Deep Inelastic Scattering Impact on NOvA

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NUSTEC Workshop on DIS

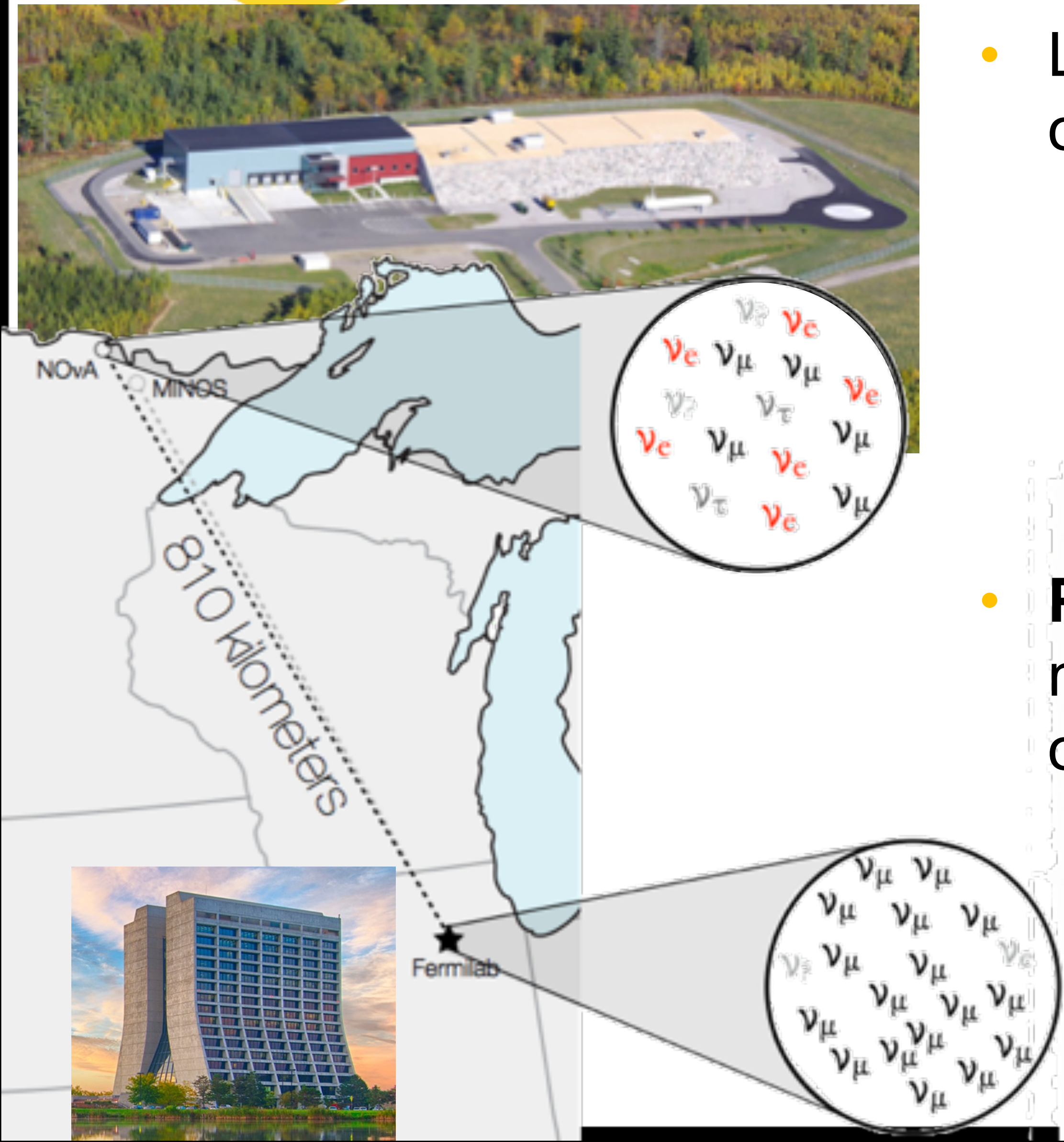
Thursday, Oct. 11th, 2018

Wichita State University

Overview

- NOvA Oscillation measurements.
- Focus on Impact of DIS.
  - Jeremy Wolcott will speak more broadly on XS model impacts in at NuInt
- Future efforts in NOvA to explore the DIS region.
  - L. Aliaga and M. Judah will present updates and results from the NOvA XS measurement effort at NuInt.

The NOvA Experiment



- 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:
  - $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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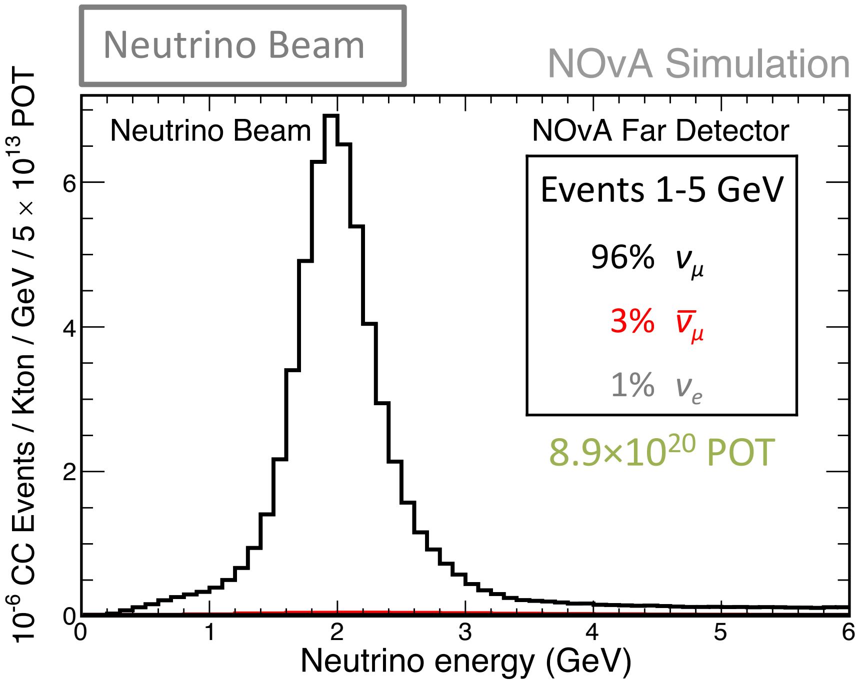
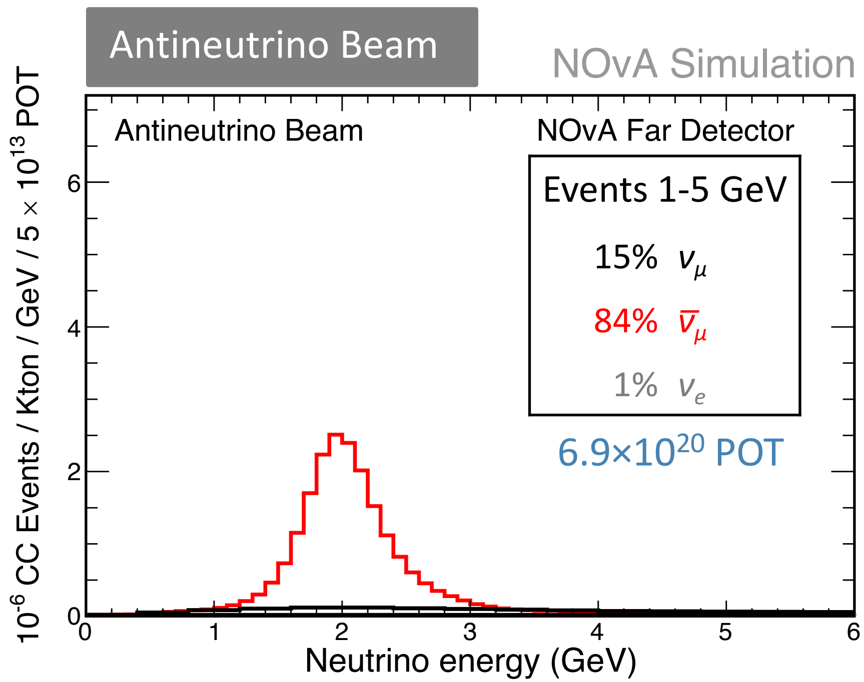
CC Interaction Spectrum in NuMI

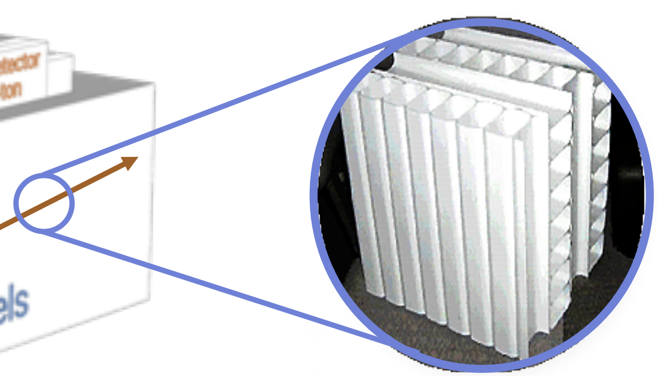




- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
- Cross section for antineutrinos is **~2.8 times lower** than for neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.

NOvA Detectors

- Far detector is 14 ktons, sits at the surface in Minnesota
- Near detector is 290 tons placed 300 ft underground at Fermilab.
- Functionally identical
  - Consist of plastic cells filled with liquid scintillator
  - Arranged in alternating directions for 3D reconstruction
  - Light collected by WLS Fiber and readout by APD



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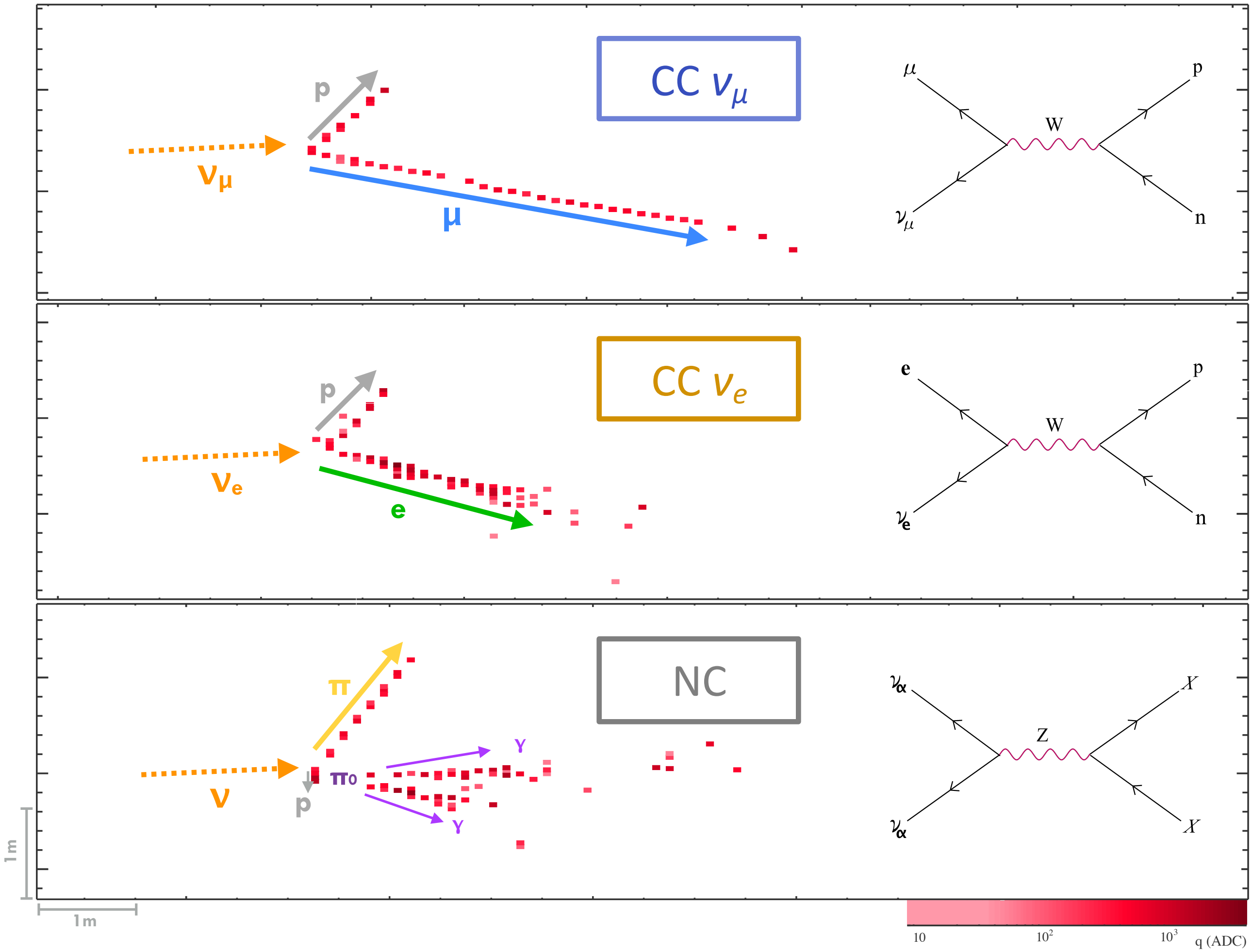
Neutrino Candidates from ND Data



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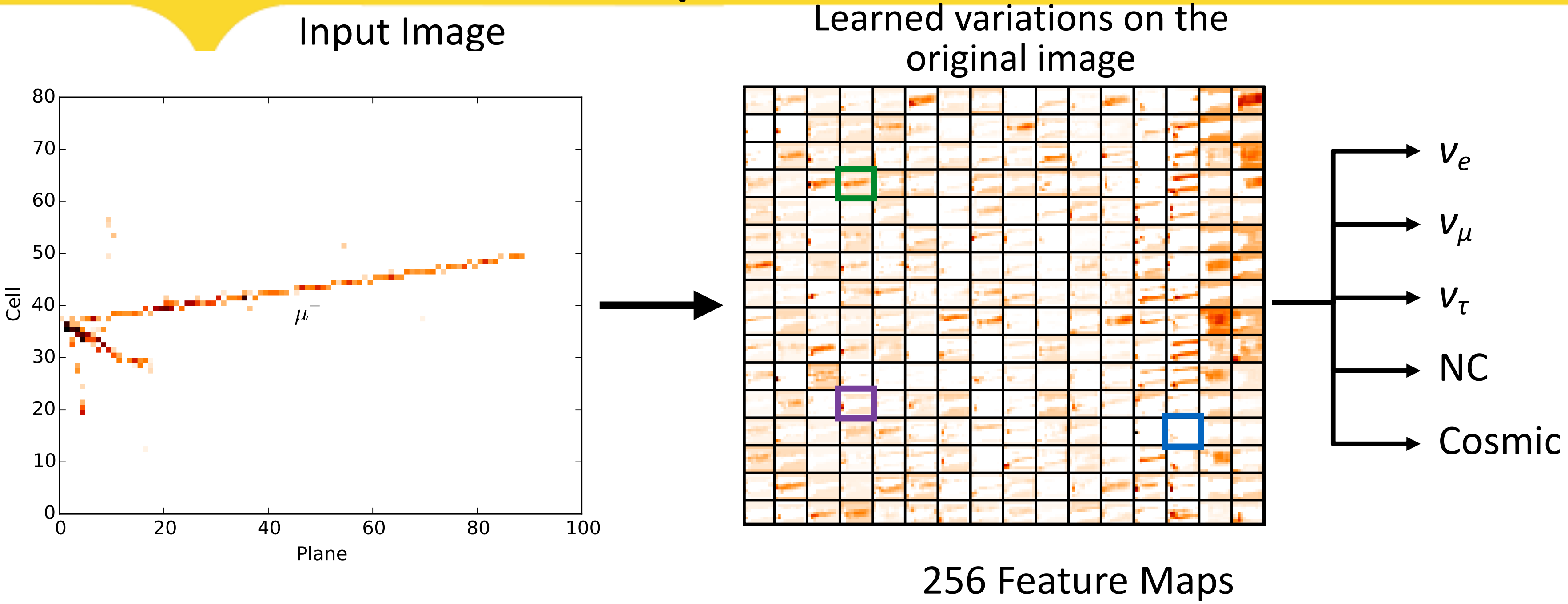
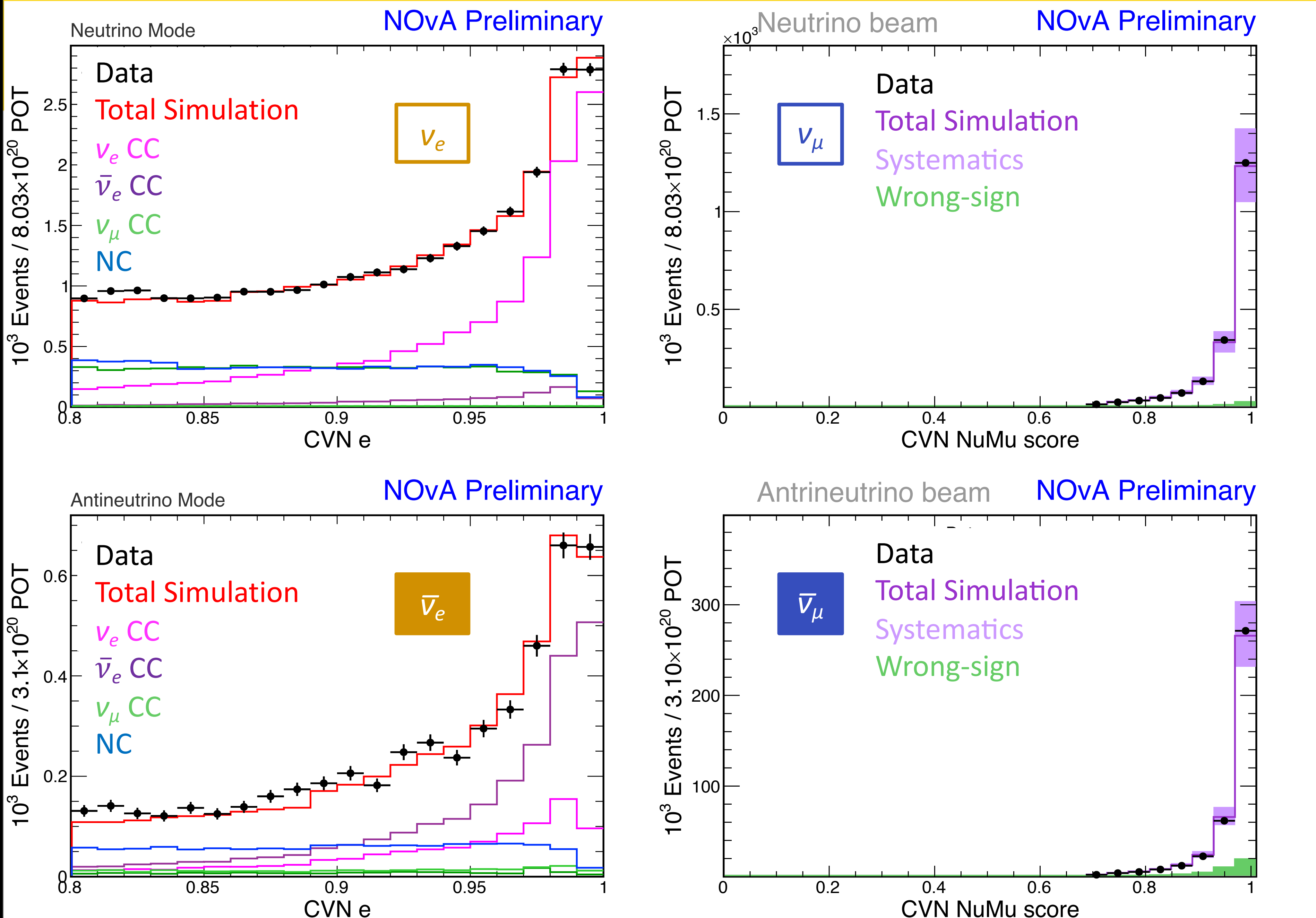
Selecting ν_e's and ν_μ's with Computer Vision



- We use a *convolutional neural network* based on the GoogLeNet.
  - "Feature maps" create variants of the original image which enhance different features.
- Multi-label classifier – the same network used in multiple analyses – based on GENIE final state labels
- Separate training for the neutrino and antineutrino beams.

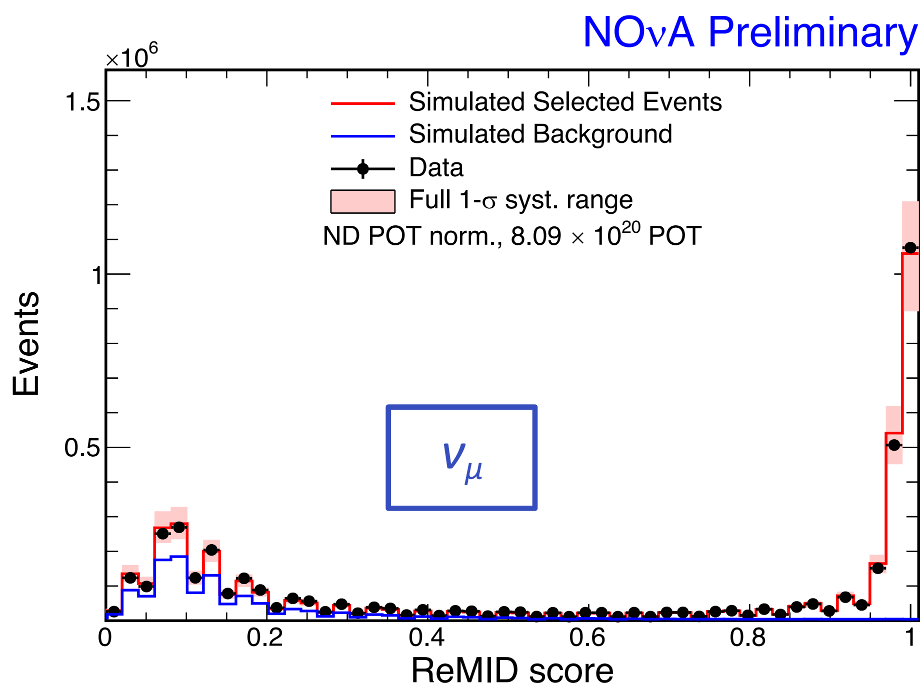
*A. Aurisano and A. Radovic and D. Rocco et. al, JINST **11** P09001 (2016)*



Neutrino Mode
NOvA Preliminary
Data
Total Simulation
ν_e CC
$\bar{\nu}_e$ CC
ν_μ CC
NC
ν_e
10^3 Events / 8.03×10^{20} POT
CVN e
Neutrino beam
NOvA Preliminary
$\times10^3$
Data
Total Simulation
Systematics
Wrong-sign
ν_μ
10^3 Events / 8.03×10^{20} POT
CVN NuMu score
Antineutrino Mode
NOvA Preliminary
Data
Total Simulation
ν_e CC
$\bar{\nu}_e$ CC
ν_μ CC
NC
$\bar{\nu}_e$
10^3 Events / 3.1×10^{20} POT
CVN e
Antrineutrino beam
NOvA Preliminary
Data
Total Simulation
Systematics
Wrong-sign
$\bar{\nu}_\mu$
10^3 Events / 3.10×10^{20} POT
CVN NuMu score

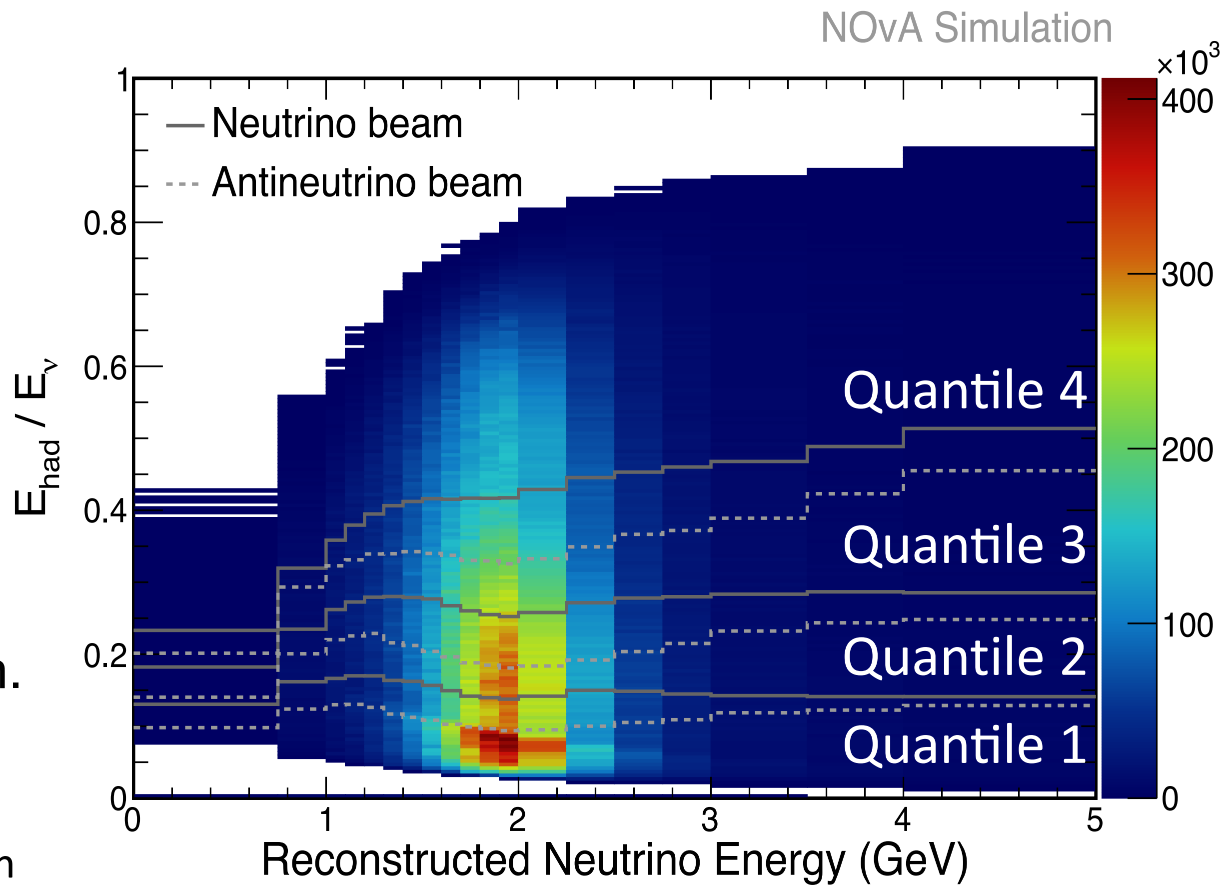
Additional Selections

- Some basic additional cuts: Contained, fiducial events, well-reconstructed, reasonable energy range, cosmic rejection at FD.
- An additional ***ν_μ* requirement**: **a track identified as a muon (ReMID>0.7)**.
  - 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



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%).

