NOVA
RESULTS AND PROSPECTS

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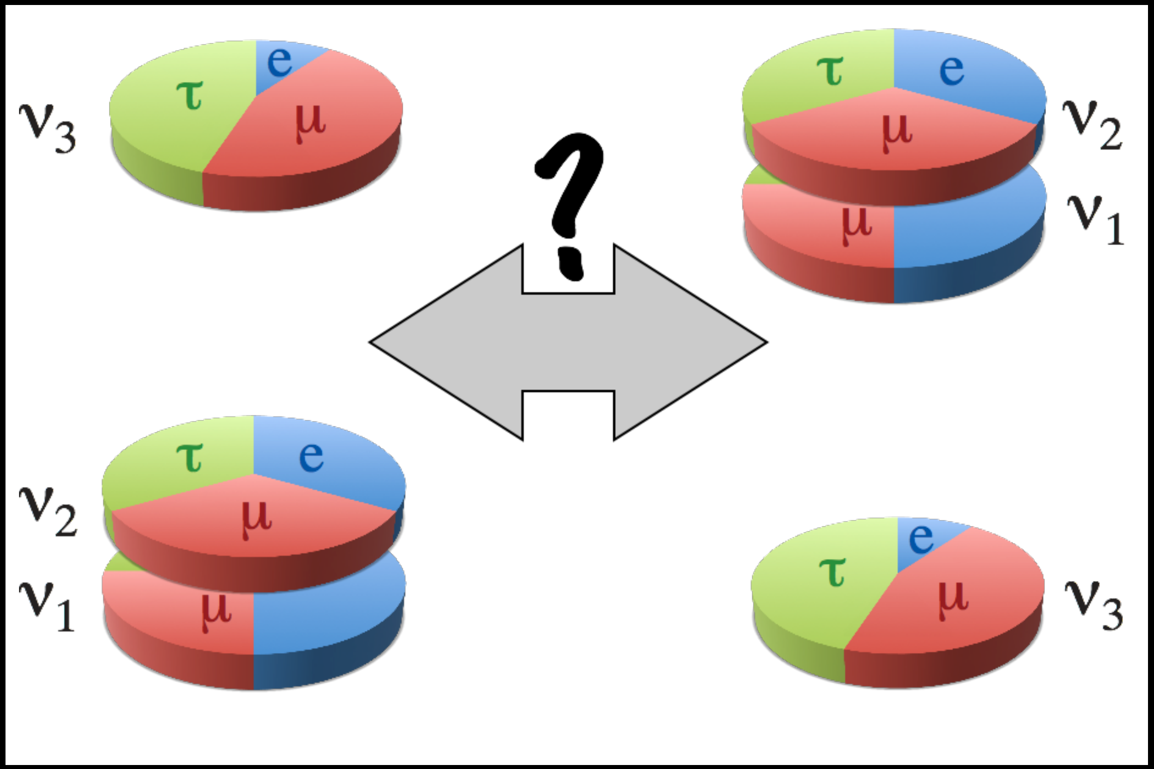
NOVA'S PHYSICS GOALS

THE NOVA PROGRAM SEEKS TO ANSWER KEY UNKNOWNS

- 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?



In addition, cross section analyses, searches for exotic phenomena and non-beam physics

NOVA POSTERS AT NEUTRINO2018

Far Detector oscillation analyses

- Data-driven Techniques for nue Signal and Background Predictions in NOvA (#80)
- Systematic Uncertainties and Cross-Checks for the NOvA Joint ν_e + ν_μ Analysis (#81)
- NOvA joint ν_e + ν_μ oscillation results in neutrino and antineutrino modes (#82)

- Muon neutrinos and anti-neutrinos in the NOvA Experiment (#75)
- First ν_μ and ν_μ + ν_μ Disappearance Results from the NOvA experiment (#66)
- Systematic Uncertainties in the NOvA ν_μ-Disappearance Analysis (#88)

- Search for sterile neutrinos in neutrino data in the NOvA near and far detectors (#141)
- First Results from the NOvA Antineutrino Neutral Current Disappearance Sterile Neutrino Search (#132)

Cross sections, exotic and other

- NOvA Short-Baseline Sterile Neutrino Search (#142)
- Status of the Neutrino-Induced Neutral Current Neutral Pion Production Cross Section Measurement from NOvA (#106)
- Measurement of Neutrino-Electron Elastic Scattering at NOvA Near Detector (#121)

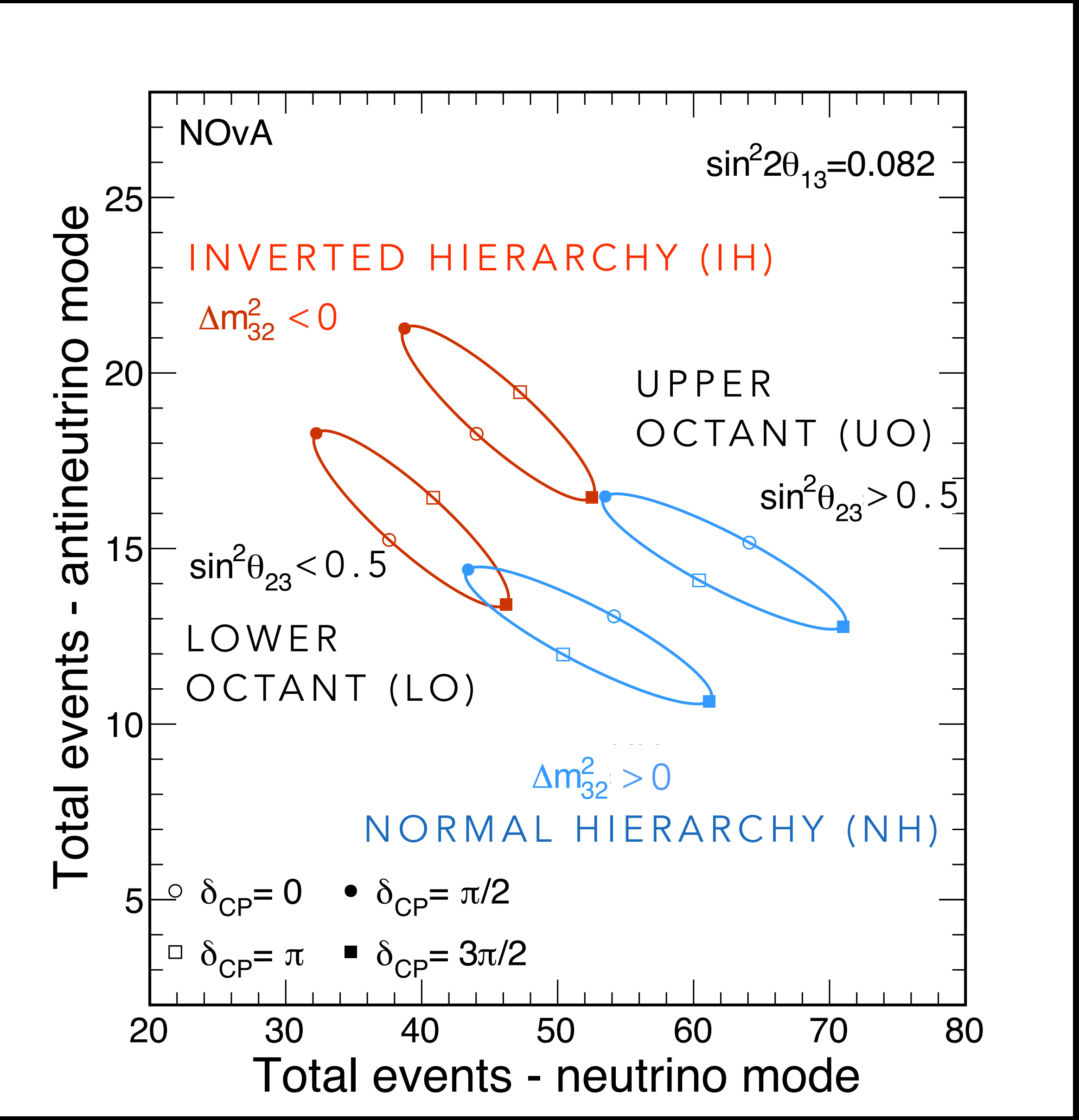
- Astrophysics with NOvA (#169)
- Detection of Galactic Supernova Neutrinos at the NOvA Experiment (#13)

- Neutrino Interaction Model Tuning at NOvA (#60)
- Reconstructing Neutrino Energies with the NOvA Detectors (#78)
- Neutrino physics with deep learning: Techniques and applications on NOvA (#79)
- The NOvA Test Beam Program (#58)

NOVA'S PHYSICS GOALS

NEUTRINO AND ANTINEUTRINO DATA ARE REQUIRED

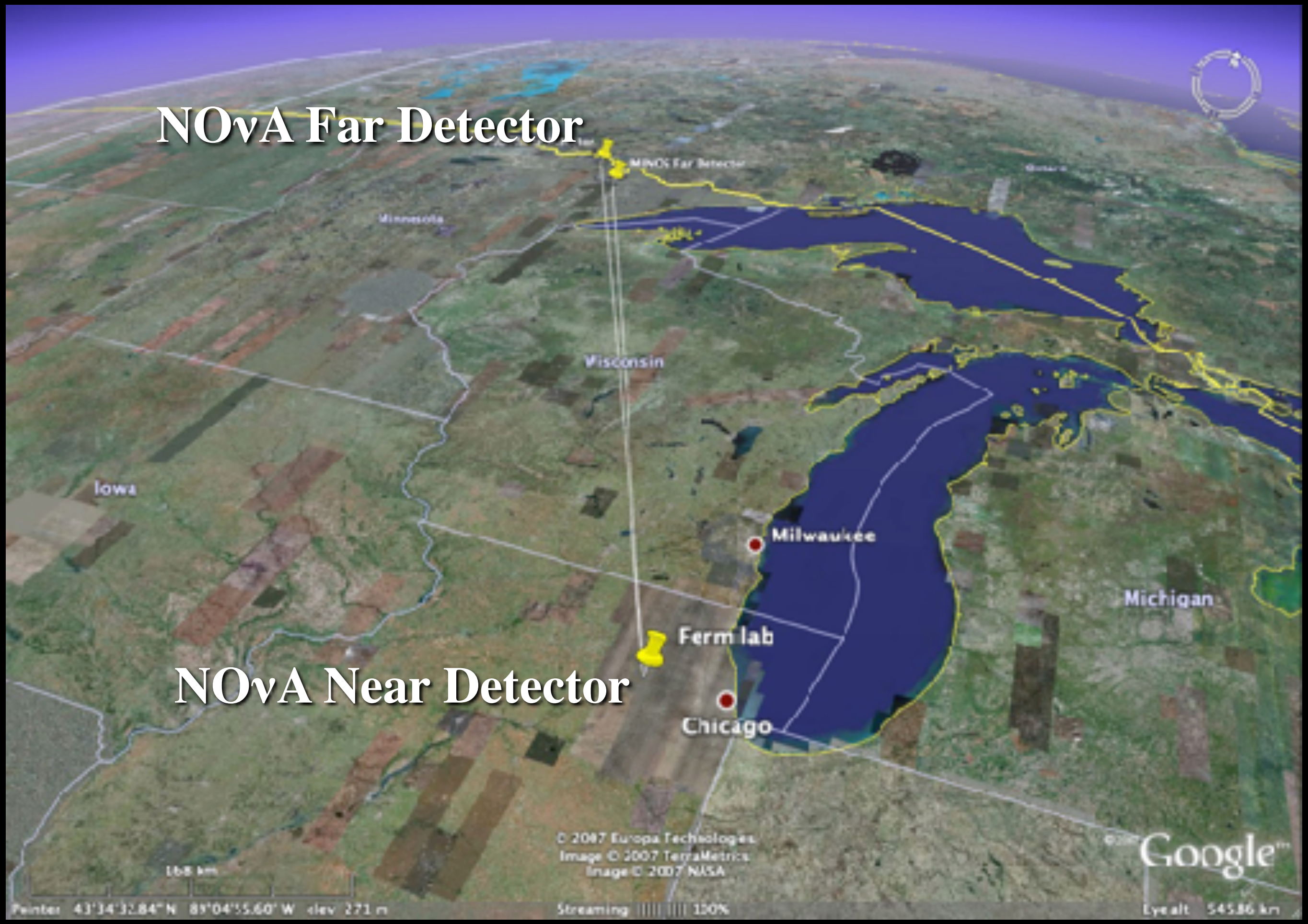
- What is the mass hierarchy or ordering for atmospheric neutrinos?
- Is there a ν_μ - ν_τ symmetry (is the large mixing angle maximal; if not, what is the octant)?
- Is CP violated in the lepton sector?
- Are there other neutrinos beyond the three known active flavors?

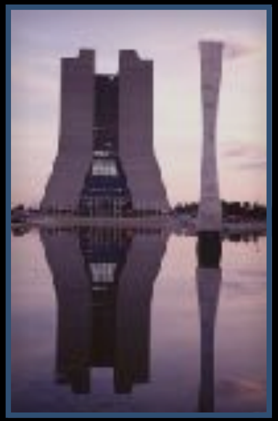


FIRST NOVA ANTINEUTRINO DATA AT THIS CONFERENCE

THE NOVA EXPERIMENT IN A NUTSHELL

- Upgraded NuMI **beam of muon neutrinos or antineutrinos** at Fermilab running at 700kW.
- Highly active liquid scintillator **14-kton detector** off the main axis of the beam.
  - Functionally identical detectors: Near Detector (ND) site at Fermilab and Far Detector (FD) 810 km away at Ash River, MN.
- NOvA observes **disappearance of muon neutrinos and antineutrinos, appearance of electron neutrinos and antineutrinos** and potential suppression of neutral current interactions.





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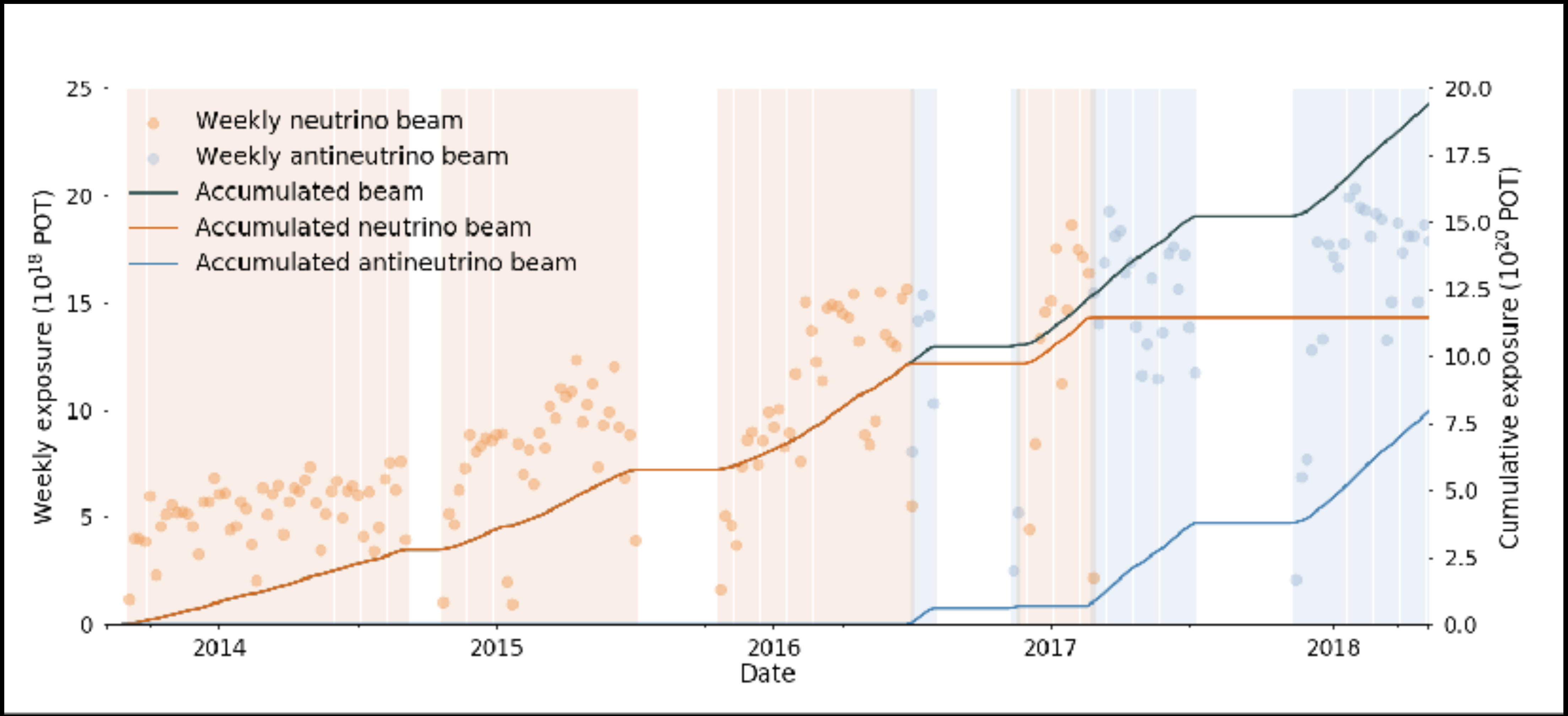
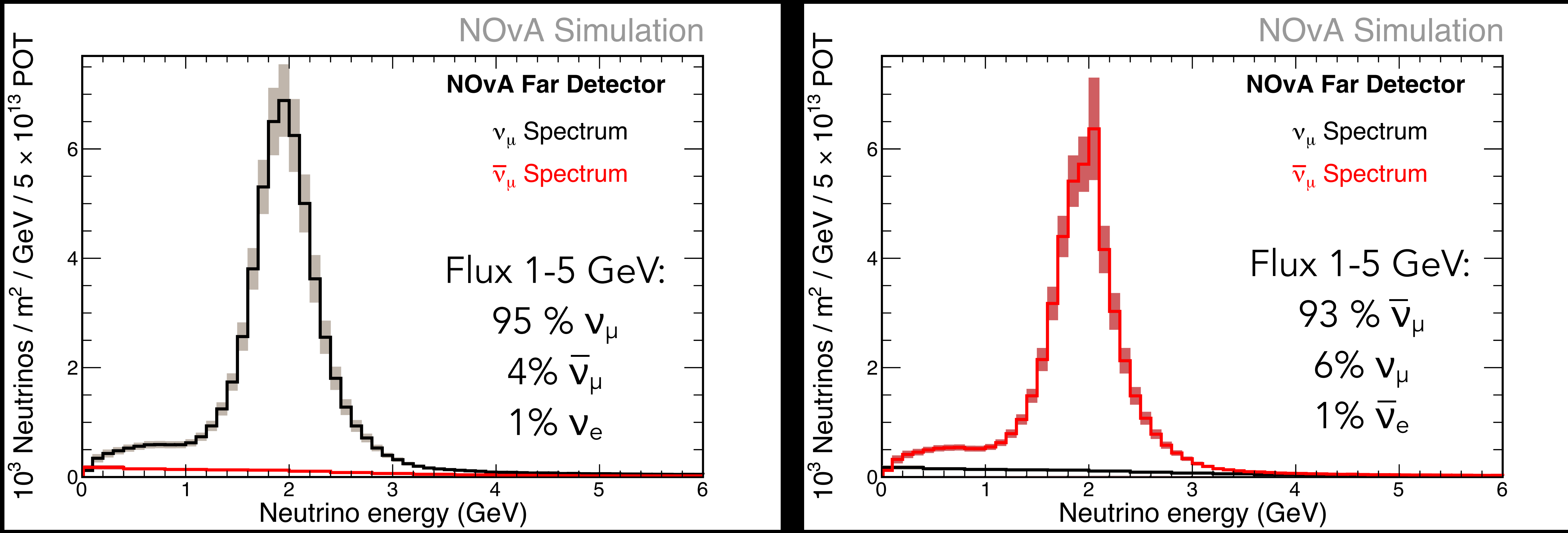
NEUTRINO AND ANTINEUTRINO BEAM PERFORMANCE



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

THE OFF-AXIS NUMI BEAM

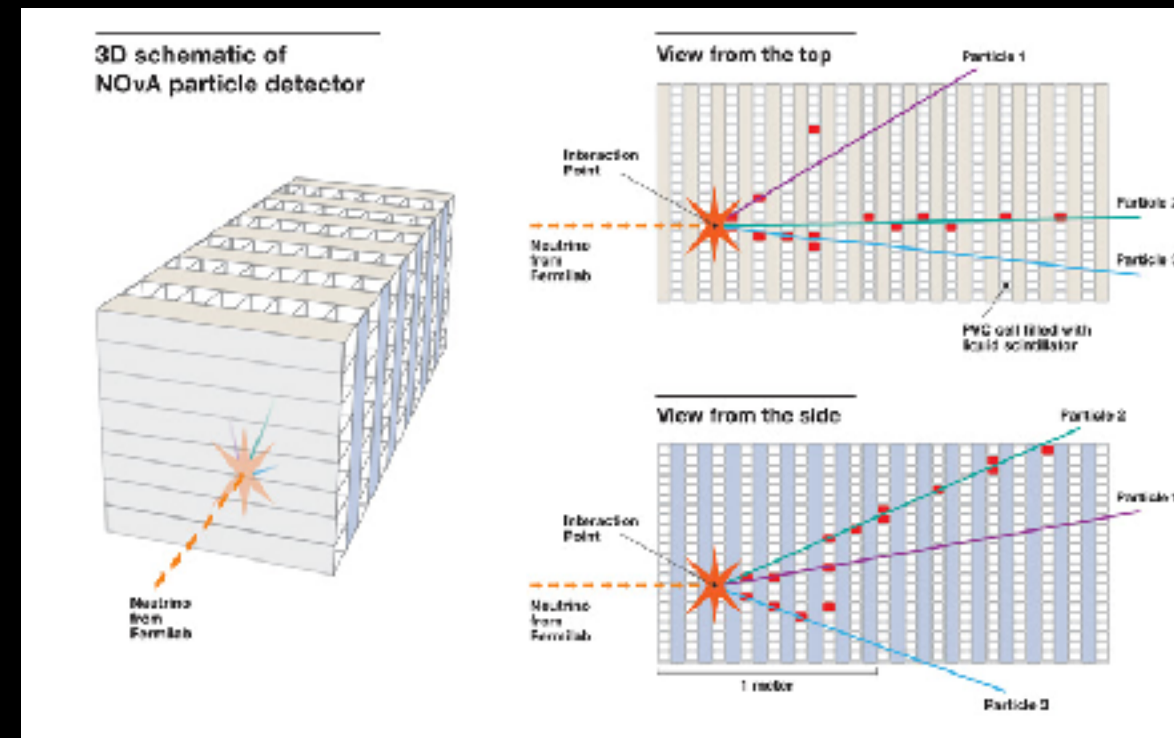


Neutrino beam | Antineutrino beam

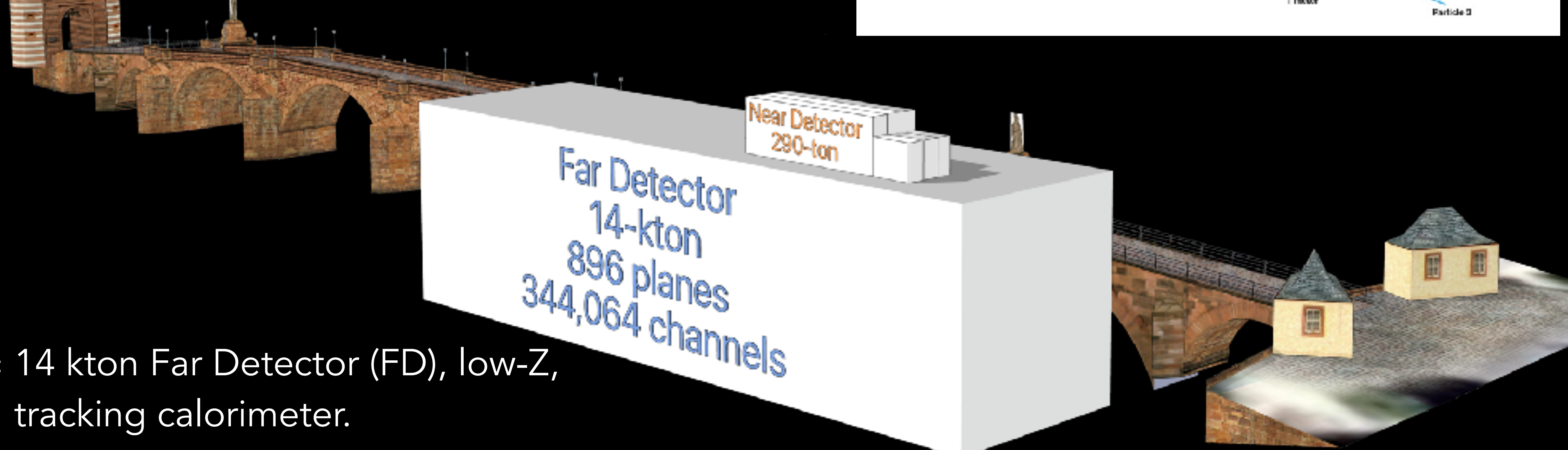
- Off-axis at 14 mrad, peaks just above the oscillation maximum. Small wrong sign component for both beams.
- The prediction of the NuMI beam at the NOvA detectors is made using the Package to Predict the FluX (PPFX), a method developed by MINERvA (Phys. Rev. D 94, 092005. 2016).
- The beam optics uncertainties 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.

THE NOVA DETECTORS

- PVC extrusions + Liquid Scintillator
- Layered planes of orthogonal views with 6-cm cells. Readout via WLS fibers to APDs.
- 0.15 X_0 per layer, excellent for e-identification.



- 0.3 kton Near Detector (ND)
  - 1 km from source, 100 m depth.

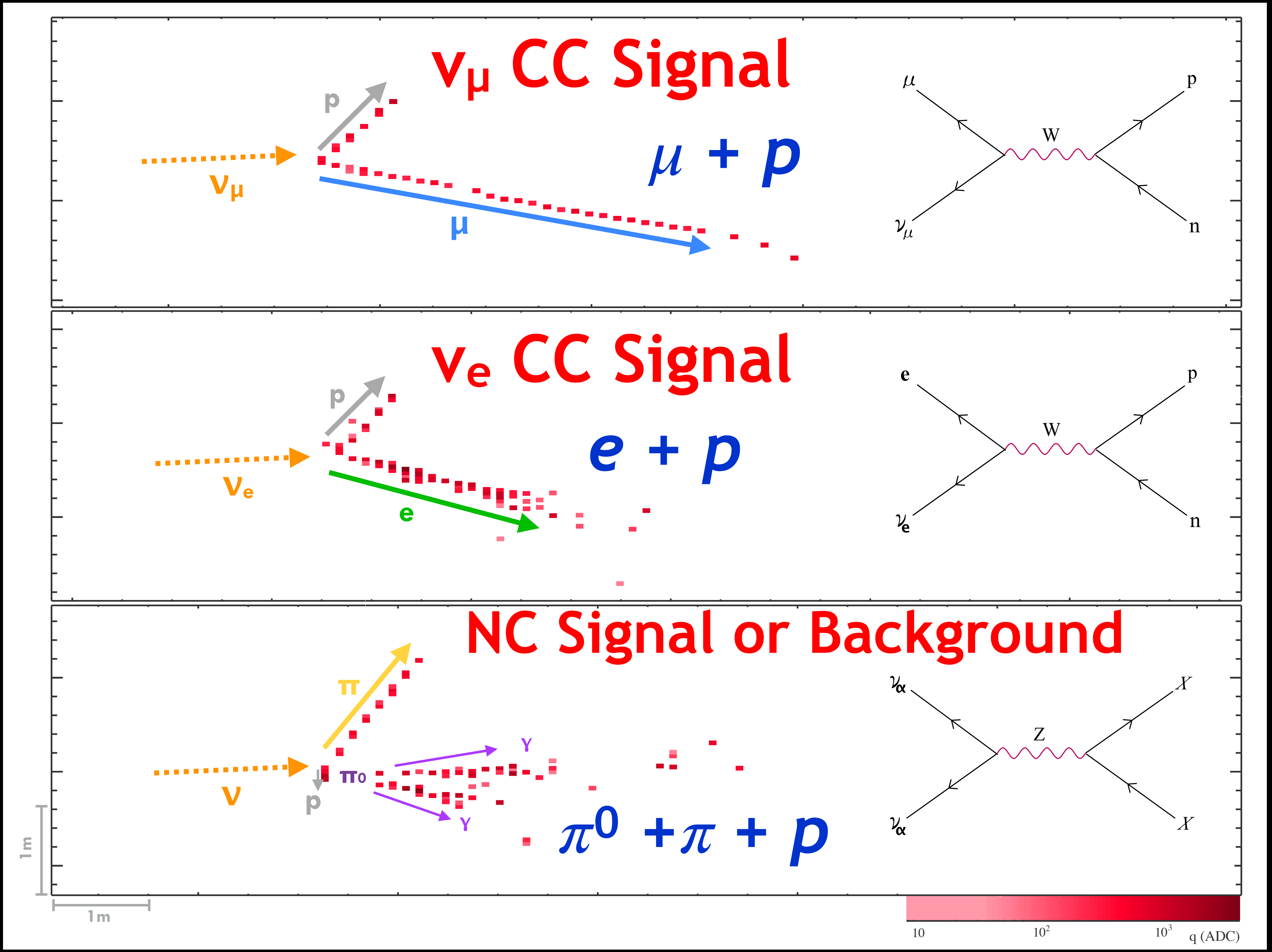


- 14 kton Far Detector (FD), low-Z, tracking calorimeter.
  - 810 km from source, on the surface, 3 m.w.e. overburden.
  - 65% active detector mass

- Detector response simulation has been significantly improved with the addition of Cherenkov light, reducing larger uncertainties of previous results.

NOVA EVENT TOPOLOGIES

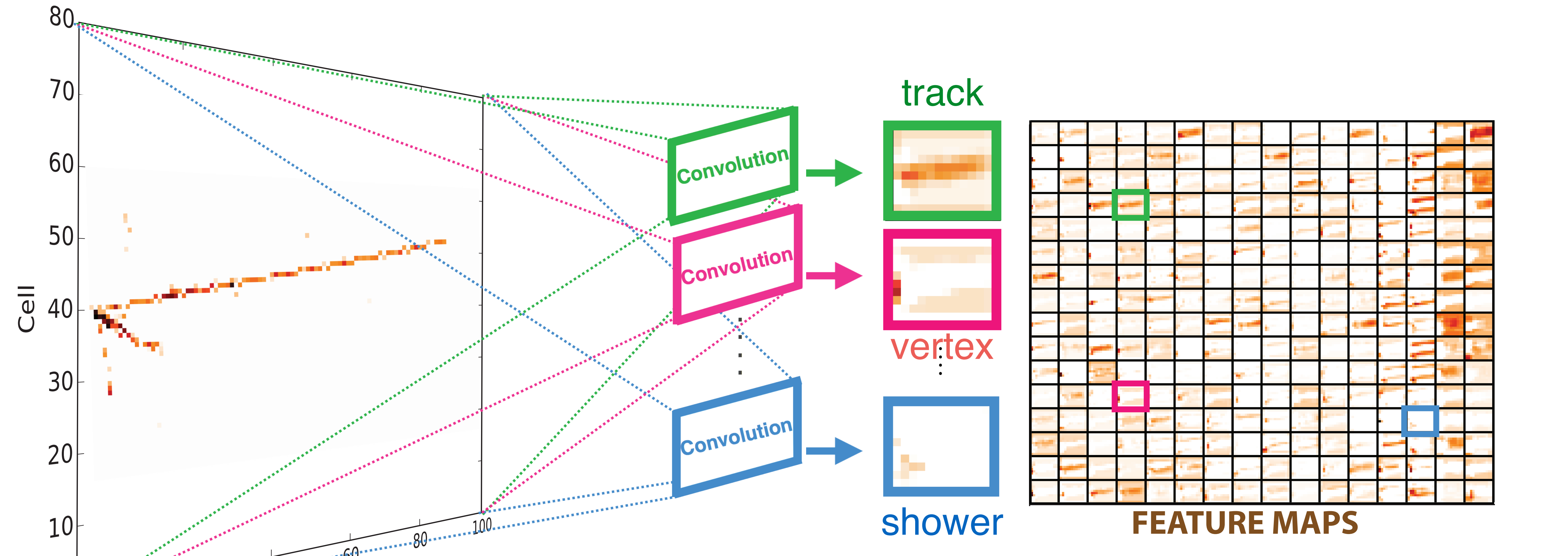
neutrino candidate interactions



see poster #79

NEUTRINO INTERACTION CLASSIFIER

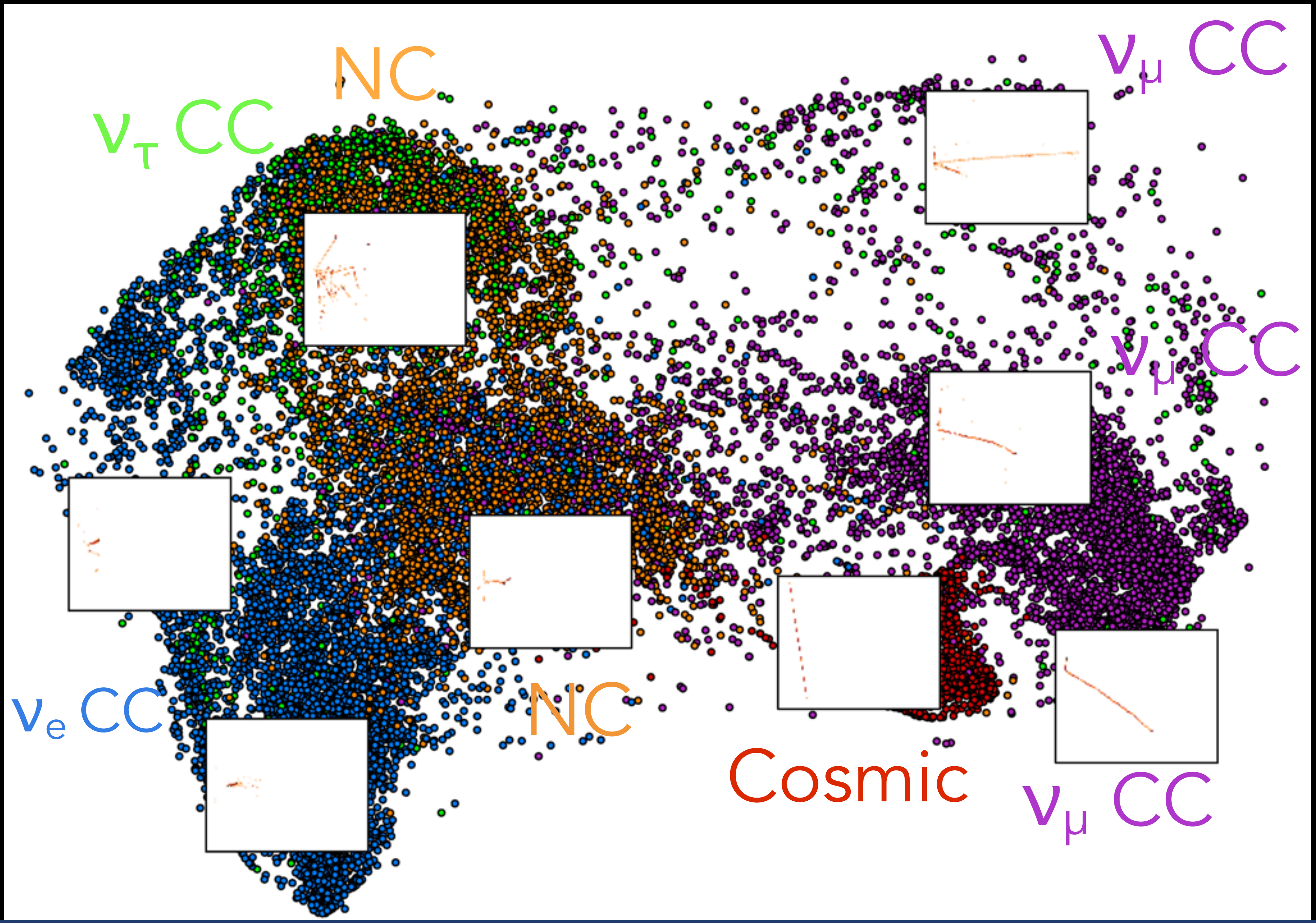
- NOvA has pioneered the use of Convolutional Neural Networks (CNN) for particle classification in neutrino physics.
- Using this technique we treat each interaction as an image with cells as pixels and charge as color value. The convolutional layers optimally extract features from the data.
- The NOvA 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.



