New neutrino oscillation results from NOvA

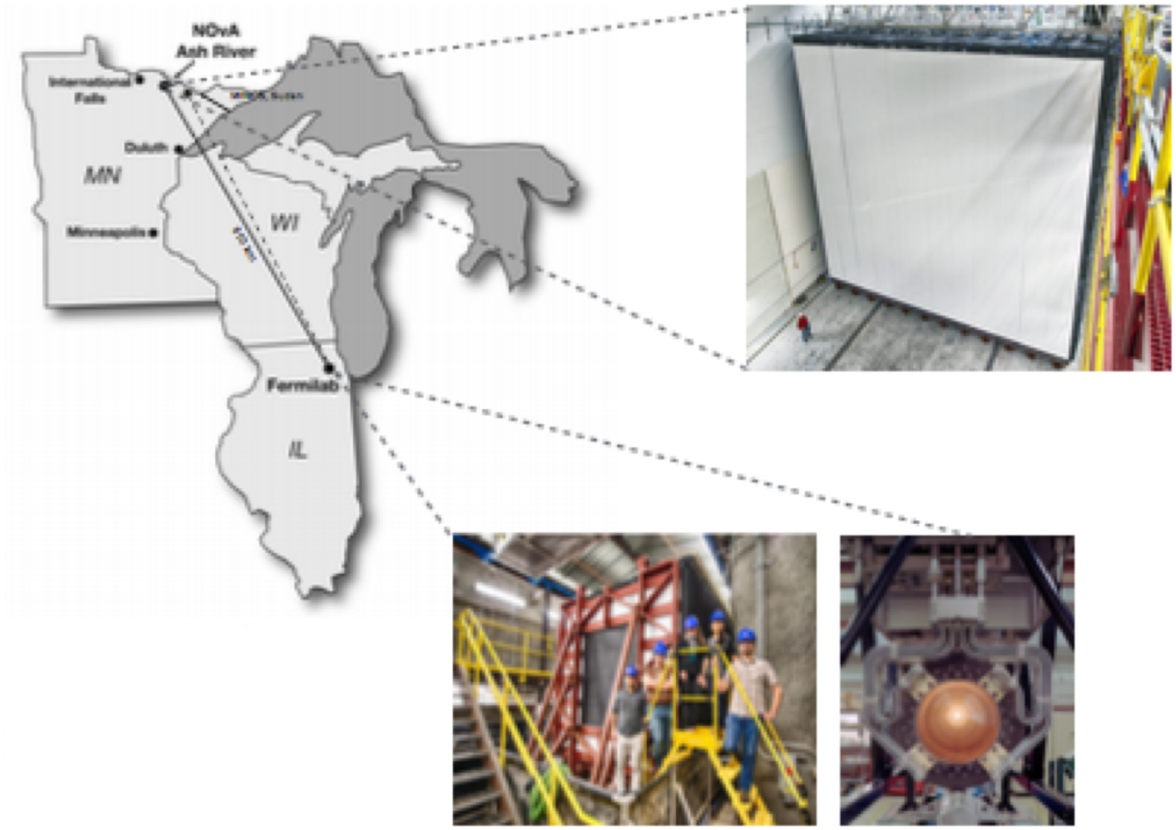
Luke Vinton

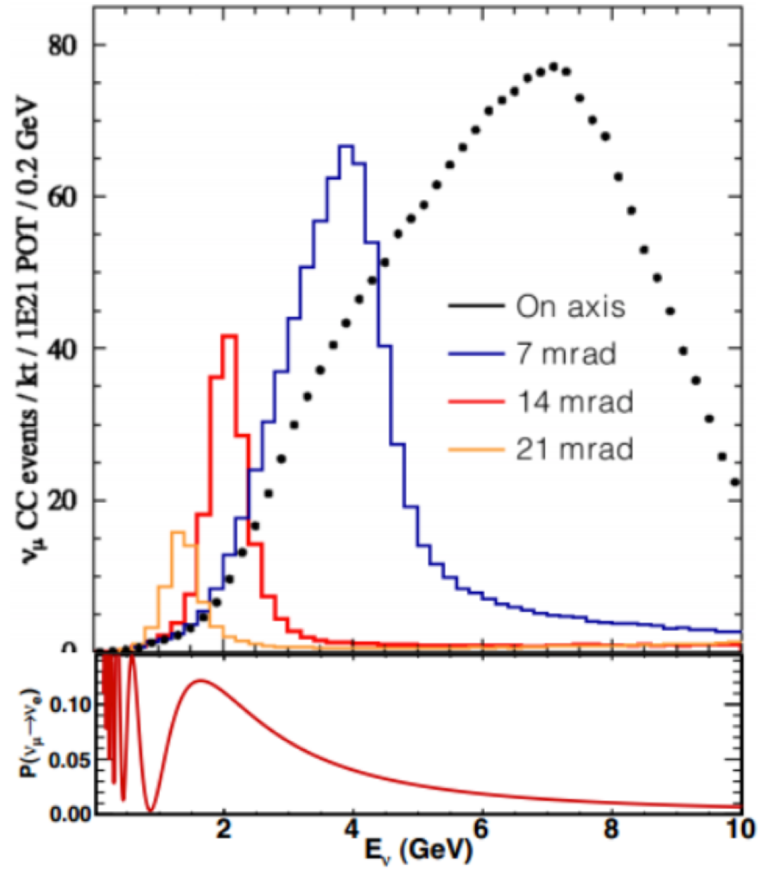
University of Sussex

Introduction

- Overview of the NOvA experiment setup
- Improvements for this round of analysis
- Muon neutrino disappearance result
- Electron neutrino appearance result
- Joint disappearance and appearance fit

The NOvA experiment

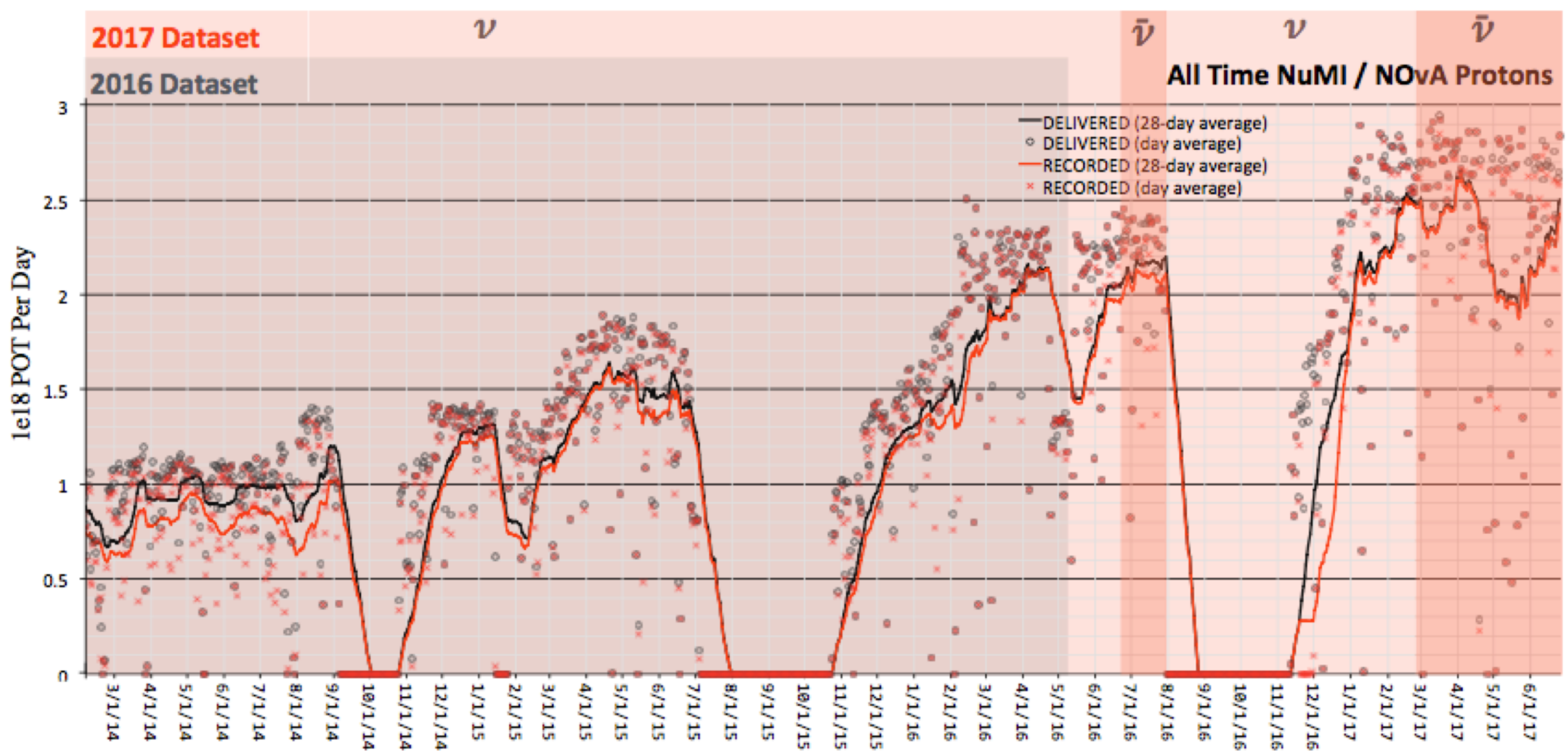




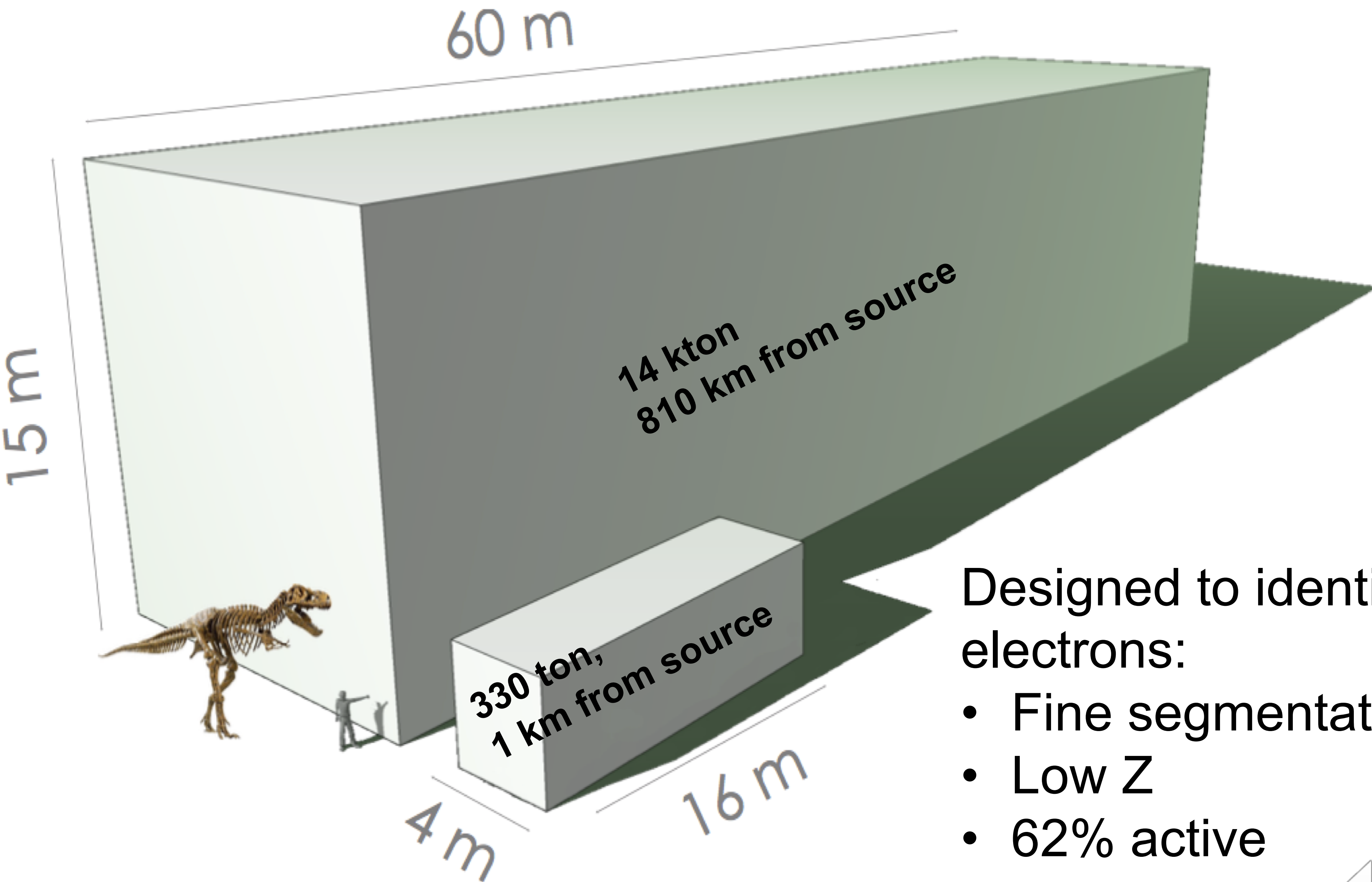
Studying oscillations of neutrinos within the NuMI beam over a 810km baseline with two functionally identical off-axis detectors