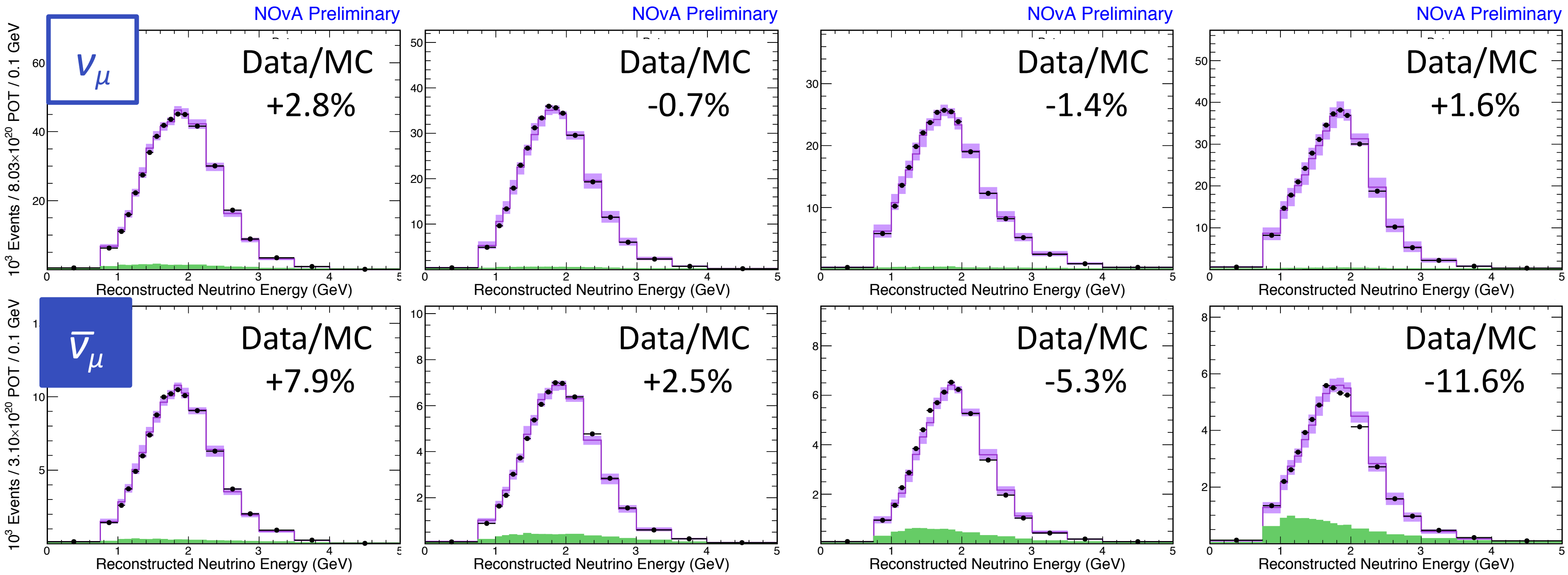


Binning for Sensitivity: ν_μ Events

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

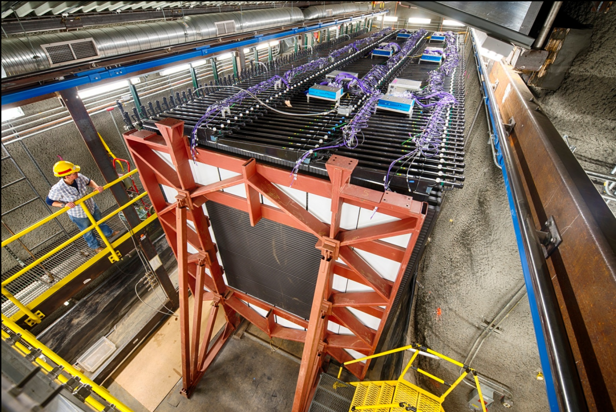
Quantile 1
Best Resolution ~6%

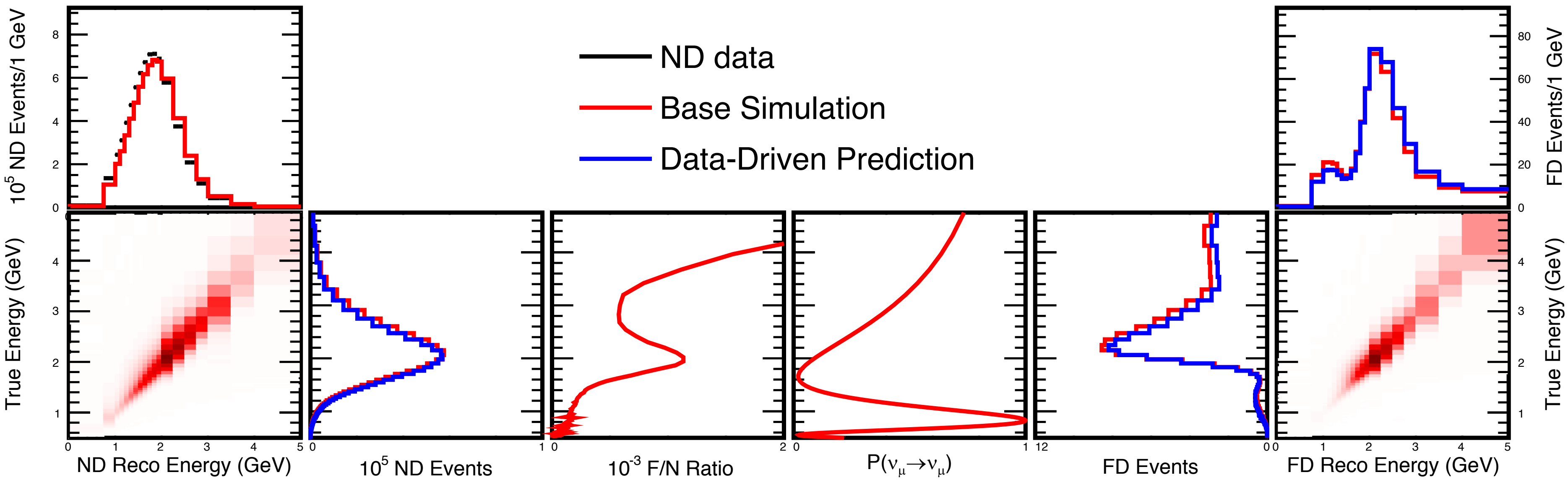
Quantile 4
Worst Resolution ~12%



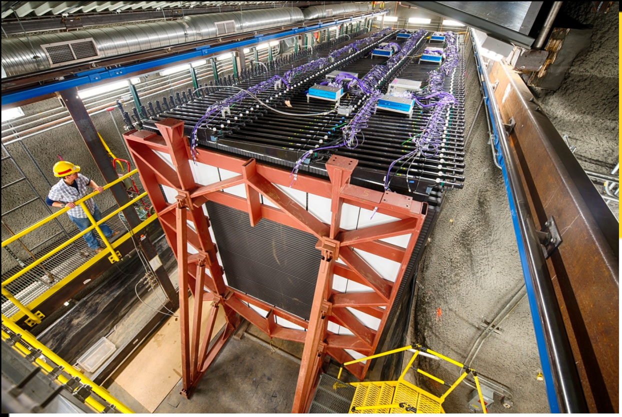
- Data-MC shape agreement good within each quantile.
- Extrapolate each separately.

Extrapolating from Near to Far

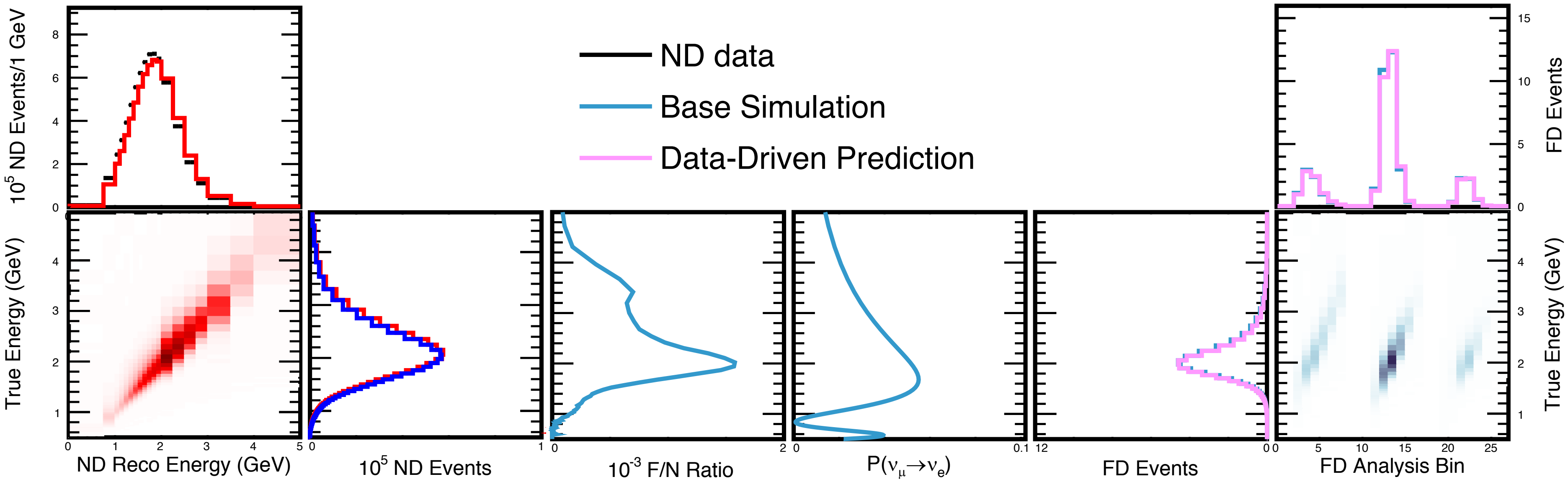




- Use the ND ν_μ sample to predict the FD ν_μ sample.

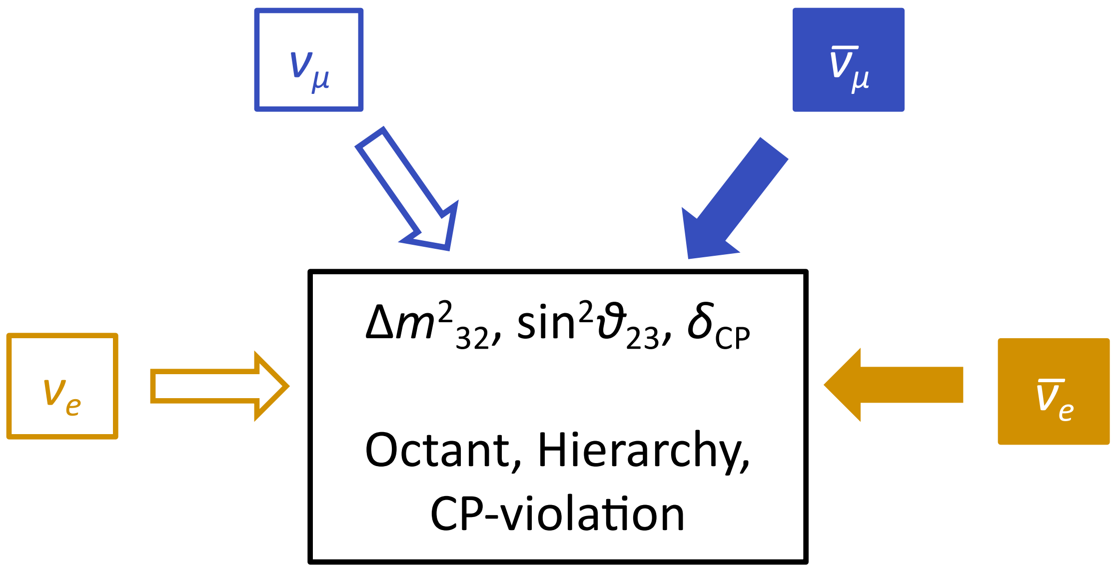


Extrapolating from Near to Far

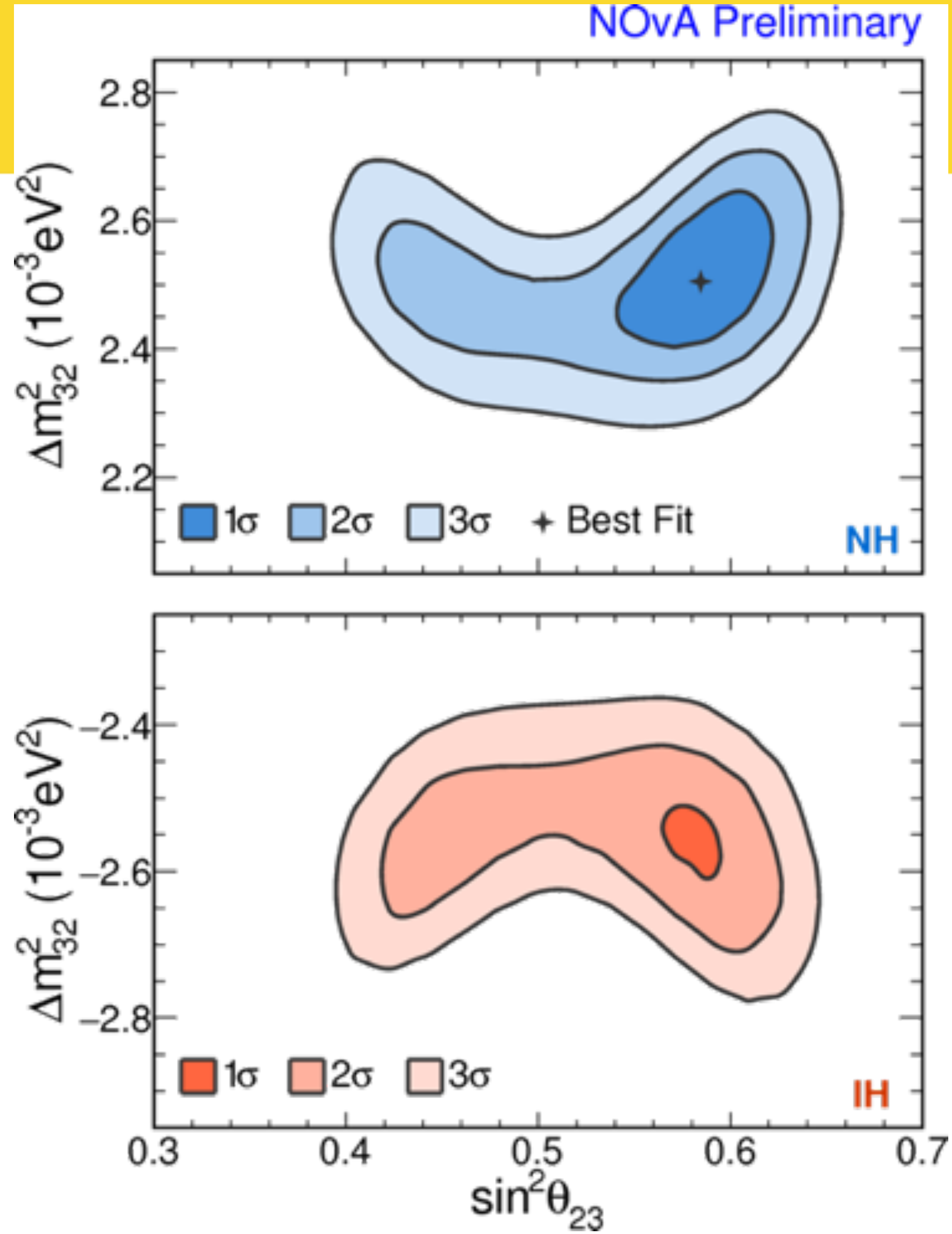


- Use the ND ν_μ sample to predict the FD ν_μ sample.
- Use the ND ν_μ sample to predict the FD ν_e signal.
- Use the ND ν_e-like sample to predict the FD ν_e backgrounds.

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 1D ranges are Feldman-Cousins corrected.
- $\sin^2 2\theta_{13}$ = 0.082 comes from the PDG average.



Best Fit

Normal hierarchy

Upper Octant

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

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

Best Fit

Normal hierarchy

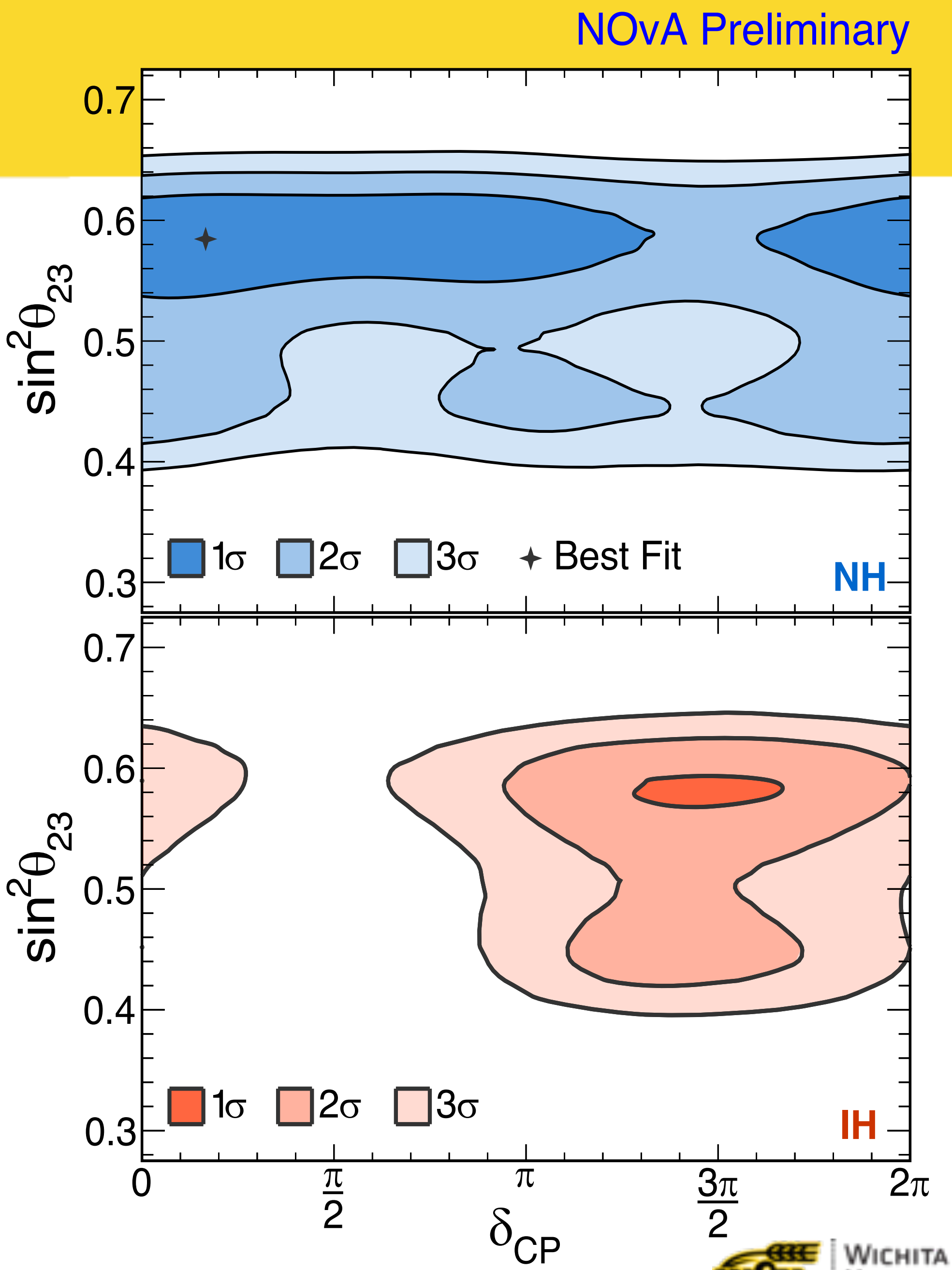
Upper Octant

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

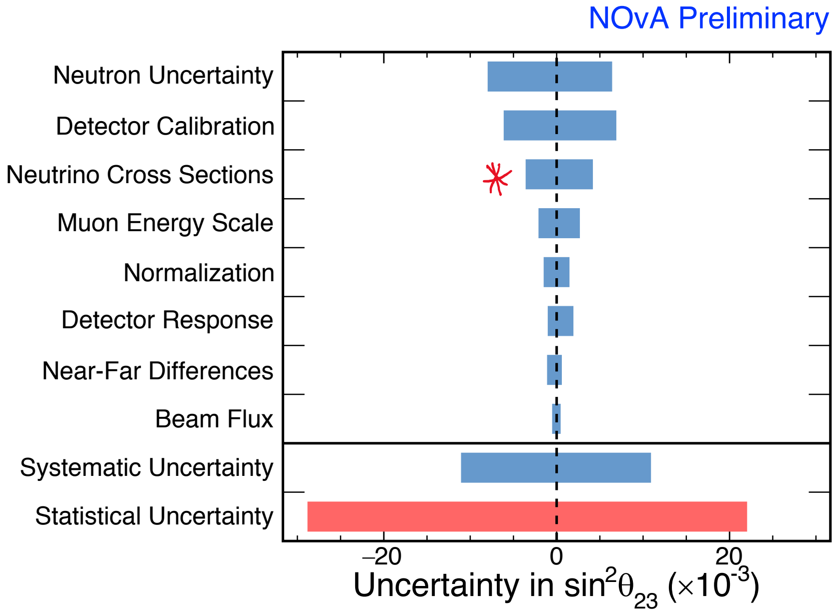
$\sin^2\theta_{23} = 0.58 \pm 0.03$

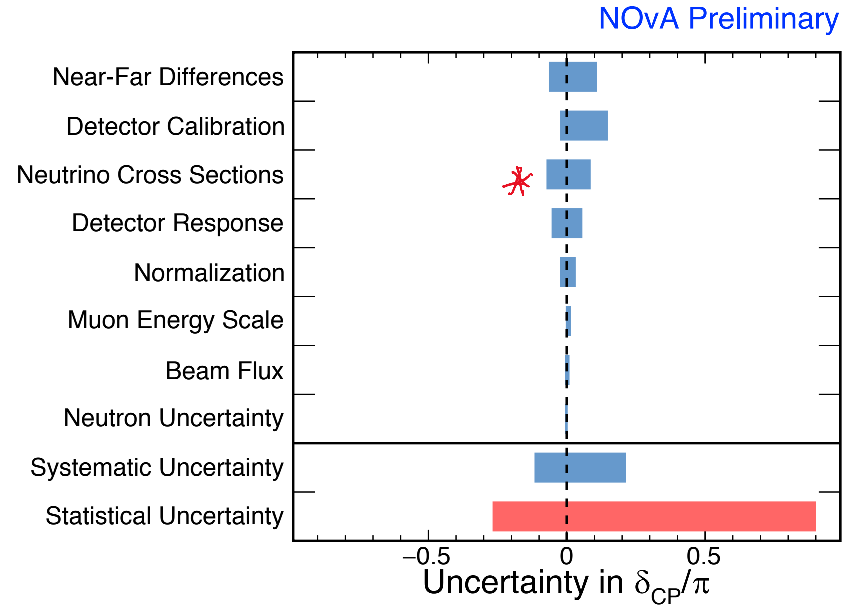
$\delta = 0.17\pi$

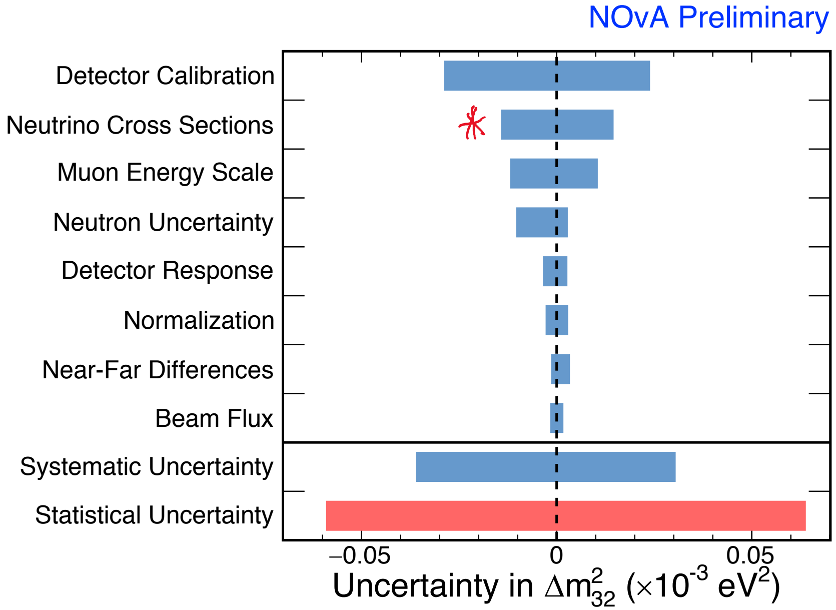
Exclude IH, $\delta=\pi/2$ at > 3σ



Systematic Uncertainties







Most important systematics:

- Detector Calibration
  - Will be improved by the 2019 test beam program
- Neutrino cross sections *
  - Particularly nuclear effects (RPA, MEC)
- Muon energy scale
- Neutron uncertainty – **new** with $\bar{\nu}$'s

GENIE Tuning

- NOvA used GENIE v2.12.2 for latest oscillation results.
- We tune our cross-section model primarily to account for **nuclear effects**.
  - We tune using a combination of **external theory** inputs and our own **ND data**.

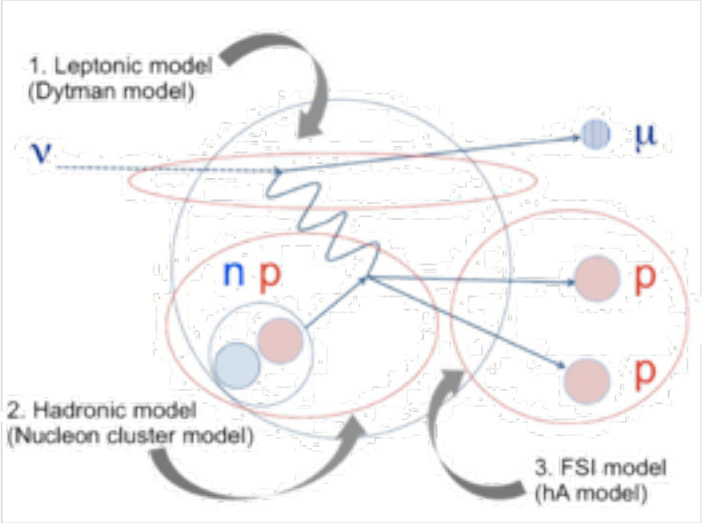
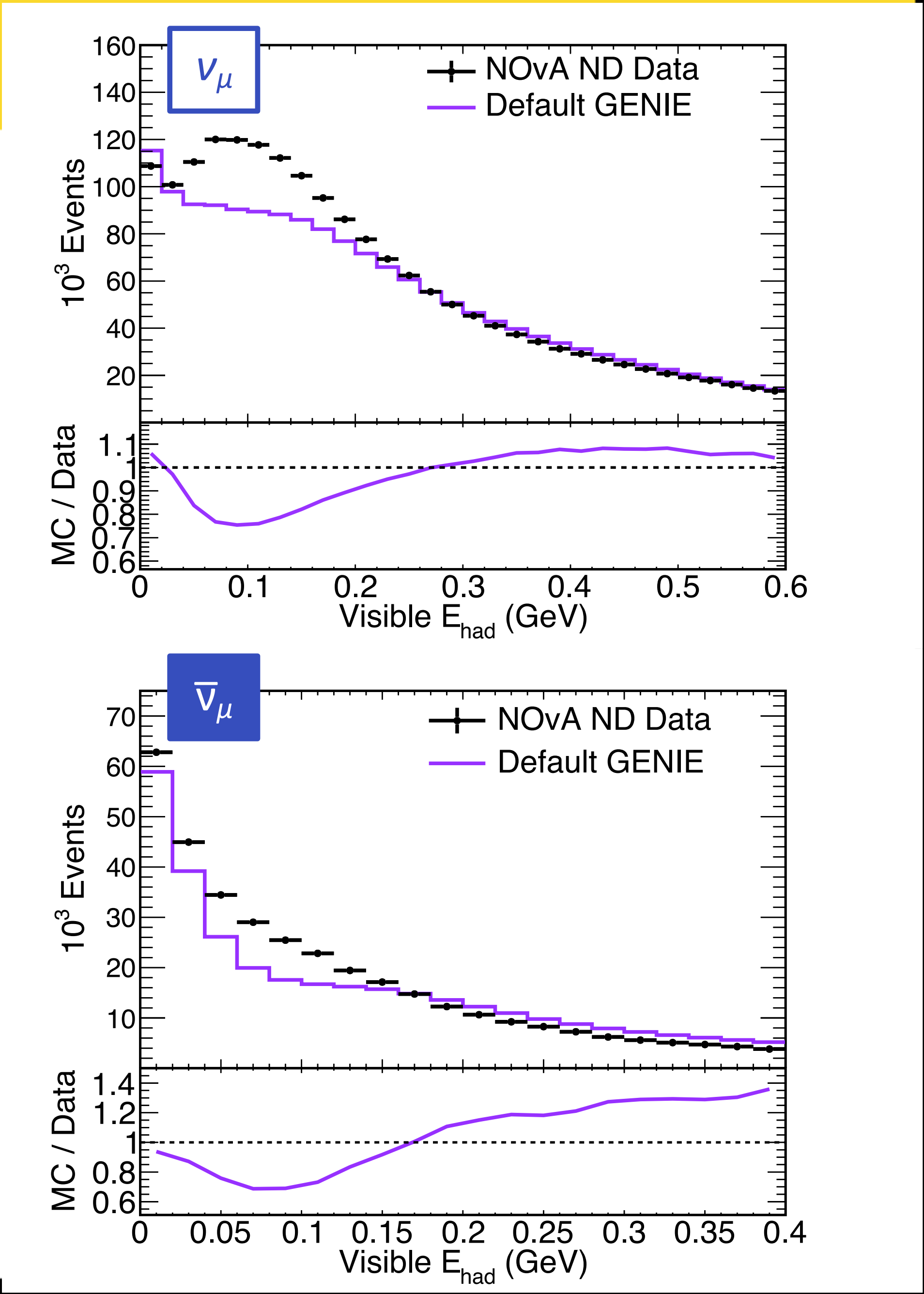


Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

GENIE Tuning

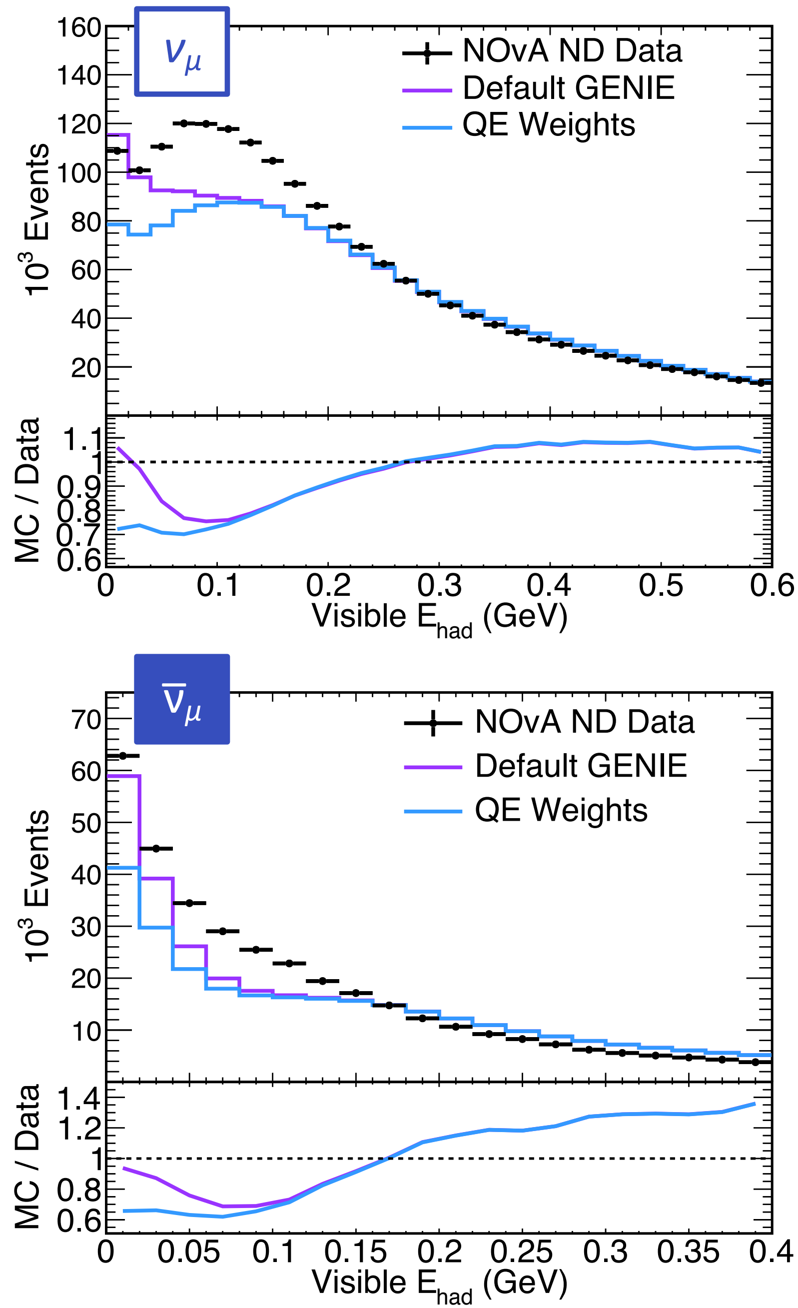


GENIE Tuning

From **external theory**:

- Valencia RPA model† of nuclear charge screening applied to QE. QE M_A moved from 0.99 -> 1.04.

