Latest Neutrino Oscillation Results from NOvA

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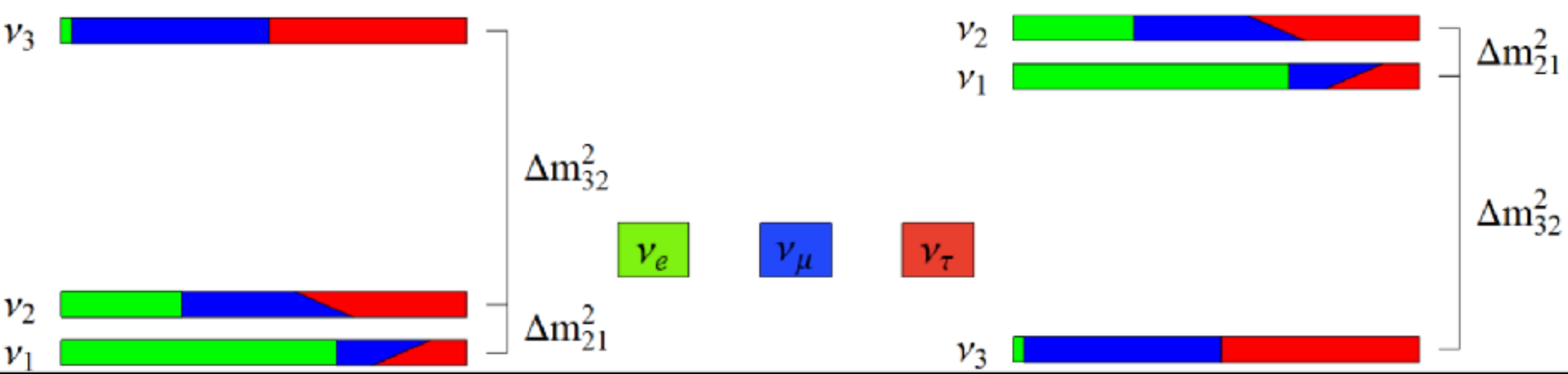
Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^* \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

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

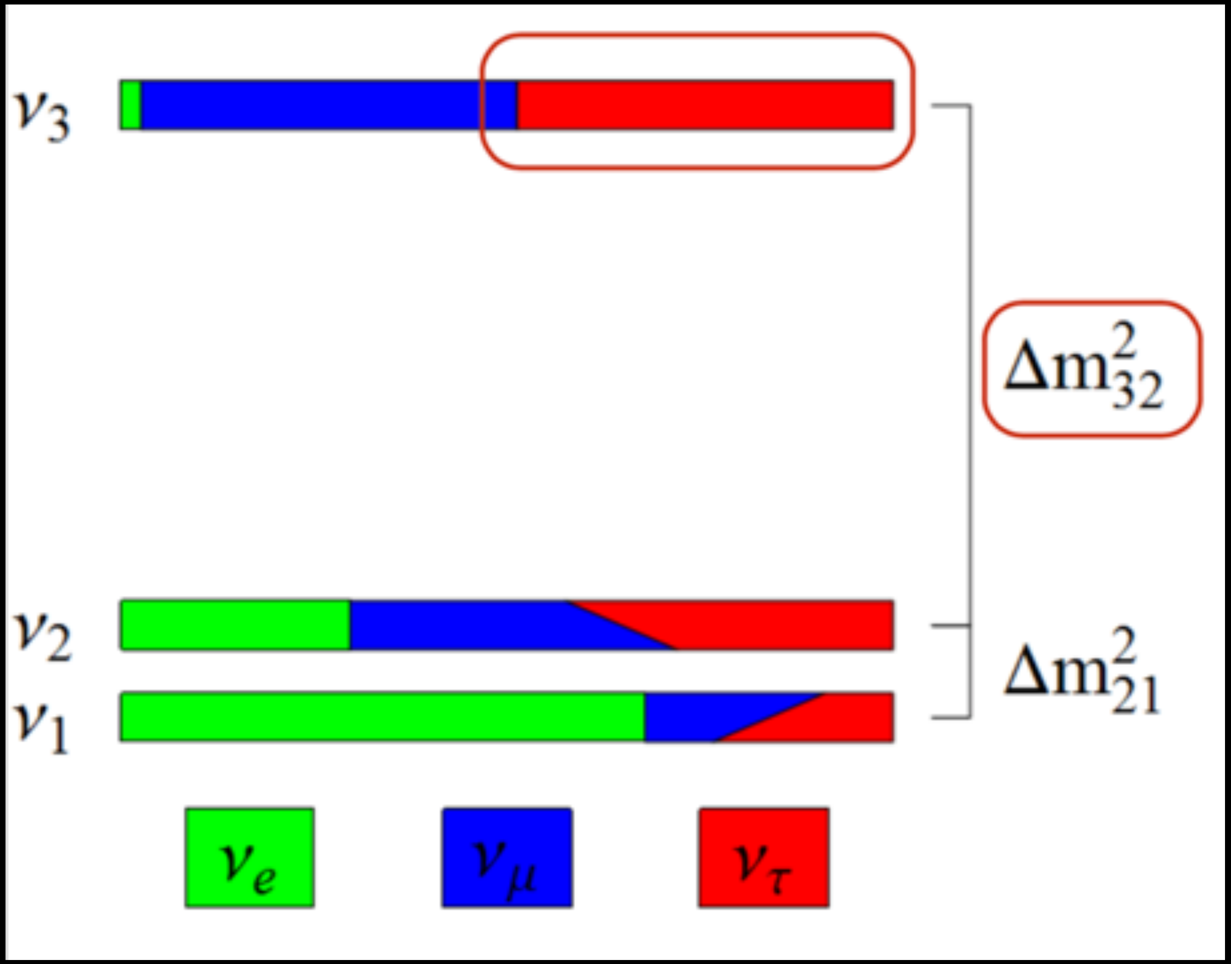


Why Study Neutrino Oscillation?

Neutrino oscillations raised as many questions as it answered:

- Why is lepton sector mixing much larger than quark sector mixing? Is θ_{23} maximal?
- What is the hierarchy of neutrino masses?
- Is there CP violation in the lepton sector?

NOvA Physics Goal



Precise measurements:

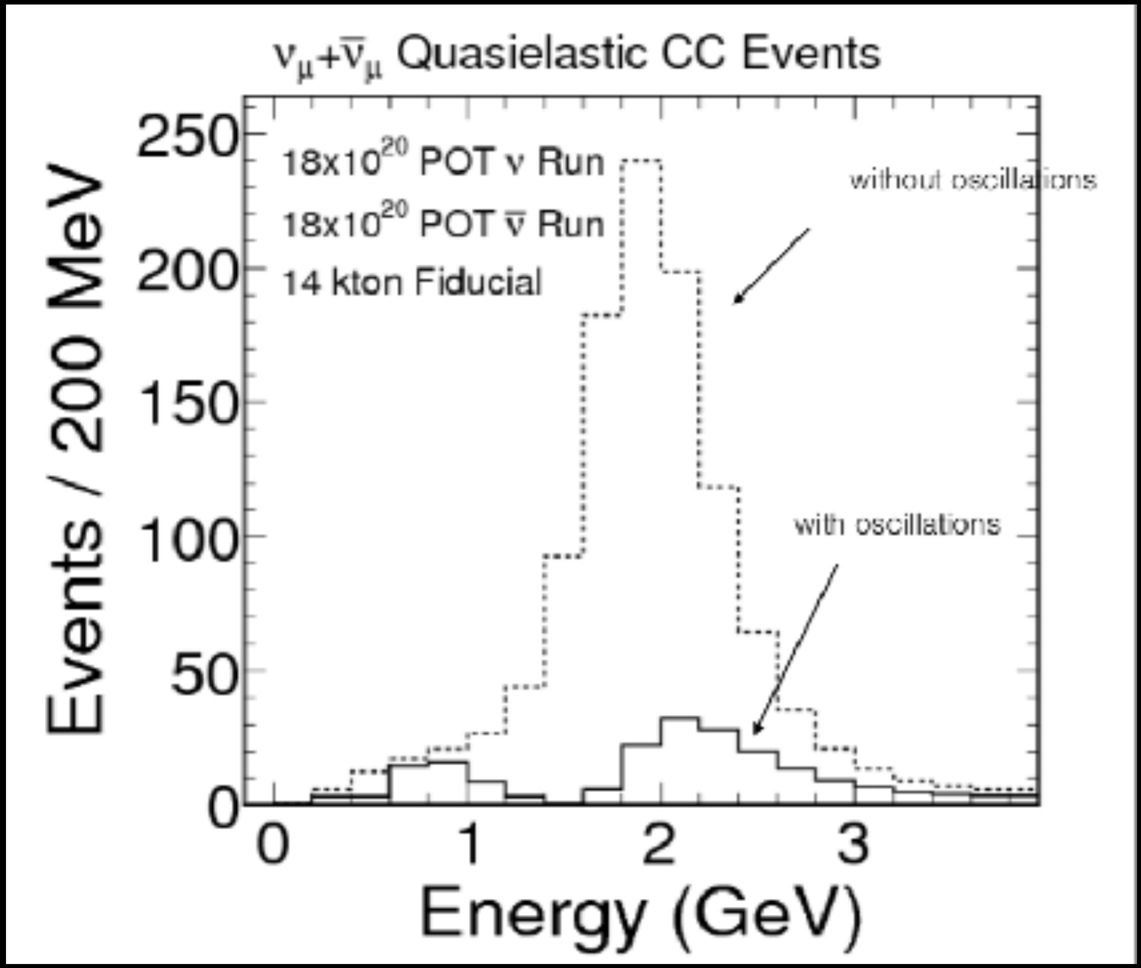
- Δm^2_{32} and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

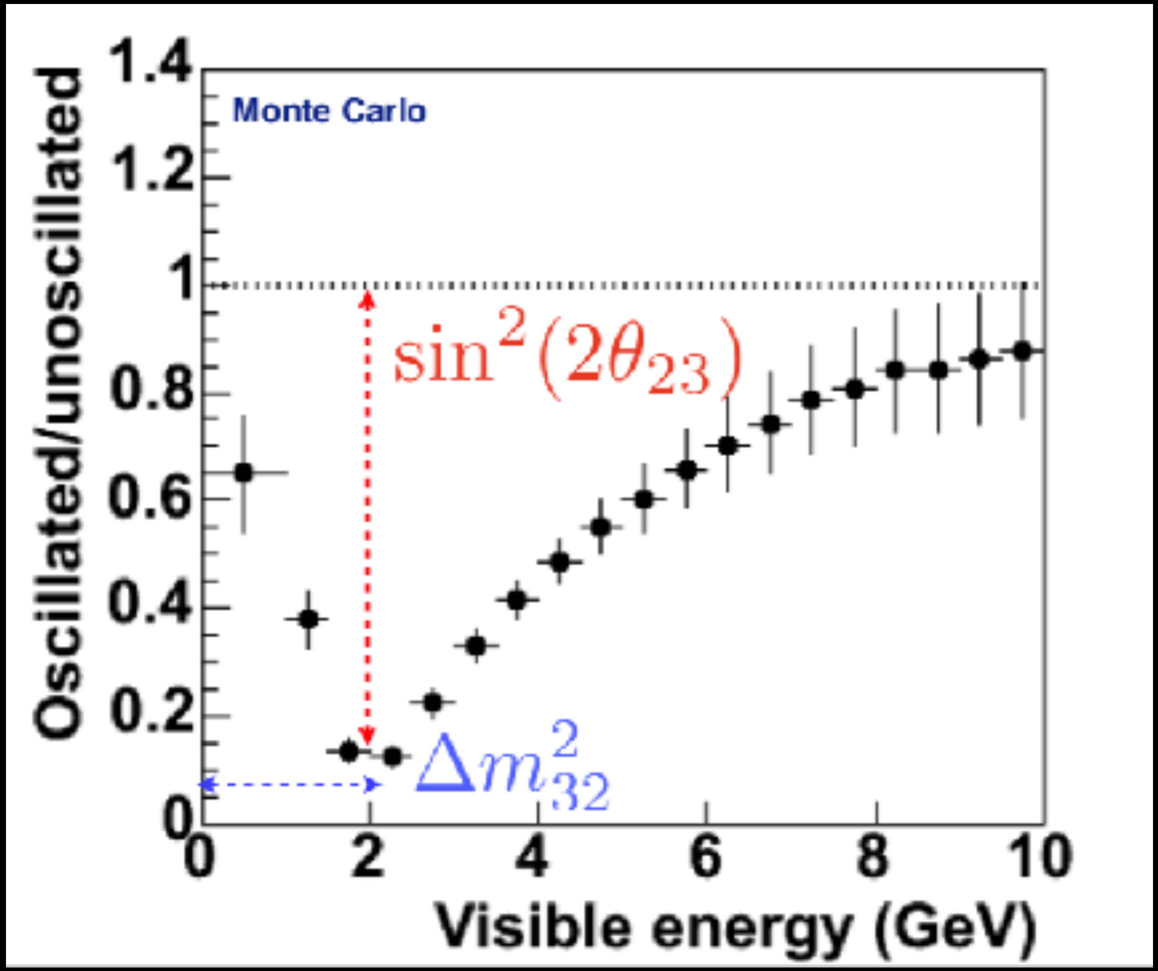
Strong constrains on:

- θ_{23} octant
- δ_{cp}
- mass hierarchy

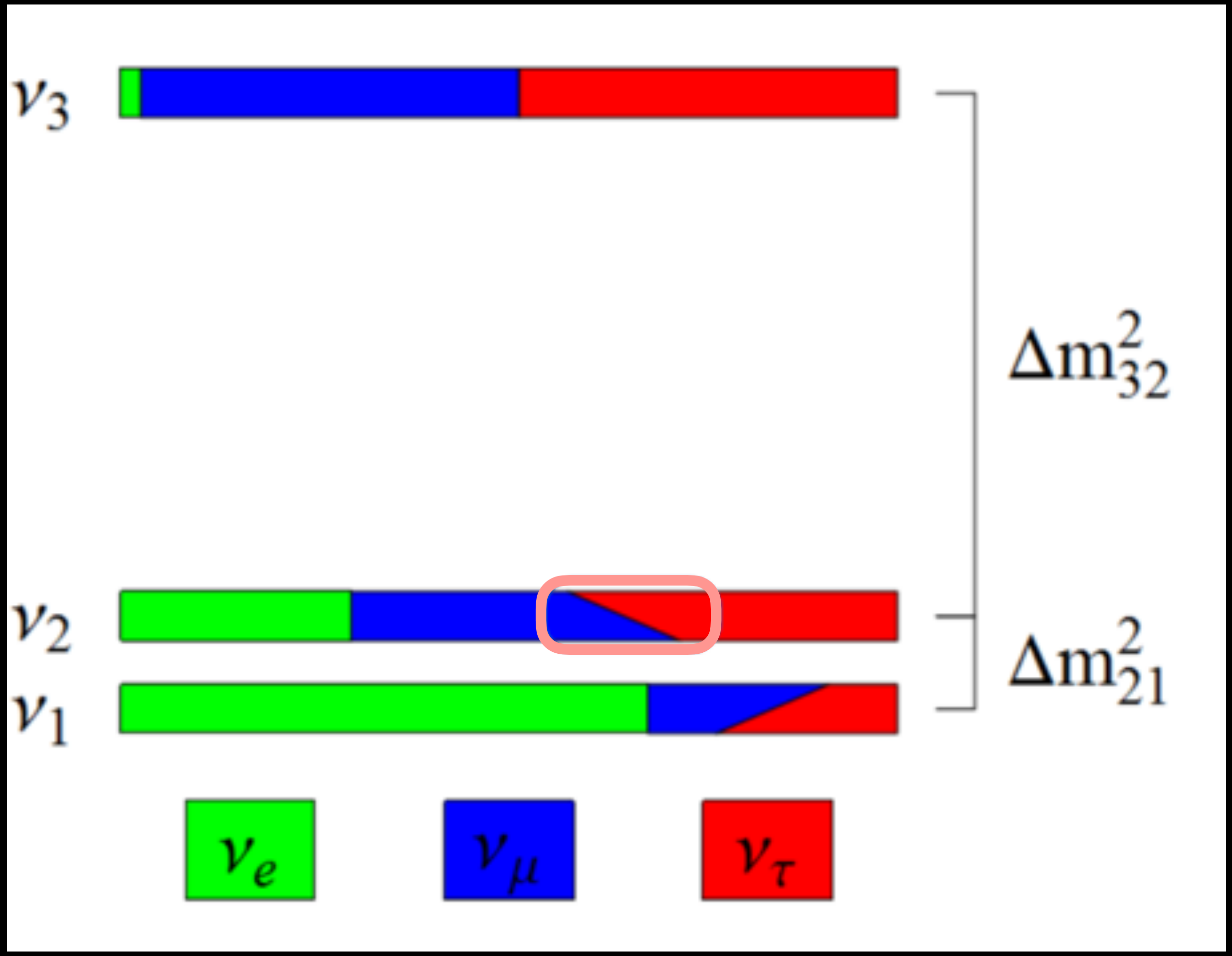
ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$





NOvA Physics Goal



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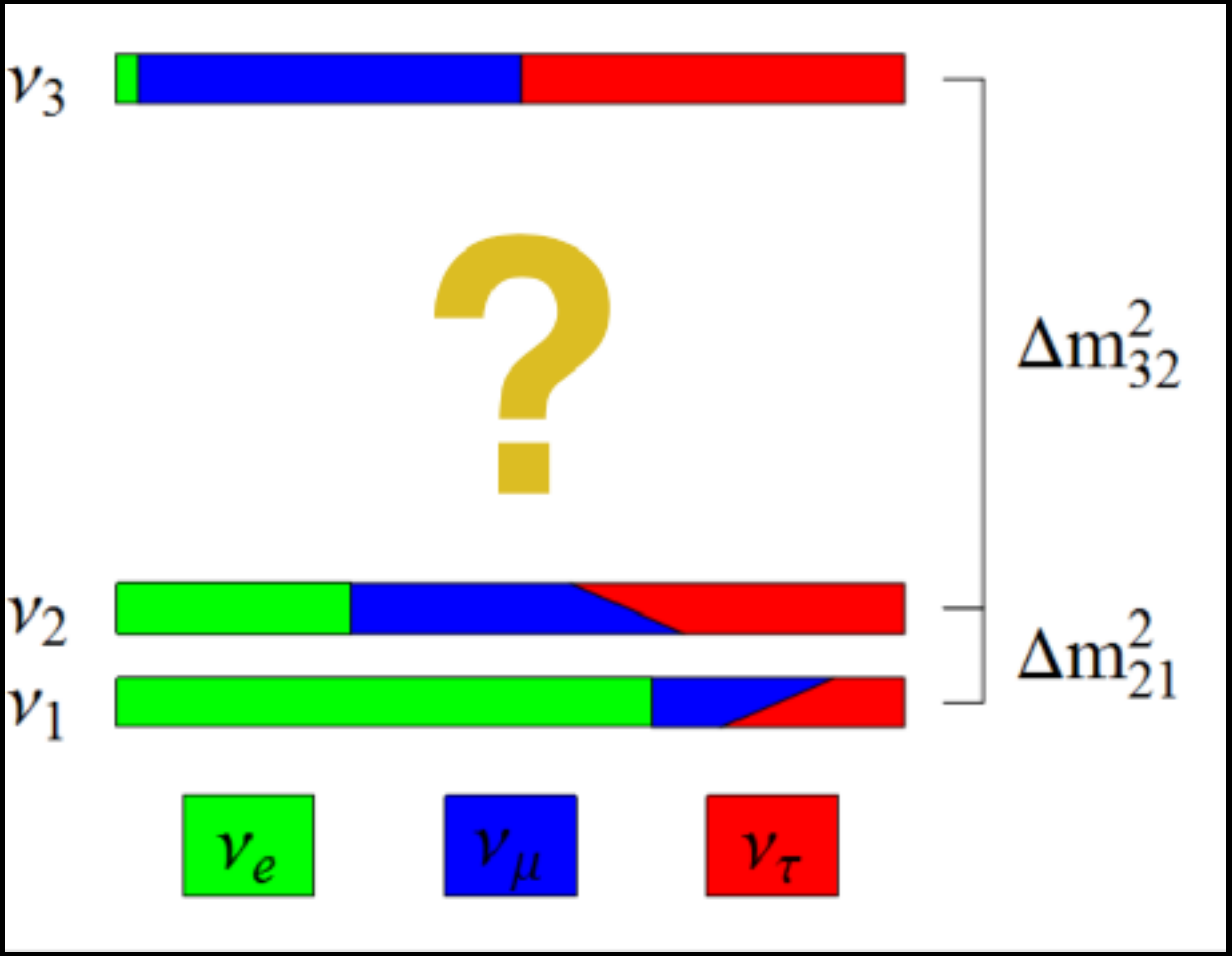

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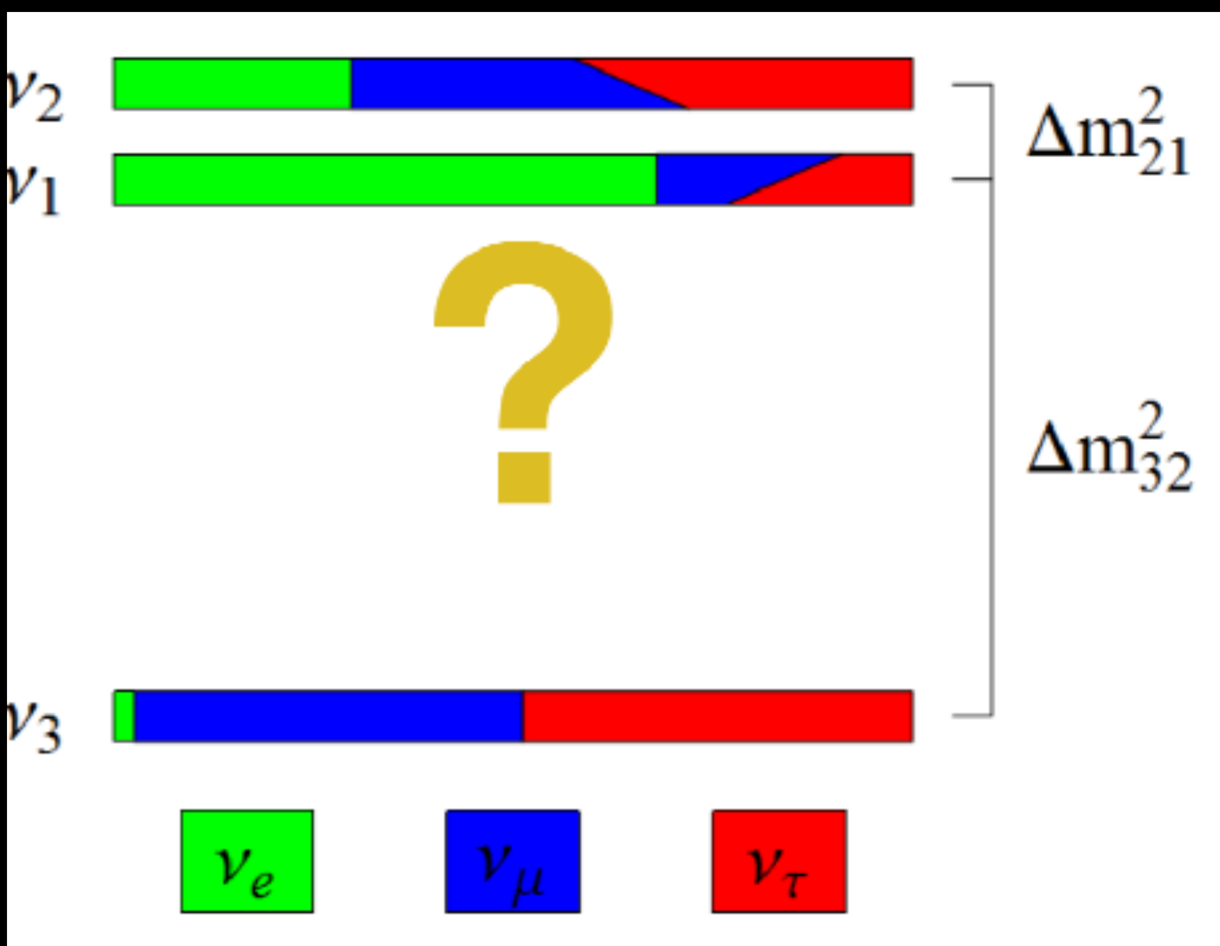


Precise measure ments:

- Δm^2_{32} and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

Strong constrains on:

- θ_{23} octant
- δ_{cp}
- **mass hierarchy**

ν_e Appearance

By measuring muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

- θ_{23} octant
- δ_{cp}
- mass hierarchy

$$P(\nu_\mu \rightarrow \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\frac{\Delta m^2_{32} L}{4E}+\delta_{CP})} + \sqrt{P_{sol}}|^2$$

$$\approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}(cos\delta m^2_{32} cos\delta_{cp} \mp sin\delta m^2_{32} sin\delta_{cp})$$

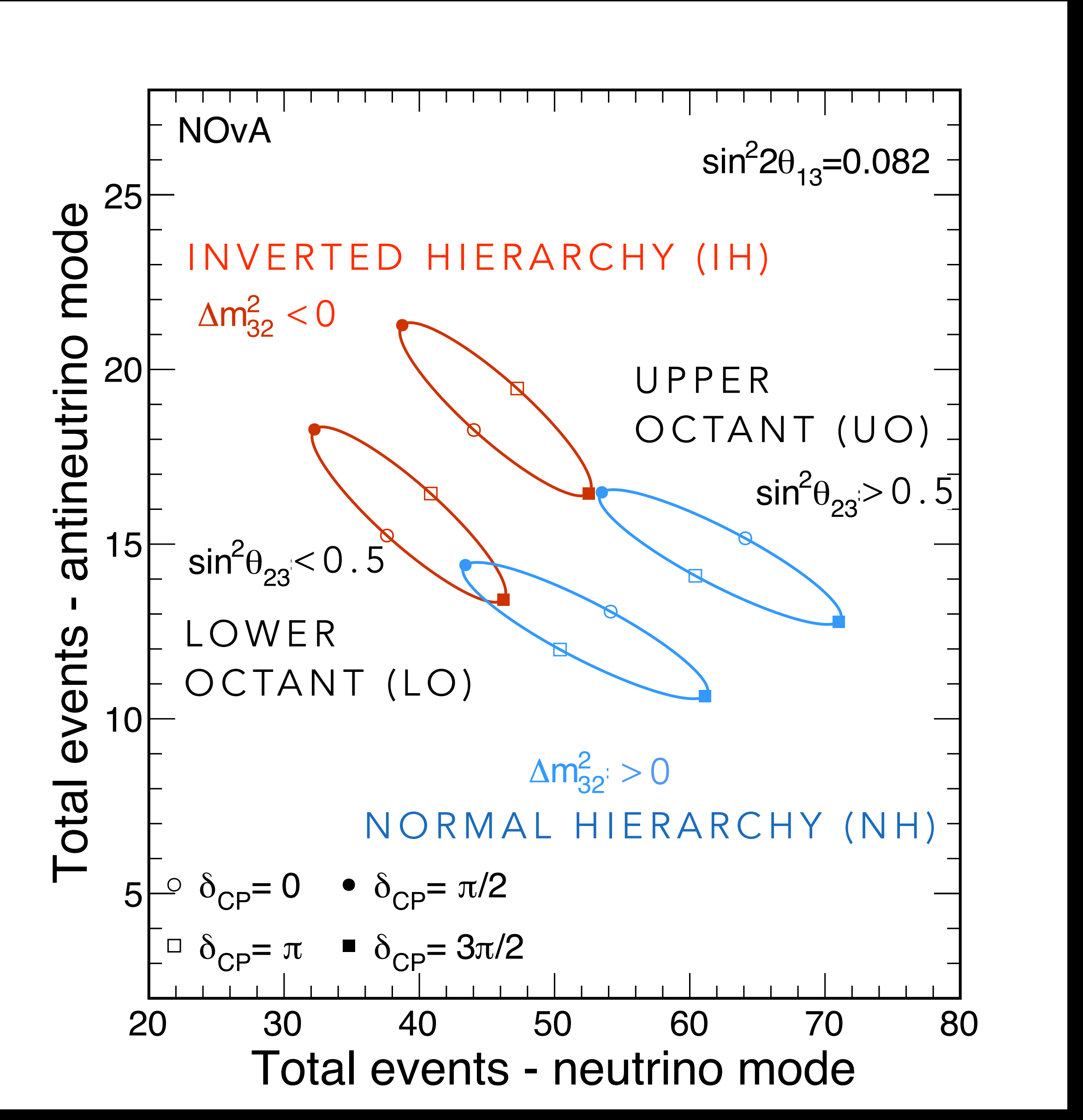
$$P_{atm} = sin^2\theta_{23} sin^2 2\theta_{13} sin^2 \frac{\Delta m^2_{31}}{4E}$$

