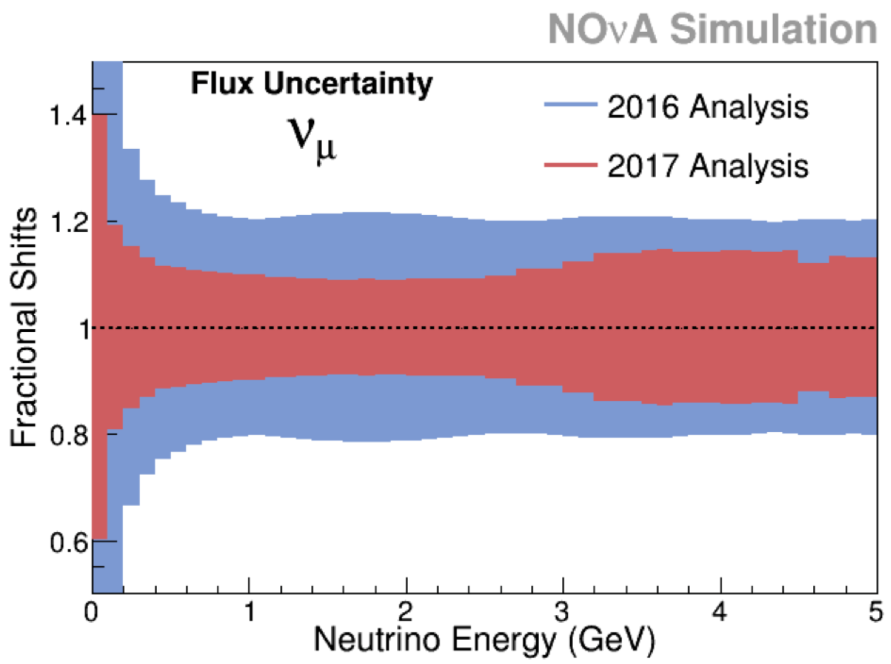
Minerva, Phys. Rev. Lett. 120, 221805 (2018)



