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NOvA

(with focus on the mass hierarchy)

European Research Council
Established by the European Commission

Jeff Hartnell
University of Sussex

Solvay Workshop, Brussels

30th November 2017

Introduction

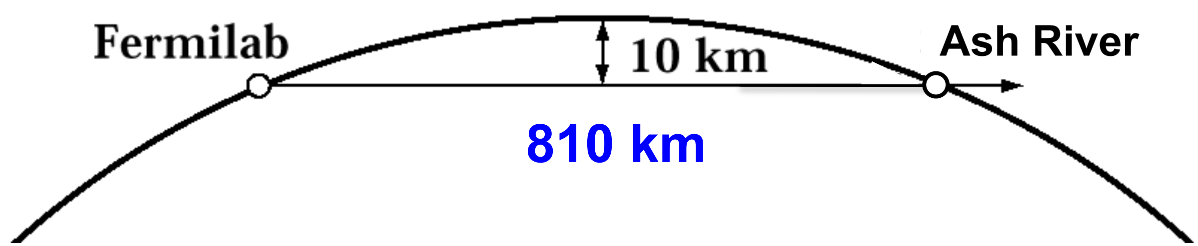
- NOvA experiment and physics goals
  - NuMI beam
  - NOvA detectors
- Mass hierarchy via MSW matter effect
- Nue and nuebar appearance probabilities
- Results:
  - Muon neutrino disappearance
  - NC analysis
  - Electron neutrino appearance
- Future sensitivity

NOvA Overview

- "Conventional" beam
- Two-detector experiment:

- Near detector
  - measure beam composition
  - energy spectrum

- Far detector
  - measure oscillations and search for new physics



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

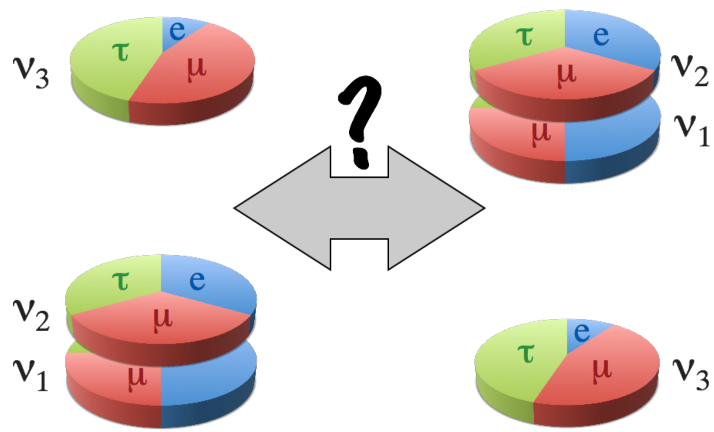
242 Collaborators
49 institutions
7 countries

Physics Goals

Results from 3 different oscillation analyses

- Disappearance of ν_μ CC events
  - clear suppression as a function of energy
  - 2016 analysis results PRL 118.151802

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

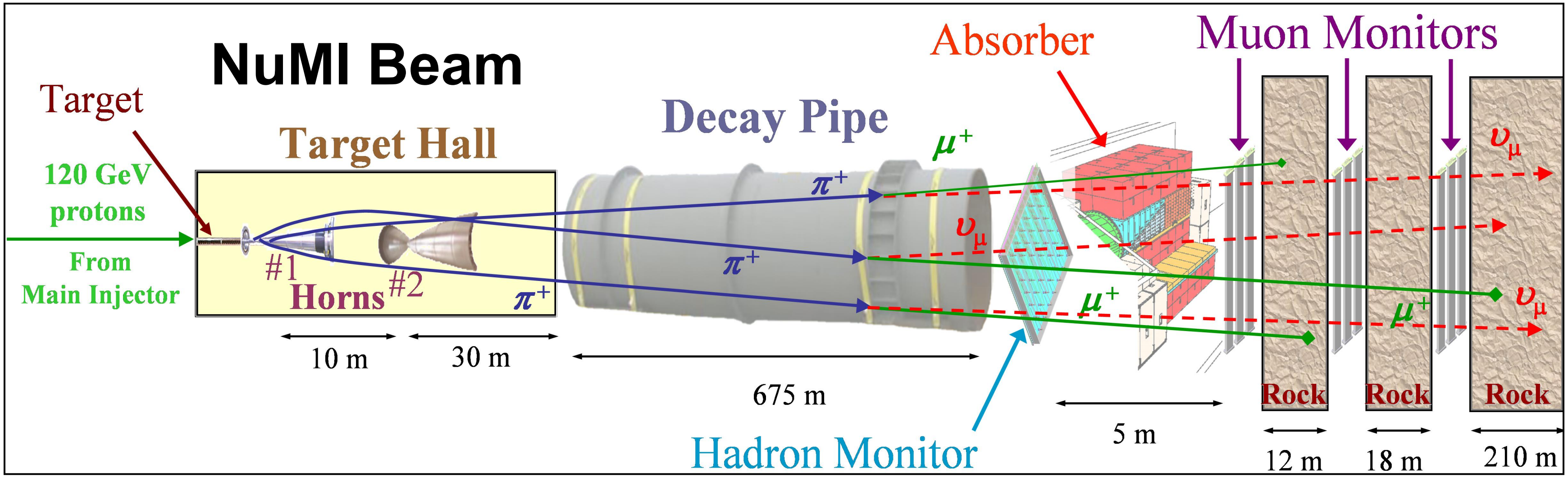


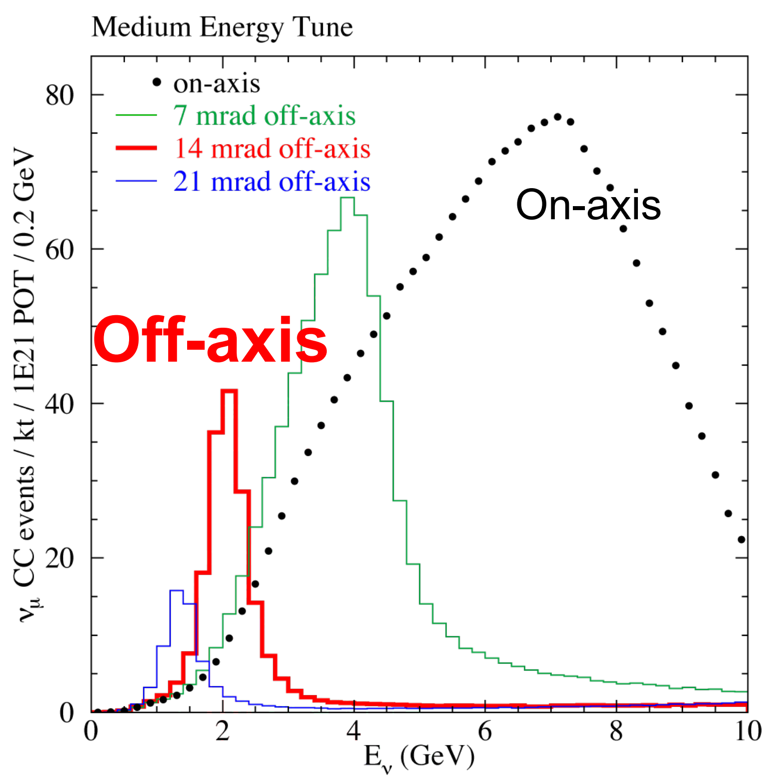
- Appearance of ν_e CC events

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

  - 2 GeV neutrinos enhances matter effects
  - ±30% effect
  - 2016 analysis results in PRL 118.231801.

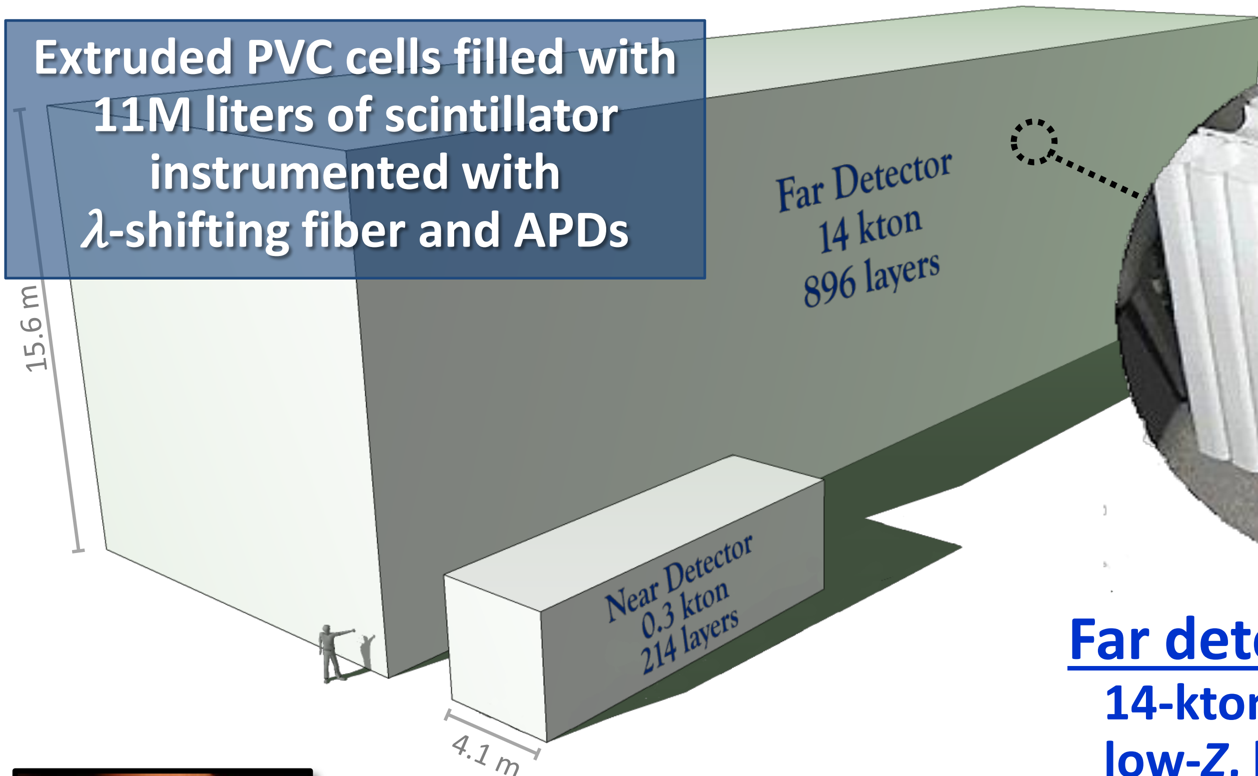
- Deficit of NC events?
  - suppression of NCs could be evidence of oscillations involving a sterile neutrino
  - Fit to 3+1model
  - new! $\Delta m^2_{41}, \theta_{34}, \theta_{24}$