Solar term contributes <1% at 400 L/E

- neutrino
+ anti-neutrino

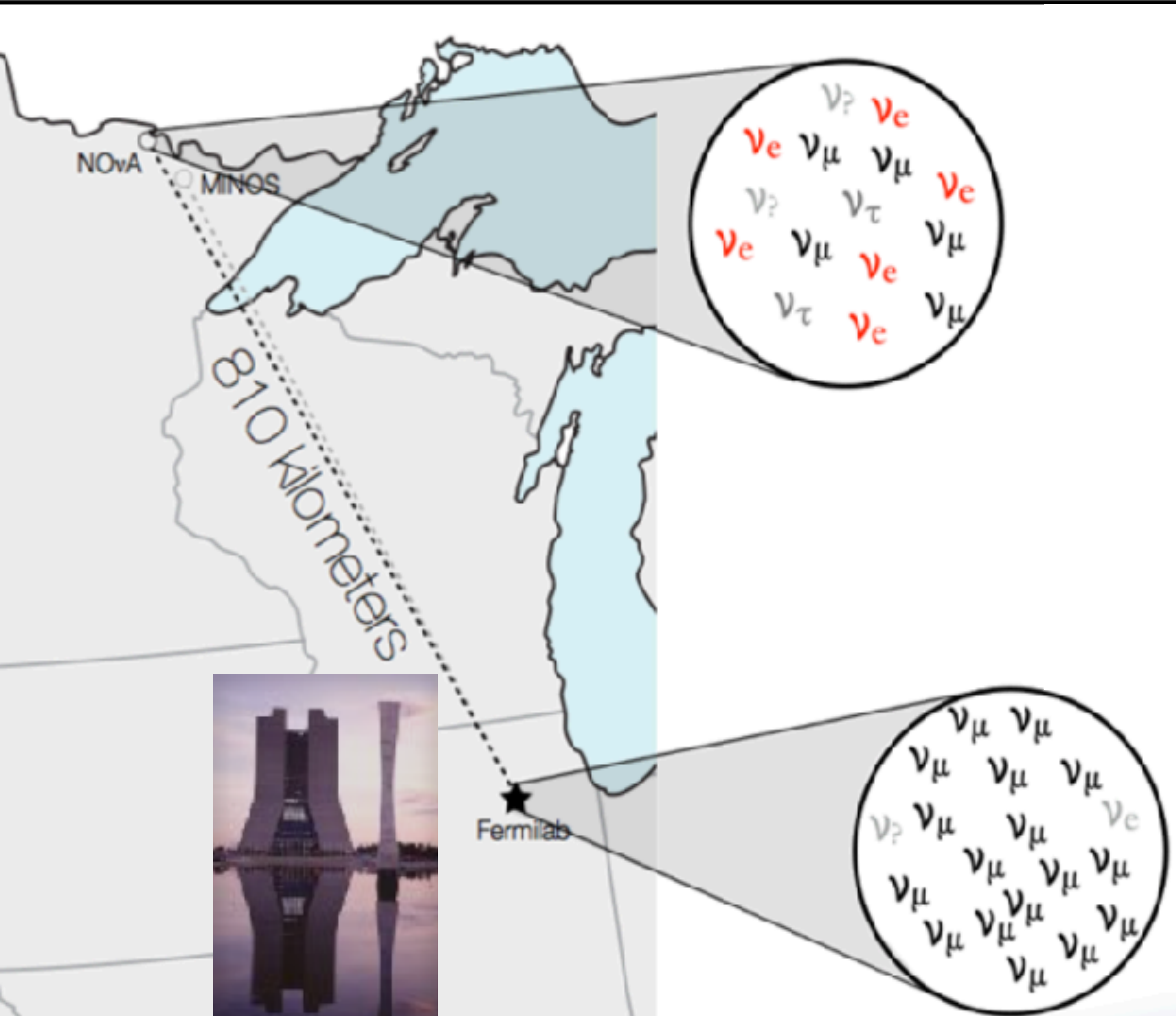
NOvA Physics Goal

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



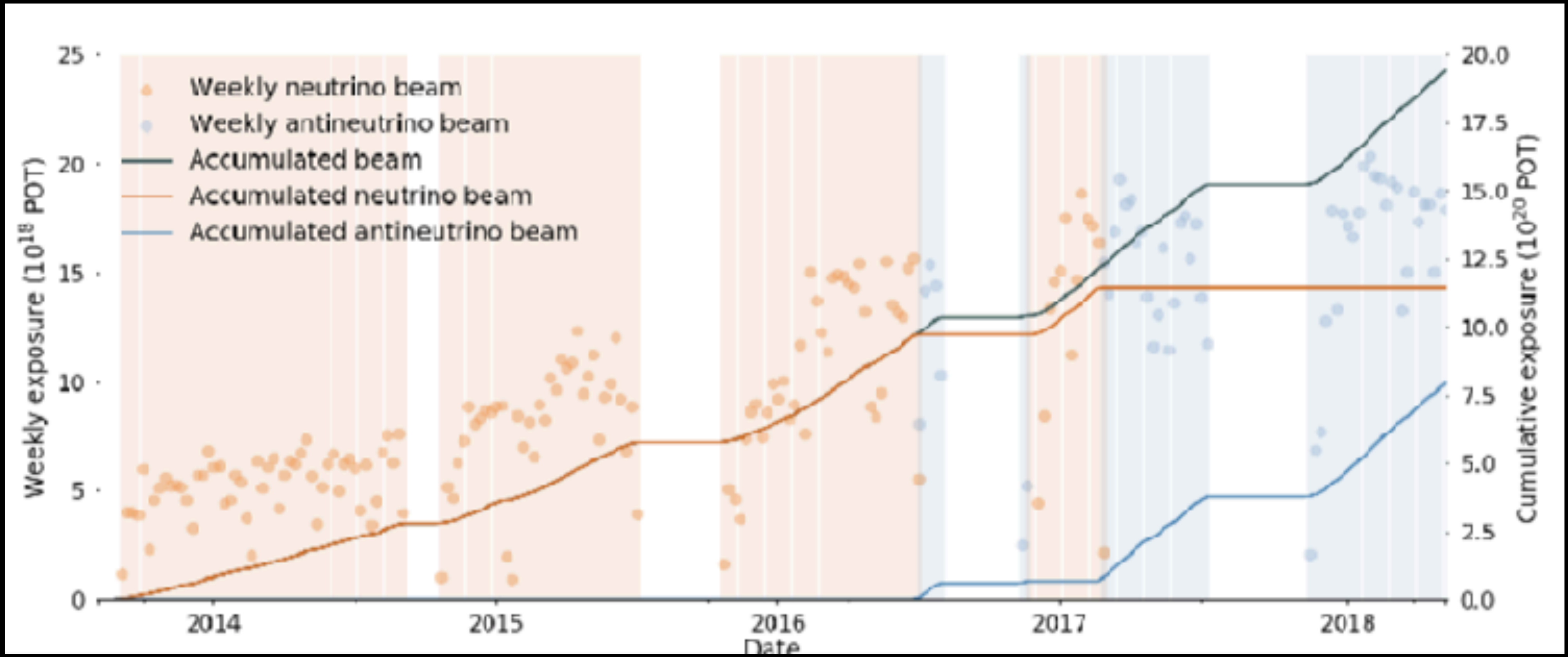
NEUTRINO AND ANTINEUTRINO DATA ARE REQUIRED

NOvA Overview



- Long-baseline neutrino oscillation experiment.
  - NuMI neutrino beam at Fermilab
  - Near Detector to measure the beam before oscillations
  - Far Detector measures the oscillated spectrum.
- Primary goal: measurement of 3-flavor oscillations via $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$
- Other goals include:
  - Searches for sterile neutrinos
  - Neutrino cross sections
  - Supernova neutrinos
  - Cosmic ray physics

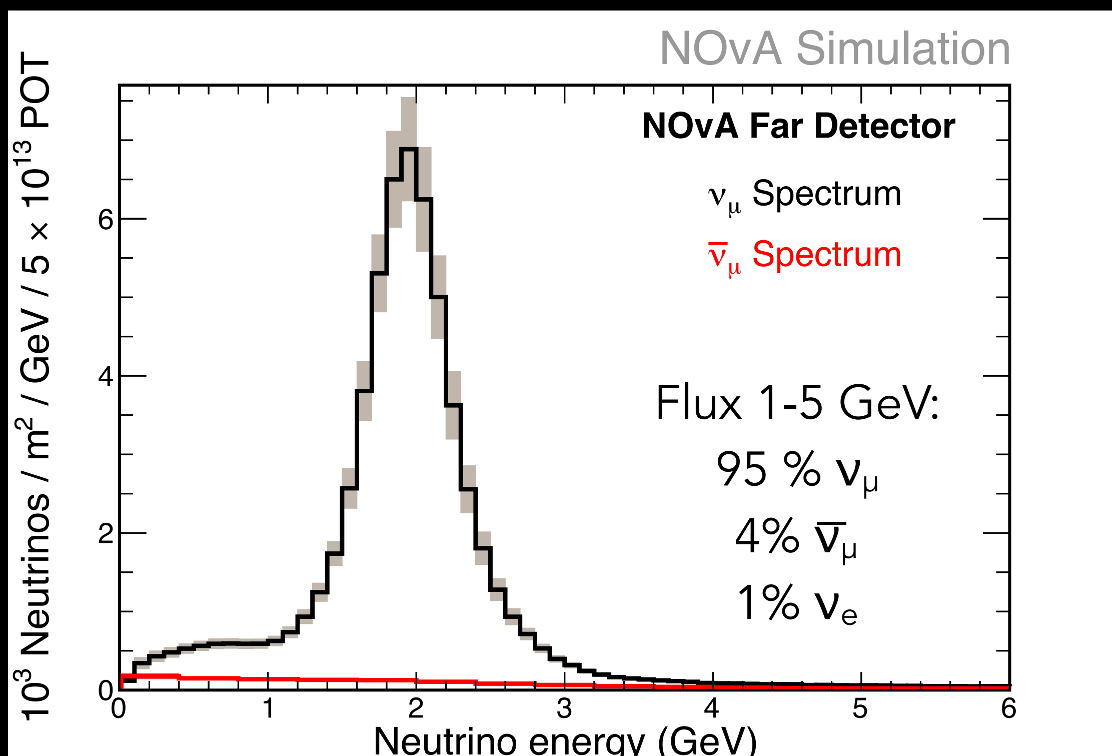
Neutrino and Anti-neutrino Beam Performance



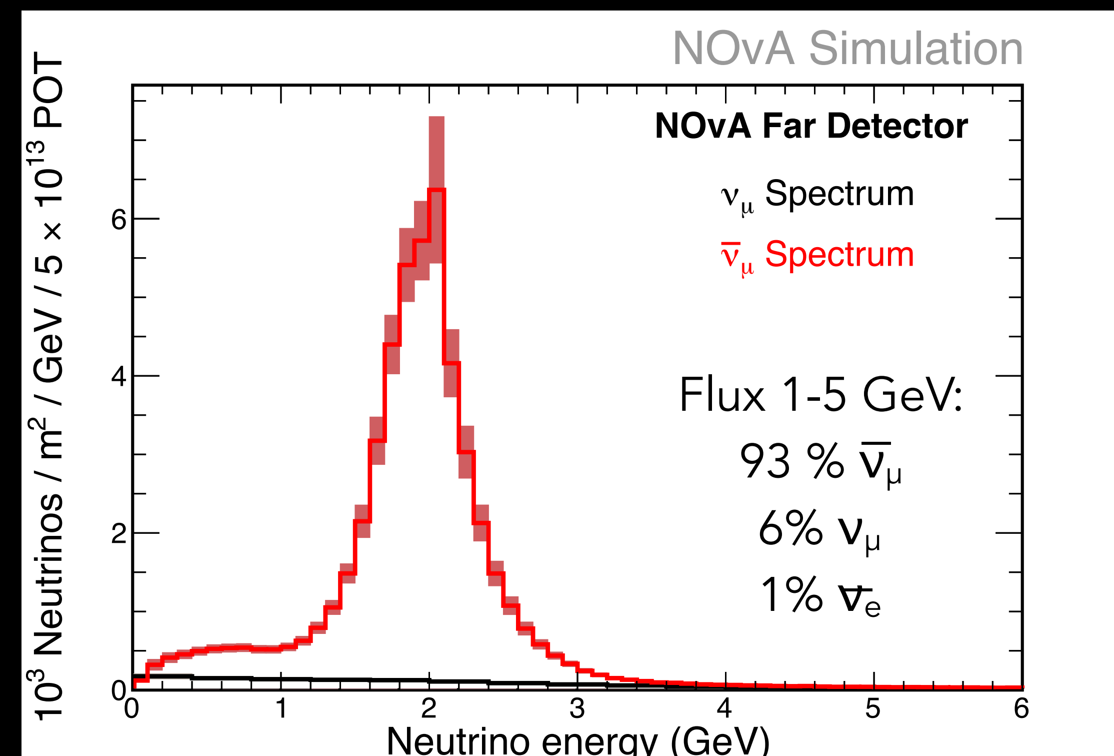
- NuMI beam running at 700 kW design power since January 2017. (> 18 * 10^{18} protons per week). Highest power neutrino beam in the World.
- Recorded neutrino-mode running 8.85 * 10^{20} protons on target (POT) in 14kton equivalent detector taken from February 2014 to February 2017.
- First antineutrino-mode running recorded between February 2017 to April 2018 resulting in 6.9 * 10^{20} POT.

Off-Axis NuMI Beam

Neutrino beam

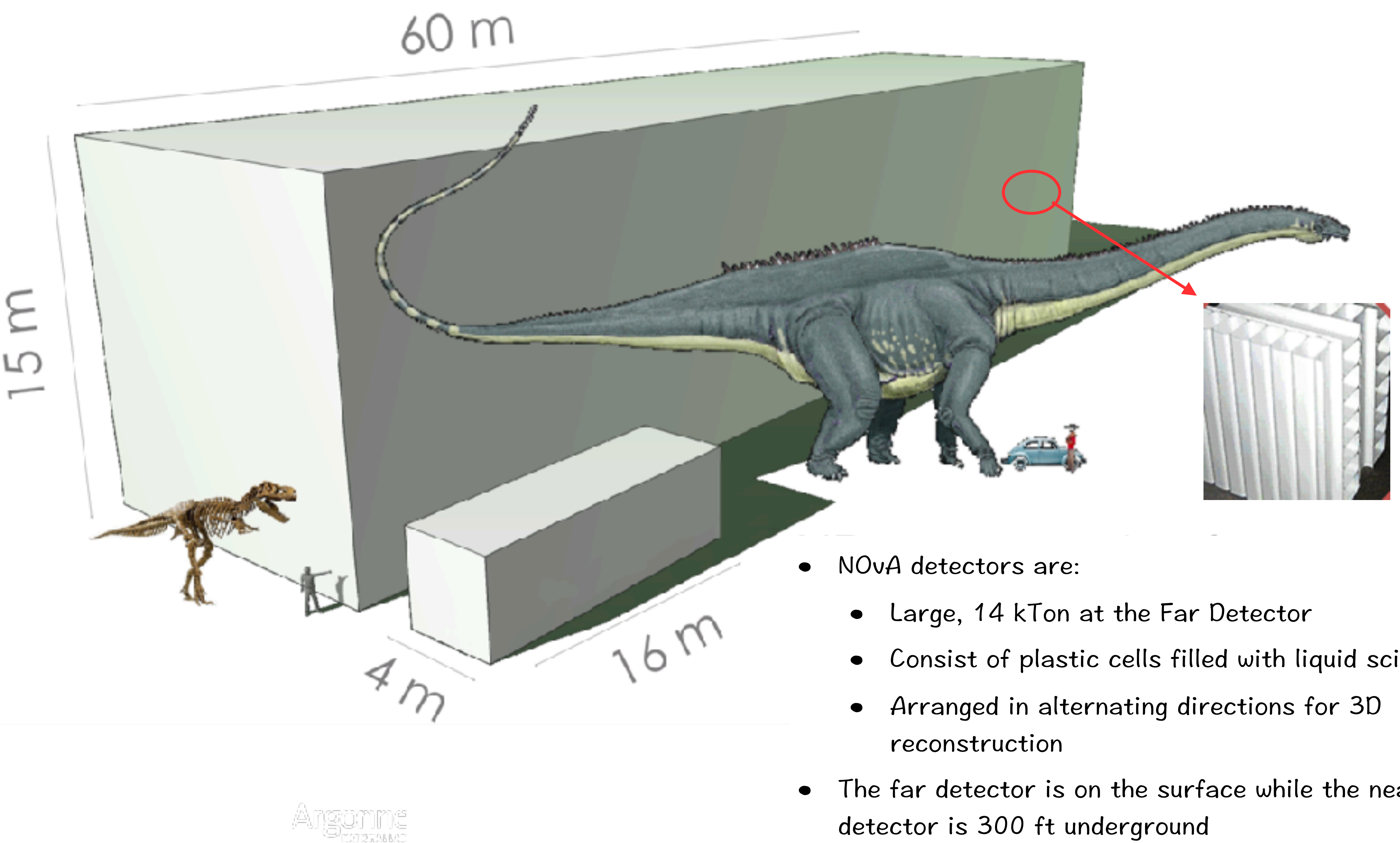


Antineutrino beam



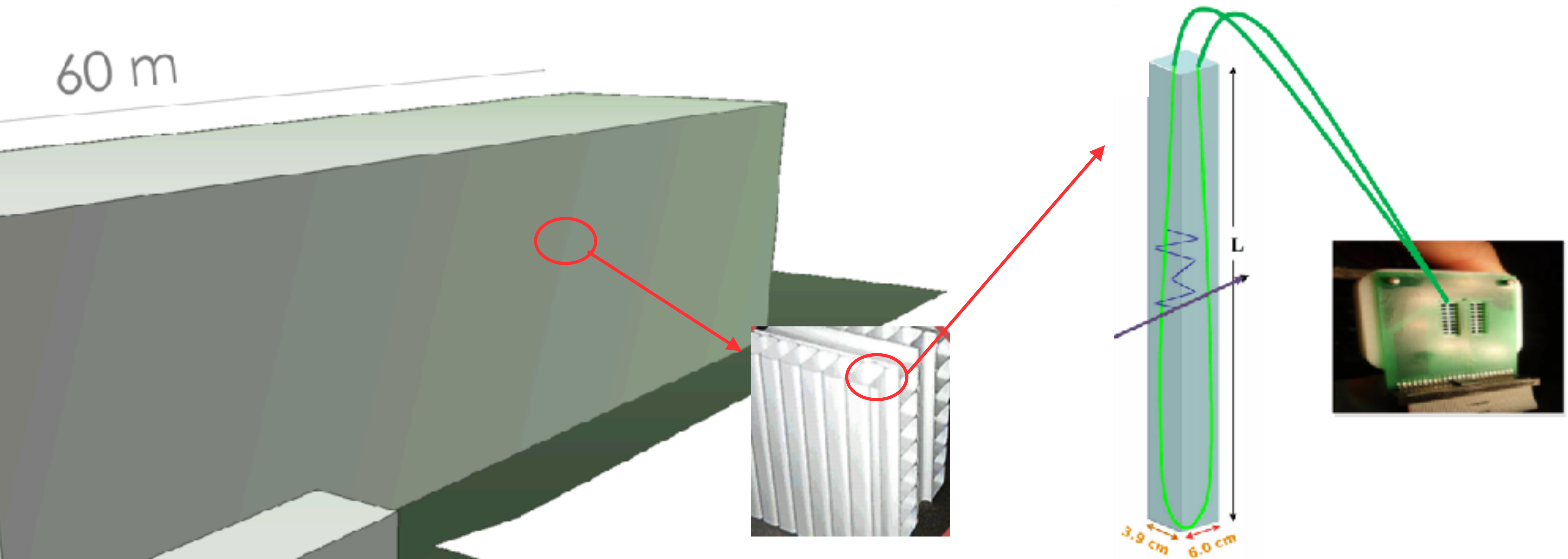
- Off-axis at 14 mrad, peaks just above the oscillation maximum. Small wrong sign component for both beams.
- The prediction of the NuMI beam at the NOvA detectors is made using the Package to Predict the FluX (PPFX), a method developed by MINERvA (Phys. Rev. D 94, 092005. 2016).
- The beam optics uncertainties are also incorporated by propagating the errors in the alignment of the beam-line elements such us the horn and NuMI target geometries, magnetic fields, etc.

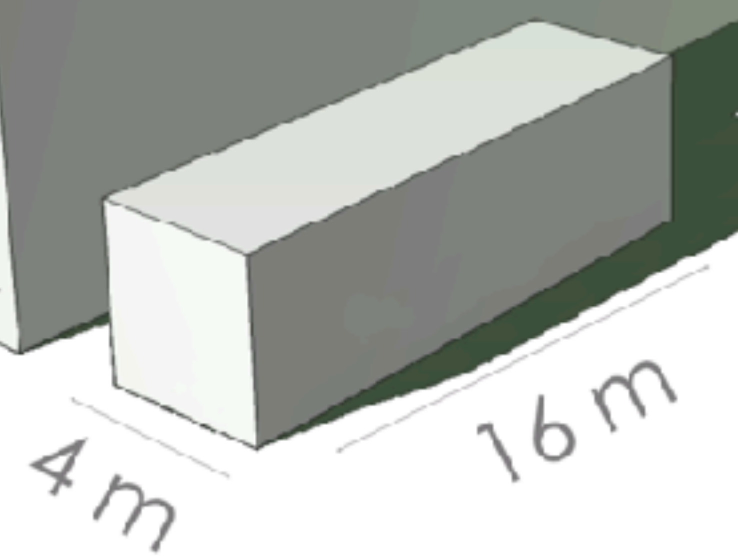
NOvA Detectors



- NOvA detectors are:
  - Large, 14 kTon at the Far Detector
  - Consist of plastic cells filled with liquid scintillator
  - Arranged in alternating directions for 3D reconstruction
- The far detector is on the surface while the near detector is 300 ft underground

NOvA Detectors

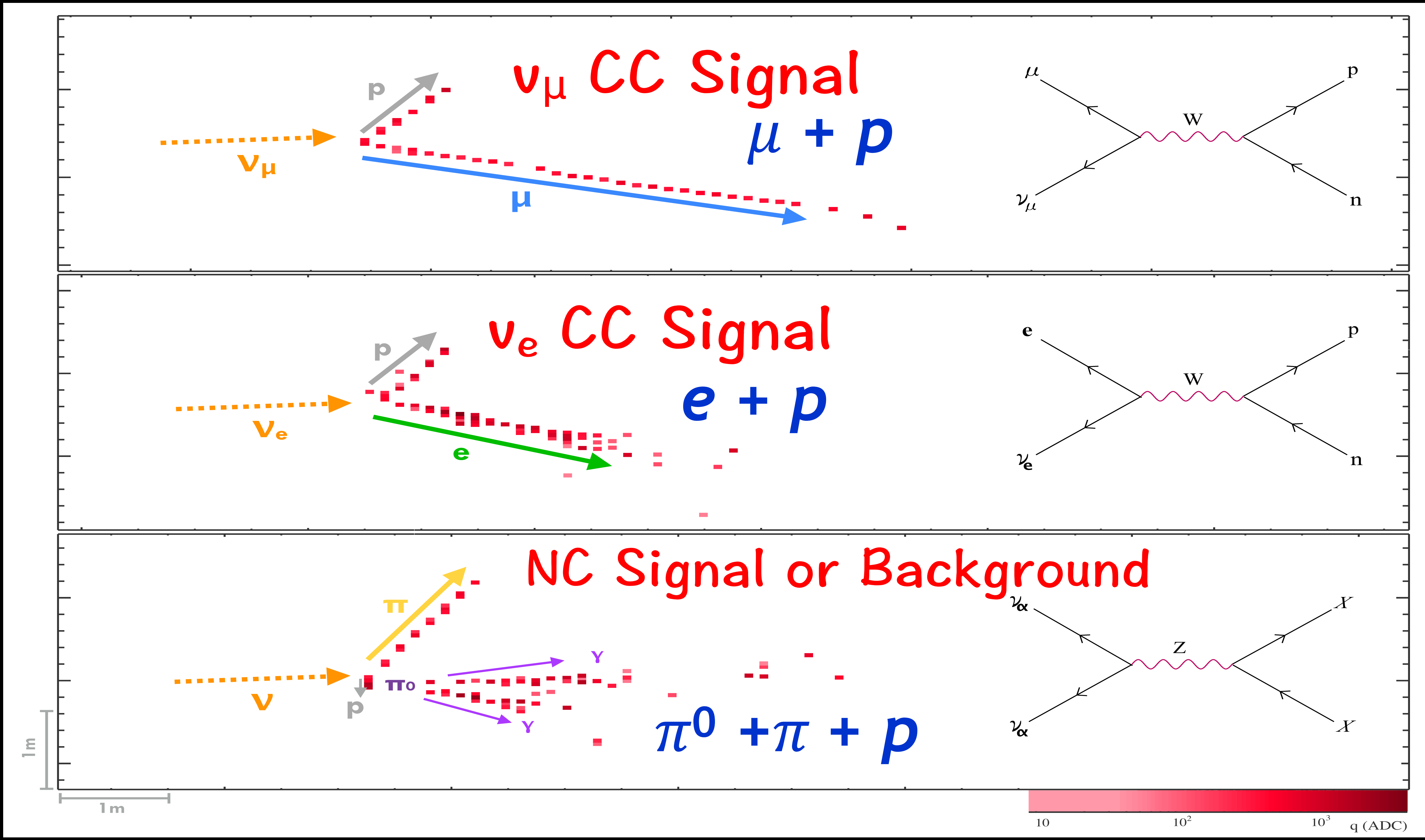




- Light is produced when charged particles pass through the cells
- The light is picked up by a wavelength shifting fiber.
- It is then transported to an Avalanche PhotoDiode where the light is collected and amplified

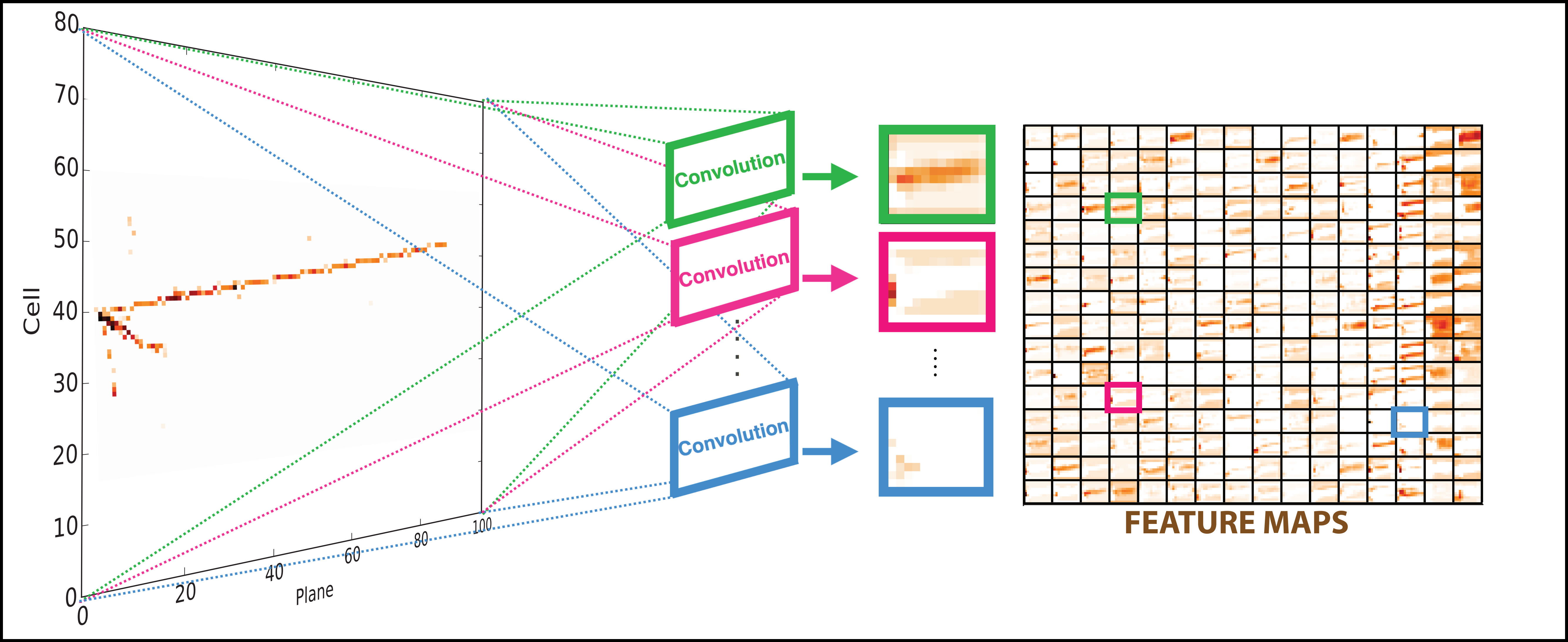
NOvA Event Topology

neutrino candidate

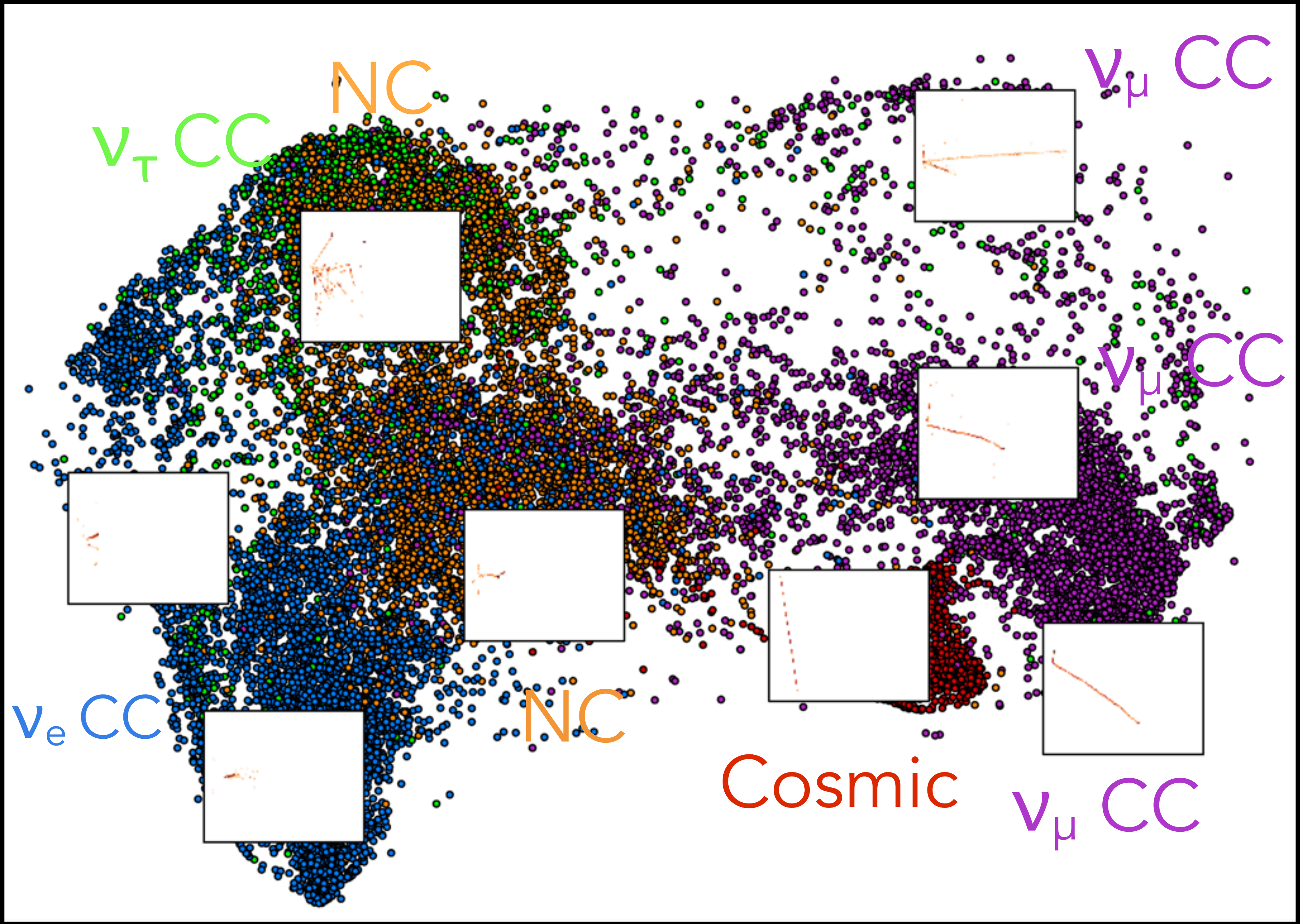


Neutrino Interaction Classifier

- NOvA has pioneered the use of Convolutional Neural Networks (CNN) for particle classification in neutrino physics.
- Using this technique we treat each interaction as an image with cells as pixels and charge as color value. The convolutional layers optimally extract features from the data.
- The NOvA architecture is a multi-classifier, assigning an output ID: ν_μ CC, ν_e CC, NC, cosmic for each interaction. New in this version, output per particle multiplicity.



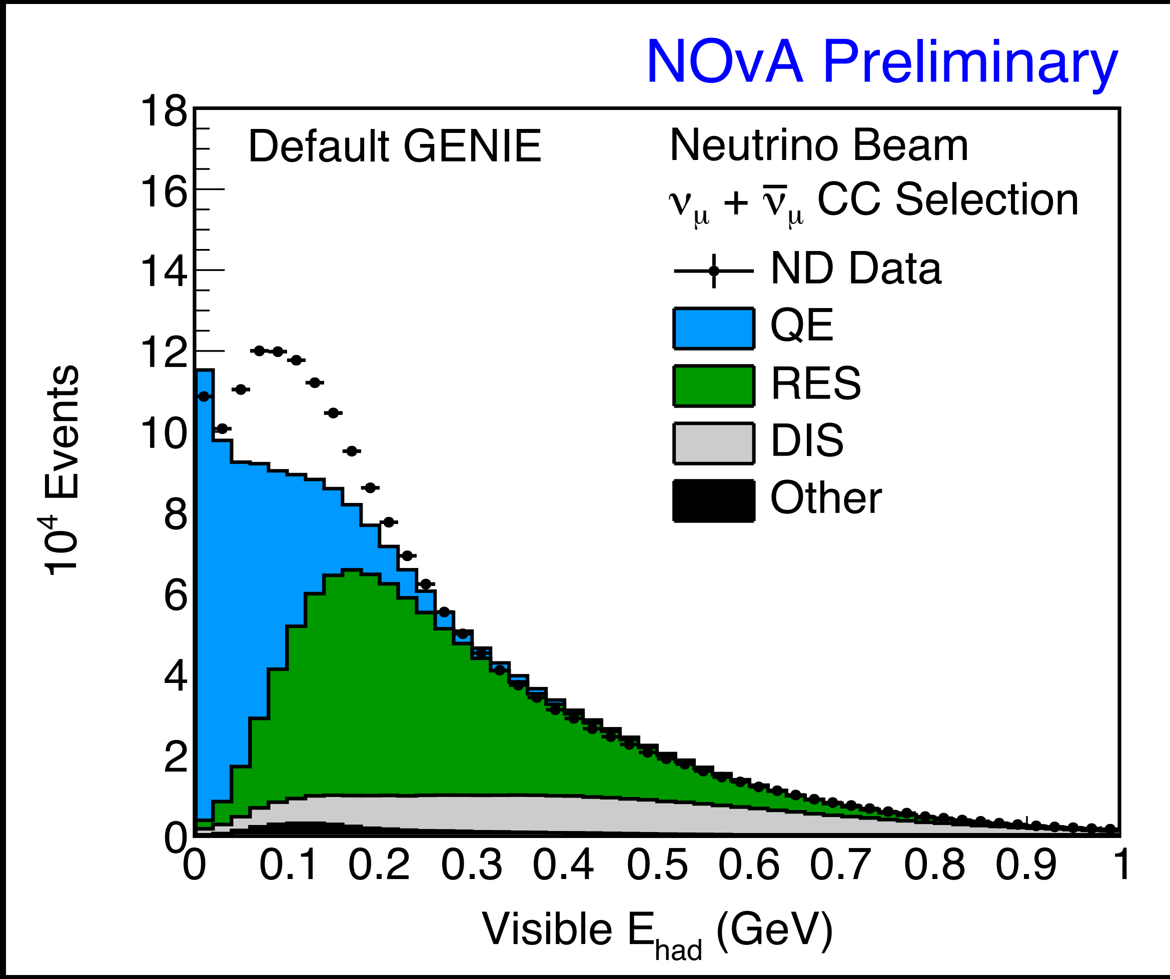
Neutrino Interaction Classifier



FOR ALL 2018 OSCILLATION ANALYSES: NEW PARTICLE ID USED WITH DIFFERENT OPTIMIZATIONS, TRAINED FOR NEUTRINO AND ANTINEUTRINO BEAM SEPARATELY, COSMIC DATA INCLUDED IN TRAINING.