"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

see poster #79

NEUTRINO INTERACTION CLASSIFIER



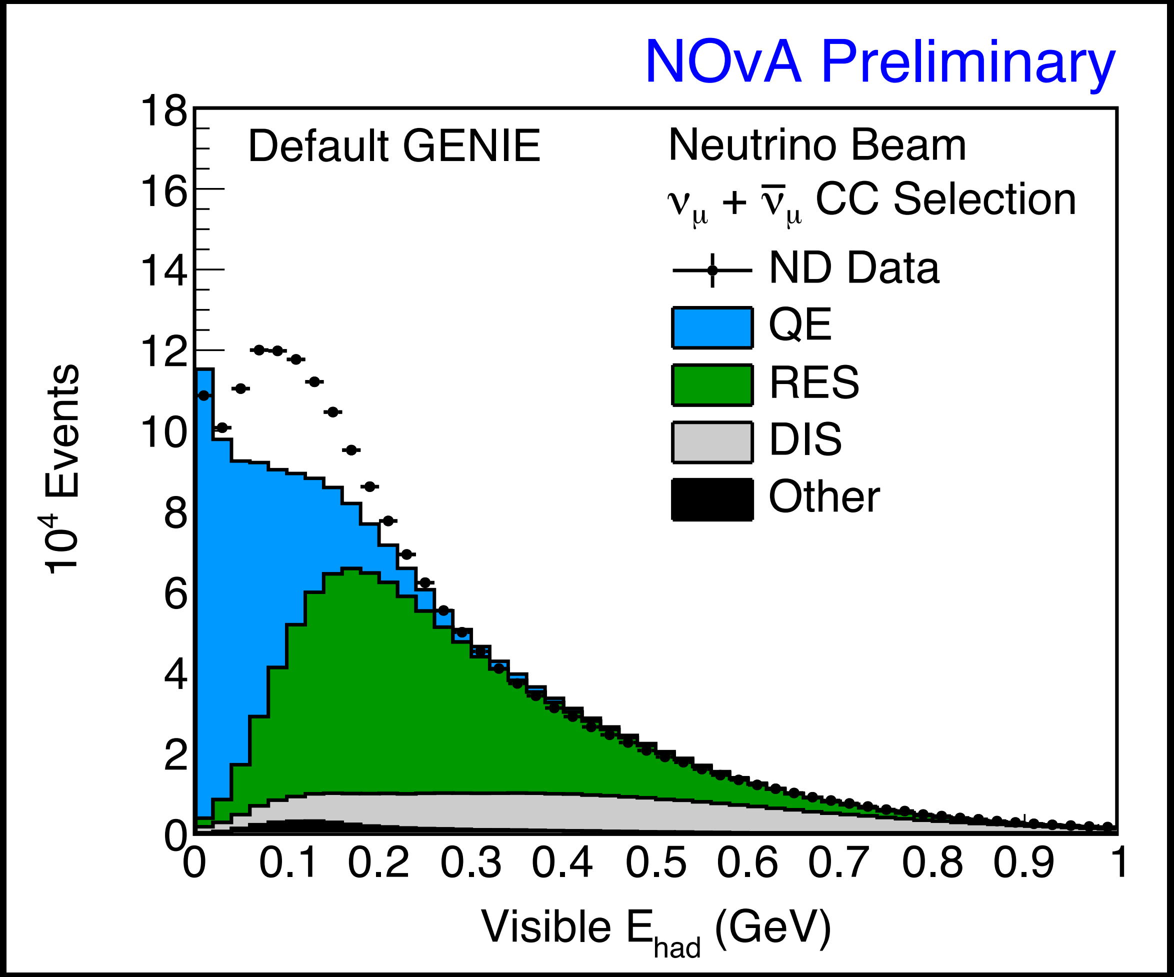
FOR ALL 2018 OSCILLATION ANALYSES: NEW PARTICLE ID USED WITH DIFFERENT OPTIMIZATIONS, TRAINED FOR NEUTRINO AND ANTINEUTRINO BEAM SEPARATELY, COSMIC DATA INCLUDED IN TRAINING.

see poster #60

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.

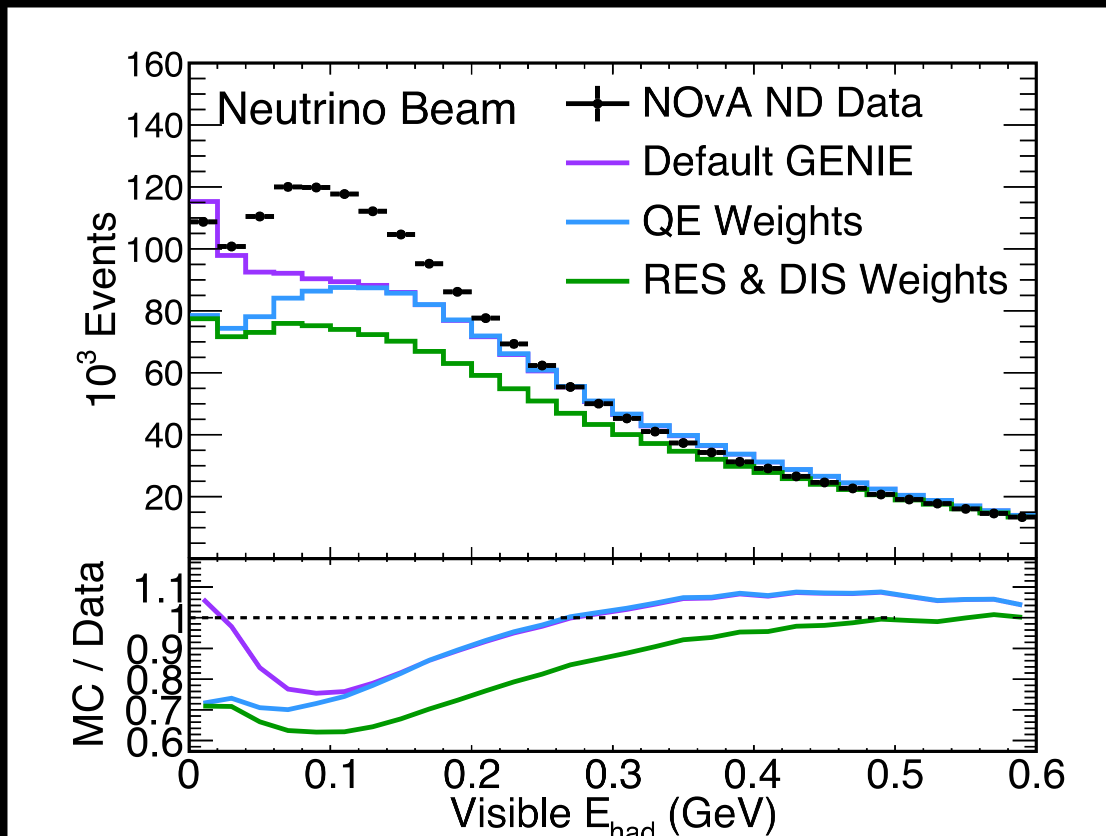
- Discrepancies thought to be due largely to complications of interactions in complex nuclear environment.

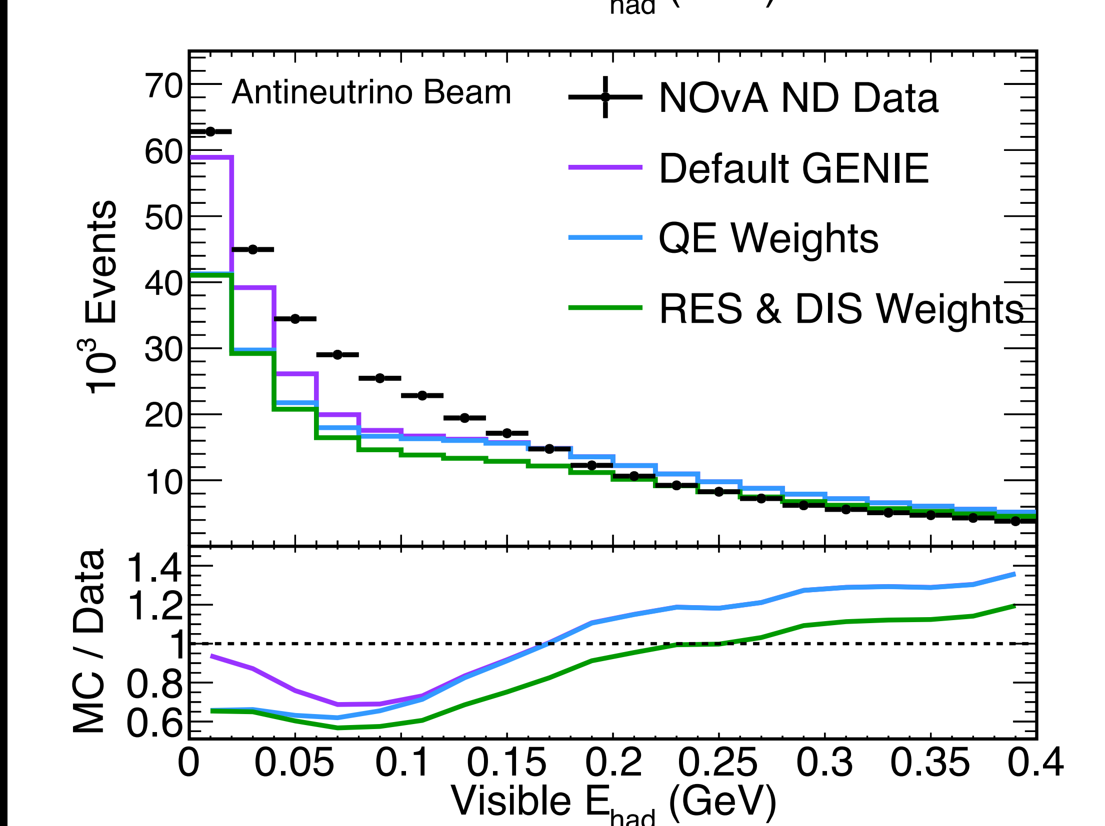


WE USE **NOVA AND EXTERNAL INFORMATION** TO TUNE THE MODEL TO OBTAIN BETTER CENTRAL VALUES AND APPROPRIATE UNCERTAINTIES

see poster #60

NEUTRINO INTERACTION TUNING



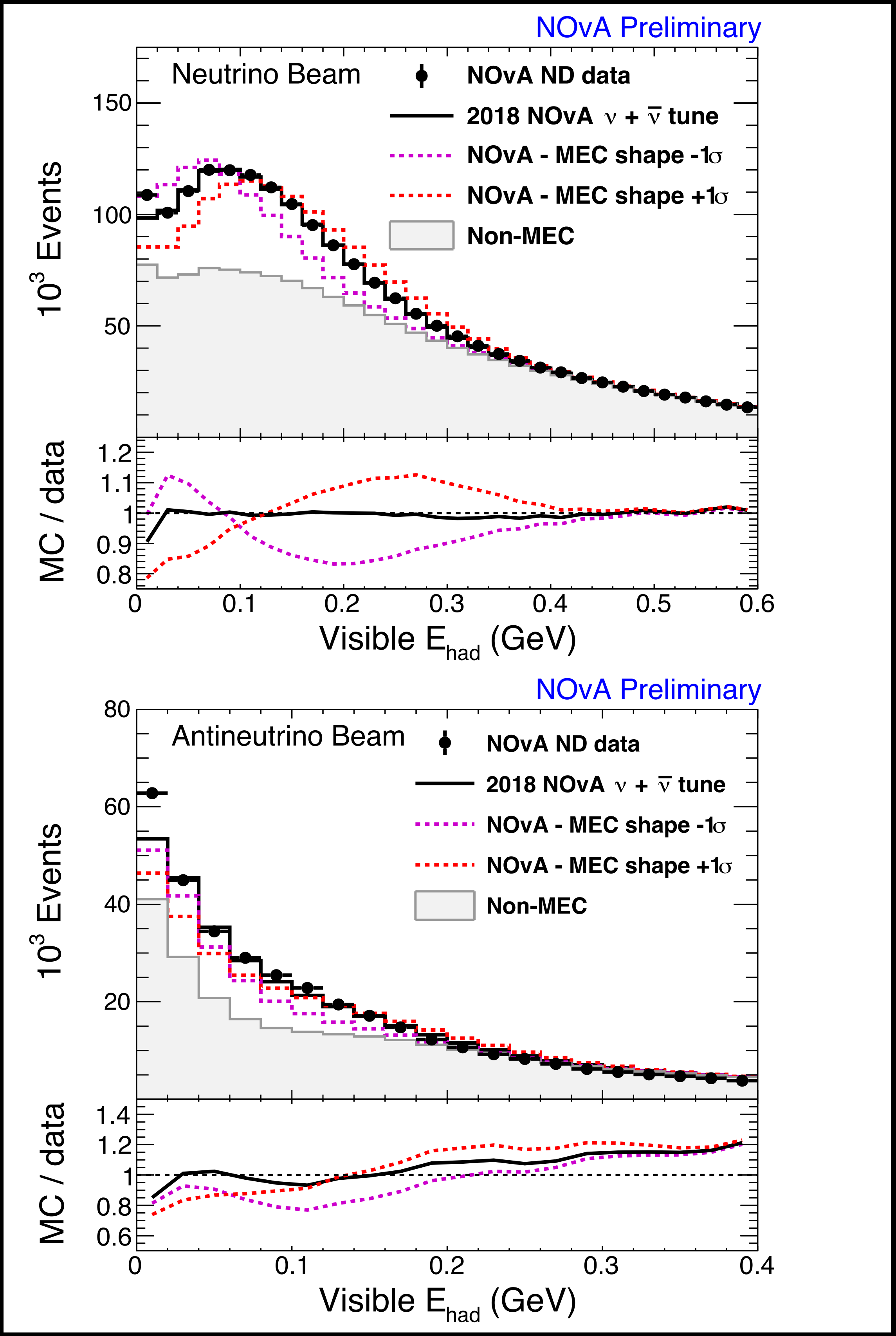


- The tuning is done independently for the neutrino vs antineutrino beam samples.
- Various corrections and tunings are applied:
  - Correct quasielastic (QE) component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]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

see poster #60

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 multinucleon 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 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.



see poster #60

NEUTRINO INTERACTION TUNING

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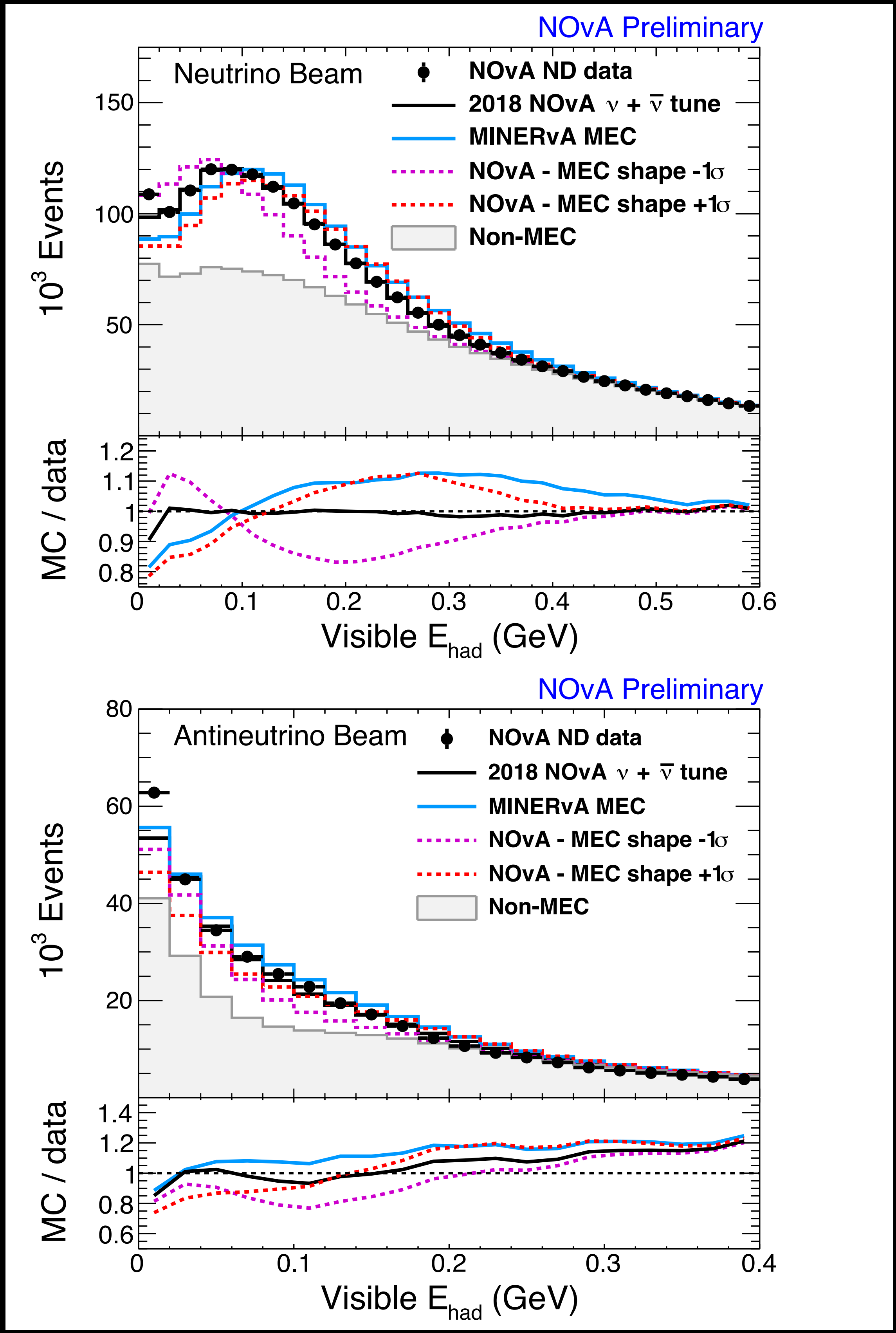
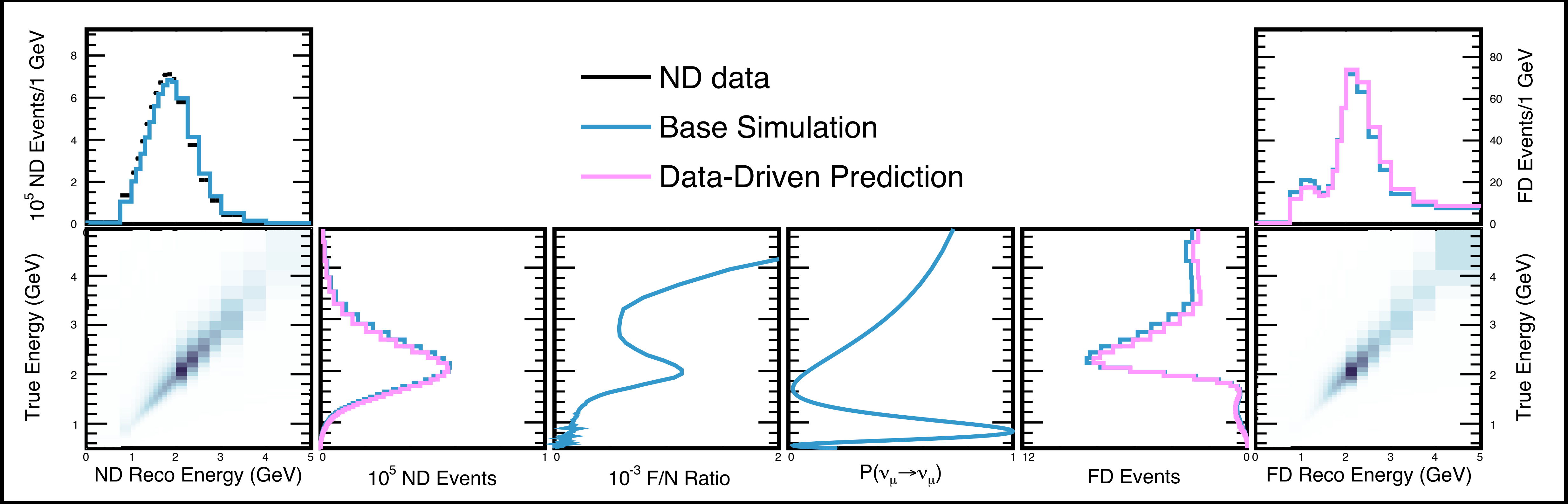
- This tuning procedure matches the added 2p2h component to the NOvA data excess in two-dimensional four-momentum transfer (q0,|**q**|) space using closely-related related observables.
- The MINERvA collaboration's tuning to their data resulted in similar shape features to our assumed uncertainties.



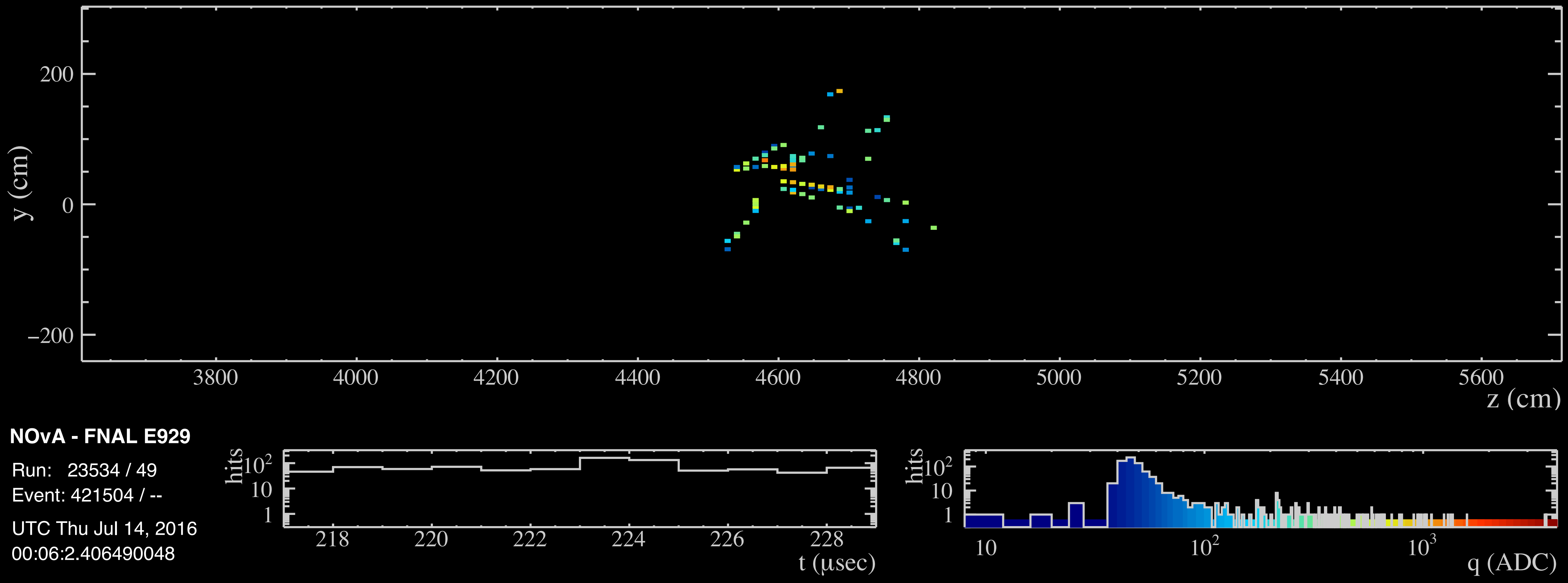
PREDICTING THE FAR DETECTOR OBSERVATIONS

- 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.



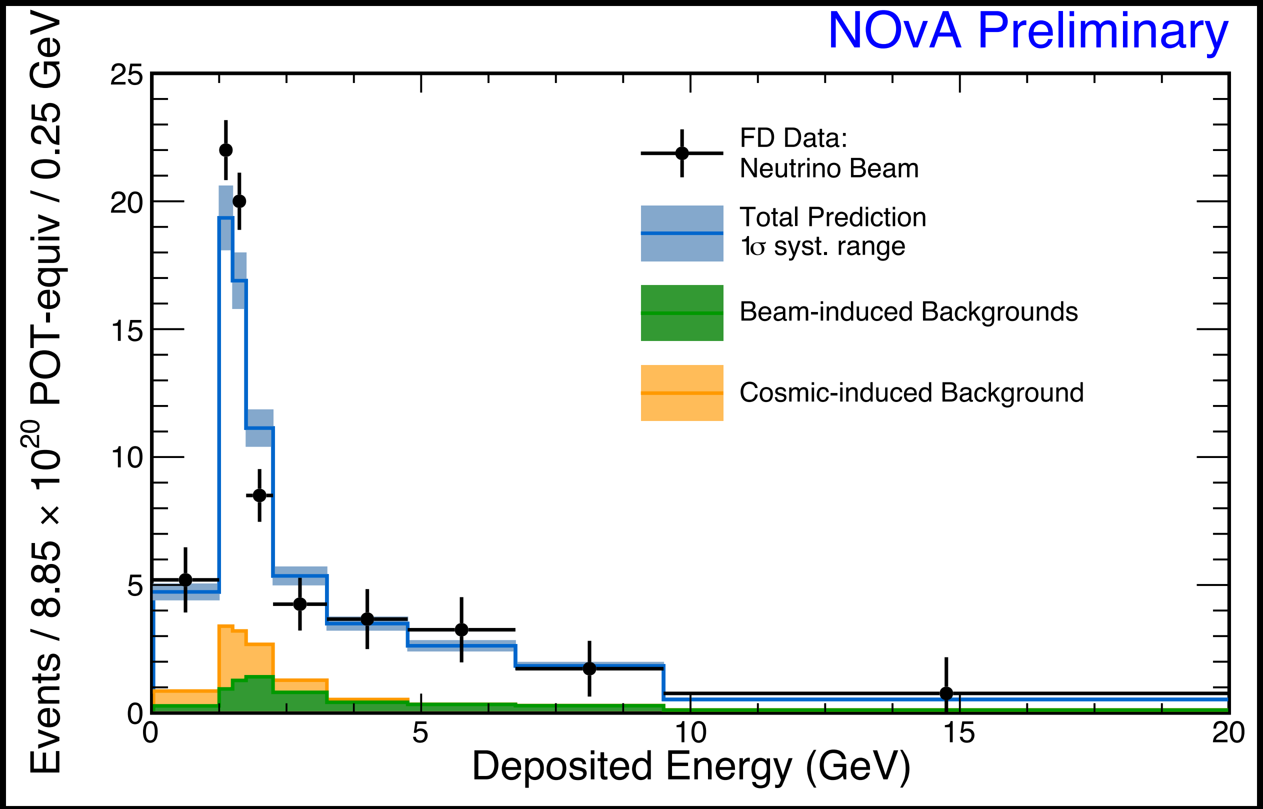
Are there other neutrinos beyond the three known active flavors?

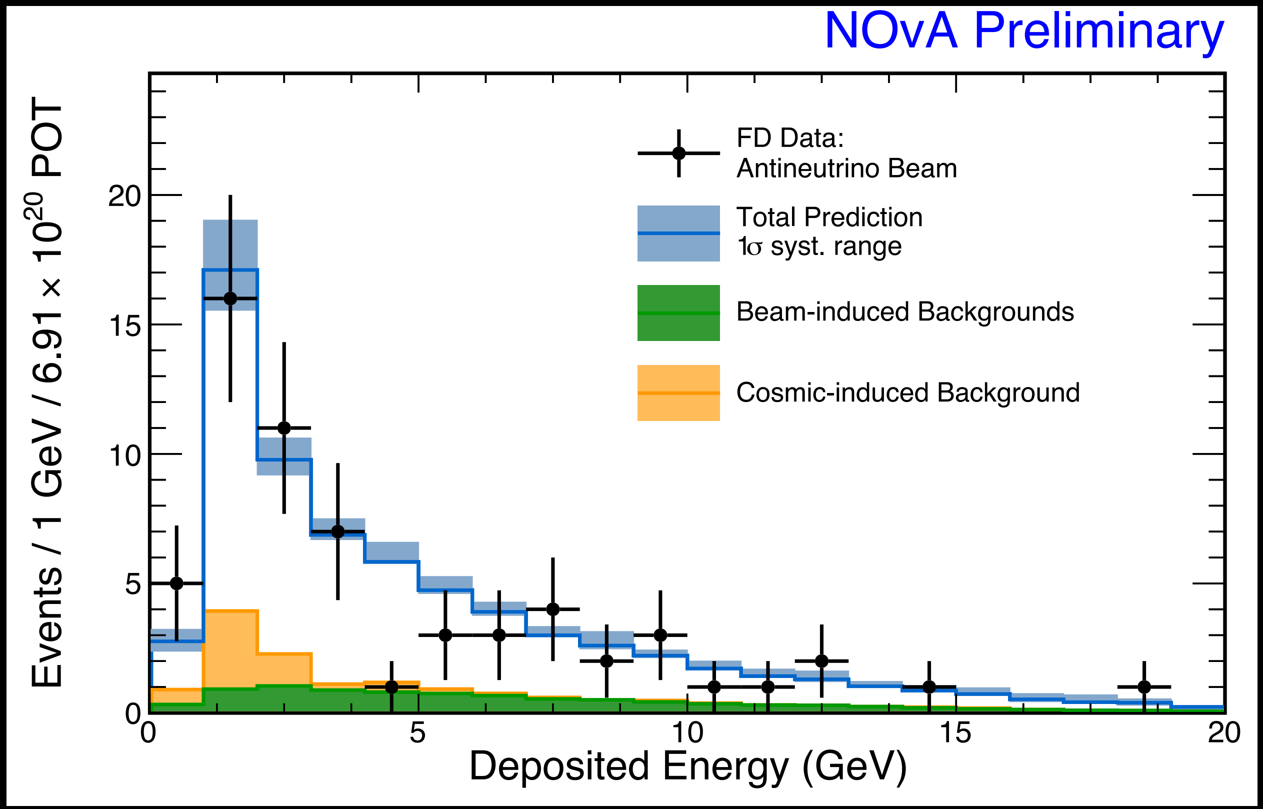
NEUTRINO AND ANTINEUTRINO NEUTRAL CURRENT DISAPPEARANCE



see poster #141 and 132

OBSERVED NEUTRAL CURRENT SPECTRA IN THE FAR DETECTOR



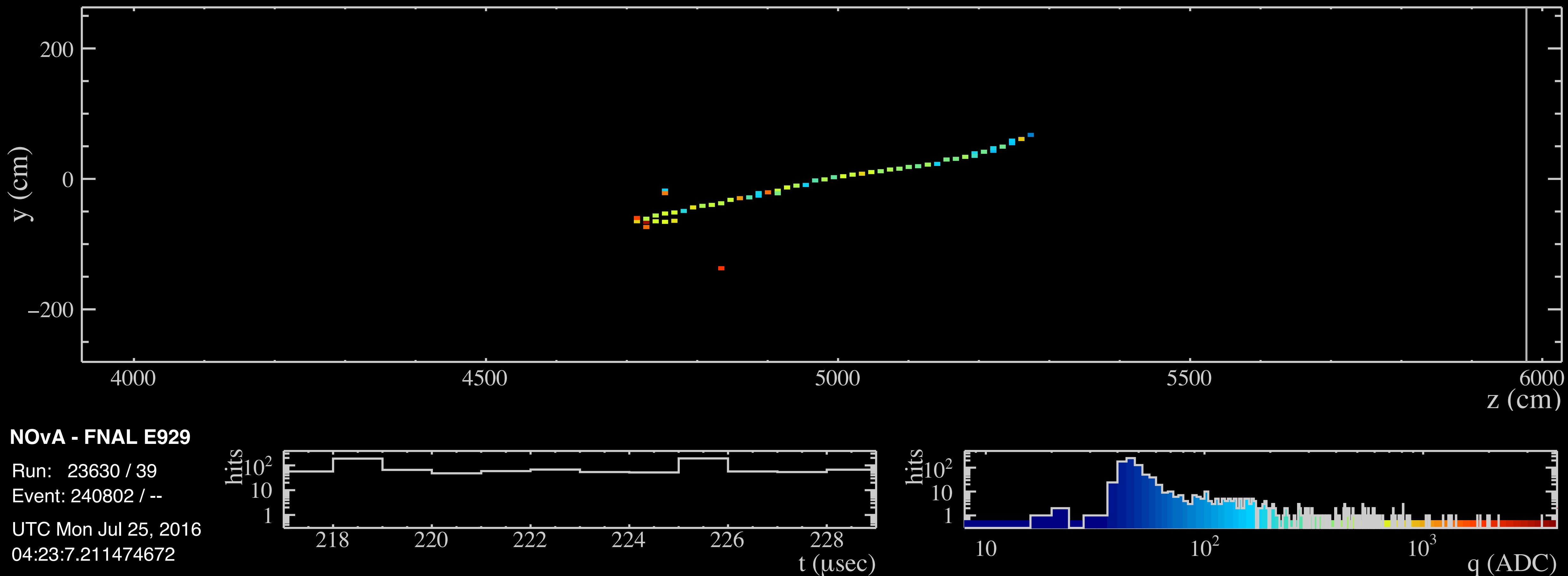


- For the neutrino beam sample we predict 188 ± 13 (syst.) interactions (38 bkg.) and observe 201.
- For the antineutrino beam sample we predict 69 ± 8 (syst.) interactions (16 bkg.) and observe 61.

NO SIGNIFICANT SUPPRESSION OF NEUTRAL CURRENT INTERACTIONS OBSERVED FOR NEUTRINOS OR ANTINEUTRINOS

Is there a ν_μ - ν_τ symmetry?

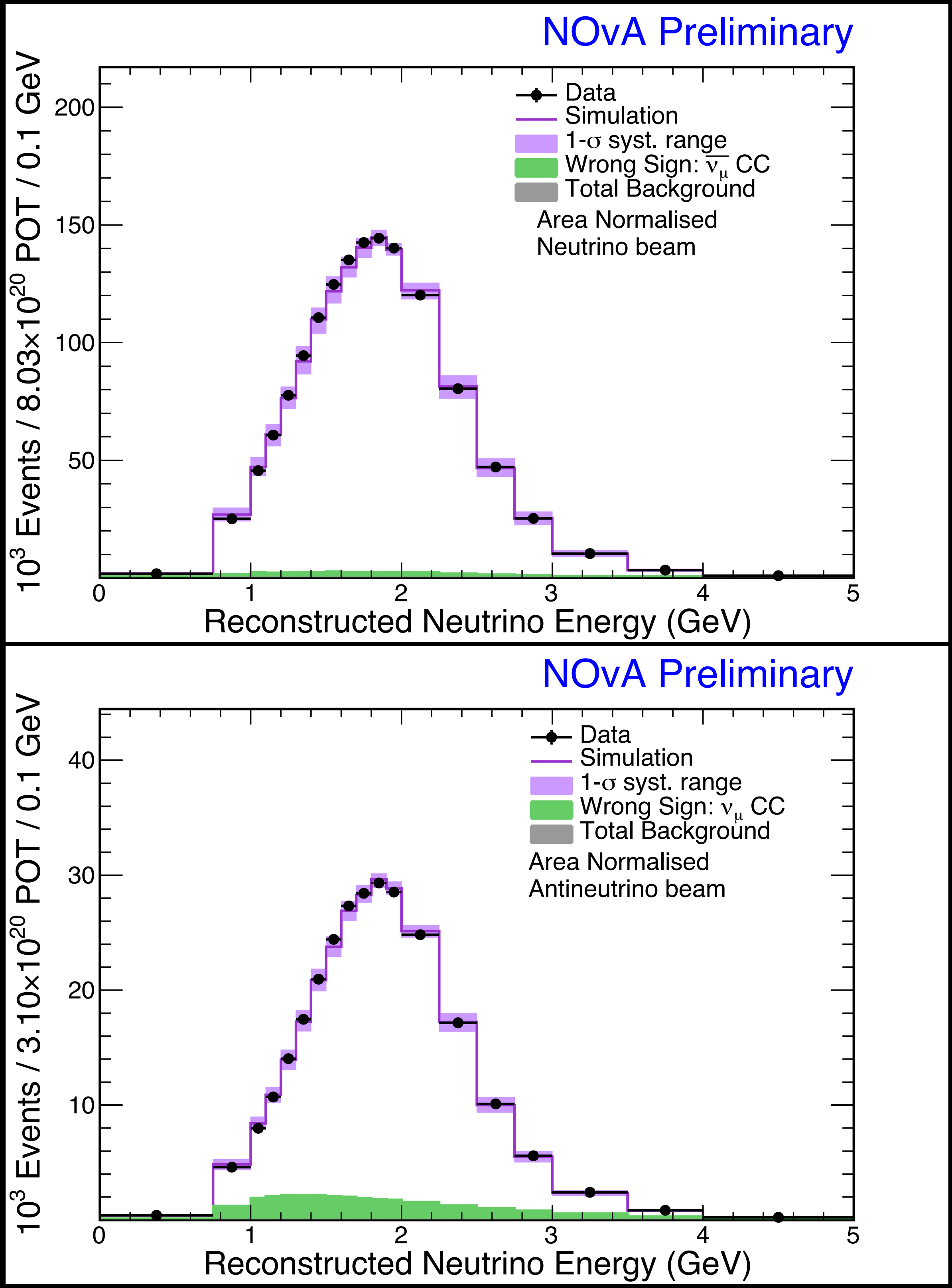
MUON NEUTRINO AND ANTINEUTRINO DISAPPEARANCE



see poster #75

NEAR DETECTOR BEAM SPECTRA

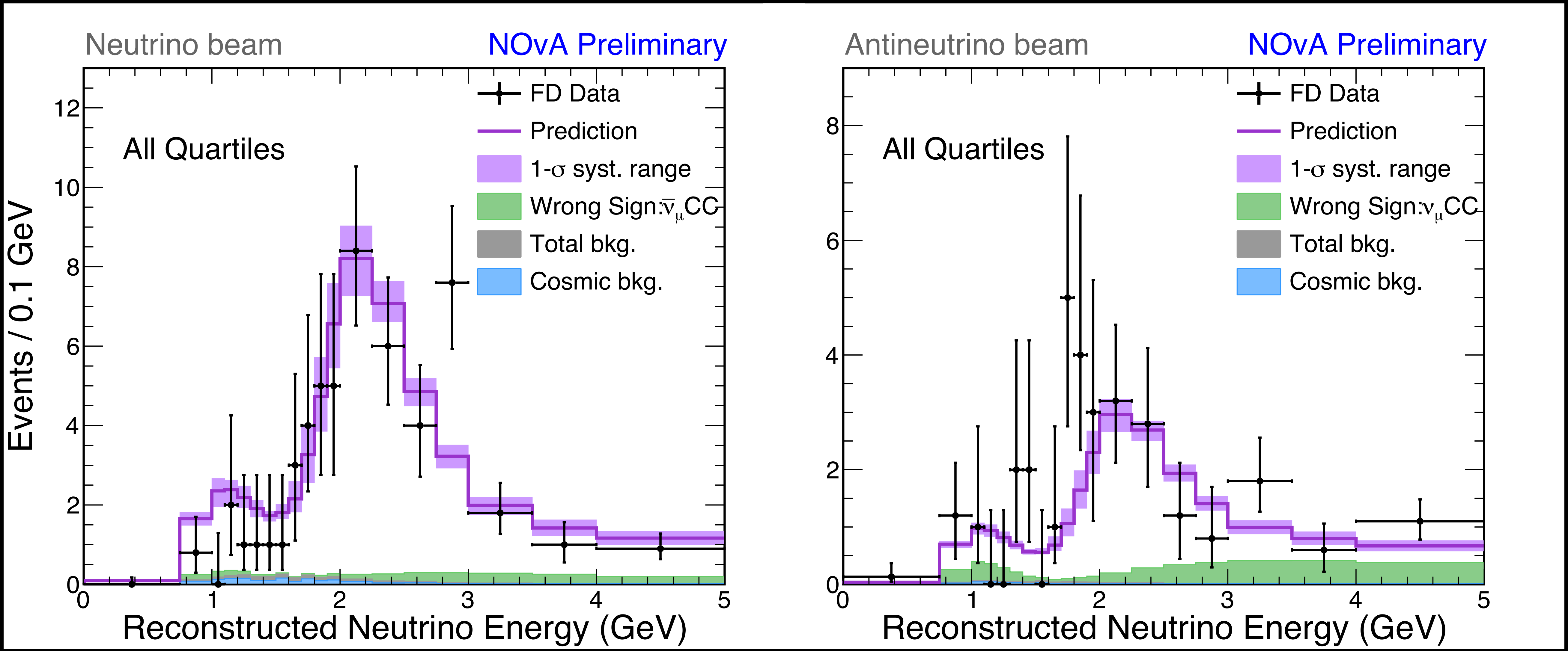
- Selected muon neutrino and antineutrino charged current interactions in ND.
  - Reconstructed neutrino energy is estimated from muon length and hadronic energy.
- Wrong sign contamination in ND is estimated to be 3% for neutrino beam and 11% for antineutrino beam.
- Systematic uncertainties shown are shape only, 1.3% and 0.5% offset for neutrinos and antineutrinos respectively is removed for display purposes.
- The data is split in four equal populations (quartiles) of hadronic energy fraction as a function of reconstructed neutrino energy.
  - Energy resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.



see poster #75

PREDICTING THE FD OBSERVATION

- Each quartile for the neutrino and antineutrino beams gets unfolded independently and the true Far/Near ratio is used to obtain a FD prediction from ND data.
- We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and cosmic trigger data.

