Latest neutrino oscillation results from NOvA

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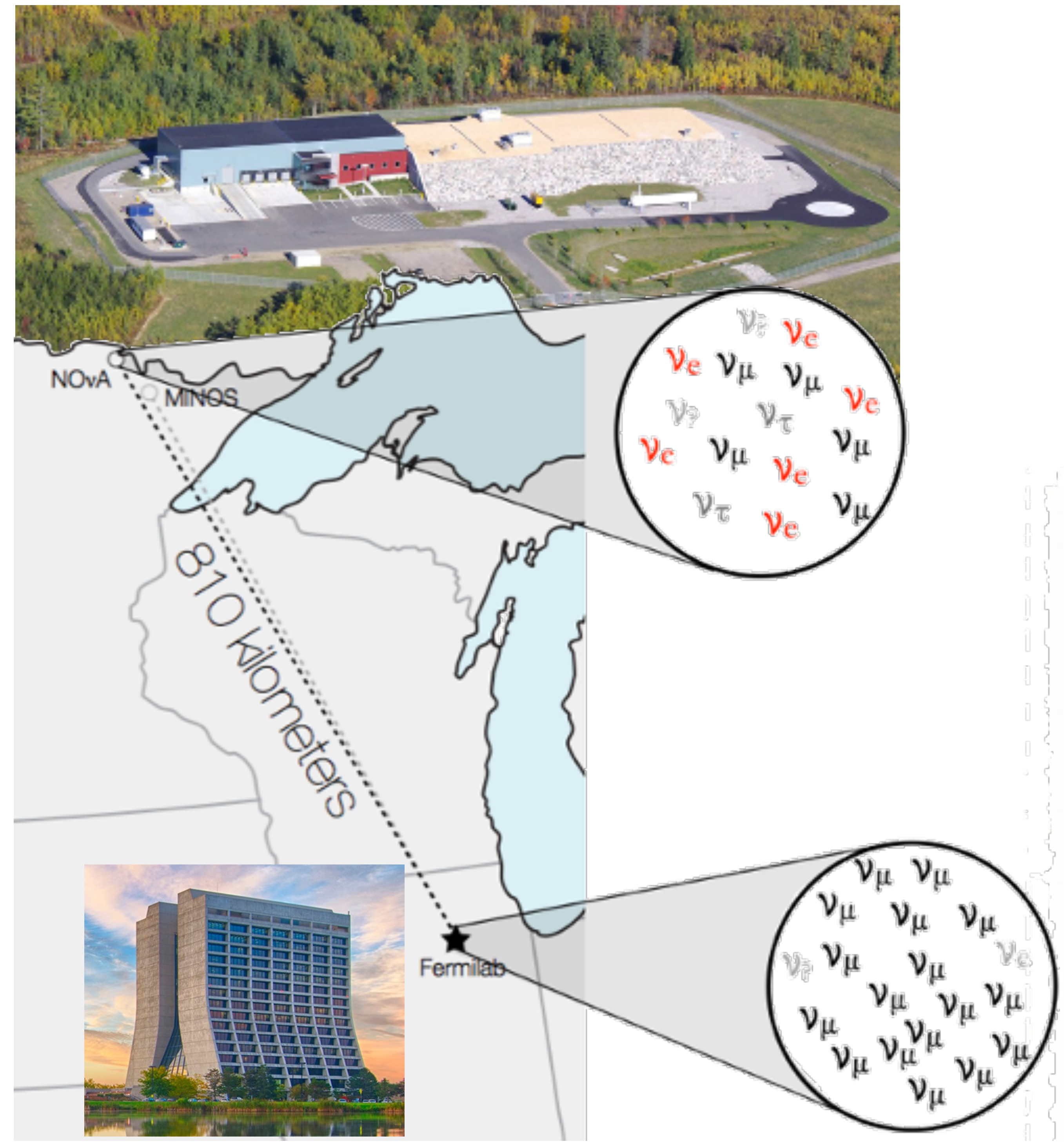
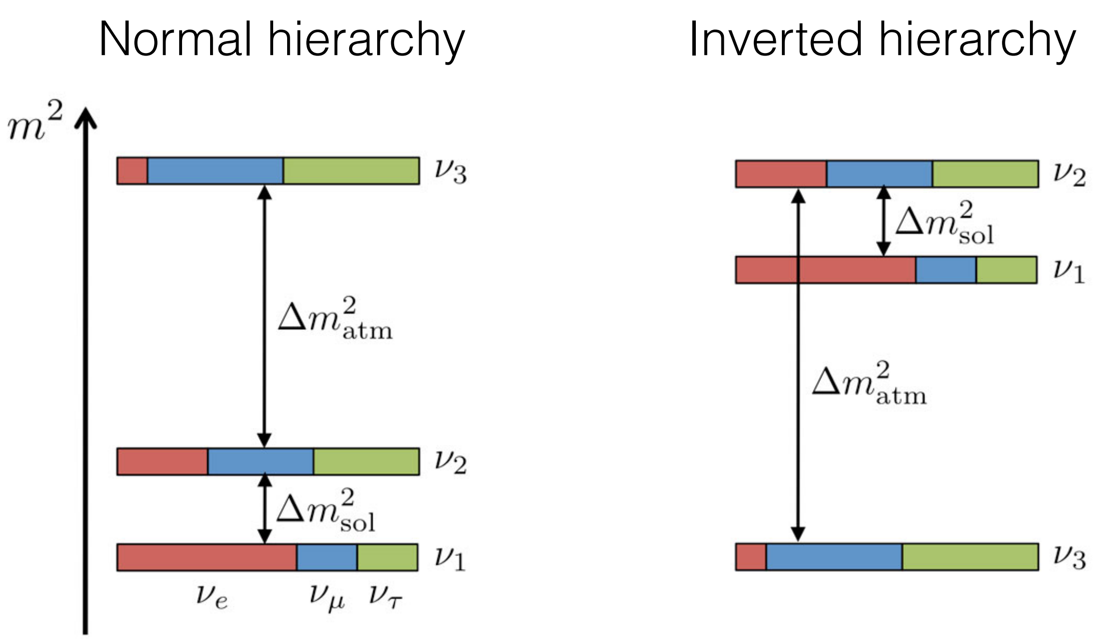
NOvA Experiment

- NOvA is a long-baseline neutrino experiment based in Fermilab, Illinois and Ash River, Minnesota
- NuMI beam can supply ν_μ or anti-ν_μ of around 2 GeV energy
- 2 off-axis liquid scintillator tracking calorimeters
  - Near detector
    - 300 T underground
    - 1 km away from the target
  - Far detector
    - 14 kT on the surface
    - 810 km away from the target

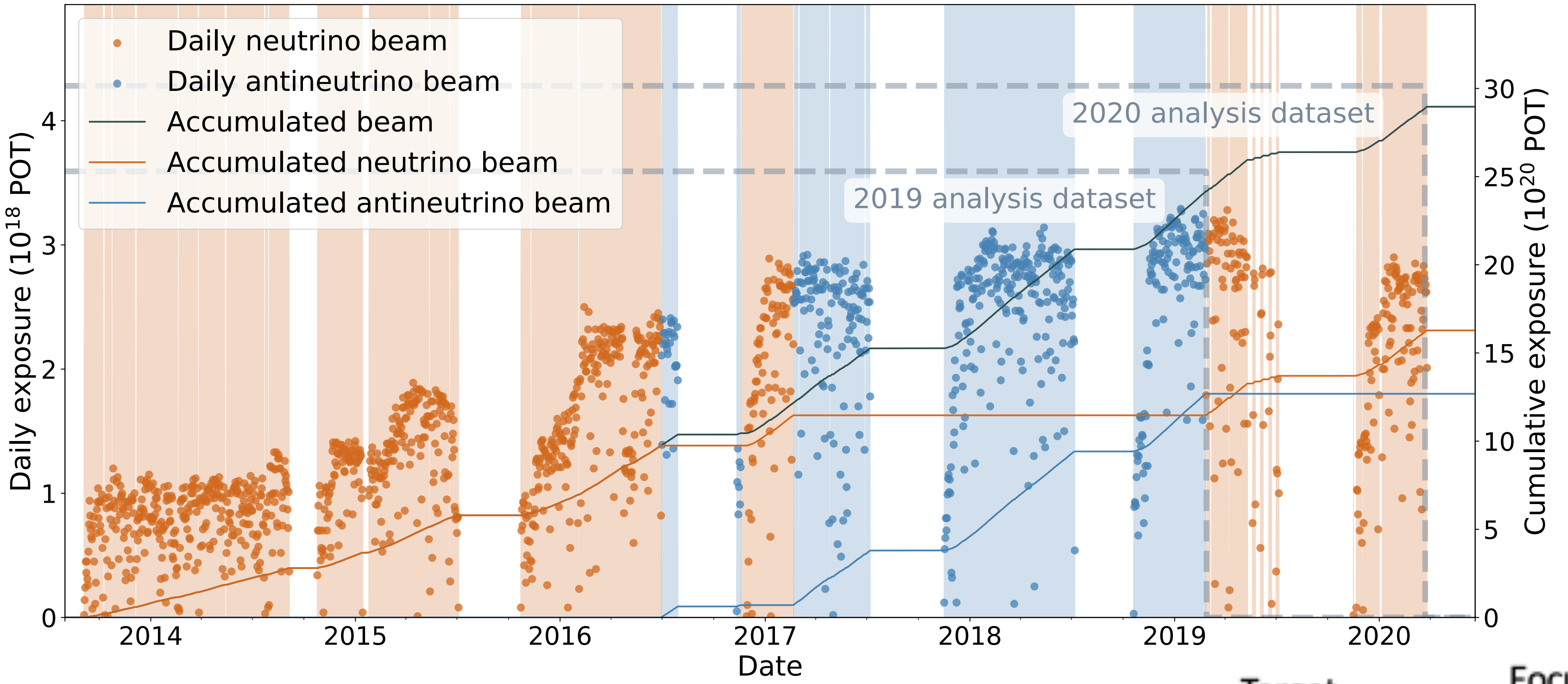


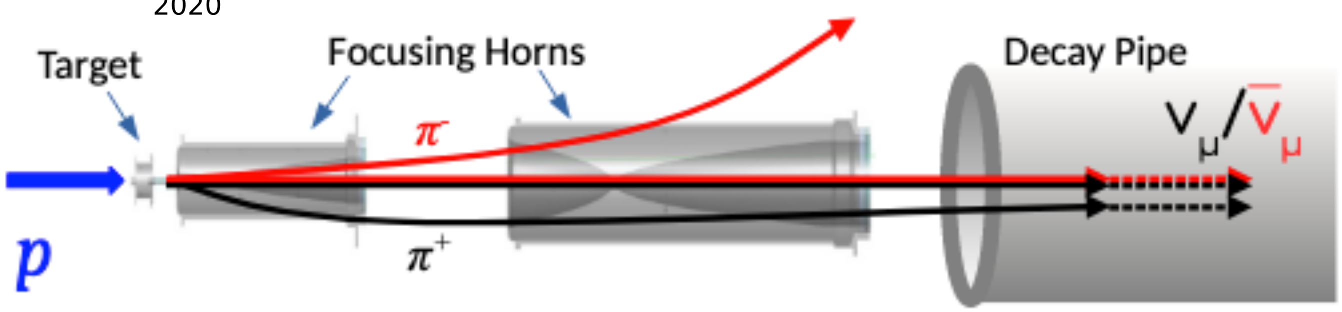
NOvA physics goals

- NOvA measures
  - (anti-) $\nu_\mu \rightarrow$ (anti-) ν_μ
  - (anti-) $\nu_\mu \rightarrow$ (anti-) ν_e
- Sensitive to neutrino mixing parameters
  - Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$
- Open questions in neutrino physics:
  - Neutrino mass hierarchy
  - CP violation
  - θ_{23} maximal