Neutrino Interaction Tuning

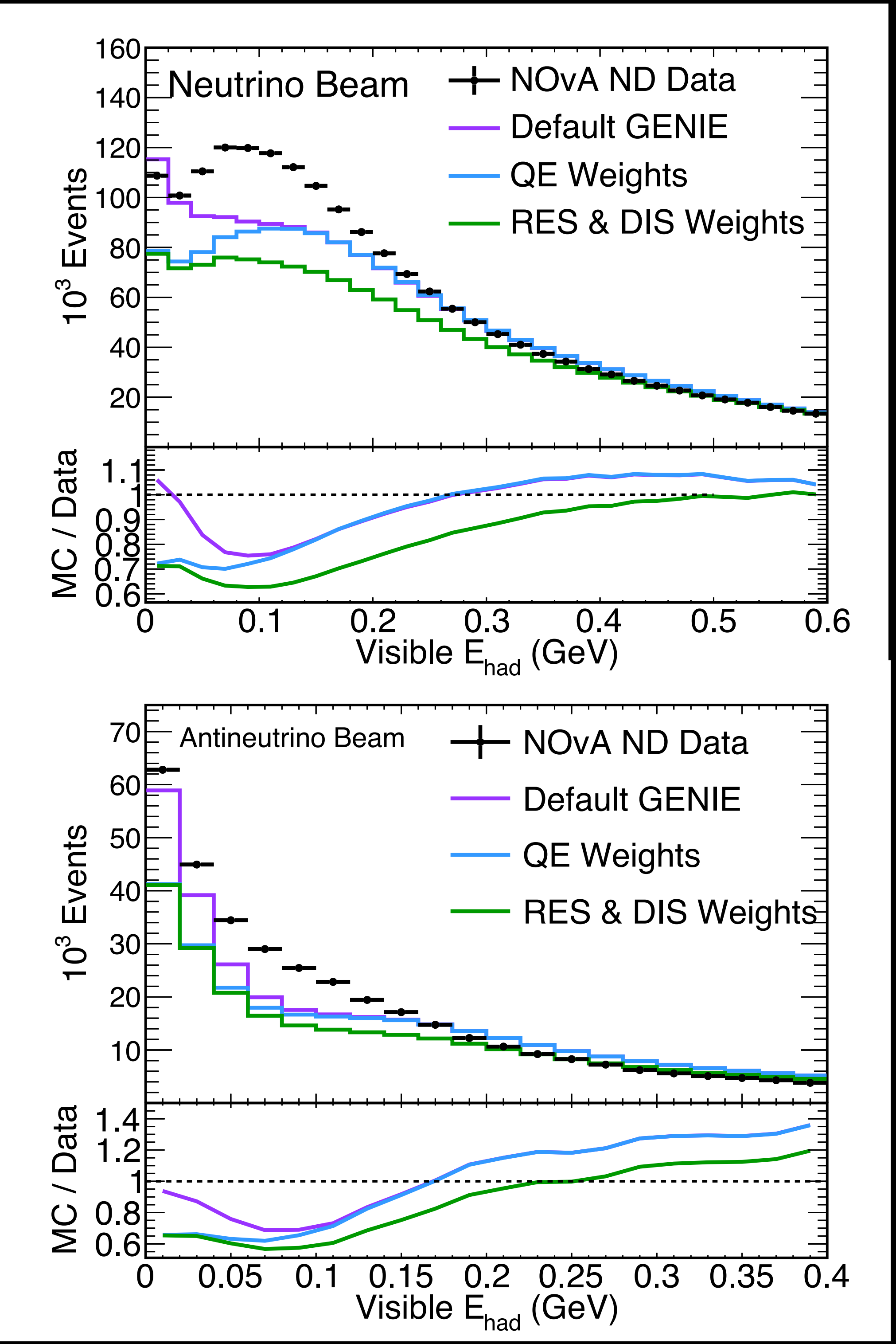
- The Default GENIE prediction is insufficient to describe NOvA ND data, e.g. the hadronic energy in ν_μ CC interactions show disagreement with the default simulation.
- Discrepancies thought to be due largely to complications of interactions in complex nuclear environment.



WE USE NOVA AND EXTERNAL INFORMATION TO TUNE THE MODEL TO OBTAIN BETTER CENTRAL VALUES AND APPROPRIATE UNCERTAINTIES

Neutrino Interaction Tuning

- The tuning is done independently for the neutrino vs antineutrino beam samples.
- Various corrections and tunings are applied:
  - Correct quasi-elastic (QE) component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
  - Apply same long-range effect as for QE to resonant (RES) baryon production.
  - Non-resonant inelastic scattering (DIS) at high invariant mass ($W>1.7$ GeV/c^2) weighted up 10% **based on NOvA data.**

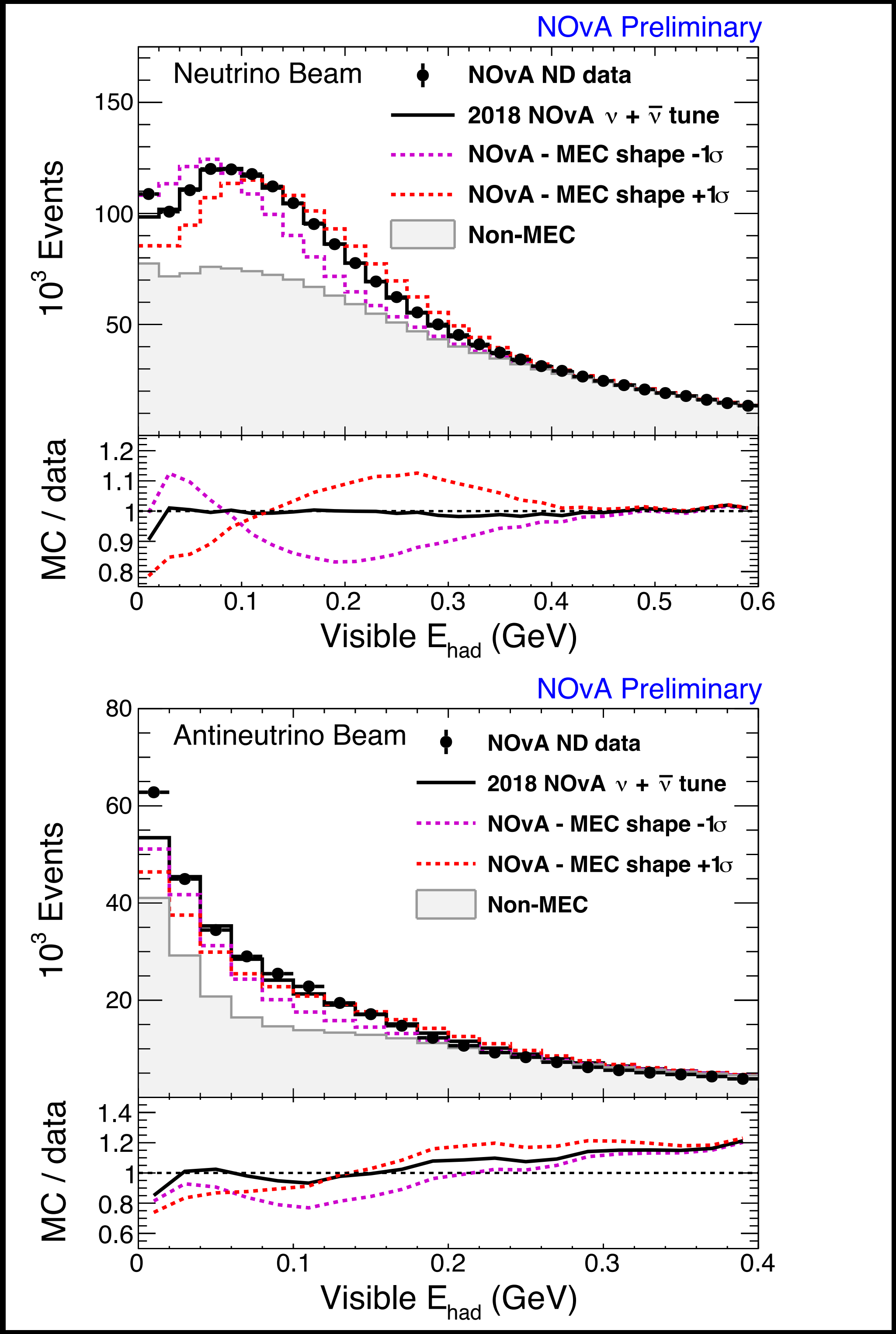


Neutrino Interaction Tuning

- Introduce custom tuning of GENIE "Empirical MEC" [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] **based on NOvA ND data** to account for multi-nucleon knockout (2p2h).

- This tuning procedure matches the added 2p2h component to the NOvA data excess in two-dimensional four-momentum transfer (q0,|**q**|) space using closely related observables.

- Shape uncertainty on the NOvA 2p2h tune is established by re-fitting using variation of the model with correlated systematic shifts to QE and RES.



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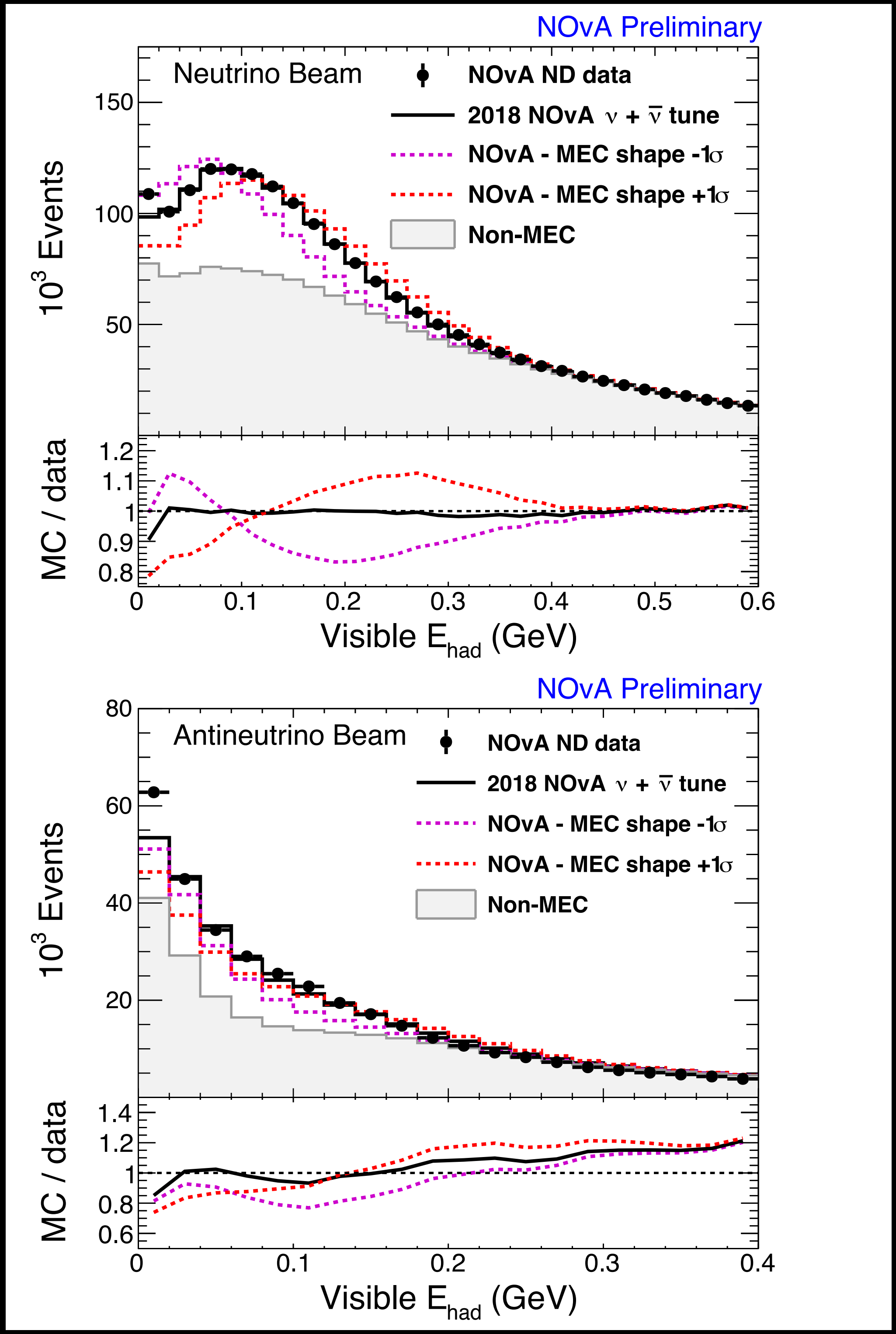
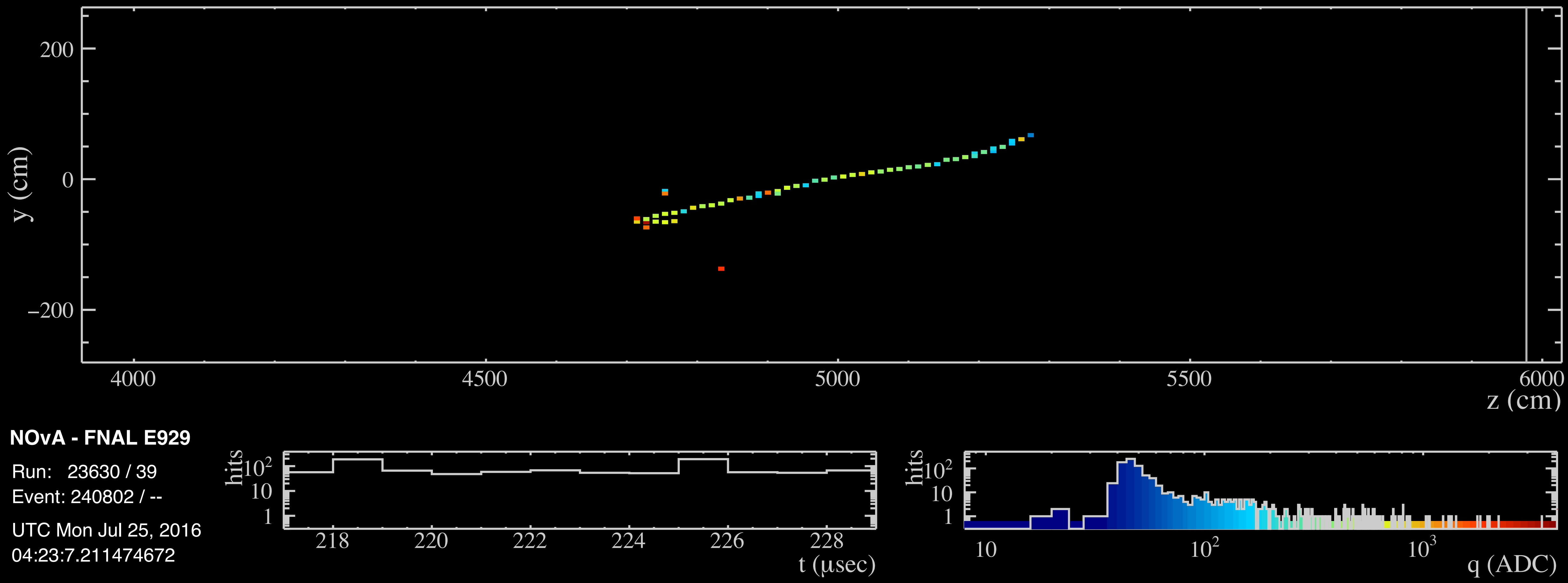
- This tuning procedure matches the added 2p2h component to the NOvA data excess in two-dimensional four-momentum transfer (q0,|**q**|) space using closely related observables.
- The MINERvA collaboration's tuning to their data resulted in similar shape features to our assumed uncertainties.



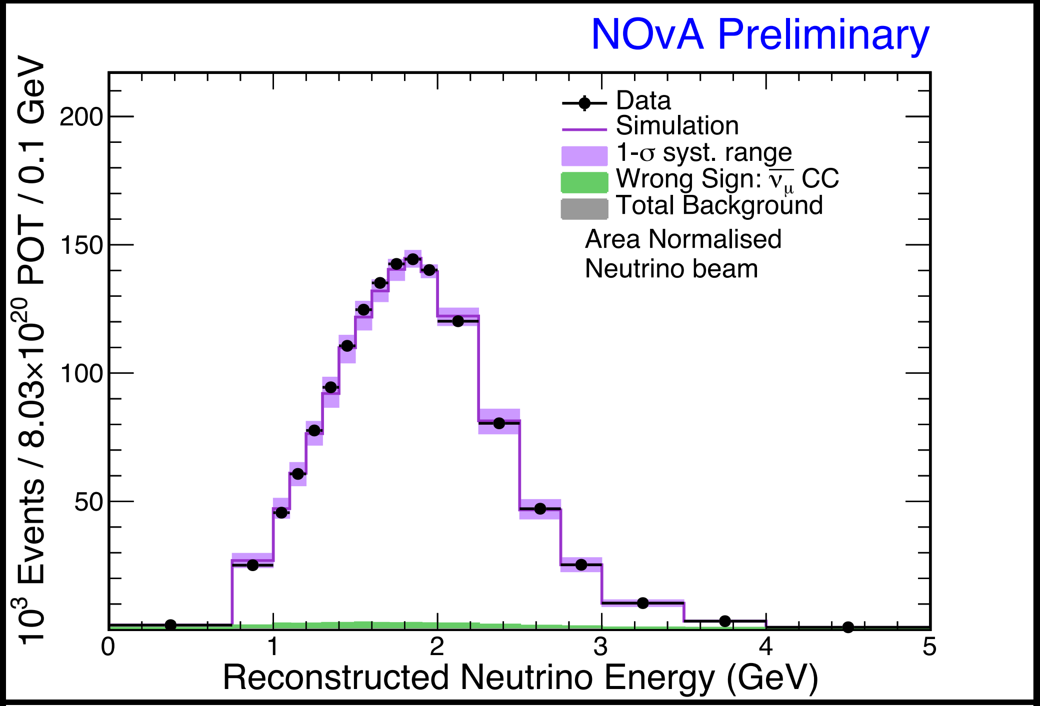
Is there a ν_μ - ν_τ symmetry?

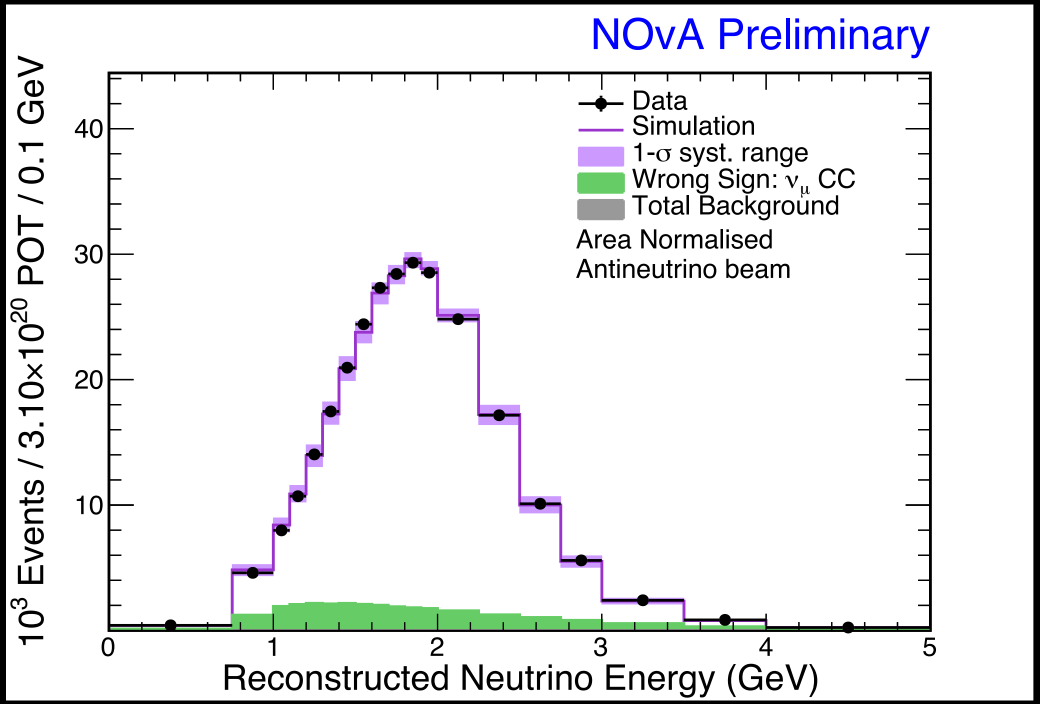
MUON NEUTRINO AND ANTINEUTRINO DISAPPEARANCE



Near Detector Beam Spectra

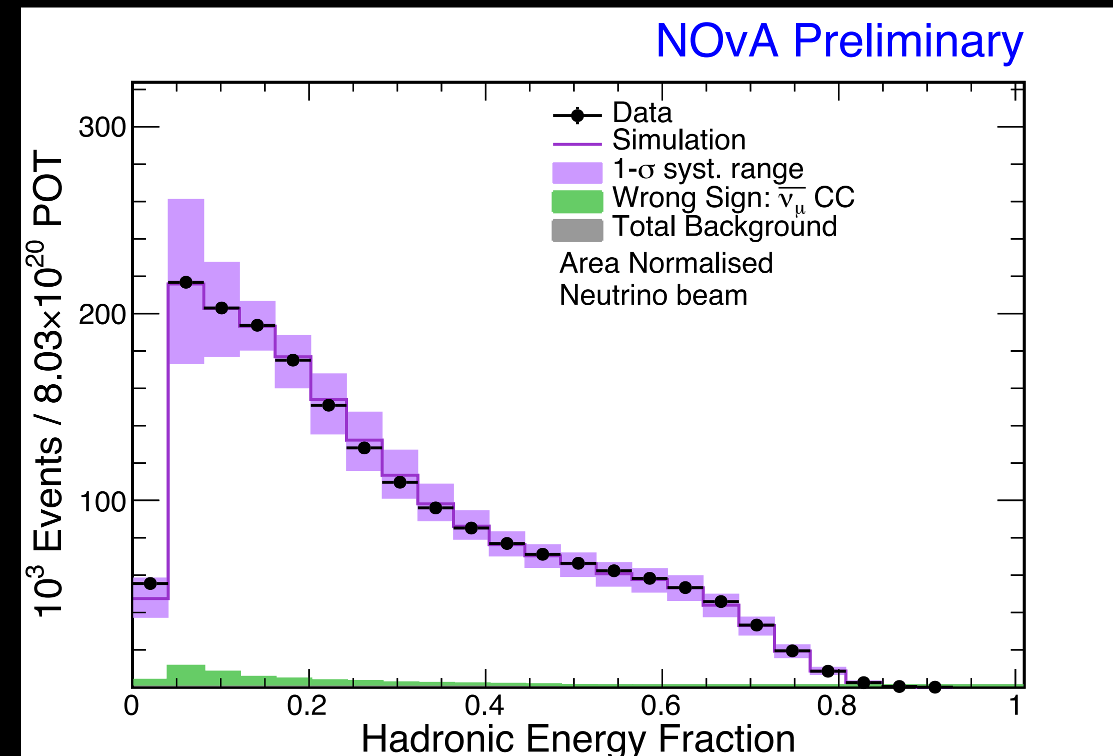
- Selected muon neutrino and antineutrino charged current interactions in ND.
  - Reconstructed neutrino energy is estimated from muon length and hadronic energy.
- Wrong sign contamination in ND is estimated to be 3% for neutrino beam and 11% for antineutrino beam.
- Systematic uncertainties shown are shape only, 1.3% and 0.5% offset for neutrinos and antineutrinos respectively is removed for display purposes.

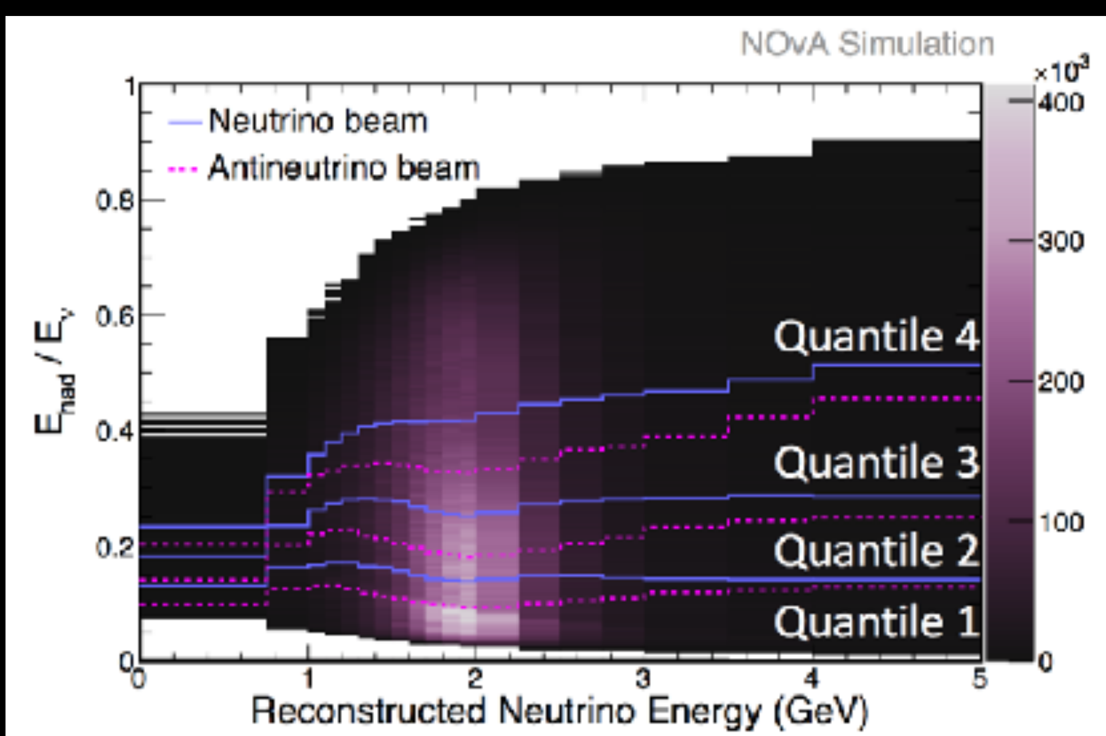


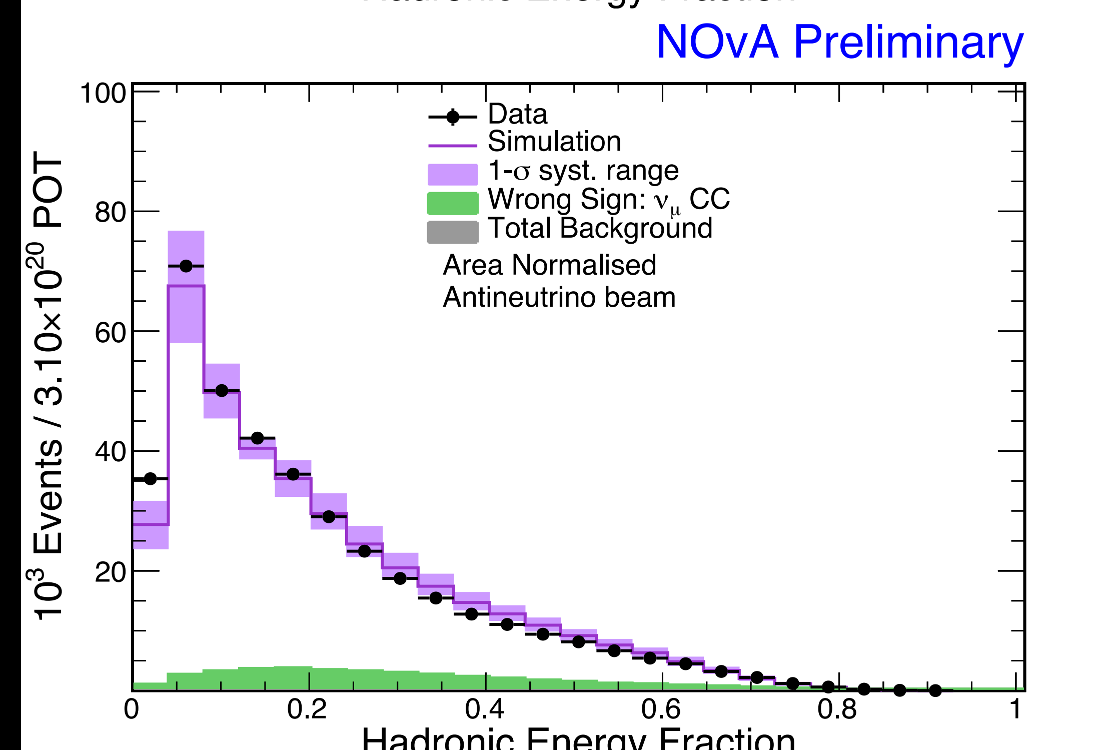


Energy Resolution Quantiles

- The data is split into four equal populations(quantiles) of hadronic energy fraction as a function of reconstructed neutrino energy.
- Done separately for neutrino versus antineutrinos
- Energy resolution varies from 5.8%(5.5%) to 11.7%(10.8%) for neutrino(antineutrino) beam.