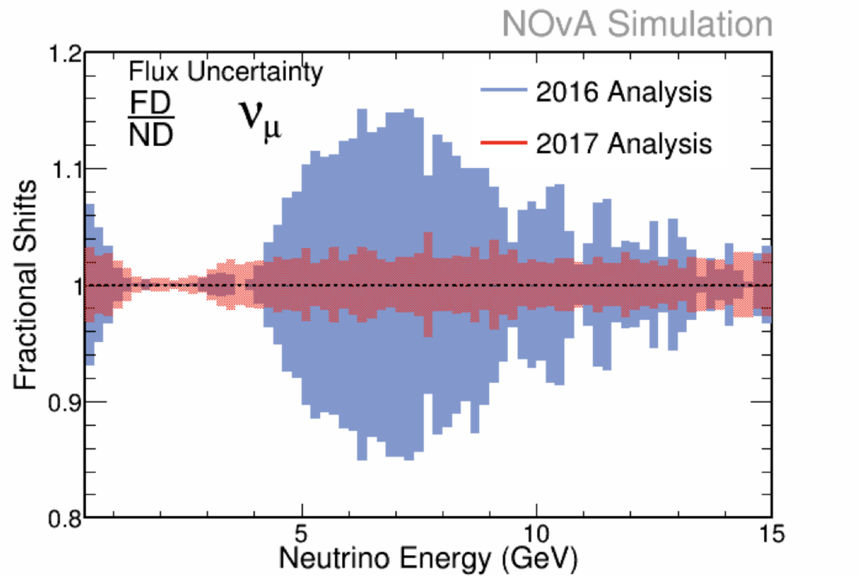


Improved Flux Model

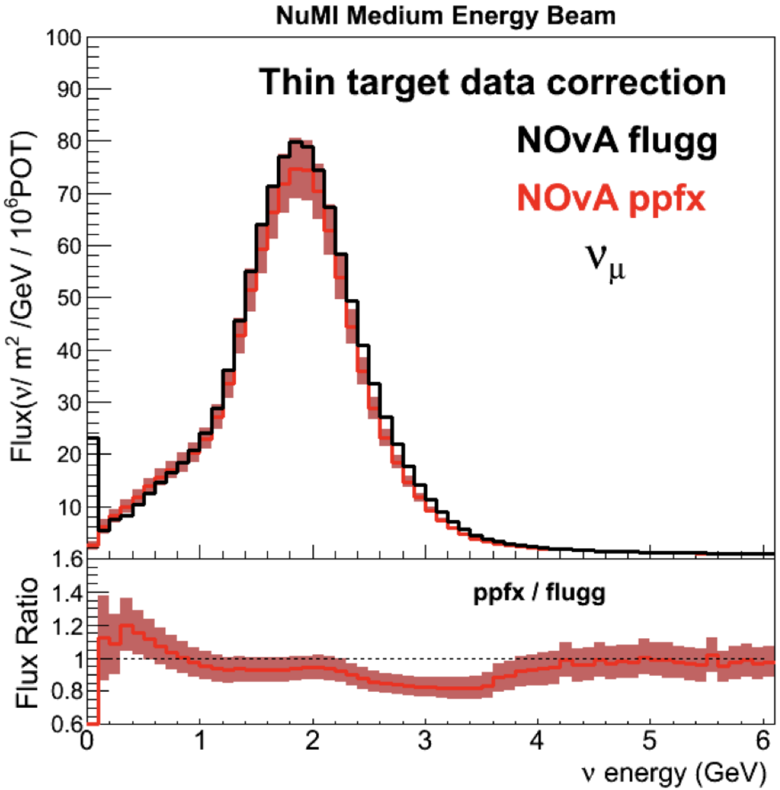
- Package to Predict the FluX (**PPFX**) from MINERvA.
  - Based on thin target hadron production data from NA49 and MIPP.
- Significantly reduced systematic uncertainties.
  - Central values also changed within prior systematics, but not shown here.



New Flux



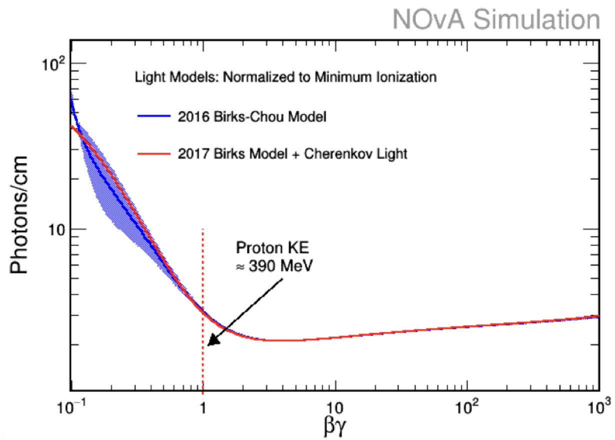
NOvA Simulation
Flux Uncertainty
FD / ND
ν_μ
2016 Analysis
2017 Analysis
Fractional Shifts
Neutrino Energy (GeV)

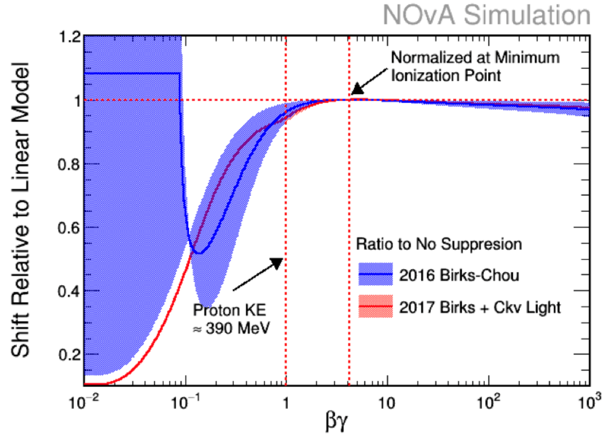


NuMI Medium Energy Beam
Thin target data correction
NOvA flugg
NOvA ppfx
ν_μ
Flux(ν/ m^2 /GeV / 10^{6}POT)
ppfx / flugg
Flux Ratio
ν energy (GeV)

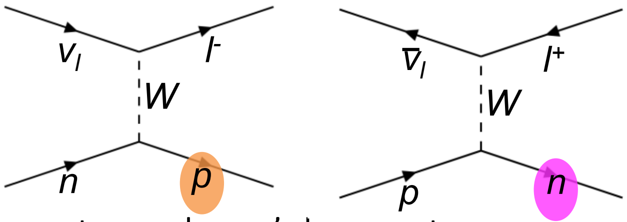
Scintillator Model

- Absorbed and re-emitted Cherenkov light is a small but important component of our scintillator response.
  - Particularly for low-energy protons in hadronic showers.
- Was one of our largest uncertainties, now reduced by an order of magnitude.
  - Previously accounted for with second order terms in our scintillator model.
  - Those terms were unusual, so we placed large systematics.
- Expected energy resolution for ν_μ CC events increased from 7% to 9%.