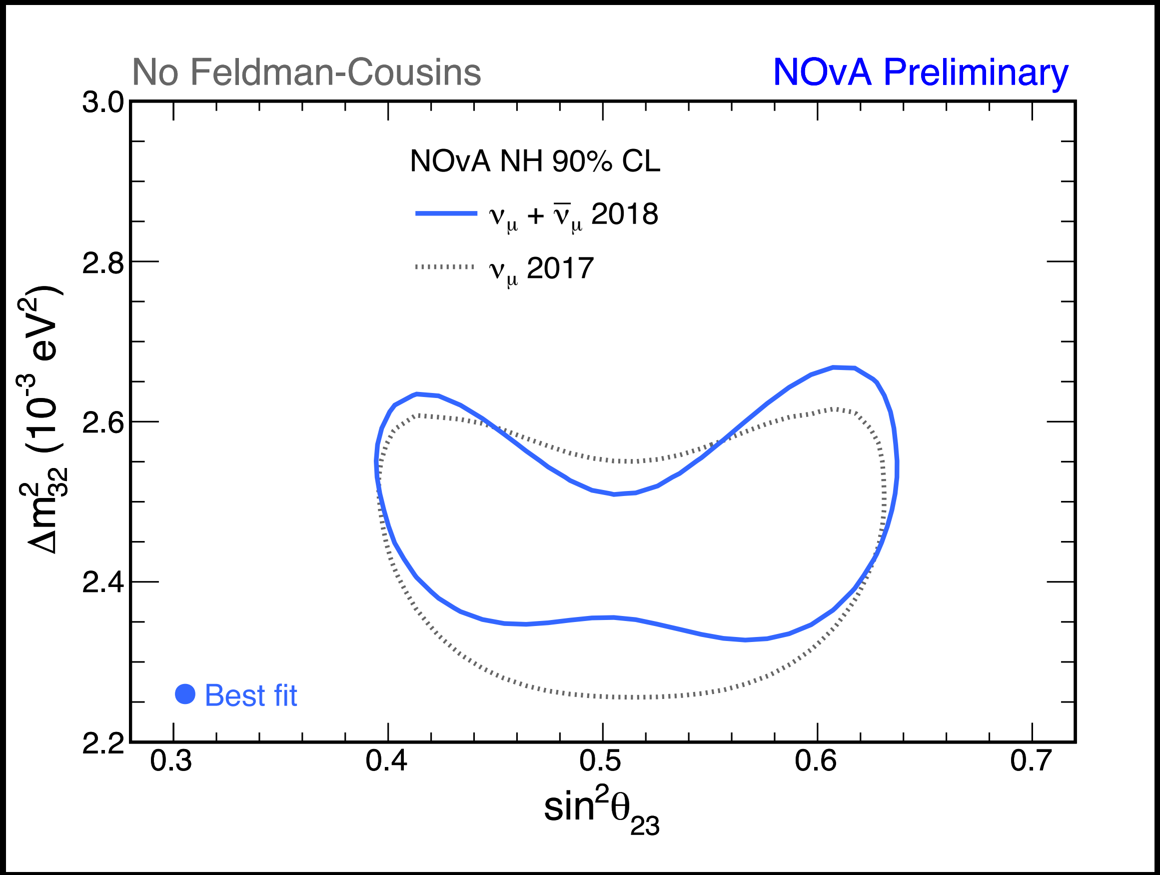


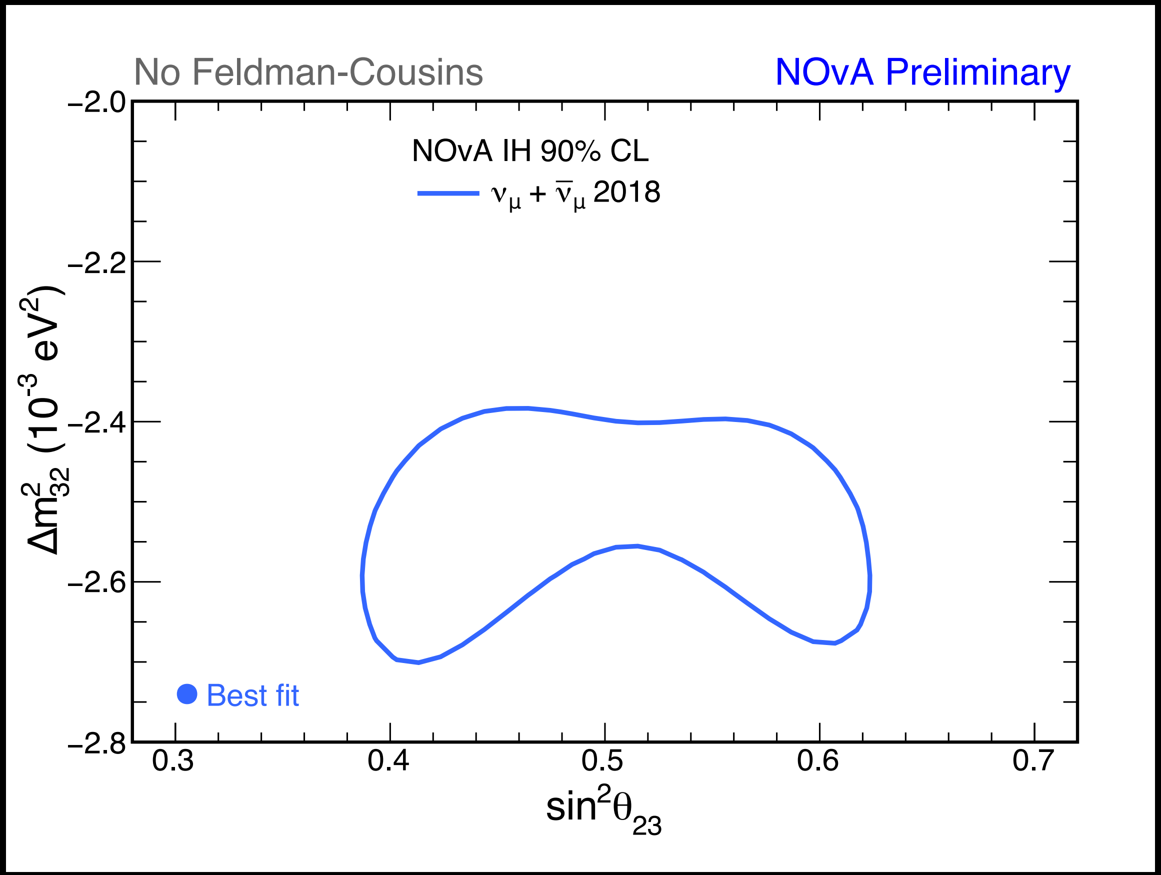
- Observe 113 events in neutrino mode (expect 730 +38/-49(syst.) w/o oscillations), 65 events in antineutrino mode (expect 266 +12/-14(syst.) w/o oscillations).

see poster #66 and 88

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, the χ^2s are consistent with the combined fit oscillation parameters with p > 4%. Also allowed region comparable to previous 2017 neutrino-only result.

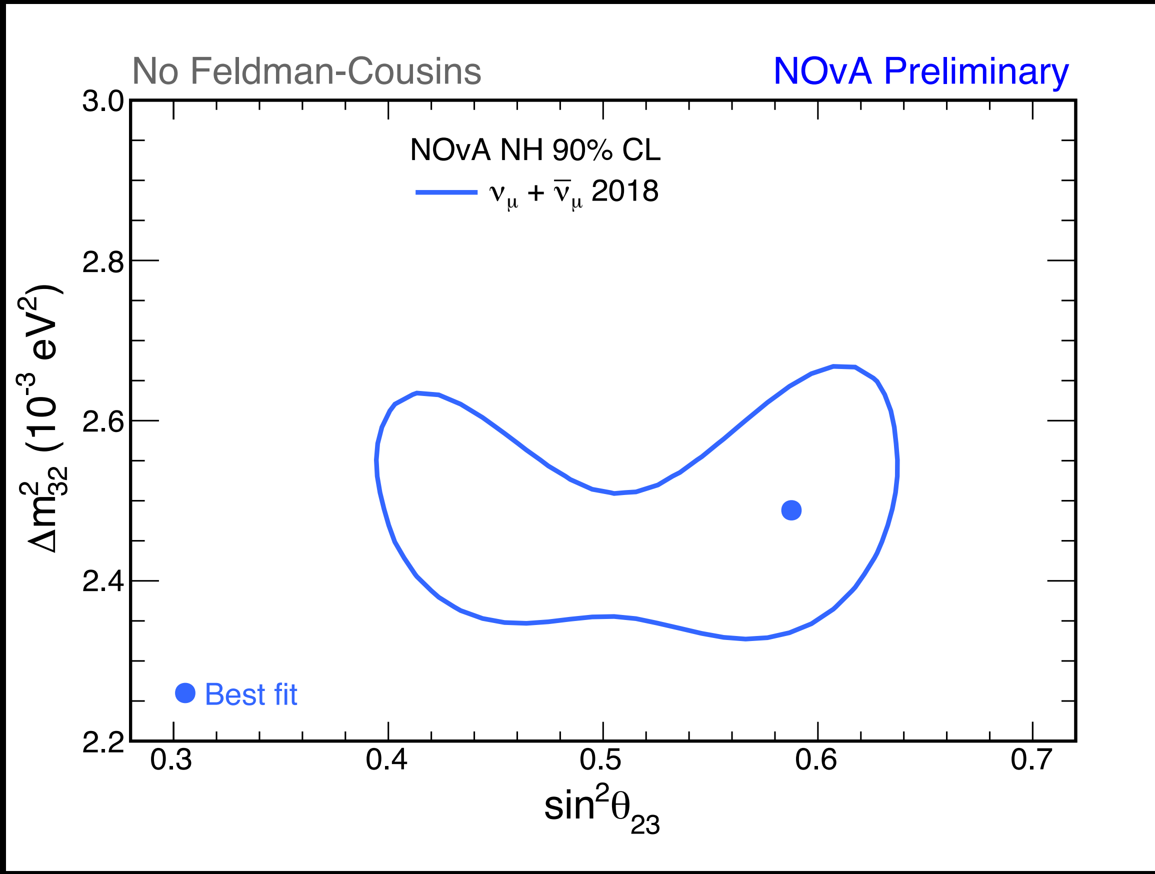


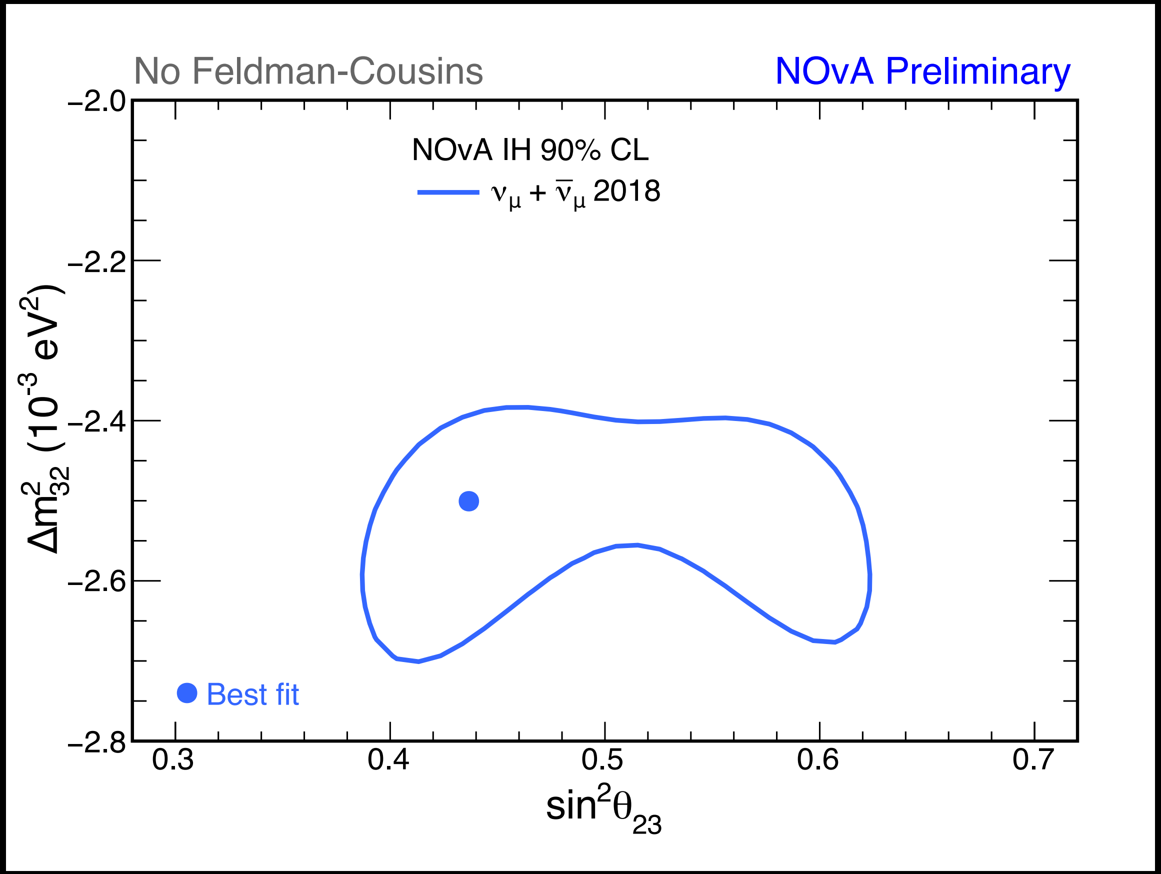


see poster #66 and 88

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).

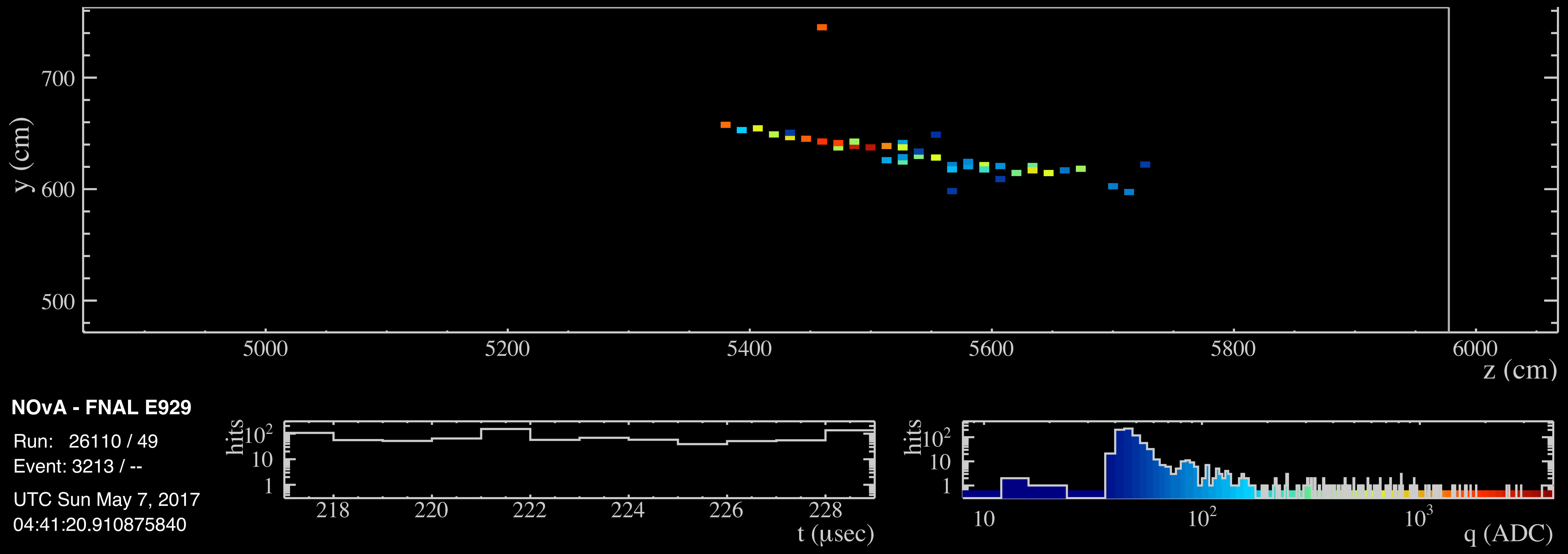




What is the mass hierarchy or ordering?

Is CP violated in the lepton sector?

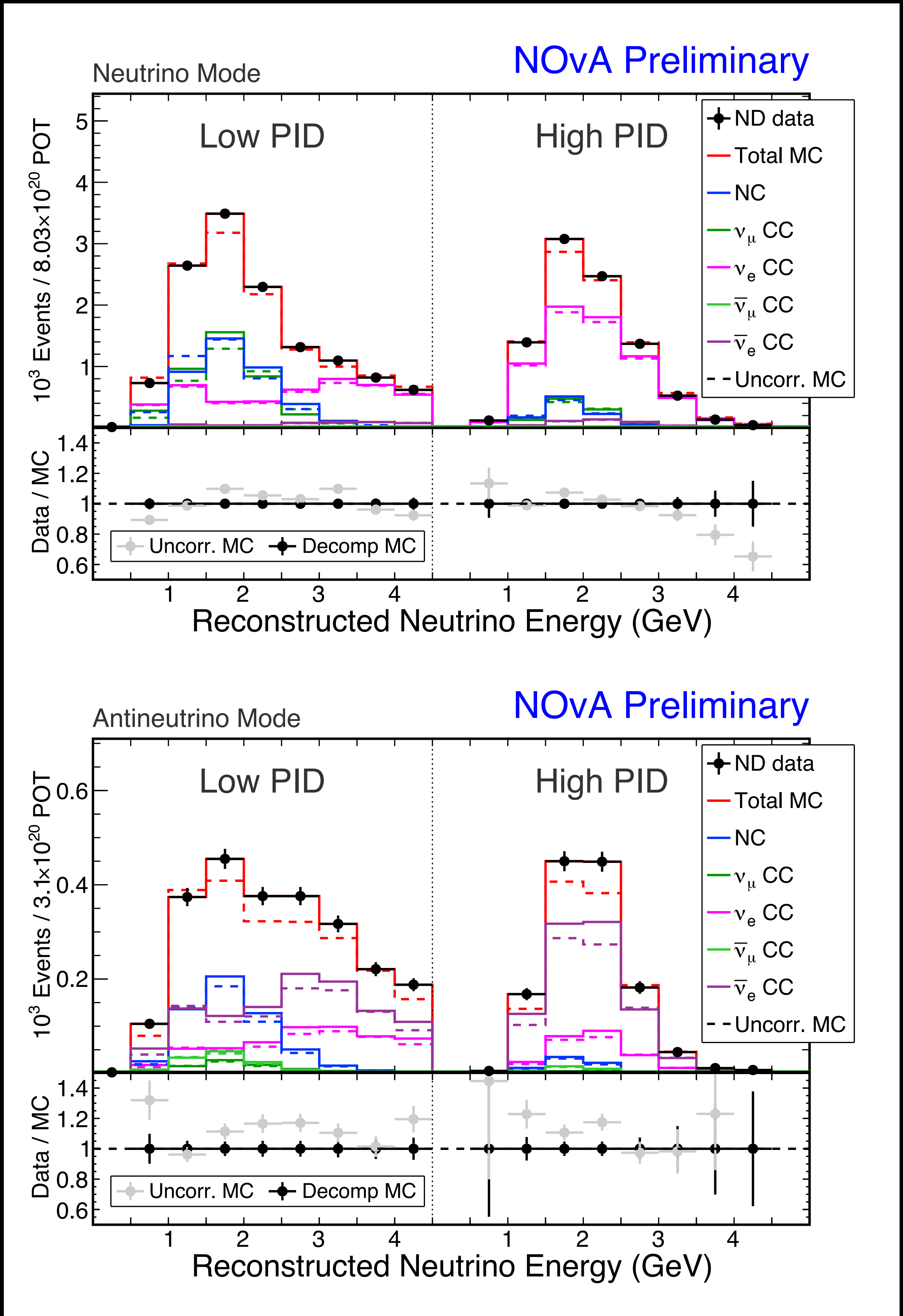
ELECTRON NEUTRINO AND ANTINEUTRINO APPEARANCE



see poster #79

NEAR DETECTOR ELECTRON NEUTRINO DATA

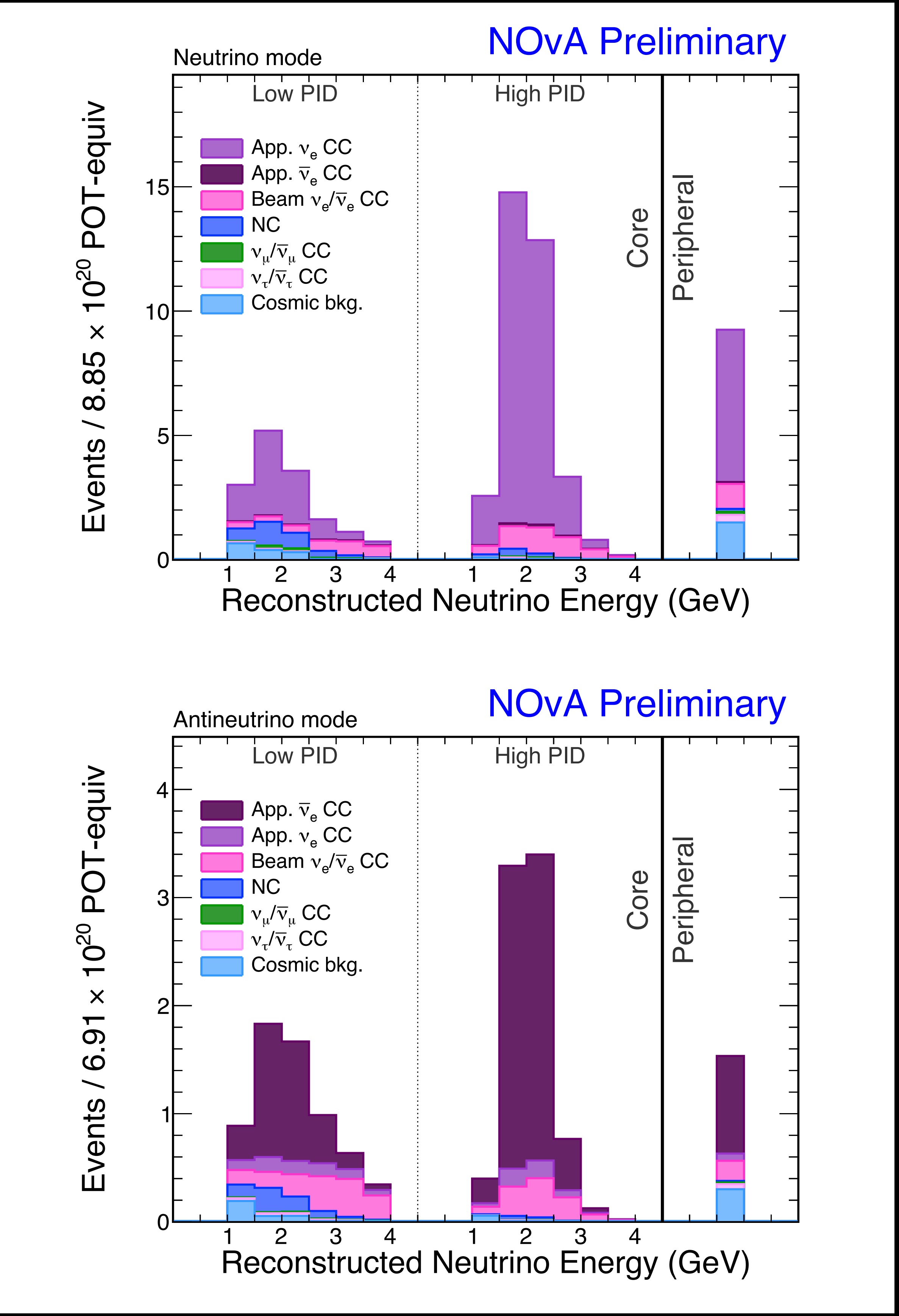
- Select electron neutrino events using particle ID in the ND for each beam mode.
  - Separate into low and high particle ID (purity) range.
- For the neutrino beam constrain:
  - the beam electron neutrinos using the muon neutrino spectrum, and
  - the muon neutrino background using Michel electrons,
  - remaining data/MC discrepancy is assigned to the neutral current component.
- For the antineutrino beam, scale all components evenly to match the data.



see poster #79

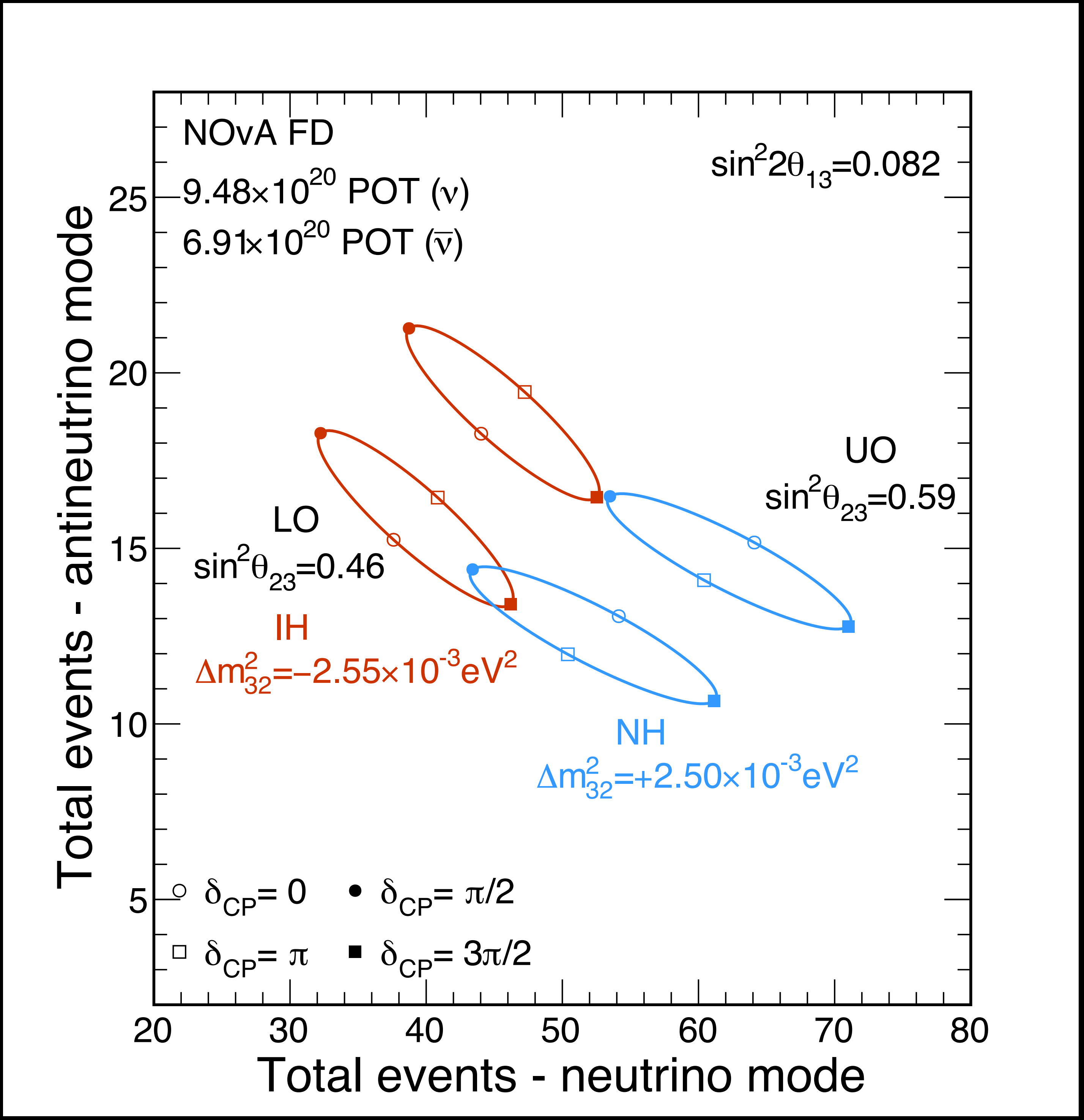
FAR DETECTOR PREDICTION

- We use the ND data to predict the background in the FD. Each component is propagated independently in bins of energy and particle ID bins.
- Add a one-bin peripheral signal sample. This sample has a less stringent containment selection, adds a different cosmic rejection boosted decision tree and high particle ID cut.
- 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 APPEARANCE EXPECTATIONS

- 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

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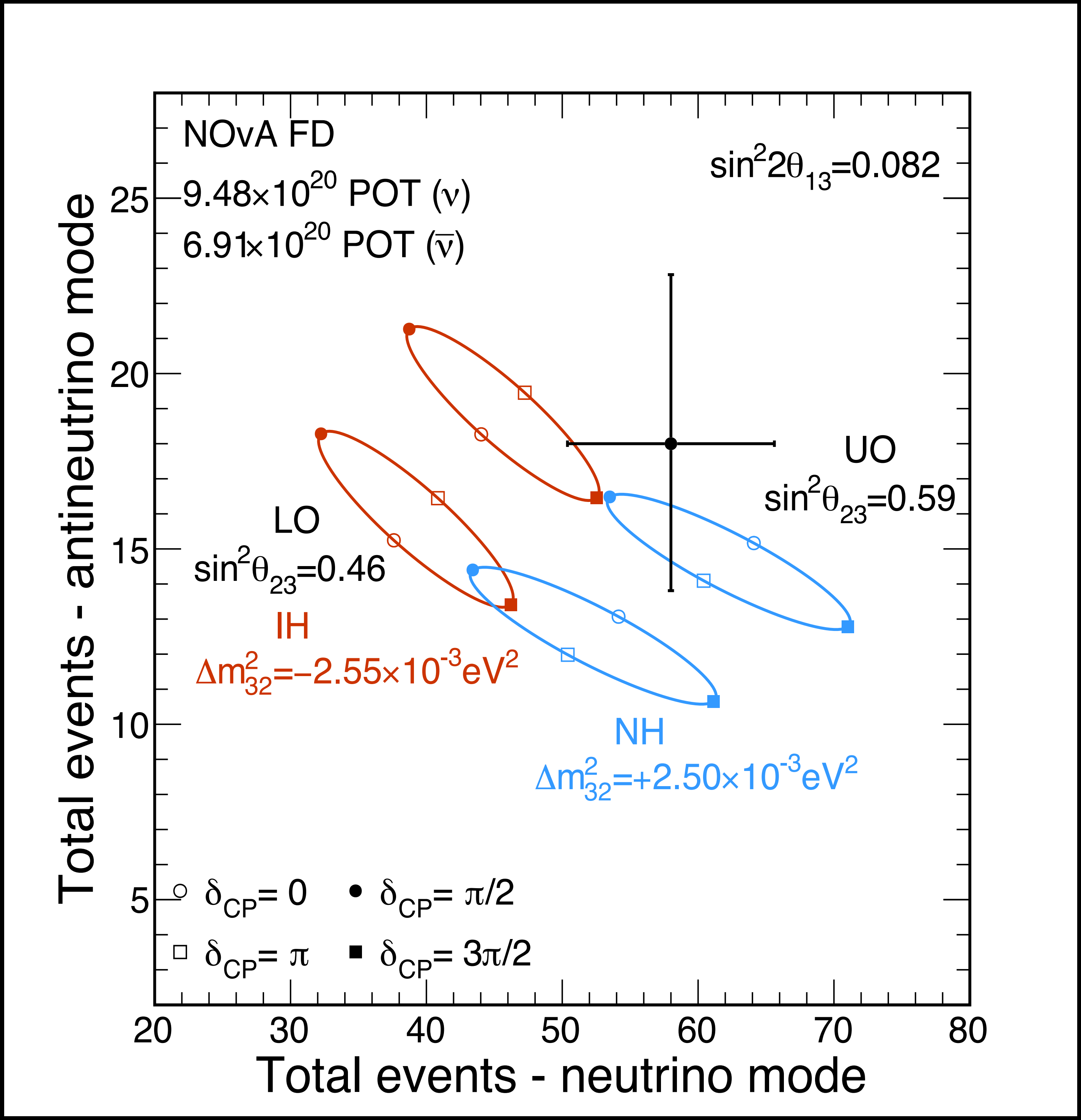
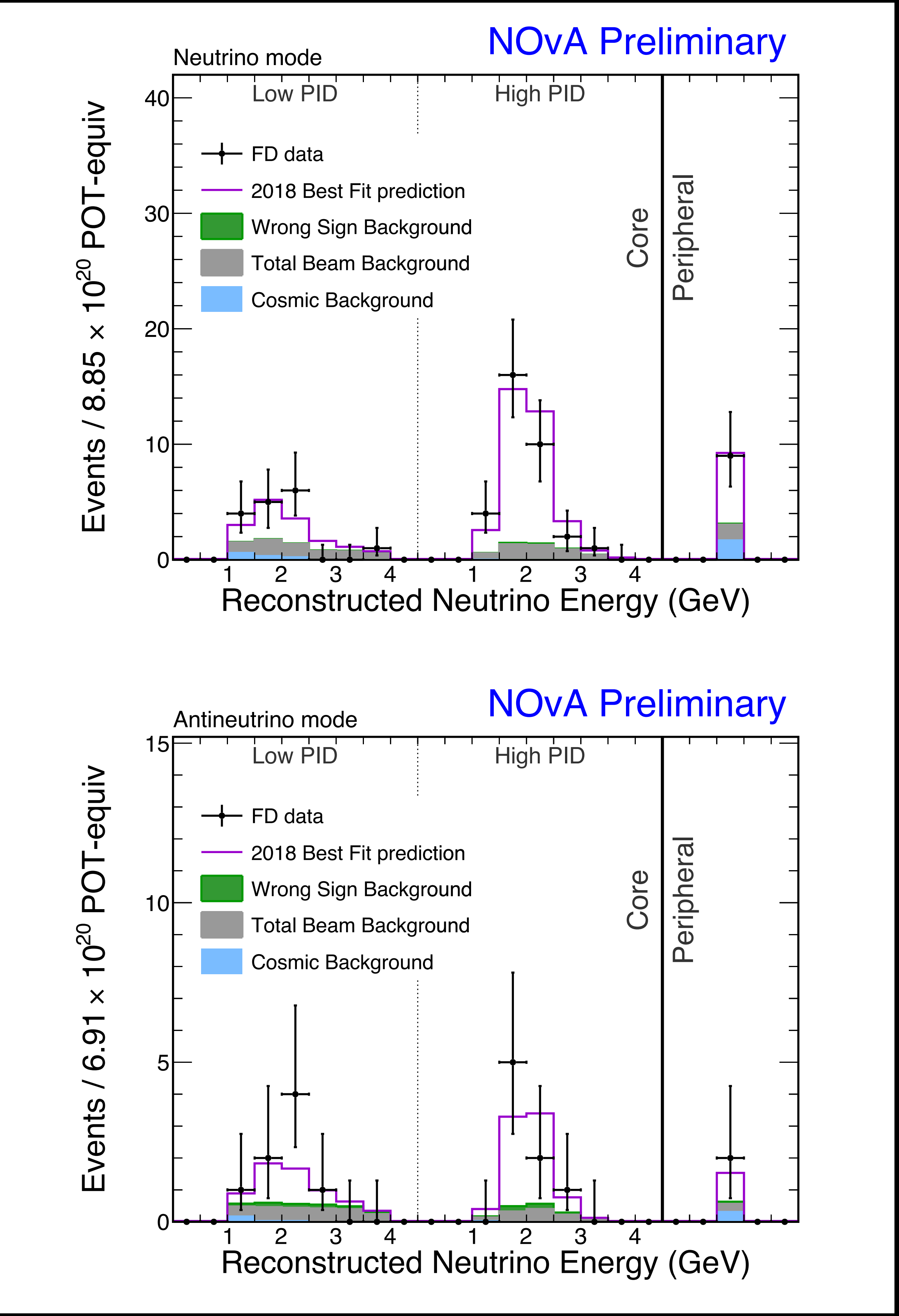


NOVA OBSERVES: 58 EVENTS IN NEUTRINO, 18 EVENTS IN ANTINEUTRINO MODE.

