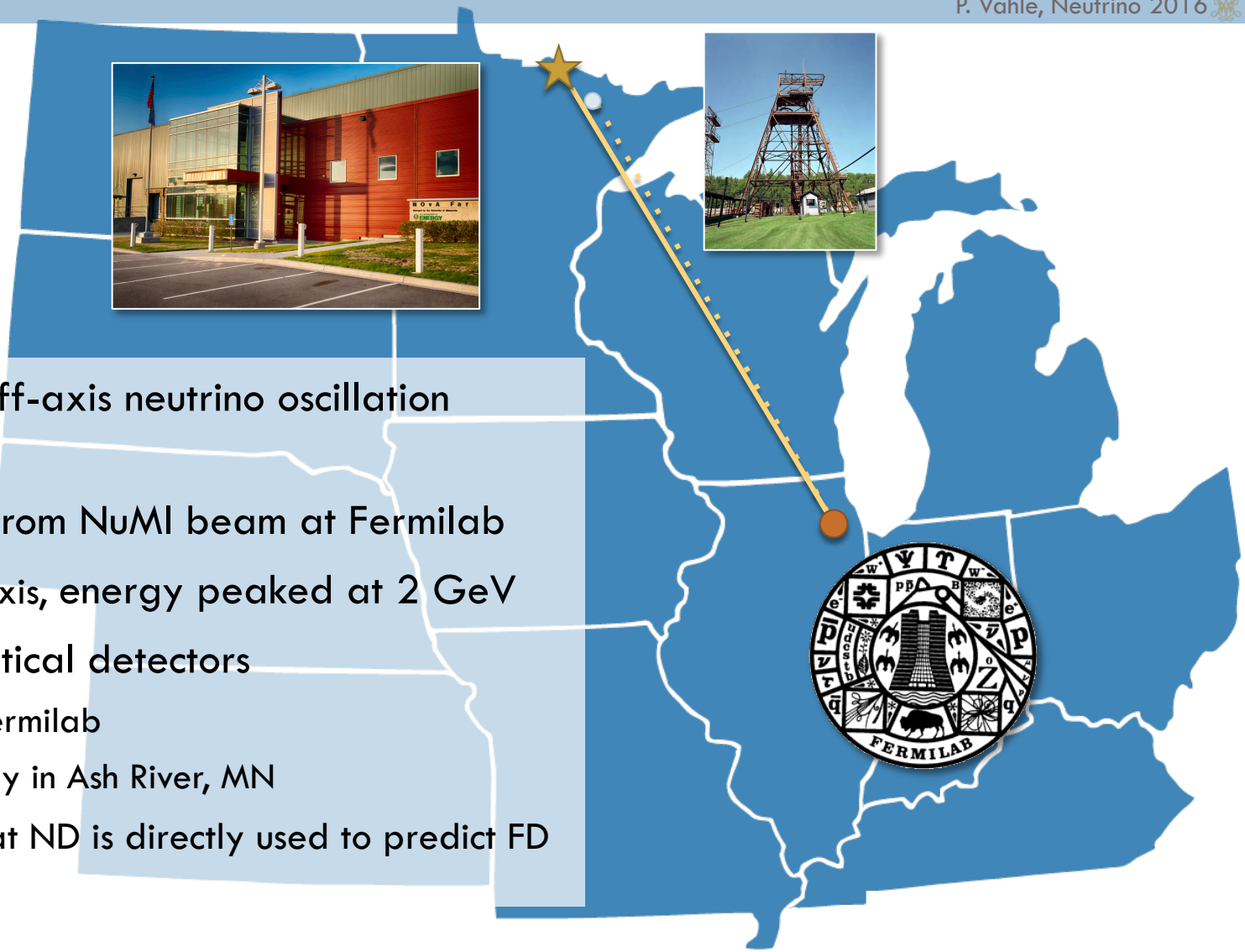
NEW RESULTS FROM NOVA

Patricia Vahle, On Behalf of the NOvA Collaboration
William and Mary

NOvA



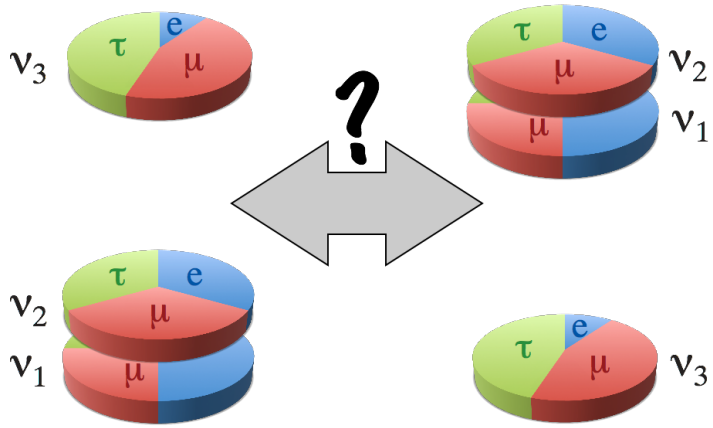
- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

Physics Goals

Results from 3 different oscillation analyses

- Disappearance of ν_μ CC events
  - clear suppression as a function of energy
  - 2015 analysis results Phys.Rev.D93.051104

$|\Delta m^2_{32}|$ $\sin^2(2\theta_{23})$



- Appearance of ν_e CC events

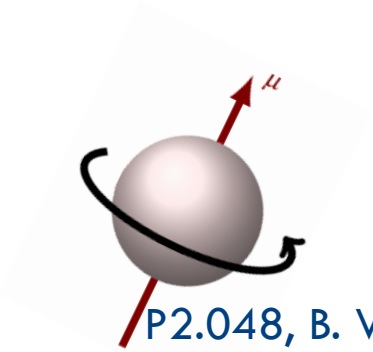
$\theta_{13}, \theta_{23}, \delta_{CP},$
and Mass Hierarchy

  - 810 km baseline enhances matter effects
  - ±30% effect
  - 2015 analysis results in PRL.116.151806

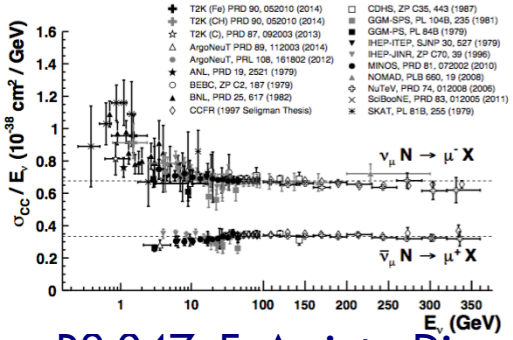
- Deficit of NC events?
  - suppression of NCs could be evidence of oscillations involving a sterile neutrino
  - Fit to 3+1model
  - new! $\Delta m^2_{41}, \theta_{34}, \theta_{24}$

Physics Goals

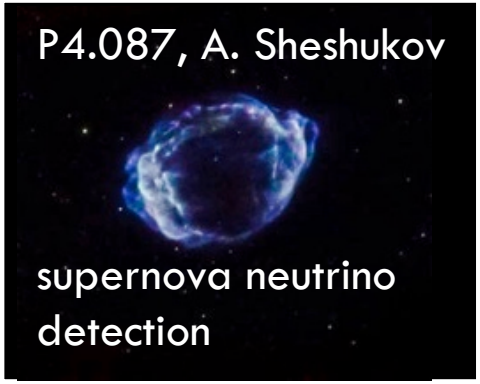
Additionally, many cross section analyses, searches for exotic phenomena, and non-beam physics studies!



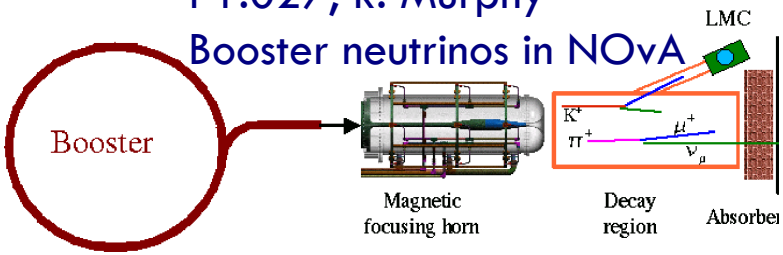
P2.048, B. Wang
elastic scattering off atomic electrons, neutrino magnetic moment, and dark matter



P2.047, E. Arrieta Diaz
inclusive CC cross section

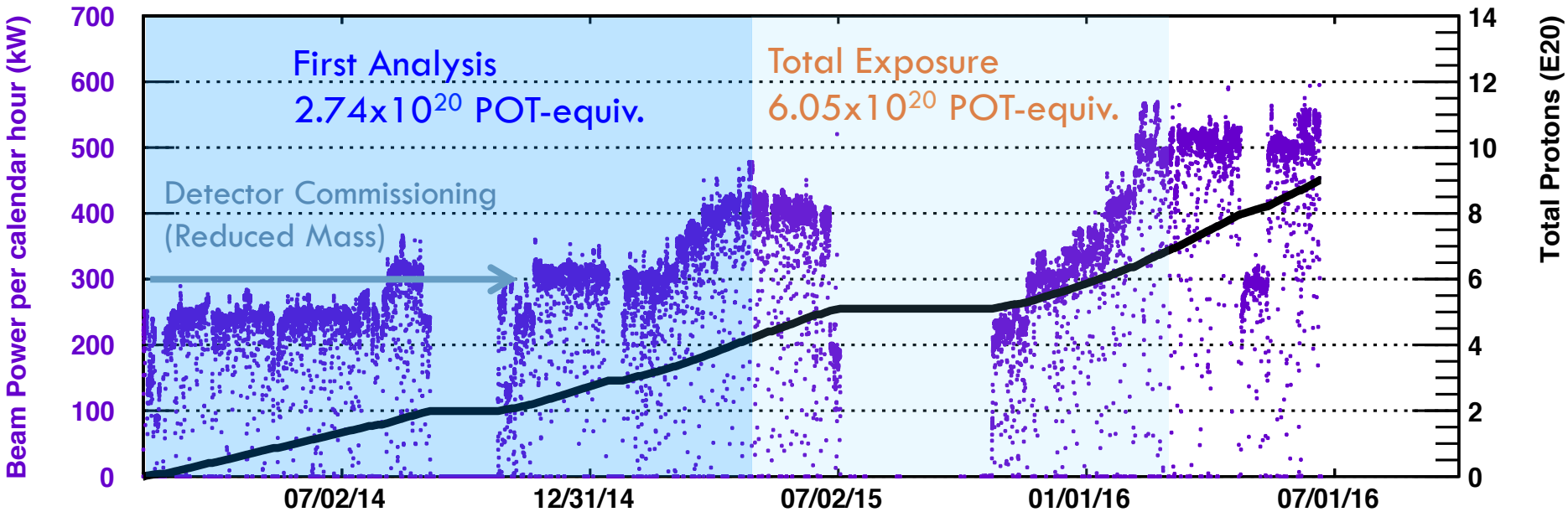


P1.027, R. Murphy
Booster neutrinos in NOvA



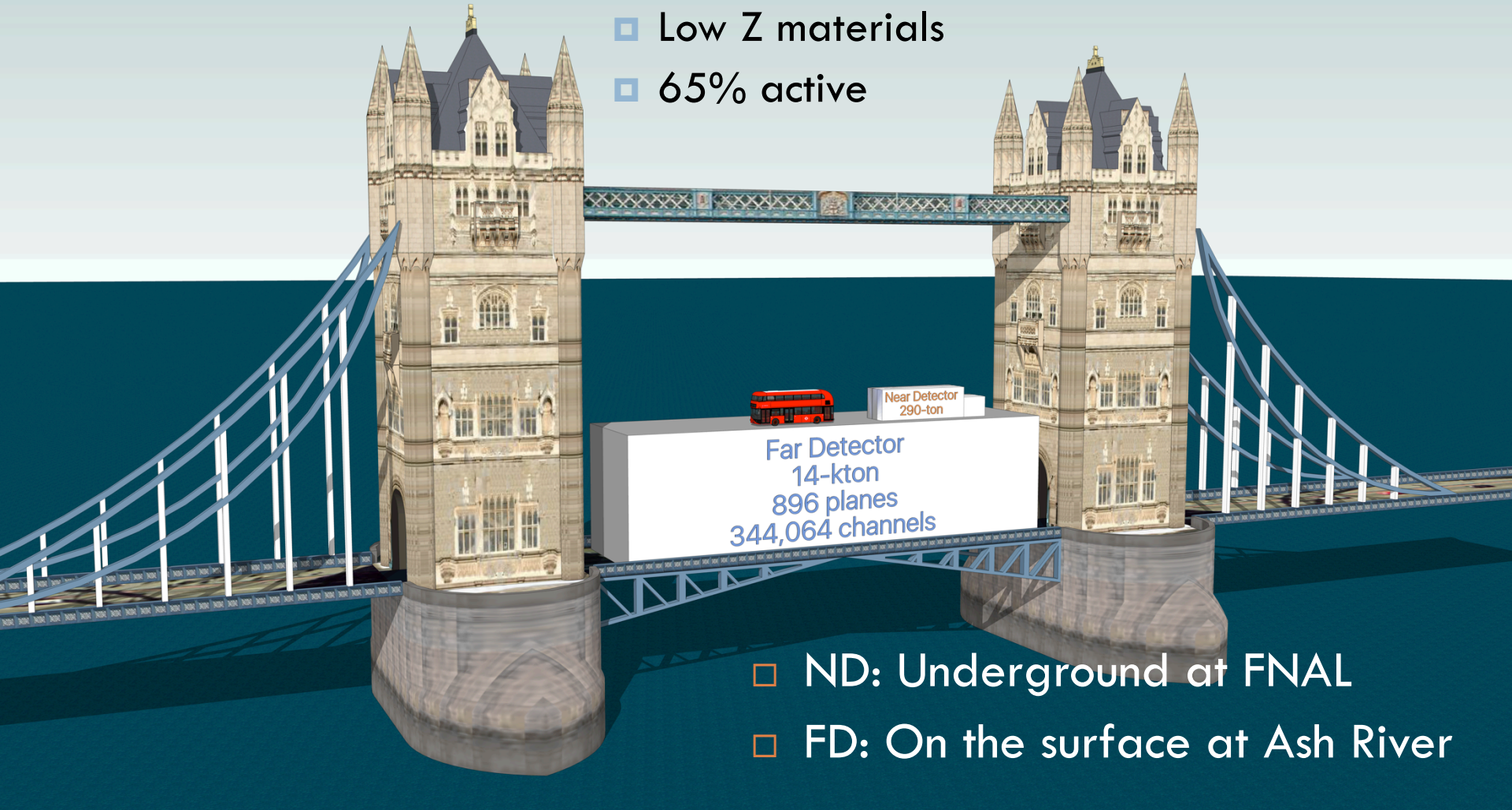
Beam Performance

- 6.05×10^{20} POT in 14 kton equivalent detector
  - More than double exposure of 2015 analysis
- Currently running at 560 kW
- Achieved 700 kW design goal in tests on June13!



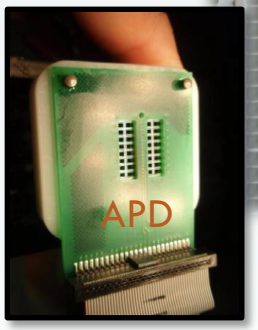
NOvA Detectors

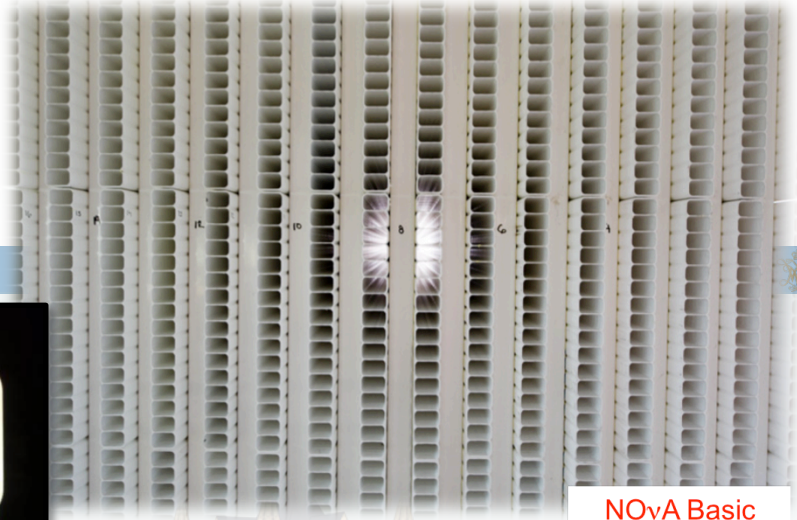
- Designed for electron ID
  - Low Z materials
  - 65% active



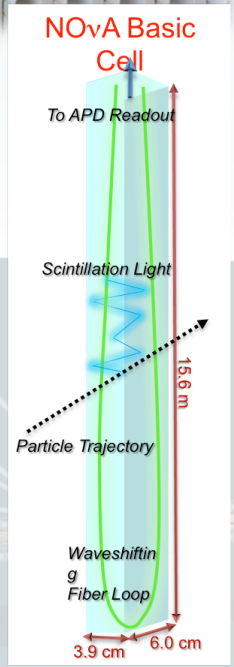
- ND: Underground at FNAL
- FD: On the surface at Ash River

NOvA Detectors





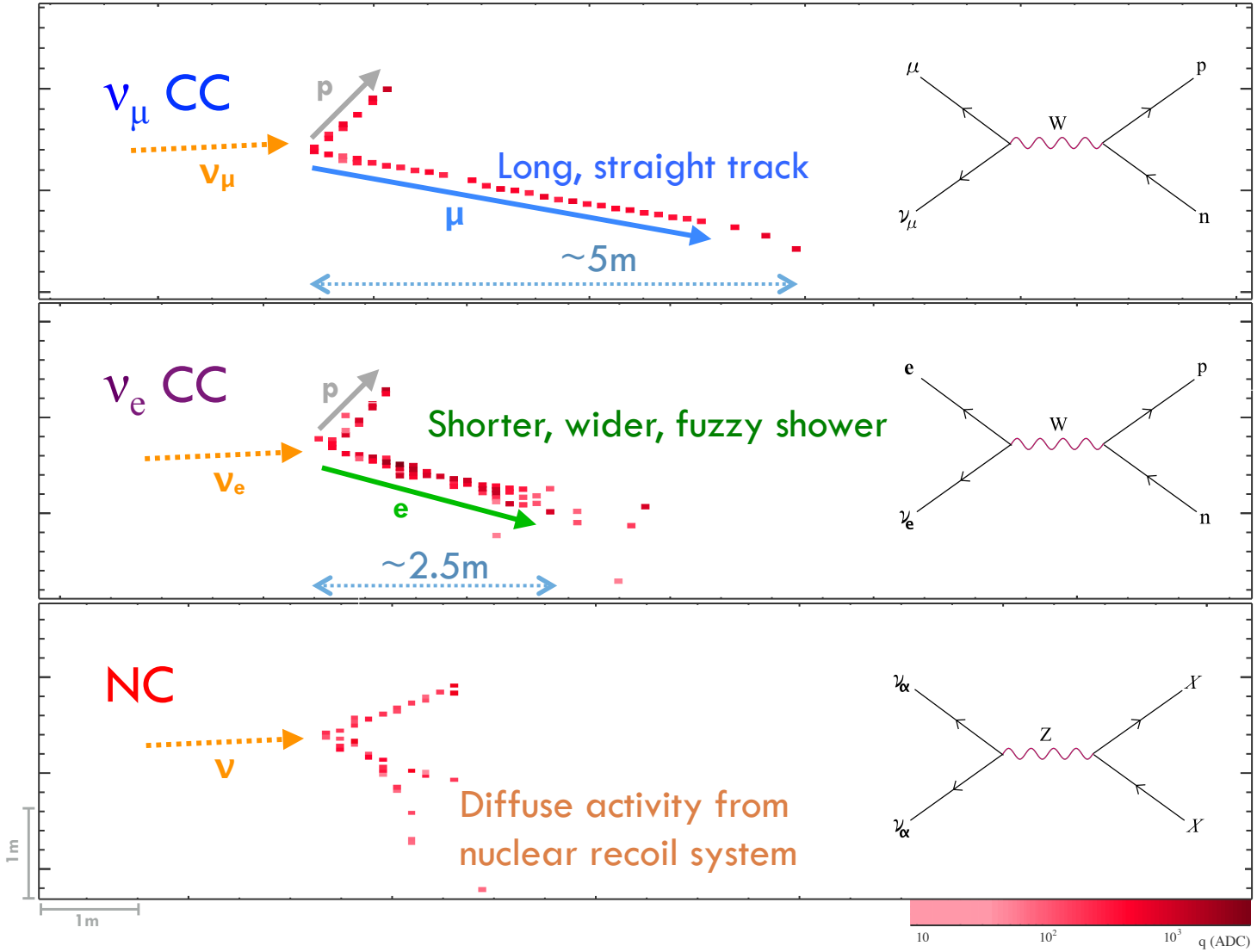
- PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer
- DAQ runs with zero deadtime
  - triggers for beam, SNEWS, cosmic ray calibration samples, exotic searches
  - 150kHz of cosmic induced events



See Poster P1.031 by D. Mendez for details on Calibration

See Poster P1.033 by G. Davies and C. Backhouse for details on Reconstruction

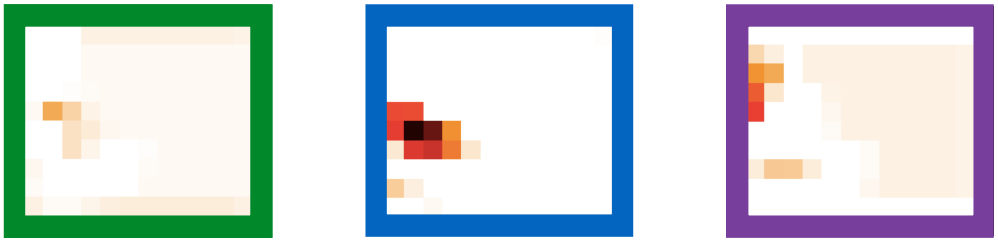
Event Selection

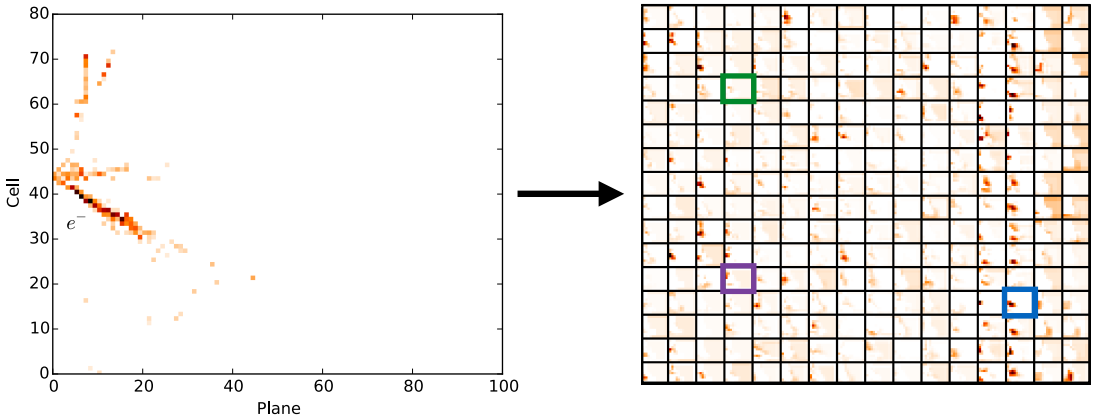


Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event





A. Aurisano et al., arXiv:1604.01444
Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

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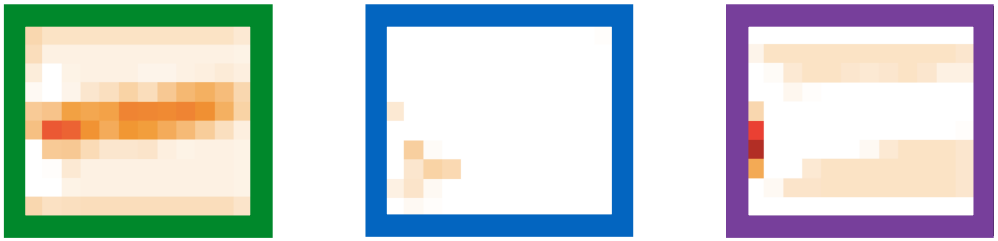