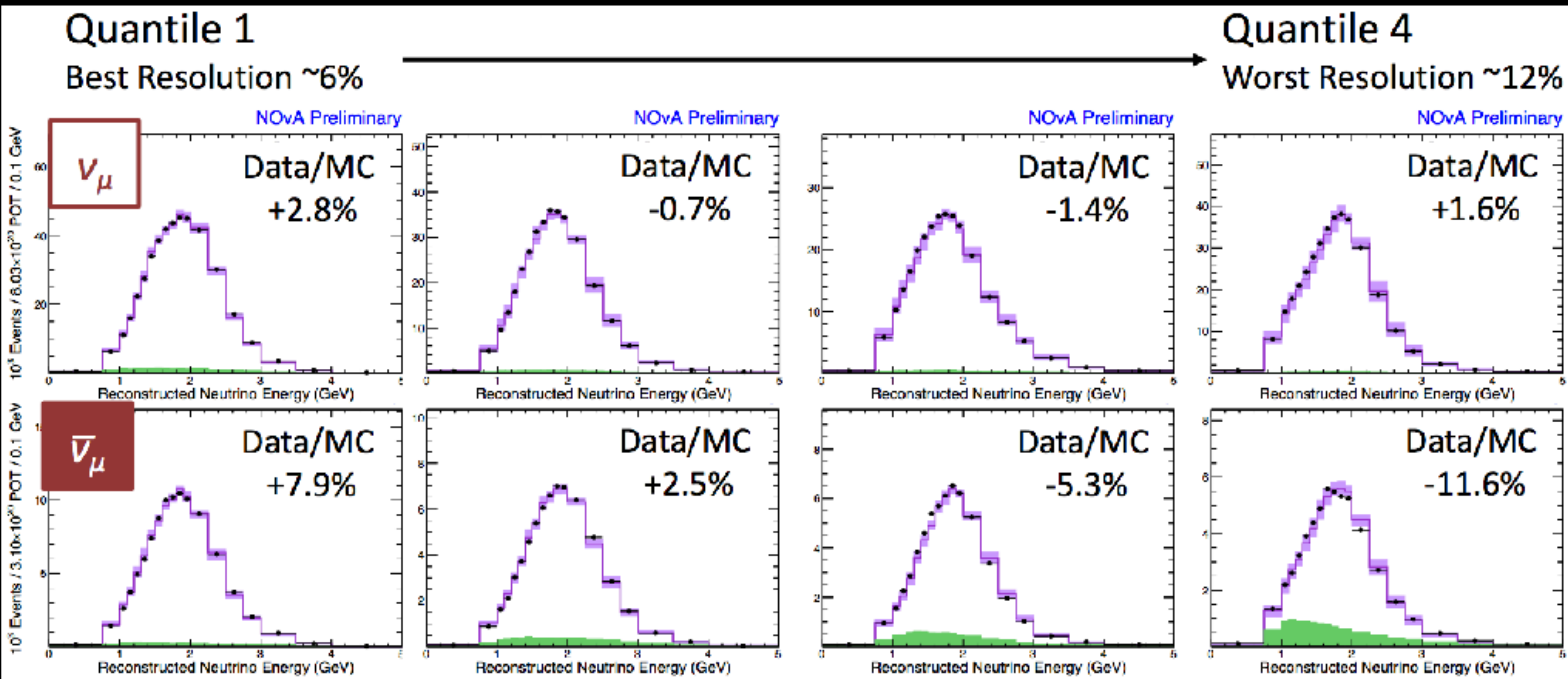






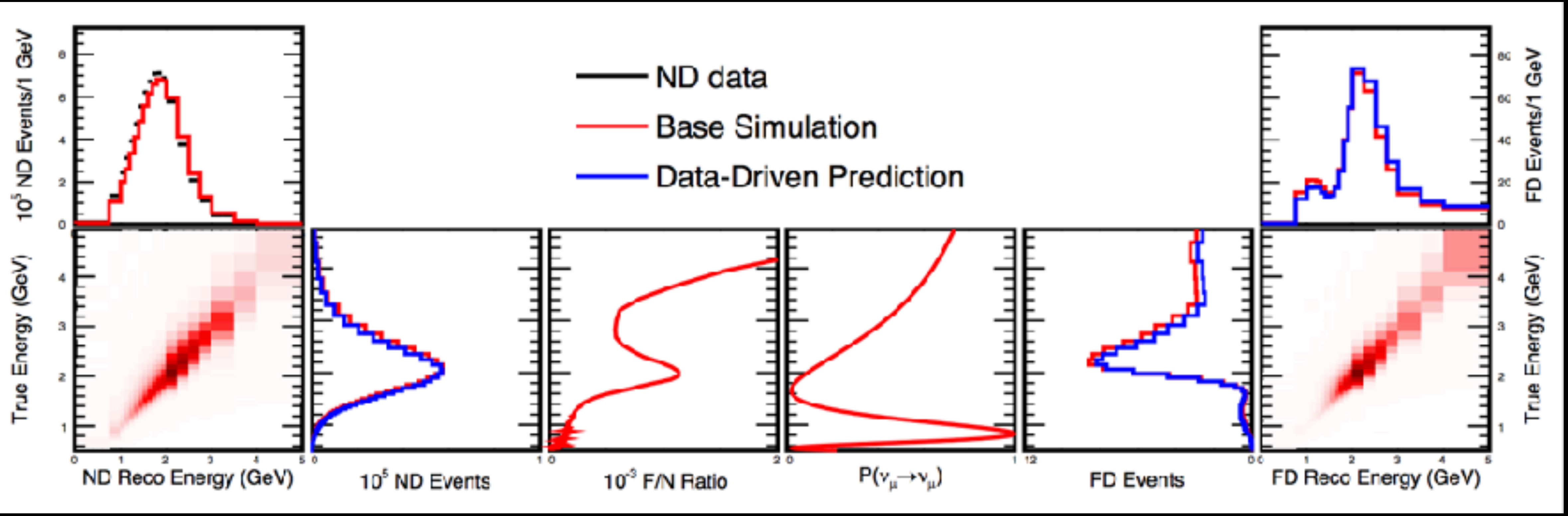
Prediction the FD Observation

- 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.



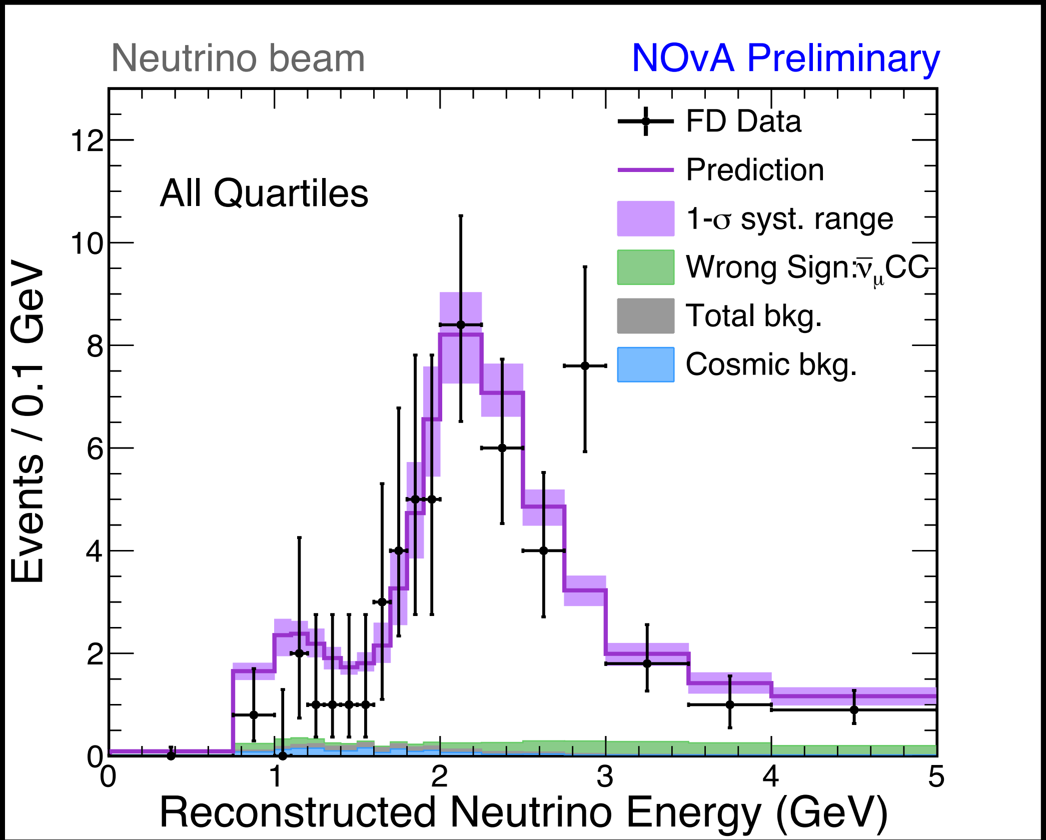
Prediction the Far Detector Observations

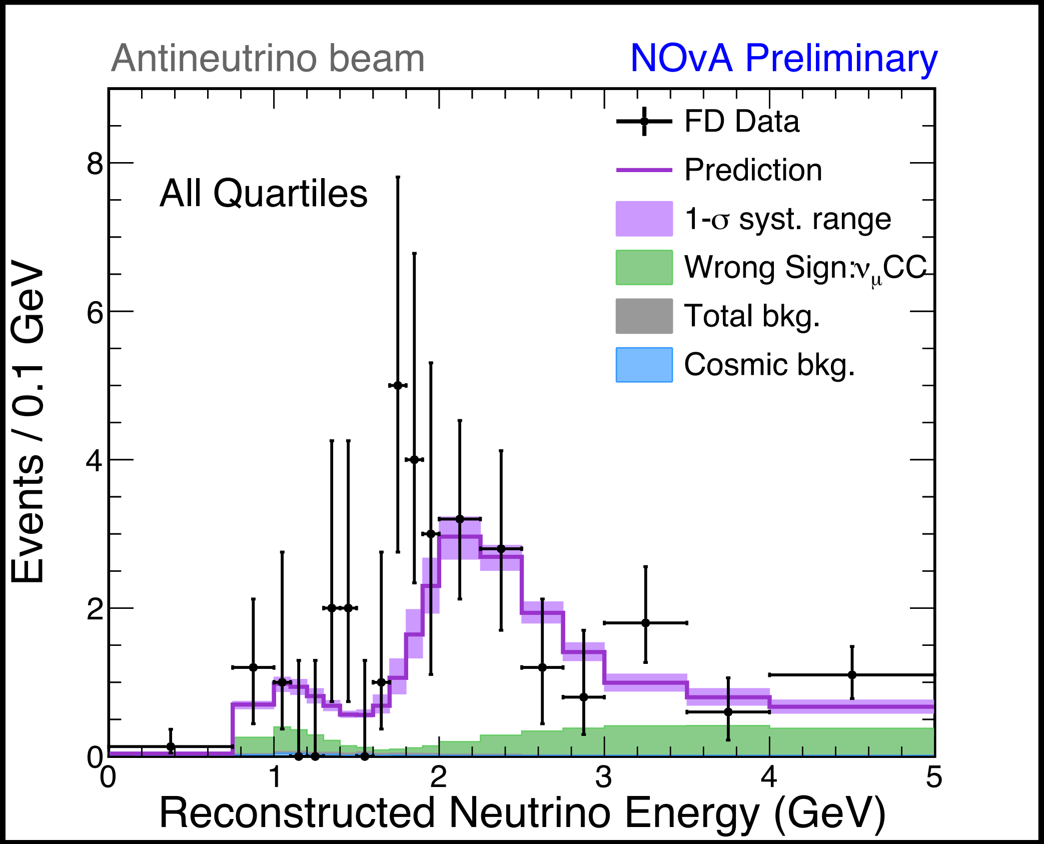
- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
- The measured spectrum is used to make a prediction of the expectation at the FD using the Far/Near ratio.
- Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.



Prediction the FD Observation

- We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and cosmic trigger data.

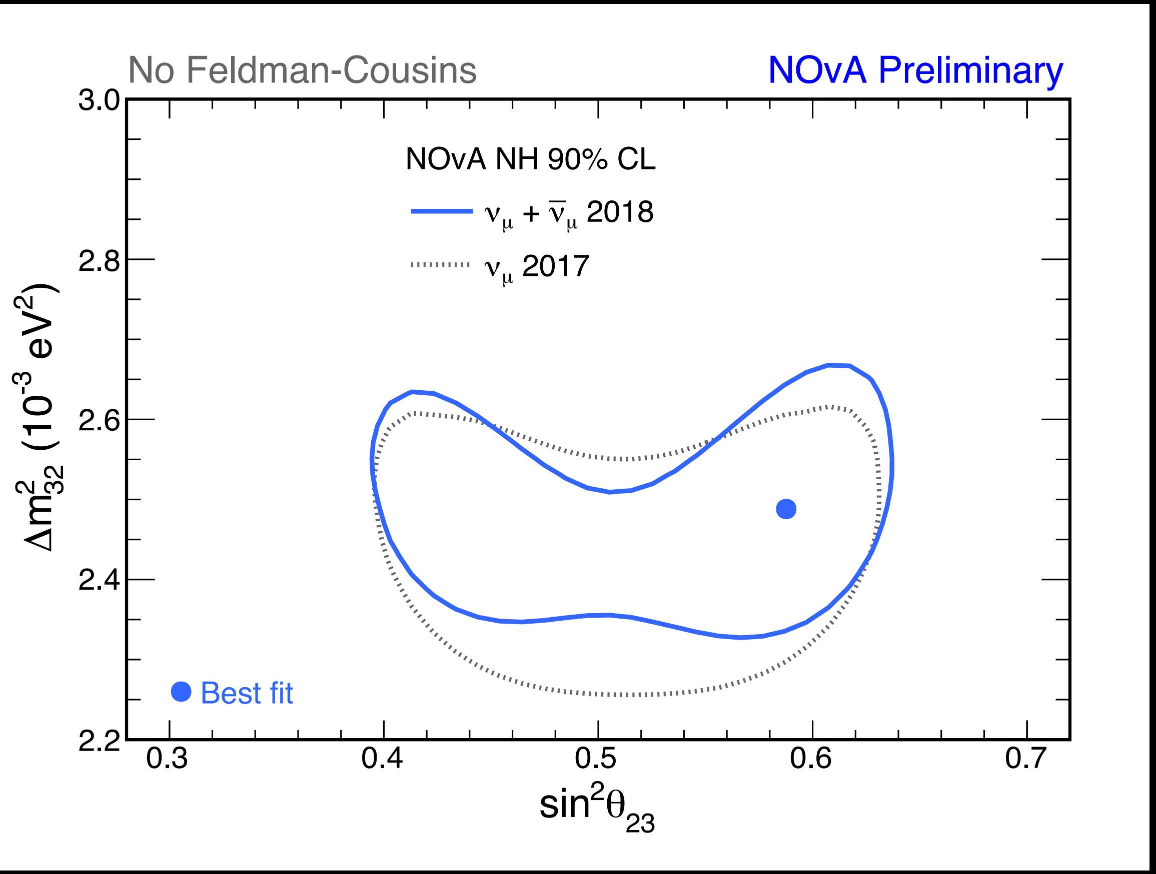




- Observe 113 events in neutrino mode (expect 730 +38/-49(syst.) w/o oscillations), 65 events in antineutrino mode (expect 266 +12/-14(syst.) w/o oscillations).

Muon Neutrino Disappearance

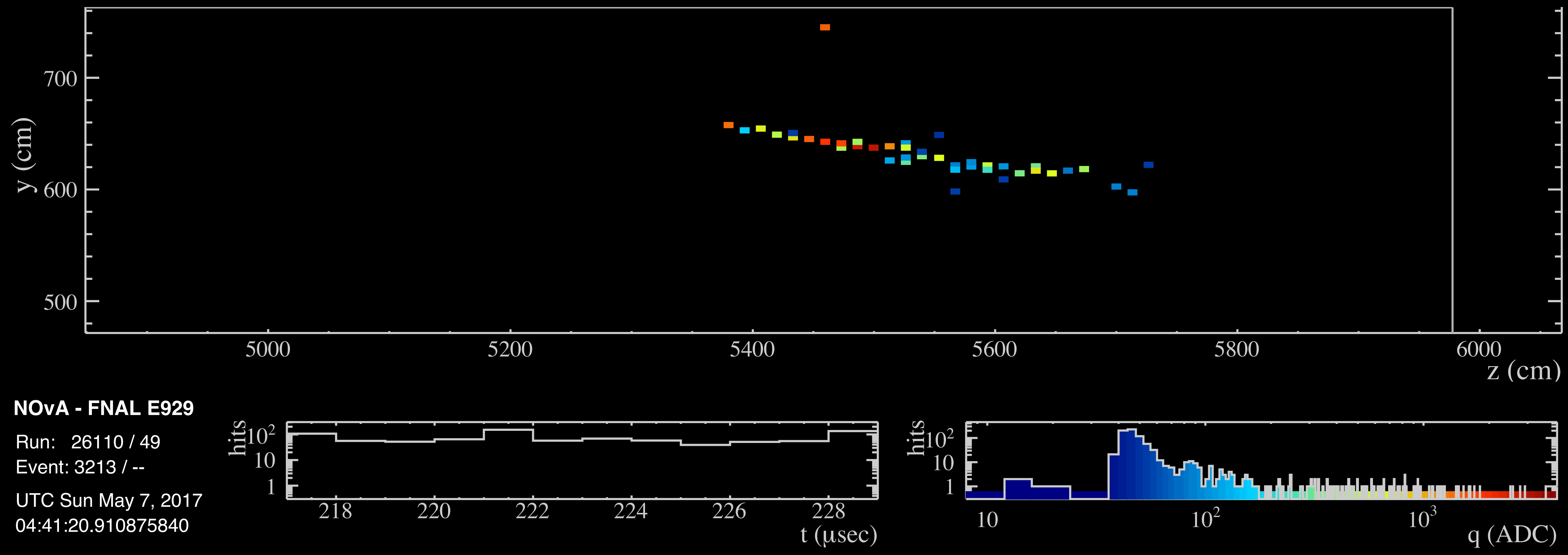
- The combined data of neutrino and antineutrino beams are fitted assuming CPT invariance.
- We observe 113 events and expect 126 at this combined best fit for the neutrino beam mode and observe 65 events and expect 52 at the best fit in antineutrino beam mode.
- If fit separately, the antineutrino beam mode prefers a more non-maximal solution than the neutrino beam mode. However, consistency with the combined fit oscillation parameters is better than 4%. Also, allowed region comparable to previous 2017 neutrino-only result.



What is the mass hierarchy or ordering?

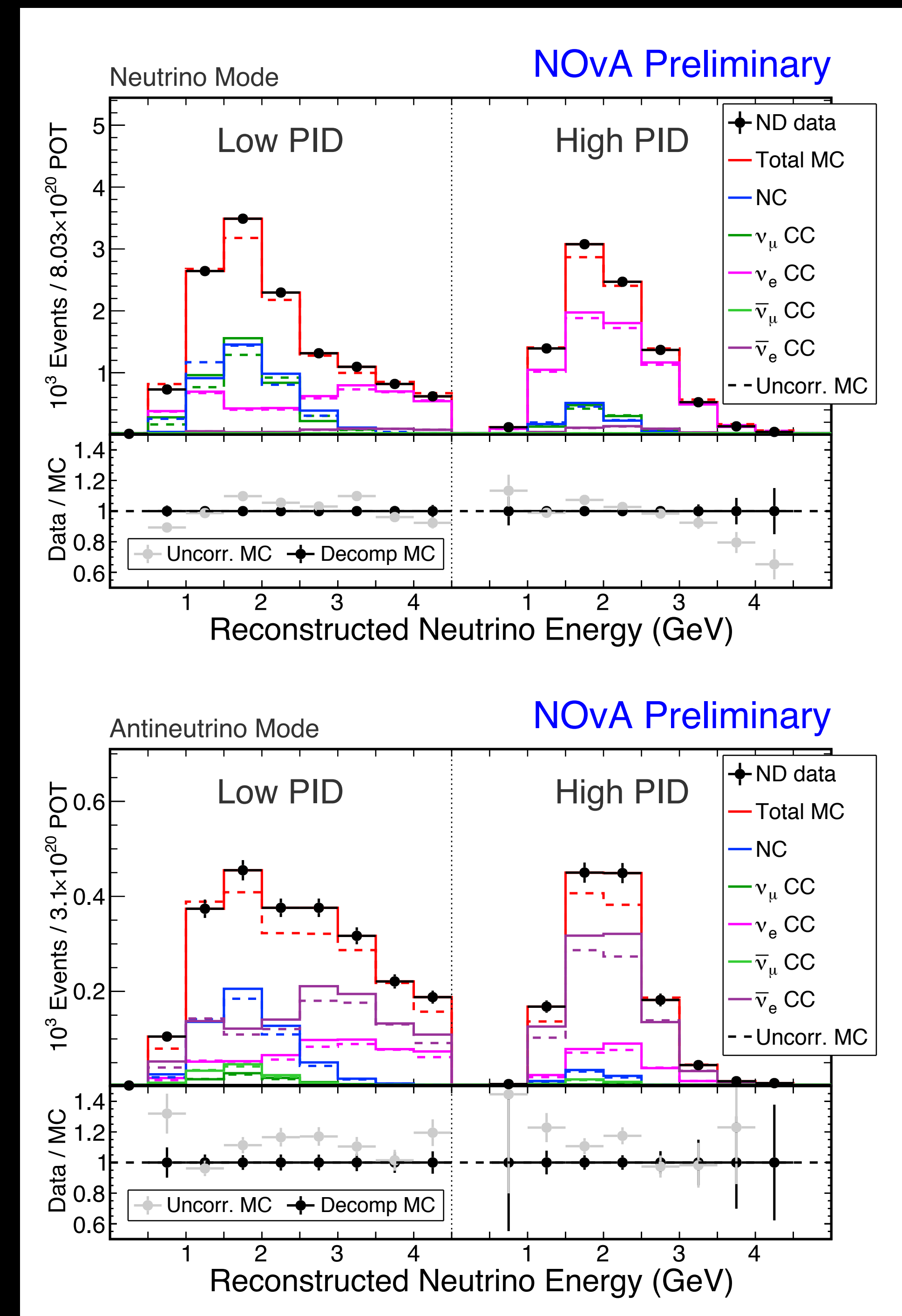
Is CP violated in the lepton sector?

ELECTRON NEUTRINO AND ANTINEUTRINO APPEARANCE



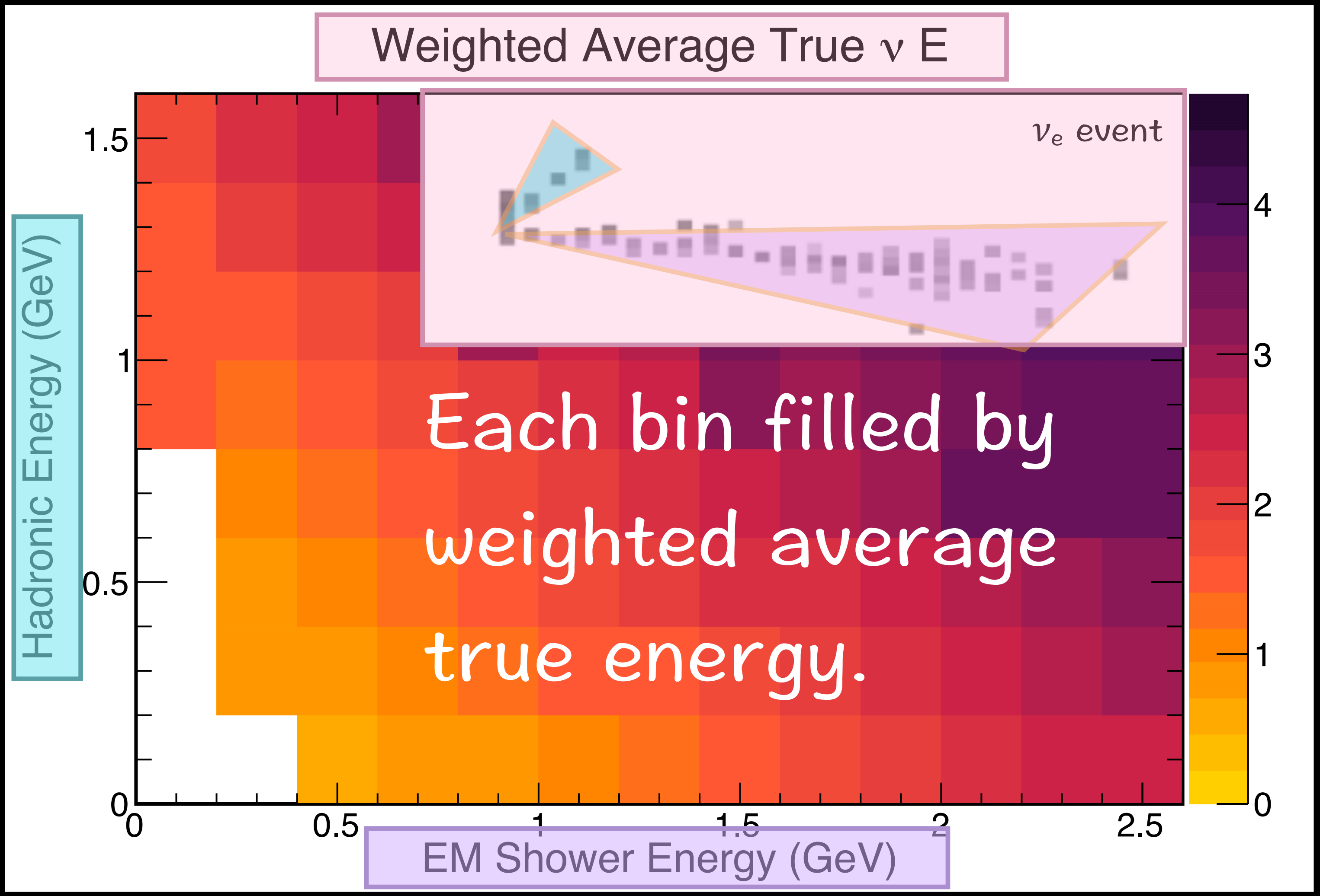
ND Electron Neutrino Spectra

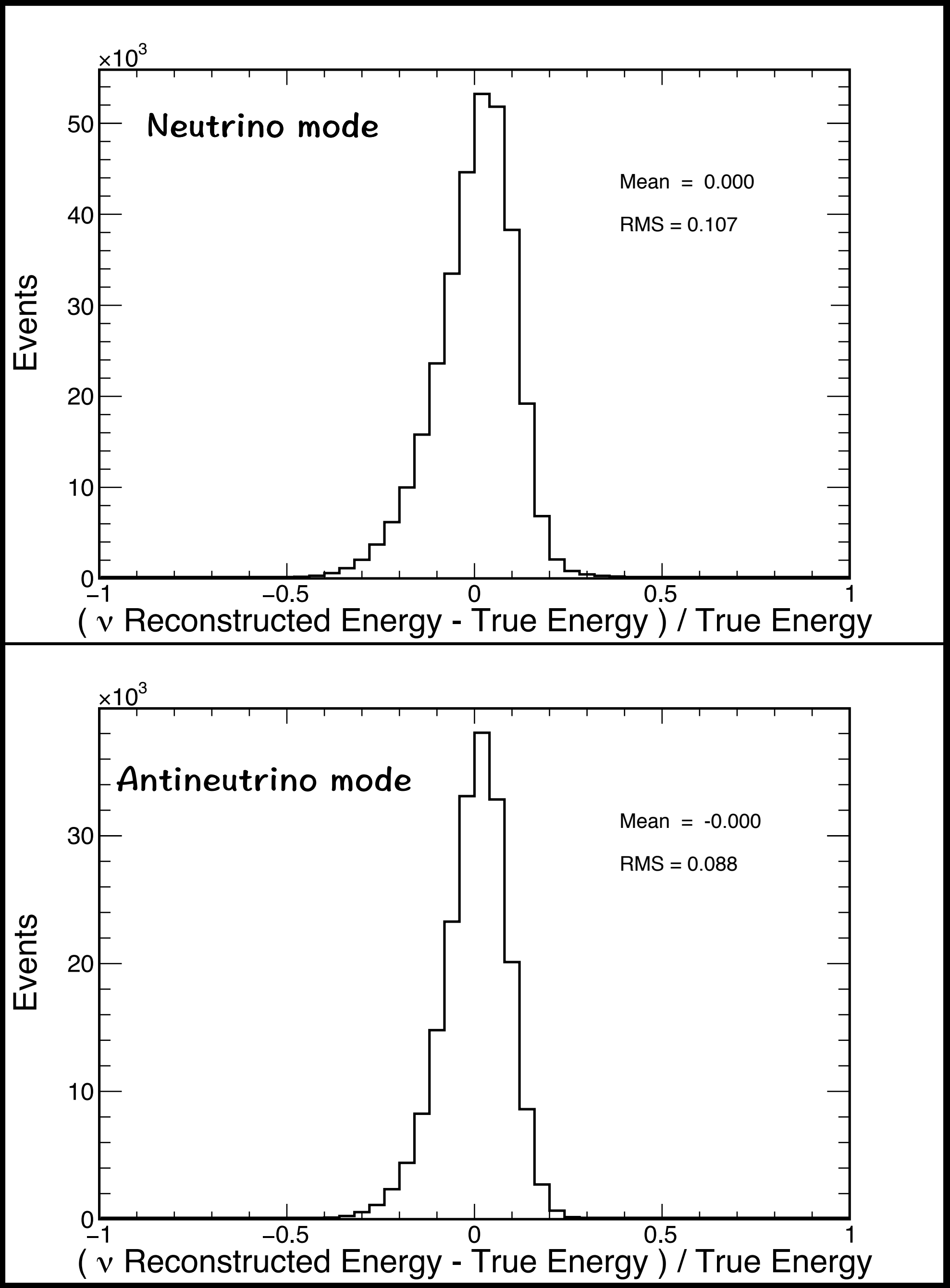
- The ND has no $\nu_e/\bar{\nu}_e$ appearance, so it predicts the far detector background.
- Electron Neutrino analysis uses a CVN/Energy binning in stead of quantiles.
- Electron neutrino energy estimator is trained independently for neutrino and antineutrino mode, resolution is 10.7%(8.8%) for neutrino(antineutrino) mode.



Reconstructed Neutrino Energy

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

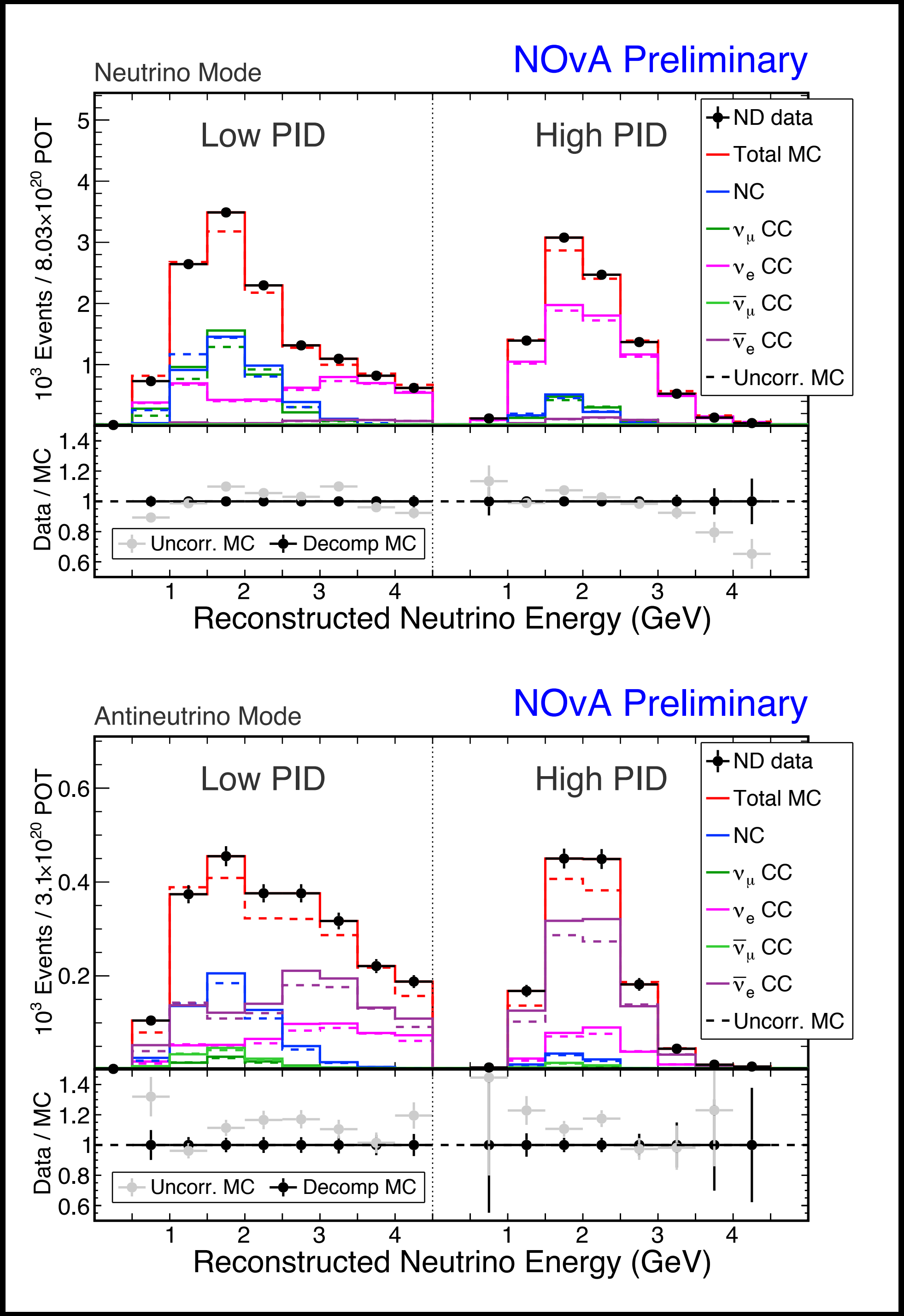




A quadratic fit to weighted average true energy as a function of EM Shower energy and Hadronic energy is used for estimation. Fitted separately for neutrino and antineutrino mode.