The NuMI beam

- 8.85 e20 POT in 14 kton equivalent detector
  - 50% more exposure than the 2016 analysis
- Now running in anti-neutrino mode
- Running at design target of 700 kW since June 2016



The Detectors

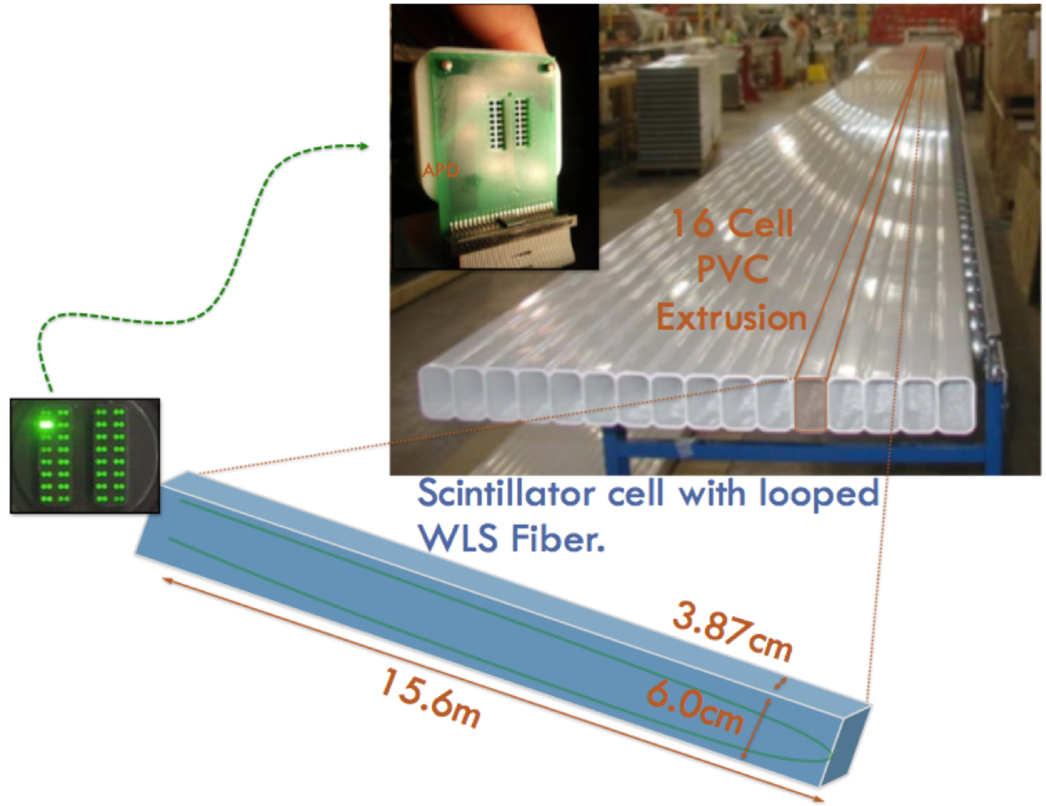


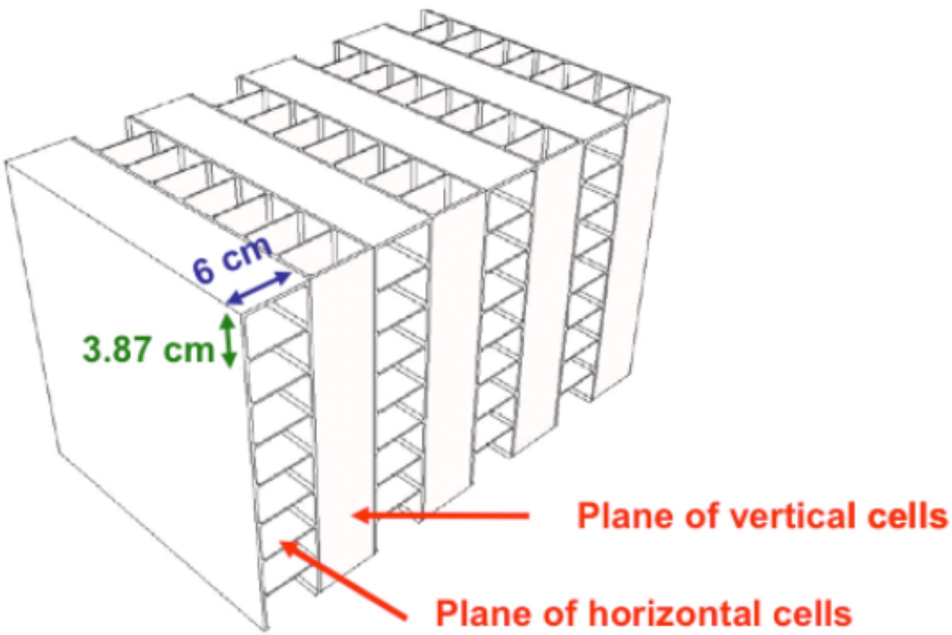
Designed to identify electrons:

- Fine segmentation
- Low Z
- 62% active

Detector Components

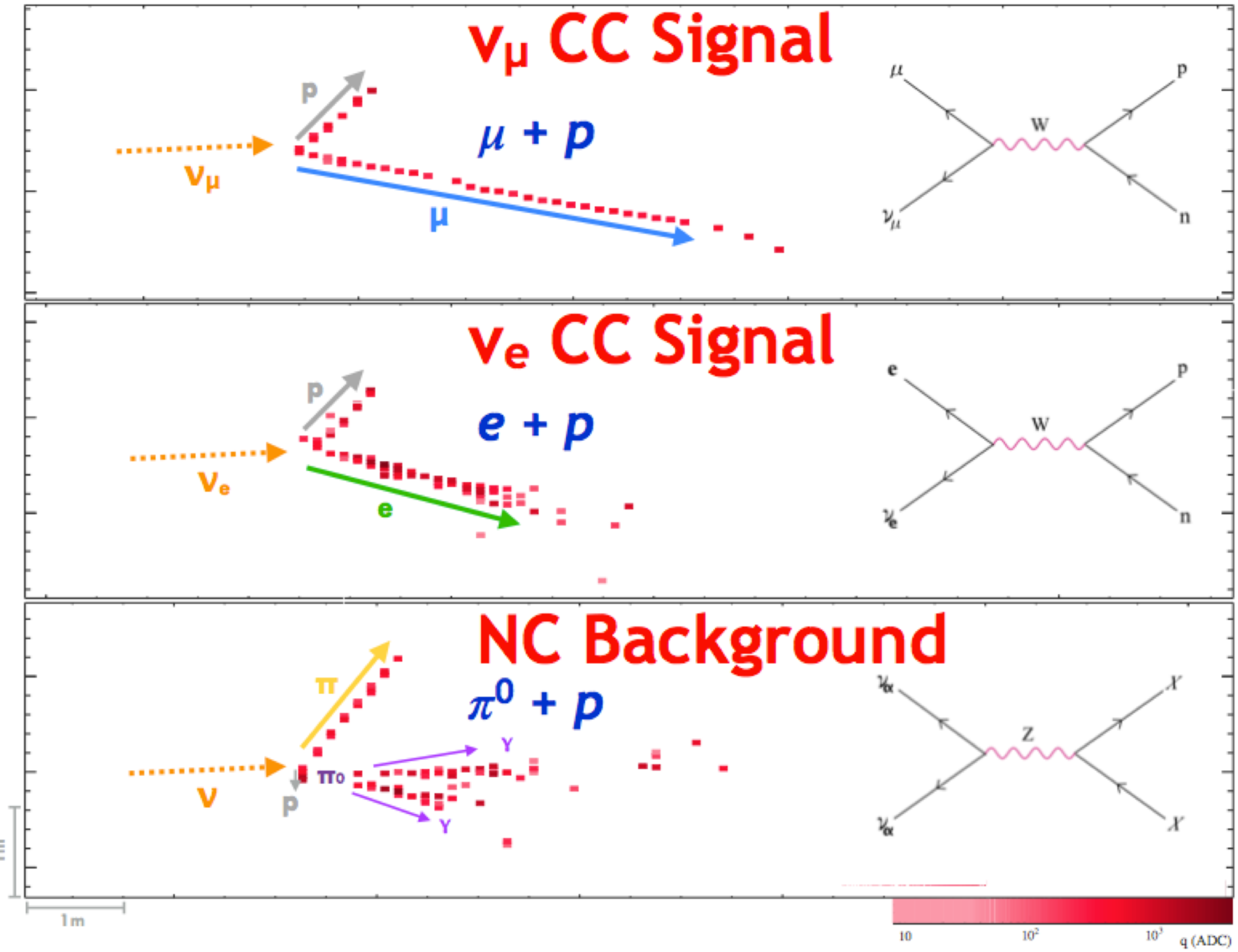
- PVC extrusions + Liquid Scintillator (mineral oil + 5% pseudocumene)
- Readout via WLS fibre to APD





- Layered planes in orthogonal views for 3D reconstruction

Event topologies



1 radiation length =

- 38 cm
- 6 cell depths
- 10 cell widths

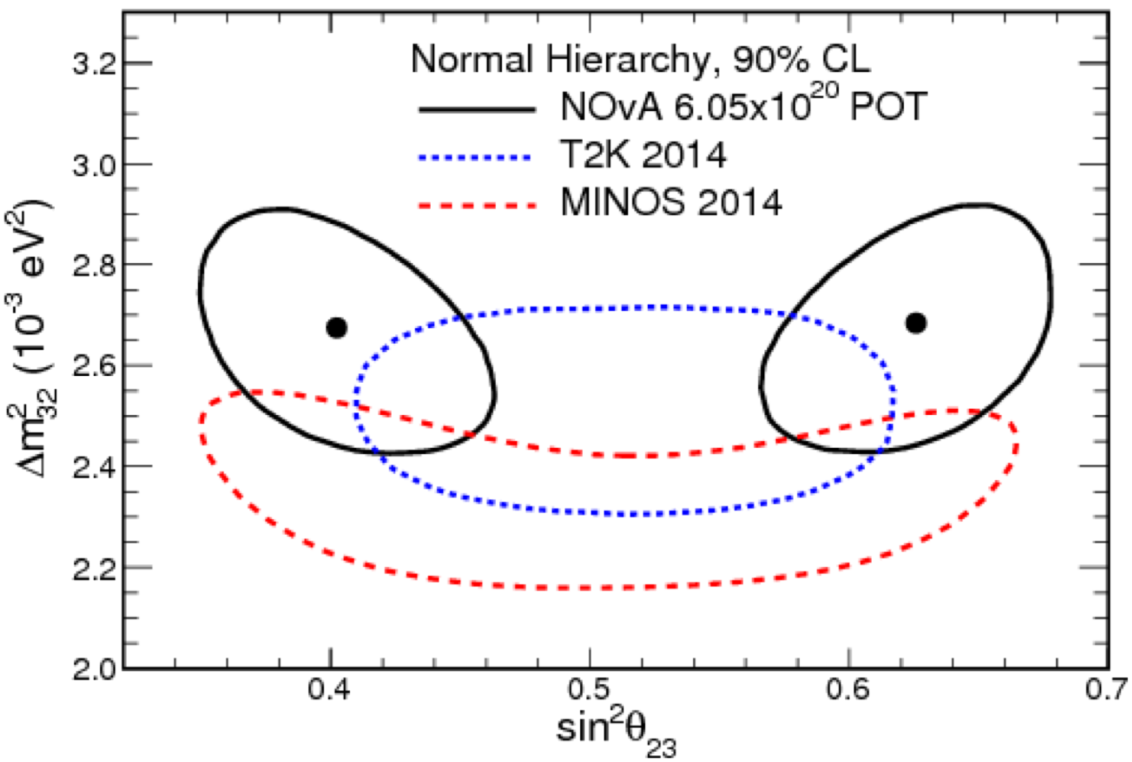
Analysis Improvements

- **50% more data! 9 e20 POT**
- **Improved analysis techniques**:
  - improved selections using deep learning,
  - separating events by energy resolution to better exploit the existing data
- Retuned cross-section modelling
  - Particularly important for multi-nucleon processes
- Detector sim improvements
- Data driven flux estimates