NuMI Beam
Target
Target Hall
120 GeV protons
From Main Injector
#1
#2
Horns
π+
Decay Pipe
μ+
υμ
Absorber
Muon Monitors
Hadron Monitor
Rock
Rock
Rock
10 m
30 m
675 m
5 m
12 m
18 m
210 m

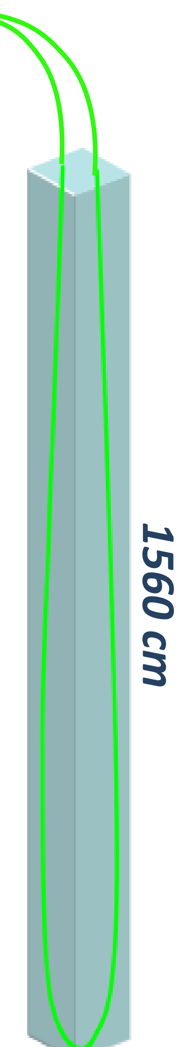

Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
On-axis
Off-axis
νμ CC events / kt / 1E21 POT / 0.2 GeV
Eν (GeV)
0
20
40
60
80
0
2
4
6
8
10

NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell

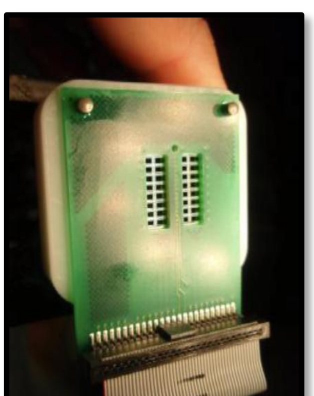


Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ 344,000 channels

Near detector:

0.3-kton version of the same
→ 20,000 channels



32-pixel APD

Fiber pairs from 32 cells

Long-baseline neutrino oscillations

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \underbrace{\sin^2 2\theta_{23}}_{\text{experimental data are consistent with unity (“maximal mixing”)}} \sin^2(\Delta m^2_{32} L/4E)$$

...to leading order

experimental data are **consistent with unity**
(“maximal mixing”)

➔ **Need a leap in precision on θ_{23} (and Δm^2_{32})**

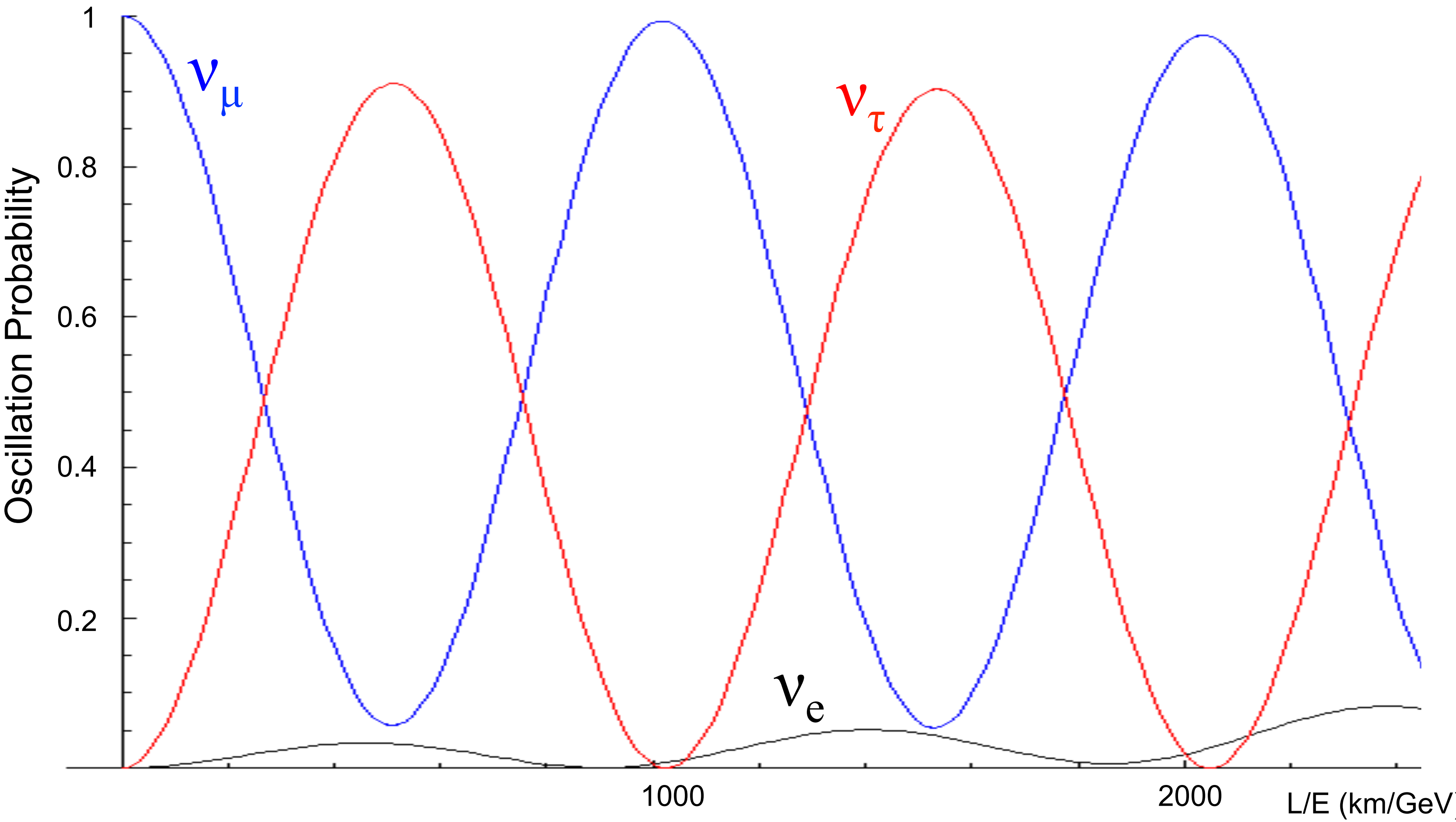
ν_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \underbrace{\sin^2 2\theta_{13}}_{\text{Daya Bay}} \sin^2(\Delta m^2_{32} L/4E)$$

Daya Bay reactor experiment:
$\sin^2(2\theta_{13}) = 0.084 \pm 0.005$

*...plus potentially large **CPv** and **matter effect** modifications!*

Starting with ν_μ



How does the mass hierarchy come into play?

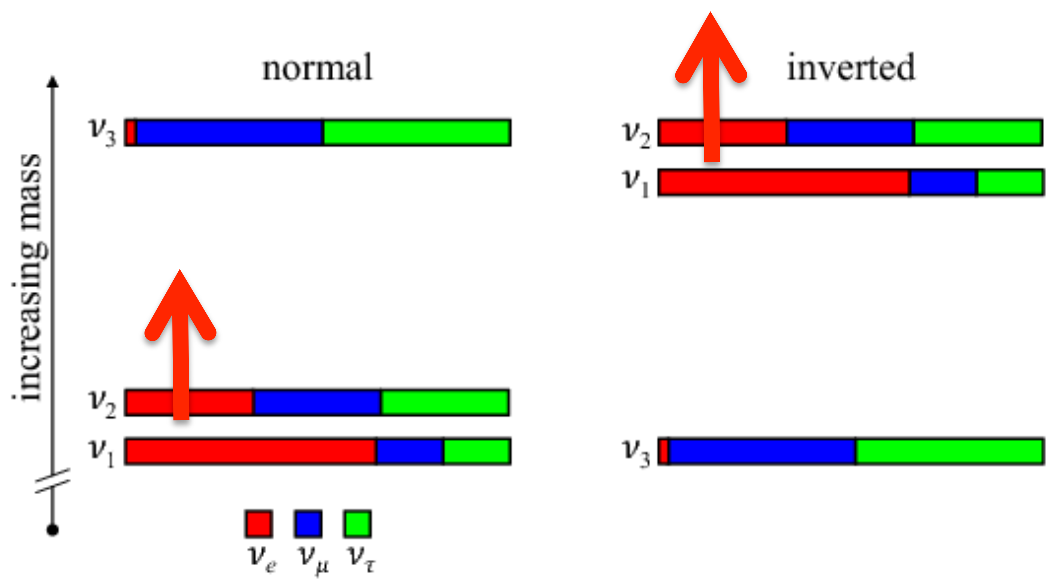
Δm^2_{31} and Δm^2_{32} differ by 3%

Small effect

JUNO's planned measurement involves this

Matter Effect & Mass Hierarchy

- Neutrinos (and antineutrinos) travel through matter not antimatter
  - electron density causes asymmetry (fake CPv!)
    - via specifically **CC** coherent forward elastic scattering
  - different Feynman diagrams for ν_e and $\bar{\nu}_e$ interactions with electrons so different amplitudes



