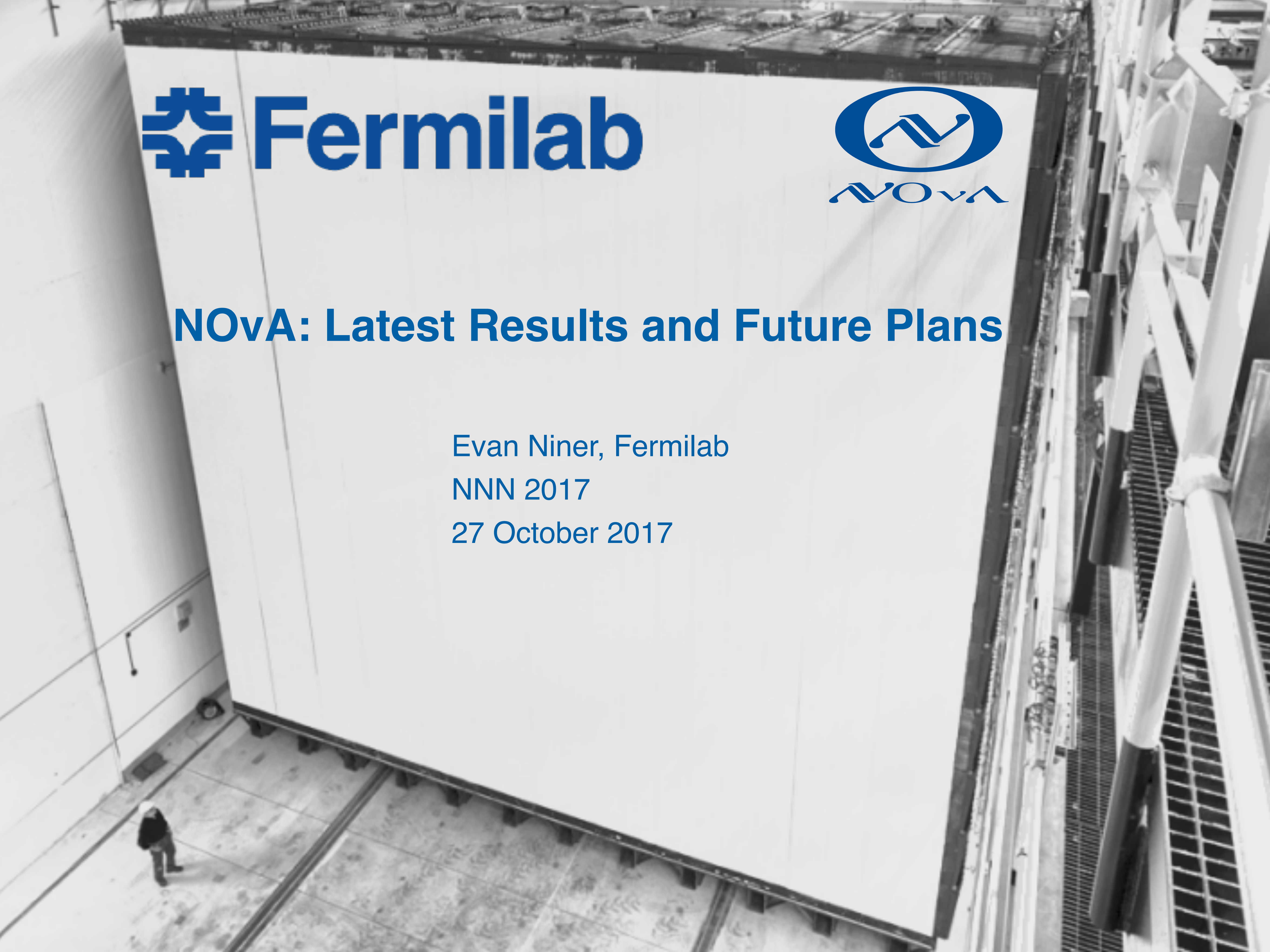

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NOvA

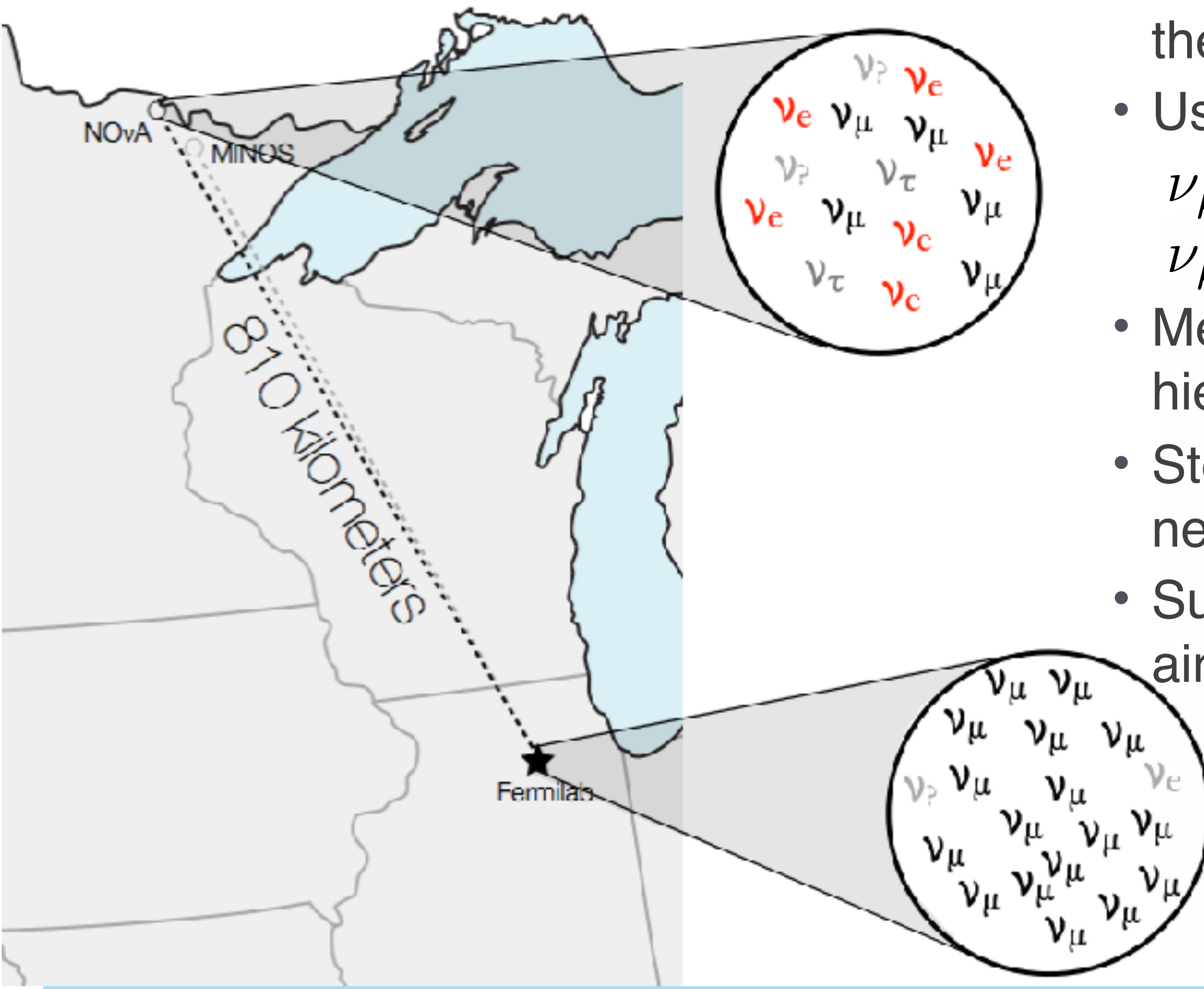
NOvA: Latest Results and Future Plans

Evan Niner, Fermilab

NNN 2017

27 October 2017

The NOvA Experiment



- Observe neutrinos from NuMI neutrino beam line at Fermilab
- Two functionally identical detectors
- 810 km baseline, the longest in the world
- Uses four oscillation channels:

$$\nu_\mu \rightarrow \nu_\mu \qquad \overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$$
$$\nu_\mu \rightarrow \nu_e \qquad \overline{\nu}_\mu \rightarrow \overline{\nu}_e$$

- Measure θ_{13}, θ_{23}, Δm^2_{32}, mass hierarchy, and δ_{cp}
- Sterile neutrino searches, neutrino cross sections
- Supernova, monopoles, cosmic air showers, exotic physics

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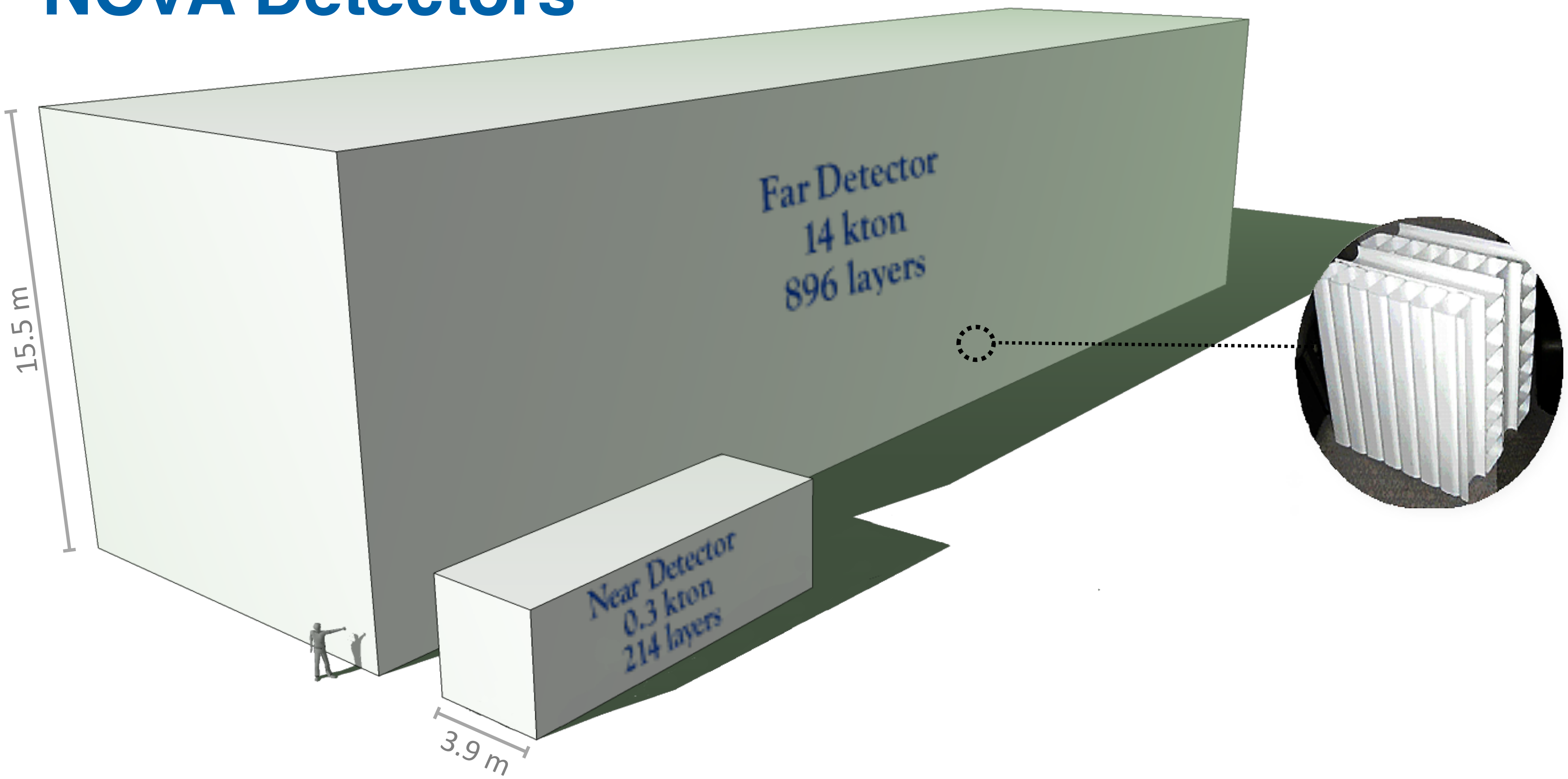
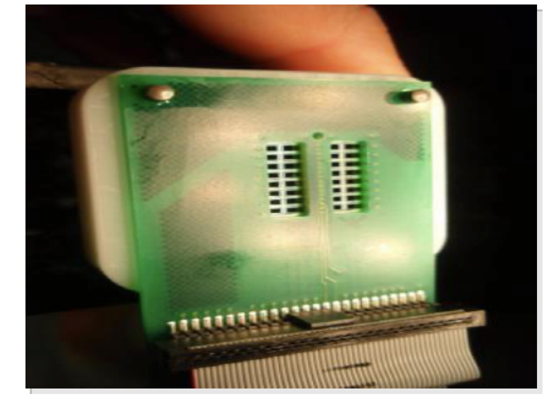
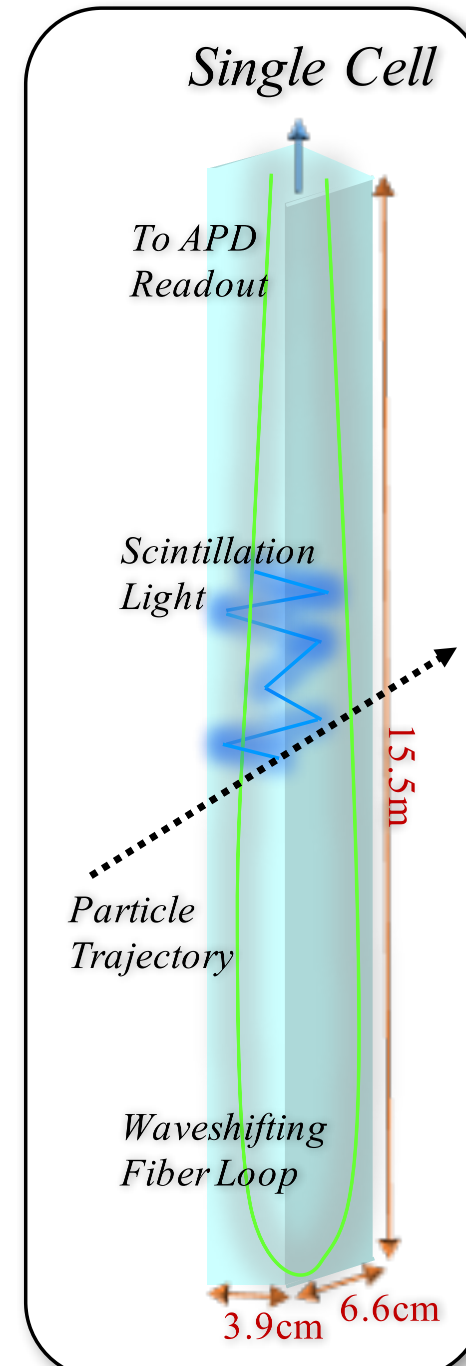
NOvA Detectors







- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator

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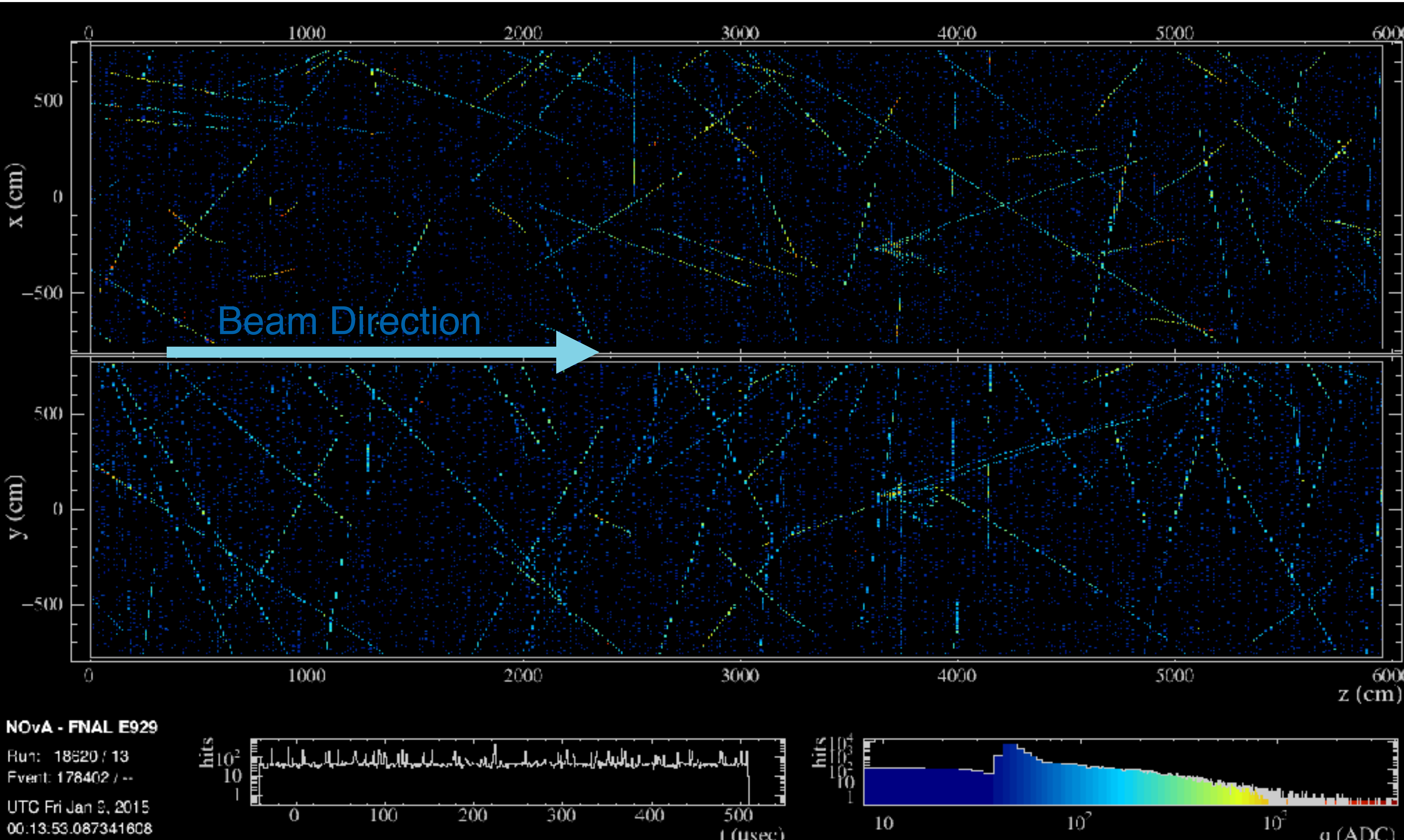
Far Detector 550 μs Readout Window

Cell hits colored by charge deposition



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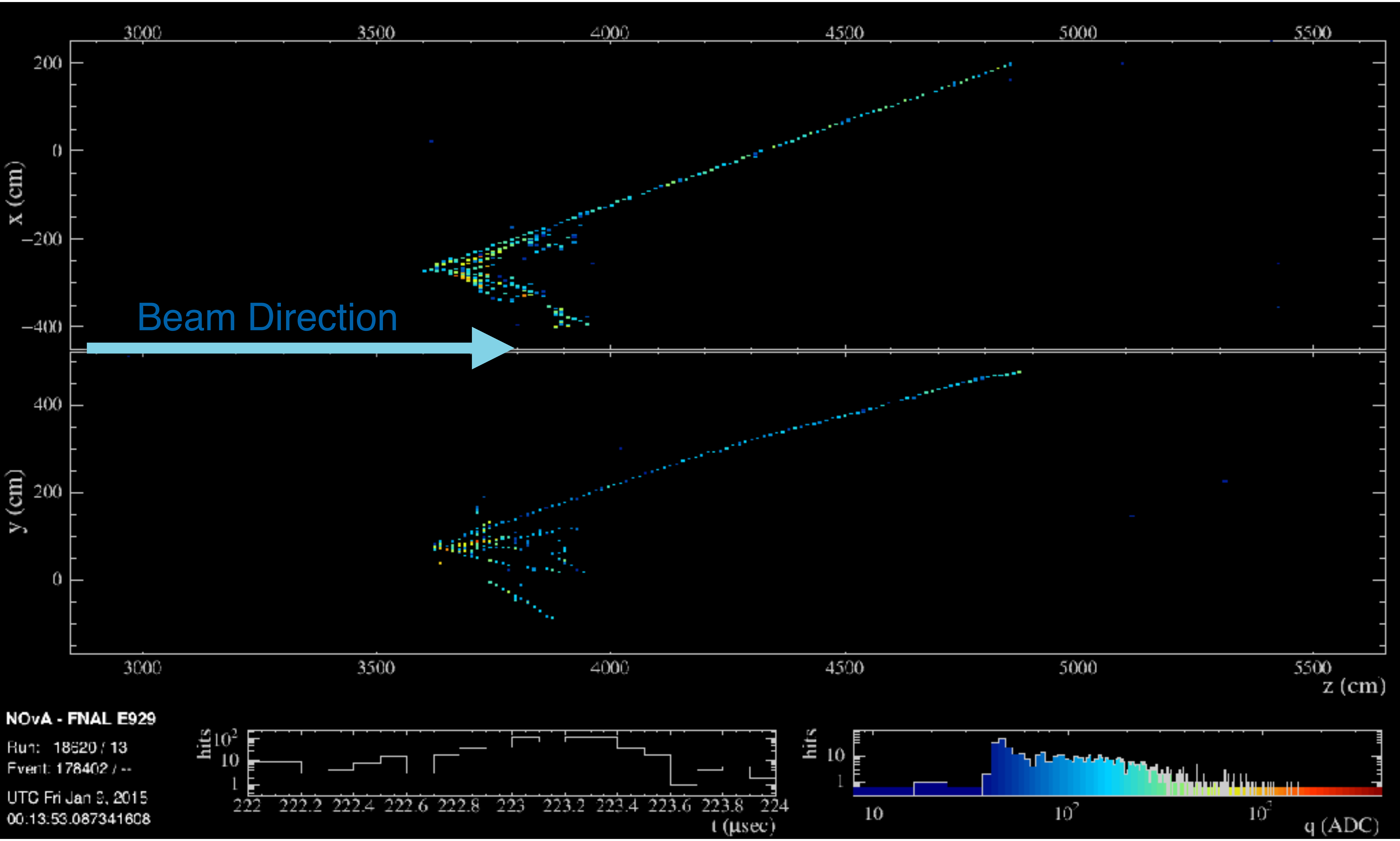
Far Detector Neutrino Interaction

Cell hits colored by charge deposition



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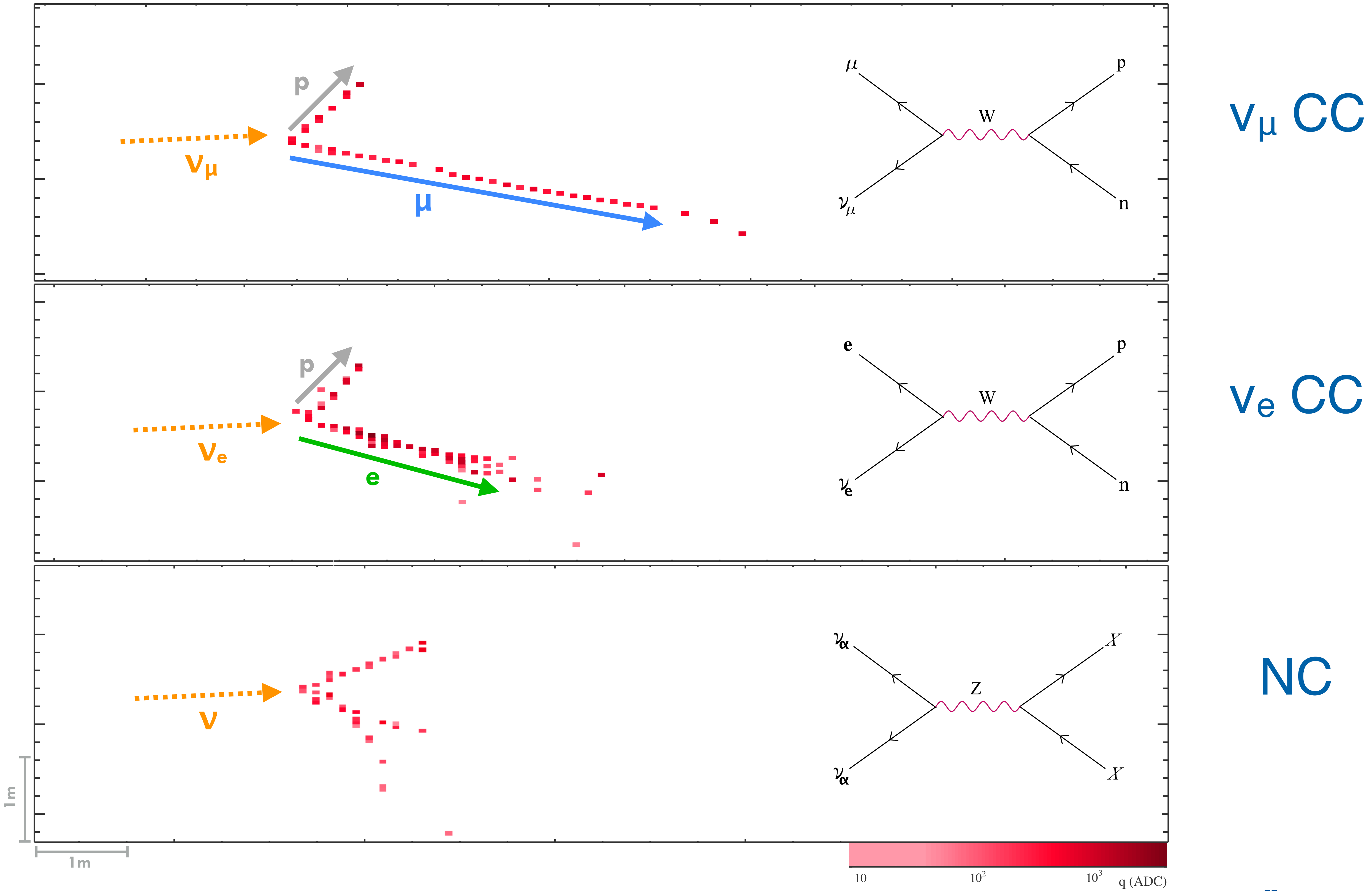
Event Topologies



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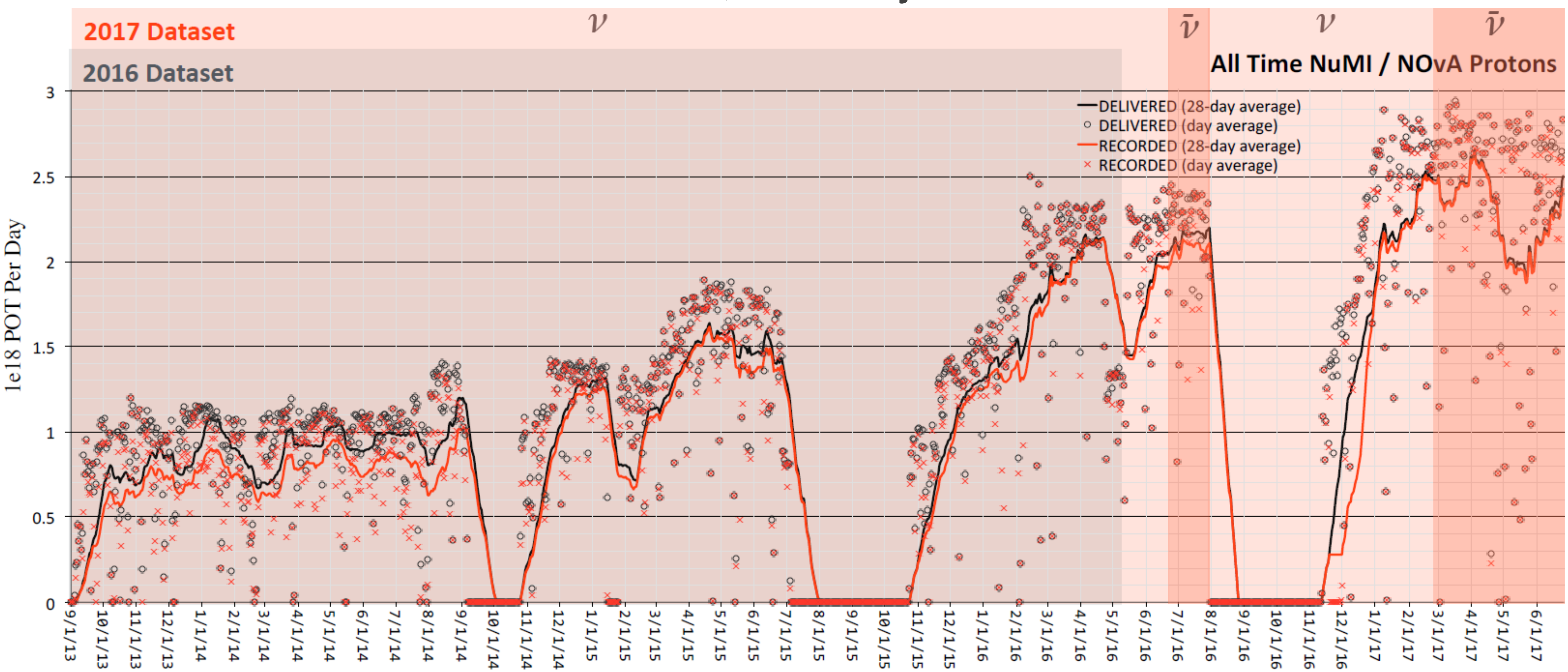
NuMI Beam Performance

