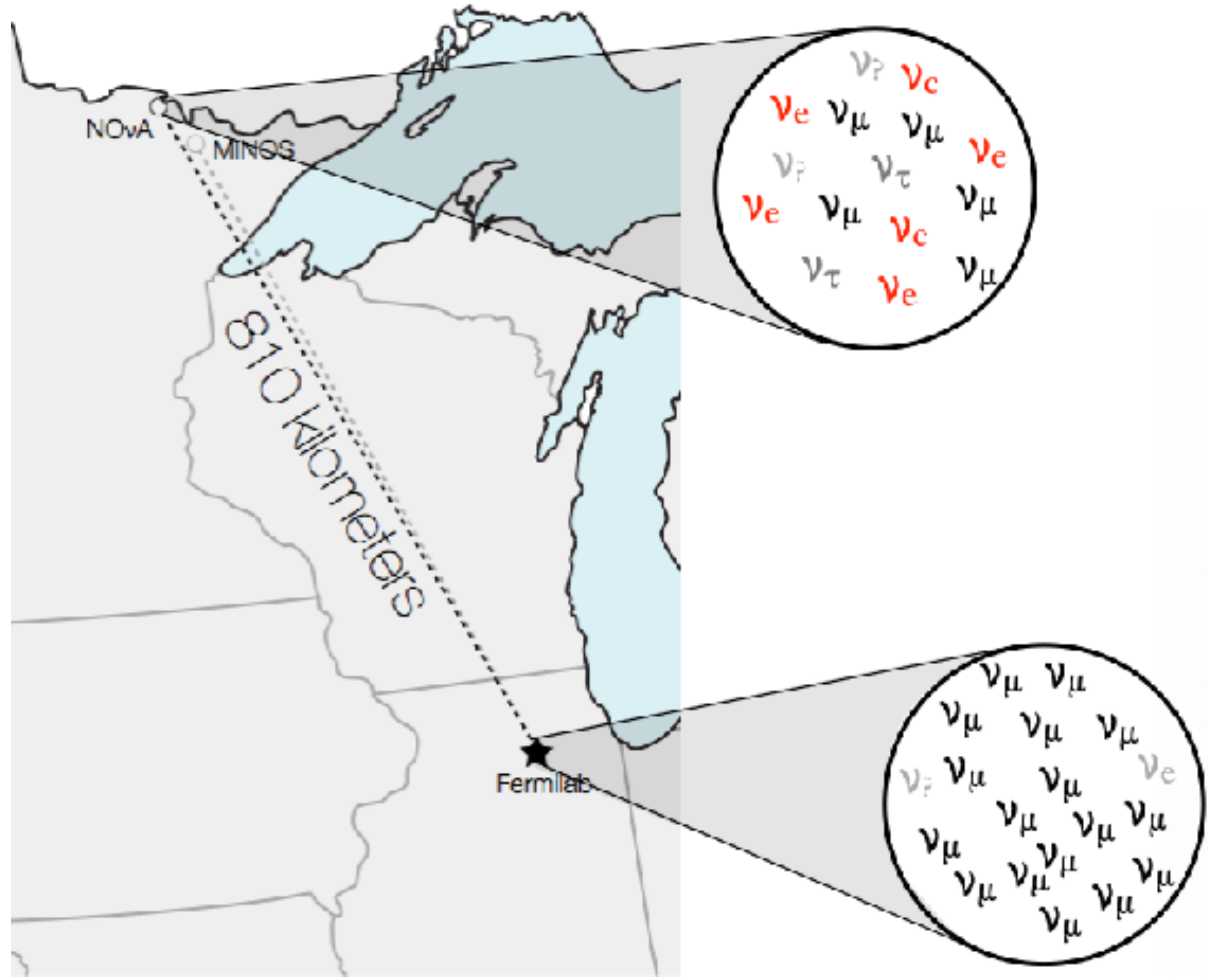
Results from NOvA

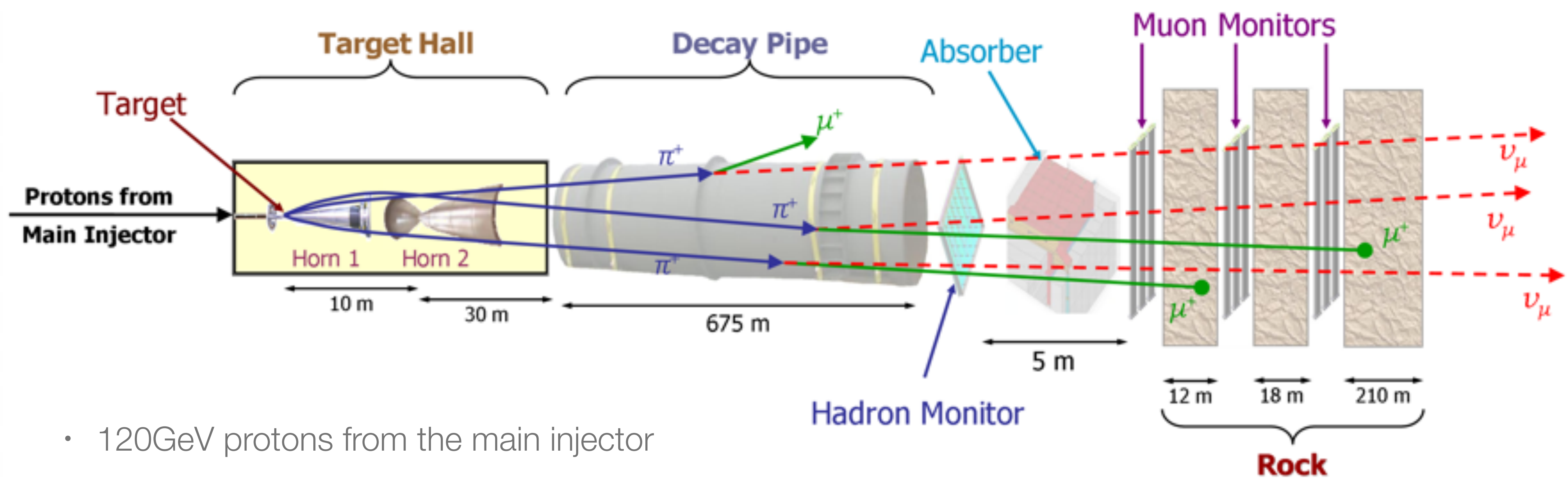
Ryan Nichol

NOvA Experiment

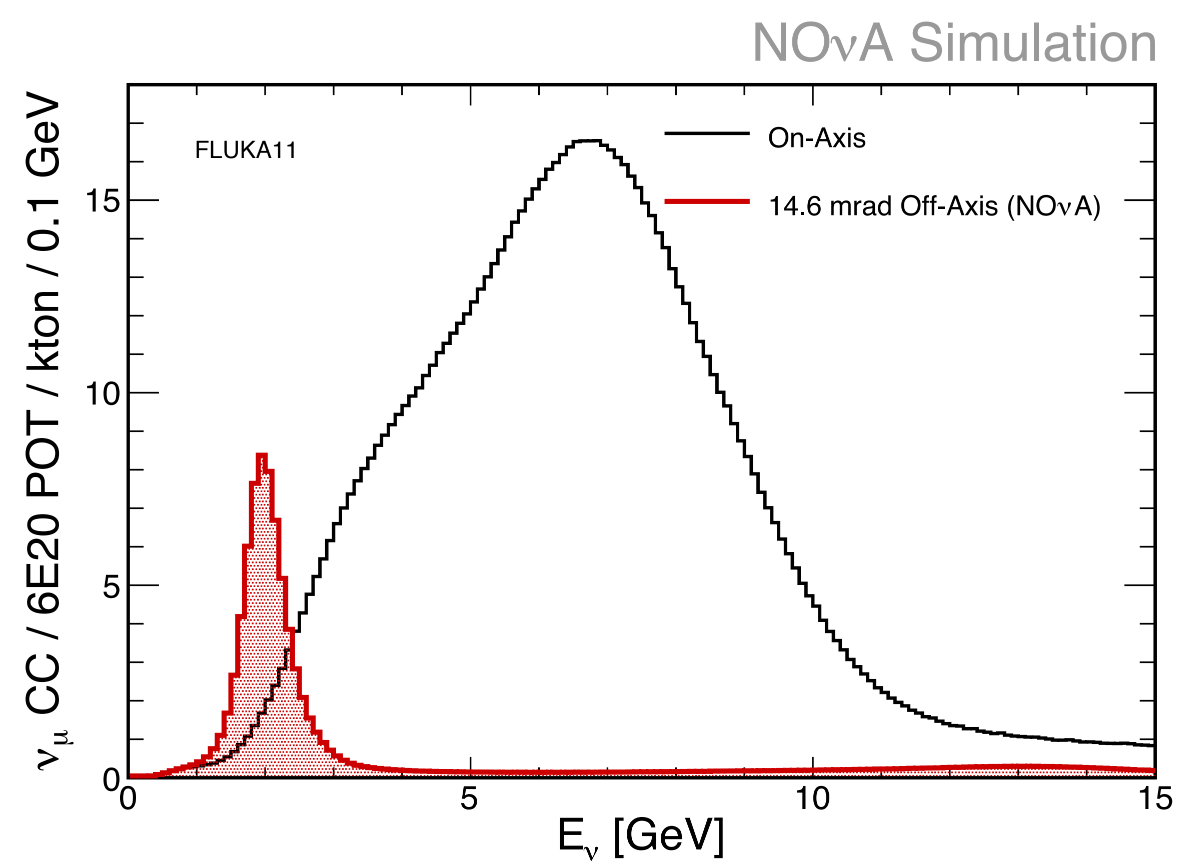
- Longest baseline accelerator neutrino search
  - NuMI is a beam of mainly muon-neutrinos created at Fermilab
  - Two functionally identical detectors
- Measured muon-neutrino disappearance and electron-neutrino appearance
  - And starting to do the same with anti-neutrinos
- Sensitive to PMNS matrix, mass hierarchy, CP violation, sterile neutrinos, interaction physics, supernova, …



How to make a neutrino beam

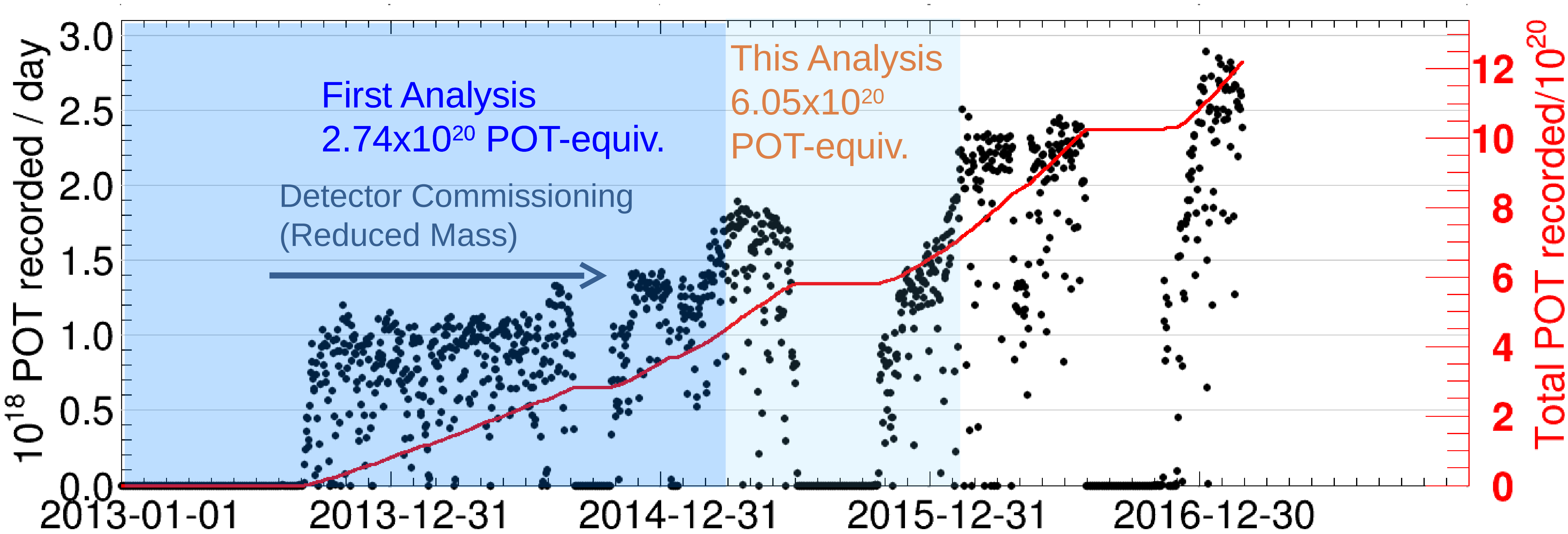


- 120GeV protons from the main injector
- Focus secondary pions using magnetic horns
  - Focus positive hadrons for neutrino beam, negative for antineutrino
- Pions decay to produce muon neutrinos
  - Decay kinematics mean a detector at 14.6mrad sees a narrowly peaked energy spectrum
- 97.5% muon-neutrino, only 0.7% electron-neutrino (remainder wrong-sign)



NuMI Beam Performance

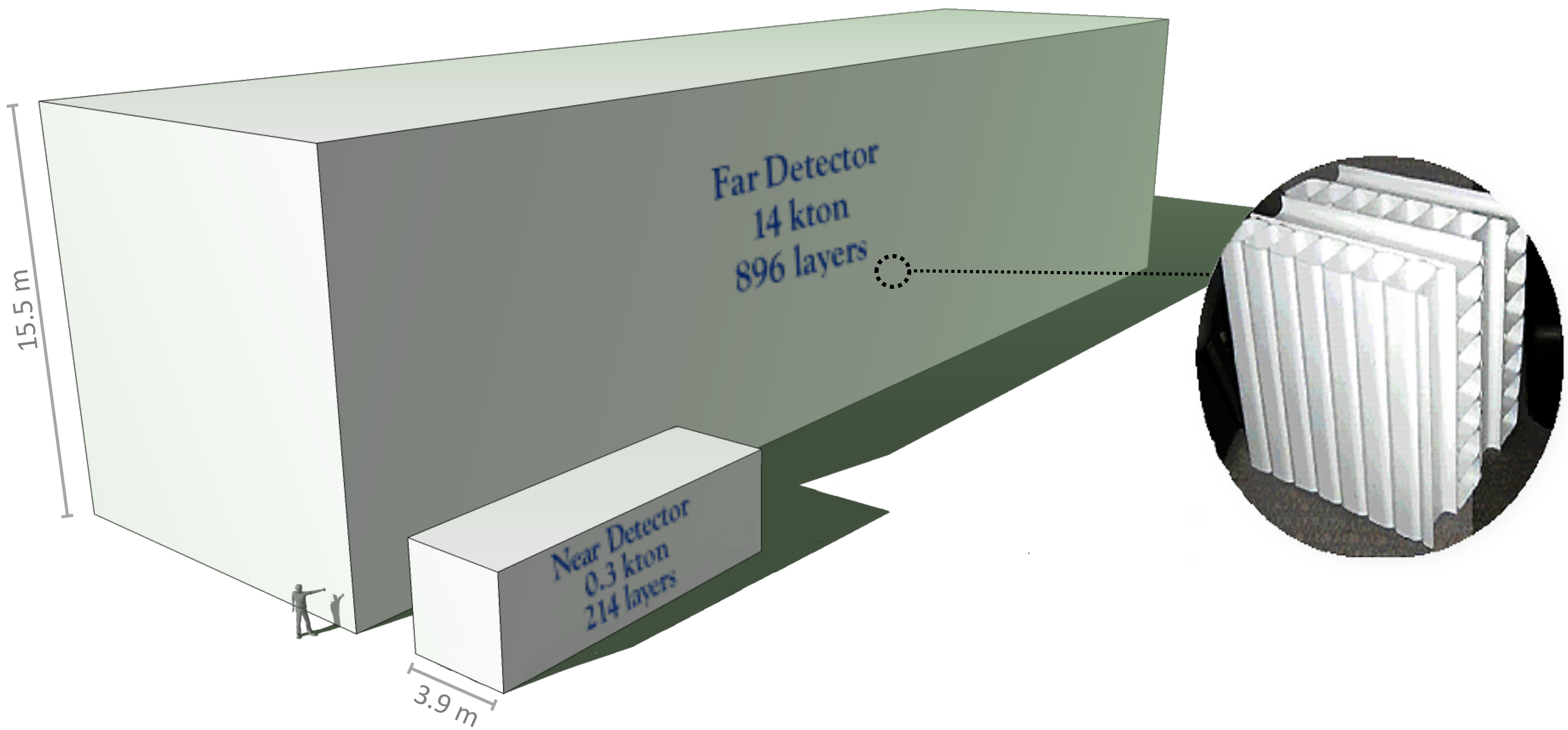
- Results today from data collected between February 6, 2014 and May 2, 2016
- Data equivalent to 6.05×10^{20} protons-on-target in a full 14 kT detector
- Achieved 700 kW design goal, most powerful neutrino beam in the world
- Switched to antineutrino beam

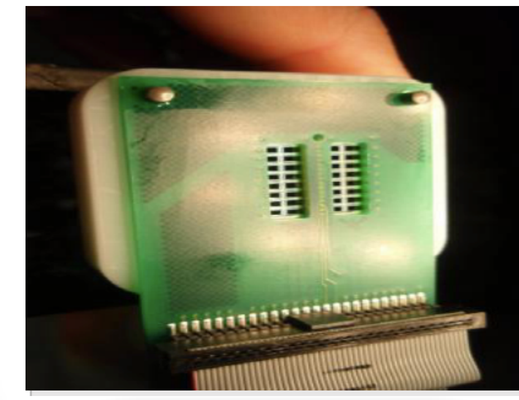


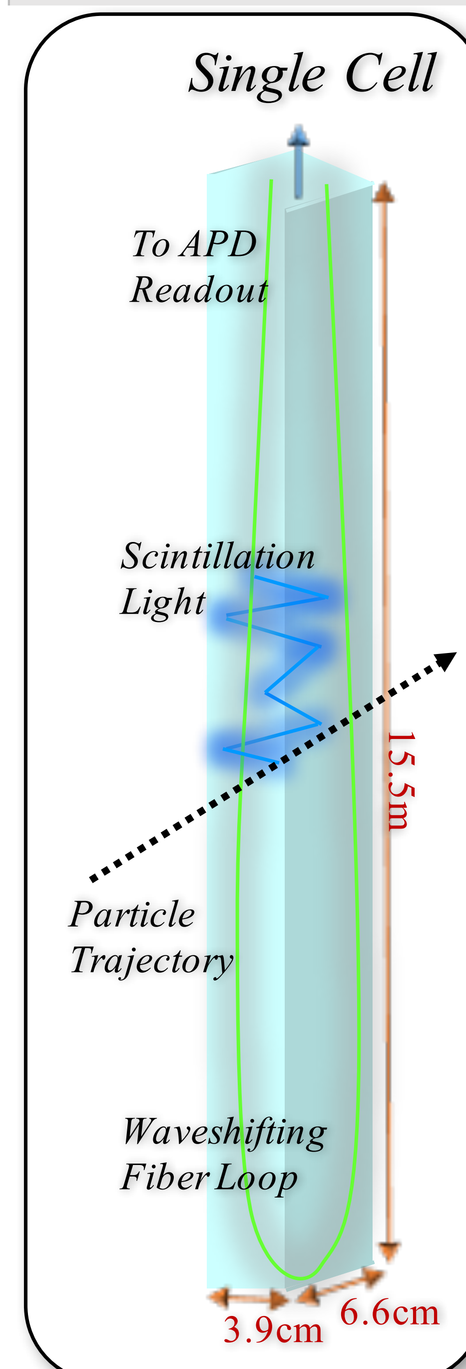
$\nu_\mu \rightarrow \nu_\mu$: Phys.Rev.D93.051104

$\nu_\mu \rightarrow \nu_e$: PRL.116.151806

NOvA Detectors

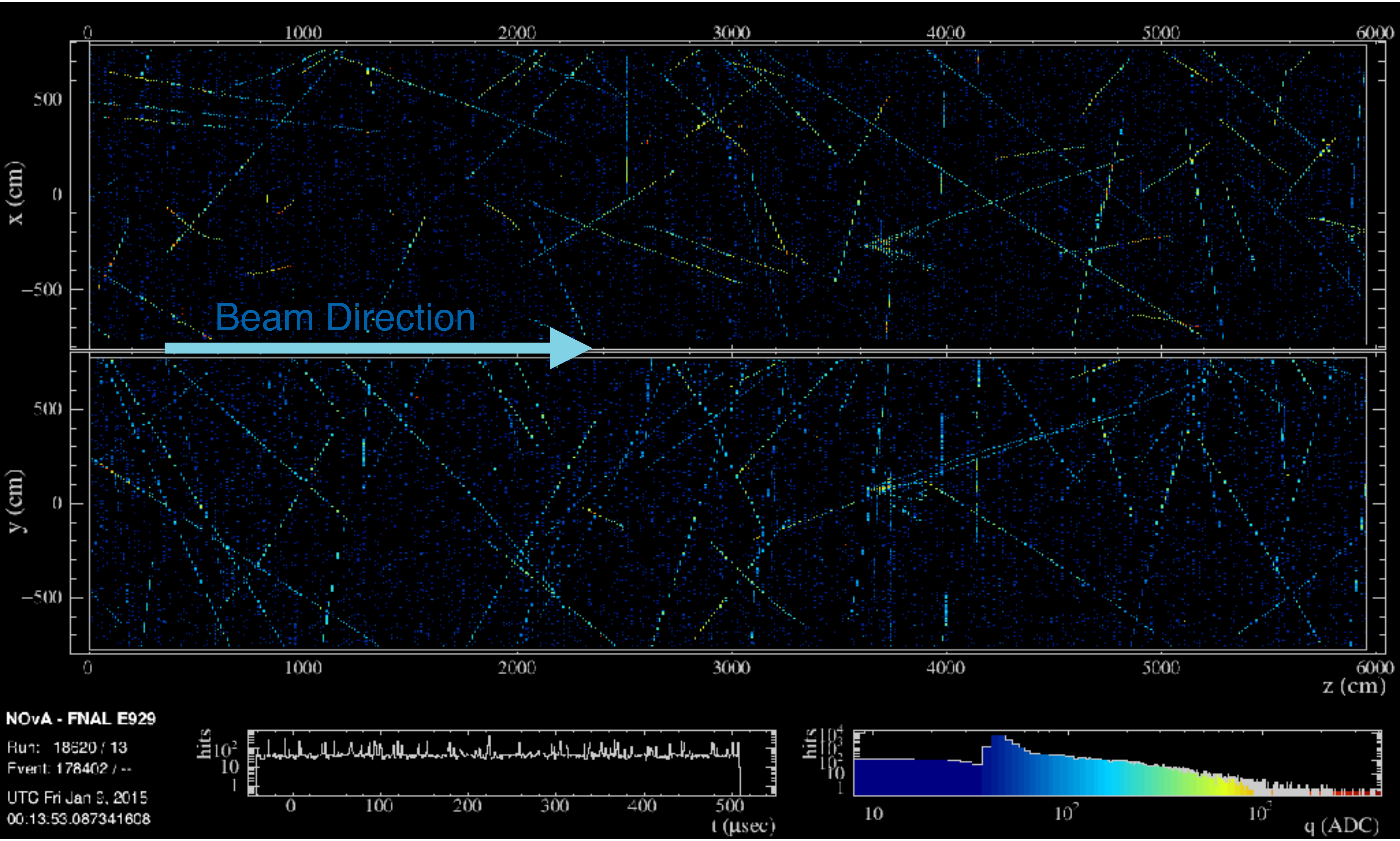






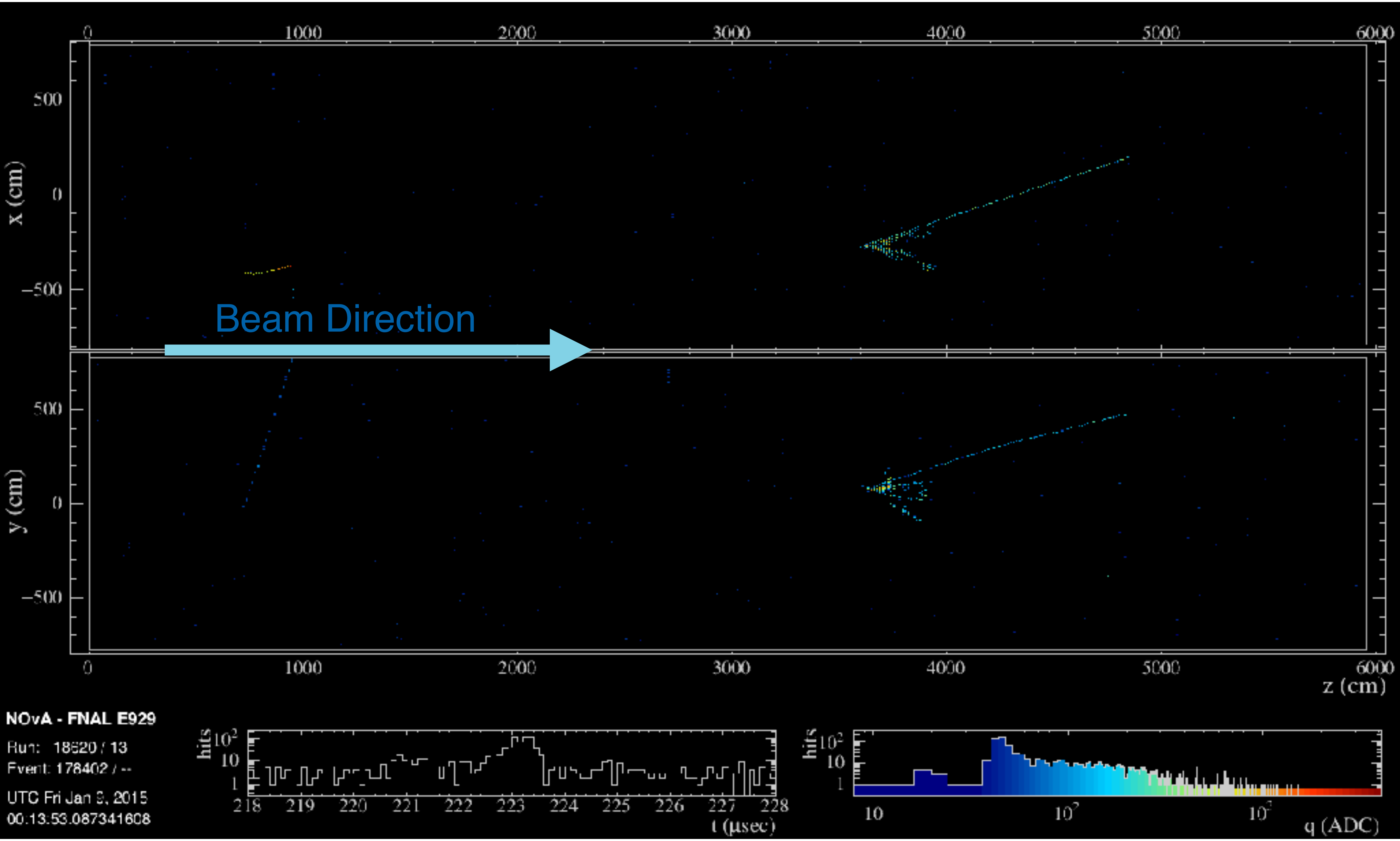
- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- Charged particles passing through cells produce light which is collected by a wavelength shifting fibre

Far Detector 550 μs Readout Window



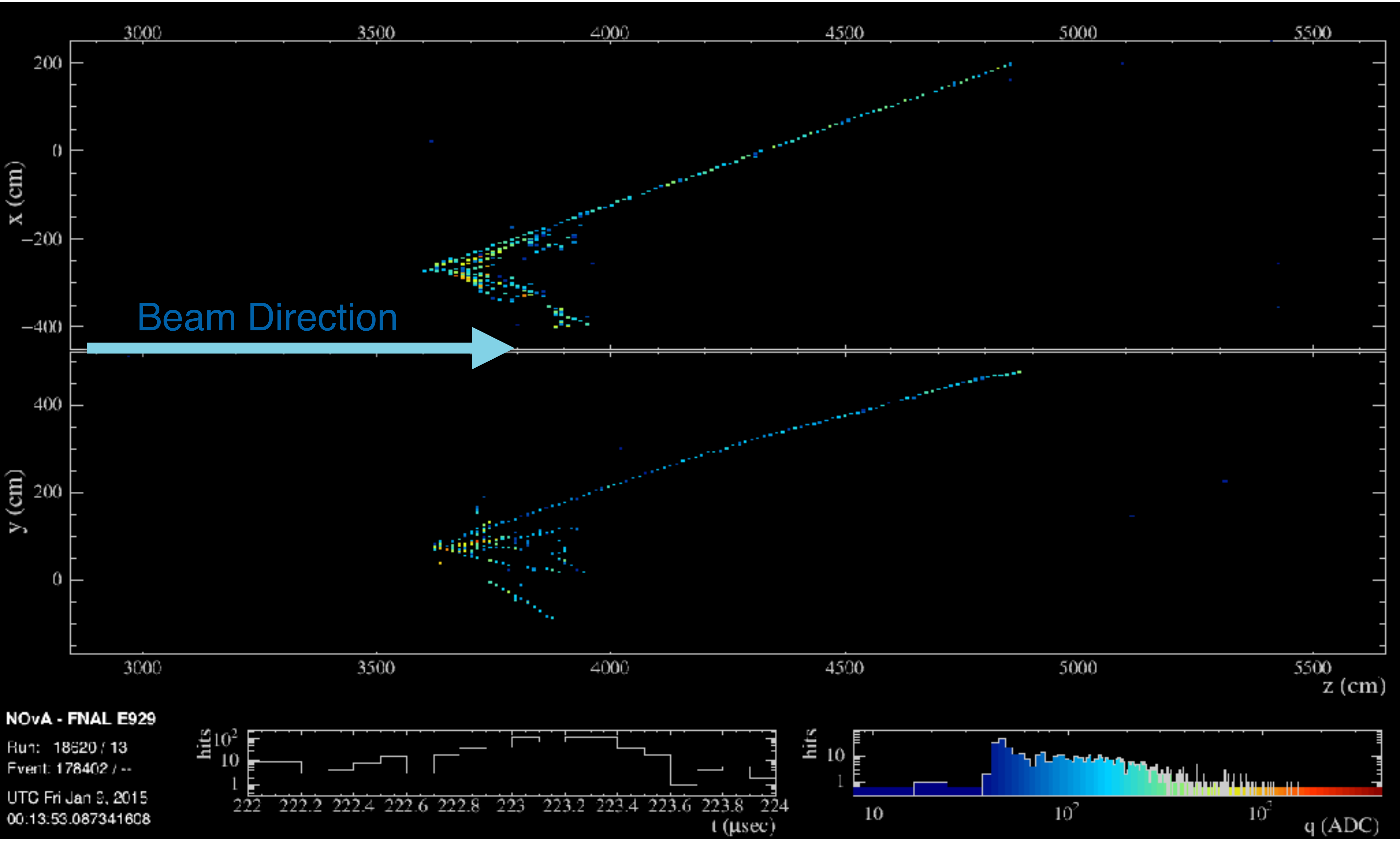
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector 10 μs NuMI Beam Window