Arrows flip for antineutrinos

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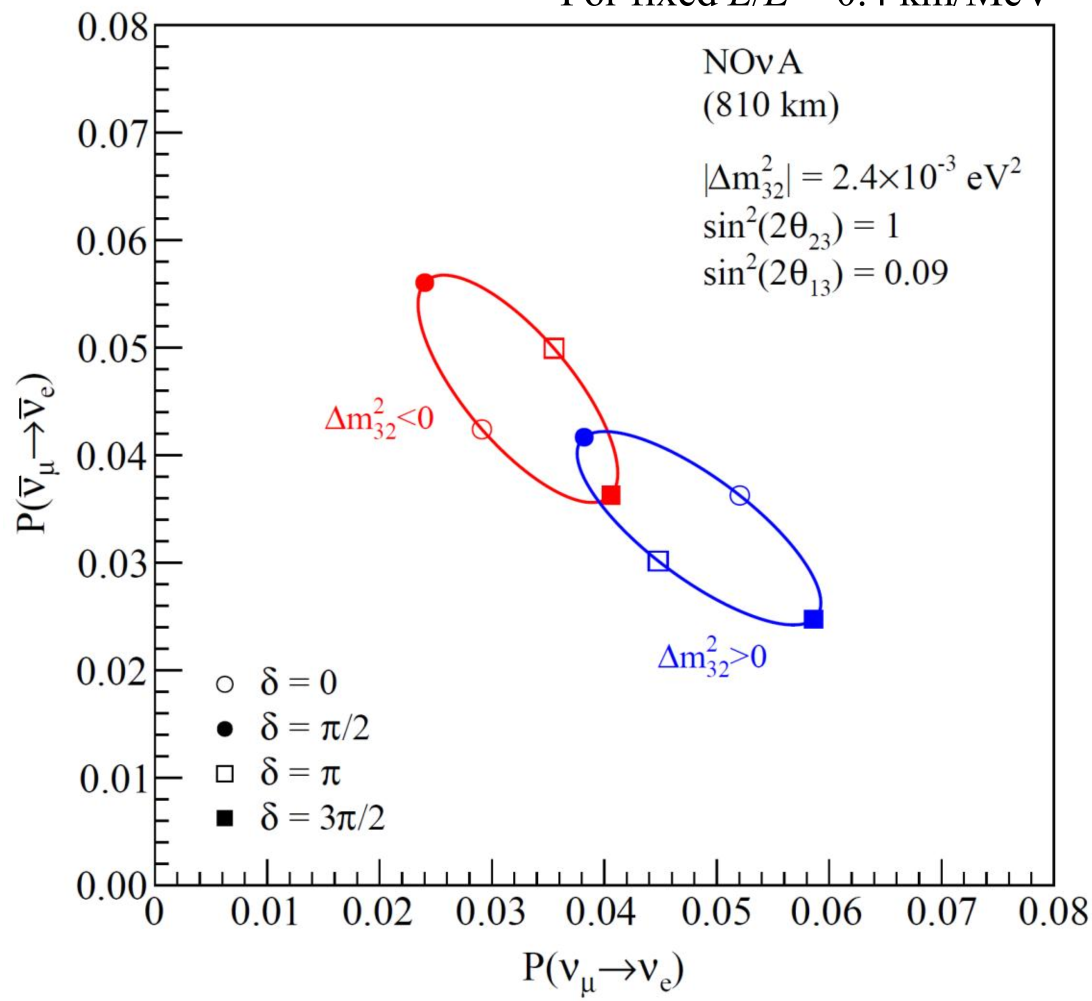
Long-baseline $\nu_\mu \to \nu_e$

A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs. $P(\nu_\mu \to \nu_e)$ plotted for a single neutrino energy and baseline

For fixed L/E = 0.4 km/MeV



Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

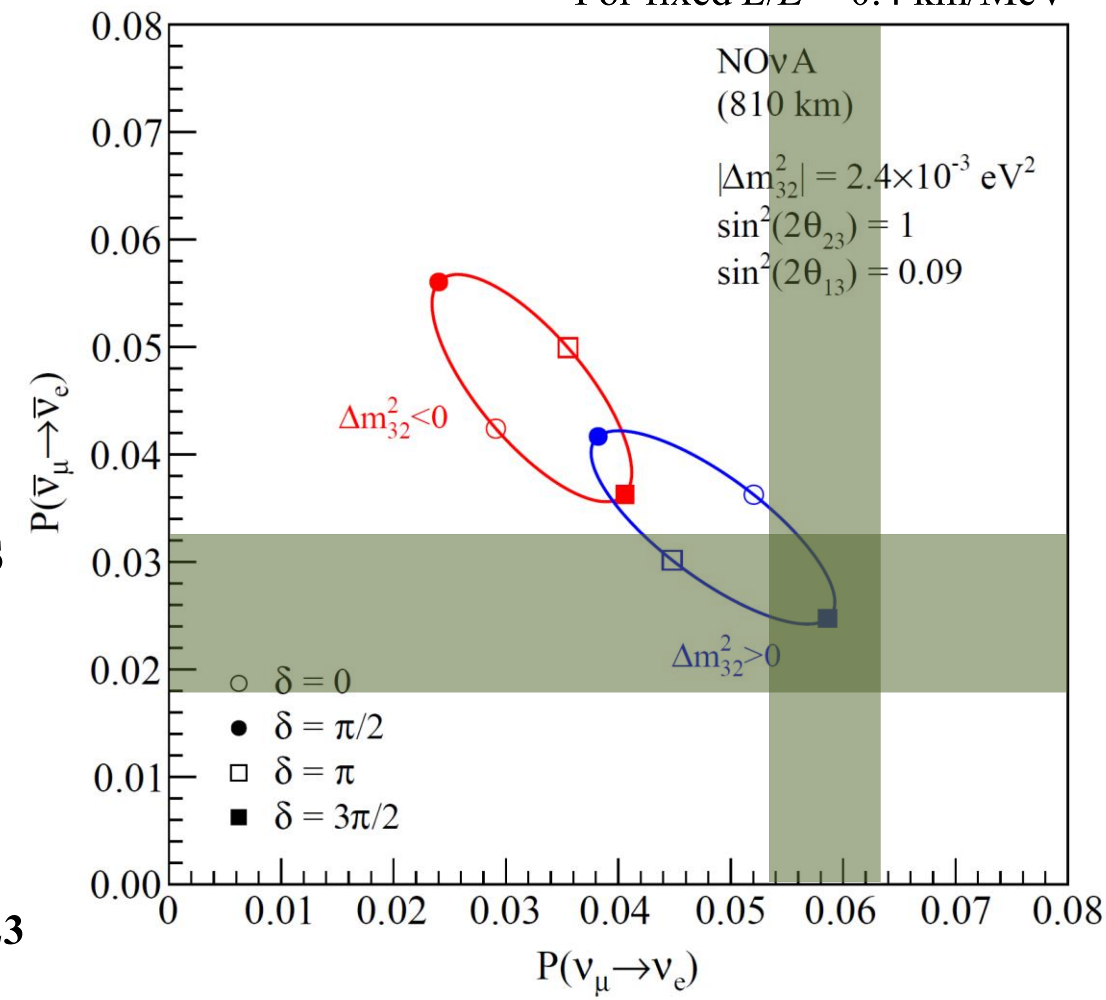
Measure these probabilities

(an example measurement of each shown)

Also:

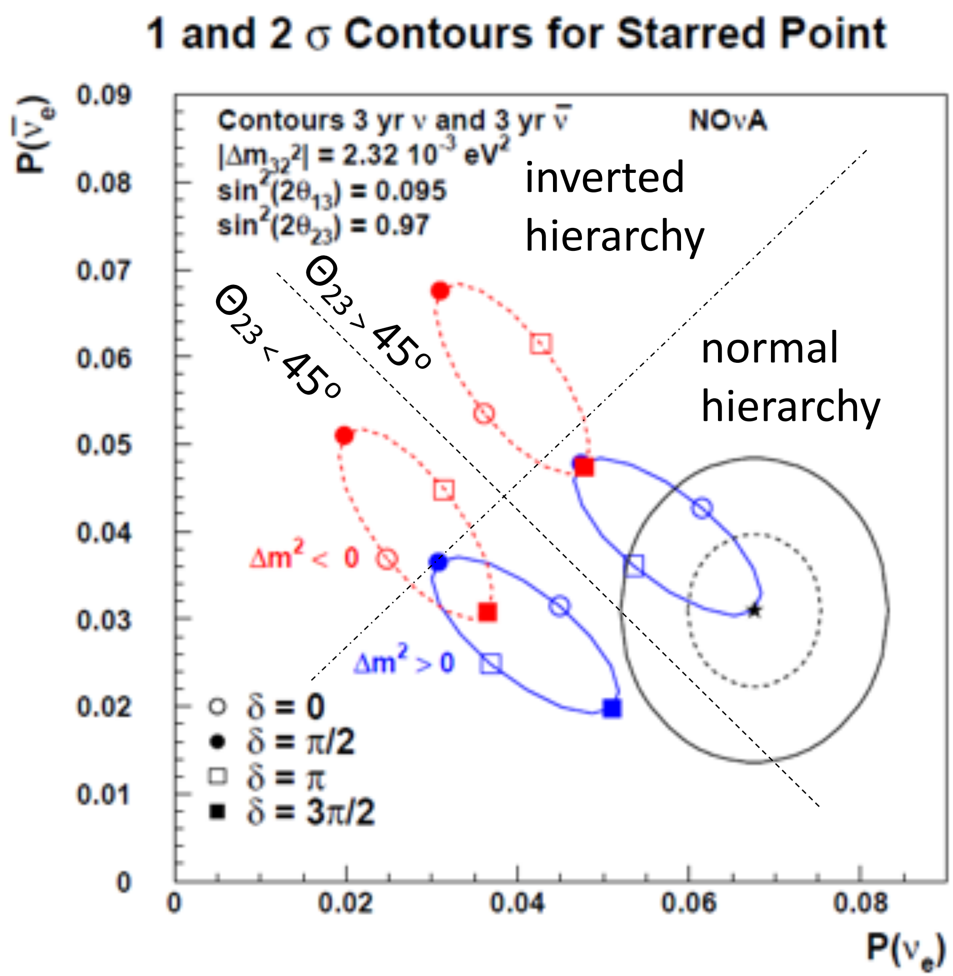
Both probabilities $\propto \sin^2\theta_{23}$