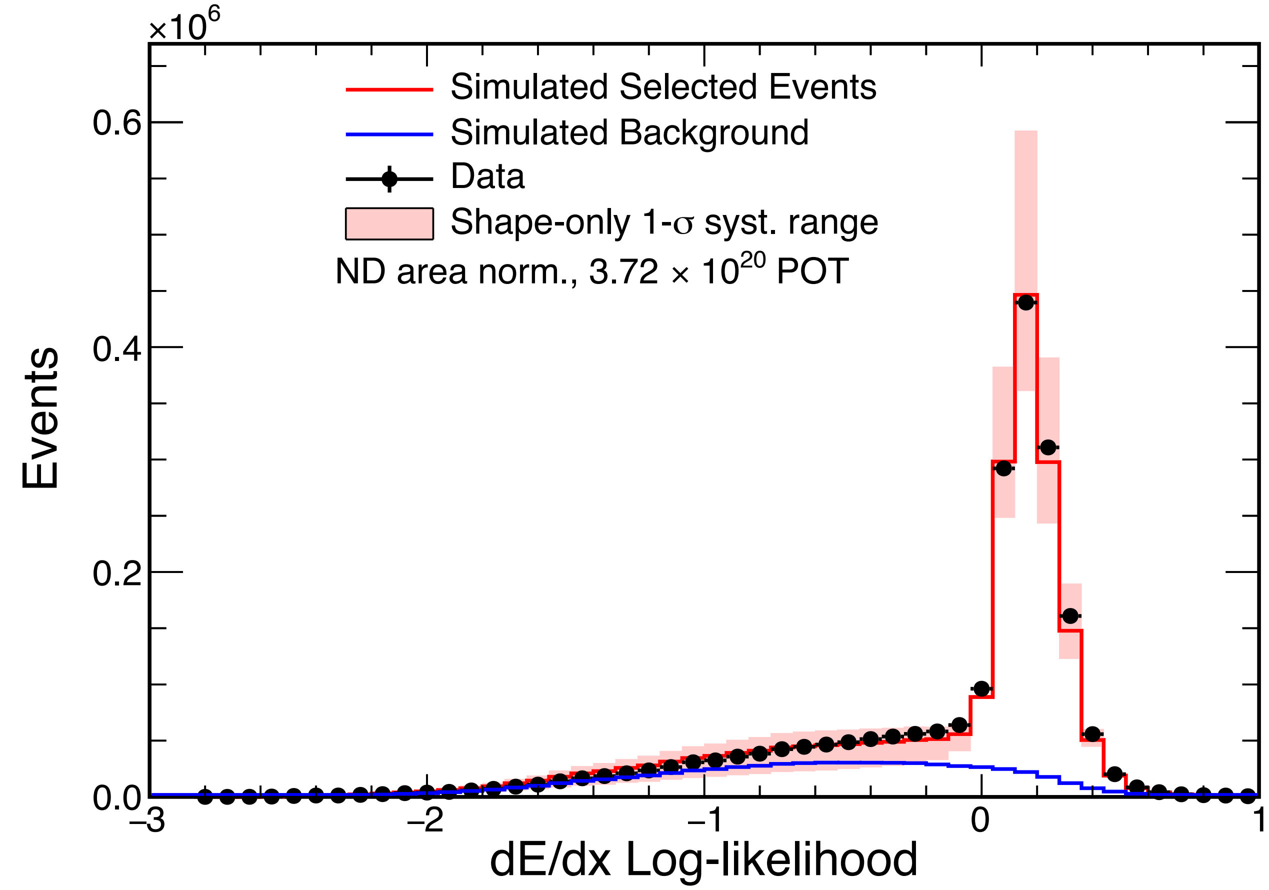
- 6.05×10^{20} full detector equivalent POT in 2016 dataset
  - ν_μ disappearance and ν_e appearance results
- 8.85×10^{20} full detector equivalent POT in 2017 dataset
  - neutral current disappearance result
- Beam in anti-neutrino mode now, routinely above 650 kW



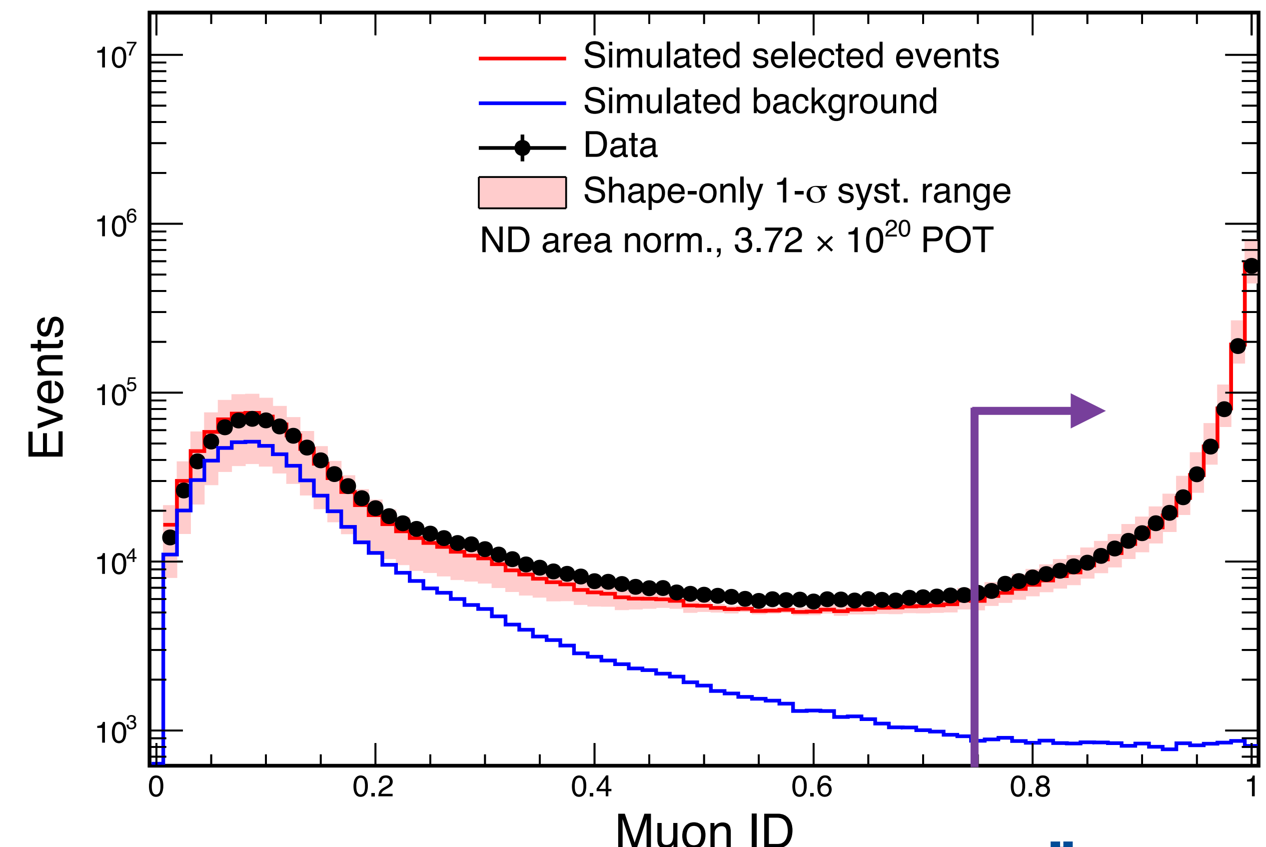
Muon Neutrino Disappearance Analysis

Muon Neutrino Selection

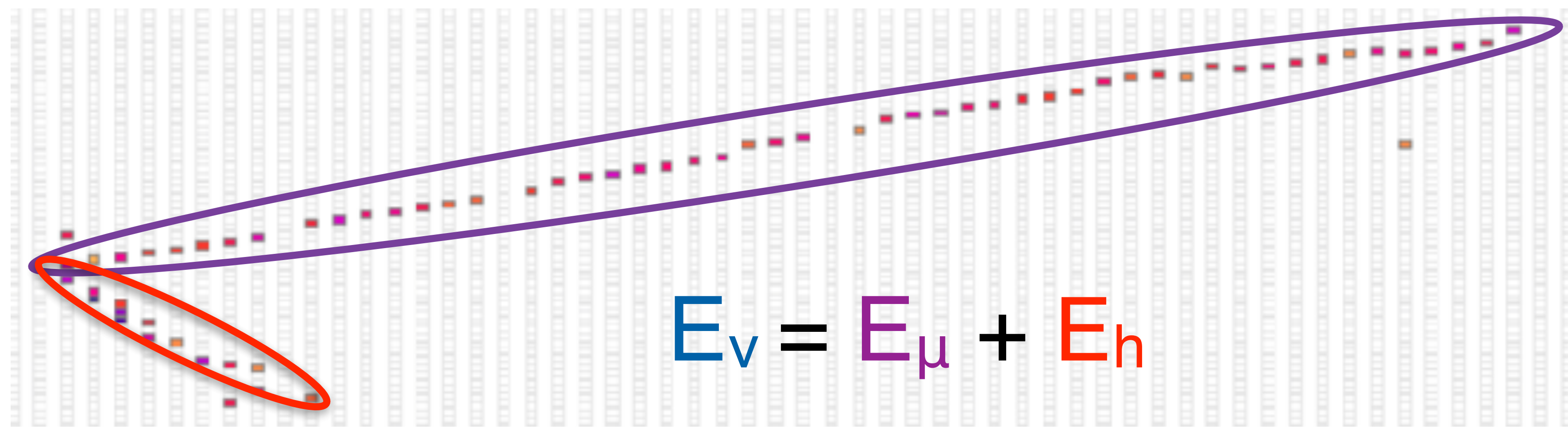
- Separate ν_μ CC interactions from NC and cosmic-ray backgrounds
- Containment cuts remove activity near walls
- Four variable k-Nearest Neighbor algorithm to select muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- Selection is 81% efficient and 91% pure



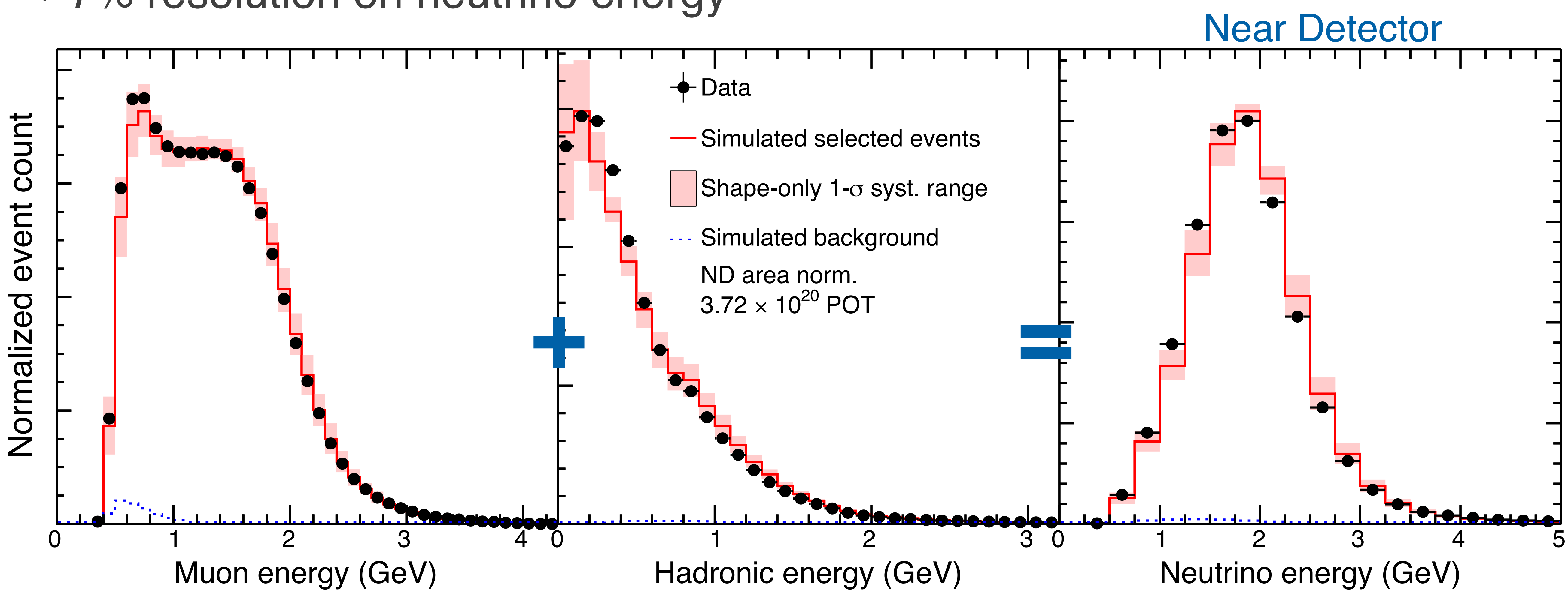
NOvA Preliminary



Energy Estimation



- Muon energy estimated from muon length
- Hadronic energy estimated calorimetrically from off-track hits
- ~7% resolution on neutrino energy



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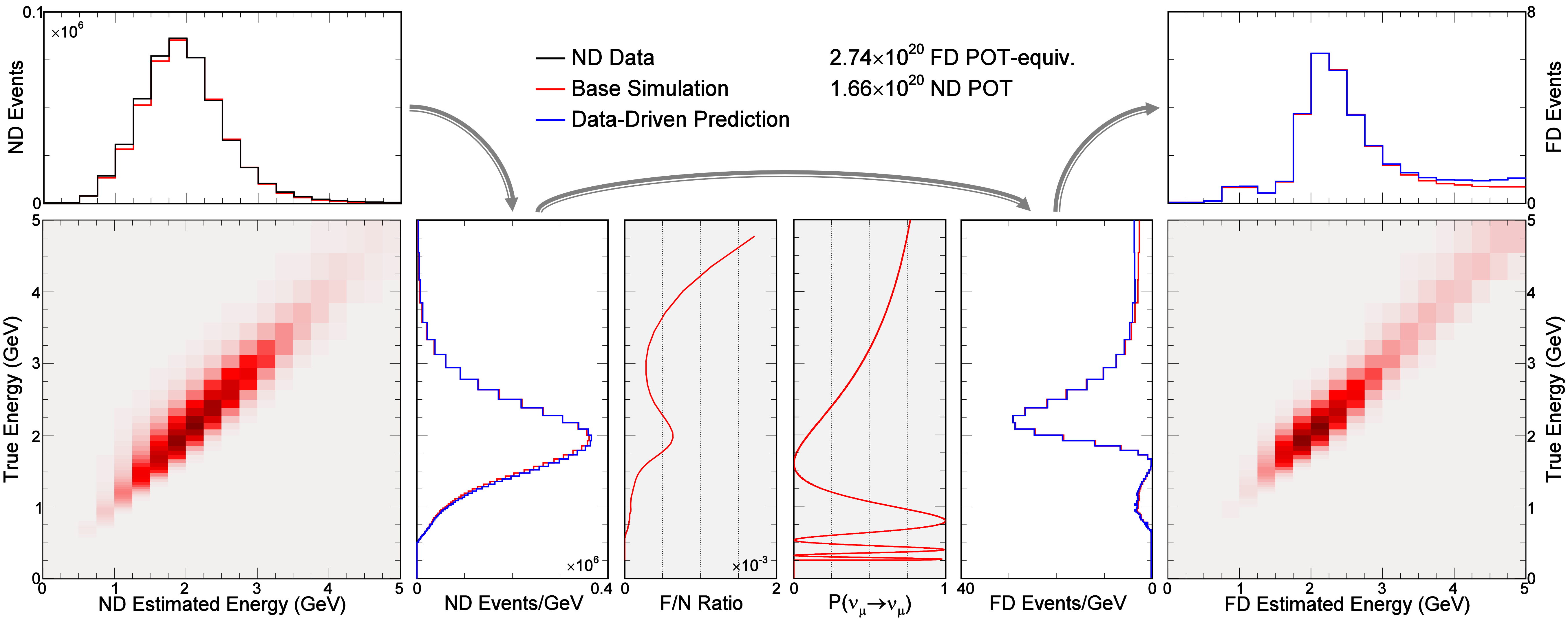
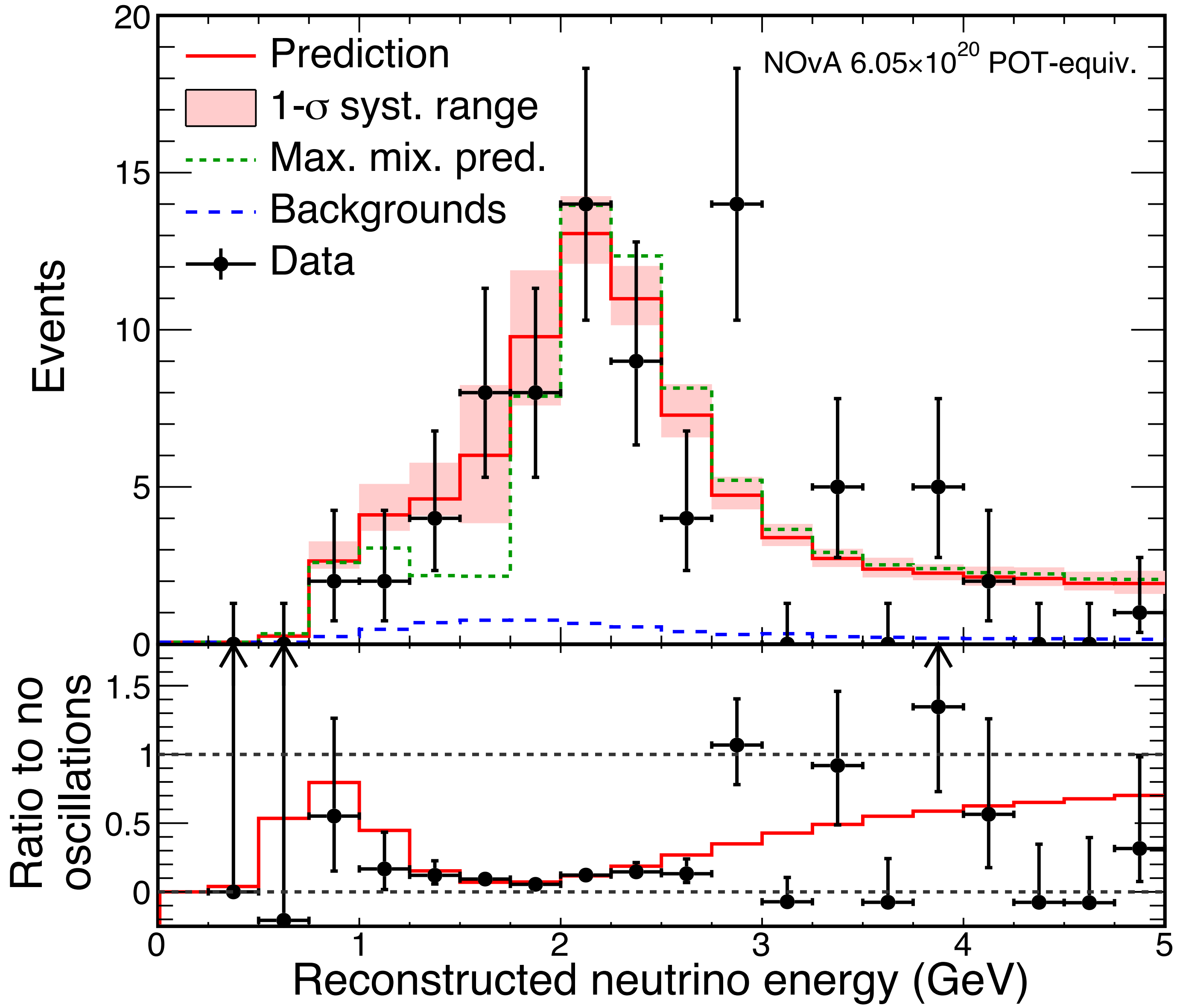
Extrapolation

- Use high statistics ND data/MC to adjust prediction at FD
  - Translate ND data/MC observation to true energy
  - Oscillate ratio to the FD
  - Smear back into reconstructed energy
- Reduces systematic uncertainties



ν_μ -> ν_μ Oscillation Results

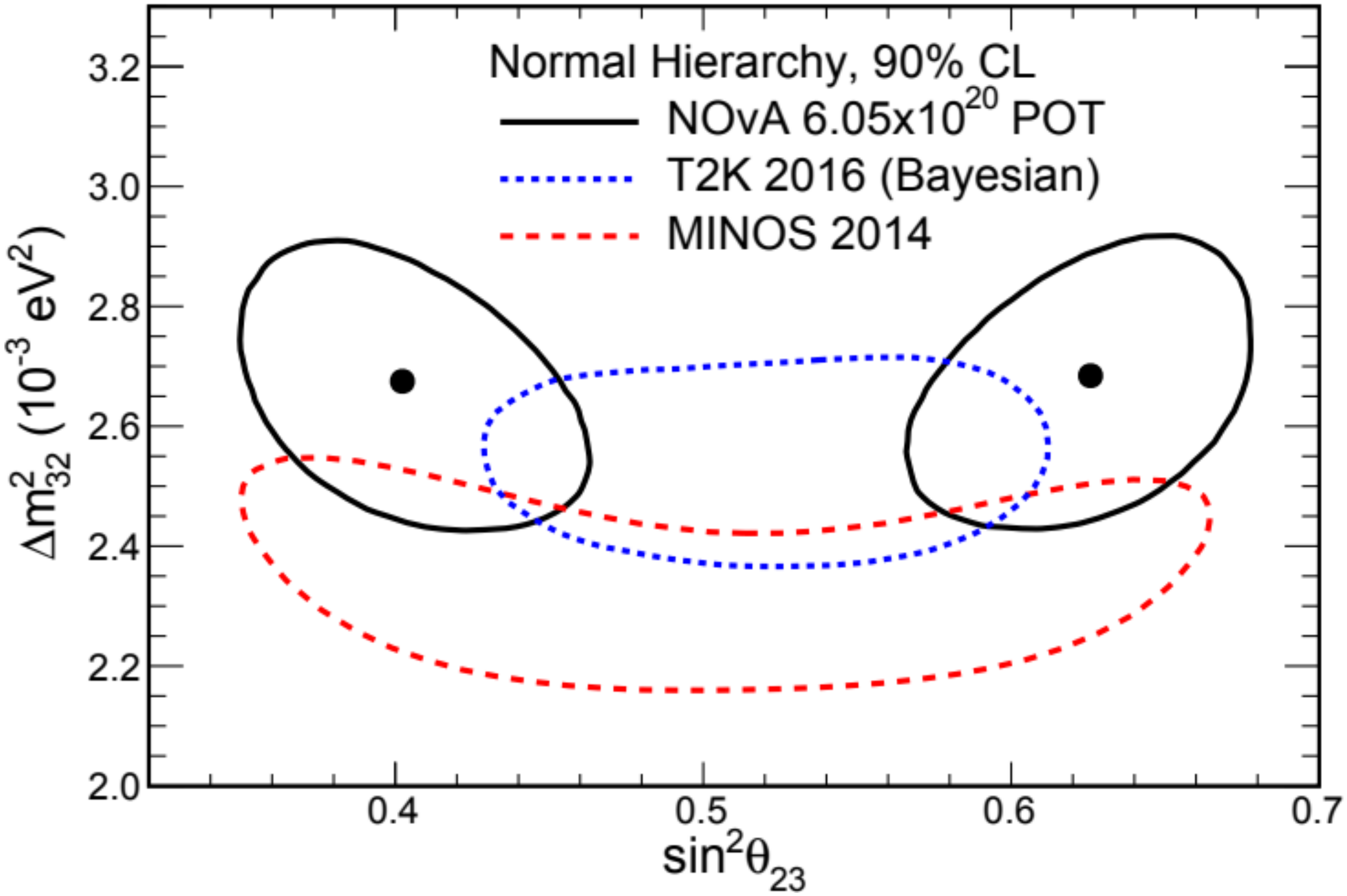
PRL 118, 151802



- 473 +/- 30 events predicted in the absence of oscillations
- Observed 78 events
- 82 events predicted at the best fit point including 3.7 beam background and 2.9 cosmic induced events
- Maximal mixing disfavored at 2.6 sigma

ν_μ -> ν_μ Oscillation Results

PRL 118, 151802



Best fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}(0.624^{+0.022}_{-0.030})$$

Update coming in fall 2017 with 50% more data

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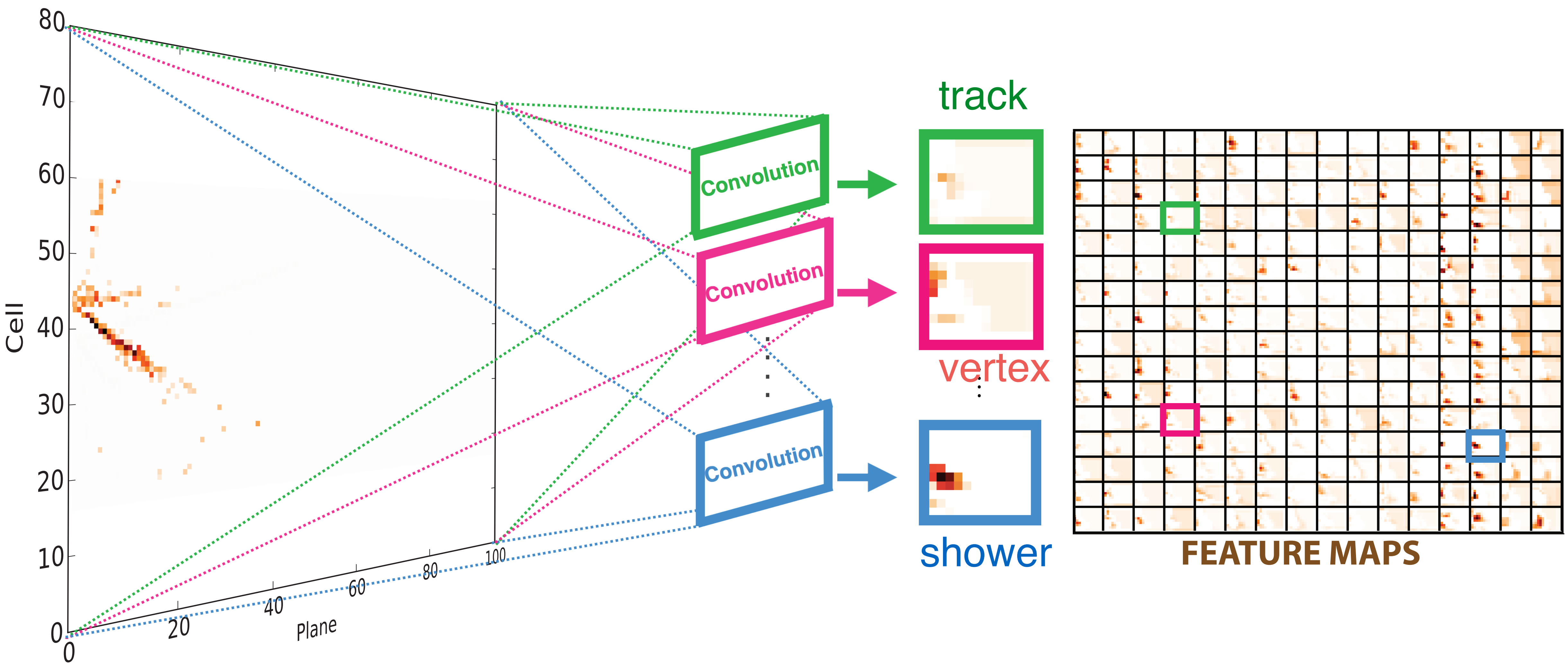
Electron Neutrino Appearance Analysis