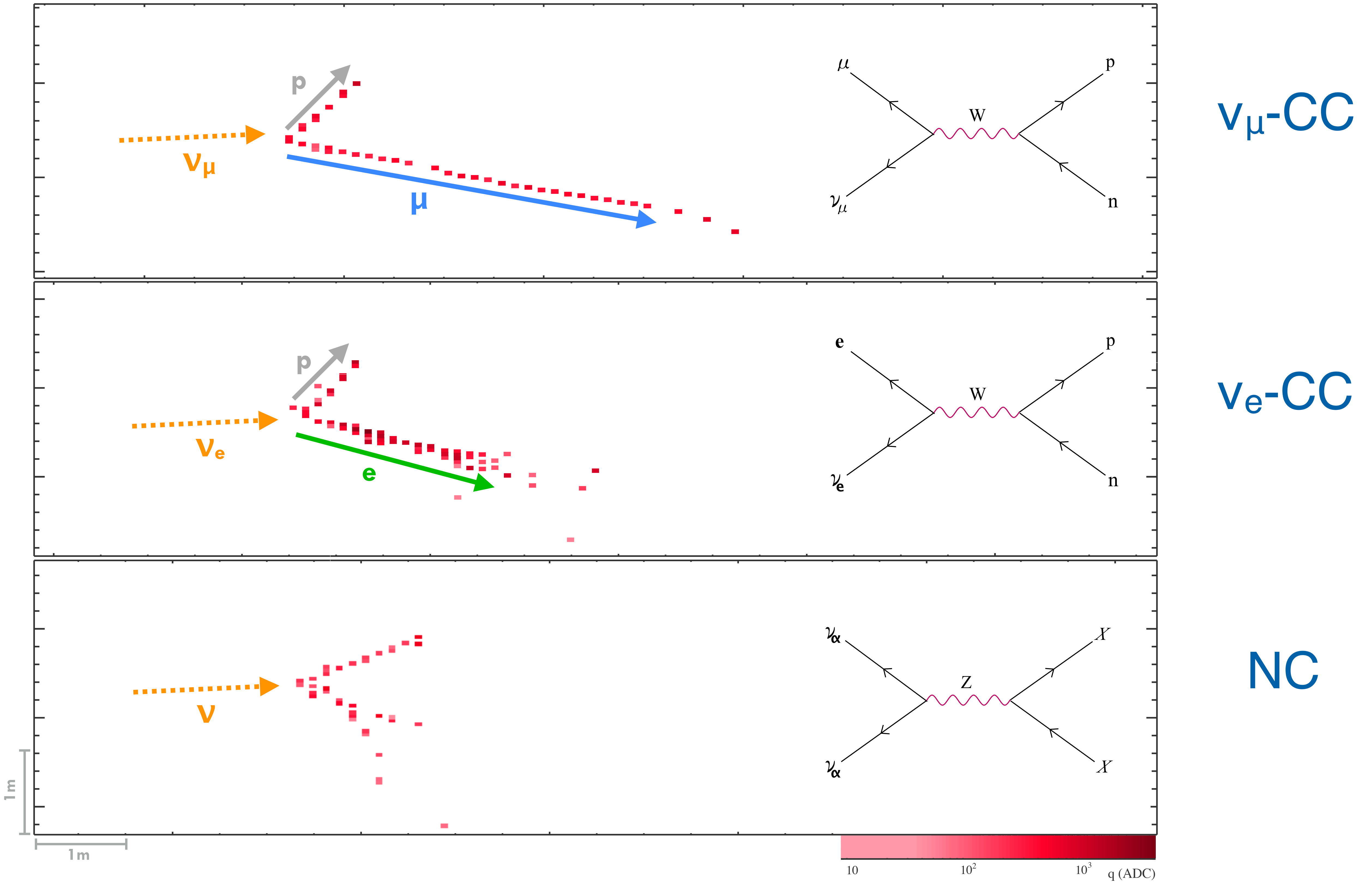
Cell hits coloured by recorded charge (~photoelectrons)

Far Detector Neutrino Interaction



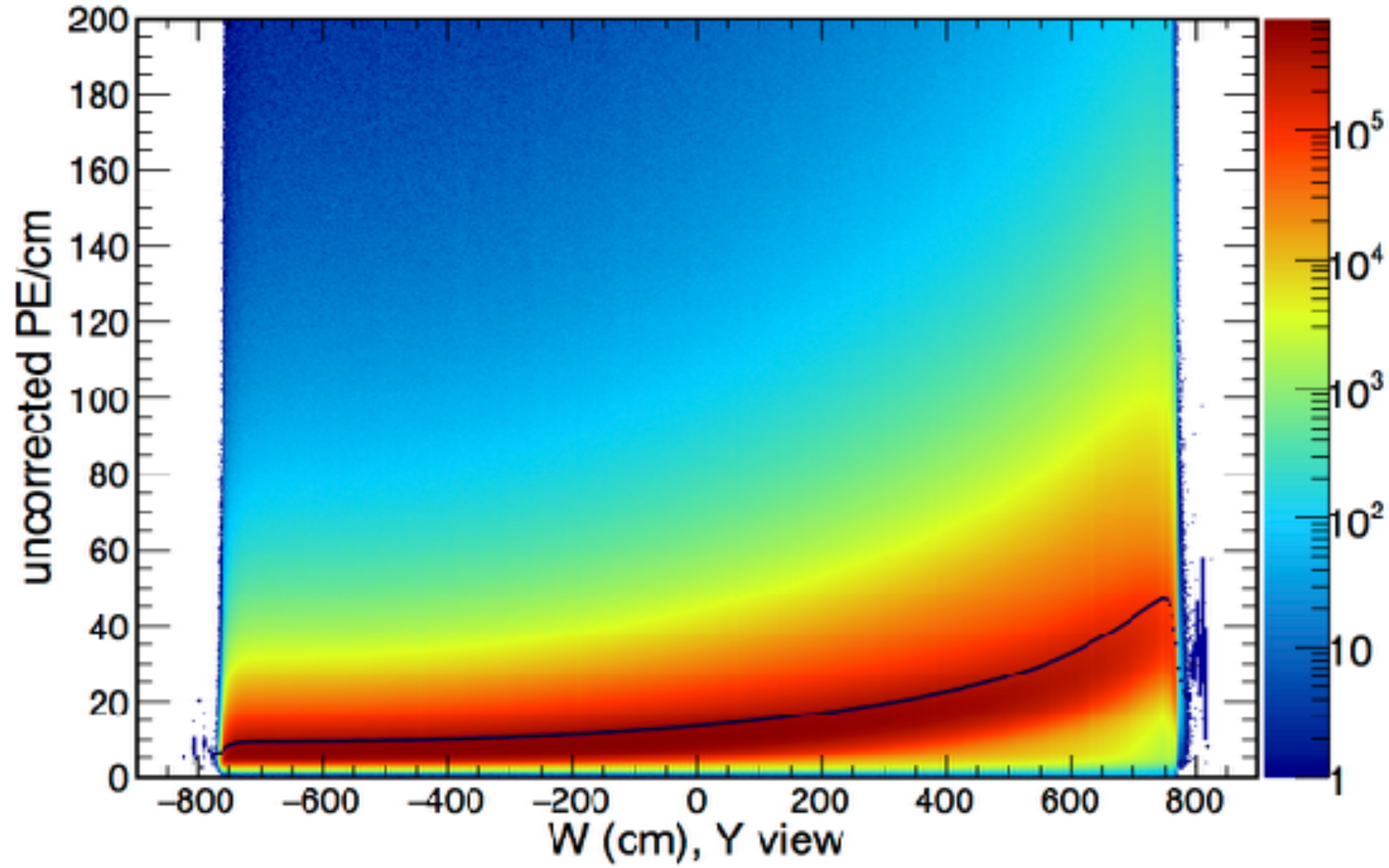
Cell hits coloured by recorded charge (~photoelectrons)

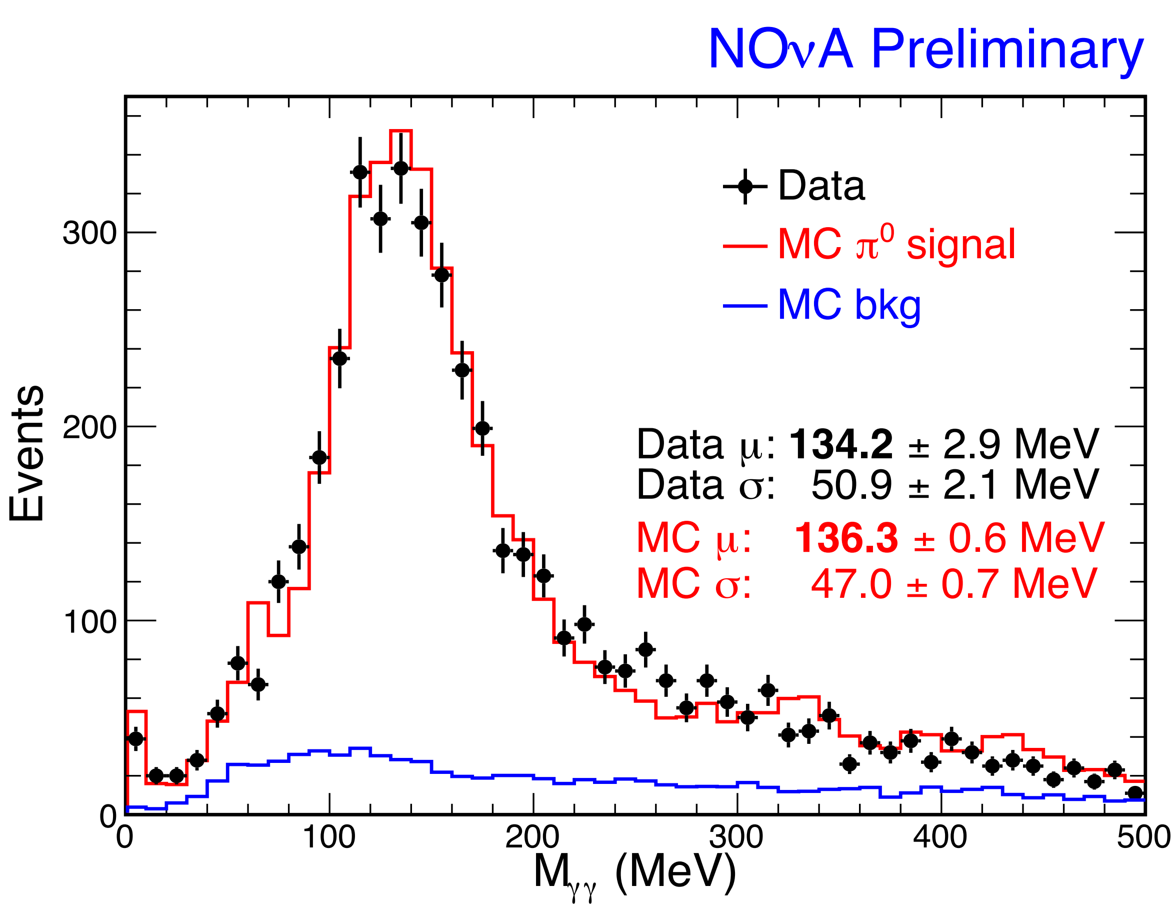
Event Topologies

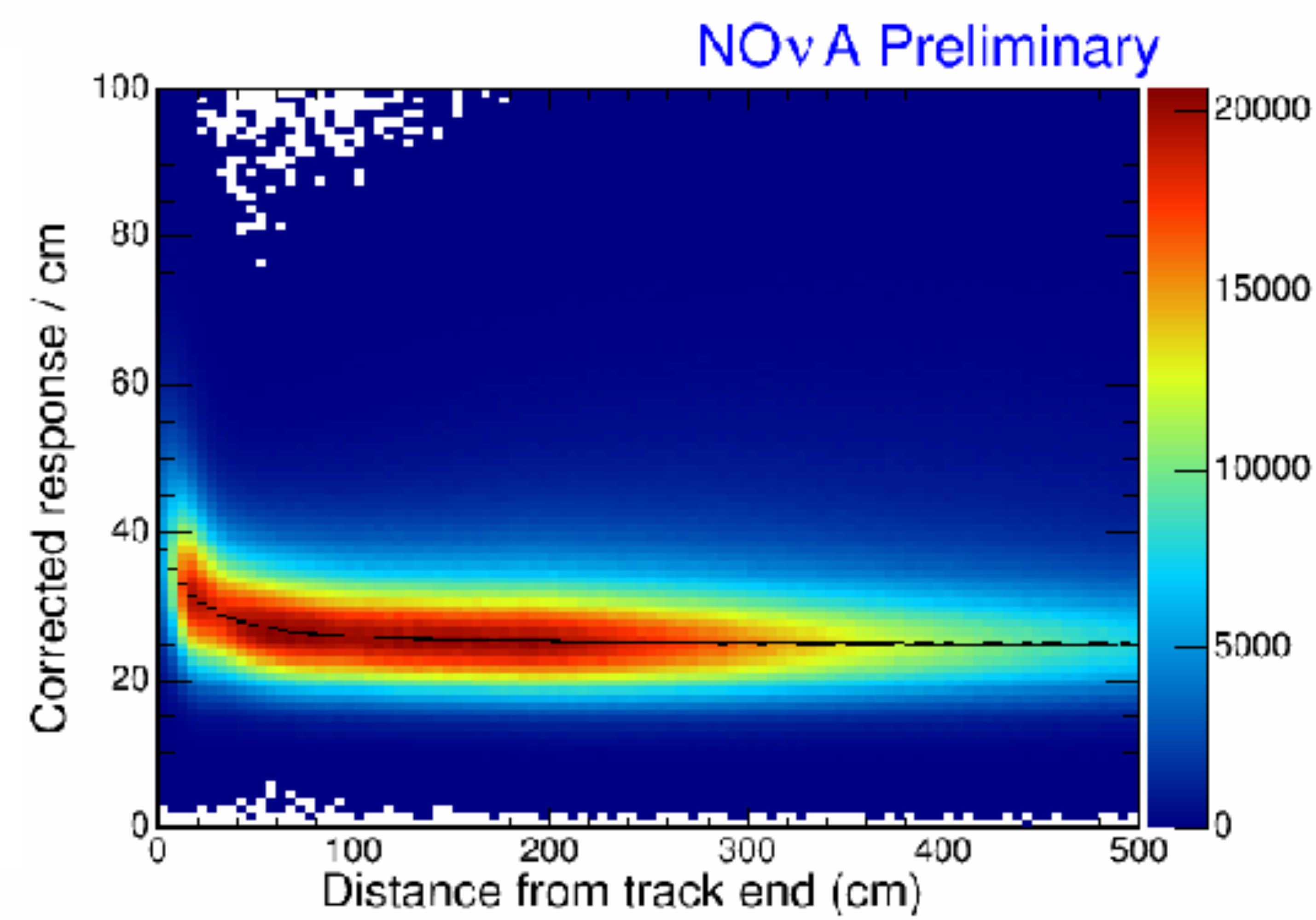


Detector Calibration

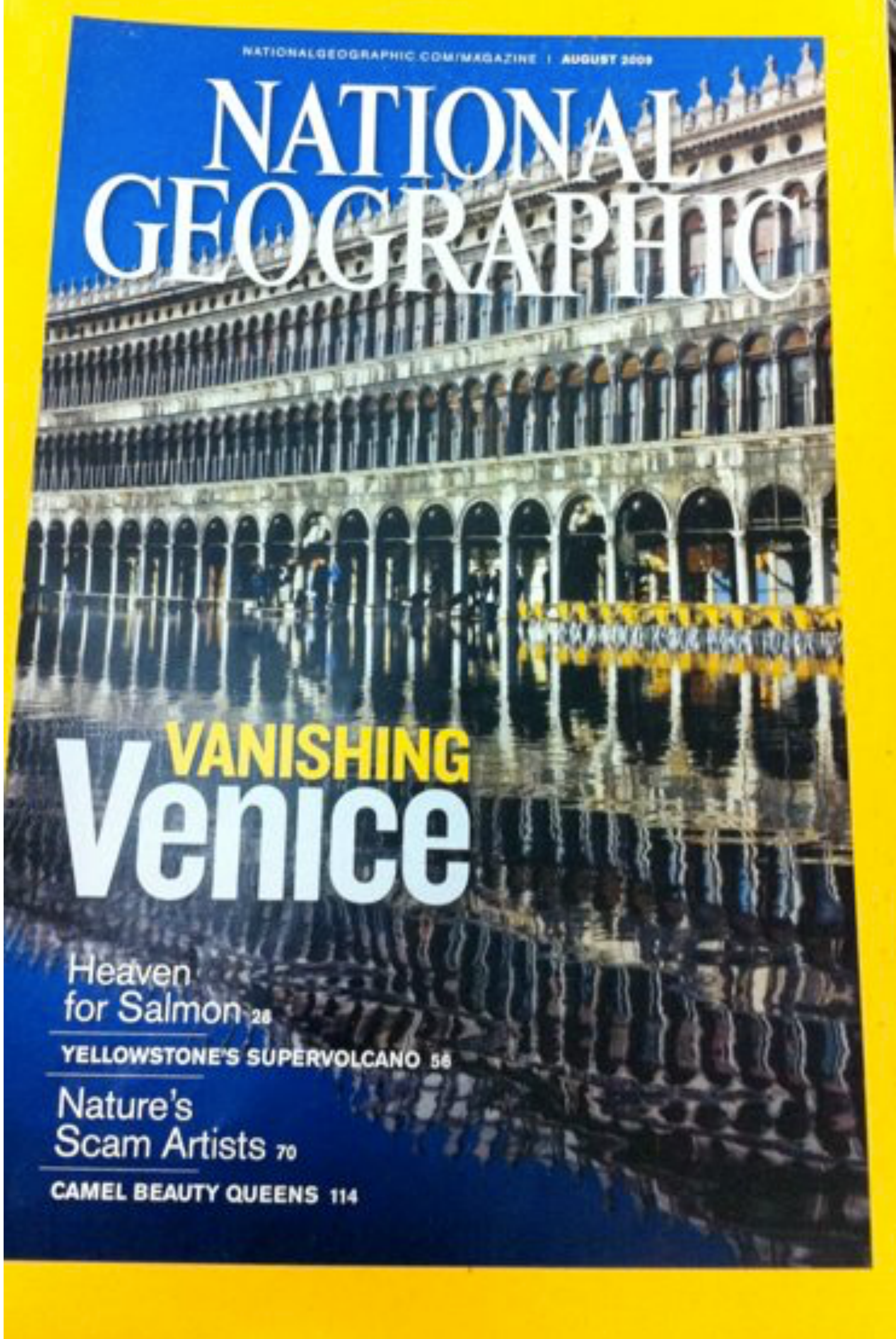
- Cosmic ray muons used to correct attenuation
- Stopping muons used as a standard candle





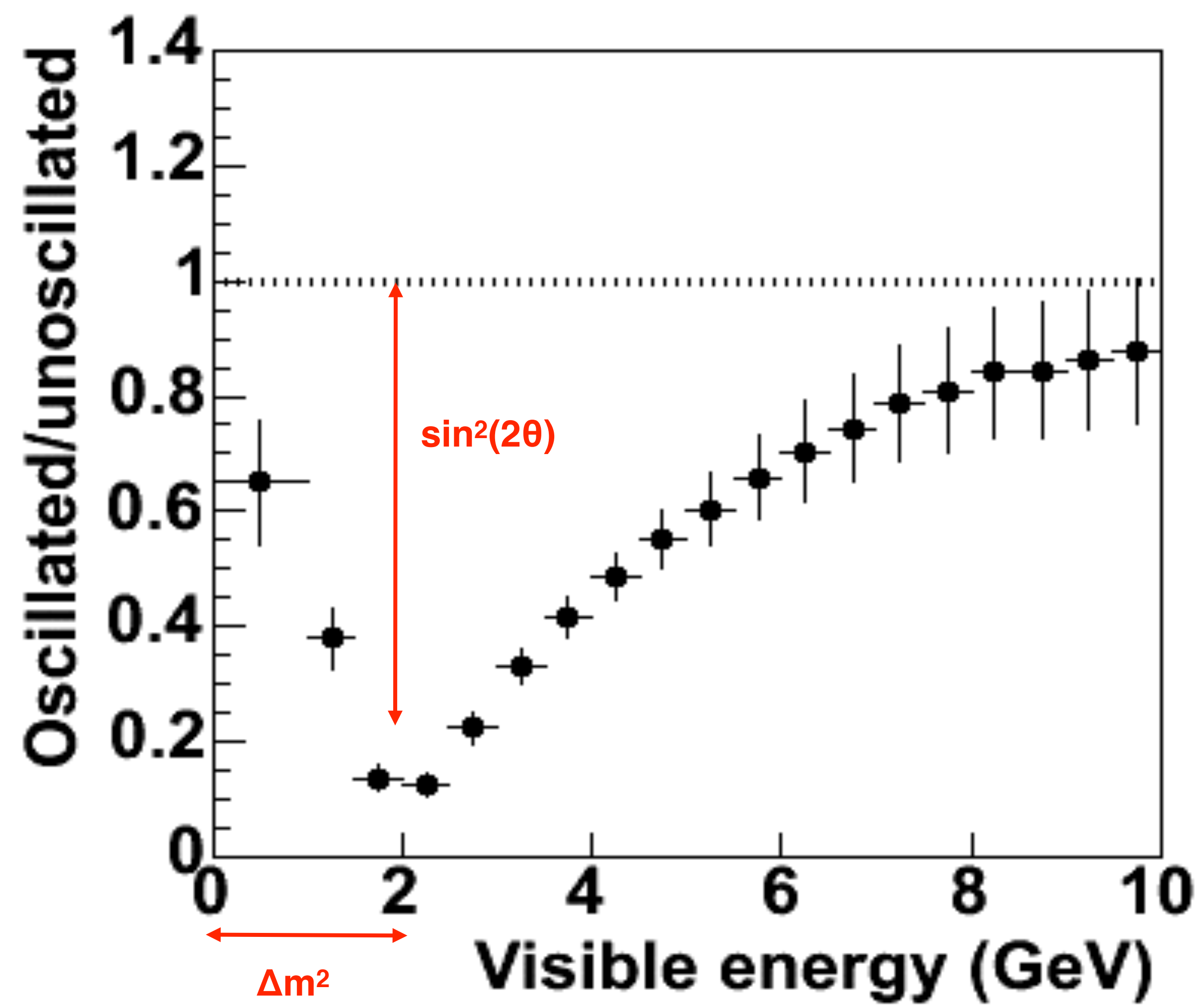


Muon-neutrino disappearance



Muon-Neutrino Disappearance

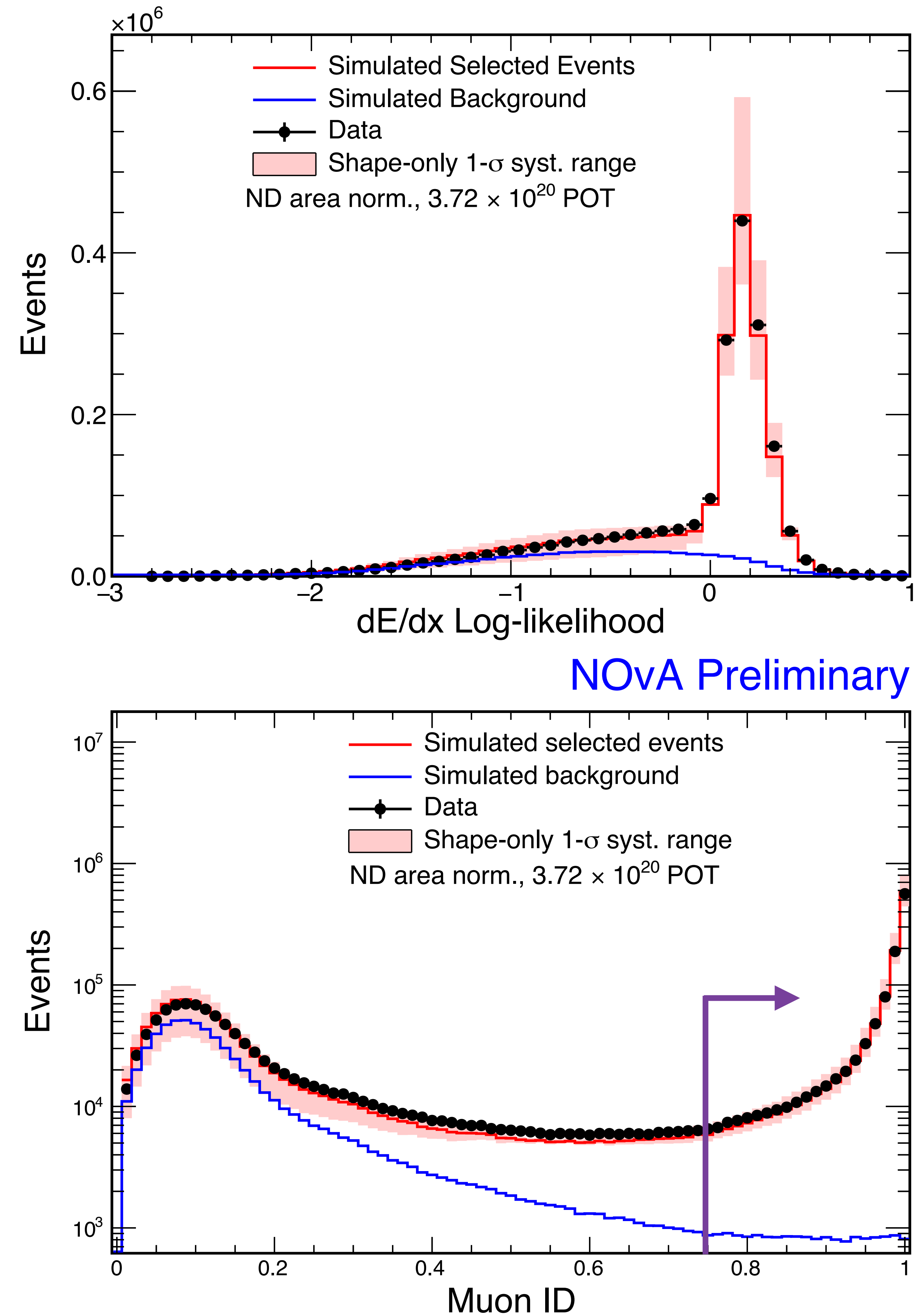
- Two-flavour approximation still basically valid (although analysis uses full three-flavour formalism)
- Measure neutrinos in the ND
- 'Extrapolate' measurements to form FD prediction
  - Taking into account geometry, efficiencies, purities, energy resolutions, etc.
- Compare FD data to predictions to find the best fit oscillation parameters



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

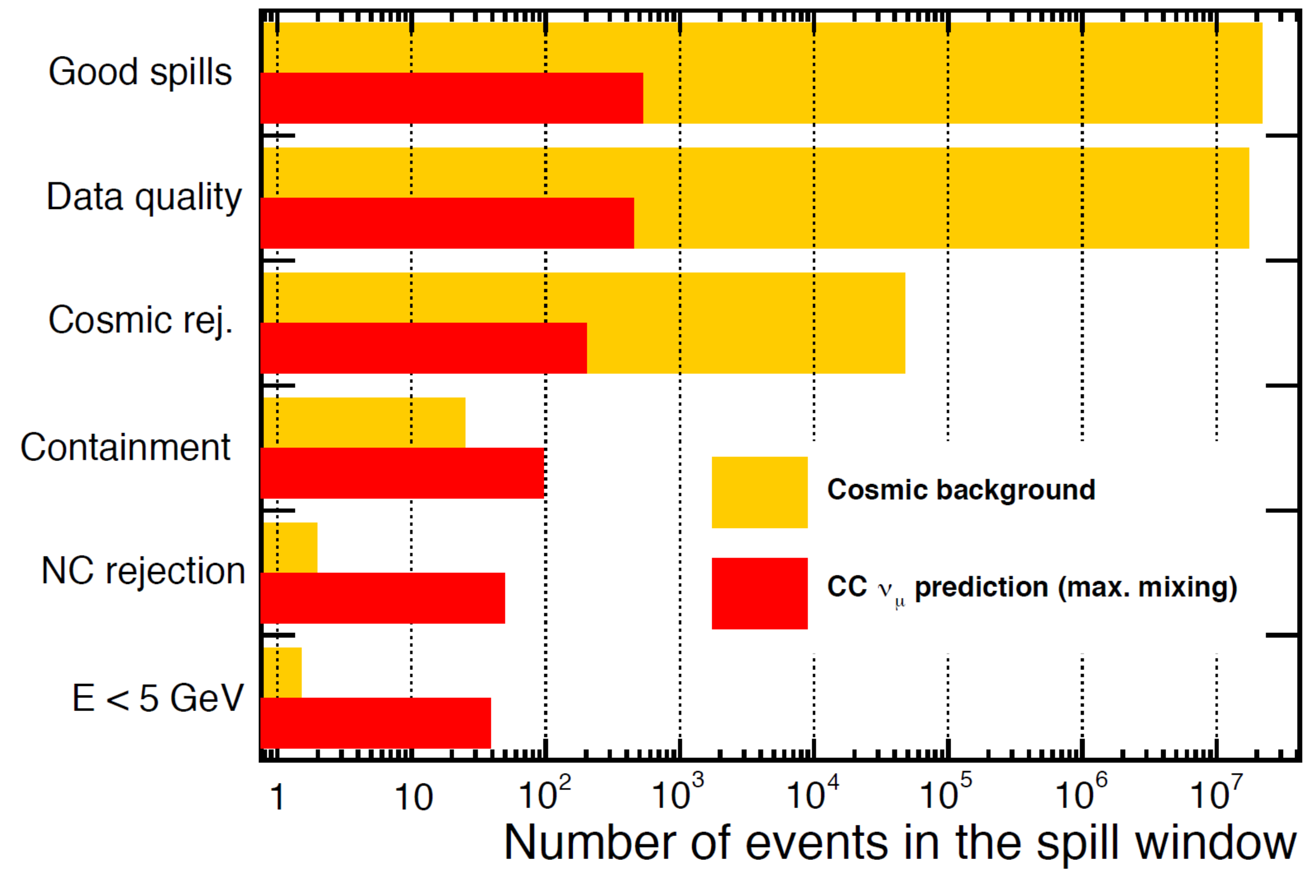
Muon-Neutrino Selection

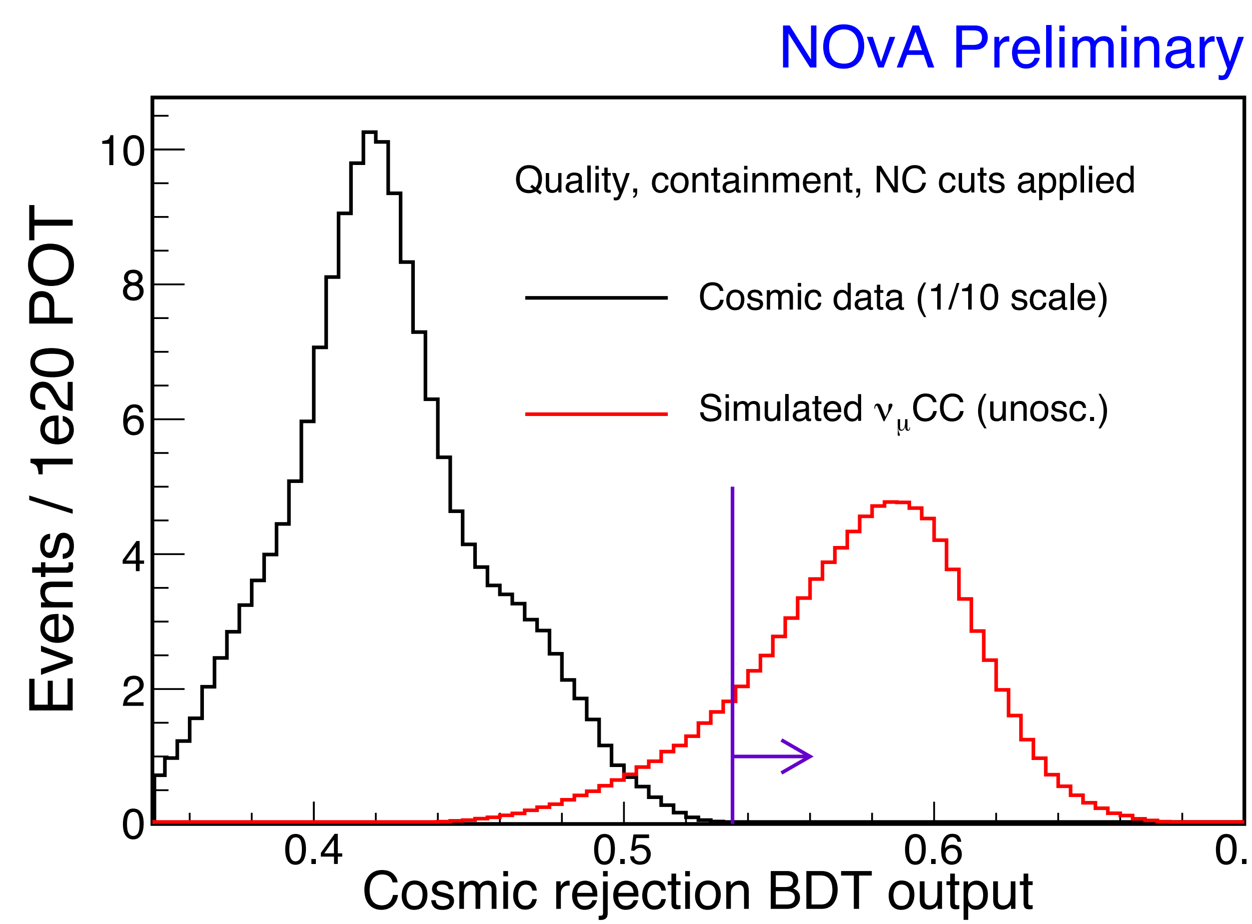
- Separate ν_μ-CC interactions from NC and cosmic-ray backgrounds
- Containment cuts remove activity near walls
- Four variable k-Nearest Neighbour to select muons
  - Track length
  - dE/dx along track
  - Scattering along track
  - Track-only plane fraction
- Selection is 81% efficient and 91% pure