For fixed L/E = 0.4 km/MeV



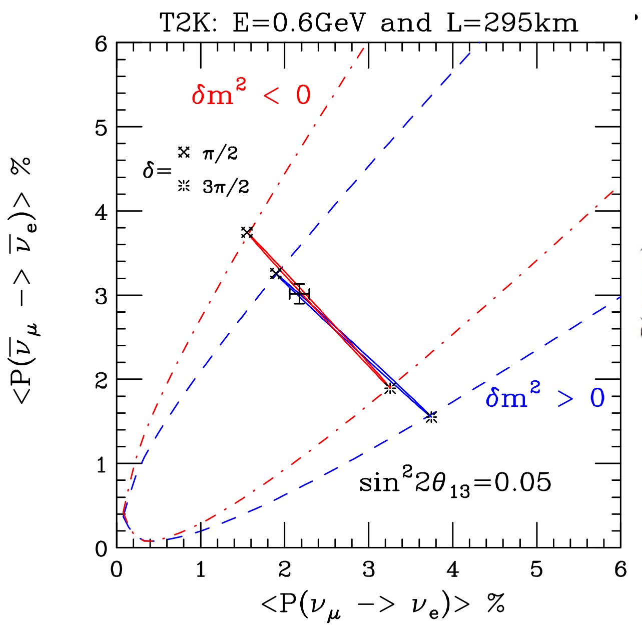
Non-maximal mixing scenario

- If θ_{23} non-maximal then effect of octant is important
- Big effect, +/- 20%



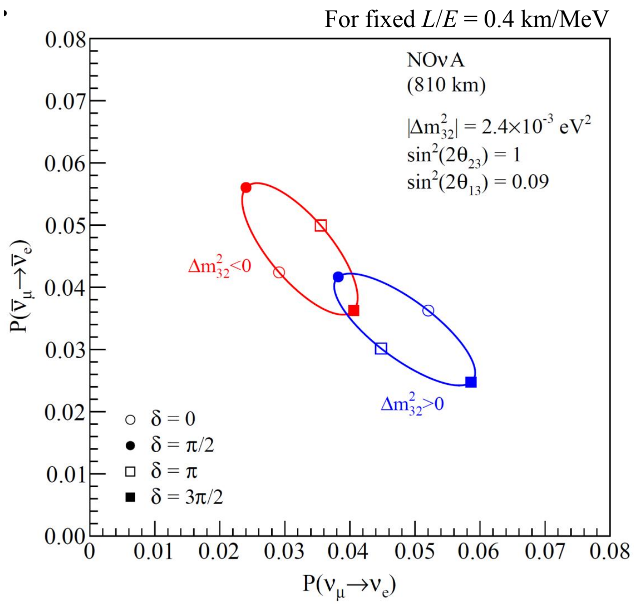
Effect of Increasing Energy

T2K



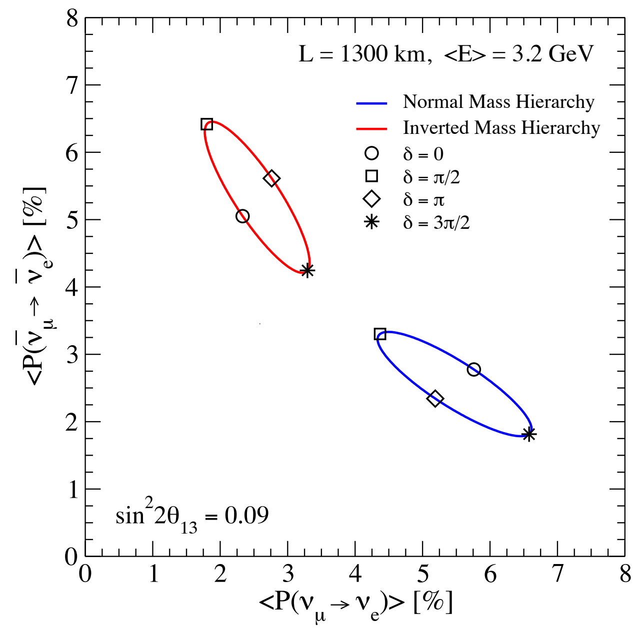
0.6 GeV

NOvA



2 GeV

DUNE



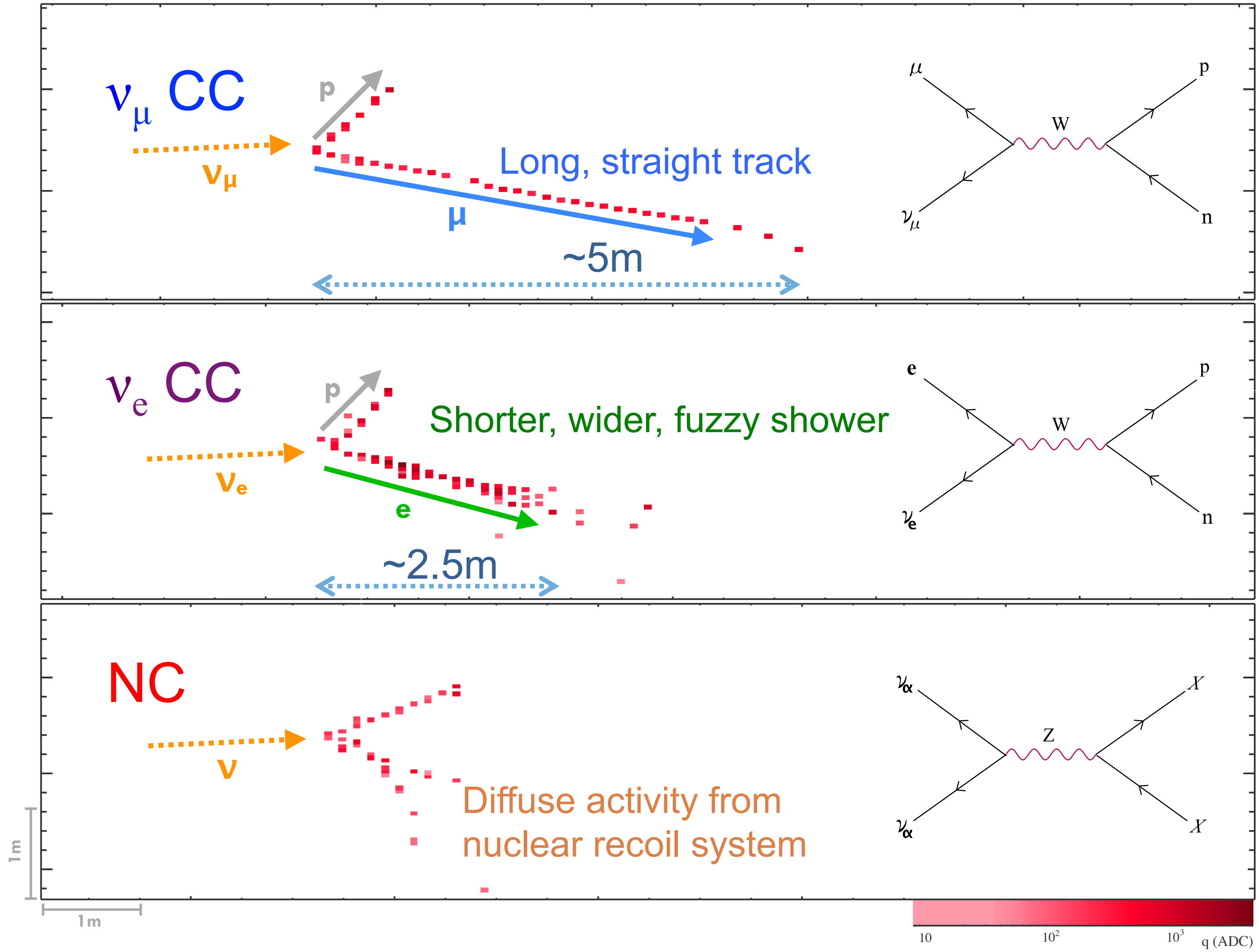
3 GeV

Increasing Energy

[→ bigger matter effect and hence bigger fake CP violation]