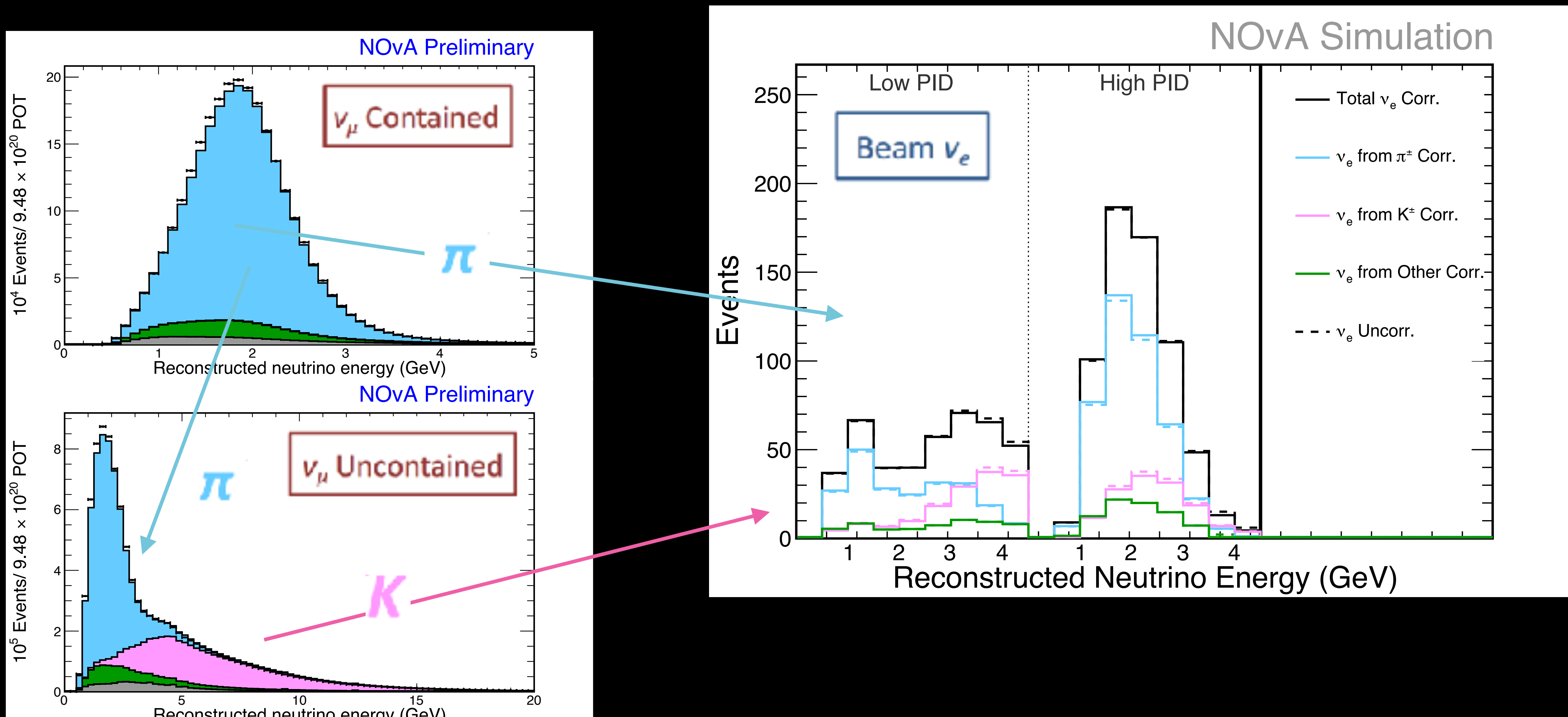
ND Electron Neutrino Decomposition

- Decomposition: Discrepancies seen must be assigned to the different components, because they have:
  - Different F/N ratio.
  - Different oscillation behaviors.
- Neutrino mode: Combo Decomposition.
- Anti-neutrino mode: Proportional Decomposition(simplest model)
  - Assume MC proportions are right and scale all together to data.



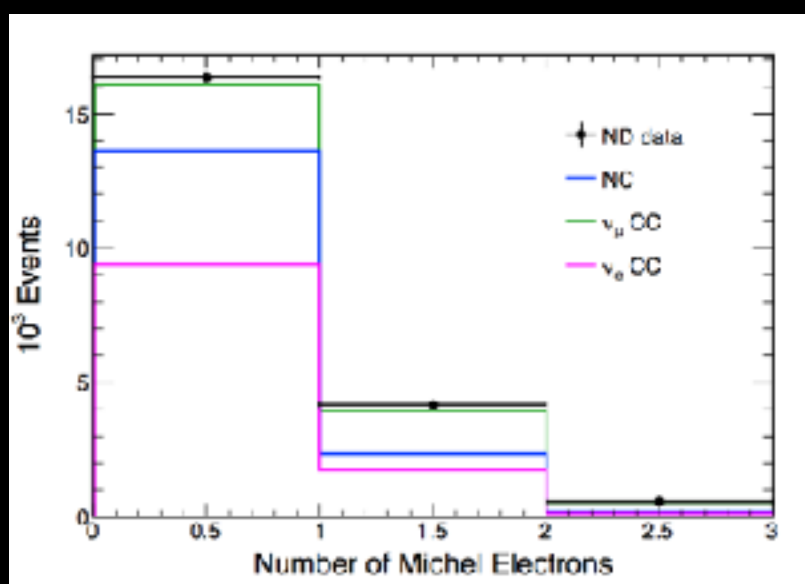
Neutrino mode : Combo Decomposition

- Combo Decomposition = BEN + Michel Decomp.
  - BEN Decomp.: The Beam Electron Neutrinos using the muon neutrino spectrum.

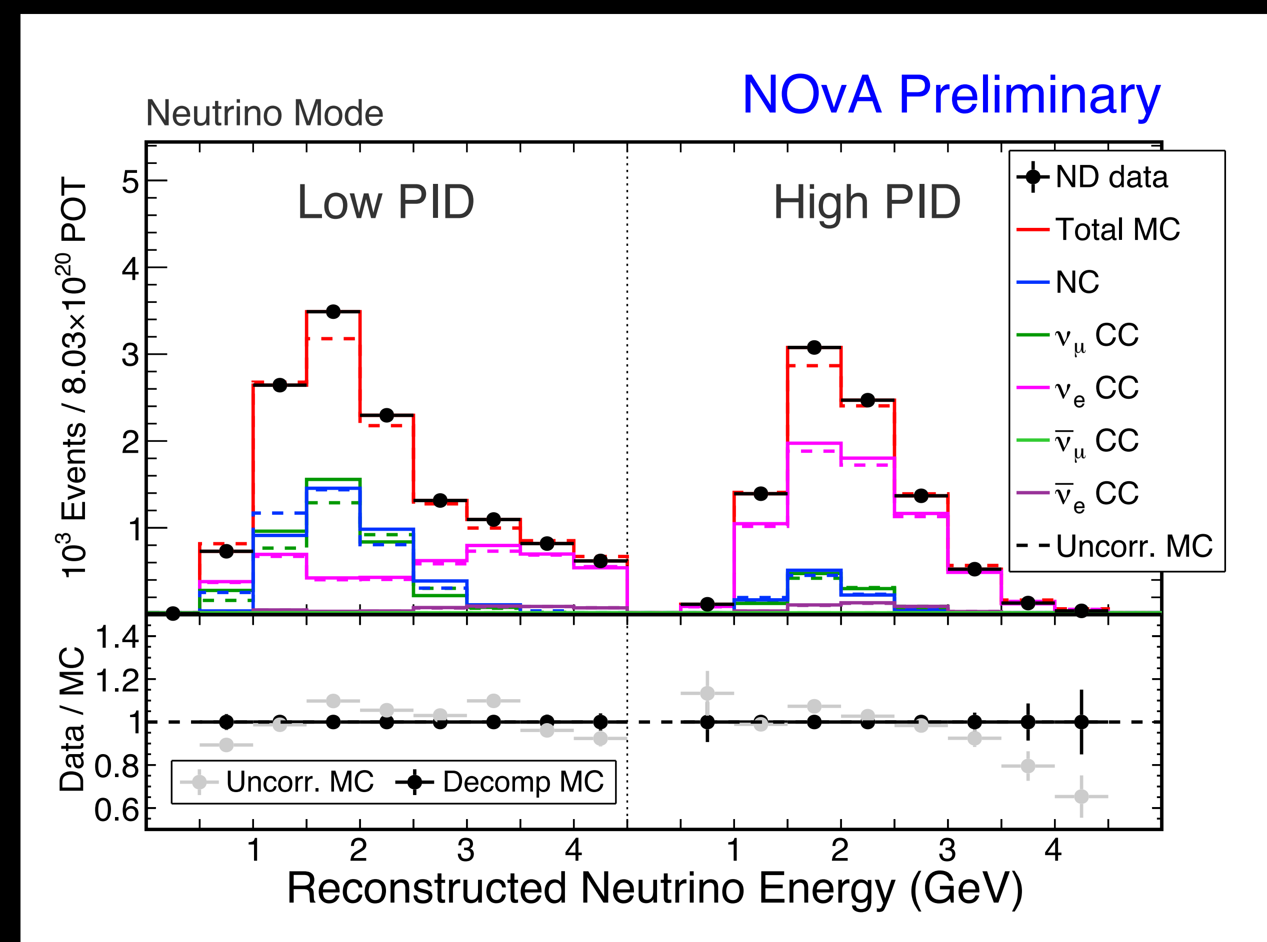


Neutrino mode : Combo Decomposition

- Combo Decomposition = BEN + Michel Decomp.
  - The CC/NC constrained using the number of observed Michel electrons.
    — Determine the fraction of the two components in each analysis bin.



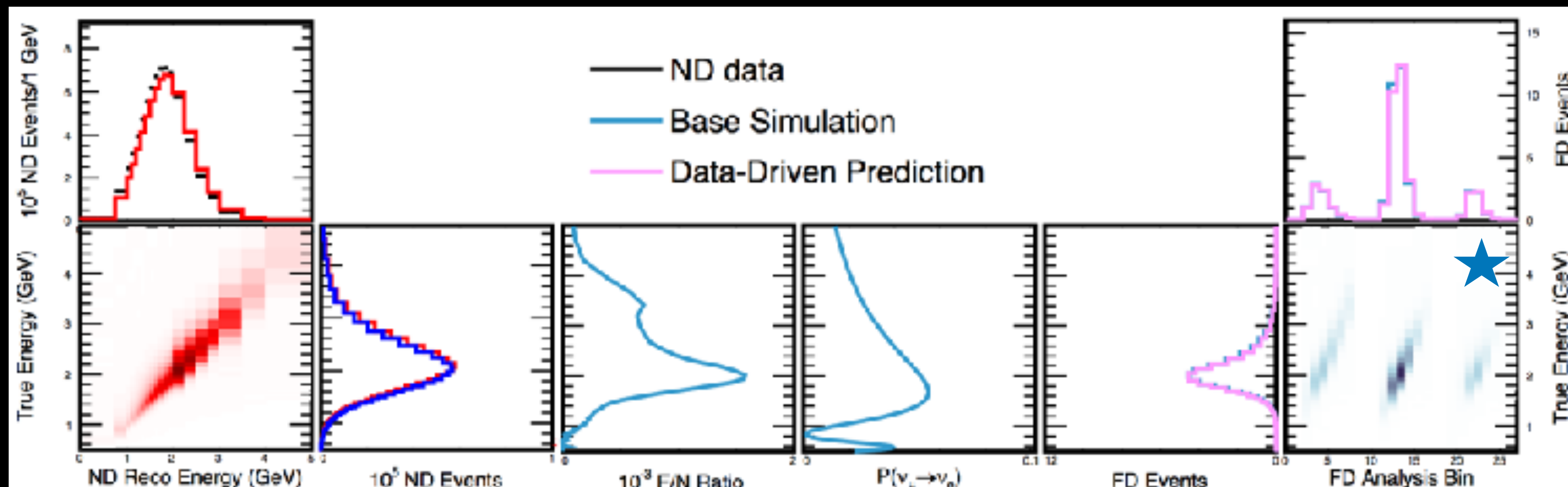
Change in Total	
ν_e CC	+3%
ν_μ CC	+7%
NC	-4%



Nue Appearance Extrapolation

Signal Extrapolation

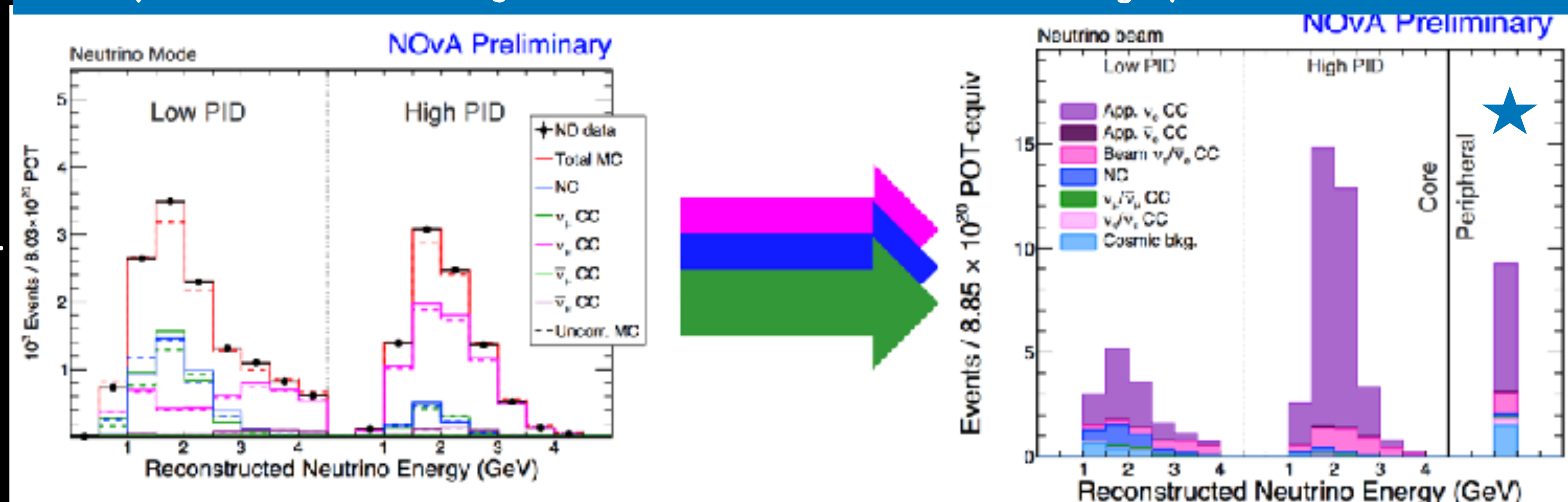
Use ND ν_μ to predict FD ν_e



★ Peripheral Bin: cosmic rejection boosted decision tree and high particle ID cut.

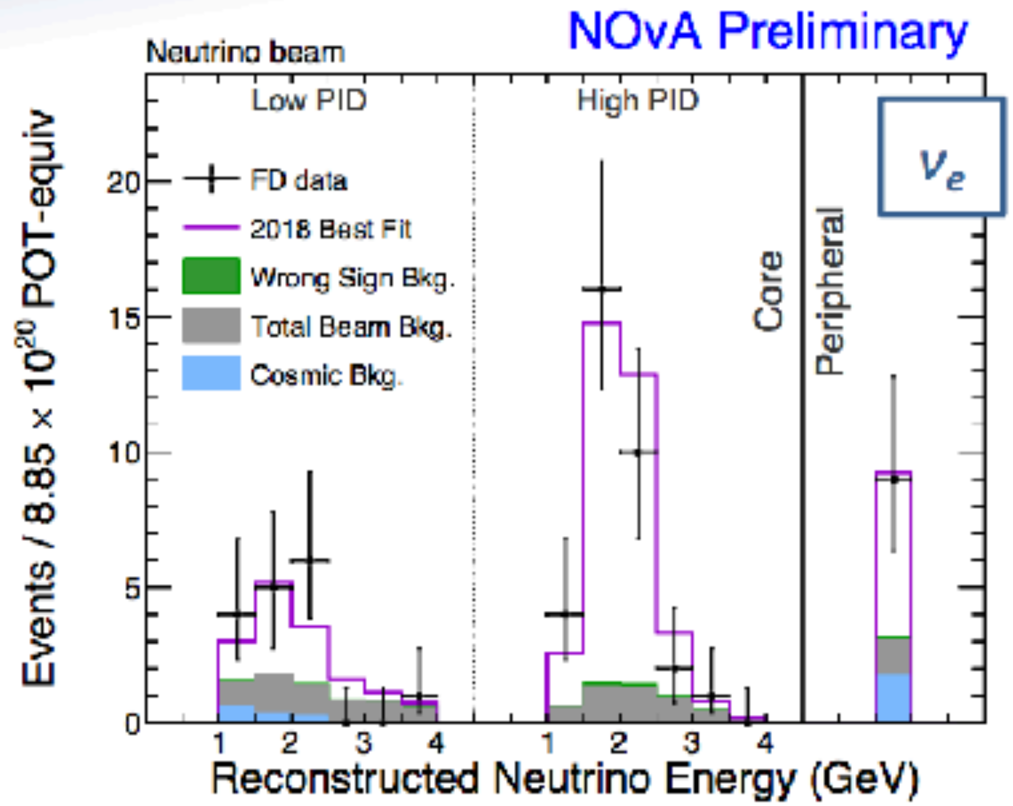
Background Extrapolation

Use ND ν_e-signal-like background to predict FD background

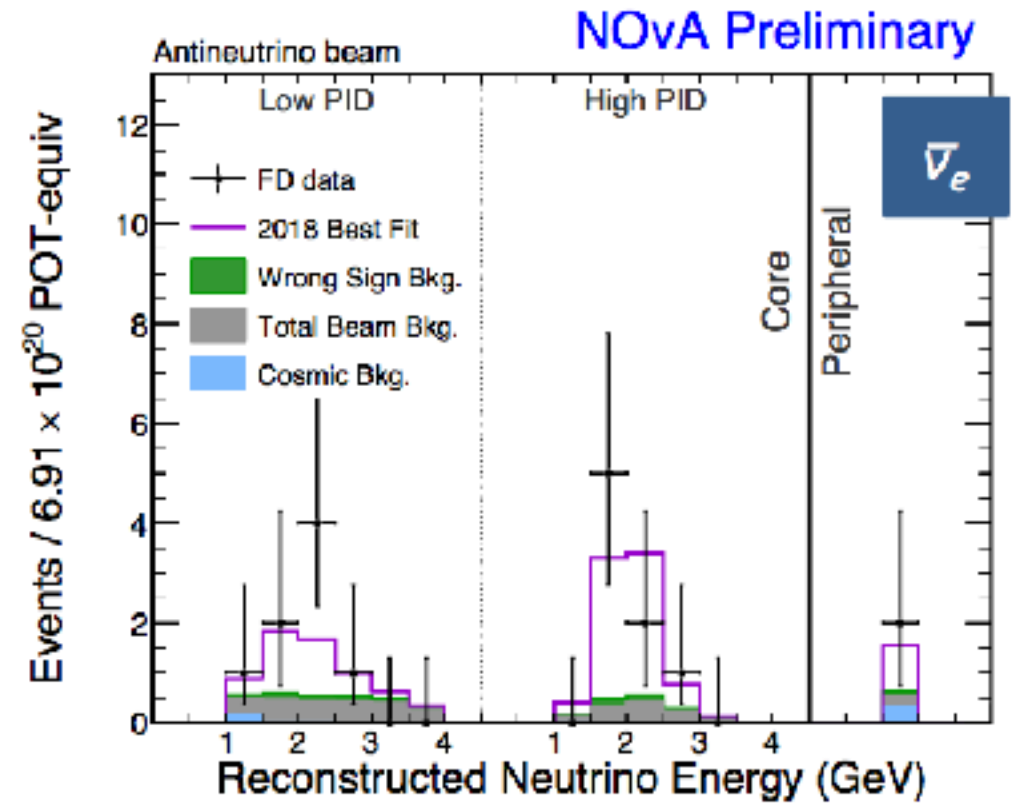


Each component is propagated independently in bins of energy and particle ID bins.

FD Electron Neutrino Prediction



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

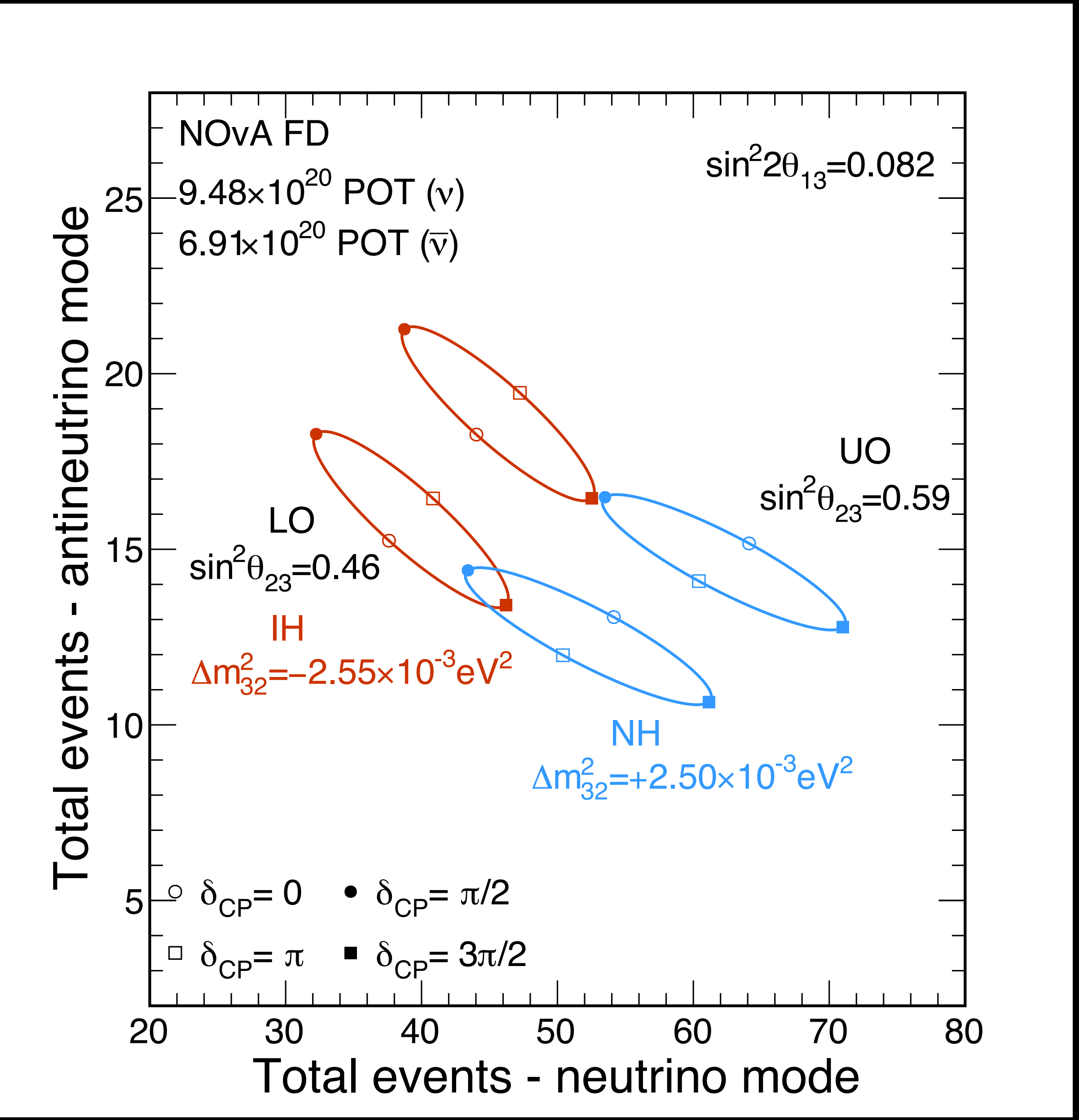


Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

> 4σ evidence of electron antineutrino appearance

Electron Neutrino Appearance Expectation

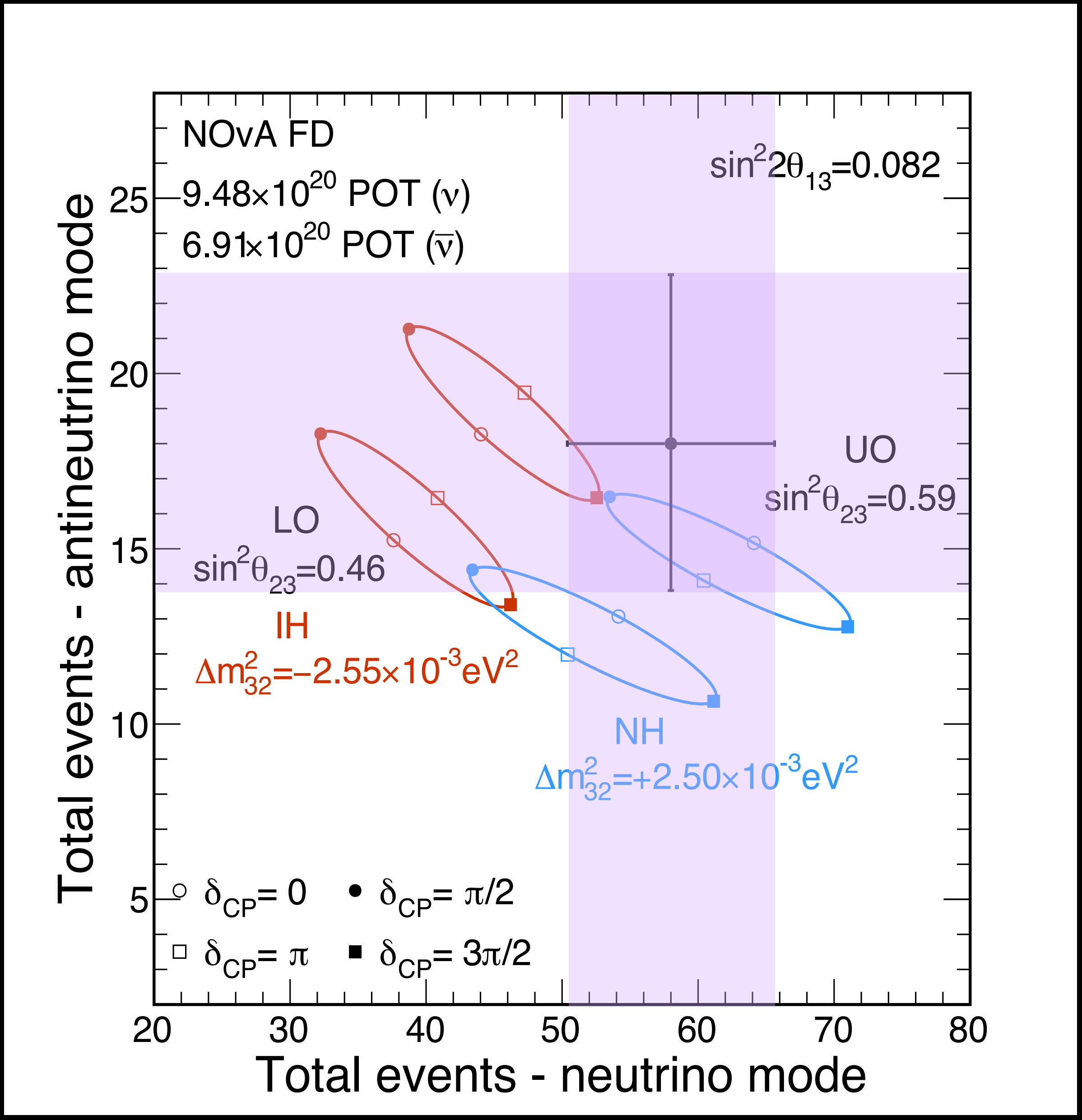
- Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.
- Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).



EXPECT 30-75 EVENTS FOR NEUTRINO MODE AND 10-22 FOR ANTINEUTRINO MODE

Electron Neutrino Appearance Expectation

- Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.
- Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).

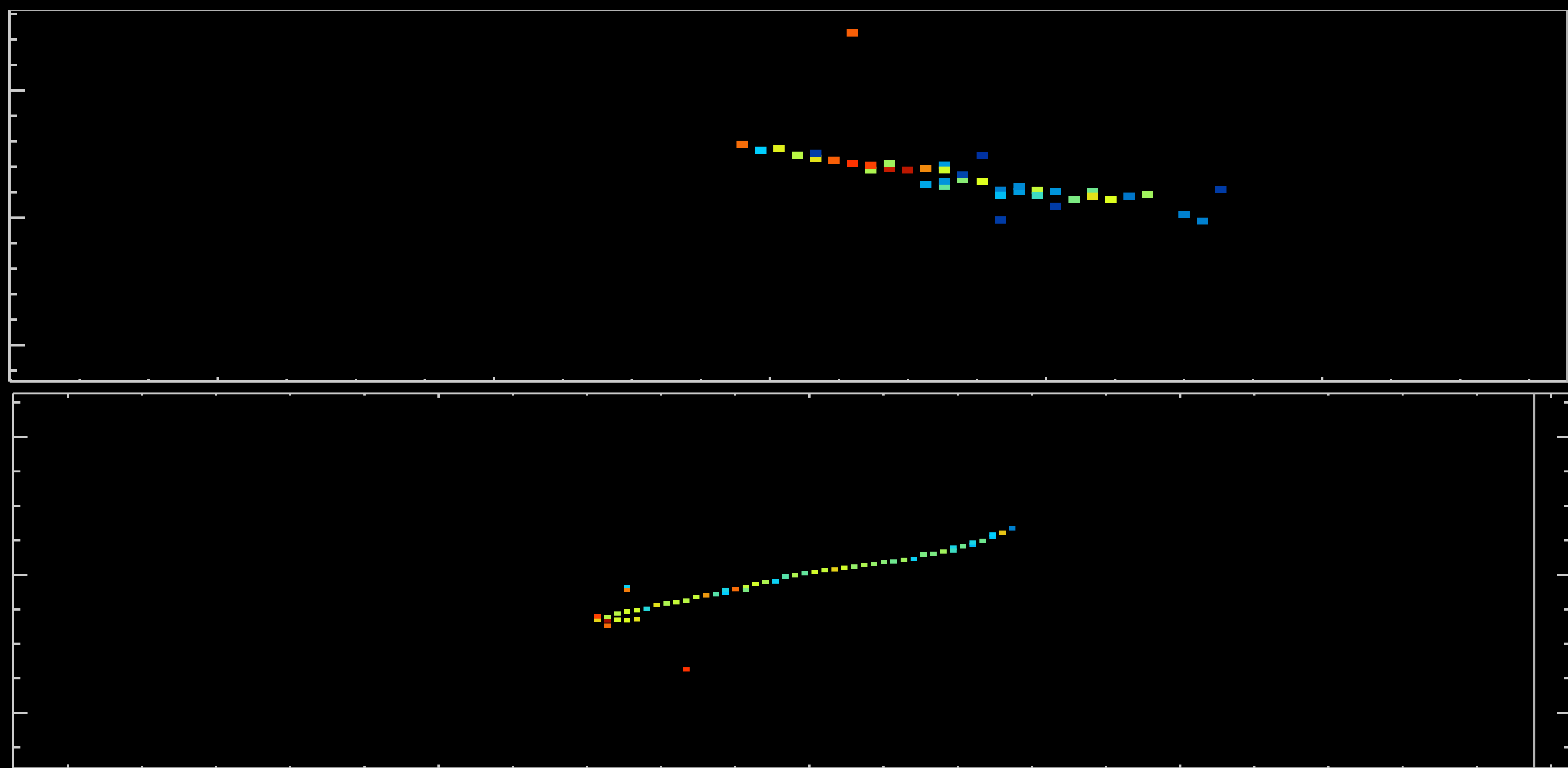


NOVA OBSERVES: 58 EVENTS IN NEUTRINO, 18 EVENTS IN ANTINEUTRINO MODE.