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



GENIE Tuning

From **external theory**:

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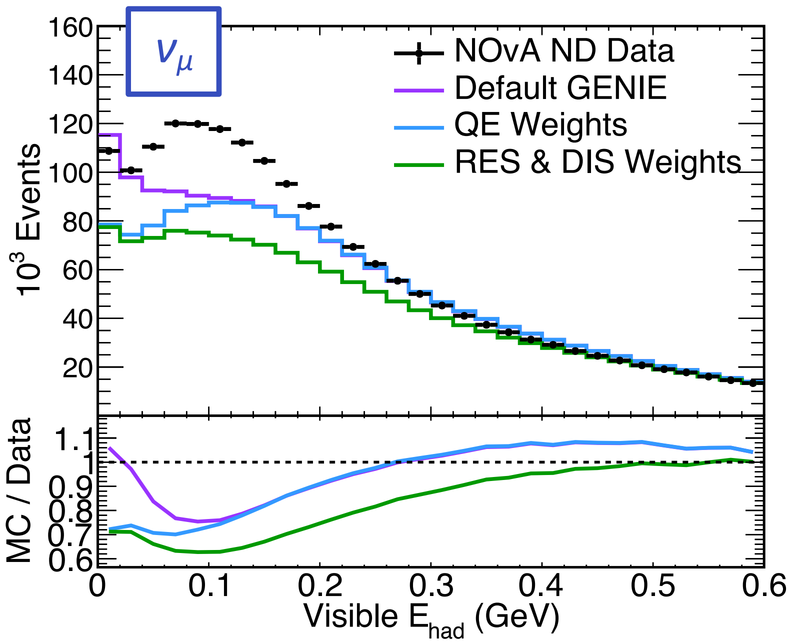
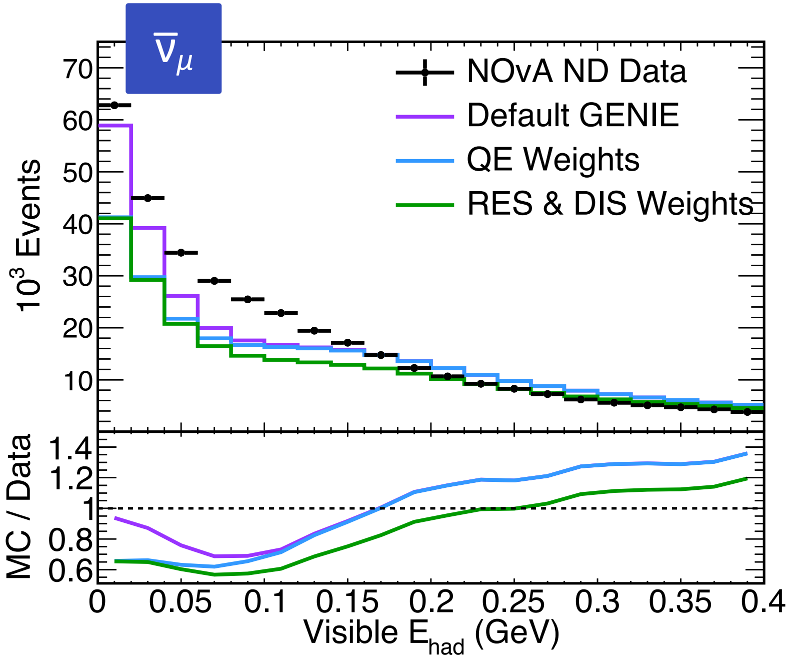
- Same model applied to resonance.
- Reduced the normalization non-resonant 1π production with W < 1.7 GeV by 57% **

** Rodrigues et al. [Eur.Phys.J. C76, 474]. Not for antineutrinos.

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.





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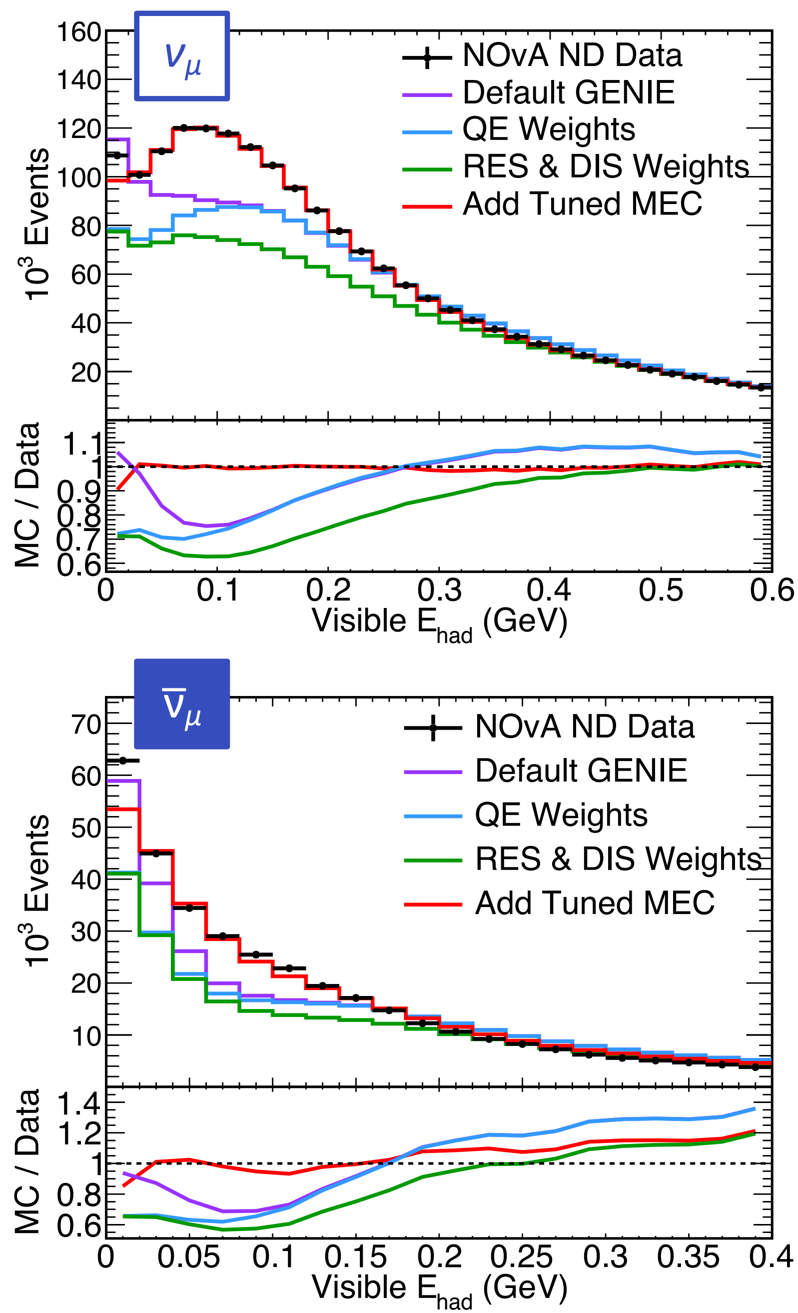
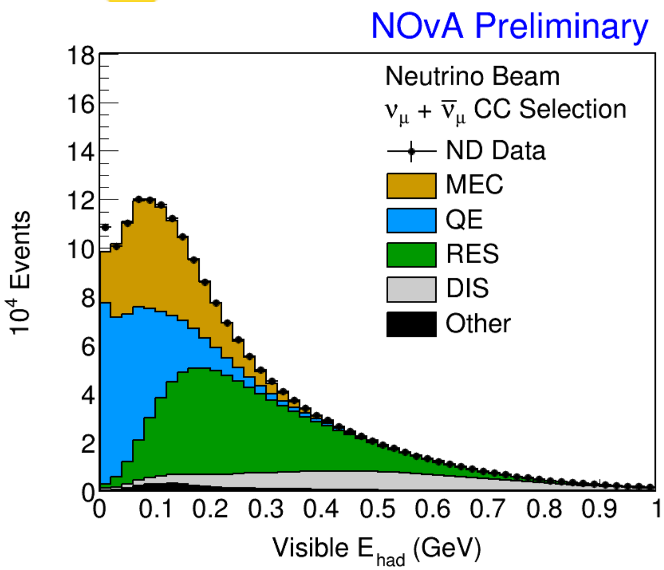
From **NOvA ND data**:

- 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 $\nu / \bar{\nu}$

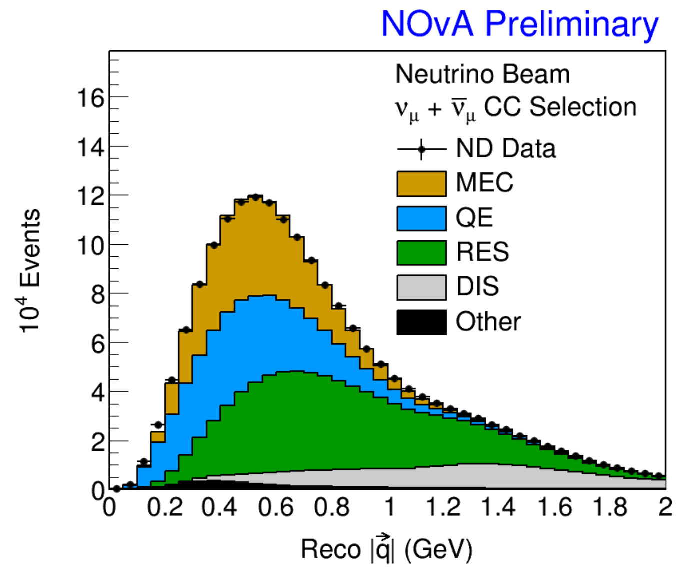


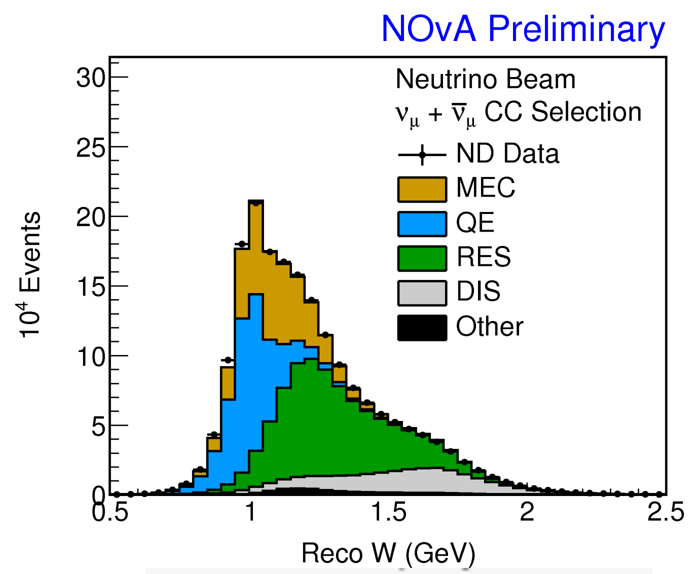
* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

FHC Tune



- Good agreement between MC and data in general.
- DIS has significant impact at high visible E_{had}.
- W distributions do not include the high-W DIS correction.
- Most DIS is in the “transition” regions.





$$W = (M_p^2 + 2 * M_p * E_{had} - Q^2)^{\frac{1}{2}}$$

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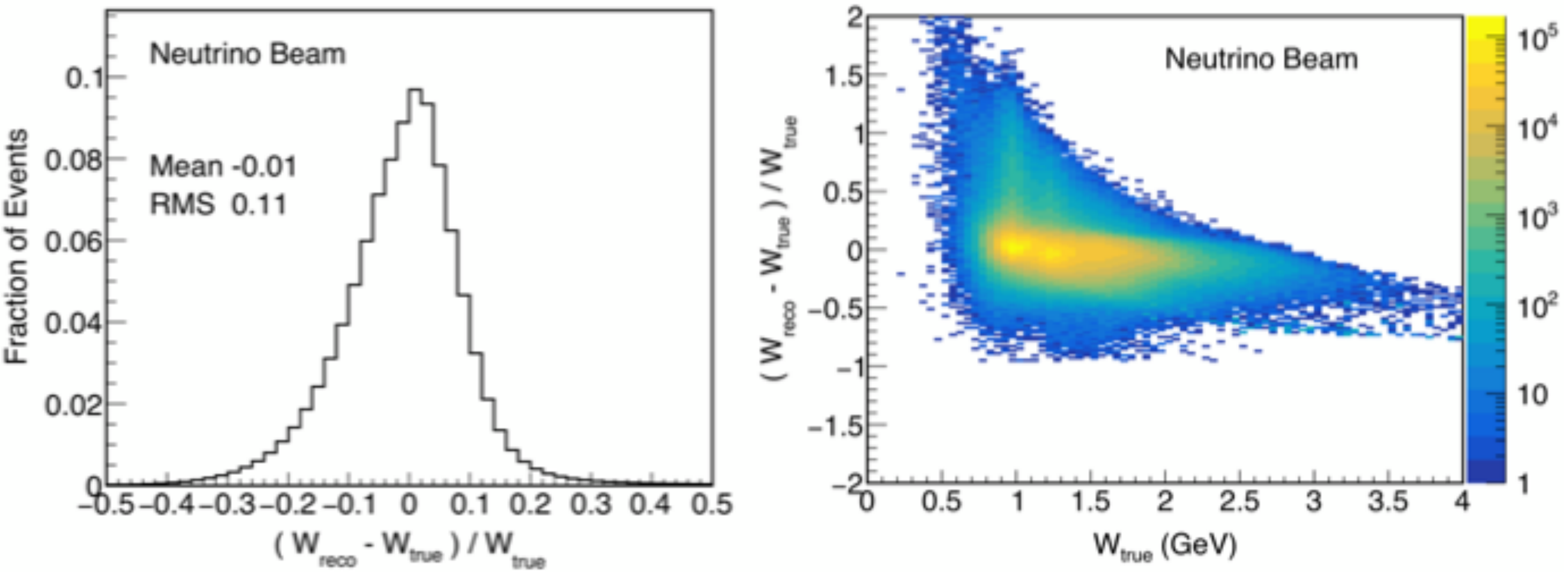
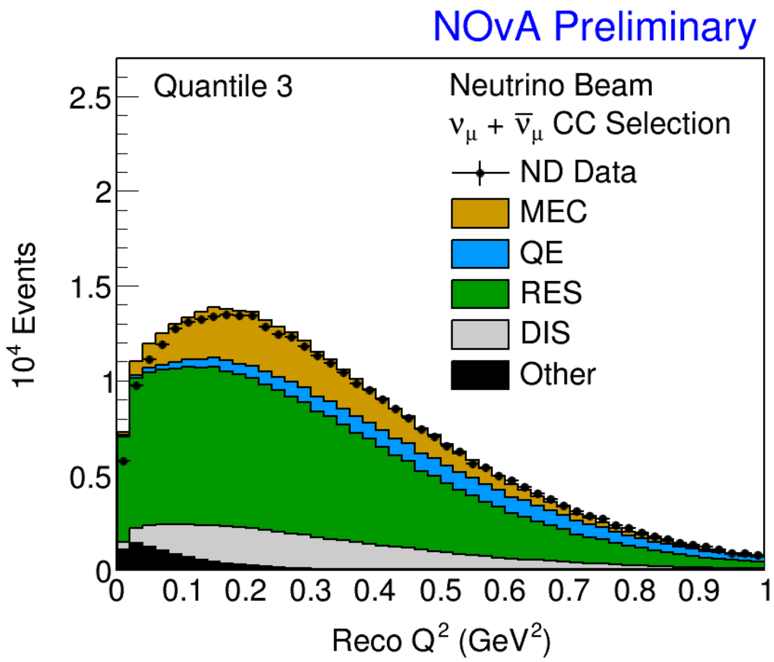
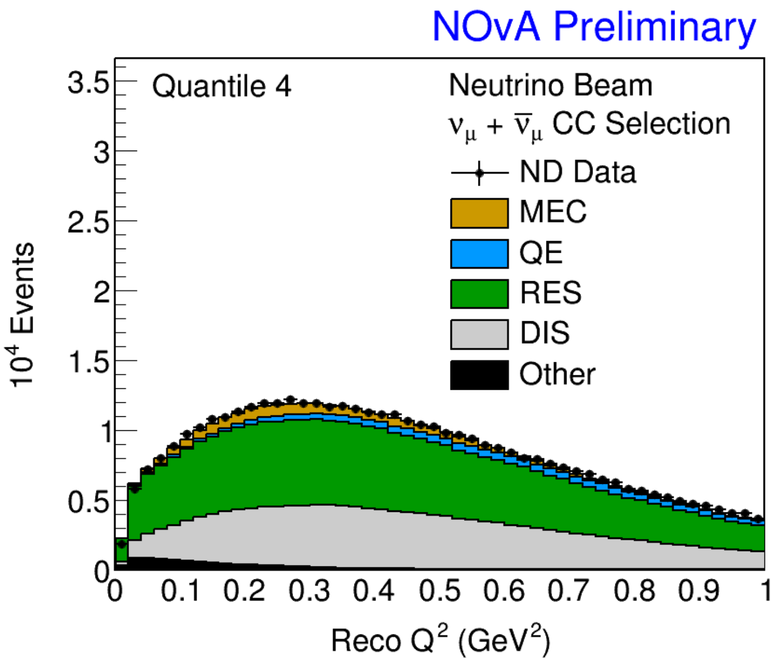
FHC W Resolution



- 10% W Resolution.
- Small bias across W.
- Resolution larger in QE/RES region.

FHC Tune In DIS Enhanced Quartiles





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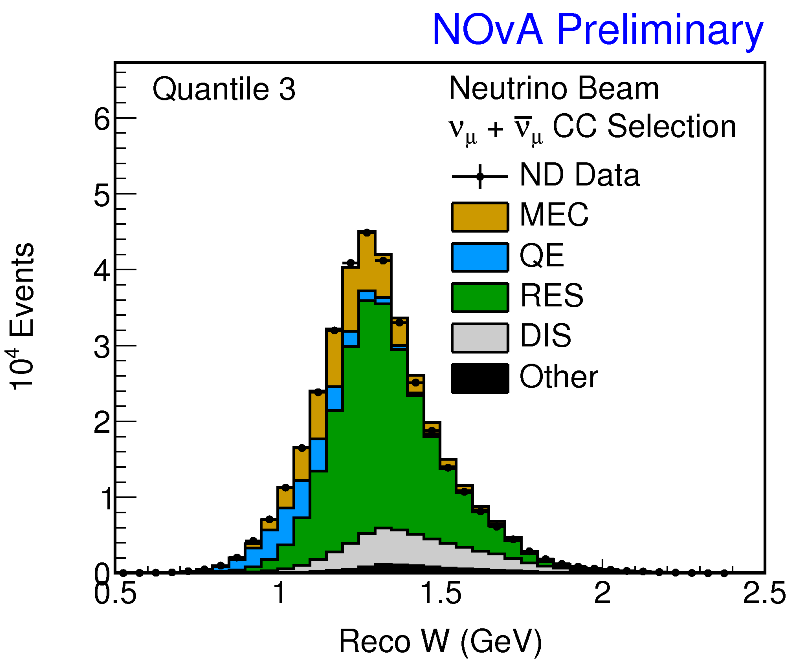
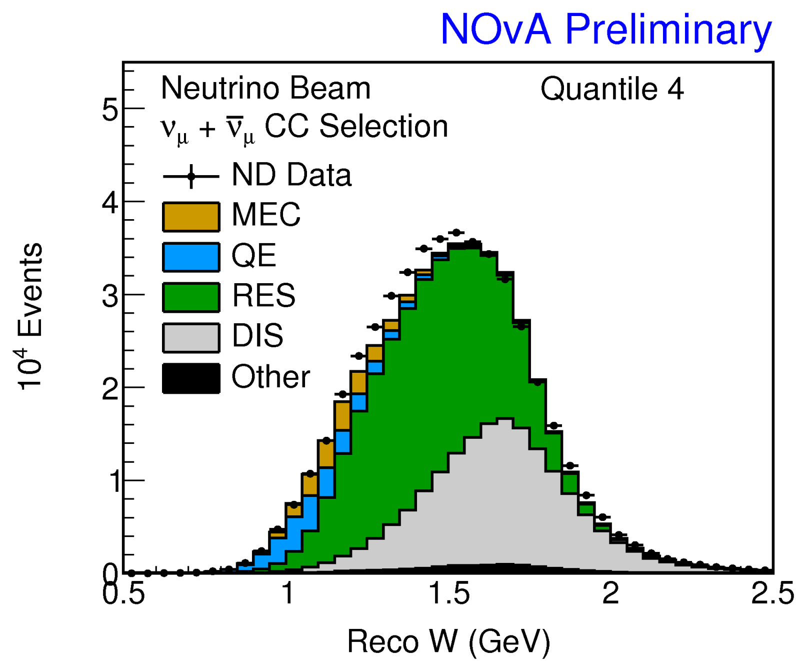
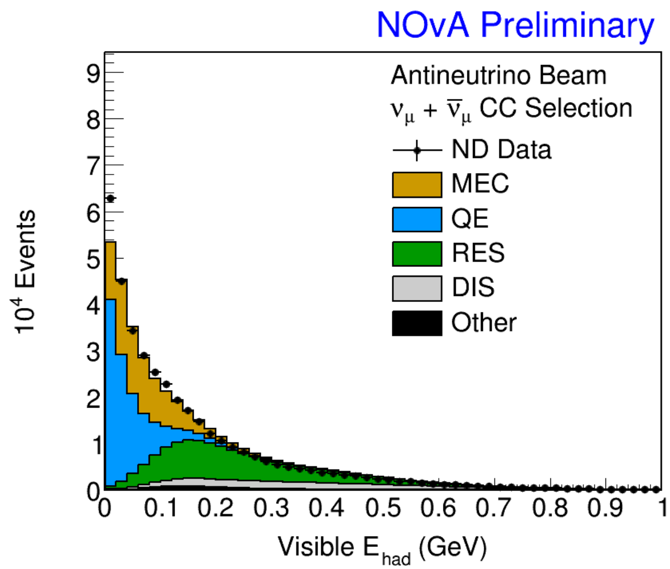


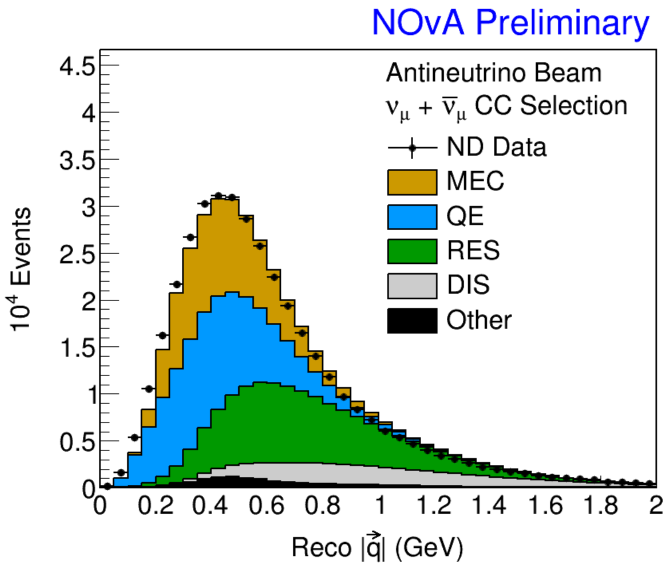


- RES and DIS are fairly muddled together in NOvA

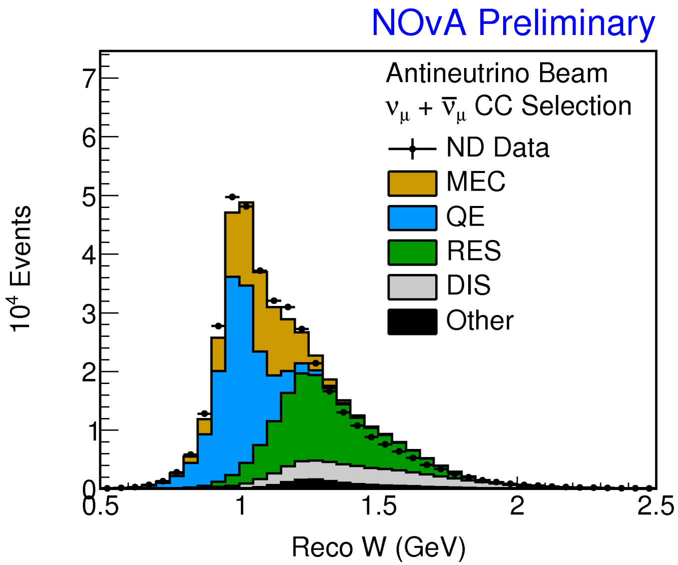
RHC Tune



NOvA Preliminary
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Visible E_{had} (GeV)

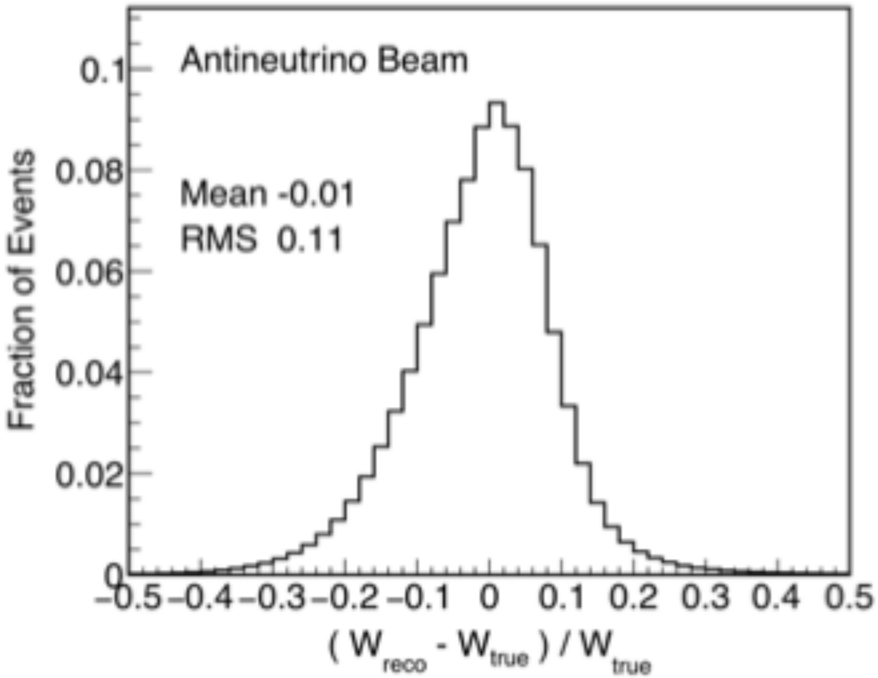


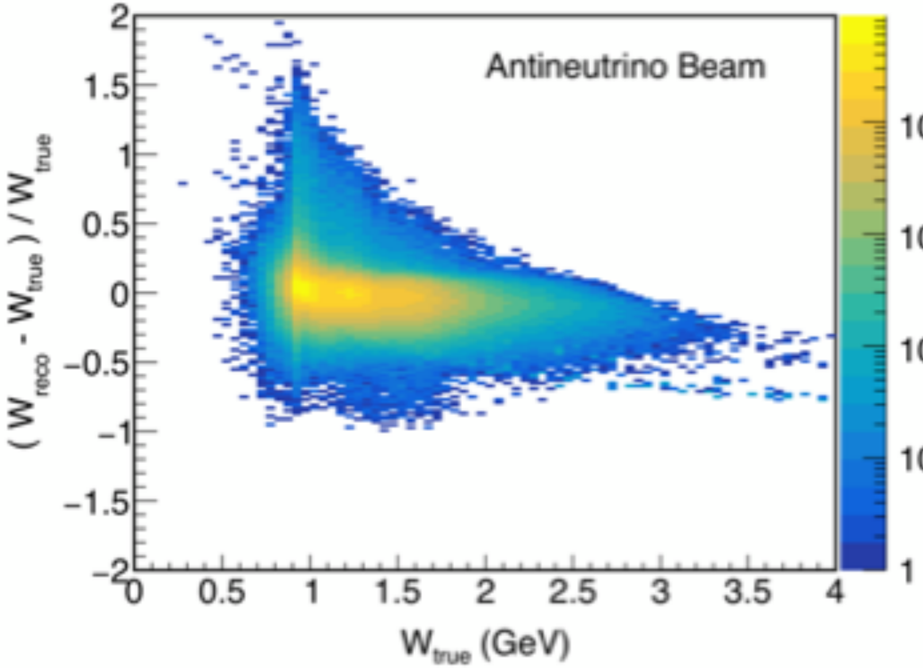
NOvA Preliminary
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco $|\vec{q}|$ (GeV)



NOvA Preliminary
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)

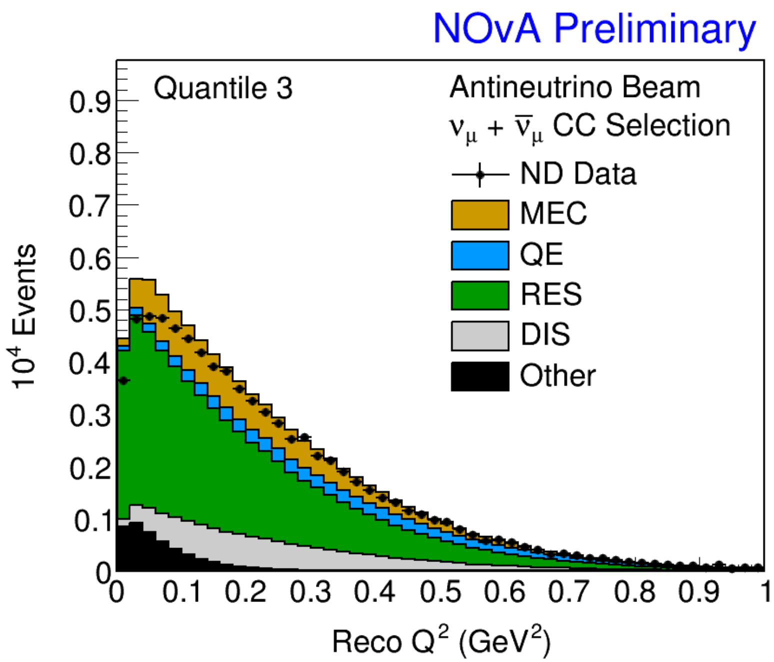
RHC W Resolution

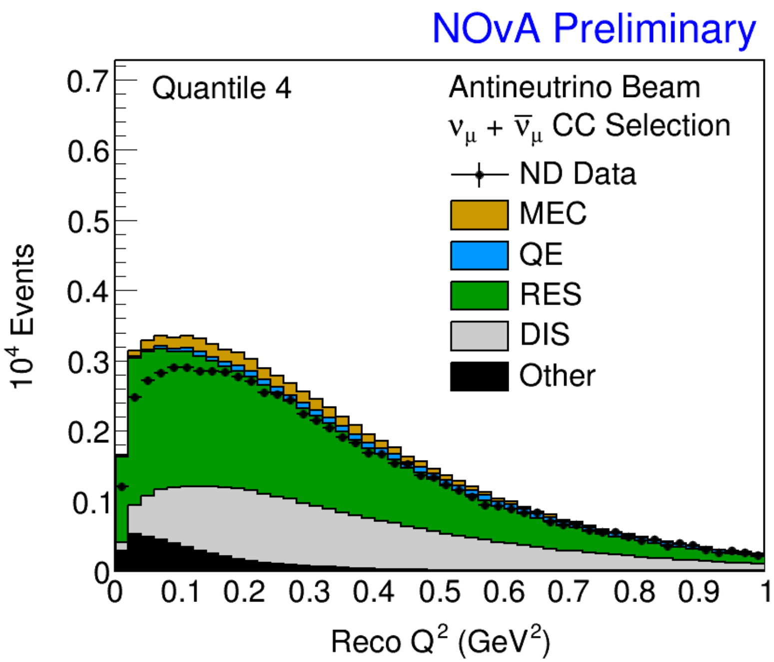




- Similar to FHC.