Electron Neutrino Selection

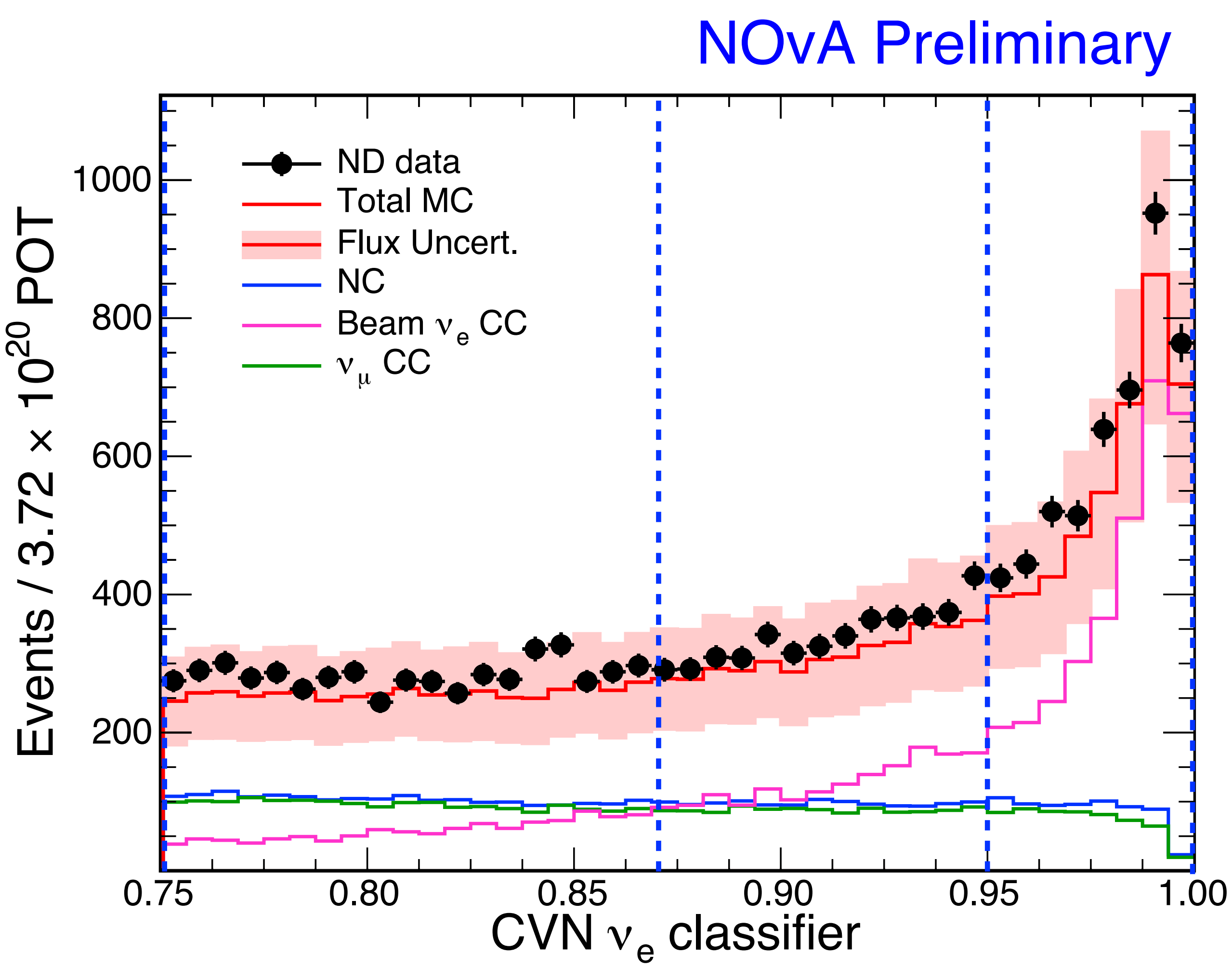
see NOvA deep learning talk from parallel session on Oct 26 by R. Murphy

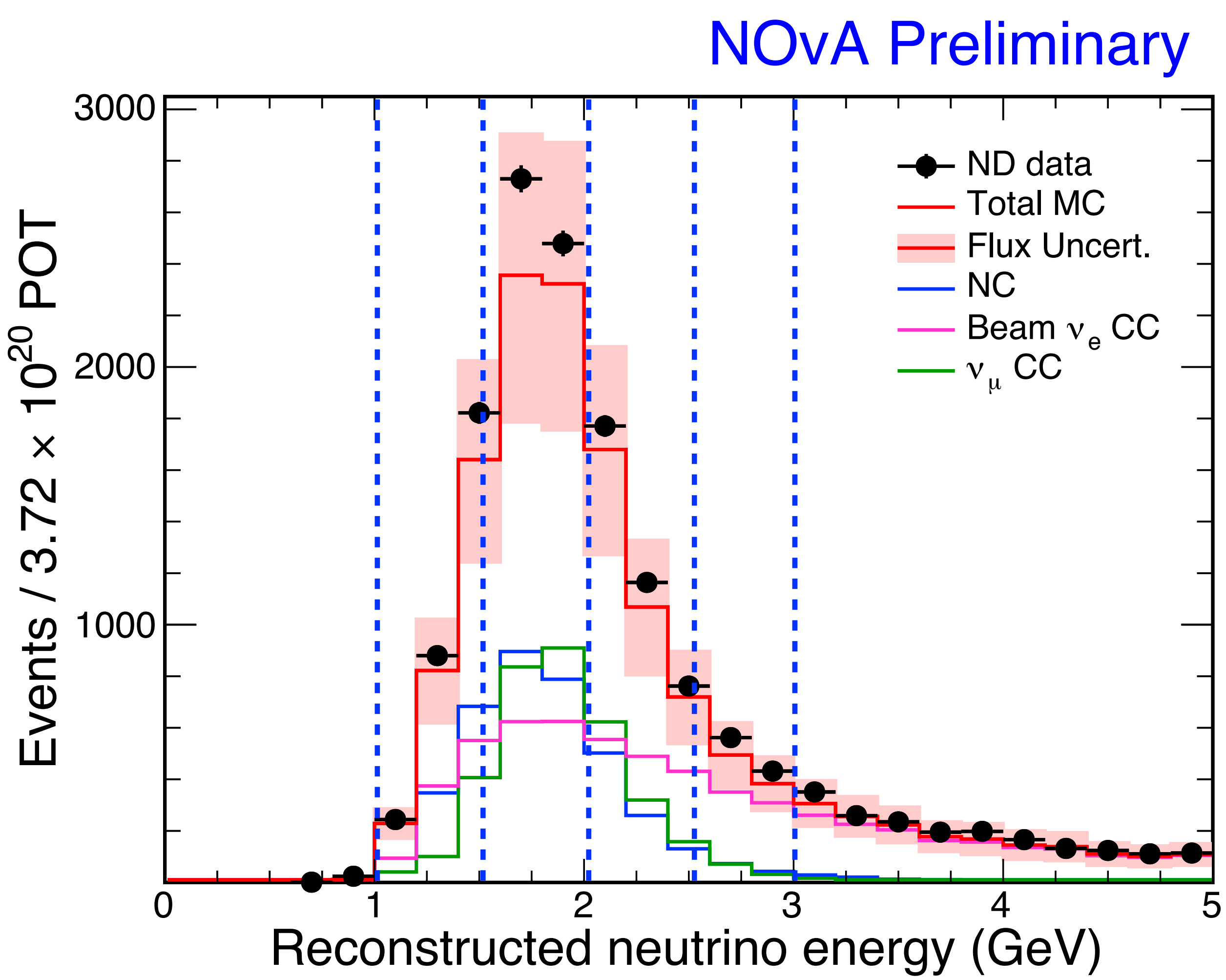
- Implemented a deep convolutional neural network
- Input 2D pixel maps of NOvA events
- Output classification as ν_μ, ν_e, ν_τ, NC, or cosmic
- Below: an electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels



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

Electron Neutrino Selection





- 73% ν_e CC selection efficiency, 76% purity with CVN classifier
- Good ND Data/MC agreement
- Equivalent to 30% increase in exposure compared to conventional IDs
- Bin analysis in four bins of energy and three of CVN

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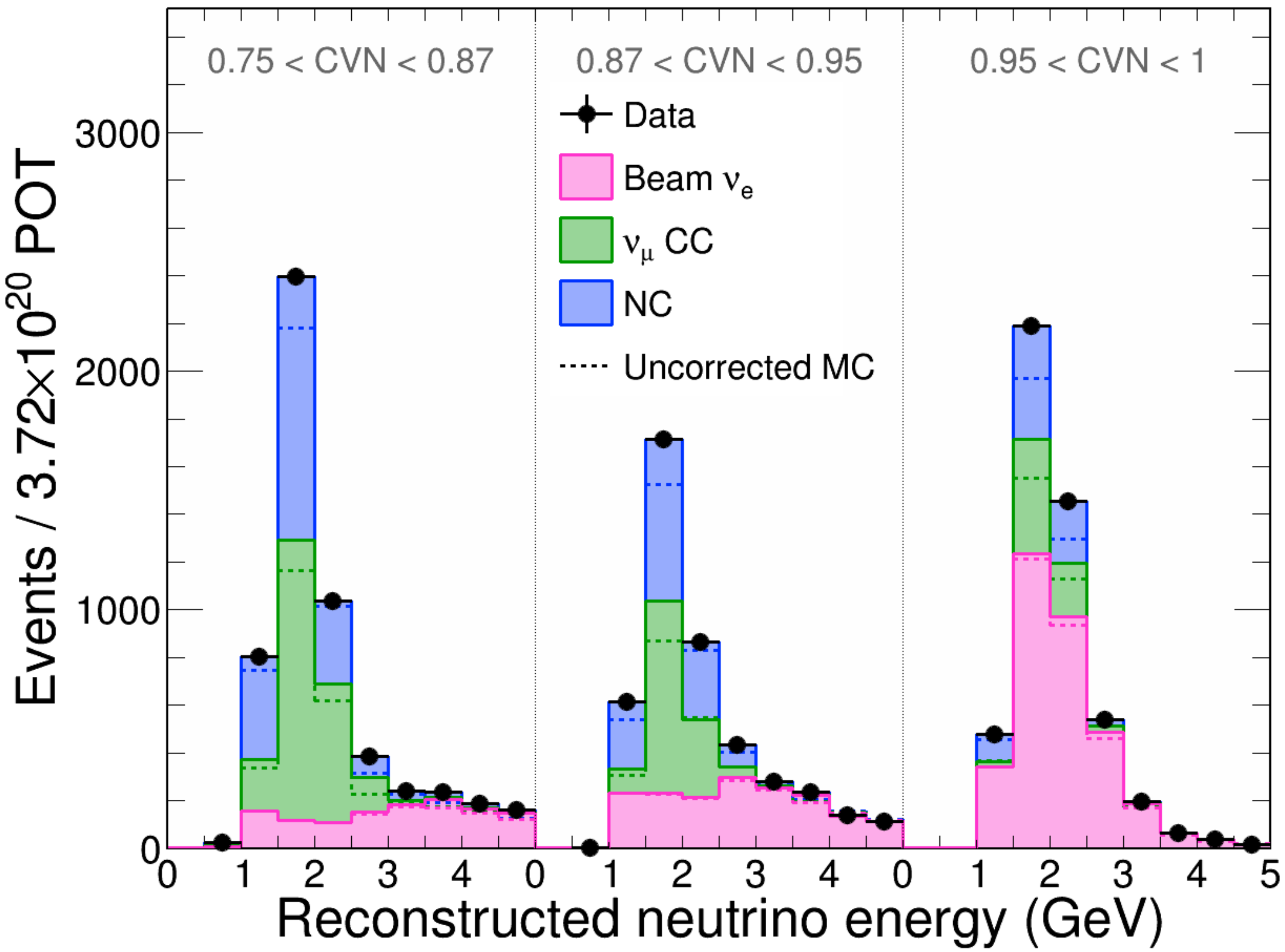
Data Driven Background Corrections

- ν_e CC selection in the ND picks out FD backgrounds
  - beam ν_e CC
  - ν_μ CC
  - NC
- ~10% excess of data over MC in the ND
- Extrapolate data/MC differences to adjust FD prediction
- Data-driven methods to decompose data into components
  - beam ν_e CC adjusted by parent π^+ and k^+
  - Michel electron templates used to adjust NC and ν_μ CC



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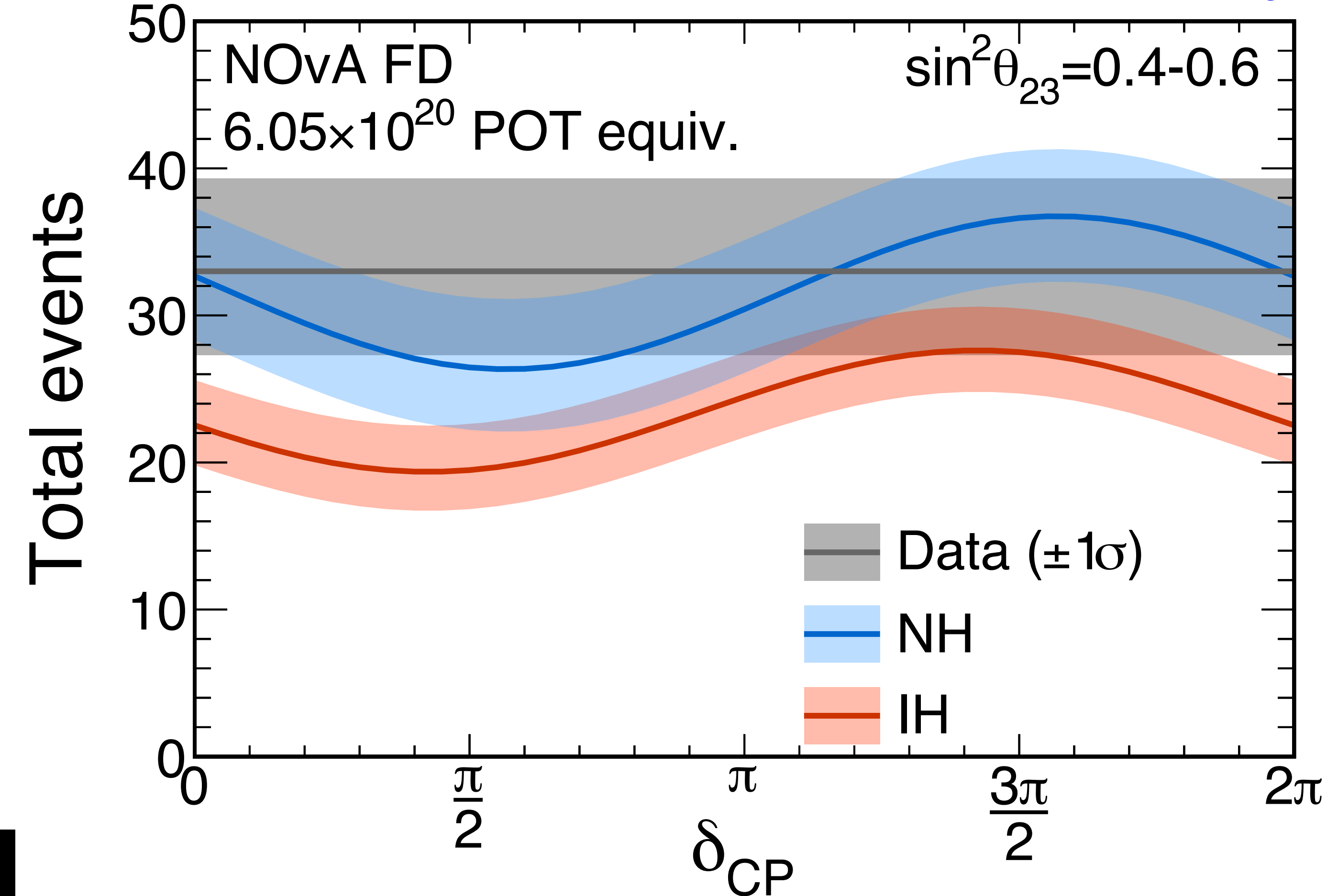
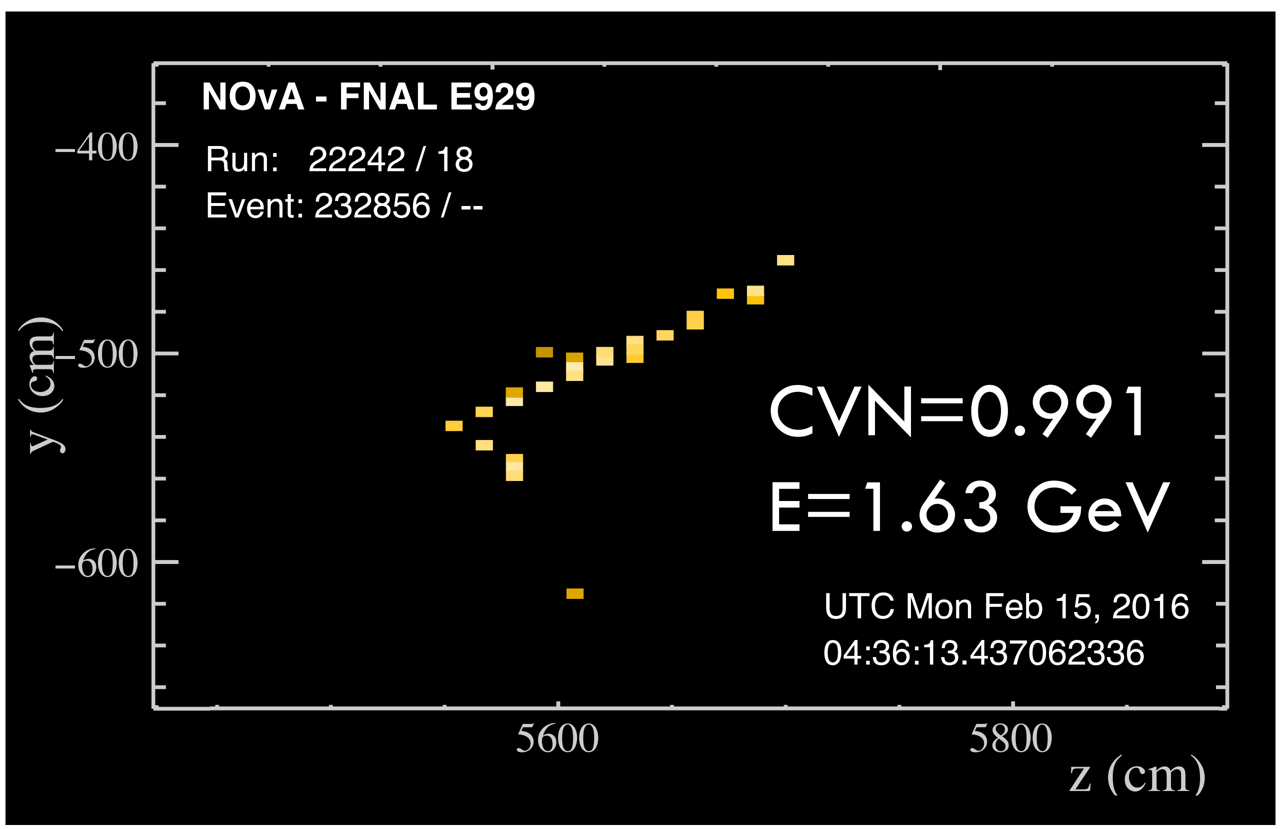
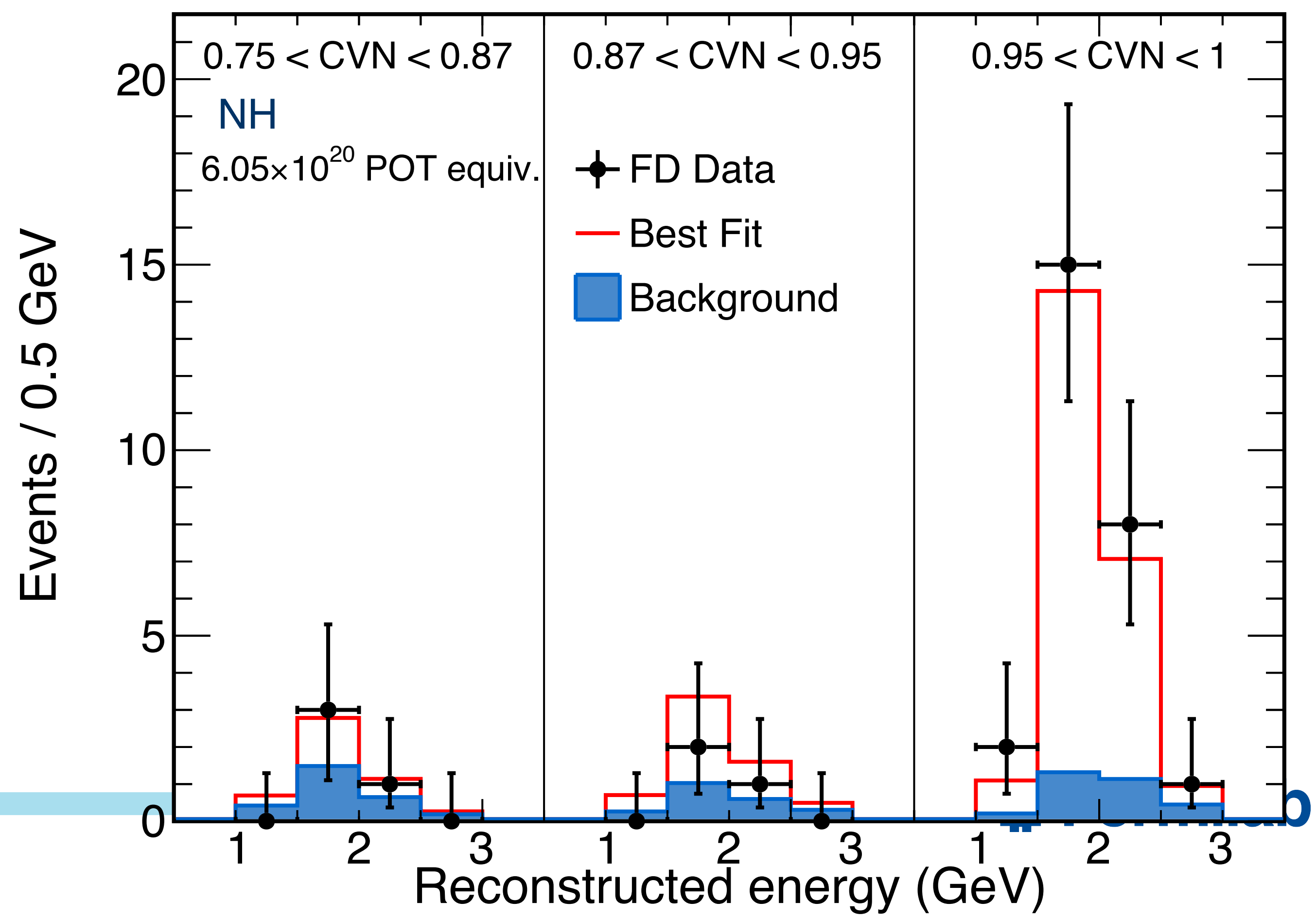
$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- Observe 33 events on background of 8.2 +/- 0.8 events

NOvA Preliminary







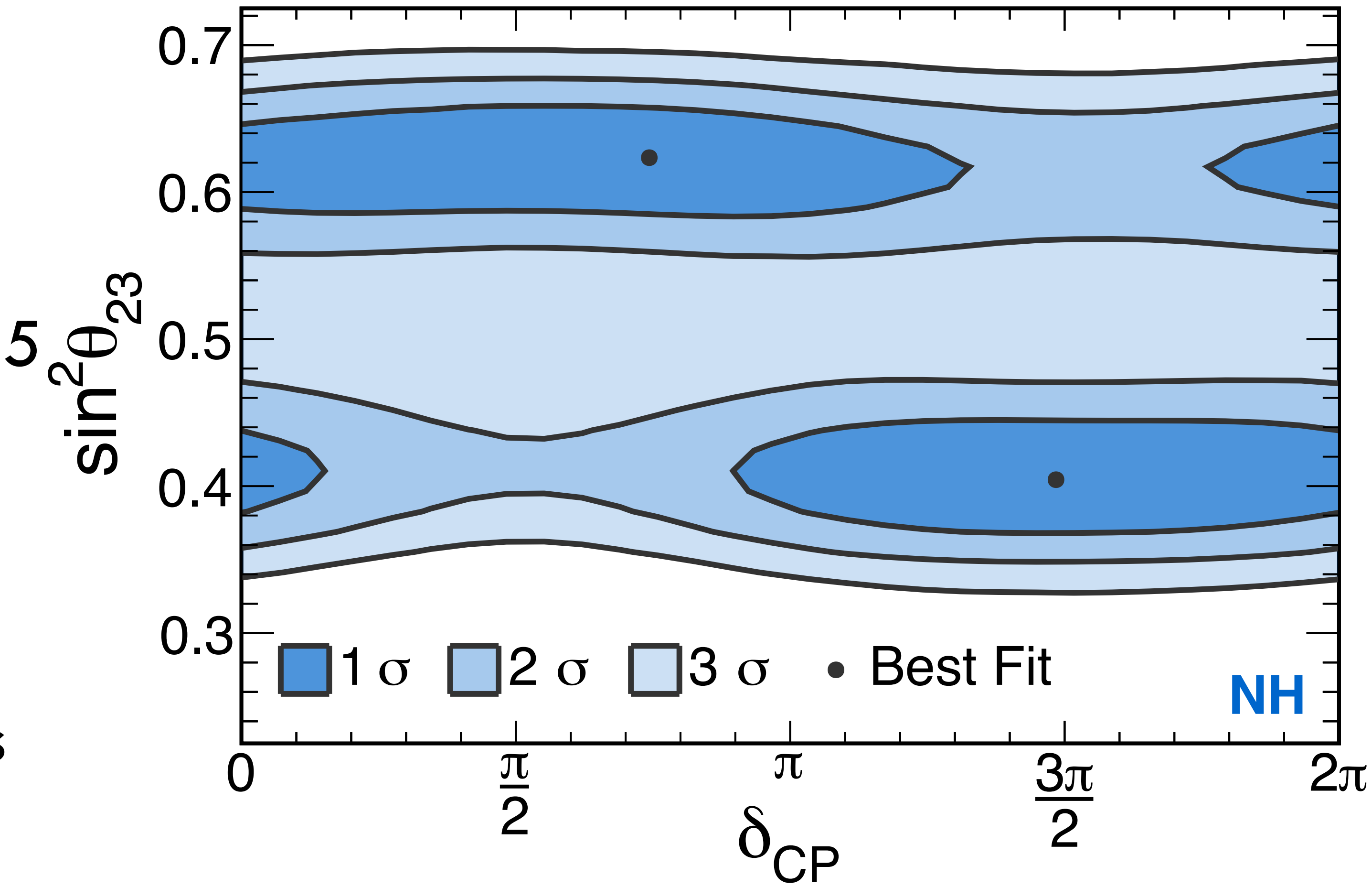
$\nu_\mu \to \nu_e$ Oscillation Results

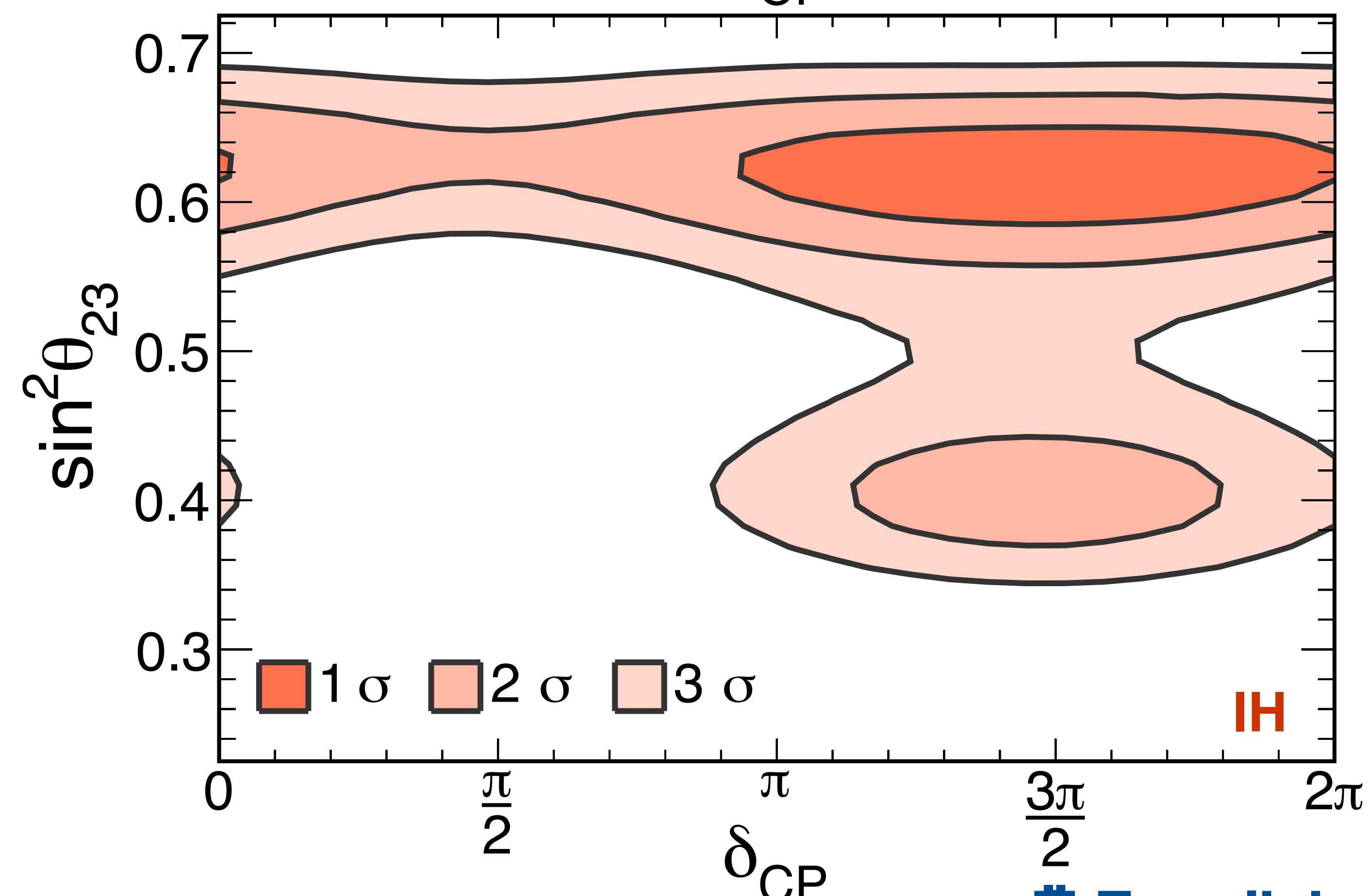
- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ from reactor experiments
  - Simultaneous fit with NOvA disappearance data