Cosmic Rejection

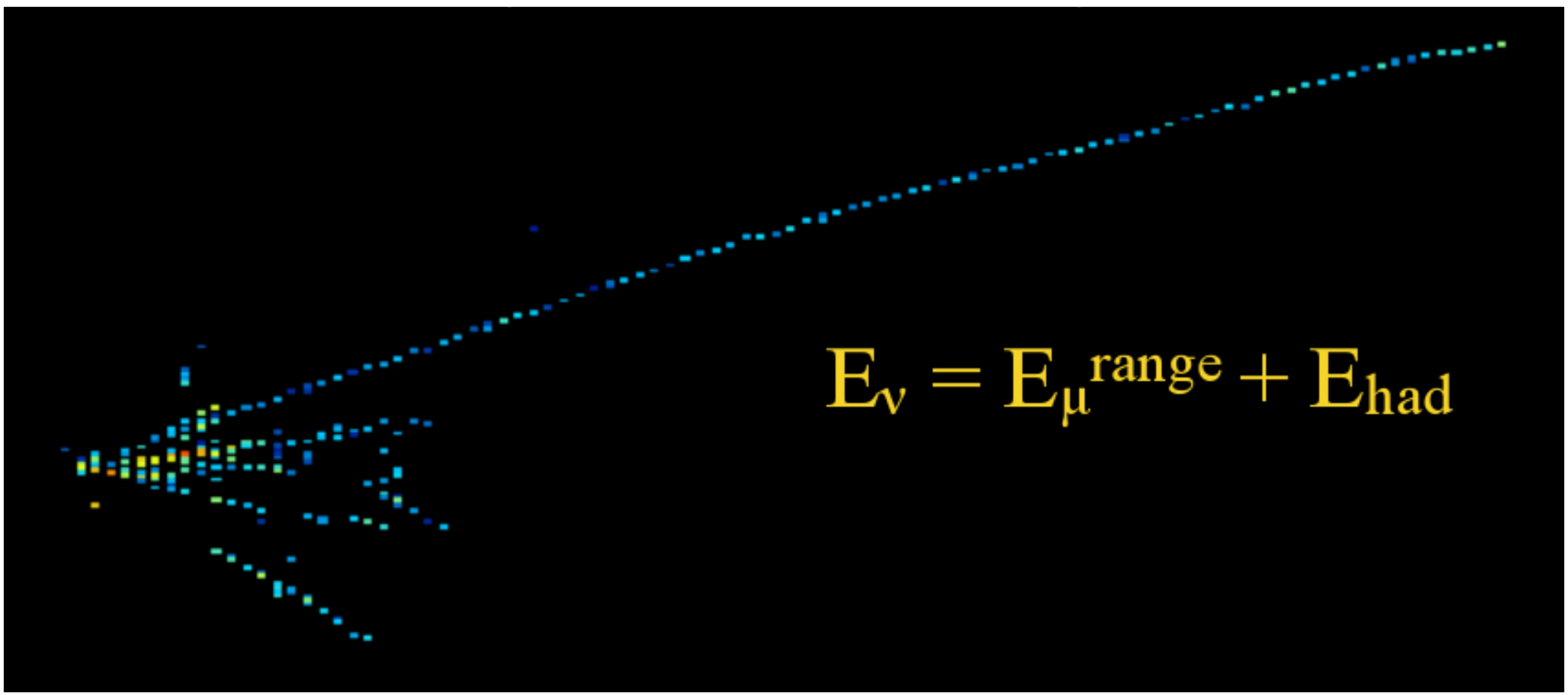
- Far Detector is on the surface and sees 150 kHz of cosmic induced events
- 10 µs beam window every 1.3s reduces background by 10^5
- Additional factor of 10^7 rejection achieved from event topology and a boosted decision tree (BDT) based on:
  - track direction
  - start/end points of track
  - track length
  - energy
  - number of hits
- Predict 2.7 cosmic background events





Energy Estimation

- Muon dE/dx used in length-to-energy conversion
- Hadronic energy estimated from calorimetric sum of non-muon hits
- ~7% resolution on neutrino energy



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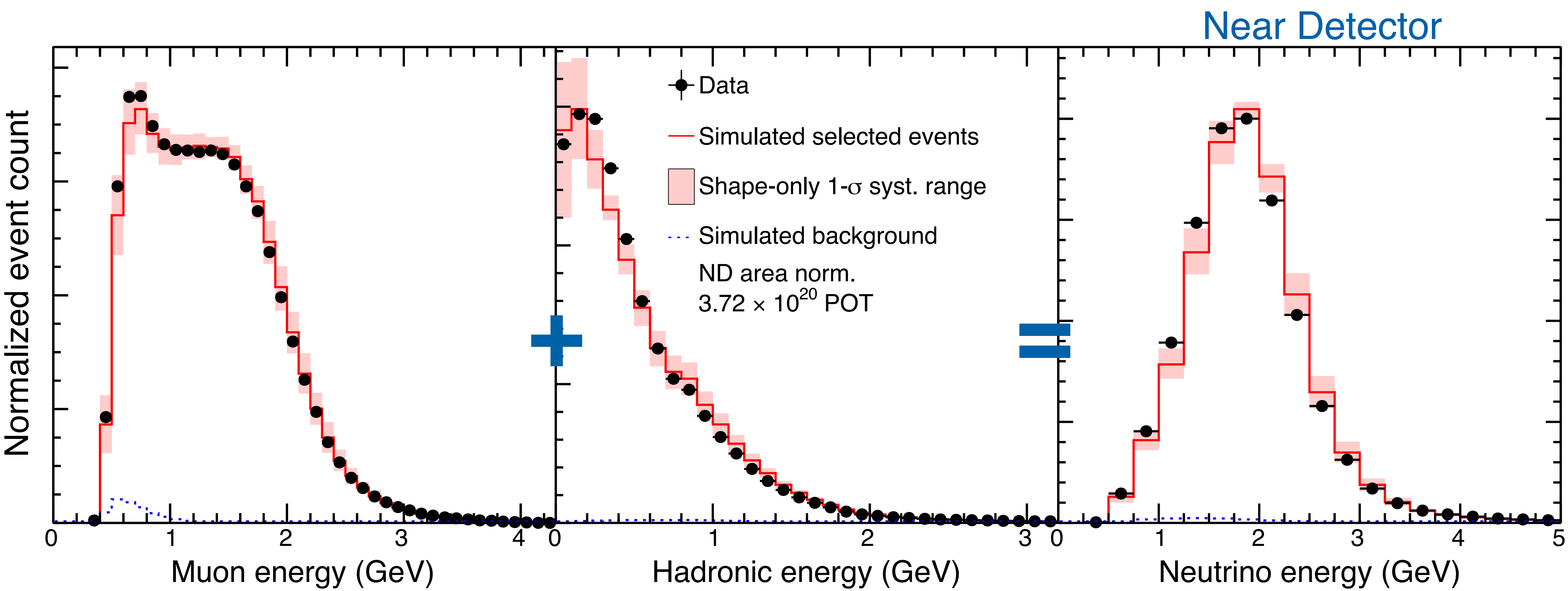
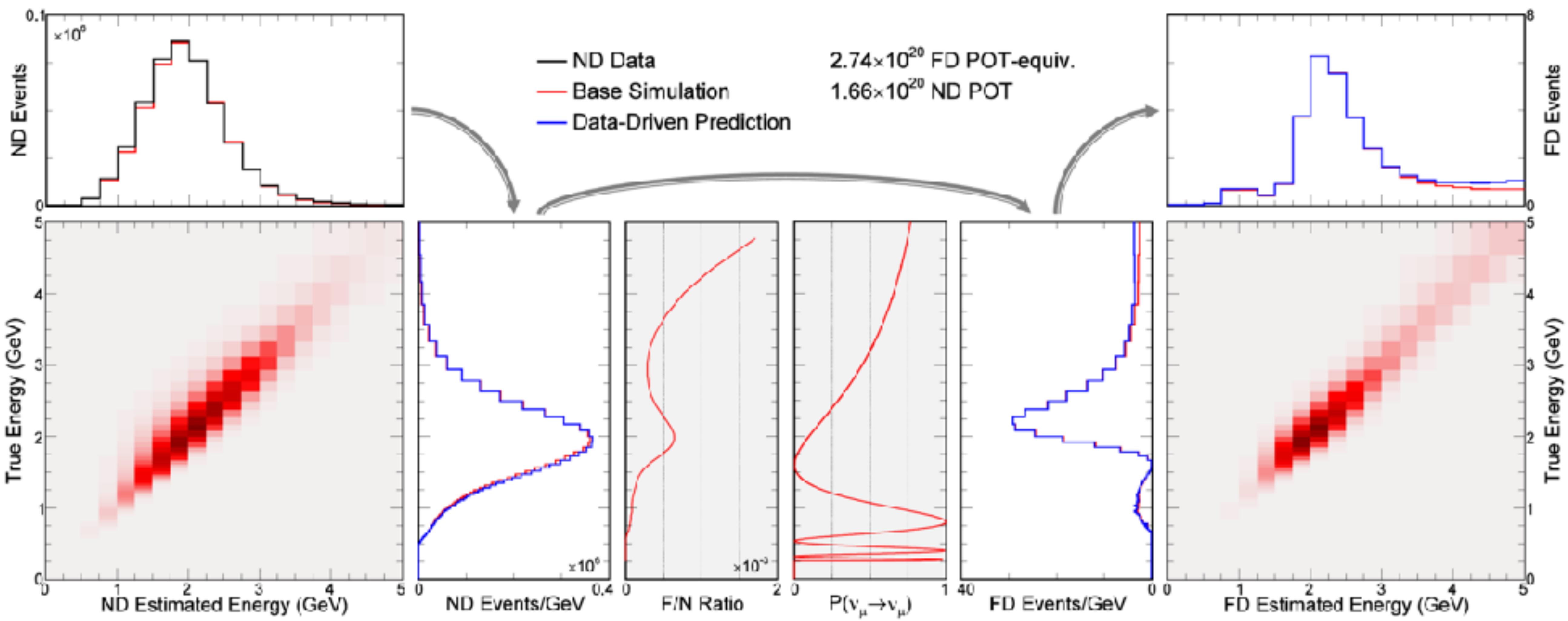


$$E_\nu = E_\mu(L_\mu) + E_h$$

Extrapolation

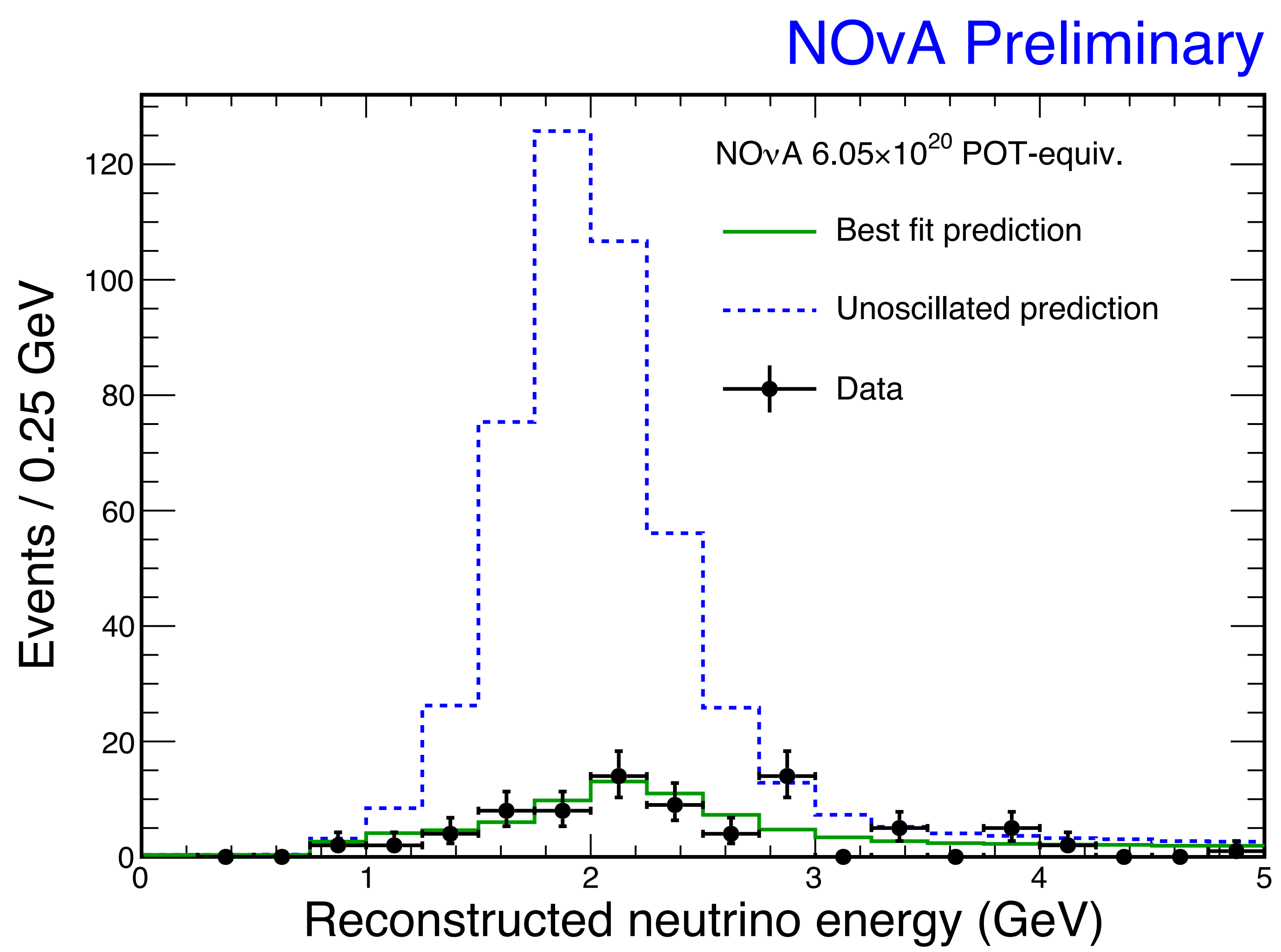
- Use high statistics ND data/MC to adjust prediction at FD
    - Translate ND data/MC observation to true energy
    - Oscillate ratio to the FD
    - Smear back into reconstructed energy



Muon-Neutrino Disappearance

arXiv:1701.05891

- Using 6.05×10^{20} POT equivalent
- 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



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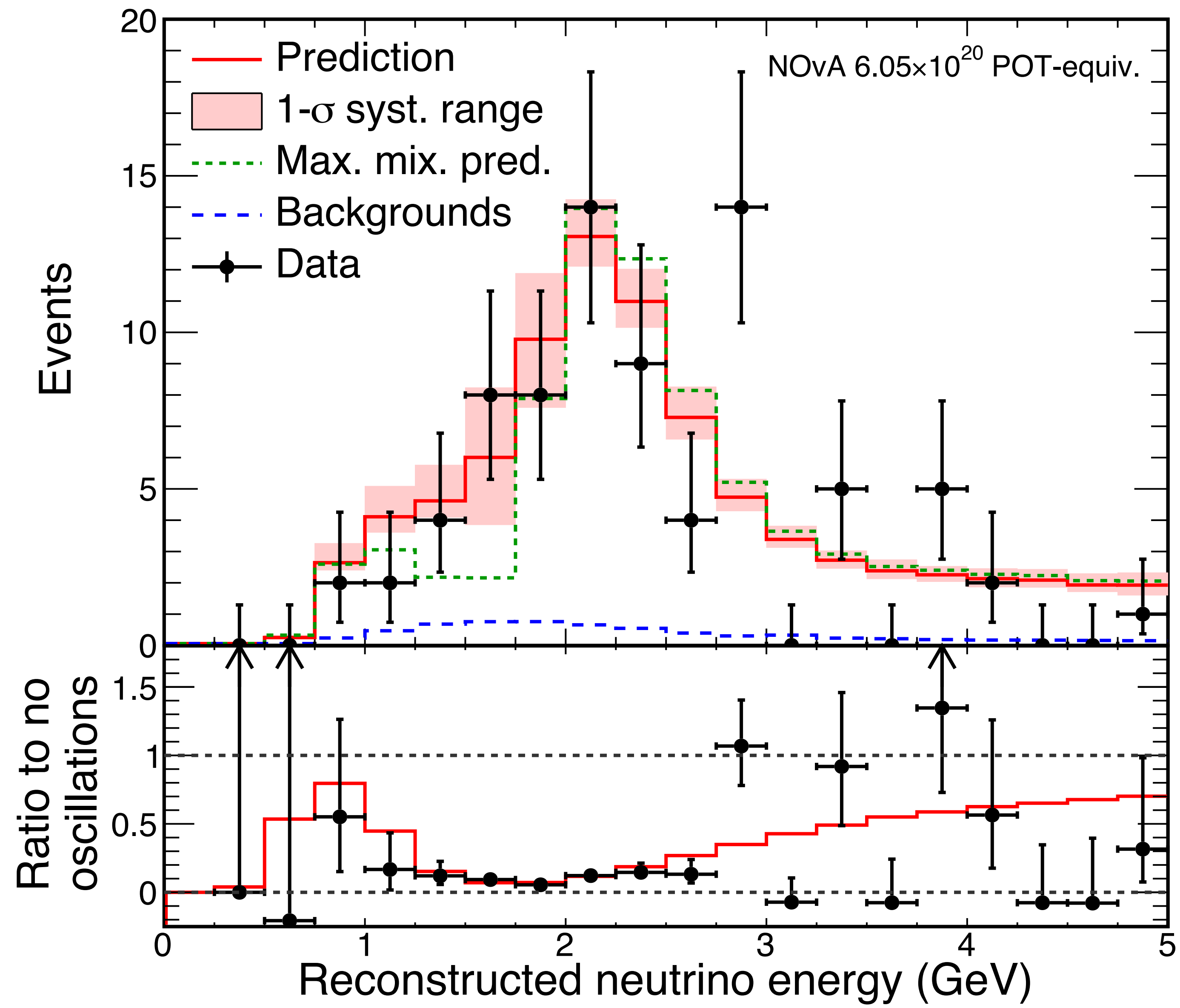

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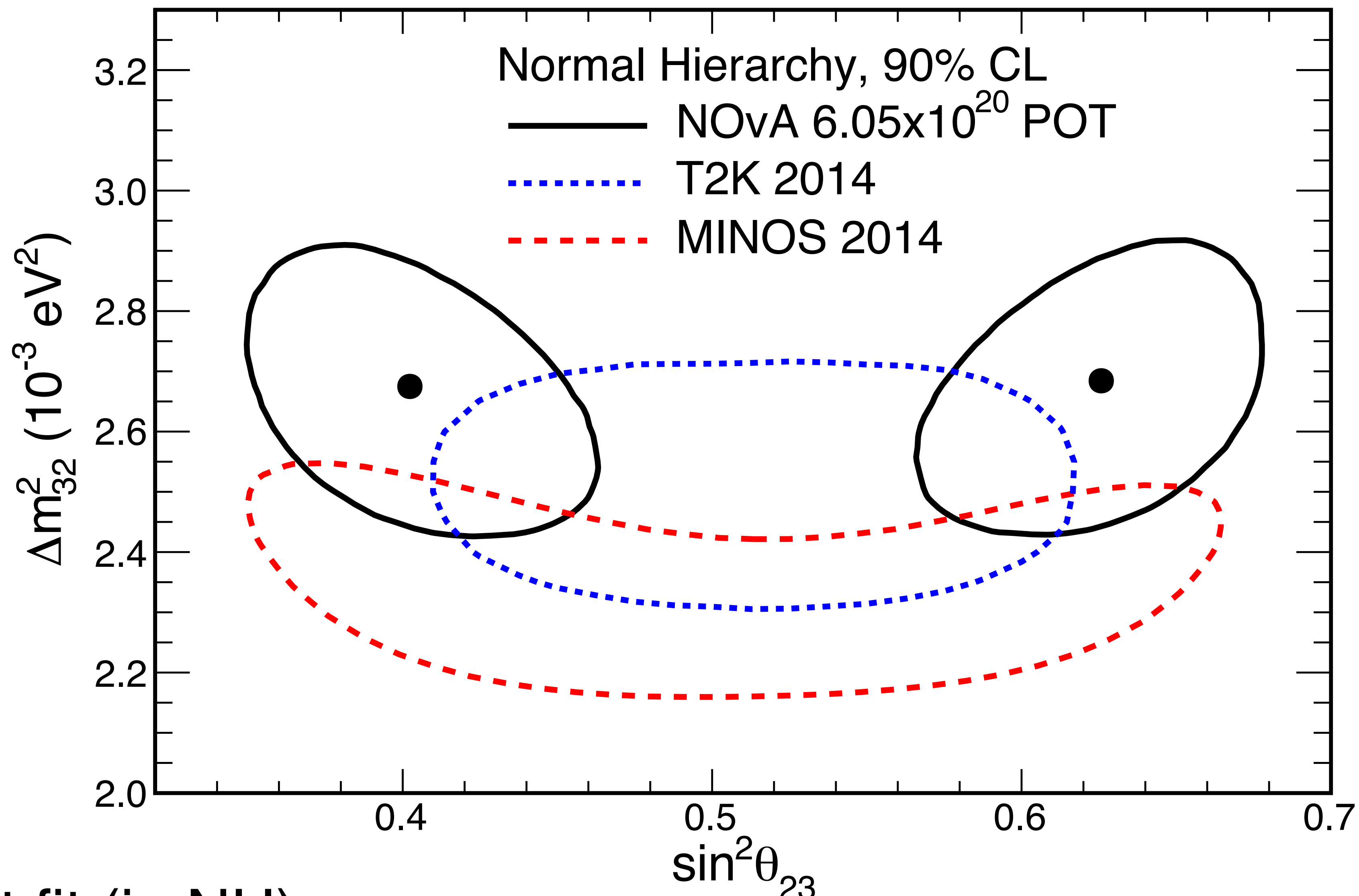


Best fit (in NH):

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

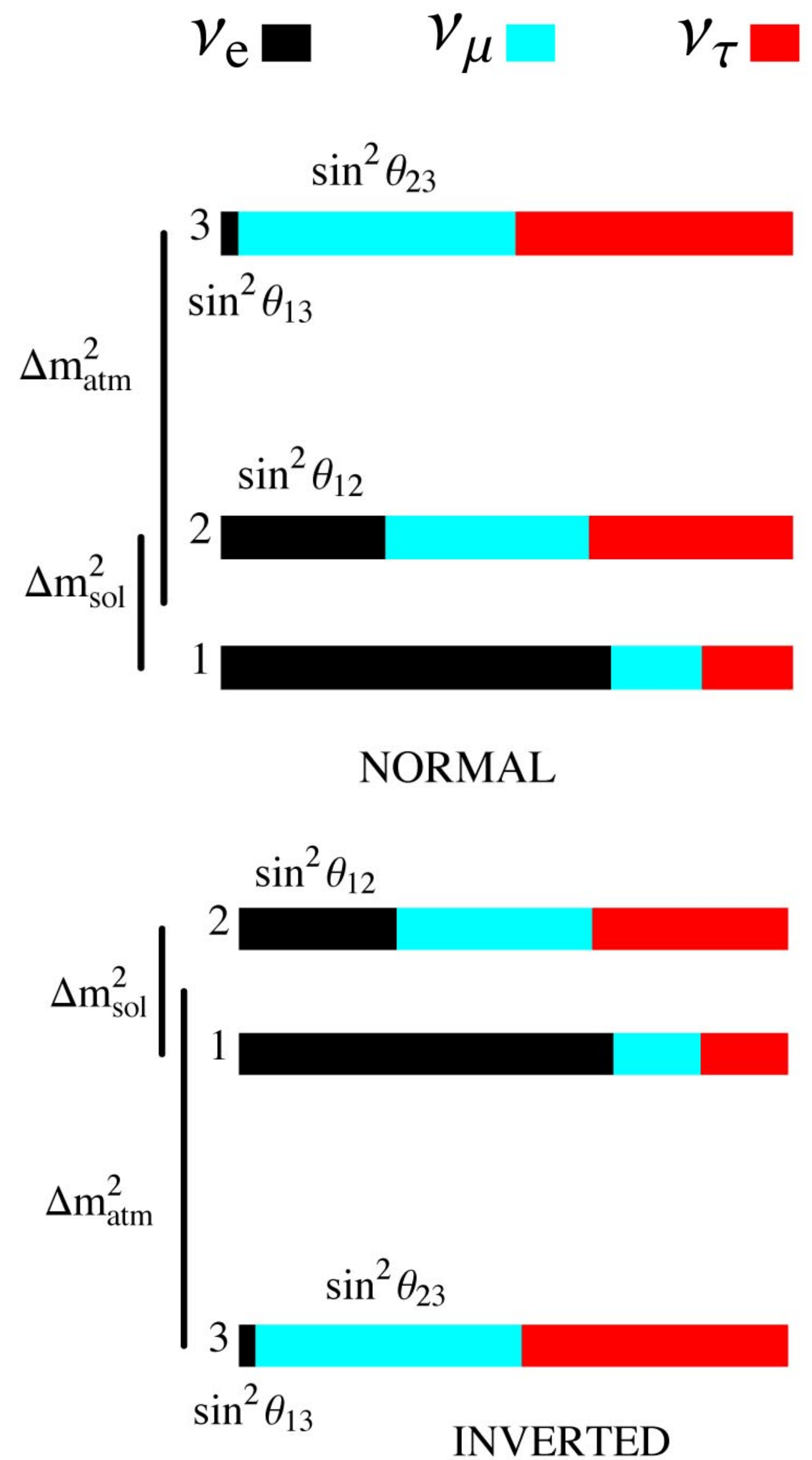
$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}(0.624^{+0.022}_{-0.030})$$

- Maximal-mixing disfavoured at 2.6 sigma
- Interesting tension between NOvA and T2K, new results eagerly anticipated

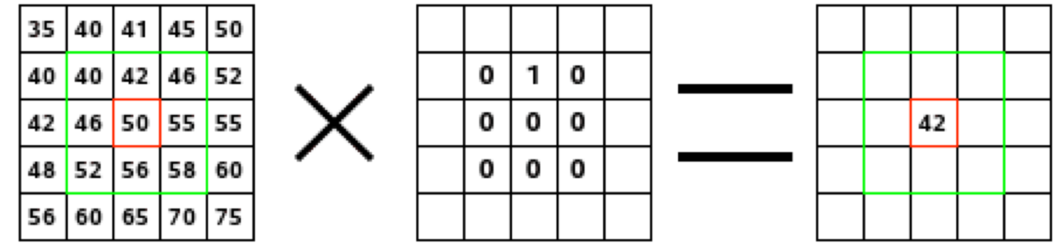
Electron-Neutrino Appearance

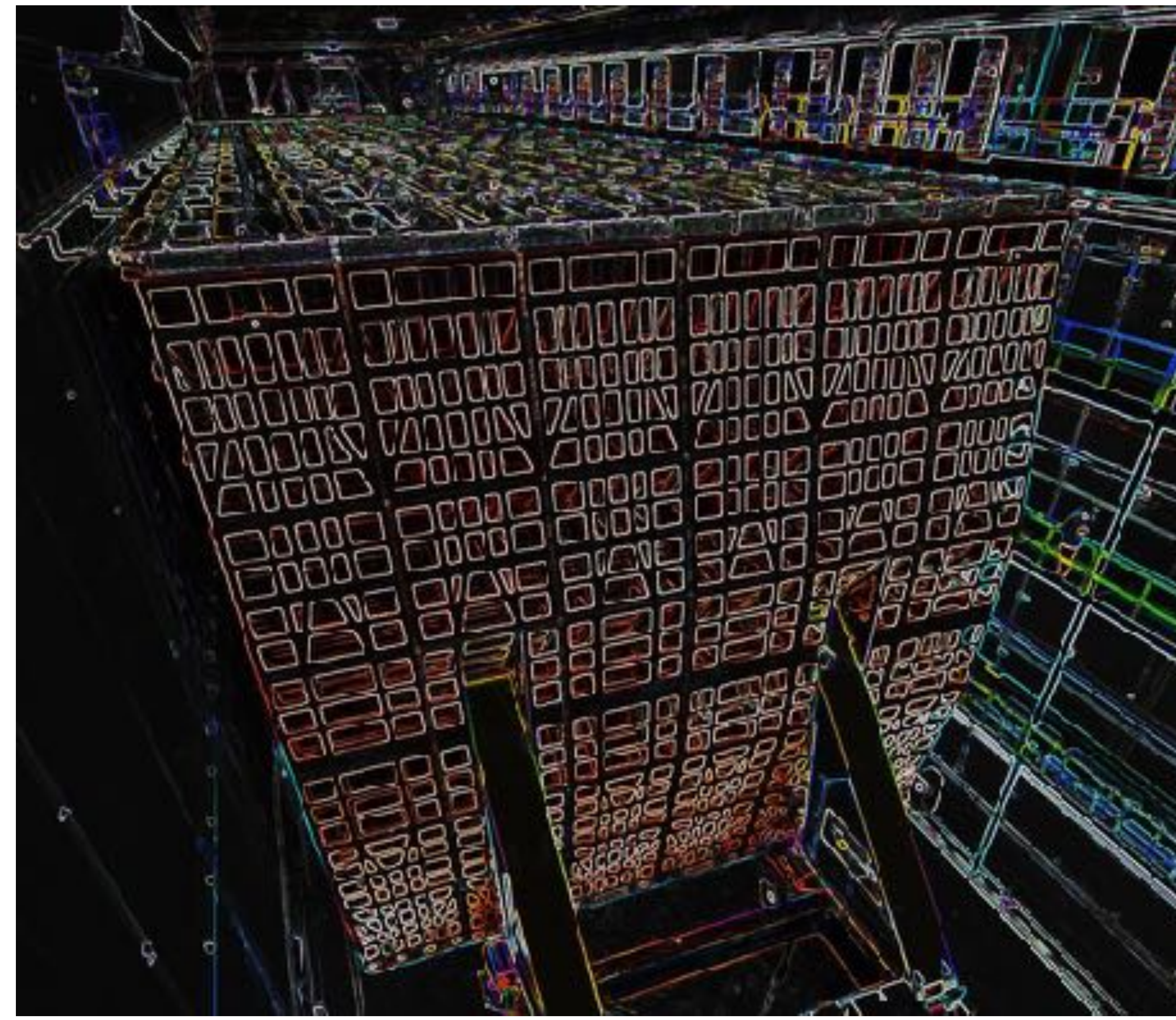
Electron-Neutrino Appearance

- Electron-neutrino appearance is a sub-dominant oscillation mode at the NOvA L/E
- Matter effects matter (almost 3 times longer baseline than T2K)
- Sensitive to
  - Mass hierarchy
  - CP violating phase
  - Octant of θ_{23}