RHC Tune In DIS Enhanced Quartiles





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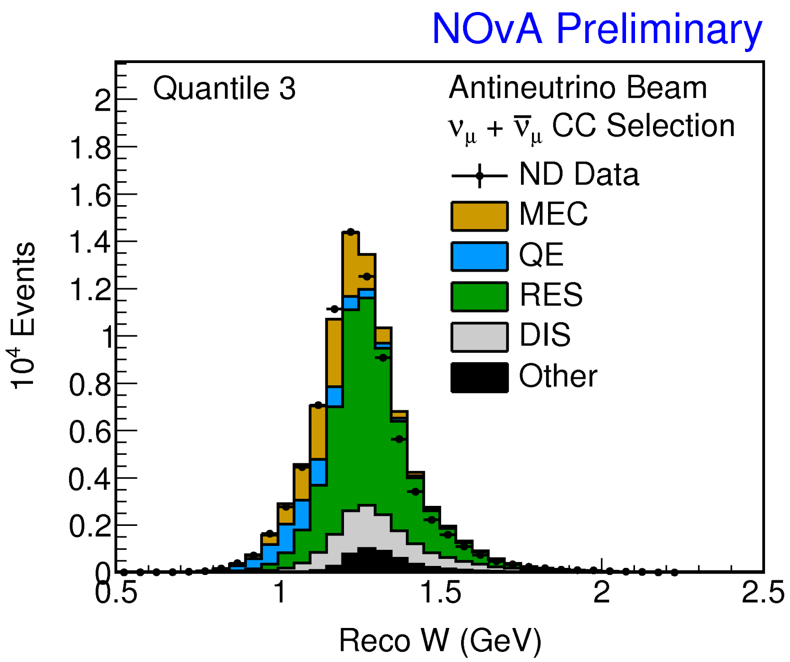
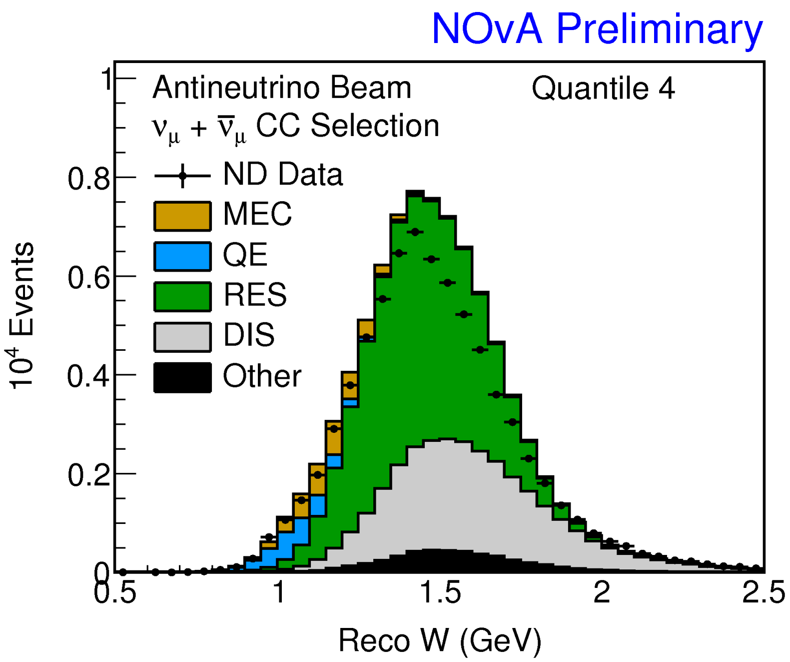


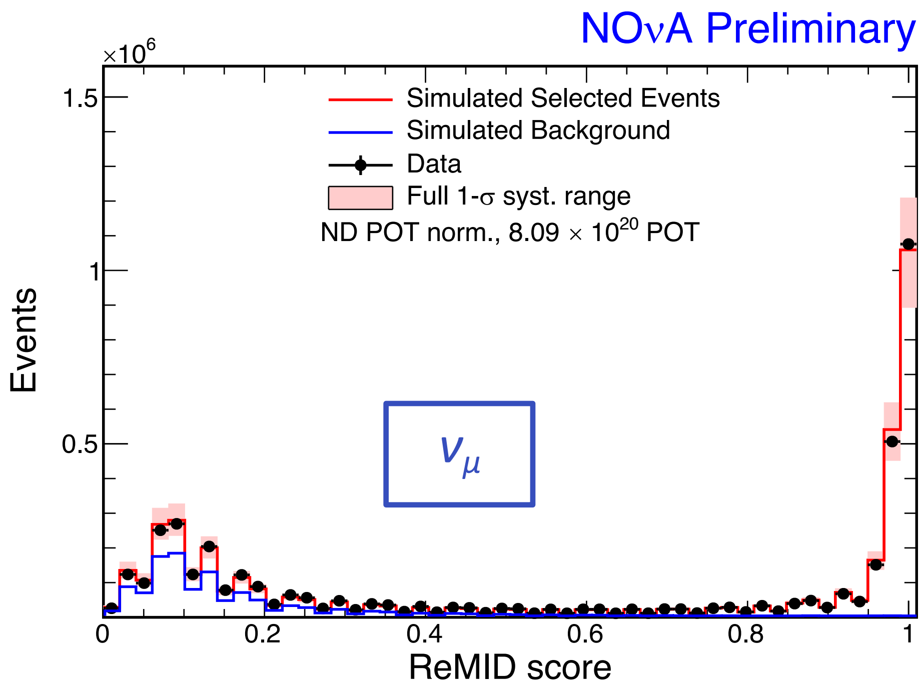


GENIE DIS Normalization Uncertainties

- GENIE includes DIS normalization systematics of 50% for 1 and 2 pion final states in events with W < 1.7 GeV.
- NOvA expands these to apply to final states with any number of pions.
- We also increased the range of the systematic to apply up to a W of 3 GeV as the discontinuity of 50% < 1.7 GeV and 0% > 1.7 GeV seems unphysical, even though we know higher energy regions are better constrained.
- We feel in general untrusting of this region in GENIE, hence the large uncertainties, and would greatly appreciate a closer look from the community at the model and the systematics GENIE provides.

Additional impact of improved DIS Modeling

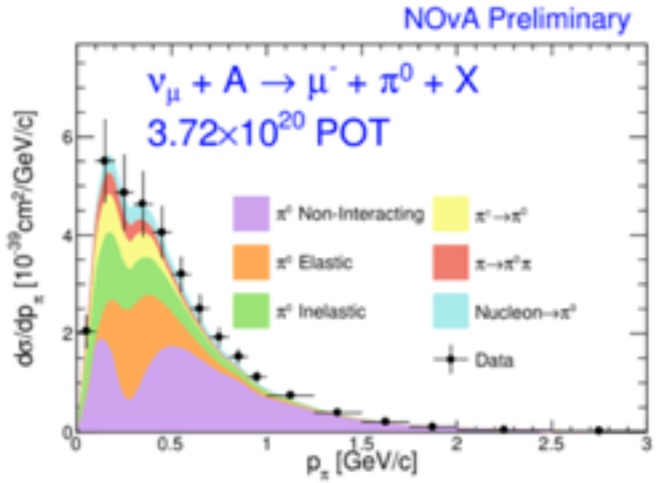
- NOvA has observed a data/MC discrepancy in the low track-length, high y region of ν_μ-selected ND events.
- CVN recovers many of the low track-length events but due to this discrepancy we continue to apply a muon selection using Remid.
- Resolving this discrepancy and relaxing ReMID requirement would boost available analysis statistics.



NOvA Cross-section measurement

- NOvA is currently working on a set of cross-section measurements which may help better understand DIS. **Results and updates on Wednesday.**

  - ν_μ and ν_e inclusive CC measurements.
  - Charged and neutral pion production measurements.



CC Neutral Pion Production

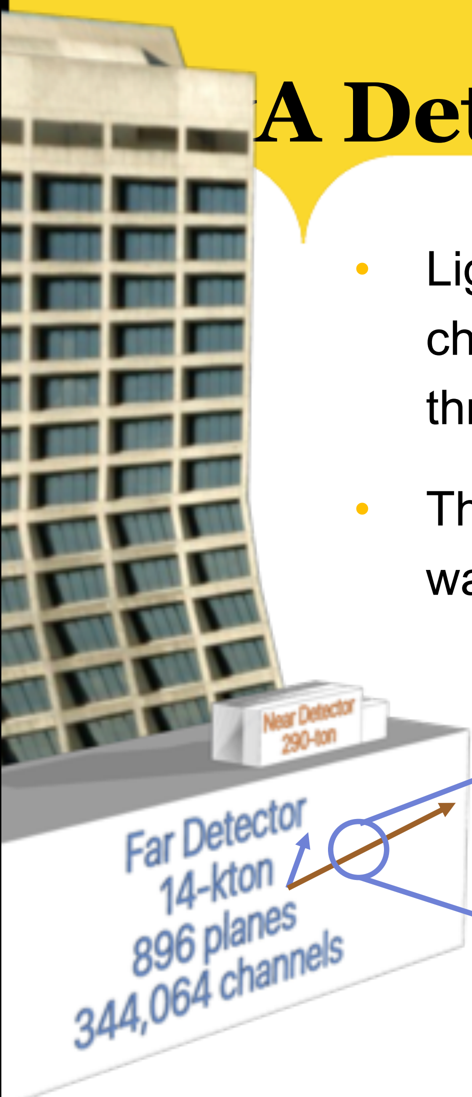
Conclusion

- The transition DIS region is important to NOvA oscillation results.
  - Improved CVN based PIDs continue to increase selection efficiency for ν_μ CC. Many of the new events are DIS and gaining confidence in including these in the NOvA sample requires continued effort on the DIS model.
  - For the existing analysis the DIS component is small but couples with RES (a major source of XS uncertainty.)
  - NOvA is continuing to fine tune our GENIE implementation to improve agreement in additional variable like W.
  - DIS uncertainties are not a standard GENIE implementation. Input from the community is welcome.

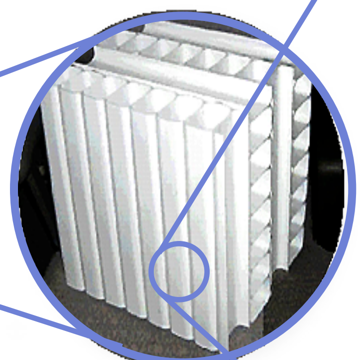

Thank you!
Fermilab

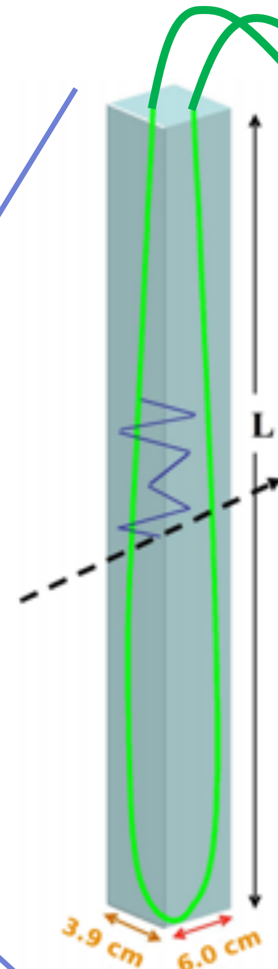
BACKUPS

A Detectors

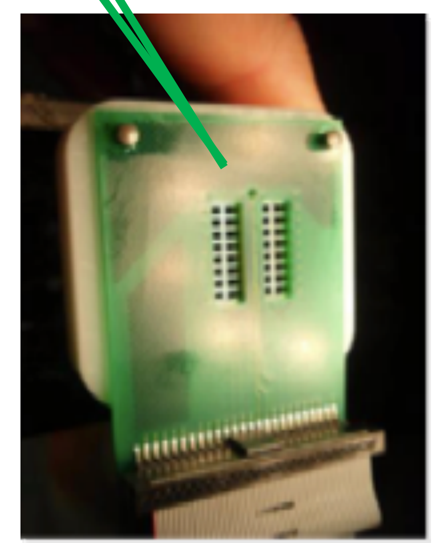


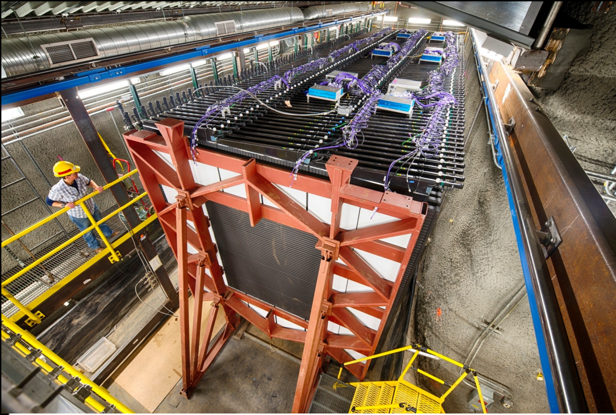
- Light is produced when charged particles pass through the cells.
- The light is picked up by a wavelength shifting fiber.



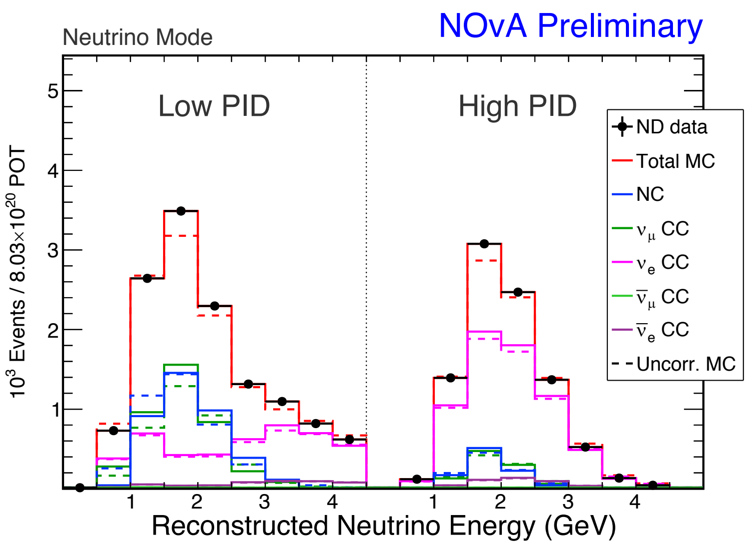


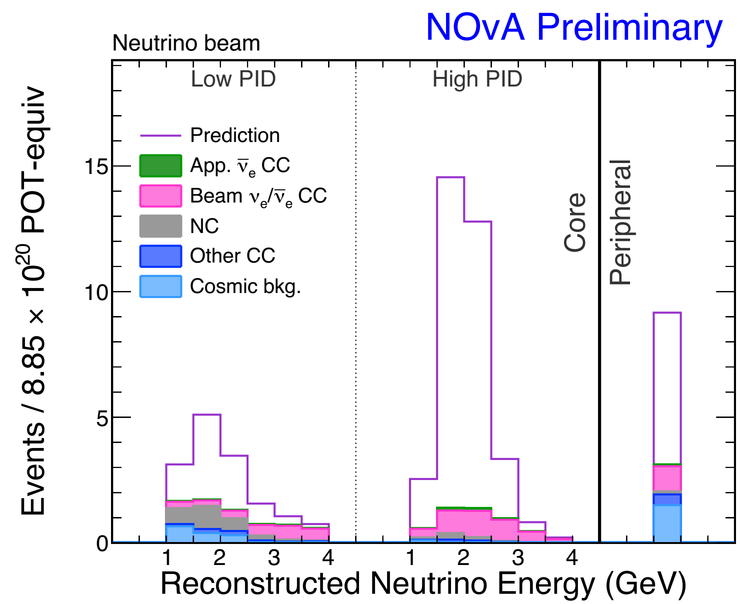
It is then transported to an **A**valanche **P**hoto**D**iode where the light is collected and amplified.



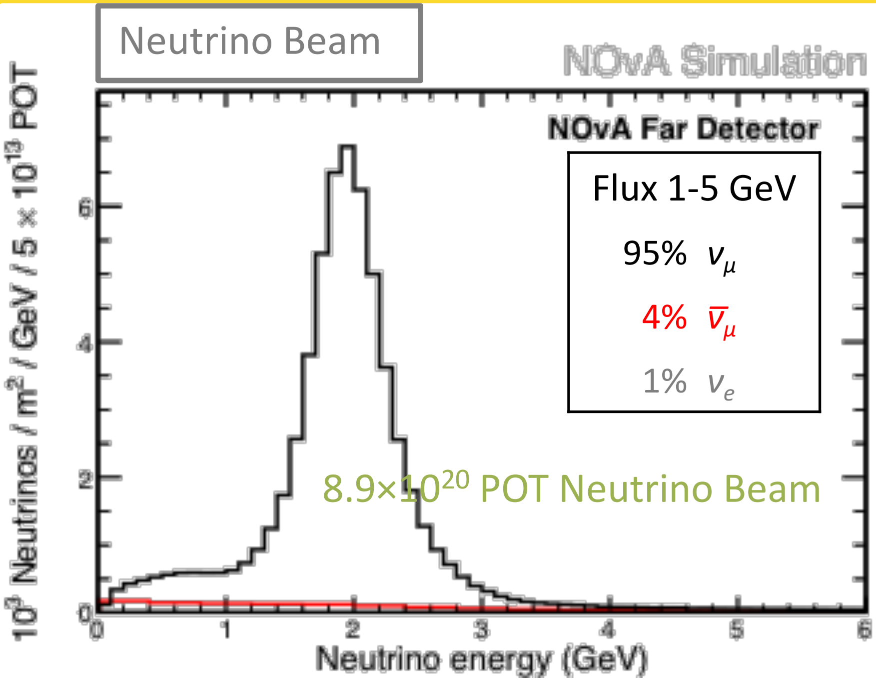


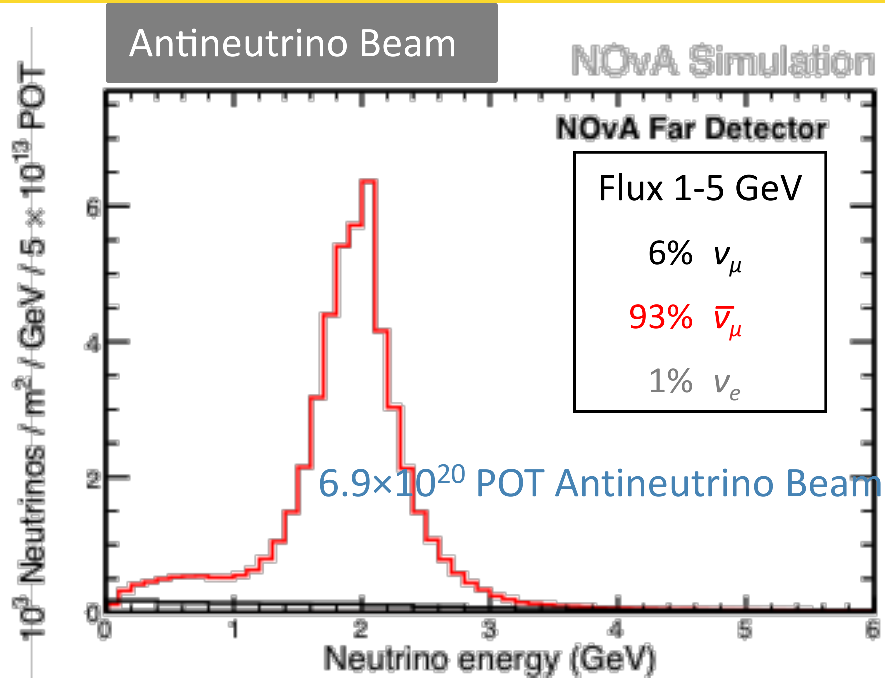
Extrapolating from Near to Far



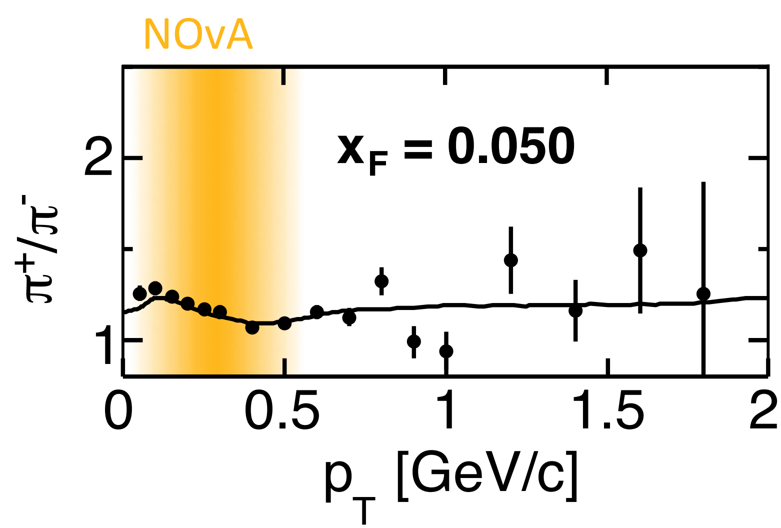


- Use the ND ν_μ sample to predict the FD ν_μ sample.
- Use the ND ν_μ sample to predict the FD ν_e signal.
- Use the ND ν_e-like sample to predict the FD ν_e backgrounds.

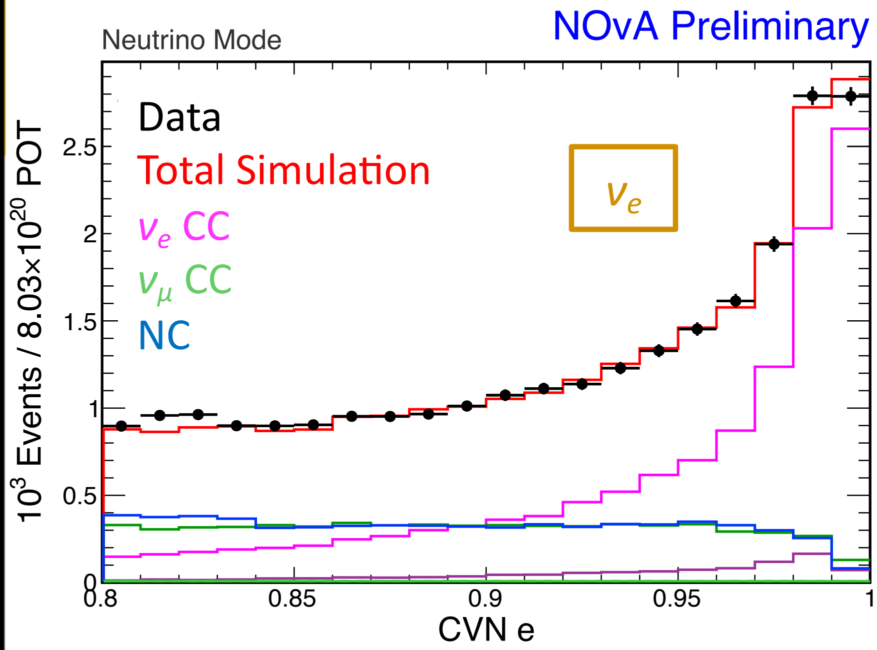


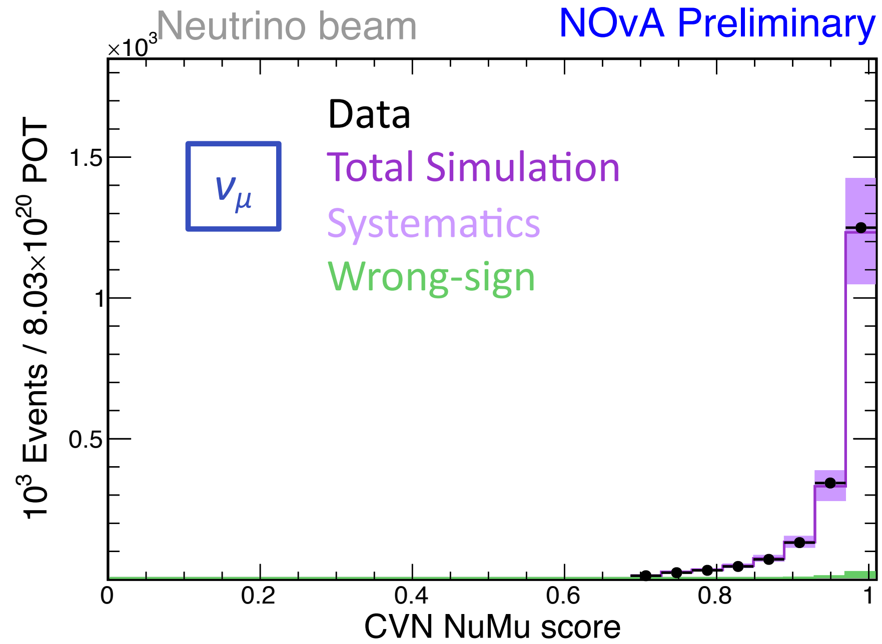


- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
  - p^+ colliding with p^+ and n^0 in the target
- *Wrong-sign*: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign.
  - WS primarily comes from the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



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





For our latest 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.