- Global best fit, two degenerate points in Normal Hierarchy

$$\delta_{cp} = 1.48\pi, \sin^2(\theta_{23}) = 0.404$$
$$\delta_{cp} = 0.74\pi, \sin^2(\theta_{23}) = 0.623$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - Lower octant, IH is disfavored at greater than 93% C.L for all values of δ_{CP}





PRL 118, 231801

ν_μ -> ν_e Oscillation Results

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ from reactor experiments
  - Simultaneous fit with NOvA disappearance data

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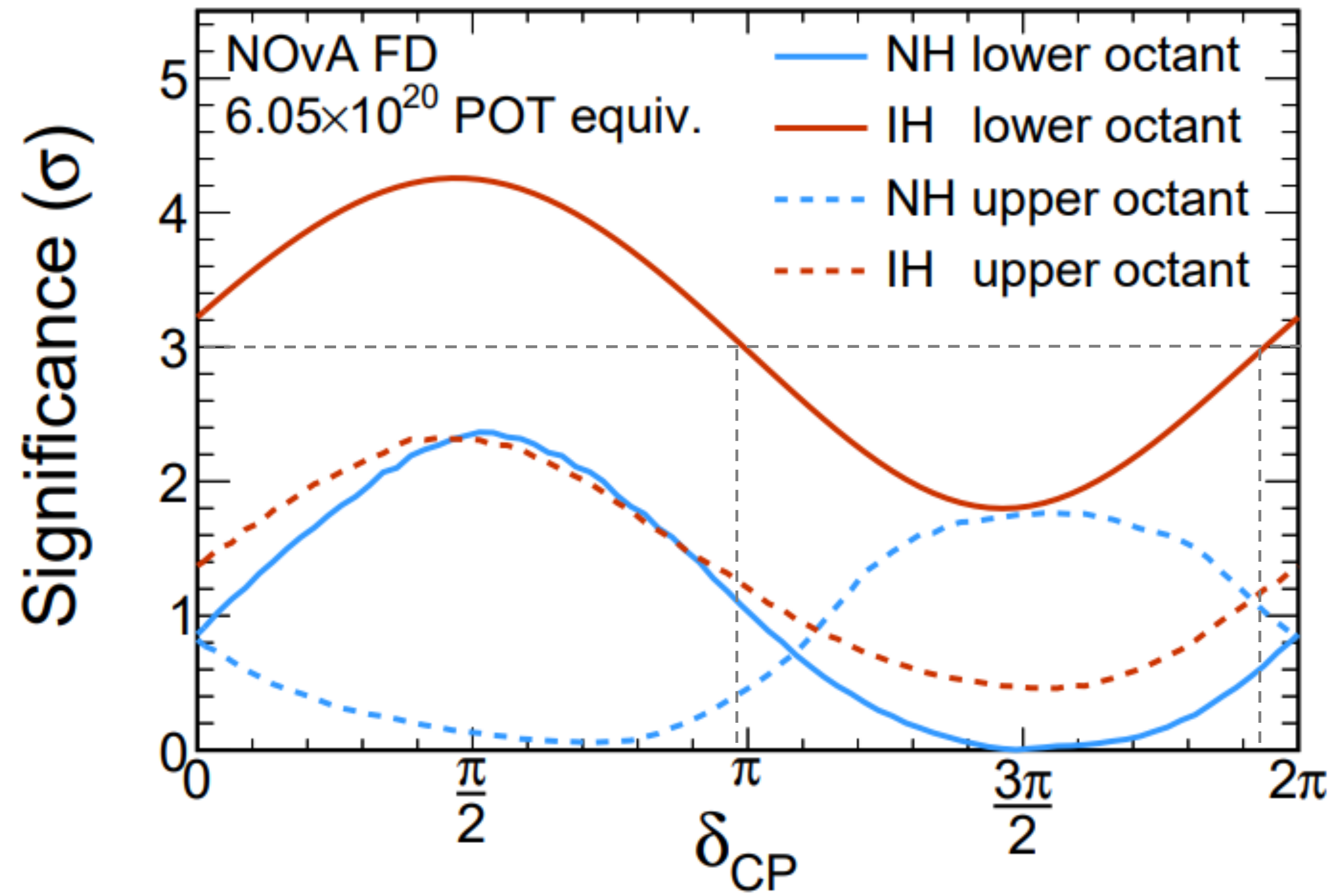
PRL 118, 231801

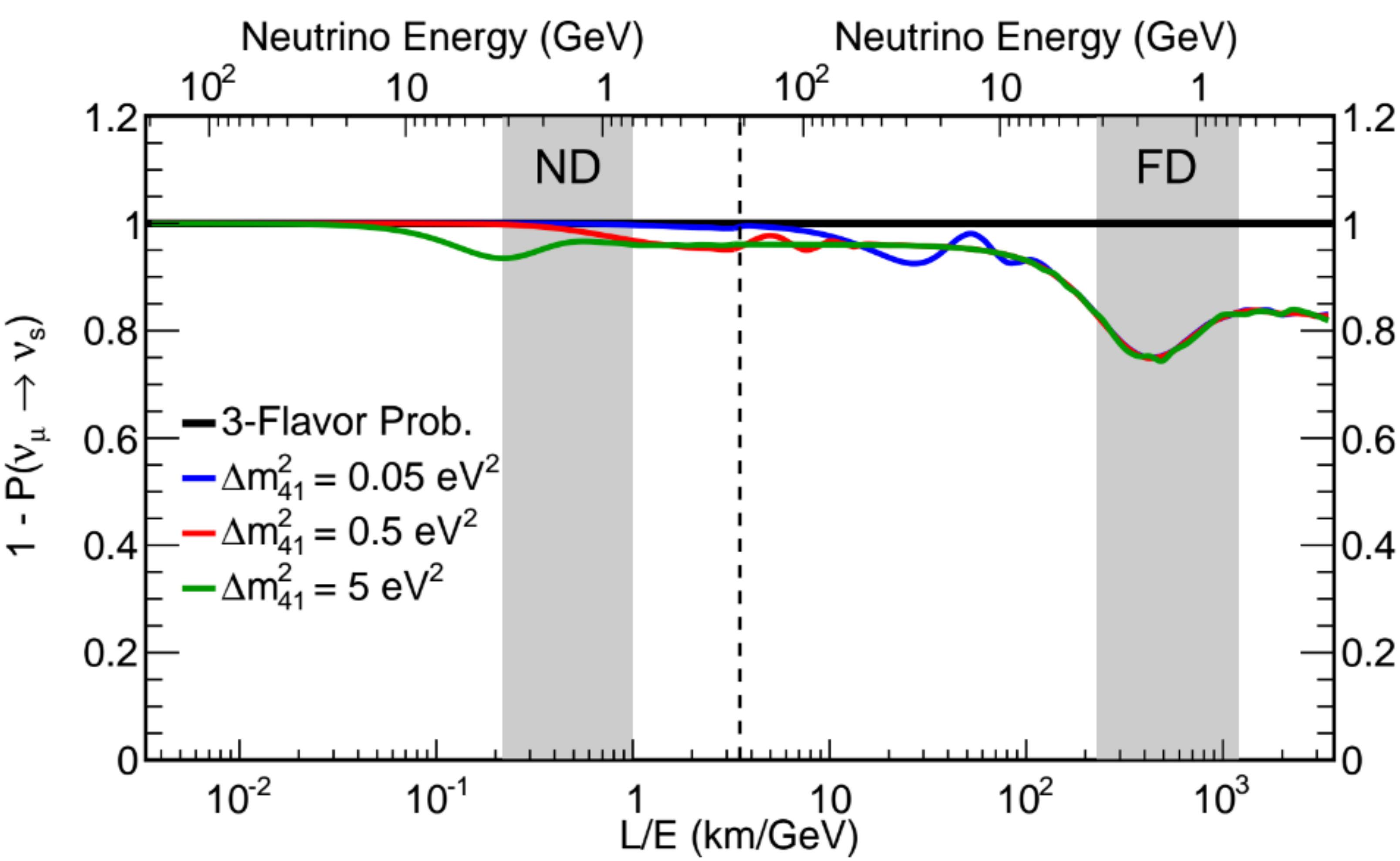


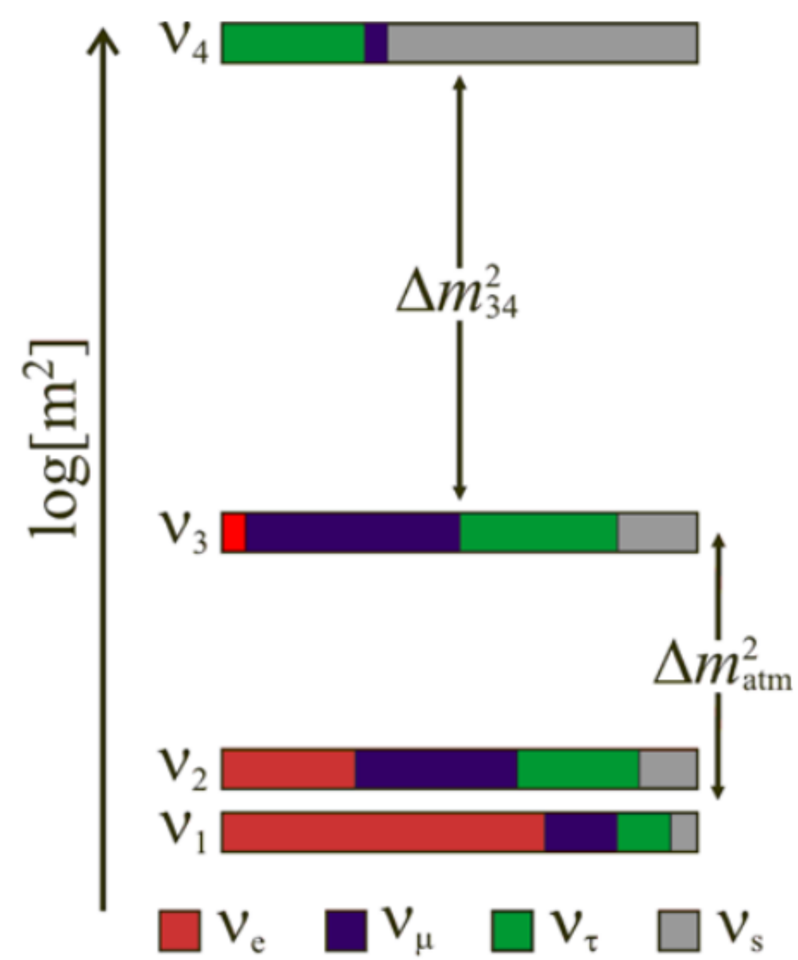
Update coming in fall 2017 with 50% more data

Neutral Current Disappearance Analysis Updated for 2017

NC Disappearance Measurement

- NC spectrum is unaffected by oscillation of active flavors
- Search for depletion of NC events in FD to interpret in a 3+1 model
- 2017 analysis updated with 50% exposure increase, simulation improvements, improvements to event selection, cosmic rejection





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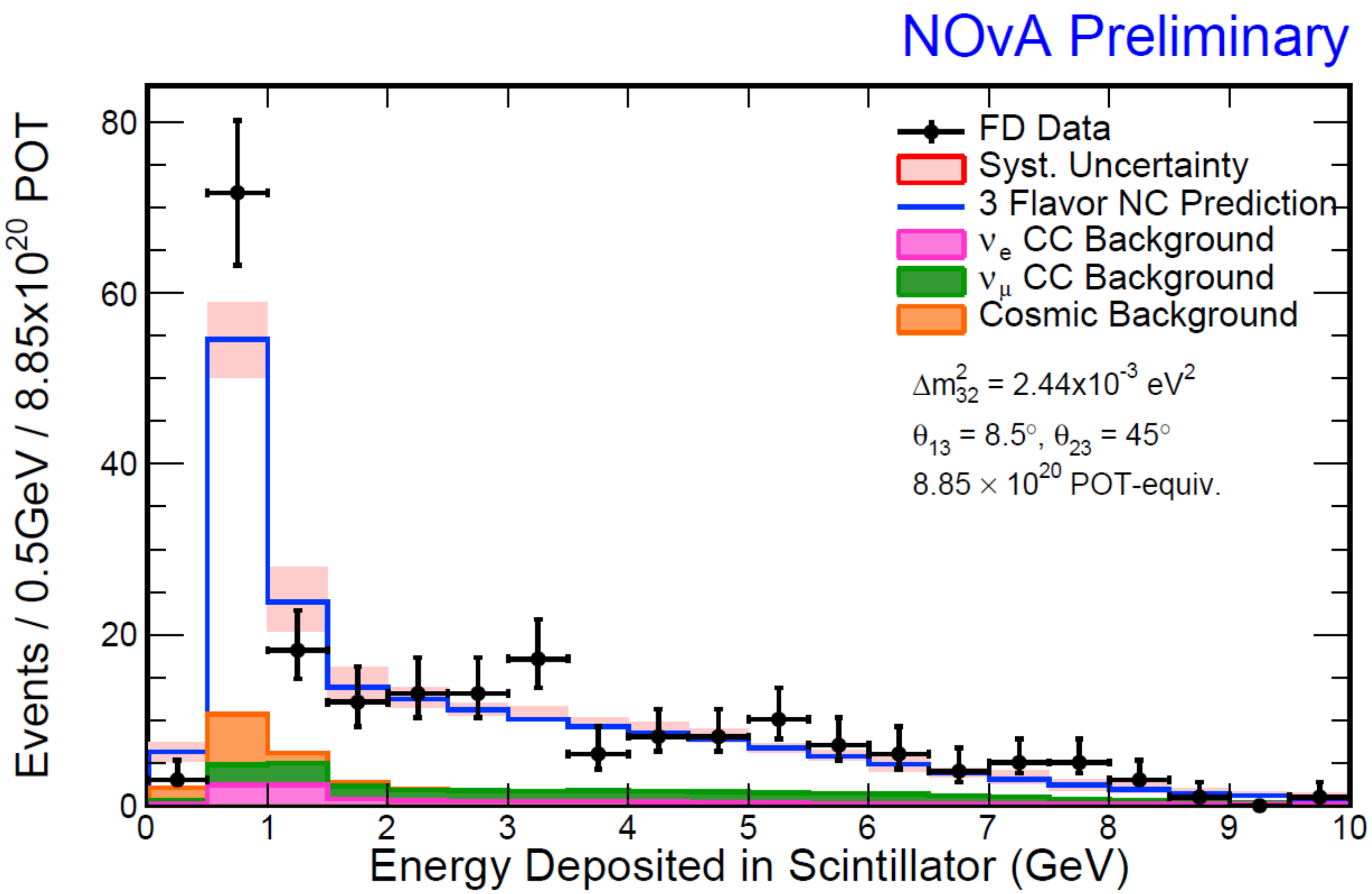
NC Disappearance Results



3 flavor prediction: 191.16 ± 13.82(stat) ± 21.99 (syst)

Measured 214 NC candidates

No evidence for a depletion of NC events

$$R_{NC} \equiv \frac{F^{\text{data}} - \sum F^{\text{pred}}(\text{bkg})}{F^{\text{pred}}(\text{NC})}$$

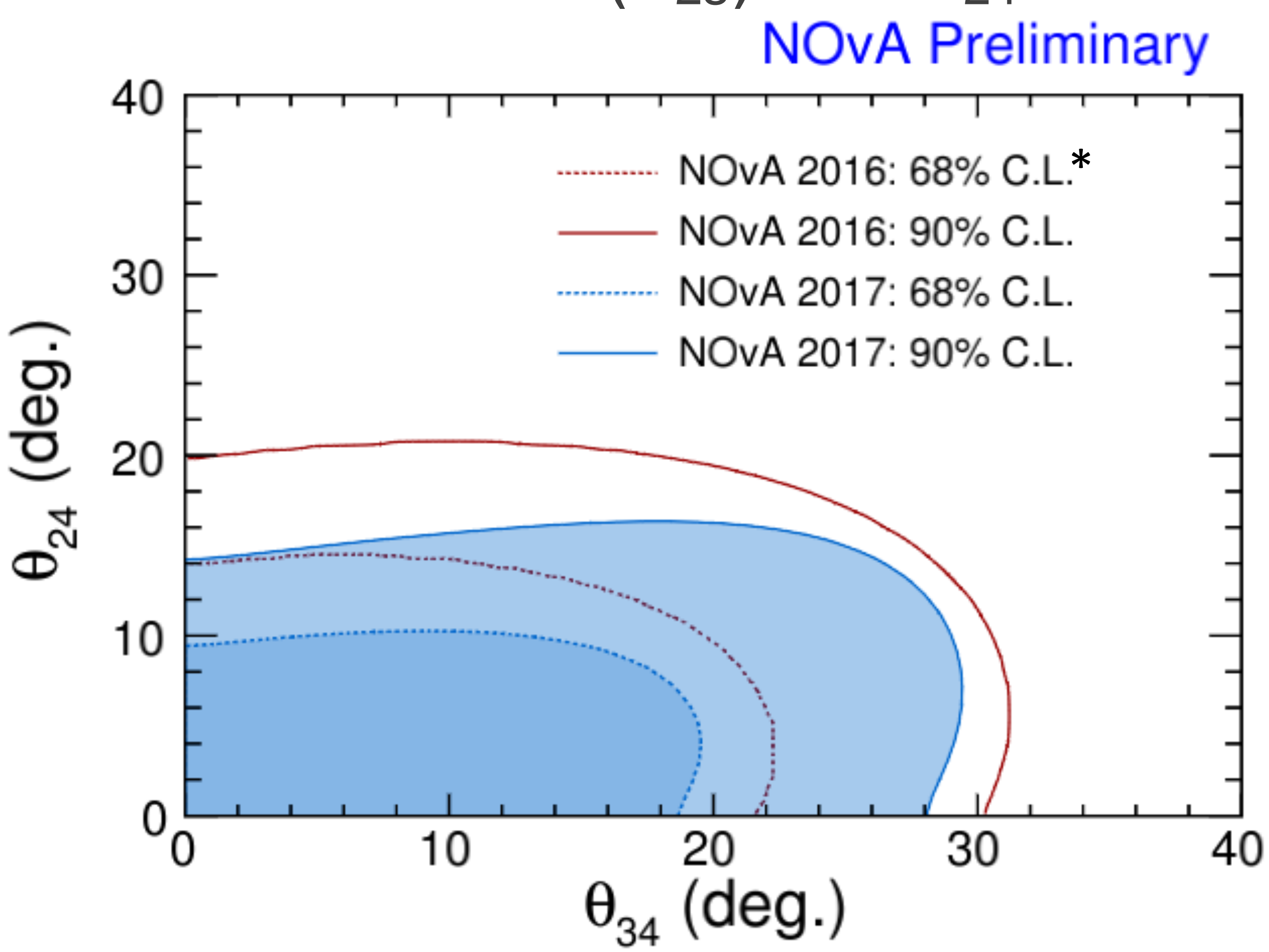
No NC disappearance → R = 1

Using **NOvA**'s two degenerate best fit points for $\sin^2(\theta_{23})$, $|\Delta m^2_{32}|$, and δ_{CP} (NH)

R-values	0 – 2.5 GeV
θ_{23} = 45 (2016)	$\mathbf{1.190} \pm 0.160\,(stat.)^{+0.080}_{-0.130}\,(syst.)$
θ_{23} = 45 (2017)	$\mathbf{1.190} \pm 0.123\,(stat.)^{+0.143}_{-0.124}\,(syst.)$
$\theta_{23} < 45$	$\mathbf{1.179} \pm 0.123\,(stat.)^{+0.142}_{-0.124}\,(syst.)$
$\theta_{23} > 45$	$\mathbf{1.176} \pm 0.123\,(stat.)^{+0.142}_{-0.124}\,(syst.)$

NC Disappearance Results

- Shape-based fit of θ_{24} and θ_{34}, no FC corrections
- Constrain with NOvA's degenerate best fit points for $\sin^2(\theta_{23})$,$|\Delta m^2_{32}|$, and δ_{CP} (NH)
- Profile over $\sin^2(\theta_{23})$ and δ_{24}



	θ_{24}	θ_{34}	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
NOvA 2016	20.8°	31.2°	0.126	0.268
NOvA 2017	16.2°	29.8°	0.078	0.228
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

In a 3+1 analysis, for Δm^2_{41} = 0.5 eV^2:

θ_{24} < 16.2 at 90% C.L.

θ_{34} < 29.8 at 90% C.L.

* 2016 fit is rate only and applies maximal mixing constraint

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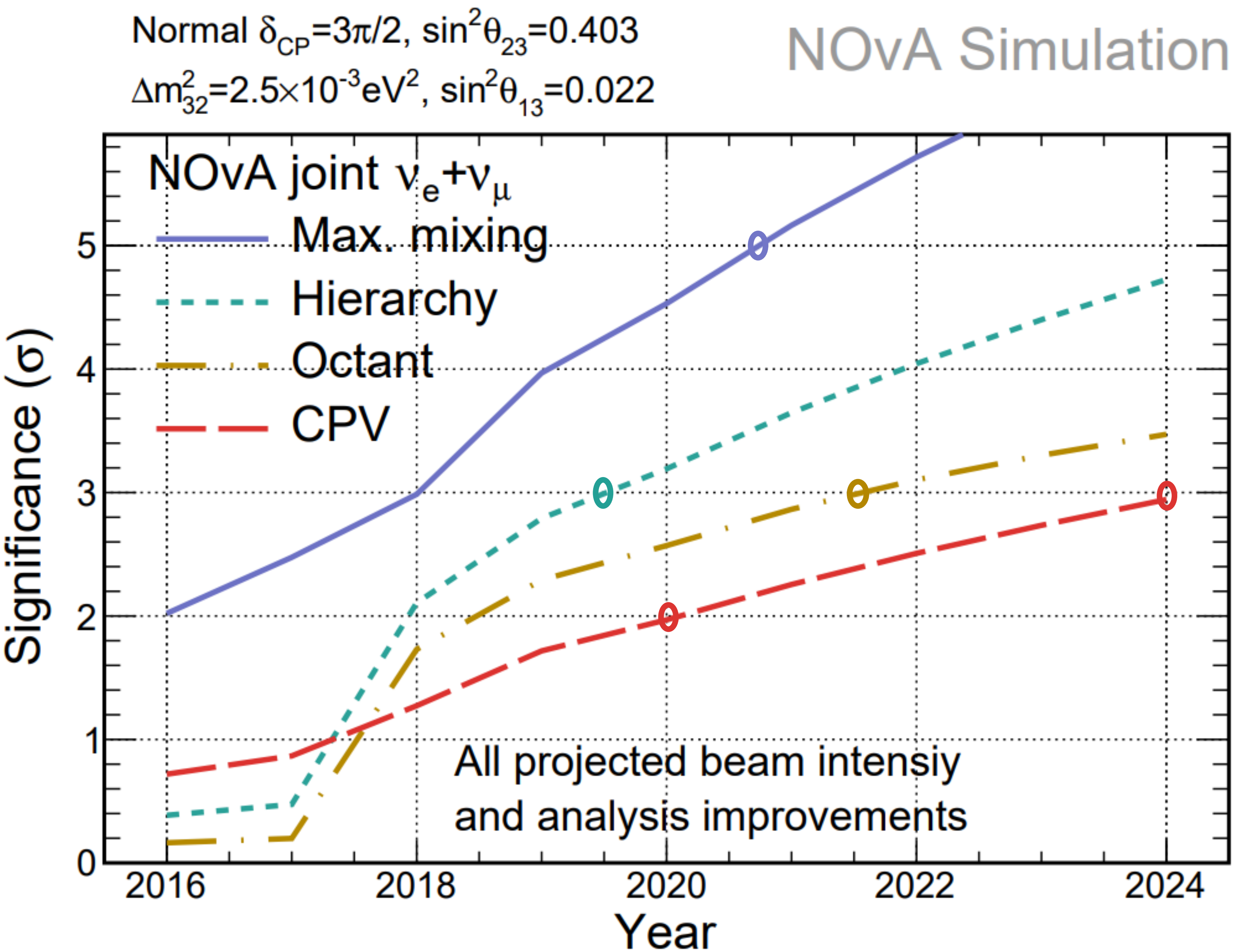
Looking Forward

- Switched to anti-neutrino running in February 2017
- Run 50% neutrino, 50% anti-neutrino after 2018



- improved systematics
- 25% exposure increase from analysis improvements
- 40 weeks of beam starting 2018
- 800 kW in 2019, 900 kW in 2021

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Conclusions

- A broad program of NOvA physics
- Best fit to ν_μ disappearance data disfavors maximal mixing at 2.6σ
- Joint fit of NOvA appearance and disappearance data
  - Weak preference for normal hierarchy
  - Inverted hierarchy, lower octant is excluded at > 93% C.L.
- Updated NC disappearance analysis with 8.85×10^{20} POT sees no evidence for sterile neutrino mixing
- Updated ν_μ disappearance and ν_e appearance with 8.85×10^{20} POT coming this fall
- Anti-neutrino running underway with results in summer 2018

Questions

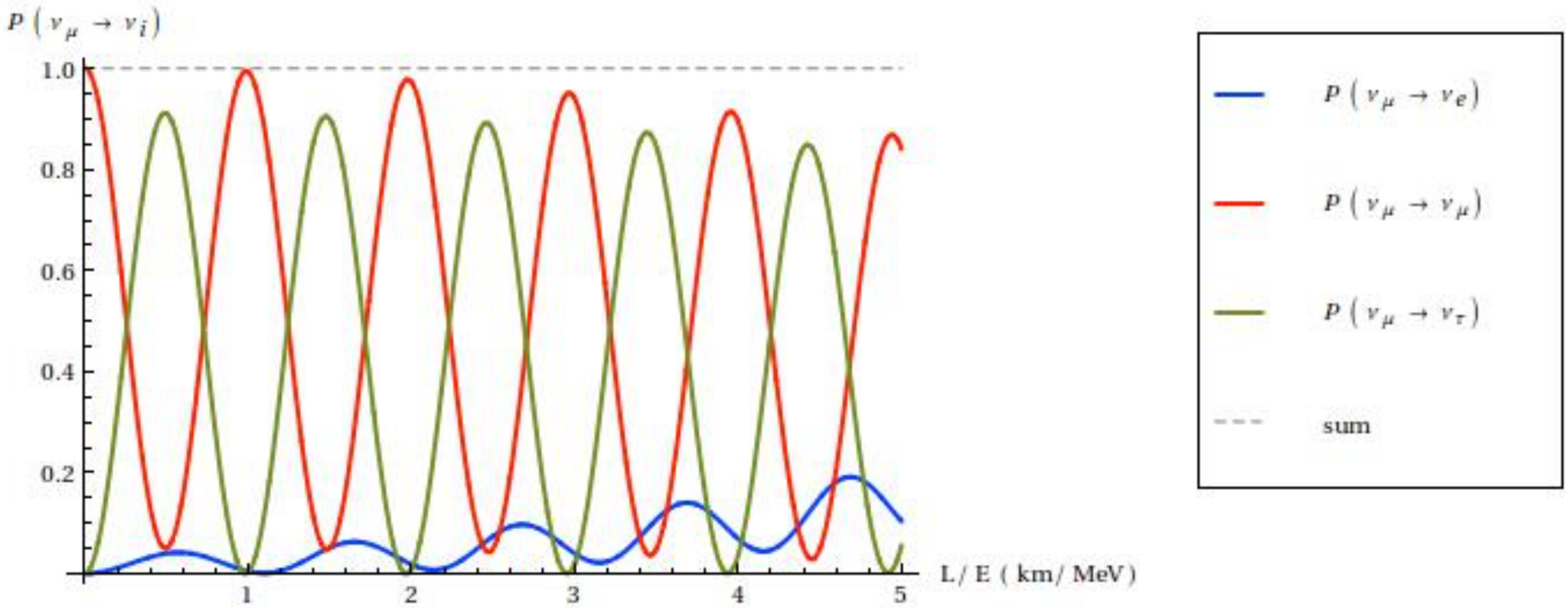

Image from: http://invisibles.eu/outreach/entry/ceaseless-transformation-three-neutrinos

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{vmatrix}\Bigg\rangle = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{vmatrix}\Bigg\rangle$$

$\nu_\mu \longrightarrow \nu_\mu$	$\nu_e \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_\tau$	$\nu_\mu \longrightarrow \nu_e$	$\nu_e \rightarrow \nu_\mu + \nu_\tau$
atmospheric and long-baseline	reactor and long-baseline	solar and reactor

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$\nu_\mu \rightarrow \nu_e$ Appearance channel

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \to \nu_e) \approx \left|\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}\right|^2$$

$$= P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta)$$

$$\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

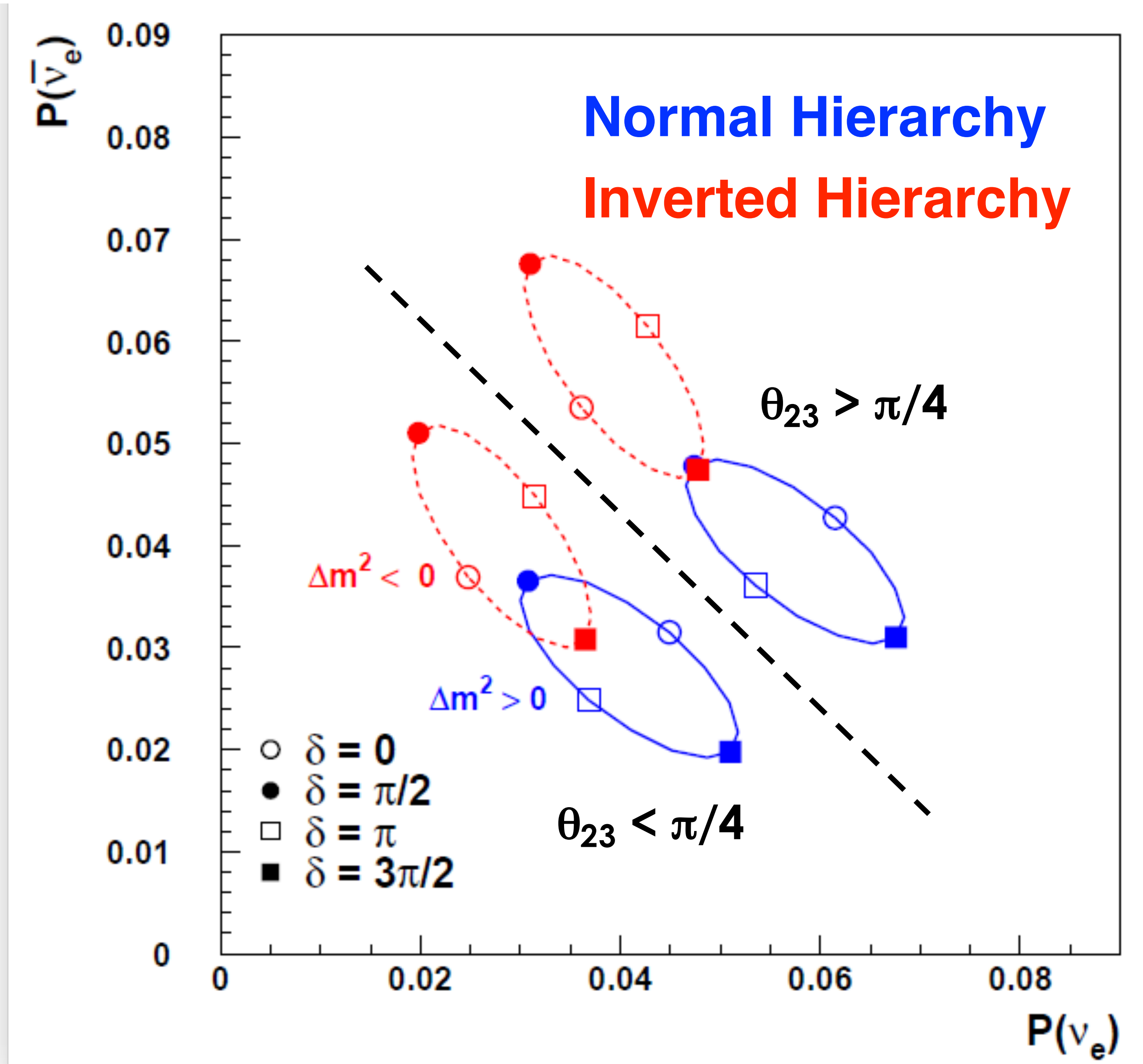
Depends on relative sign of "a" and Δ_{31}

$$\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}$$

$$a = \frac{G_F N_e}{\sqrt{2}} \approx \frac{1}{3500km}$$

aL=0.08 for L=295km T2K baseline
aL=0.23 for L=810km NOvA baseline

Oscillation probability is sensitive to: mass ordering, CP violating phase, and θ_{23} octant.