New Classification Algorithm



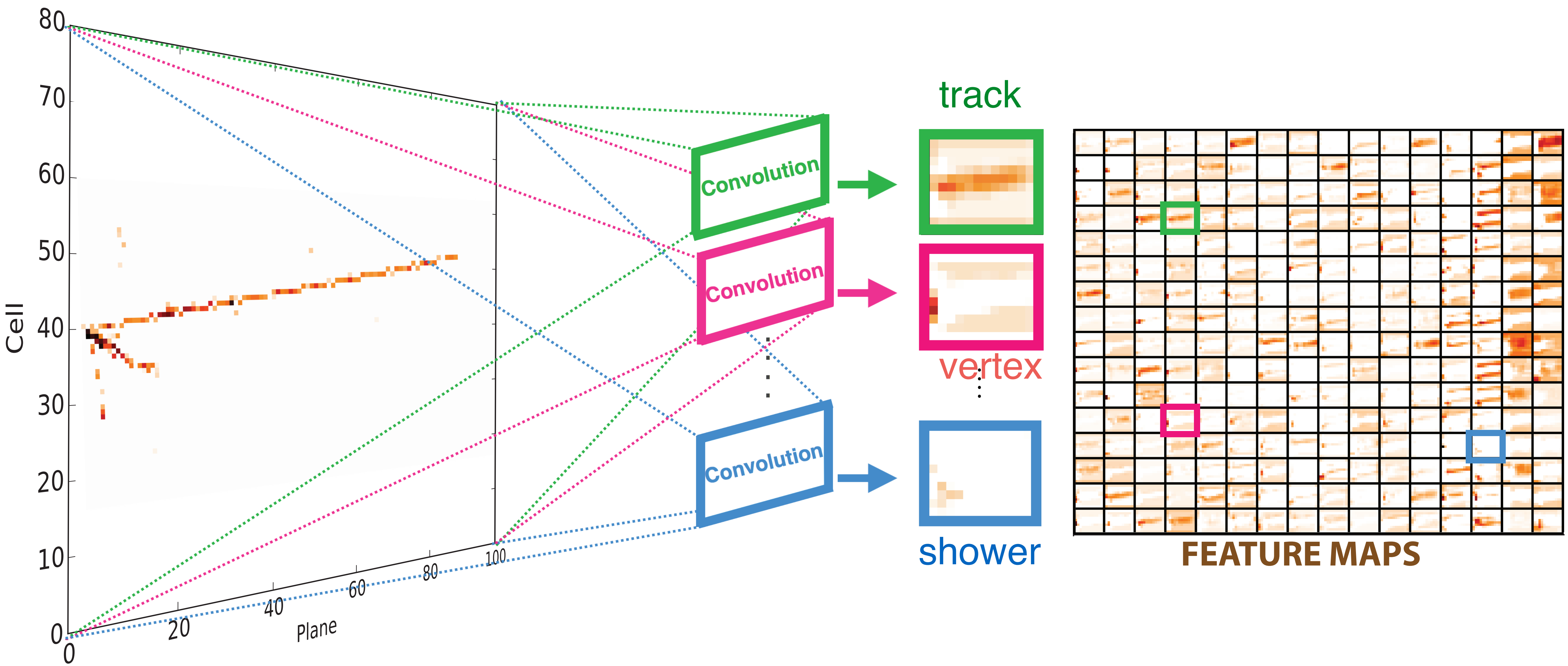


- Take advantage of recent advances in machine learning/computer vision
- Deep networks extract complex features from input data, GPUs greatly improve training time
- Inputs to the network are pixels in image
- Apply convolutional kernels to pull out event features

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

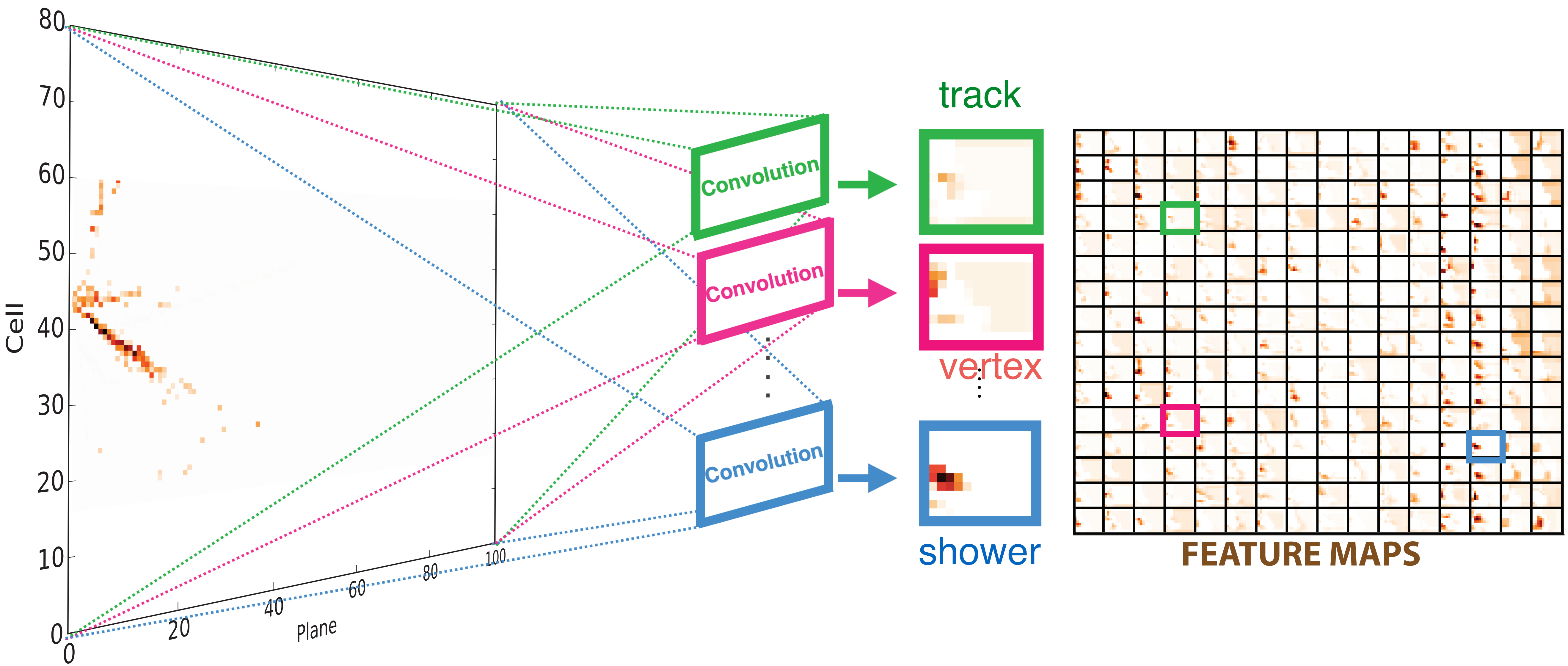
Convolutional Visual Network (CVN) Selection

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



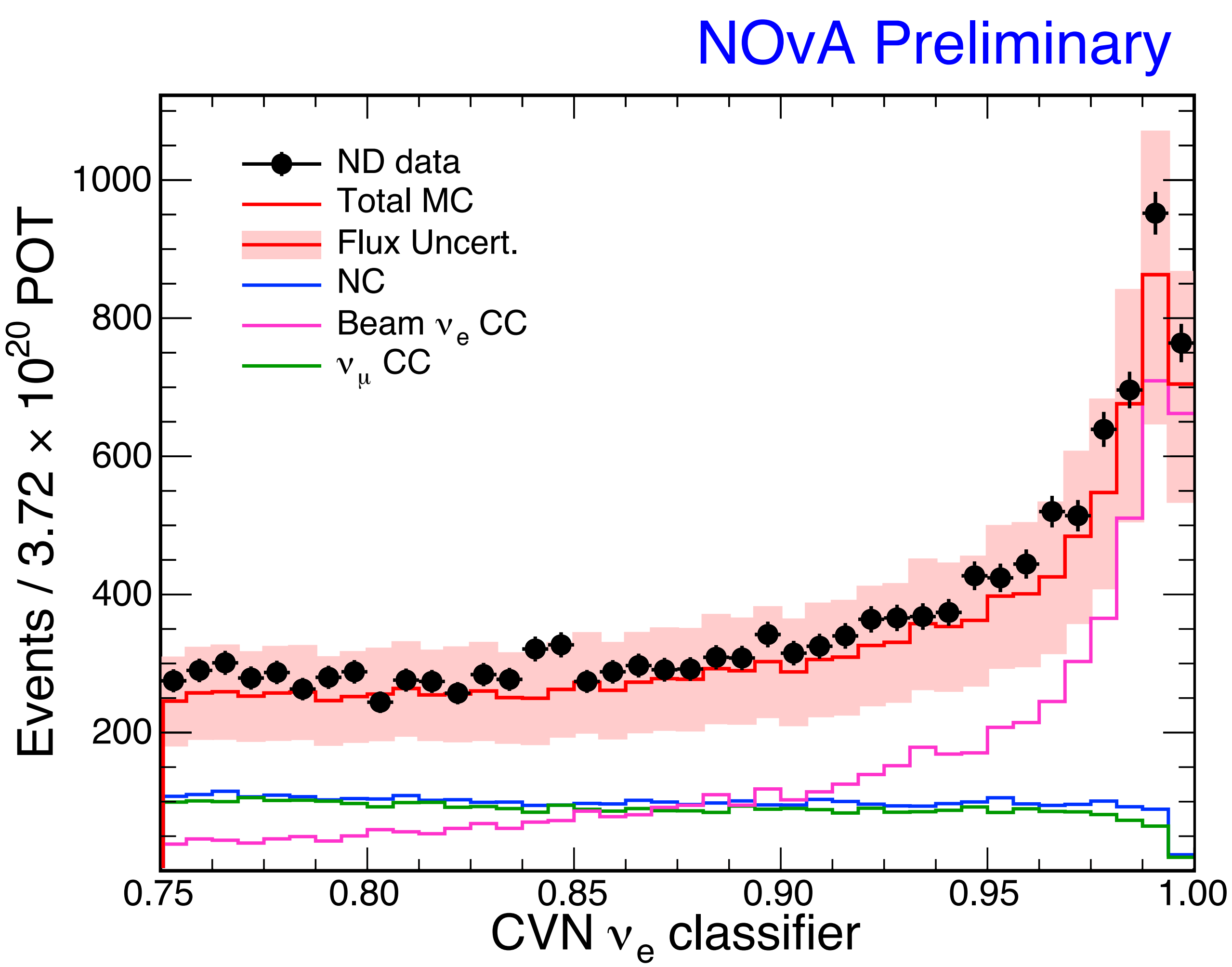
Convolutional Neural Networks

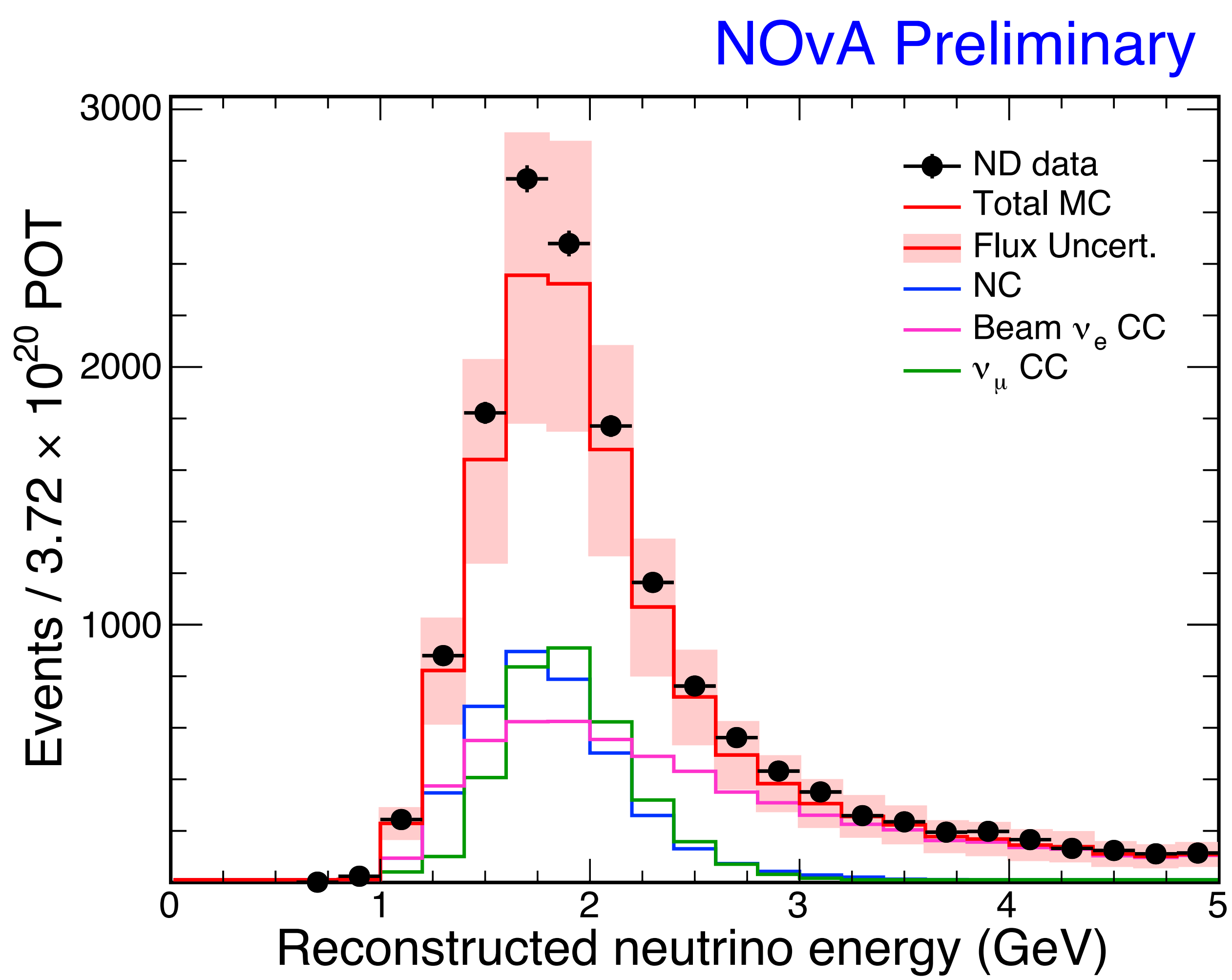
- Showing a electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
- The strong features extracted are the shower as opposed to the track



Electron Neutrino Selection

arXiv:1703.03328

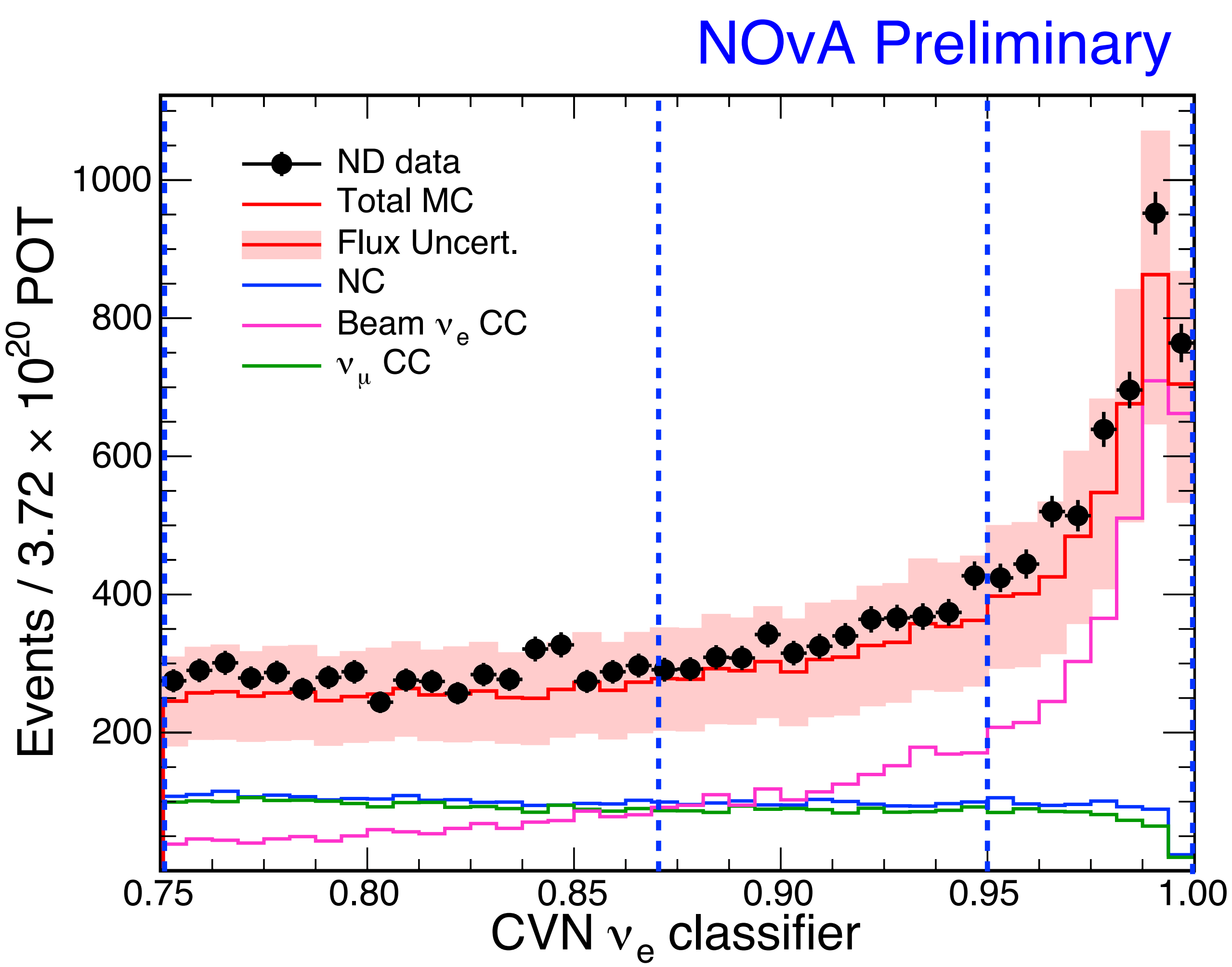


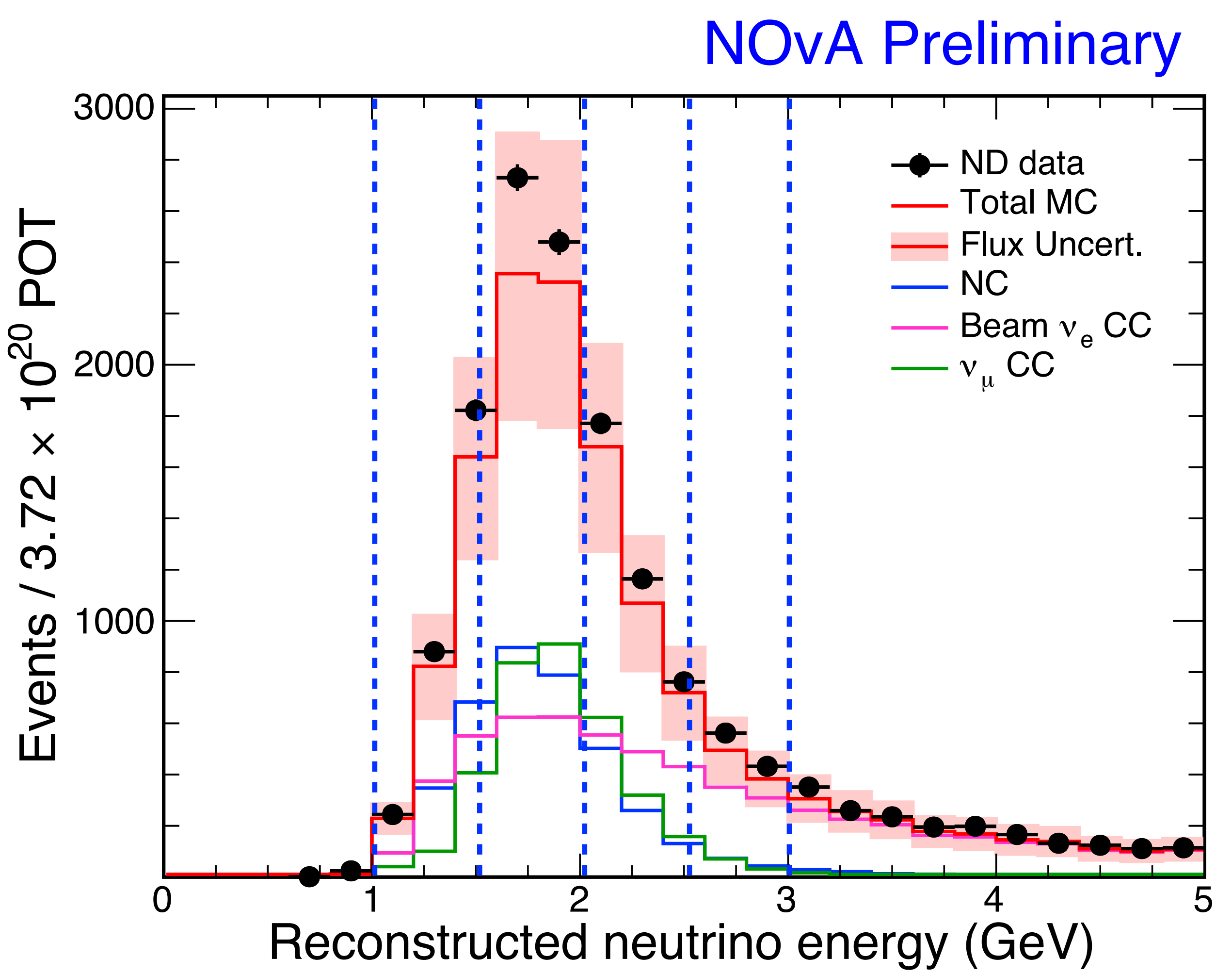


- 73% ν_e CC selection efficiency, 76% purity with CVN classifier
- Good ND Data/MC agreement
- CVN provides better cosmic rejection and similar systematics to 2015 classifiers

Electron Neutrino Selection

arXiv:1703.03328



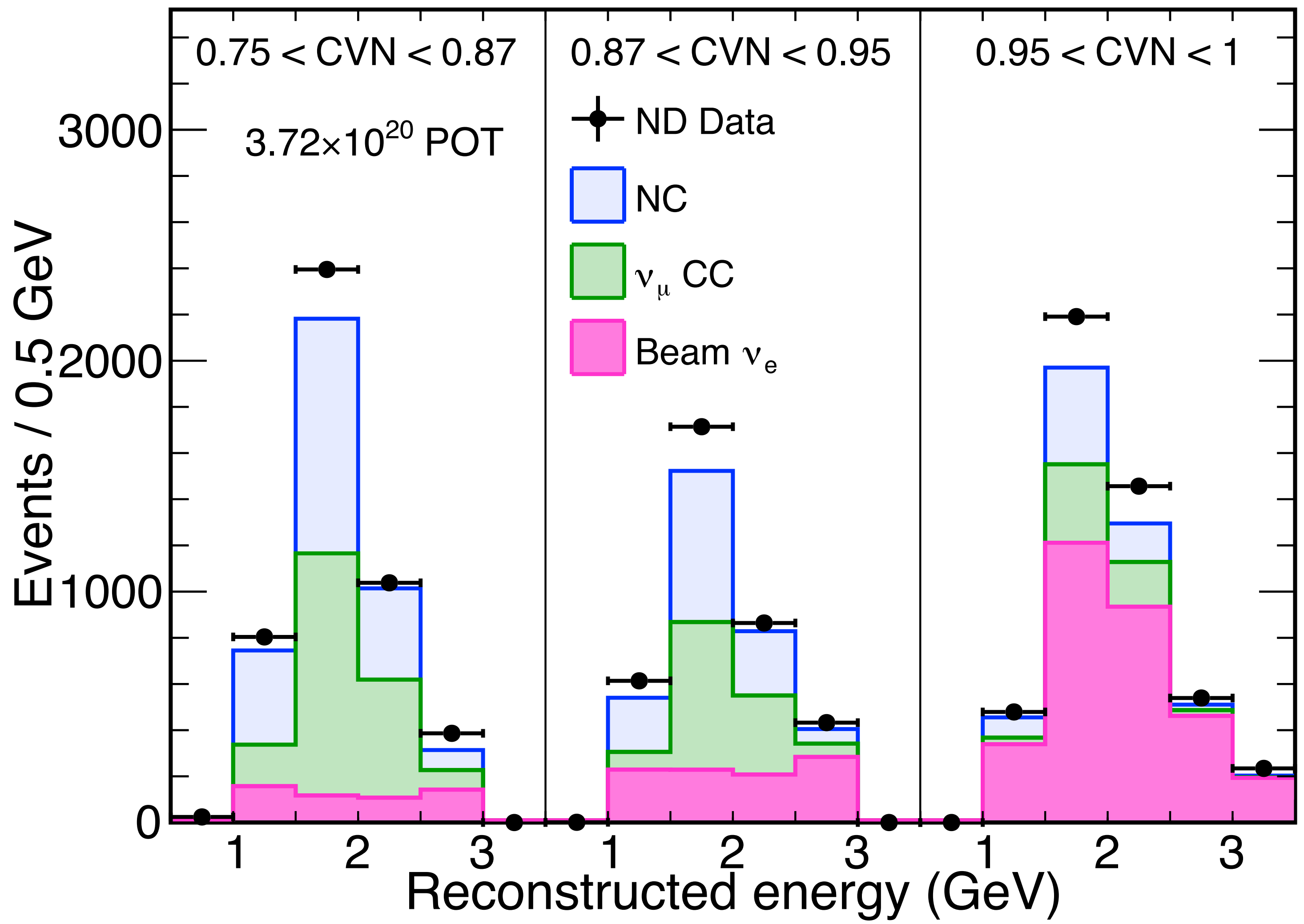


- Bin analysis in four bins of energy and three of CVN

Data Driven Background Corrections

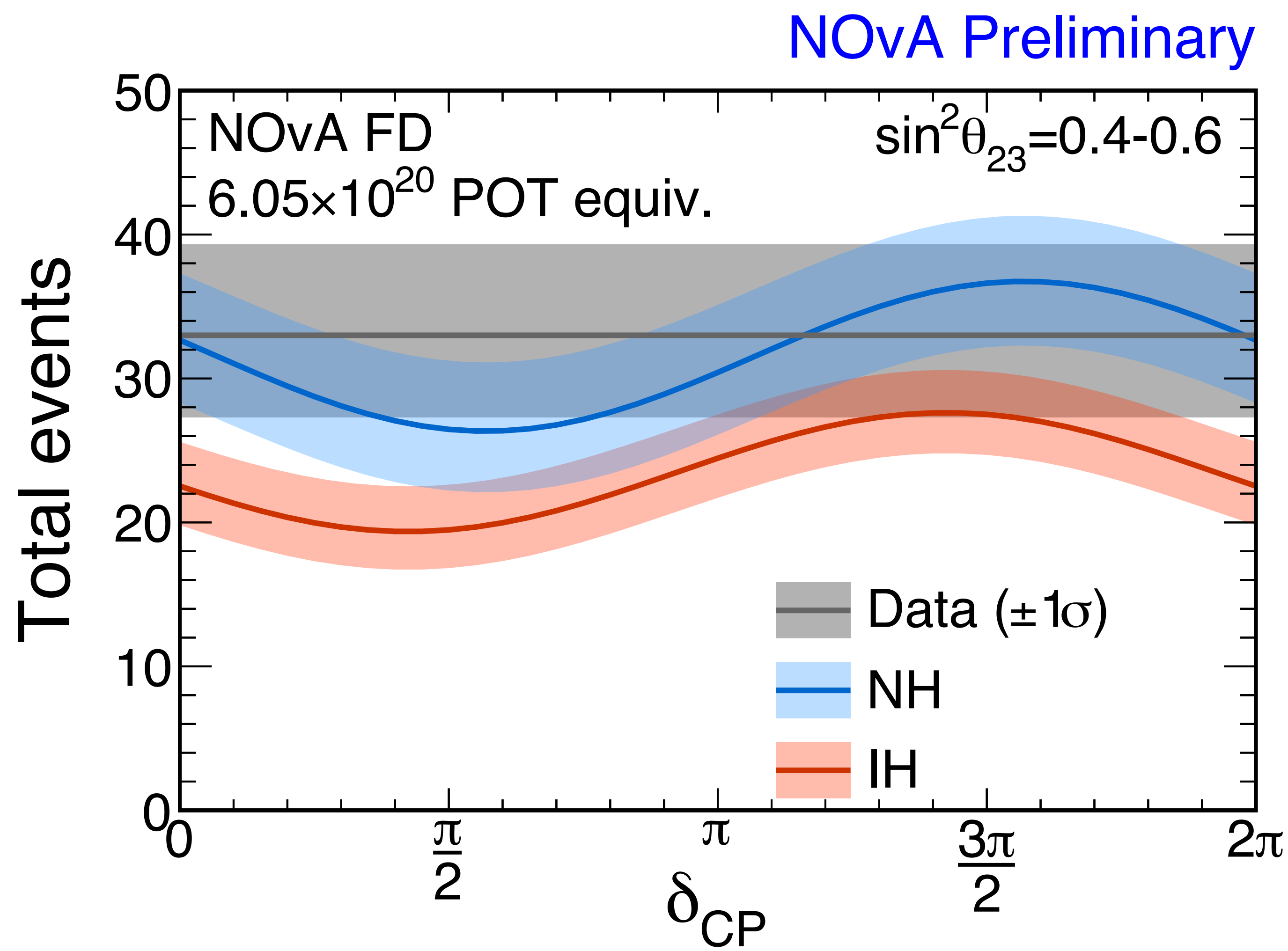
arXiv:1703.03328

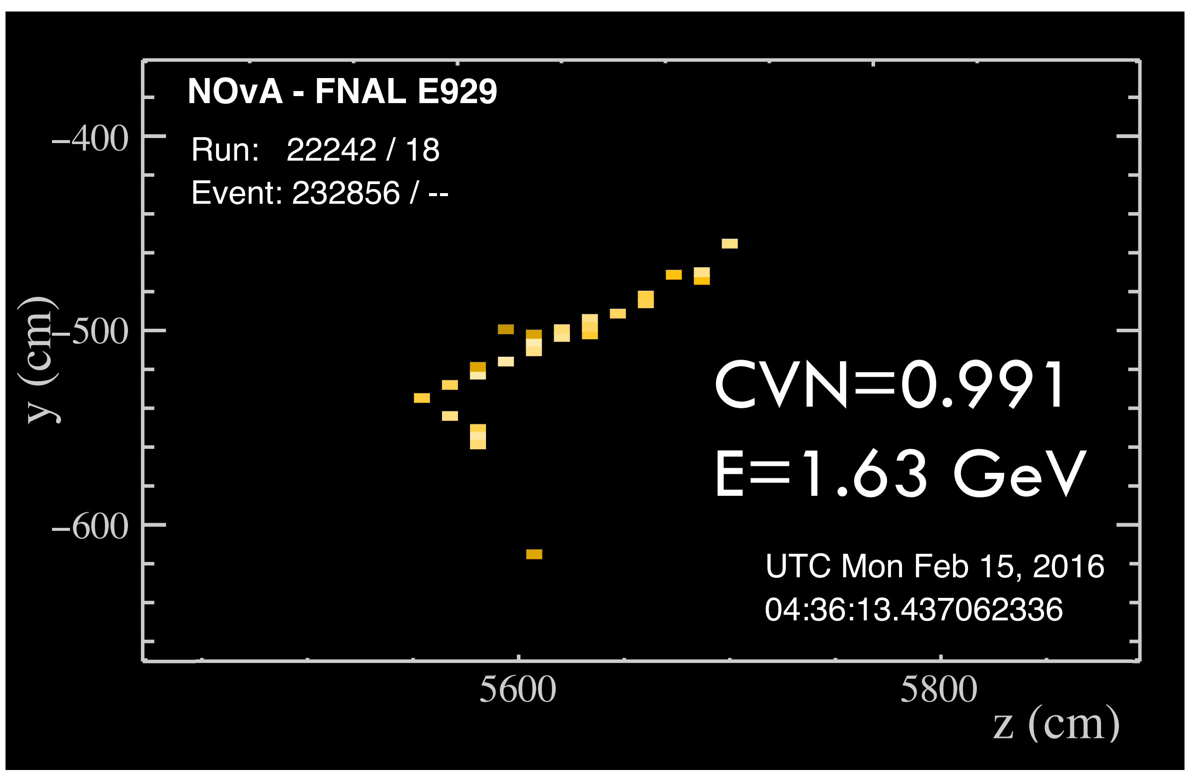
- ν_e-CC selection in the ND picks out FD backgrounds
  - Beam ν_e-CC
  - ν_μ-CC
  - Neutral current
- ~10% excess of data over MC in the ND
- Extrapolate data/MC differences to adjust FD prediction
- Each component oscillates differently
- Must decompose the data into constituent components