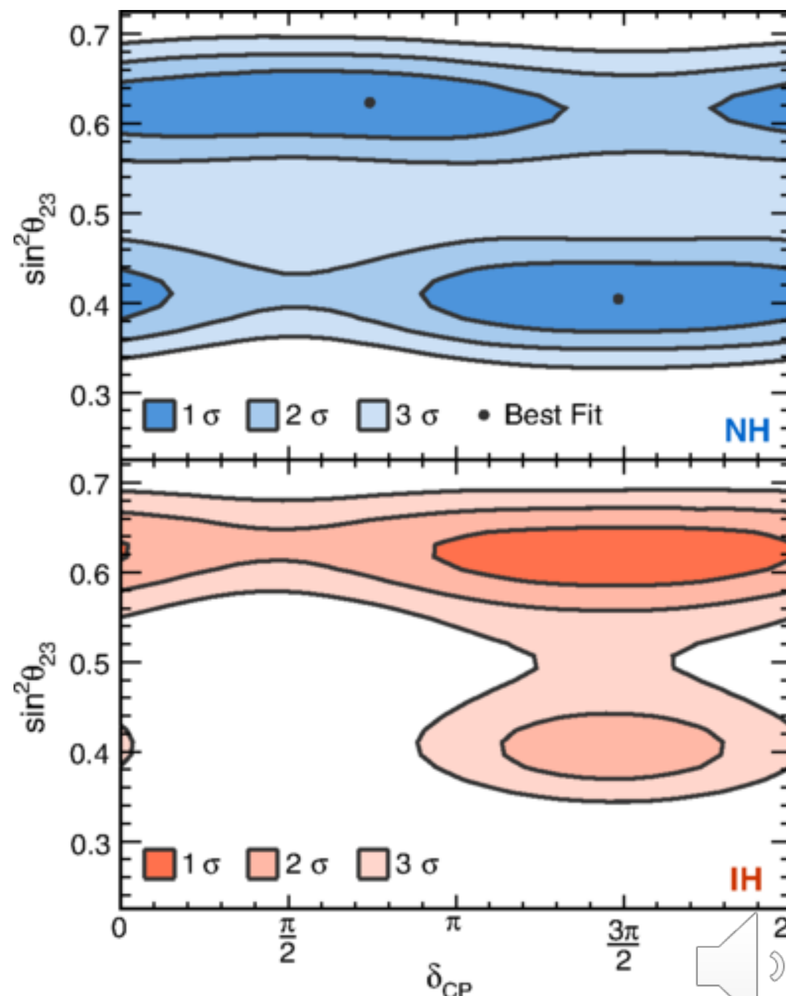
Previous results

Previous appearance and disappearance results
6.05 e20 protons on target

arXiv:1701.05891

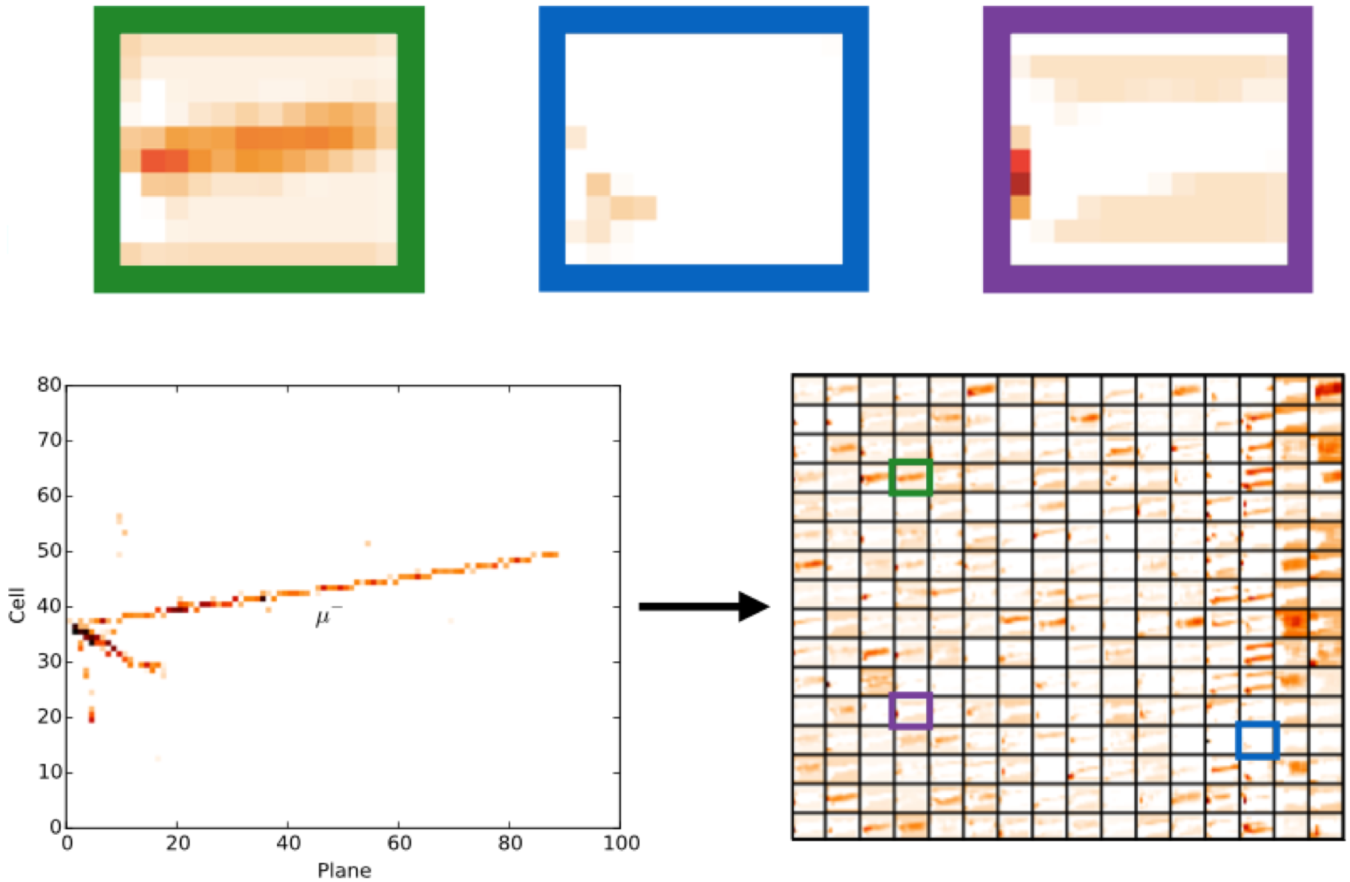


arXiv:1703.03328



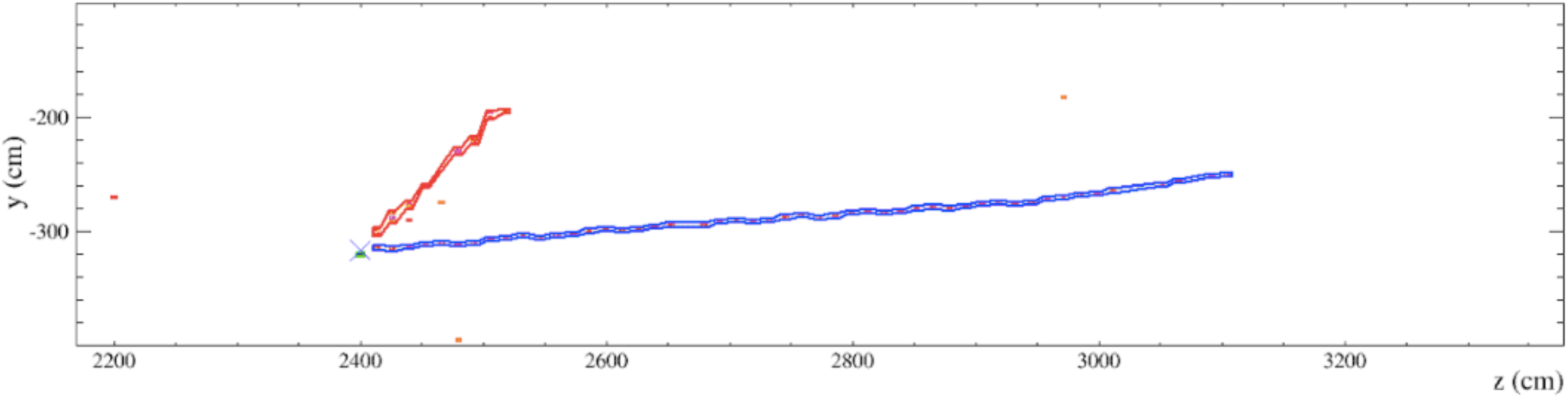
Deep learning inspired PID

Deep learning methods used to identify muons and electrons using features of the event topology



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

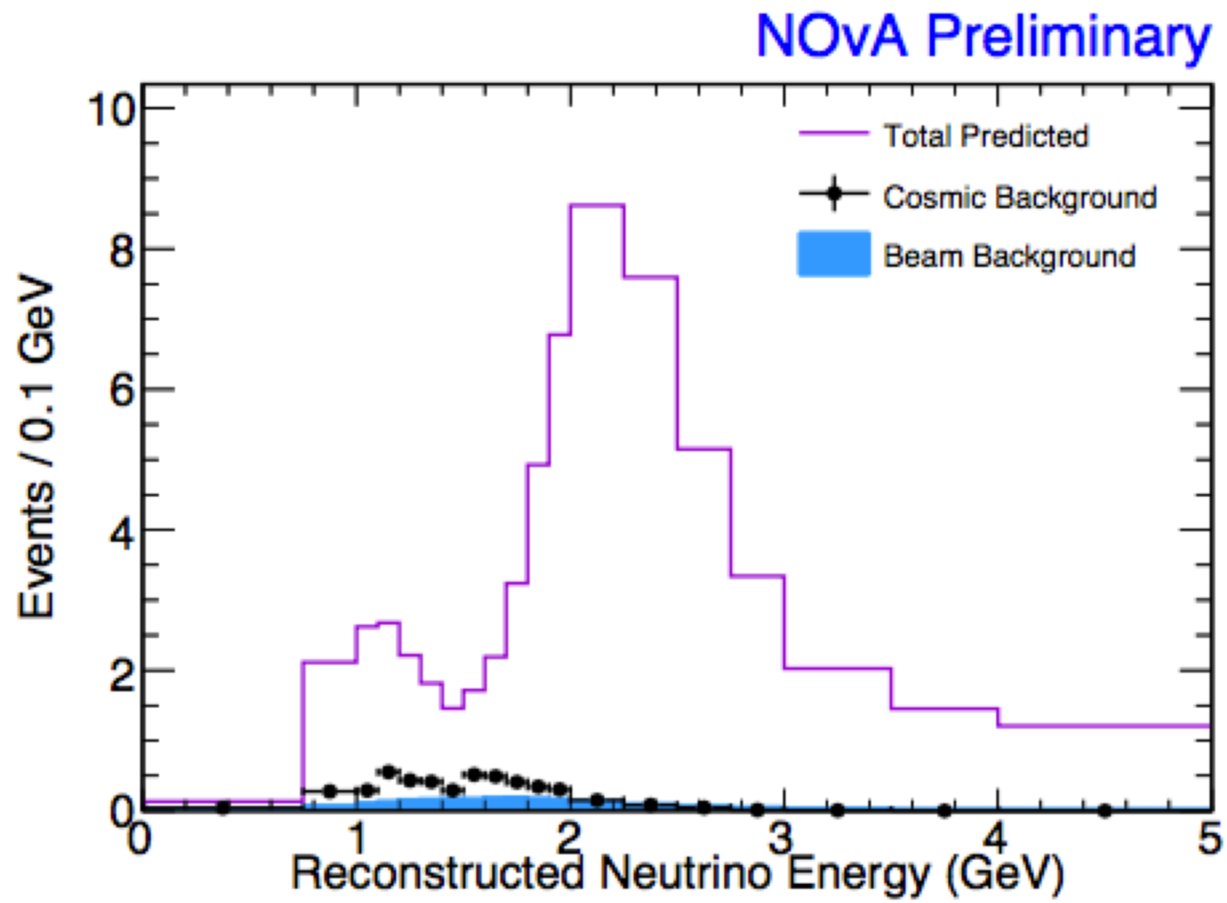
υ_μ Disappearance



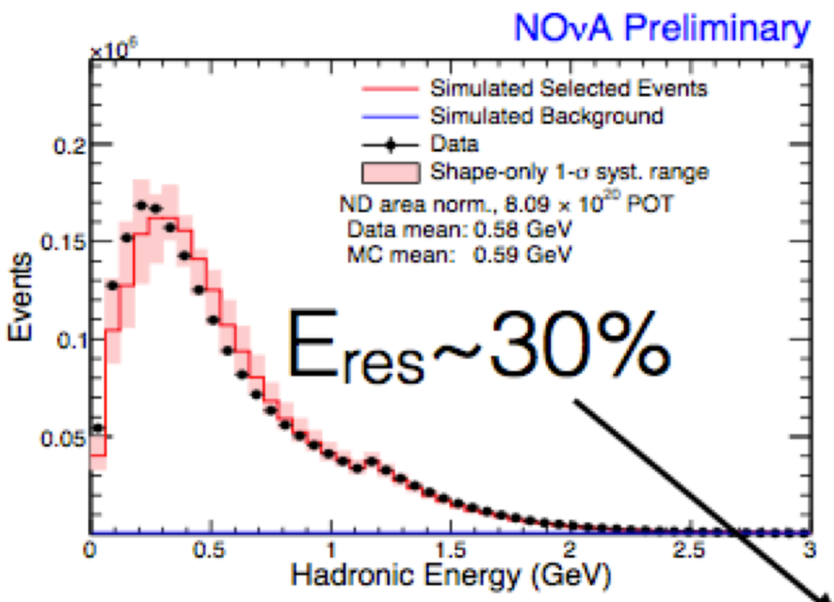
- Select and measure υ_μ events in both detectors
- Extrapolate beam expectation to far detector
- Measure cosmic background expectation using far detector data outside the beam spill window
- Compare measured far detector energy spectrum with expectation