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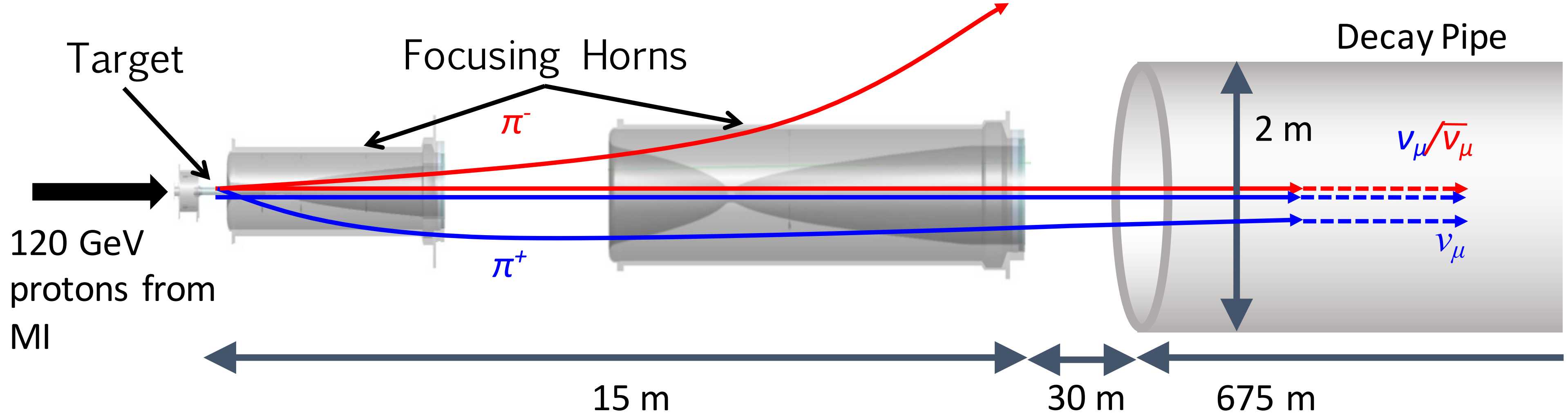
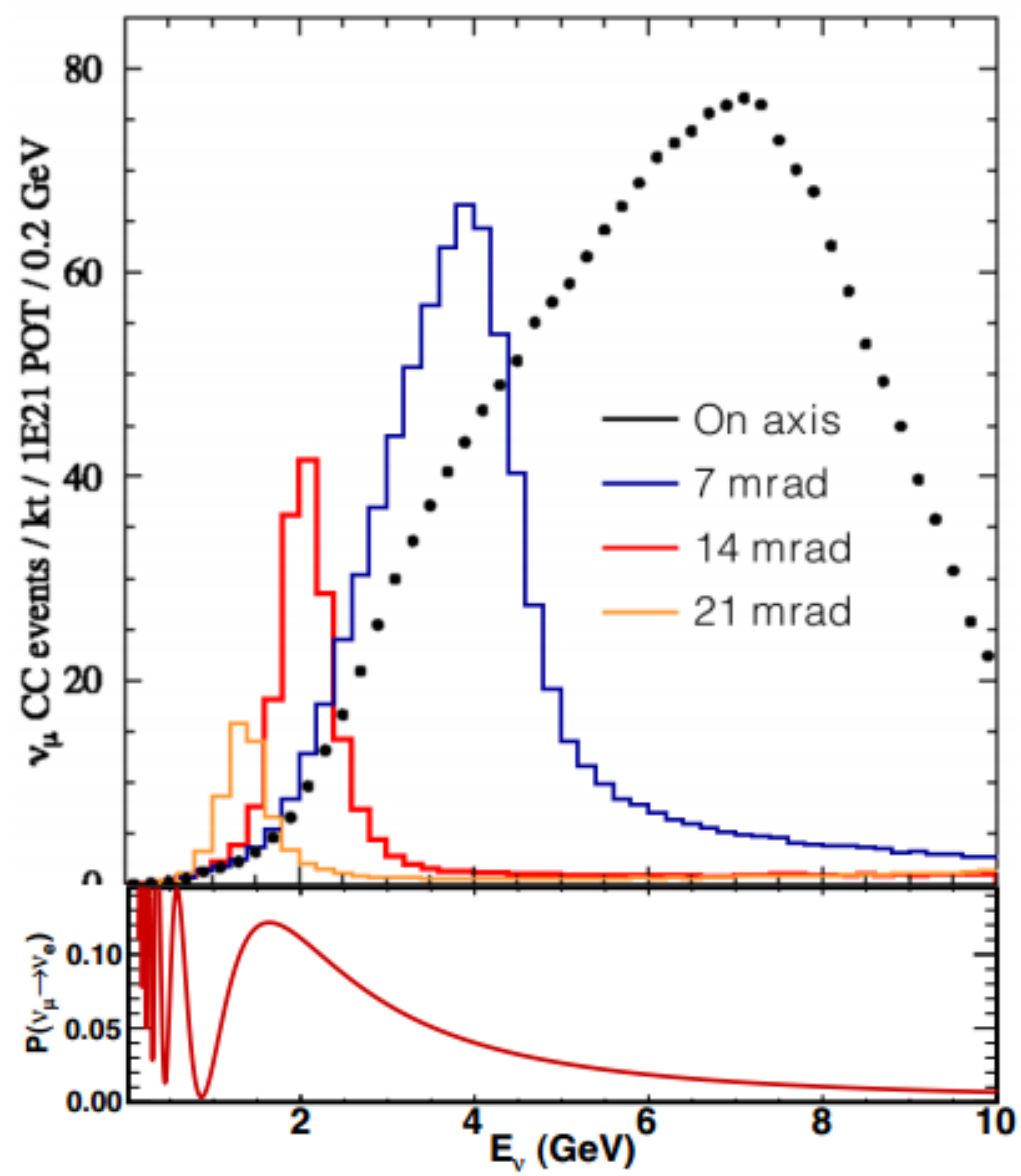
NuMI Beam



- 120 GeV protons extracted from the Main Injector at Fermilab in 10 μs spills
- Magnetic focusing horns allow selection of charge sign for selecting a neutrino or anti-neutrino beam
- 14.6 milli-radians off-axis, narrow beam around oscillation maximum
- Beam 97.5% ν_μ with 0.7% ν_e and 1.8% wrong-sign contamination



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Looking Forward

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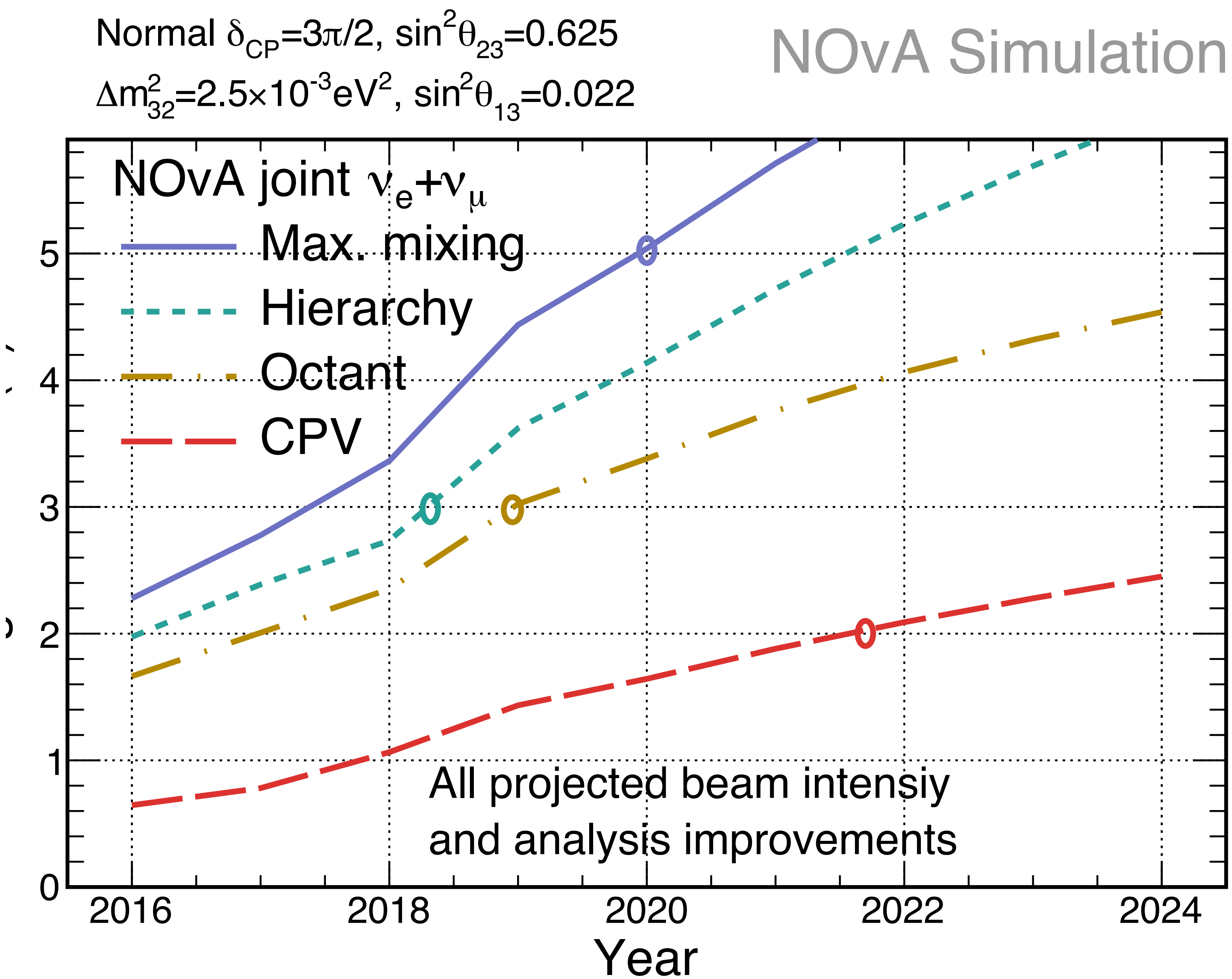
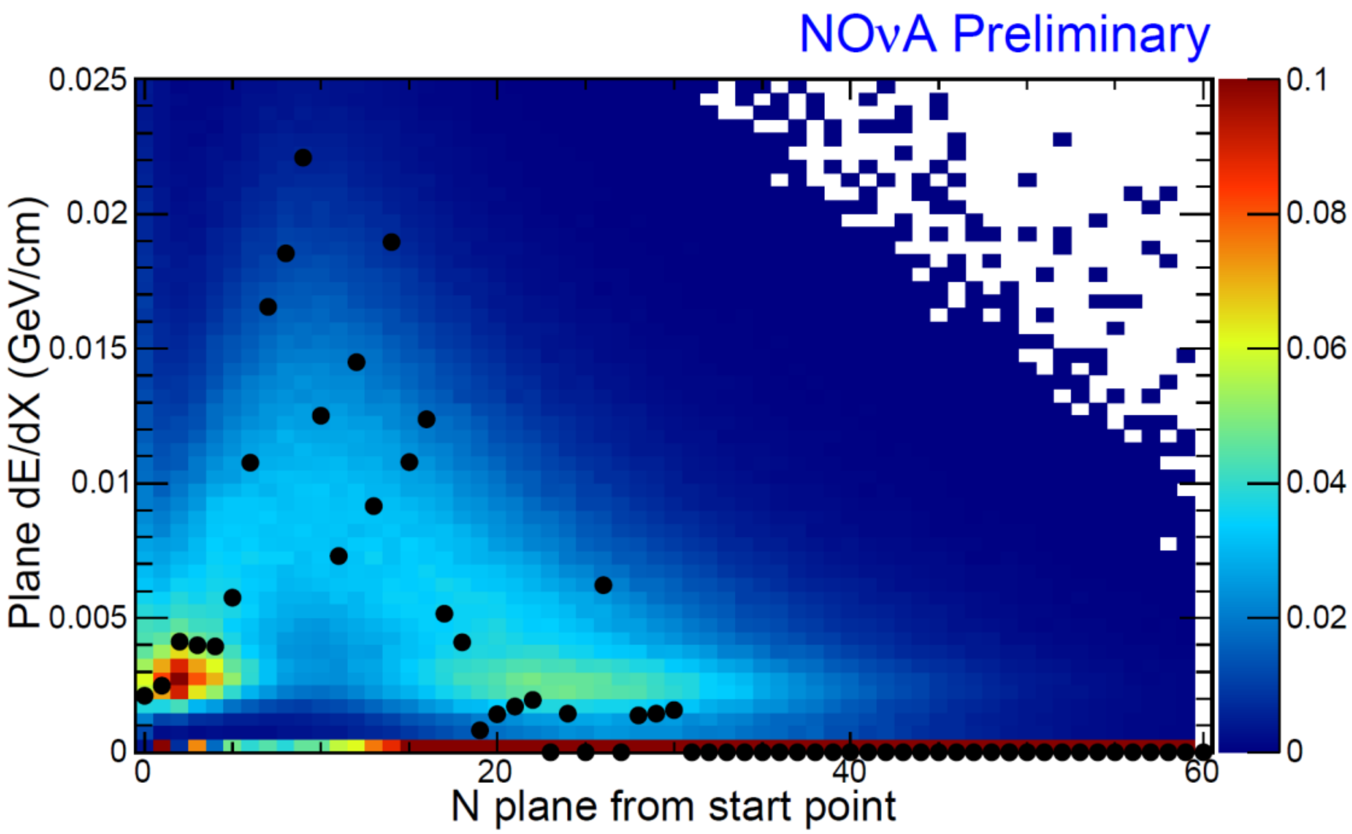
- Run 50% neutrino, 50% anti-neutrino after 2018

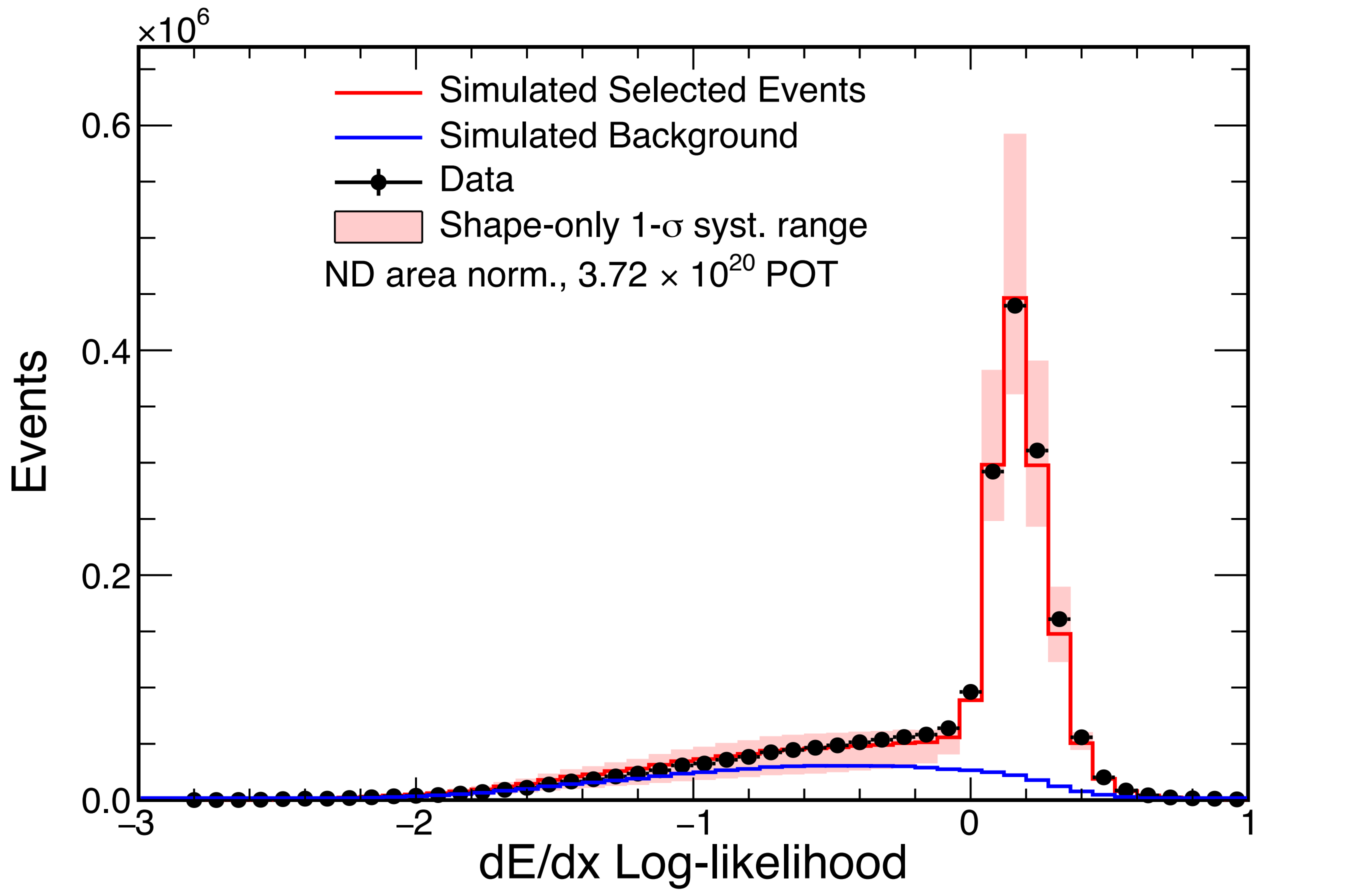


- improved systematics
- 25% exposure increase from analysis improvements
- 40 weeks of beam starting 2018
- 800 kW in 2019, 900 kW in 2021

Event Classification before Deep Learning

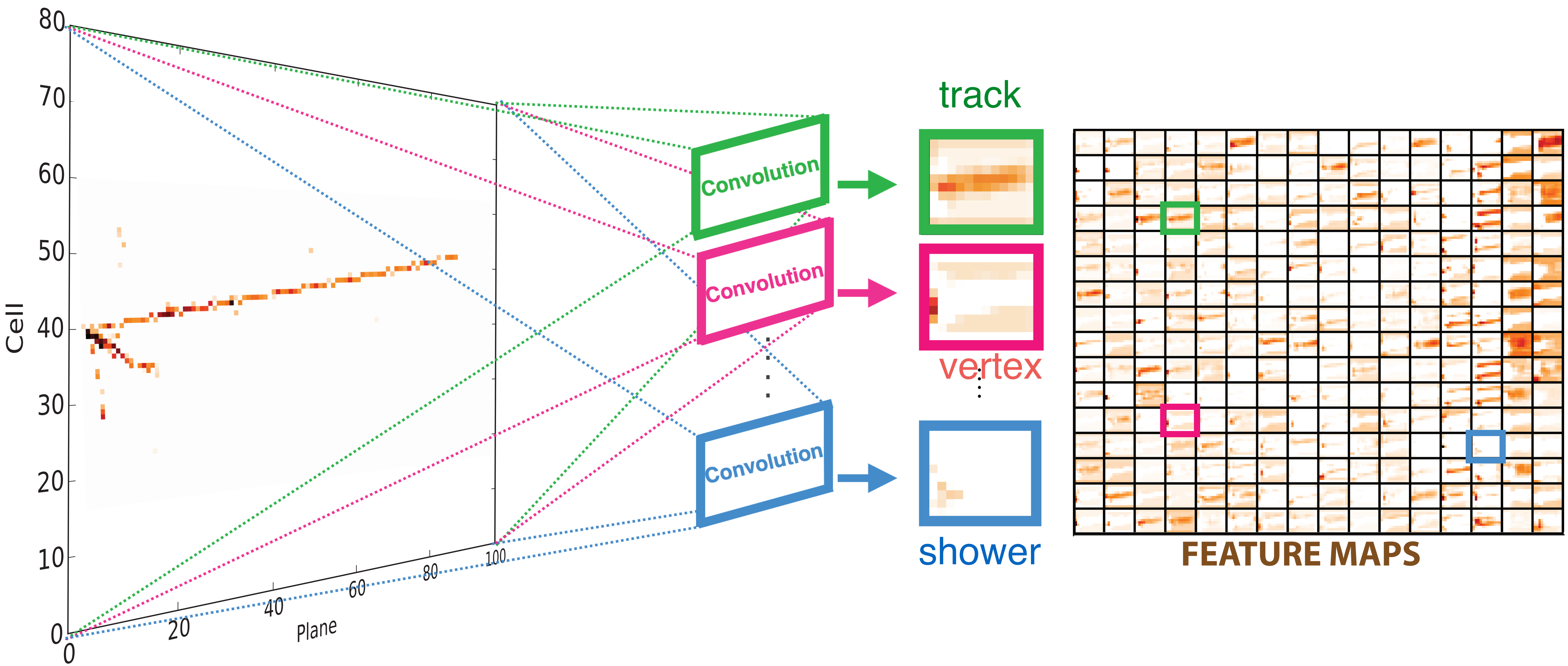
- Likelihood Identifier (LID)
  - Compare longitudinal and transverse dE/dx in leading shower to templates for different particle hypotheses
  - Build neural net from these inputs and reconstructed quantities.
  - Identifies electron neutrinos
- ReMID
  - Build a KNN classifier from four reconstructed quantities related to muons (length, dE/dx, scattering)
  - Identifies muon neutrinos





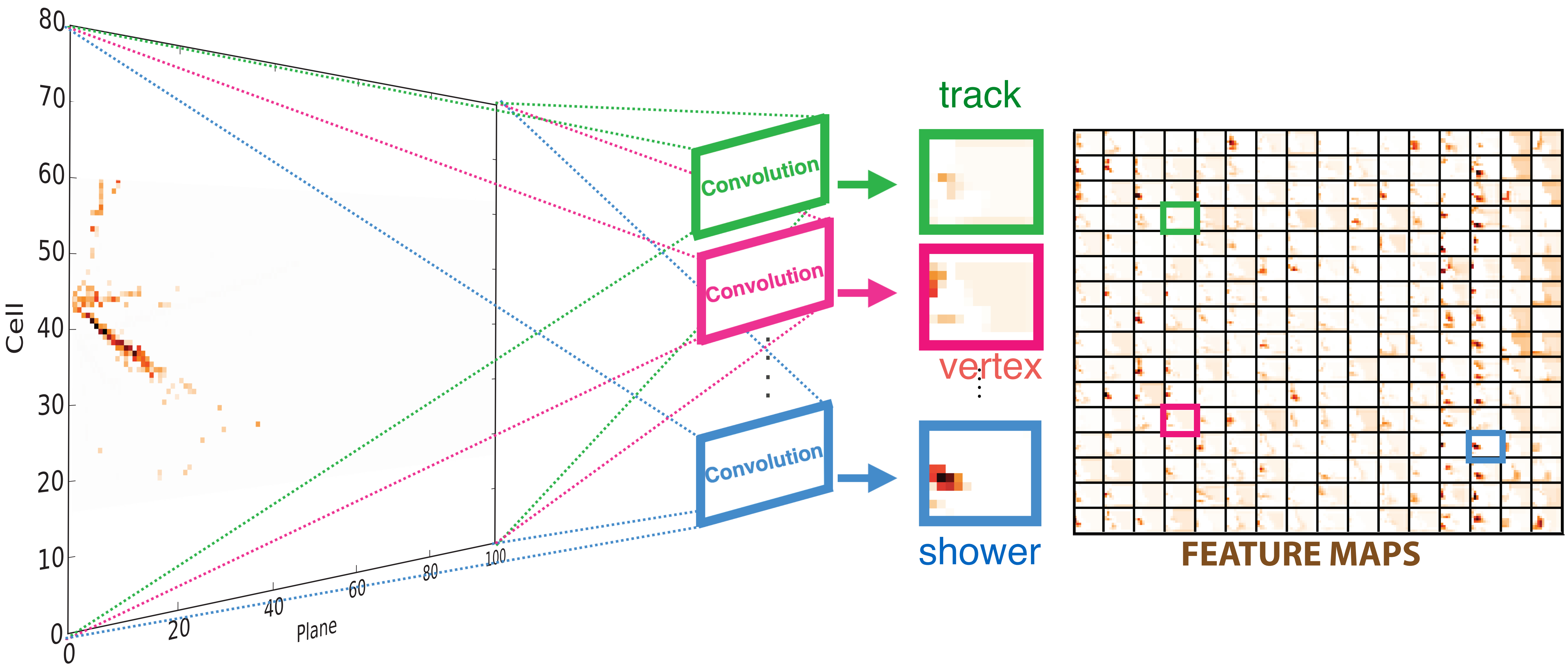
Convolutional Visual Network (CVN) Selection

- Showing a muon neutrino interaction and the first layer of feature maps extracted from the convolutional kernels



Convolutional Visual Network (CVN) Selection

- Showing a electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
- The strong features extracted are the shower as opposed to the muon track