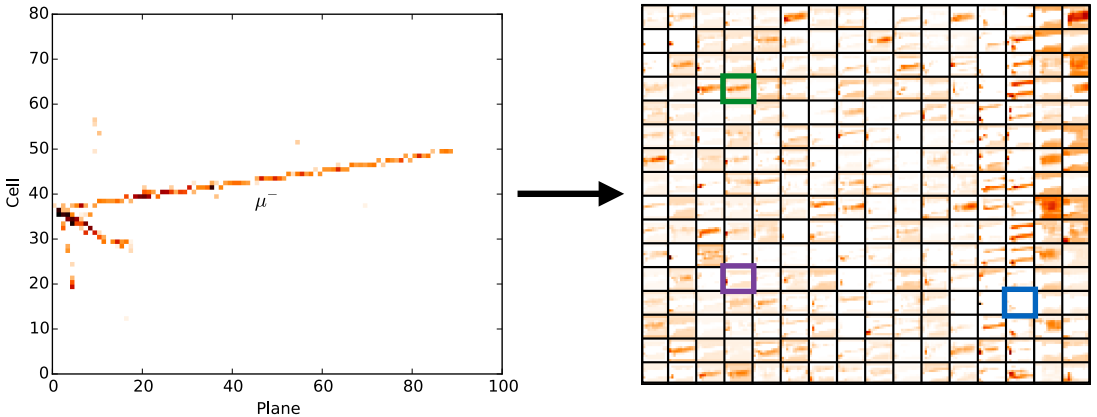

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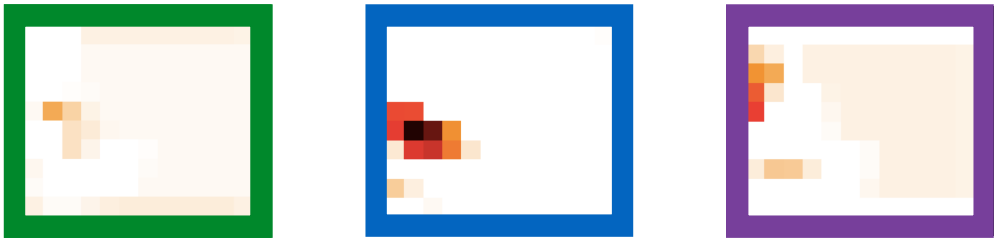
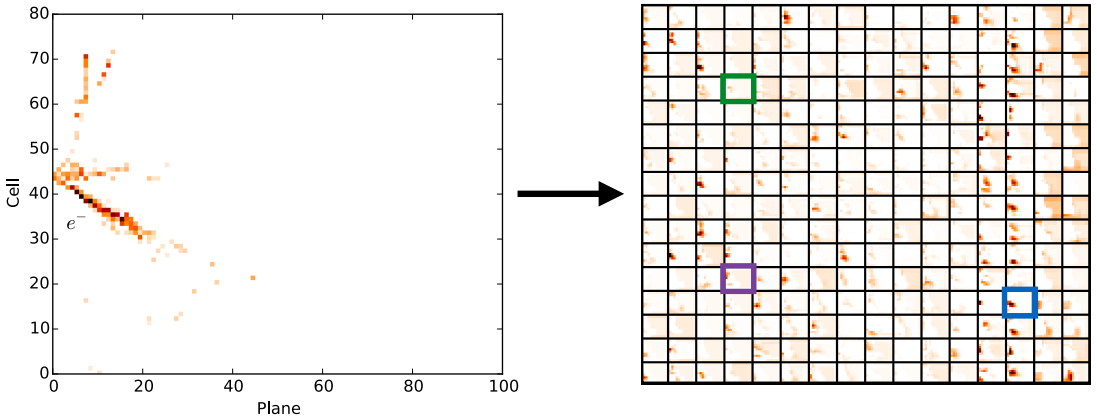
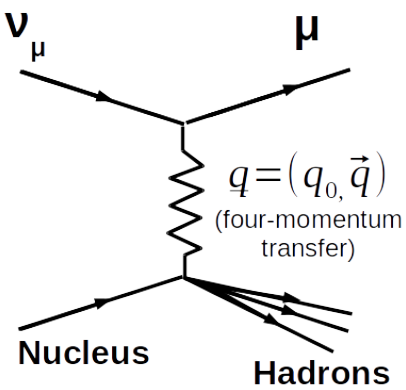


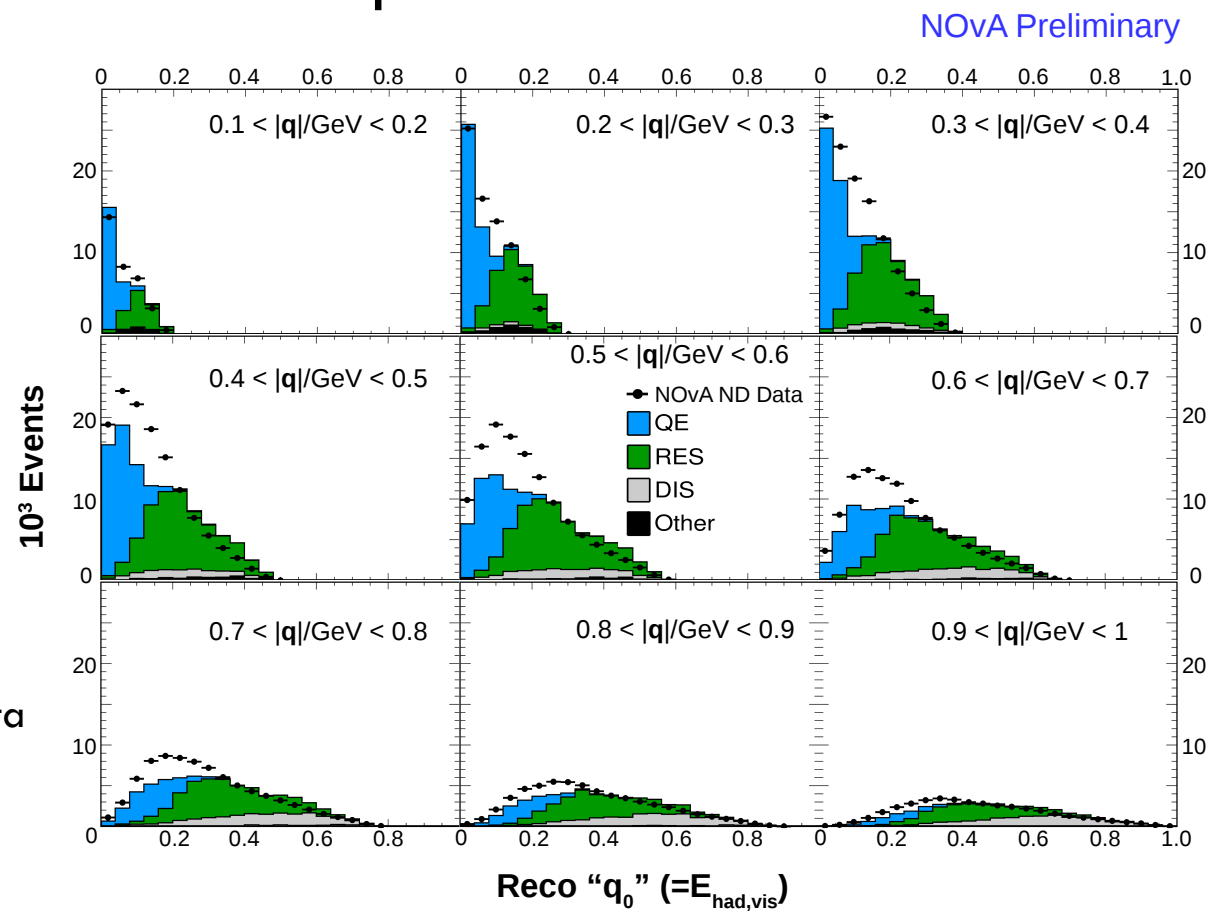


Improvement in sensitivity from CVN equivalent to 30% more exposure

Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production



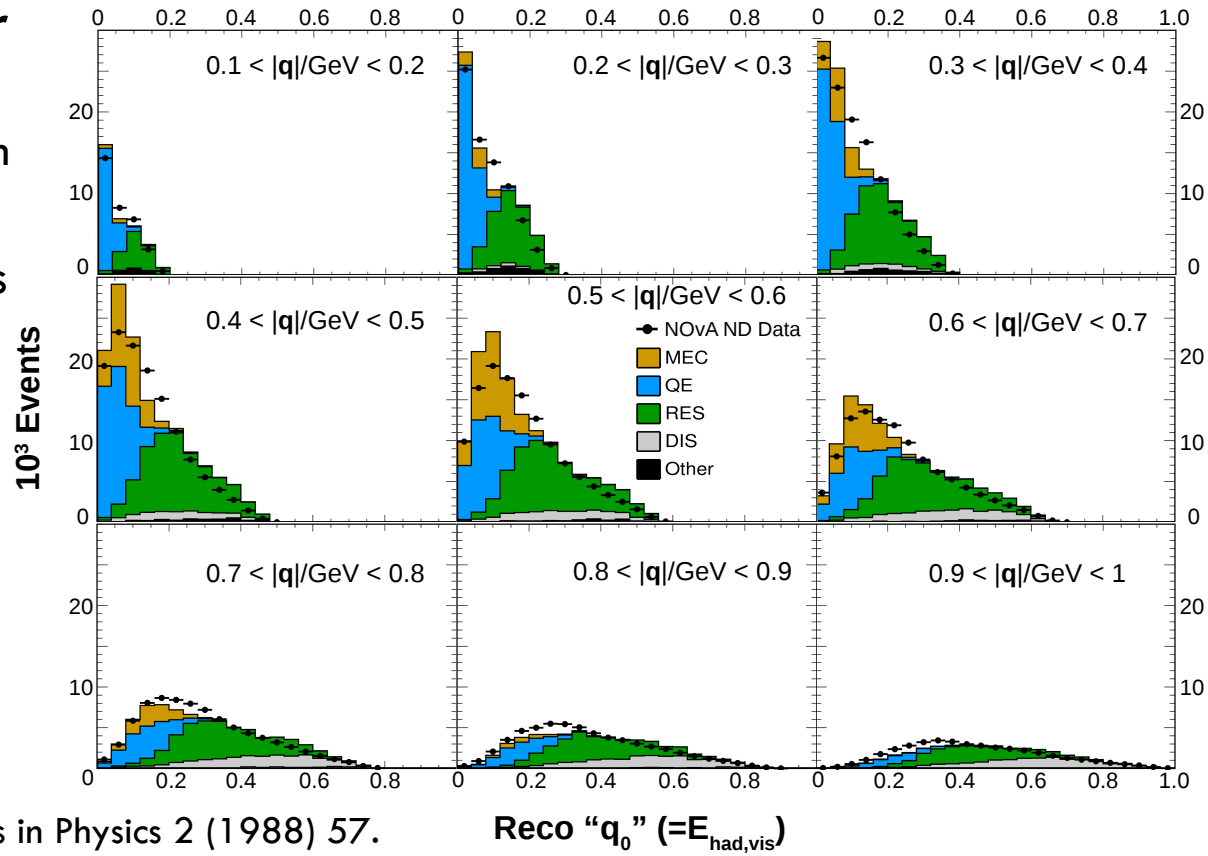


Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

- Enable GENIE empirical Meson Exchange Current Model
- Reweight to match NOvA excess as a function of 3-momentum transfer

- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50% (P.A. Rodrigues et al, arXiv:1601.01888.)



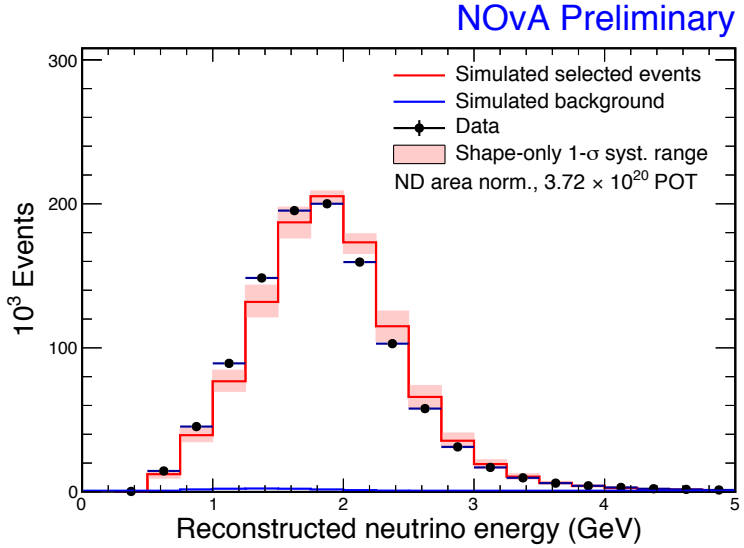
MEC model by S. Dytman, inspired by J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

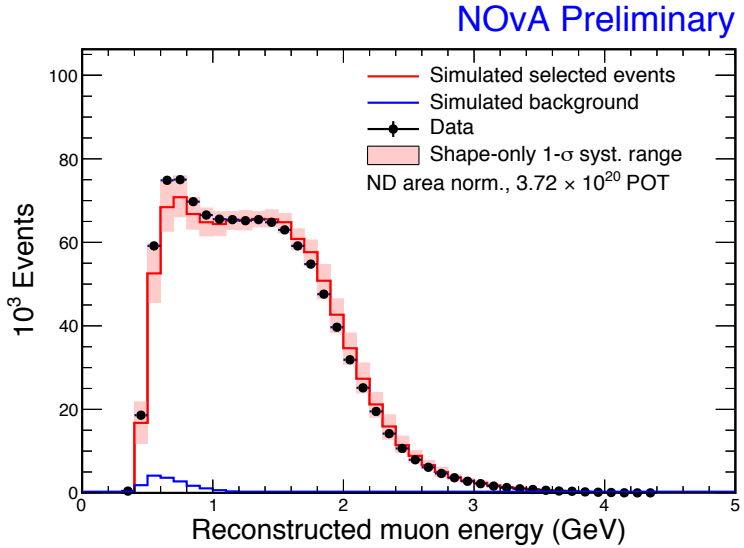
Muon Neutrino Disappearance

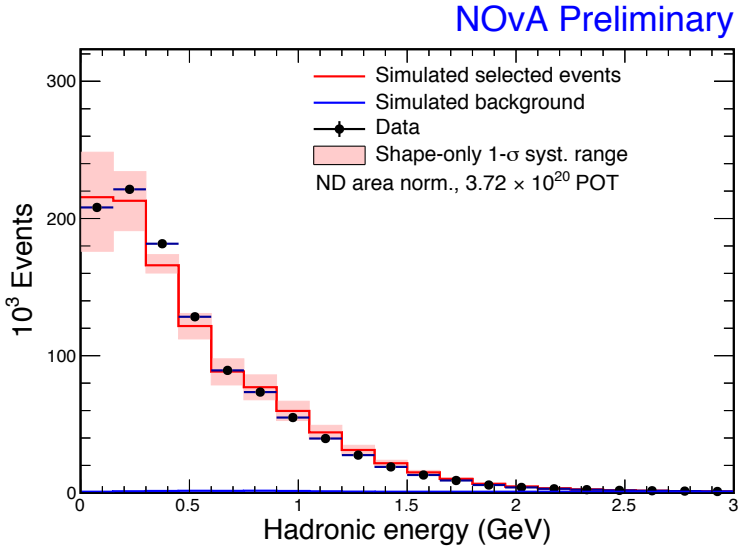
See Poster P1.035 by K. Bays for more detail

Muon Neutrino ND data

- Addition of MEC events substantially improves simulated hadronic energy distribution
  - hadronic energy scale uncertainty reduced (14% to 5%)
- Reconstructed neutrino energy unfolded, true Far/Near ratio used to extrapolate ND data for a FD prediction



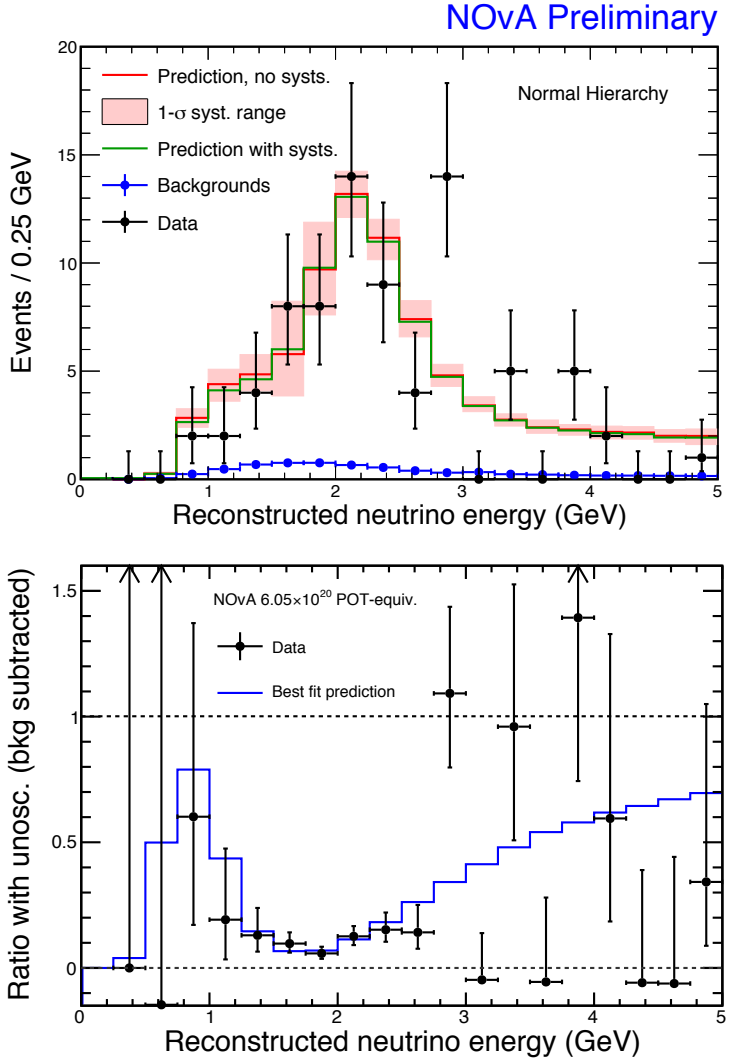




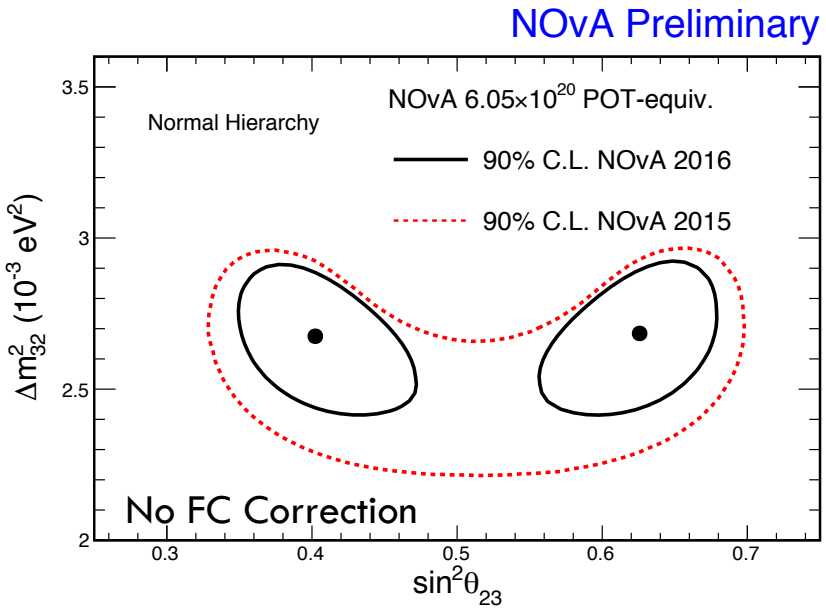
Muon Neutrino FD Data

- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit



Contours



- Fit for Δm^2 and $\sin^2\theta_{23}$
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

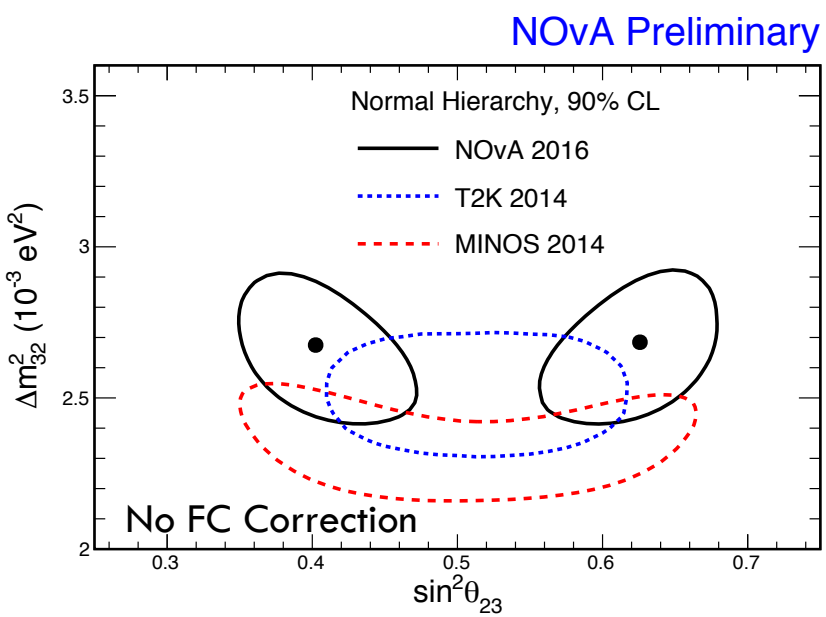
Best Fit (in NH):