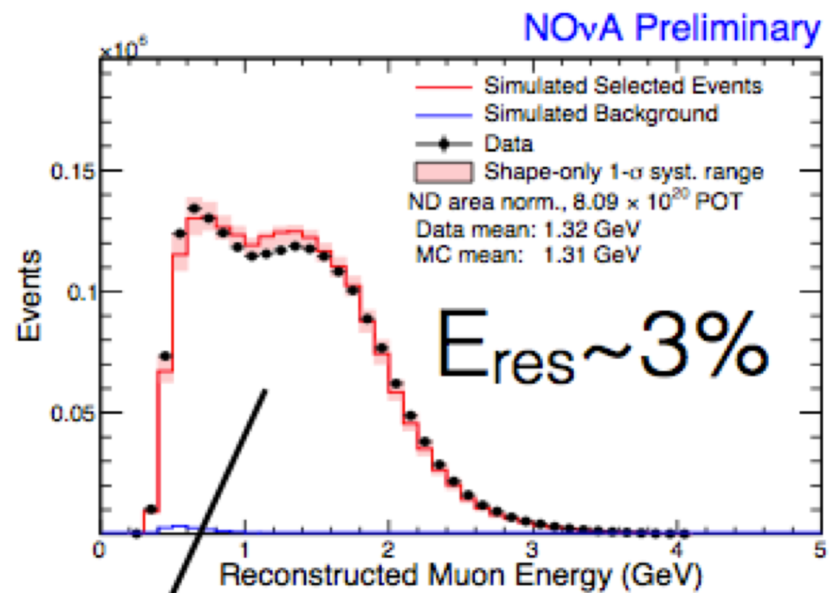
υ_μ Disappearance

- New selection using deep learning selector and retuned cosmic BDT
- Equivalent background rejection with 11% more signal selected

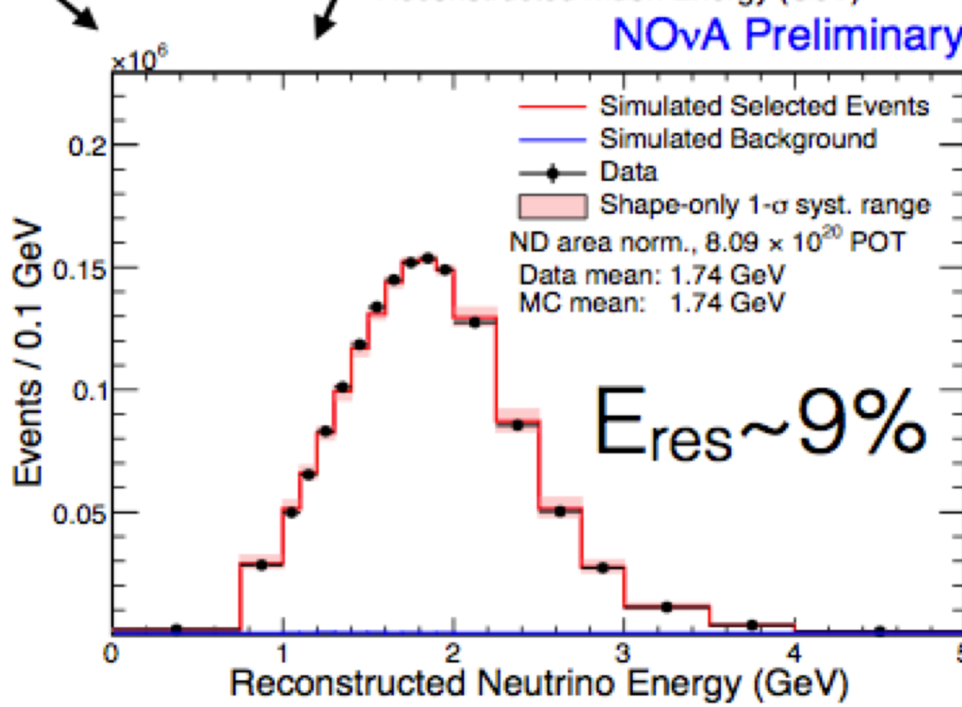


υ_μ Energy Estimator



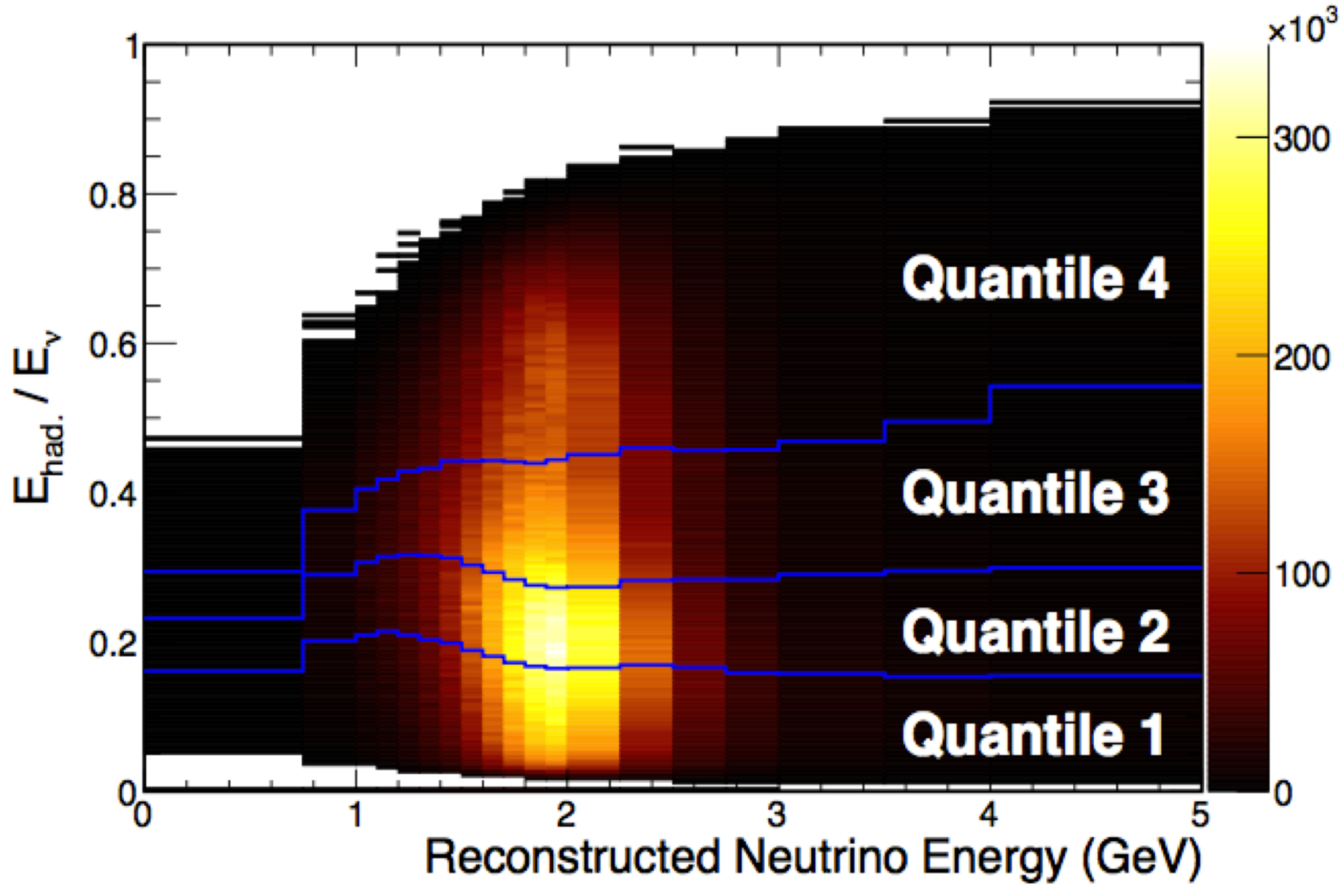


Final reconstructed energy combines E_{had} and E_μ via a piecewise linear fit



Resolution Binning

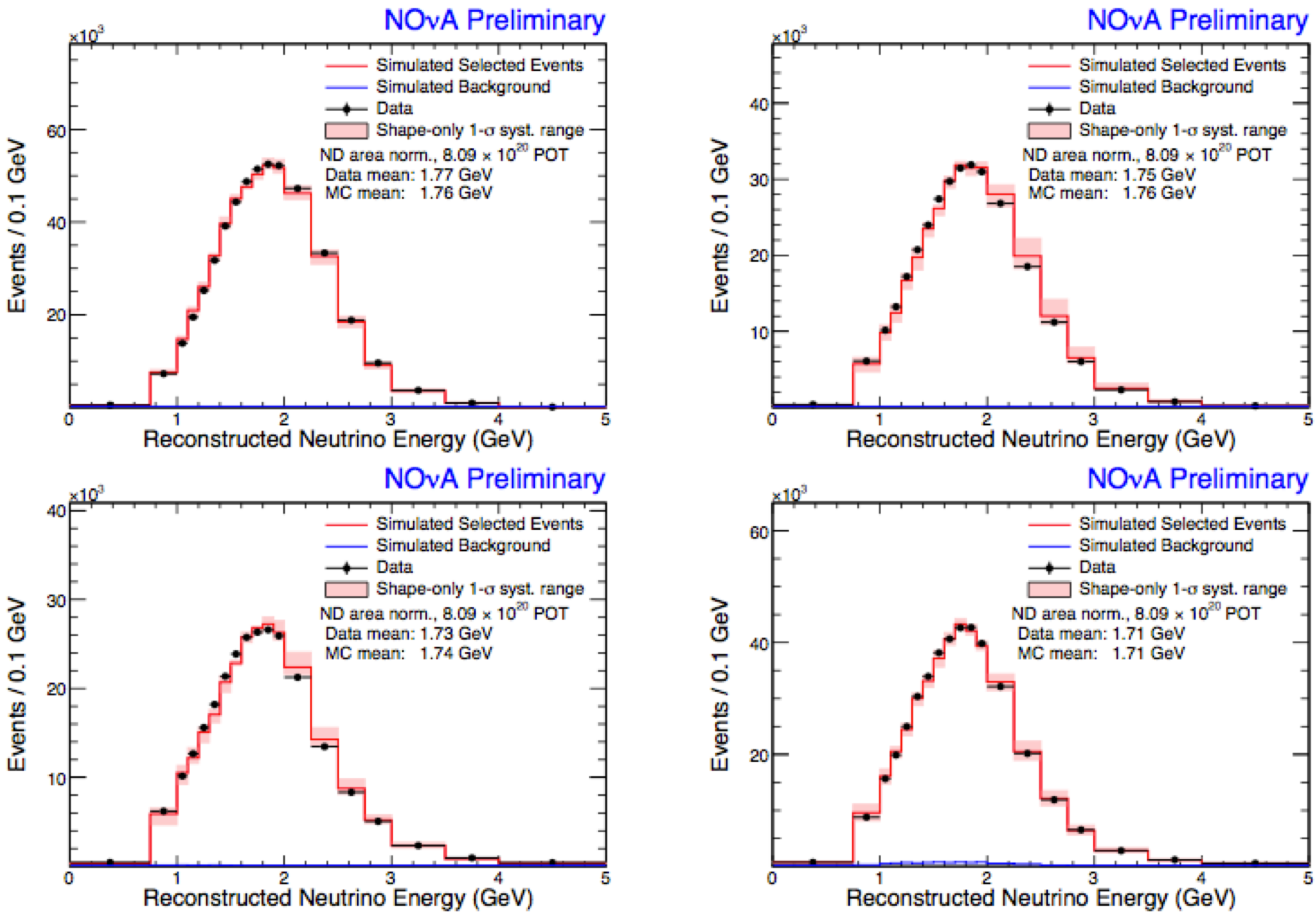
4 quantiles in the far detector split by hadronic energy fraction for each reconstructed neutrino energy bin