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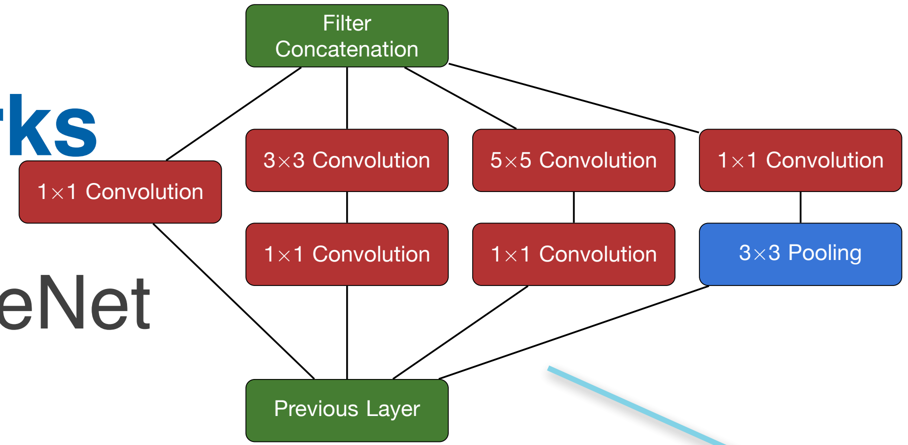
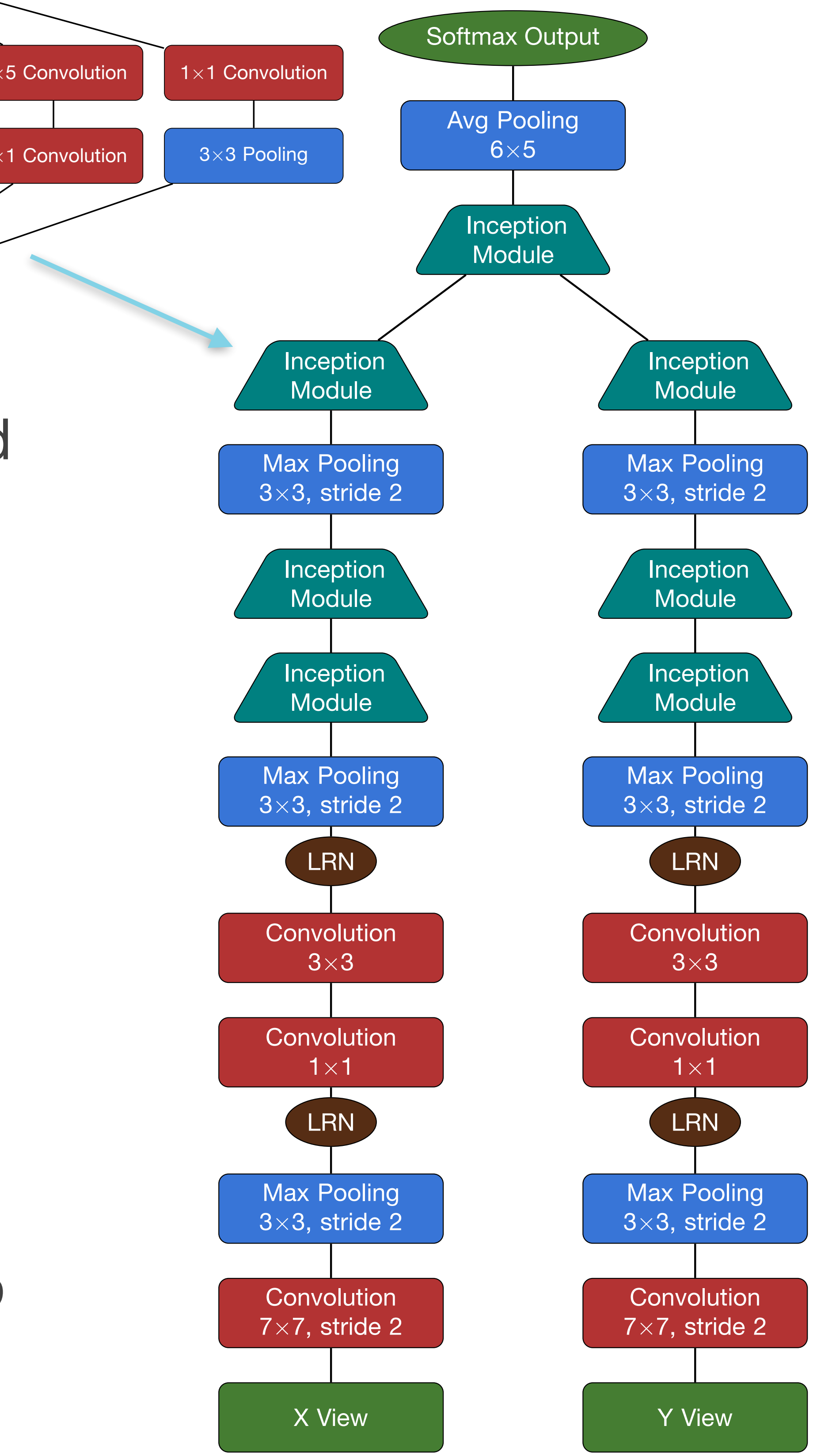
Convolutional Neural Networks





- Architecture adapted from GoogLeNet
  - C. Szegedy et al., arXiv:1409.4842
  - Input is 80 cell x 200 plane detector pixel map
  - Each event view processed separately and then merged

- Network implemented and trained in the Caffe Framework (Y. Jia et al., arXiv:1408.5093)
- Trained on 4.7 million simulated events on Fermilab GPU cluster

- Output classifies neutrino interaction type (ν_μ,ν_τ,ν_e,NC)
- Used in appearance analysis.
  - Performance gain over previous classifiers equivalent to adding 30% more detector mass

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

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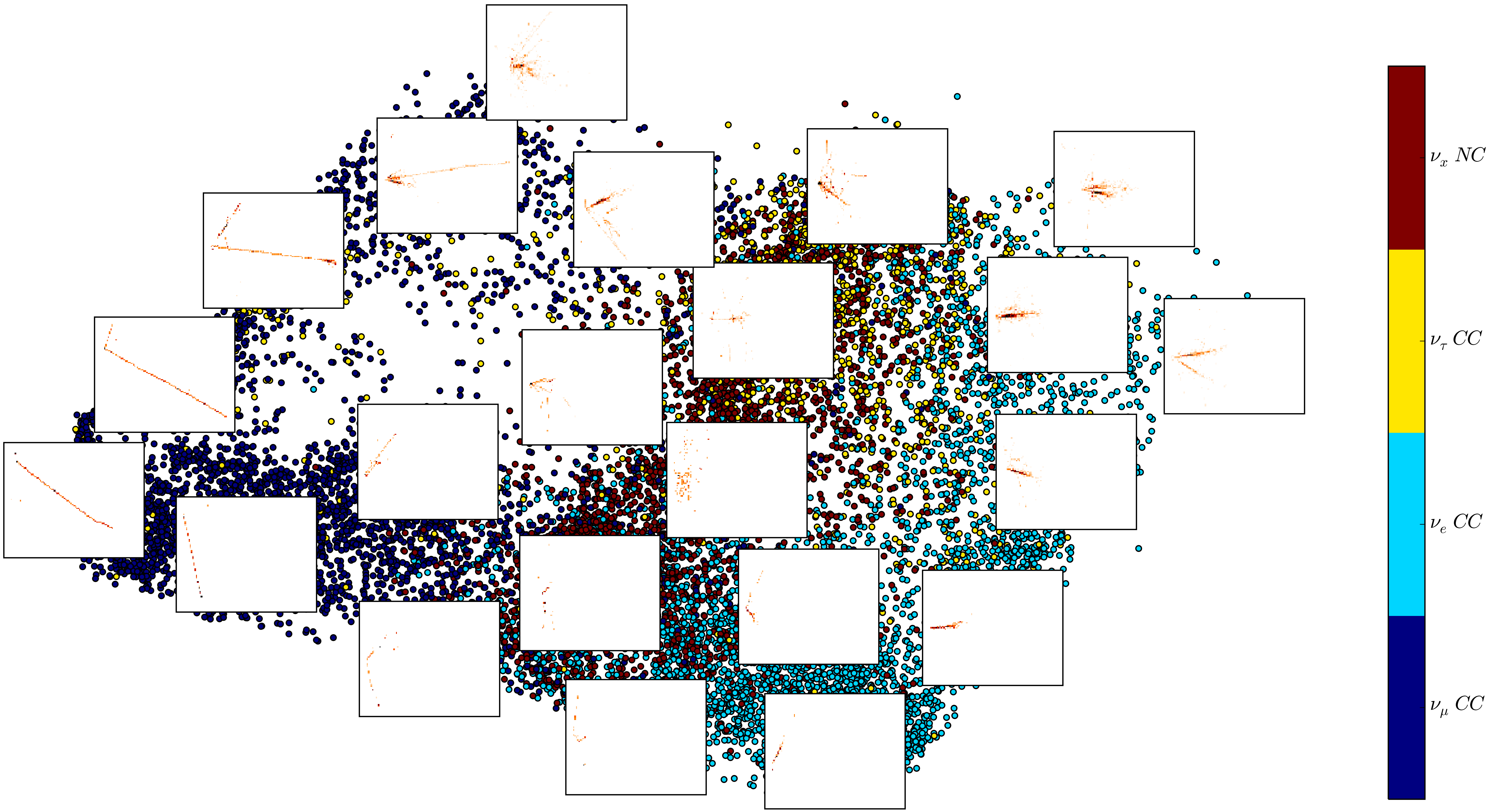
t-SNE representation of CVN classification. Truth labels shown for the training sample.



t-SNE representation of CVN classification. Truth labels shown for the training sample.

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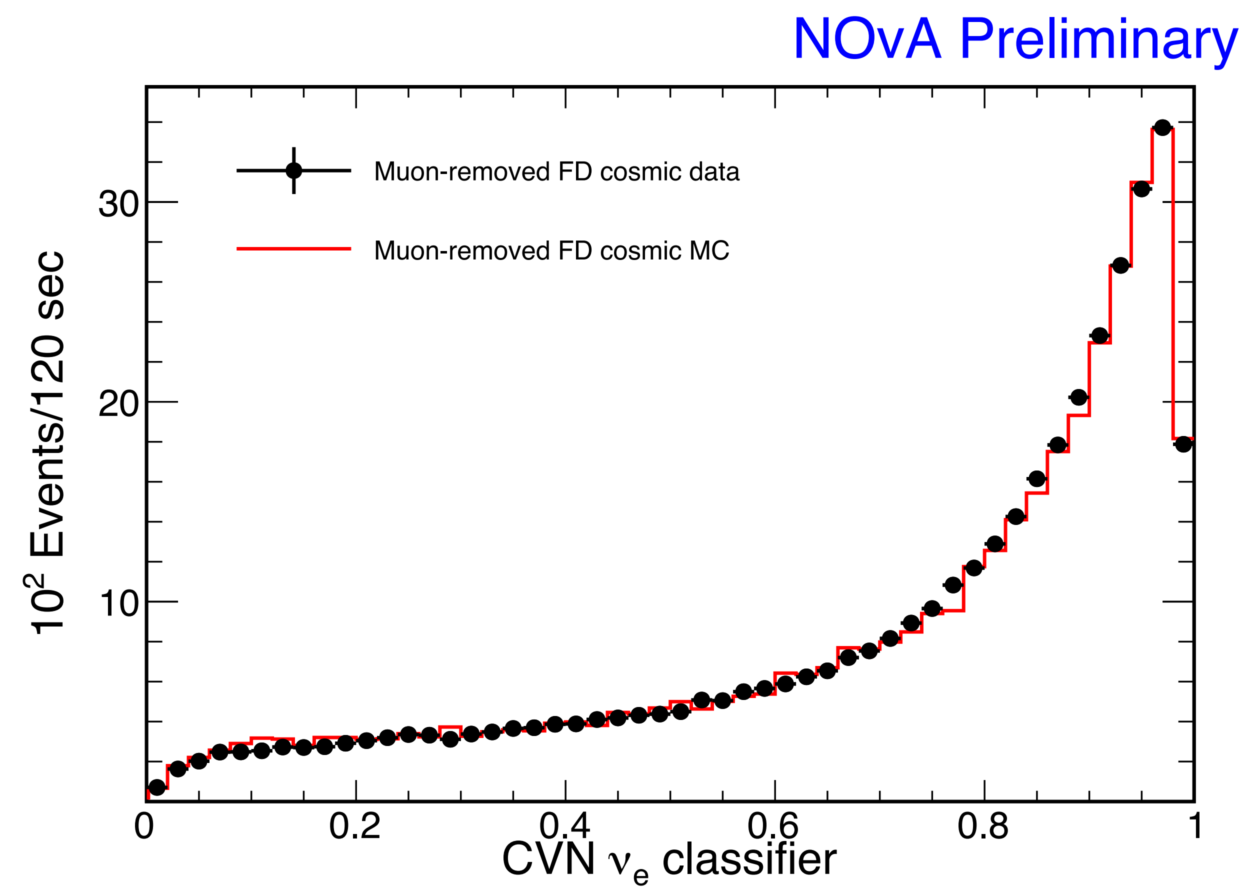
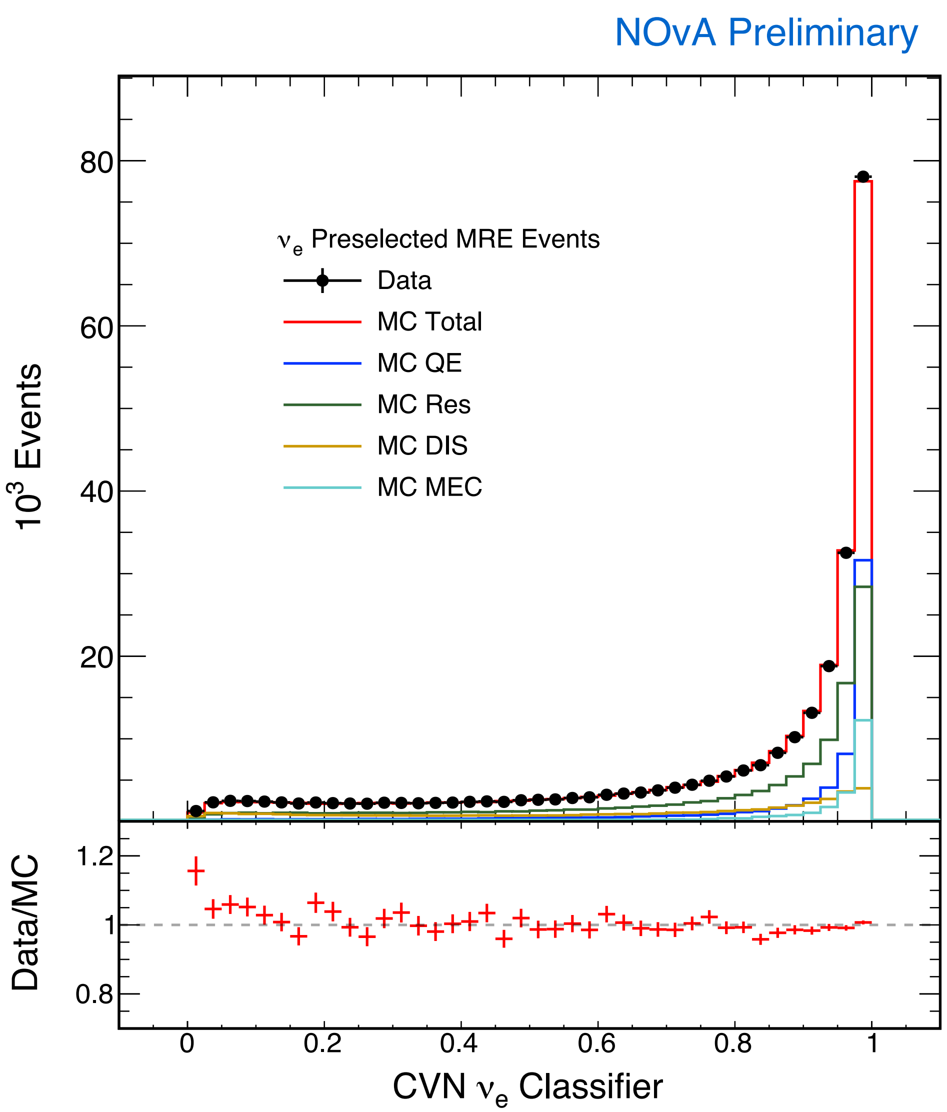
Evaluating Signal Efficiency

- Remove cosmic ray muon from FD events in data and simulation
- Apply selection to remaining bremstrahlung shower to benchmark simulation of electron selection



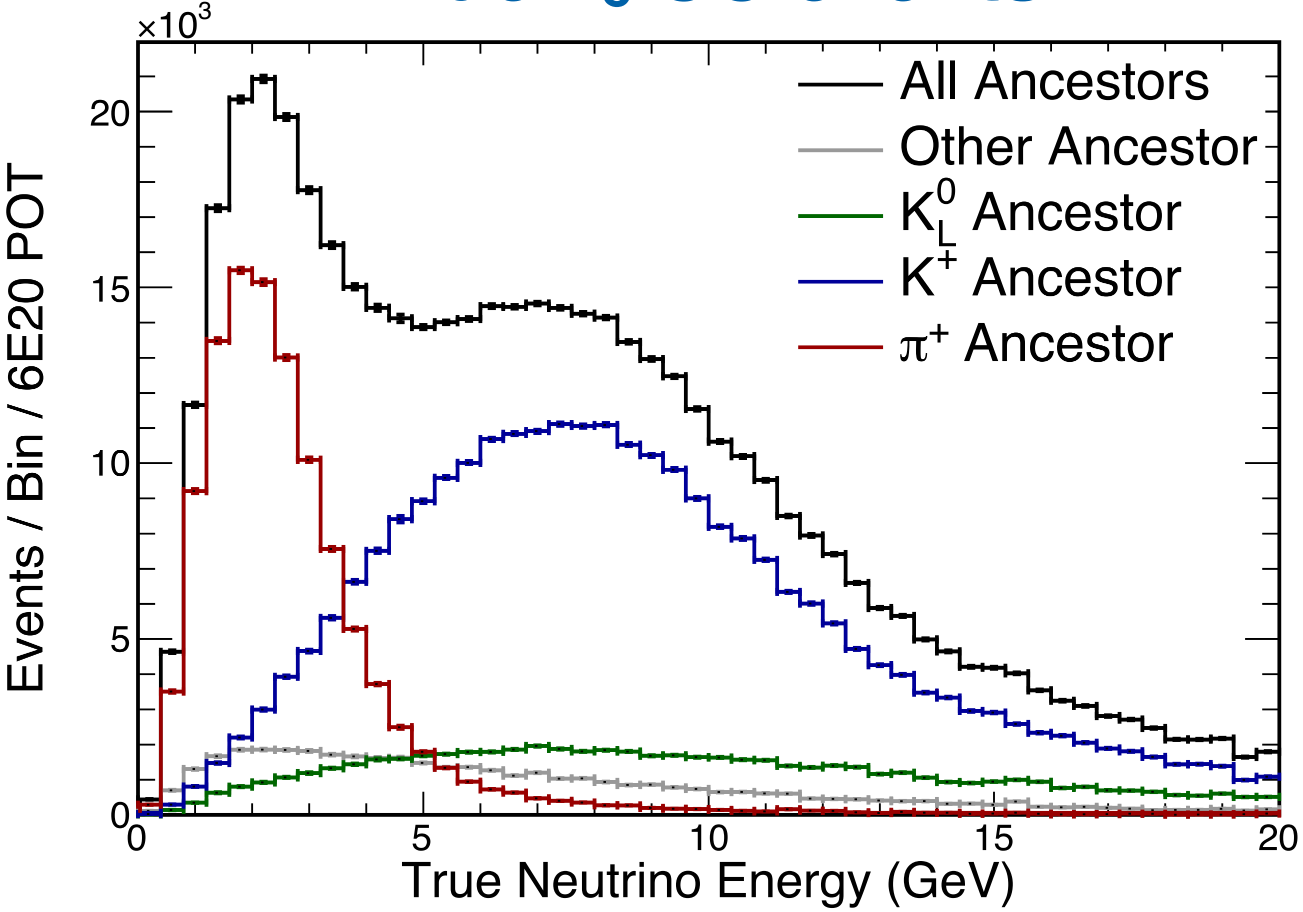


- EM showers should be well modeled, check if selection efficiency differences come from hadronic side
- Remove reconstructed muons from selected ν_μ events, replace with simulated electron (MRE)
  - better than 1% agreement between efficiency for selecting data MRE events and efficiency for selecting MC MRE events

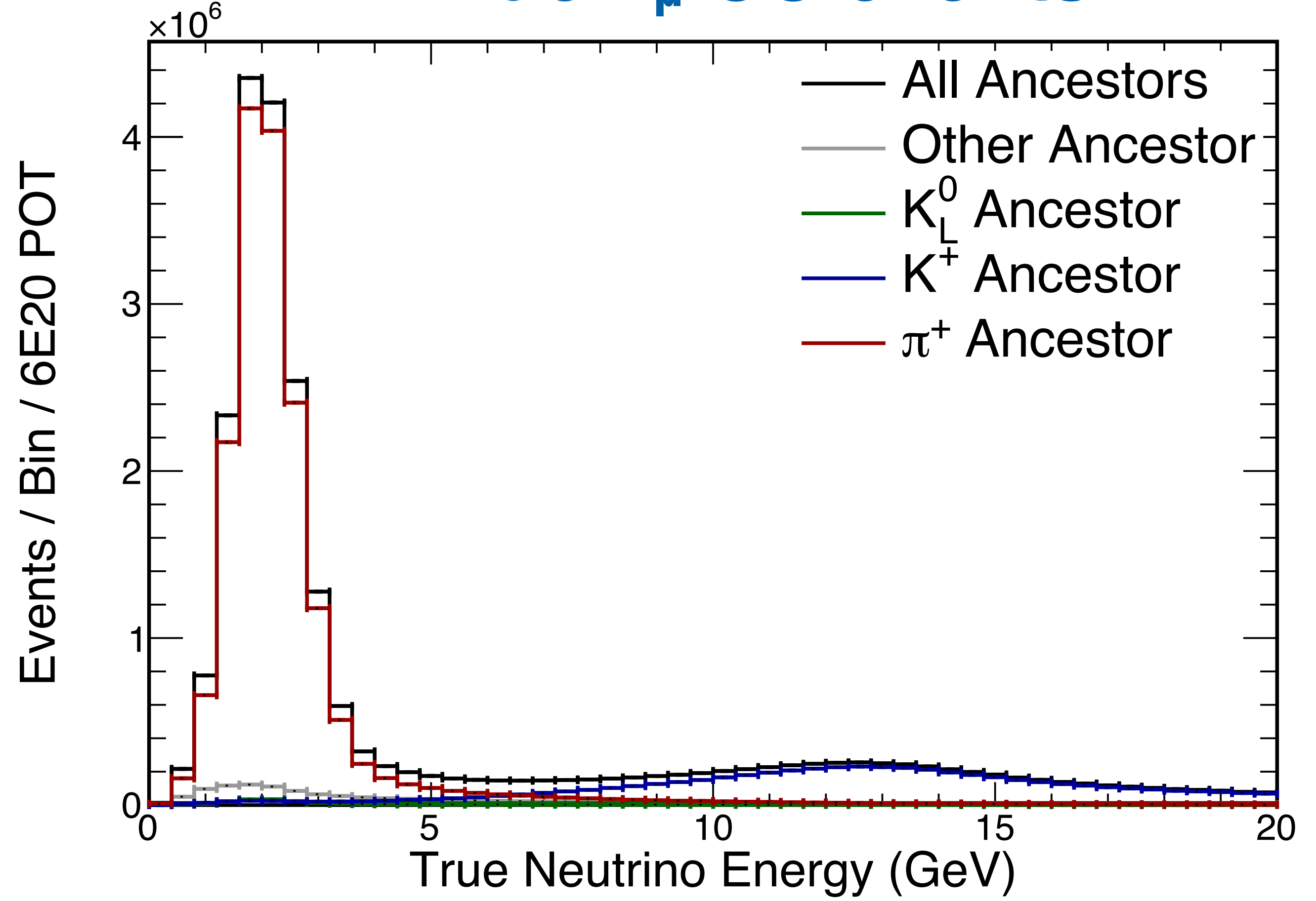
ND Data Decomposition: Beam ν_e CC

- Low energy ν_μ and ν_e trace back to the same π ancestors
- Use ν_μ at lower energy to reweight decaying pions in (pT , pz) space
- Decreases ν_e with π+ parent 3-4%
- Weight ν_e with K+ parents up 17% based on ν_μ high-E tail
- Overall effect is 1% increase in 1-3 GeV range in intrinsic beam ν_e CC events

True ν_e CC events



True ν_μ CC events



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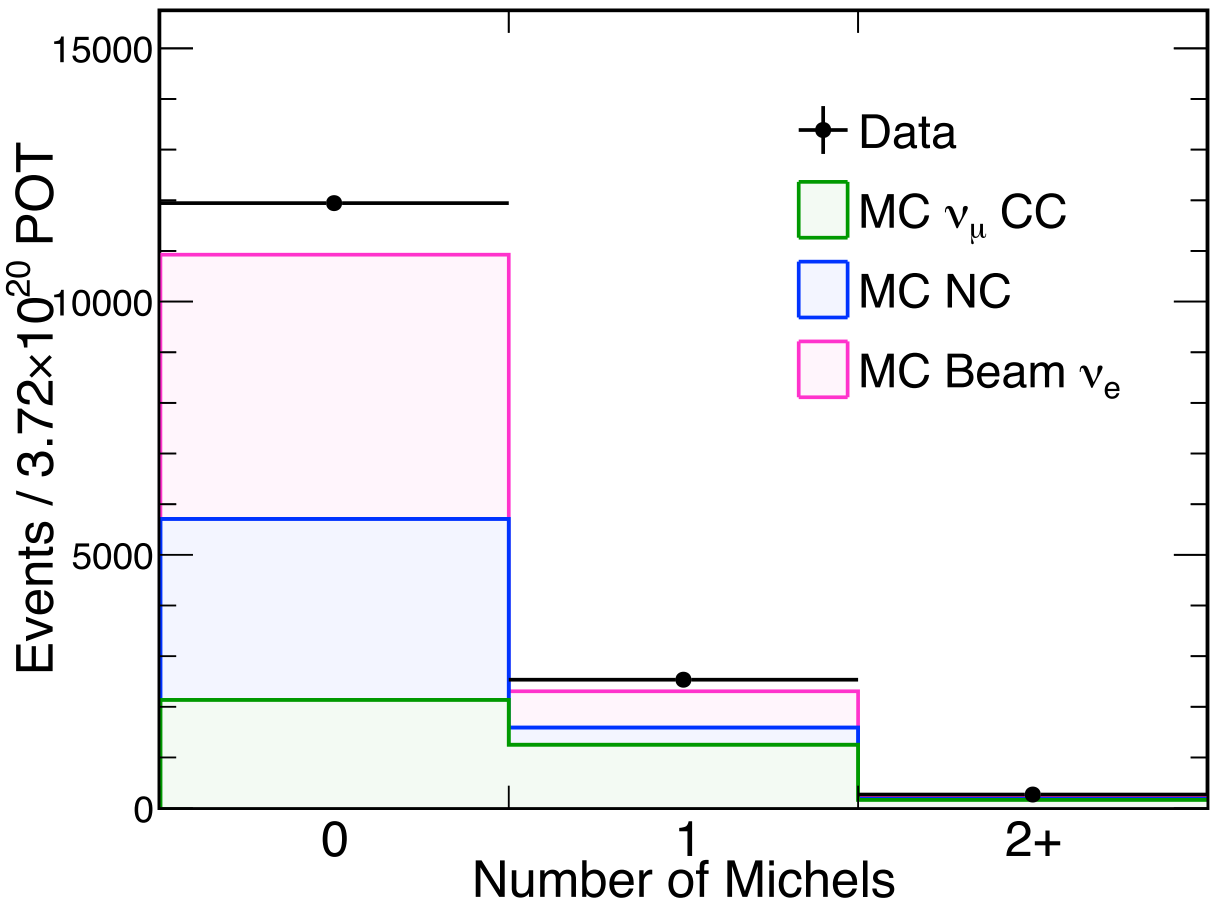
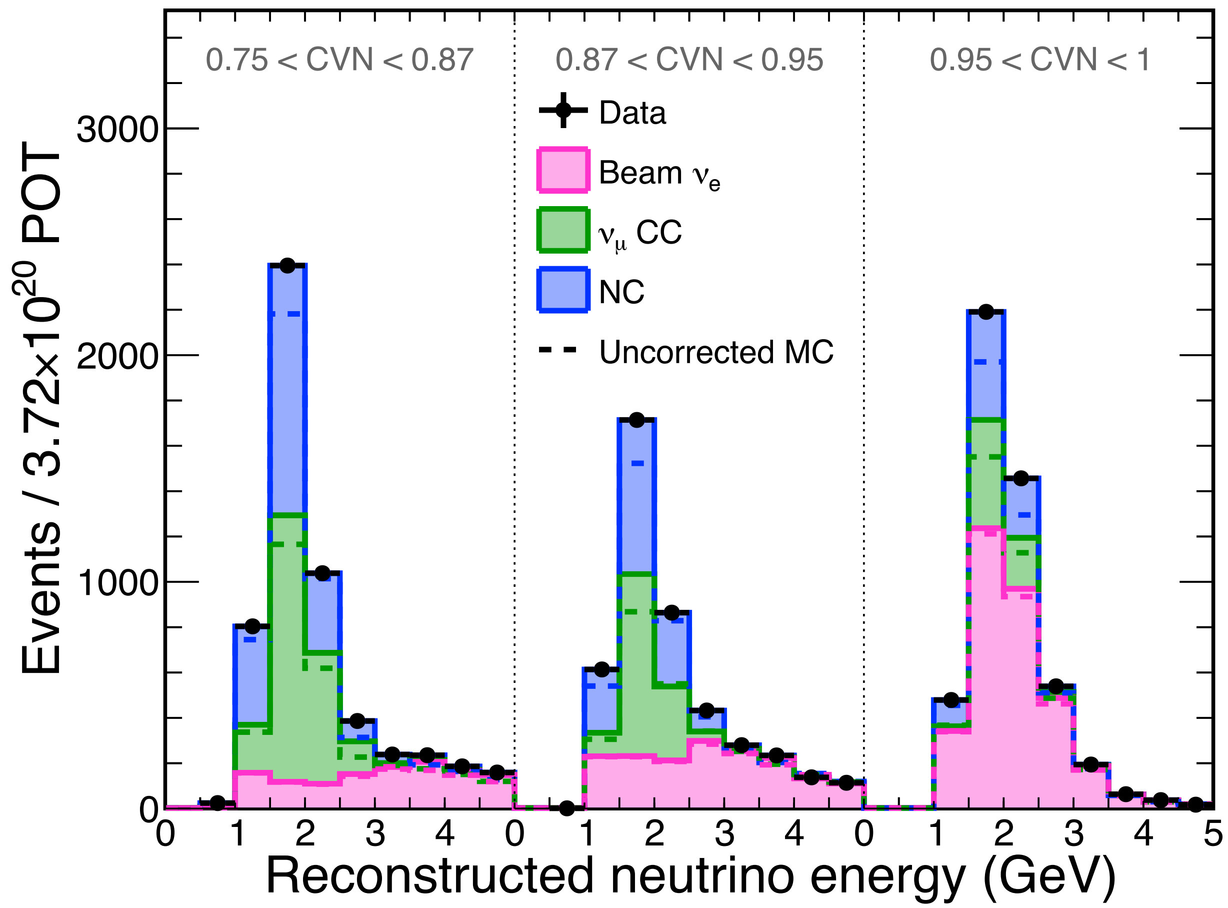
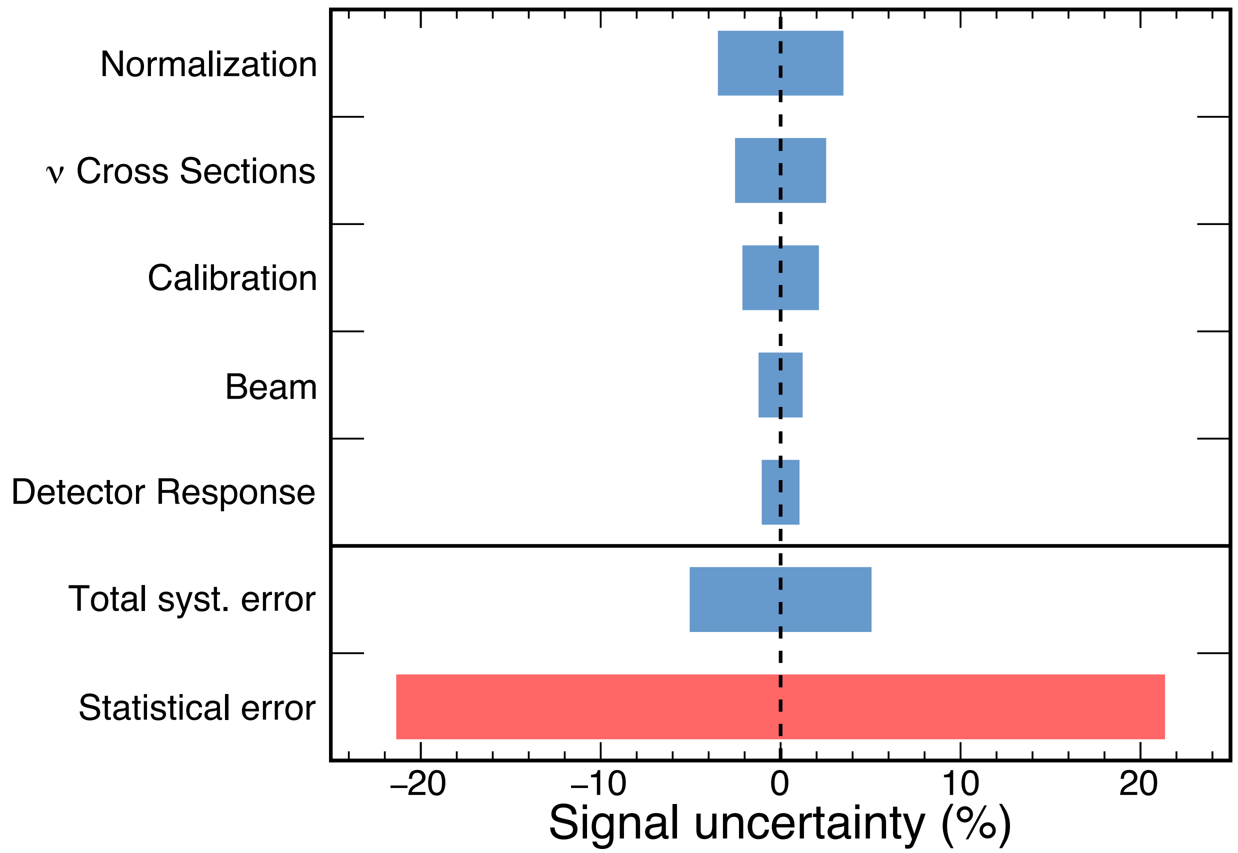
ND Data Decomposition: Michel Electrons