What is the mass hierarchy or ordering?

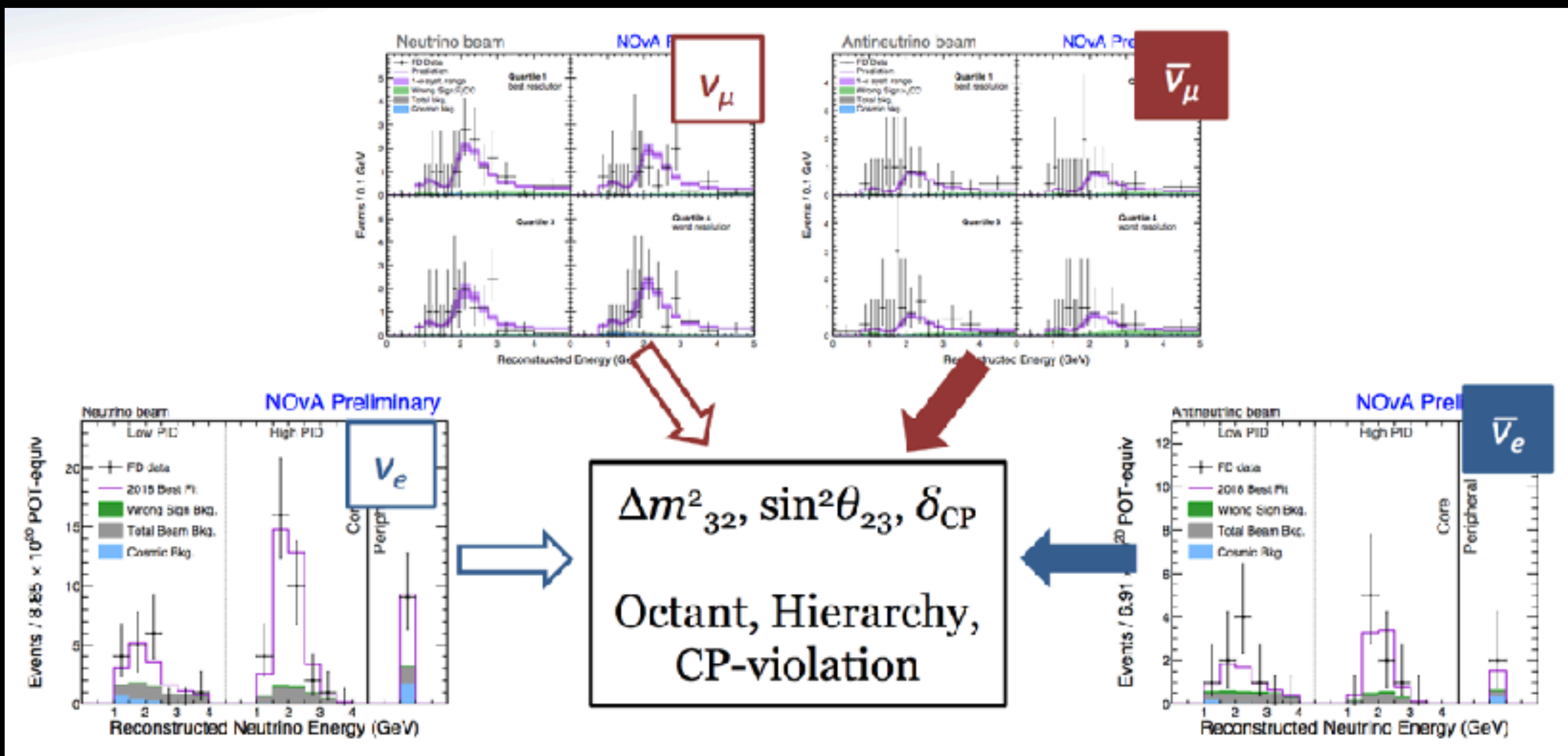
Is CP violated in the lepton sector?

JOINT APPEARANCE AND DISAPPEARANCE

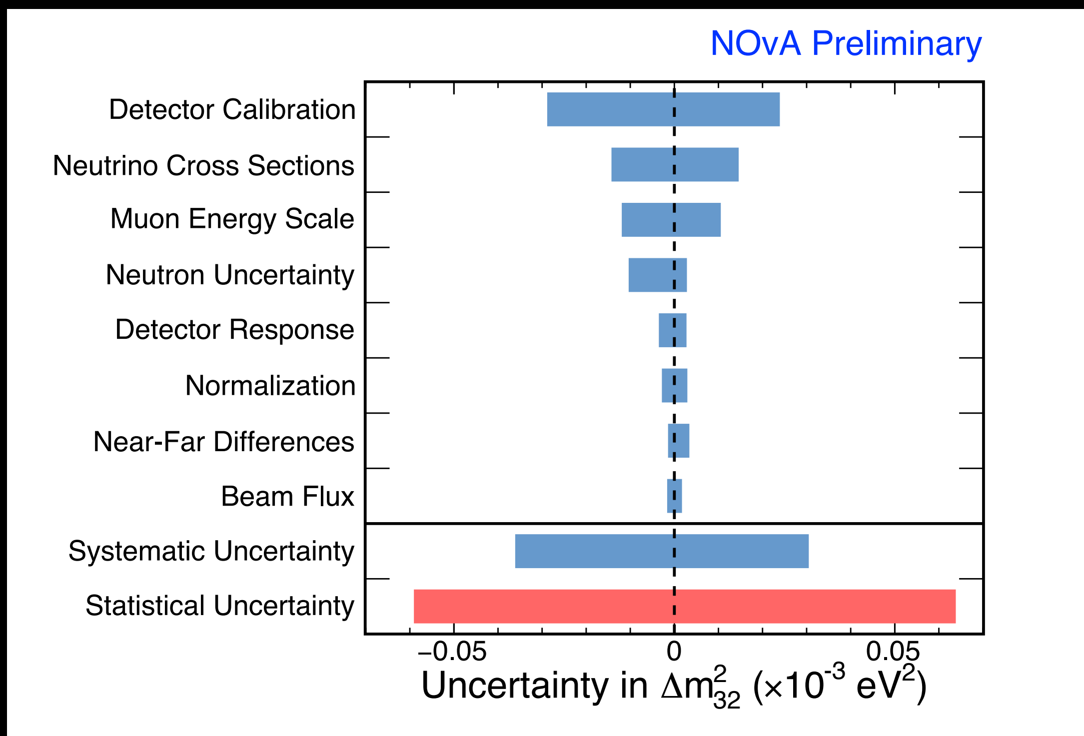


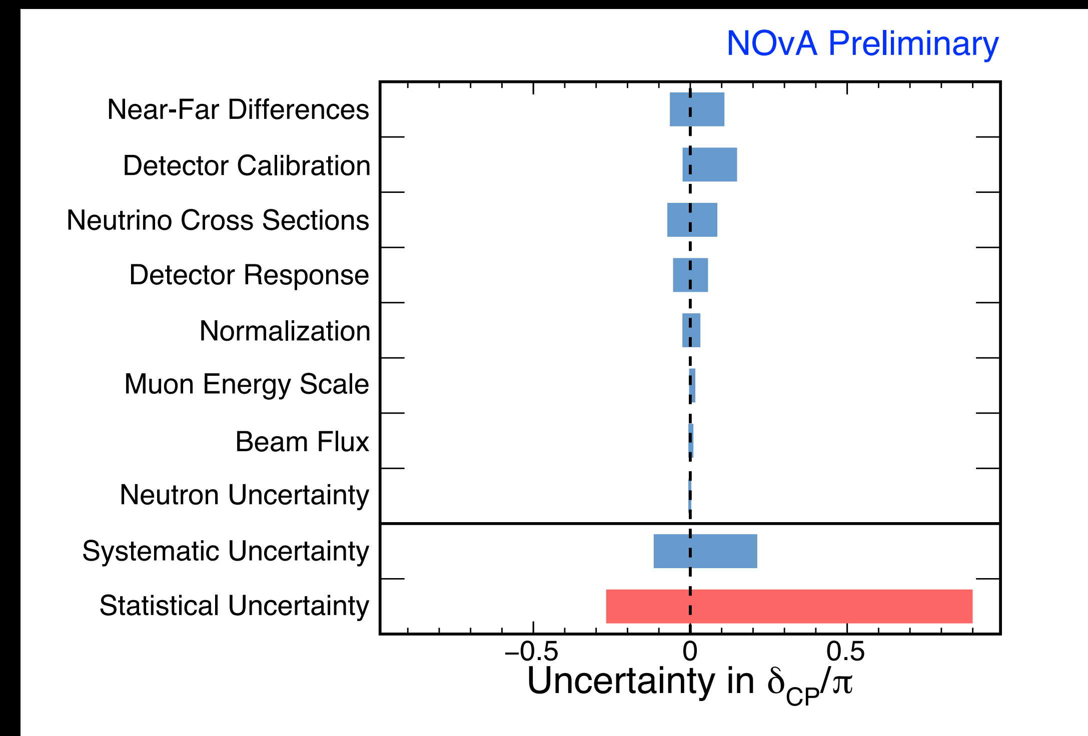
Oscillation Fit

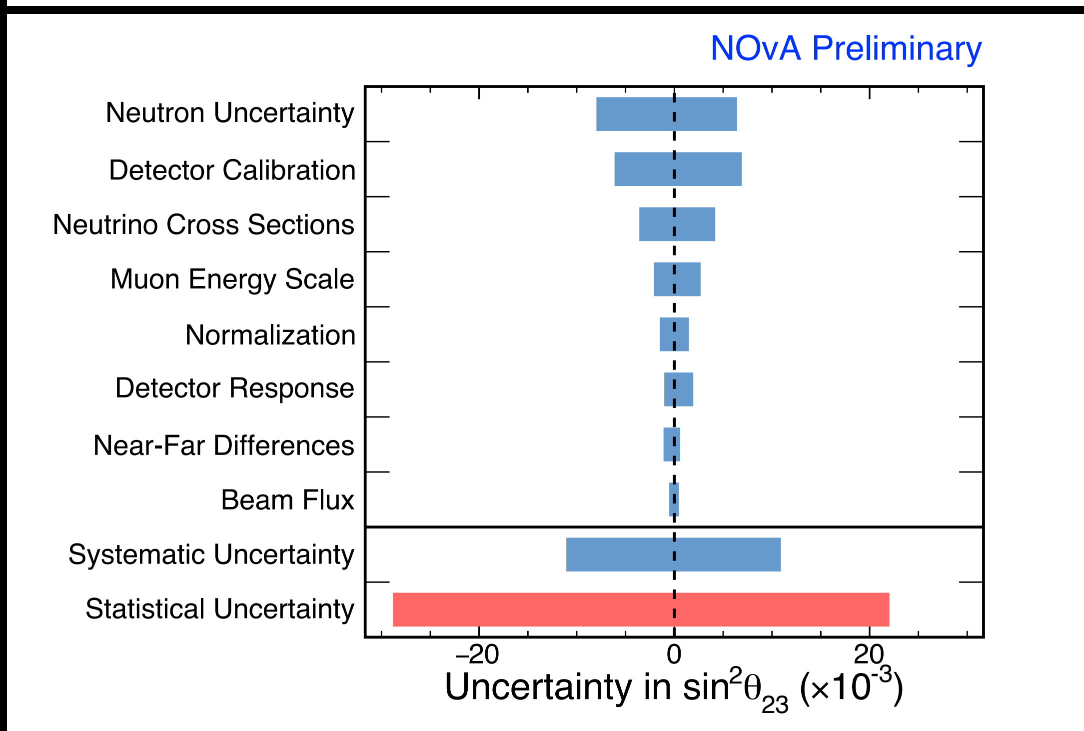
- All results come from a joint fit to neutrinos + antineutrinos, ν_e + ν_μ
- Systematics are treated together, though some affect the samples differently.
- All contours and most of 1D ranges are Feldman-Cousins corrected.
- $\sin^2 2\theta_{13}$ = 0.082 comes from the PDG average.



Systematic Uncertainties

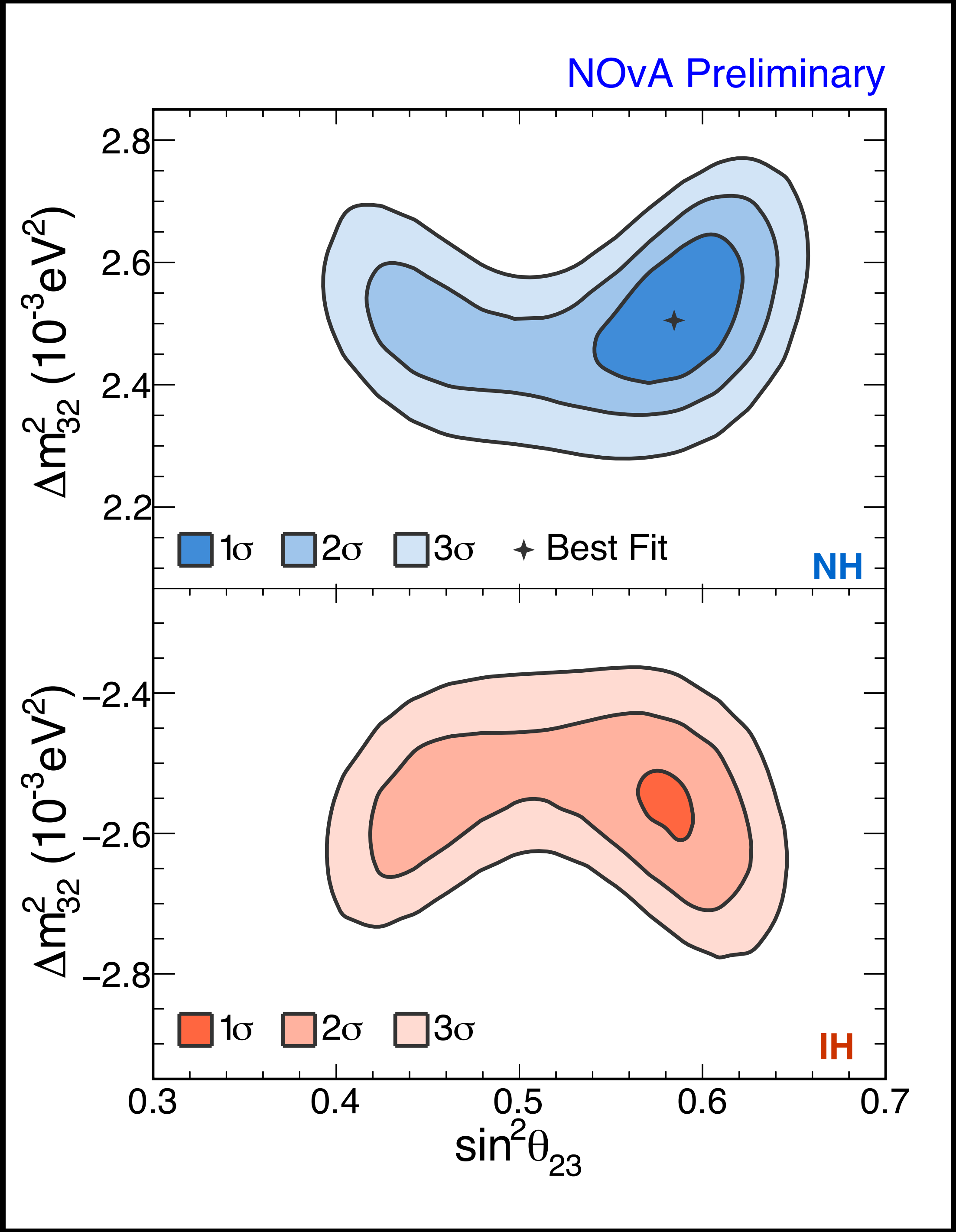


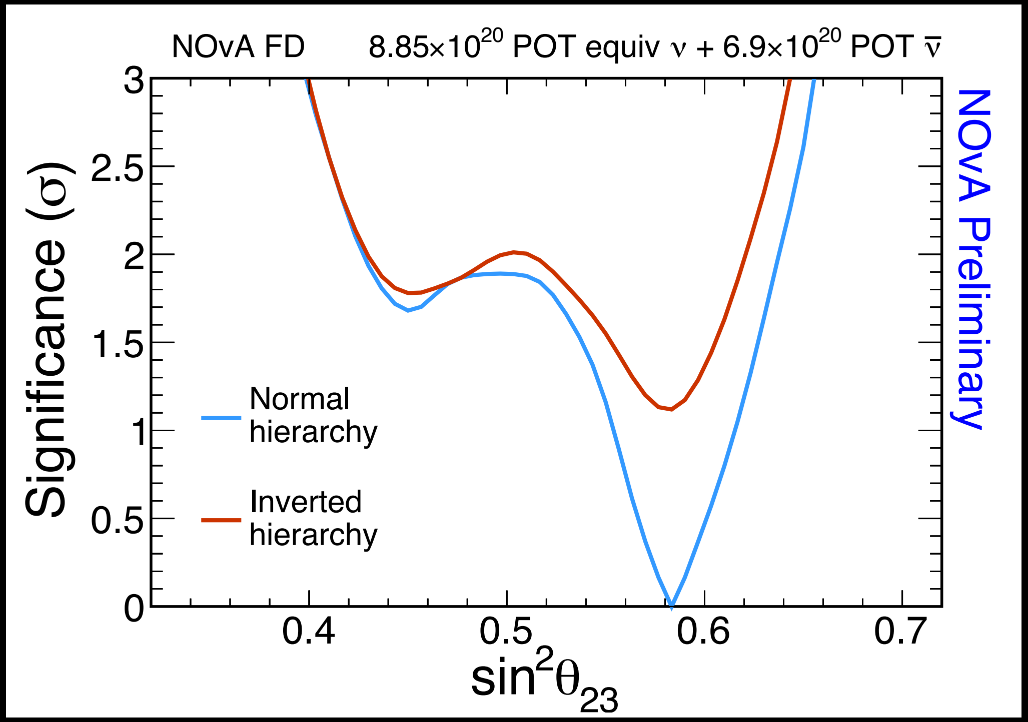




- Improved systematic uncertainties. We are still statistics limited but calibration and cross sections are the largest uncertainties.
- Our upcoming test beam program will address the calibration and detector response uncertainties.

Allowed Oscillation Parameters





- Best fit:

  Normal Hierarchy

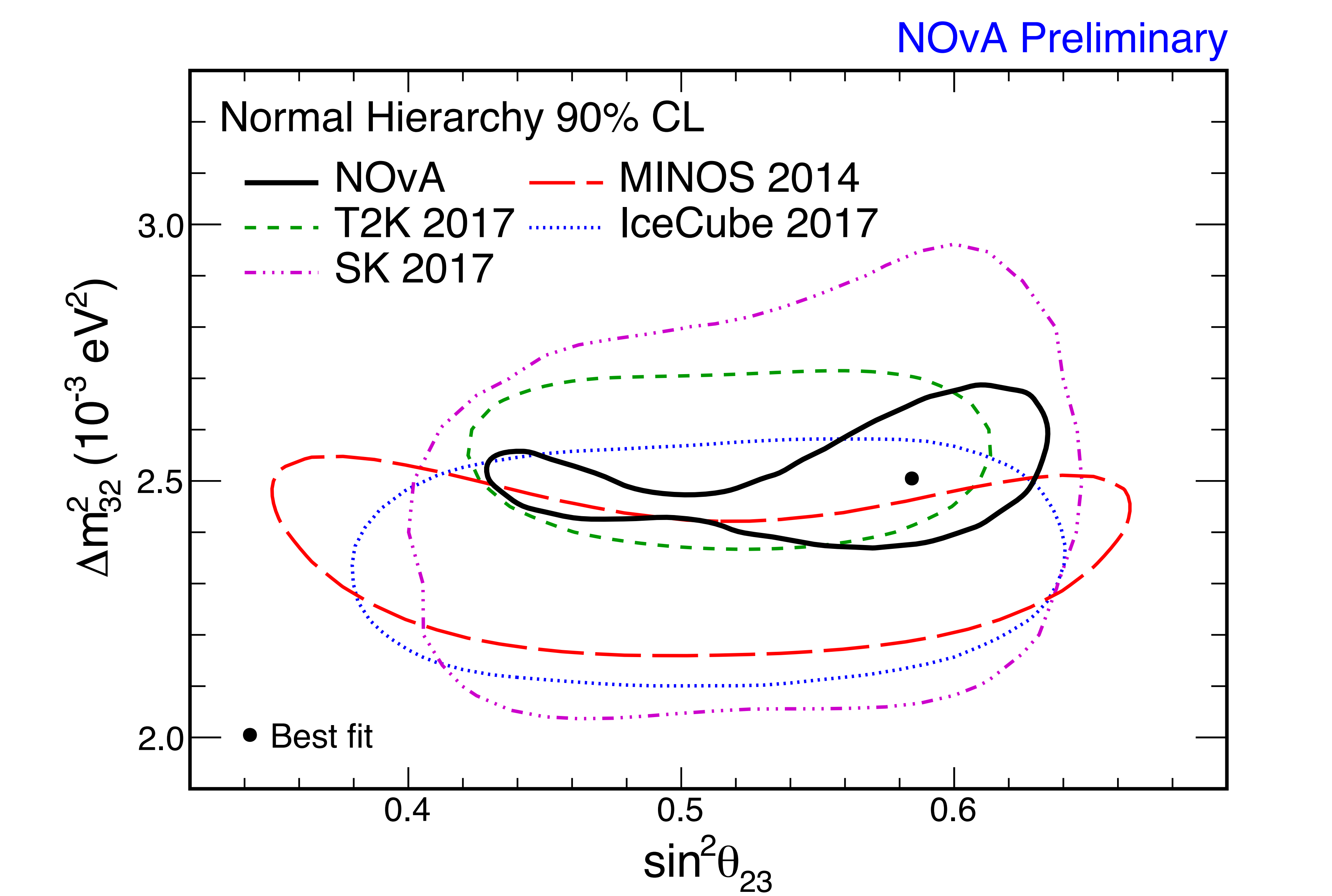
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)

  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2$

Prefer non-maximal at 1.8σ
Exclude LO at similar level

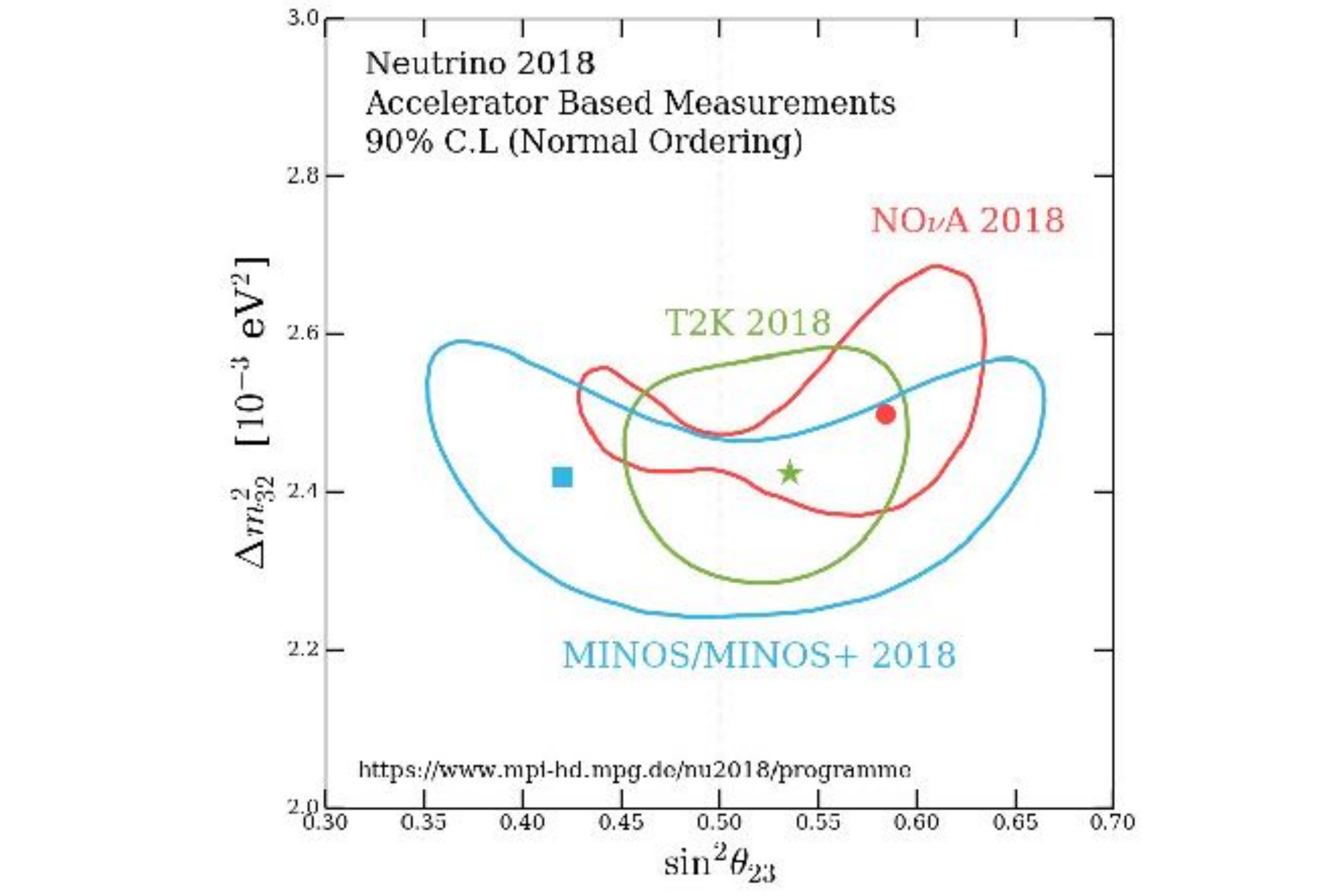
Allowed Region of Appearance and Disappearance

- NOvA's results compared to other experiments. Allowed 90% C.L. regions are compatible.

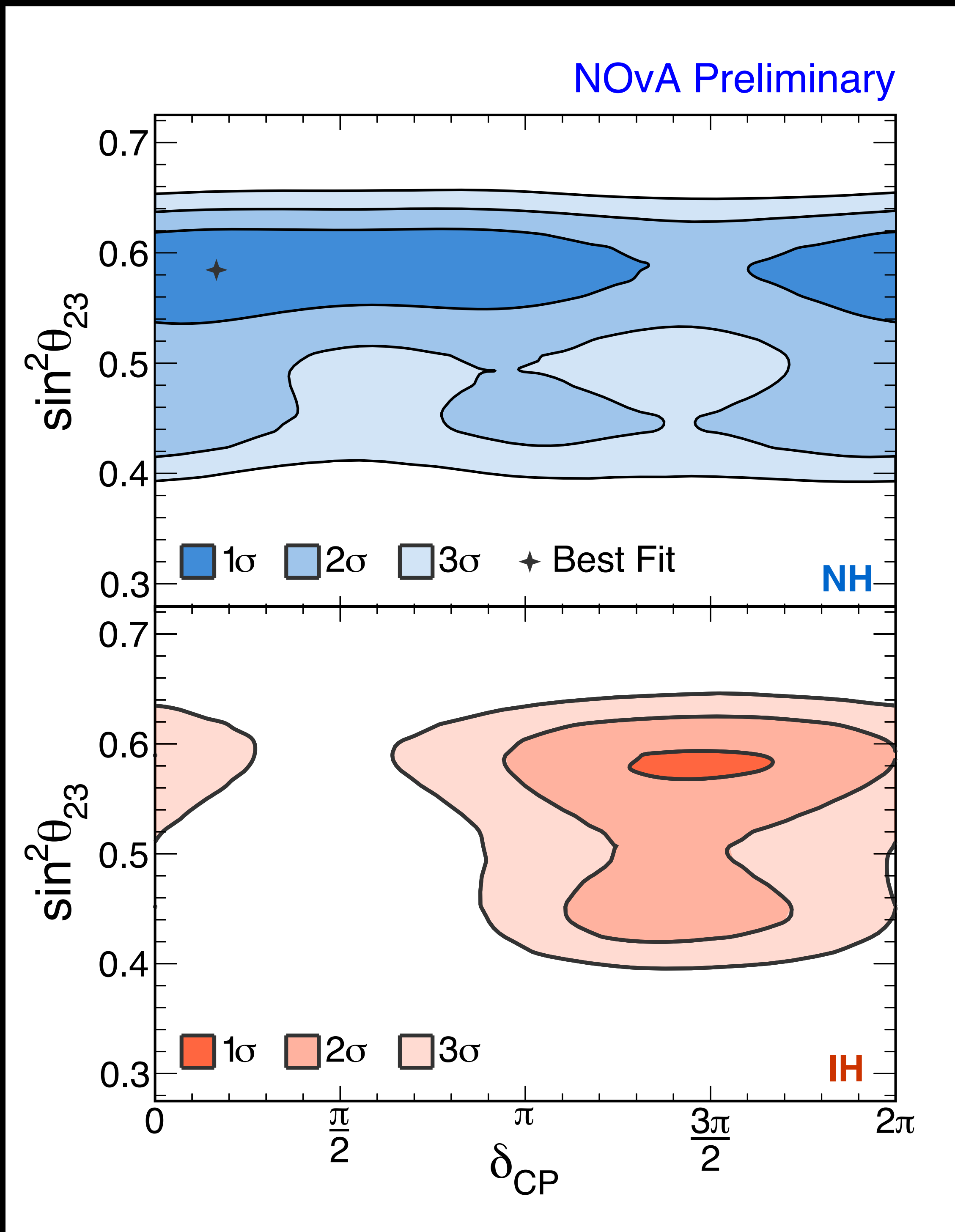


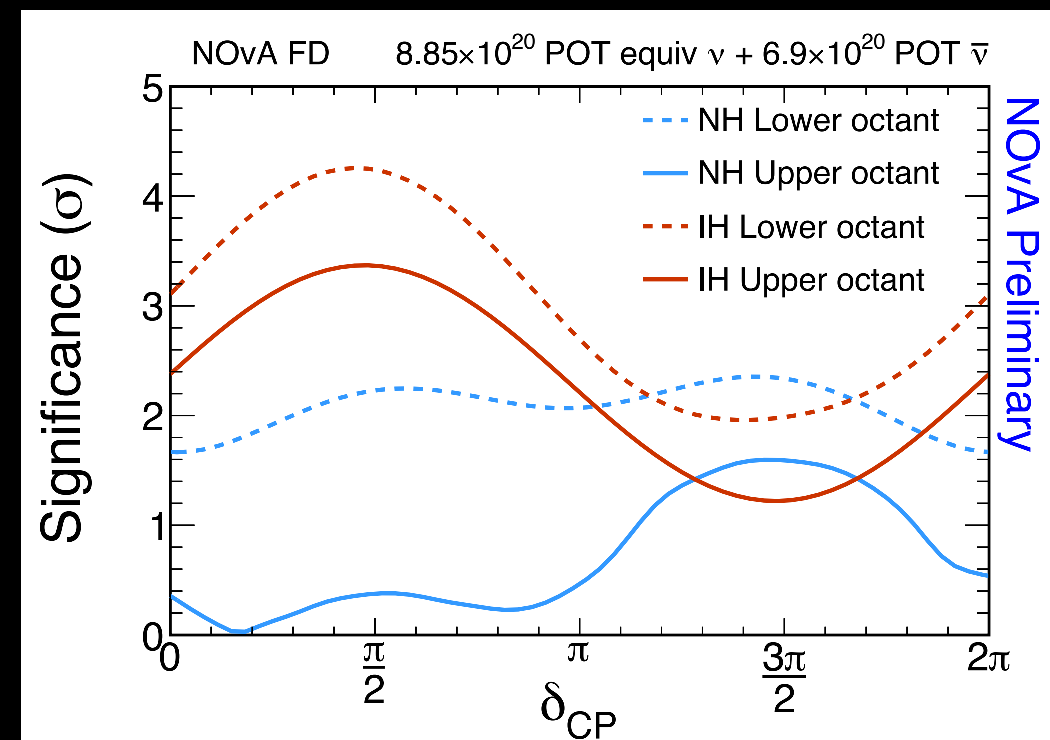
Allowed Region of Appearance and Disappearance

- NOvA's results compared to other experiments.(From Neutrino2018) Still compatible.