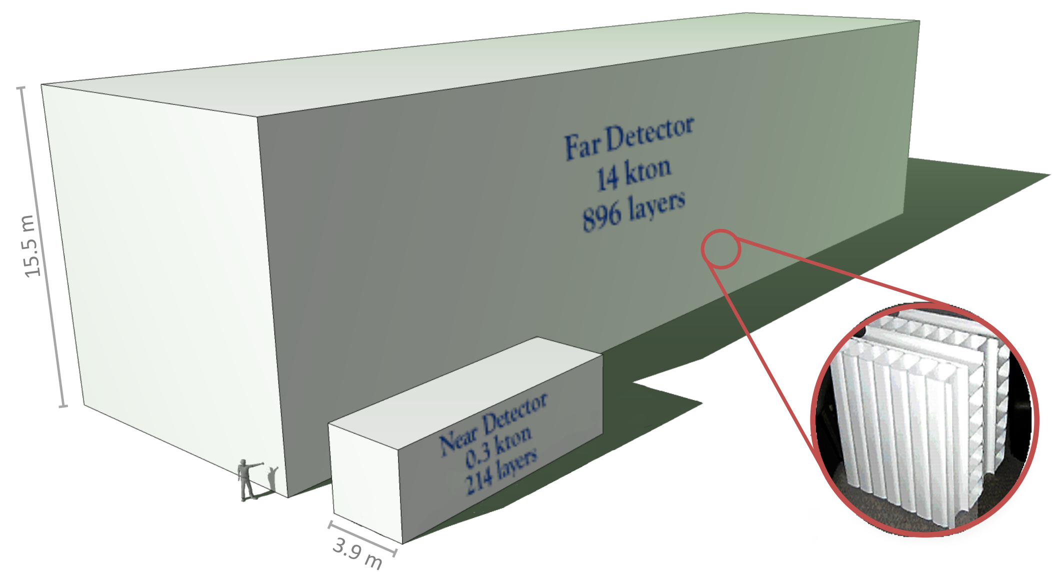
NuMI beam

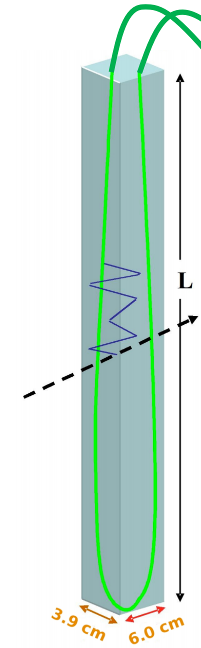


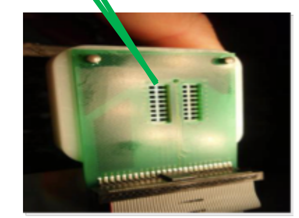


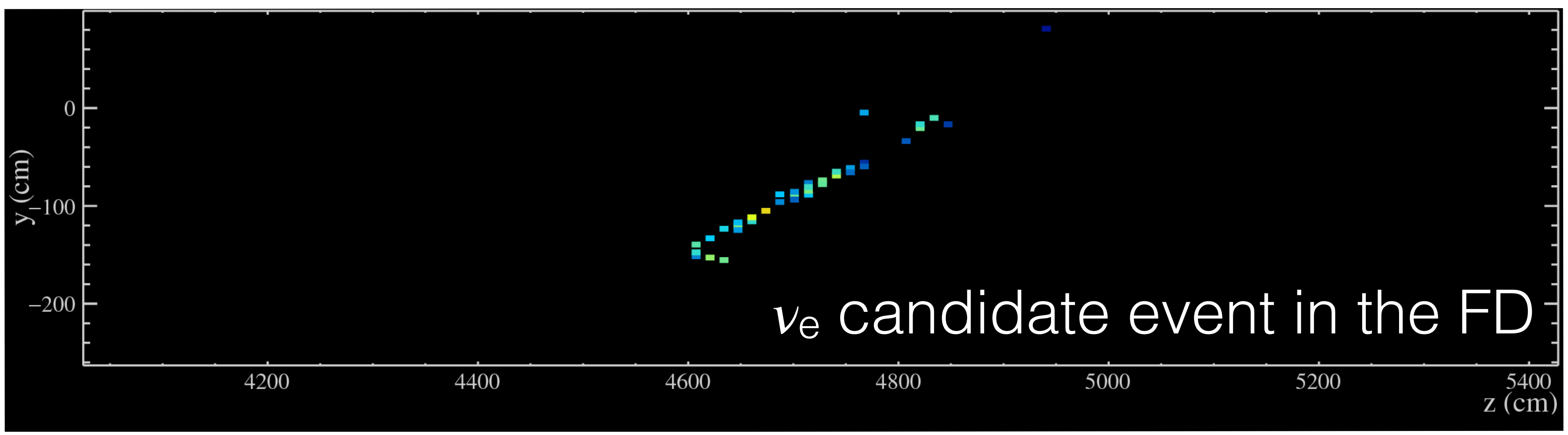
- Neutrinos mainly created with pions decay in flight, after protons impact the target
- Typical power 670 kW, peaking at 812 kW
- Working towards > 900 kW beam

NOvA detectors





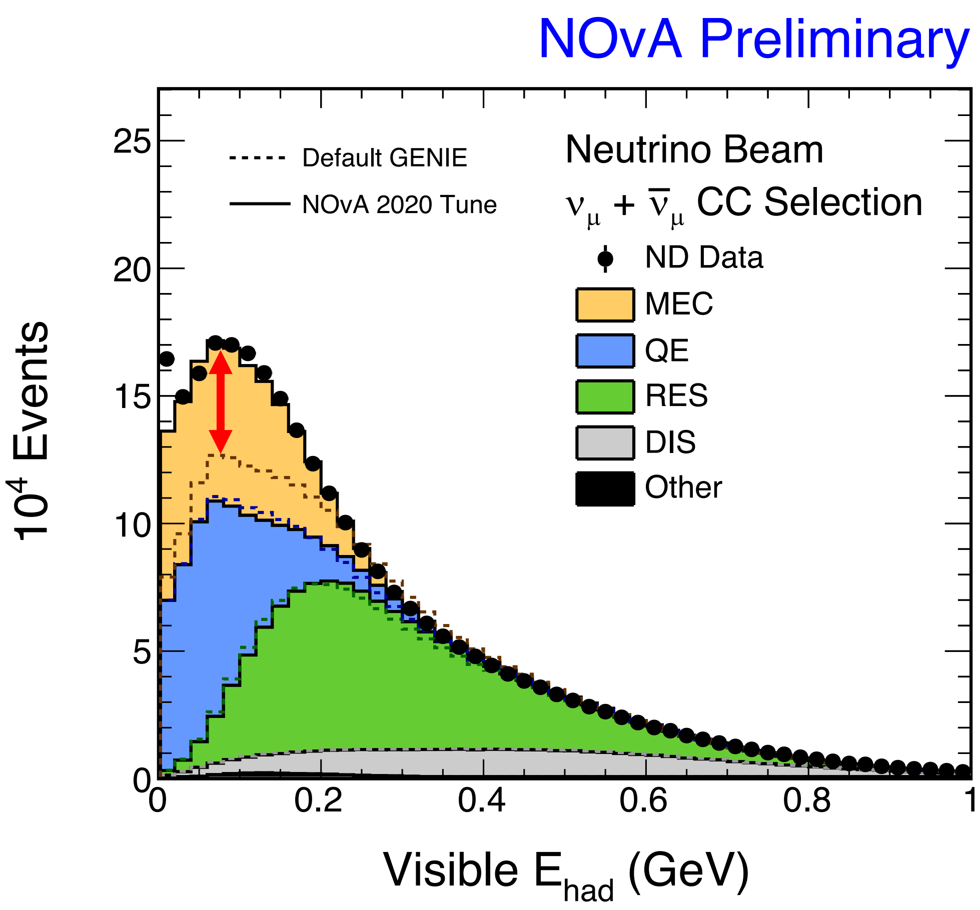




- 2 functionally identical near and far detectors
- Composed of extruded PVC cells, filled with liquid scintillator
- Wavelength shifting fibres carry the light to the avalanche photo-diodes
- Produces neutrino images

Simulation

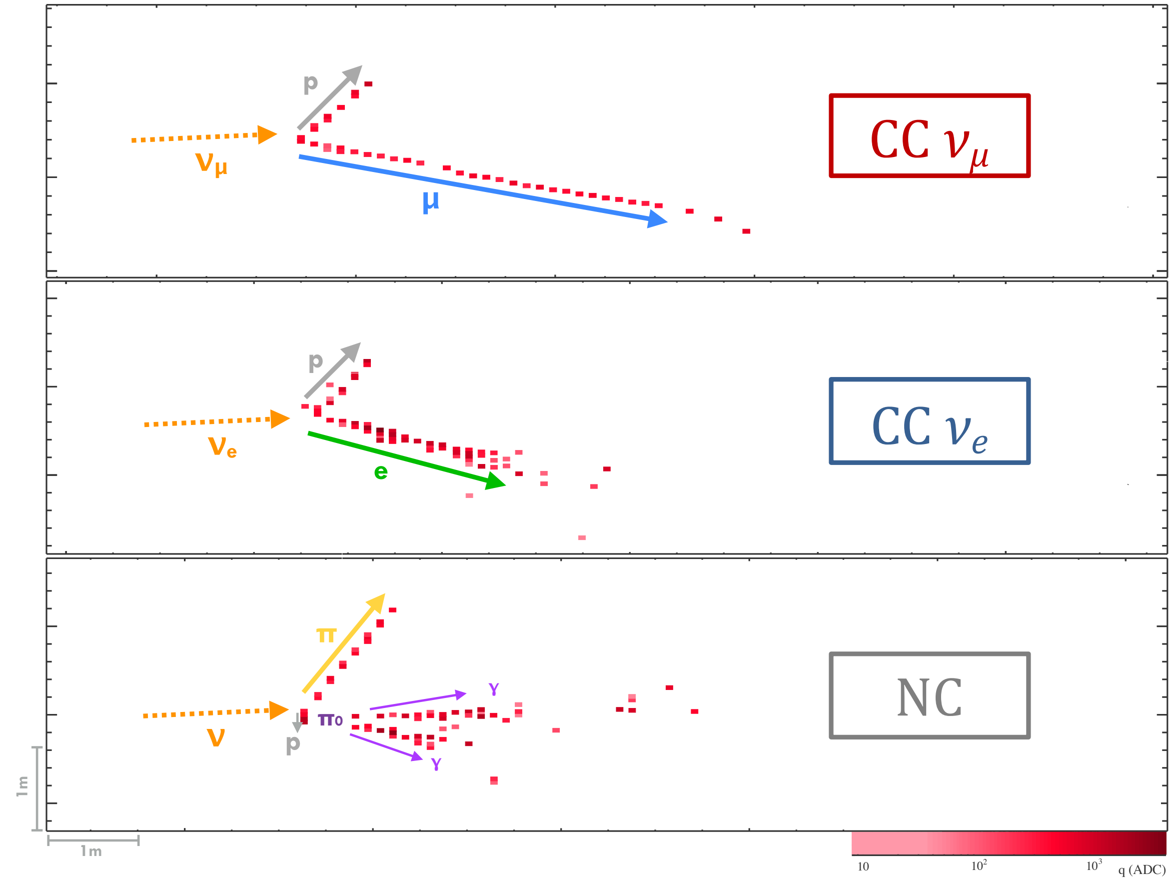
- Neutrino interactions are generated with GENIE (v3.0.6)
  - Retune of GENIE collaboration's cross section parameters
- Still not enough to explain ND data, additional data-driven tune is required
- Particle propagation done with GEANT4



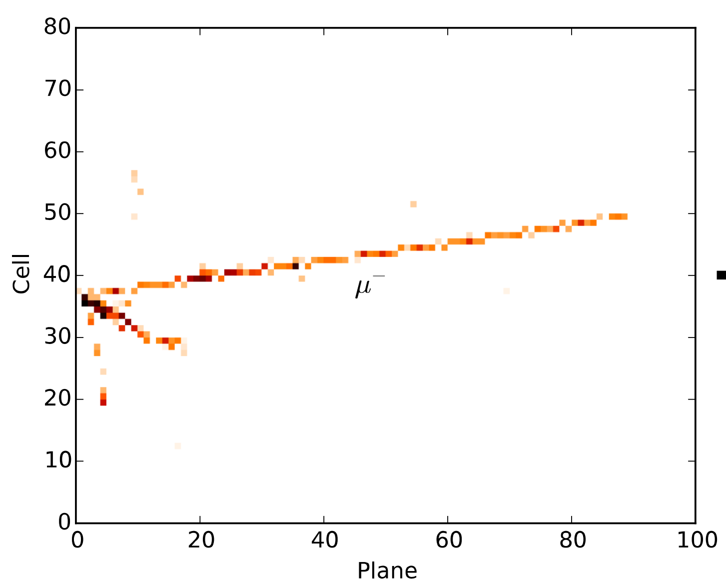
Process	Model	Reference
Quasielastic	Valencia 1p1h	J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C 70 (2004) 055503
Form Factor	Z-expansion	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
Multi-nucleon	València 2p2h	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D 88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D 76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Int.	hN semi-classical cascade	S. Dytman, Acta Physica Polonica B 40 (2009)