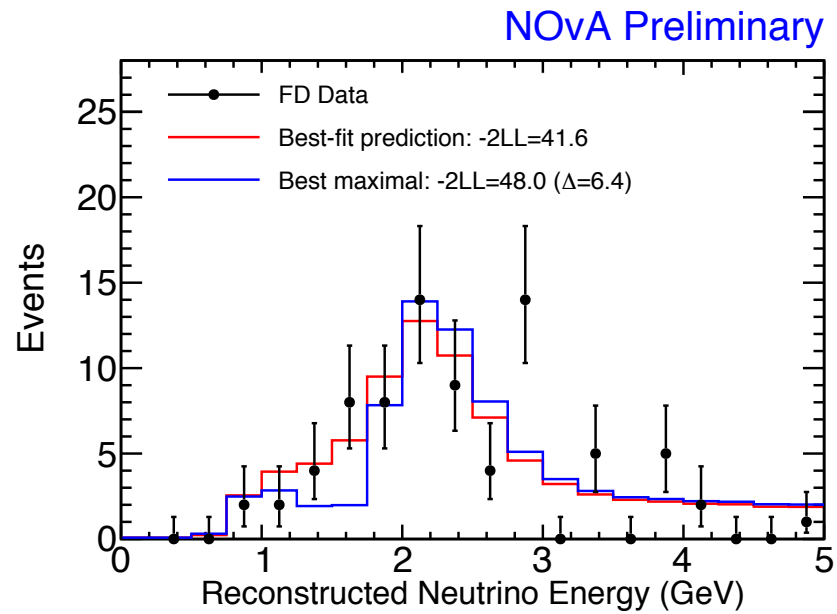
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

See Poster P1.029 by L. Vinton and B. Zamorano for more detail on systematics

Contours





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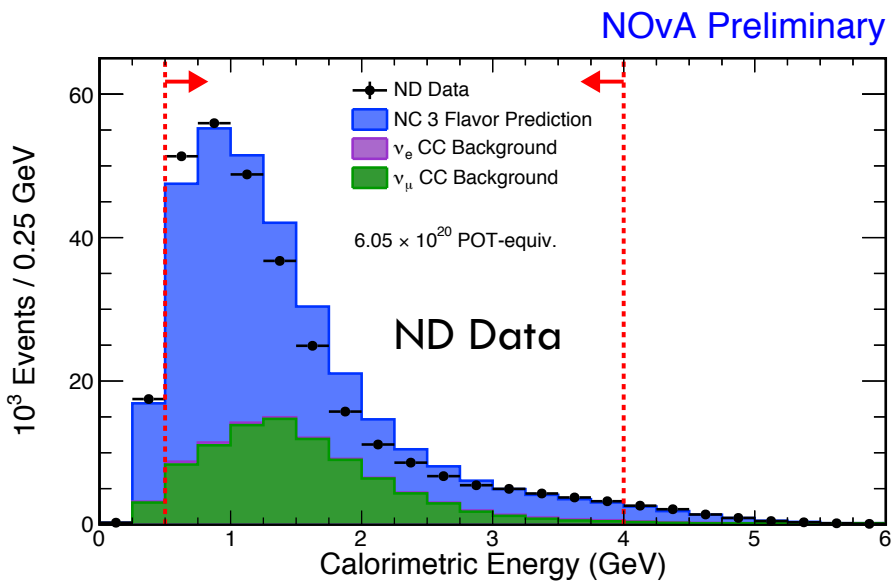
Neutral Current Disappearance

Neutral Current ND Data

- Events classified using CVN
- Normalization agrees well
- Data shifted to lower energy relative to MC
  - No MEC model for NC events
  - Large uncertainties on NC cross section



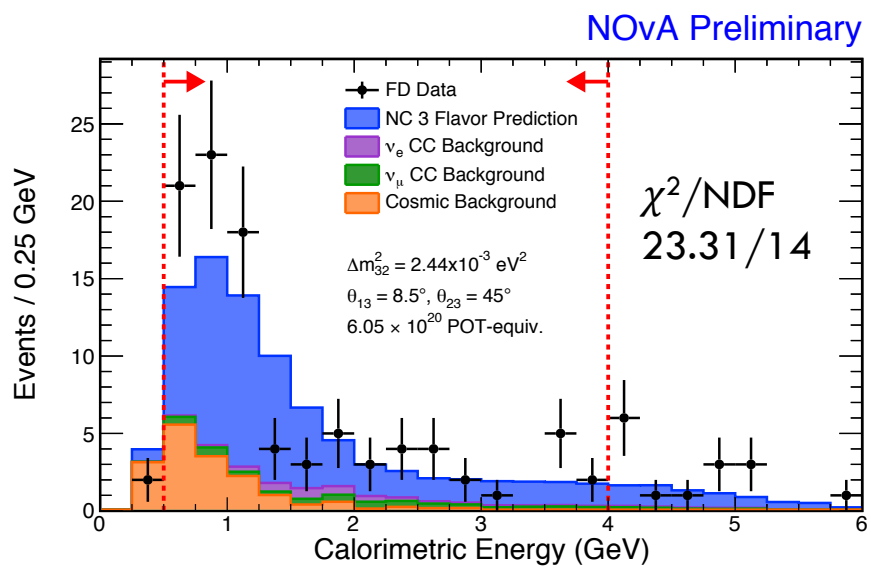
Extrapolation of ND data using F/N in reconstructed energy gives a prediction of:

Total	NC	ν_μ CC	Beam ν_e	Cosmics
83.7±8.3	60.6	4.8	3.6	14.3

See Posters P1.026 by G. Kafka et al., P2.082 by L. Suter, P2.081 by A. Aurisano

Neutral Current FD Data

- Observe 95 events
- No evidence of oscillations involving steriles



$$\text{For } 0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$$

$$\theta_{34} < 35°,\ \theta_{24} < 21°\ (90\%\text{C.L.})$$

Excellent NC efficiency (50%) and purity (72%) promise strong future limits on θ_{34}

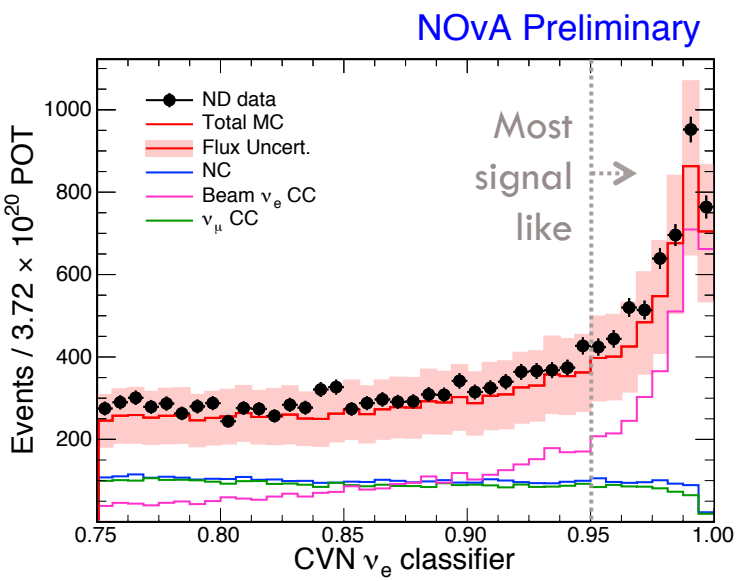
Electron Neutrino Appearance

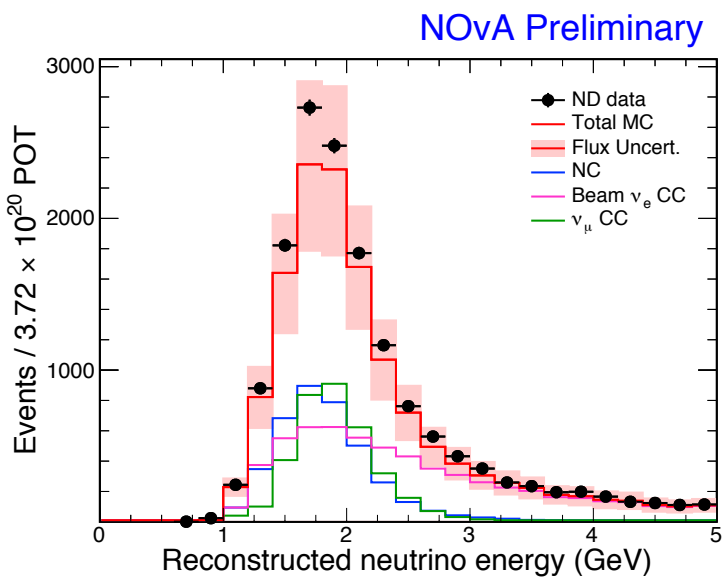
Electron Neutrino ND Data

- Selection reoptimized to favor parameter measurement
  - both cosmic rejection and classifier cut
  - increased signal efficiency, including lower purity bins
- Use ND data to predict background in FD
  - NC, CC, beam ν_e each propagate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain ν_μ CC using Michel Electron distribution

See Poster P1.030 by E. Catano-Mur

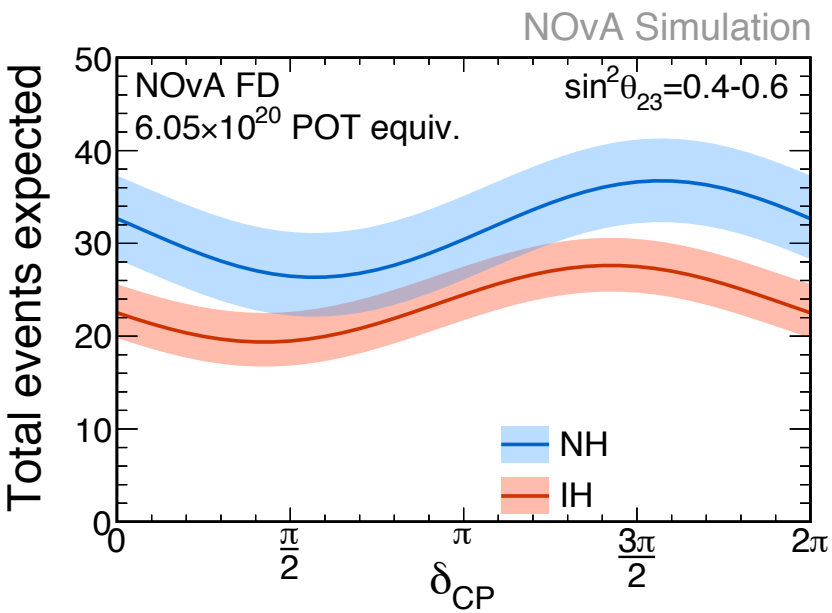
beam ν_e up by 4%
NC up by 10%
ν_μ CC up by 17%





Prediction

- Extrapolate each component in bins of energy and CVN output
- Expected event counts depend on oscillation parameters



Signal events
(±5% systematic uncertainty):

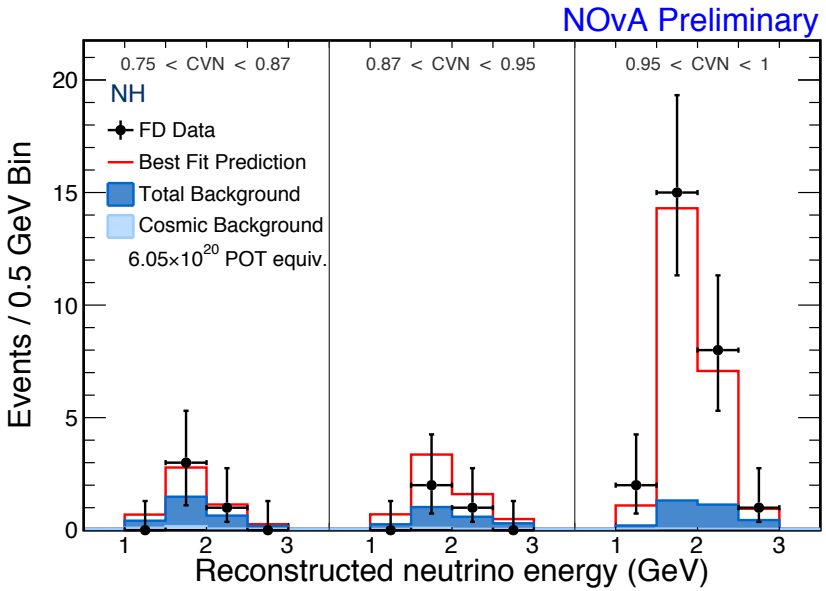
NH, 3π/2,	IH, π/2,
28.2	11.2

Background by component
(±10% systematic uncertainty):

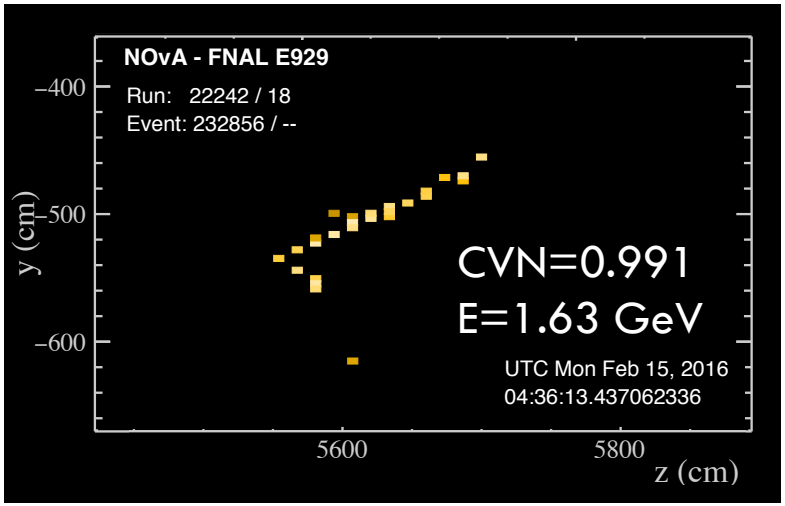
Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

Electron Neutrino FD Data

>8σ electron neutrino appearance signal



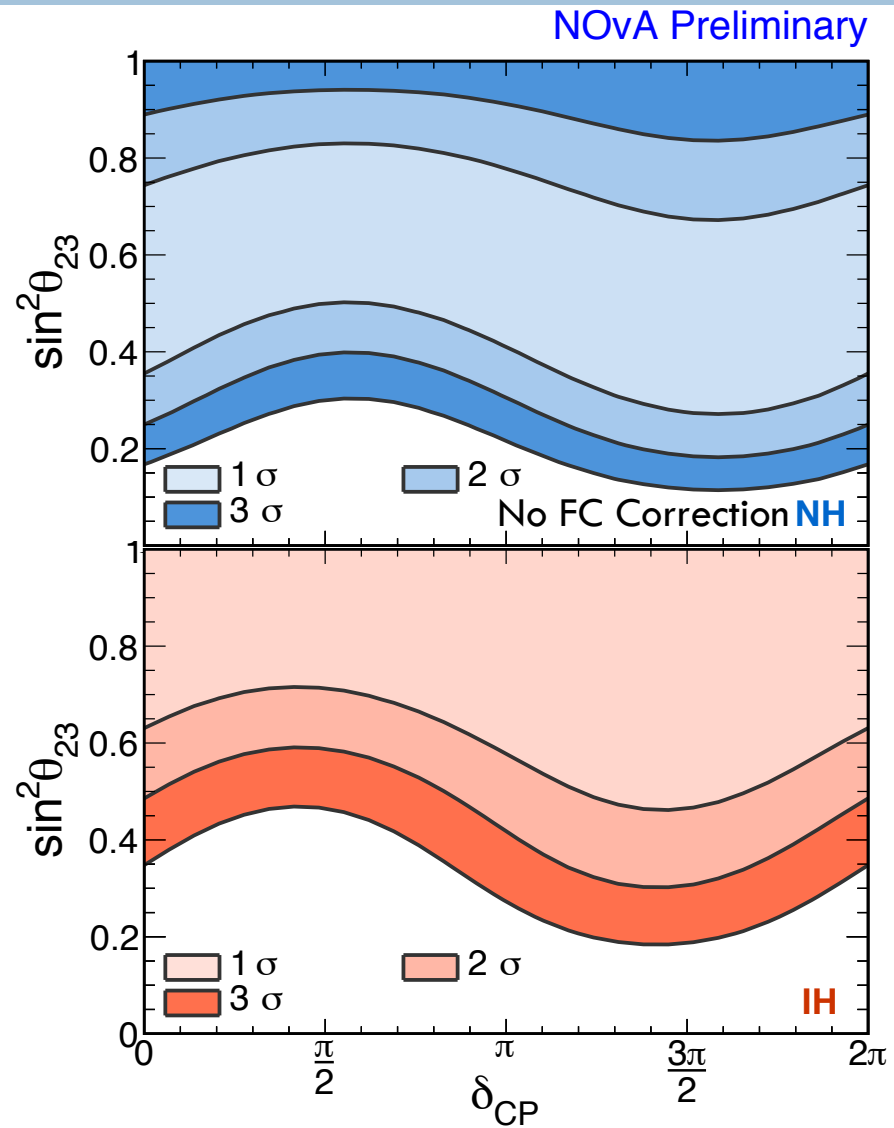
- Observe 33 events in FD
  - background 8.2±0.8



Alternate selectors from 2015 analysis show consistent results
LID: 34 events, 12.2±1.2 BG expected
LEM: 33 events, 10.3±1.0 BG expected

Contours

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13})=0.085\pm0.05$
  - Constrain $\Delta m^2=2.44\pm0.06\times10^{-3}$ eV^2 ($-2.49\pm0.06\times10^{-3}$ eV^2, IH)
  - Systematic effects included as nuisance parameters (normalization, flux, calibration, cross section, and detector response effects)

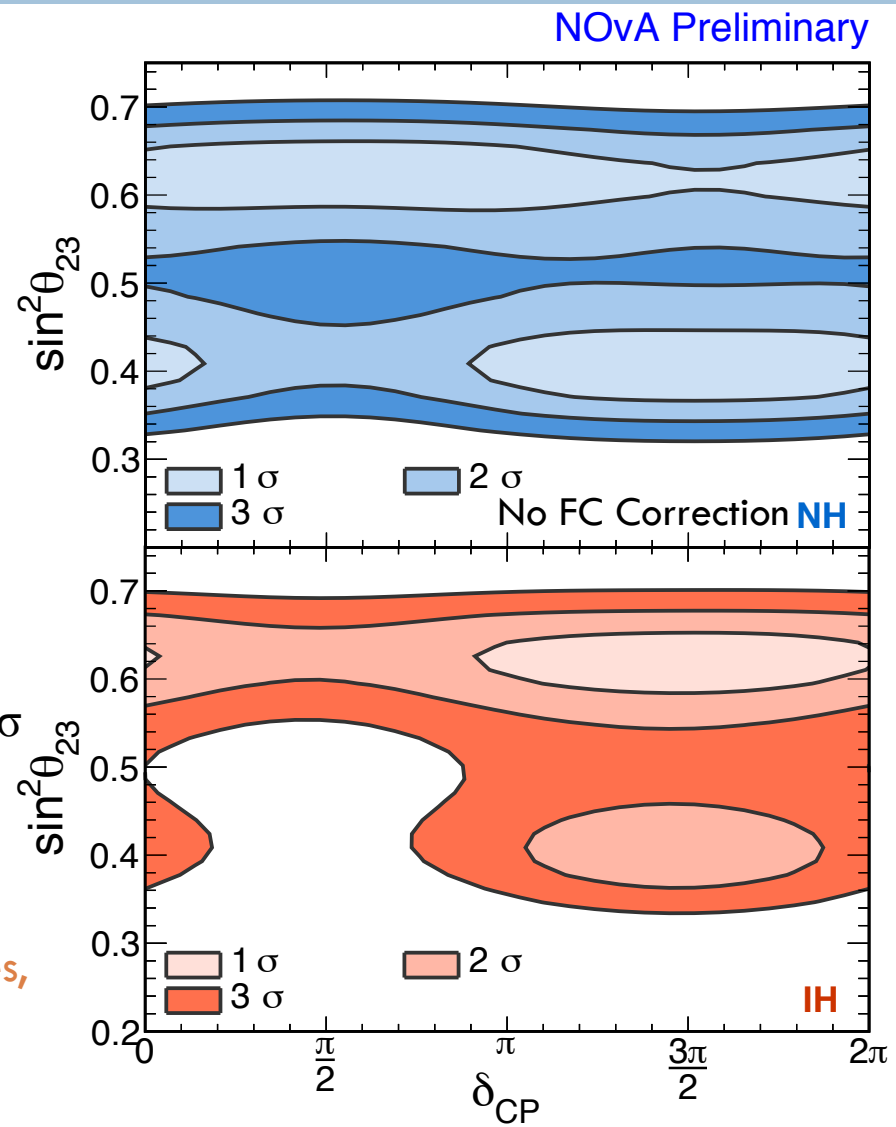


Contours

- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{CP}$=π/2



Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing

Planned for Spring 2017

Summary

With 6.05×10^{20} POT, NOvA finds:

- Muon neutrinos disappear
  - Best fit is non-maximal
  - Maximal mixing excluded at 2.5 σ
- Neutral current event rate shows no evidence of steriles
  - With more data, expect strong limits on θ_{34}
- Electron neutrinos appear
  - Data prefers NH at low significance
  - Region in IH, lower octant around $\delta_{CP}=\pi/2$ is excluded
- Looking forward to more neutrinos and antineutrino running planned, Spring 2017

The NOvA Collaboration

www-nova.fnal.gov

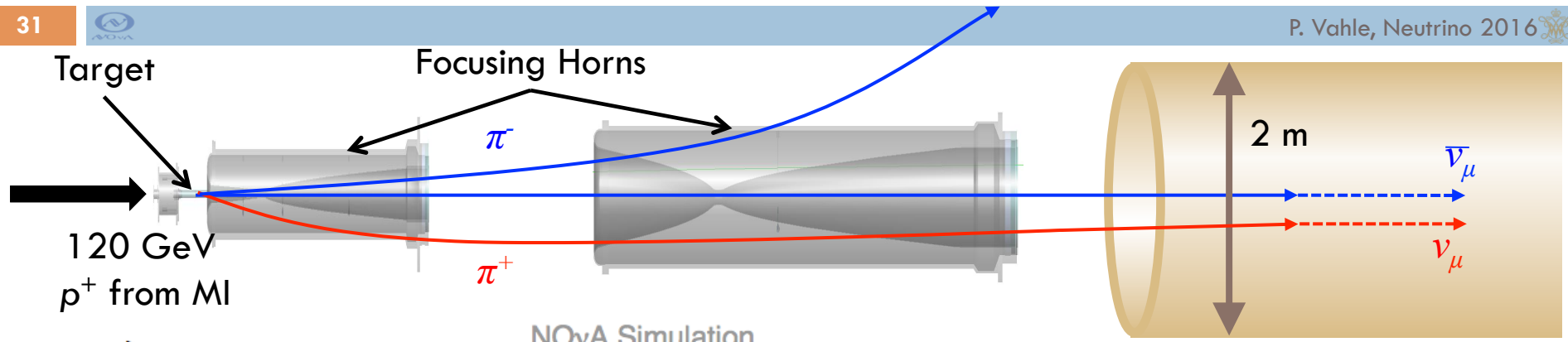
Argonne, Atlantico, Banaras Hindu University, Caltech, Cochin, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, U. Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, South Carolina, SD School of Mines, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL,Virginia, Wichita State, William and Mary, Winona State

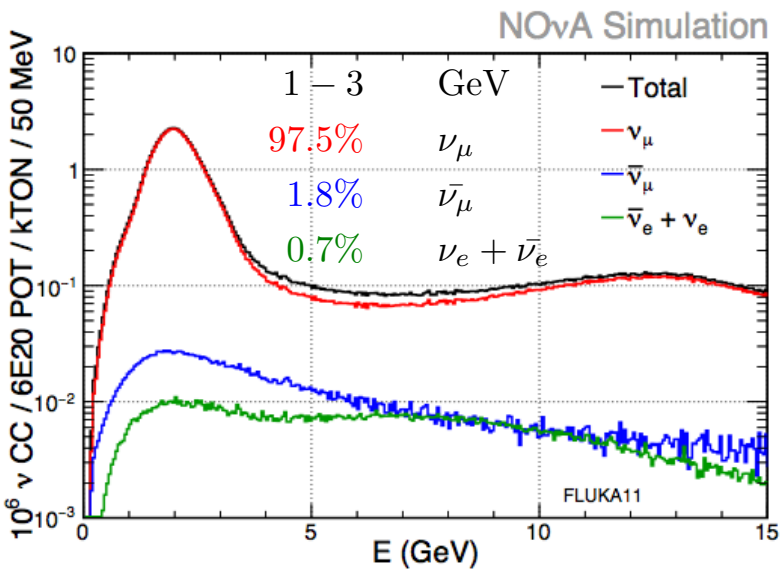
234 Collaborators
41 institutions
7 countries

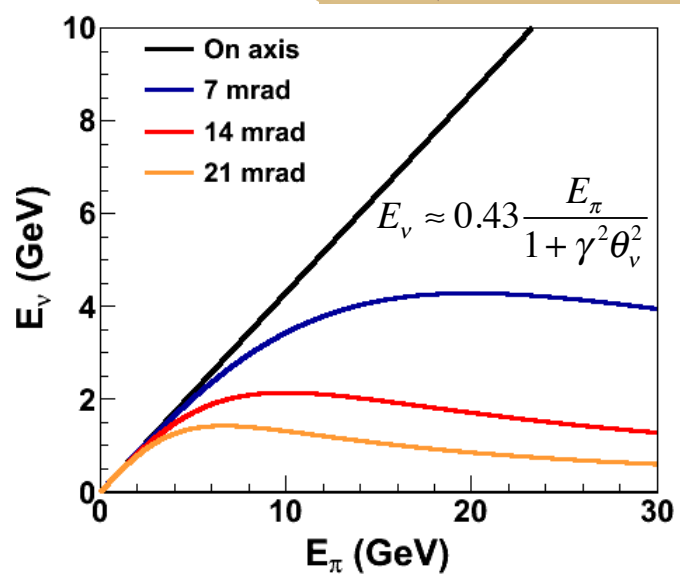
Thank you!