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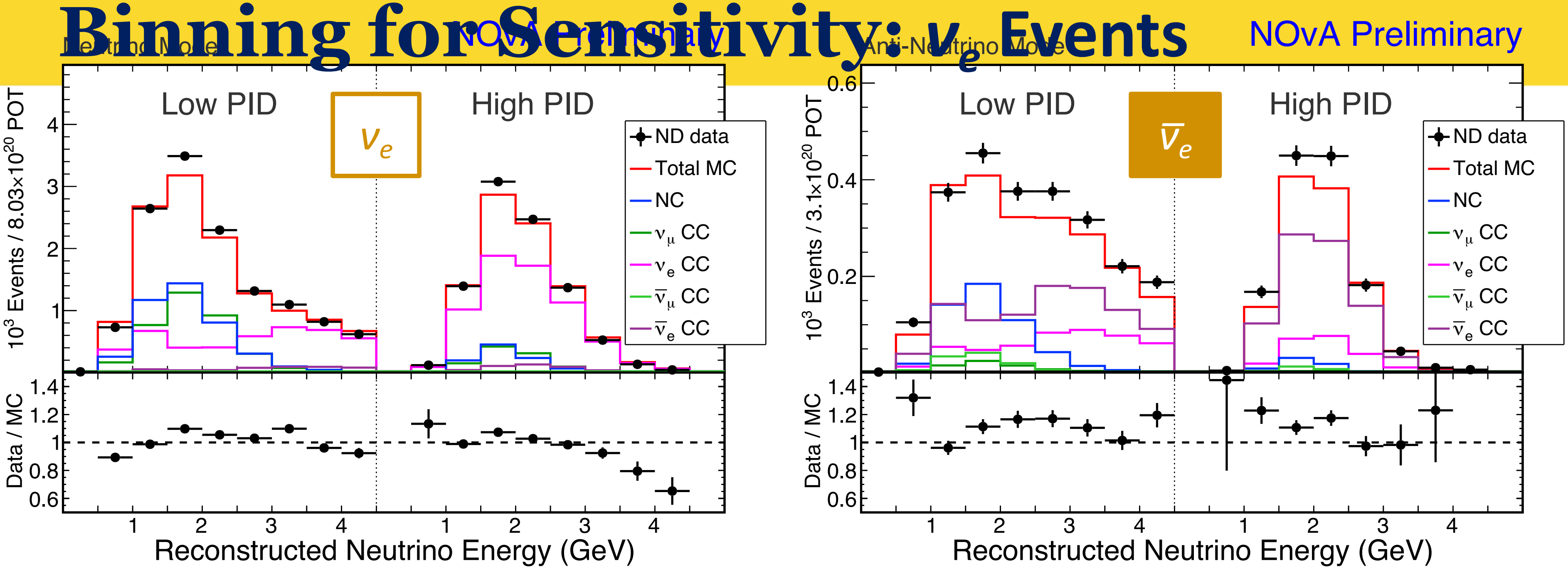
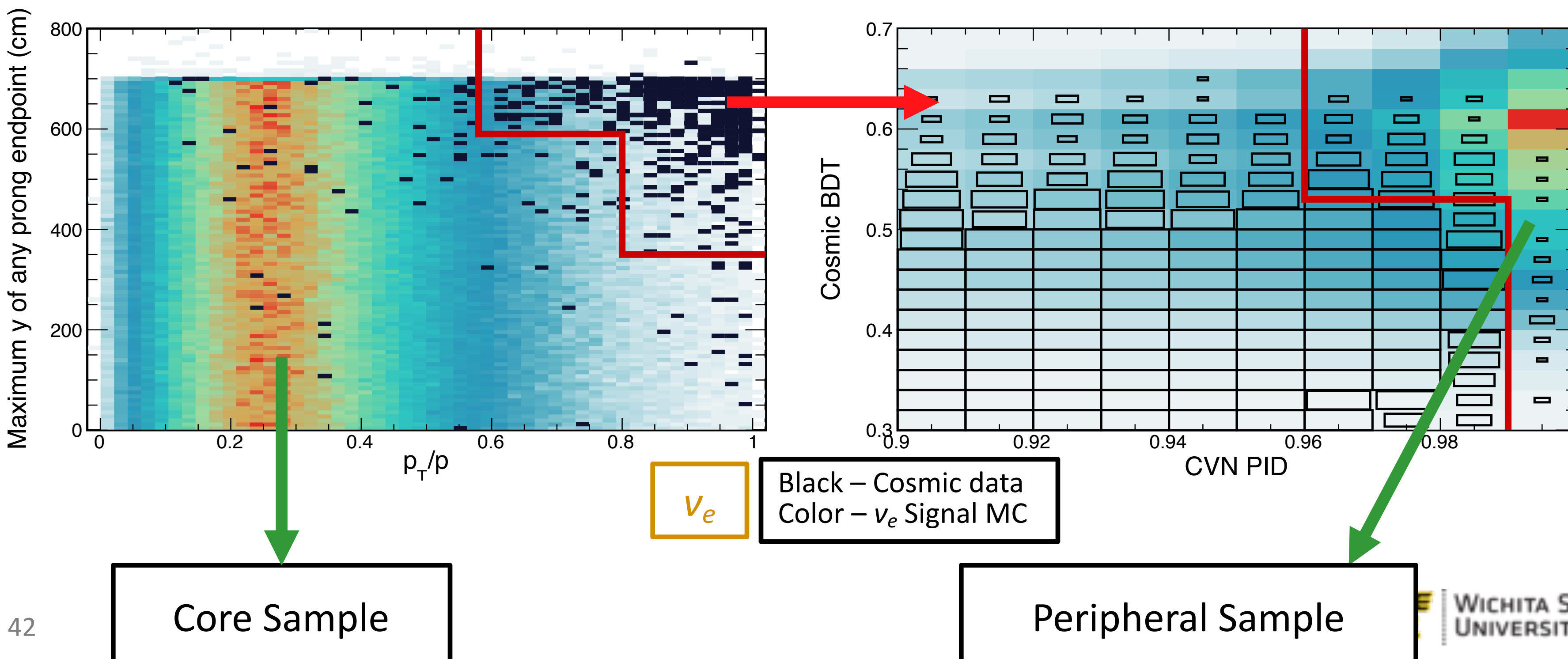
Binning for Sensitivity: ν_e Events



- The ND ν_e-like sample has no $\nu_e/\bar{\nu}_e$ appearance – all background.
- For the neutrino beam we use two data-driven techniques to constraint the background composition.
- For the antineutrino beam scale all components proportionally for now.

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

- 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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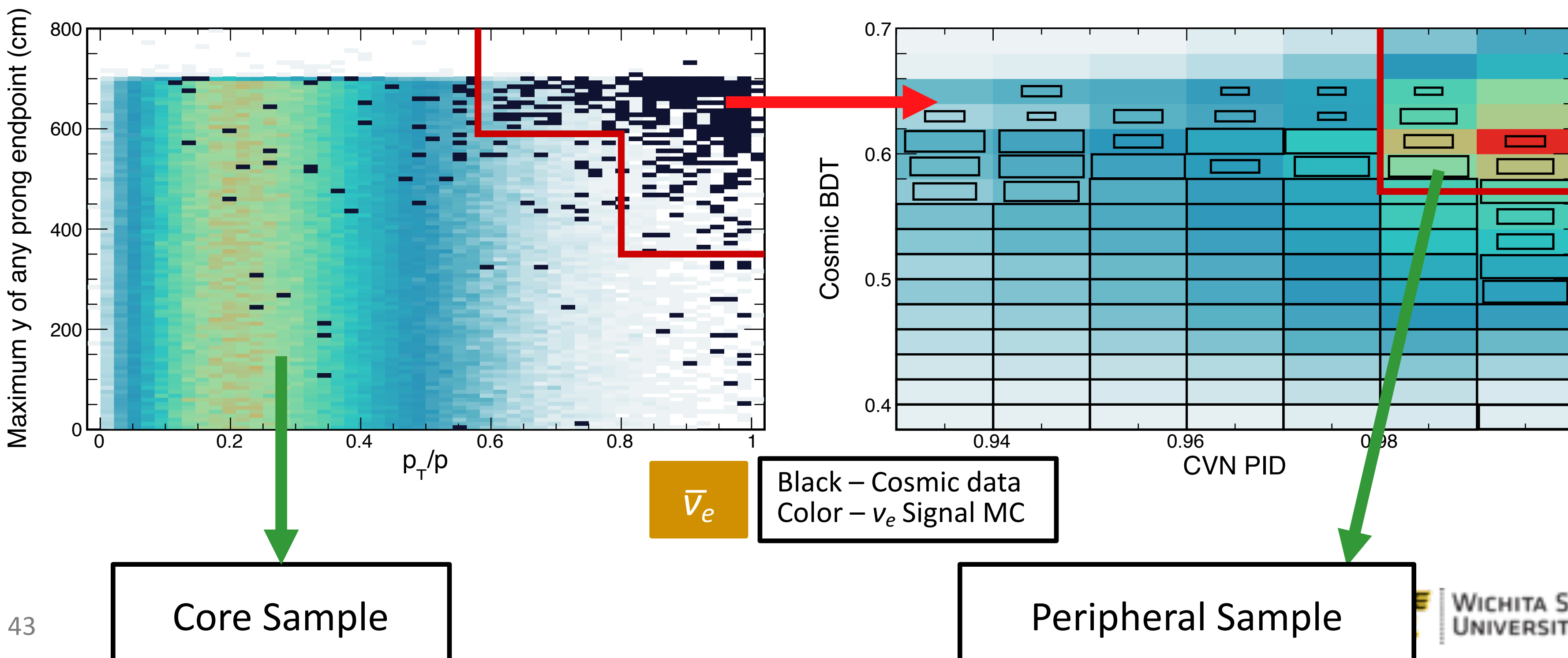
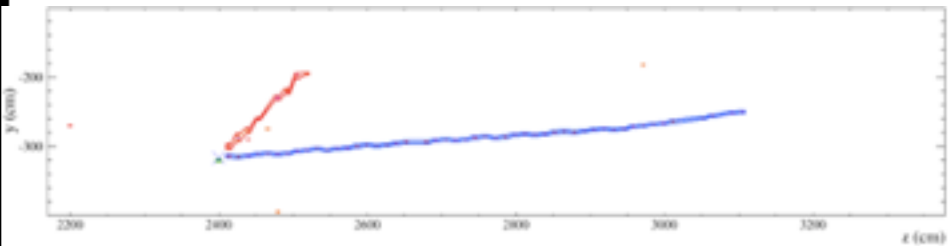


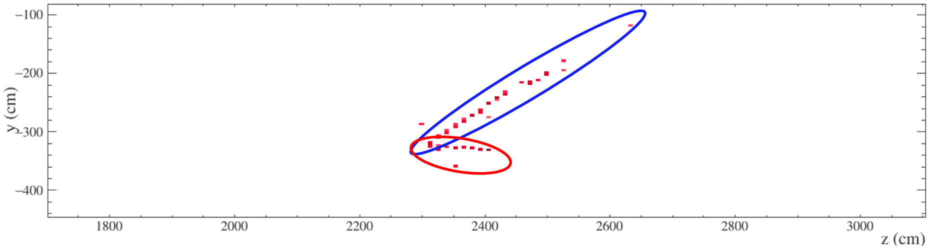
Measuring Neutrino Energy

ν_μ Events



- Neutrino energy is the sum of muon and hadronic energy.
- Muon energy is a function of track length.
- Hadronic energy reconstructed calorimetrically.
  - Includes activity overlapping the muon track.

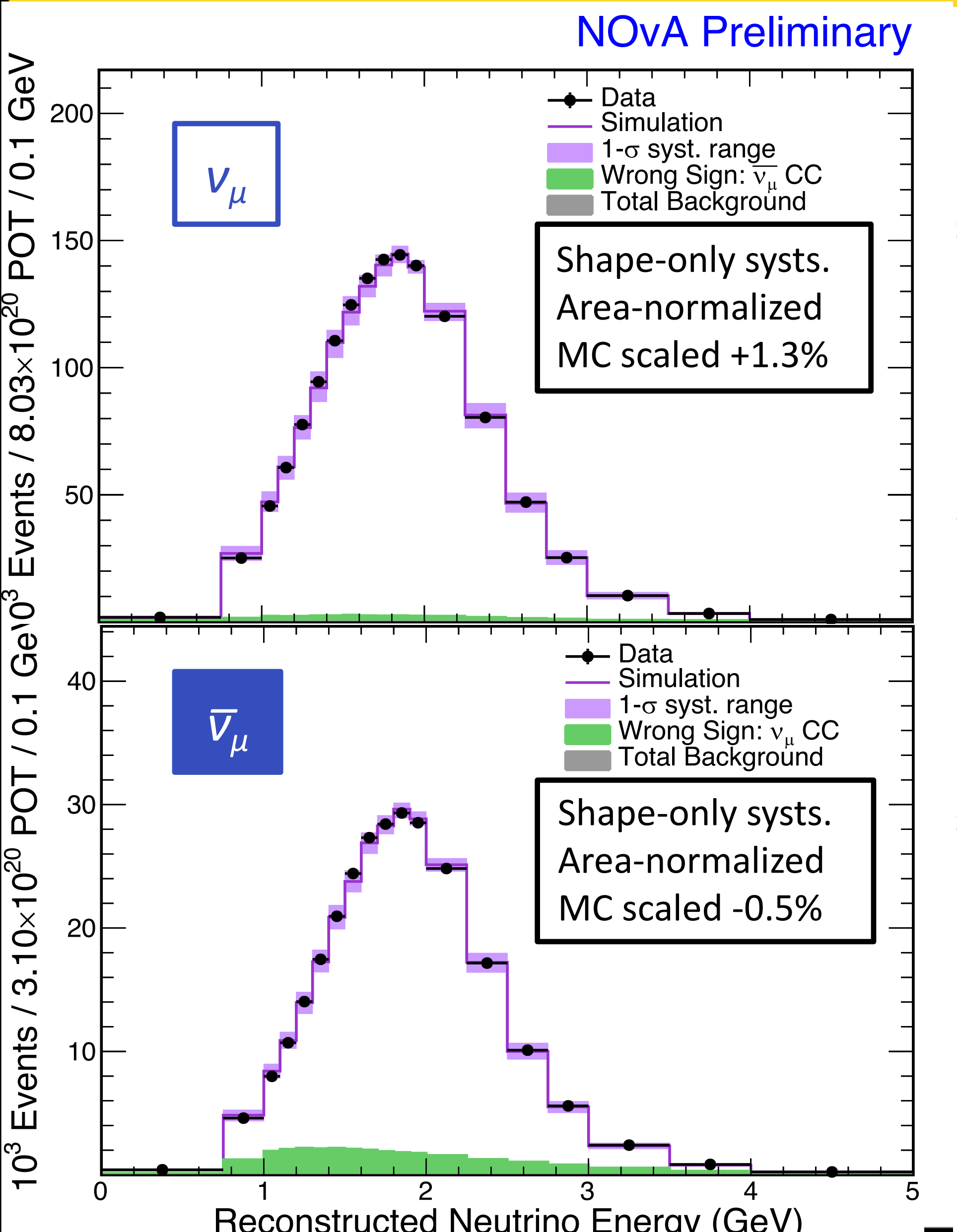
ν_e Events

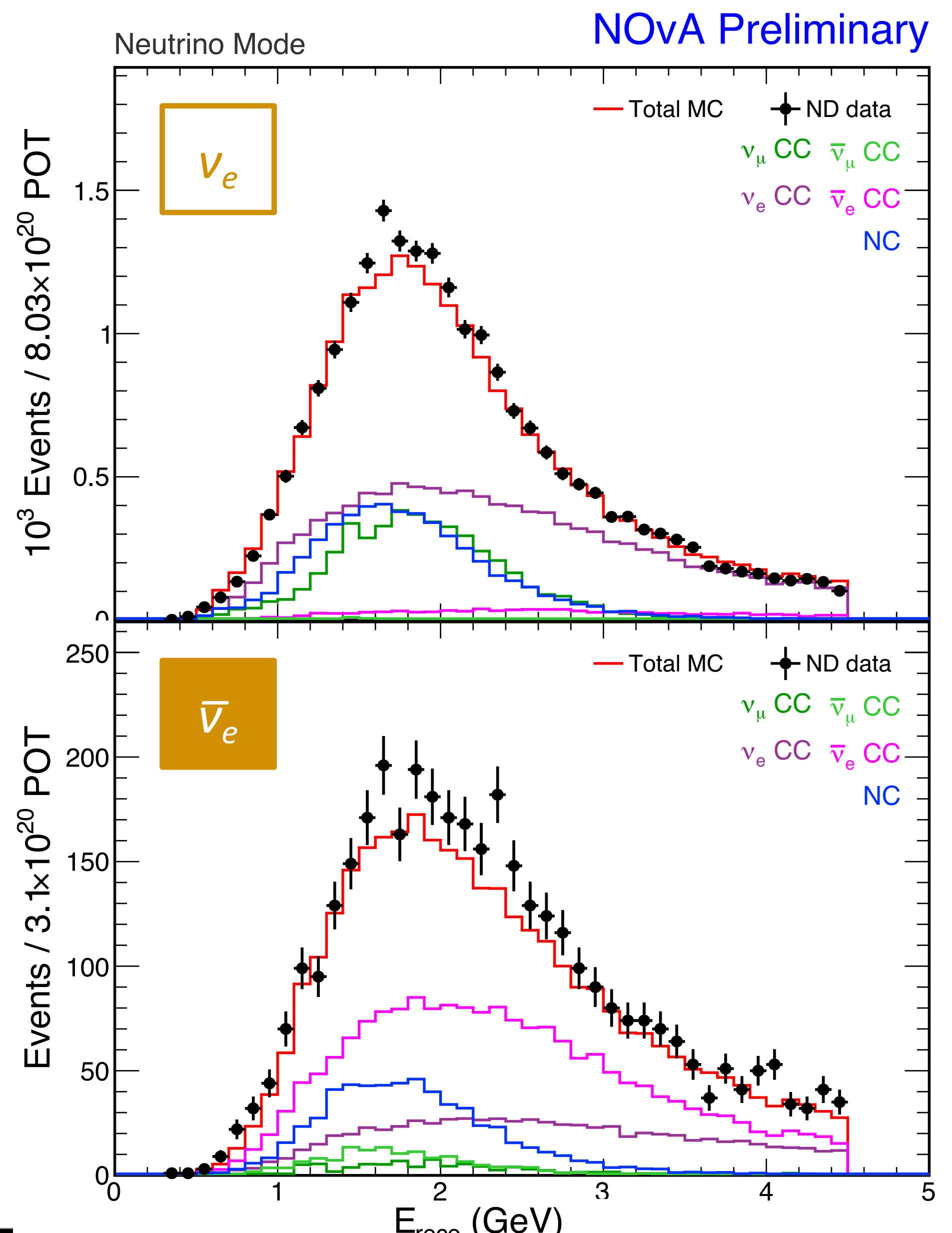


- Neutrino energy is a function of EM and hadronic energy.
- EM "prongs" are identified with a single-prong CVN variant.
  - All remaining activity is hadronic.
- Both energies reconstructed calorimetrically.

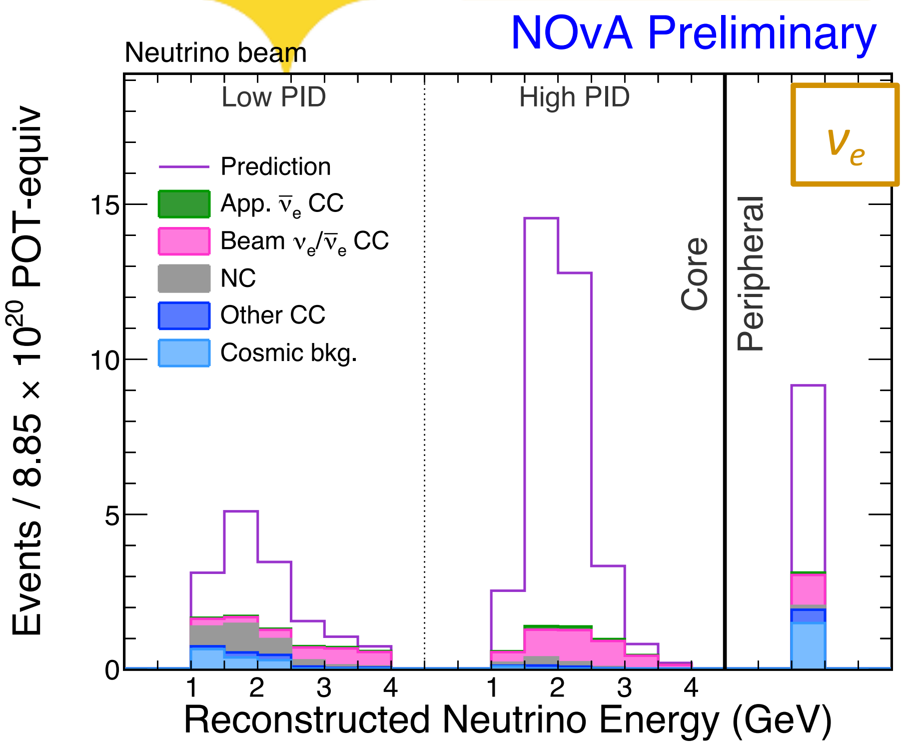
ν_μ Spectra

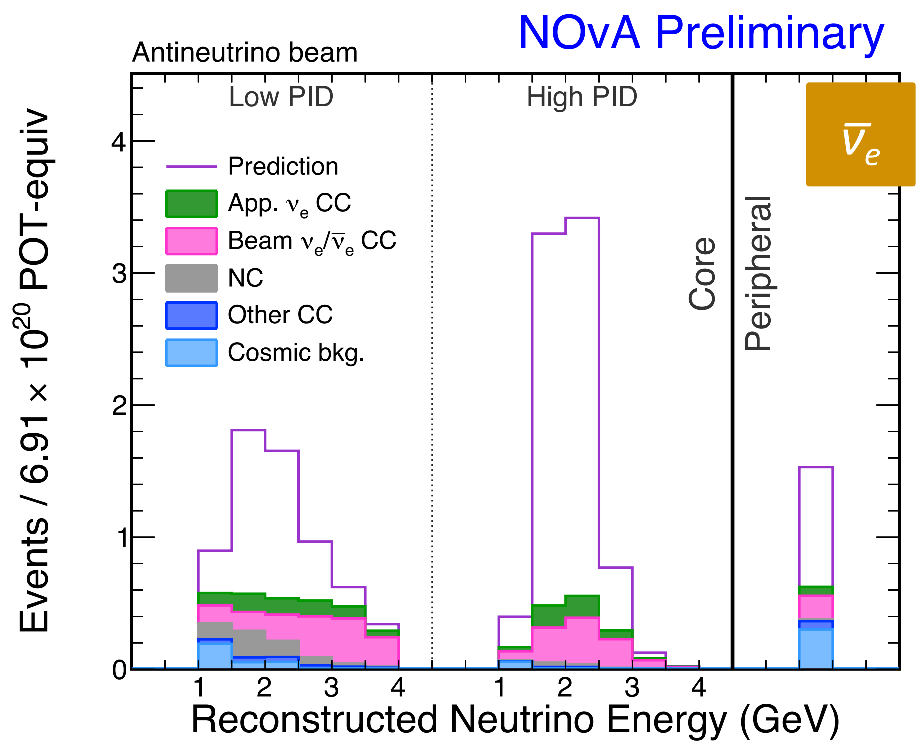
ν_e-like Spectra



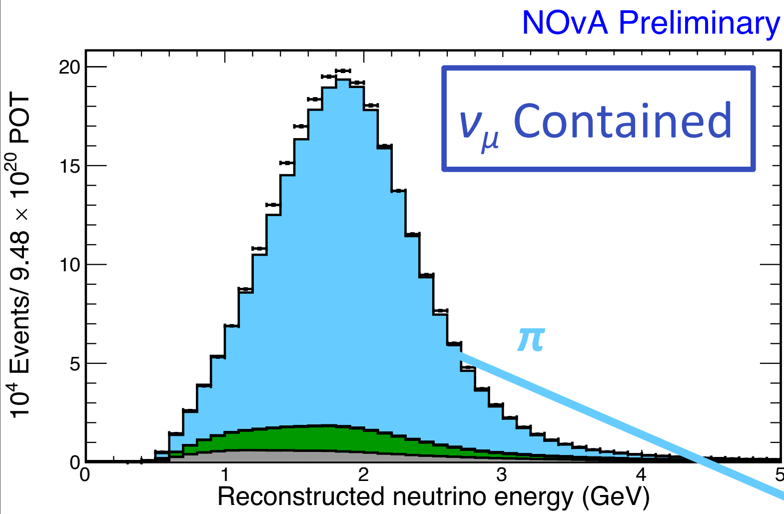


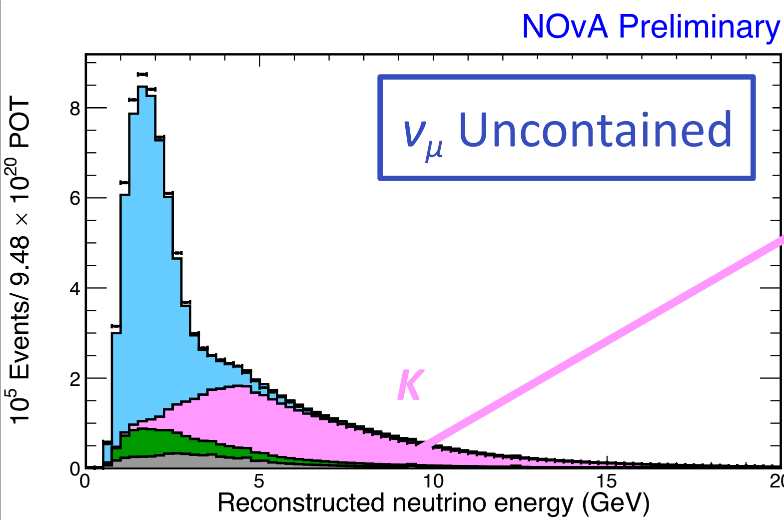
Binning for Sensitivity: ν_e Events

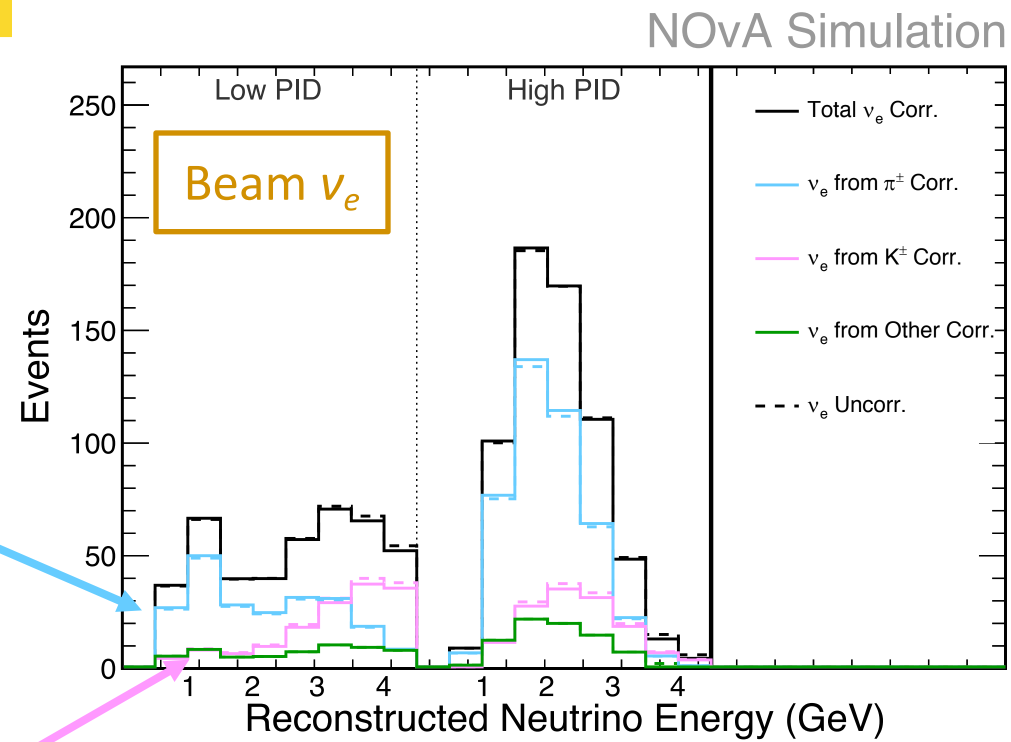




- Oscillation sensitivity depends on separating ν_e signal from background.
- Bin by PID to separate a high-purity and low-purity sample.
- Energy binning separates appearing ν_e from beam ν_e and has minor δ sensitivity.
  - No energy bins in the peripheral sample where uncontained events make energy unreliable.