Particle Identification

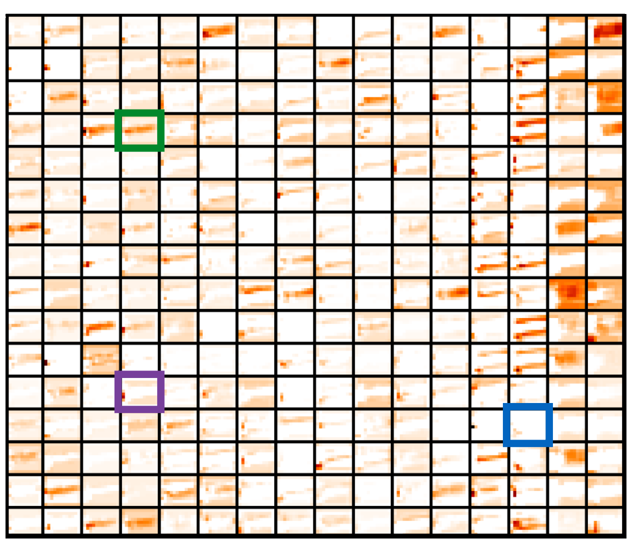
- Convolutional neural network used to identify neutrino species and interactions
  - Machine vision, artificial intelligence technique
  - Learns topological features
  - Differentiate between ν_e, ν_μ, NC and cosmic



Input Image



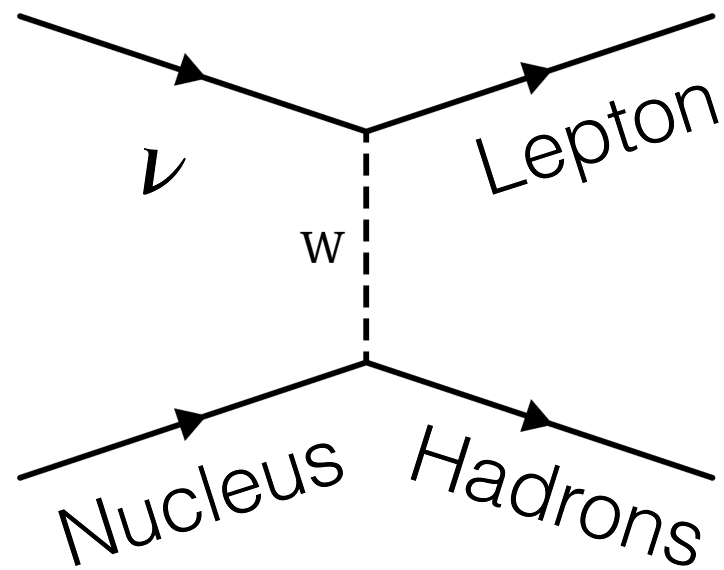
Learned variations on the original image



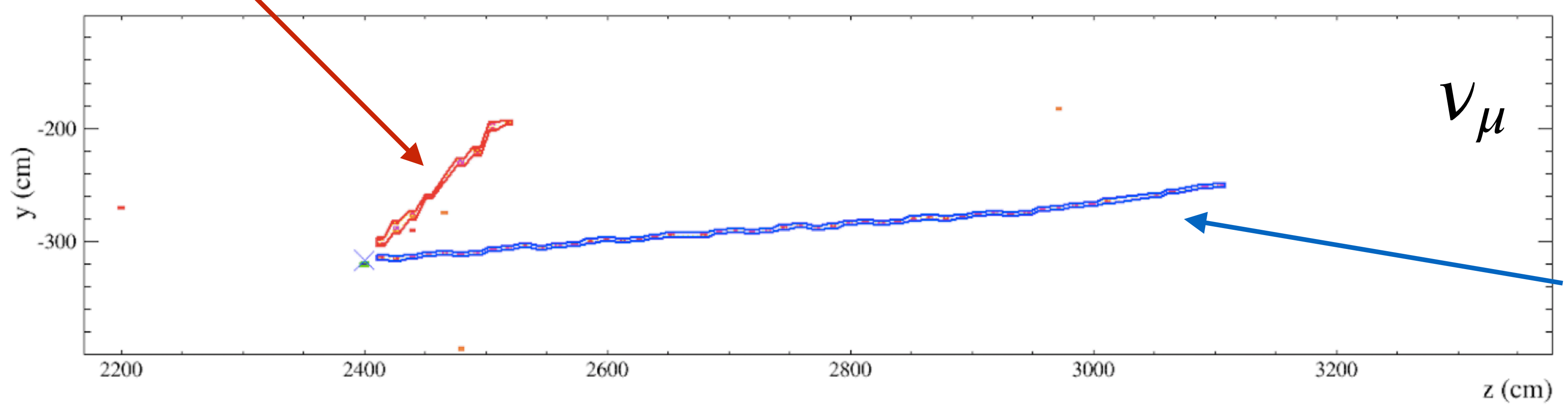
ν_e
ν_μ
NC
Cosmic

Energy reconstruction

- $E\nu_\mu = f\,(E_\mu, E_{hadronic})$
- $E\nu_e = f\,(E_{EM}, E_{hadronic})$

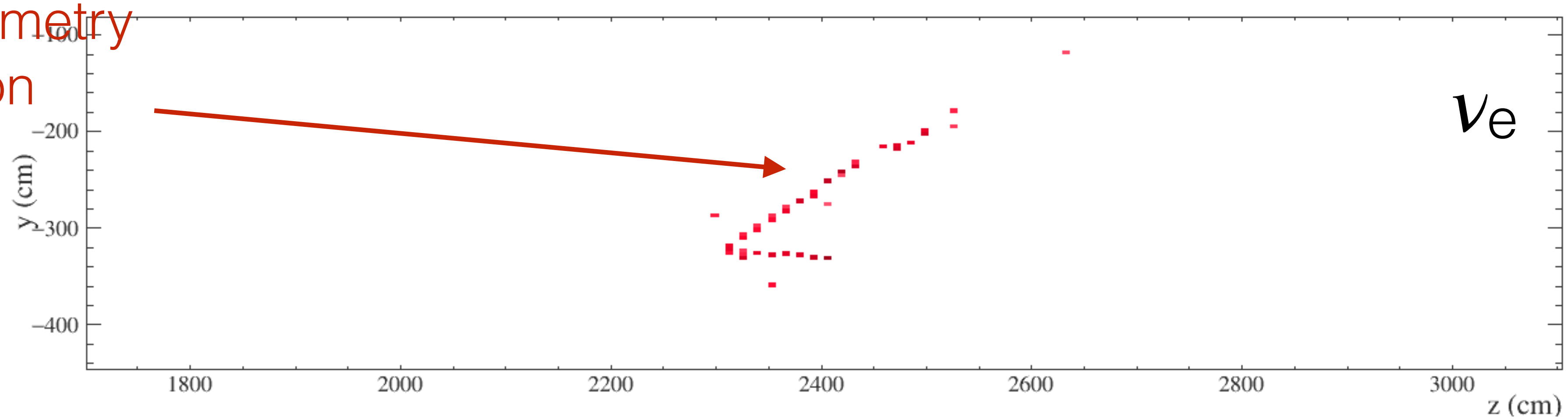


Hadrons:
$E_{hadronic}$ from calorimetry
~30% resolution



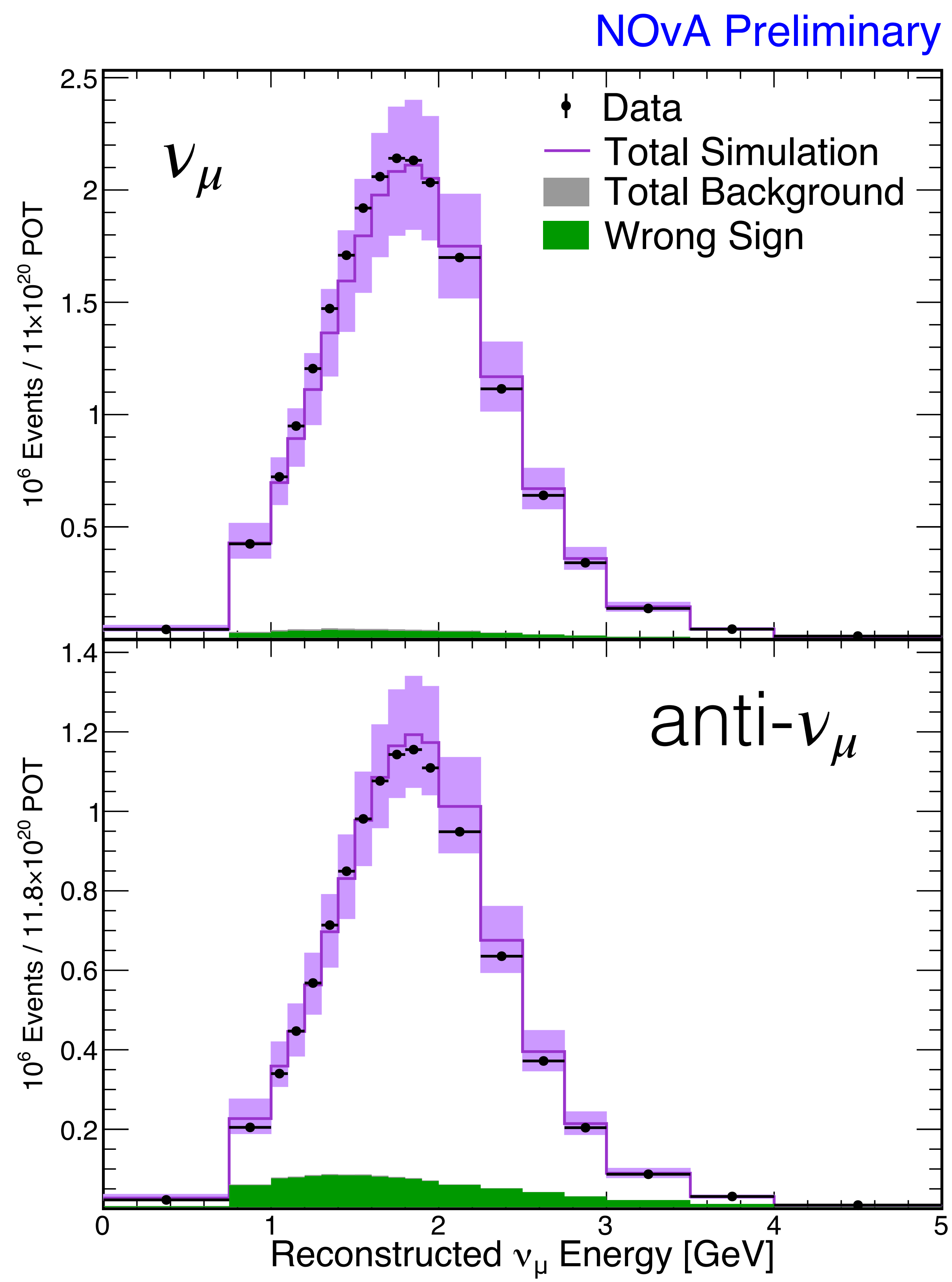
Muon:
E_μ from range
~4% resolution

EM shower:
E_{EM} from calorimetry
~10% resolution



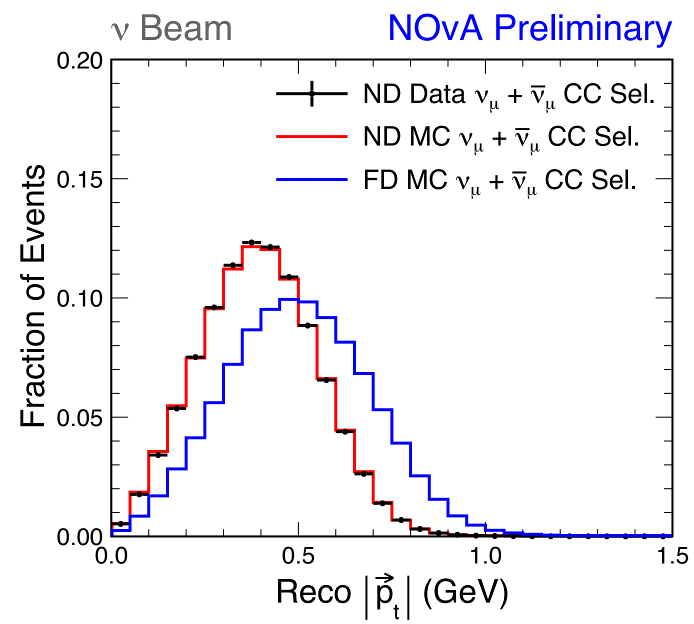
ND ν_μ samples

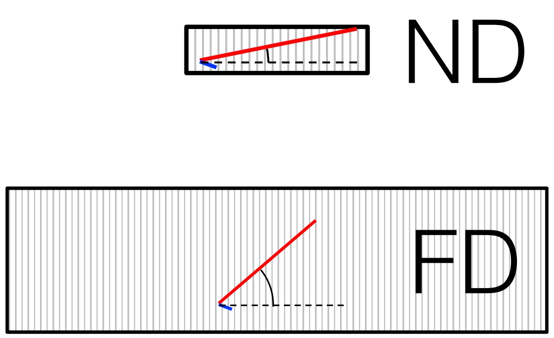
- ND muon neutrinos are used to infer the energy distribution of the neutrinos at the FD
- Systematic uncertainties dominate on absolute, single detector measurement
  - Able to test flux and cross section model in detail