ELECTRON NEUTRINO AND ANTINEUTRINO APPEARANCE

- 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



What is the mass hierarchy or ordering?

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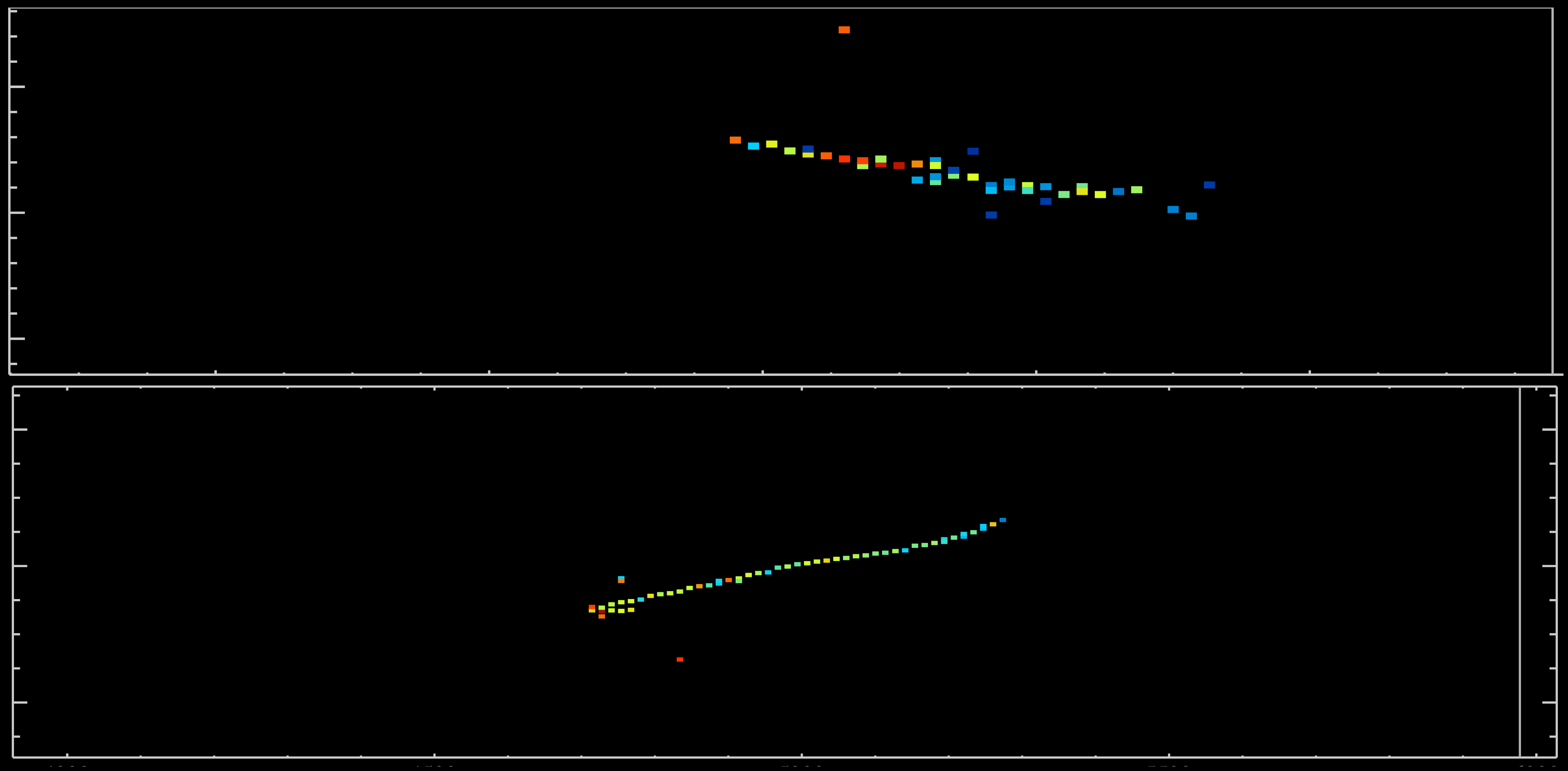
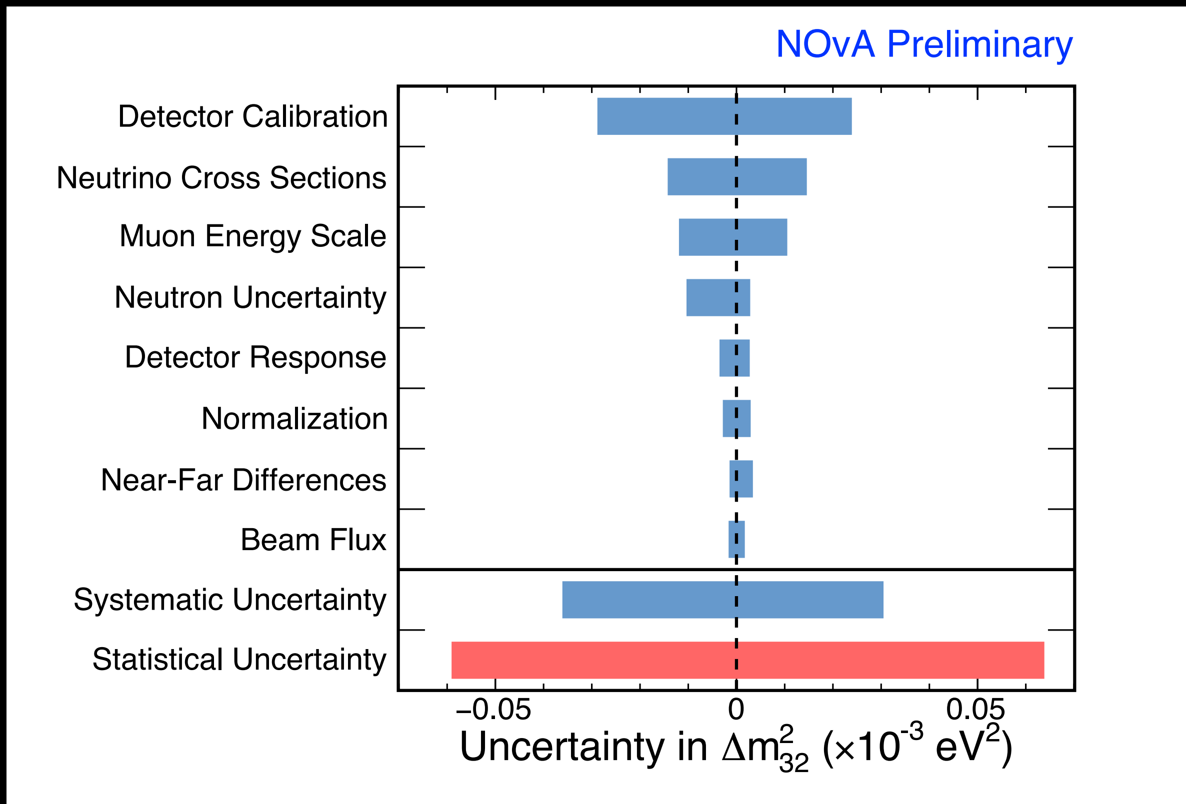
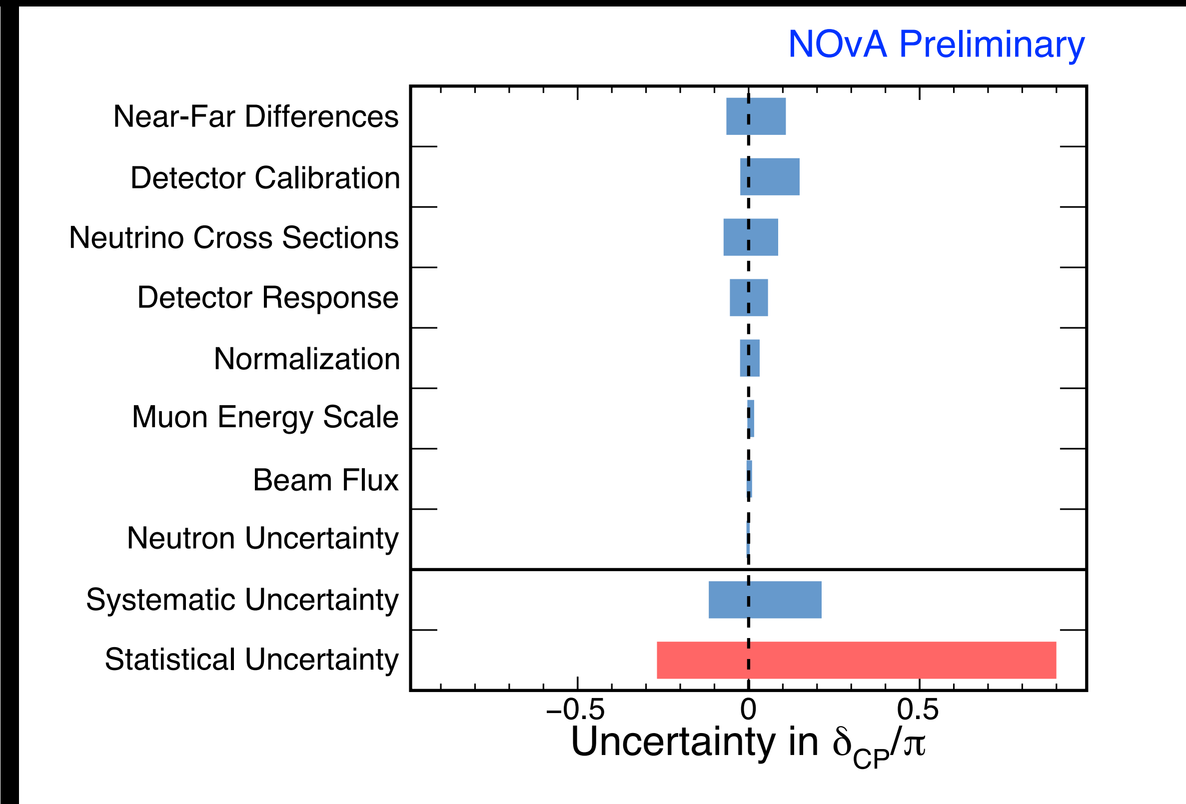
JOINT APPEARANCE AND DISAPPEARANCE

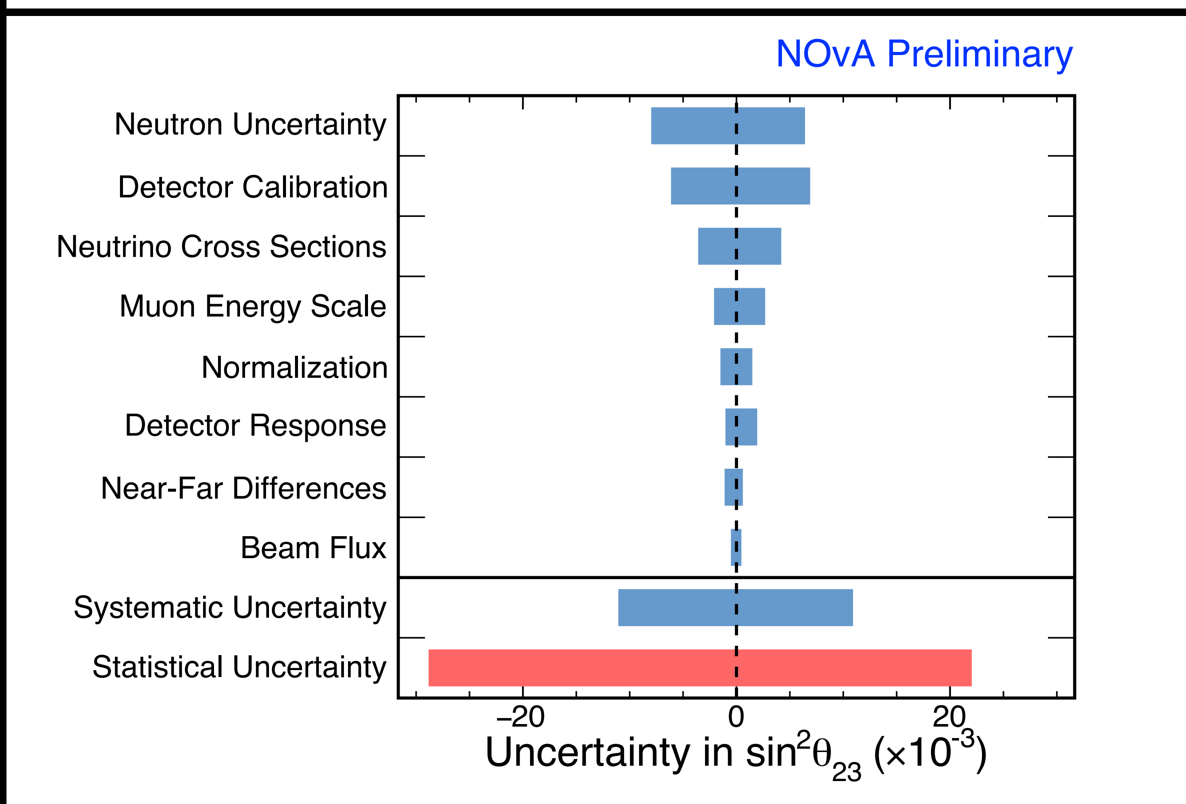


see poster #58 see poster #80

SYSTEMATIC UNCERTAINTIES



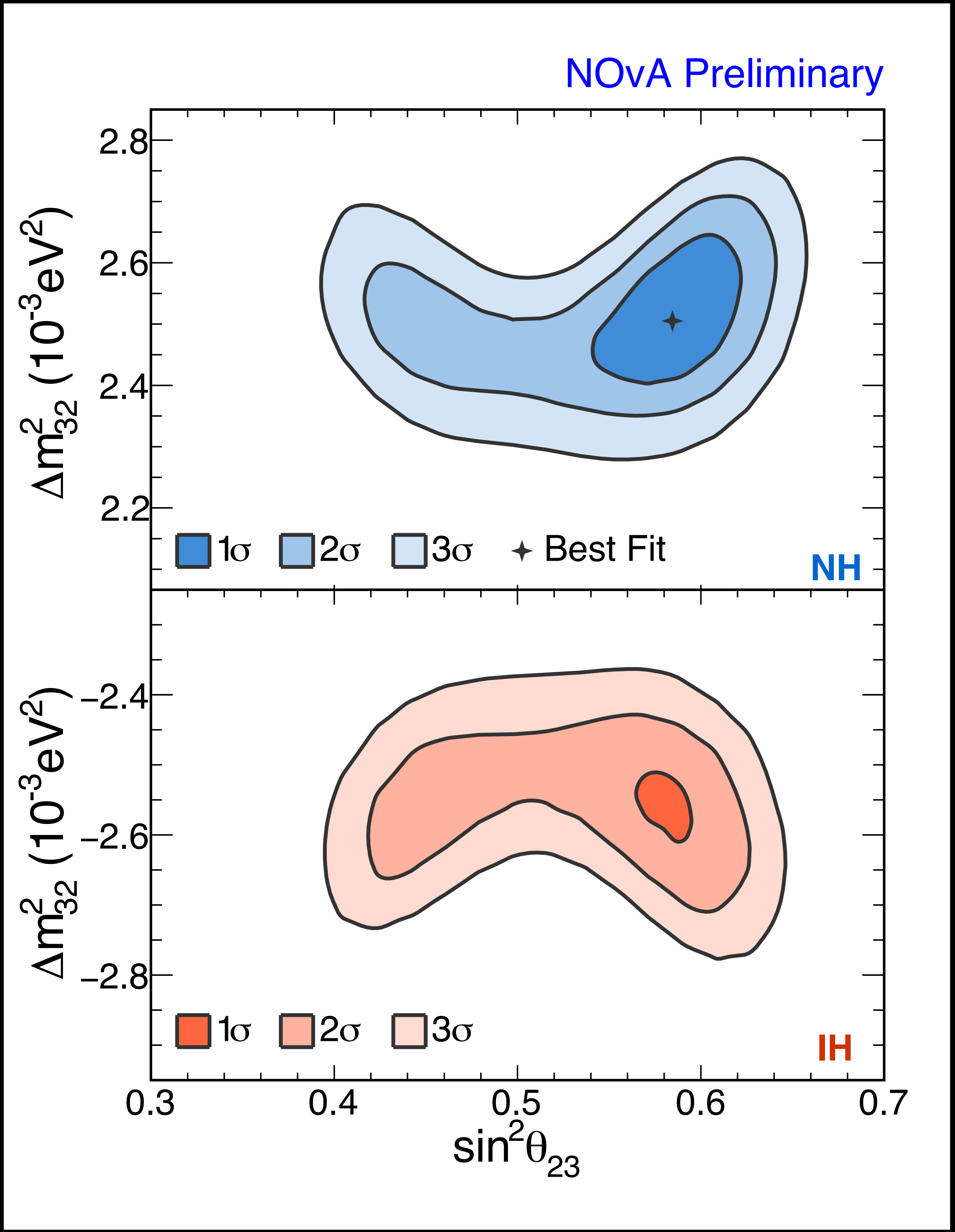


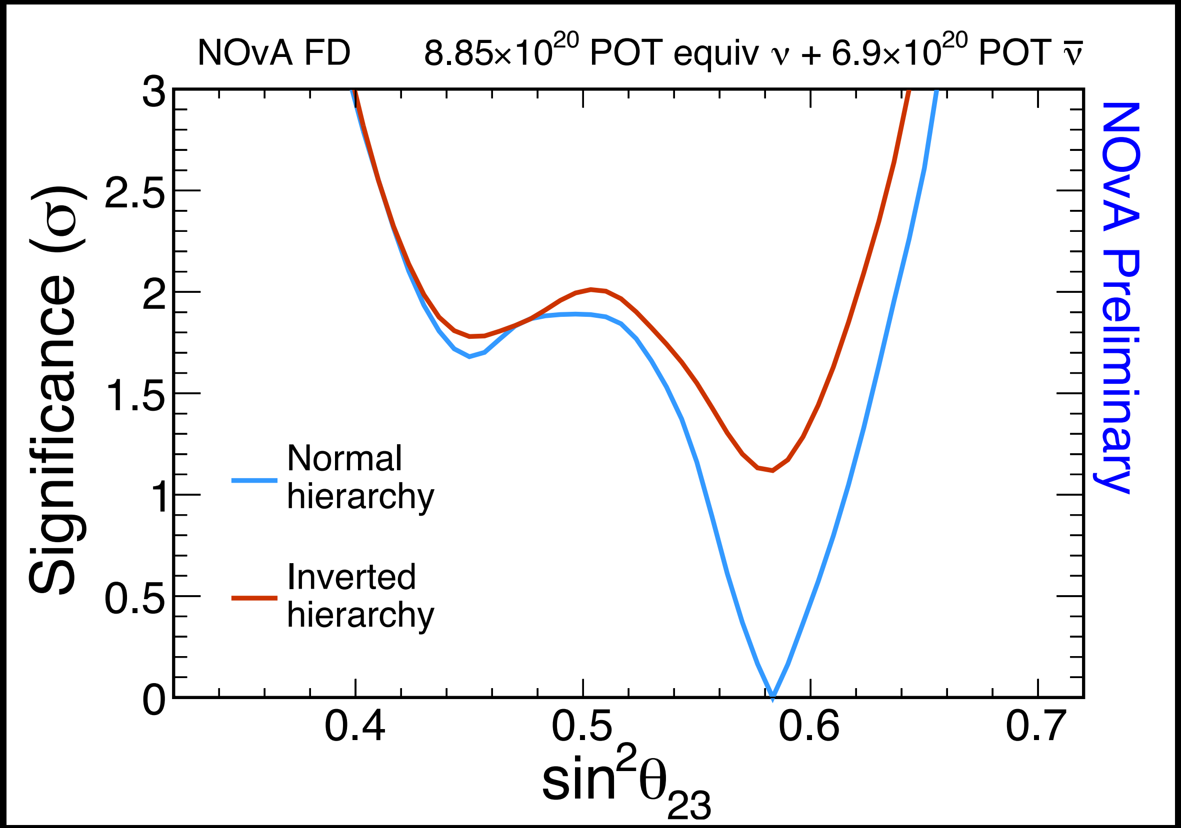


- Improved systematic uncertainties. We are still statistics limited but calibration and cross sections are the largest uncertainties.
- Our upcoming test beam program will address the calibration and detector response uncertainties.

see poster #81

ALLOWED OSCILLATION PARAMETERS





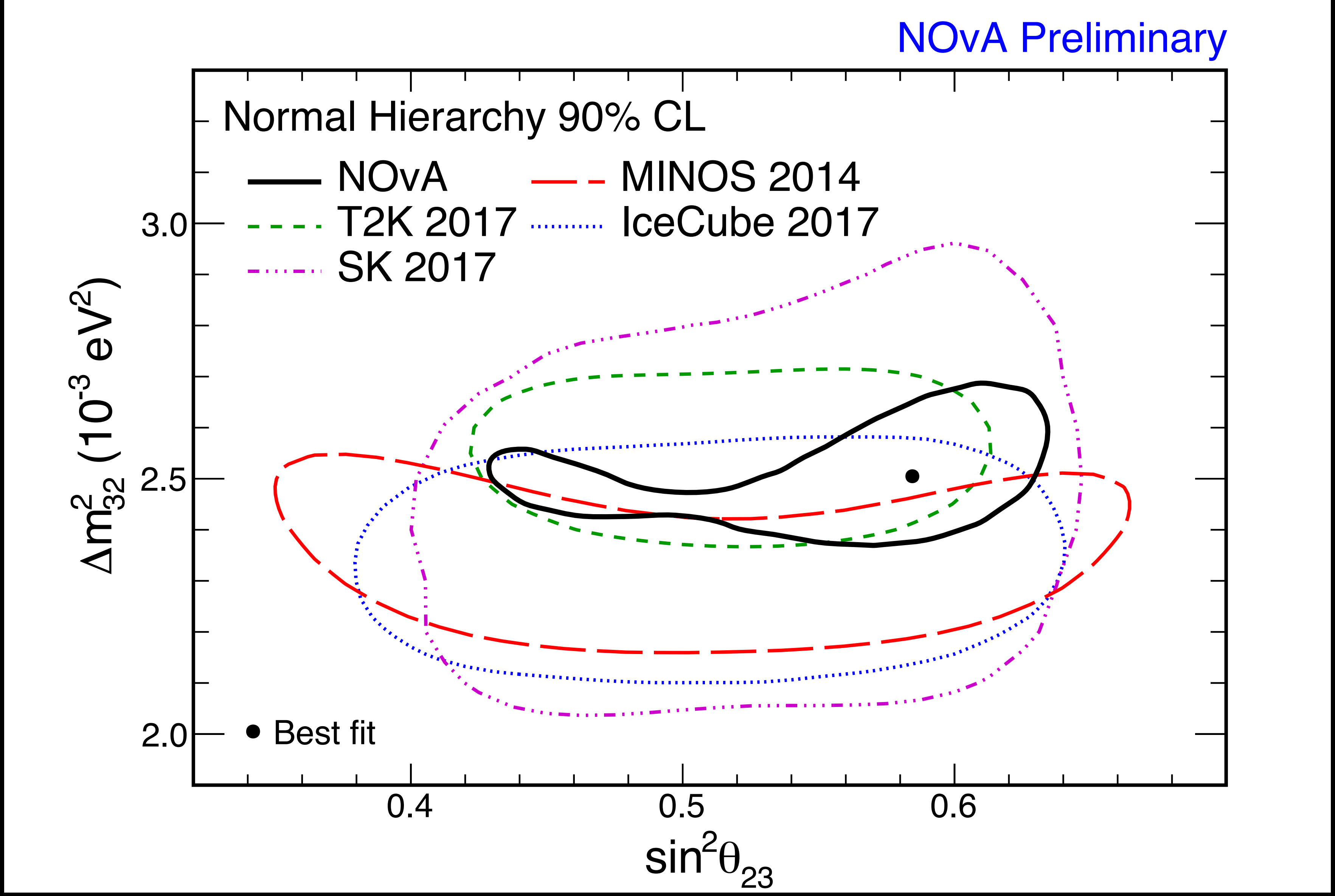
- Best fit:
  Normal Hierarchy
  $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08})\cdot10^{-3}\ \mathrm{eV}^2$

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

see poster #81

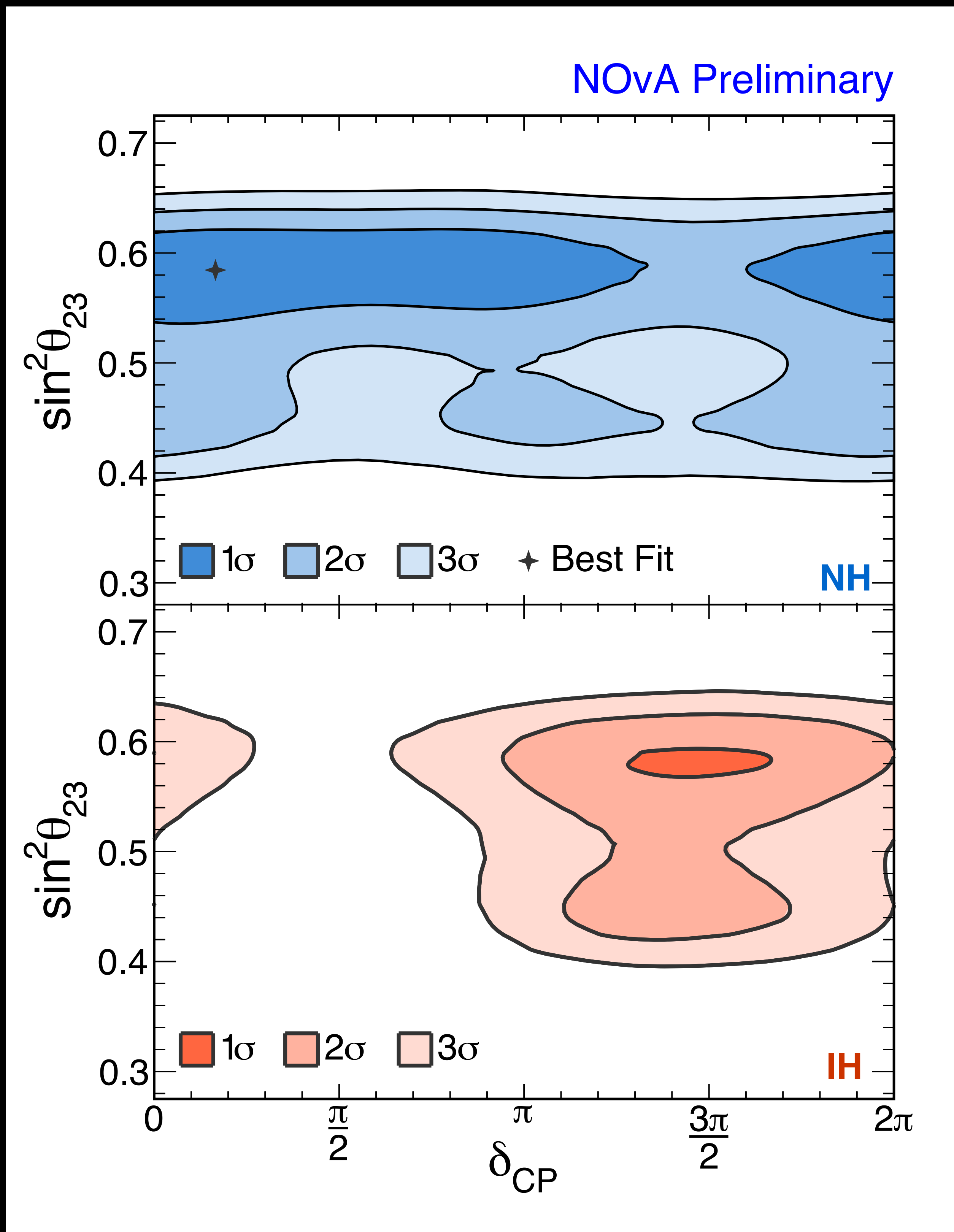
ALLOWED REGION FOR JOINT APPEARANCE AND DISAPPEARANCE

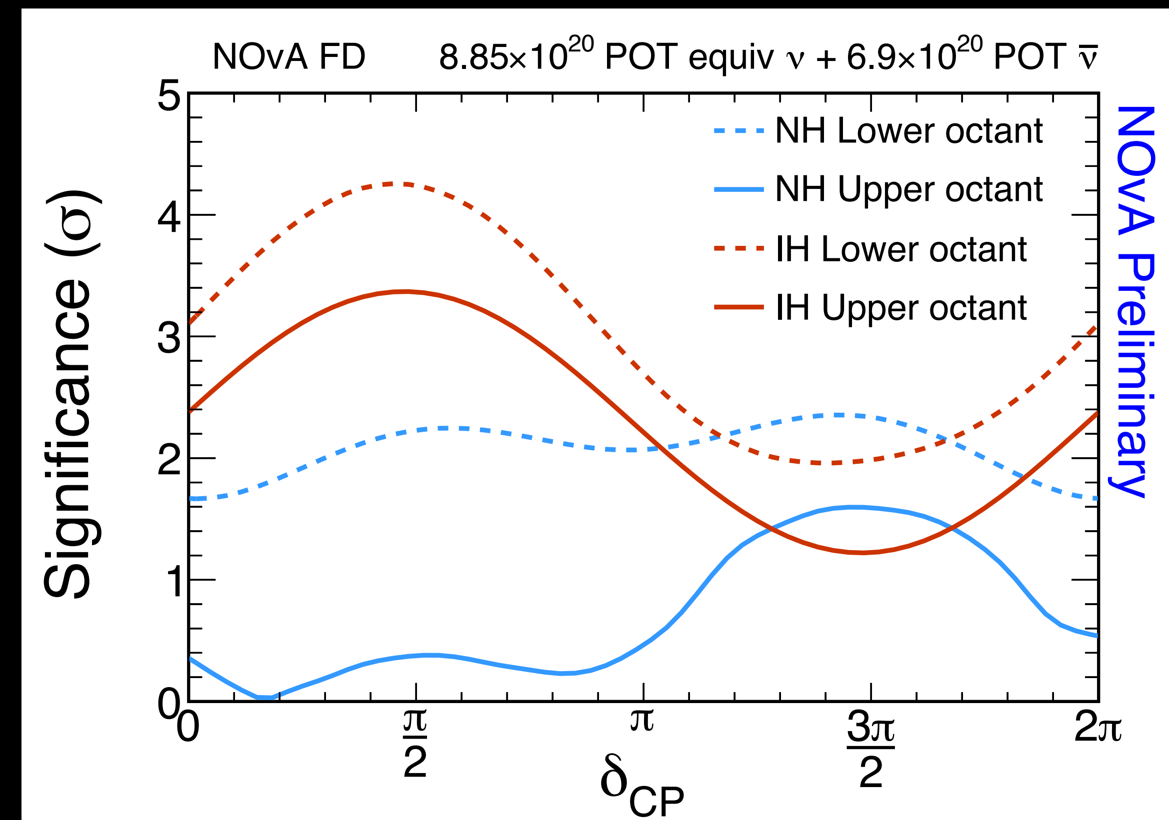
- NOvA's results compared to other experiments. Allowed 90% C.L. regions are compatible.



see poster #81

ALLOWED OSCILLATION PARAMETERS





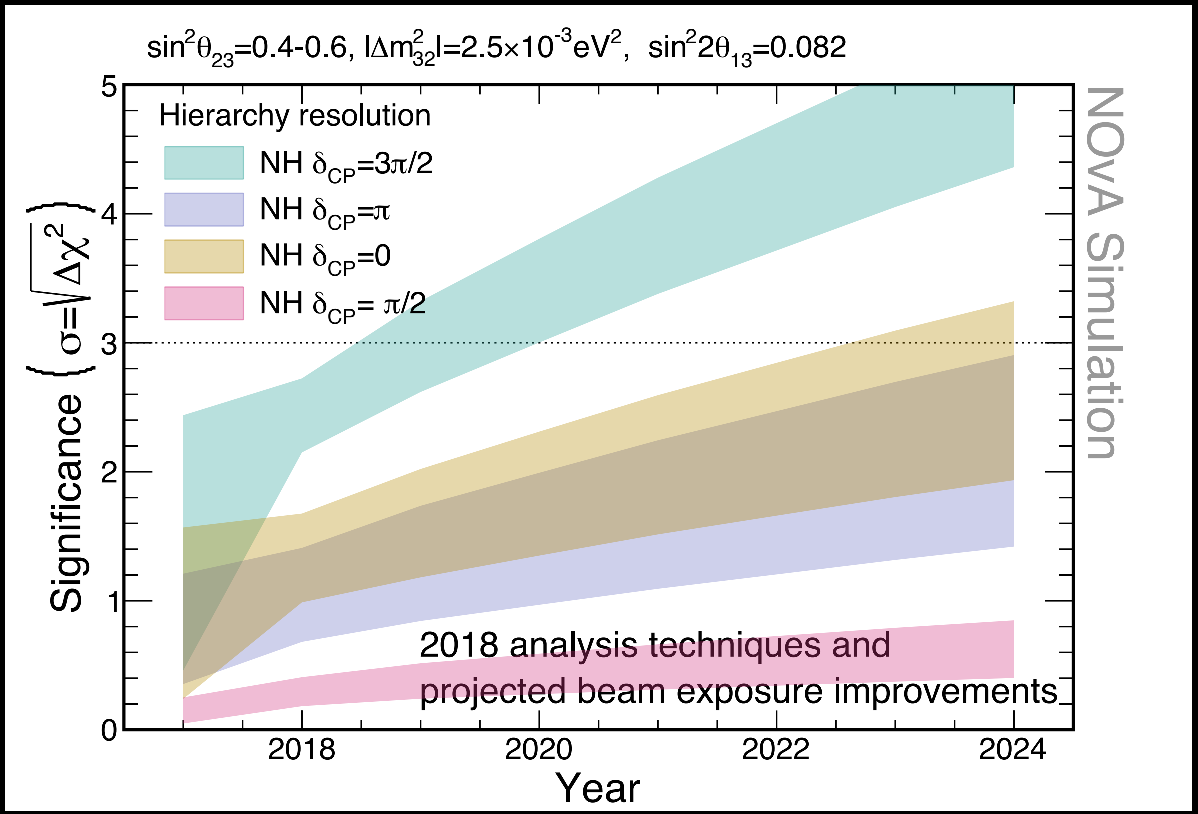
- Best fit: Normal Hierarchy
  $\delta_{CP} = 0.17\pi$
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2$

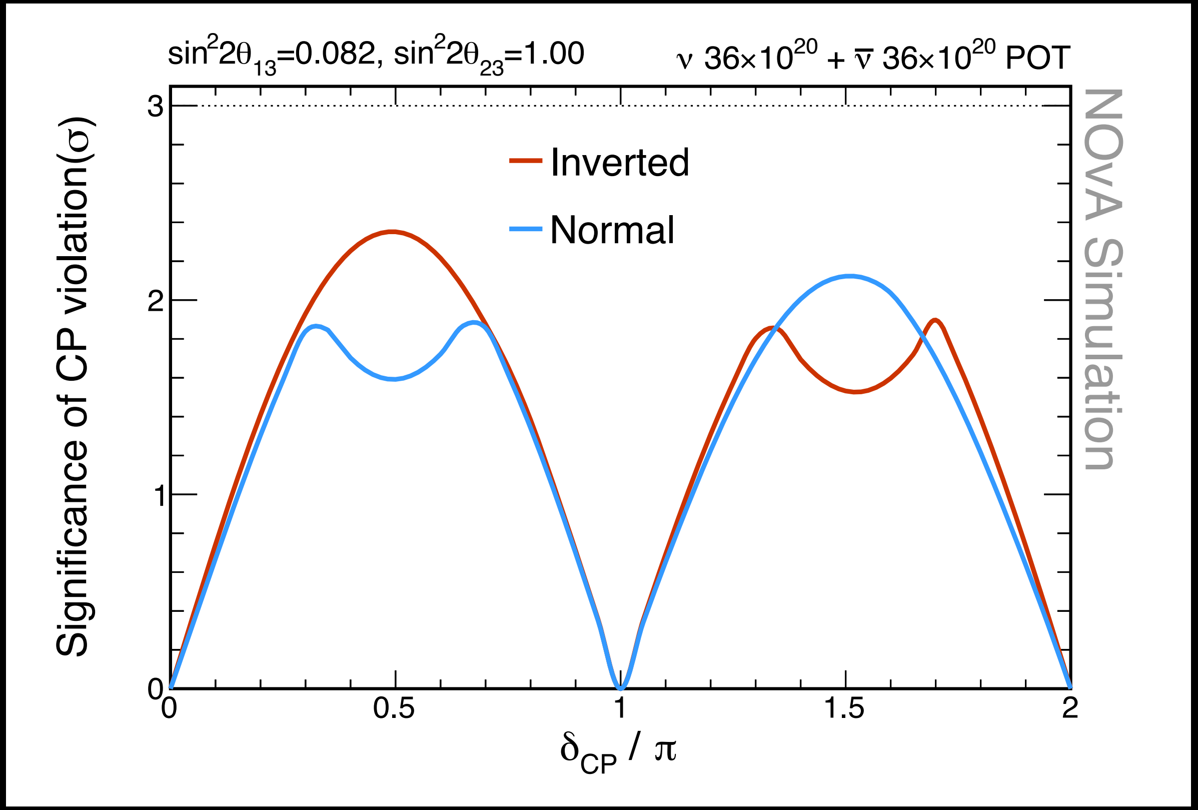
Prefer NH by 1.8σ
Exclude δ=π/2 in the IH at > 3σ

THE FUTURE

NOVA PROSPECTS

- Currently running anti-neutrino beam. Run 50% neutrino, 50% anti-neutrino after 2018.
- 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.
- 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.