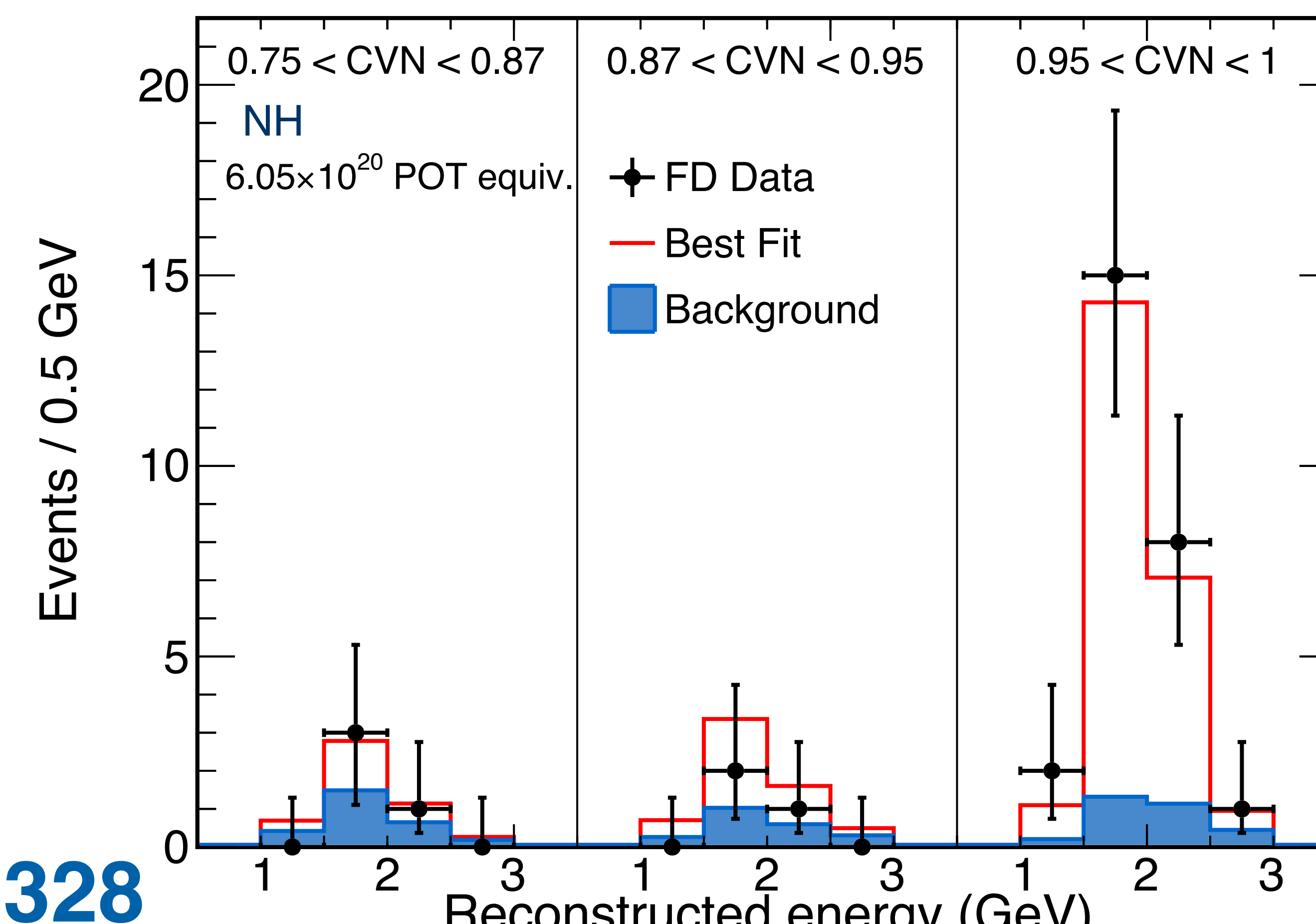


Electron-neutrino appearance

- Observe 33 events on background of 8.2 +/- 0.8 events
- Over 8σ significance of electron-neutrino appearance







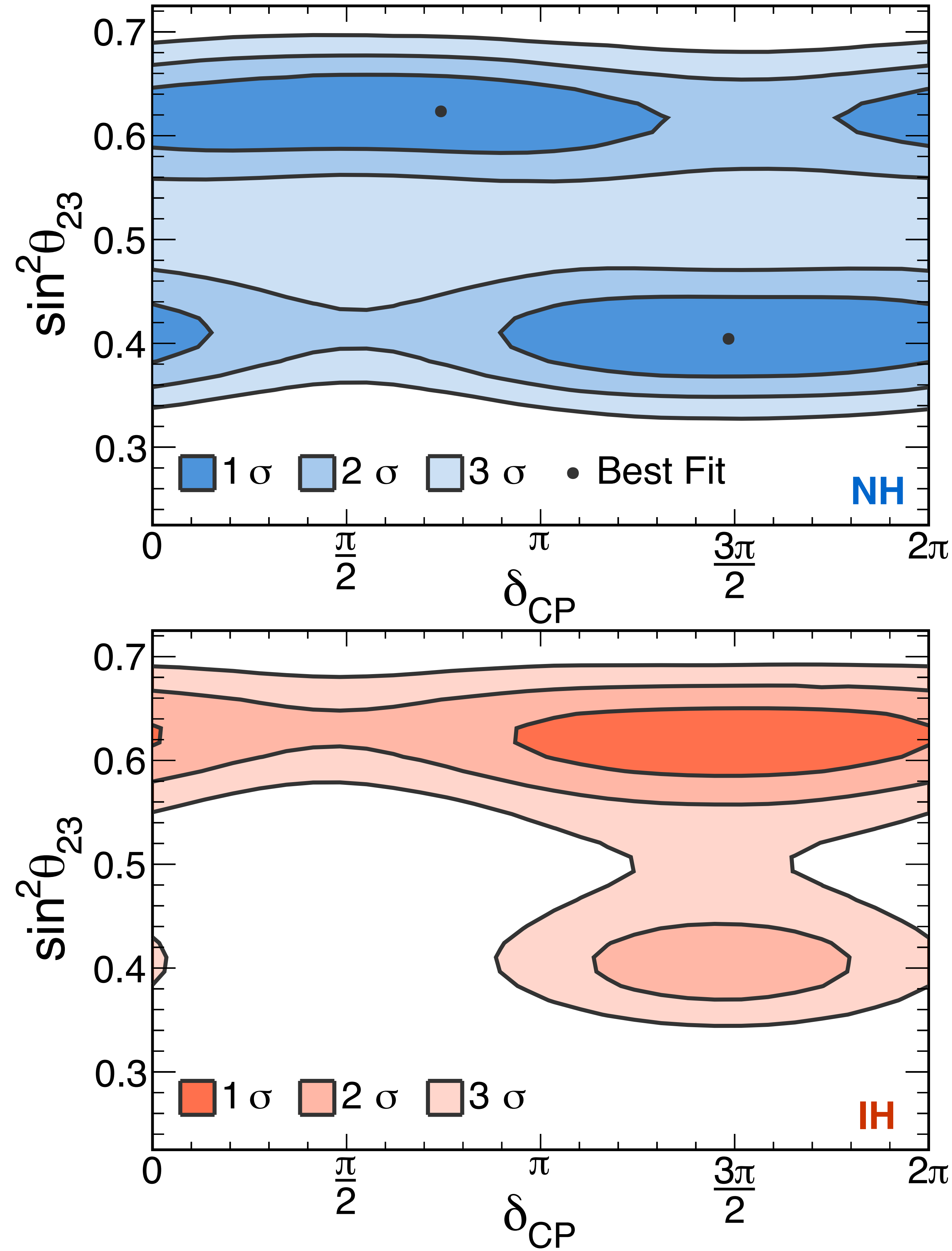
arXiv:1703.03328

$\nu_\mu \rightarrow \nu_e$ 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 NOvA disappearance data
- Global best fit, two degenerate points in Normal Hierarchy

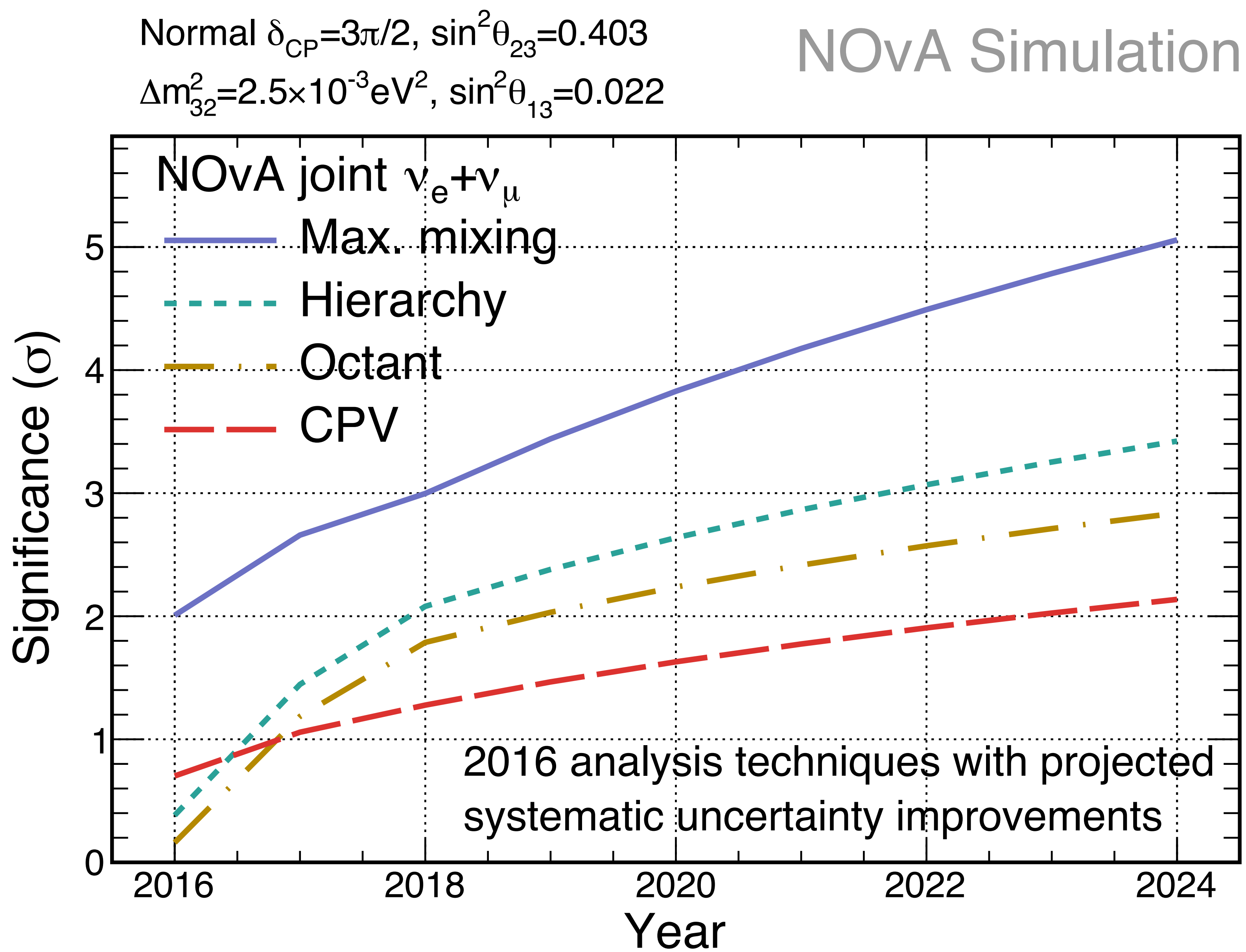
$$\delta_{cp} = 1.48\pi, \sin^2(\theta_{23}) = 0.404$$
$$\delta_{cp} = 0.74\pi, \sin^2(\theta_{23}) = 0.623$$

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



arXiv:1703.03328

Looking Forward



- Switched to anti-neutrino running in February 2017
- Run 50% neutrino, 50% anti-neutrino after 2018
  - 3 σ sensitivity to maximal mixing of θ_{23} in 2018
  - 2 σ sensitivity to mass hierarchy and θ_{23} octant in 2018-2019

Conclusions

- Analysis of 6.05×10^{20} POT of NOvA data (1 nominal year)
- Muon-neutrino disappearance (arXiv:1701.05891)
  - Best fit is non-maximal value of θ_{23}, maximal mixing disfavoured at 2.5σ
- Electron neutrinos appearance (arXiv:1703.03328)
  - First joint fit of NOvA appearance and disappearance data
  - Weak preference for normal hierarchy
  - Inverted hierarchy, lower octant is disfavoured at > 93% C.L.
- Didn't mention sterile neutrino search, neutrino interaction, supernova, monopoles, and a lot more
- Switched to anti-neutrino running just a few weeks ago

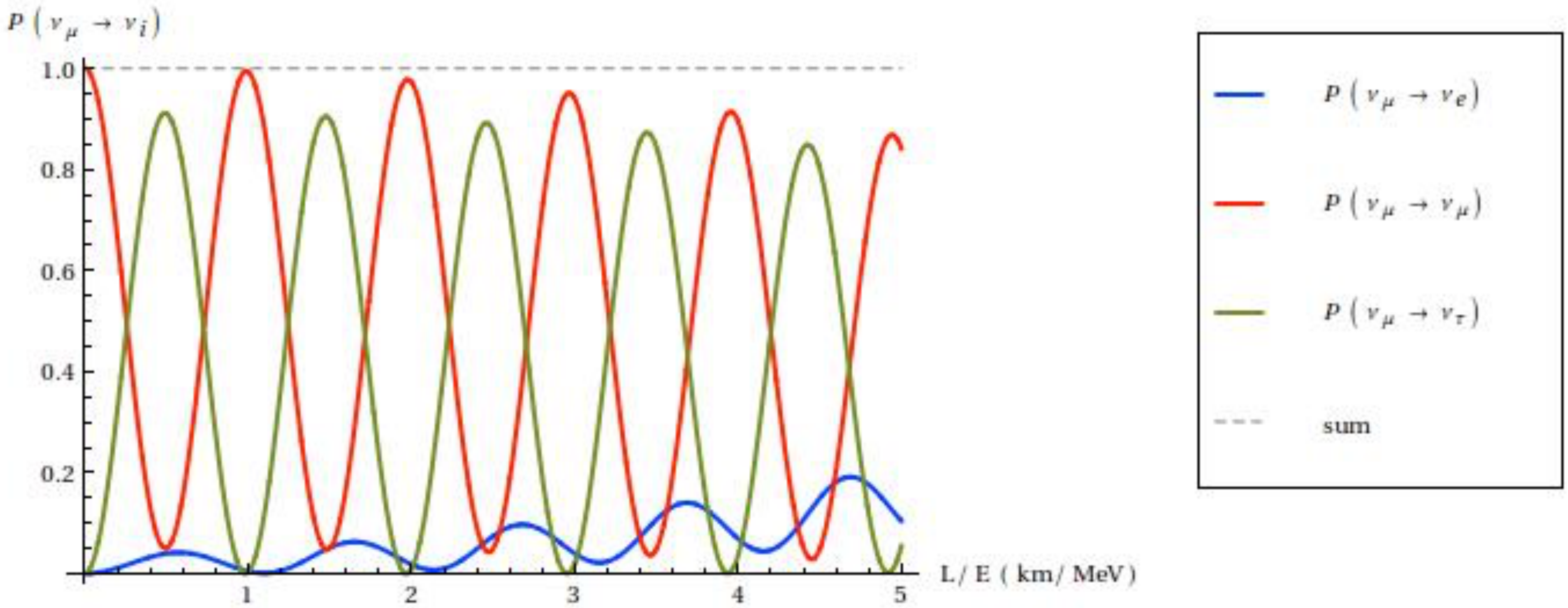


Image from: http://invisibles.eu/outreach/entry/ceaseless-transformation-three-neutrinos

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

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

$\nu_\mu \longrightarrow \nu_e$ 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]

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

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

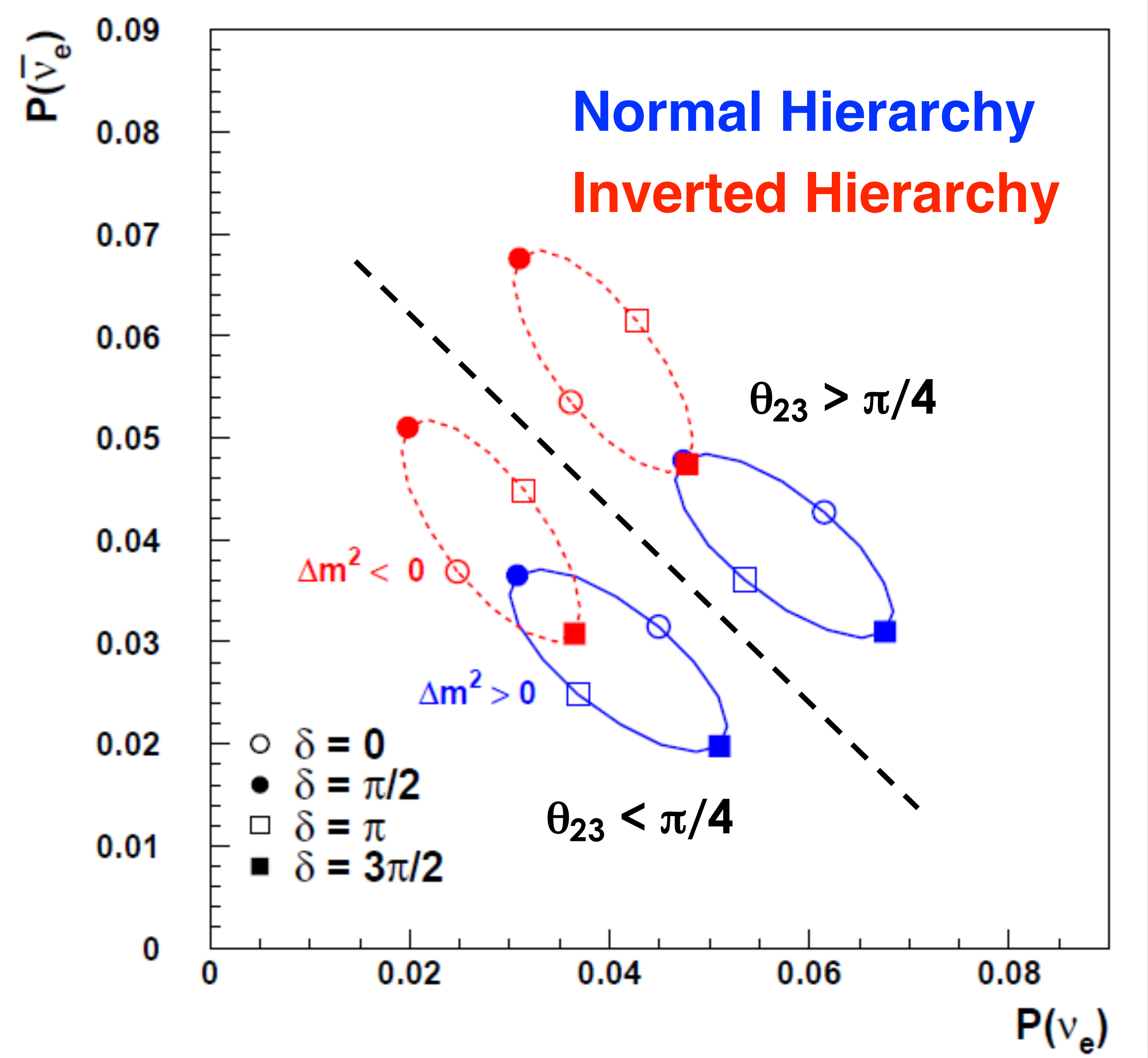
$$\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

Depends on relative sign of “a” and Δ_{31}

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

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

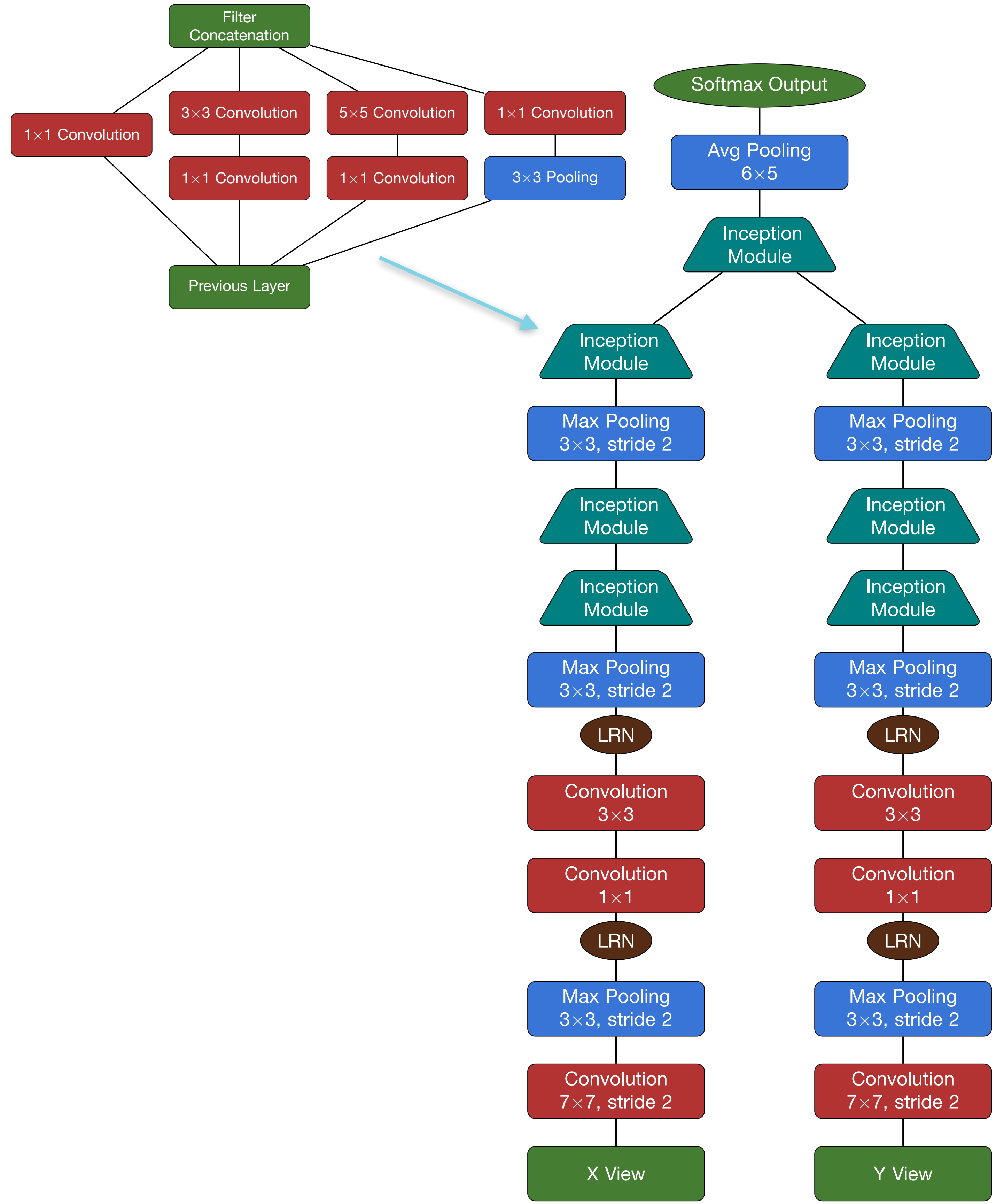
aL=0.08 for L=295km T2K baseline
aL=0.23 for L=810km NOvA baseline



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

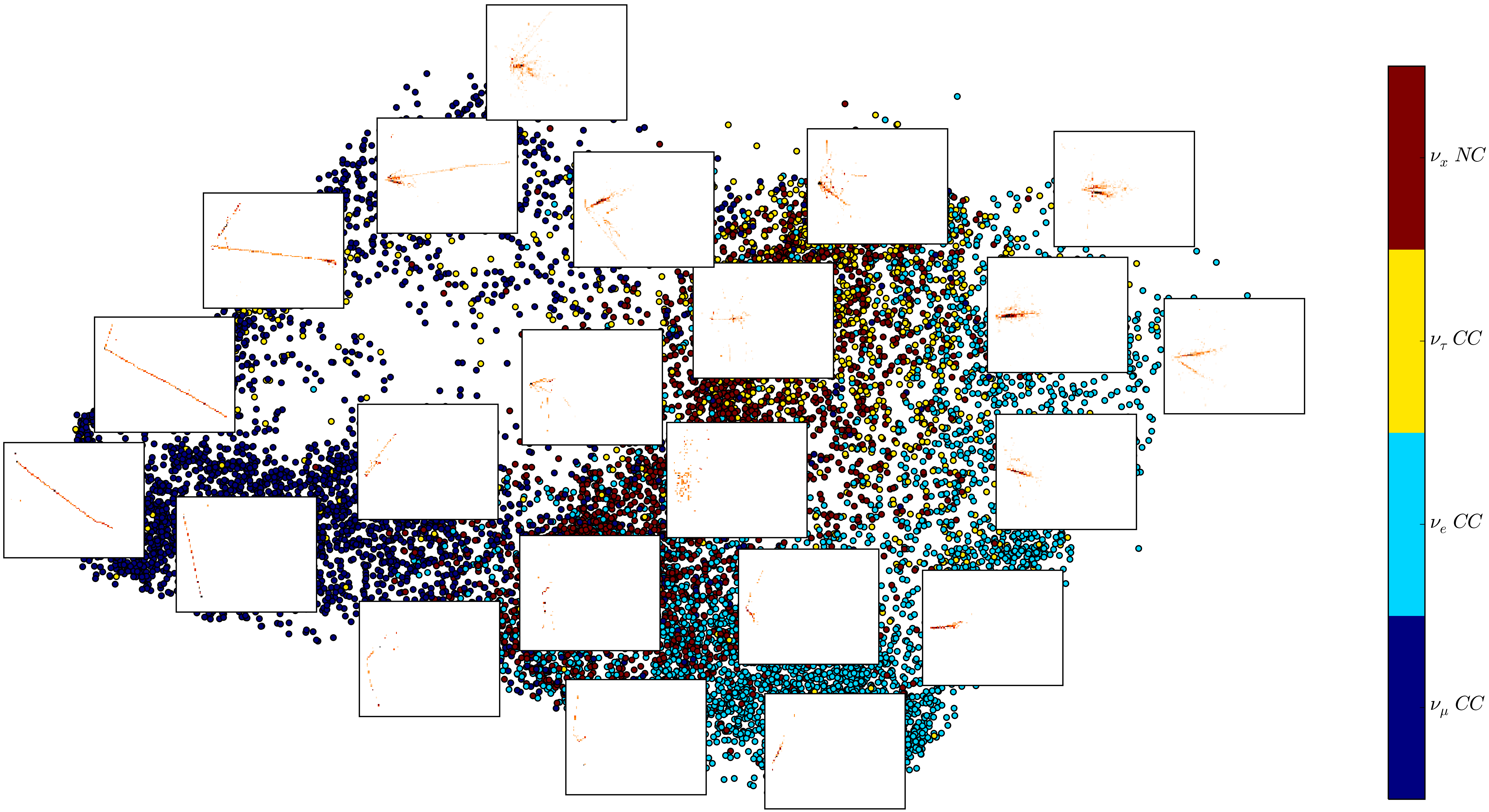
Convolutional Neural Networks

- 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)

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



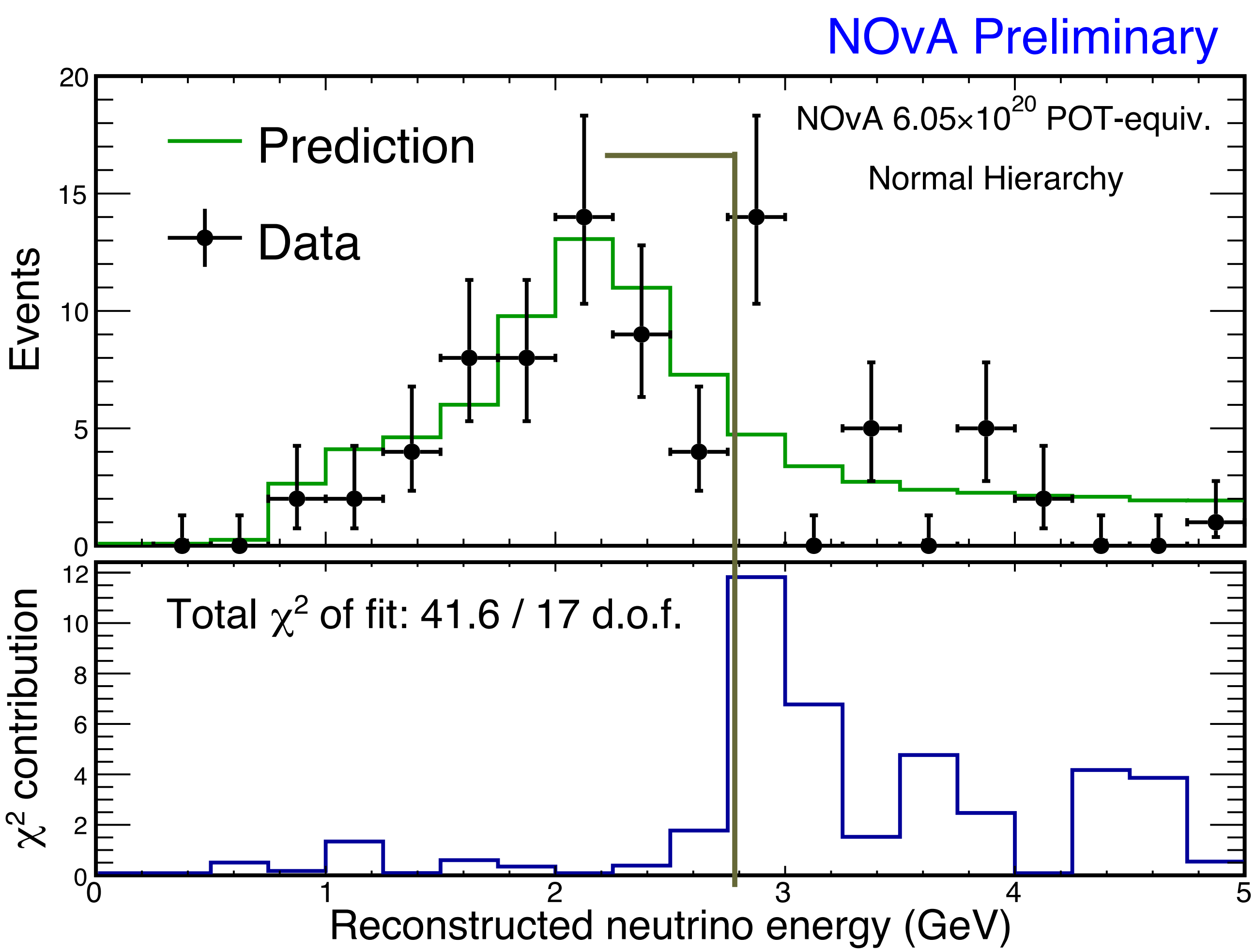
t-SNE representation of CVN classification. Truth labels shown for the training sample.