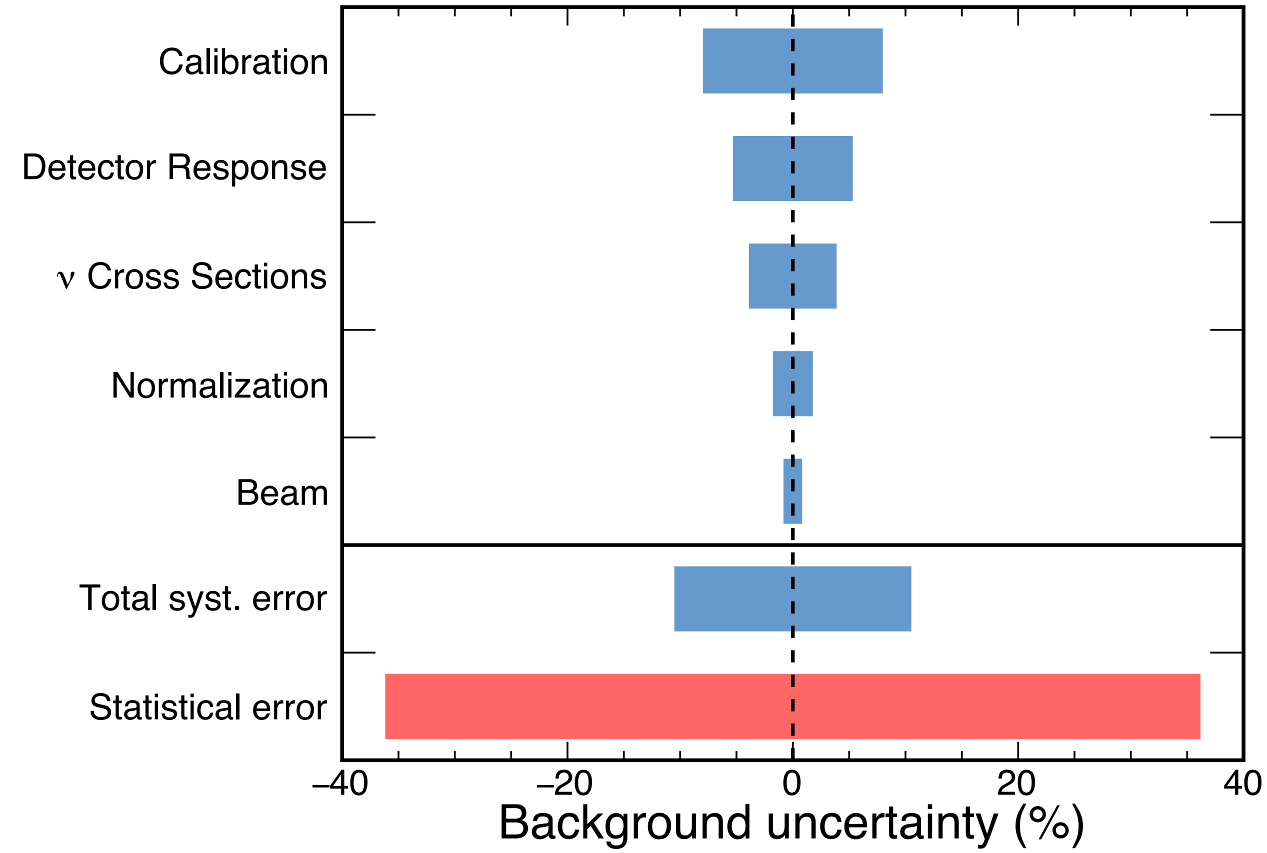




- ν_μ CC events contain Michel electron from muon decay
- ~1 more Michel in ν_μ events then ν_e or NC
- Fit observed number of Michels in each bin of energy and PID by adjusting ν_μ/NC ratio
- Data excess assigned between NC (+17%) and ν_μ CC (+10%)

Systematic Uncertainties

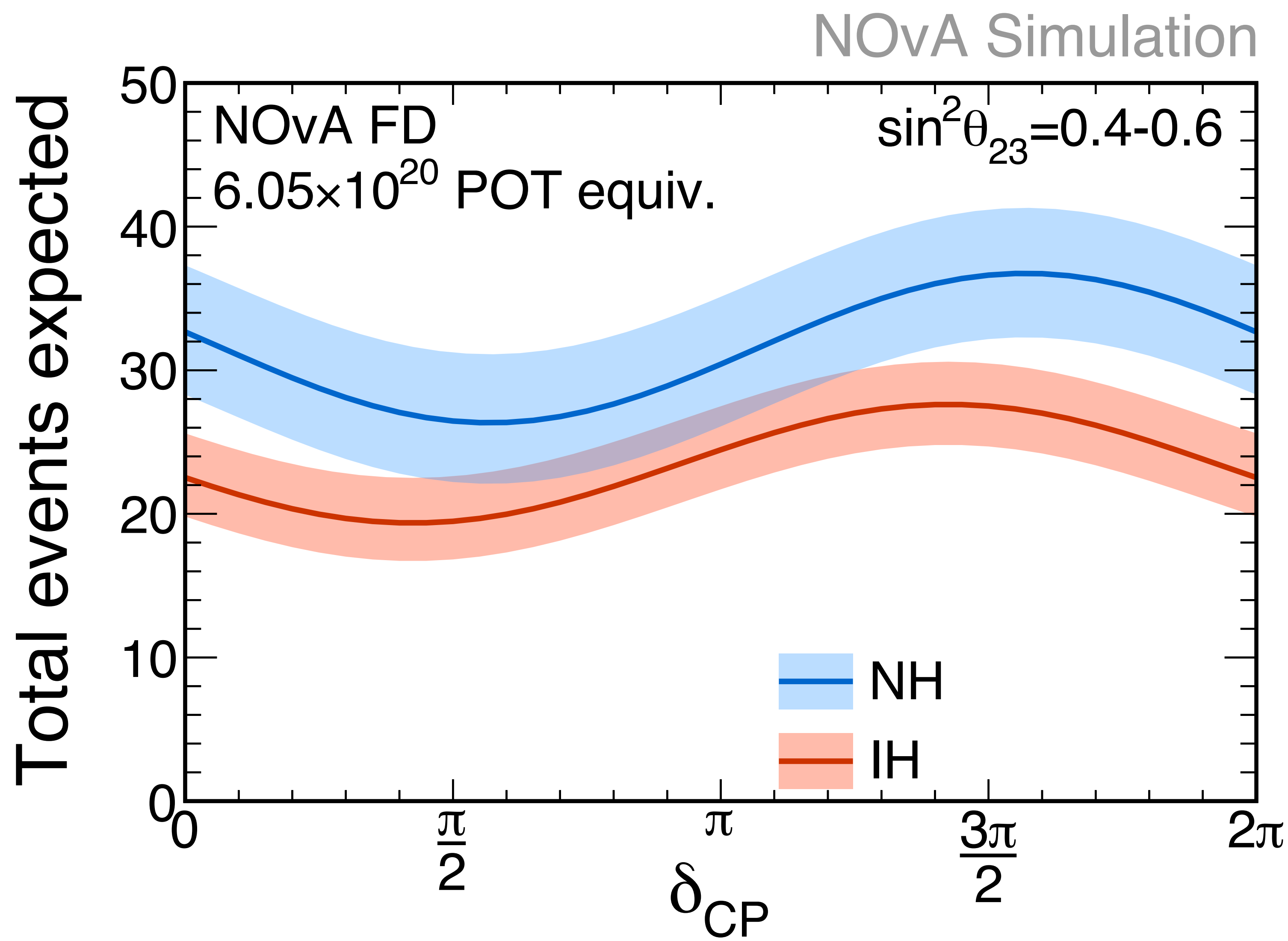




- Multiple sources of systematic error considered
- Extrapolate FD predictions with special MC samples for each effect.
- Uncertainty quoted as difference between shifted and nominal predictions
- Fit nuisance parameters as pull terms
- Statistical uncertainties dominate

$\nu_\mu \to \nu_e$ Oscillation Prediction

- Prediction dependent on oscillation parameters



Signal events
(±5% systematic uncertainty):

NH, 3π/2,	IH, π/2,
28.2	11.2

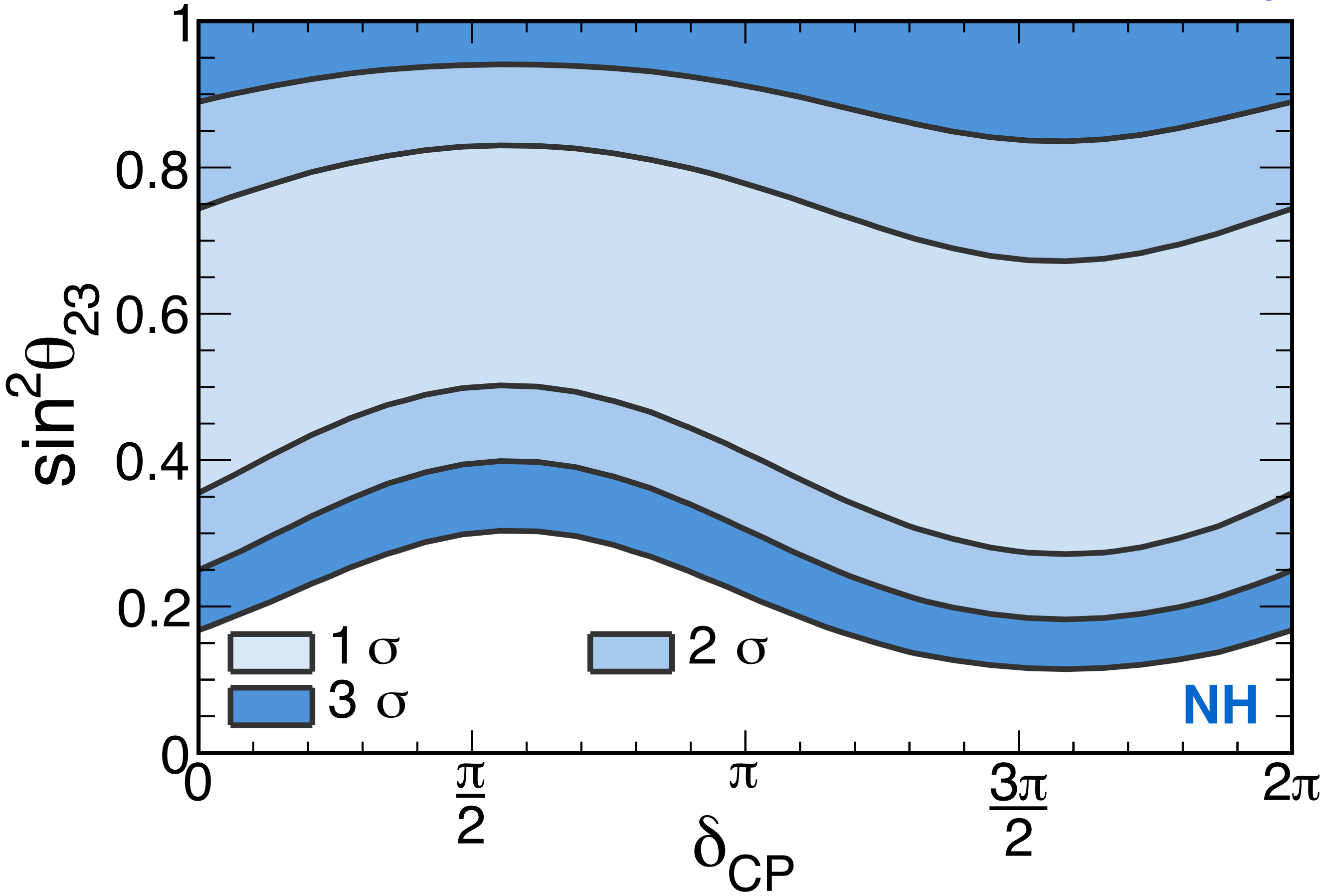
Background by component
(±10% systematic uncertainty):

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

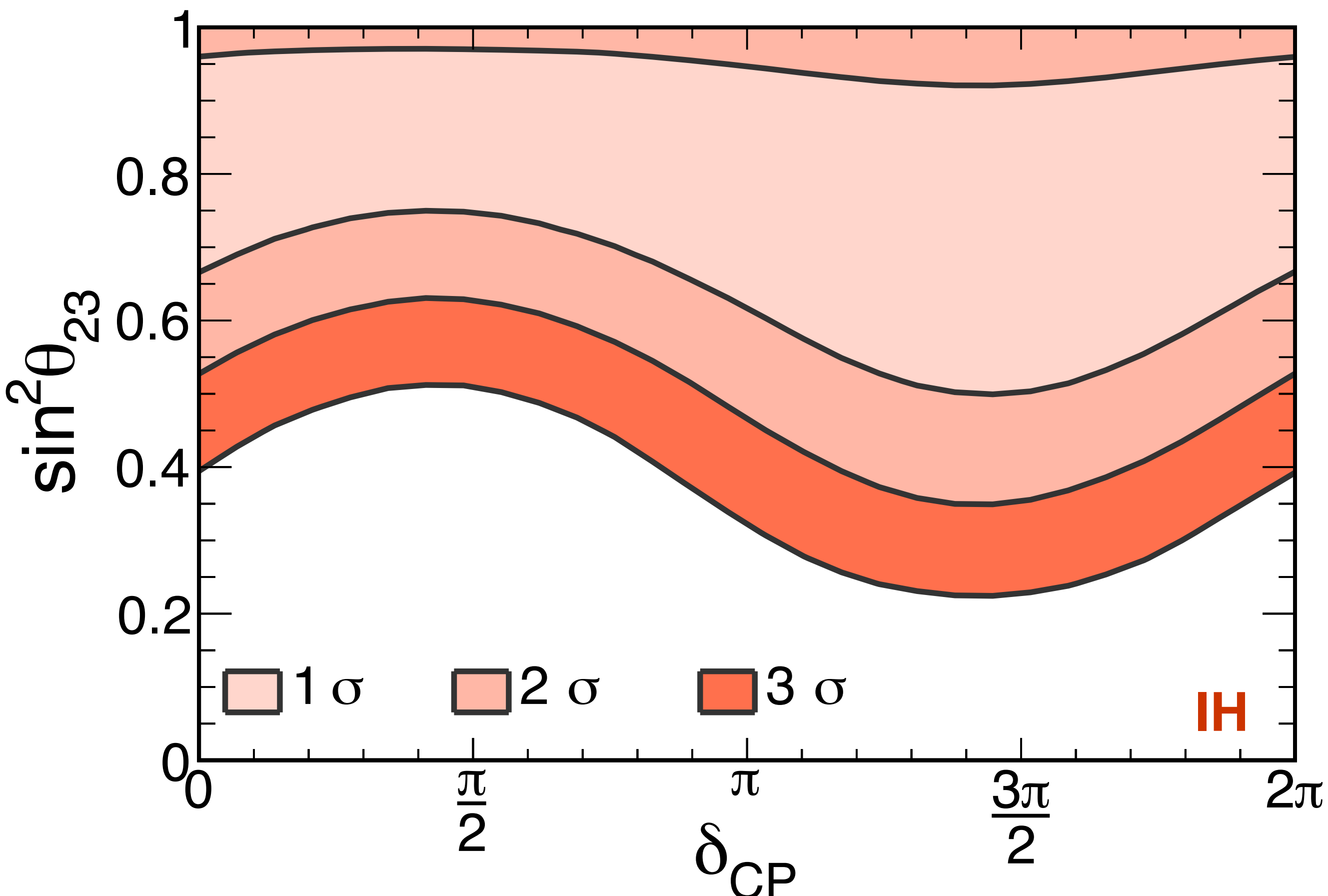
NOvA Preliminary

ν_μ -> ν_e Oscillation Results

- 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, NH
  - ($-2.49\pm0.06\times10^{-3}$ eV^2, IH)



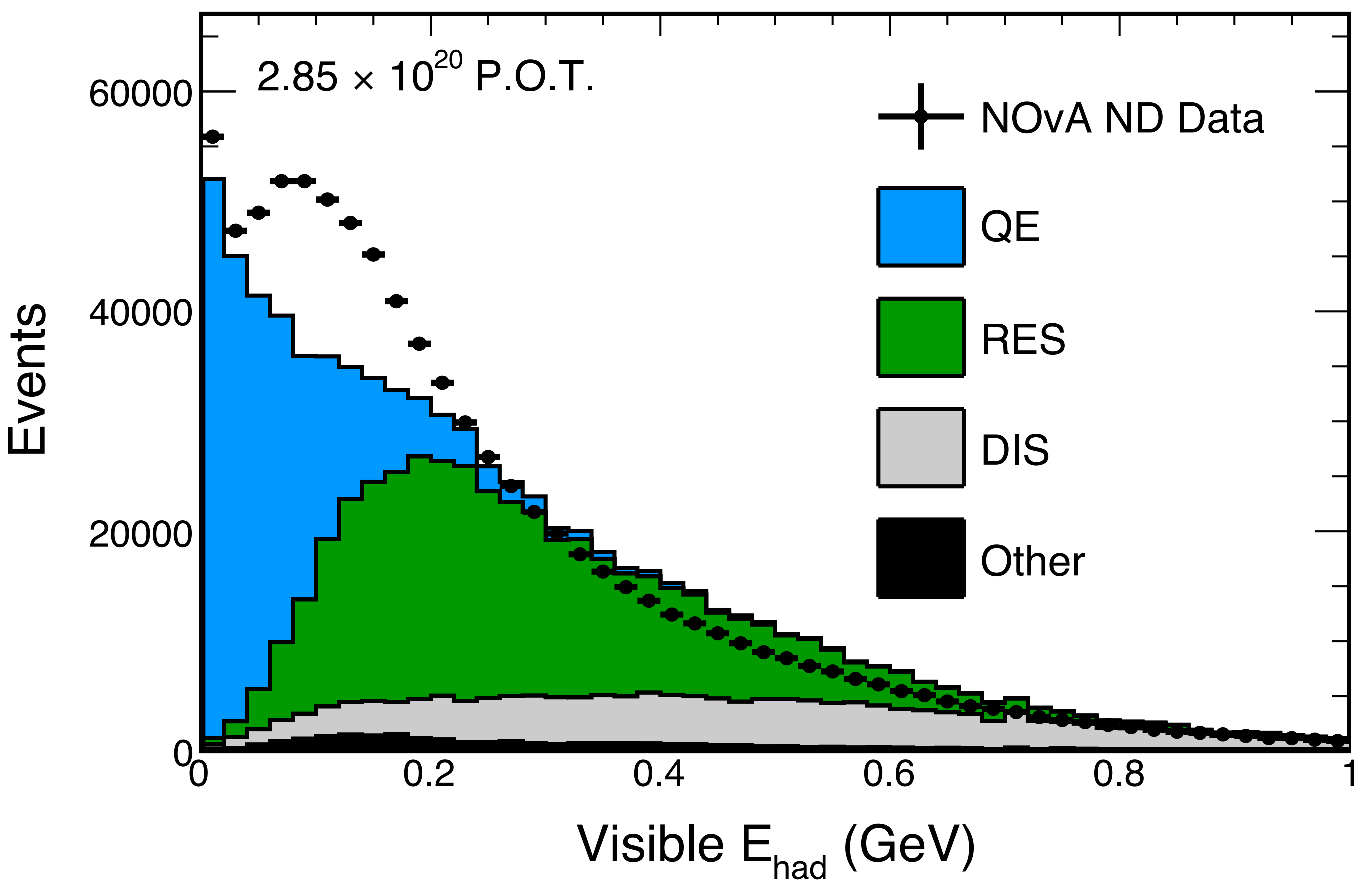
- Systematic effects included as nuisance parameters (normalization, flux, calibration, cross section, and detector response effects)

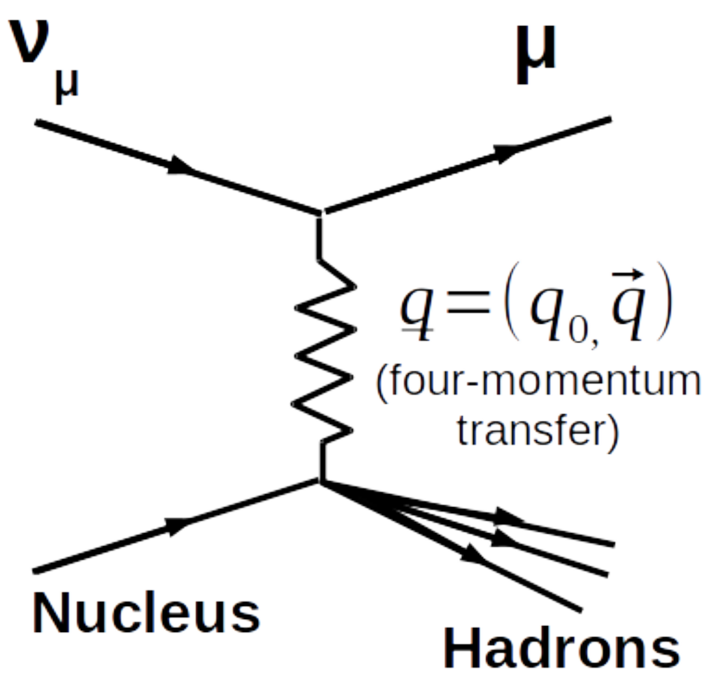


Nuclear Model Corrections

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

NOvA Preliminary



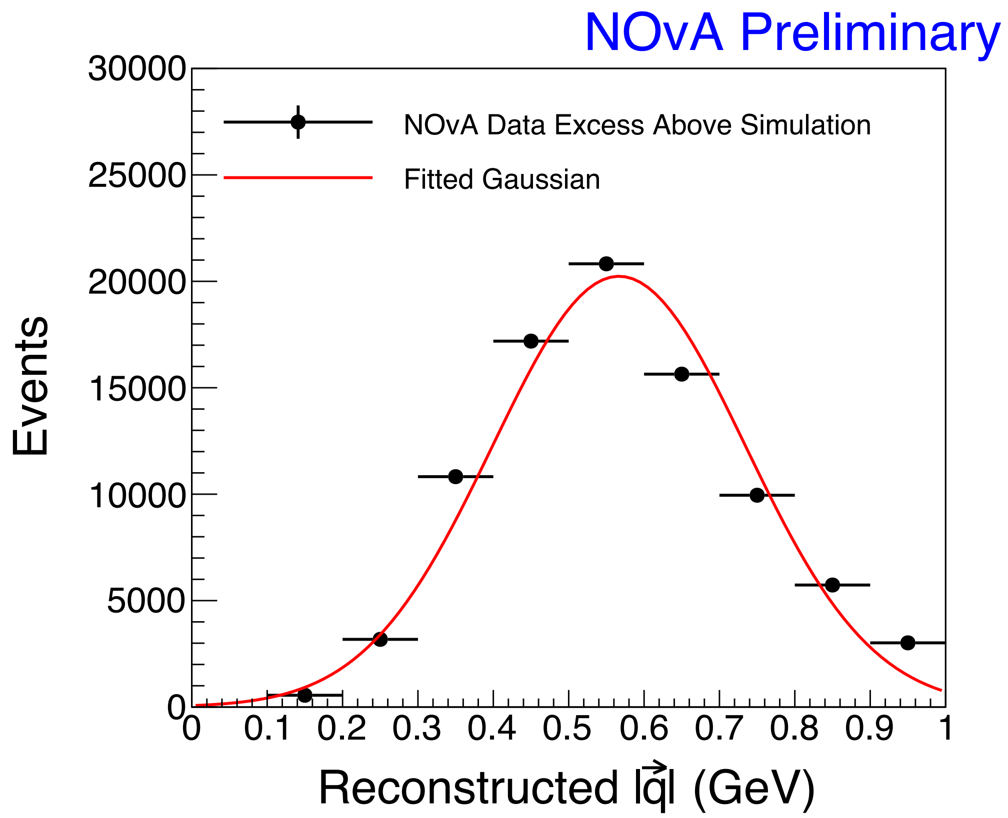


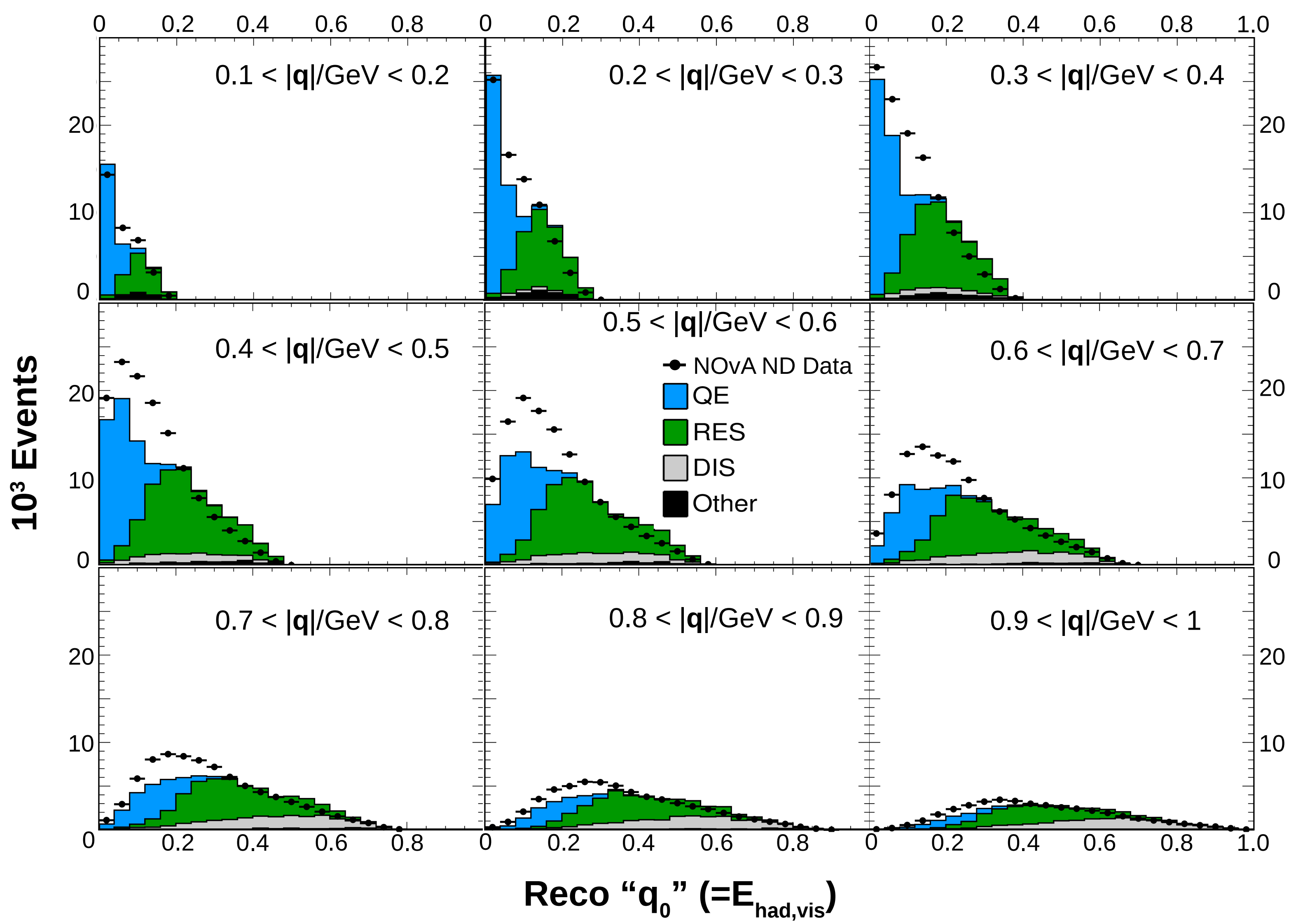
Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Solution: 2-particle, 2-hole (2p2h) events where neutrino is scattering off a nucleon-nucleon pair