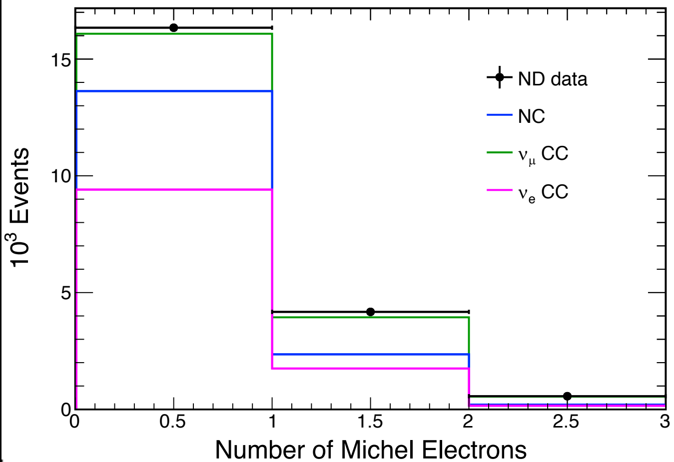


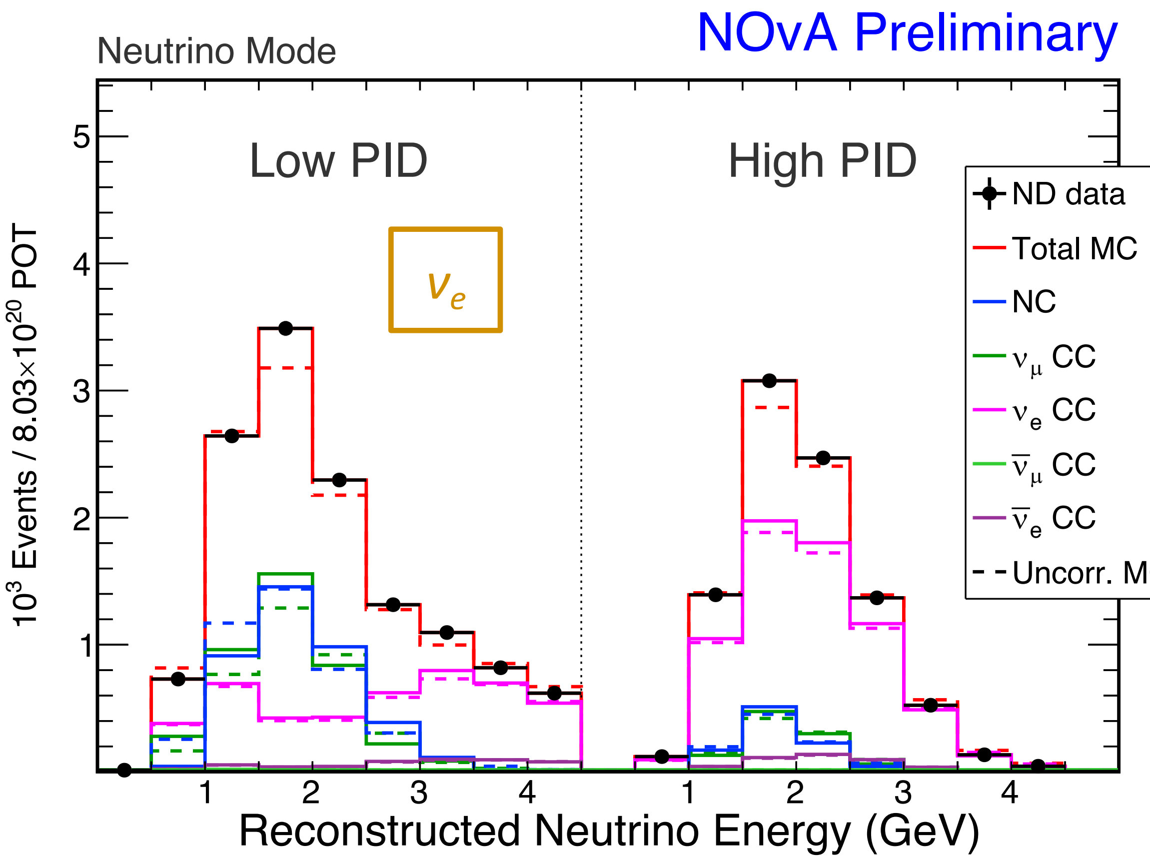


- ν_e and ν_μ events come from the same parents:
  - Lower energy neutrinos come primarily from π decay.
  - Higher energy neutrinos come primarily from K decay.
- Use contained ν_μ data to constrain the **π flux**
- Use higher energy uncontained events to constraint the **K flux**.

ν_e Decomposition

- The CC/NC constrains 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%

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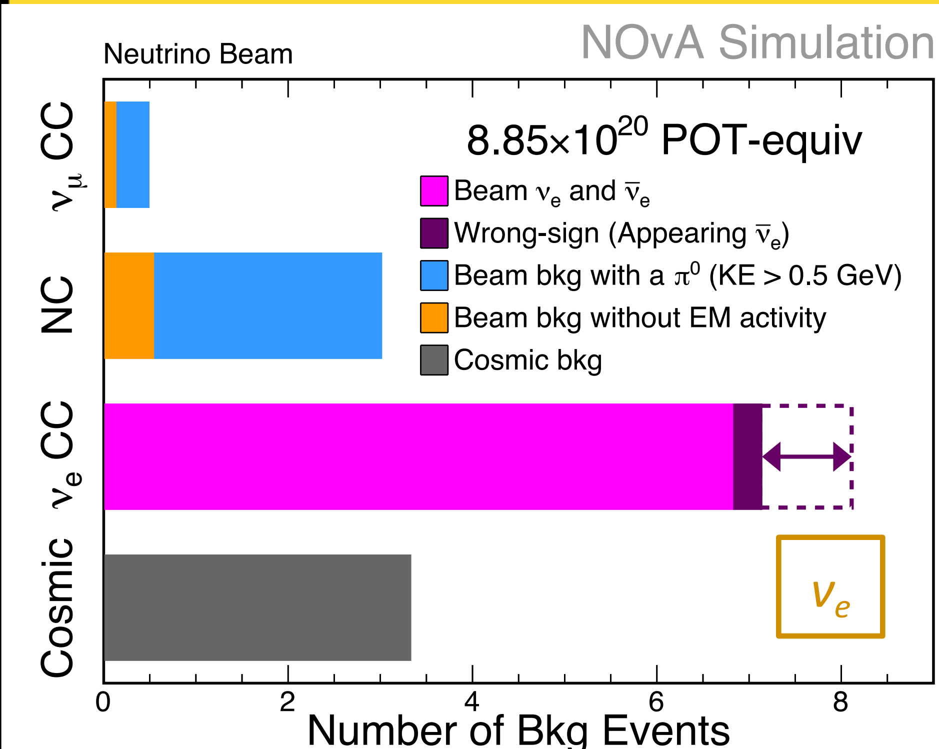
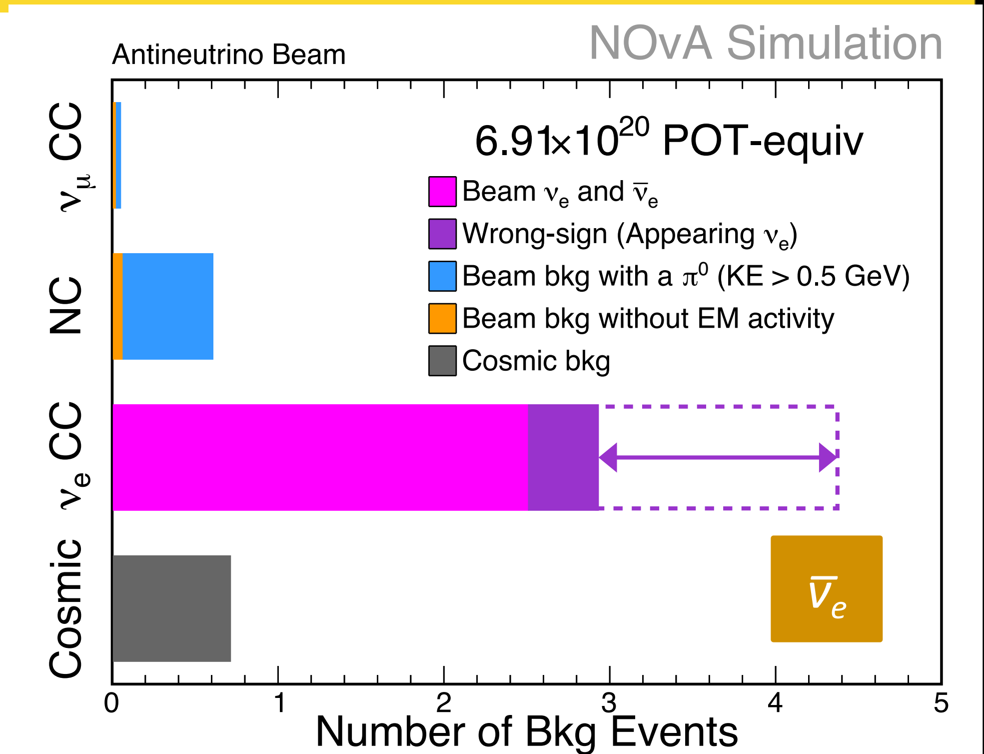
ν_e and $\bar{\nu}_e$ Background at the Far Detector





- 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.

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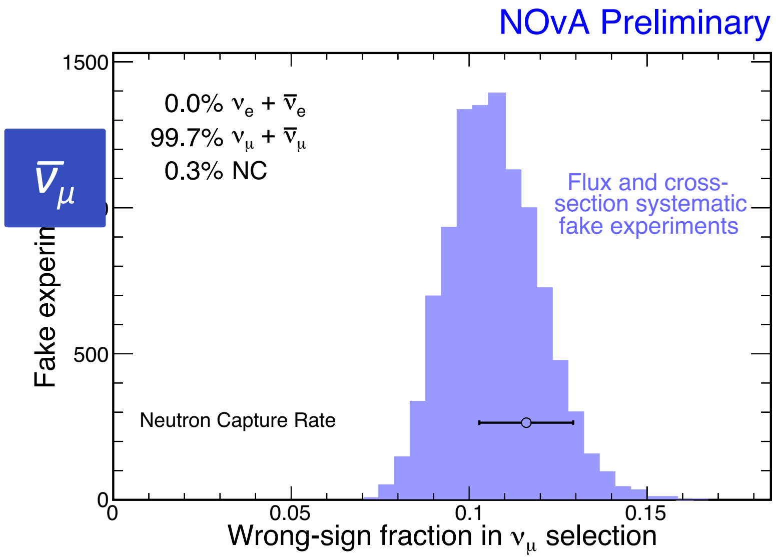
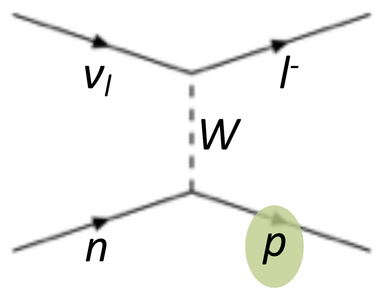
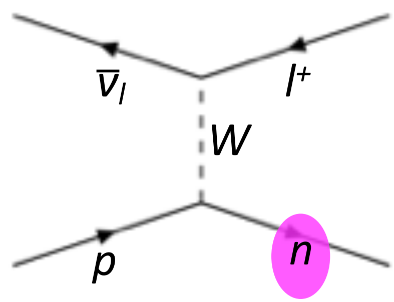
Wrong-sign Background

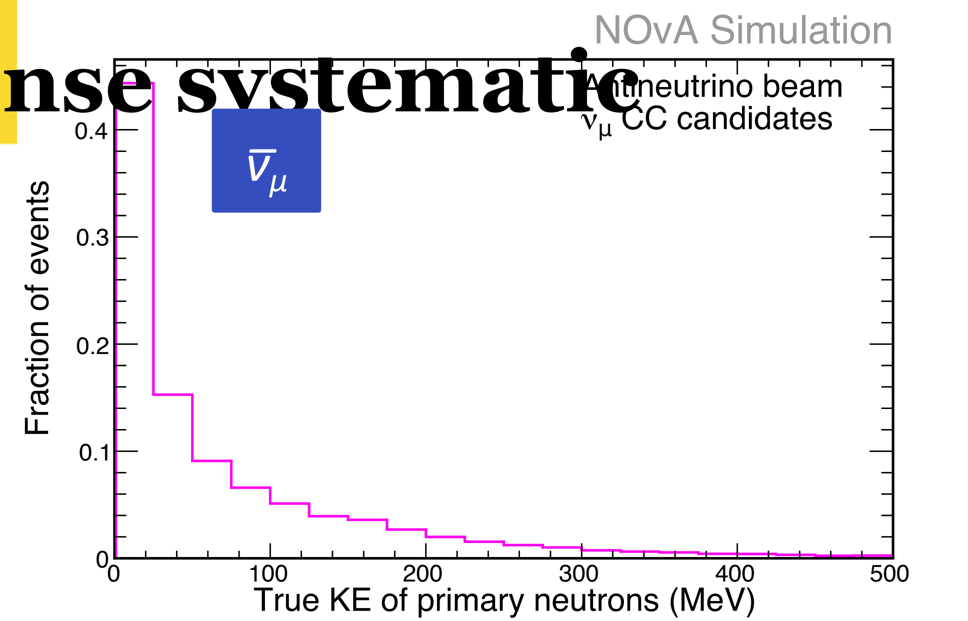


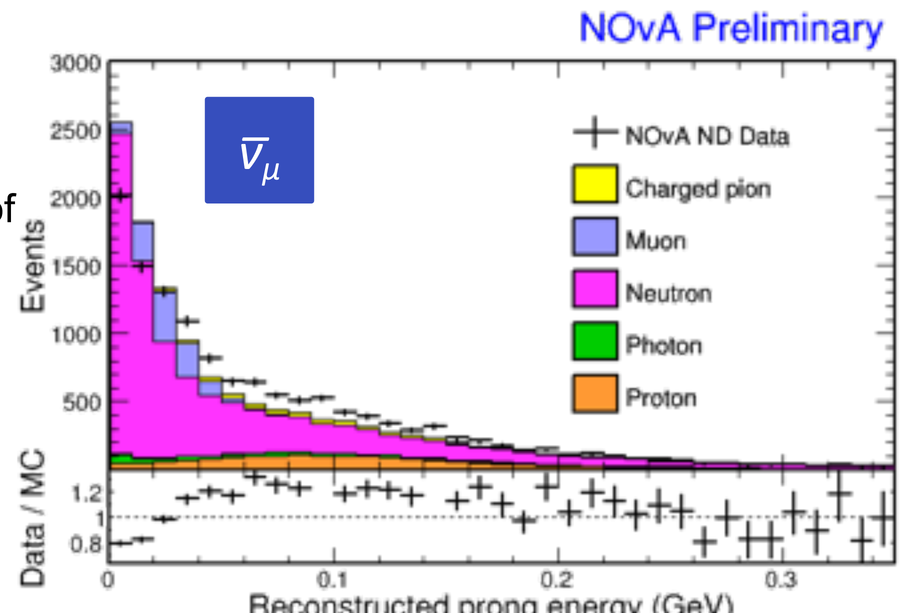
- The 11% wrong-sign fraction of the $\overline{\nu}_\mu$ **events** is important since it becomes the WS background in the $\overline{\nu}_e$ **appearance analysis**.
- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirmed using data-driven cross-check of the wrong-sign contamination
  - 11% wrong-sign in the $\overline{\nu}_\mu$ sample checked using neutron captures in the neutrino and antineutrino beams.

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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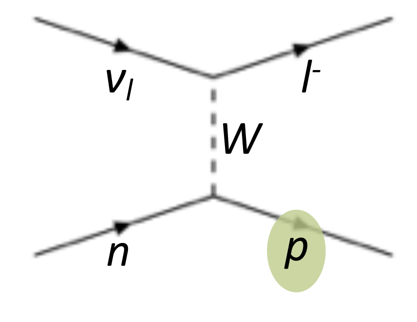
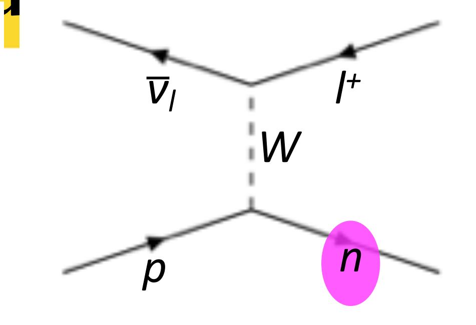
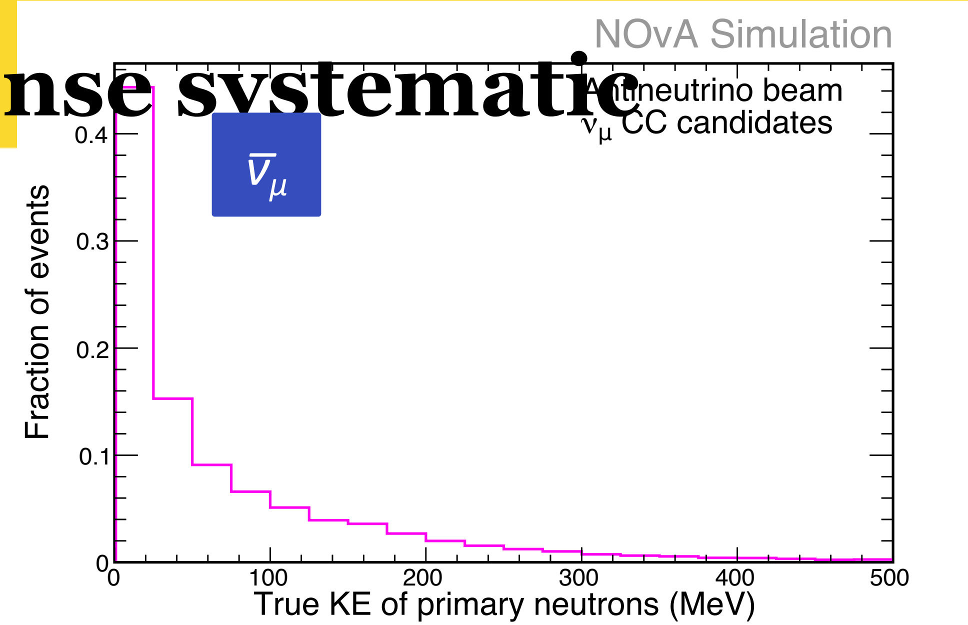
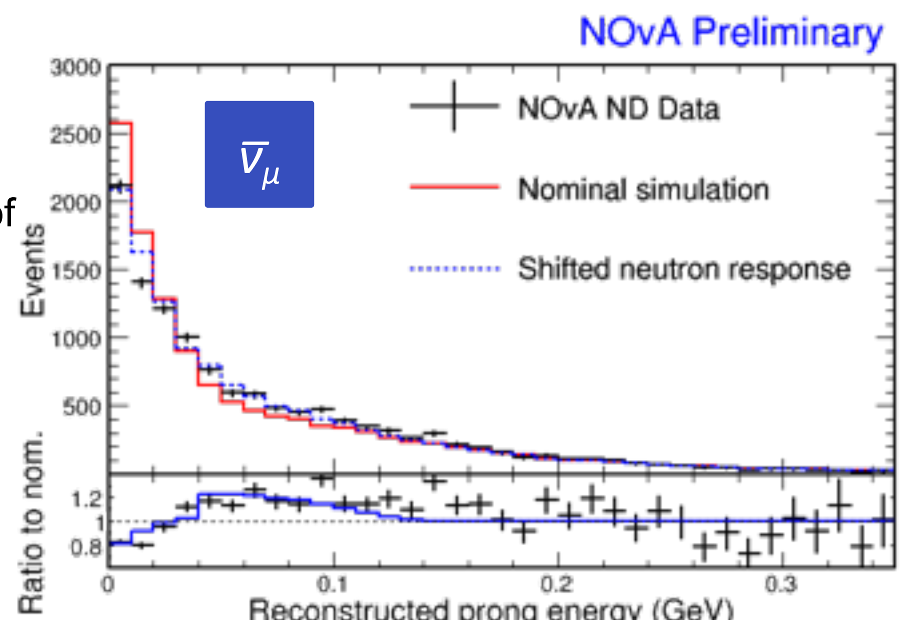
New neutron response systematic









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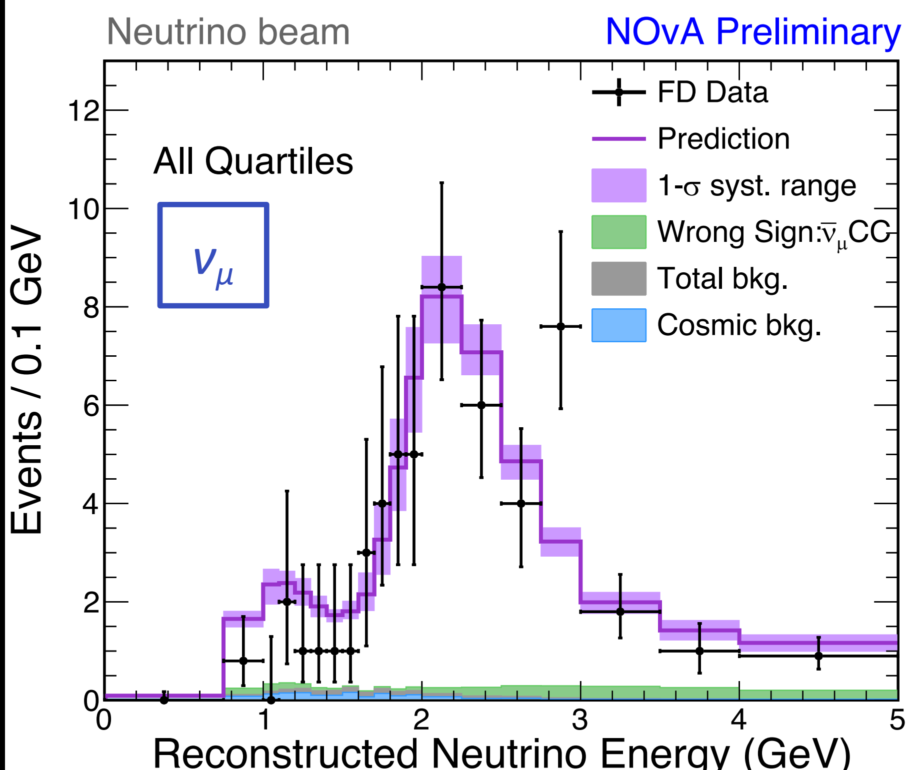
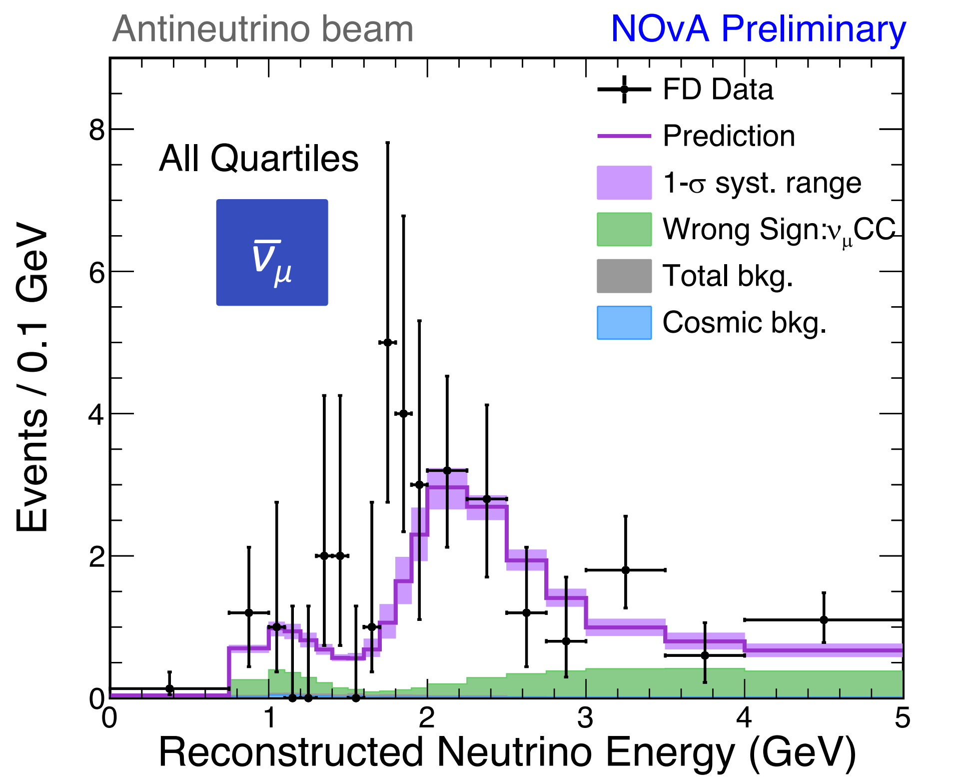
ν_μ and $\bar{\nu}_\mu$ Data at the Far Detector