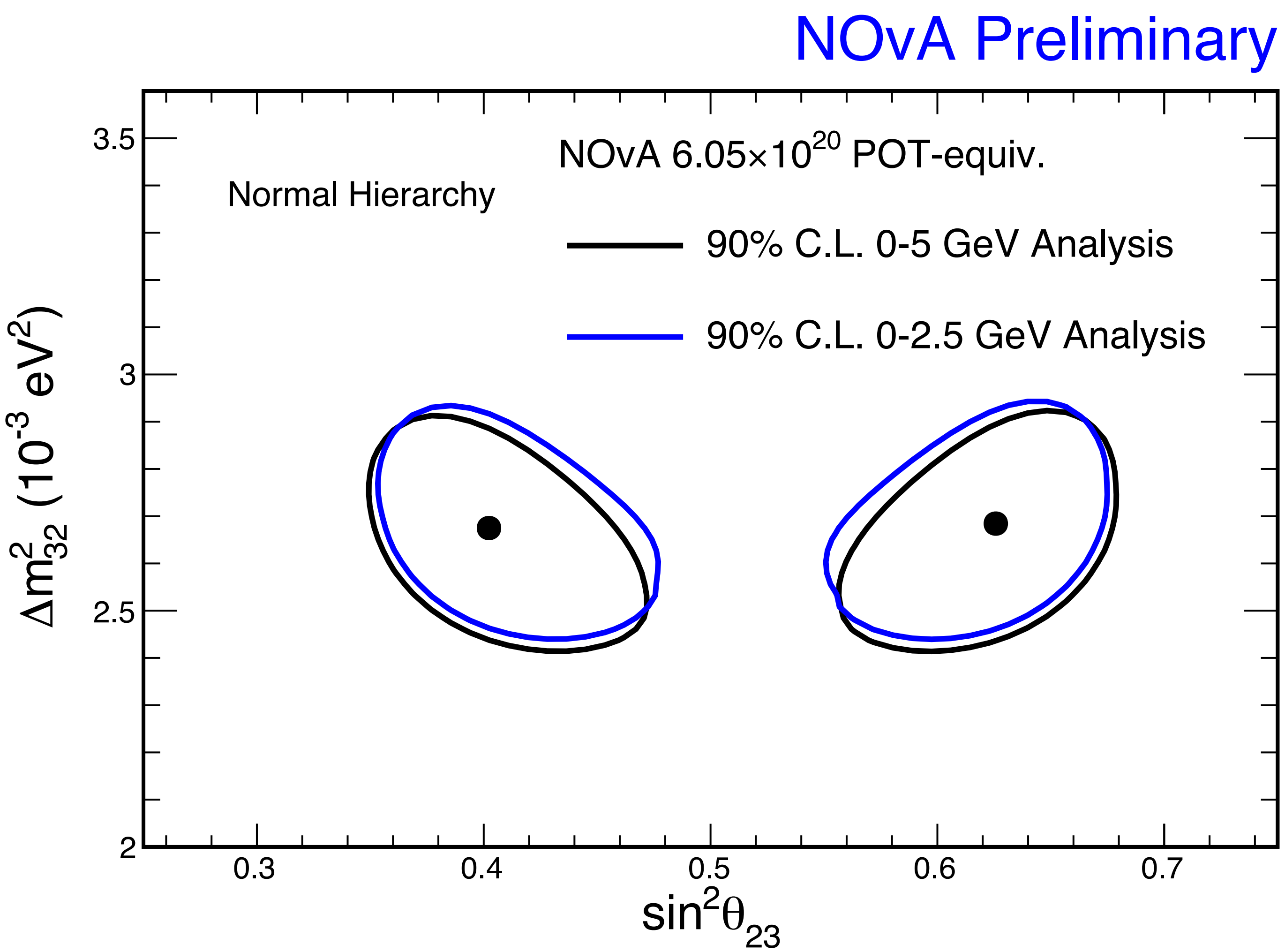
Systematic Uncertainties

- 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 %**

νμ -> νμ Oscillation Results



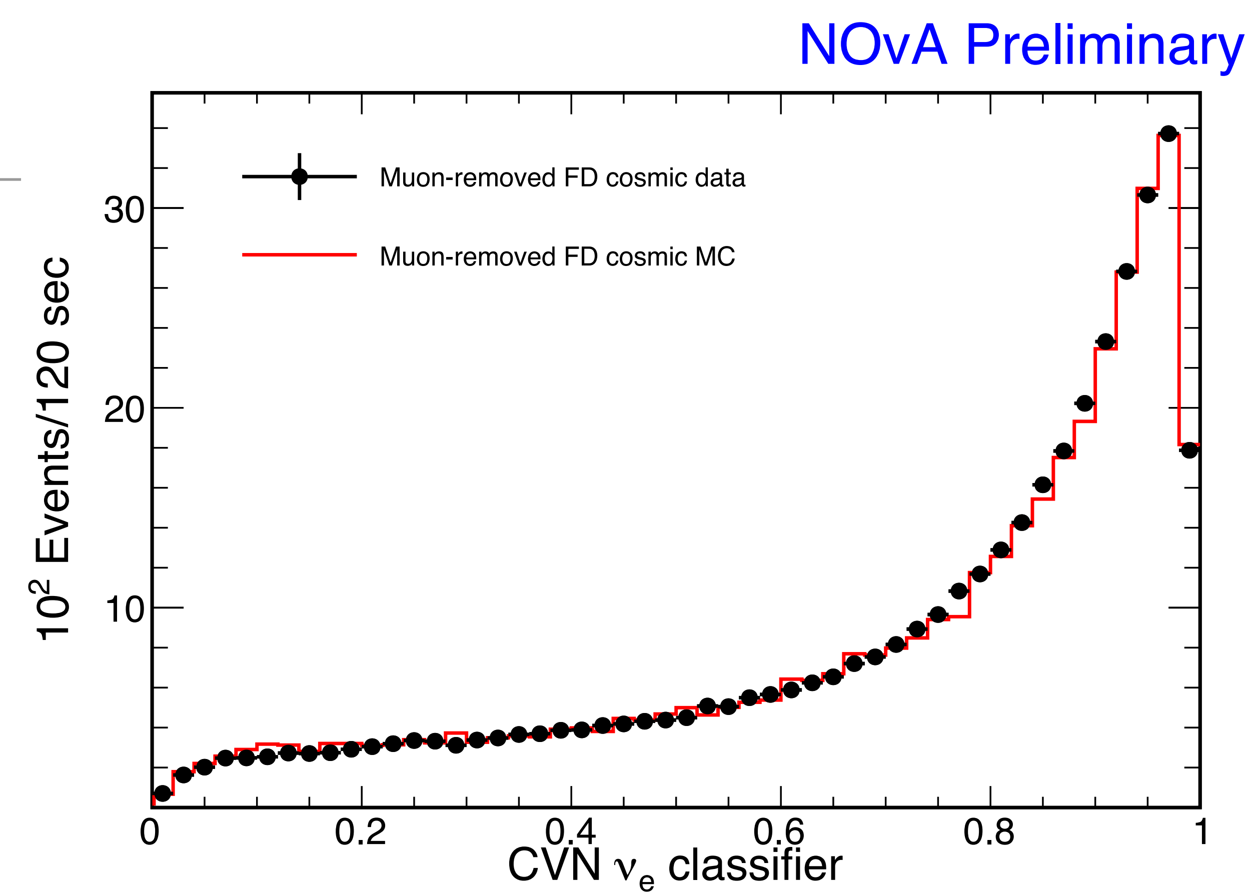


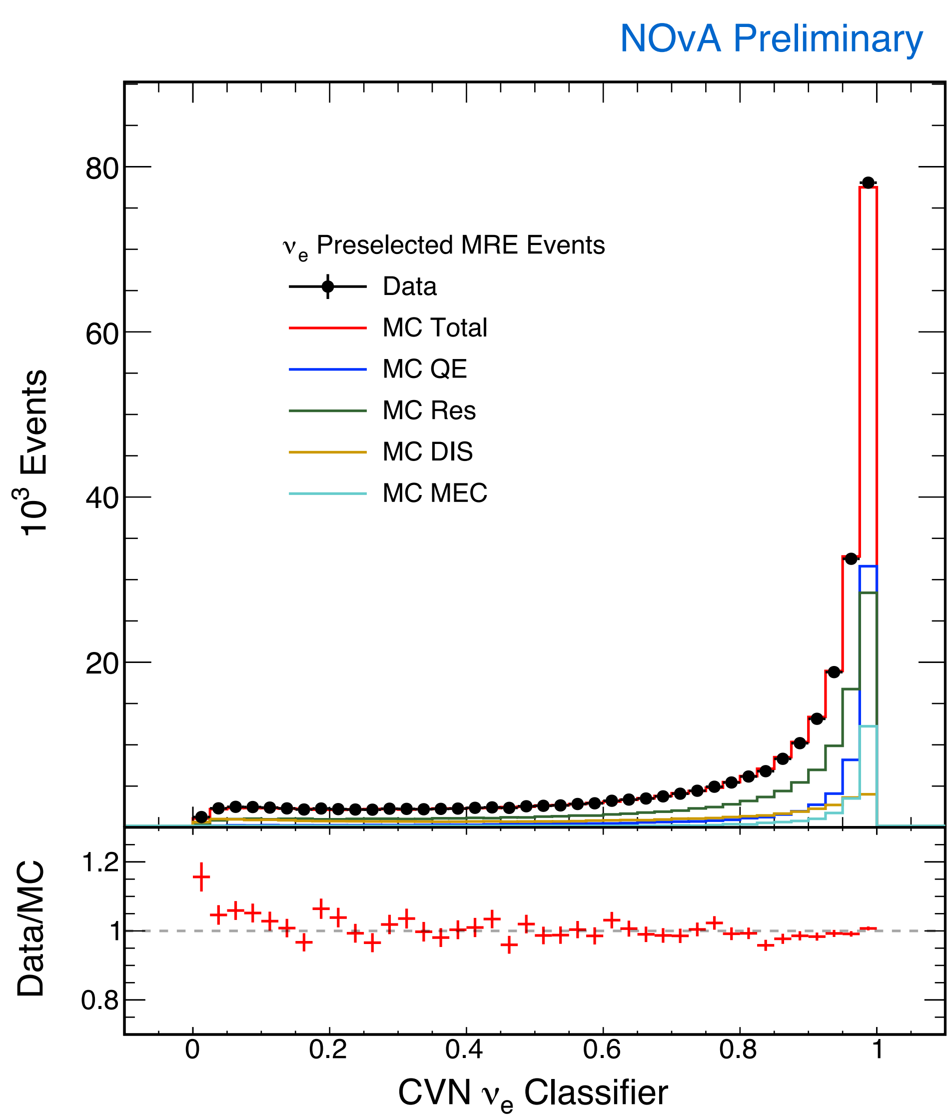
Best fit χ2/DOF = 41.5/17 is driven by the high energy tail

There is no pull in the oscillation fit from the tail

Evaluating Signal Efficiency

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



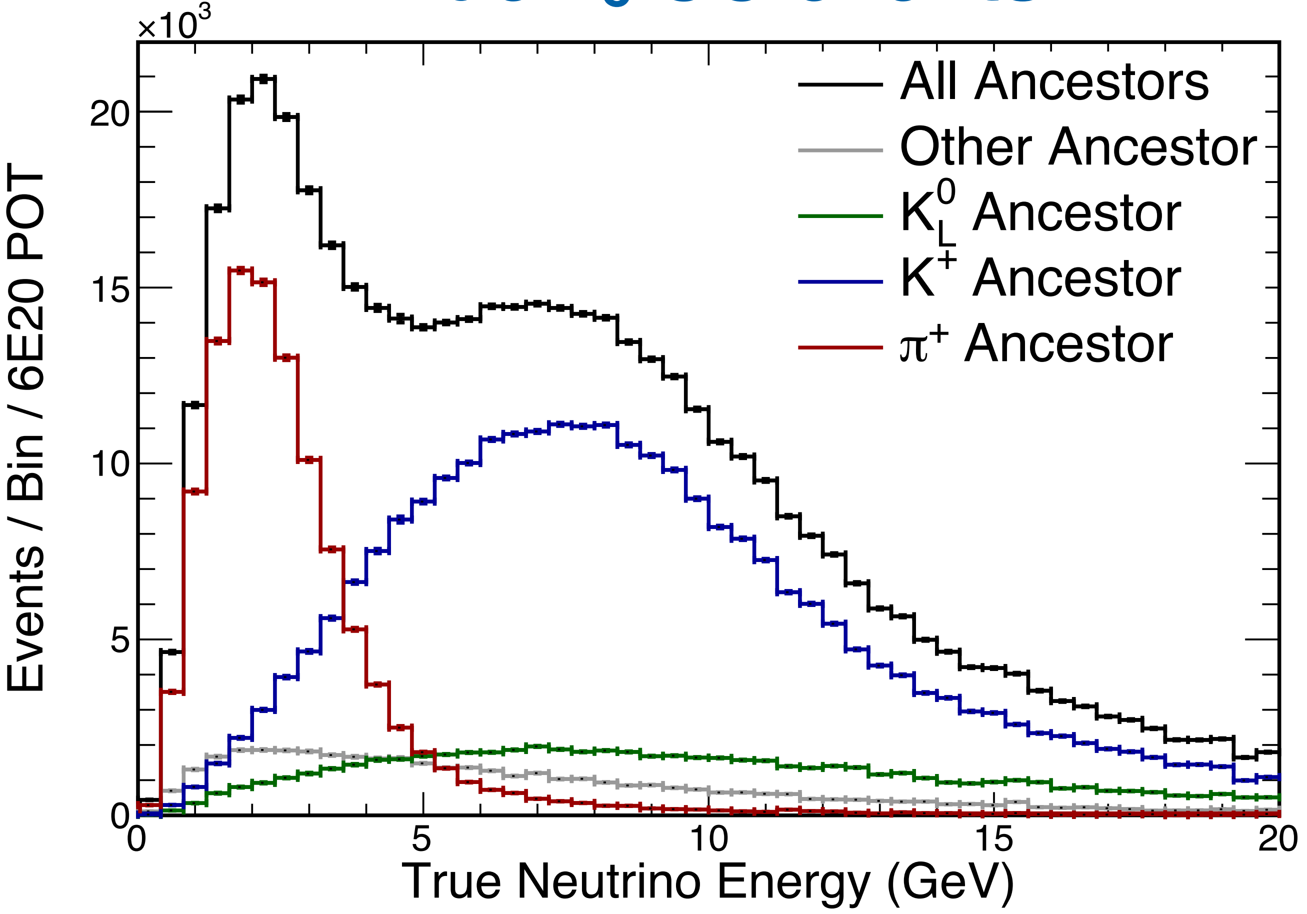


- EM showers should be well modelled, check if selection efficiency differences come from hadronic side
- Remove reconstructed muons from selected νμ events, replace with simulated electron (MRE)
- better than 1% agreement between efficiency for selecting data MRE events and efficiency for selecting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