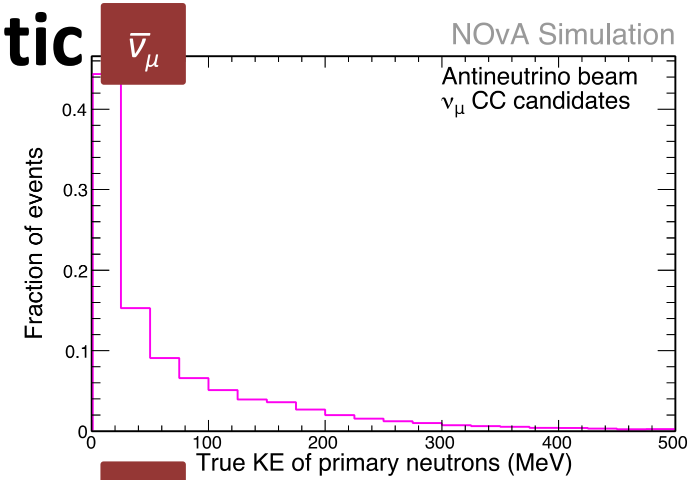


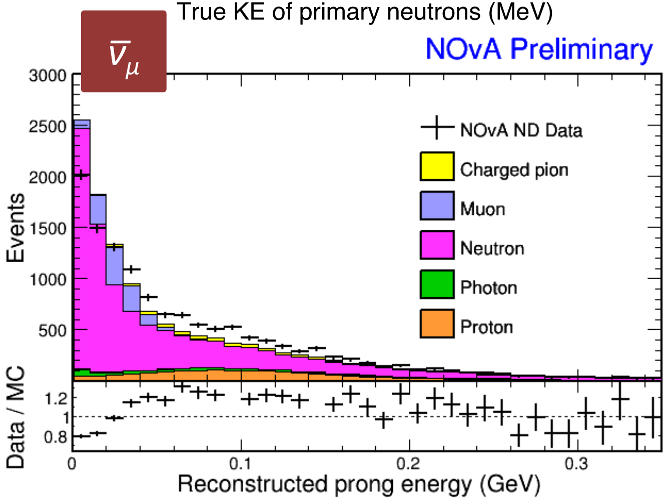


New neutron response systematic



- $\bar{\nu}$'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.





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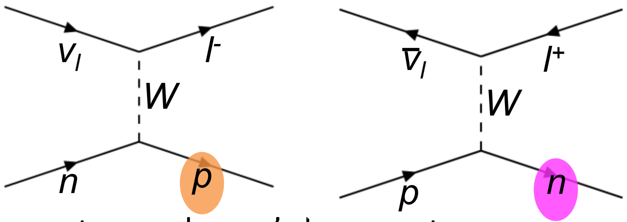