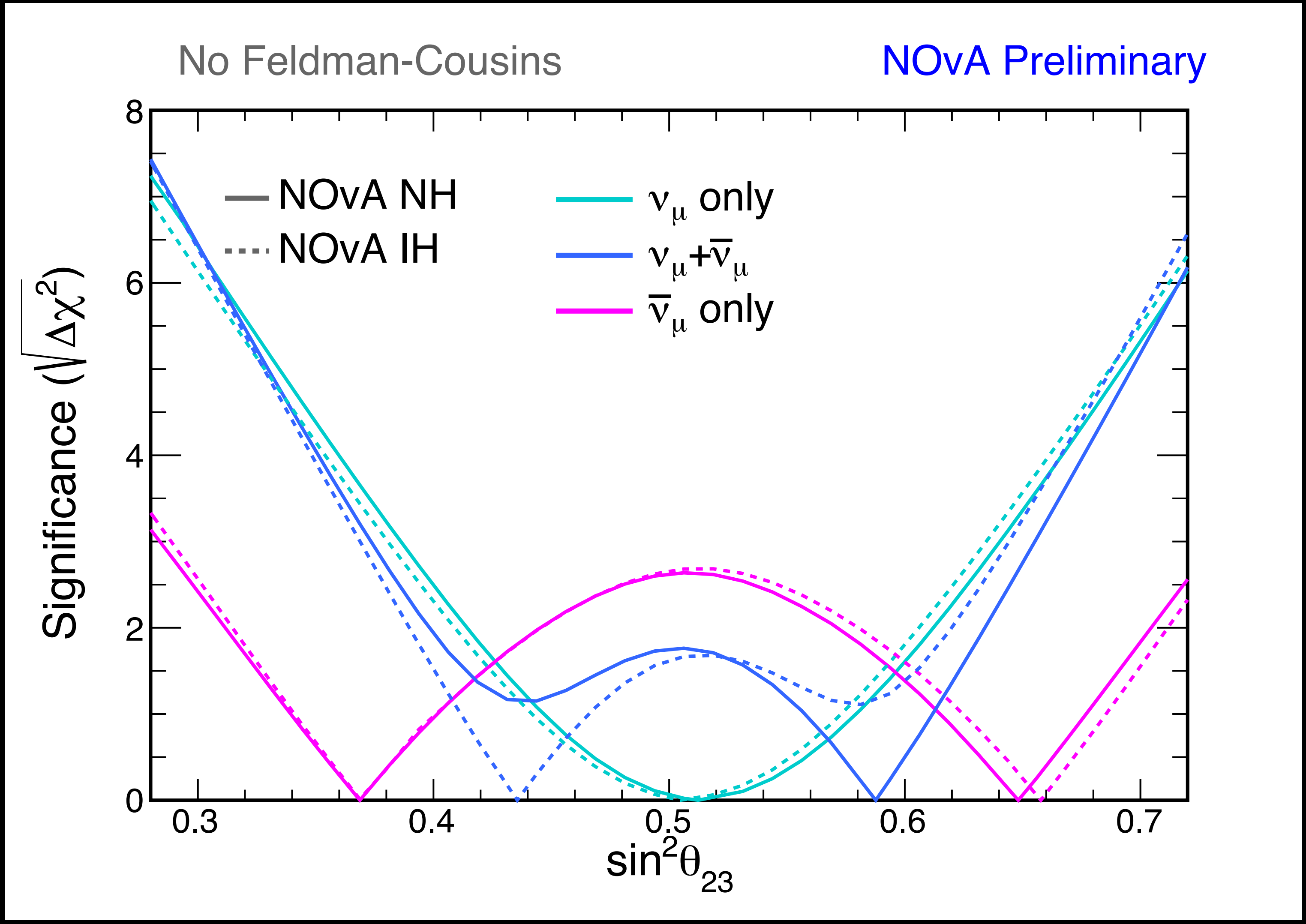


SUMMARY AND OUTLOOK

- First NOvA 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 on the arXiv today.
  - 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.

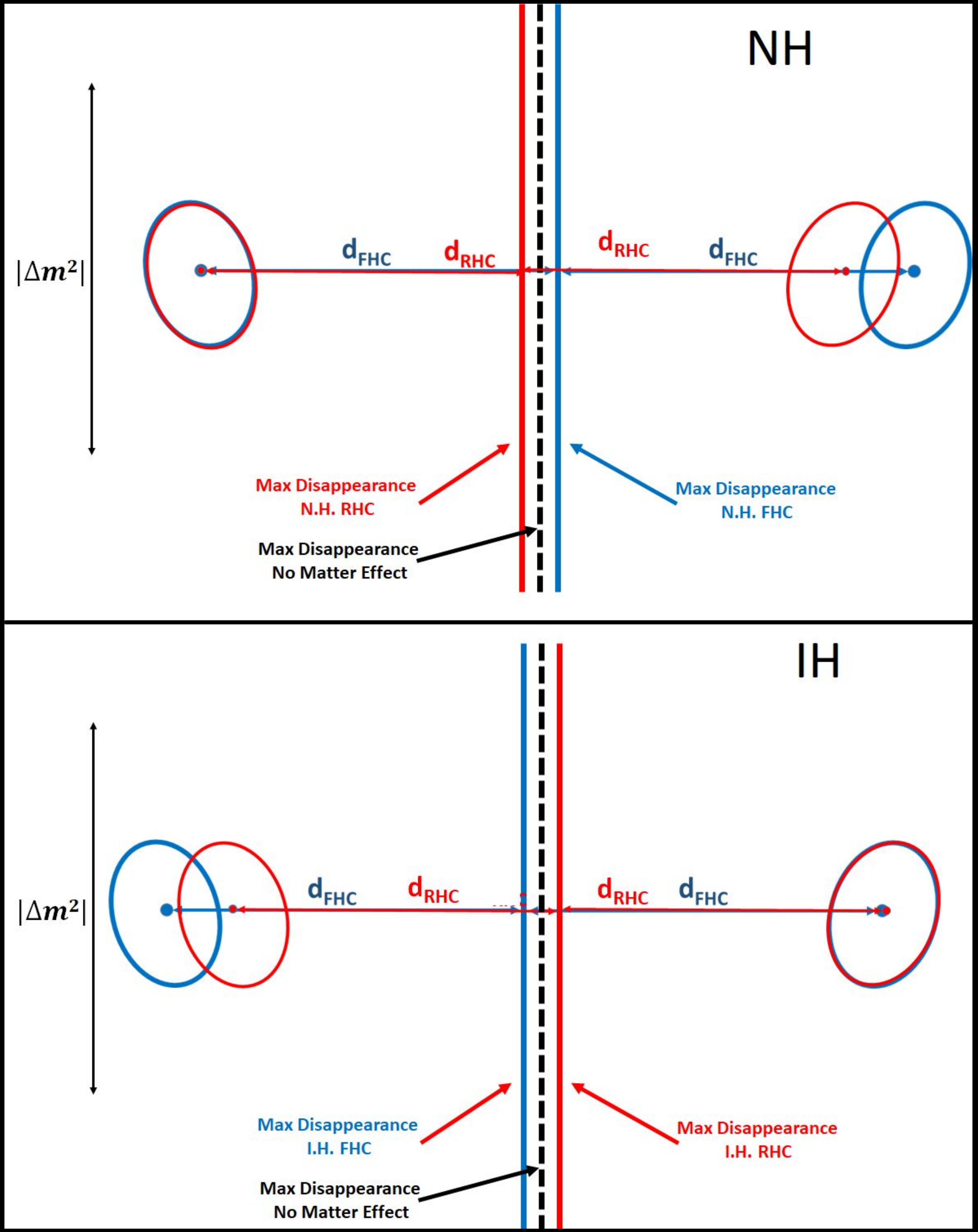
MUON NEUTRINO DISAPPEARANCE

- The combined data of neutrino and antineutrino beams are fit assuming CPT invariance.
- We expect 126 at the best fit and observe 113 events in the neutrino beam mode and expect 52 at the best fit and observe 65 events in antineutrino beam mode.
- If fit separately, the antineutrino beam mode prefers a more non-maximal solution.
- Consistency with the combined fit oscillation parameters for the neutrino and antineutrino datasets is better than 4%. Combined result is consistent with previous result.

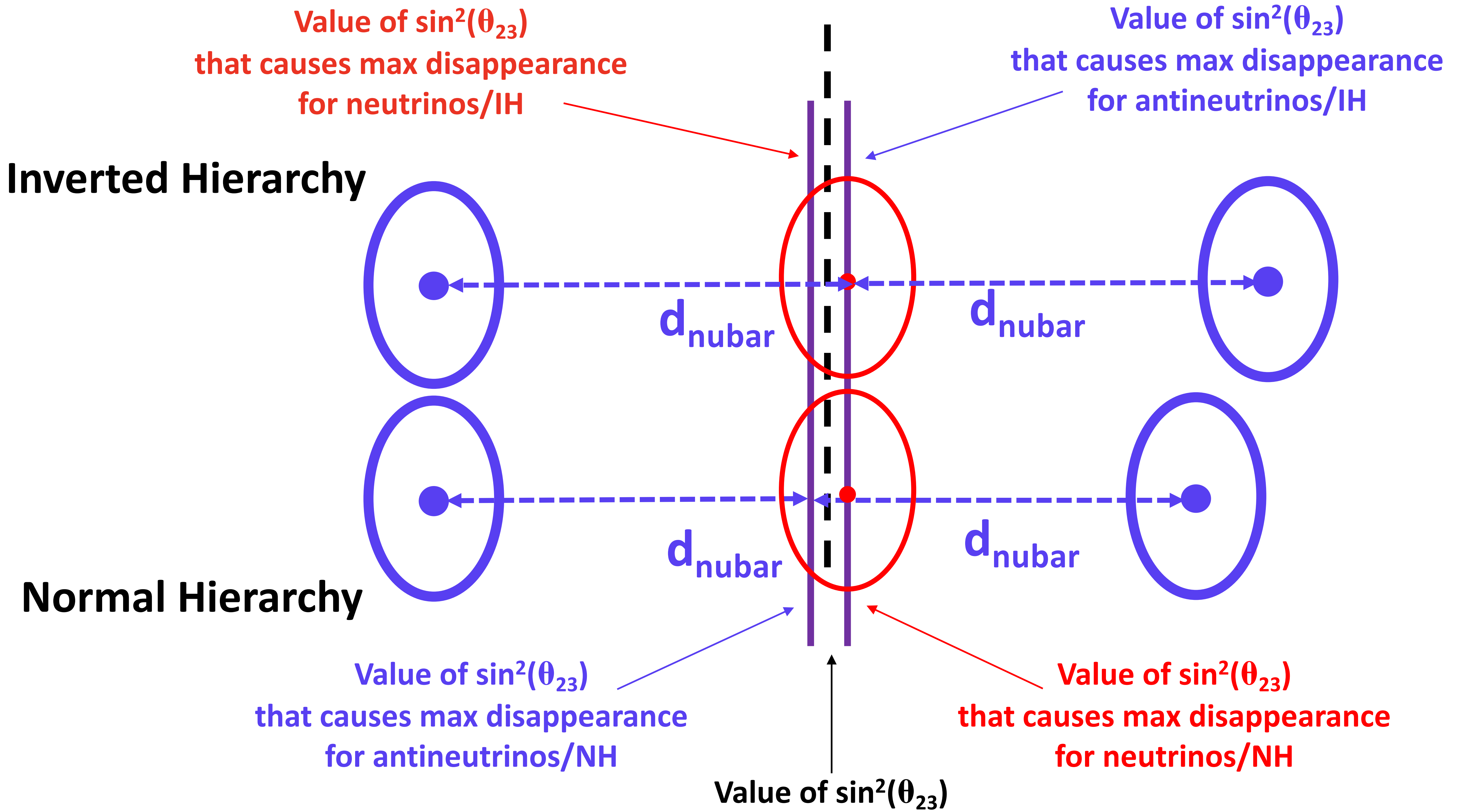


OCTANT-HIERARCHY SENSITIVITY IN DISAPPEARANCE

- Maximal disappearance in vacuum with θ_{13} =0 is at $\sin^2\theta_{23}$ = 0.5.
- In vacuum with reactor value of θ_{13}, it is at 0.511. Not at maximal mixing.
- In matter :
  - For ν_μ and NH it is at 0.514.
  - For $\overline{\nu}_\mu$ and NH it is at 0.508.
  - For IH it flips from the above values.

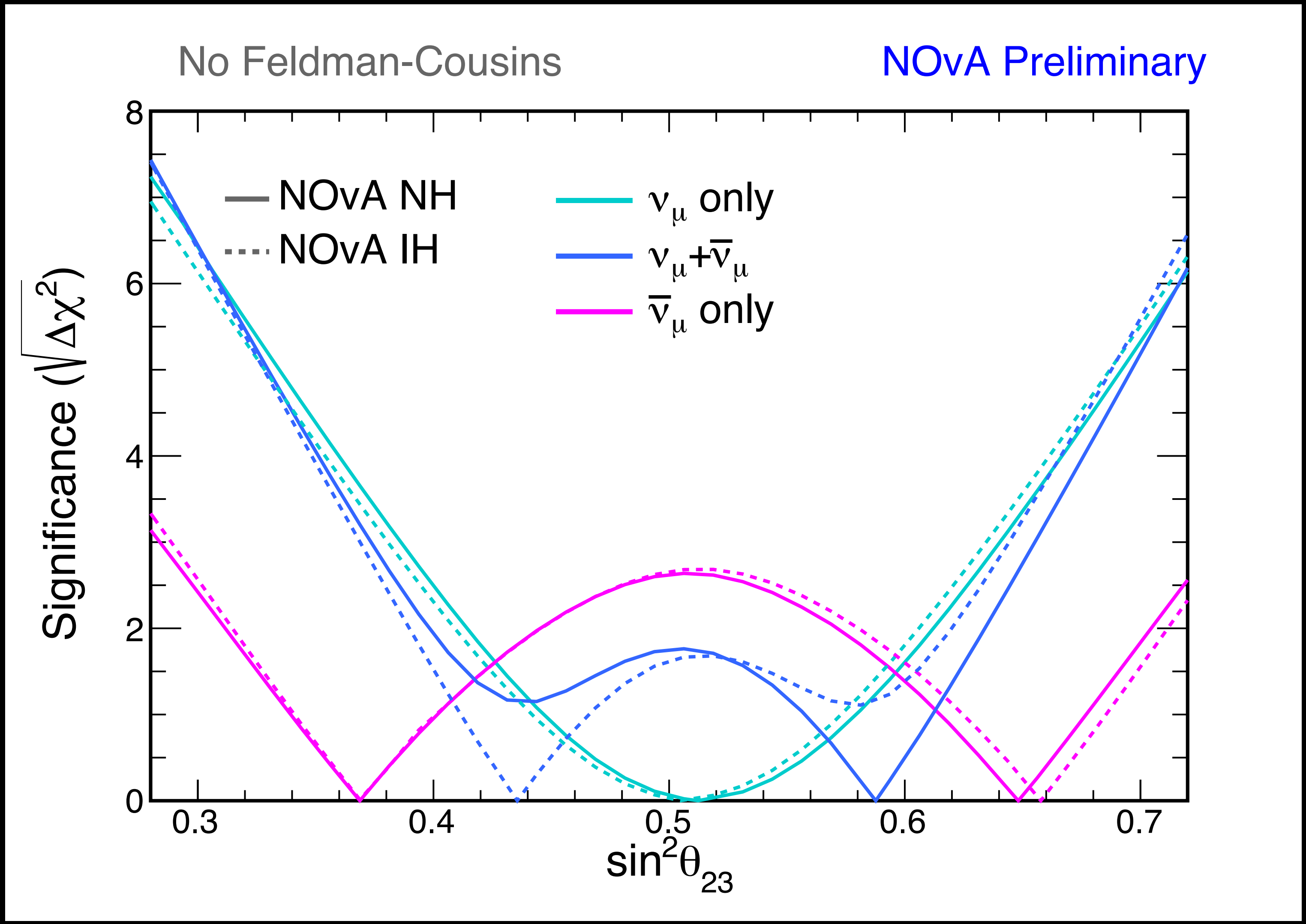


OCTANT-HIERARCHY SENSITIVITY IN DISAPPEARANCE



OCTANT-HIERARCHY SENSITIVITY IN DISAPPEARANCE

- In our current results, the antineutrino mode picks same value in the lower octant for both NH and IH which mirrors to different points in the upper octant.
- The neutrino mode prefers to be closer to maximal disappearance, and therefore is nearest to the NH/UO value of antineutrino mode and the IH/LO of neutrino mode.
- The combined result therefore prefers these values for the combined best fit.

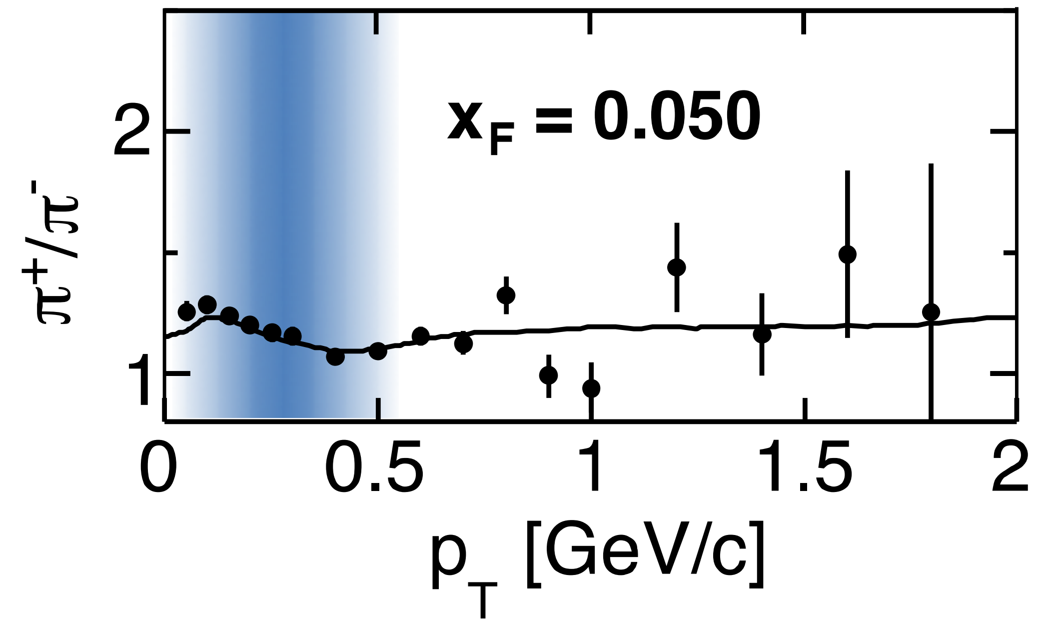


OCTANT-HIERARCHY SENSITIVITY IN DISAPPEARANCE

- The matter effect boosts (suppresses) nue appearance for NH (IH) and vice versa for nuebar.
- By unitarity, those extra nue for NH must cause more disappearance of numu and/or less nuTau appearance.
- At maximal disappearance the extra nue appearance due to matter has to involve less nuTau appearance.
    - At maximal disappearance, there are no numu left to disappear.
- In vacuum dCP causes identical numu and numubar disappearance due to CPT symmetry
    - CPv can happen because the e/tau appearance split can be different for neutrinos and antineutrinos.
- Matter effects split the extra nue appearance for NH between more numu disappearance and less nutau appearance.
    - Numu and numubar disappear (slightly) differently in matter!

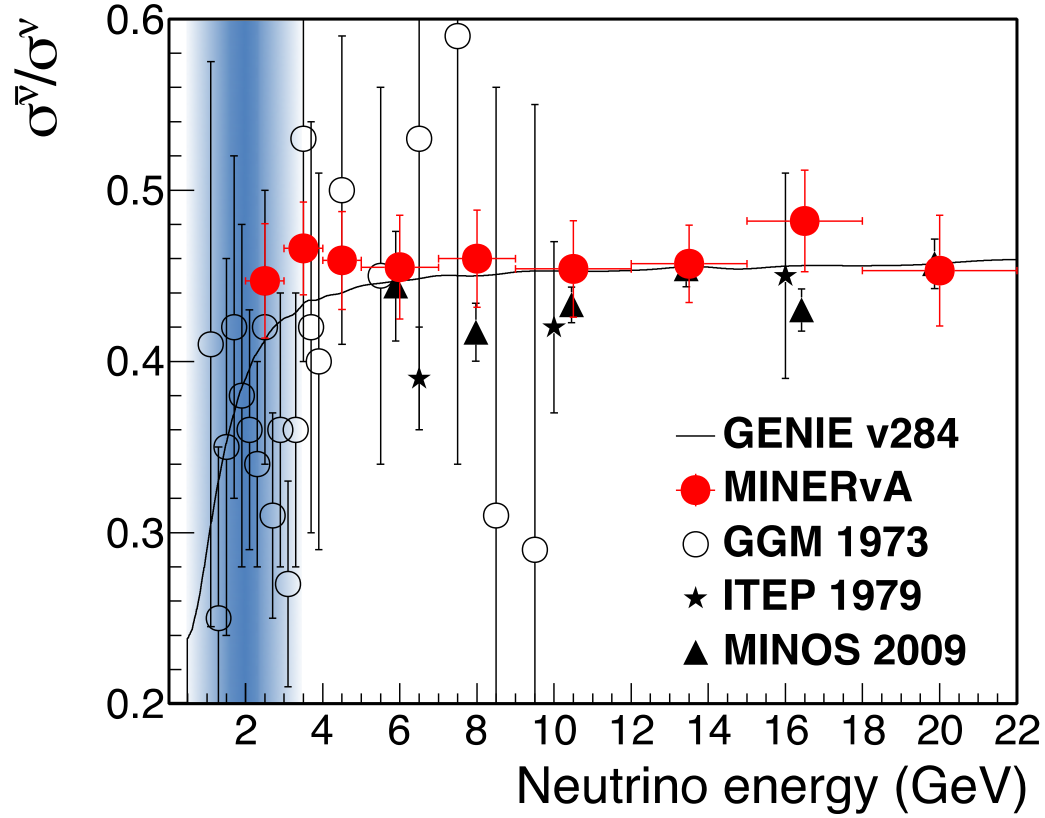
WHAT IS DIFFERENT IN ANTINEUTRINOS?

- Production cross section is higher for π^+ ($\rightarrow \nu_\mu$) than for π^- ($\rightarrow$ anti-ν_μ).
  - p^+ colliding with p^+ and n^0 in the target
- Interaction cross section is lower for antineutrinos than neutrinos.
- Benefit from being off-axis.
  - Wrong-sign events are part of the unfocused tail, which is suppressed.



NA49, Eur. Phys. J. C 49 897 (2007)

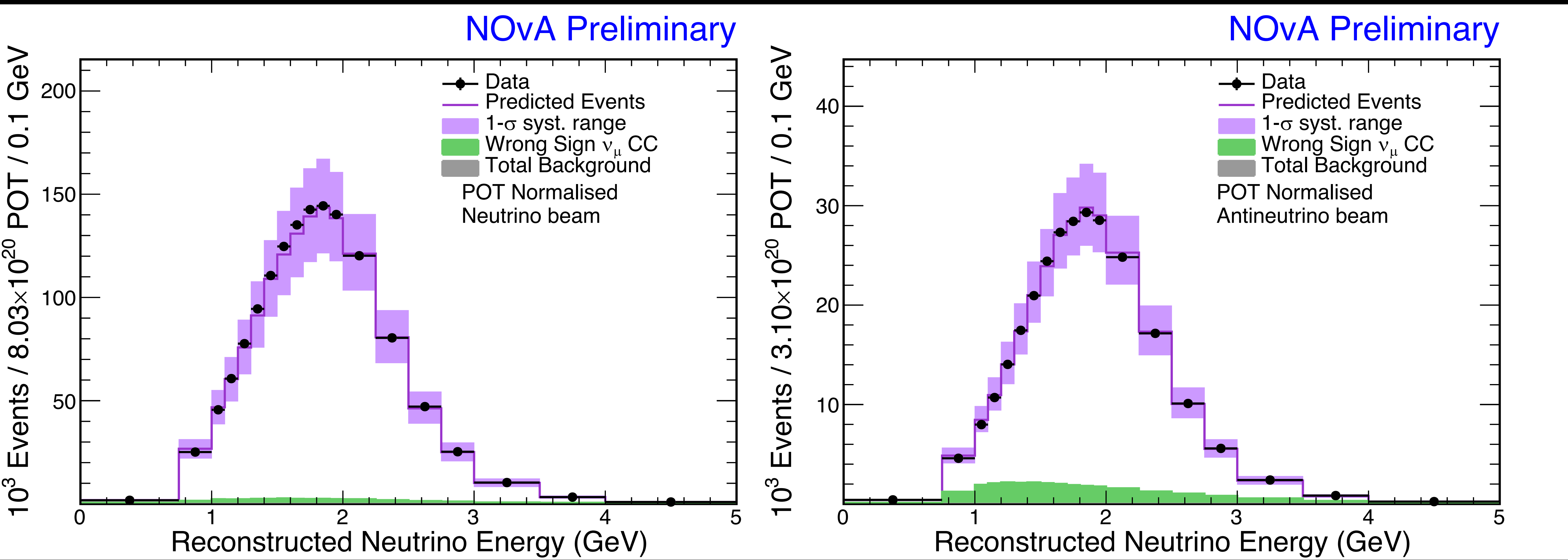
NOvA Focusing Peak



MINERvA, Phys.Rev. D95 (2017) no.7, 072009

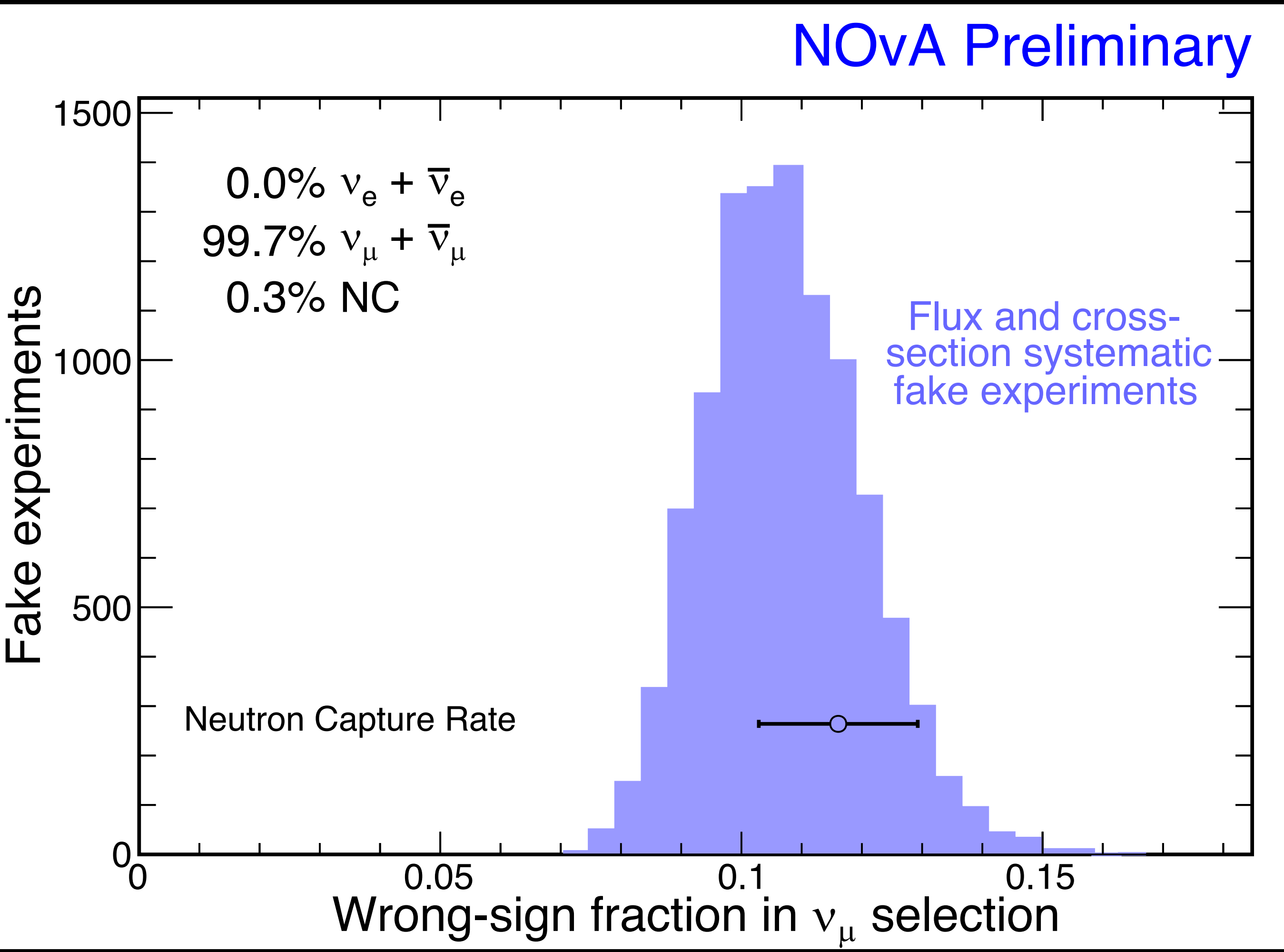
NOvA Focusing Peak

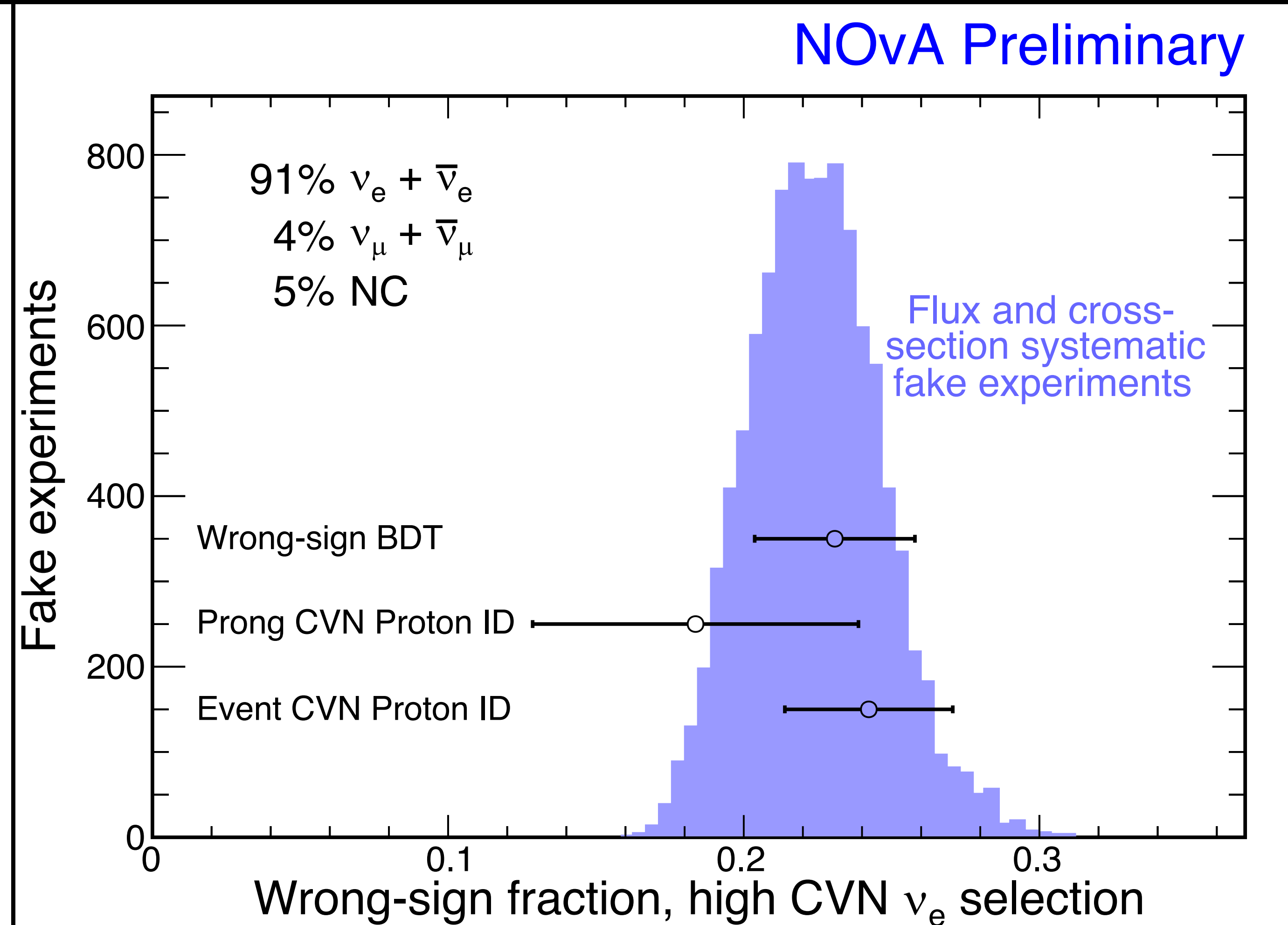
WHAT IS DIFFERENT IN ANTINEUTRINOS? WRONG-SIGN CONTAMINATION



- Neutrino mode: 3% WS
  - Focused component is enhanced
  - Unfocused component is suppressed
- Antineutrino mode: 11% WS
  - Focused component is suppressed
  - Unfocused component is enhanced

WHAT IS DIFFERENT IN ANTINEUTRINOS? WRONG-SIGN CONTAMINATION

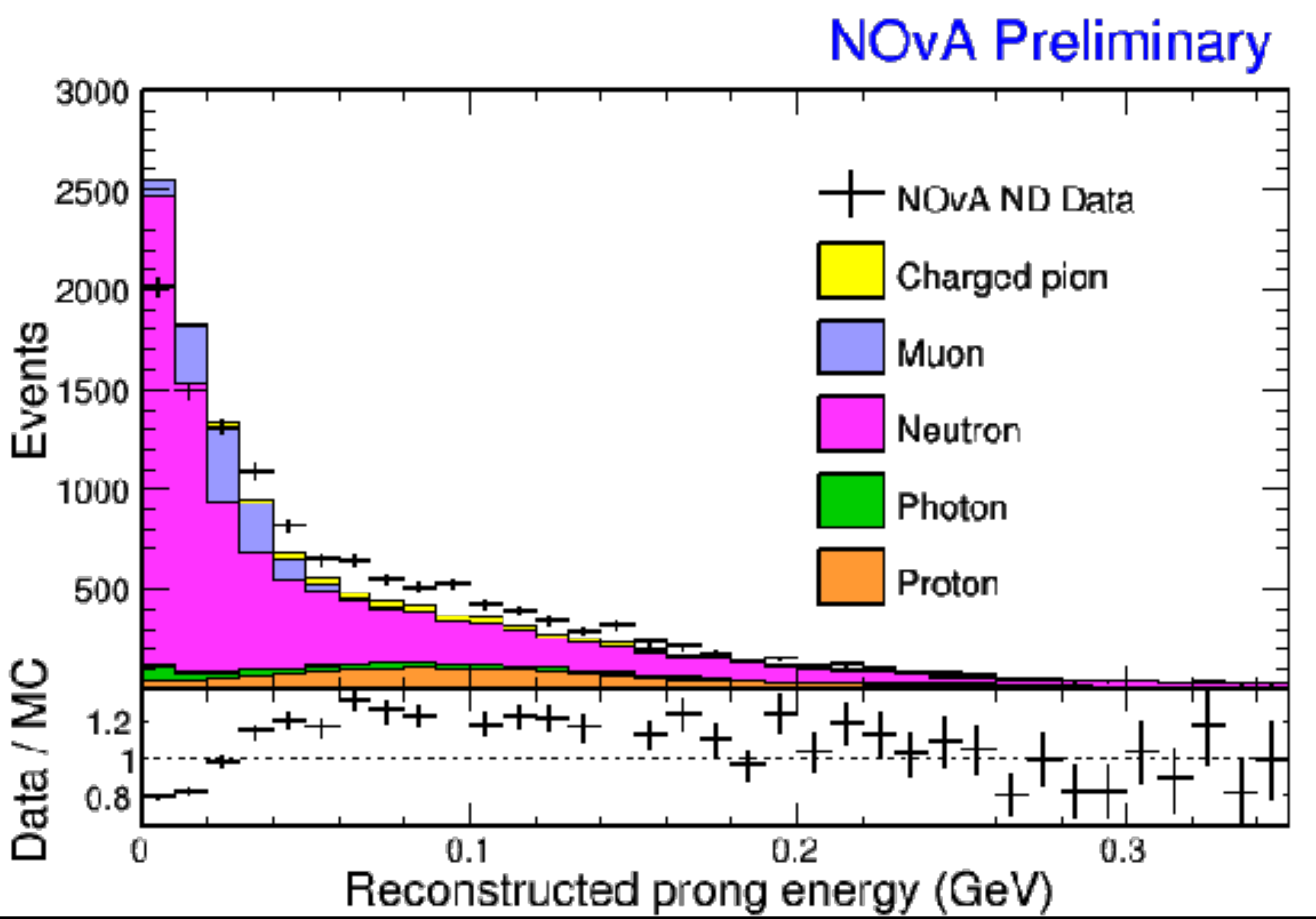




- 11% wrong-sign in the ν_μ ND sample background
  - Consistent with data-based cross-check using neutron captures.
- 22% (32%) in the ν_e ND background in the high (low) PID bin
  - Consistent with data-based cross-checks using identified protons and event kinematics.
- •~10% systematic uncertainty from flux and cross section
- Does not include uncertainties from detector effects.

WHAT IS DIFFERENT IN ANTINEUTRINOS? NEUTRONS

- Anti-ν's produce neutrons where ν's produce protons.
- E_n are typically several hundred MeV.
    - Modeling these fast neutrons is a challenge.
- We identified an enriched sample of neutron-like prongs which shows some discrepancies.
- We introduced a systematic which covers them.
    - Scales the amount of deposited energy of some neutrons.