Backup

Making an off-axis neutrino beam



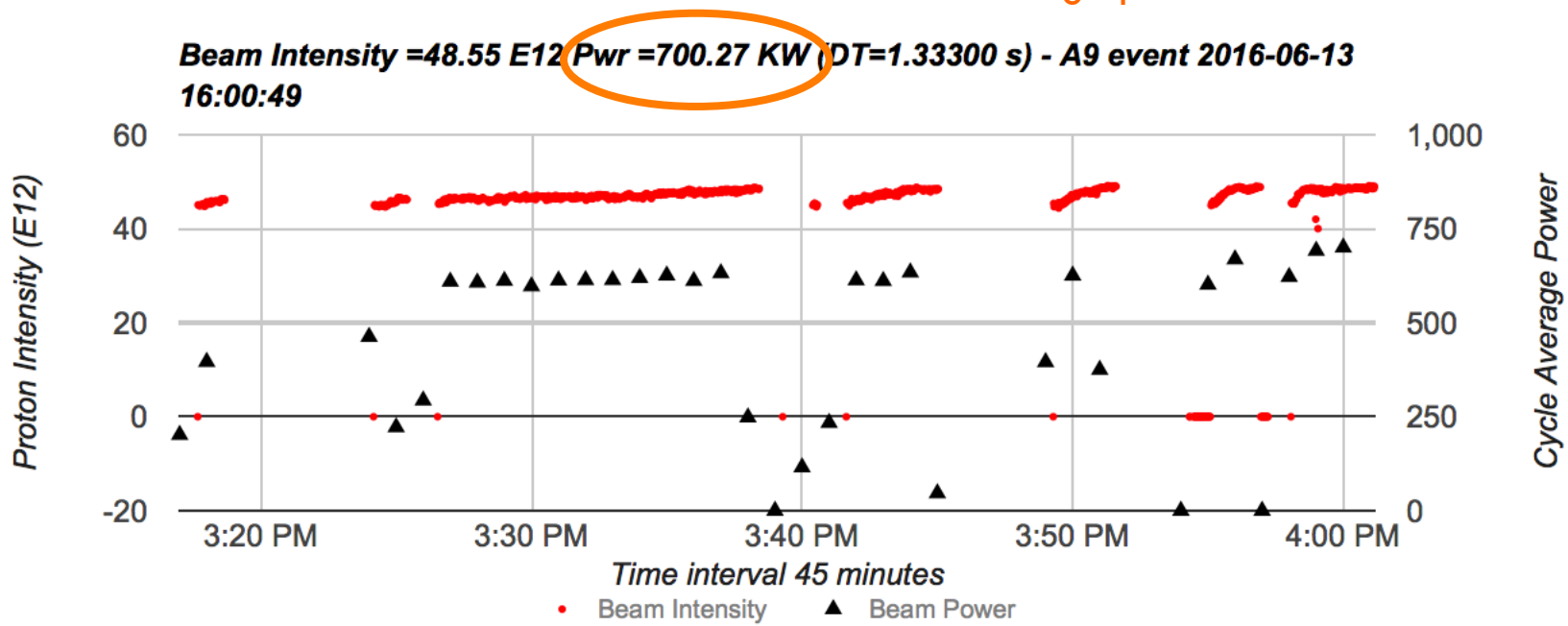




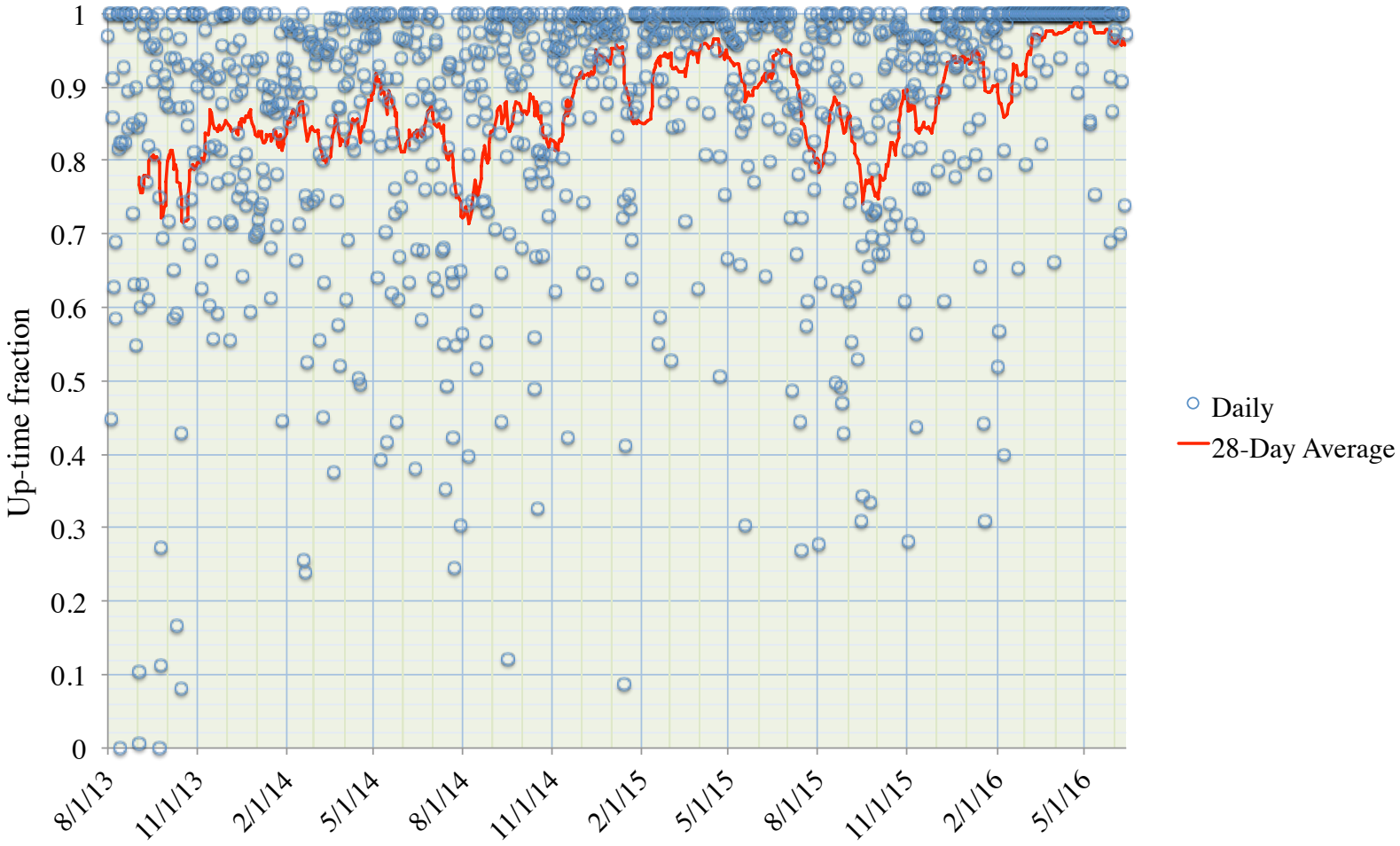
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events

Beam Performance

Achieved design power 700kW!

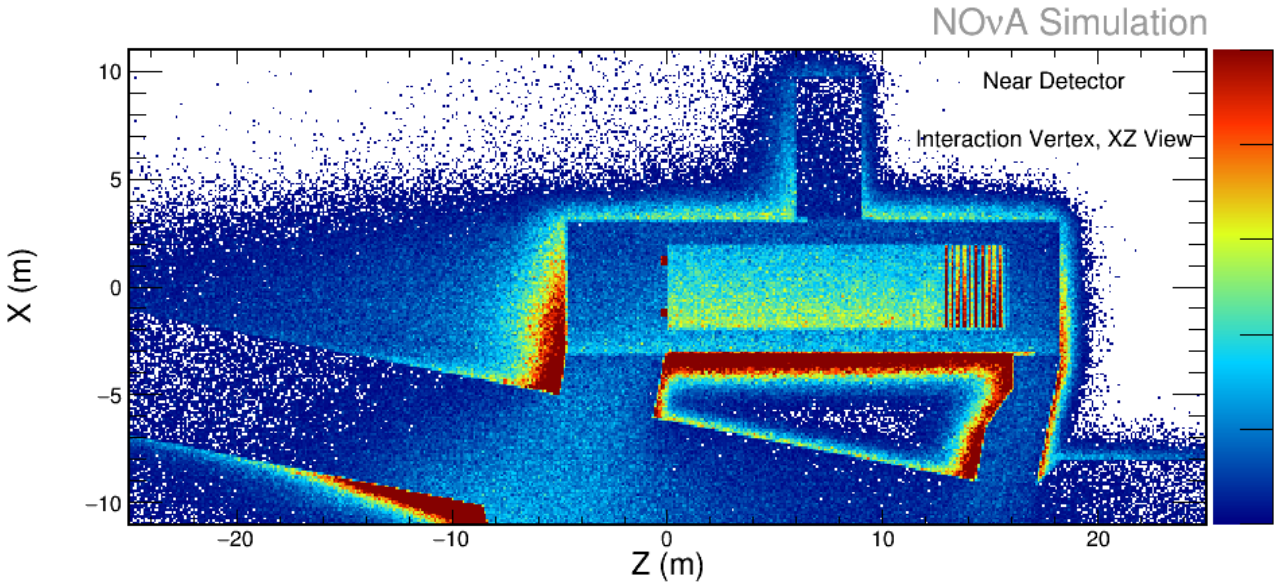


Detector Performance



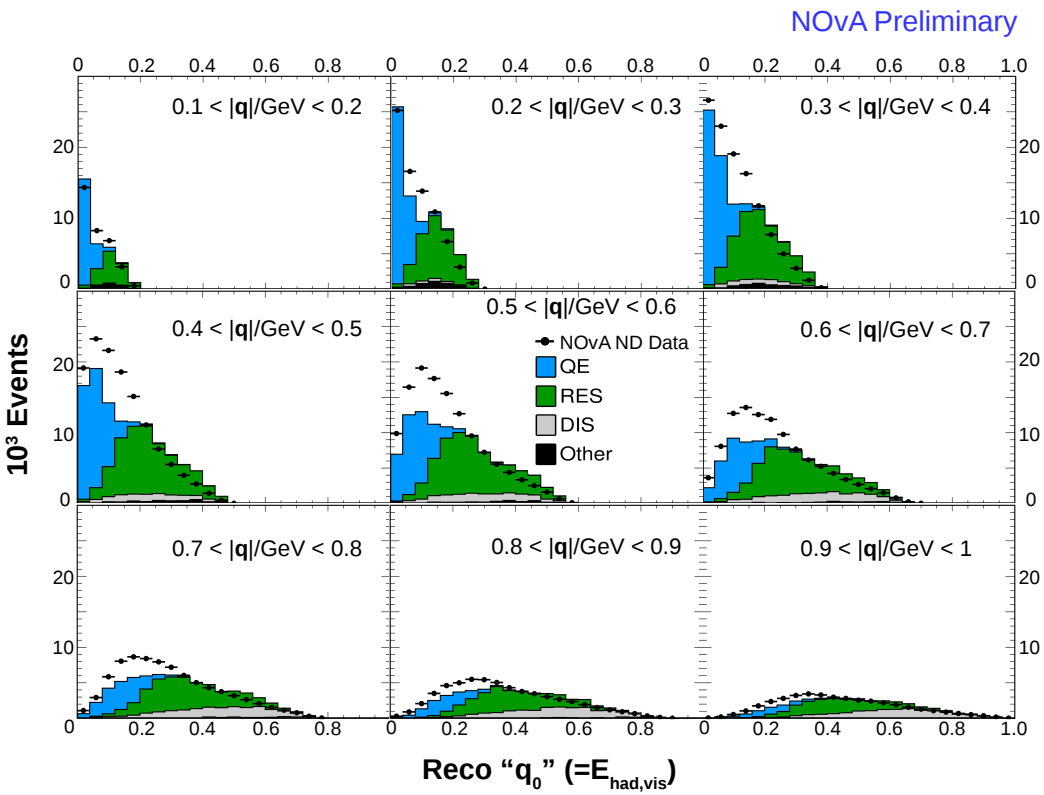
Simulation

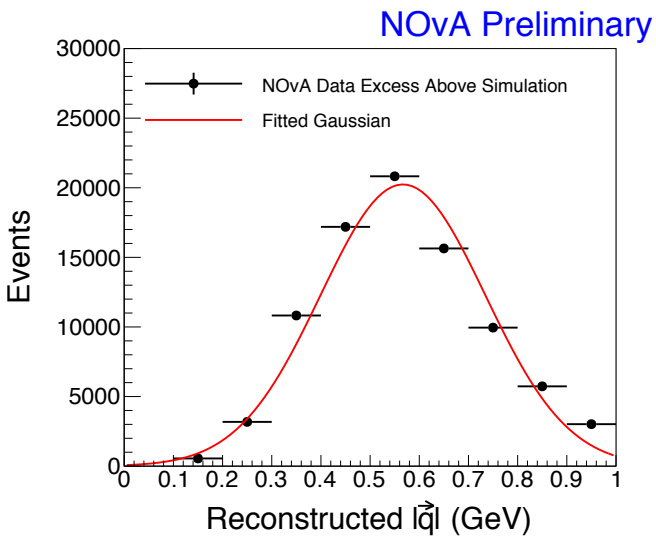
- Beam line production, propagation and neutrino flux: FLUKA/Flugg
- Cosmic Ray flux: CRY
- Neutrino interaction and FSI: GENIE
- Detector: Simulation: Geant4
- Detector response: Custom simulation Routines



Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production

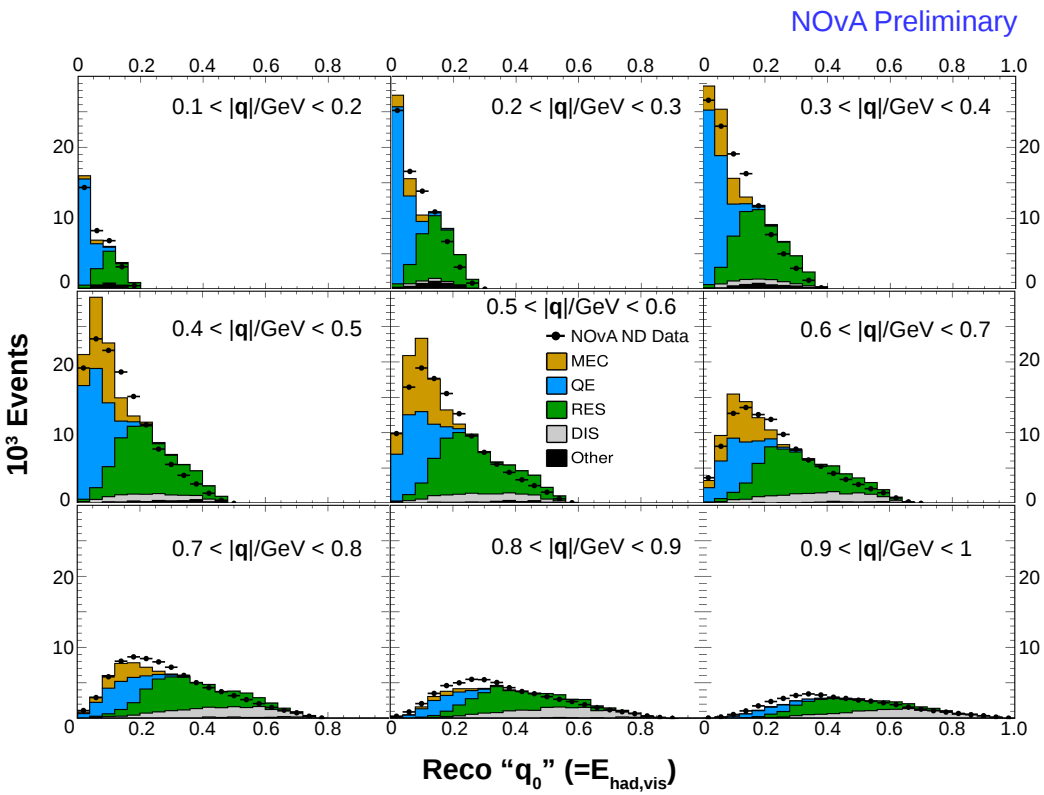




Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

- Enable GENIE empirical Meson Exchange Current Model
- Reweight model to match NOvA excess as a function of 3-momentum transfer

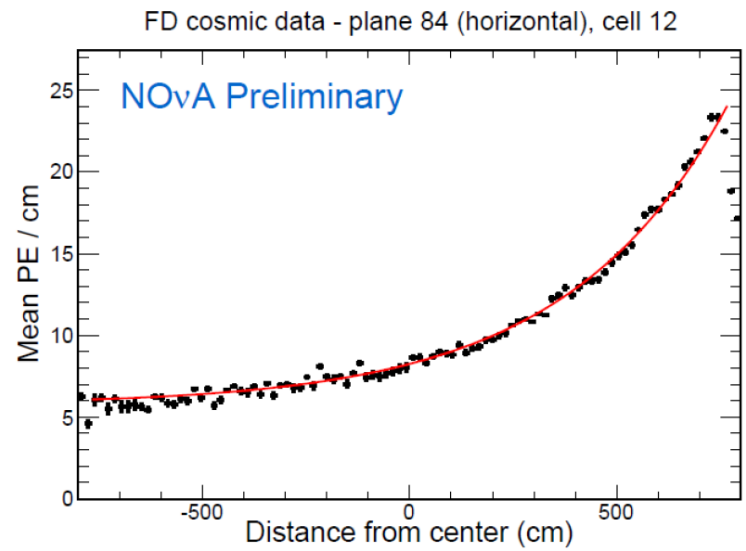


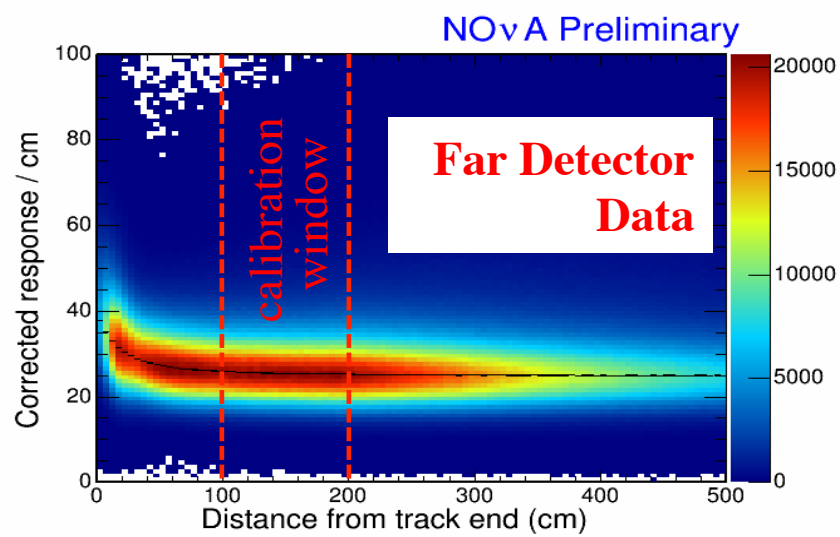
- Eliminate falloff of xsec with energy
- Fix final state nucleon composition
- Match MEC q_0 distribution to quasi-elastic distribution
- scale normalization in bins of 3-momentum transfer to match data/mc disagreement
- Include 50% systematic uncertainty on size of MEC component
- Additionally, reduce single non-resonant pion production by 50%

(P.A. Rodriques et al, arXiv:1601.01888.)