Allowed Region of Appearance and Disappearance





- Best fit: Normal Hierarchy

  $\delta_{CP} = 0.17\pi$

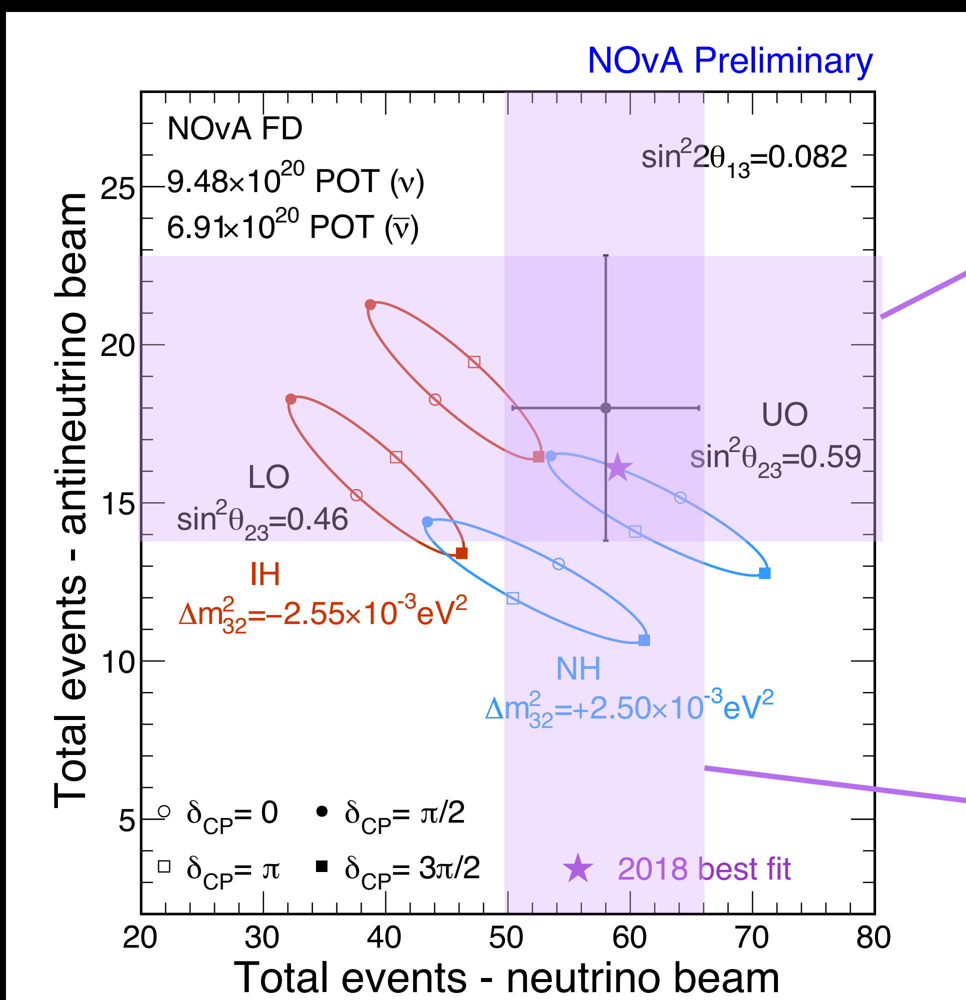
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)

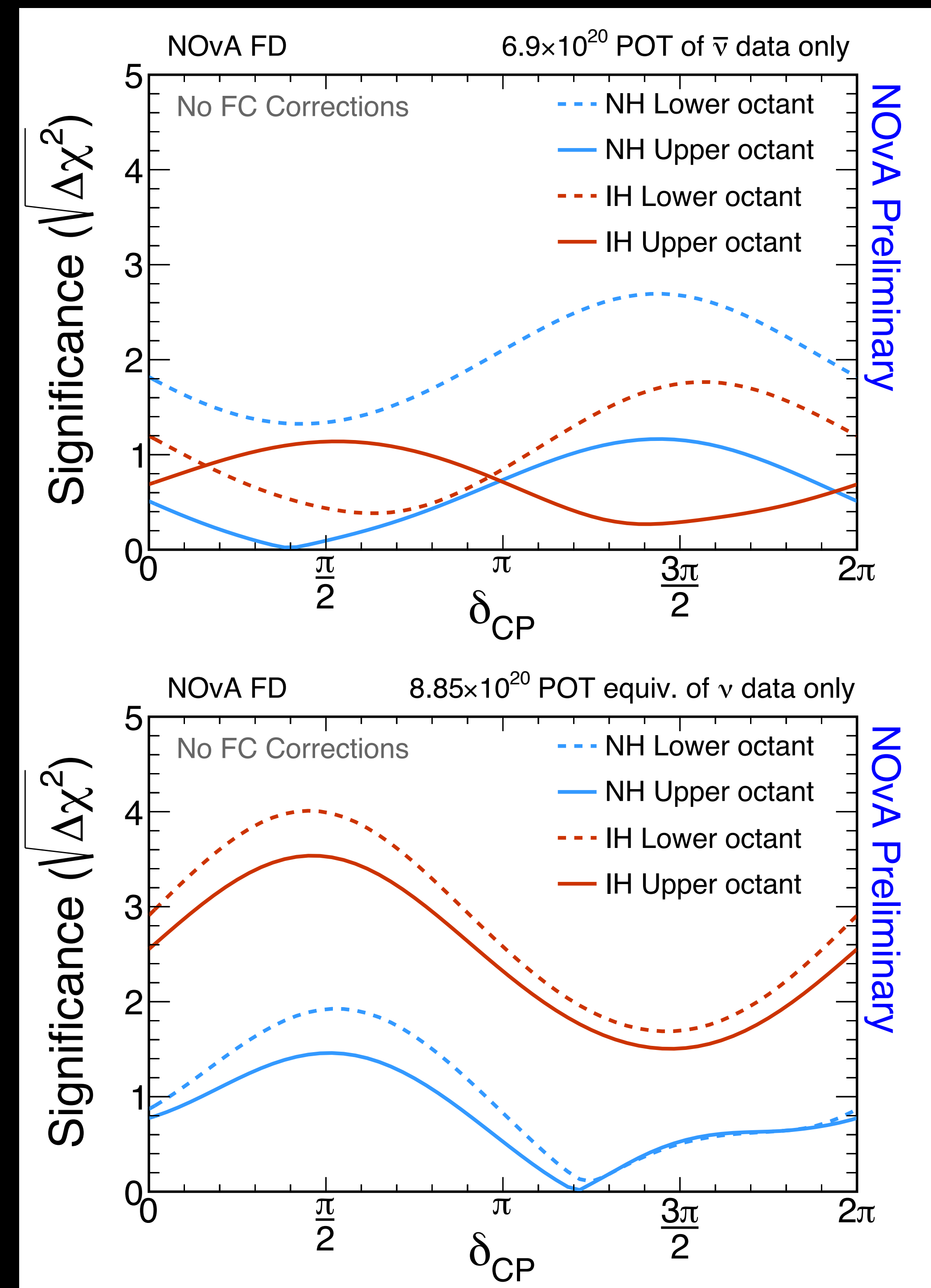
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ eV^2$

Prefer NH by 1.8σ
Exclude δ=π/2 in the IH at > 3σ

Neutrino Only vs. Antineutrino Only

Antineutrino data favors the upper octant in either hierarchy

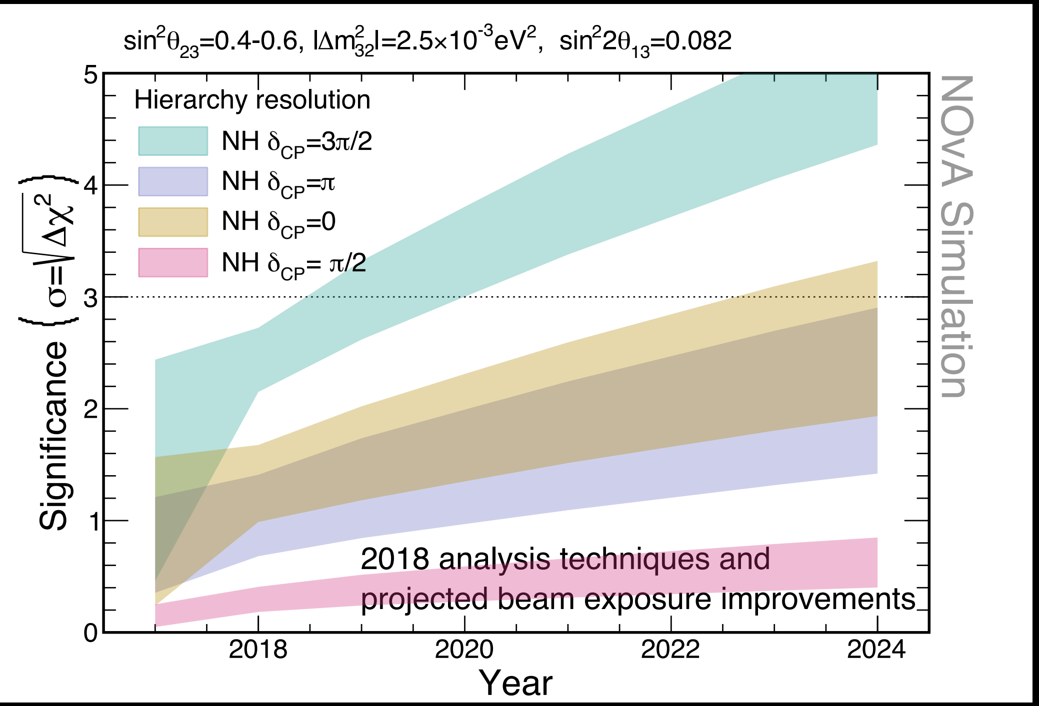


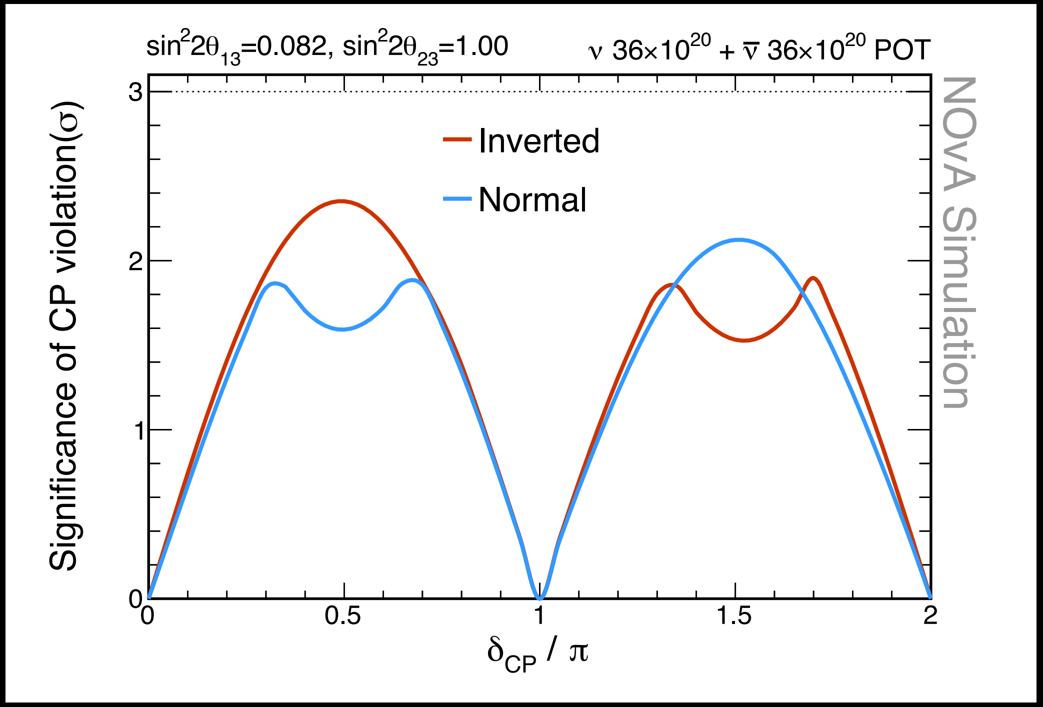


Neutrino data favors the normal hierarchy in either octant

NOvA Prospects

- Currently running anti-neutrino beam.
- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach. Planning on equal amounts of neutrino/ antineutrino running in the future.
- 3σ sensitivity to hierarchy (if NH and $\delta_{CP}=3\pi/2$) for allowed range of θ_{23} by 2020. 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.
- 2σ 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 antineutrino data ($6.9 \cdot 10^{20}$ POT) has been analyzed together with $8.85 \cdot 10^{20}$ POT of neutrino data.
  - Publication on analysis of $8.85 \cdot 10^{20}$ POT of neutrino data.
  - More antineutrino beam running up to the summer shutdown.
- We observe no evidence for mixing with sterile neutrinos or antineutrinos from the neutral current channel.
- We observe >4 σ evidence of electron antineutrino appearance.
- A joint appearance and disappearance analysis for these data:
  - Prefers Normal Hierarchy at 1.8 σ and excludes $\delta_{CP} = \pi/2$ at > 3 σ.
  - Rejects 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.

Thank you!

Backup

ν_e Appearance

By measuring muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

- θ_{32} octant
- δ_{cp}
- mass hierarchy

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}} e^{-i(\frac{\Delta m^2_{32} L}{4E} + \delta_{CP})} + \sqrt{P_{sol}}|^2$$

$$\approx |\sqrt{P_{atm}} + \sqrt{P_{sol}} + 2\sqrt{\sqrt{P_{atm}}\sqrt{P_{sol}}}(cos\Delta m^2_{32} cos\delta_{CP} \mp sin\Delta m^2_{32} sin\delta_{CP})$$

$$P_{atm} = sin^2\theta_{23} sin^2 2\theta_{13} sin^2 \frac{\Delta m^2_{31}}{4E}$$

Solar term contributes <1% at 400 L/E

- neutrino
+ anti-neutrino

ν_e Appearance

By measuring muon neutrinos which have oscillated to electron neutrinos we gain the power to constrain:

- θ_{32} octant
- δ_{cp}
- mass hierarchy

$$\approx |\sqrt{P_{atm}} + \sqrt{P_{sol}} + 2\sqrt{\sqrt{P_{atm}}\sqrt{P_{sol}}}(cos\Delta m^2_{32} cos\delta_{CP} \mp sin\Delta m^2_{32} sin\delta_{CP})$$

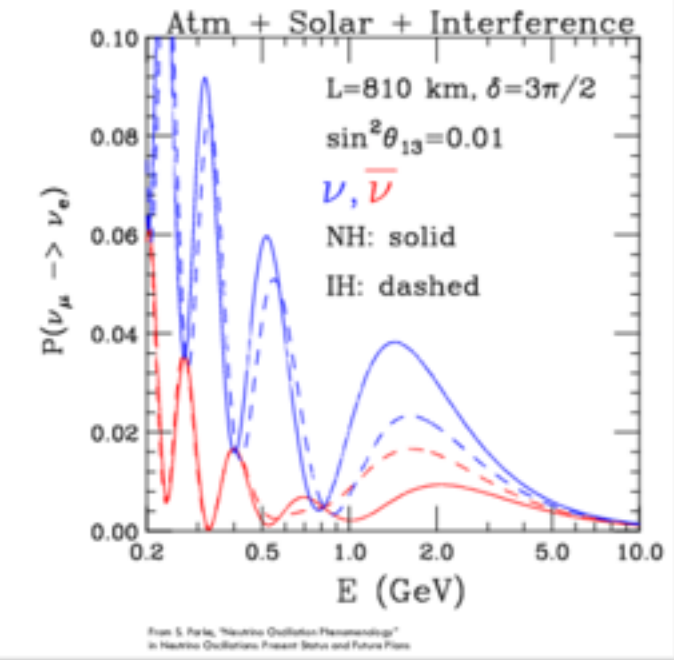
Depends on:

- δ_{cp}
- **Mss hierarchy and matter effects**

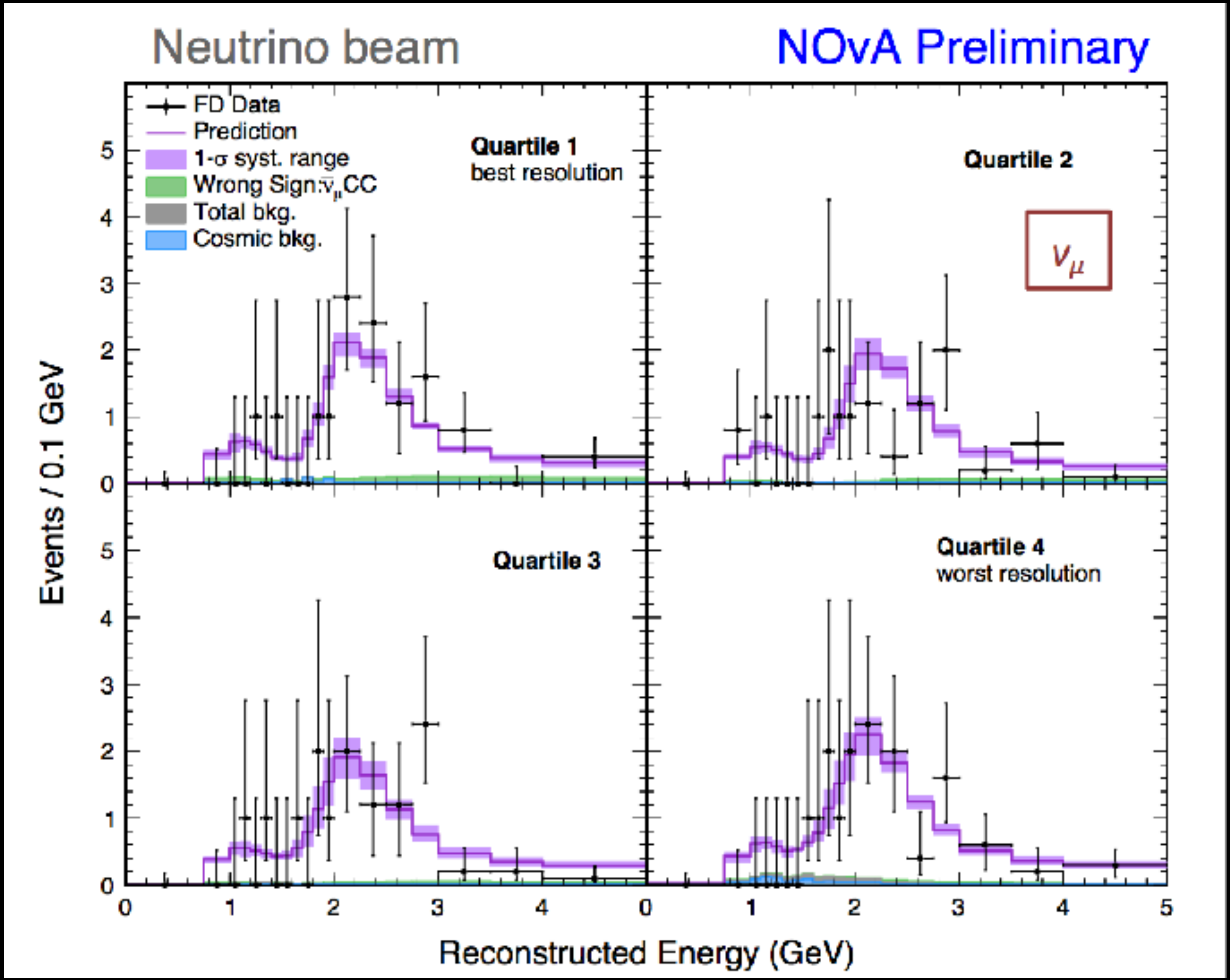
- **Atmospheric parameters: $\sin^2\theta_{23}$, Δm^2_{32}**
- **The smallest mixing angle: θ_{13}**
- **Solar parameters $\sin^2\theta_{12}$, Δm^2_{12}**

Disappearance constrains:

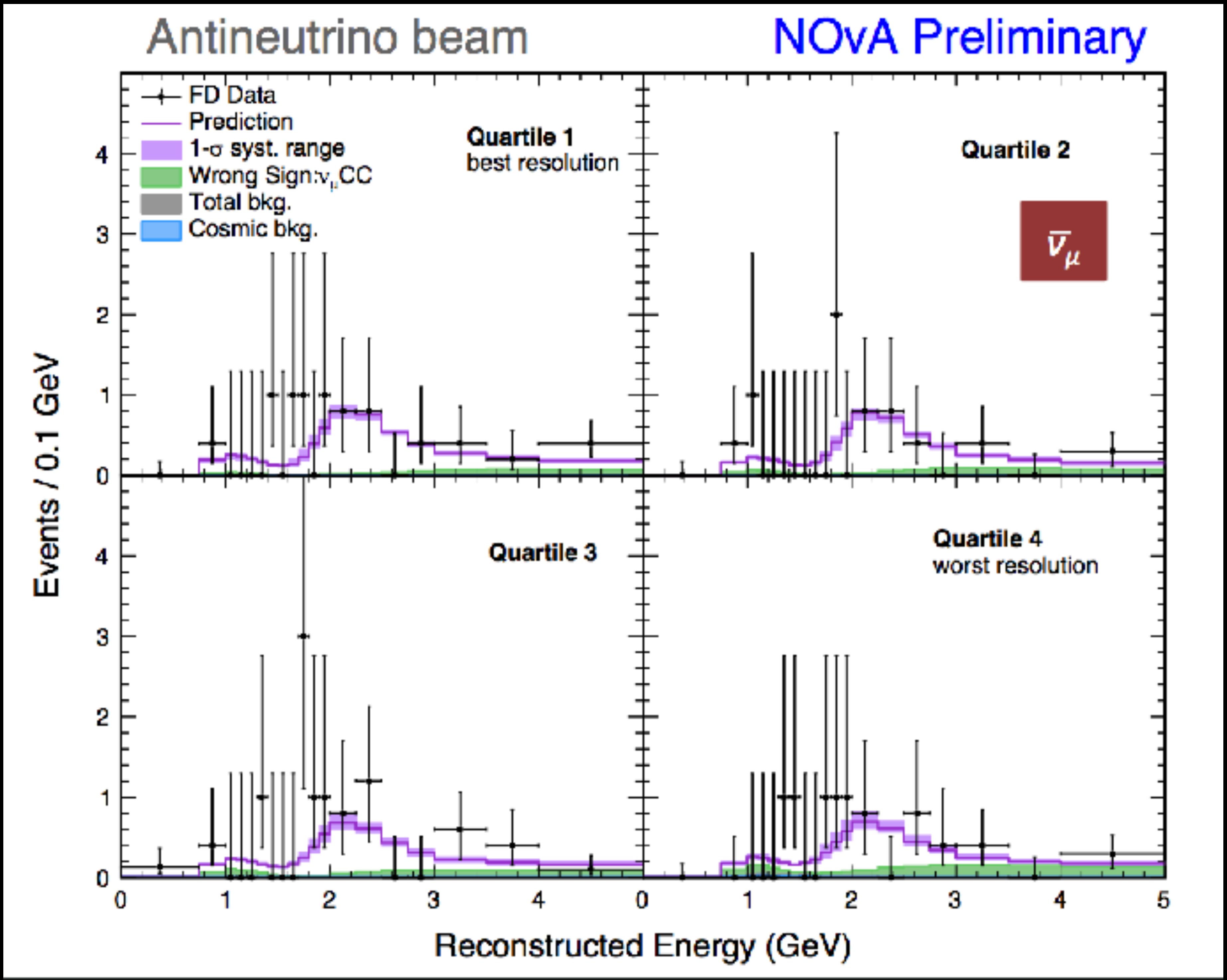
Reactor: ν_e -> ν_e
Solar: ν_e -> ν_e
NOvA: ν_μ -> ν_μ



FD Numu Prediction in quantiles

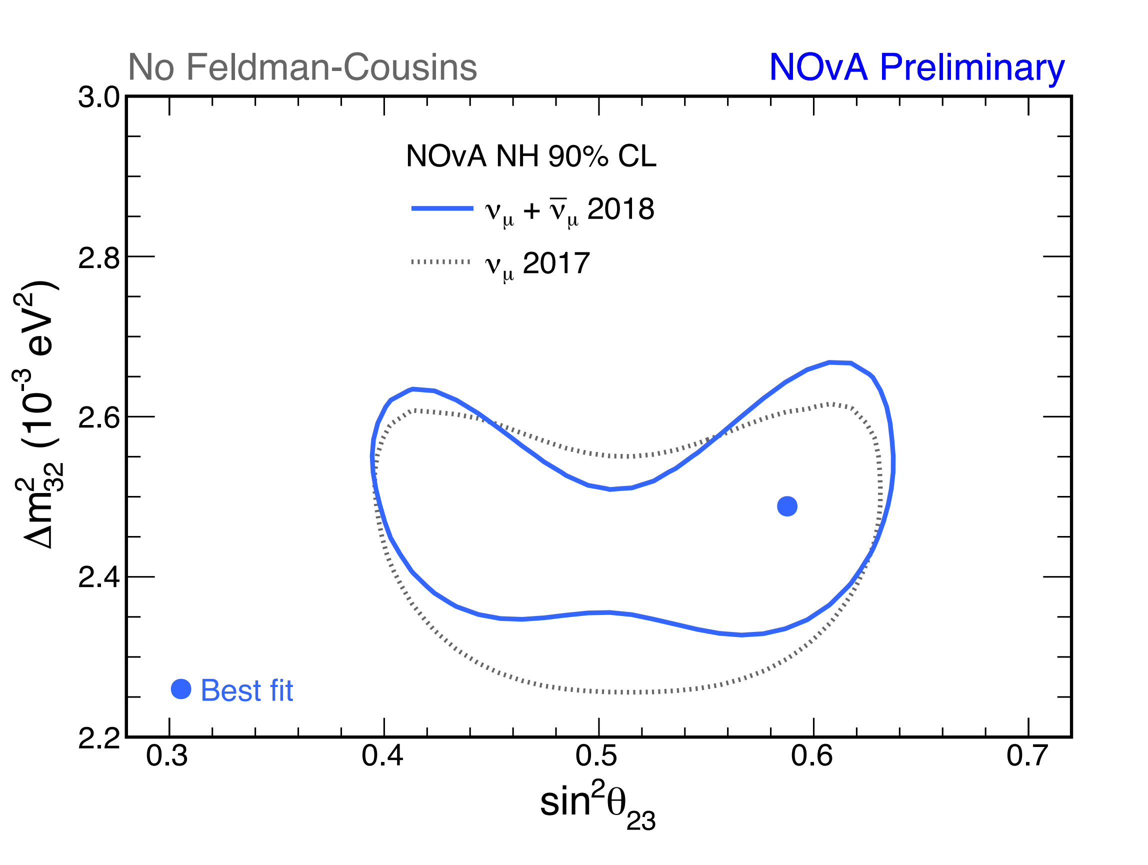


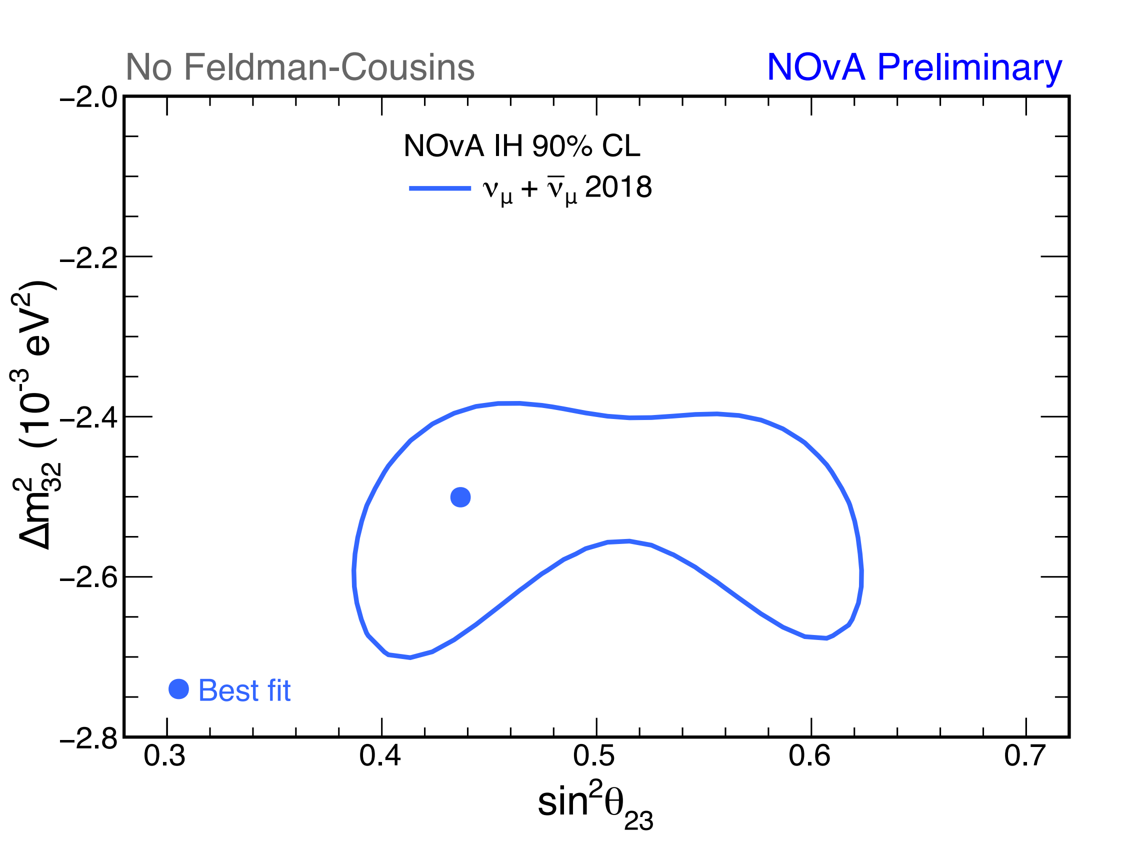
FD Numu Prediction in quantiles



Muon Neutrino Disappearance

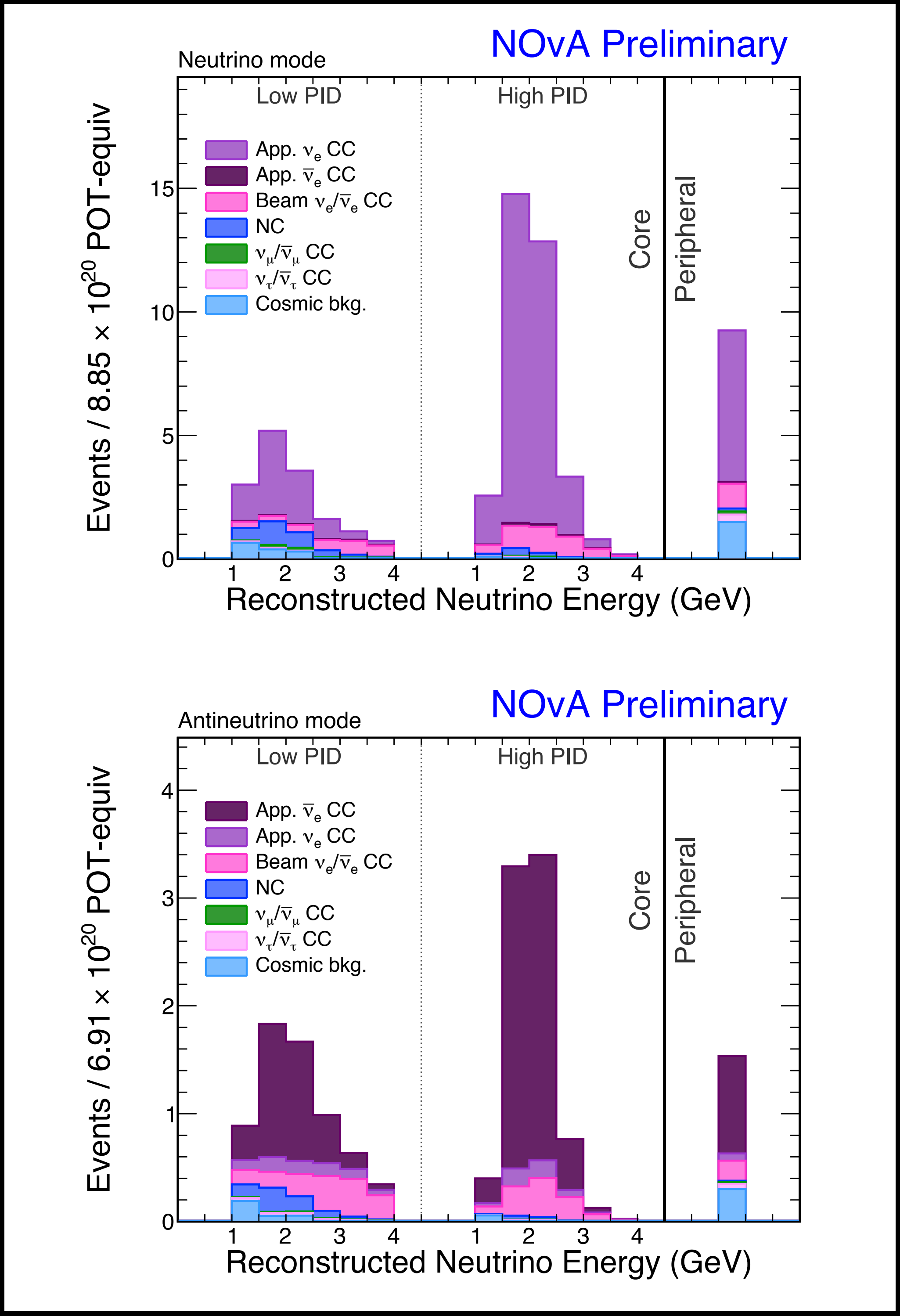
- Matter effects introduce a small asymmetry in the maximal disappearance point between neutrinos and antineutrinos.
- Tension between the muon neutrino and antineutrino datasets (at the 1 σ level) favors upper octant (UO) for normal hierarchy (NH) and lower octant (LO) for inverted hierarchy (IH).