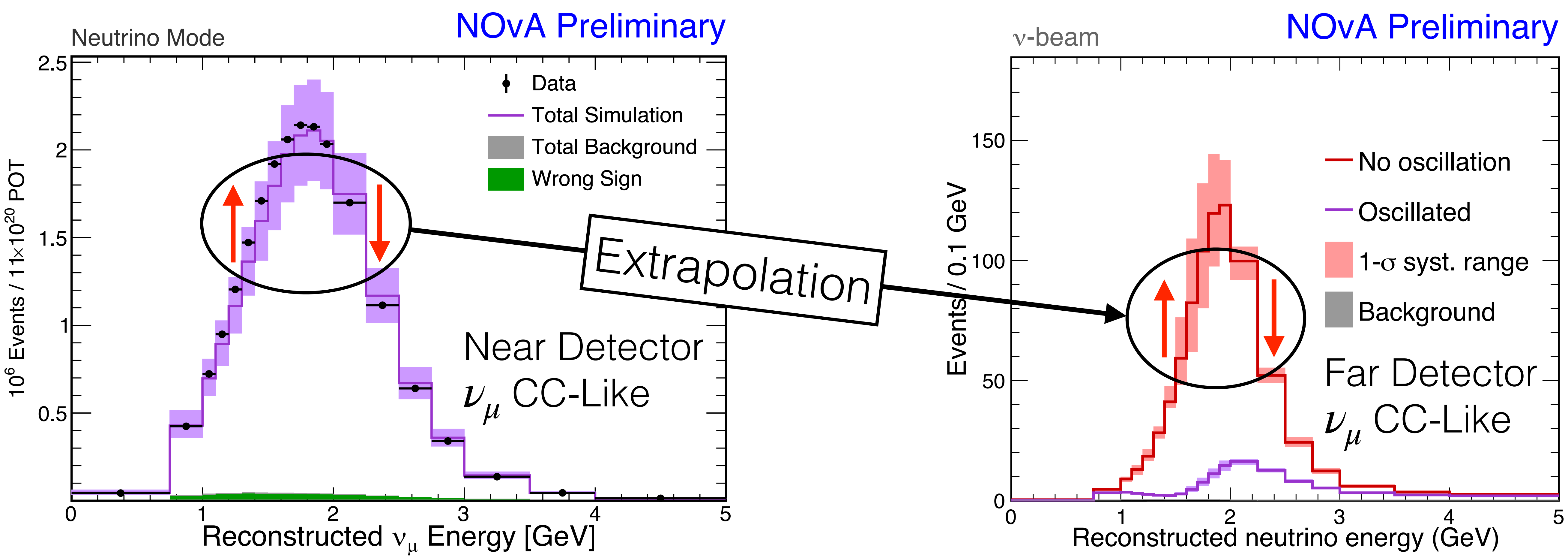


Extrapolation

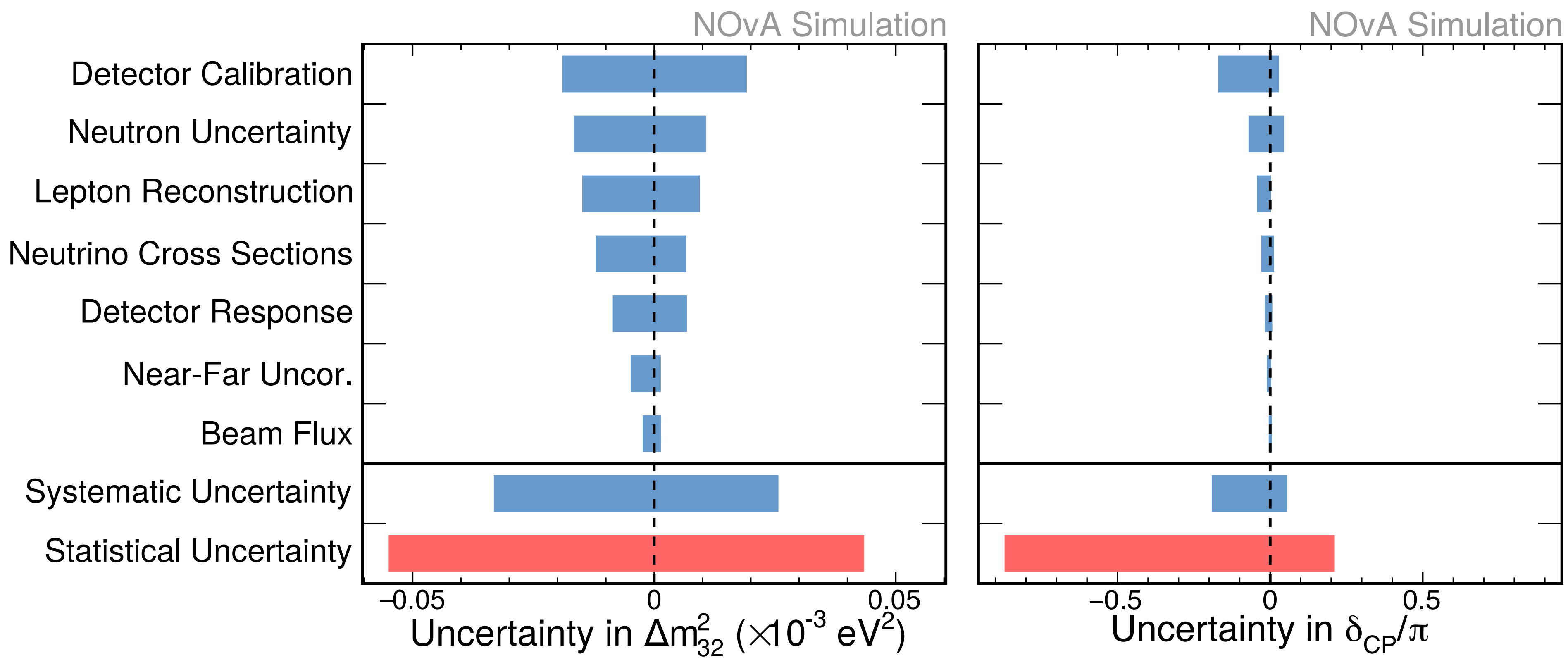
- Extrapolation procedure designed to mitigate impact of systematics
  - Neutrino energy
  - Reconstructed hadronic energy fraction
  - Reconstructed lepton transverse momentum