The measurements

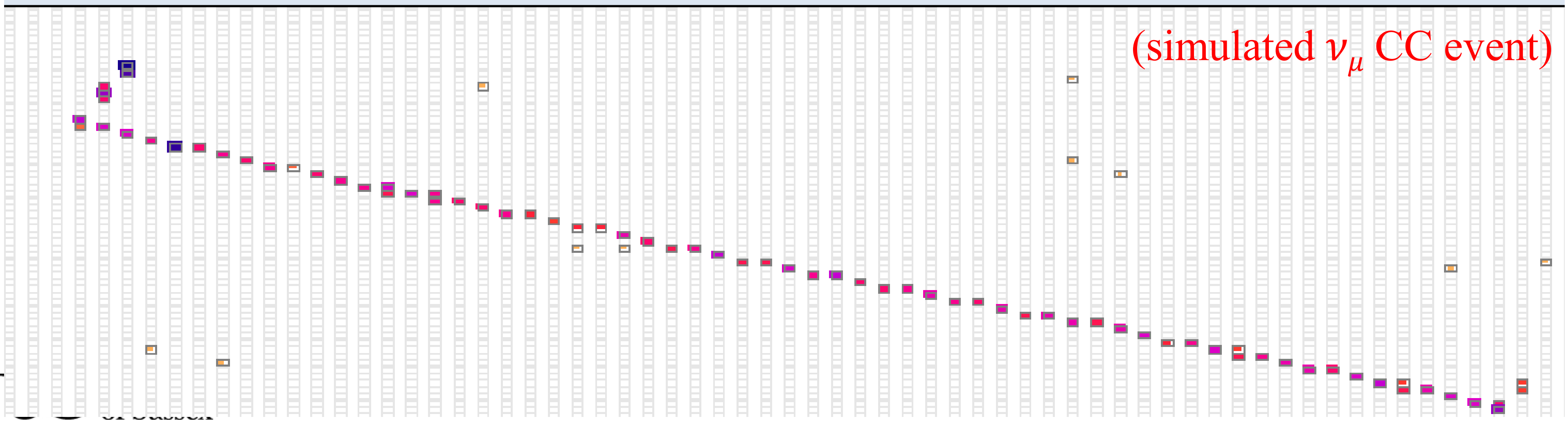
Event Types



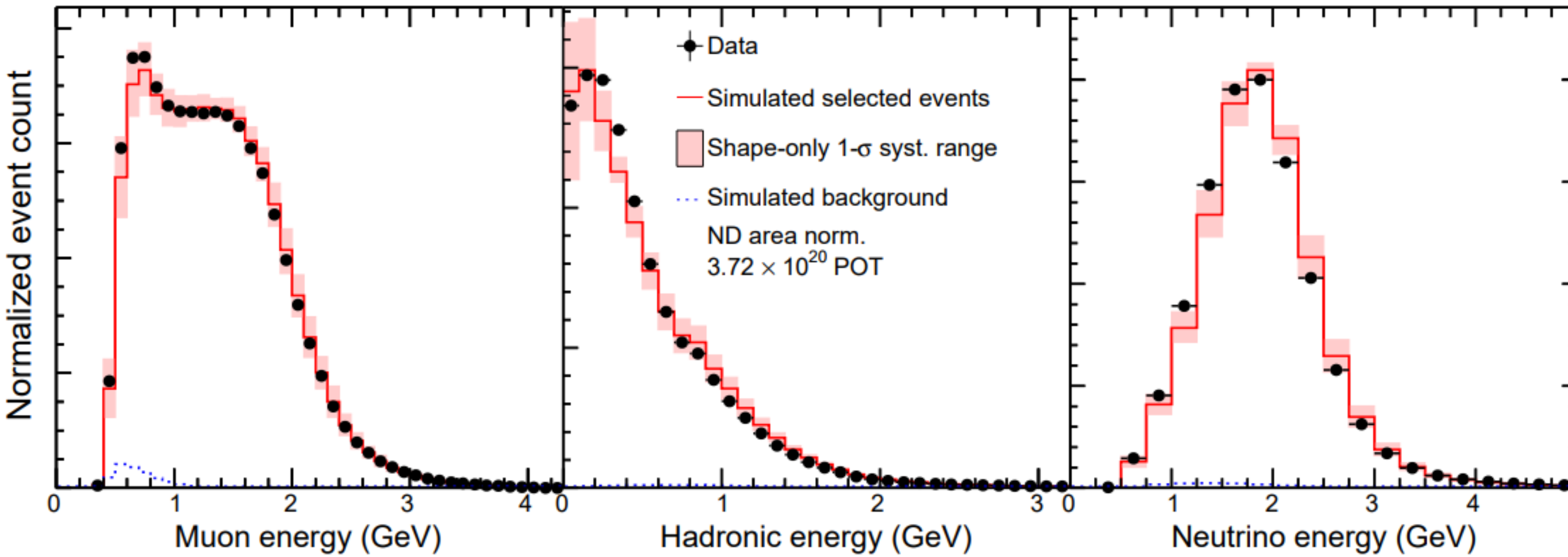
ν_μ CC
p
ν_μ
Long, straight track
μ
~5m
μ
p
W
ν_μ
n
ν_e CC
p
Shorter, wider, fuzzy shower
ν_e
e
~2.5m
e
p
W
ν_e
n
NC
ν
Diffuse activity from
nuclear recoil system
ν_α
X
Z
ν_α
X
1 m
1 m
10
10^2
10^3
q (ADC)

ν_μ disappearance

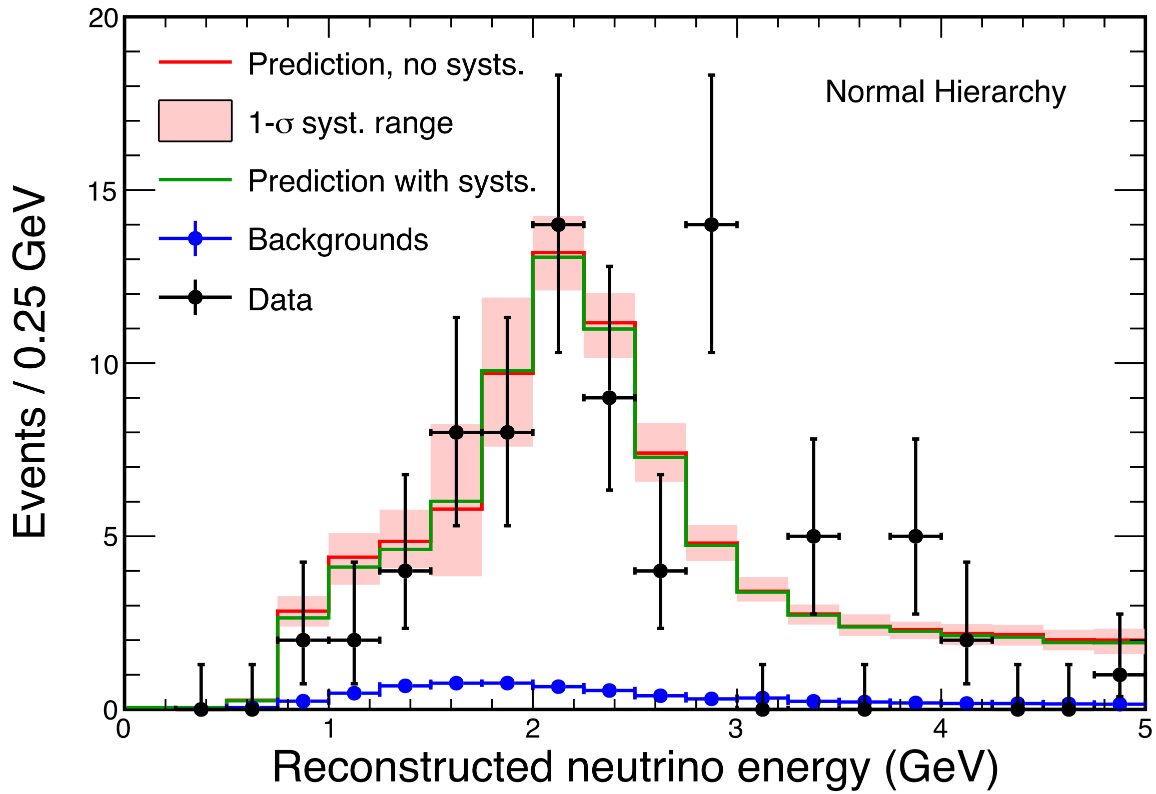
- Identify **contained ν_μ CC events** in each detector
- Measure their **energies**
- Extract oscillation information from differences between the **Far and Near energy spectra**