Calibration

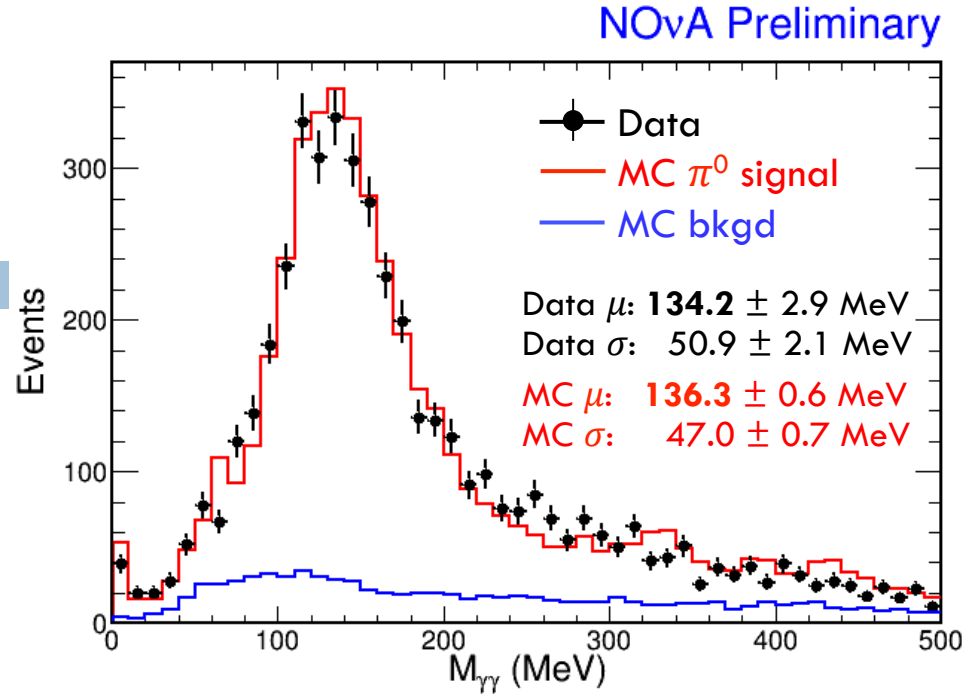
- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

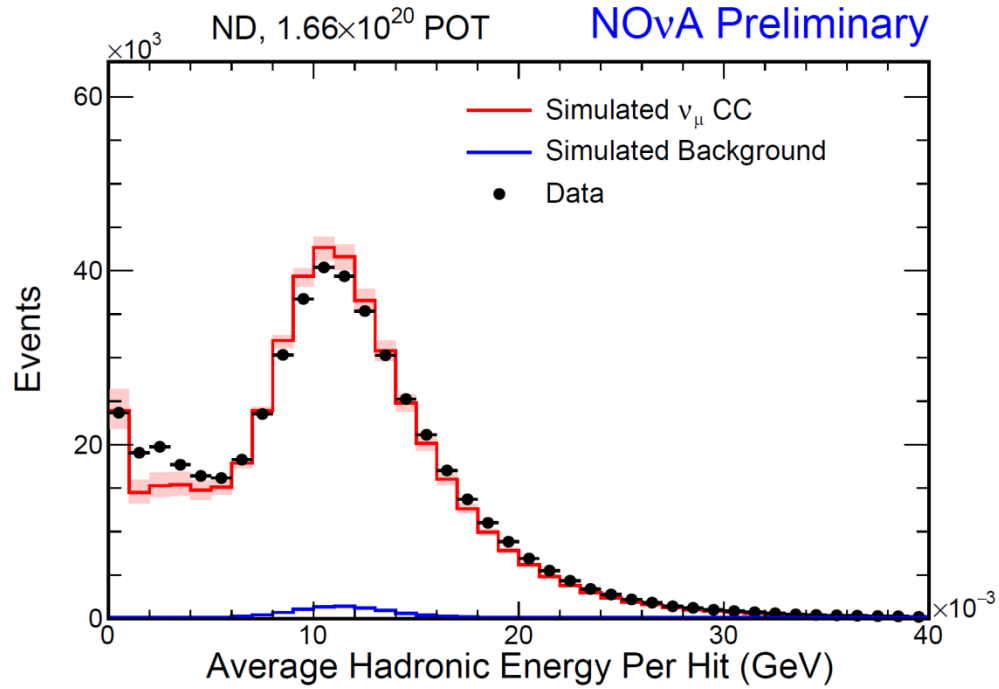




Energy Scale

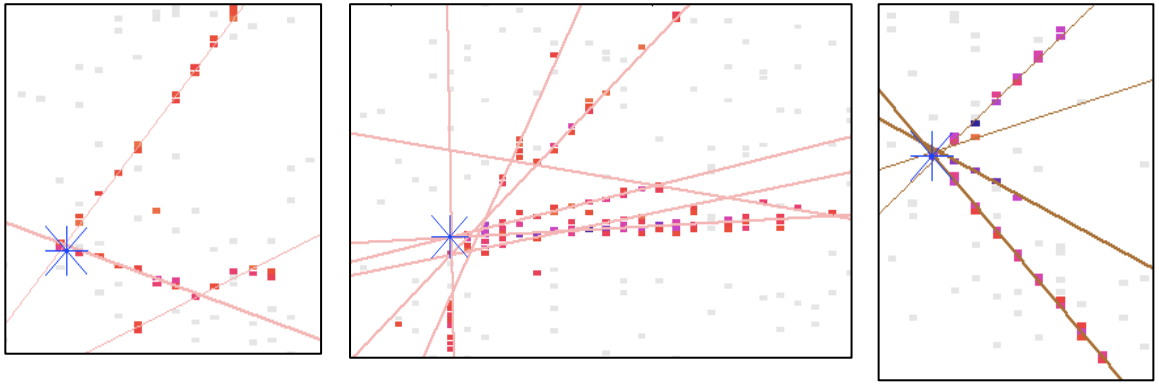
- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
  - π^0 mass
  - hadronic shower *E*-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e^- spectrum
- All agree to 5%



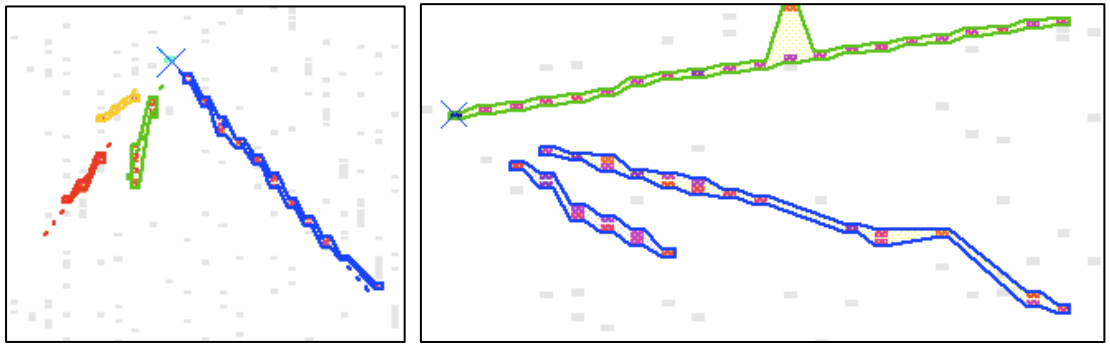


Reconstruction

Vertexing: Find **lines of energy depositions** w/ Hough transform CC events: 11 cm resolution

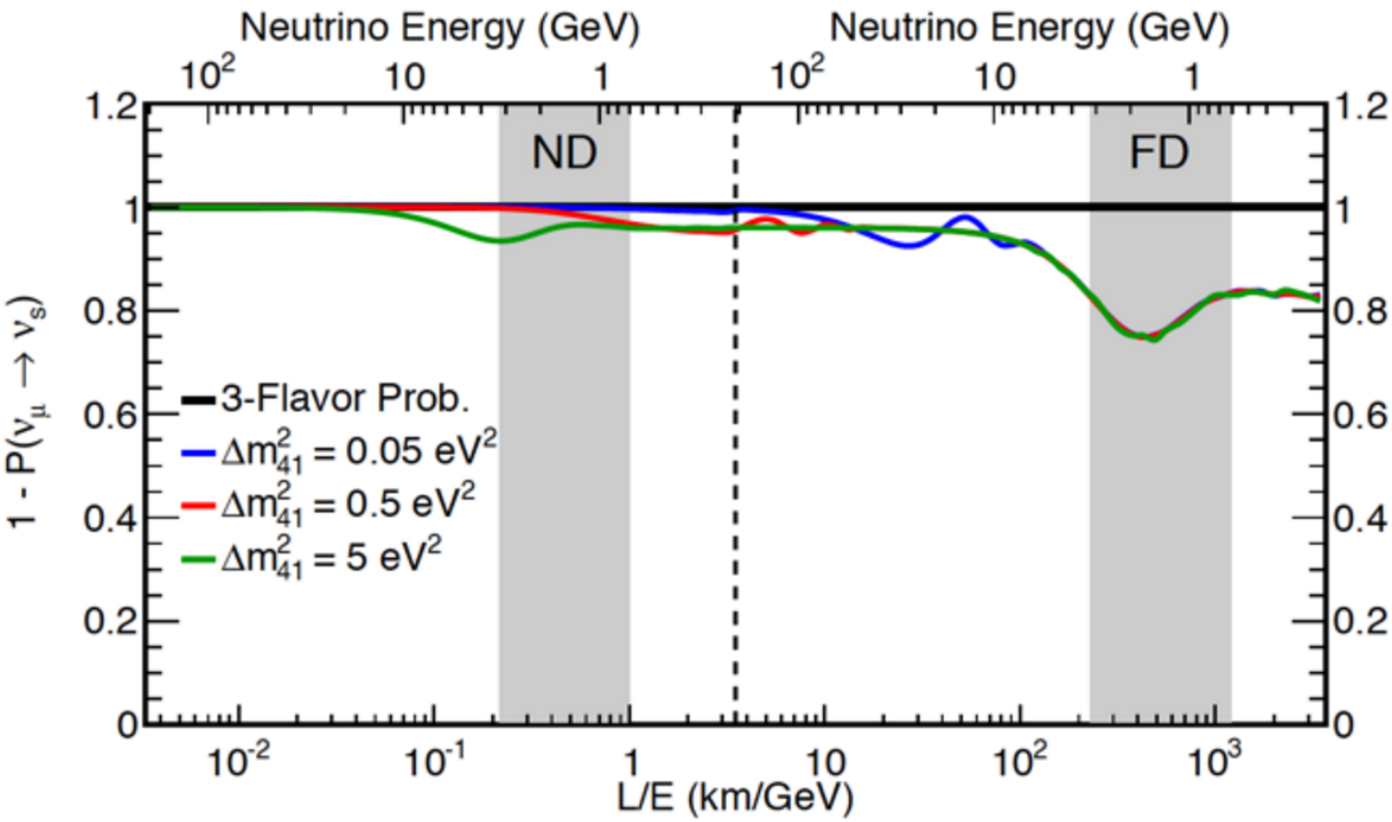


Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong dE/dx



Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.

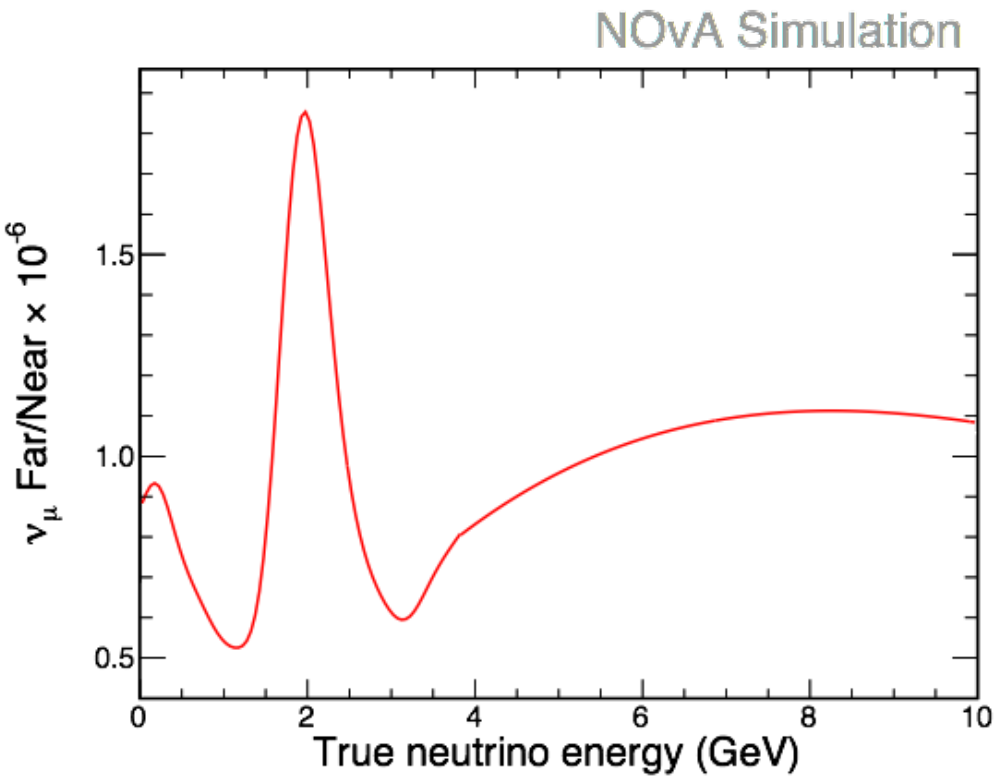
Sterile Oscillations



Extrapolation

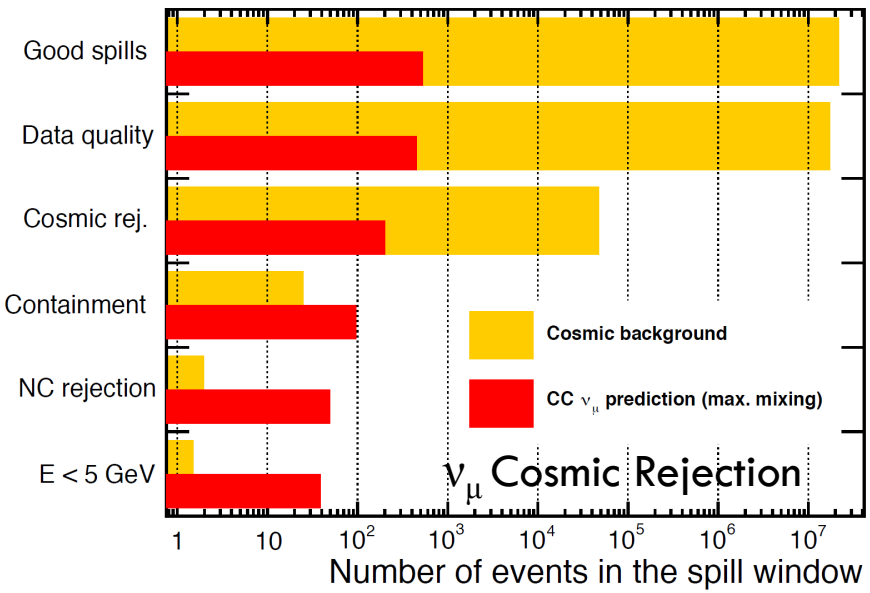
- All NOvA analyses use ND data to predict the FD spectrum

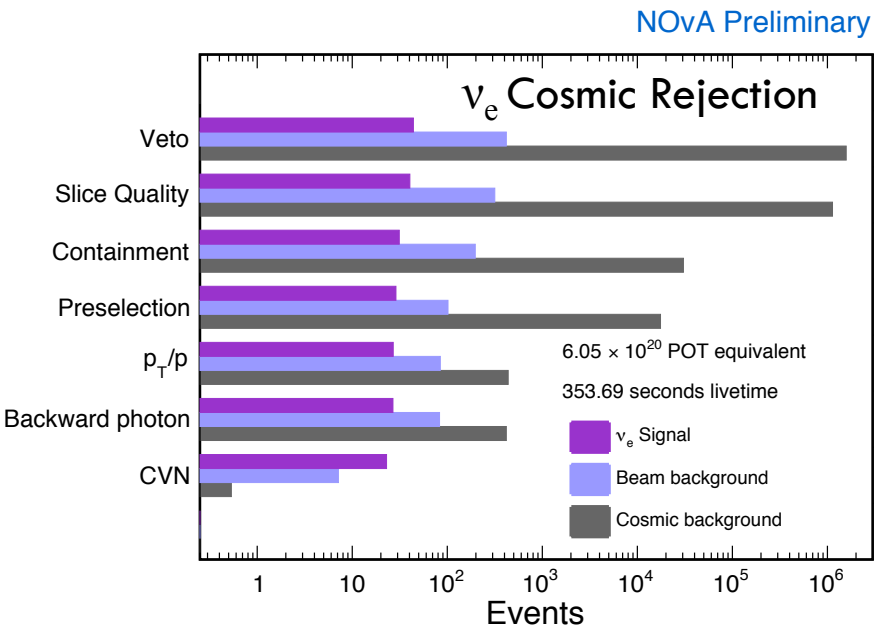
- Muon Neutrino analyses: unfold reco energy, use true F/N ratio for FD prediction of track events
- Electron Neutrino signal: use Muon-neutrino FD prediction
- NC and Electron Neutrino background analyses: Far to Near spectrum in reconstructed energy ratio for FD prediction of shower events



Cosmic Rejection

- NOvA FD sees 150kHz of cosmic induced events
- Beam timing gives 10^5 rejection factor
- Combination of containment and event topology gives another ~10^7 in rejection

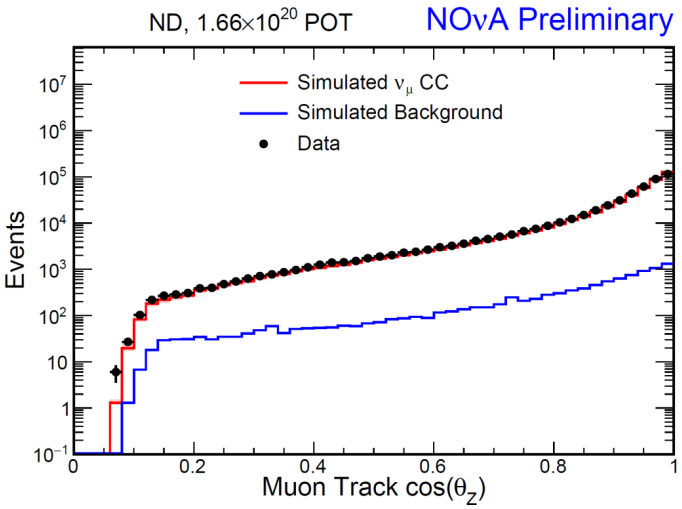


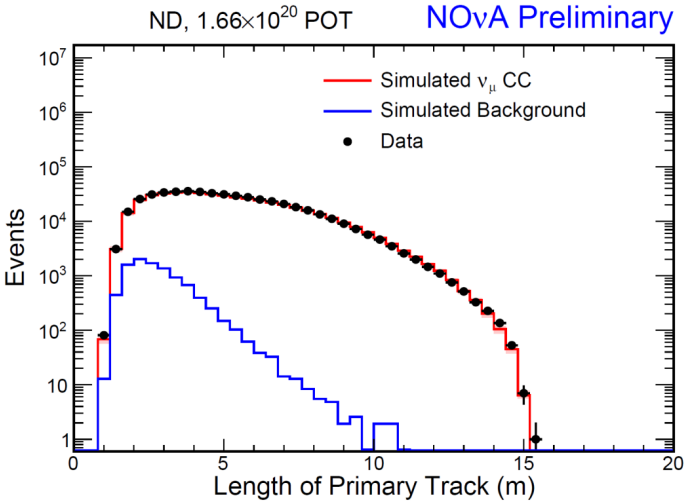


Backup—Disappearance Results

Selecting Muon Neutrinos

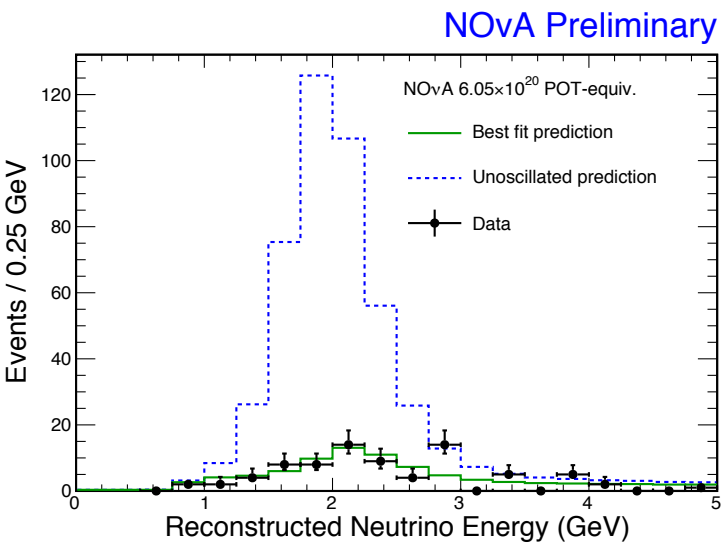
- Goal: Isolate a pure sample of ν_μCC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- ND Data matches simulation well for muon variables

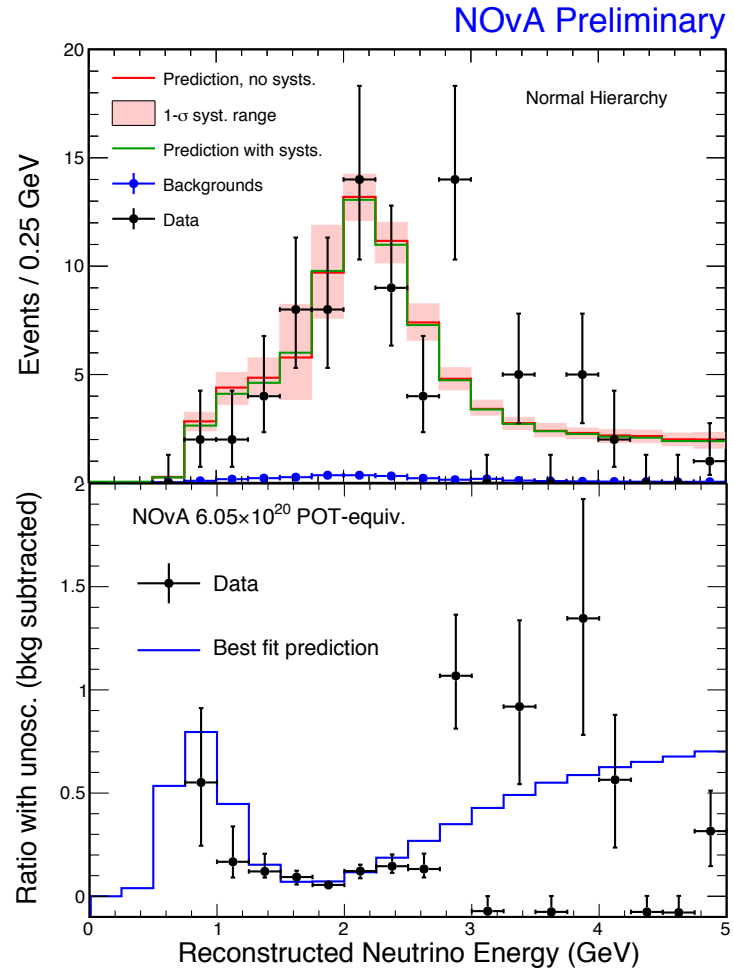




Muon Neutrino FD Data

- 78 events observed in FD
  - 473±30 with No Oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