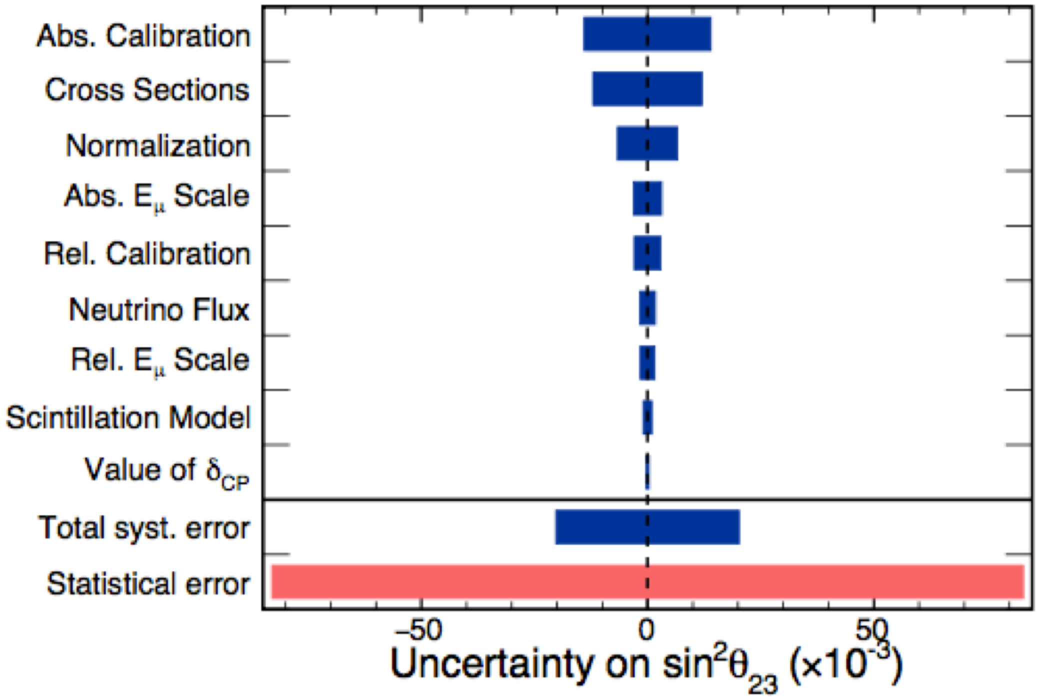
Energy resolution best for lower hadronic energy fraction

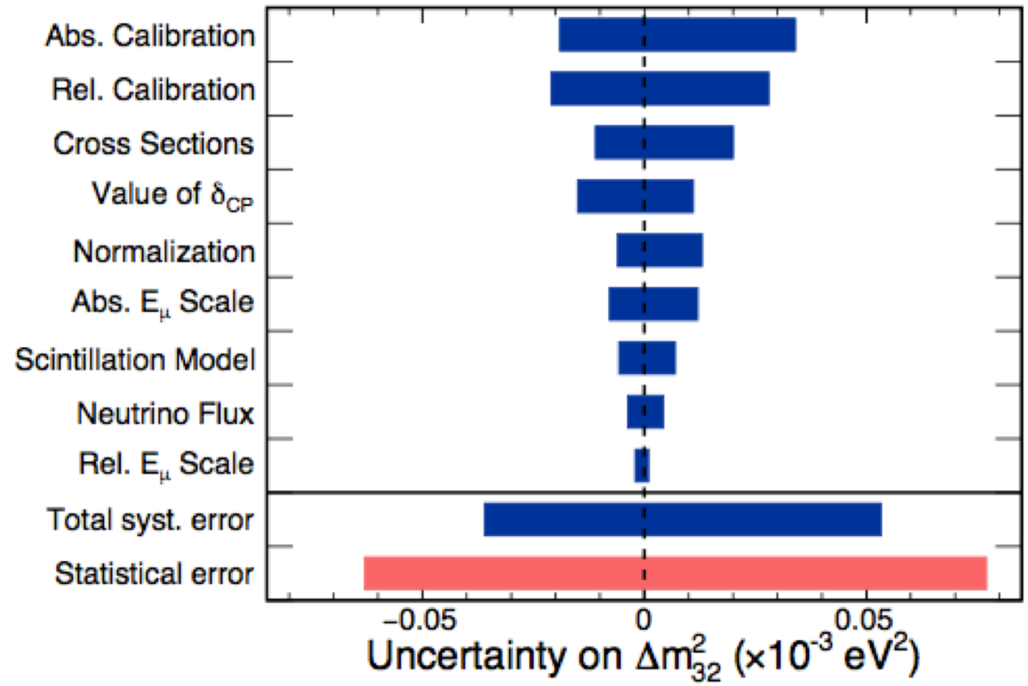
- Resolution varies from 6% to 12% from best to worst resolution bins

Resolution Binning



υ_μ Systematics



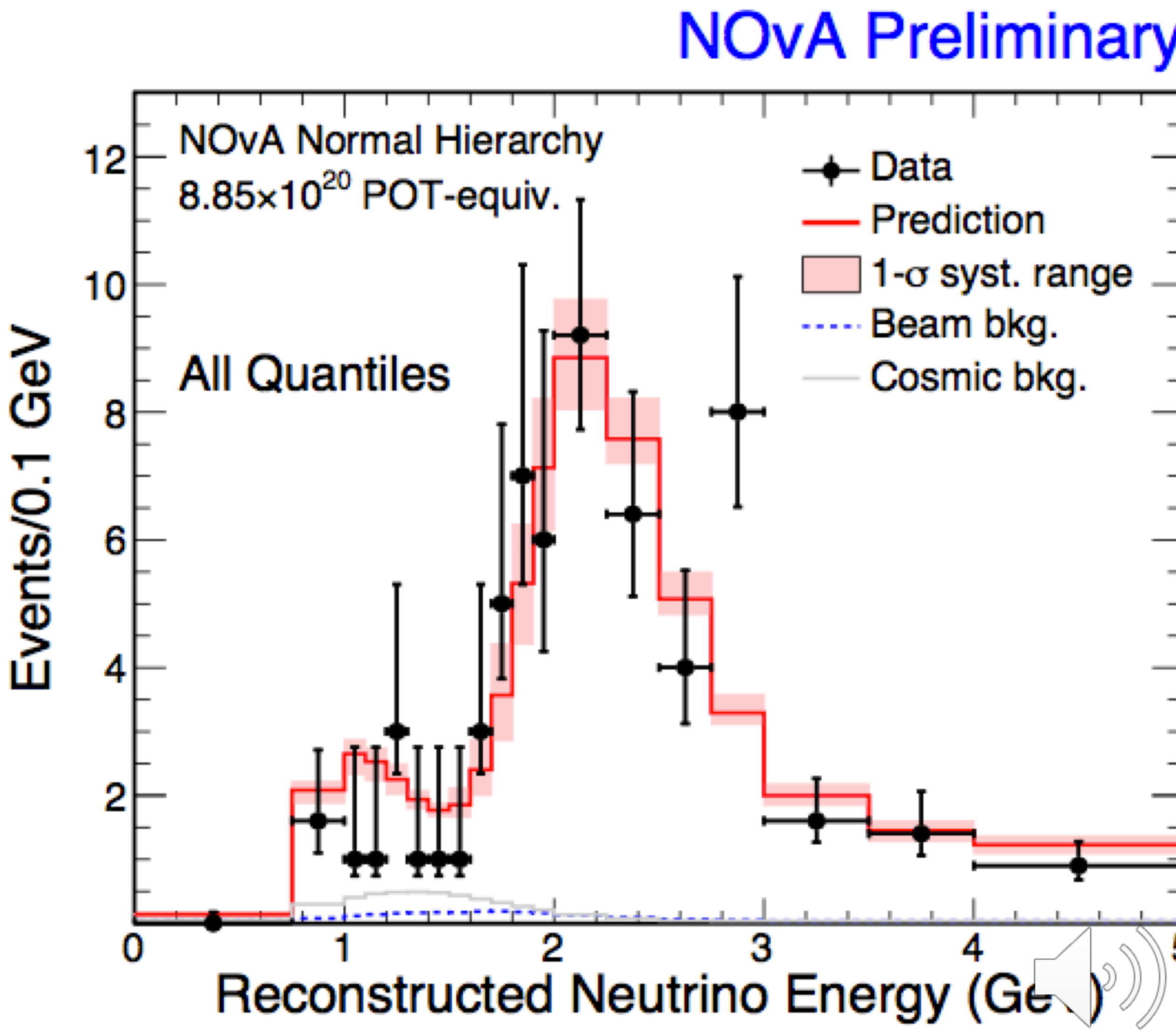


- Systematics assessed using sets of shifted MC
- Impact on the result of each systematic is assessed by allowing the systematic uncertainty to shift as a penalty term in the fit

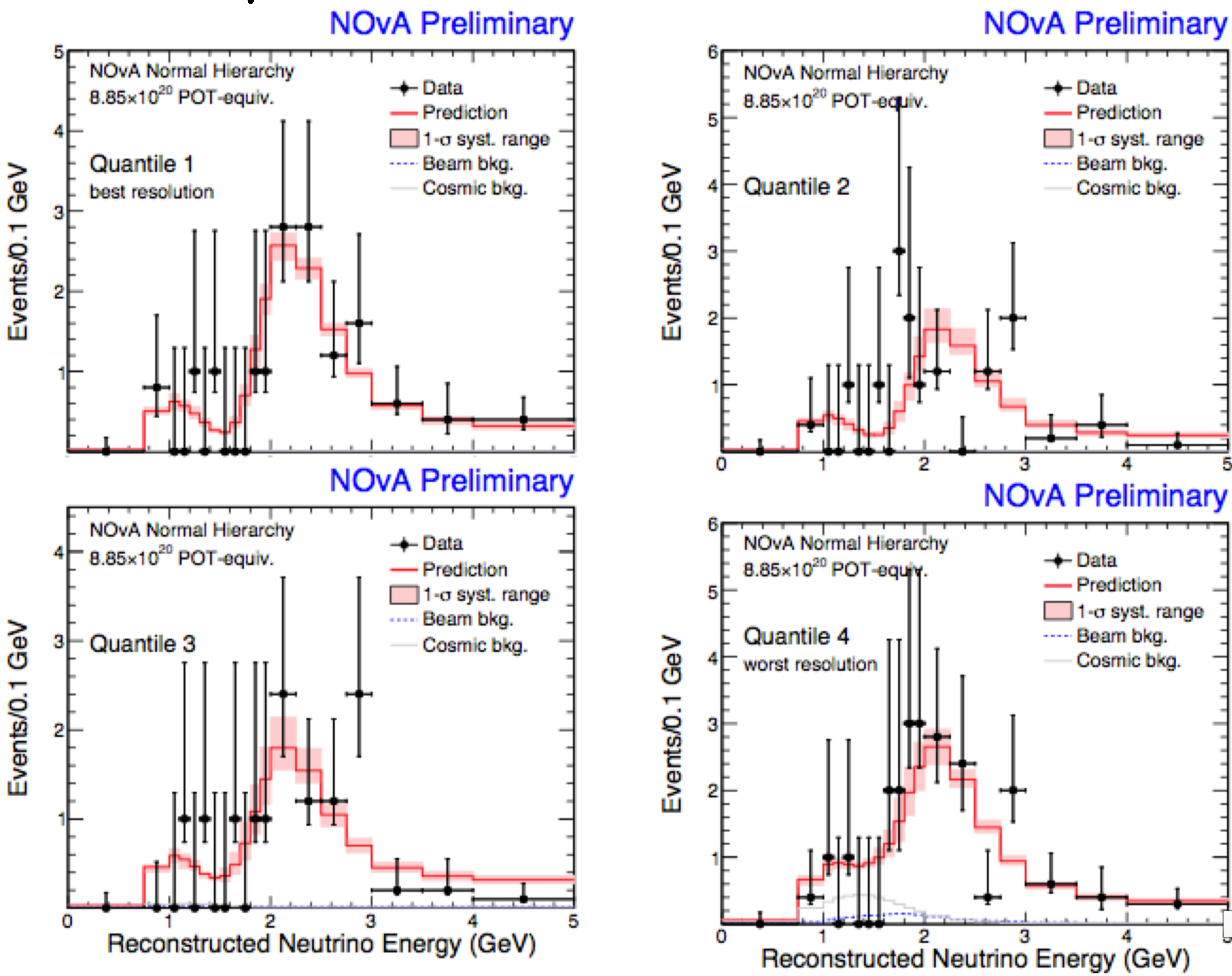
υ_μ Far Detector Events

In the absence of oscillations we expect 763 events
126 were observed

	Events
Total	126
Expected	129
Total Background	9.24
Cosmic	5.82
Neutral Current	2.50
Other Beam	0.96