ν_μ Near Detector Data



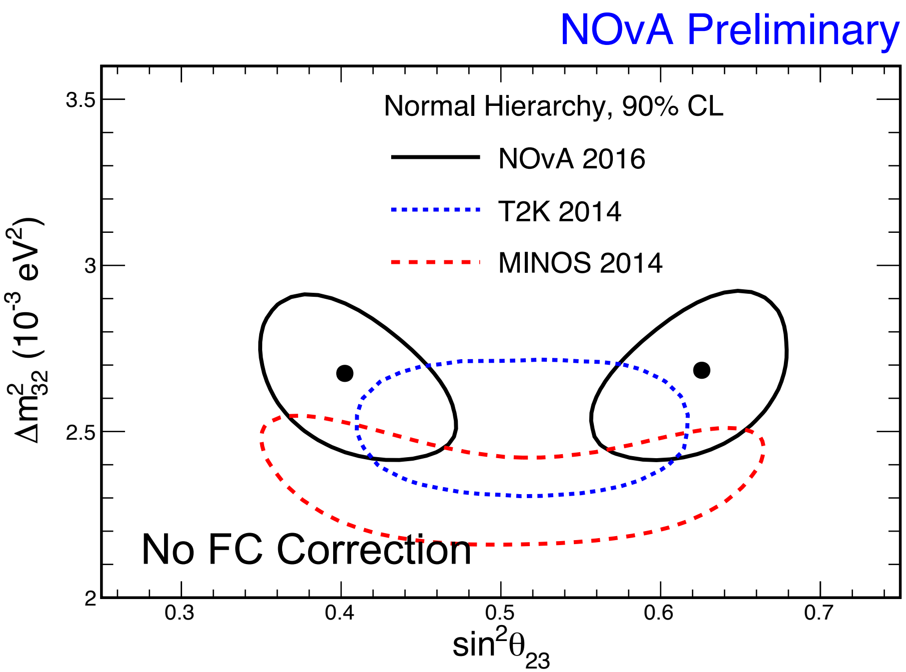
ν_μ Far Detector Data

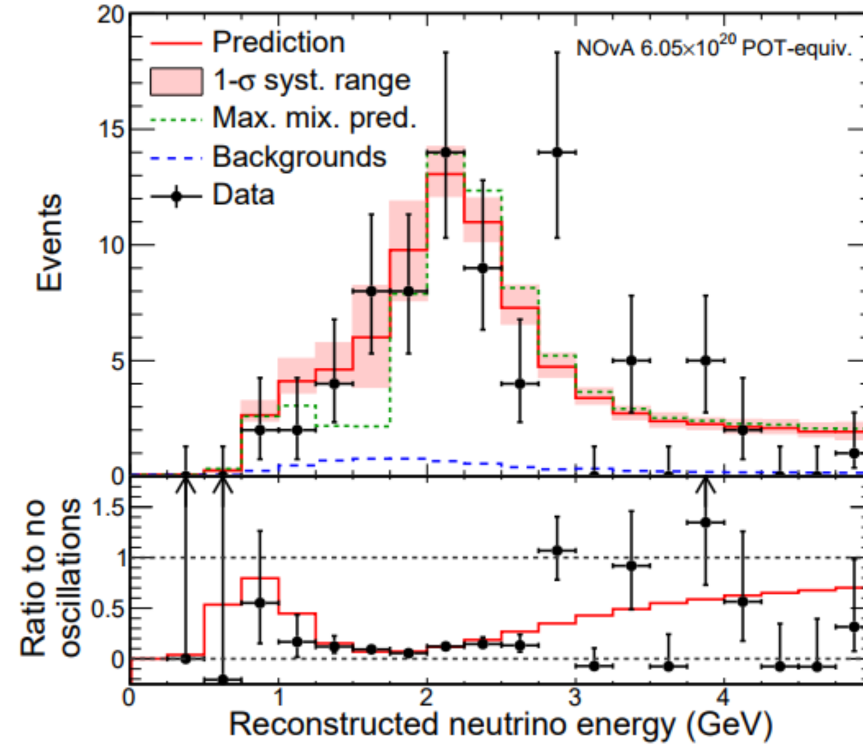


78 events observed in FD

- **473±30 with no oscillation**
- 82 at best oscillation fit
- 3.9 beam BG + 2.7 cosmic

ν_μ Disappearance Result





Best Fit (in NH):

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

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

Maximal mixing excluded at 2.6σ

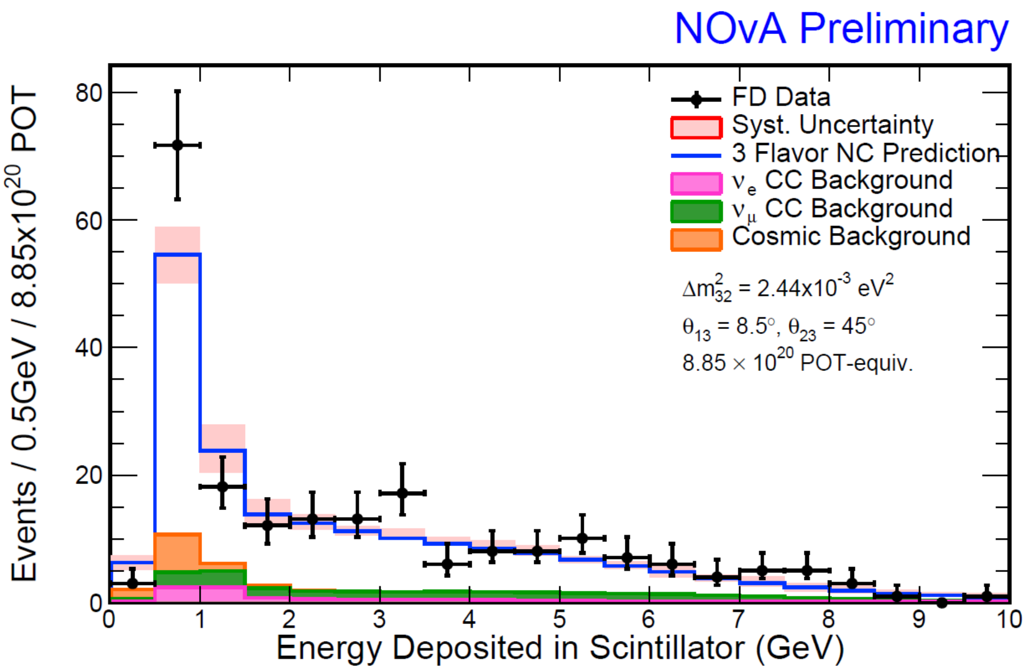
Driven by bins in oscillation dip (1-2 GeV).
Forcing maximal mixing gives:

$$\Delta m^2_{32} = (2.46) \times 10^{-3}\mathrm{eV}^2$$

Neutral Current Result

(NOvA's first 2017 dataset result, presented at NuFact Sep/17)

NC Far Detector Data & Results



Observed **214** NC candidates

Prediction 191.16 ± 13.82(stat.)±21.99 (syst.)

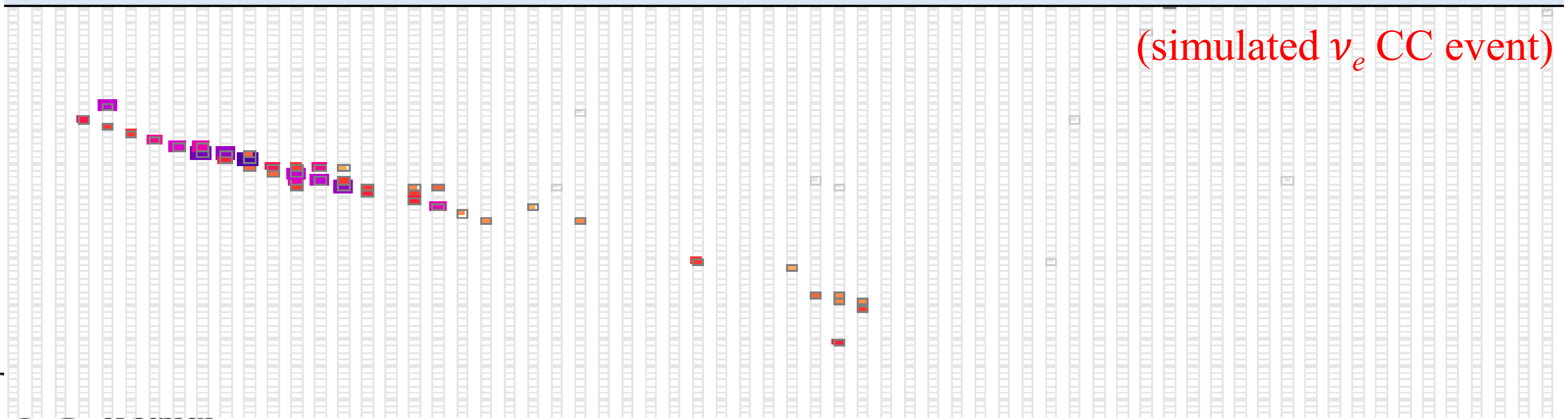
No depletion of NC events observed

NOvA sees no evidence for ν_s mixing

	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
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