Nuclear Model Corrections

- Enable GENIE's emperical Meson Exchange Current model[1]
- Reweight to matched observed excess as a function of momentum transfer
- Weight single non-resonant pion production down by effectively 50%[2]



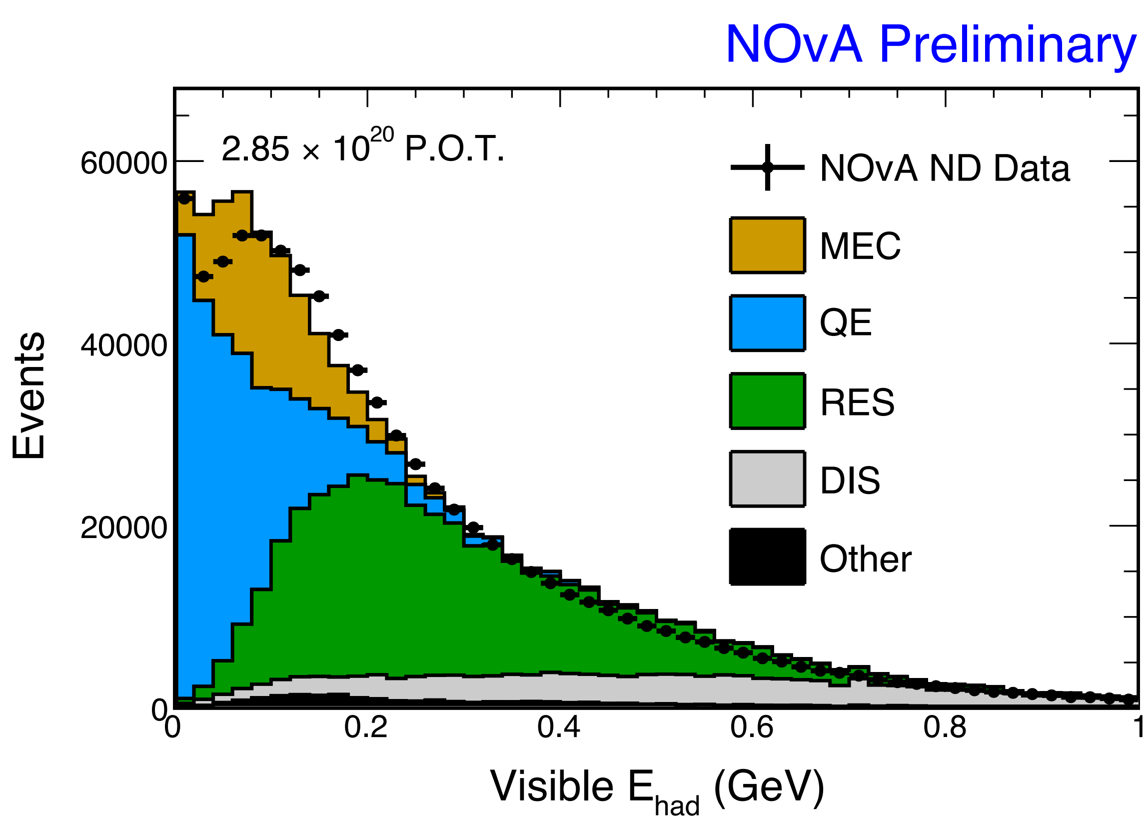


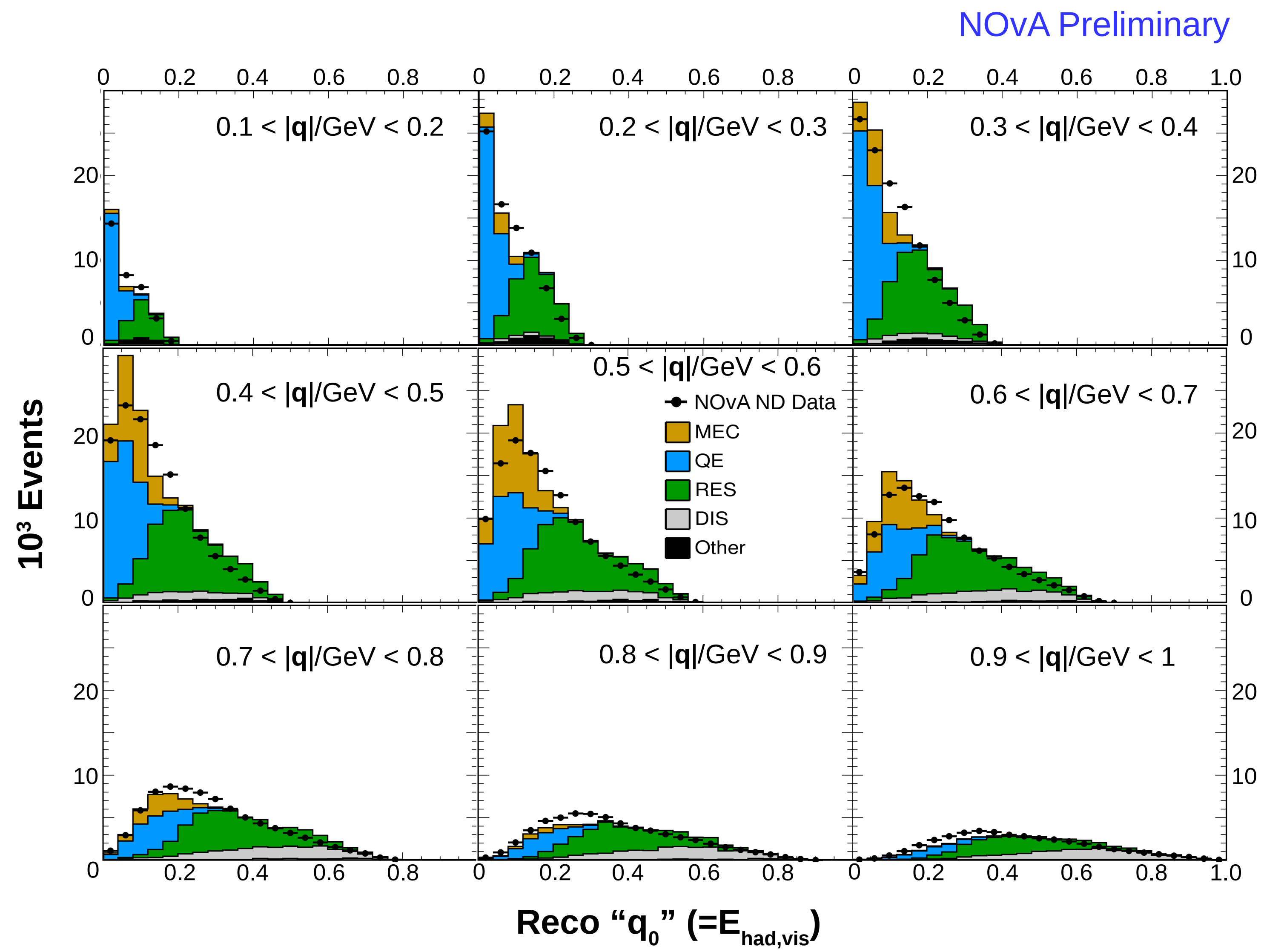
[1]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57

[2]P.A. Rodrigues et al., arXiv:1601.01888

Nuclear Model Corrections

- Take 50% systematic uncertainty on MEC component
- Reduces hadronic energy scale and quasi-elastic cross section systematic uncertainties

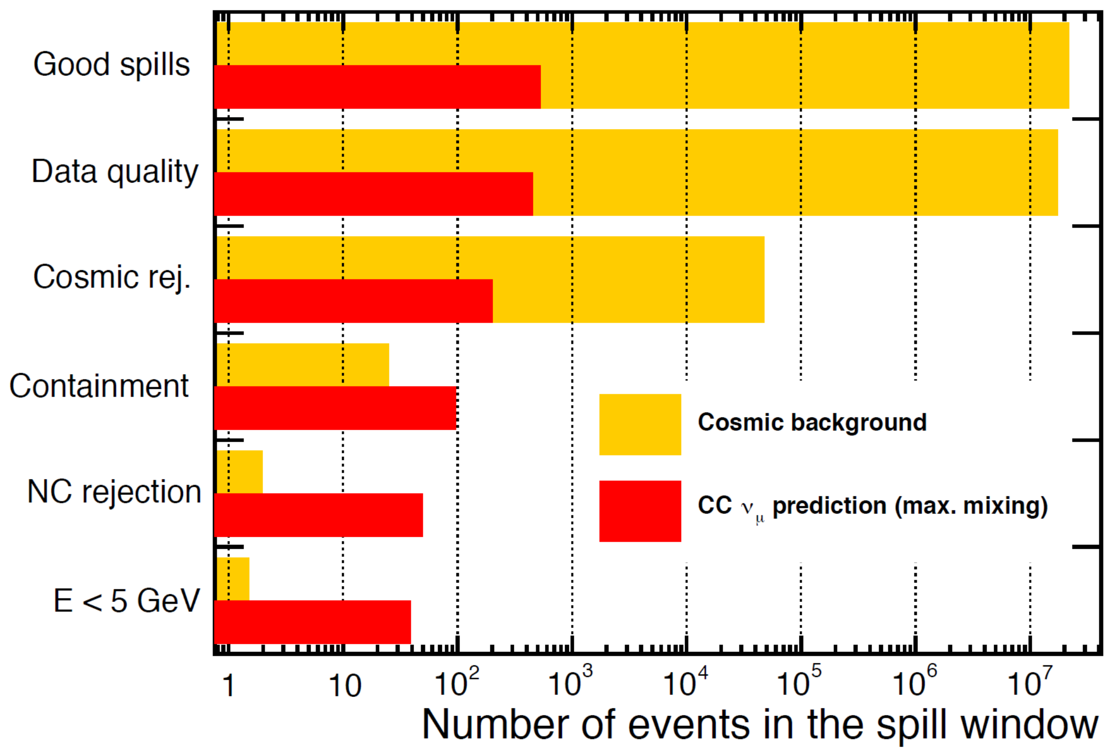


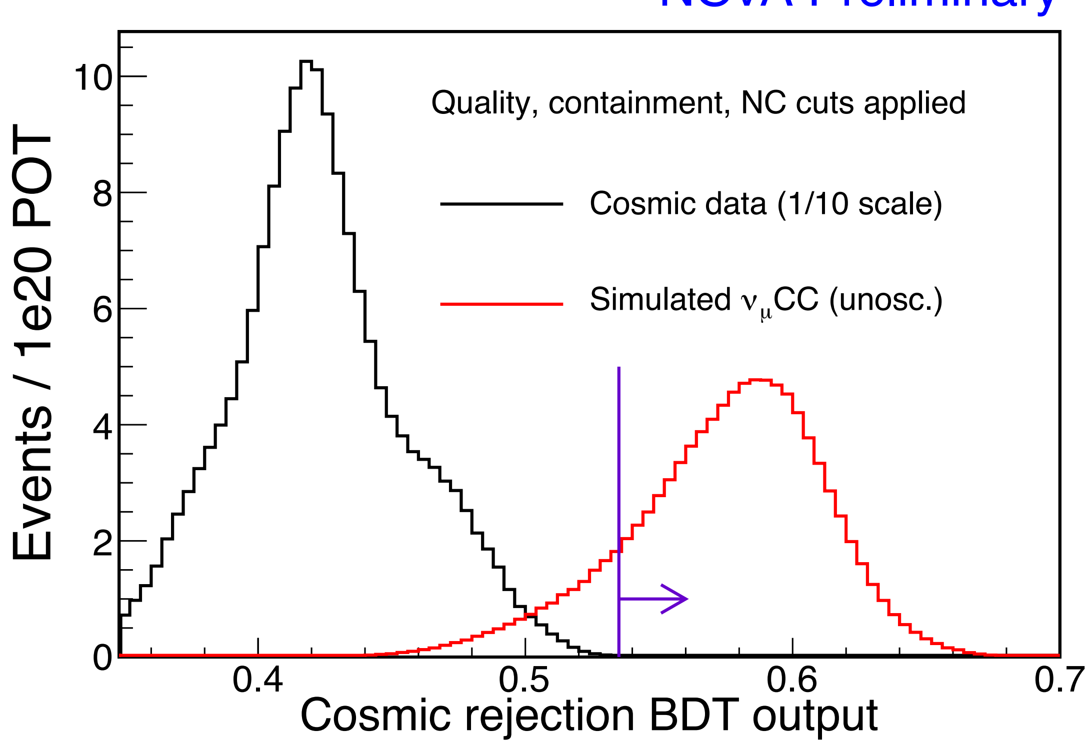


[1]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57

[2]P.A. Rodrigues et al., arXiv:1601.01888

Cosmic Rejection





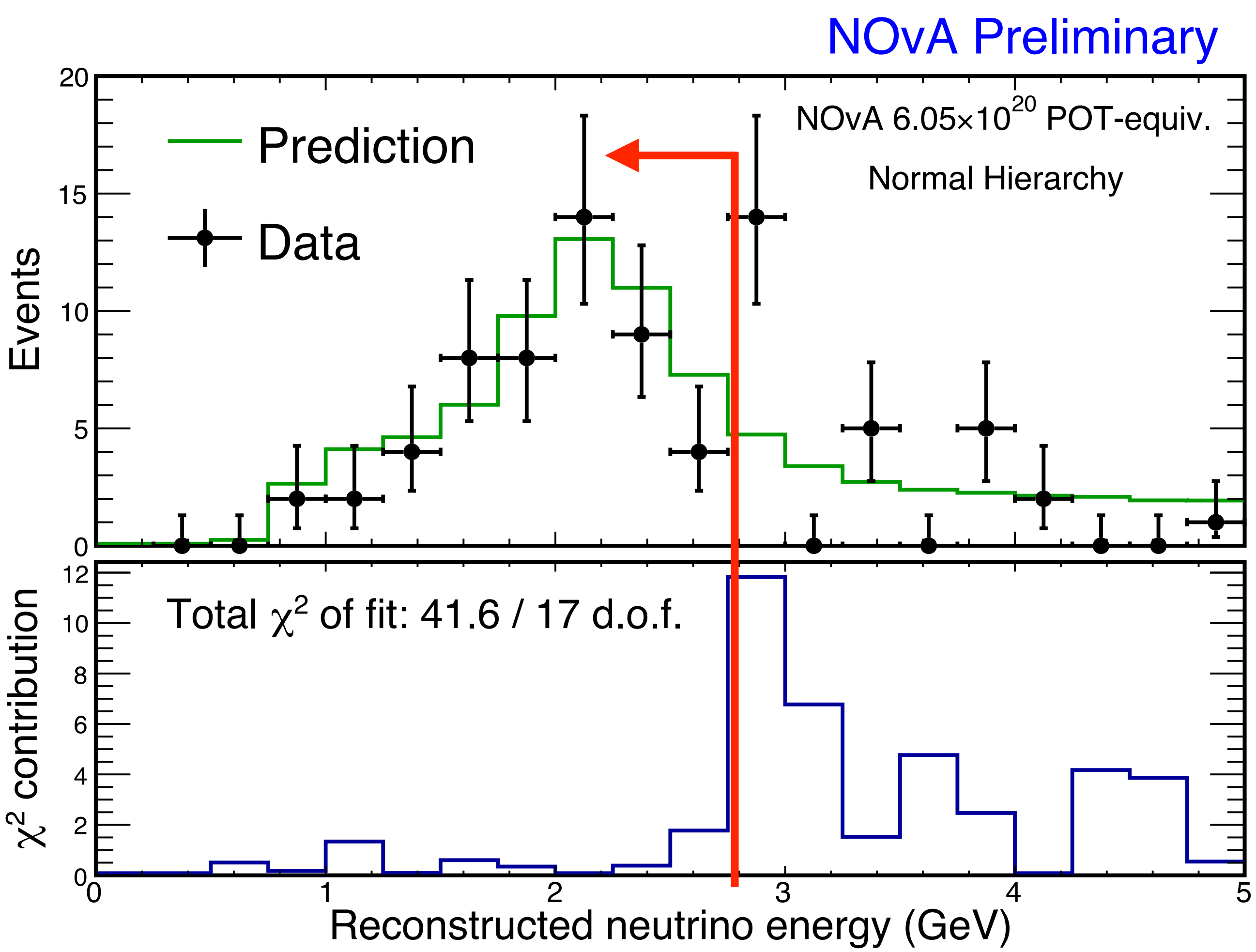
- Far Detector sees 150 kHz of cosmic induced events
- 10 μs beam window at a rate of ~0.8 Hz reduces background by 10^5
- Additional factor of 10^7 rejection achieved from event topology and a boosted decision tree (BDT) based on:
  - track direction
  - start/end points of track
  - track length
  - energy
  - number of hits
- Predict 2.7 cosmic background events

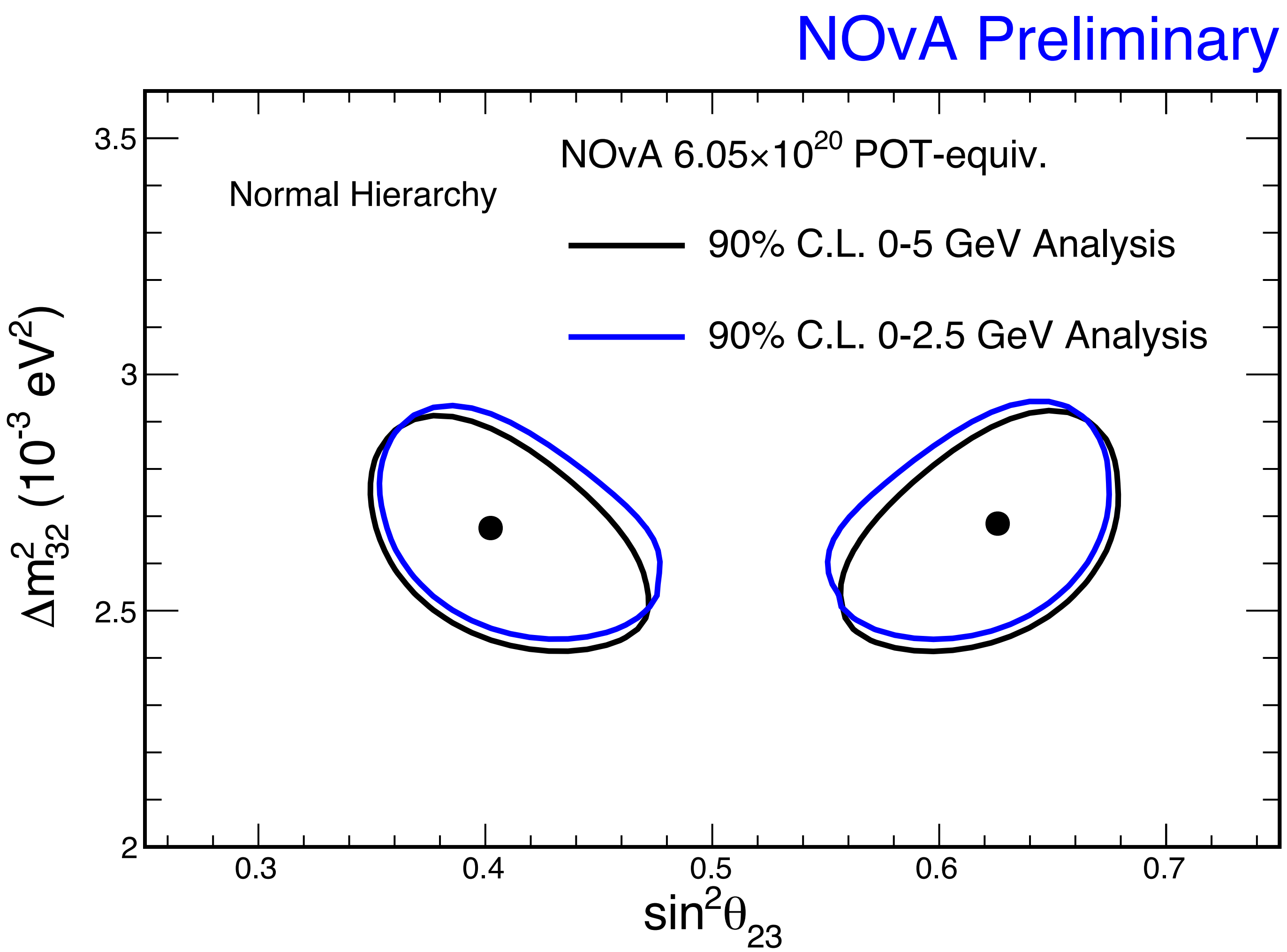
Systematic Uncertainties

- Various sources of systematic uncertainty considered
- Propagate the effect of each though the extrapolation with specially modified MC samples
- Include as pull terms in fit
- Table shows increase in quadrature of measurement uncertainty

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 %**

ν_μ -> ν_μ Oscillation Results





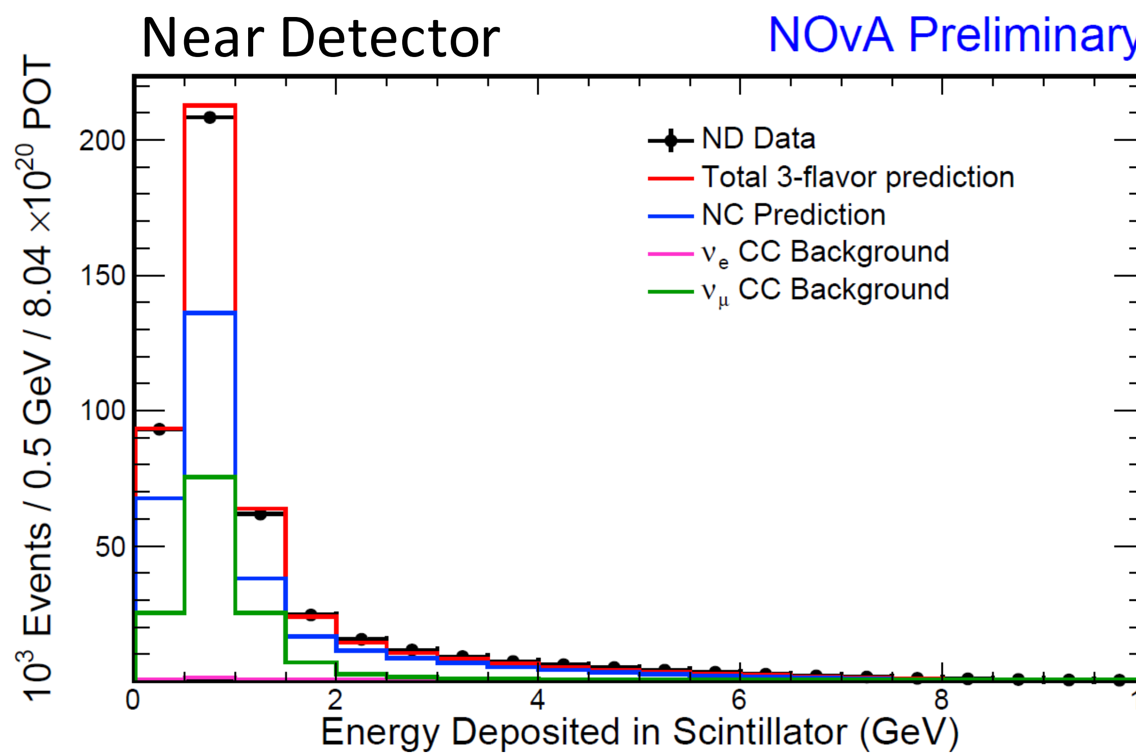
- Best fit χ^2/DOF = 41.5/17 is driven by the high energy tail
- There is no pull in the oscillation fit from the tail

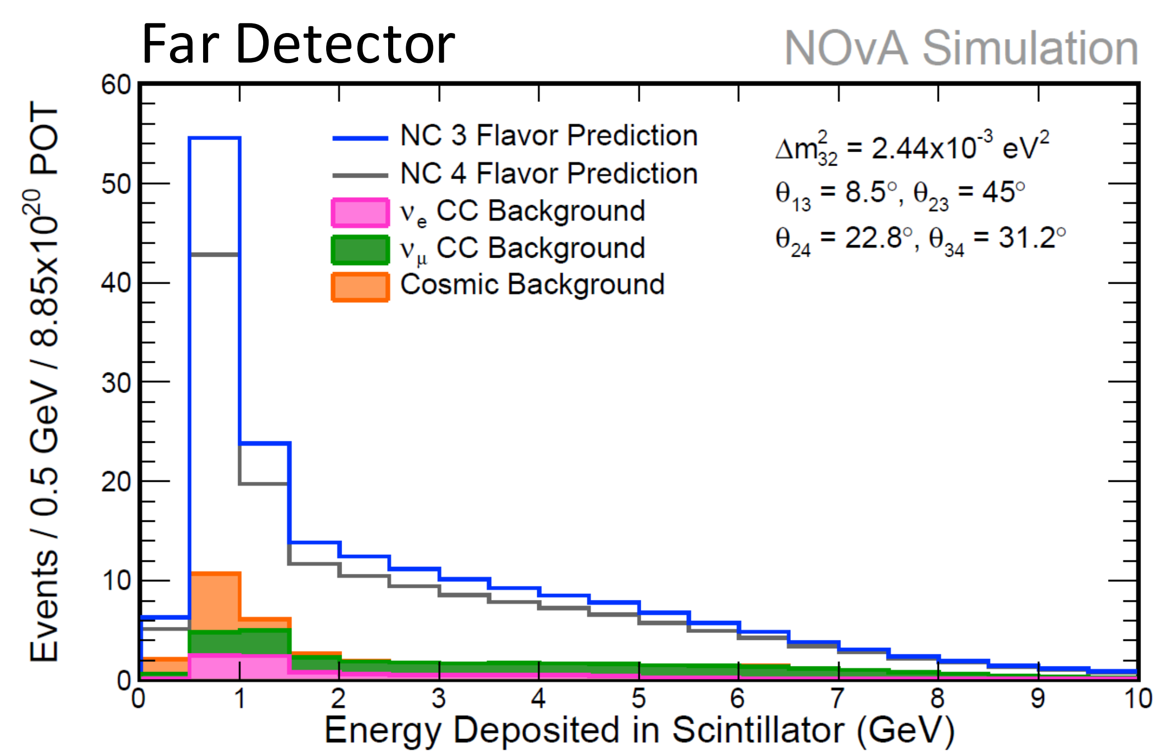
NC Disappearance Results

- Events classified using CVN
- Analysis Upgrades:
  - Increase of 50% more data
  - Improved cosmic rejection
  - Energy fit
  - 50% improvement to NC selection efficiency
  - Improved cross-section modeling
  - Improved detector response modeling

Background	Estimate
Total Bkgd	42.8
ν_μ CC	22.2
ν_e CC	9.9
ν_τ CC	2.8
Cosmic	7.9

Total Signal Prediction: **148.3**





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