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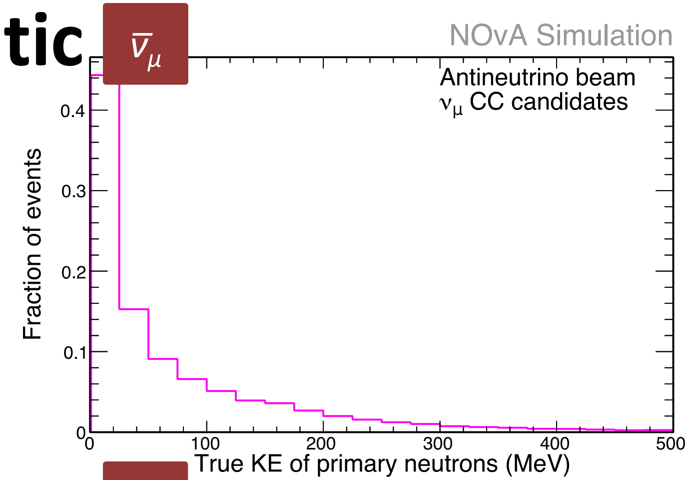
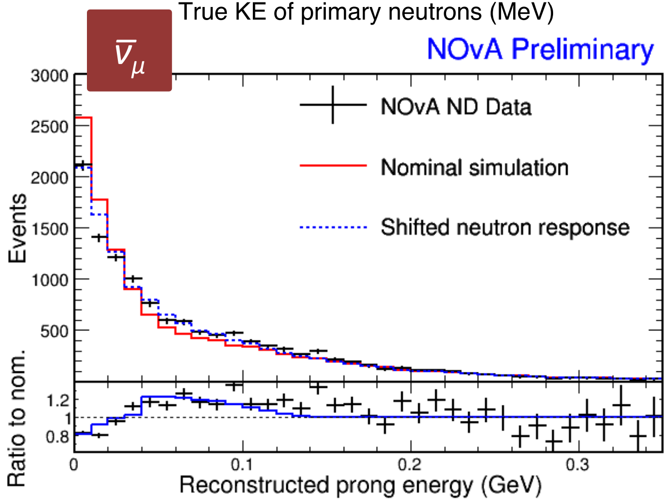
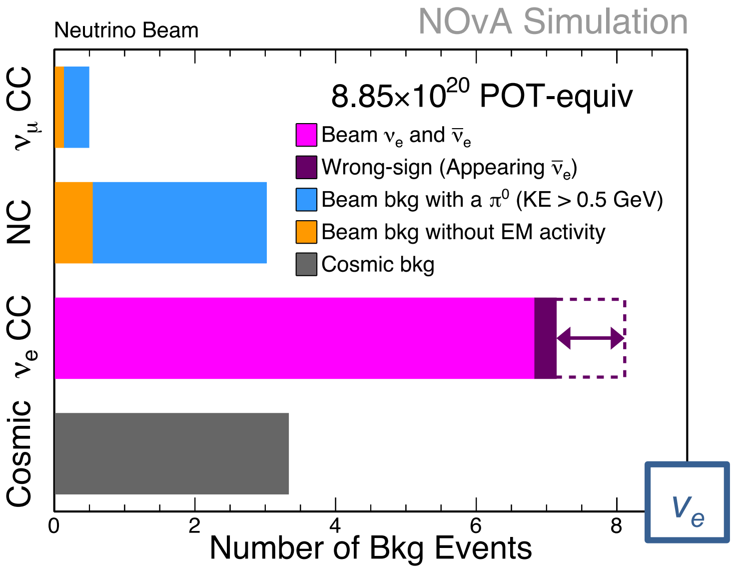
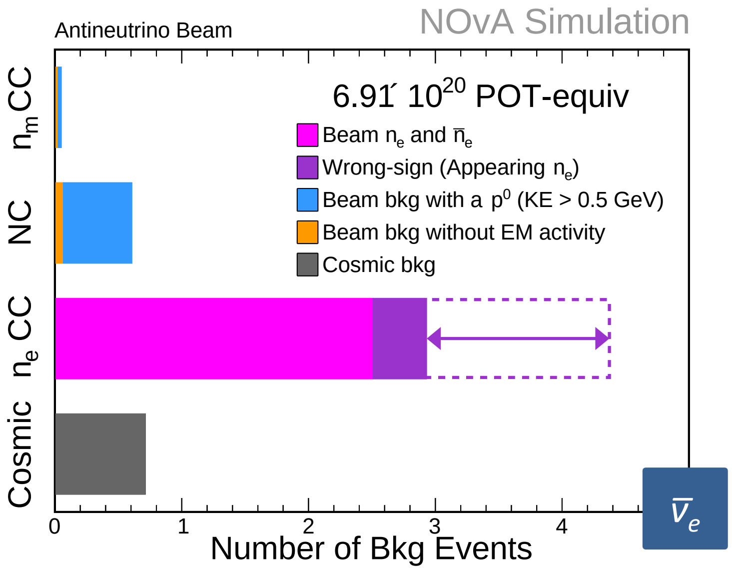