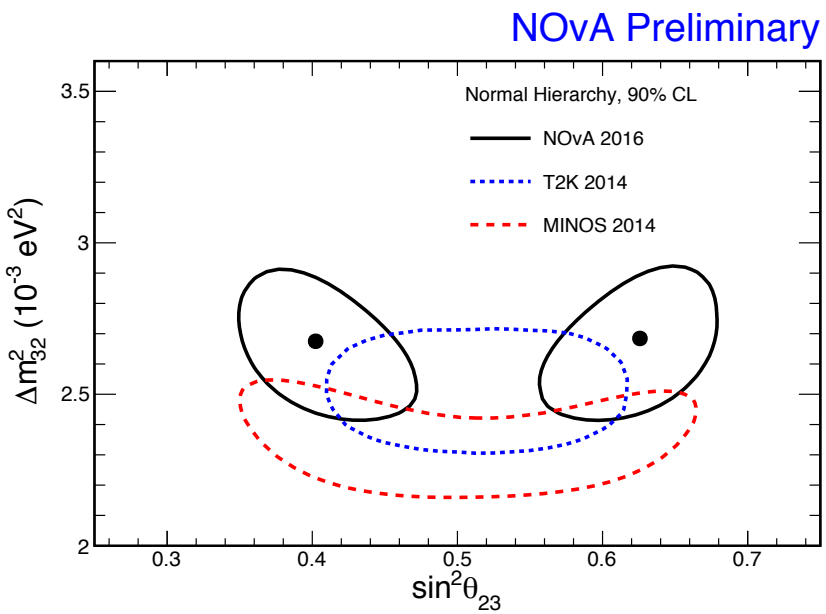


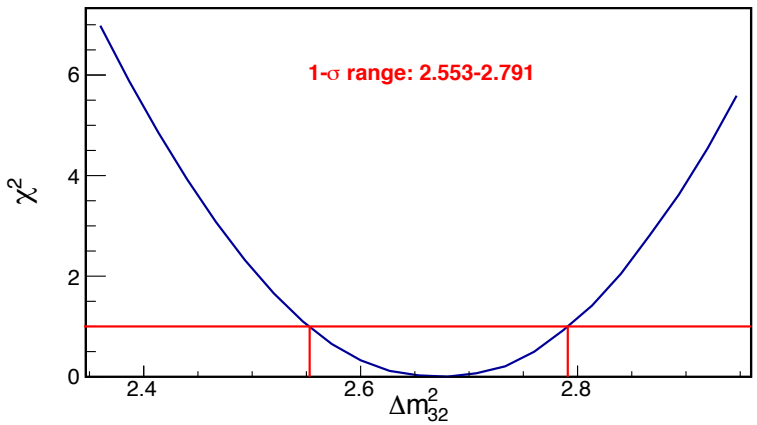


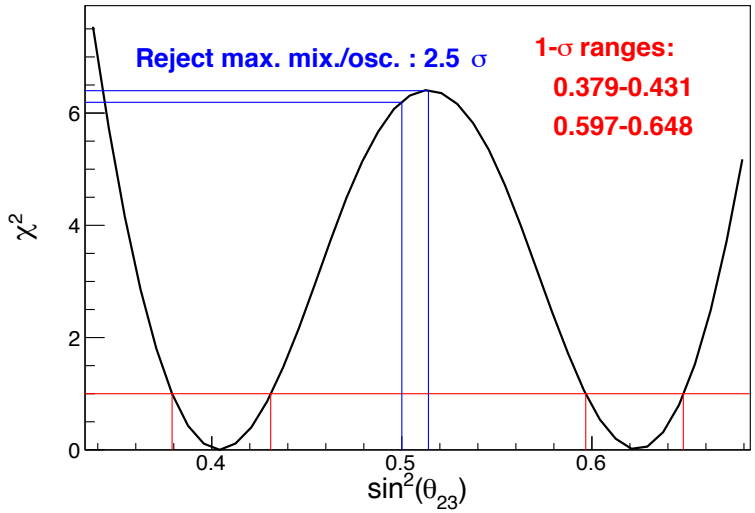
χ^2/NDF=41.5/16

Driven by fluctuations in tail, no pull in oscillation fit

Contours





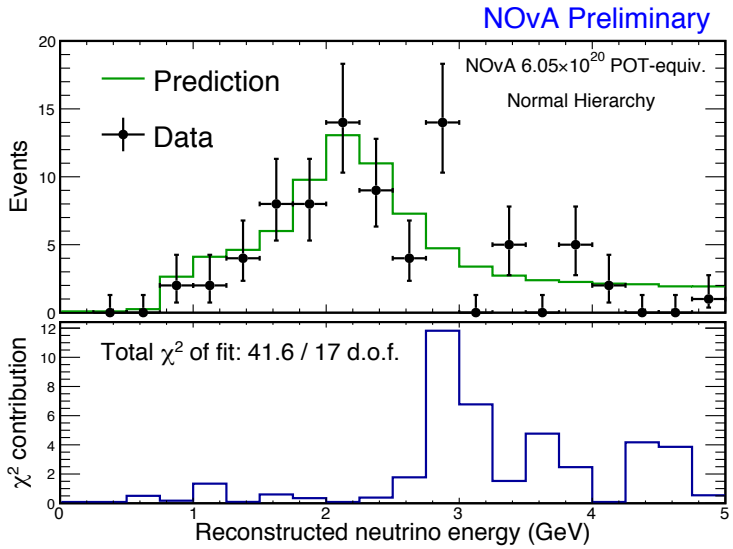


Best Fit:

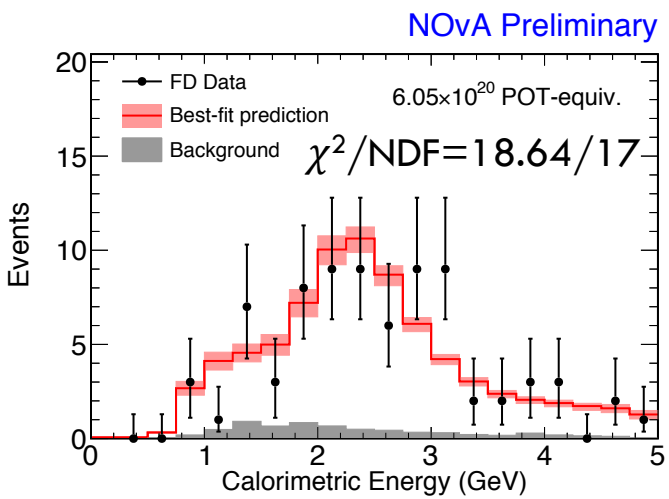
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

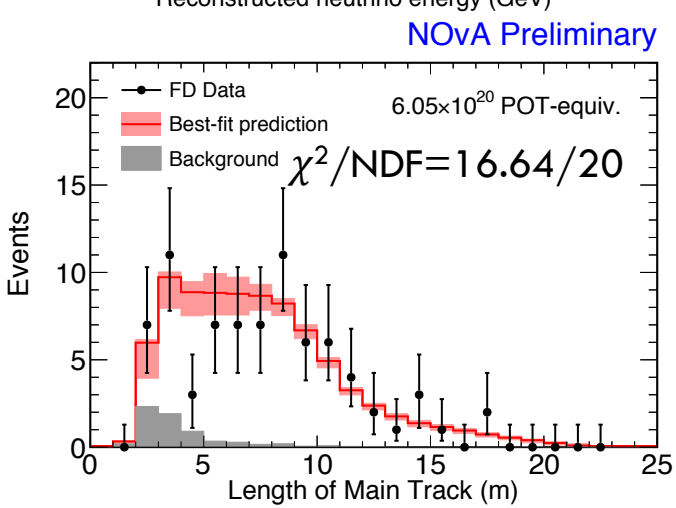
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Checking the Fit

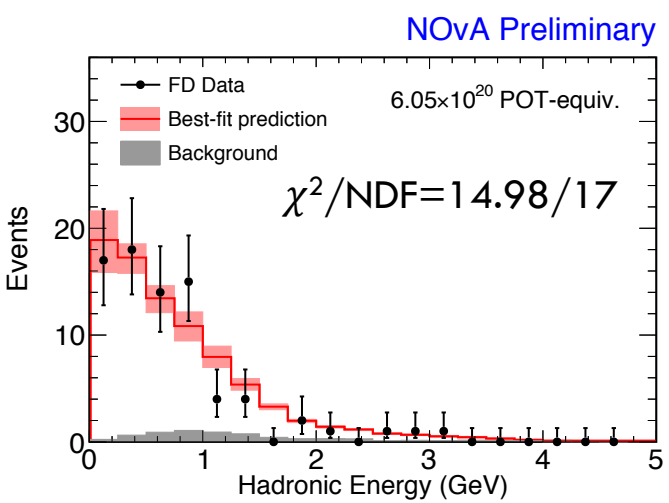


Performing the fit below 2.5 GeV improves χ^2 substantially but does not change fit results, sensitivity, or exclusion of maximal mixing

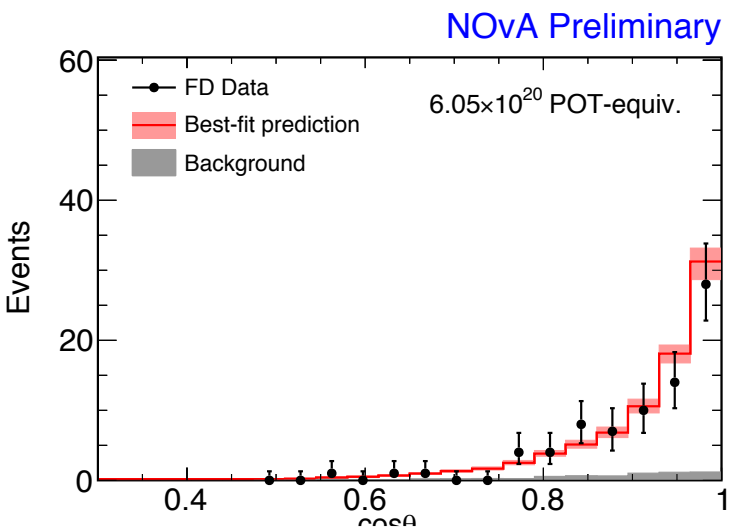


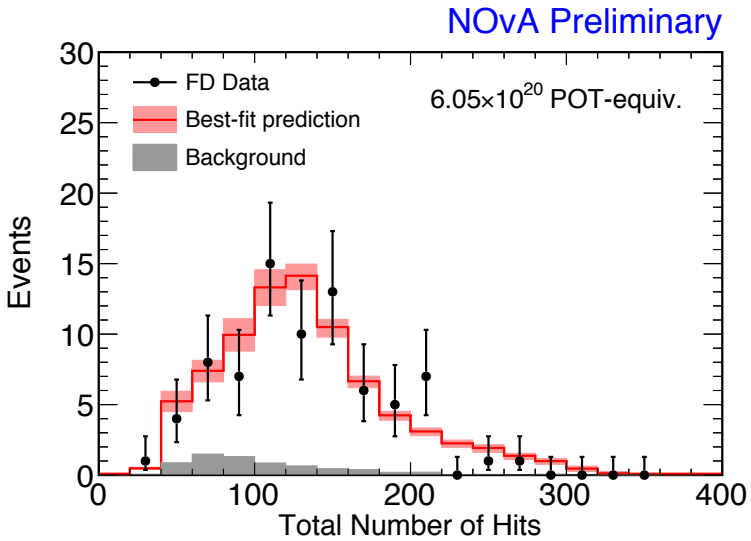


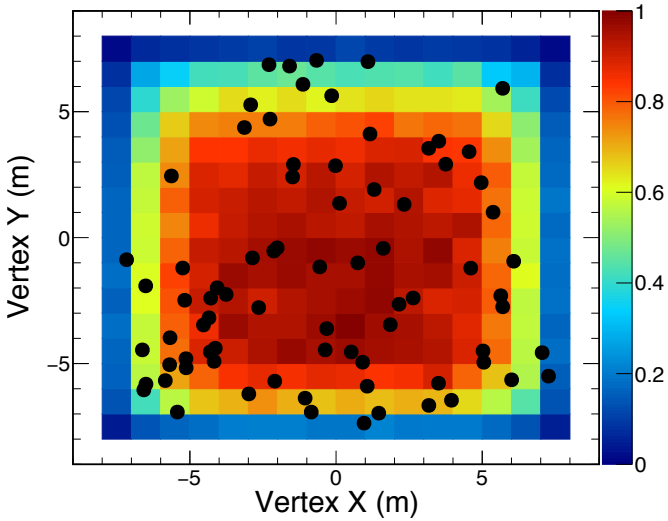
Best fit oscillation prediction matches other distributions well

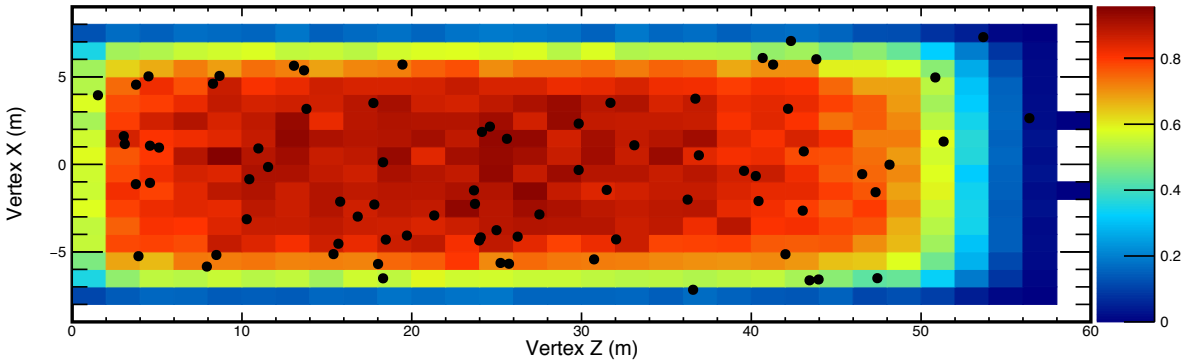


Muon Neutrino FD Data

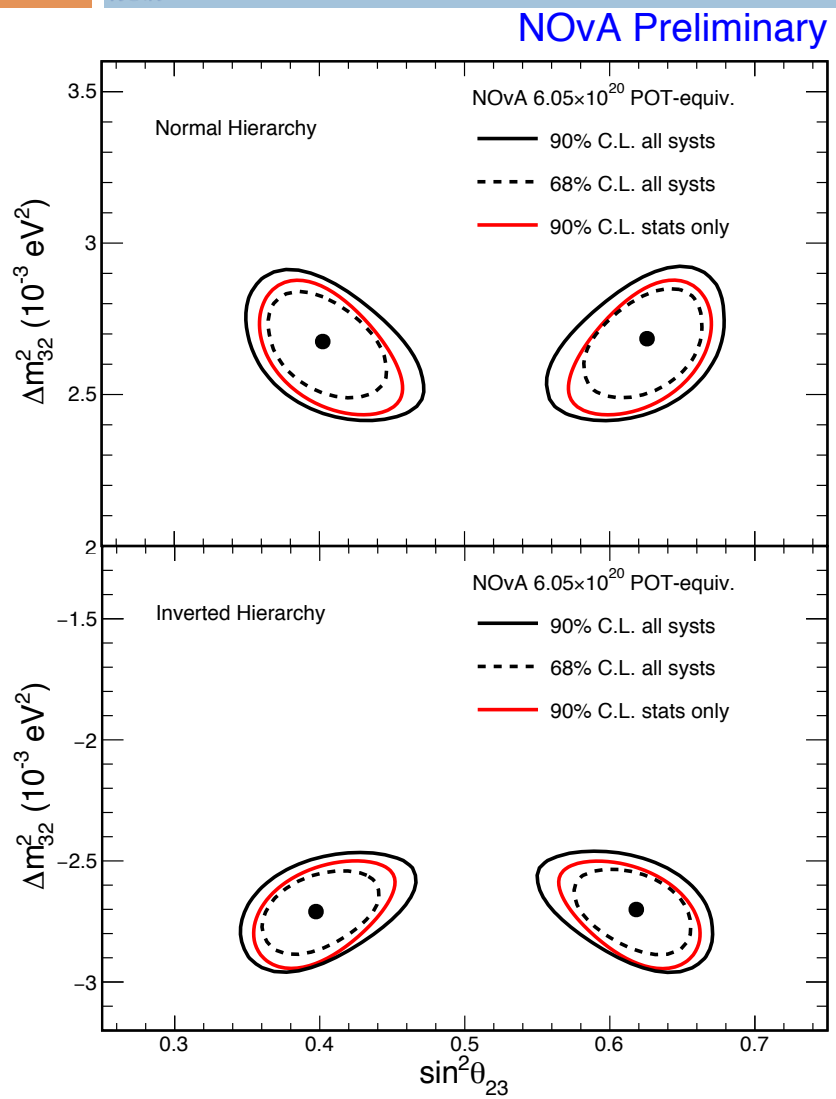








Disappearance Systematics



Systematic	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

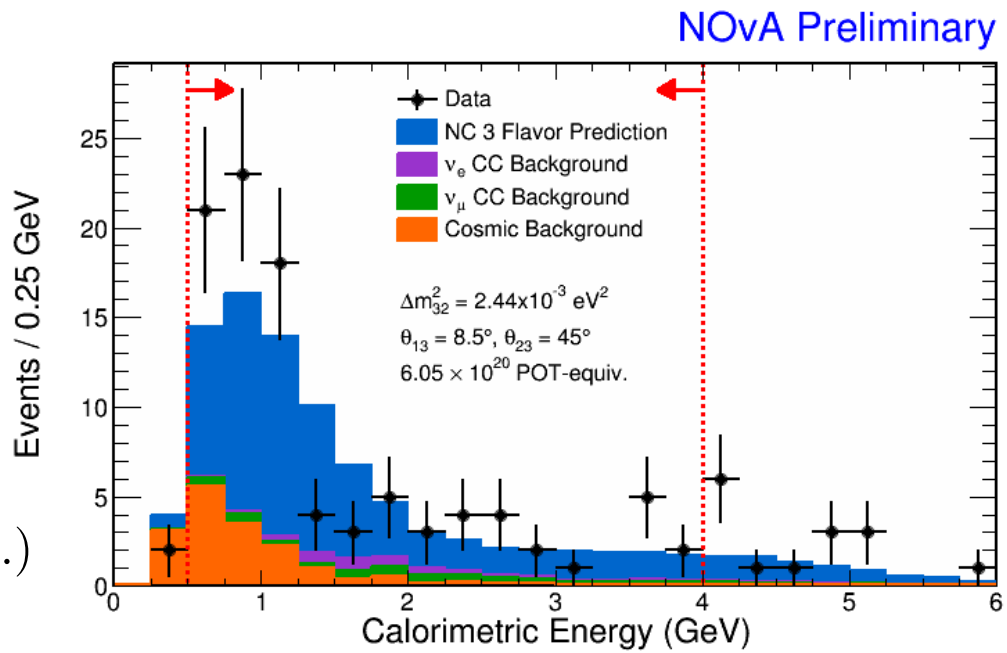
Backup—NC Results

See Posters P2.082 by L. Suter, P2.081 by A. Aurisano, P1.026 by G. Kafka

Neutral Current FD Data

- Observe 95 events
- No evidence of oscillations involving steriles

$$R = \frac{N_{data} - BG}{S_{NC}} = 1.19 \pm 0.16(\text{stat.}) \pm 0.11(\text{syst.})$$



$$\text{For } 0.05 \text{ eV}^2 < \Delta m^2_{41} < 0.5 \text{ eV}^2$$

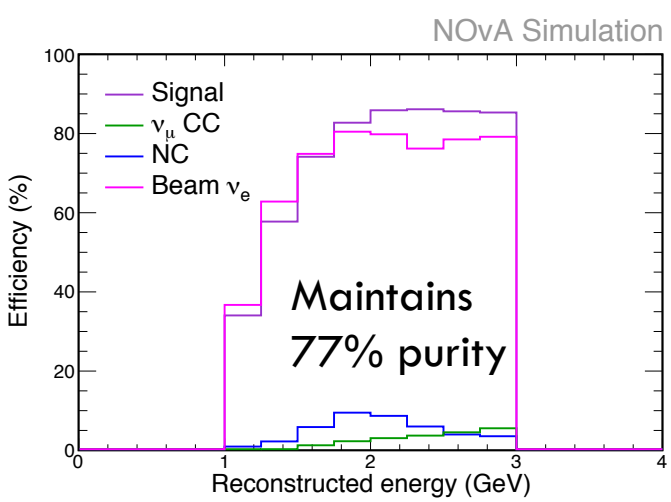
$$\theta_{34} < 35°, \ \theta_{24} < 21° \ (90\%\text{C.L.})$$

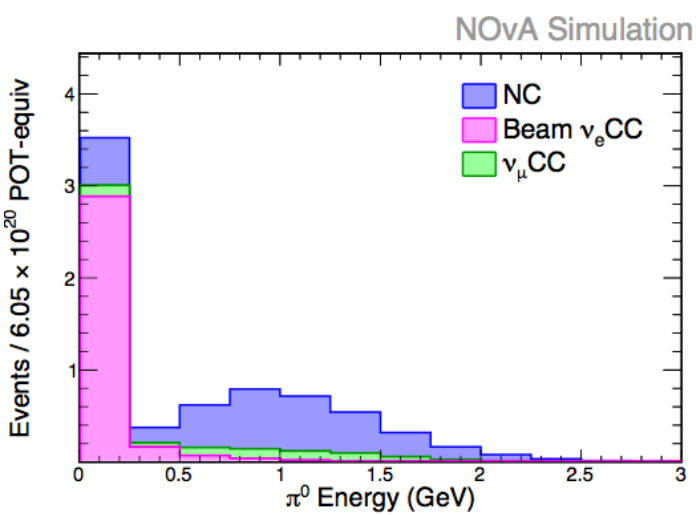
Excellent NC efficiency (50%) and purity (72%) promise strong future limits on θ_{34}

Backup—Appearance Results

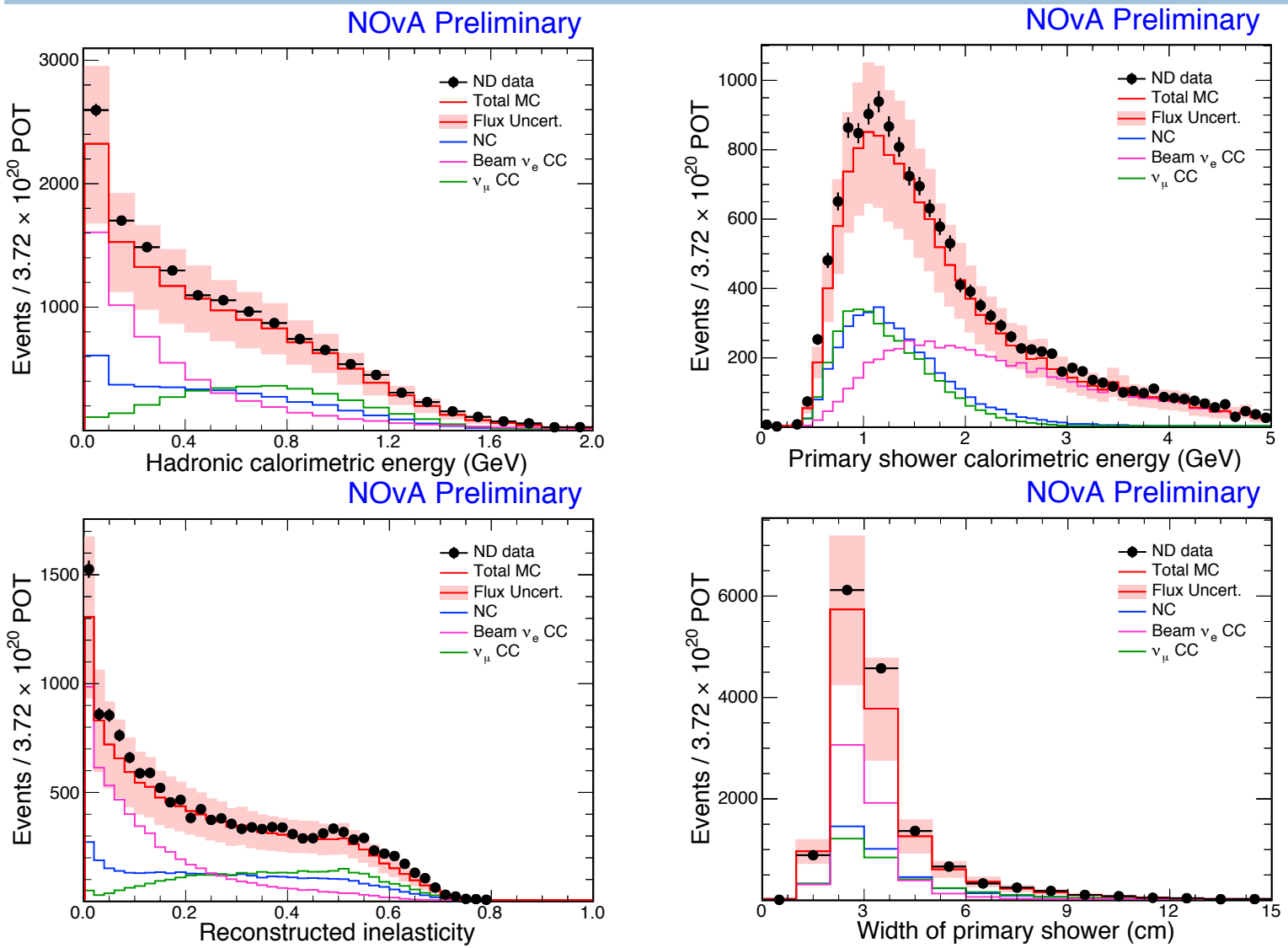
Electron Neutrino Event Selection

- Selection reoptimized to favor parameter measurement (both cosmic rejection and classifier cut)
  - increased signal efficiency, somewhat degraded purity relative to 2015 analysis
  - 91% of selected events have an EM shower