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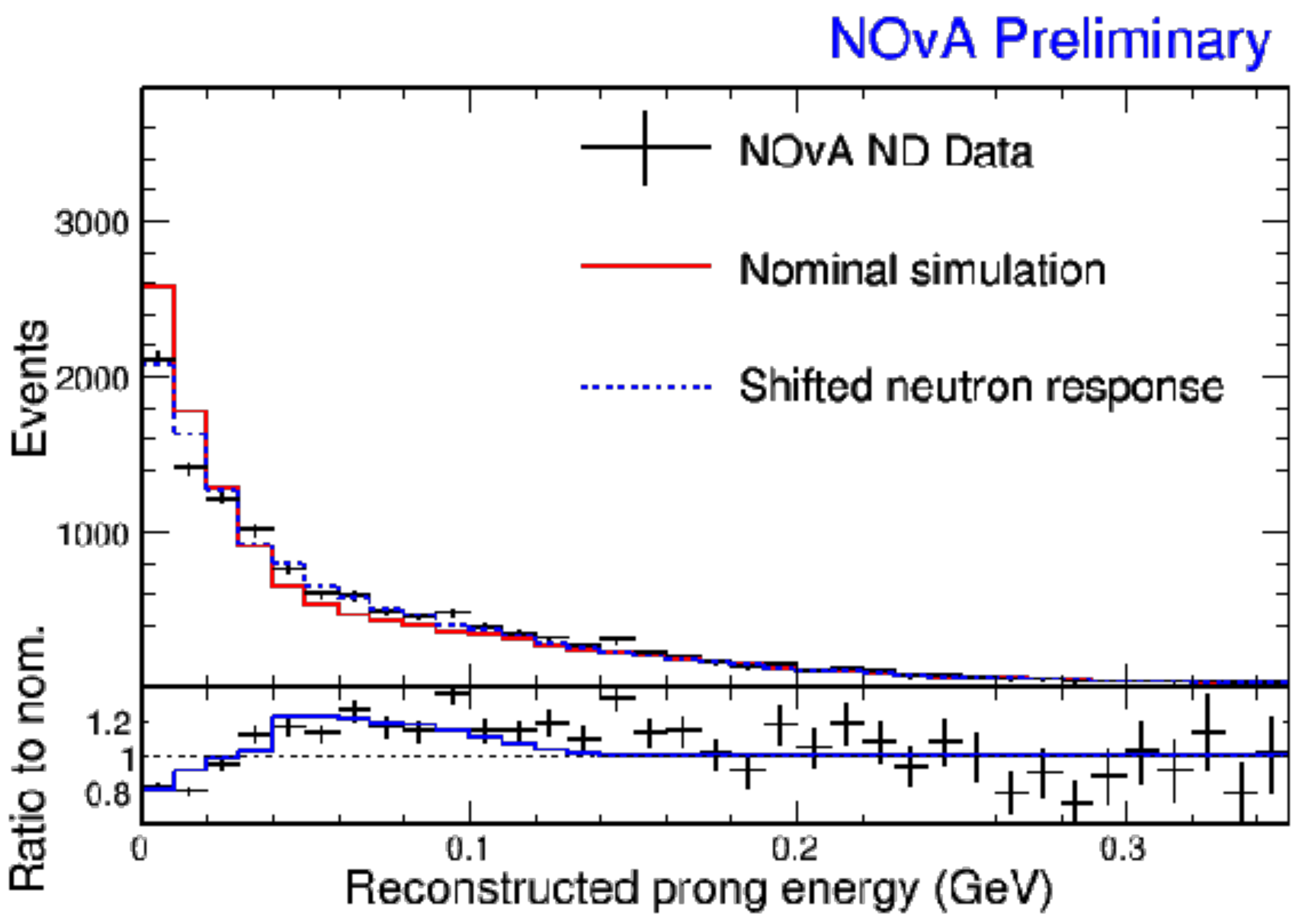

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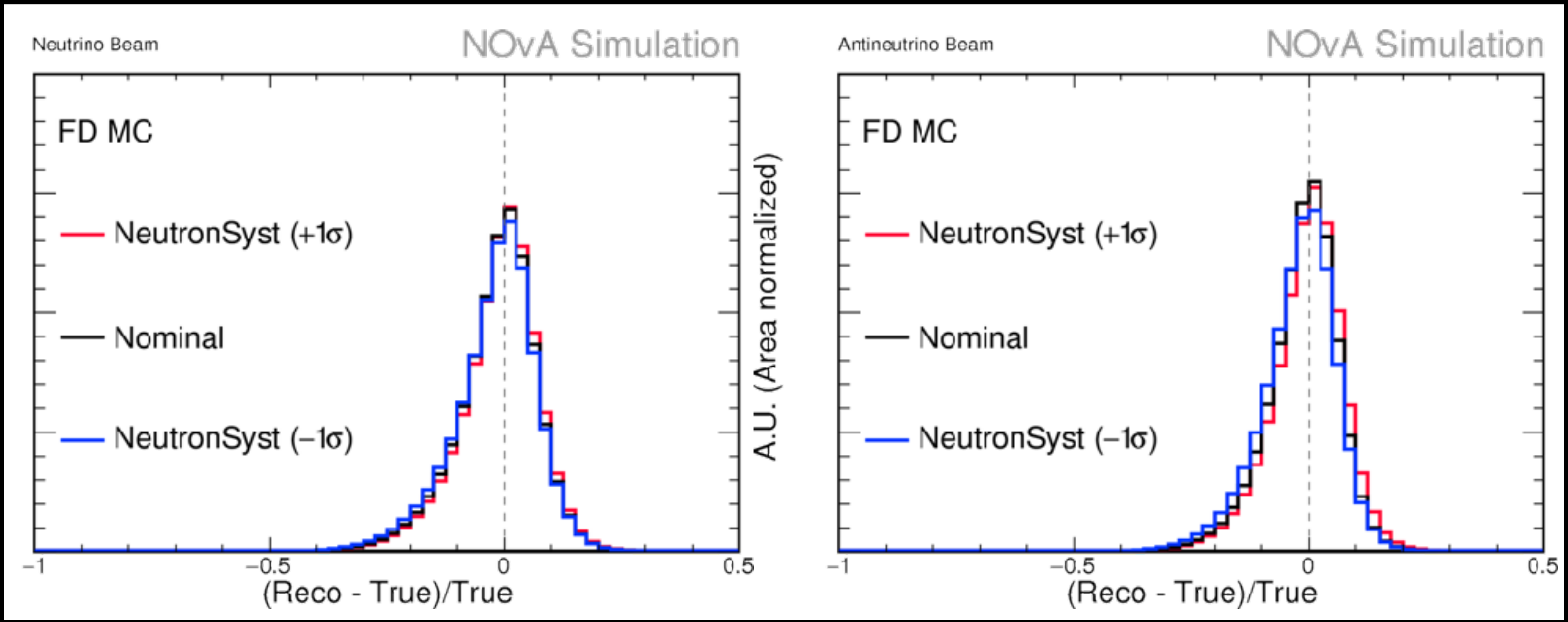
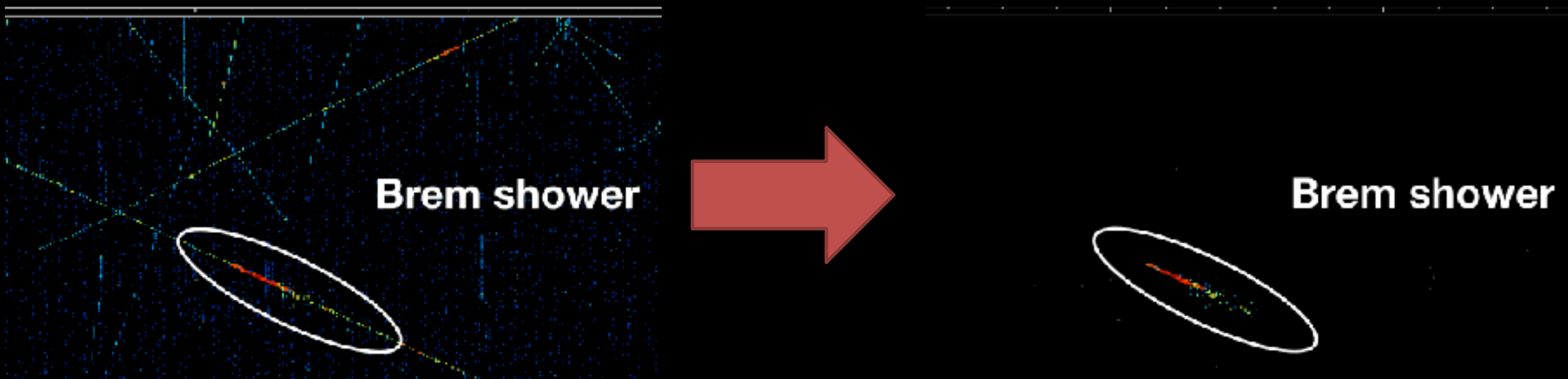
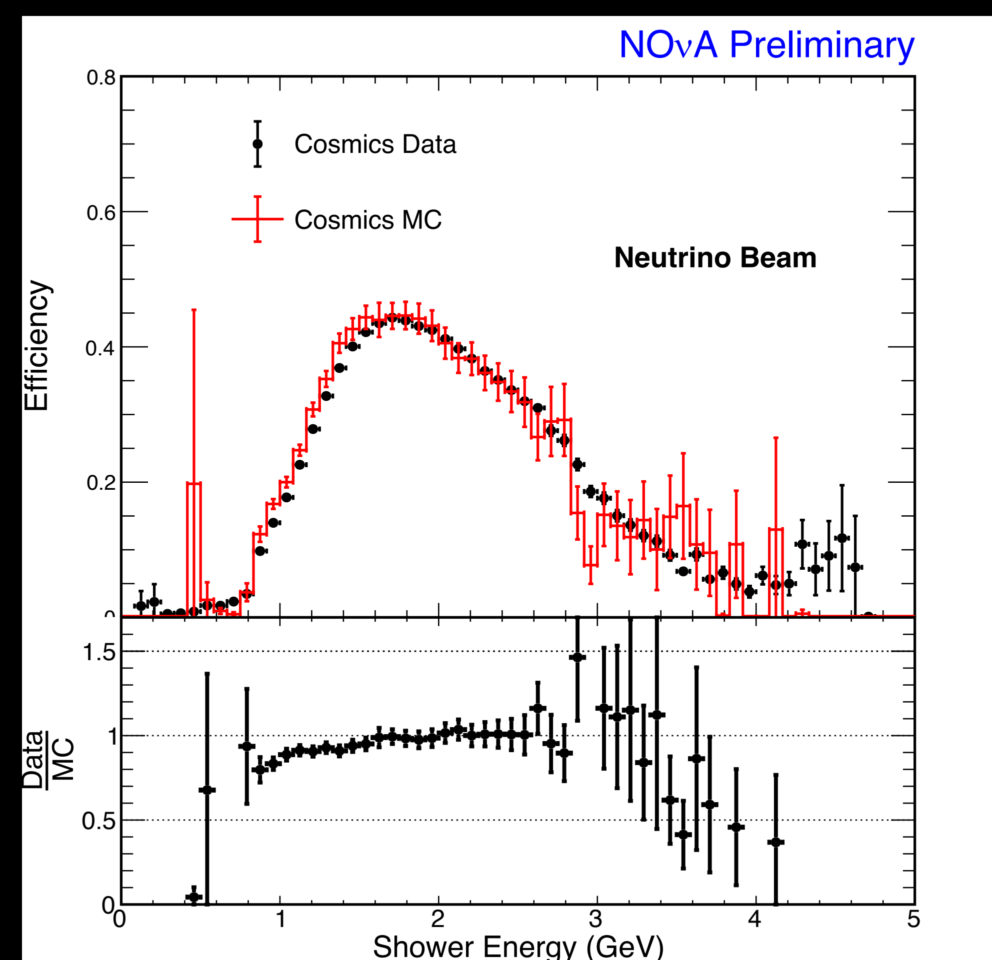


- The neutron systematic shifts the mean ν_μ energy by 1% in the antineutrino beam and 0.5% in the neutrino beam.
- Resolution is changed by a fraction of a percent.
- Negligible impact was seen on selection efficiencies.

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.
- Compare efficiency between data and simulated brem showers.
  - Look at both the neutrino and antineutrino tunes of CVN, but the underlying brem showers are of course the same.



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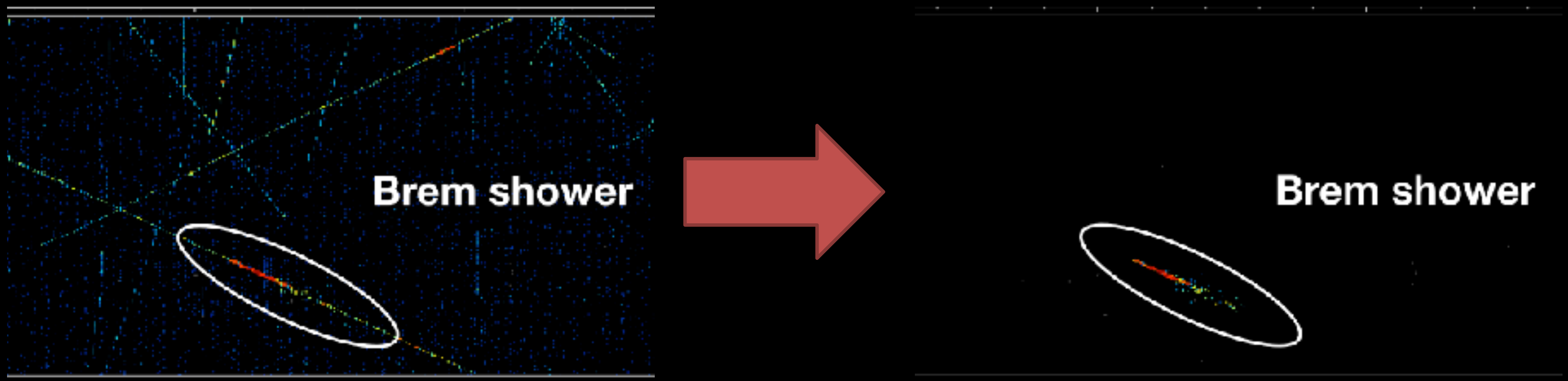

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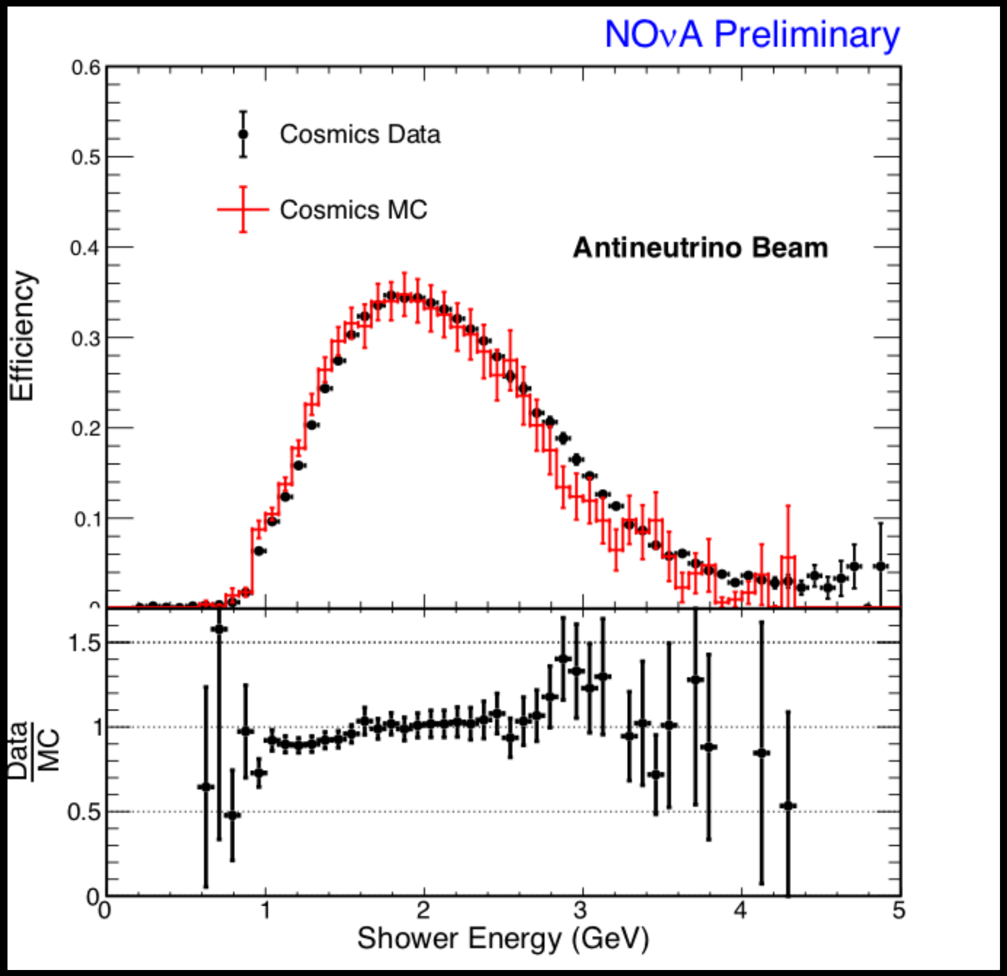
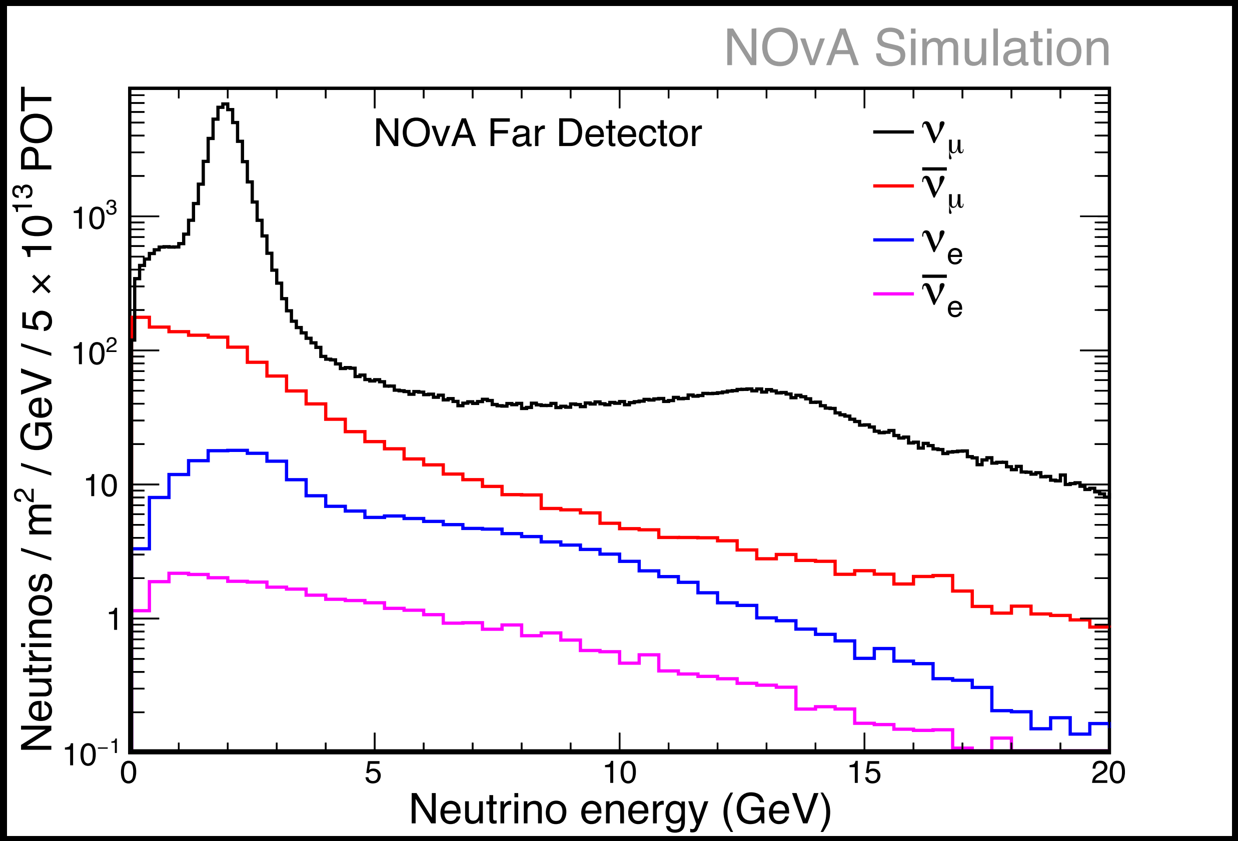
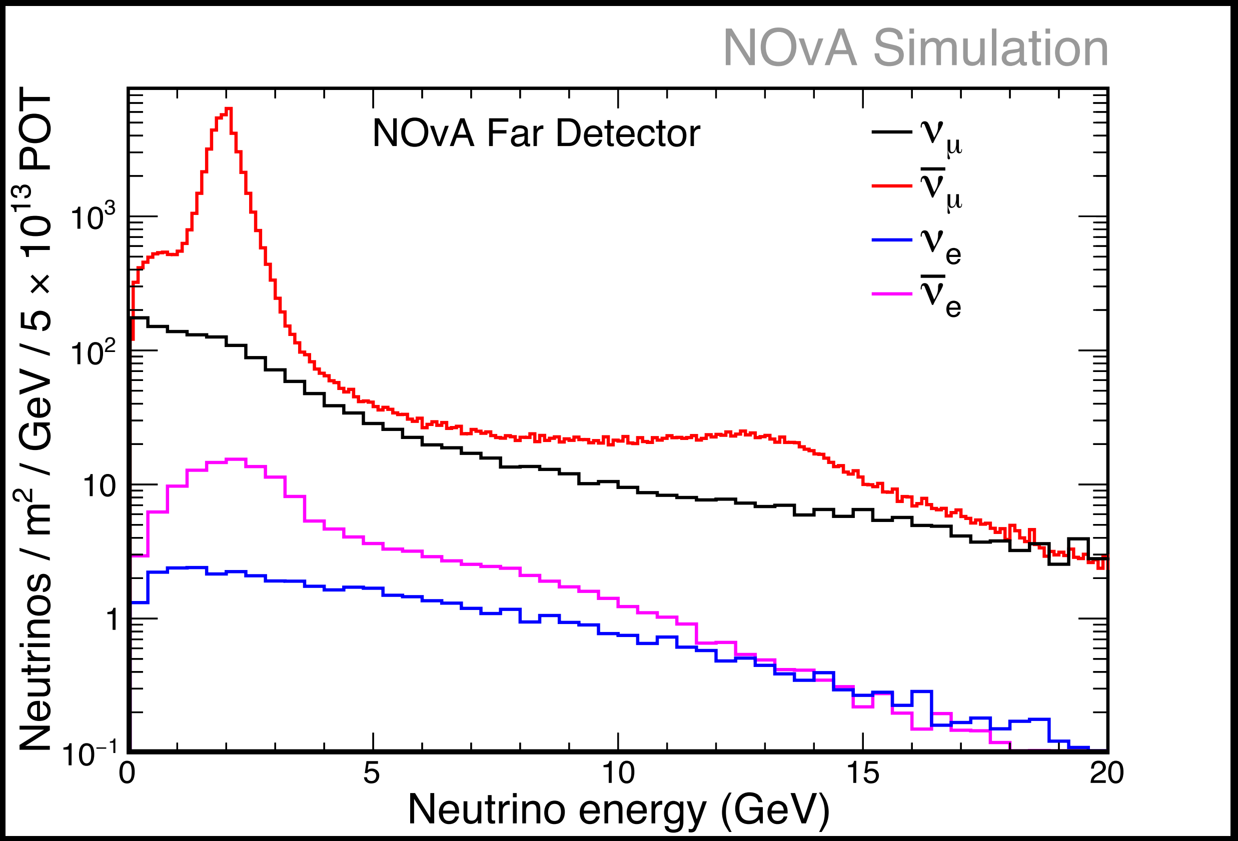


THE OFF-AXIS NUMI BEAM



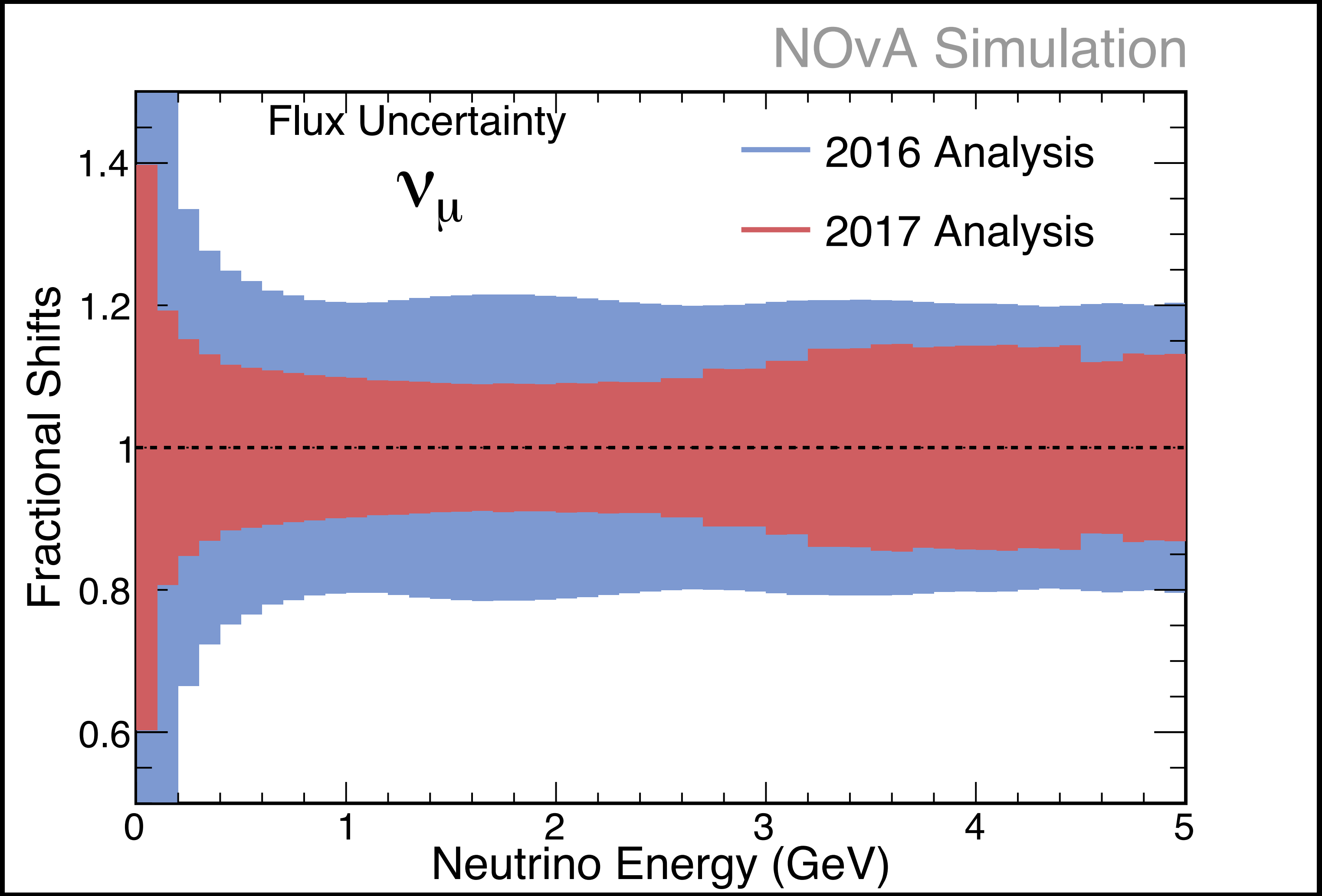
Neutrino beam



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 by constraining the hadron production model used in the beam simulation with external measurements on thin targets. We use the Package to Predict the FluX (PPFX) 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.

NUMI BEAM UNCERTAINTIES



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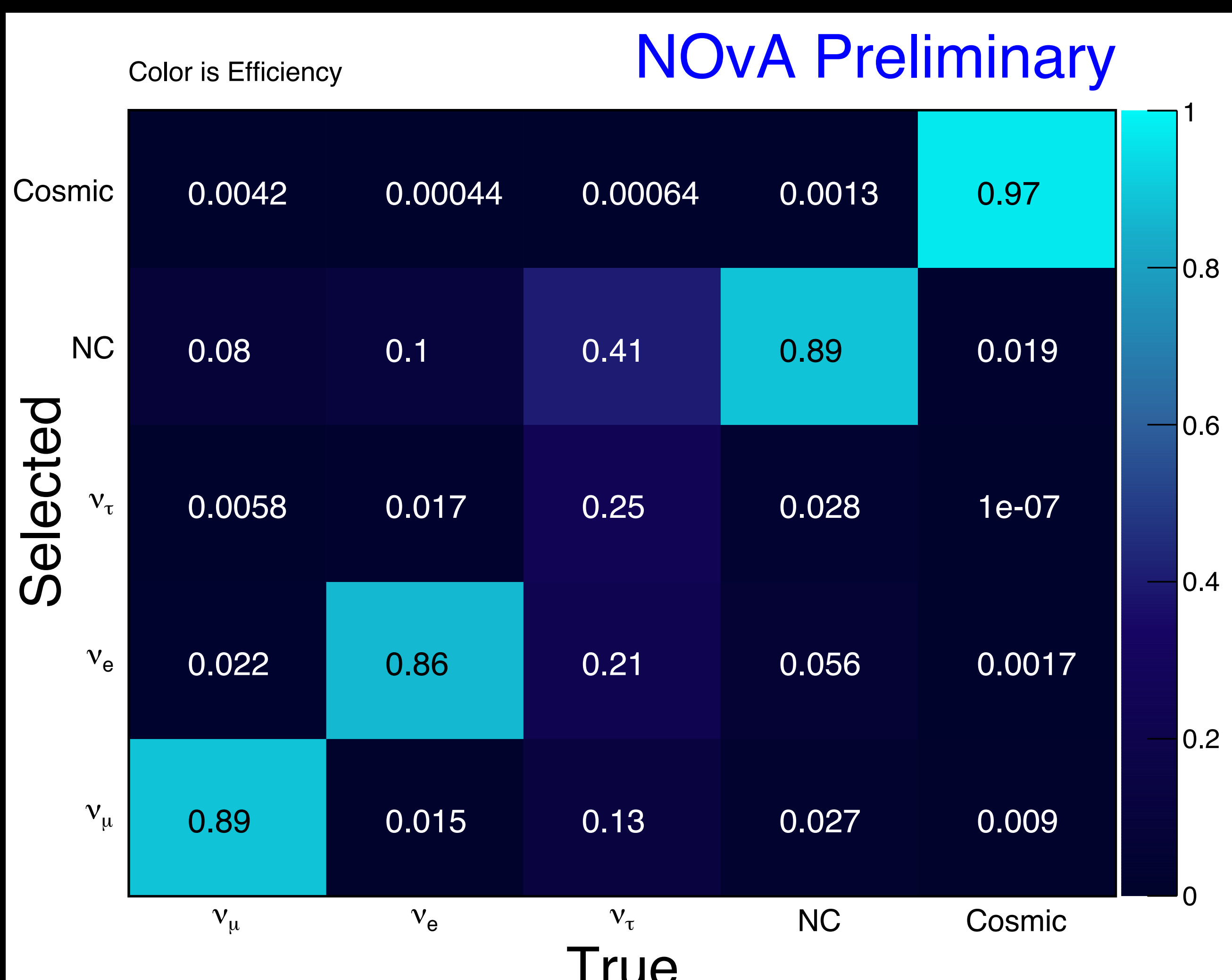
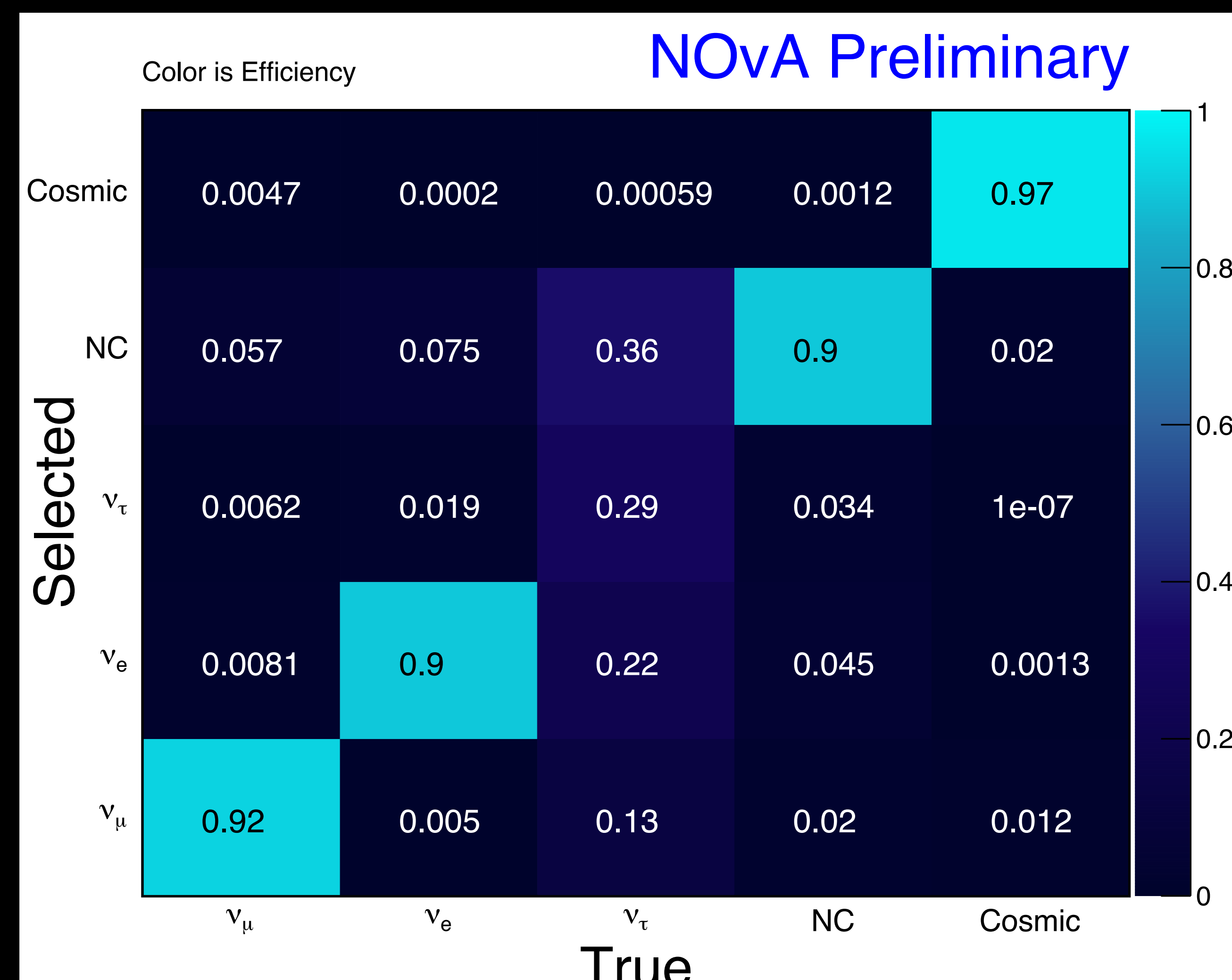
see poster #79