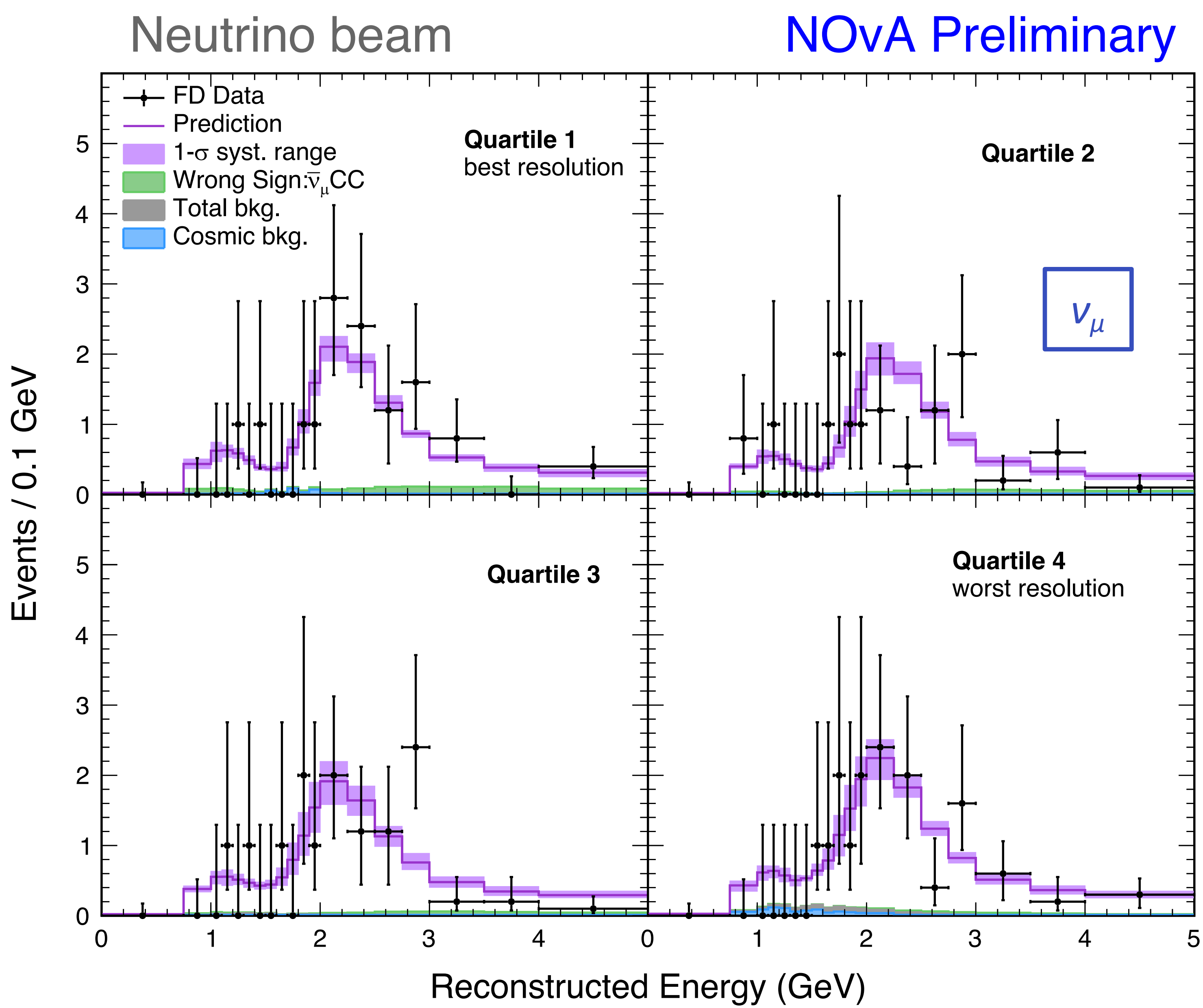




Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

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

Neutrino beam



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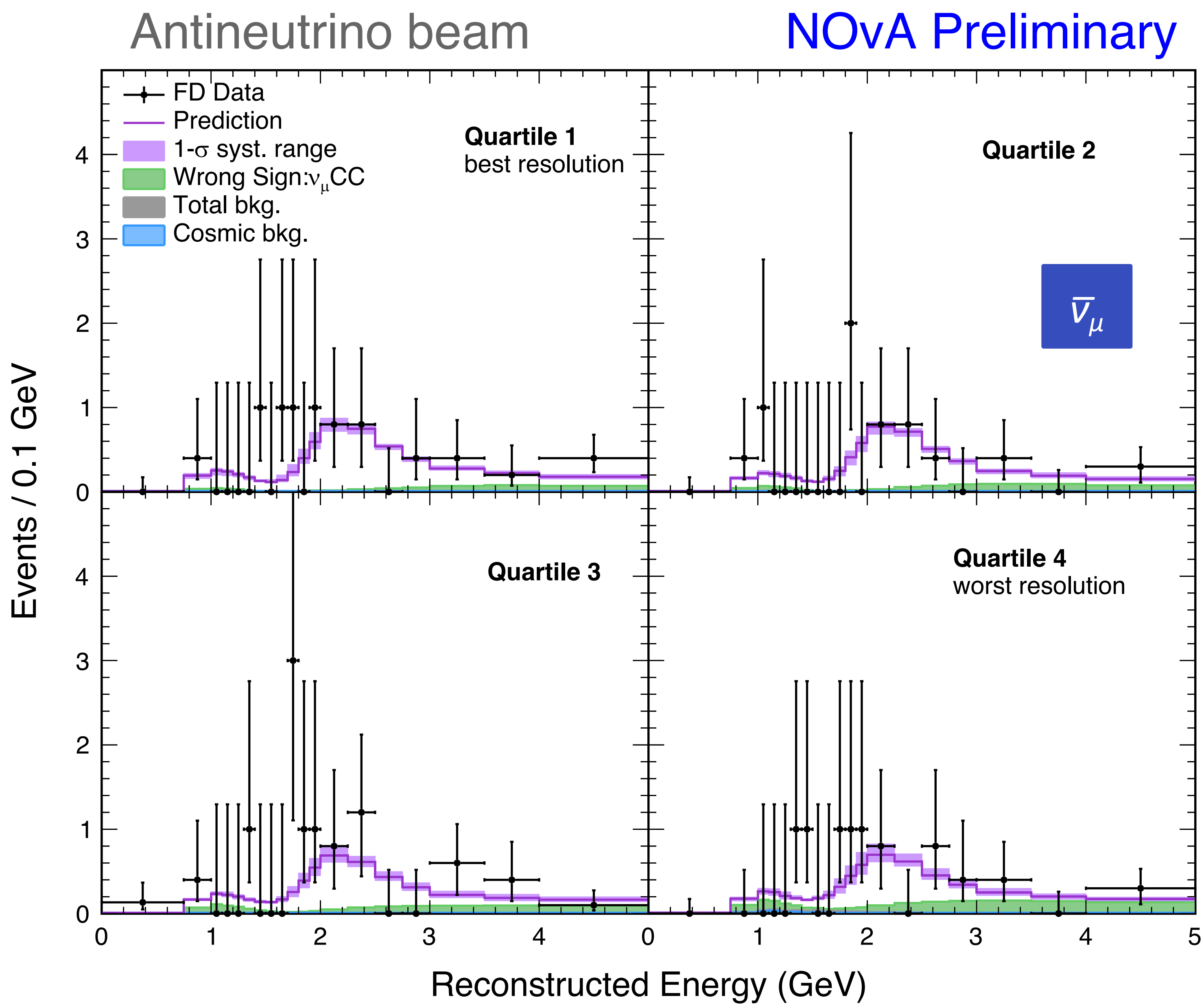
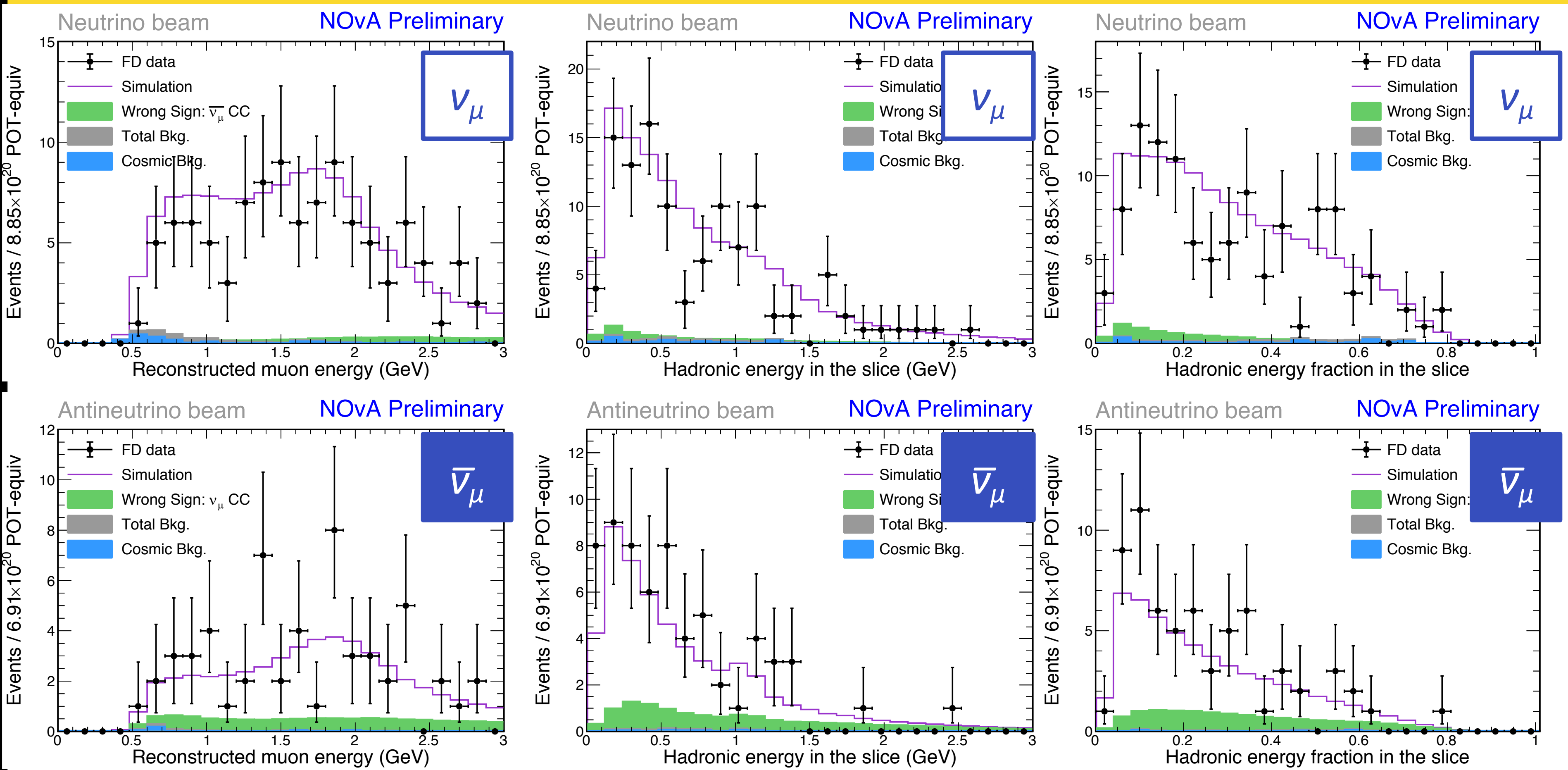
Antineutrino beam





- Good agreement in FD data distributions of muon and hadronic energy and inelasticity.

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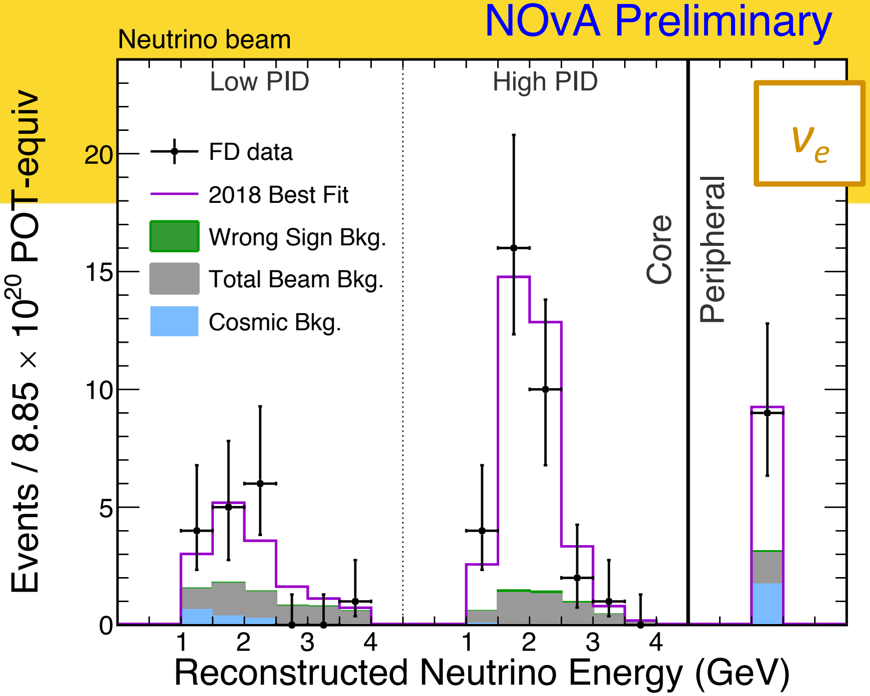
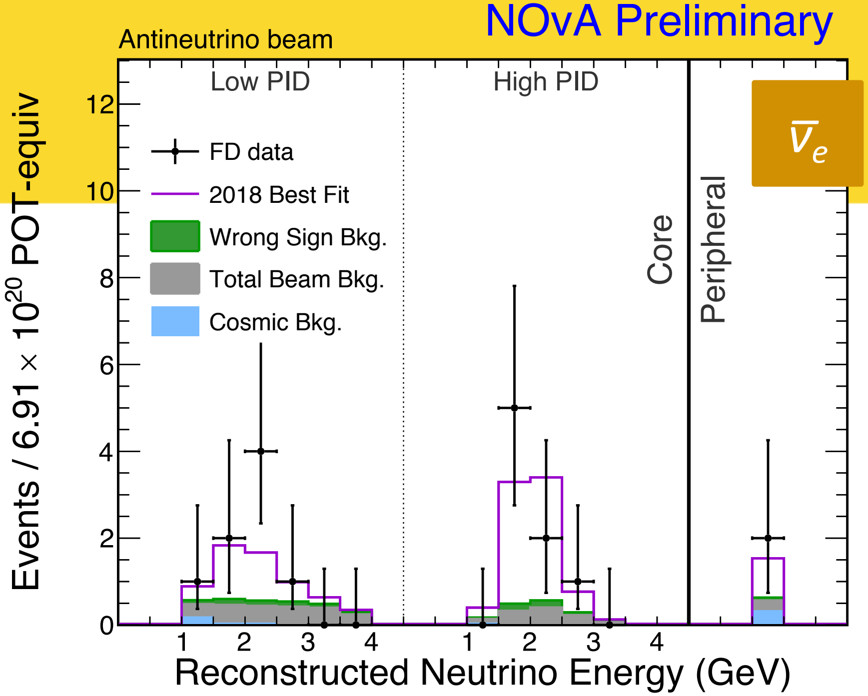




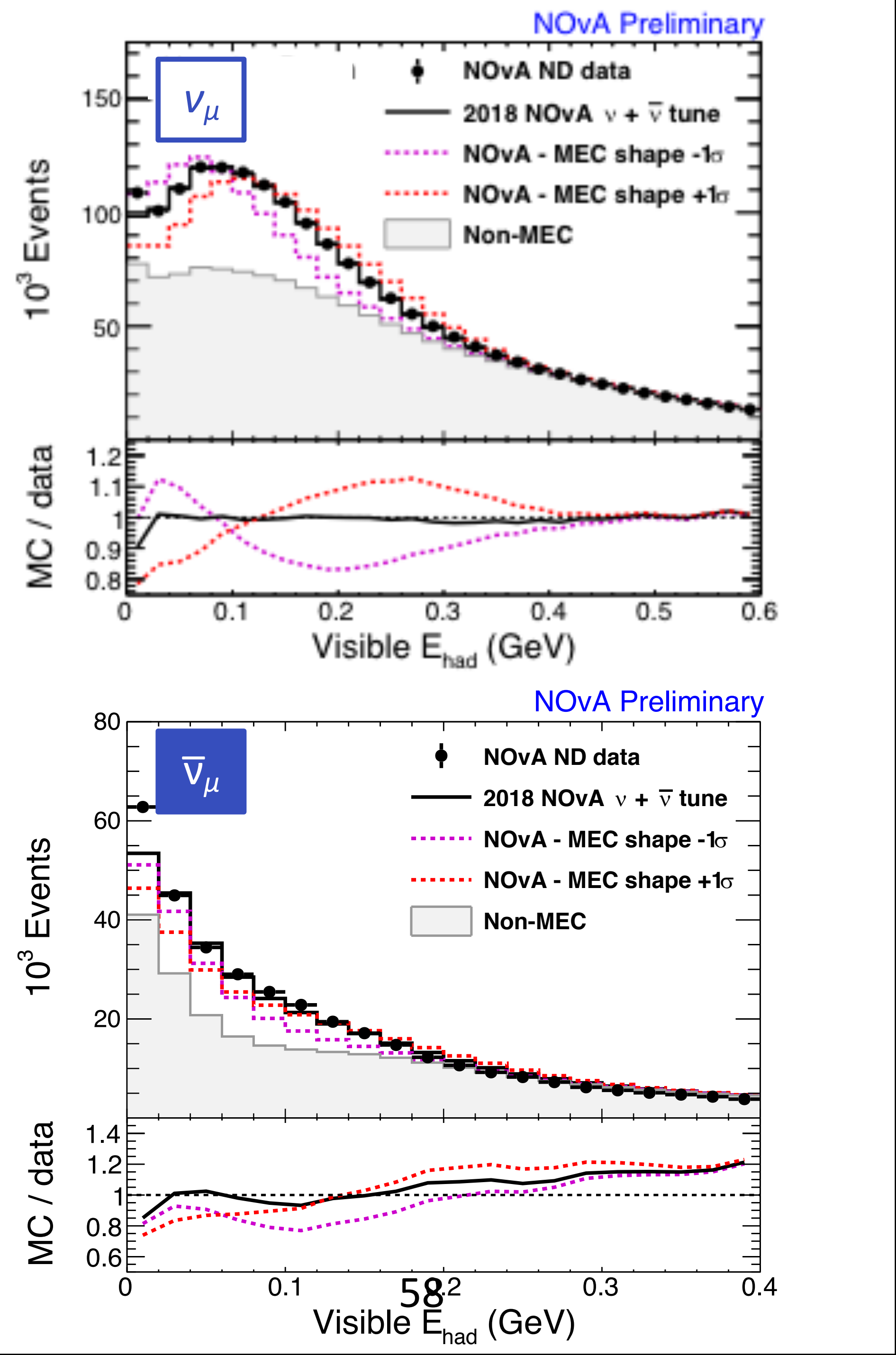
Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

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

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

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.



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- Repeat the tuning procedure with shifts in the Genie model.
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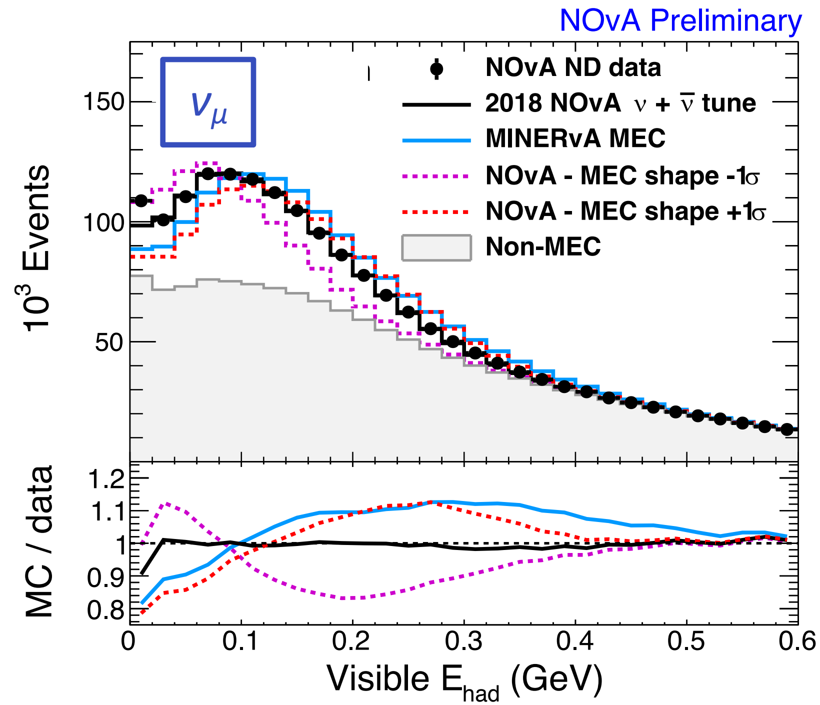
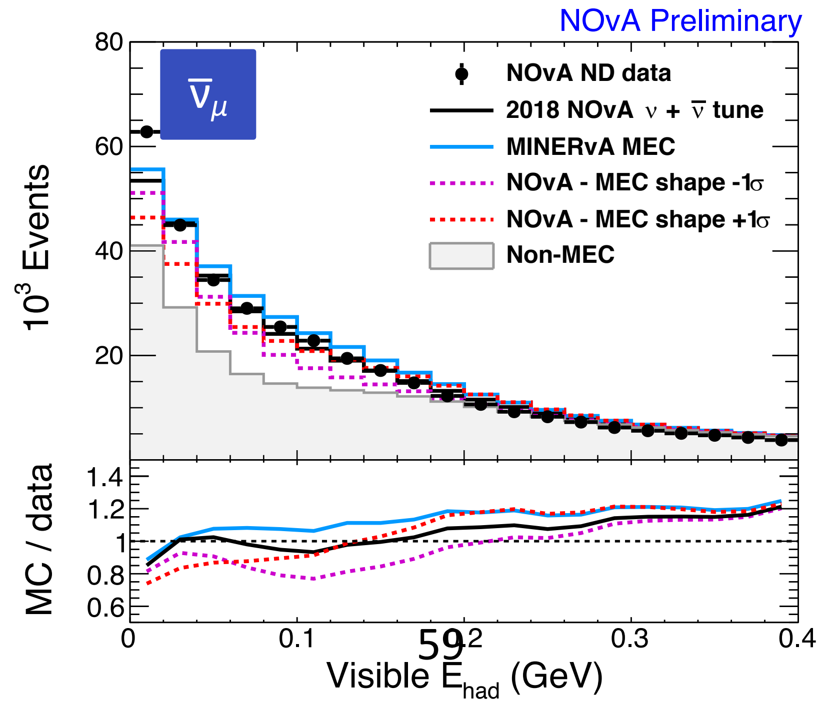
- Independently, **Minerva*** has also tuned a multi-nucleon component to their data.
- The resulting tune is ~1σ away from the NOvA tune.





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

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

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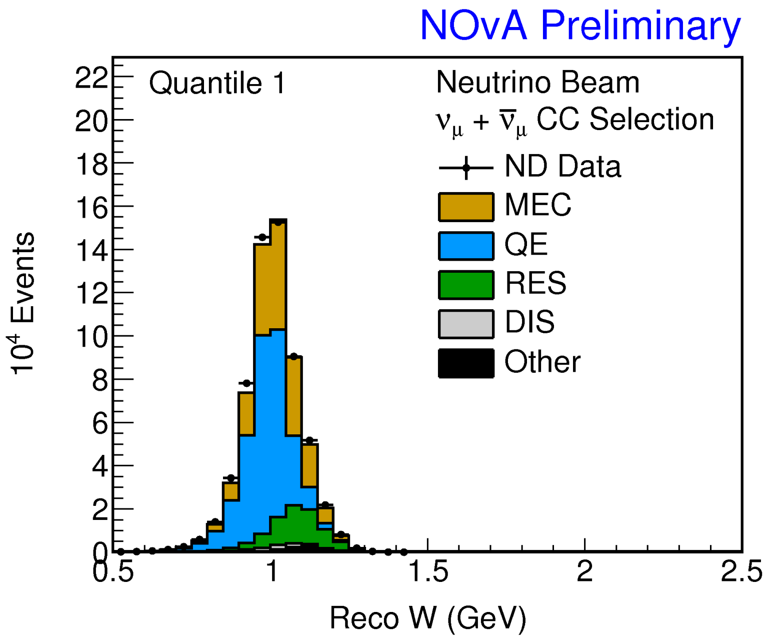
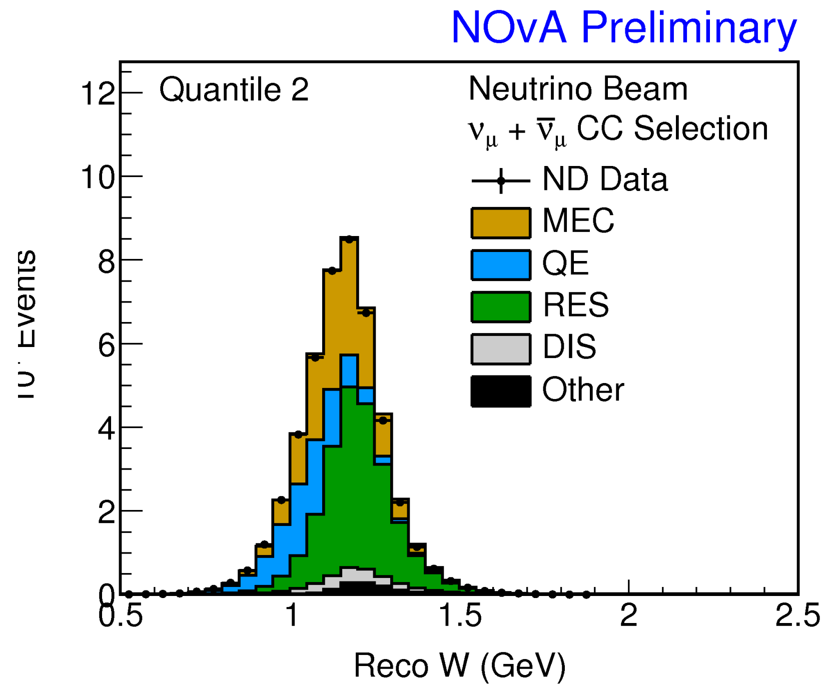
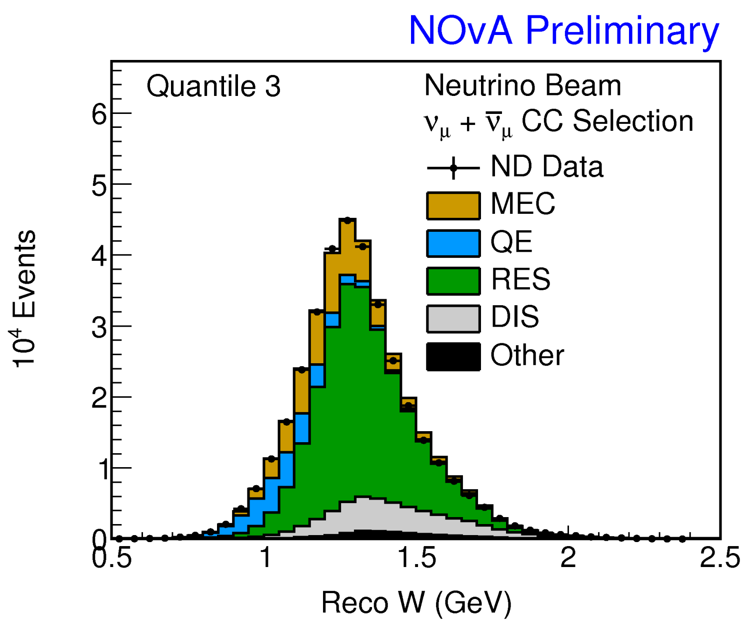
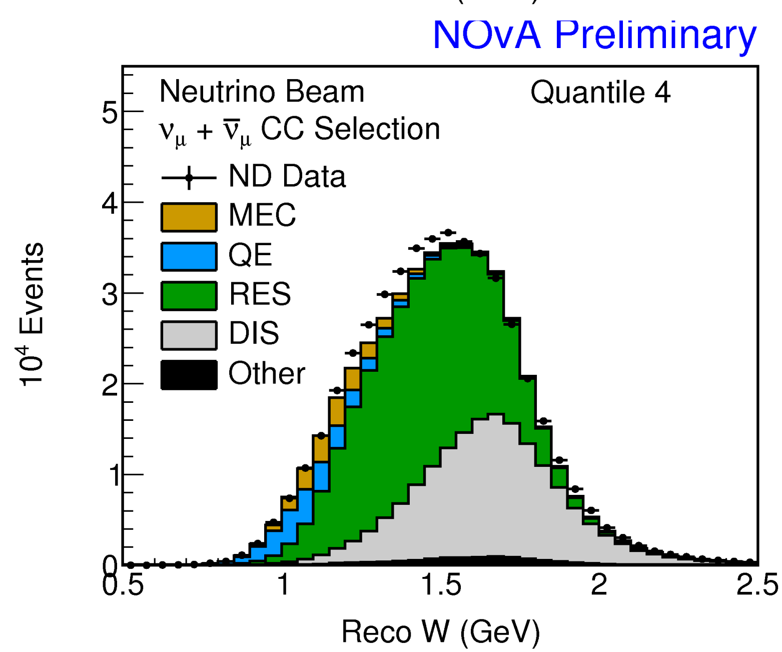
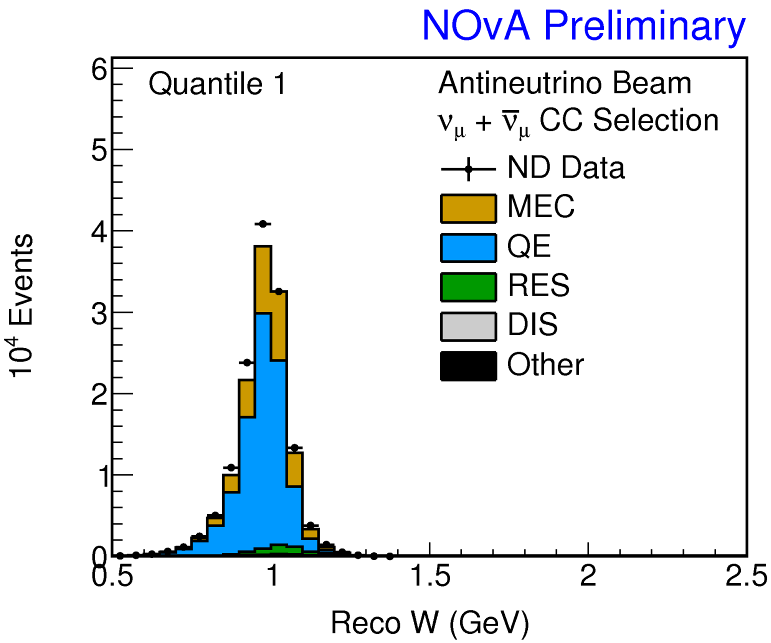
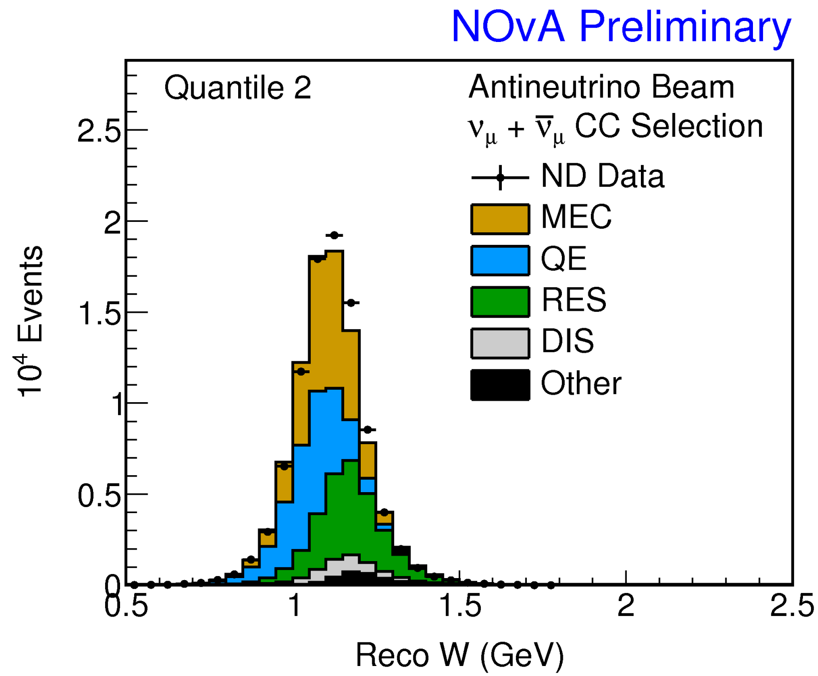

NOvA Preliminary
Quantile 1
Neutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)

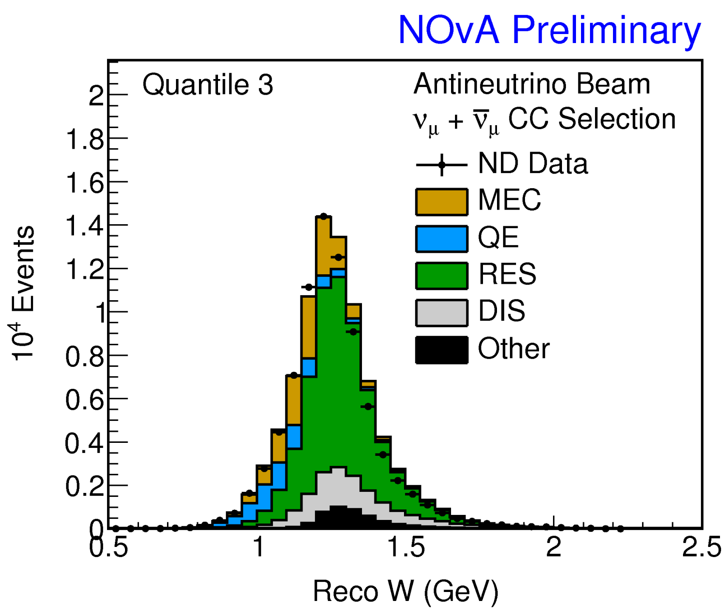

NOvA Preliminary
Quantile 2
Neutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
Events
Reco W (GeV)