υ_μ Far Detector Events



Joint fit

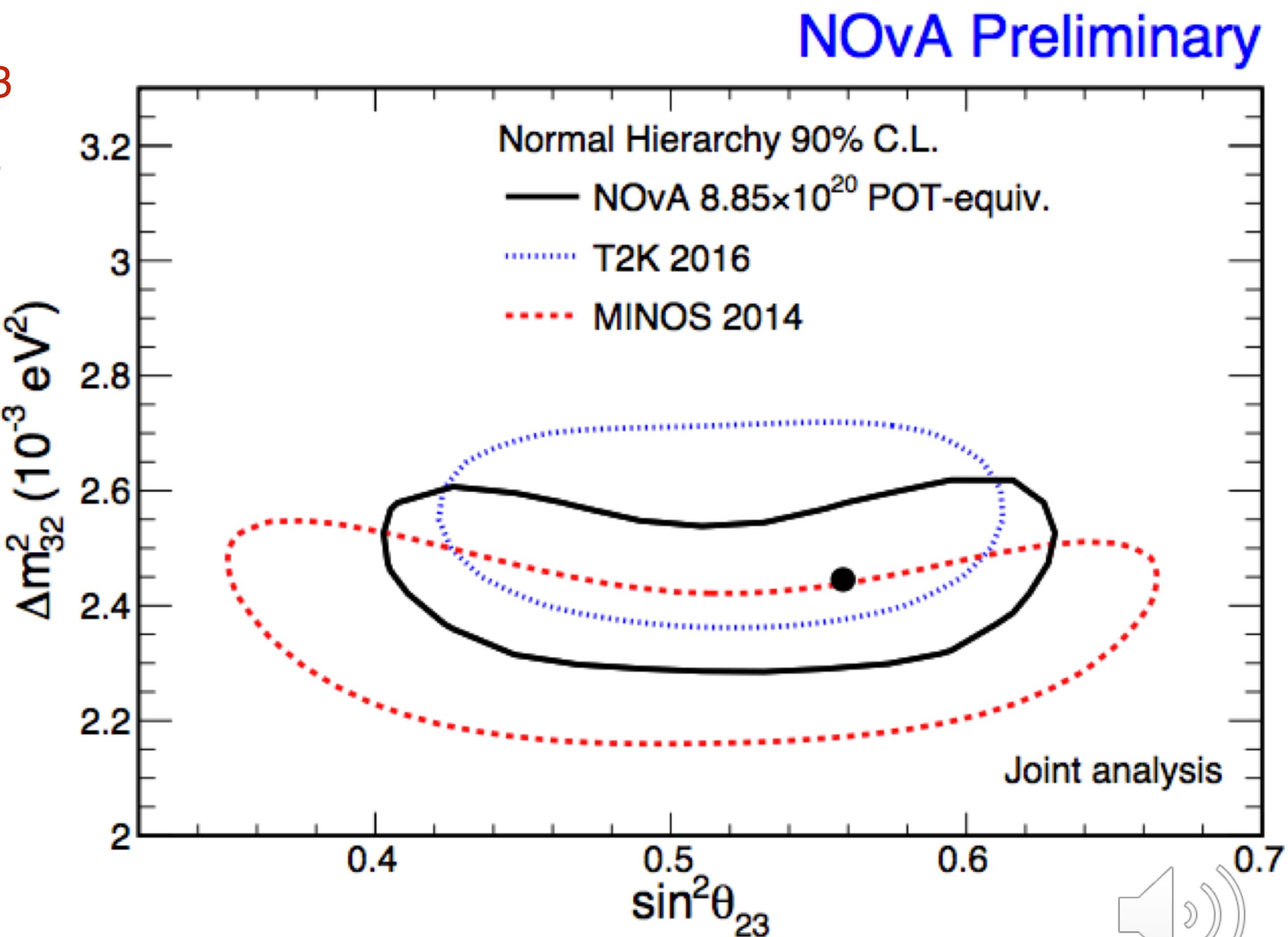
UO preferred at 0.2σ

$\sin^2\theta_{23}$ =

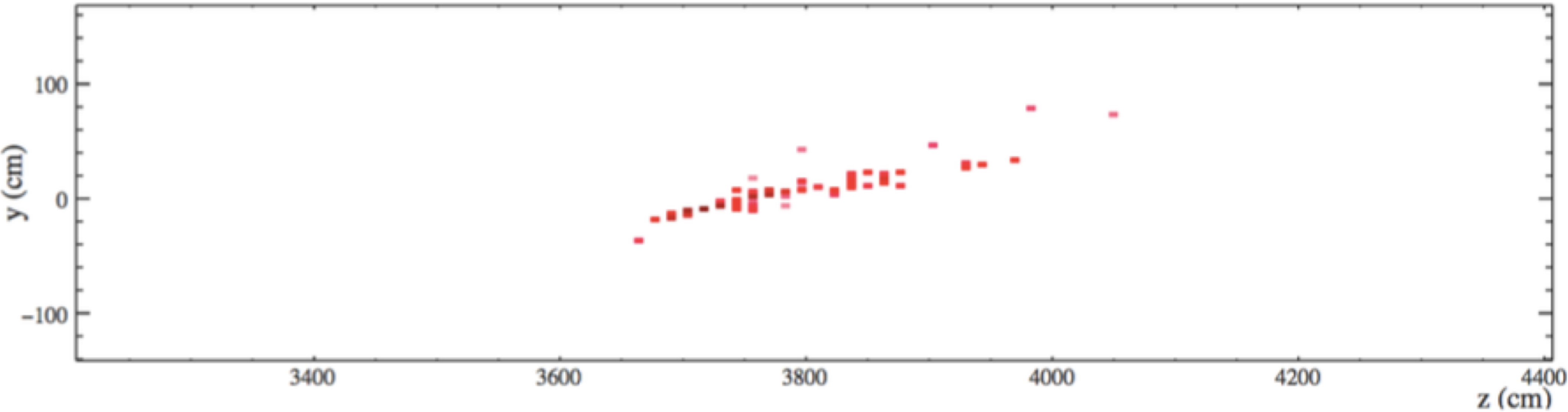
UO: $0.558^{+0.041}_{-0.033}$

LO: $0.475^{+0.036}_{-0.044}$

$\Delta m^2_{32} = 2.444^{+0.079}_{-0.077} \times 10^{-3}\ eV^2$



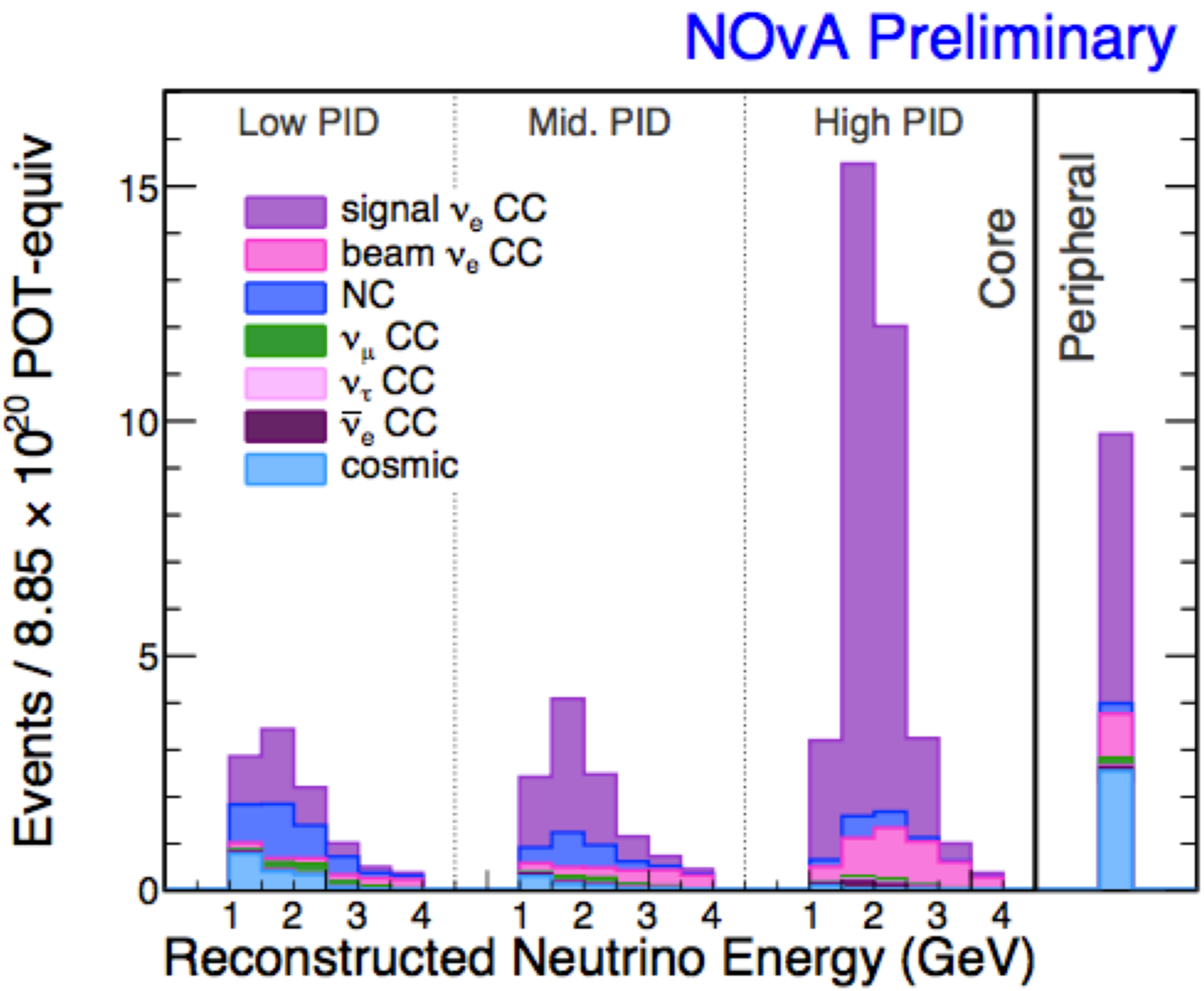
υ_e Appearance



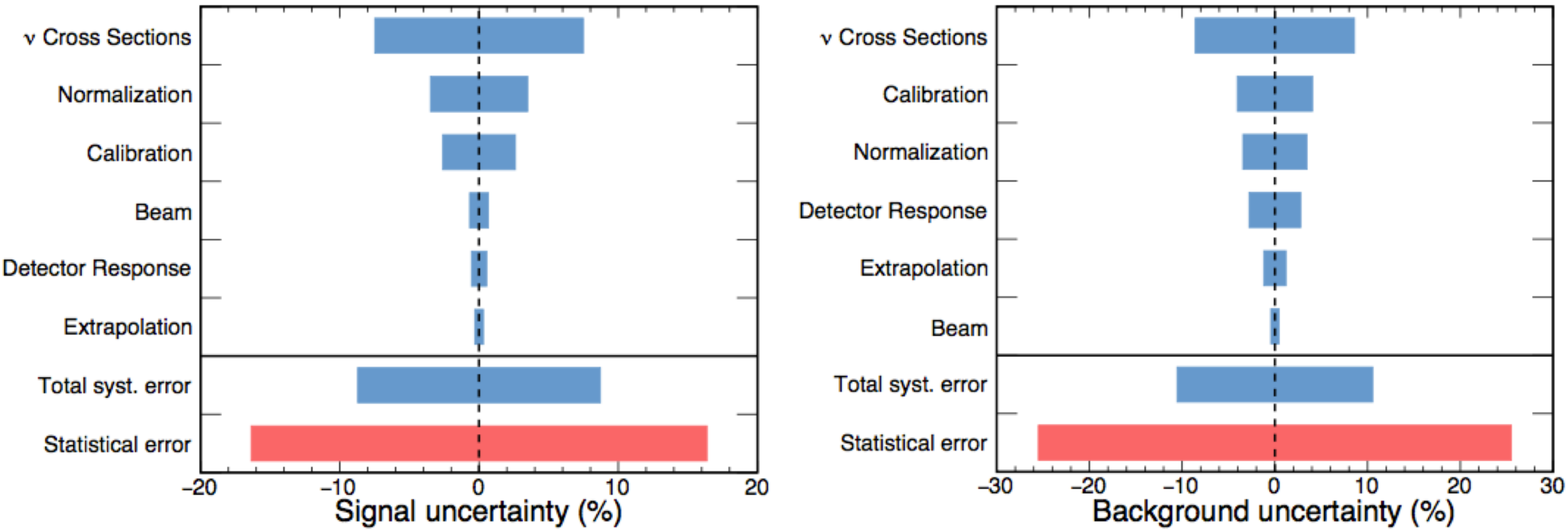
- Measure ND and FD ν_e and ν_μ energy Spectra
- Break down ND ν_e selected events to separately extrapolate background components
- Extrapolate ND ν_μ selected events estimate to the FD
- Use FD data from outside of the beam spill to estimate cosmic backgrounds
- Compare measured FD spectrum to expectation