ν_e appearance

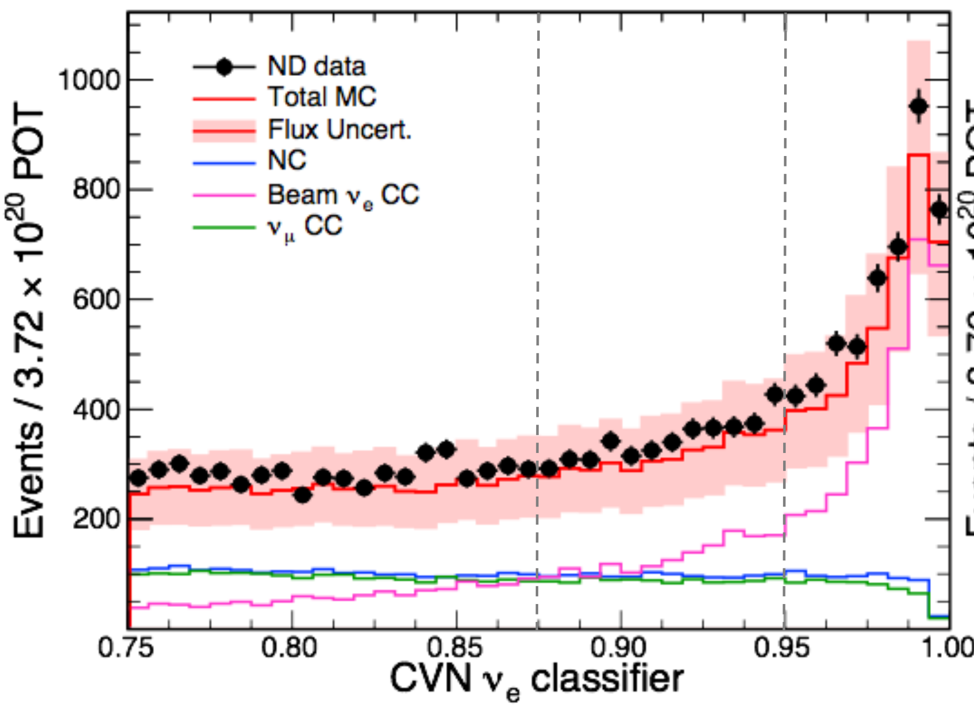
- Identify **contained ν_e CC candidates** in each detector
- Use Near Det. candidates to **predict beam backgrounds** in the Far Detector
- Interpret any **Far Det. excess** over predicted backgrounds as ν_e appearance

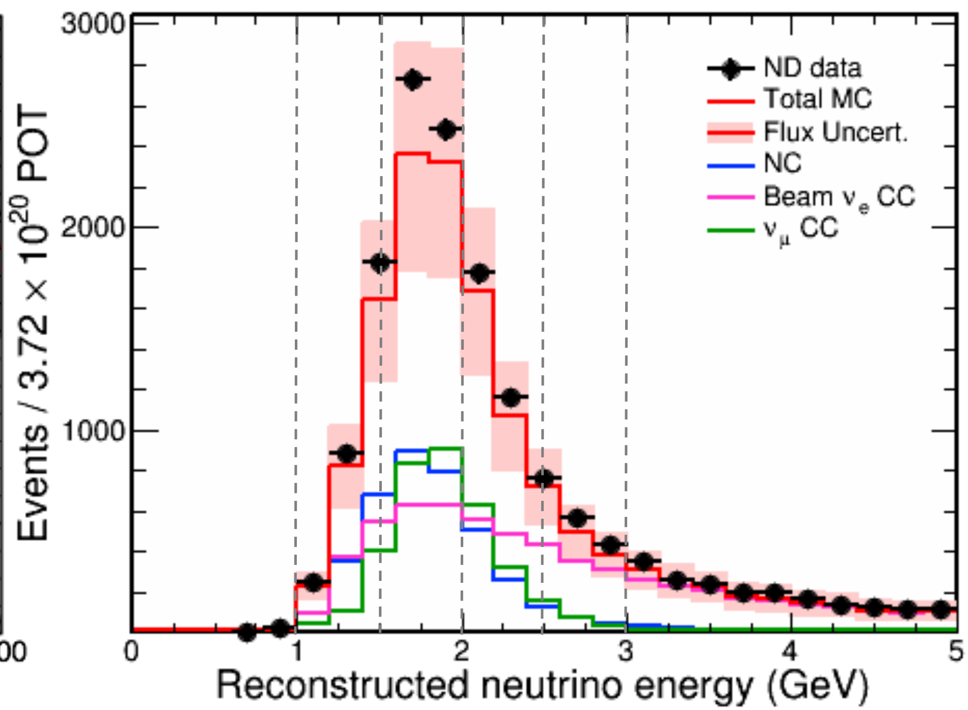


ν_e Near Detector Data

- Select ν_e CC interactions with 73% efficiency and 76% purity
- 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

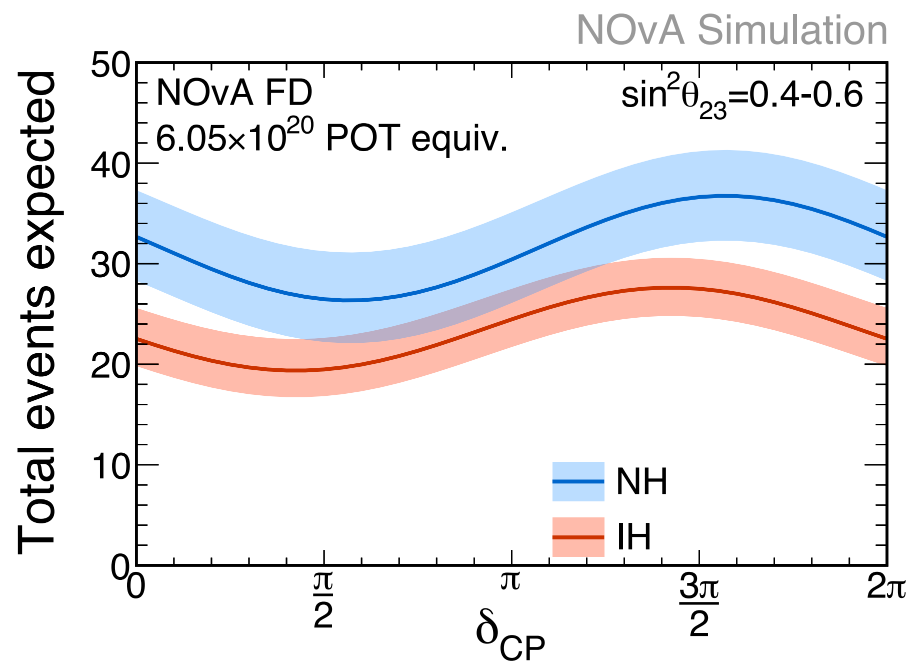
beam ν_e up by 4%
NC up by 17%
ν_μ CC up by 10%





Prediction

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



Signal events
(±5% systematic uncertainty):