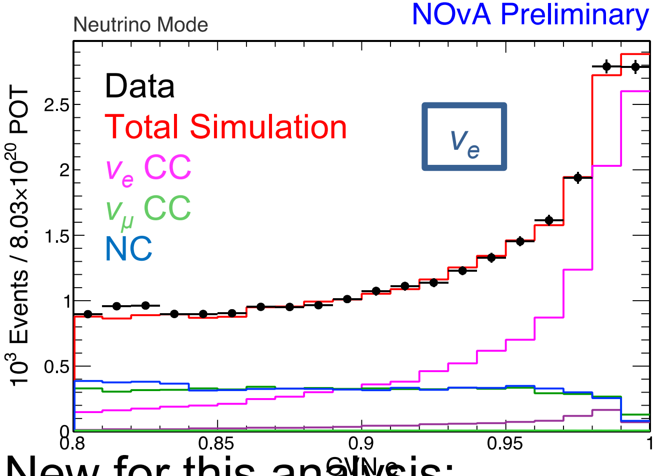
ν_e and $\bar{\nu}_e$ Background at the Far Detector

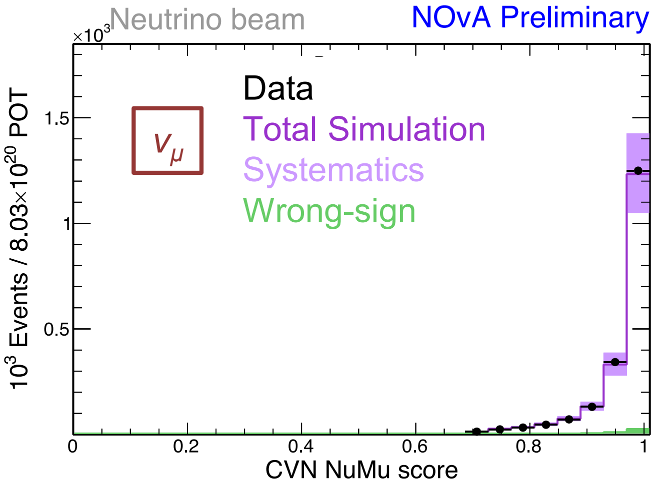




- 14.7 – 15.4 total ν_e background 4.7 – 5.7 total $\bar{\nu}_e$ background
  - Wrong-sign background depends on the oscillation parameters.
- Largest backgrounds are from real electrons: beam $\nu_e/\bar{\nu}_e$ and wrong-sign.
  - The amount of wrong-sign background varies with the oscillation parameters.
- Most other beam backgrounds contain a π^0.

CVN for Antineutrinos

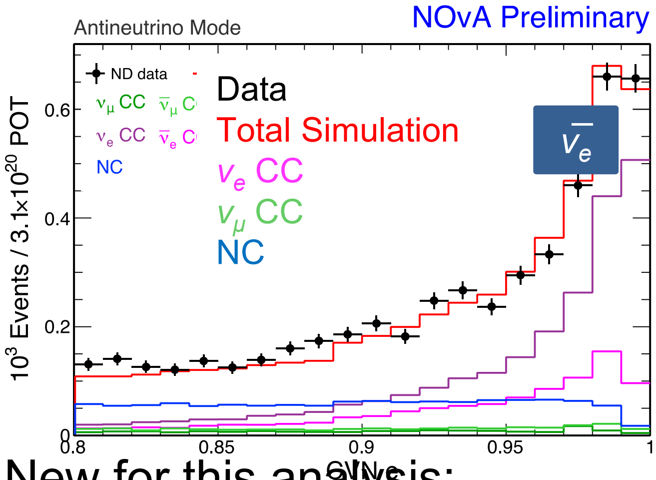


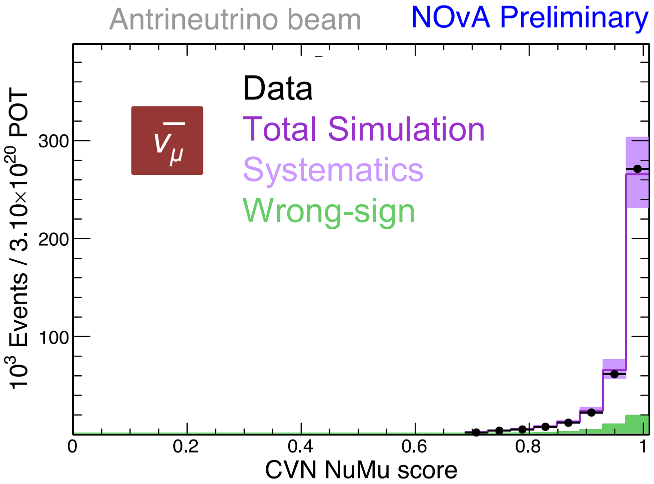


New for this analysis:

- A shorter, simpler architecture trained on updated simulation.
- Replaced GENIE truth labels with final state labels.
  - Exploring using final states with protons to constrain WS backgrounds.
- Separate training for the neutrino and antineutrino beams.
  - Wrong-sign treated as signal in training.
  - 14% better efficiency for $\bar{\nu}_e$ with a dedicated network.