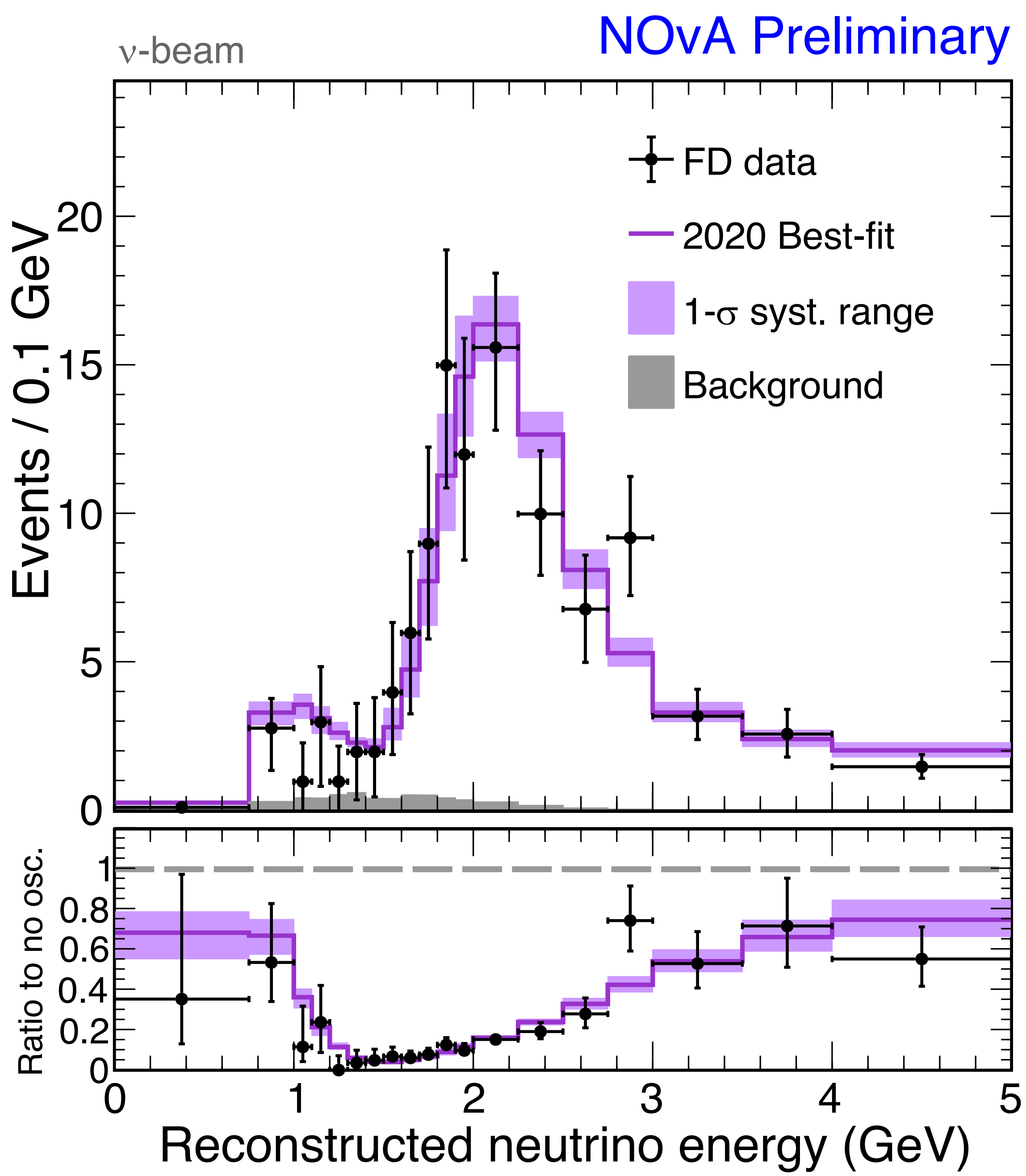


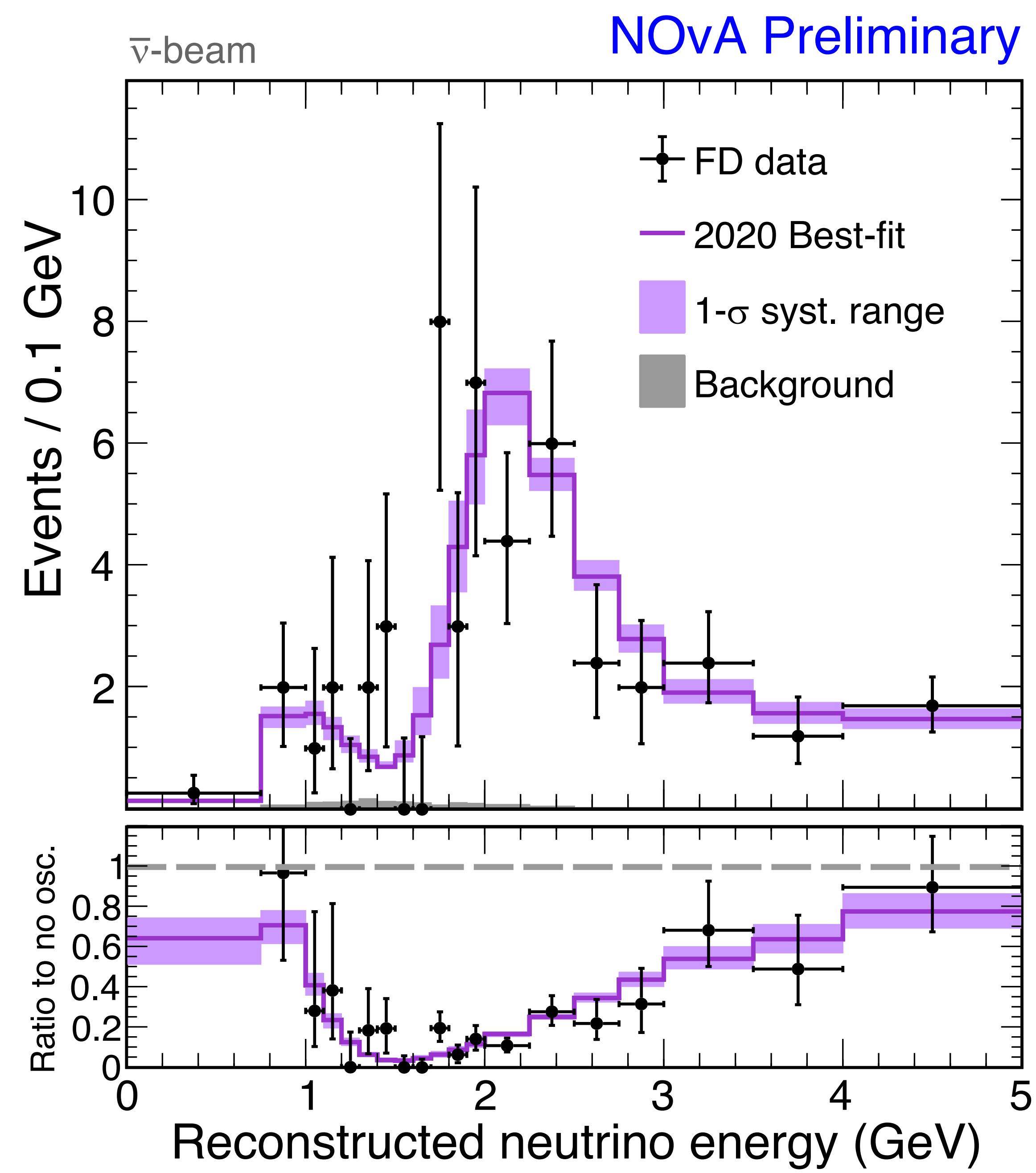
Systematic uncertainties



- δ_{CP} largely dominated by statistical uncertainty, Δm^2_{32} less so
- Largest systematic is the detector calibration across all our measured parameters
  - Test beam can help us understand these
- Neutrino cross section *is not* the main source of uncertainty
  - Similarity of the ND and the FD
  - Robustness of our energy reconstruction and the extrapolation procedure
- Work ongoing to improve our neutron model

FD ν_μ samples

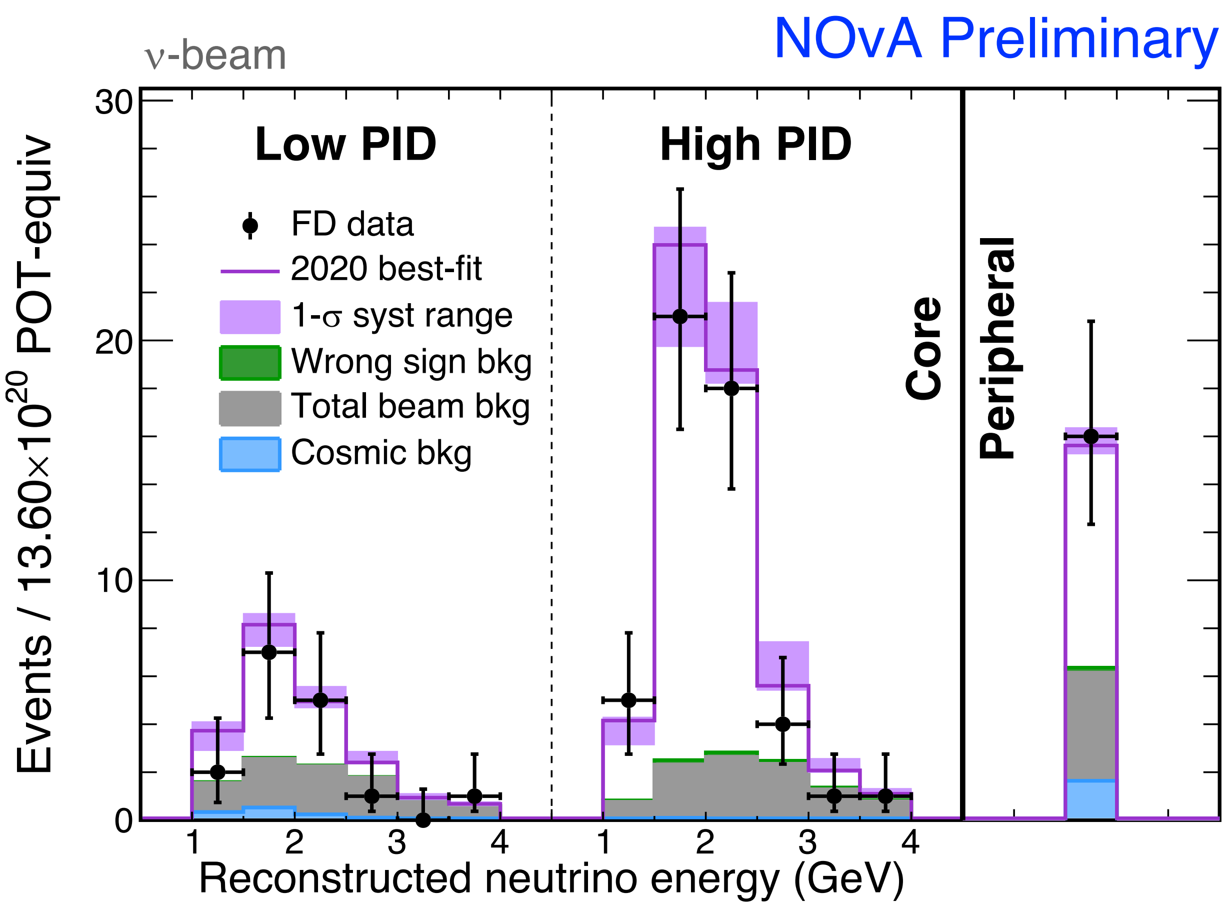


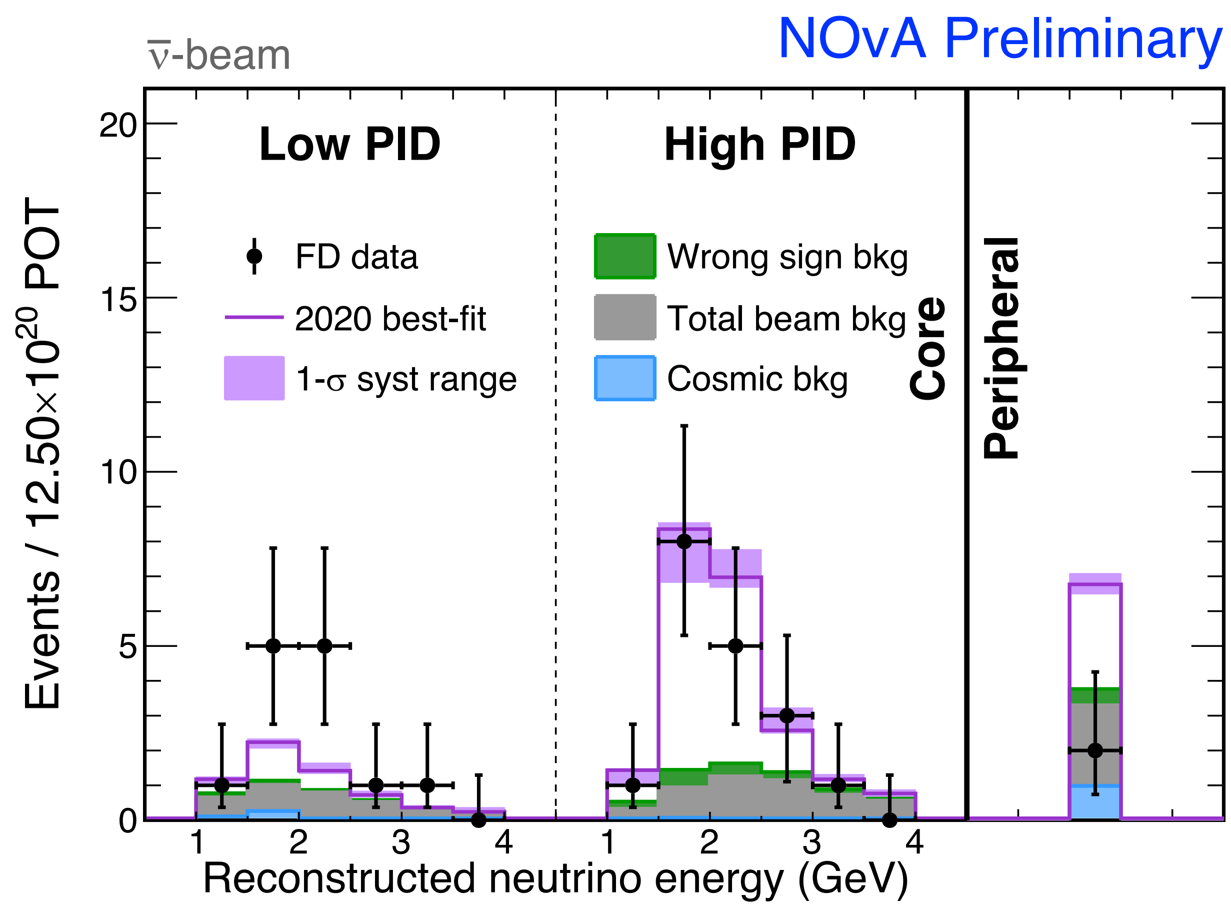


211 events in neutrino mode
8.2 background events

105 events in anti-neutrino mode
2.1 background events

FD ν_e samples

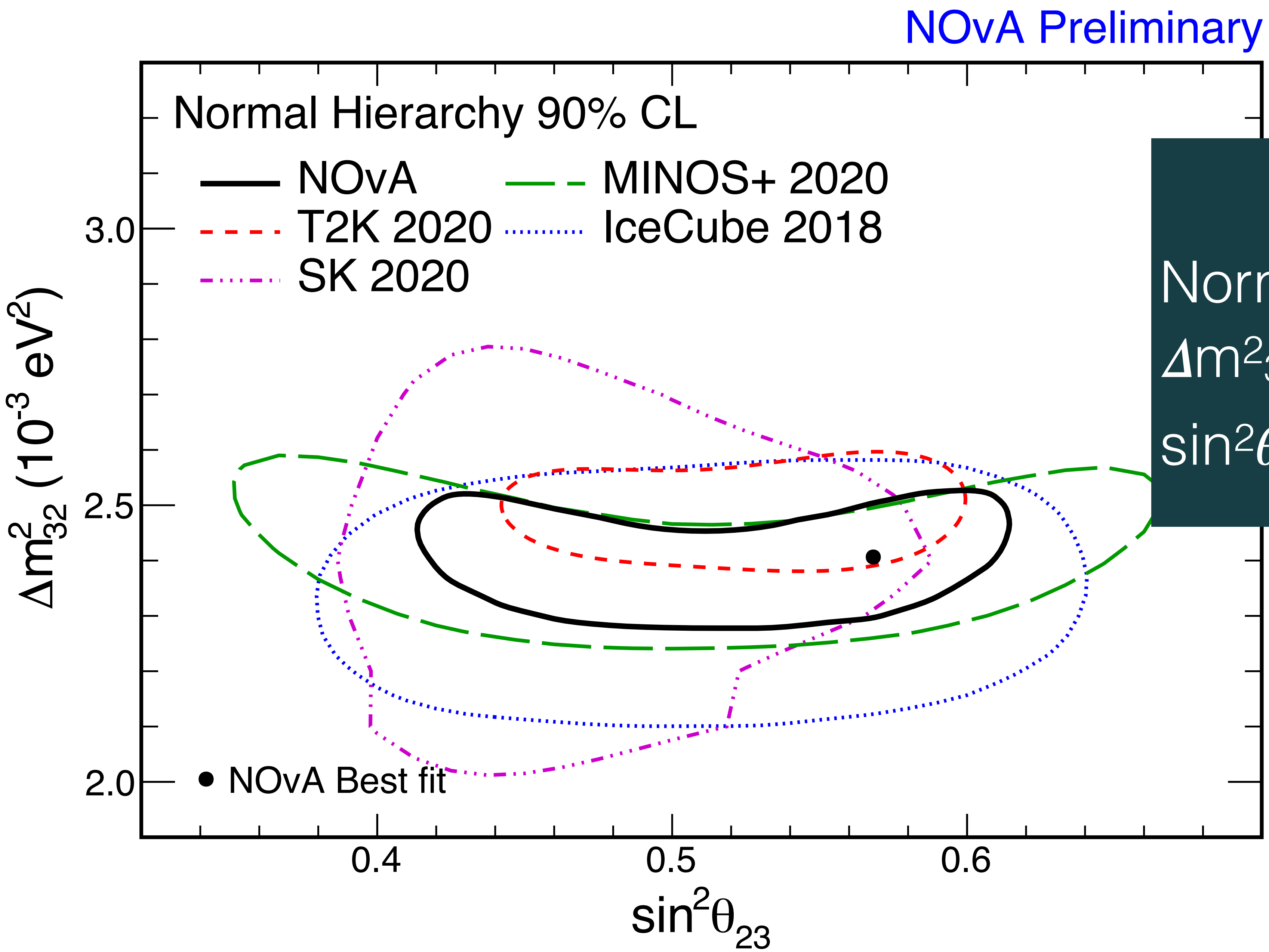




	N events	1 σ range
Total Prediction	85.8	52 - 110
- Wrong Sign	1.0	
- Beam Bkgd.	22.7	
- Cosmic Bkgd.	3.1	
Total Bkgd	26.8	26 - 28
Total Observed	82	