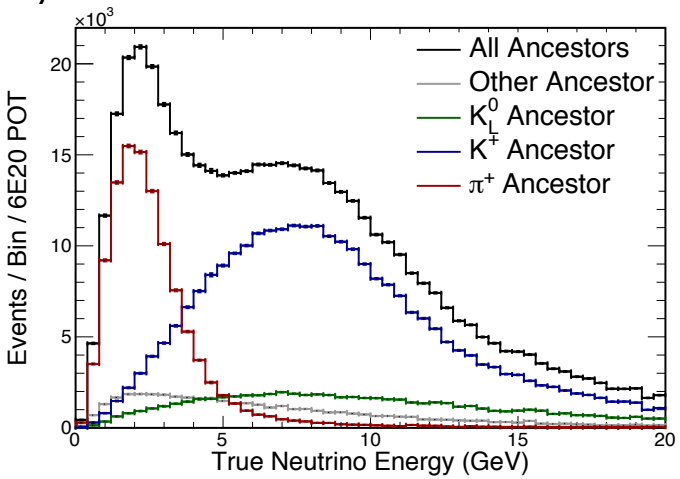


Electron Appearance ND Data/MC

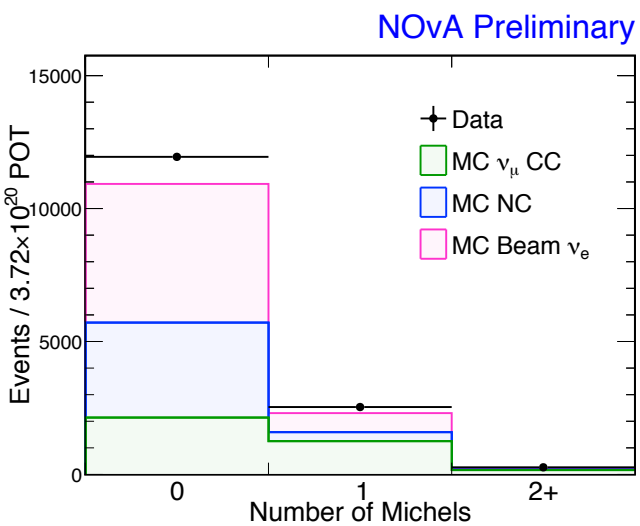


Decomposition

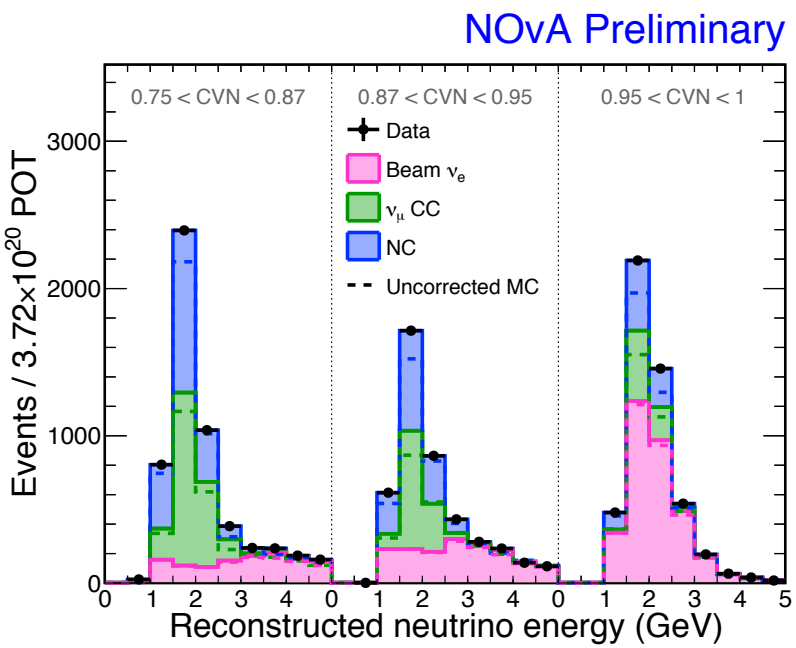
See Poster P1.030
by E. Catano-Mur



- Use ND data to predict FD background
- NC, CC, beam ν_e extrapolate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain CC with Michel Electron distribution

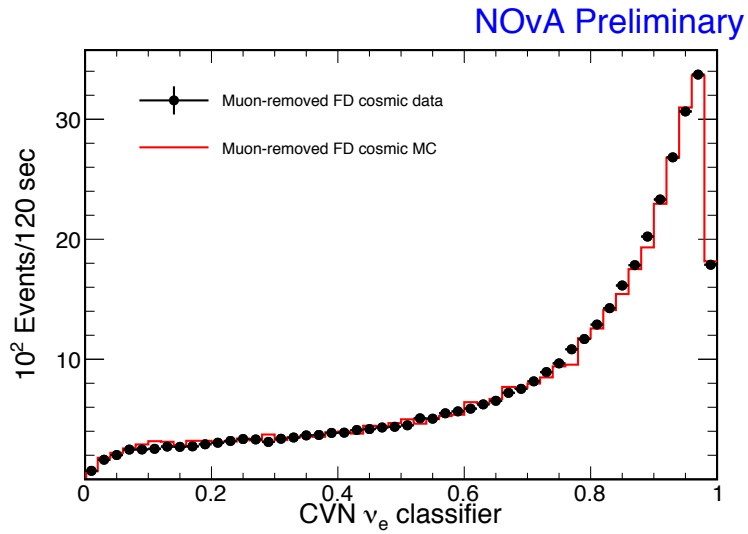


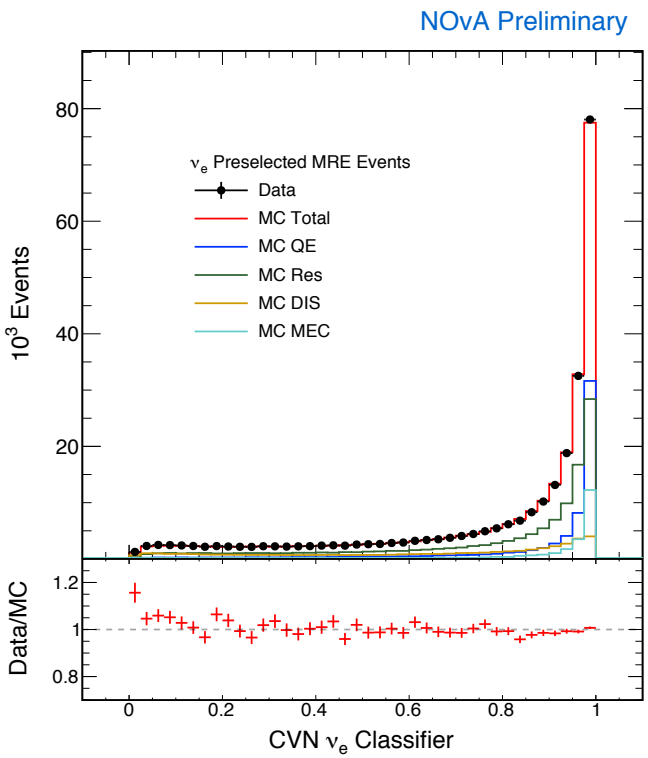
beam ν_e up by 4%
NC up by 10%
CC up by 17%



Checking the Signal Efficiency

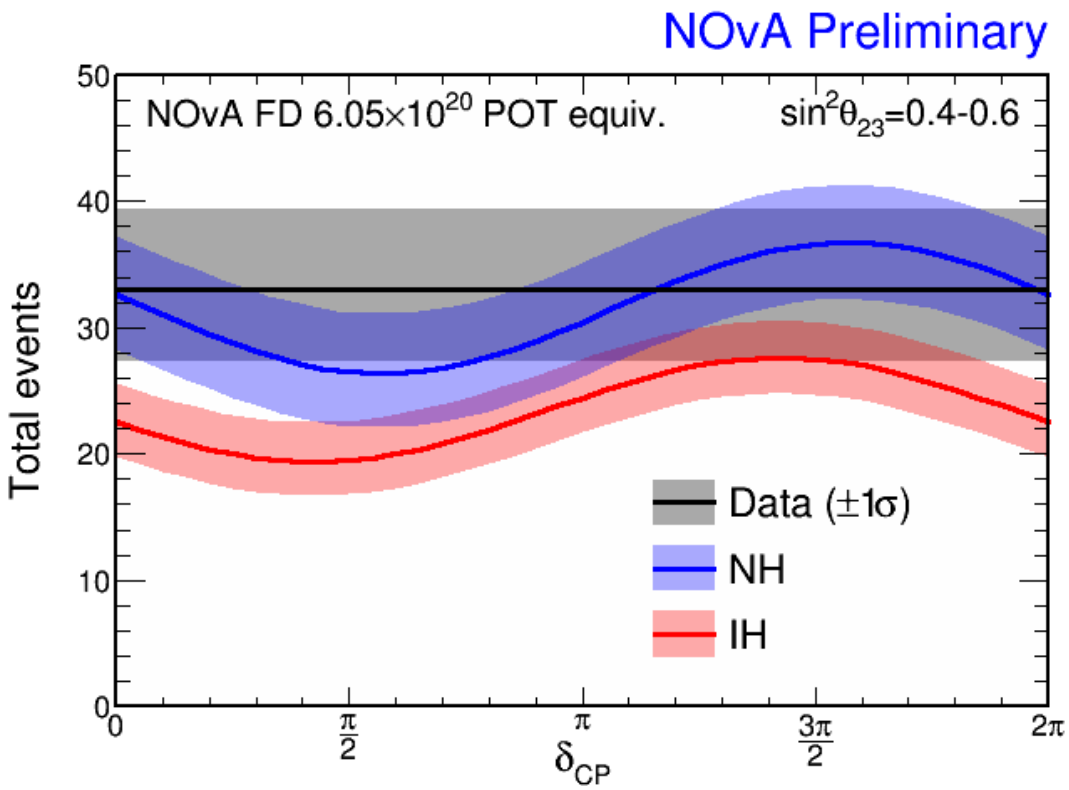
- Use bremstrahlung from cosmic ray muons to benchmark simulation of electron selection
  - event classifier distributions match well



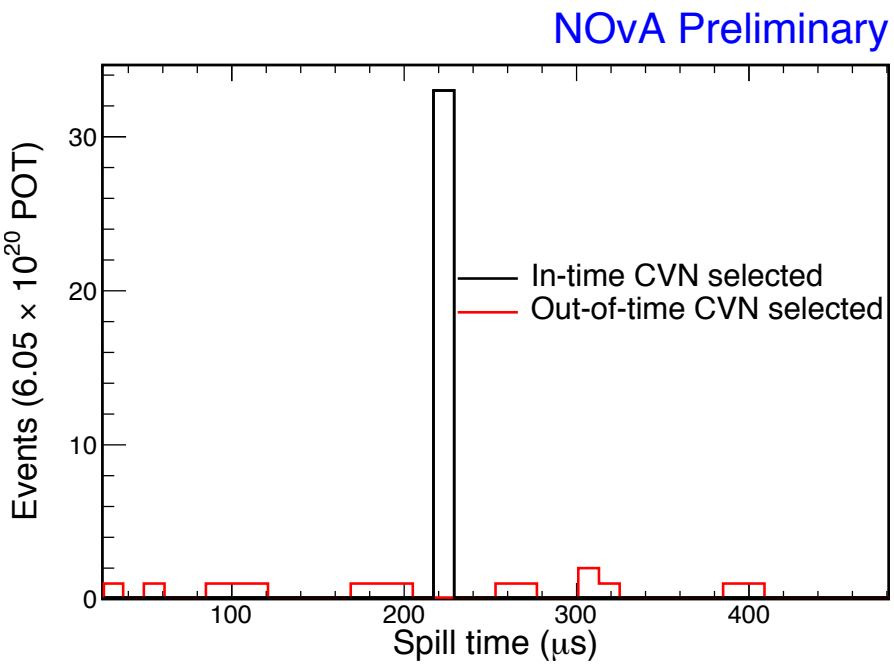


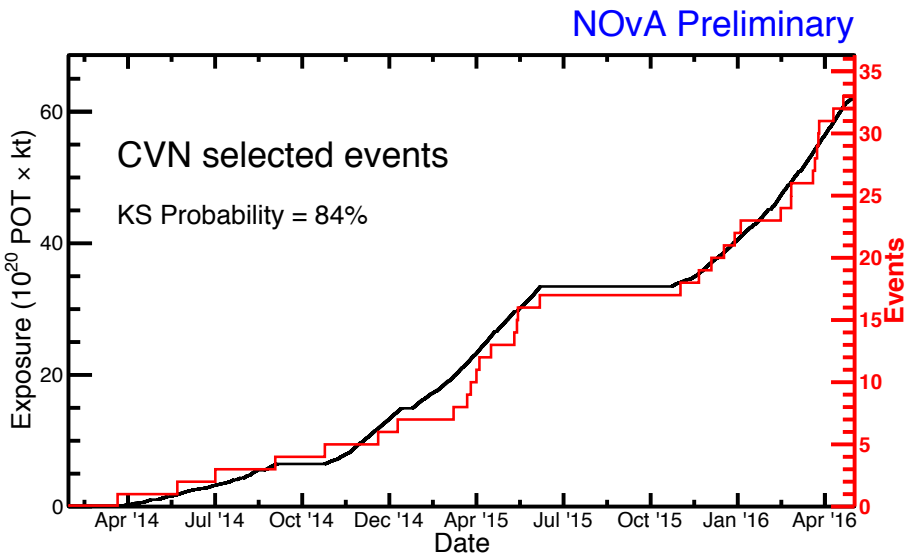
- Remove reconstructed muons from selected ν_μ events, replace with simulated electron (MRE)
  - better than 1% agreement between efficiency for selecting data MRE events and efficiency for selecting MC MRE events