CVN for Antineutrinos





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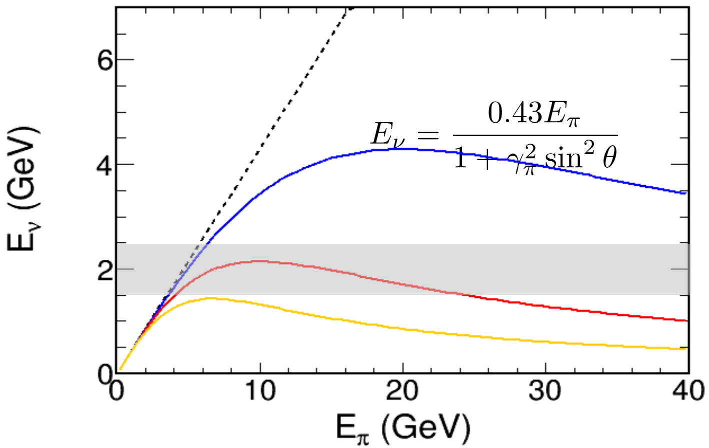
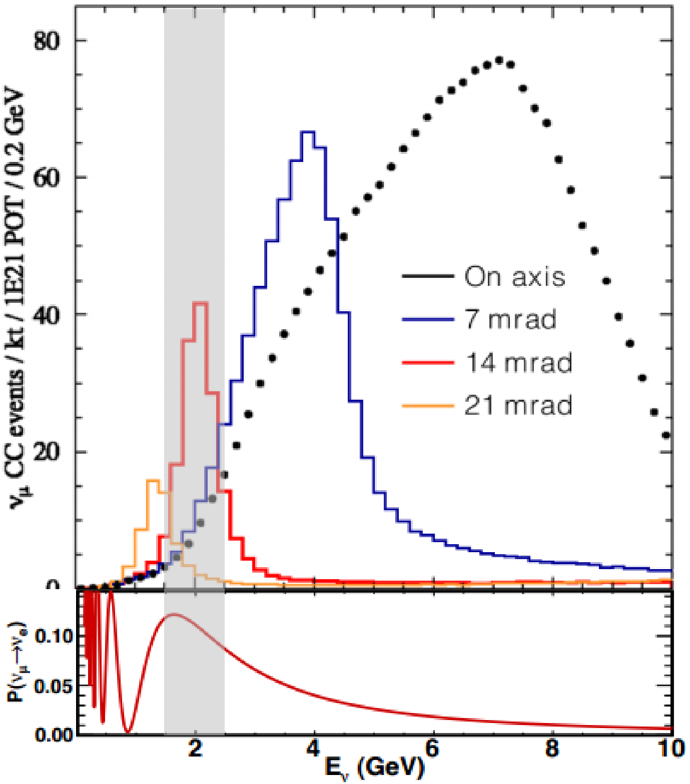
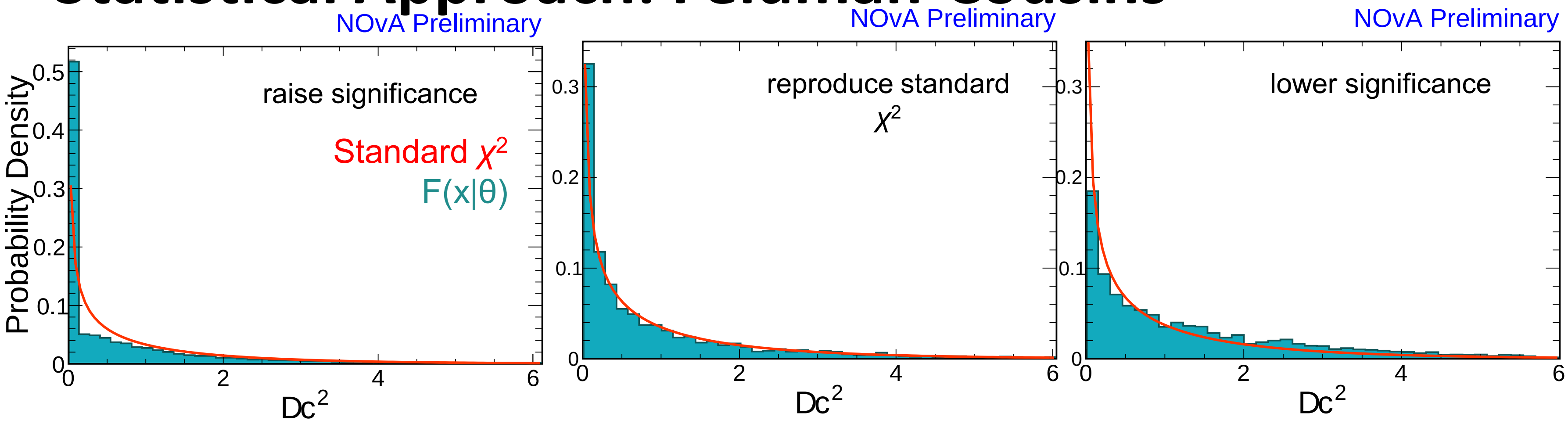
NuMI off-axis