NEUTRINO INTERACTION CLASSIFIER

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



Neutrino beam

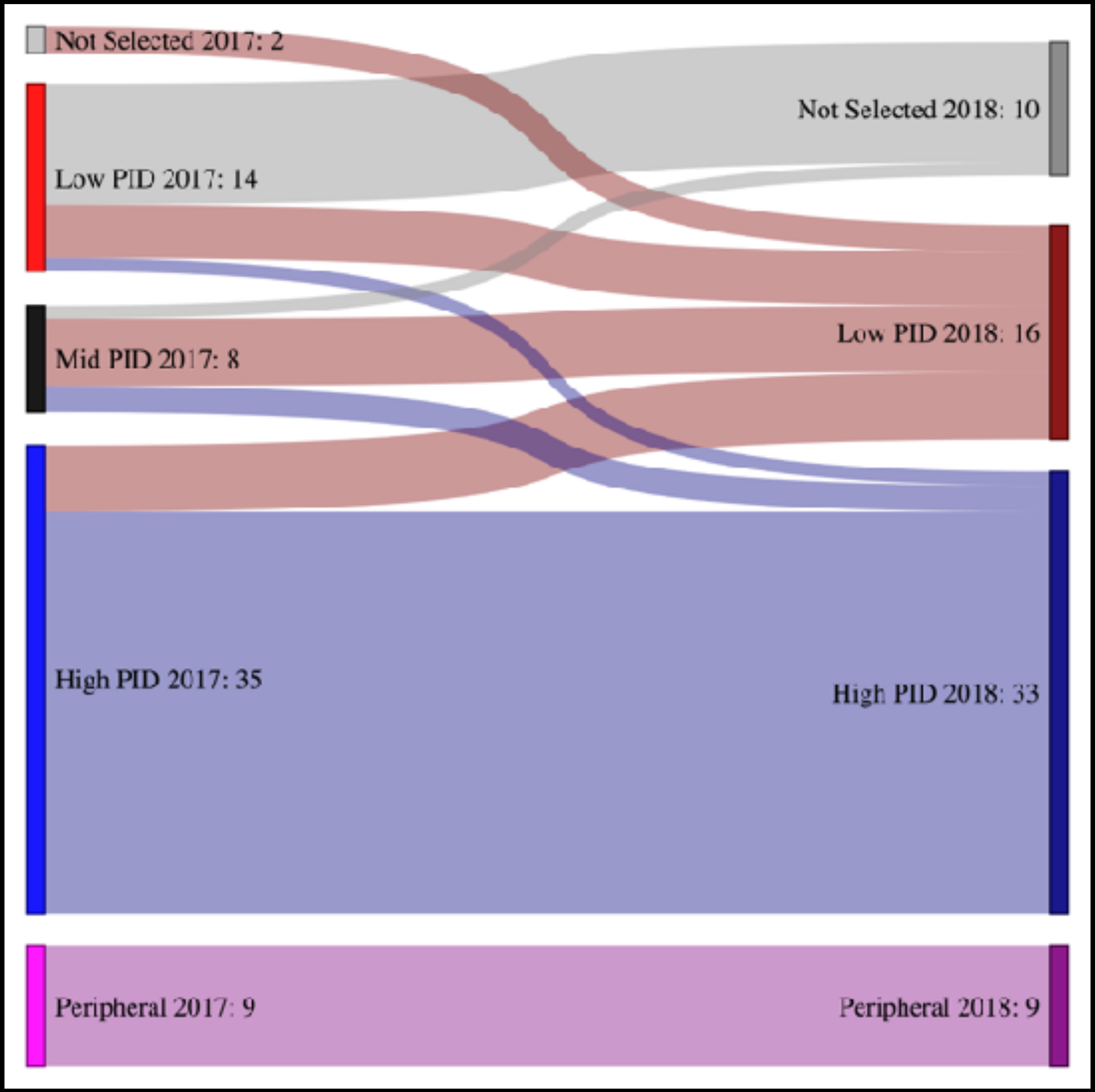


Antineutrino beam

see poster #79

NEUTRINO INTERACTION CLASSIFIER

66 events in 2017 analysis

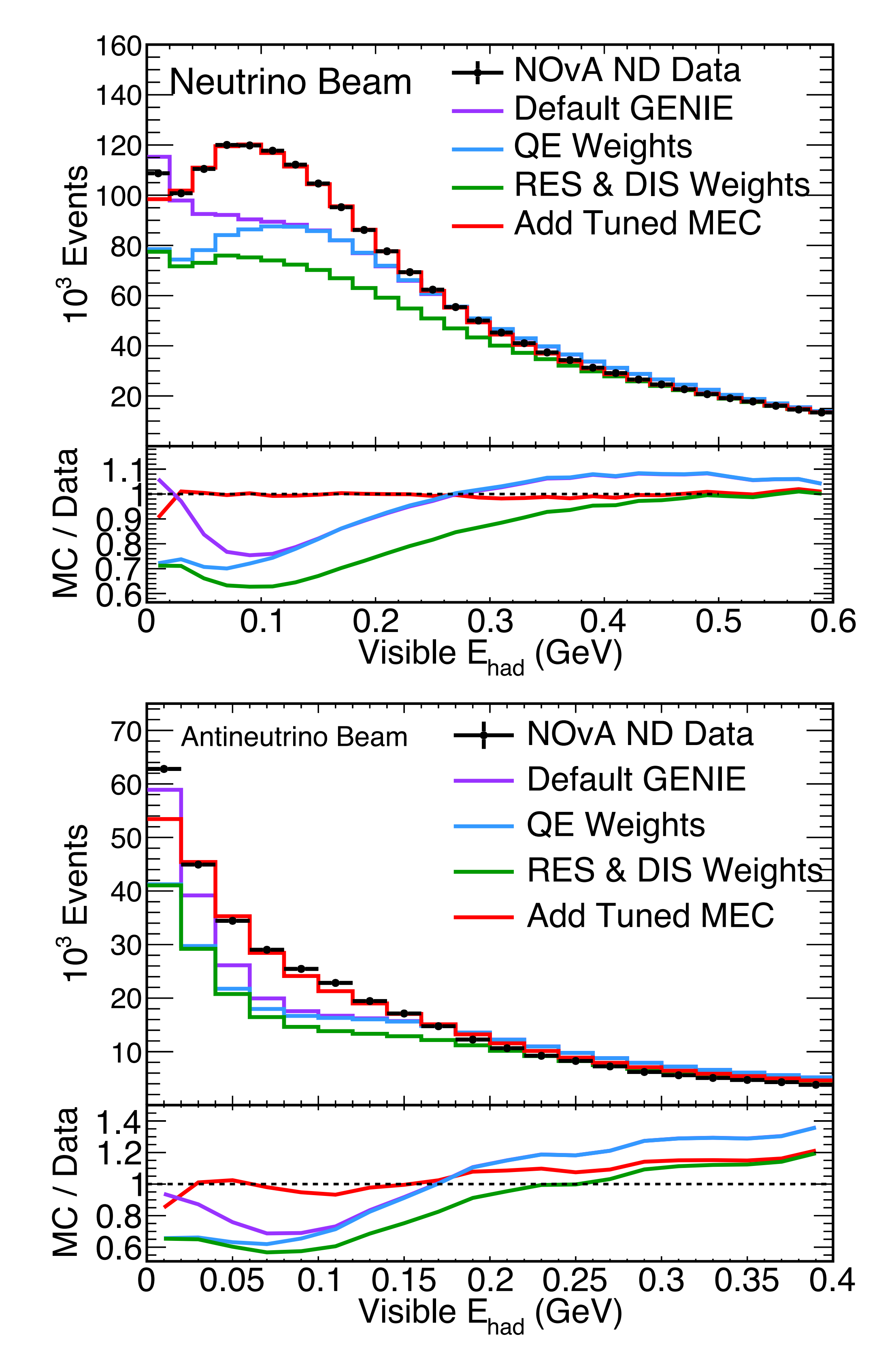


58 events in 2018 analysis

Change in data events after retraining of PID

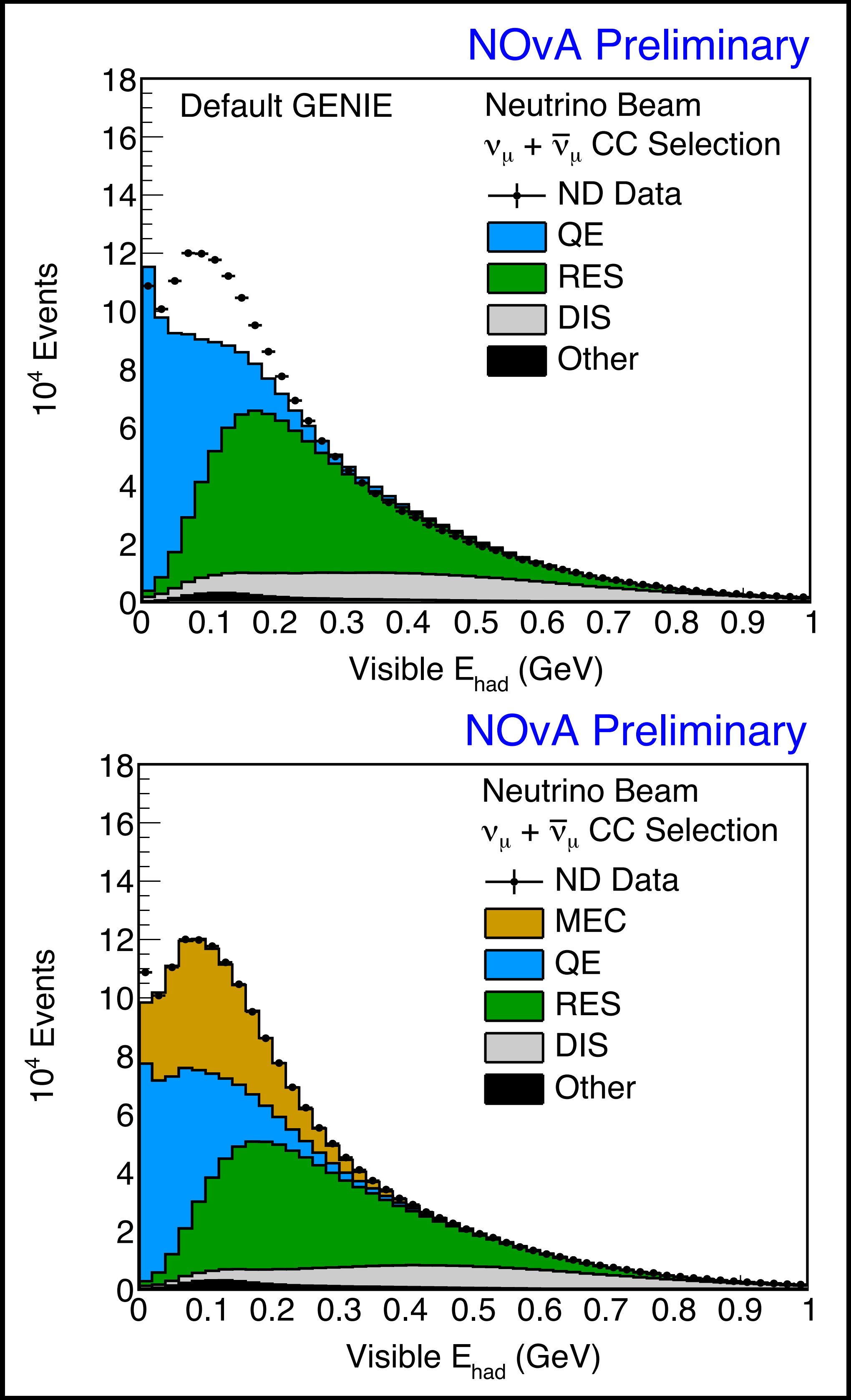
see poster #60

NEUTRINO INTERACTION TUNING



- The tuning is done independently for the neutrino vs antineutrino beam samples.
- Various corrections and tunings are applied:
  - Correct quasielastic 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 baryon production as well. Nonresonant inelastic scattering (DIS) at high invariant mass (W>1.7 GeV/c^2) weighted up 10% **based on NOvA data**.
  - Introduce custom tuning of GENIE "Empirical MEC" [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] **based on NOvA ND dat**a to account for multinucleon knockout (2p2h).

NEUTRINO INTERACTION TUNING



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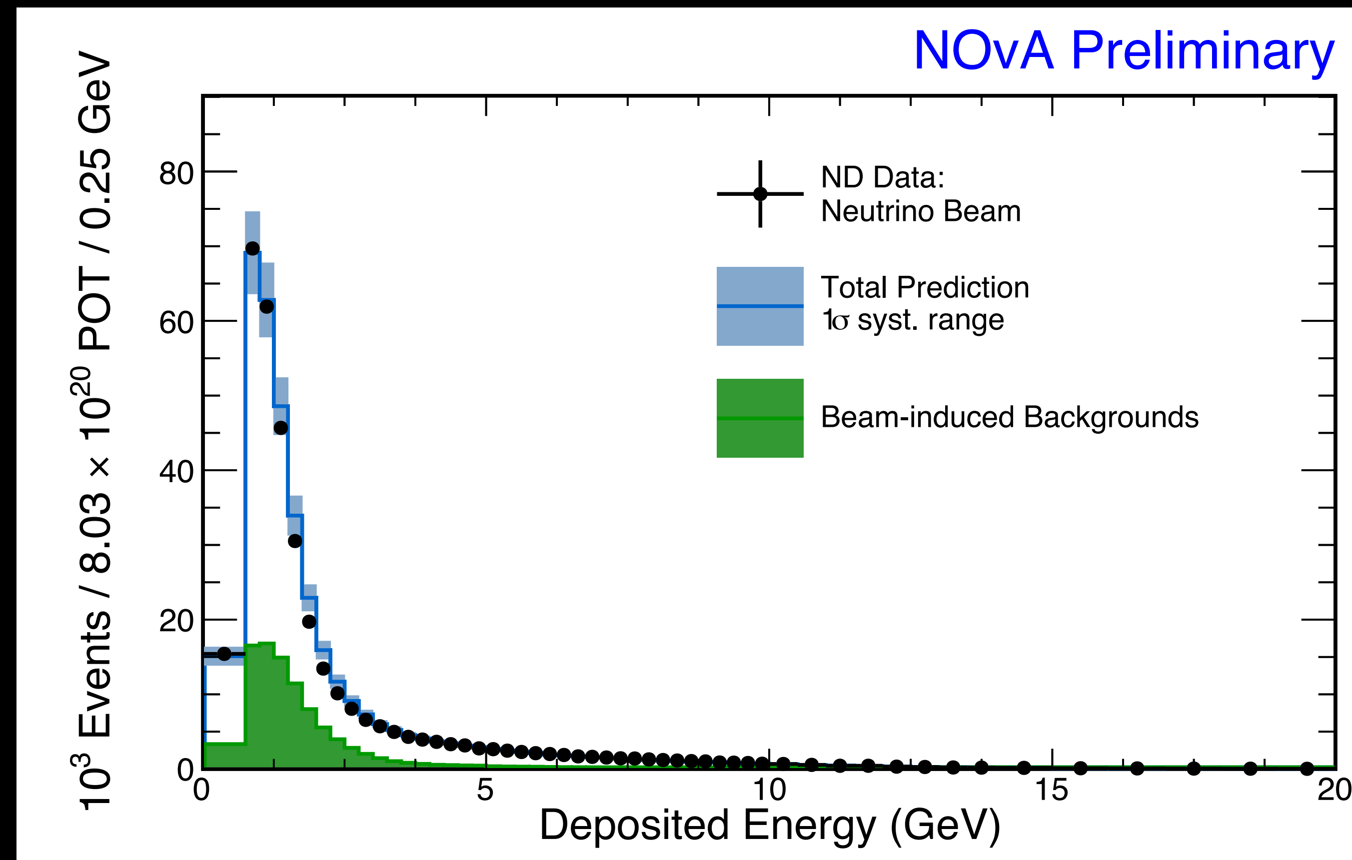
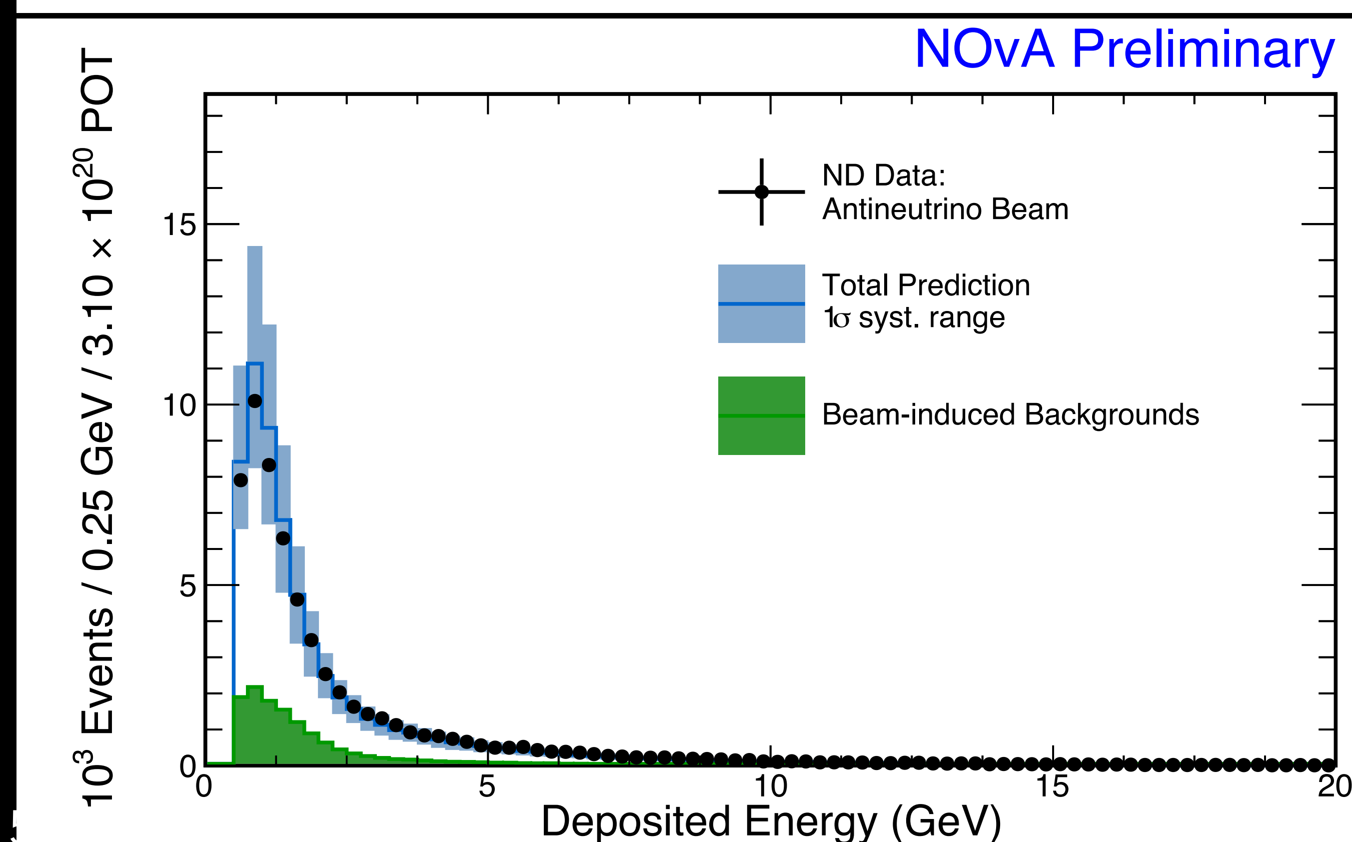
see poster #141 and 132

NEUTRAL CURRENT INTERACTIONS IN NEAR DETECTOR

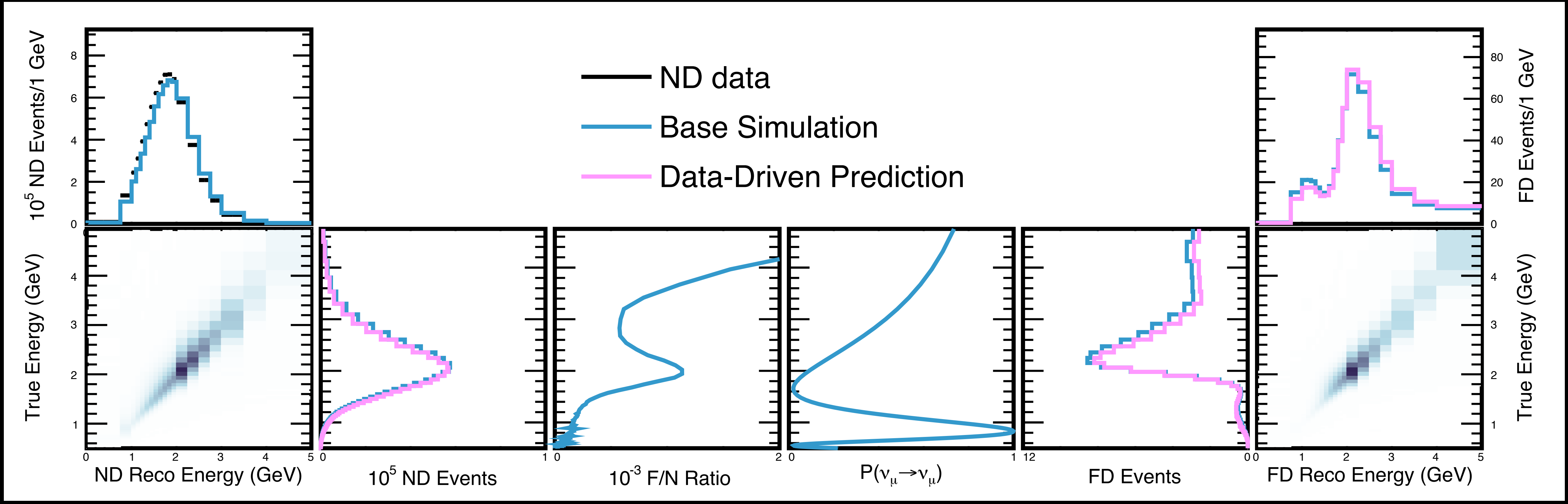
- Near Detector neutral current data selected for neutrino and antineutrino beams.
    - Using same particle ID trained on separate beams.
    - Each beam analyzed separately.
    - Planned neutrino analysis includes ND oscillations and has simultaneous fit of ND and FD data.
    - Antineutrino analysis done using extrapolation and ignoring ND oscillations for the moment.





PREDICTING THE FAR DETECTOR OBSERVATIONS

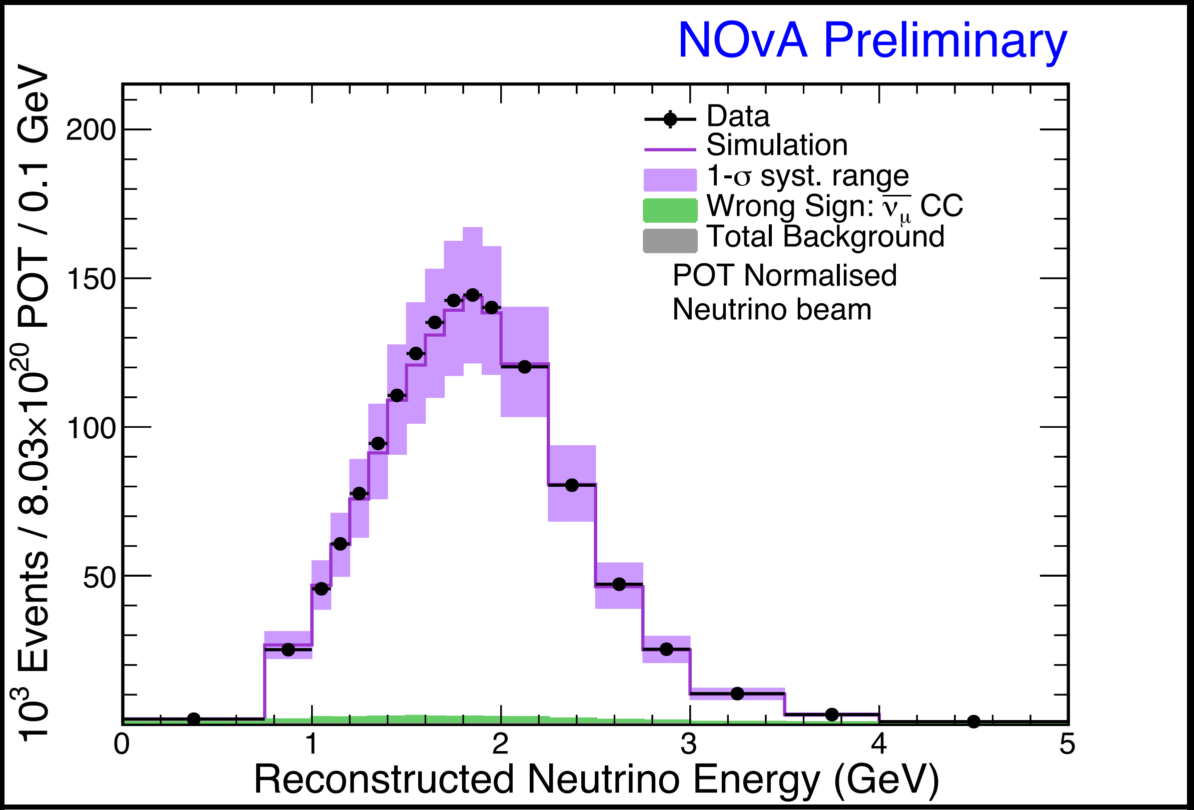
- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
    - Estimate the underlying true energy distribution of selected ND events.
- The measured spectrum is used to make a prediction of the expectation at the FD
    - Multiplying the true energy distribution by the Far/Near Ratio, applying oscillation probabilities and then converting to a predicted reconstructed energy distribution
- Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.

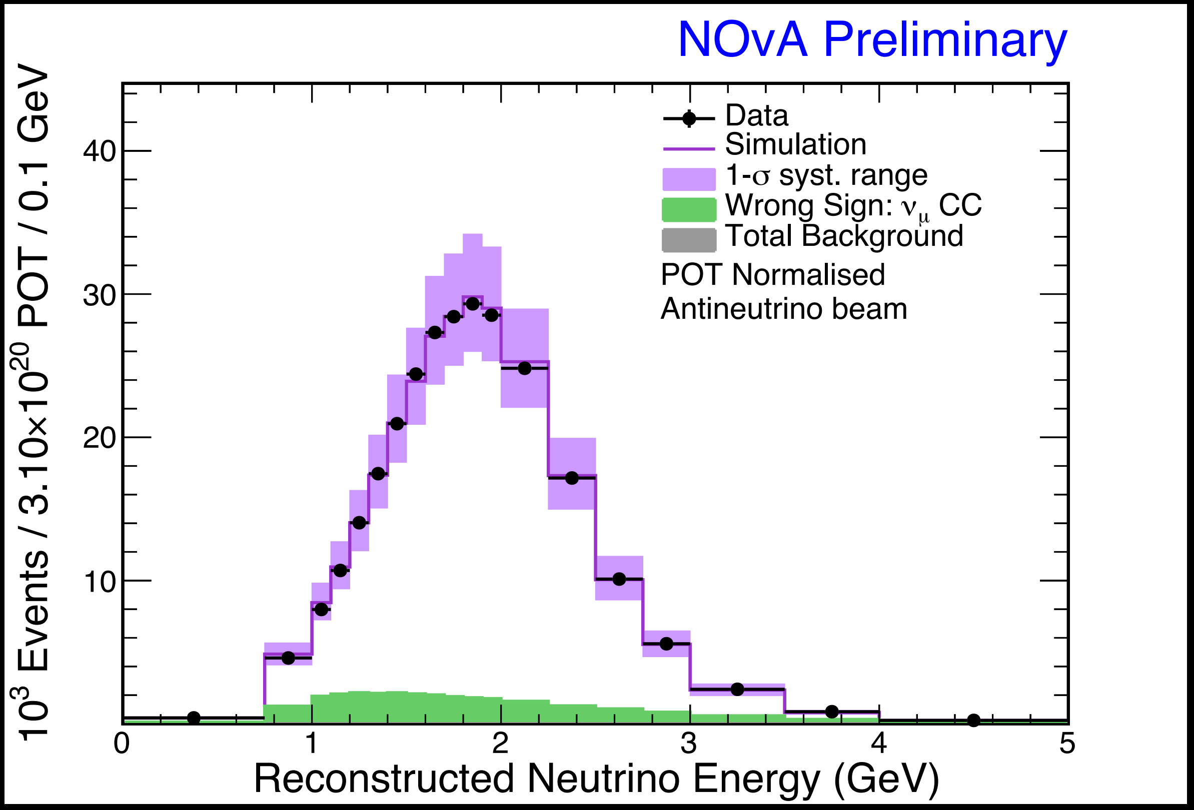


see poster #75

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 is estimated to be 3% for neutrino beam and 11% for antineutrino beam.
- Systematic uncertainties shown are shape and normalization. A small 1.3% and 0.5% offset is observed for neutrinos and antineutrinos respectively.

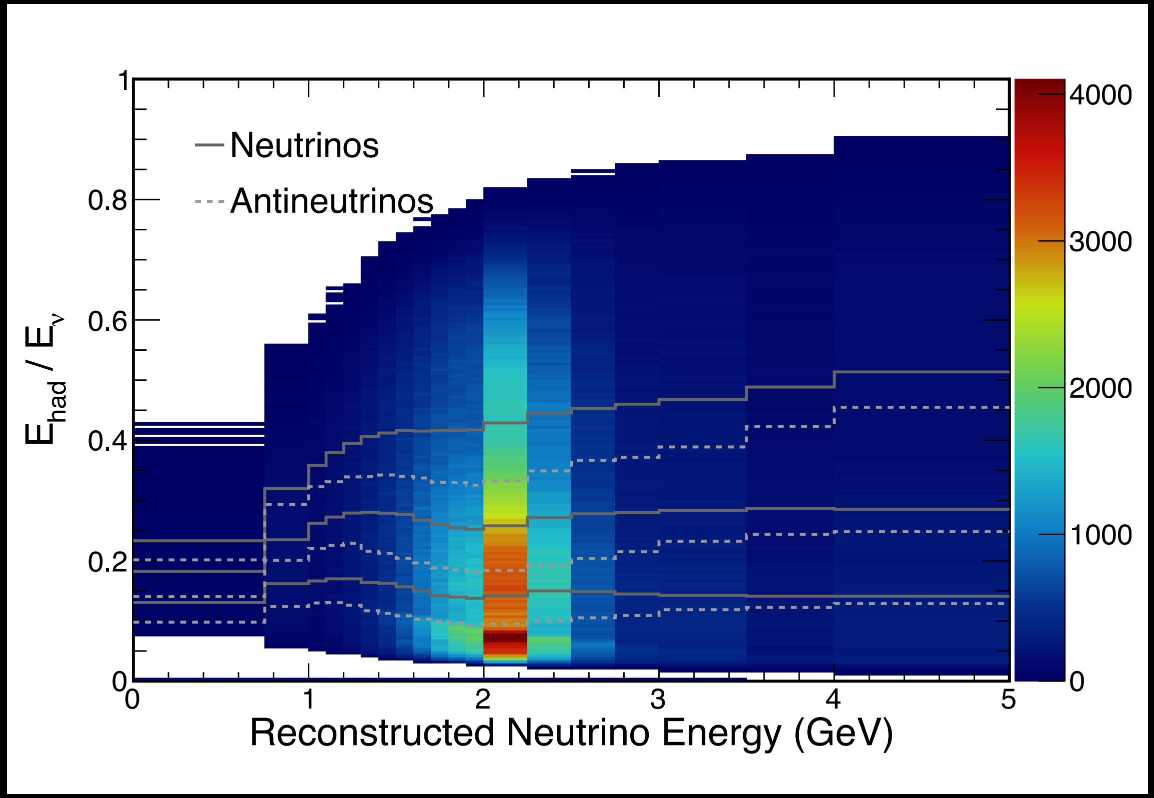


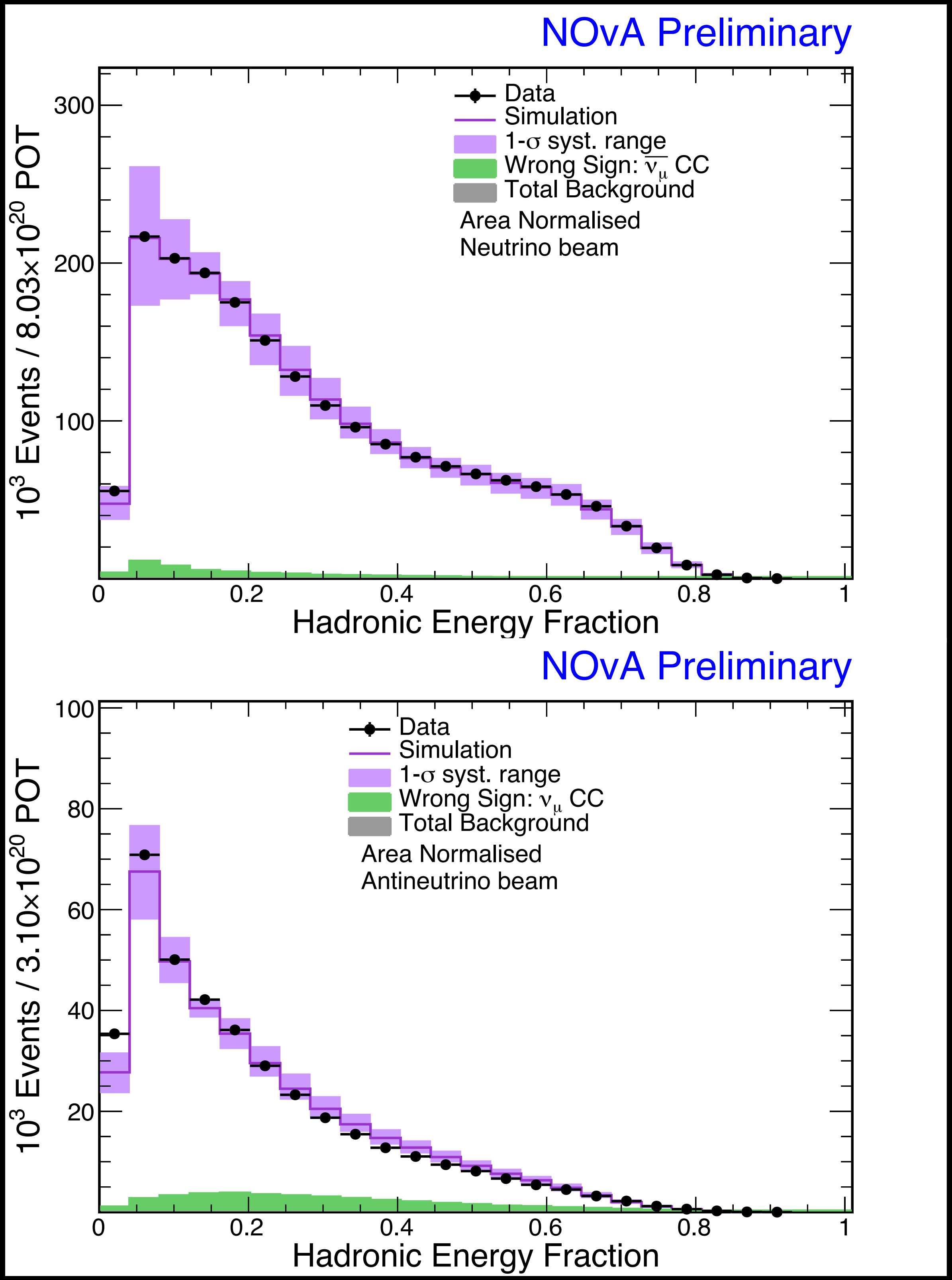


see poster #75

ENERGY RESOLUTION QUARTILES

- The data is split in four equal populations (quartiles) 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.

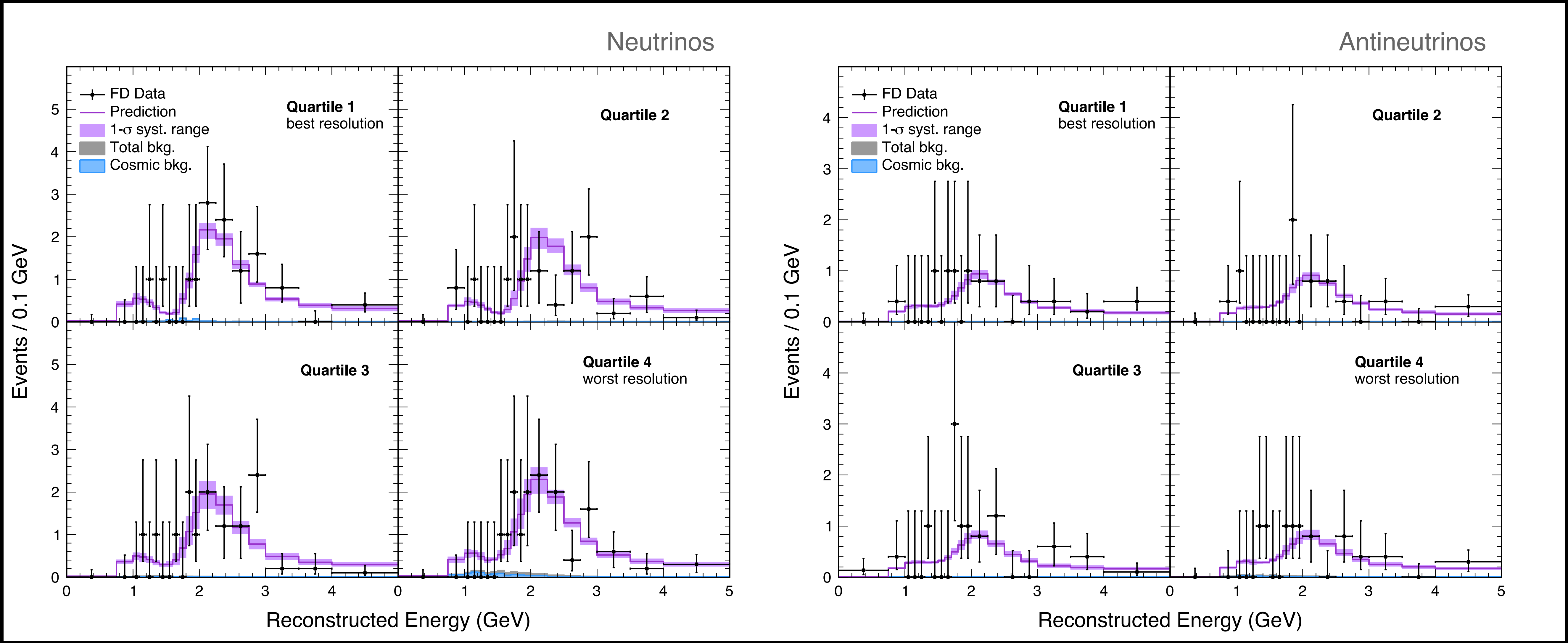




see poster #75

PREDICTING THE FD OBSERVATION

- Each quartile for the neutrino and antineutrino beams gets unfolded independently and the true Far/Near ratio is used to obtain a FD prediction from ND data.
- Cosmic background rate estimates from the timing sidebands of the NuMI beam triggers and cosmic trigger data.



see poster #66 and 88

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 the χ^2s are consistent with the combined fit oscillation parameters with $p > 4\%$.