	N events	1 σ range
Total Prediction	33.2	25 - 45
Wrong Sign	2.3	
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd	14.0	13 - 15
Total Observed	33	

Oscillation parameters



Best Fit

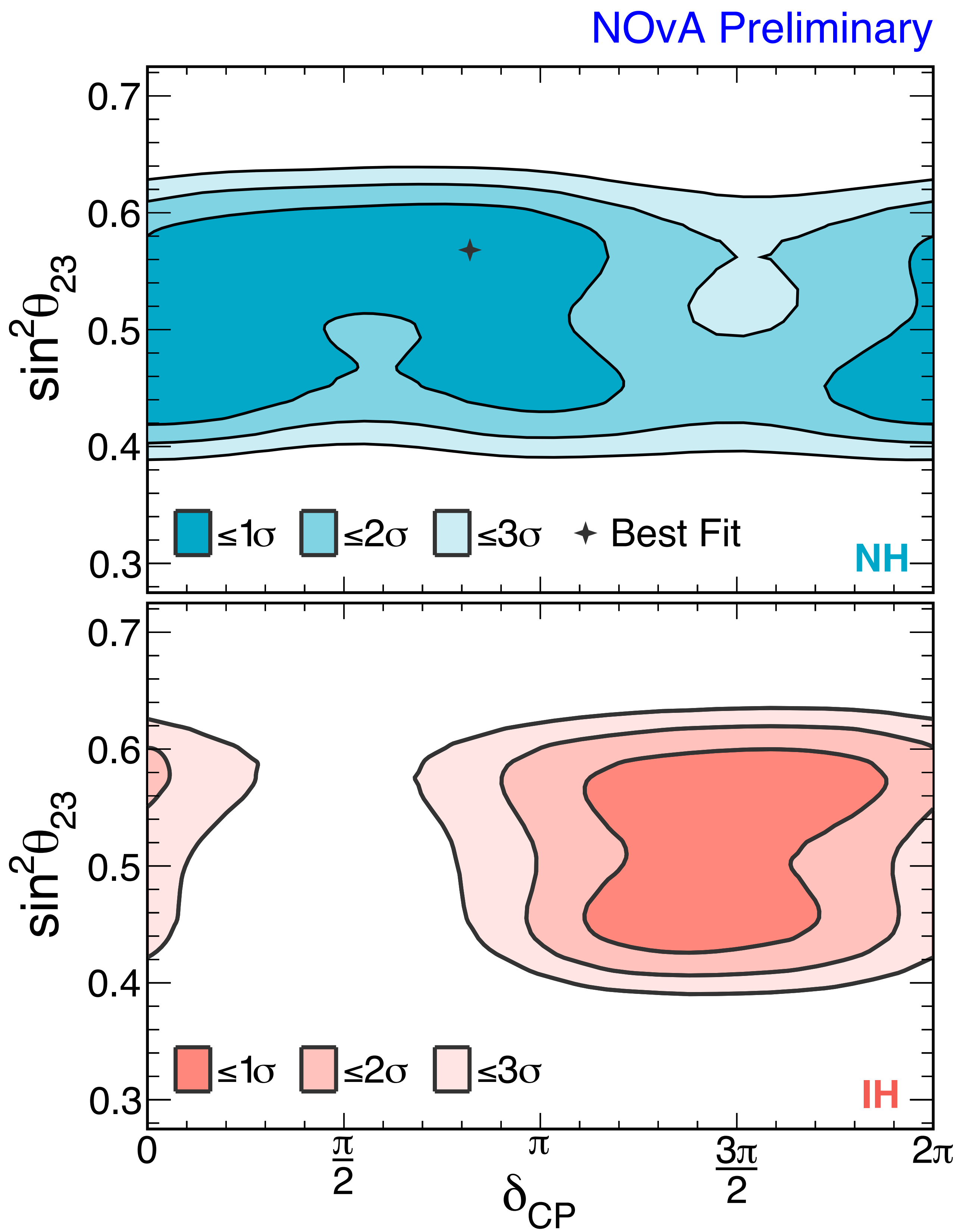
Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

- Best fit point is in the Normal Hierarchy, upper octant
  - Maximal mixing disfavoured at the 1.1 σ level.

Oscillation parameters



Best Fit

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$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ eV^2$

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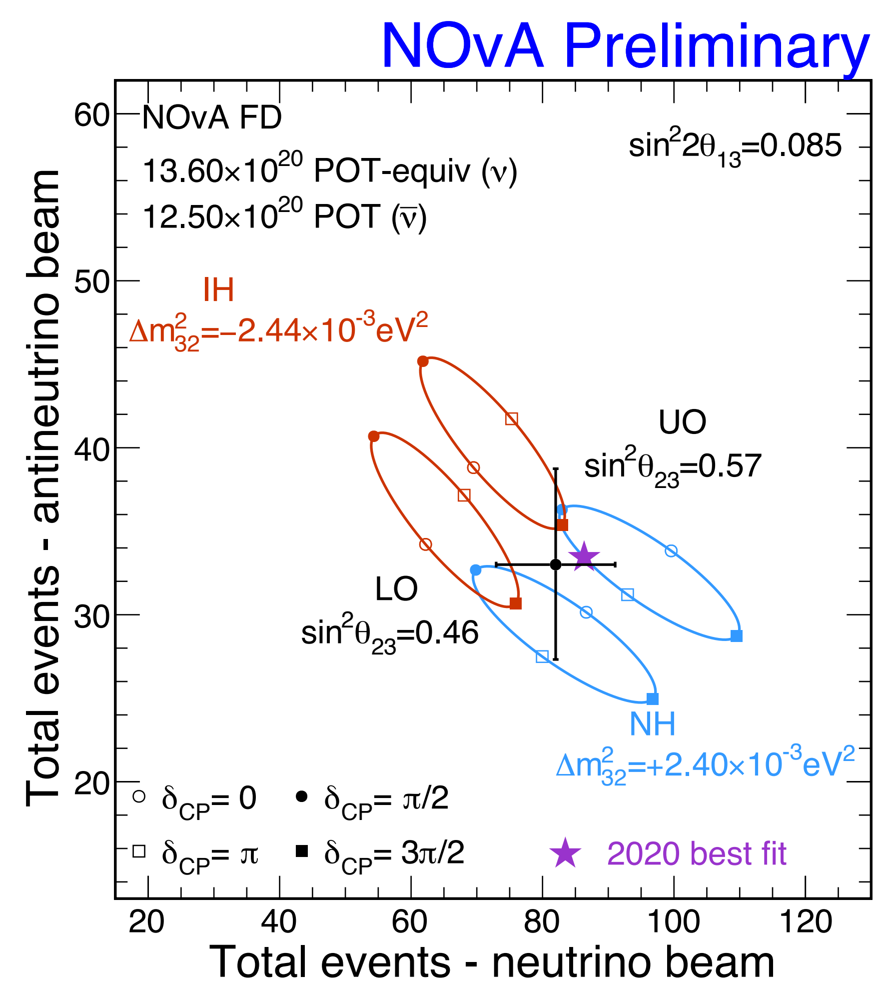
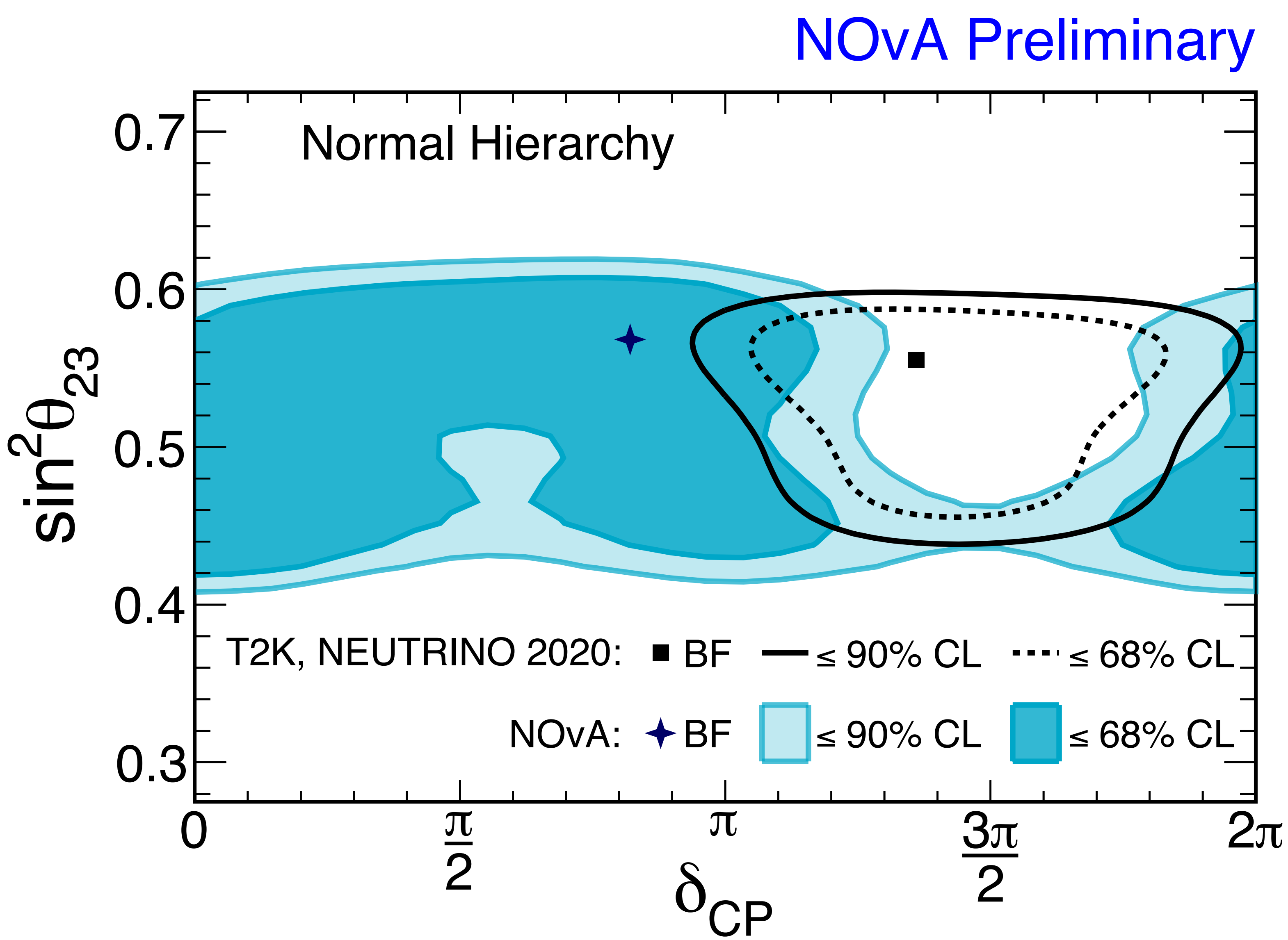
$\delta_{CP} = 0.82\ \pi$



Oscillation parameters



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$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
$\delta_{CP} = 0.82\,\pi$

- Some tension with T2K's most recent results
- Being investigated in the context of a joint analysis