- FD located 14 mrad off-axis angle
  - 2-body π decay gives narrow range of ν energies
- Tune peak energy for oscillations
  - More events at max oscillations
  - Fewer backgrounds.





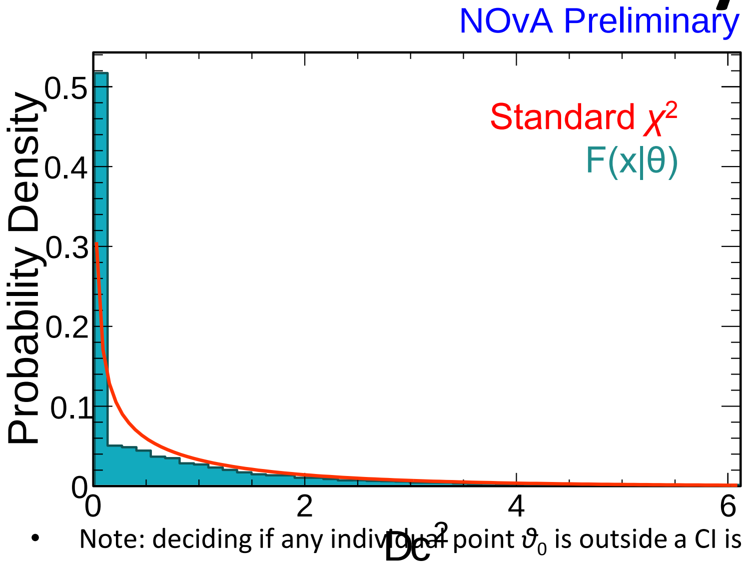
Statistical Approach: Feldman-Cousins



- Replace the standard χ^2 with an empirical distribution, $F(x|\vartheta)$ = Fraction of N experiments where [χ^2(fixed ϑ) - χ^2(best fit) = x]
- Pseudo-experiments are generated from the data profile at ϑ.
  - i.e. fit all other parameters to data holding ϑ fixed at a particular value.
  - This procedure gives proper coverage while minimizing over-coverage.*
- A point ϑ is inside the (1-α) confidence interval if less than (1-α) experiments are more extreme than the data.
  - i.e. if the integral of $F(x|\vartheta)$ up to the observed $\Delta\chi^2$ at ϑ is < (1-α).

* Test coverage using method from: R. L. Berger and D. D. Boos, J. Amer. Statist. Assoc., 89, 1012 (1994)

FC for Mass Hierarchy



Limiting Case: No sensitivity

- Half of experiments in each hierarchy and $\Delta\chi^2 = 0$
- $p = 0.5$
- 50% for either NH or IH
- All “prior”

- Note: deciding if any individual point ϑ_0 is outside a CI is equivalent to a hypothesis test where H_0 is $\vartheta = \vartheta_0$.
  - The same technique applies to this mass hierarchy hypothesis test.
- Since our best fit is in the NH, we want to know how strongly we reject the IH - H_0 is IH and we generate pseudo-experiments at our best fit in the IH.
- Follow the FC procedure with: χ^2(fixed ϑ) - χ^2(best fit) → χ^2(IH) - χ^2 (best fit)
  - If an experiment has a best fit in the IH, then the difference is 0.
  - This pile-up at 0 behaves like a physical boundary: it increases significance.