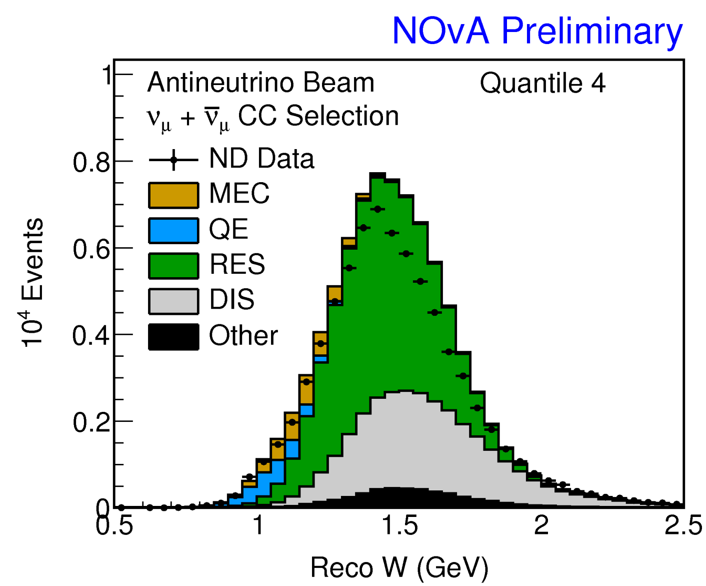

NOvA Preliminary
Quantile 3
Neutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)


NOvA Preliminary
Neutrino Beam
Quantile 4
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)

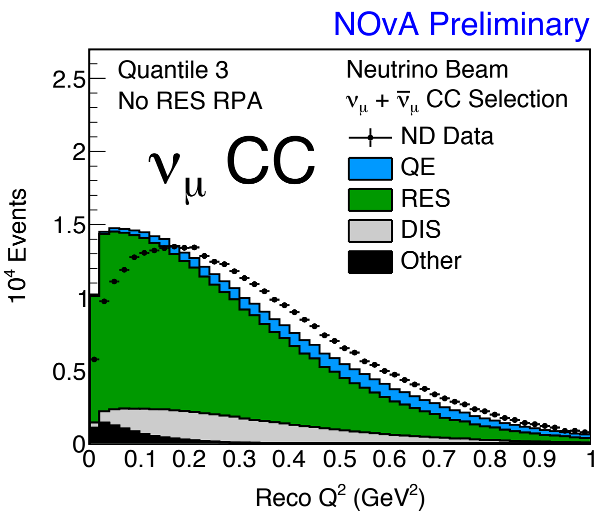

NOvA Preliminary
Quantile 1
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)
0
1
2
3
4
5
6
0.5
1
1.5
2
2.5

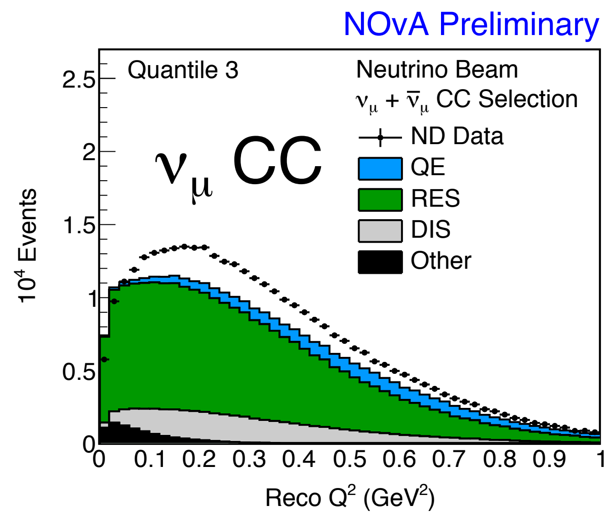

NOvA Preliminary
Quantile 2
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)
0
0.5
1
1.5
2
2.5
0.5
1
1.5
2
2.5


NOvA Preliminary
Quantile 3
Antineutrino Beam
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.5
1
1.5
2
2.5

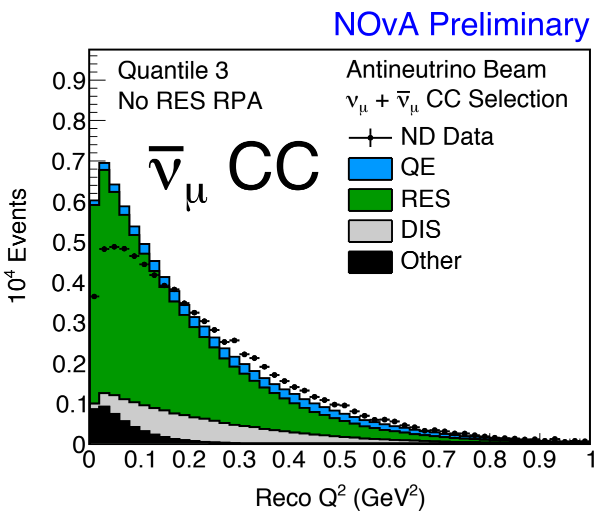

NOvA Preliminary
Antineutrino Beam
Quantile 4
$\nu_\mu + \bar{\nu}_\mu$ CC Selection
ND Data
MEC
QE
RES
DIS
Other
10^4 Events
Reco W (GeV)
0
0.2
0.4
0.6
0.8
1
0.5
1
1.5
2
2.5

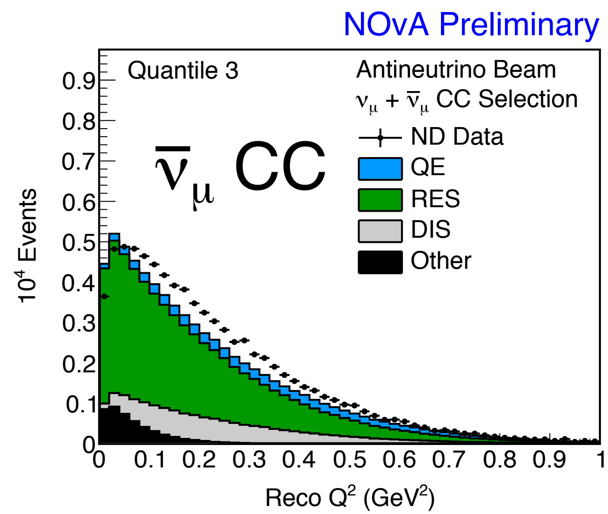
Resonance RPA





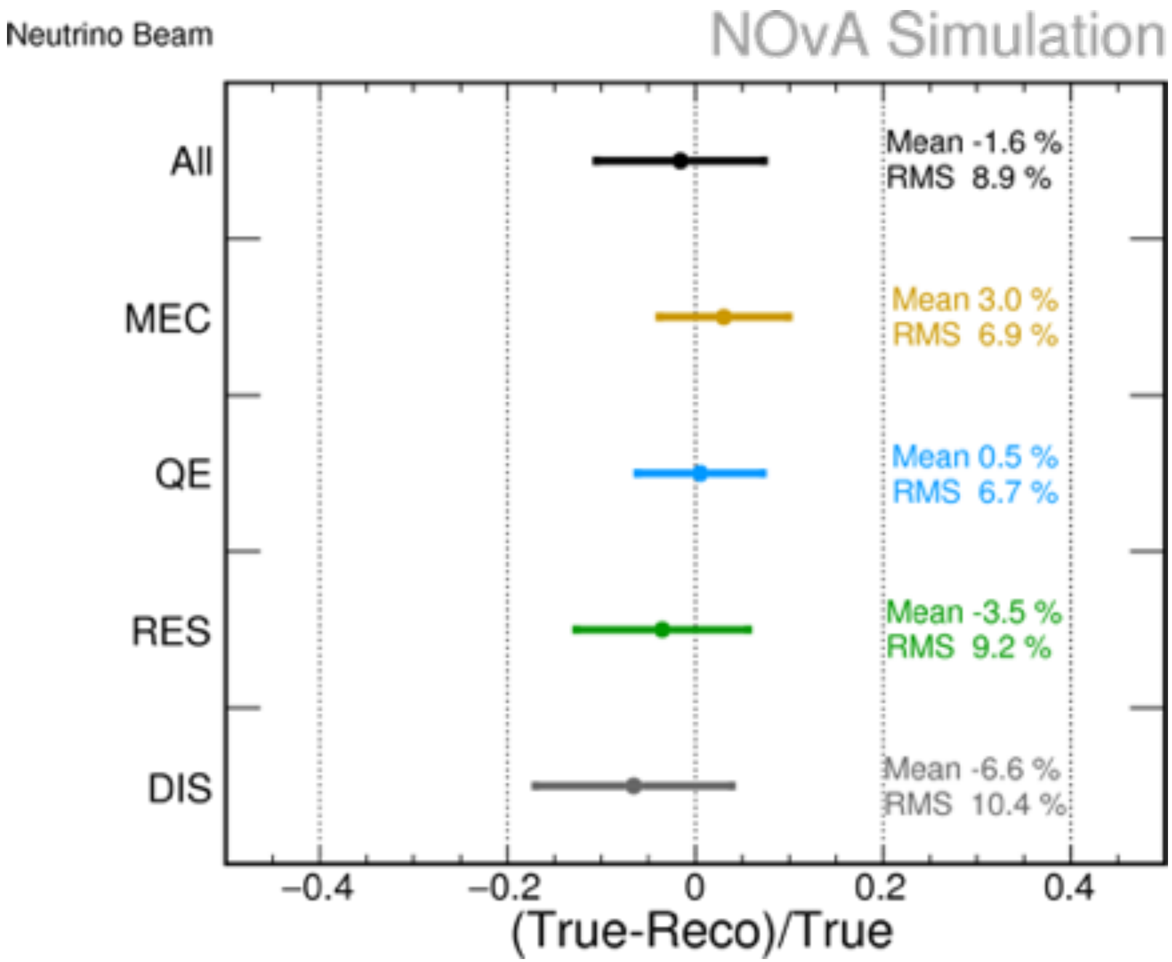
Applying
f(Q^2) Valencia
CCQE RPA
Effect to RES





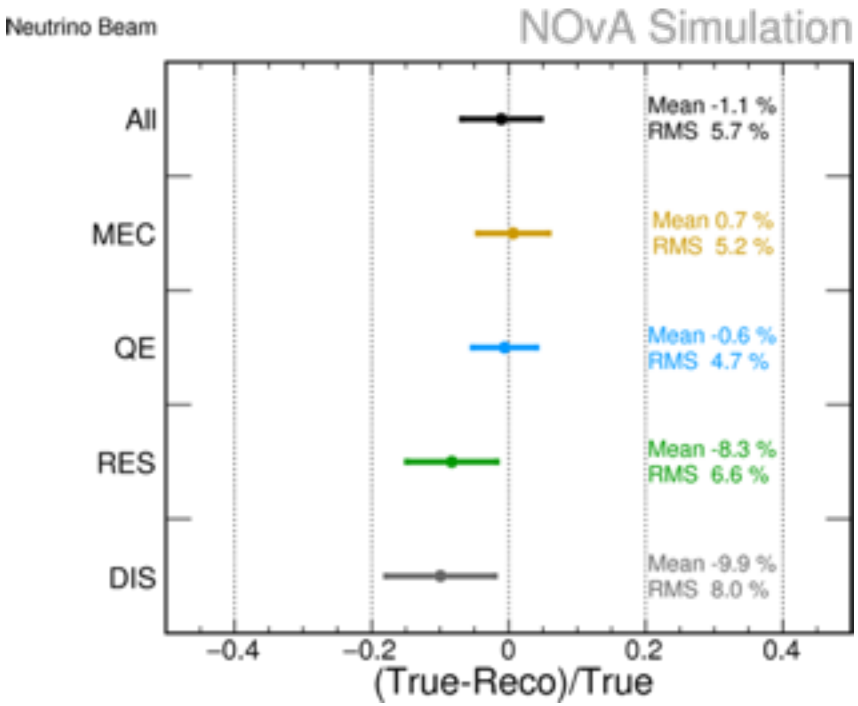
X

Energy difference and resolution for ν_μ events

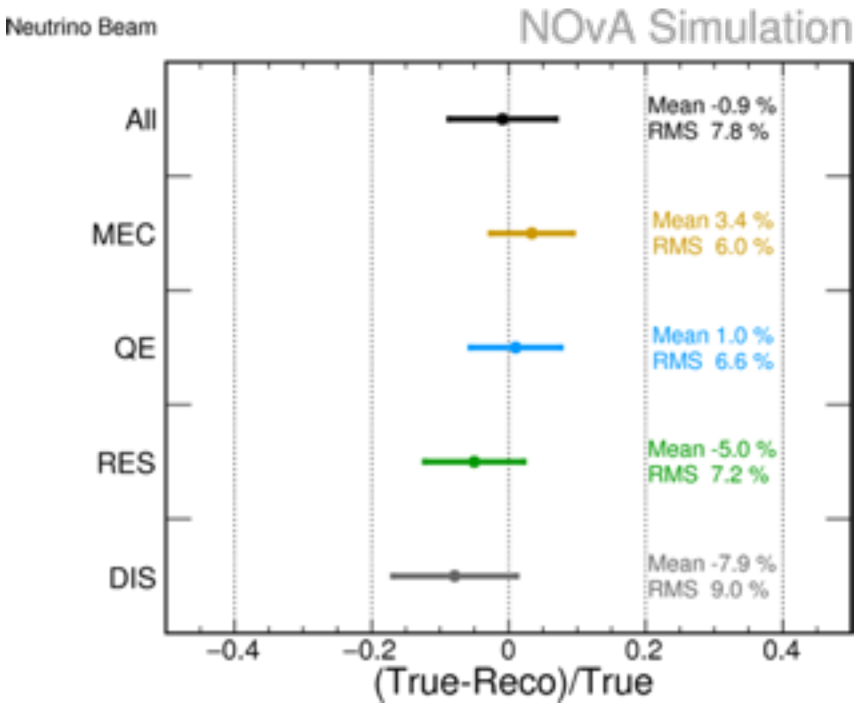


Energy difference and resolution for ν_μ events

Q1

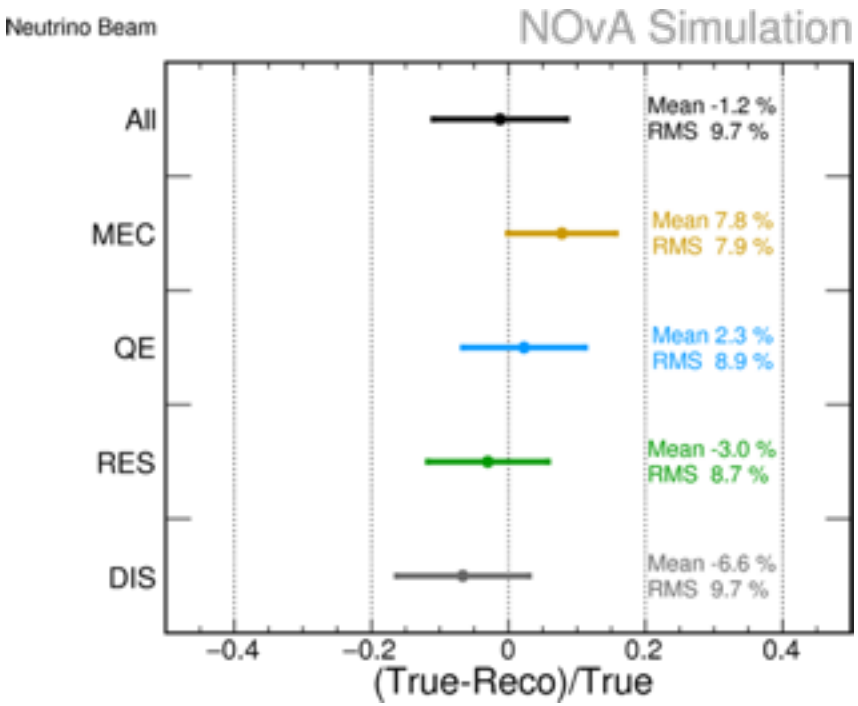


Q2

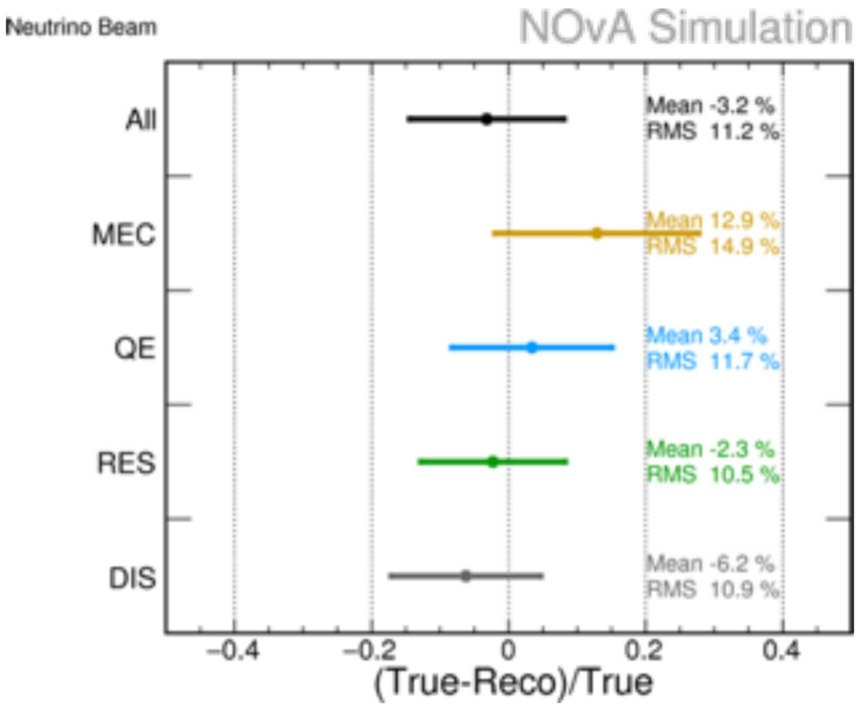


Energy difference and resolution for ν_μ events

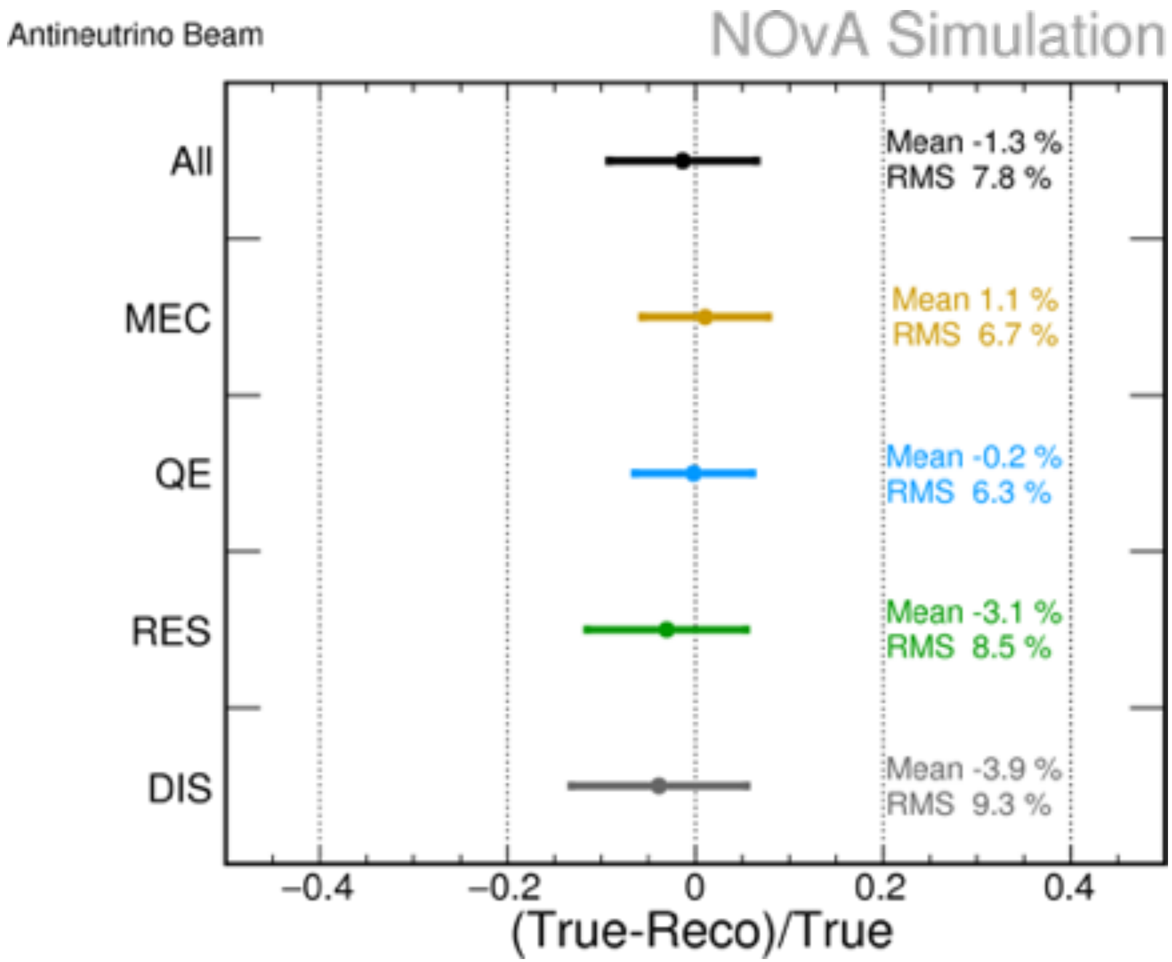
Q3



Q4

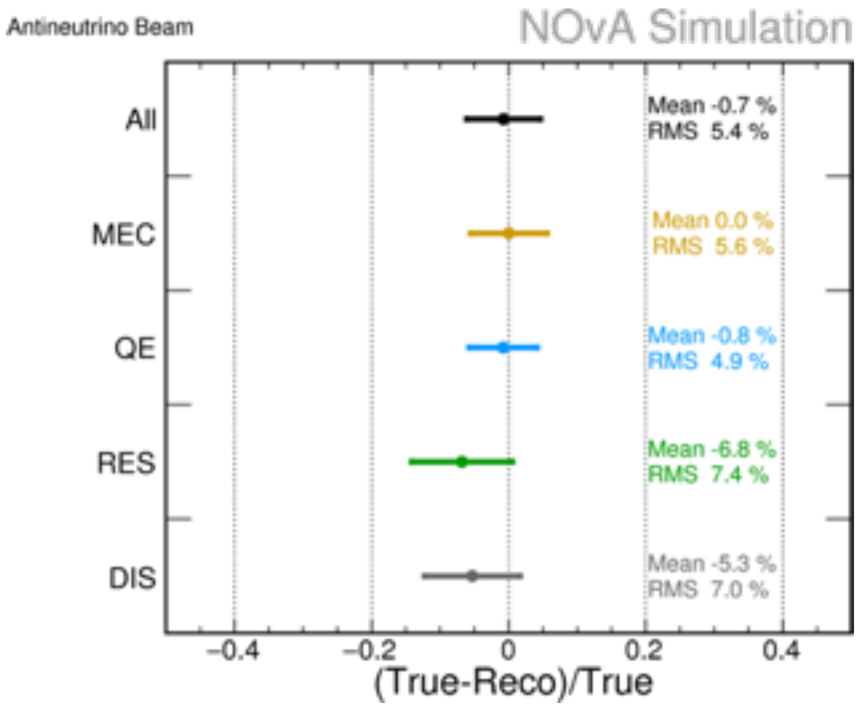


Energy difference and resolution for ν_μ events

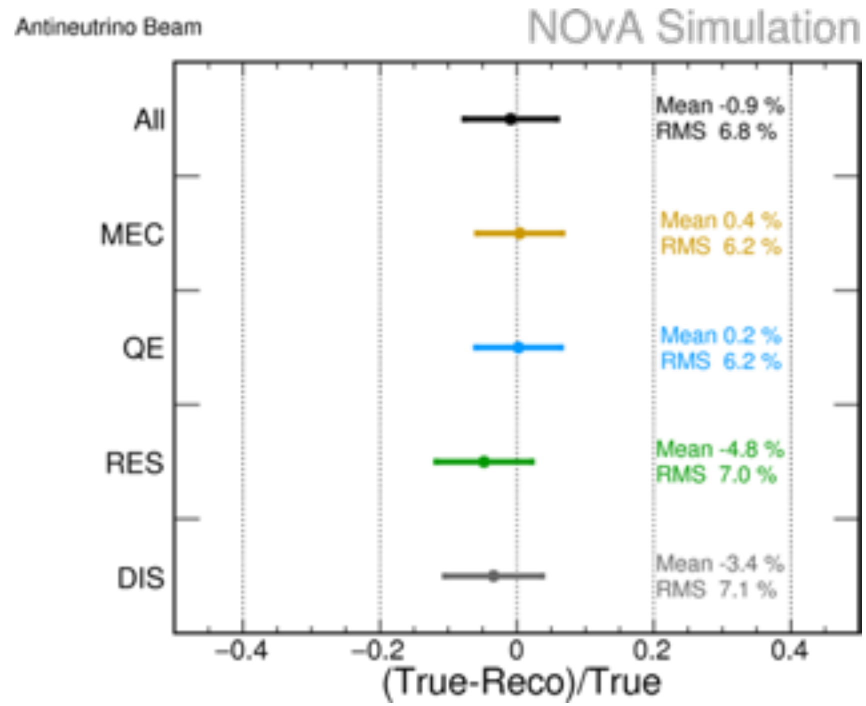


Energy difference and resolution for ν_μ events

Q1



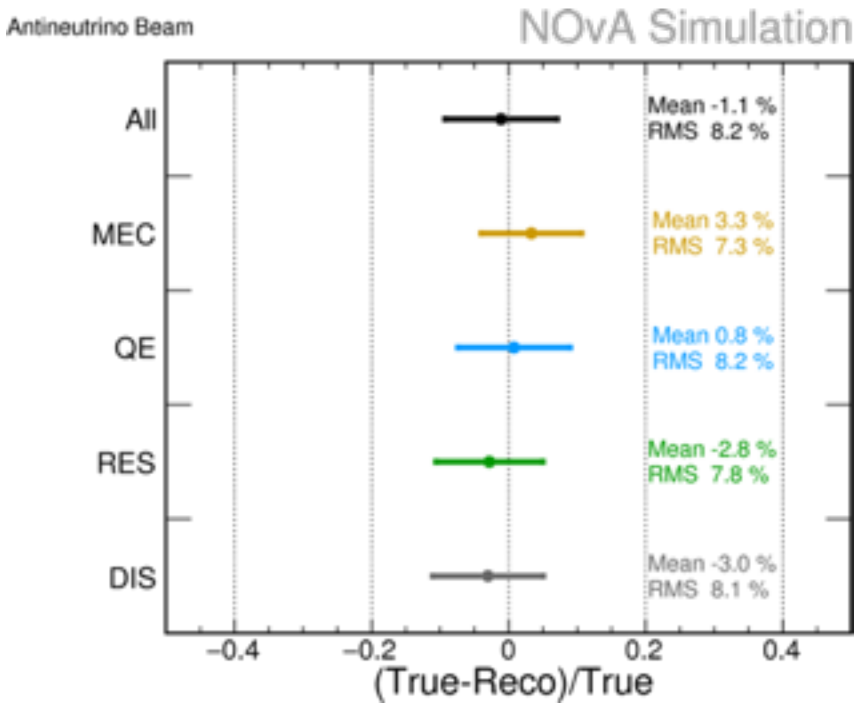
Q2

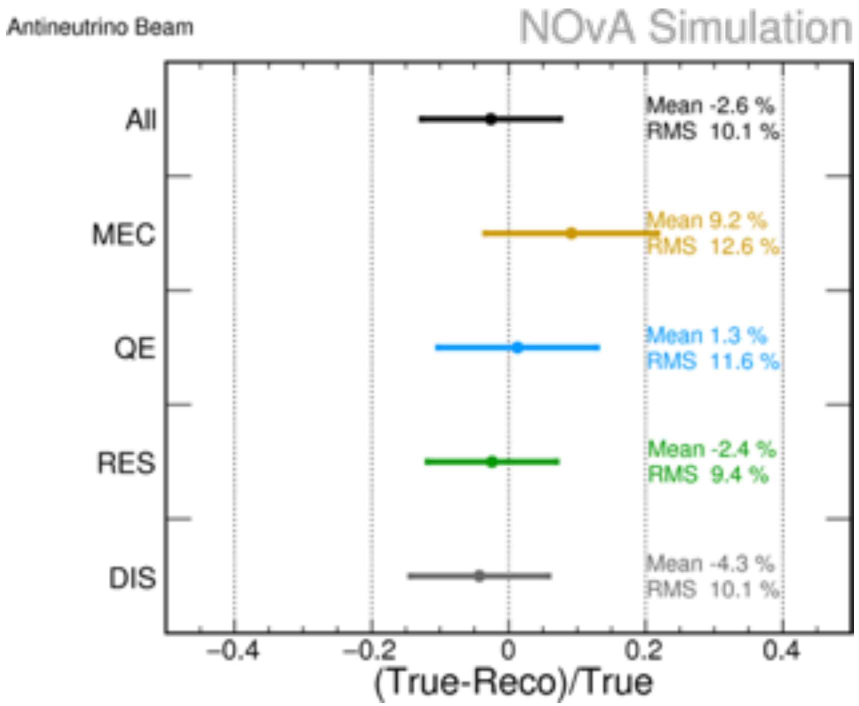


Energy difference and resolution for ν_μ events

Q3

Q4





Wichita State University