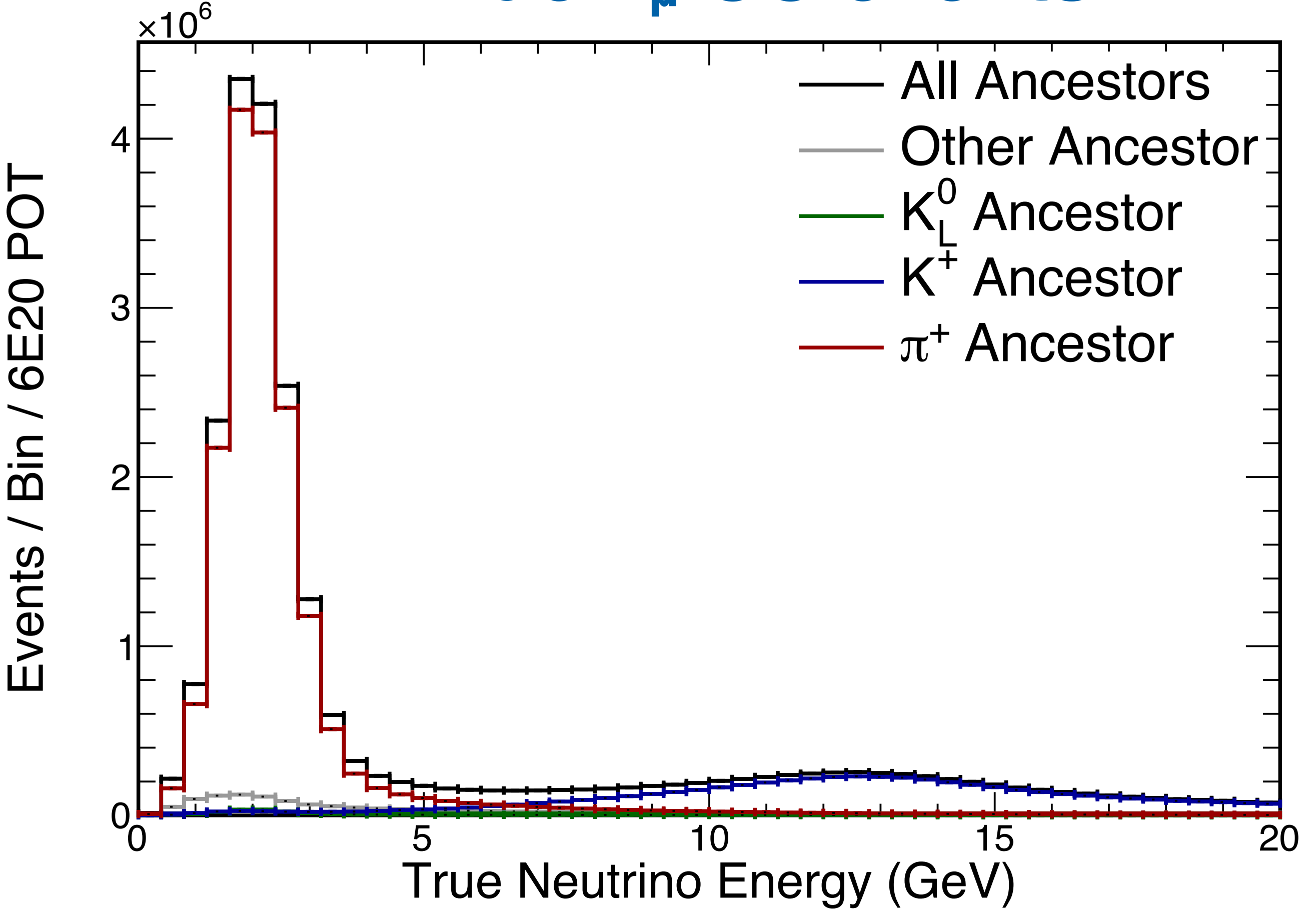
ND Data Decomposition: Beam ν_e CC

- 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

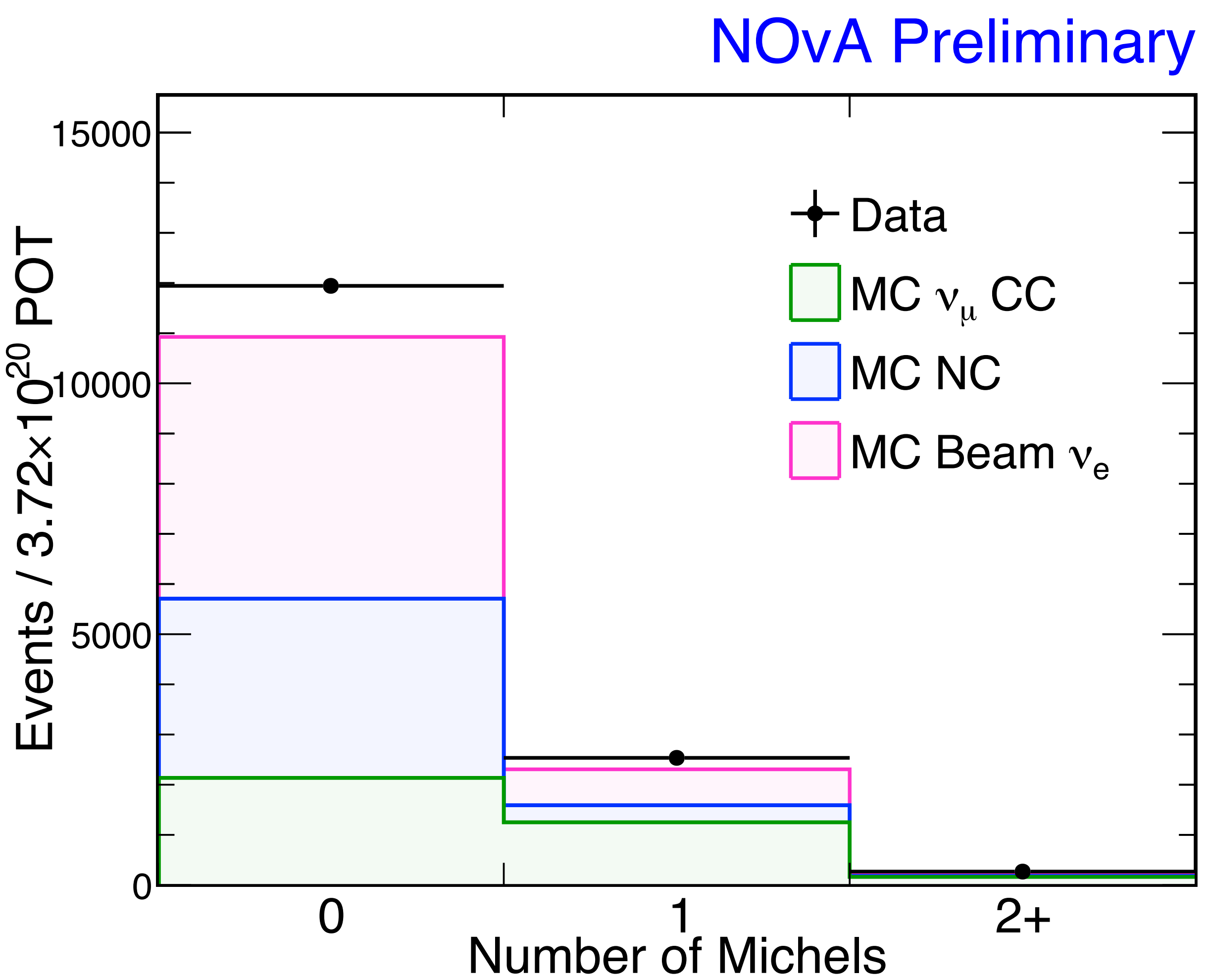
True ν_e CC events

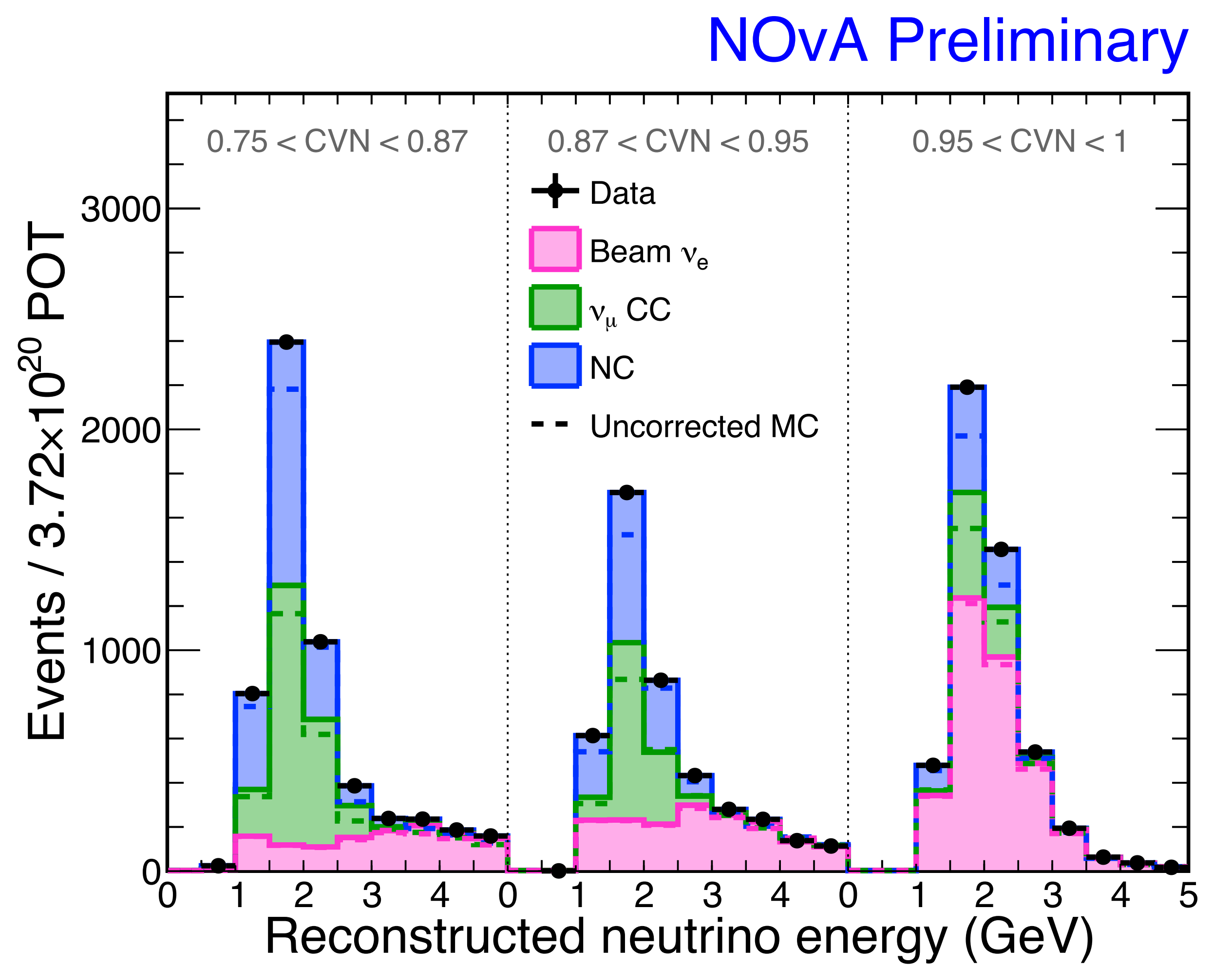


True ν_μ CC events



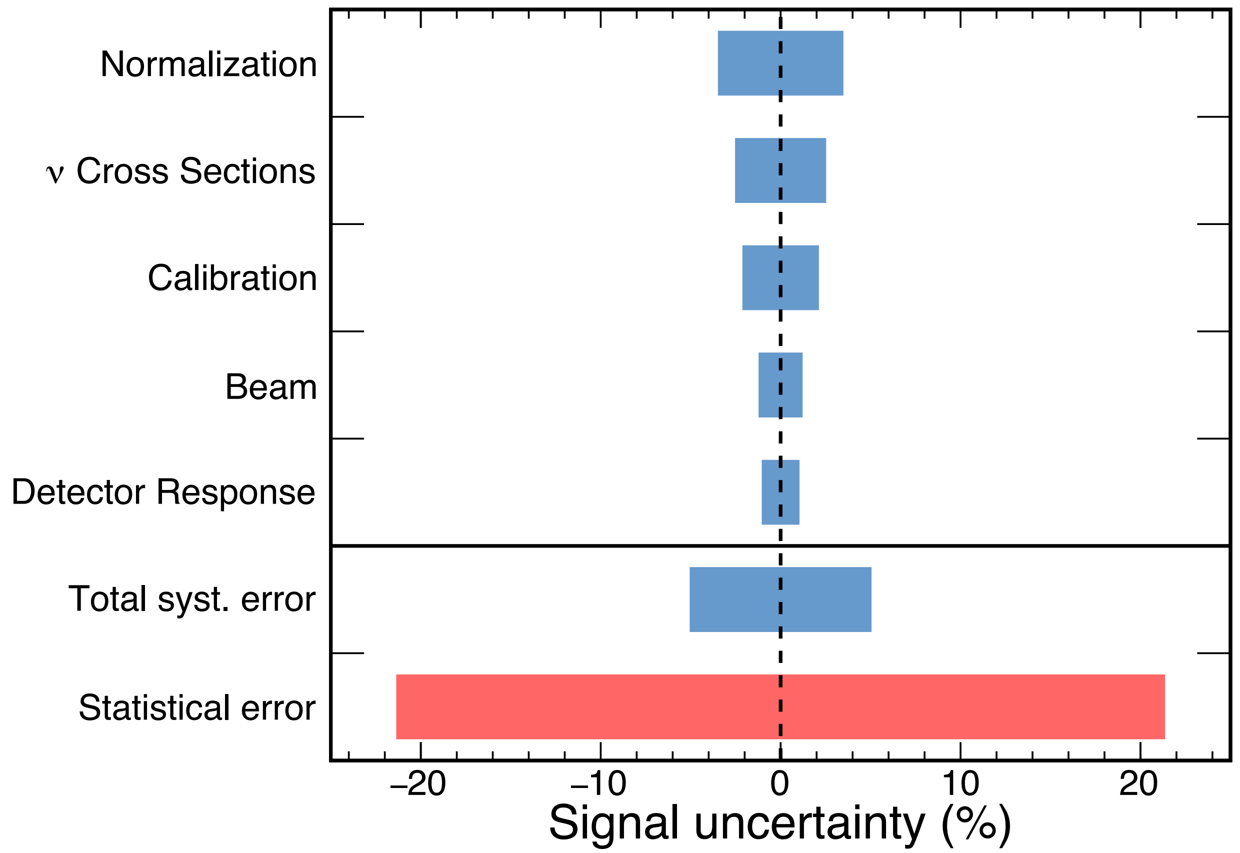
ND Data Decomposition: Michel Electrons

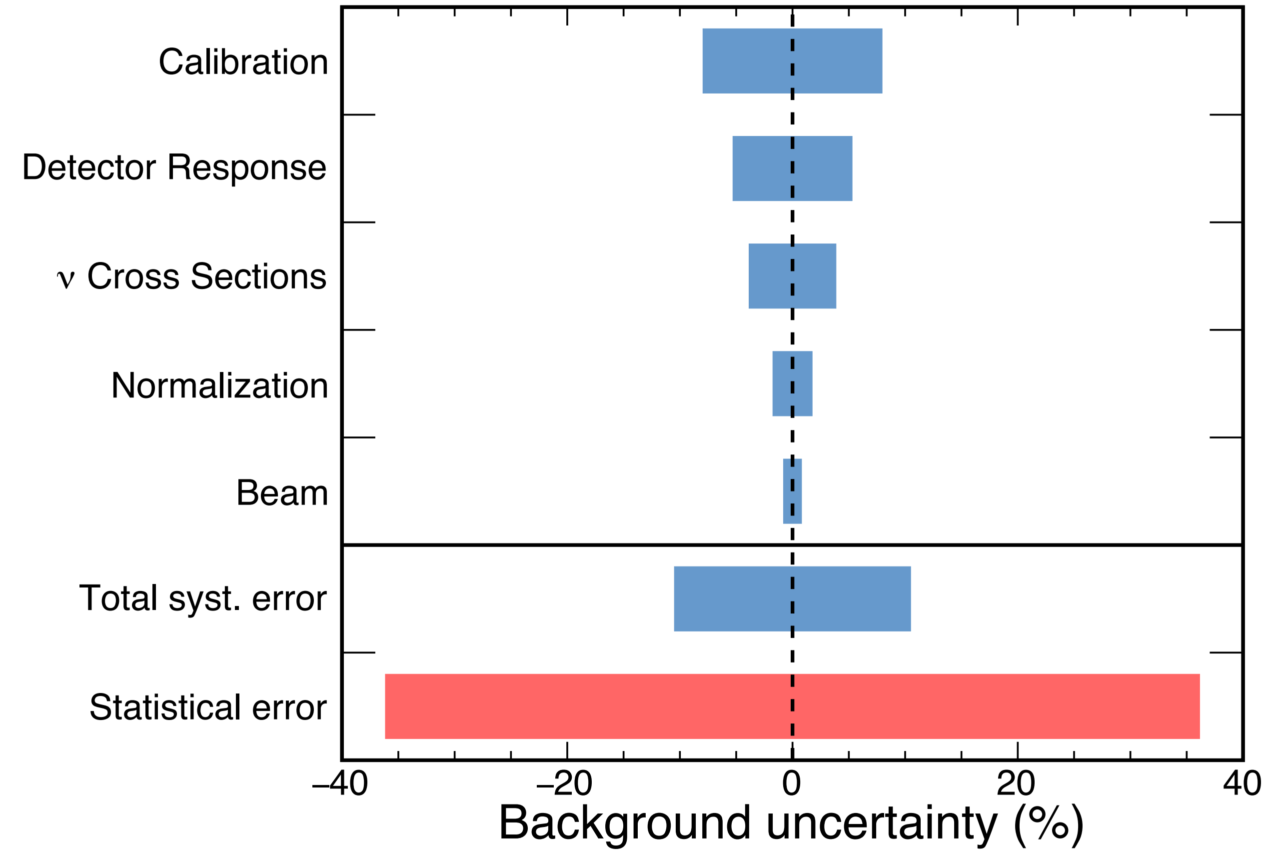




- ν_μ CC events contain Michel electron from muon decay
- ~1 more Michel in ν_μ events then ν_e or NC
- Fit observed number of Michels in each bin of energy and PID by adjusting ν_μ/NC ratio
- Data excess assigned between NC (+17%) and ν_μ CC (+10%)

Systematic Uncertainties

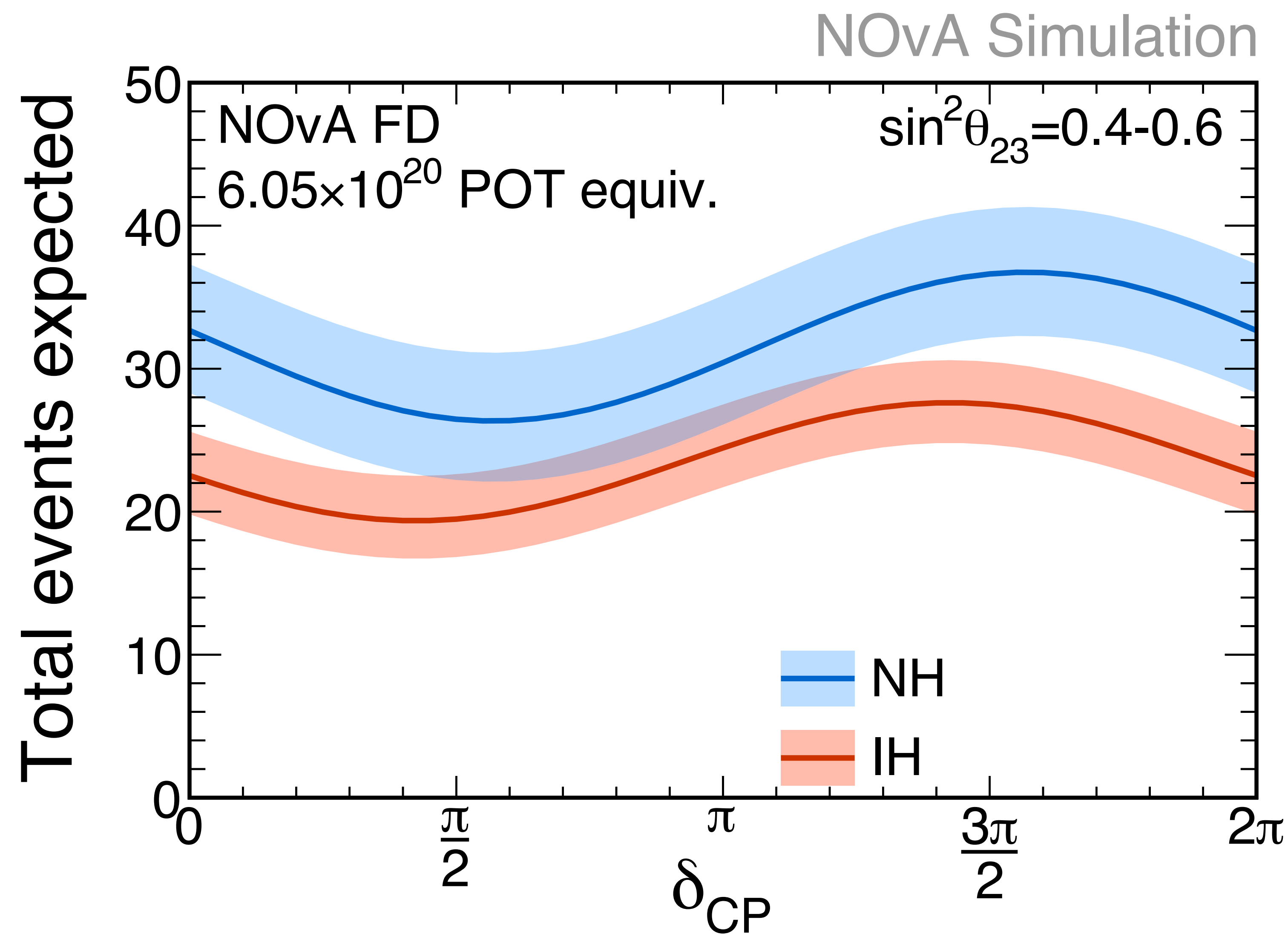




- Multiple sources of systematic error considered
- Extrapolate FD predictions with special MC samples for each effect.
- Uncertainty quoted as difference between shifted and nominal predictions
- Fit nuisance parameters as pull terms
- Statistical uncertainties dominate

νμ -> νe Oscillation Prediction

- Prediction dependent on oscillation parameters



Signal events ($\pm$5% systematic uncertainty):

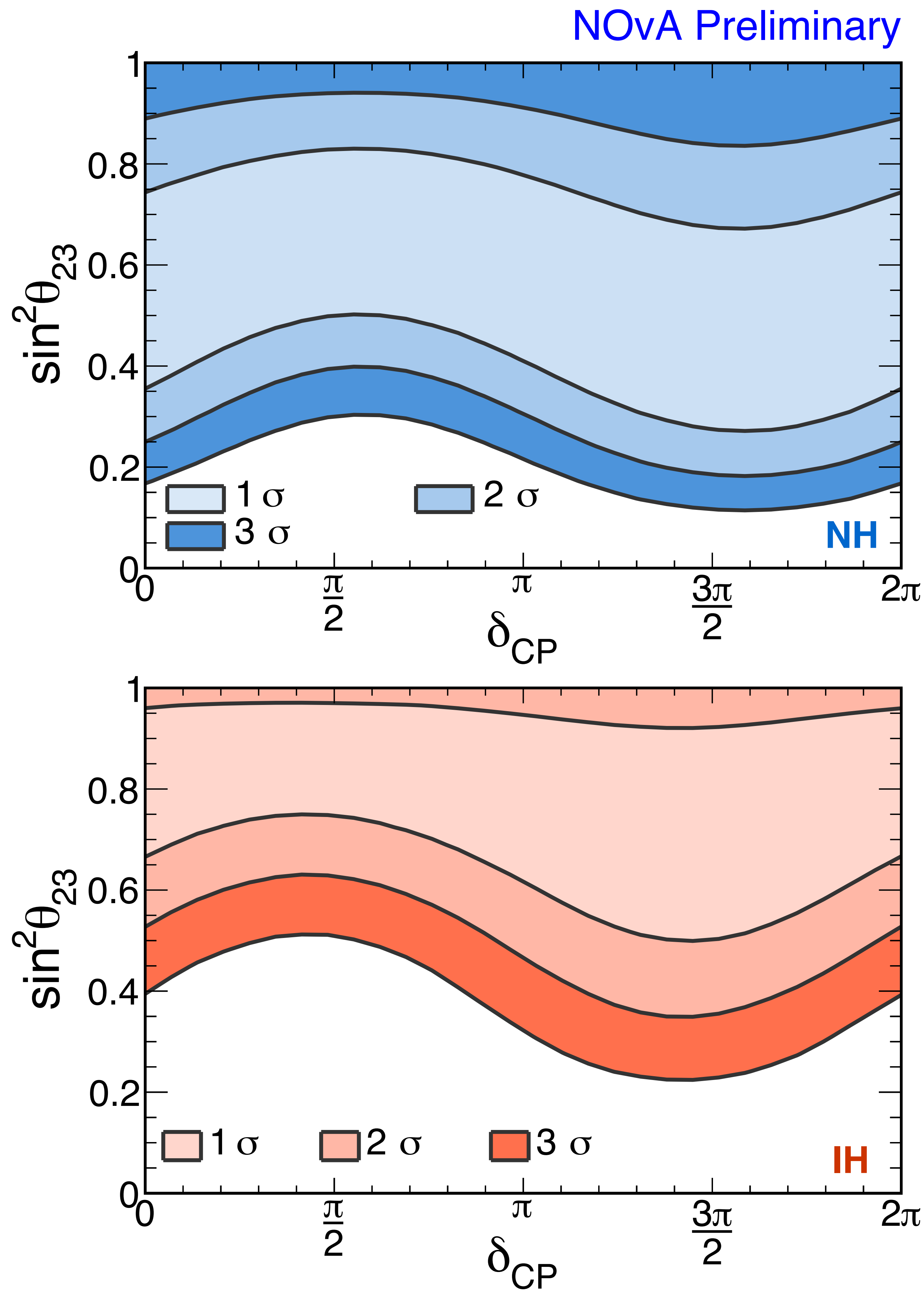
NH, $3\pi/2$,	IH, $\pi/2$,
28.2	11.2

Background by component ($\pm$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

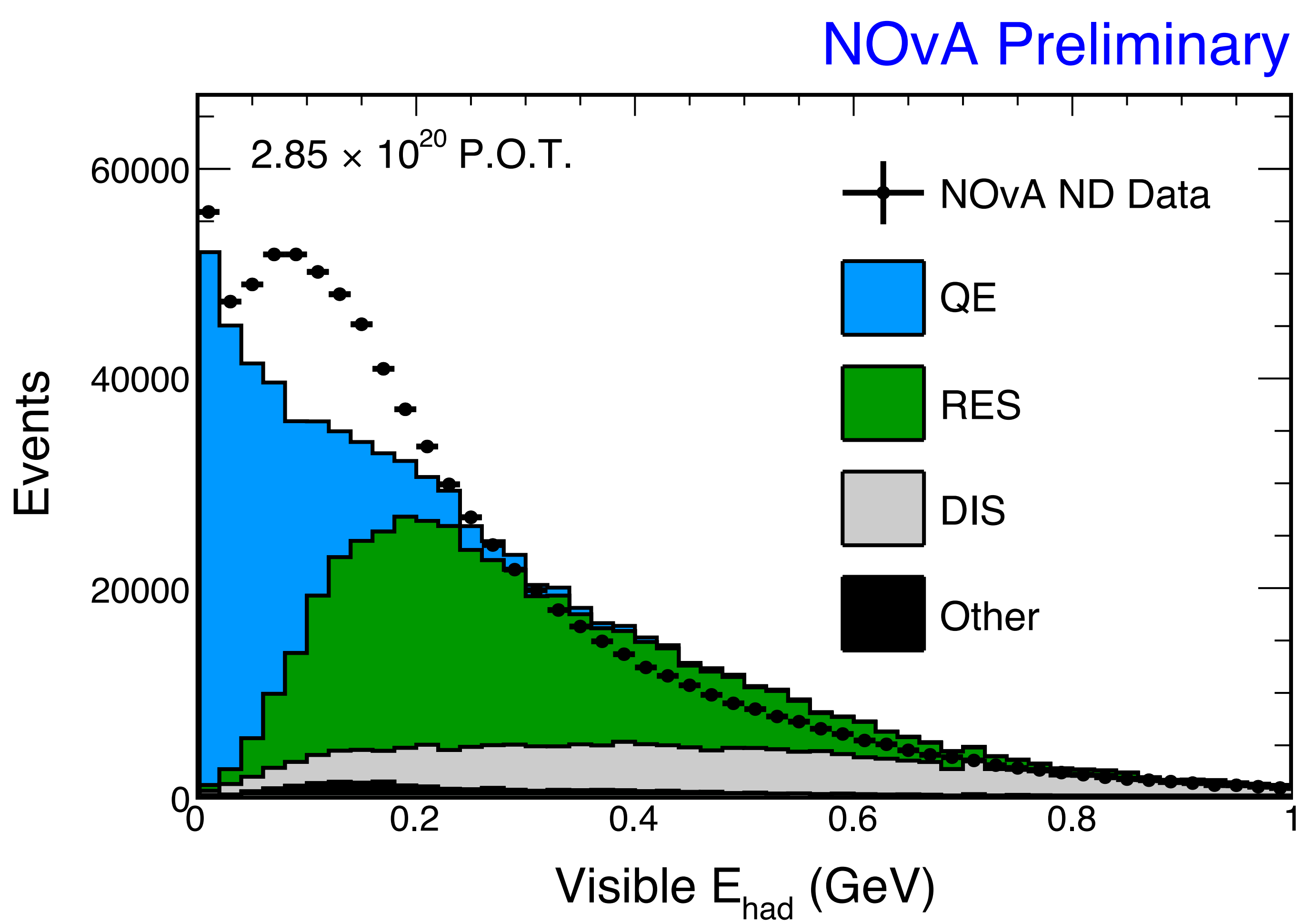
ν_μ -> ν_e Oscillation Results

- Fit for hierarchy, δCP, sin2θ23
  - Constrain sin2(2θ13)=0.085±0.05
  - Constrain Δm2=2.44±0.06x10-3 eV2, NH
  - (-2.49±0.06x10-3 eV2, IH)
- Systematic effects included as nuisance parameters (normalization, flux, calibration, cross section, and detector response effects)

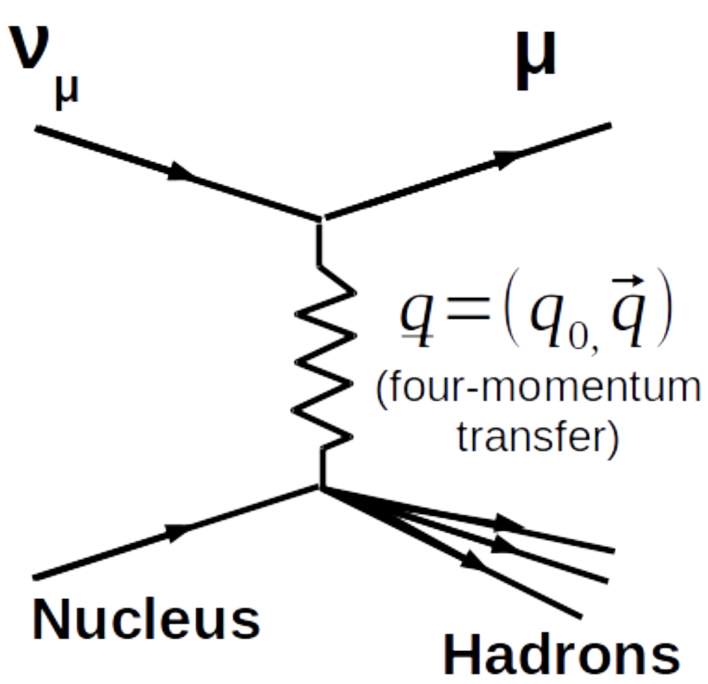


Nuclear Model Corrections

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



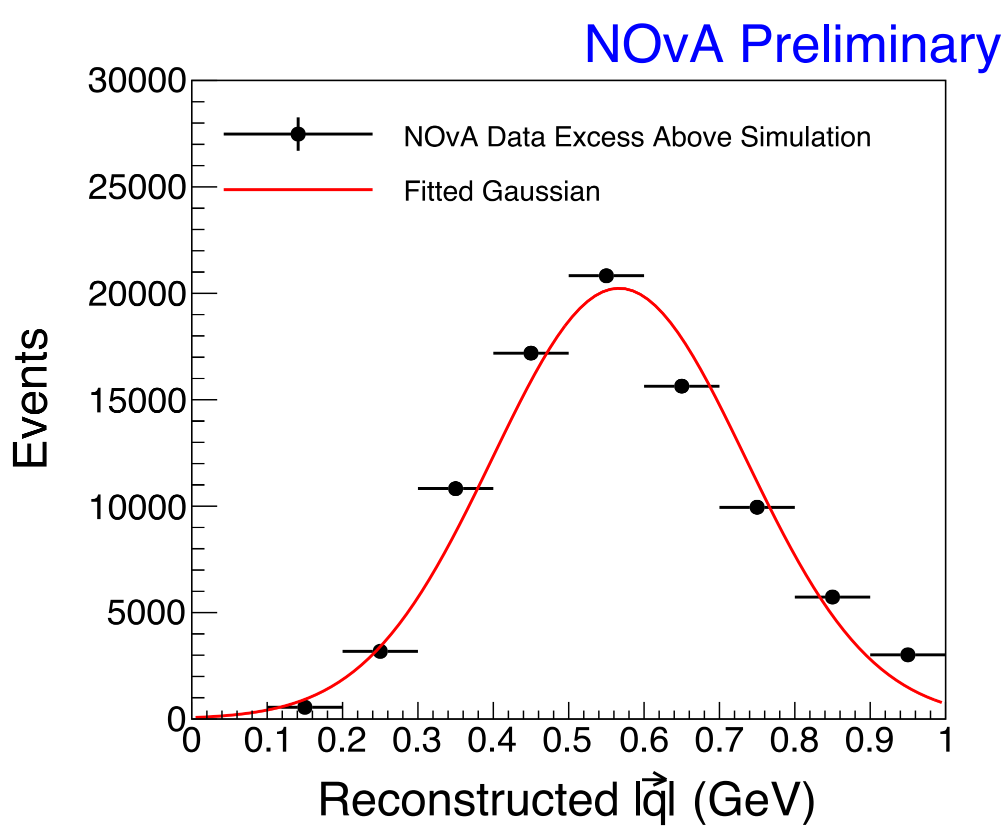
Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

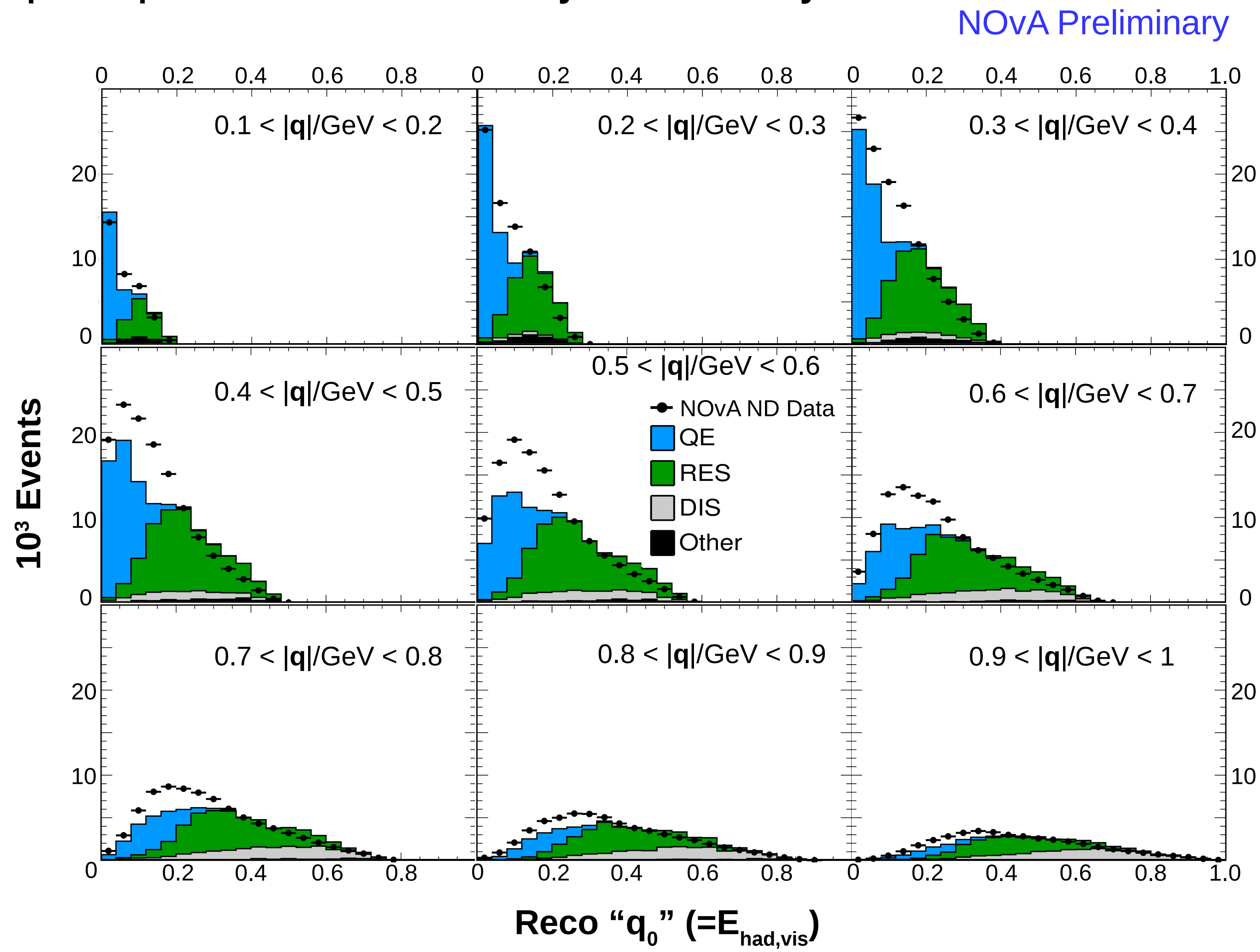


Solution: 2-particle, 2-hole (2p2h) events where neutrino is scattering off a nucleon-nucleon pair

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]



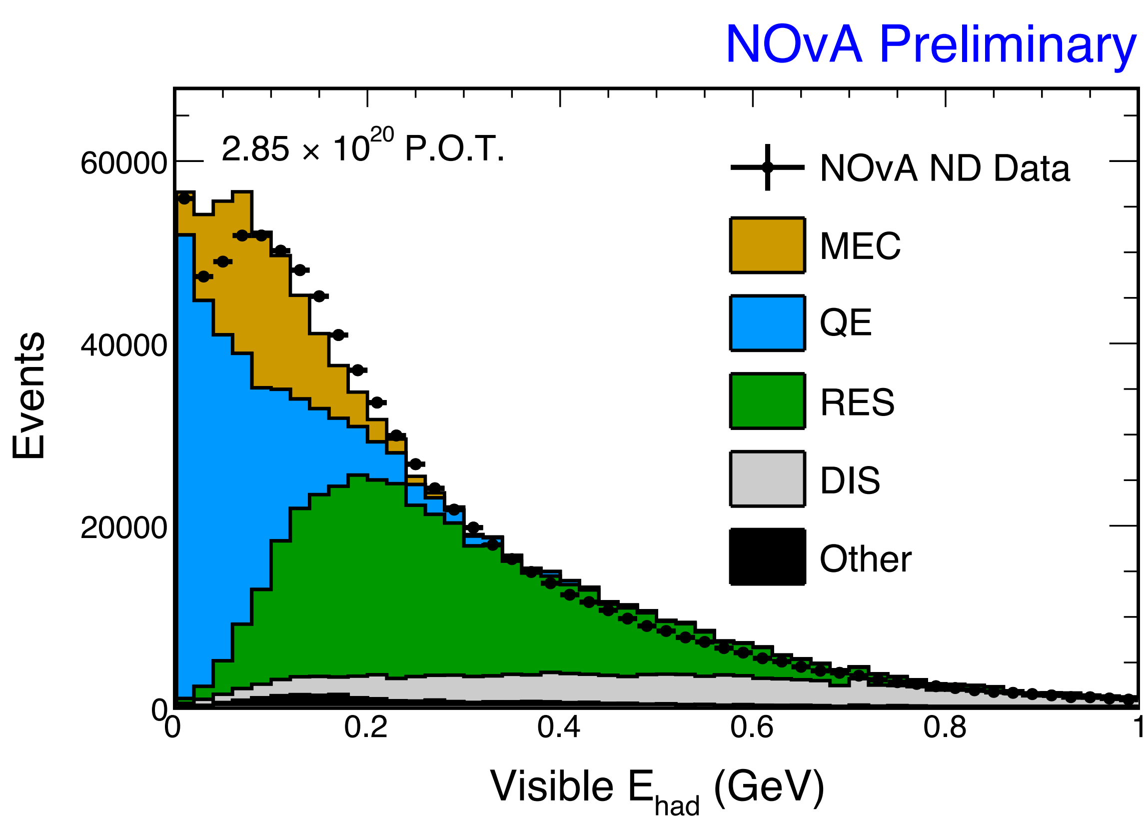


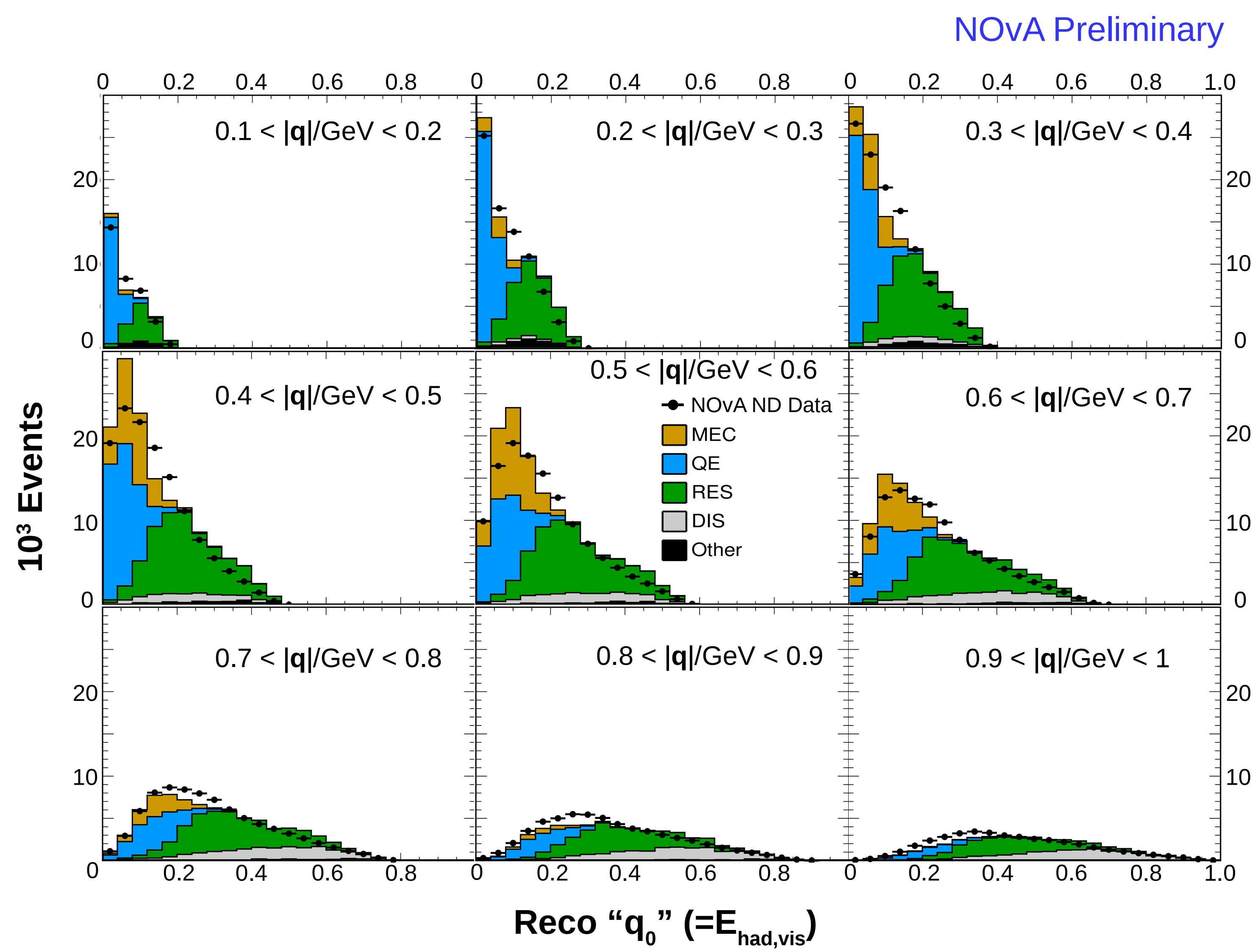
[1]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57

[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

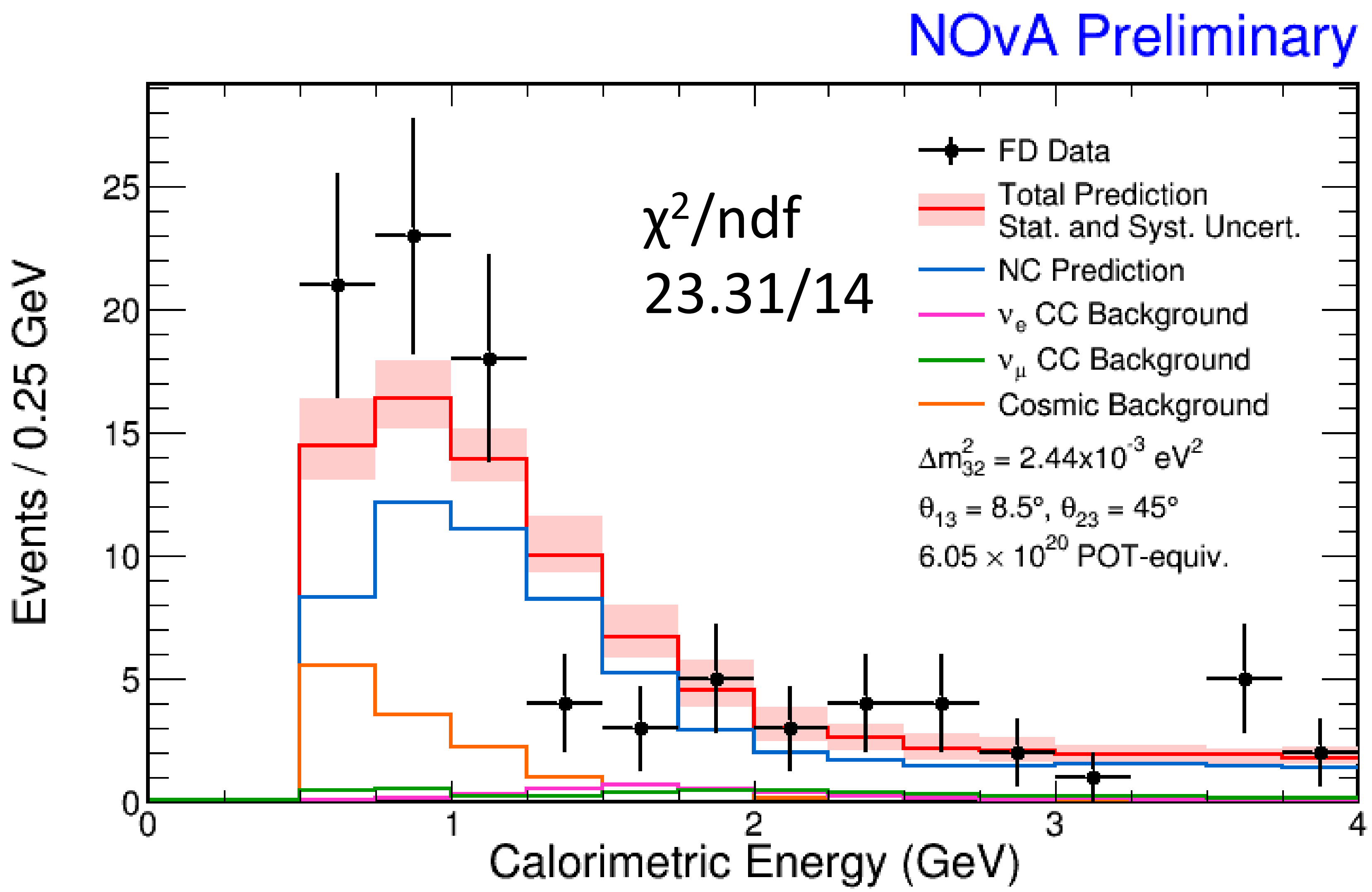
NC disappearance results

Observe 95 NC-like event in Far Detector

MC extrapolated prediction: 83.71 ± 9.15 (stat.) ± 8.28 (syst.)