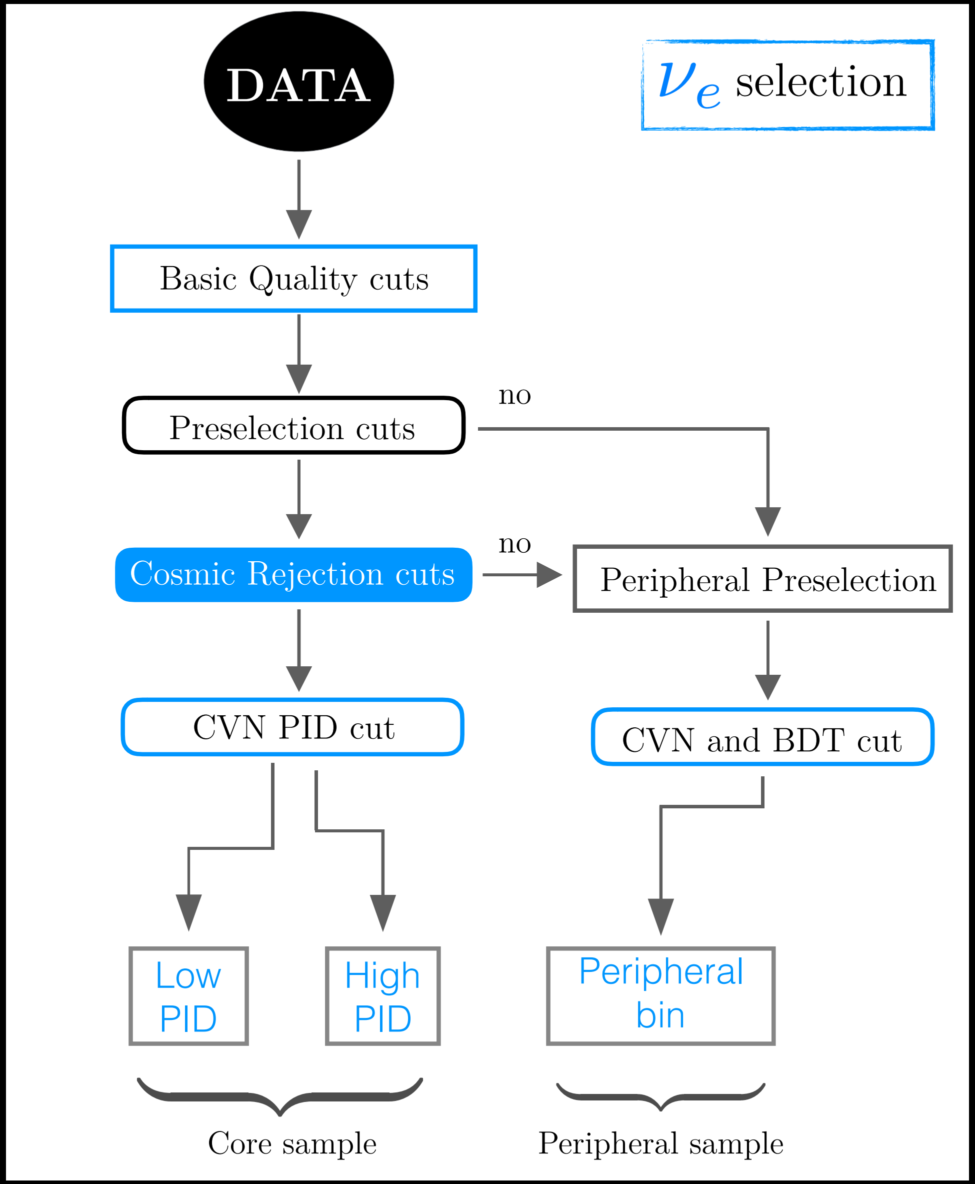


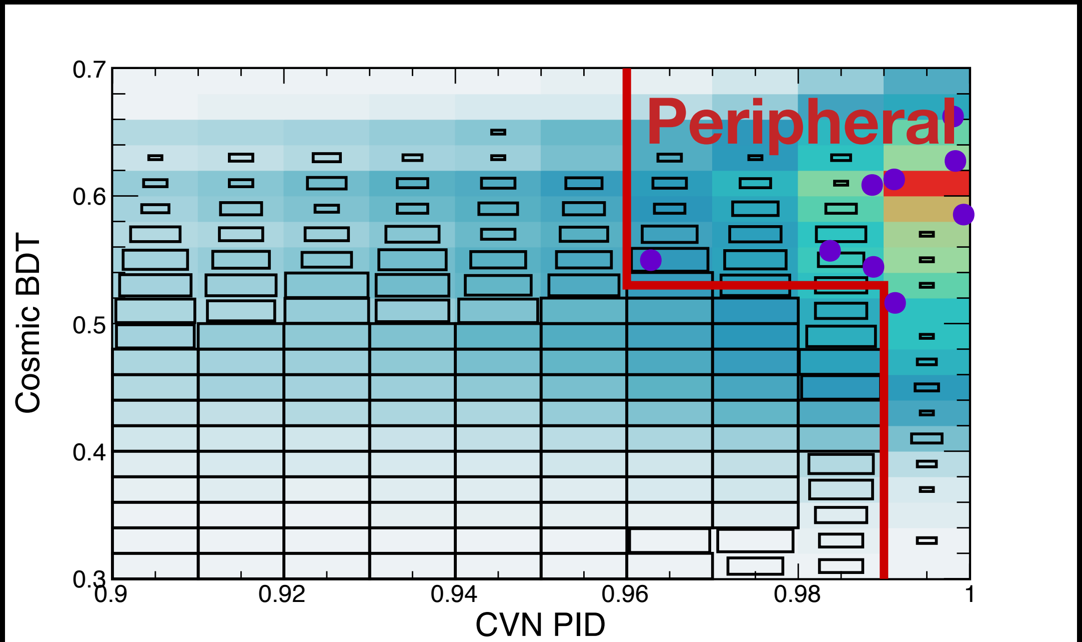
ND Electron Neutrino Spectra

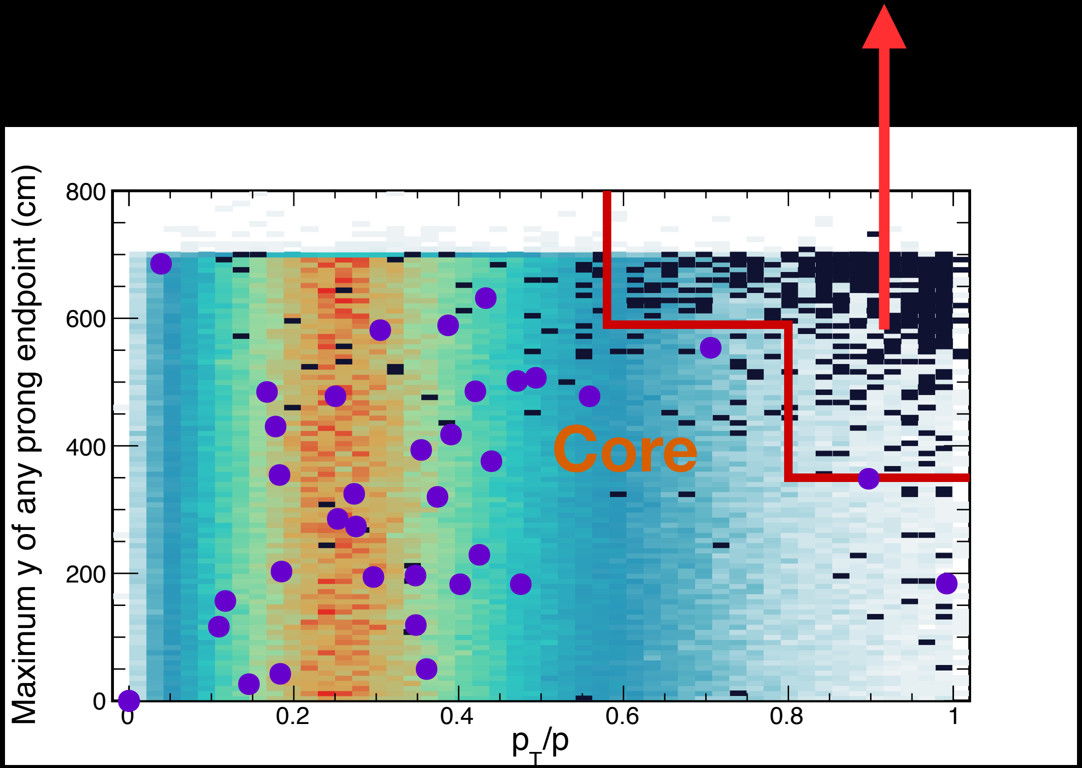
- ND wrong sign component is 22% (32%) of the ν_e background for the high (low) PID bin.
    - Data-based cross-checks using identified protons and event kinematics within systematic uncertainty.



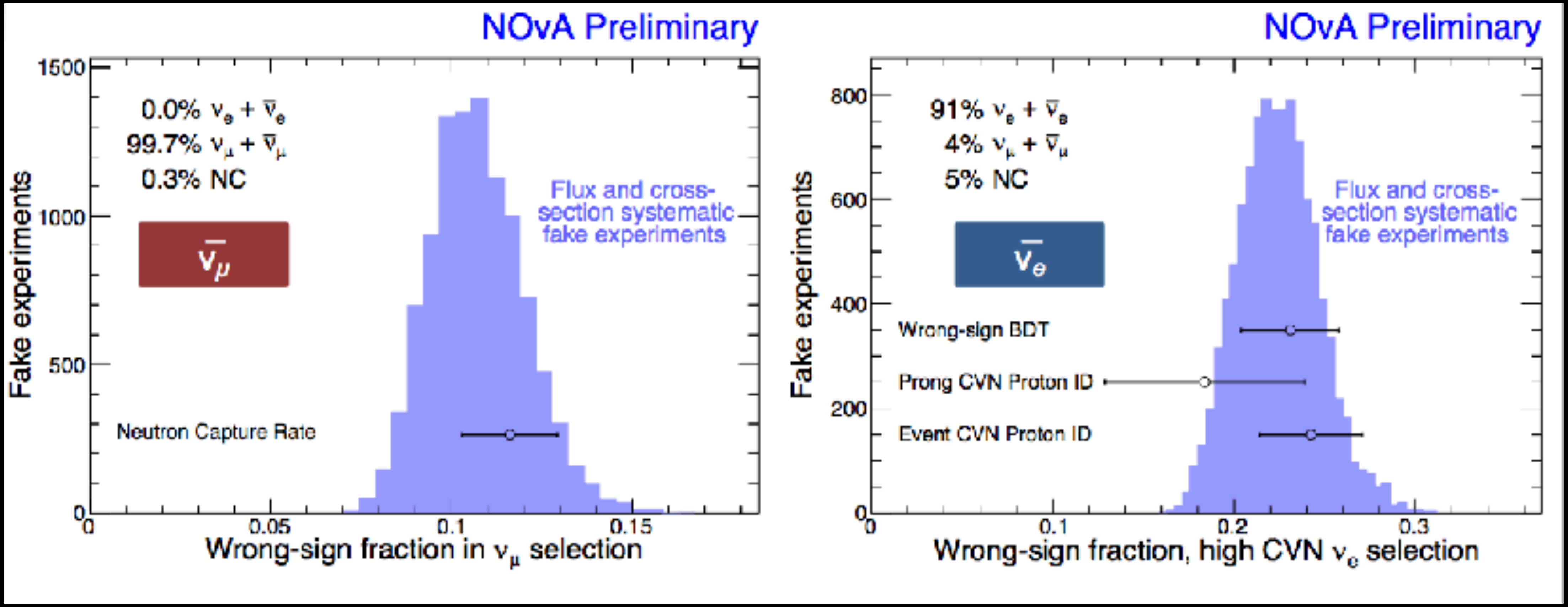
Electron Neutrino Selection







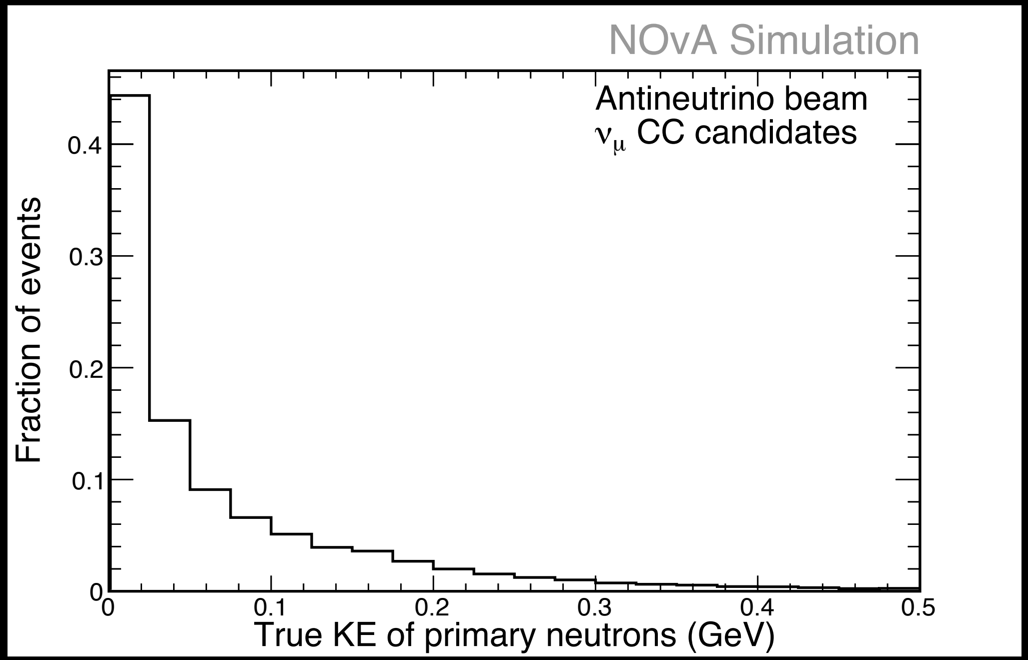
Wrong Sign Cross-Check

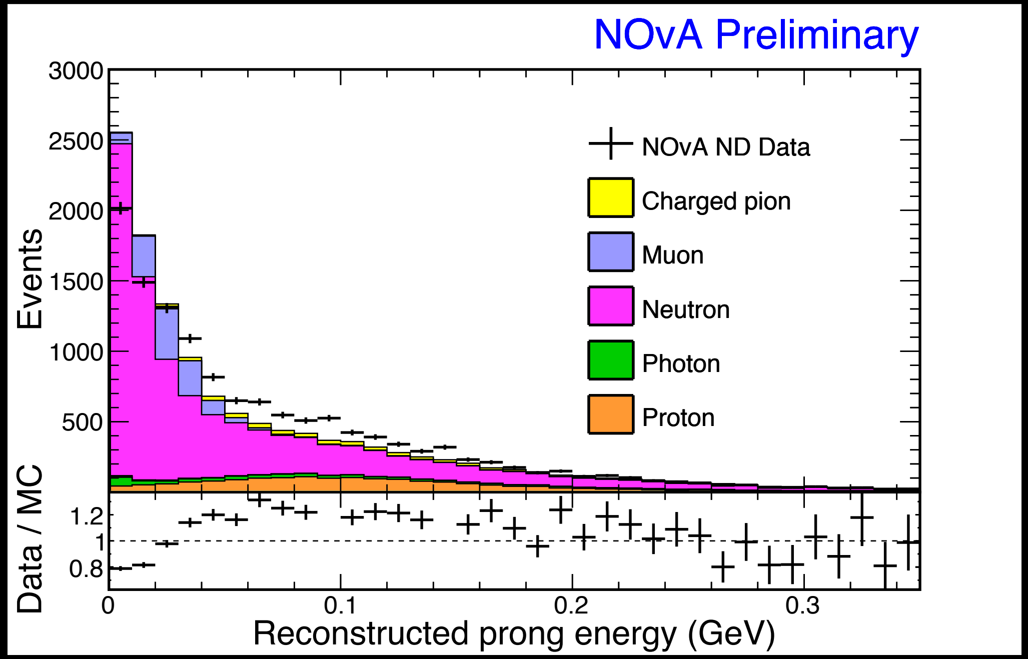


- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Confirmed using data-driven cross-check of the wrong-sign contamination
- 11% wrong-sign in the $\bar{\nu}_\mu$ sample checked using many PIDs in the neutrino and antineutrino beams.

Neutron Uncertainty

- 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.





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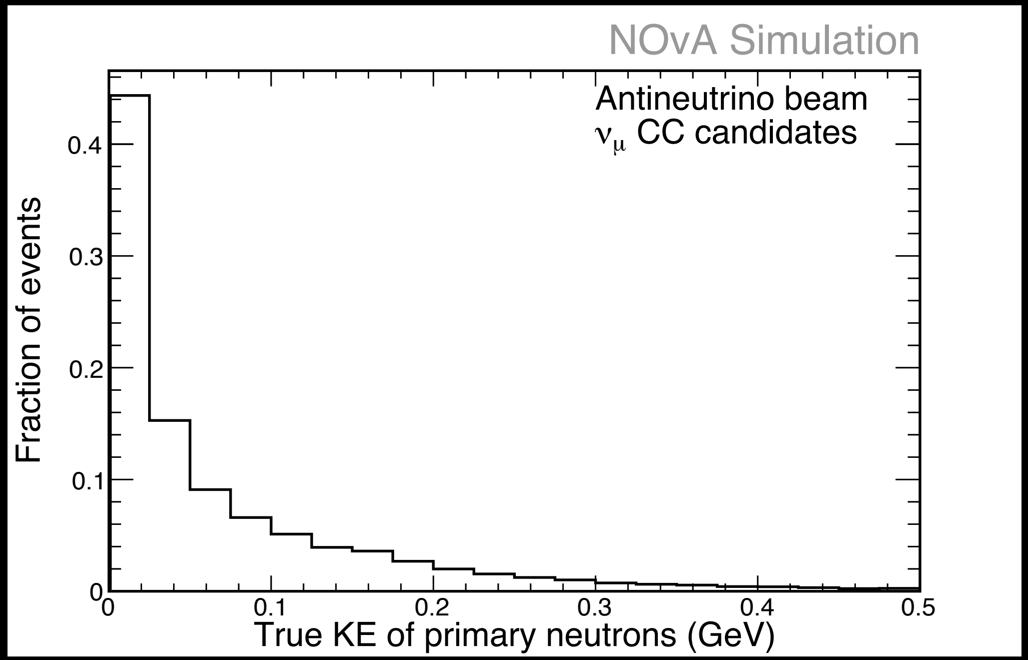
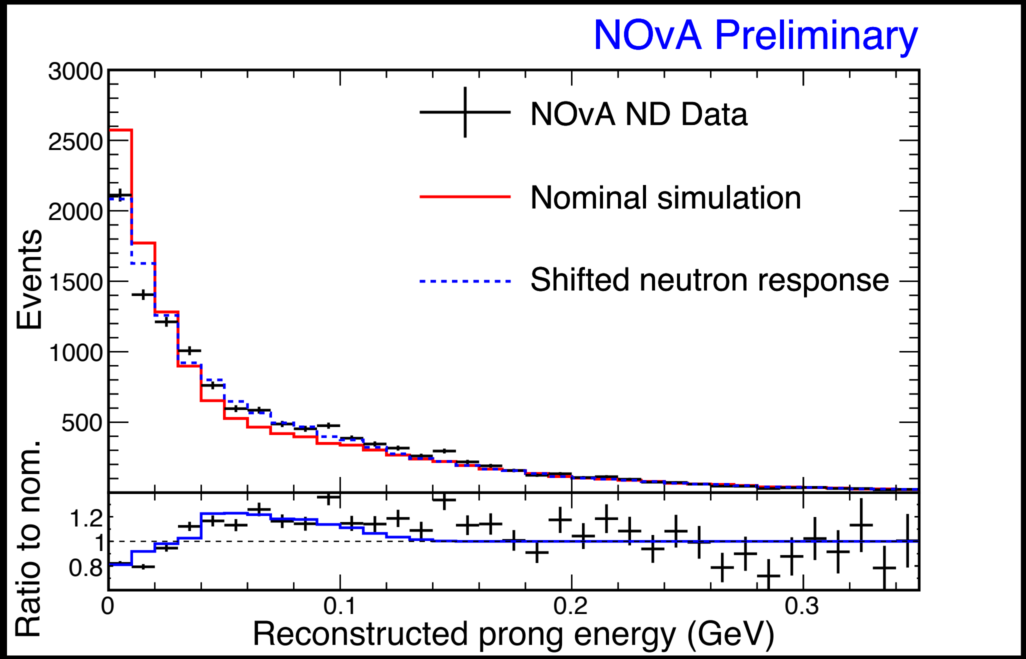
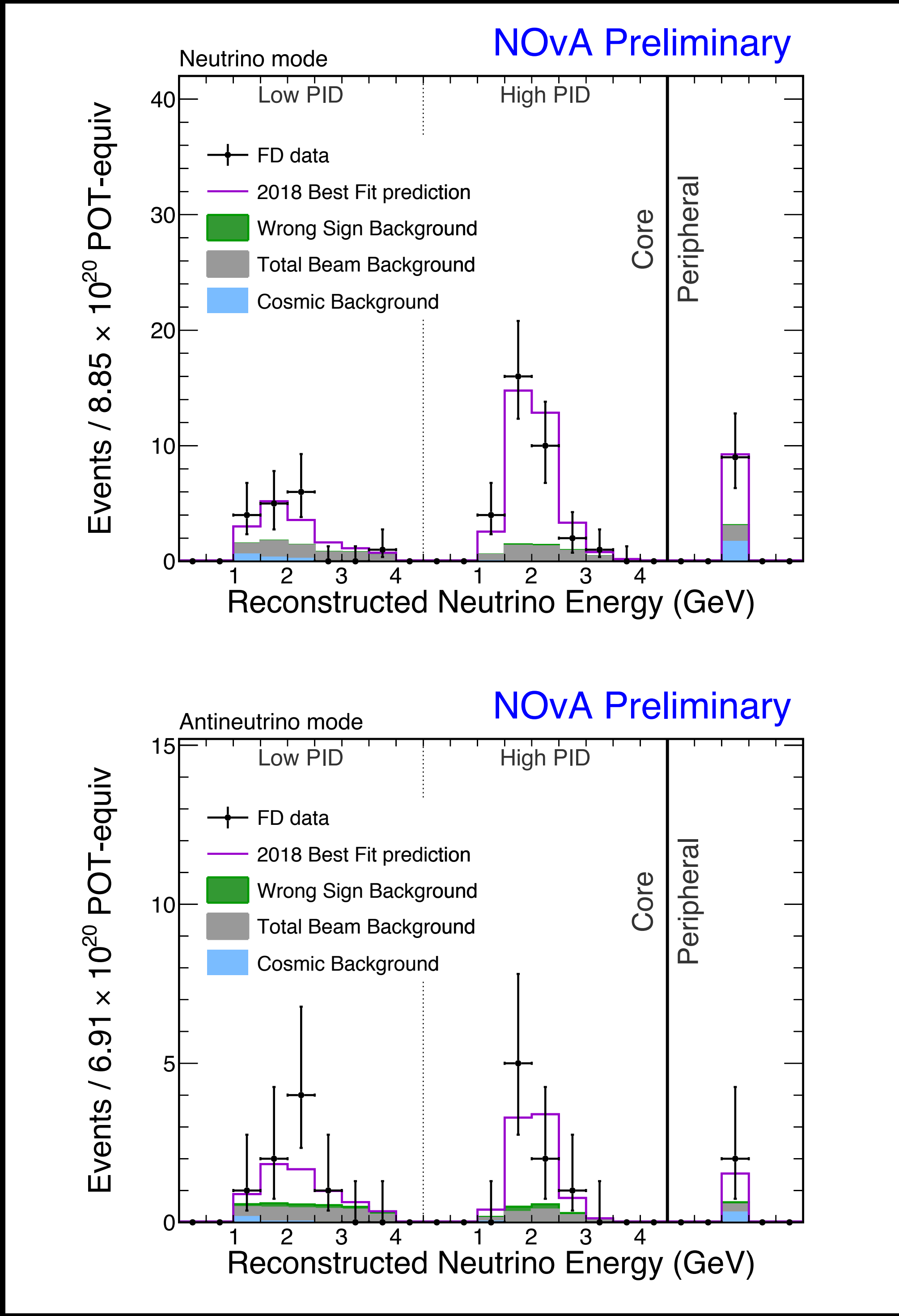




Electron Neutrino Appearance Expectation

- On the neutrino beam we observe 58 events and expect 15 background interactions:
  - 11 beam, 3 cosmic background and < 1 wrong sign background.
- For the antineutrino beam we observe 18 and expect 5.3 background interactions:
  - 3.5 beam background, < 1 cosmic background and 1 wrong sign background.

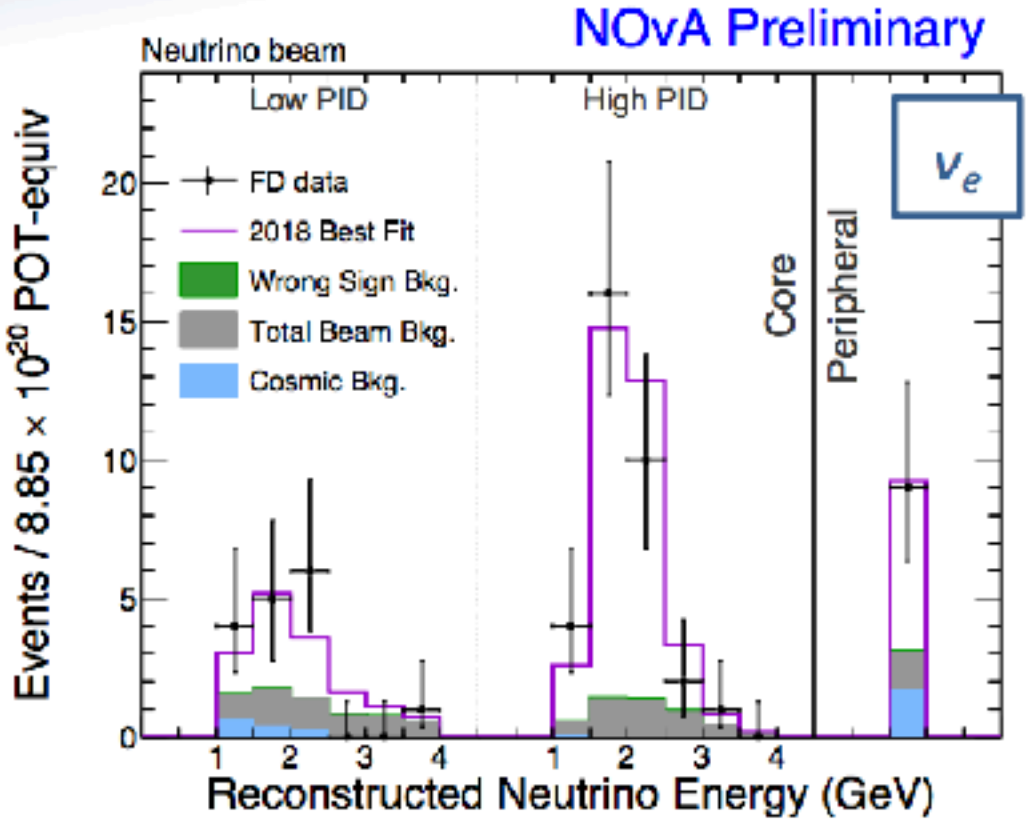
> 4σ evidence of electron antineutrino appearance



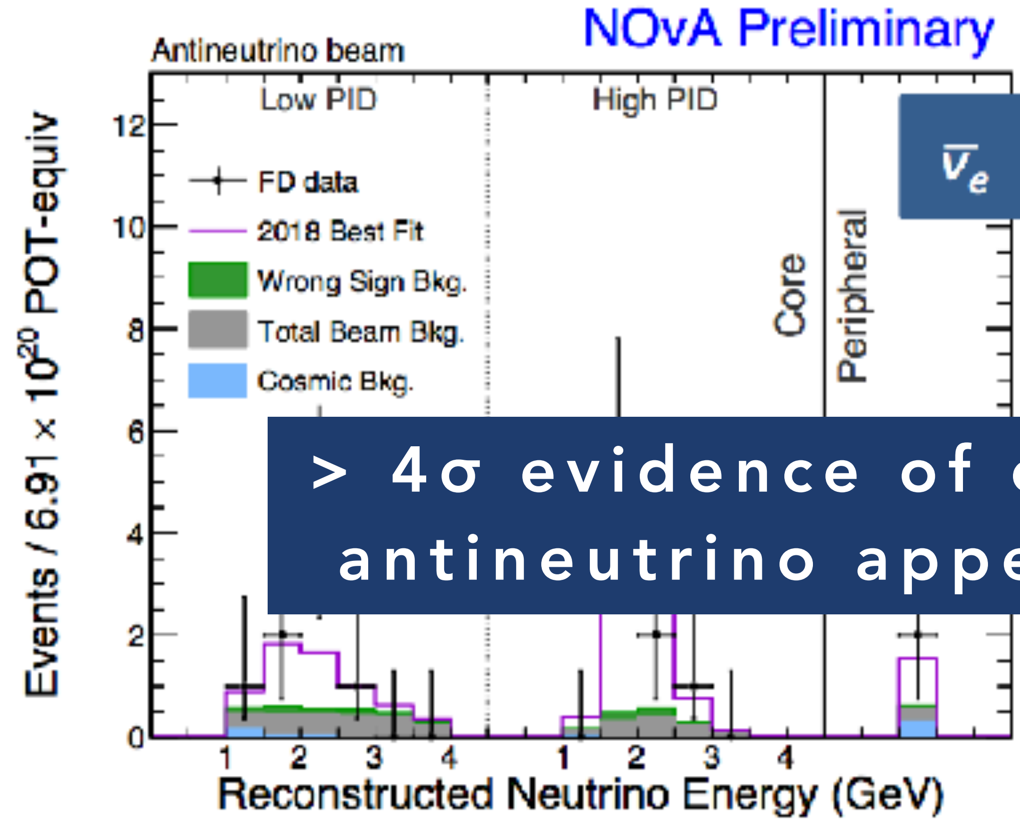
FD Electron Neutrino Prediction

62->58

12->18



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



> 4σ evidence of electron antineutrino appearance

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