υ_e Selection

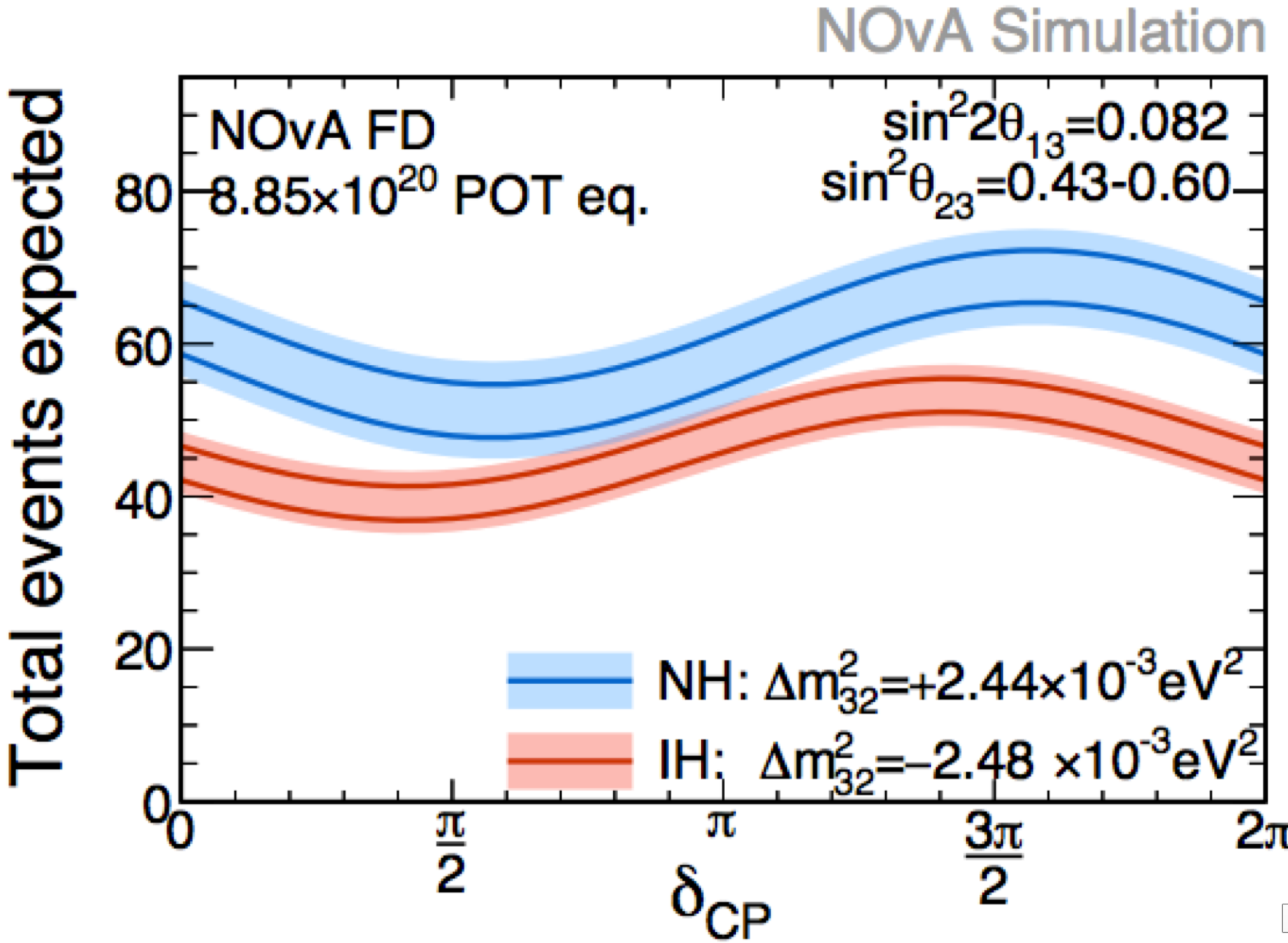
Optimized to maximally exploit the power of our our CVN ID. Select down to low PID values to recover as many signal events as possible. Binning in PID to retain the full power of the high purity subsample of events