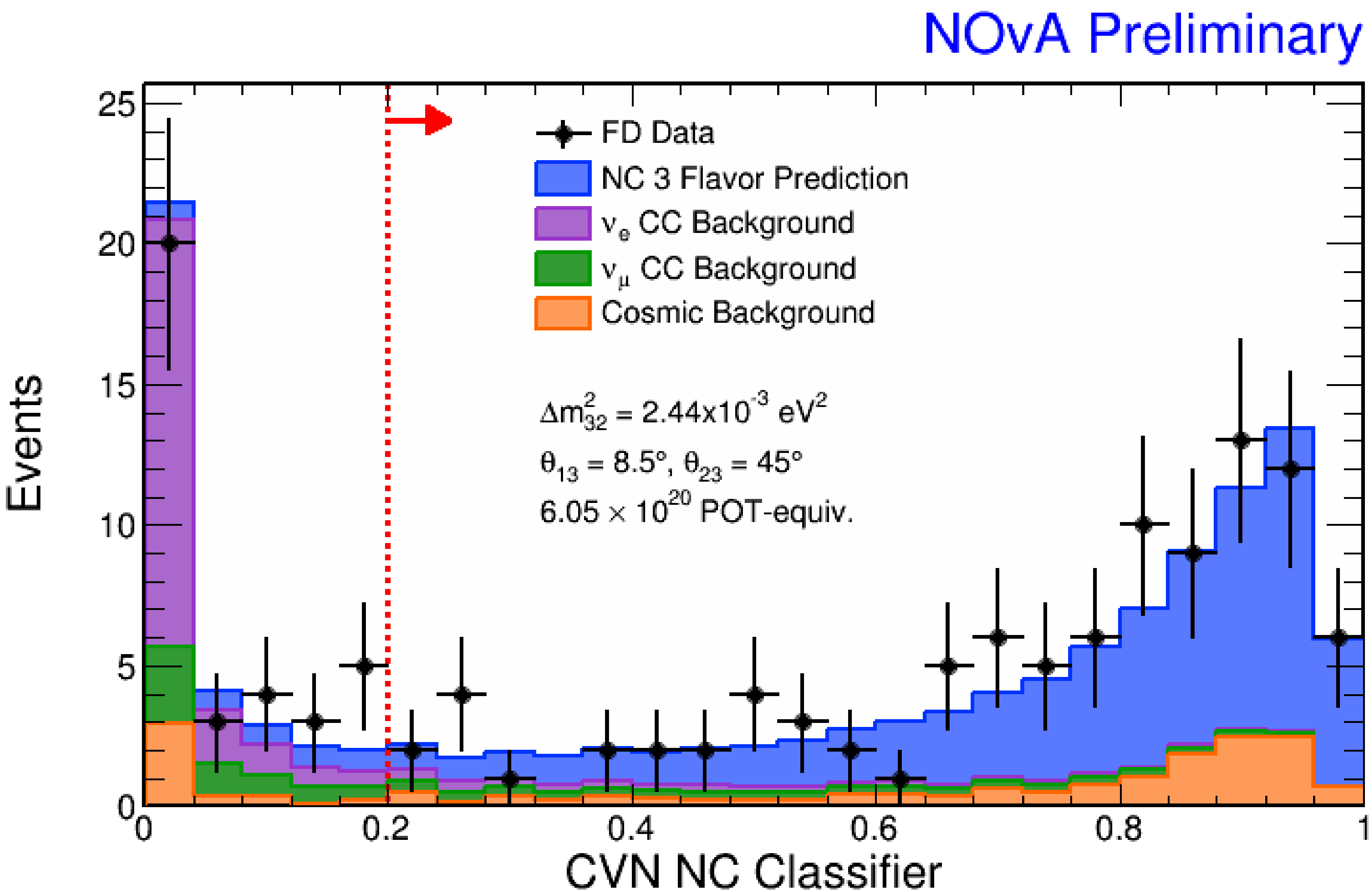
within 1σ of three-flavour prediction

NOvA sees no evidence for sterile neutrino mixing



Far detector NC selection

FD NC selection uses the same variables as the ND selection, with identical cut values



R-ratio comparison with 3-flavour

$$R = \frac{N_{Data} - \sum B_{(CC+cosmic)}}{S_{NC}}$$

Predicted background from all ν flavours and cosmics

Predicted NC signal

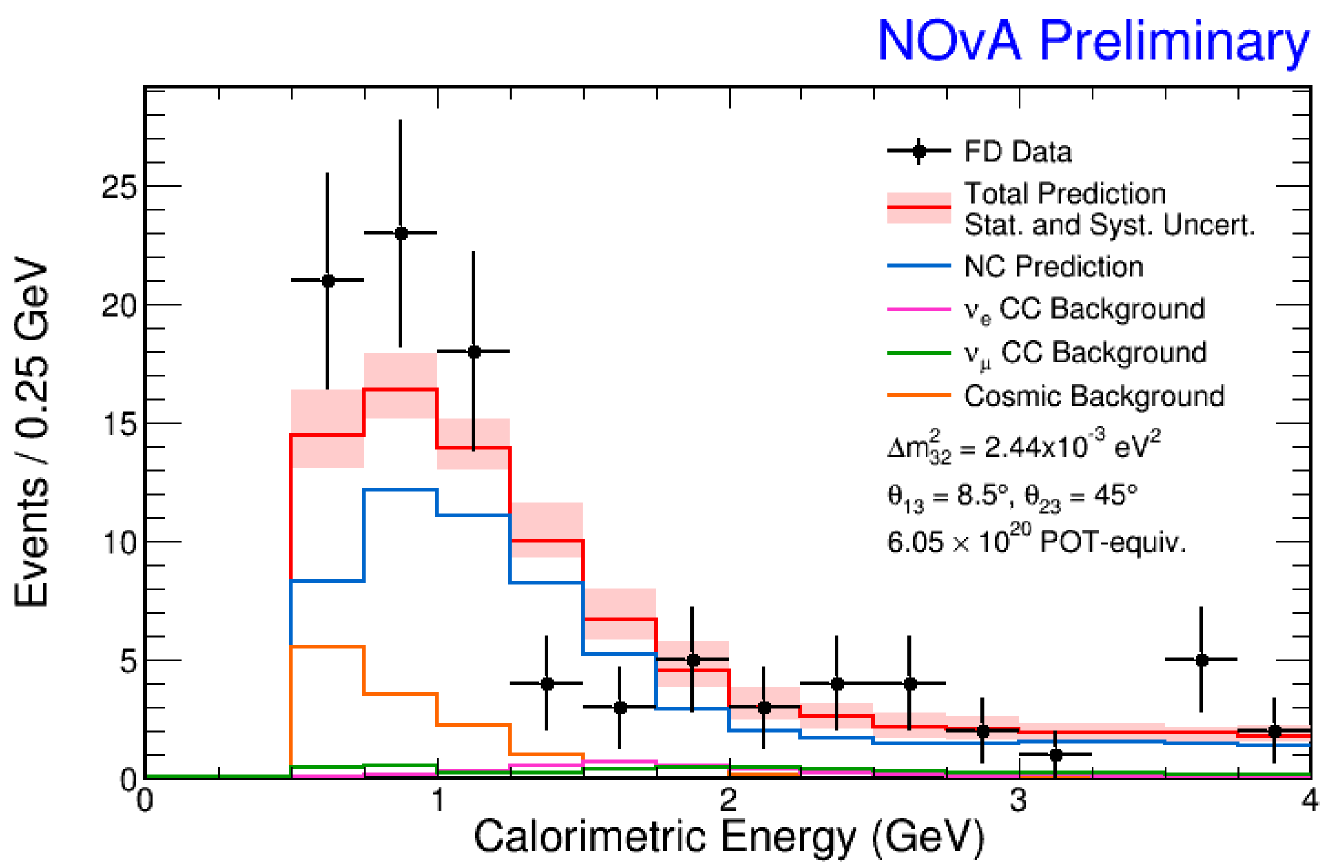
FD Data NC-like: **95**

MC prediction: **83.71 ± 9.15 (stat.) ± 8.28 (syst.)**

For 0.5 GeV < Calorimetric energy < 4.0 GeV

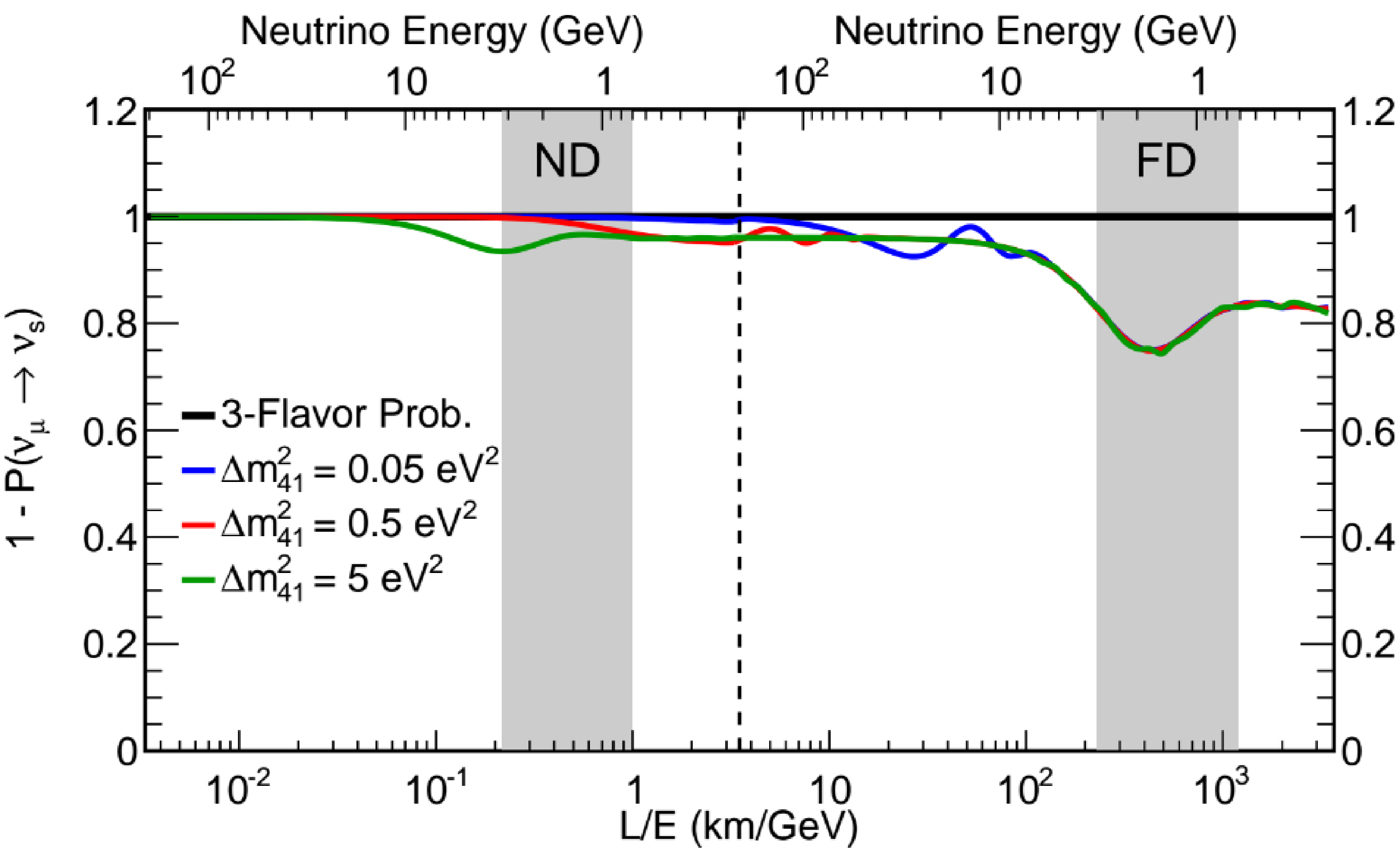
$$R = 1.19 \pm 0.16\ (stat.)^{+0.08}_{-0.13}\ (syst.)$$

Consistent with 3-flavour oscillations (R = 1.0)



3+1 model

$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4_{14}\cos^2_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41} - \sin^2_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} - \frac{1}{2}\sin\delta_{24}\sin_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin 2\Delta_{31}$$



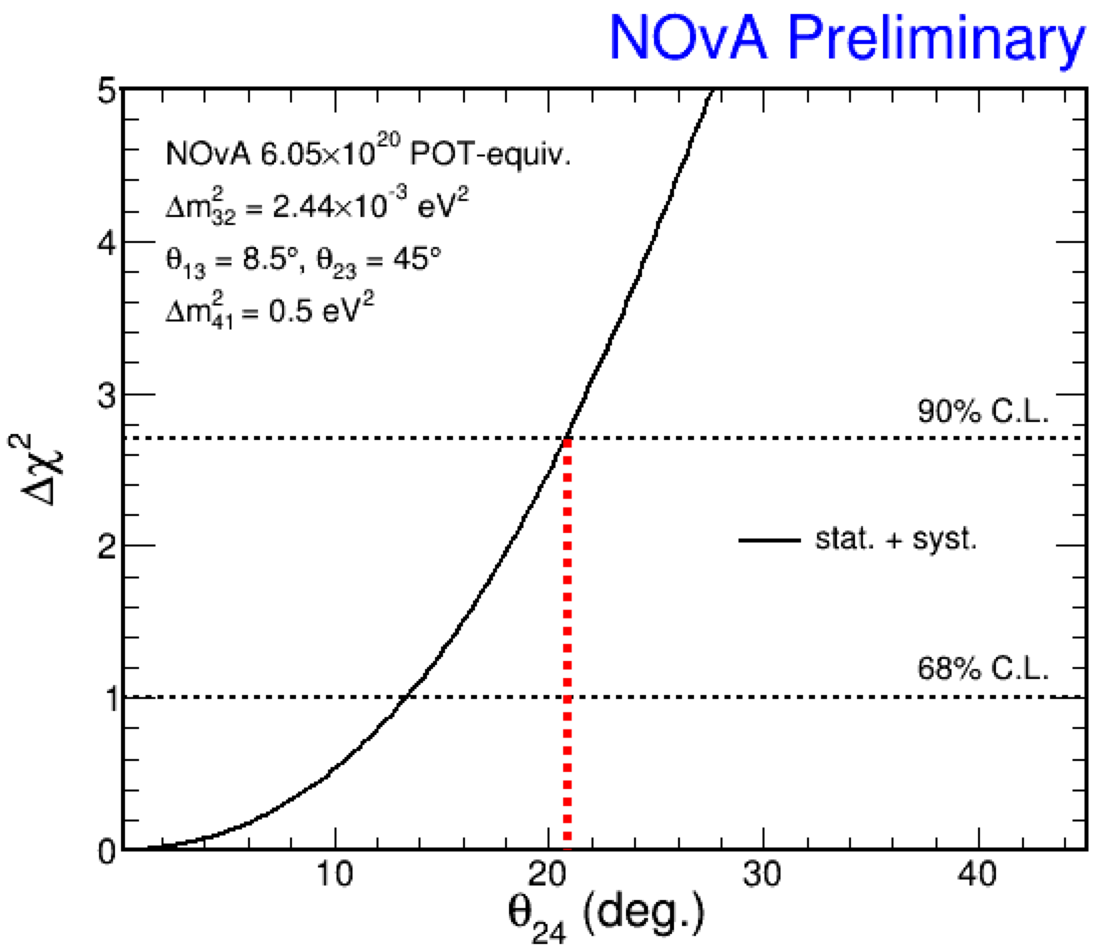
- Solar and reactor neutrino data constrains $\sin^2\theta_{14} < 0.041$
  - Assume $\theta_{14} = 0$
- $0.05\ eV^2 < \Delta m^2_{41} < 0.5\ eV^2$
  - no ND oscillations
- Constraint on θ_{23}
  - $\sin^2(\theta_{23}) = 0.514$
  - Particle Data Group

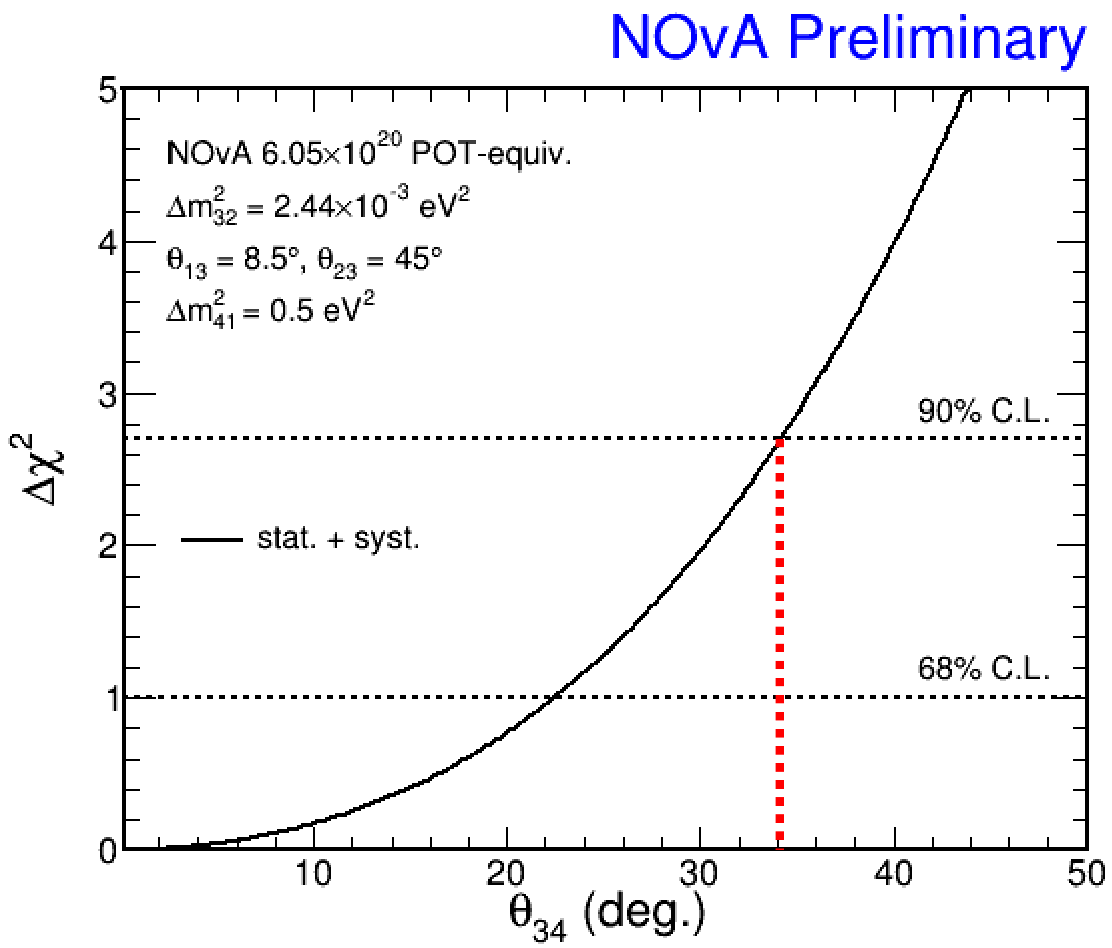
$|U_{e4}|^2 = \sin^2\theta_{14} = 0, \cos^2\theta_{14} = 1$

$|U_{\mu4}|^2 = \cos^2\theta_{14} \sin^2\theta_{24}$

$|U_{\tau4}|^2 = \cos^2\theta_{14} \cos^2\theta_{24} \sin^2\theta_{34}$

3+1 1D limits



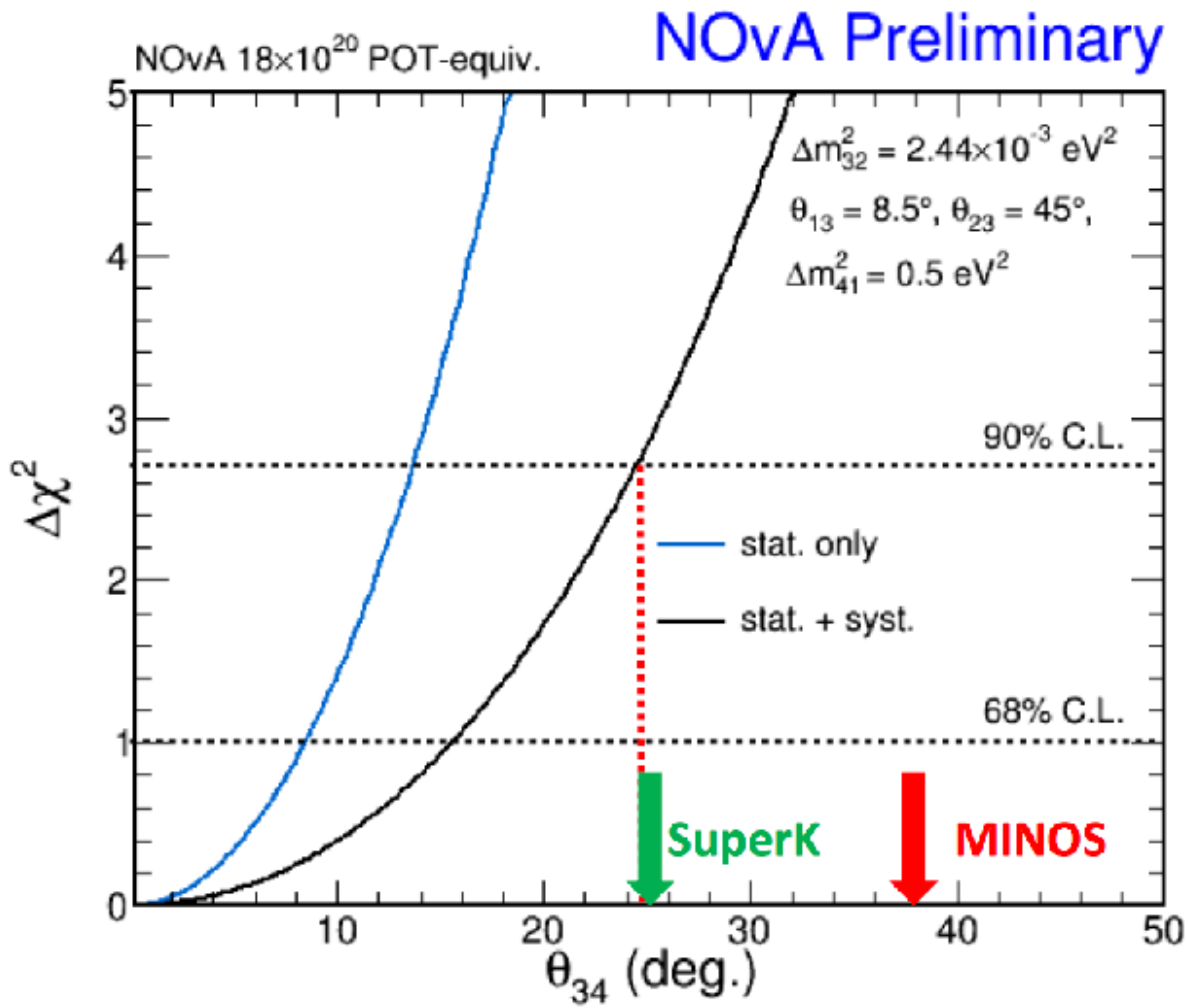


For 0.05 $eV^2 < \Delta m^2_{41} < 0.5$ eV^2:

$\theta_{24} < 21°$ at 90% C.L. **$|U_{\mu 4}|^2 < 0.14$ at 90% C.L.**

$\theta_{34} < 35°$ at 90% C.L. **$|U_{\tau 4}|^2 < 0.33$ at 90% C.L.**

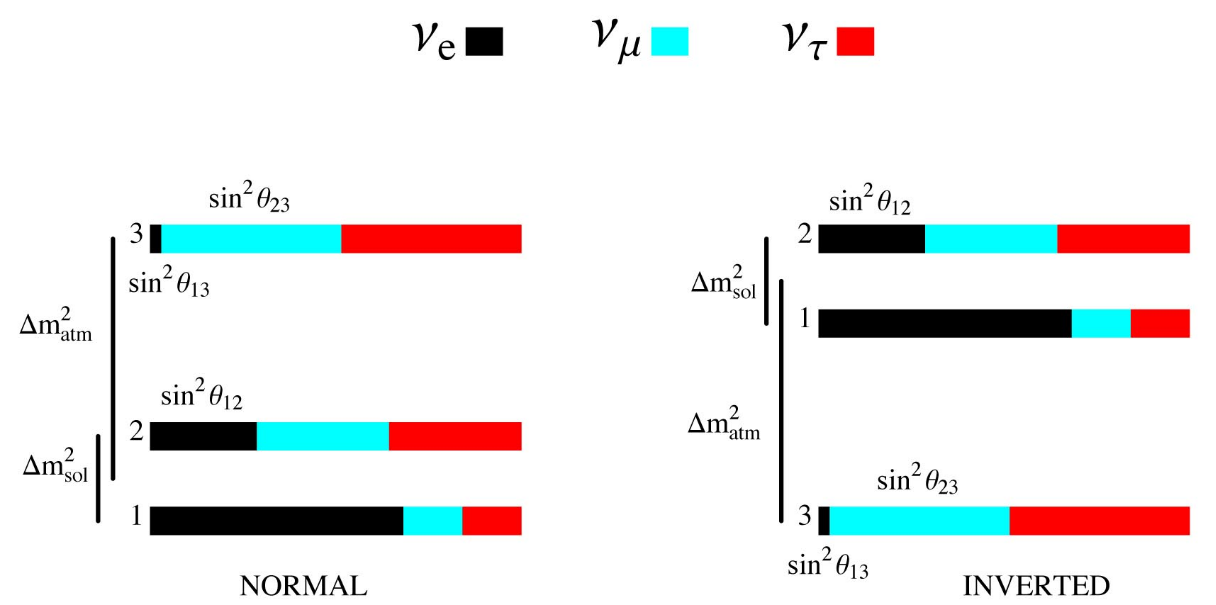
Future Sterile Sensitivities



Competitive with current best θ_{34} limits (Super-K)

NOvA Physics Results

1. $\nu_\mu \longrightarrow \nu_\mu$ disappearance channel
   - Clear deficit of ν_μ CC events as a function of energy
   - Sensitive to $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
   - 2015 analysis results Phys.Rev.D93.051104



2. $\nu_\mu \longrightarrow \nu_e$ appearance channel
   - Matter effect enhanced by 810 km baseline
   - Sensitive to θ_{13}, θ_{23}, δ_{CP}, and mass hierarchy
   - 2015 analysis results PRL. 116.151806

3. Disappearance of neutral current events
   - Evidence for oscillations involving additional sterile neutrinos
   - Fit to a 3+1 neutrino model
   - Δm^2_{41}, θ_{34}, θ_{24}
   - New result

Additionally, many cross section measurements, exotic physics searches and non-beam physics studies underway.