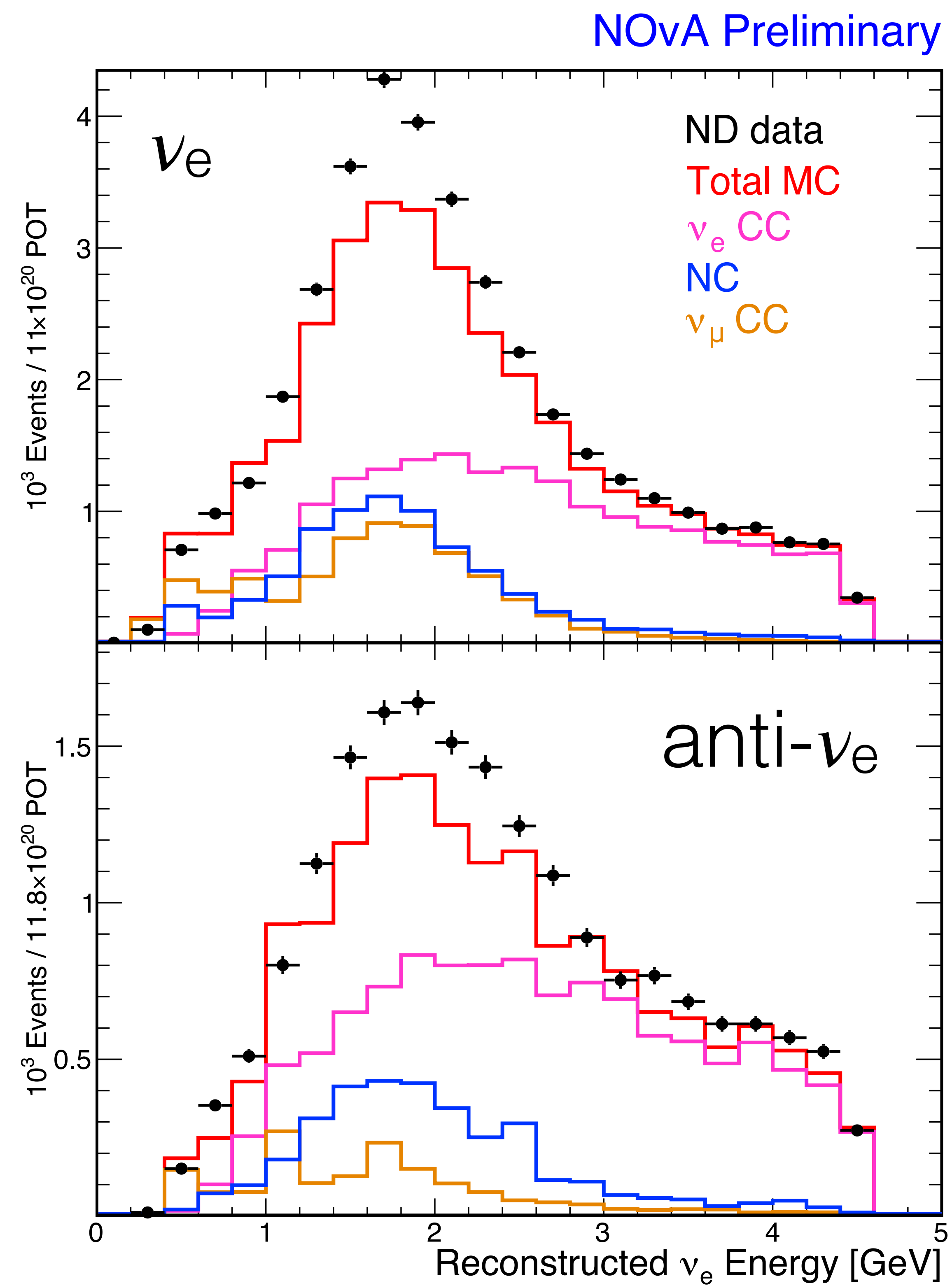
Conclusion

- Latest oscillation results from NOvA:
  - See no strong asymmetry between $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-ν_e
  - Exclude Inverted hierarchy and $\delta_{CP} = \pi/2$ at $> 3\sigma$
  - Disfavour Normal hierarchy and $\delta_{CP} = 3\pi/2$ at $\sim 2\sigma$
- Future for NOvA:
  - Joint analysis with T2K to understand tensions
  - Test beam experiment which will decrease our detector systematic uncertainties

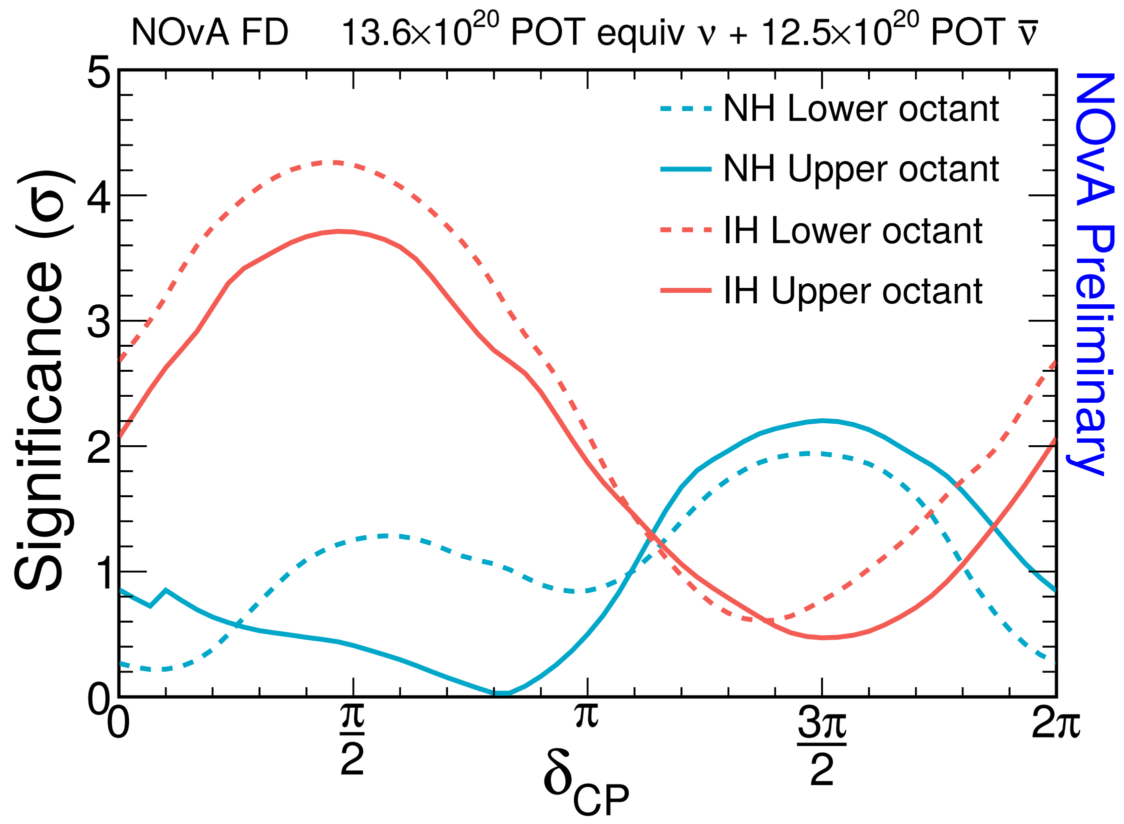
Questions

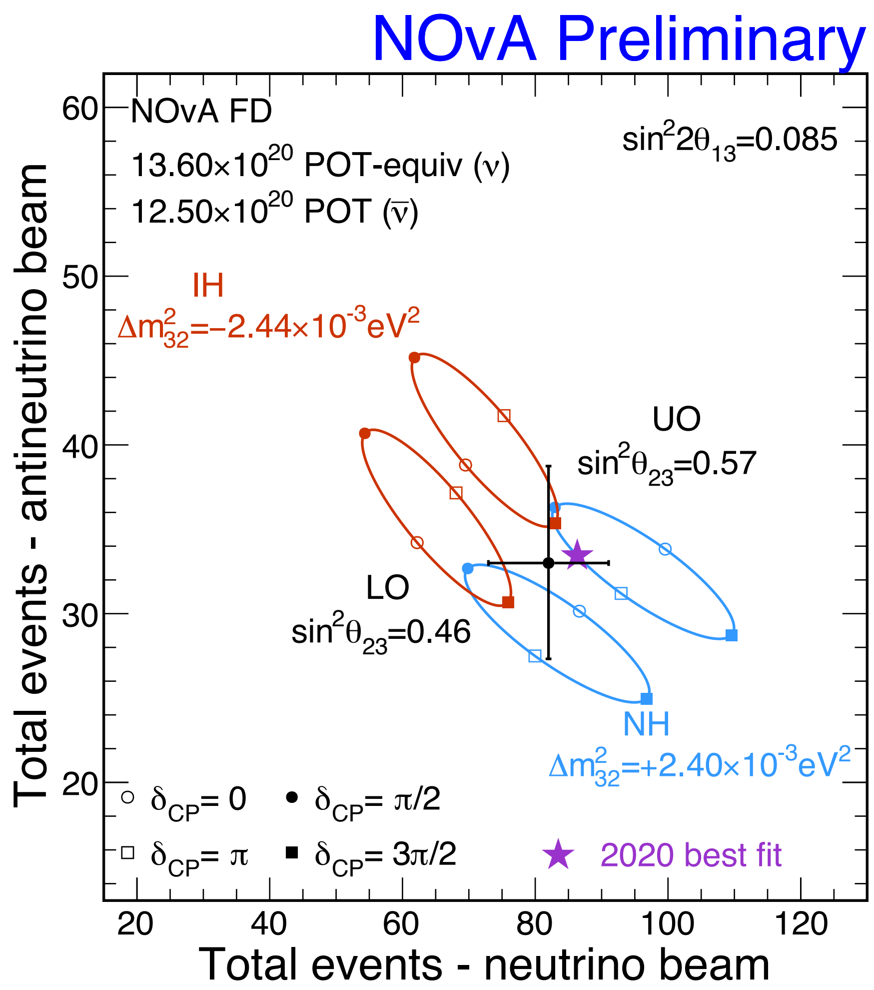
ND electron neutrinos signal

- The beam has a small component (~1%) of ν_e
  - Kaon and rare pion decays
- Irreducible background at the FD
- Visible in ND
- Can be used to predict the FD ν_e signal