Electron Neutrino FD Data

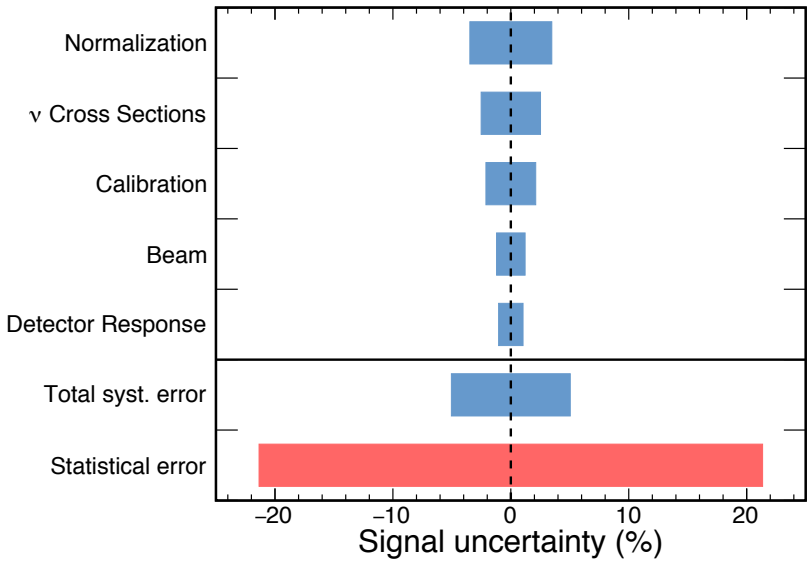


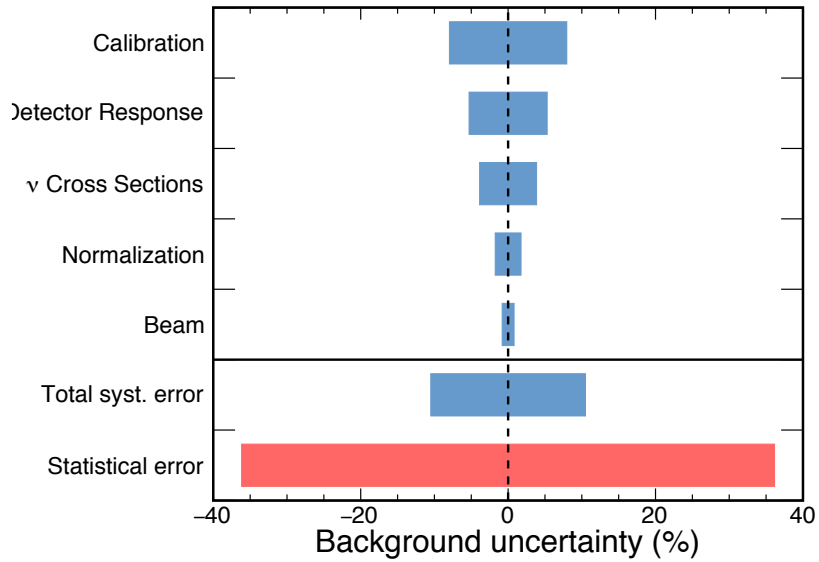
Electron Neutrino FD Data



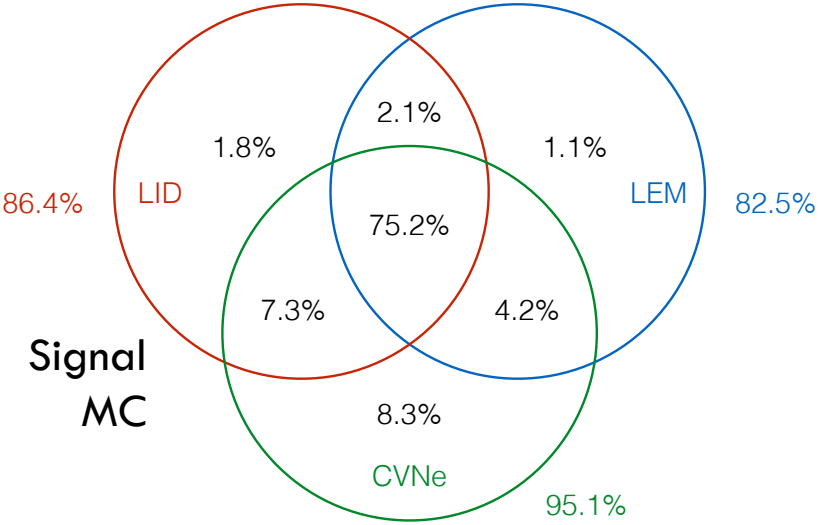


Appearance Systematics

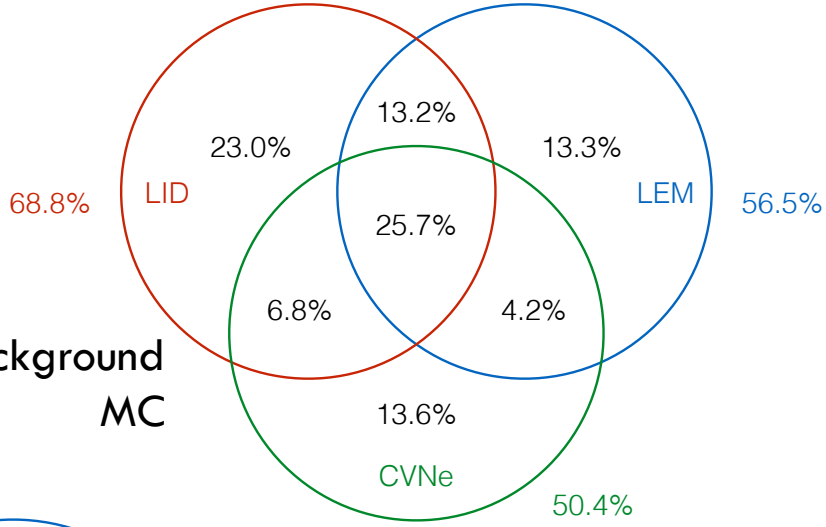




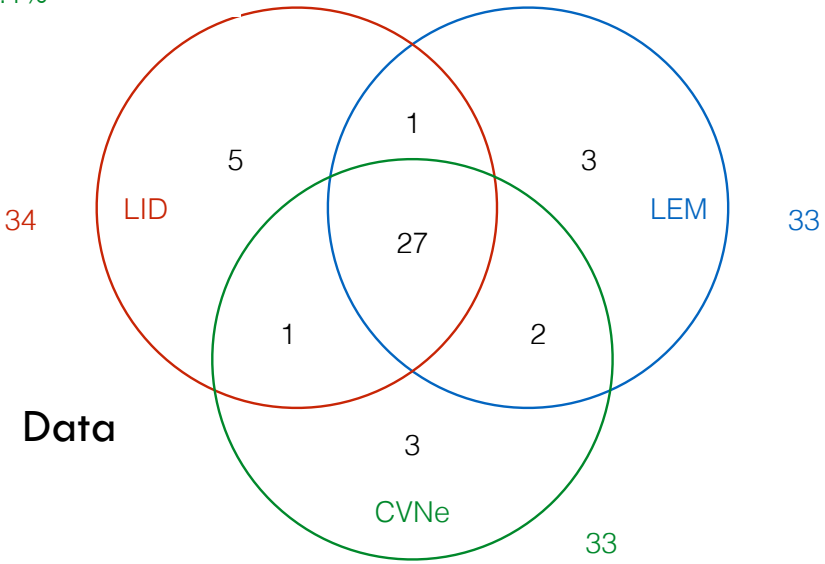
Electron Neutrino Selection Techniques



Signal MC

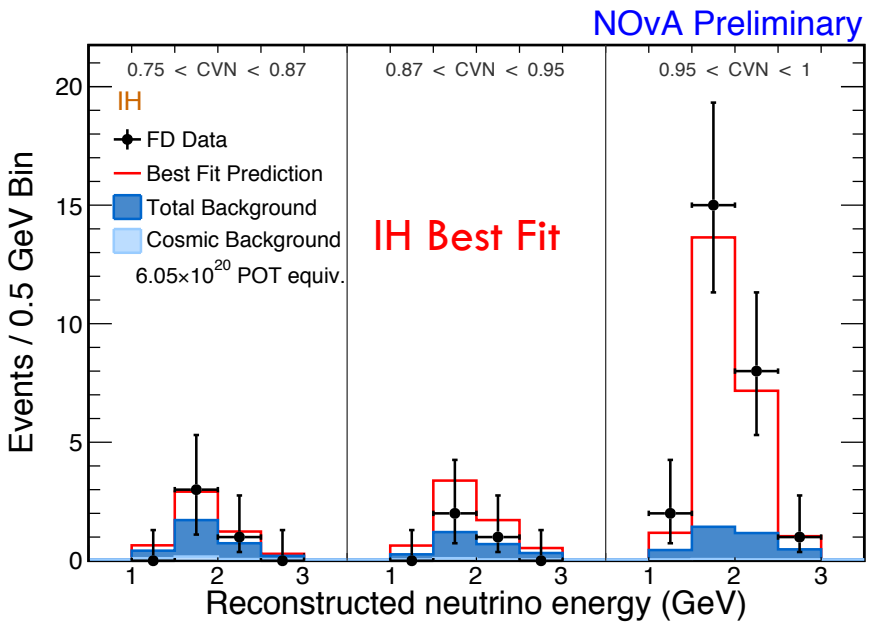


Background MC



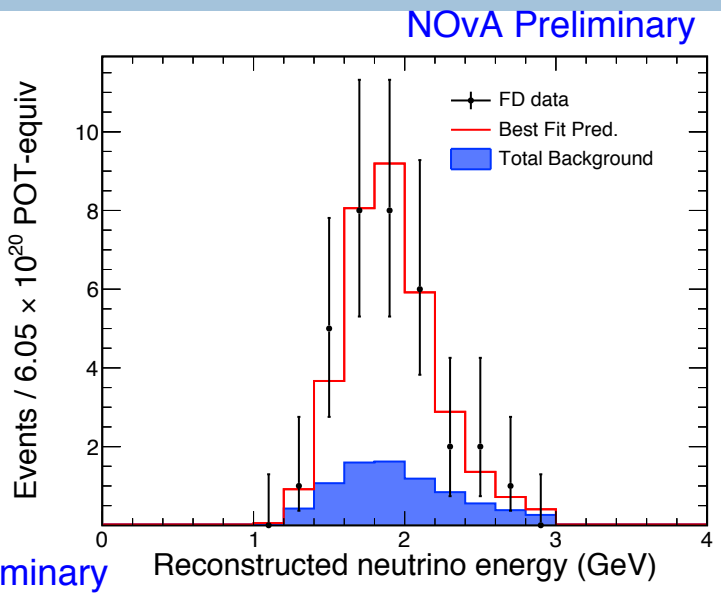
Data

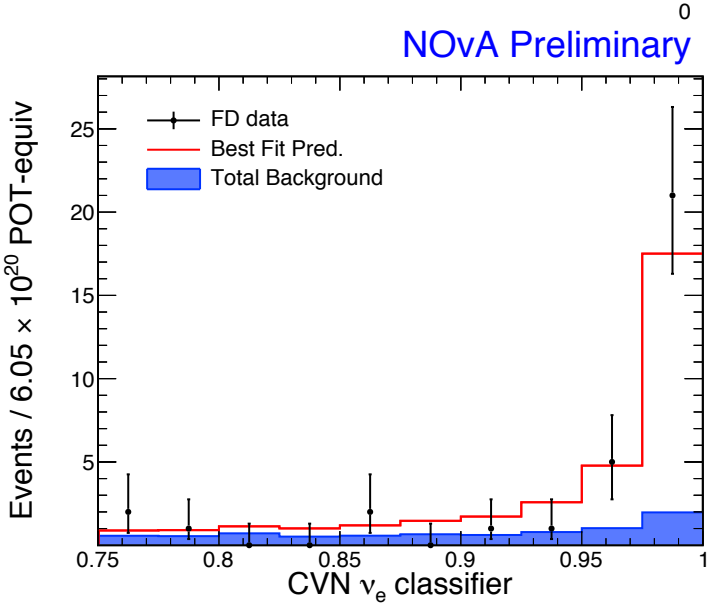
Electron Neutrino FD Data

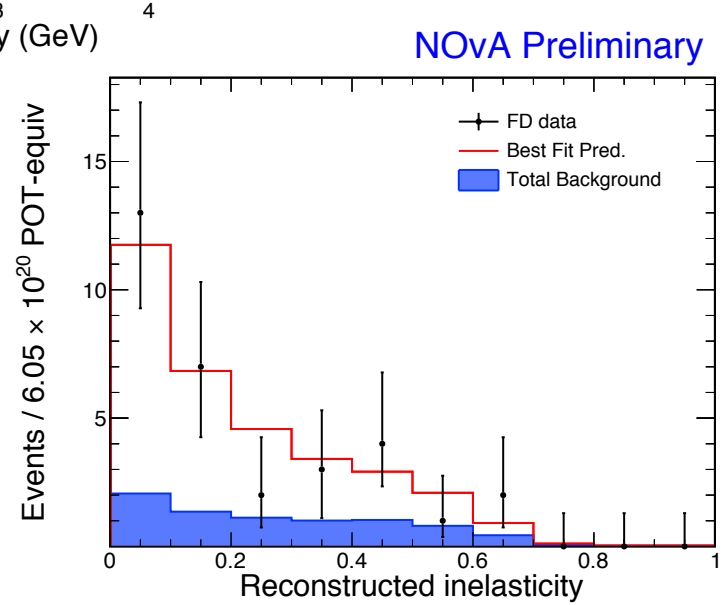


Best fit in Inverted Hierarchy

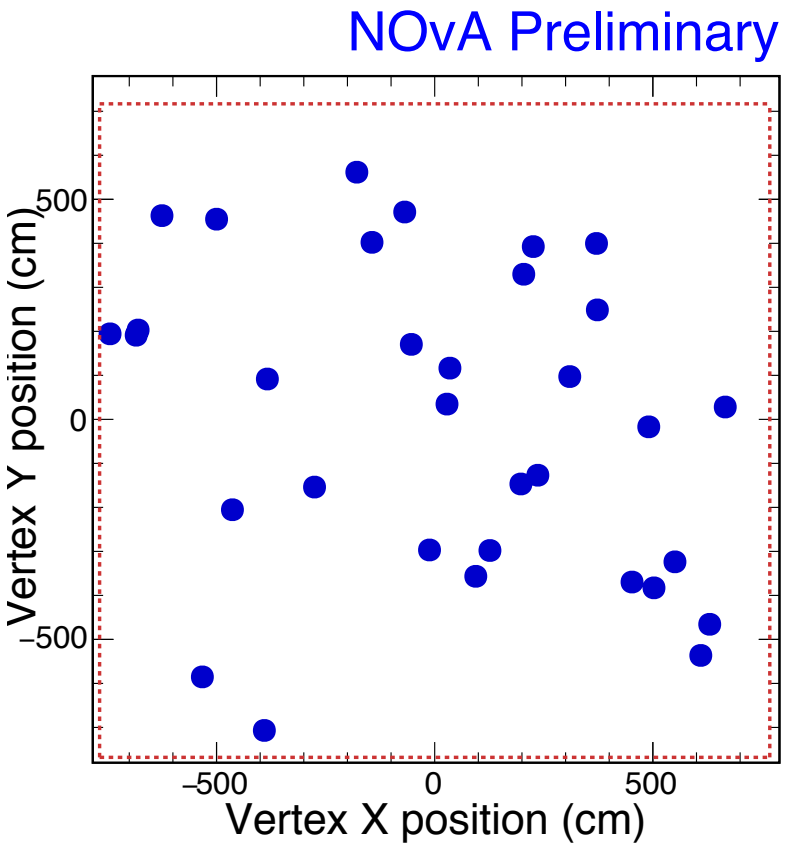
Electron Neutrino FD Data

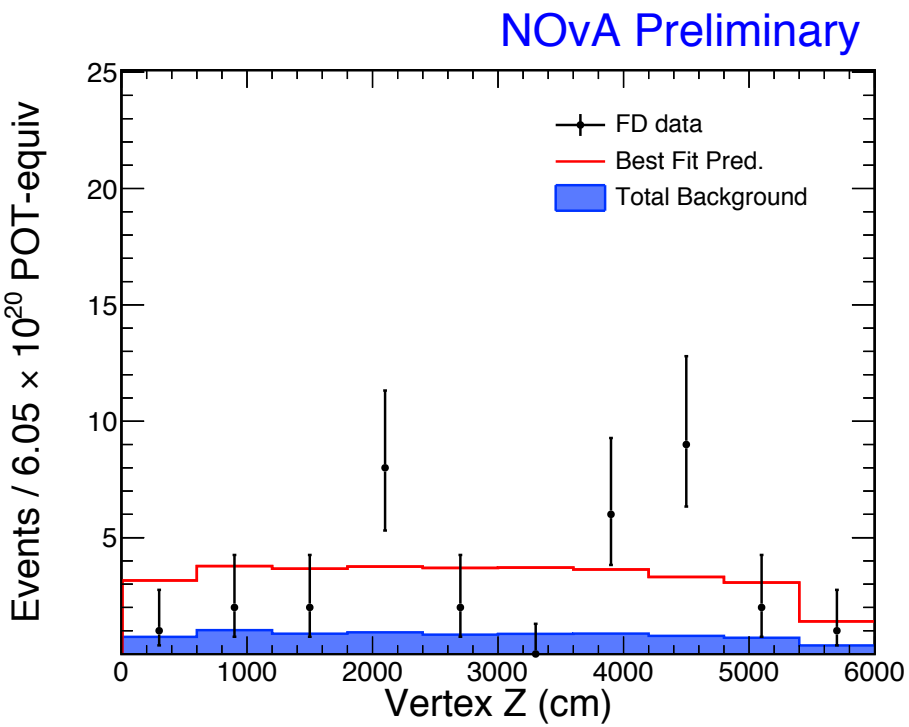




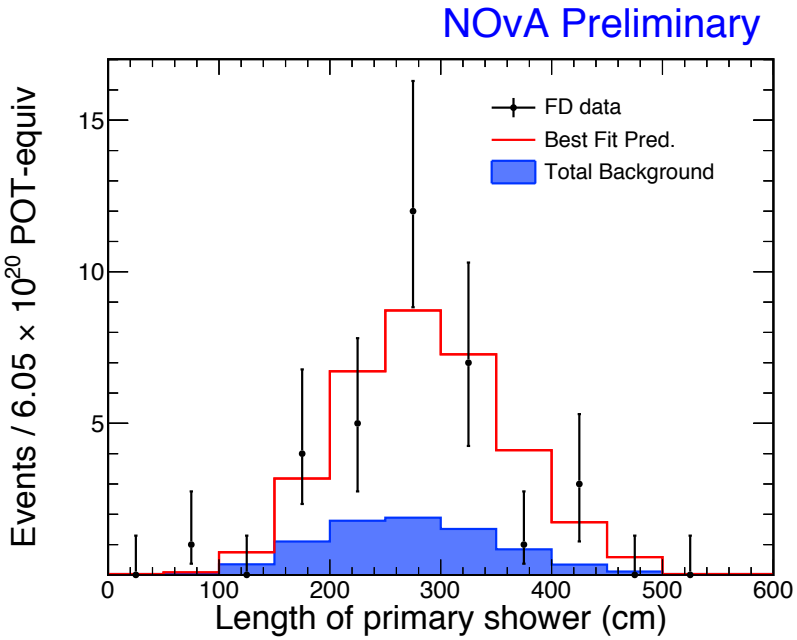


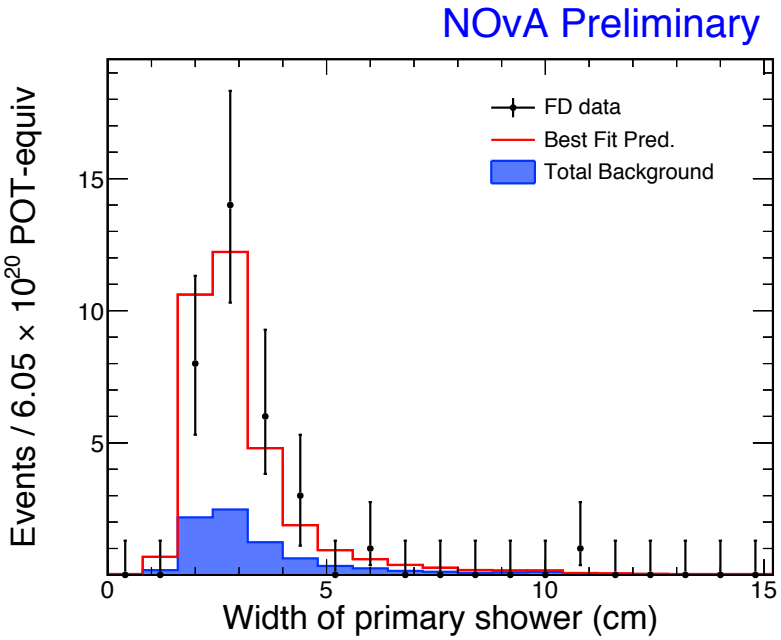
Electron Neutrino FD Data





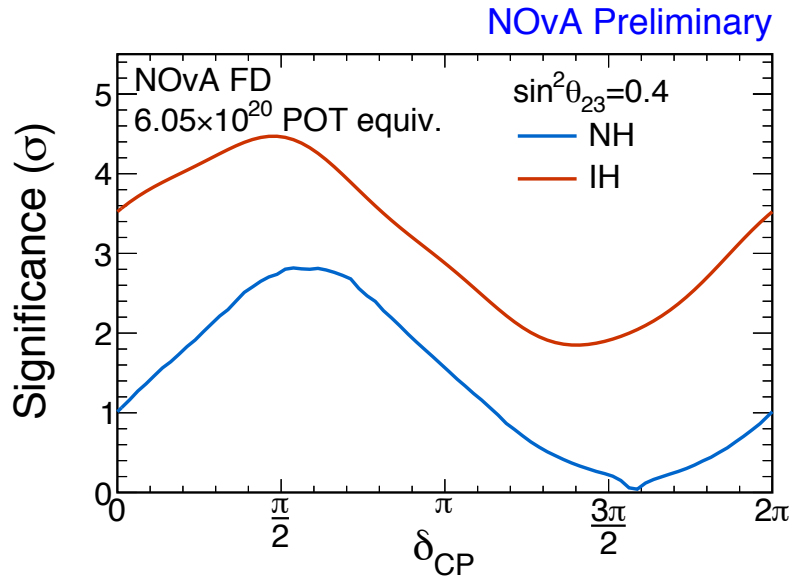
Electron Neutrino FD Data

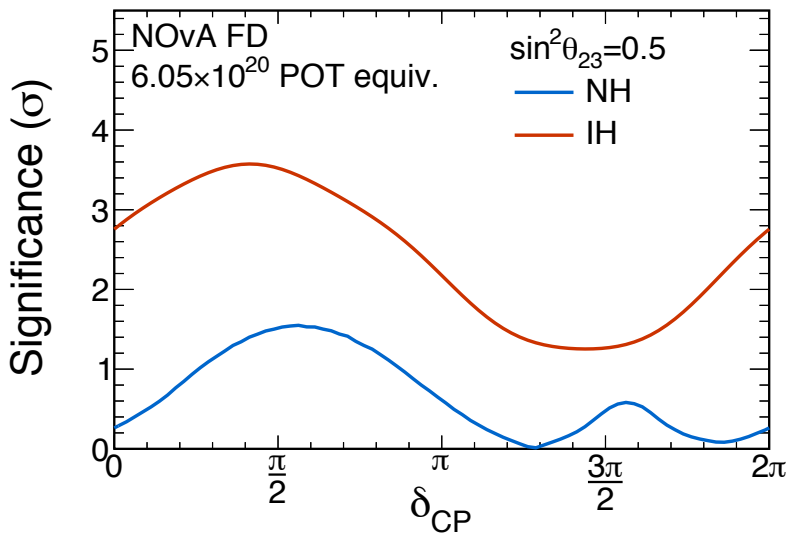


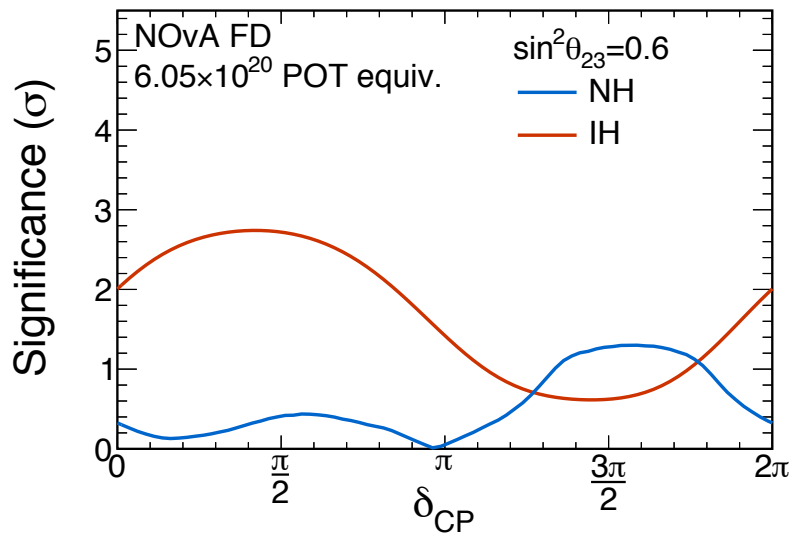


Contours

- Significance of hierarchy exclusion as a function of δ for fixed values of $\sin^2\theta_{23}$

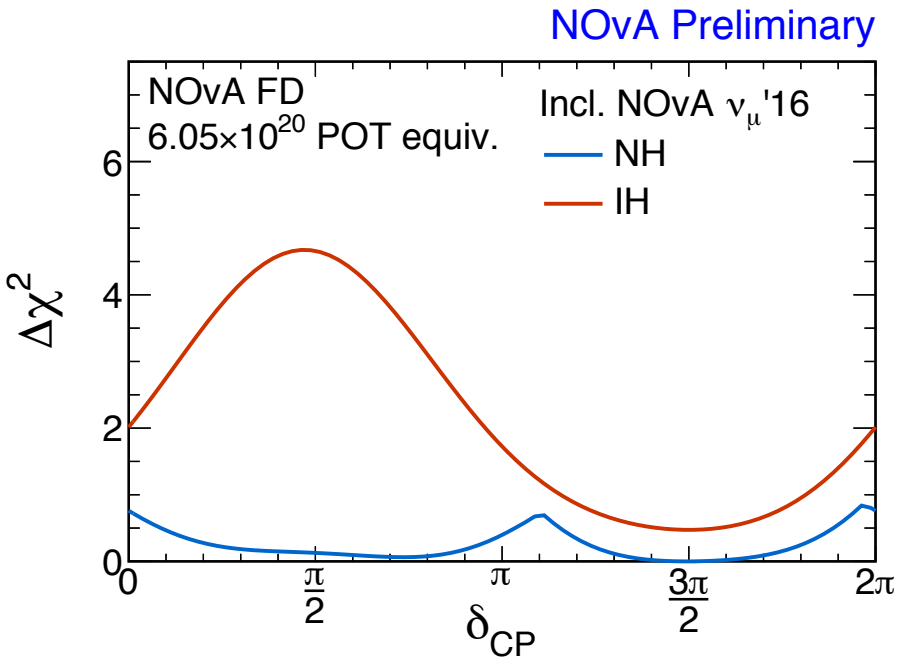






Contours

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated between the two samples
  - No Feldman-Cousins corrections

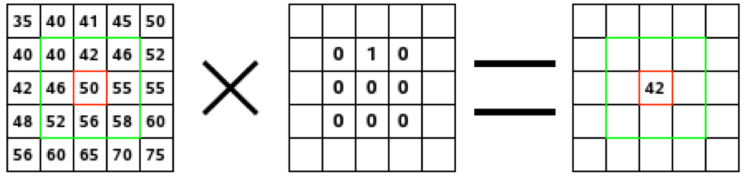


A. Aurisano et al., arXiv:1604.01444

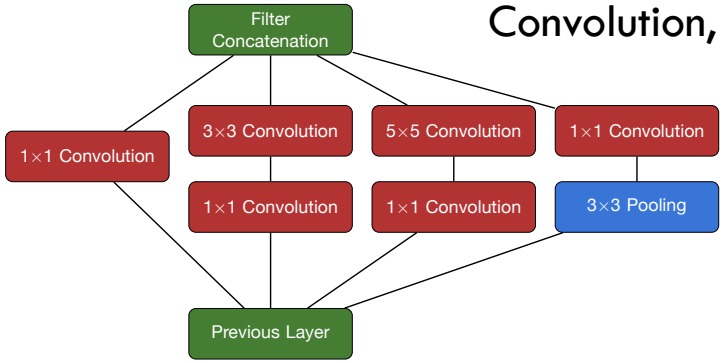
Posters P1.028 by A. Radovic and A. Himmel, P1.032 by F. Psihas

CVN Architecture

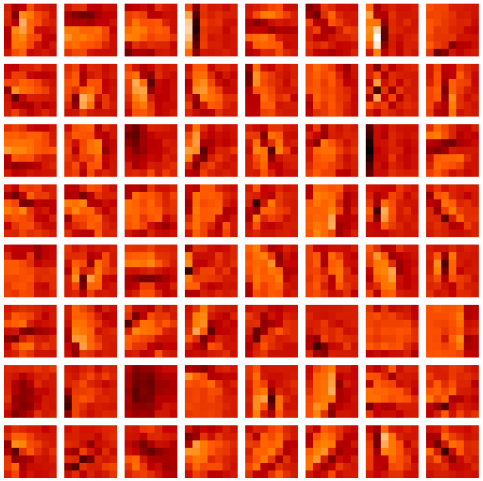
GoogLeNet
Inception Module
C. Szegedy et al.,
arXiv:1409.4842



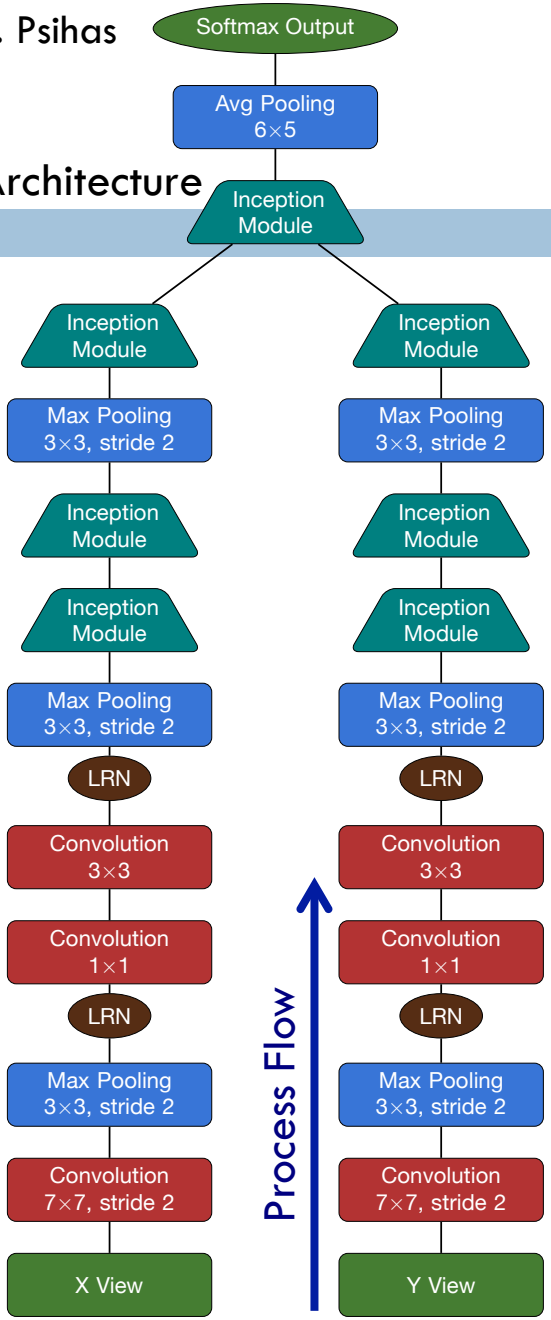
Example image processing transformation
Convolution, or kernel map



Example Convolutional Filter Layer



Network implemented and trained in the Caffe Framework
(Y. Jia et al., arXiv:1408.5093)

Trained over 4.7M simulated events,
Trained on FNAL GPU farm

CVN Architecture