	Neutrino mode ν_μ	Antineutrino mode $\bar{\nu}_\mu$
Expected signal	122.62	51.40
Expected background (NC, beam, cosmics)	1.19, 0.51, 2.07	0.39, 0.23, 0.46
Observation	113	65

see poster #66 and 88

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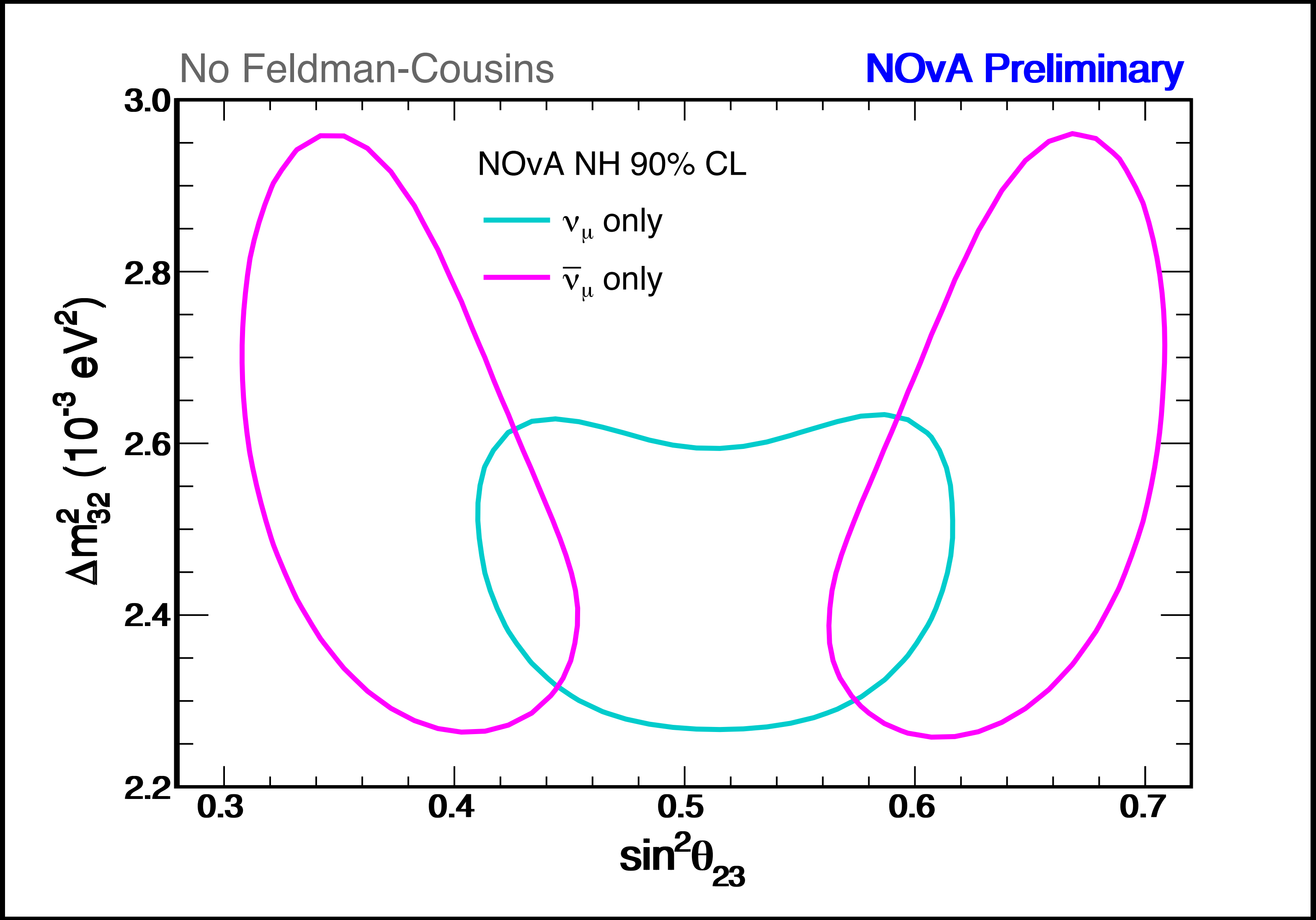

see poster #66 and 88

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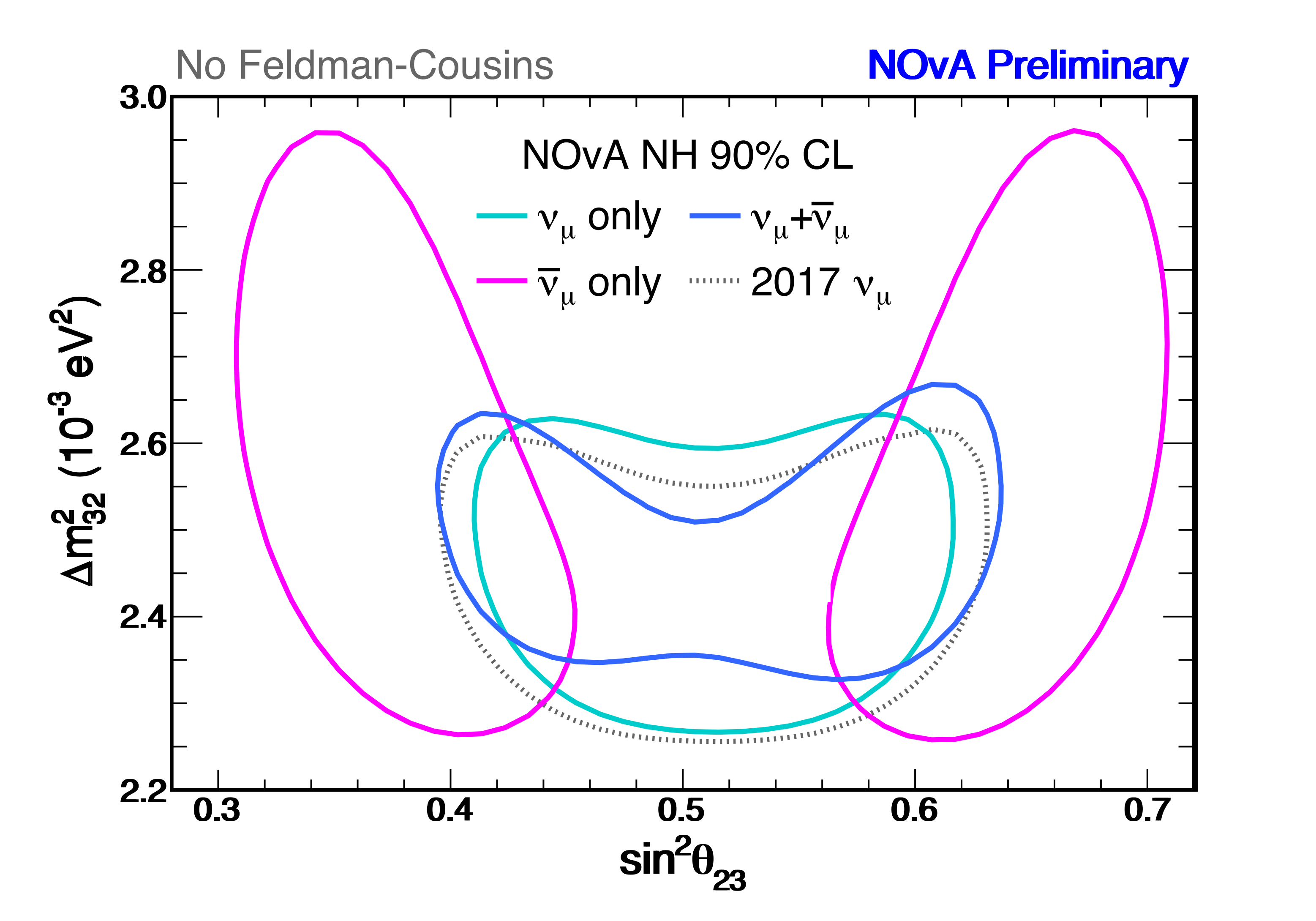
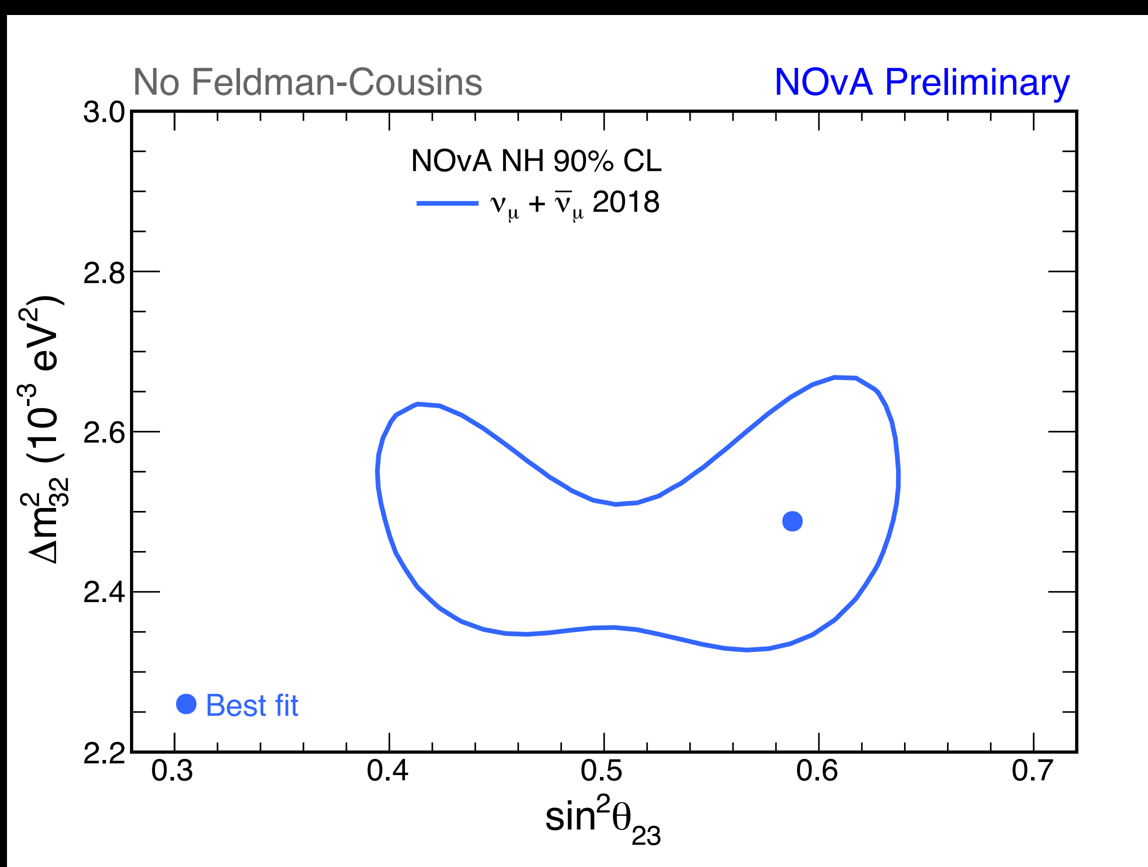
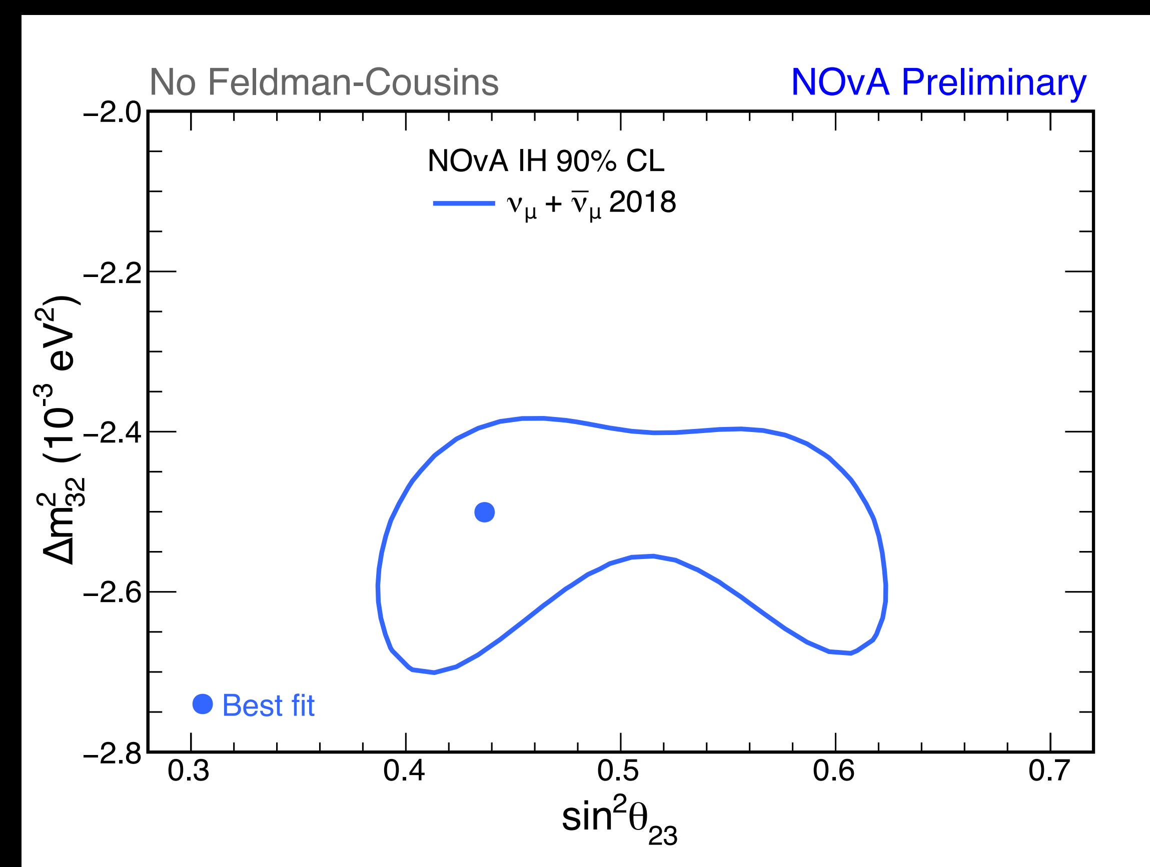


see poster #66 and 88

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 favors (at the 1 σ level) upper octant (UO) for normal hierarchy (NH) and lower octant (LO) for inverted hierarchy (IH).
    - 1.5% probability of this happening for true octant, 0.5 in the false octant.

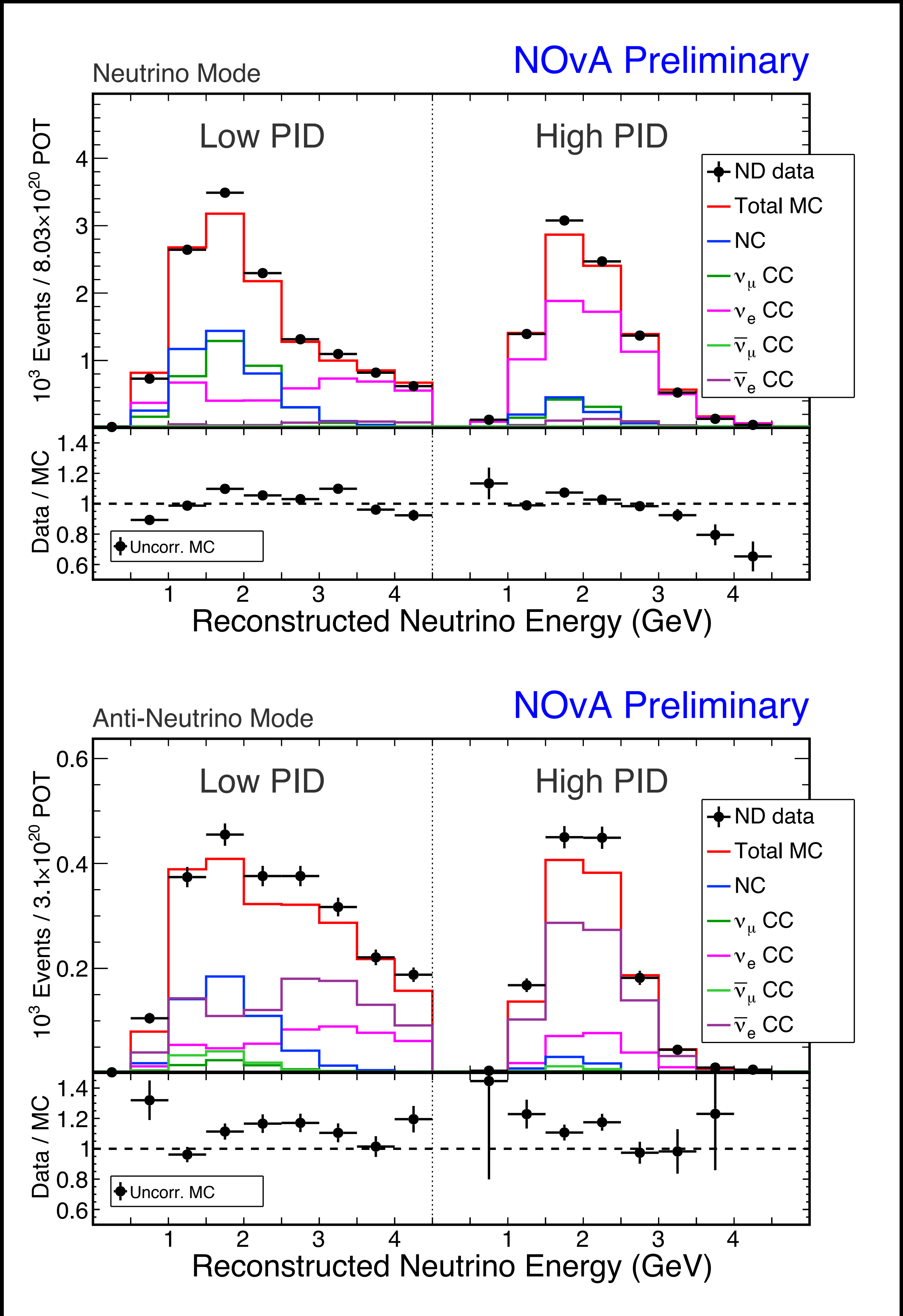




see poster #79

NEAR DETECTOR ELECTRON NEUTRINO DATA

- Select electron neutrino events using particle ID in the ND for each beam mode.
  - Separate into low and high particle ID (purity) range.
- For the neutrino beam constrain:
  - the beam electron neutrinos using the muon neutrino spectrum, and
  - the muon neutrino background using Michel electrons,
  - remaining data/MC discrepancy is assigned to the neutral current component.
- For the antineutrino beam, scale all components evenly to match the data.

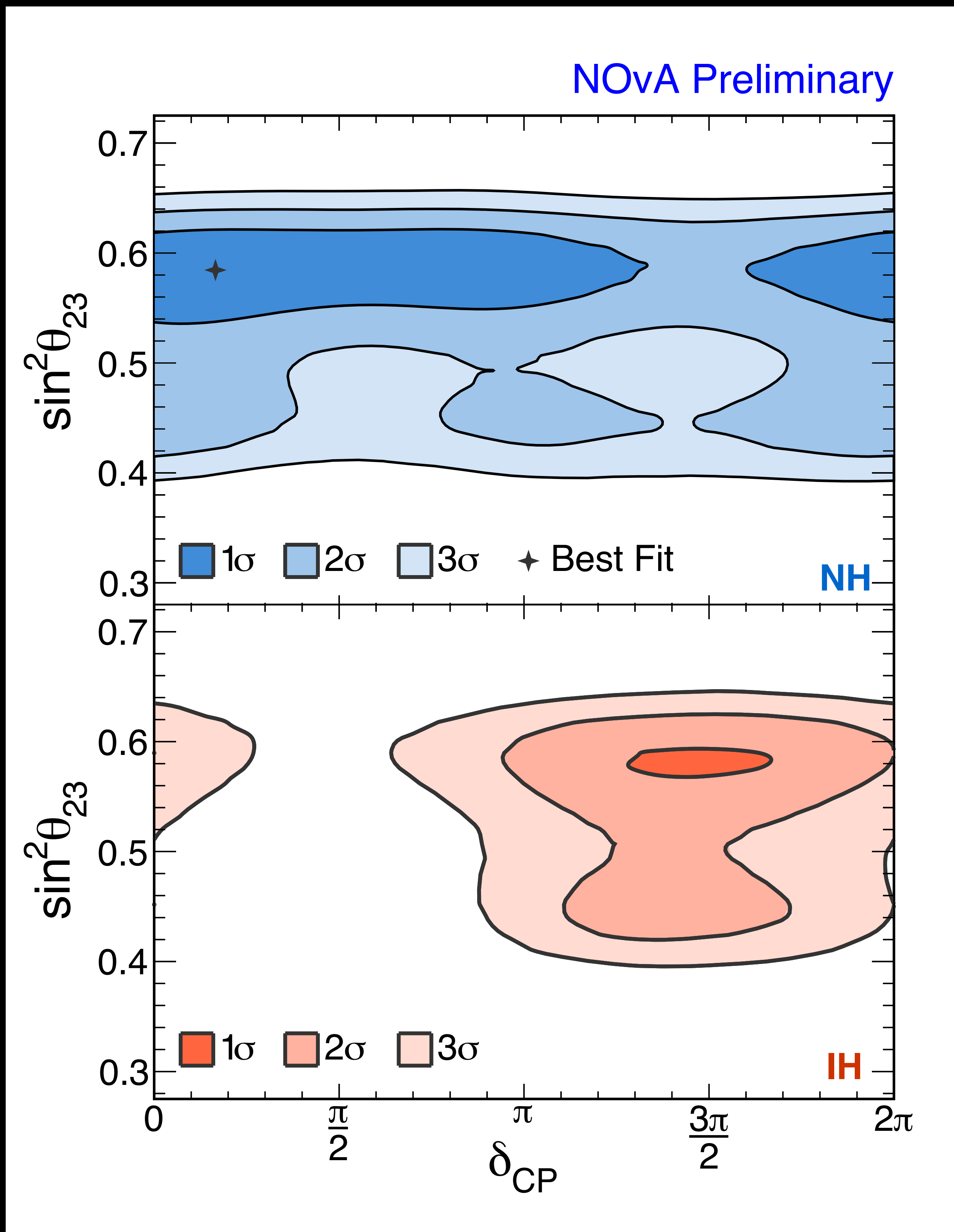


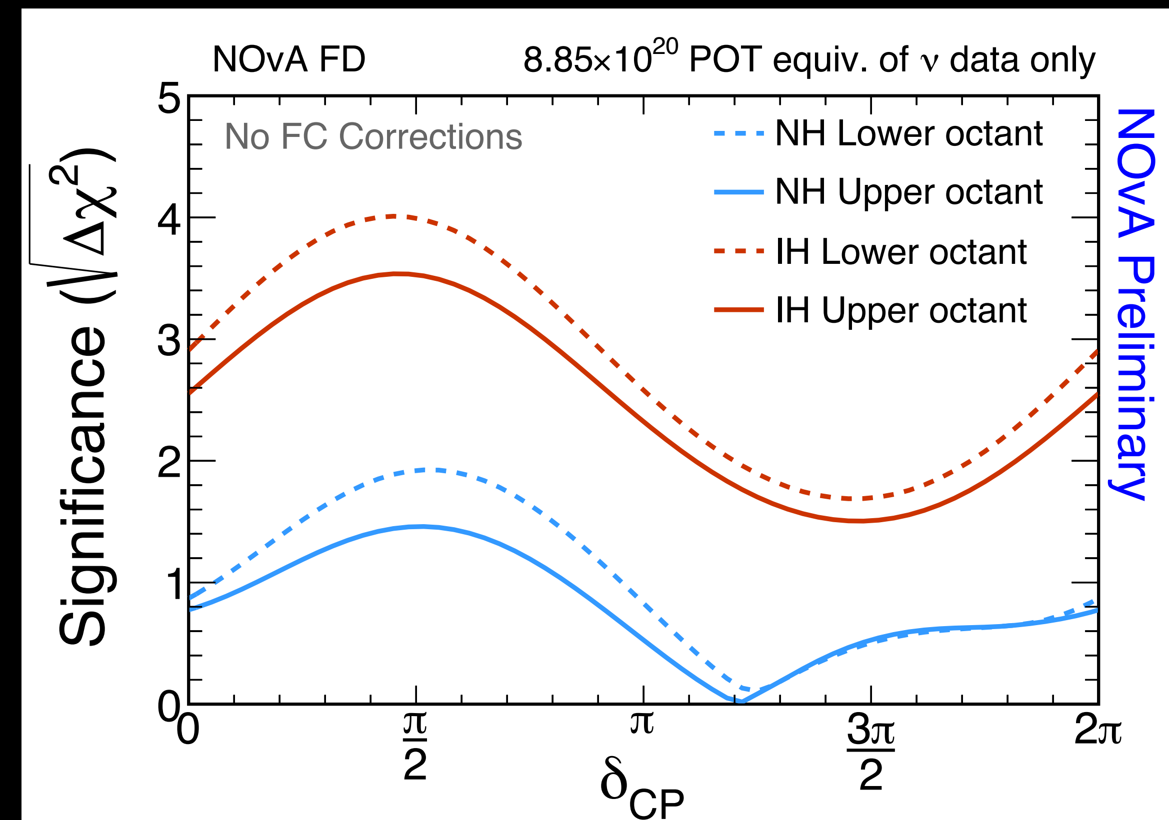
SYSTEMATIC UNCERTAINTIES

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

- Improved systematic uncertainties. Most significant uncertainties are coming from calibration, cross sections, and neutron uncertainty. However, we are still statistics dominated.

ALLOWED OSCILLATION PARAMETERS

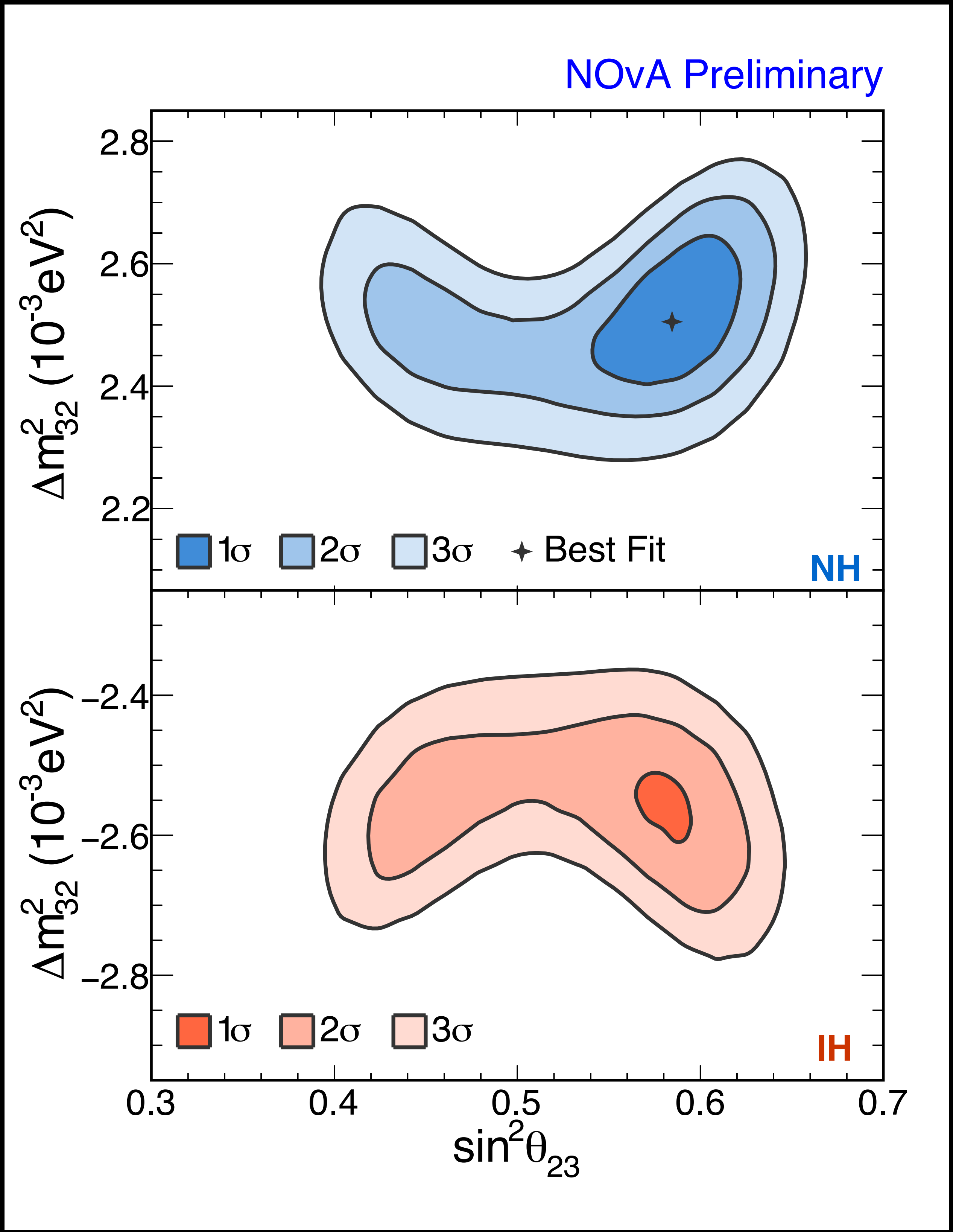


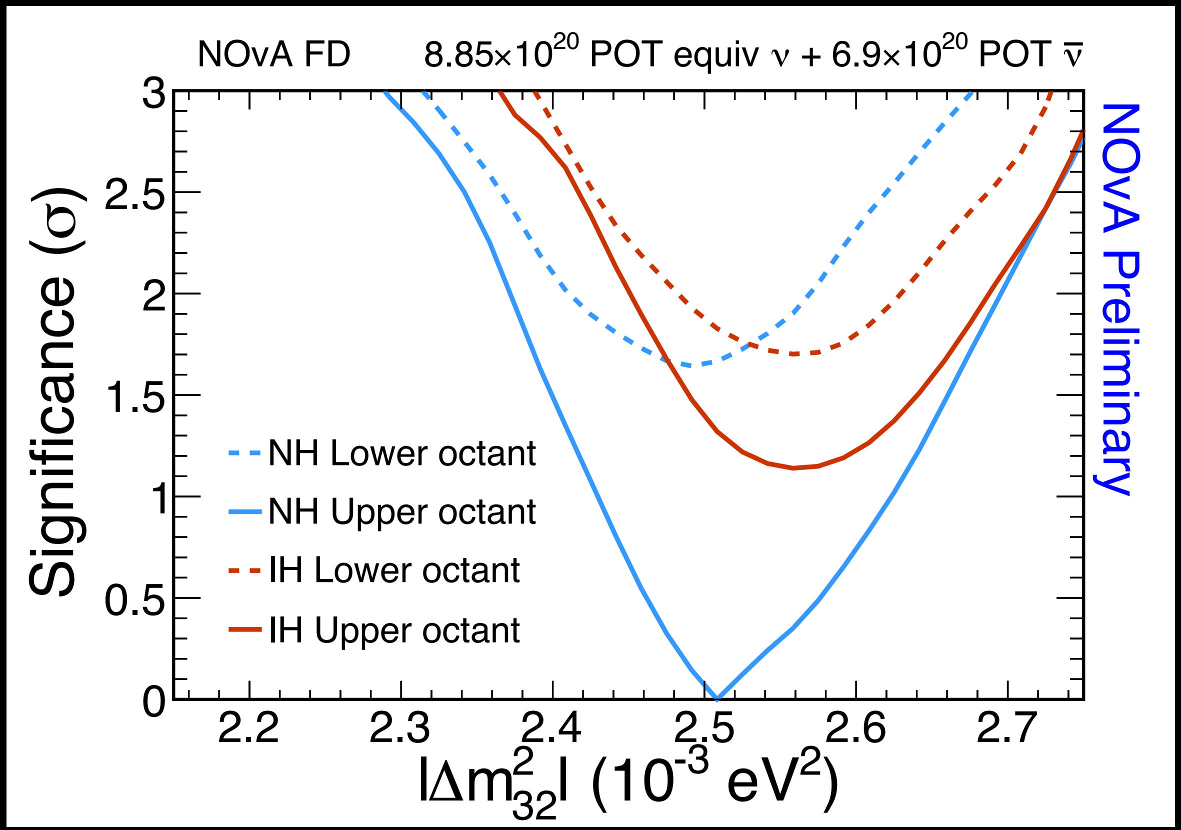


- Best fit: Normal Hierarchy
  $\delta_{CP} = 0.17\pi$
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2$

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

ALLOWED OSCILLATION PARAMETERS





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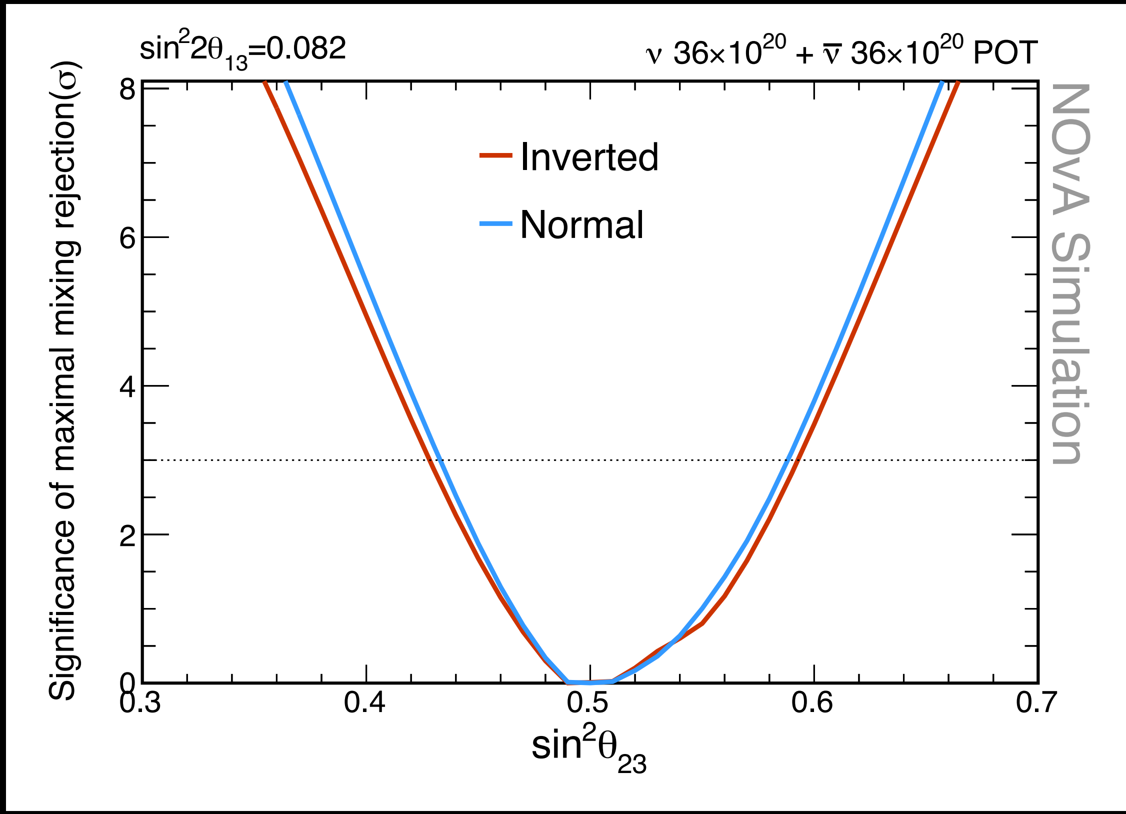
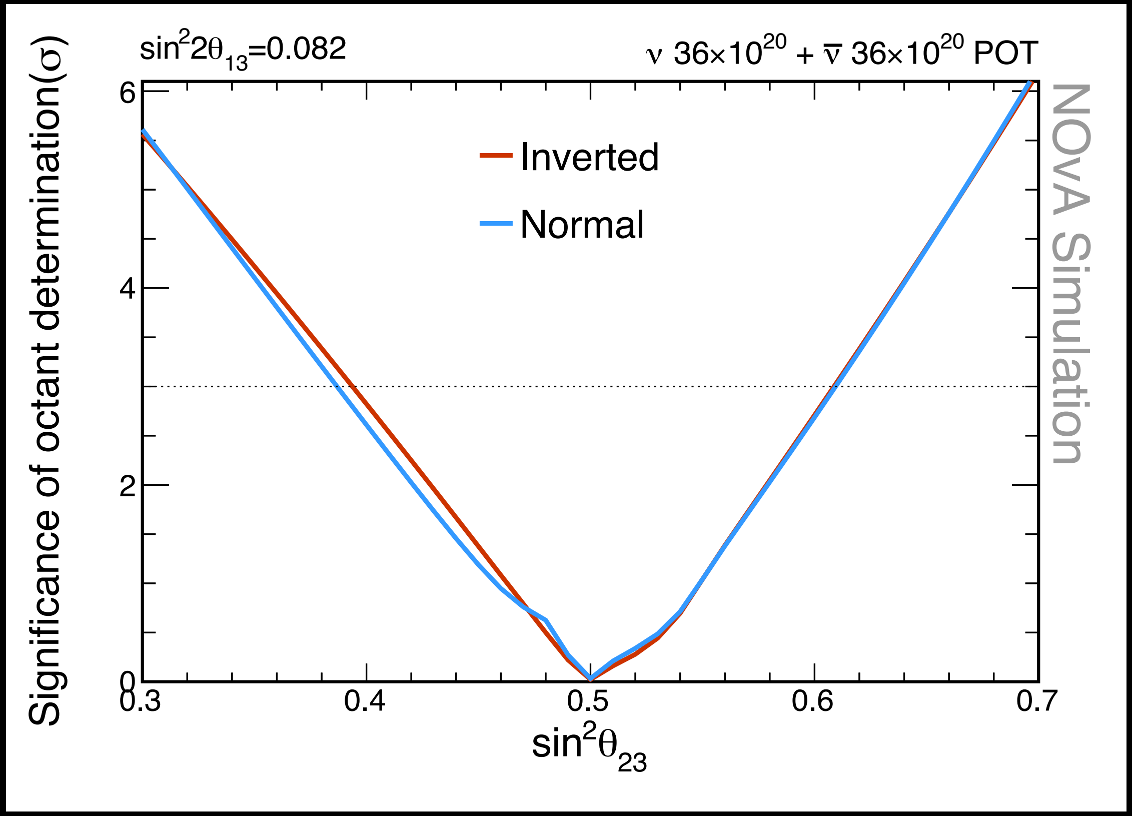
Prefer NH by 1.8σ
Exclude δ=π/2 in the IH at > 3σ

NOVA PROSPECTS

- Currently running anti-neutrino beam. Run 50% neutrino, 50% anti-neutrino after 2018.
- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach.
- 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.





CALIBRATION AND THE ABSOLUTE ENERGY SCALE

- Stopping muons provide a standard candle for setting absolute energy scale.
- Several samples demonstrate successful energy scale calibration:
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
  - **π^0 mass**
  - **hadronic shower energy/hit**

ALL SAMPLES AGREE WITHIN ±5%