υ_e Systematics



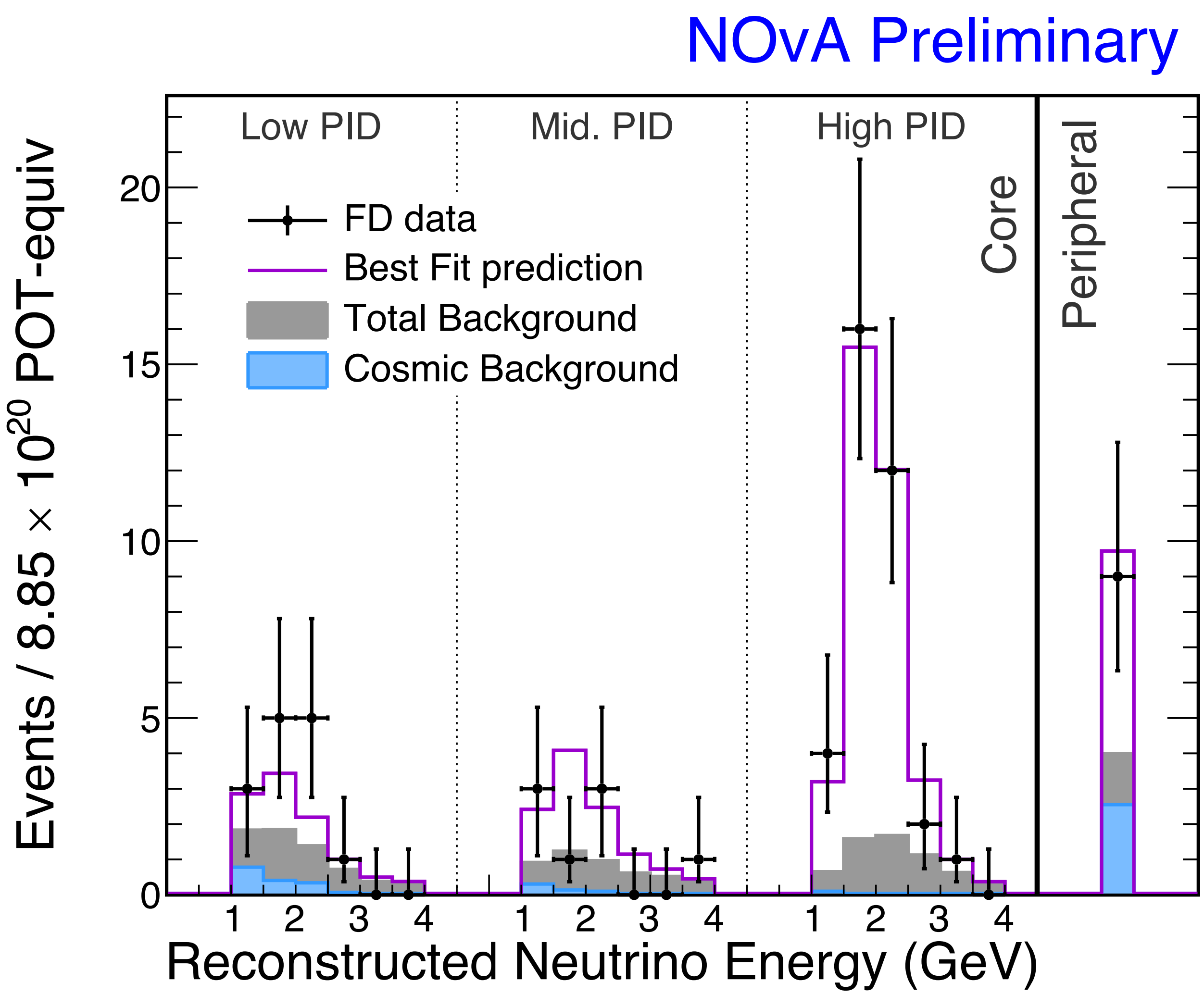
υ_e Predicted Events



ν_e Selected Events

Observe **66 events in FD**

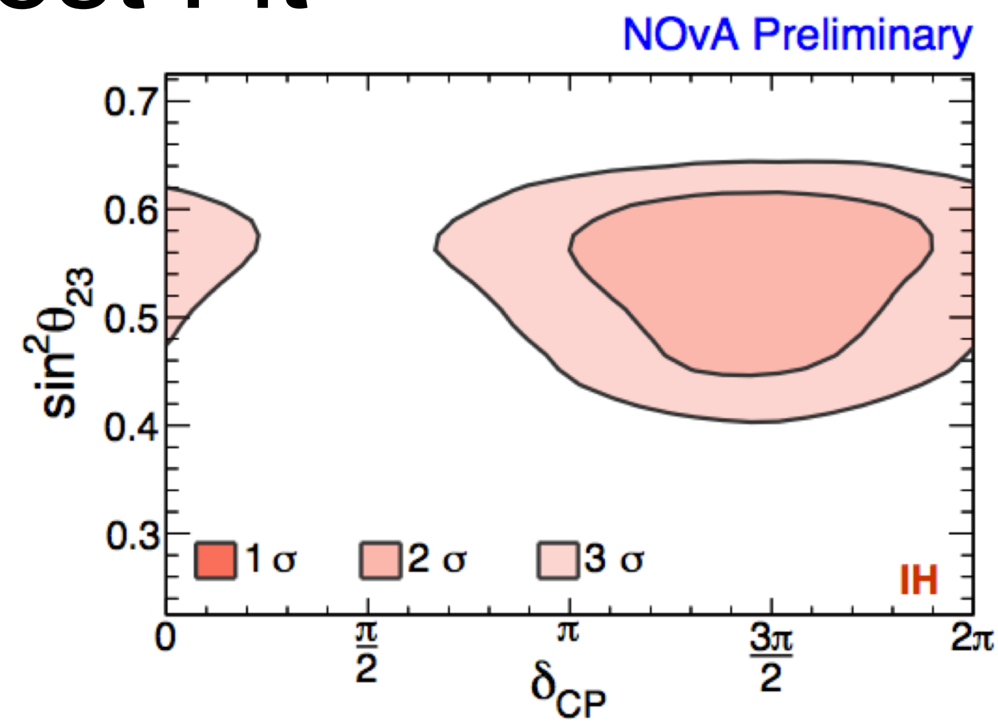
Background Expectation 20.5±2.5

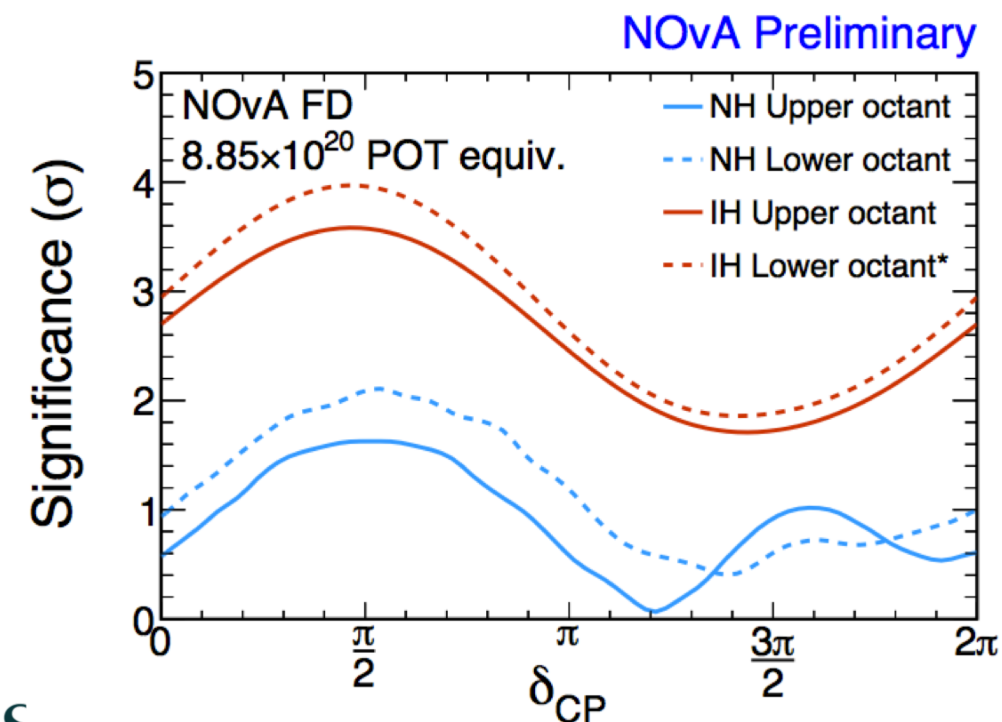


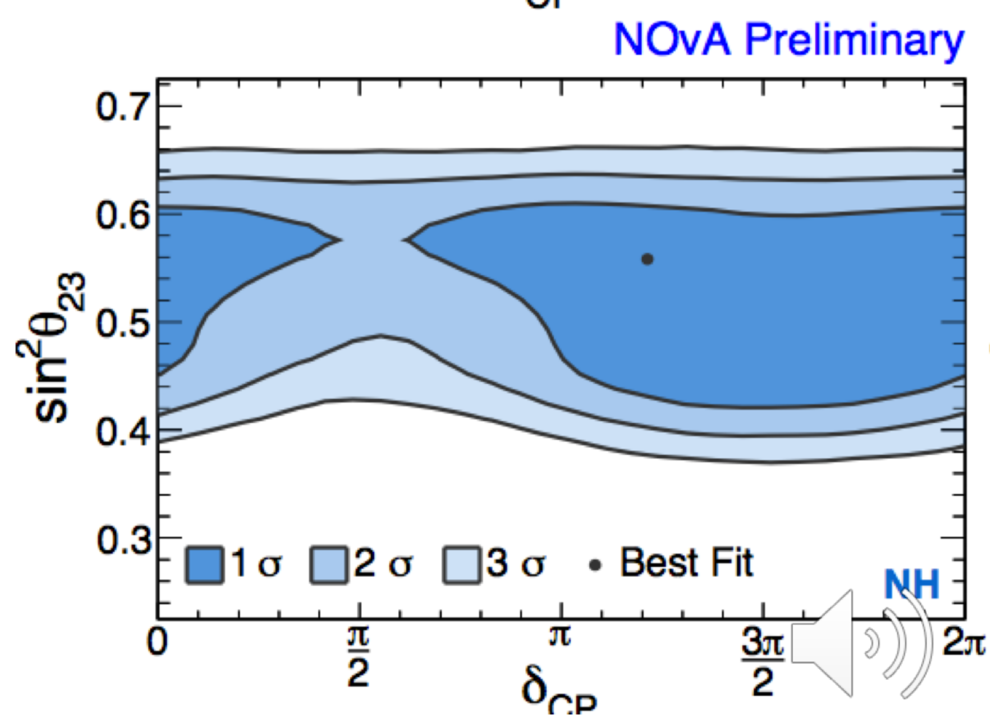
Joint Best Fit

IH at δcp = π/2 disfavoured at greater than 3σ

Approaching IH rejection at 2σ







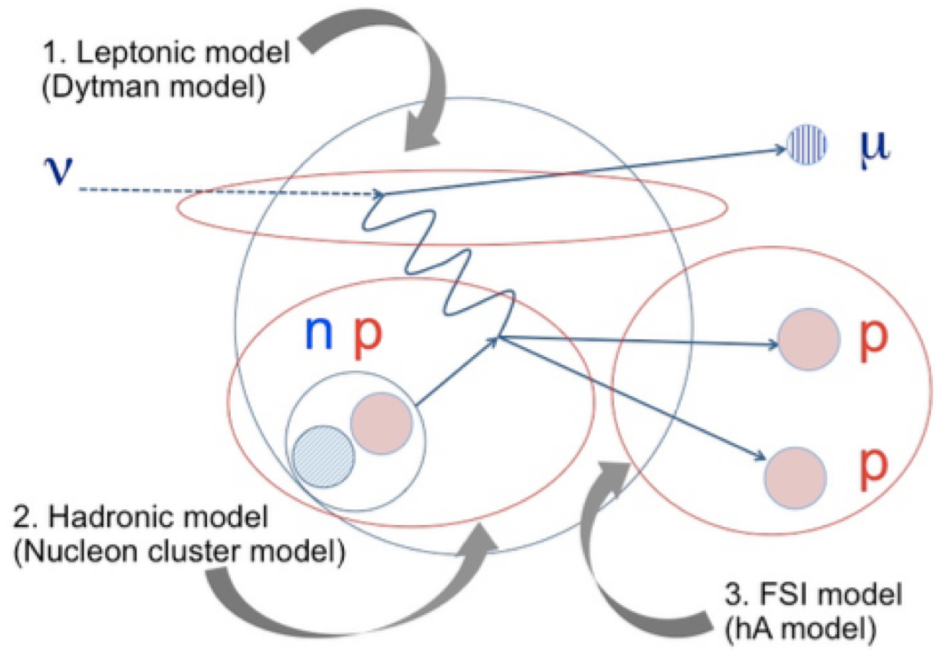
Conclusions

- At 8.85 e20 POT, NOvA finds:
  - **Muon neutrinos disappear:** Competitive measurement of Δm^2_{32}, new analysis prefers mixing near-maximal
  - **Electron neutrinos appear:** Inverted Hierarchy at $\delta_{cp} = \pi/2$ disfavoured at greater than 3σ. Approaching 2σ IH rejection
- **Excellent detector and beam performance**
- **Significant improvement in our analysis tools.** Expected to continue, benefiting from efforts like the NOvA test beam.
- Looking forward to opening the box on our first antineutrino data this summer!
- Expect NOvA to continue to contribute to key questions:
  - Is δ_{cp} nonzero?
  - What is the mass hierarchy?

Thank you!

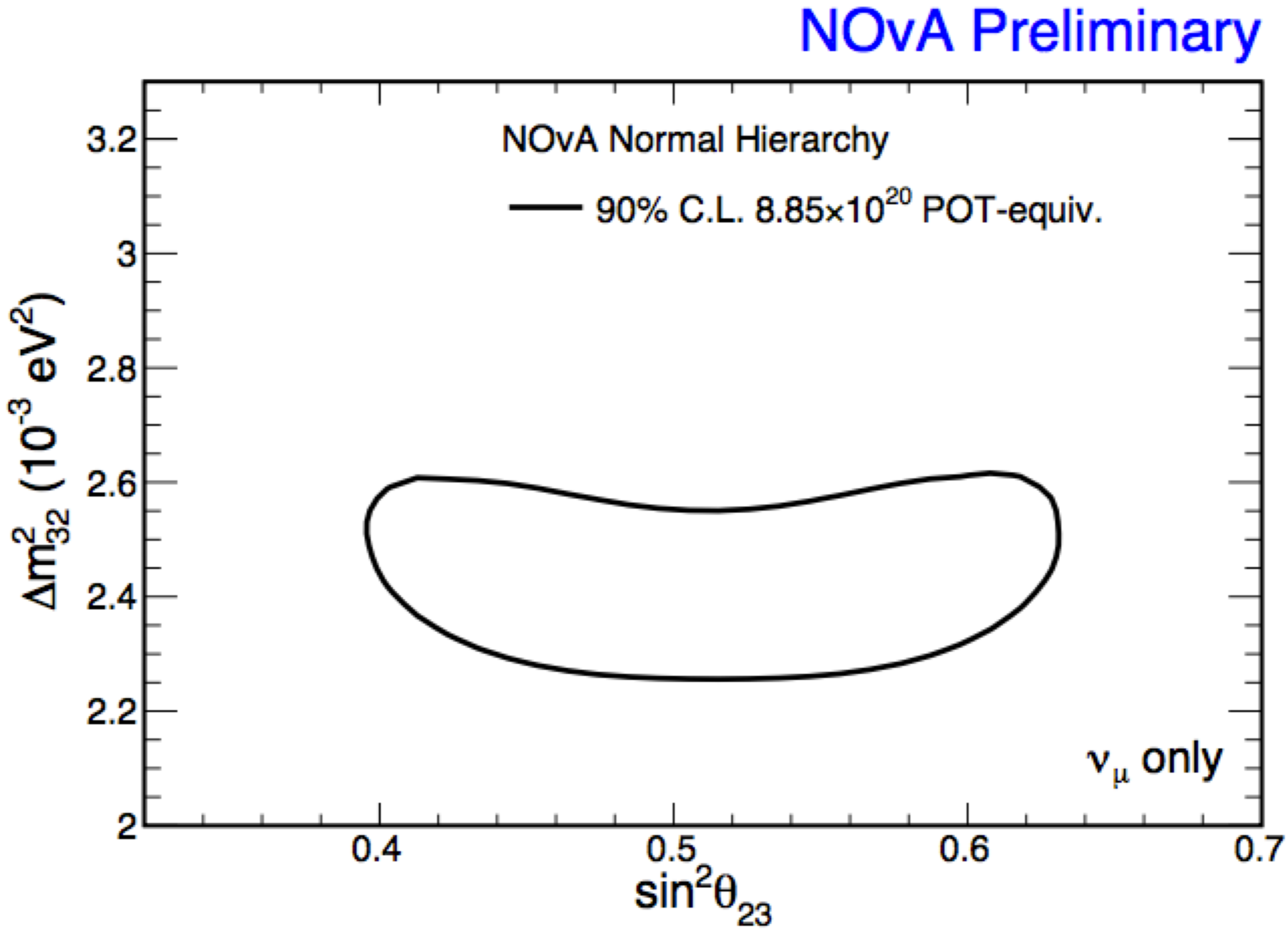
Tuned interaction modelling

- Nuclear effects on the initial state (nuclear charge screening/"RPA" effect) and reactions themselves (multi-nucleon ejection e.g. 2p2h via Meson Exchange Currents (MEC)) are important components of our interaction model, particularly of the hadronic energy component
- Theory for these effects and how they fit together remains incomplete
- Important that we not just have the best possible central value tune, but also appropriately conservative uncertainties

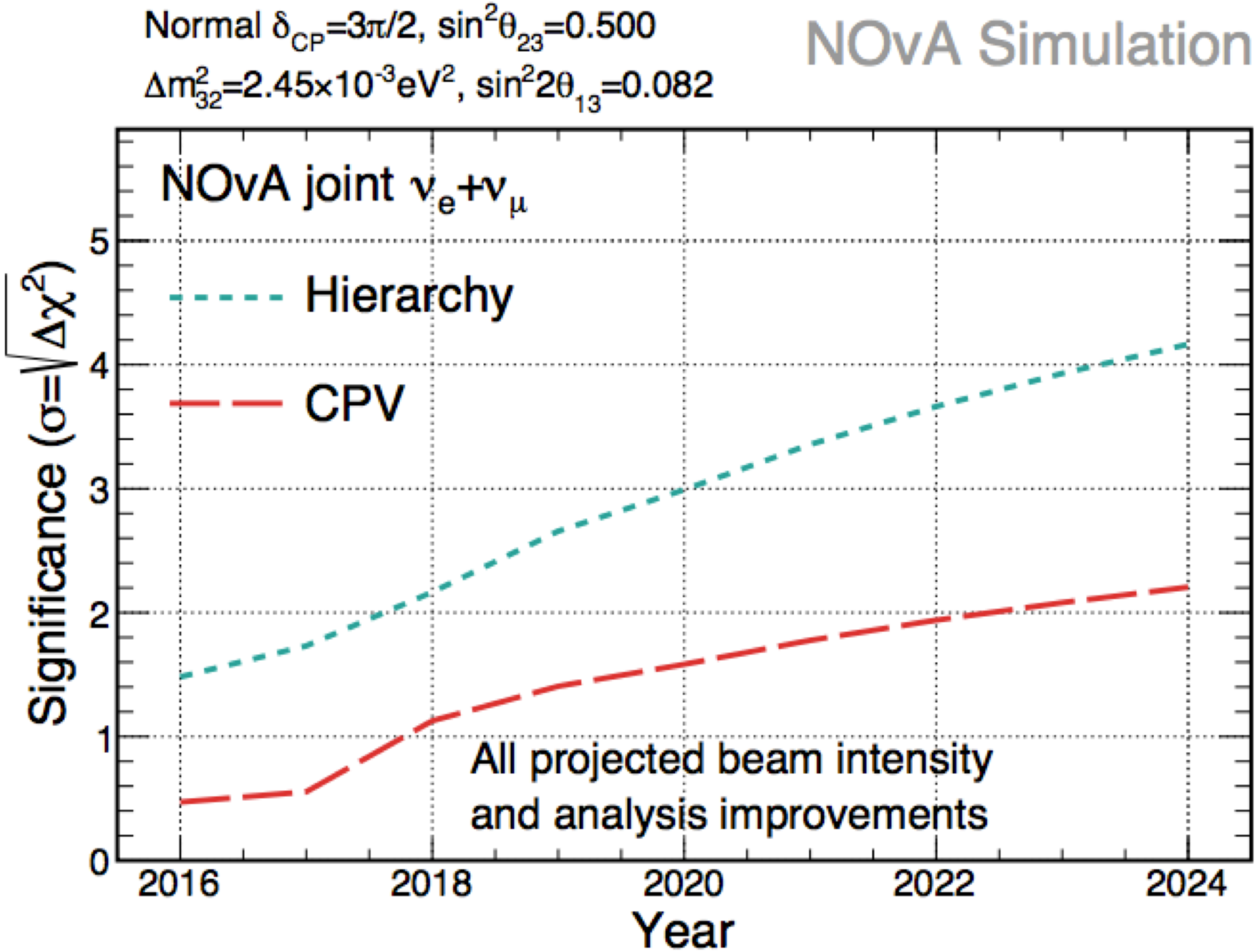


"Meson Exchange Current (MEC) Models in Neutrino Interaction Generators"
AIP Conf.Proc. 1663 (2015) 030001
Teppei Katori

υ_μ Result



Future



Normal δ_{CP}=3π/2, $\sin^2\theta_{23}$=0.500
Δm^2_{32}=2.45×10^{-3}eV^2, $\sin^2 2\theta_{13}$=0.082
NOvA Simulation
NOvA joint ν_e+ν_μ
Hierarchy
CPV
All projected beam intensity
and analysis improvements
Significance ($\sigma=\sqrt{\Delta\chi^2}$)
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024