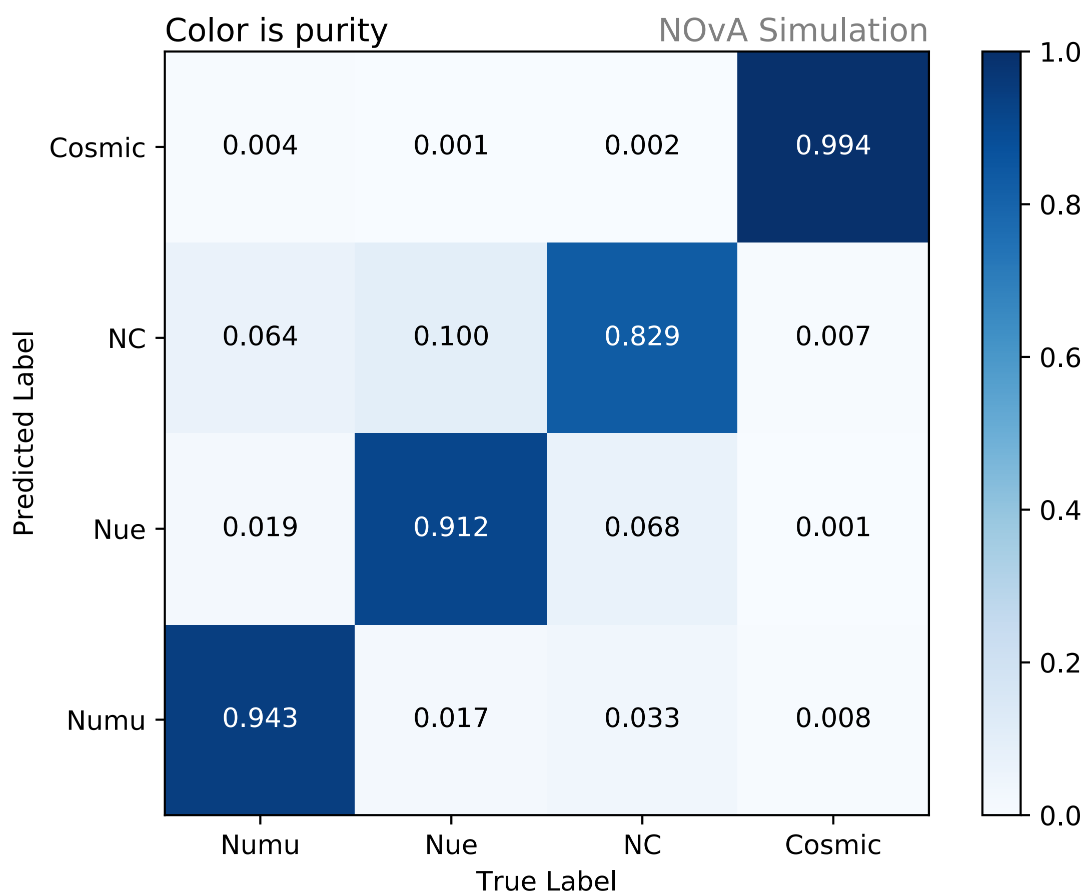
Oscillation parameters

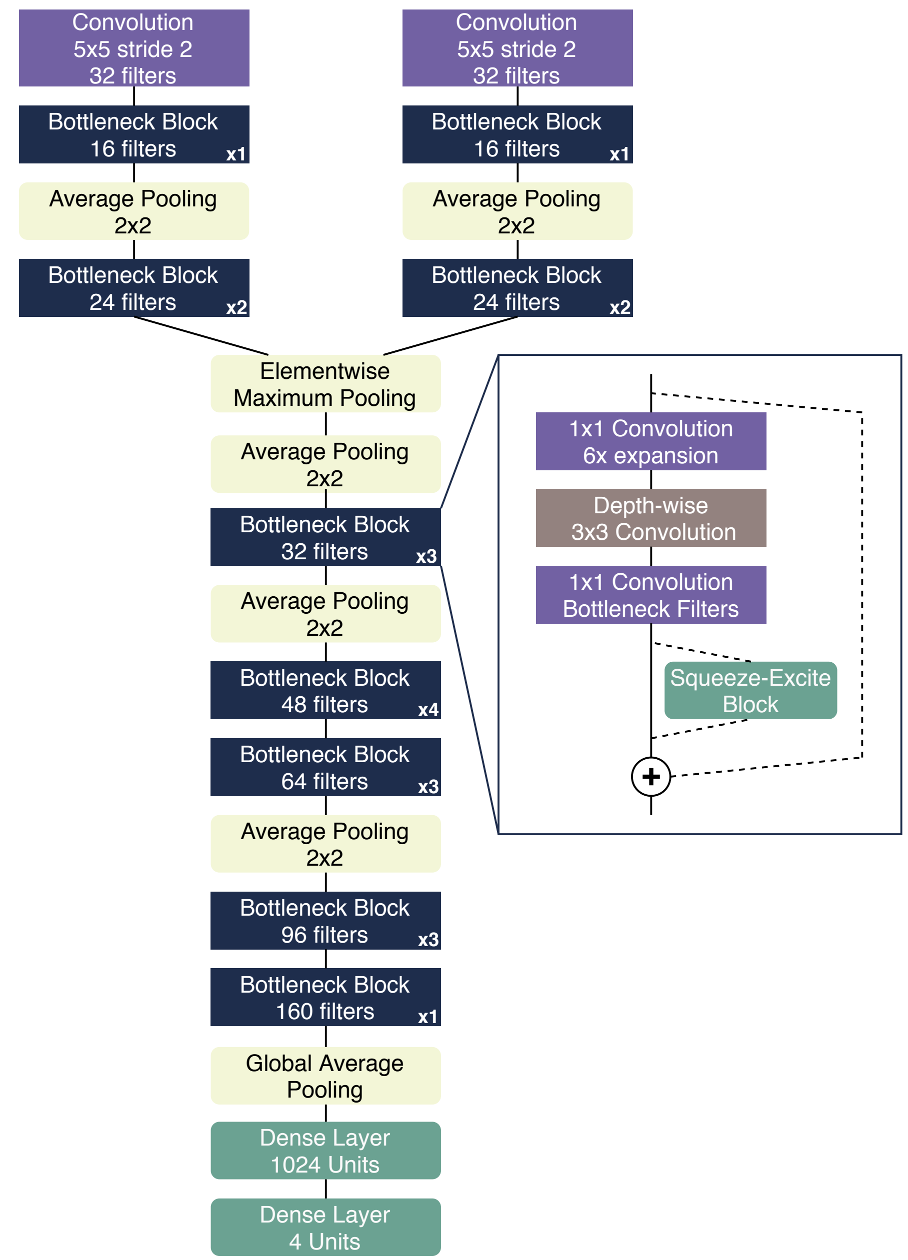




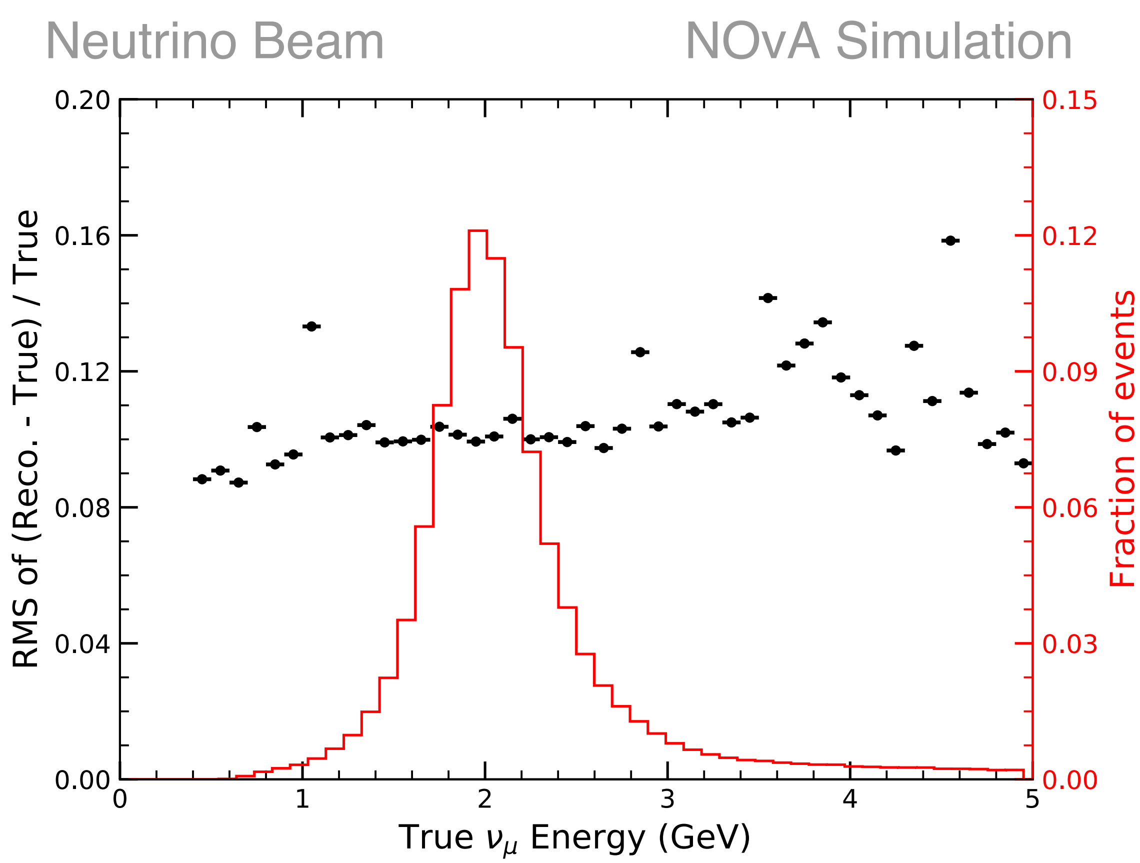
- Inverse hierarchy excluded at > 3 σ for $\delta_{CP} = \pi/2$
- Normal hierarchy excluded at > 2 σ for $\delta_{CP} = 3\pi/2$
- No strong asymmetry observed in the ν_e and anti-ν_e rate

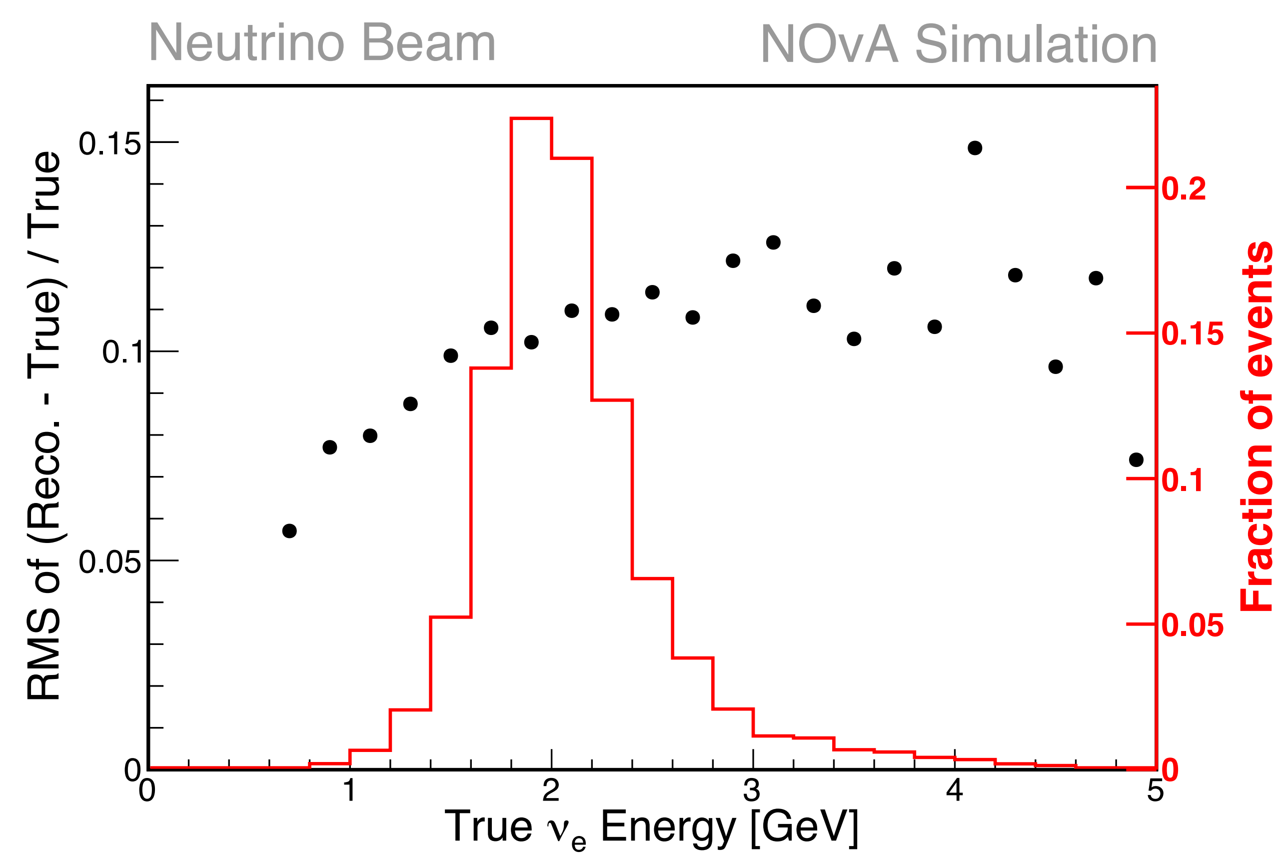
CVN


Color is purity
NOvA Simulation
Cosmic
NC
Nue
Numu
Predicted Label
Numu
Nue
NC
Cosmic
True Label
0.004
0.001
0.002
0.994
0.064
0.100
0.829
0.007
0.019
0.912
0.068
0.001
0.943
0.017
0.033
0.008
1.0
0.8
0.6
0.4
0.2
0.0


Convolution 5x5 stride 2 32 filters
Bottleneck Block 16 filters x1
Average Pooling 2x2
Bottleneck Block 24 filters x2
Convolution 5x5 stride 2 32 filters
Bottleneck Block 16 filters x1
Average Pooling 2x2
Bottleneck Block 24 filters x2
Elementwise Maximum Pooling
Average Pooling 2x2
Bottleneck Block 32 filters x3
Average Pooling 2x2
Bottleneck Block 48 filters x4
Bottleneck Block 64 filters x3
Average Pooling 2x2
Bottleneck Block 96 filters x3
Bottleneck Block 160 filters x1
Global Average Pooling
Dense Layer 1024 Units
Dense Layer 4 Units
1x1 Convolution 6x expansion
Depth-wise 3x3 Convolution
1x1 Convolution Bottleneck Filters
Squeeze-Excite Block

E_μ resolution





ν_μ CC E_ν reconstructed from muon track length and hadronic calorimetric energy

ν_e CC E_ν reconstructed from electron shower and hadronic calorimetric energies

ν_μ quantiles