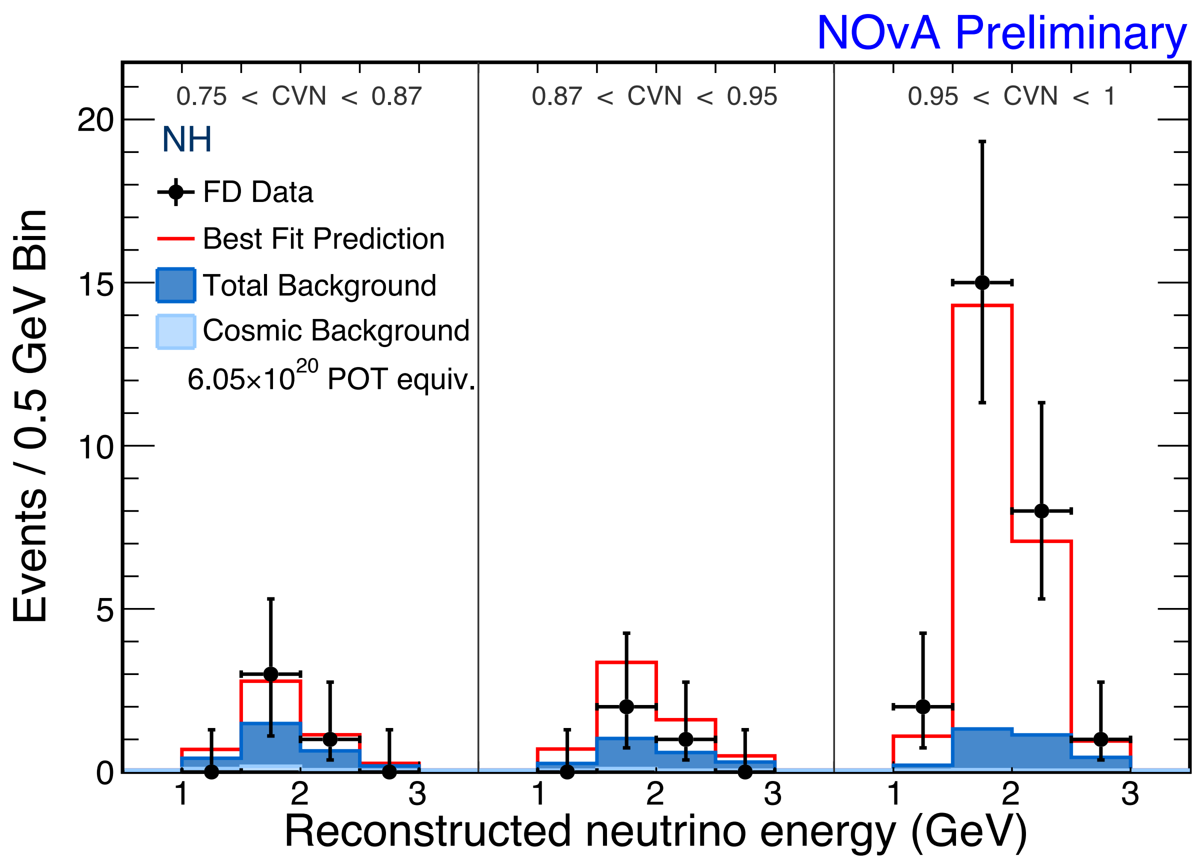
NH, $3\pi/2$,	IH, $\pi/2$,
28.2	11.2

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

ν_e Far Detector Data

- Observe 33 events
  - background 8.2 ± 0.8



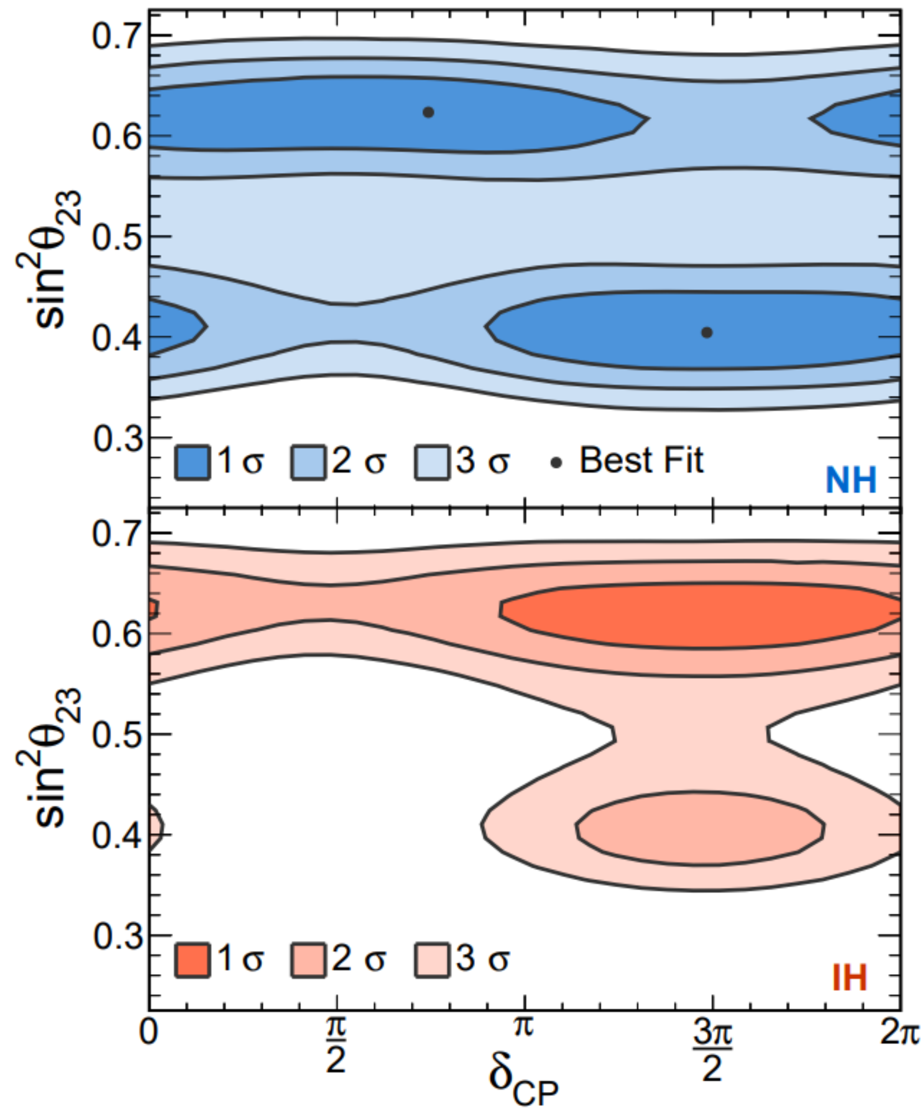
>8σ electron neutrino appearance signal

Joint $\nu_e + \nu_\mu$ Fit Contours

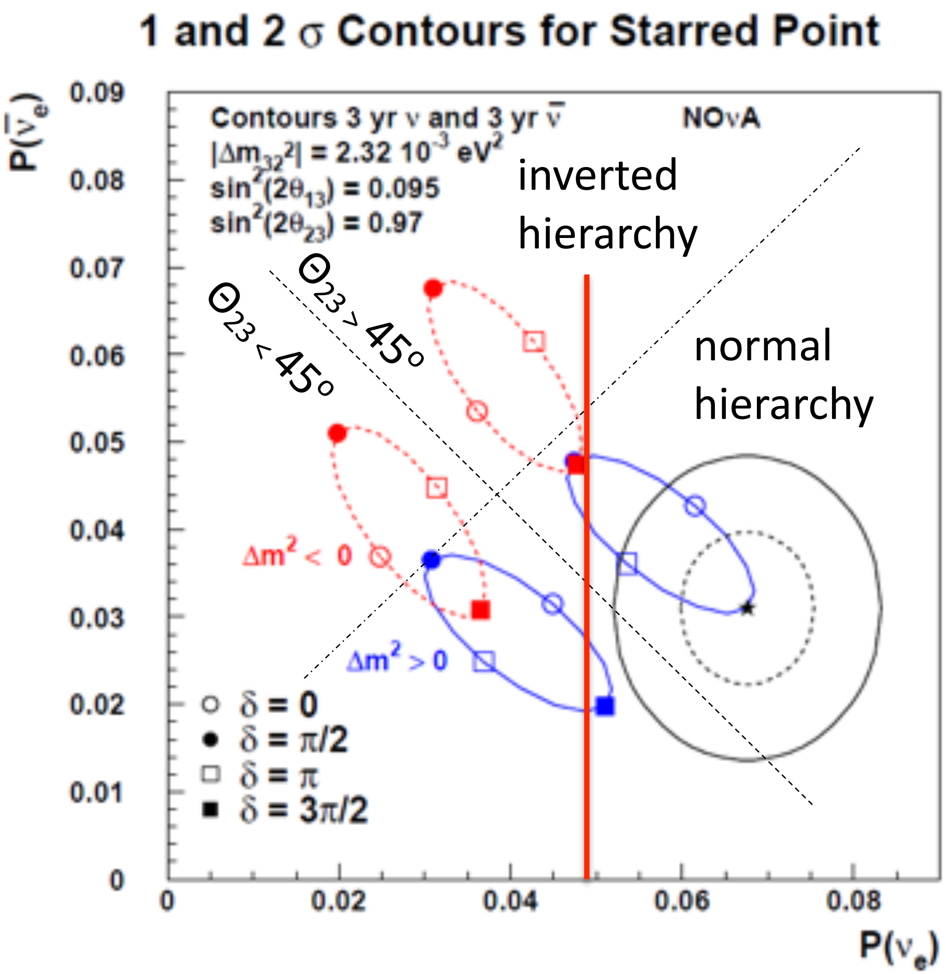
- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13})=0.085\pm0.05$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
- Global best fit Normal Hierarchy

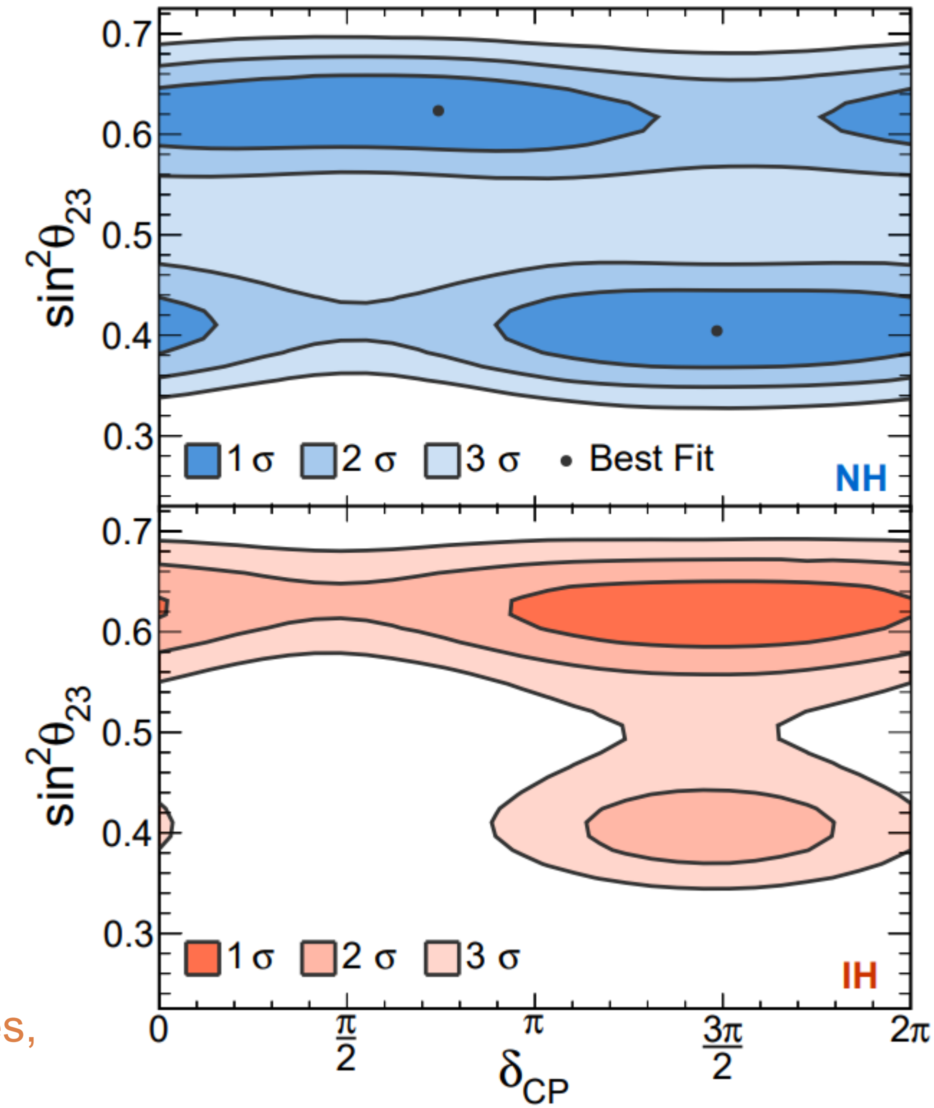
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants & hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\delta_{CP}=\pi/2$



Contours



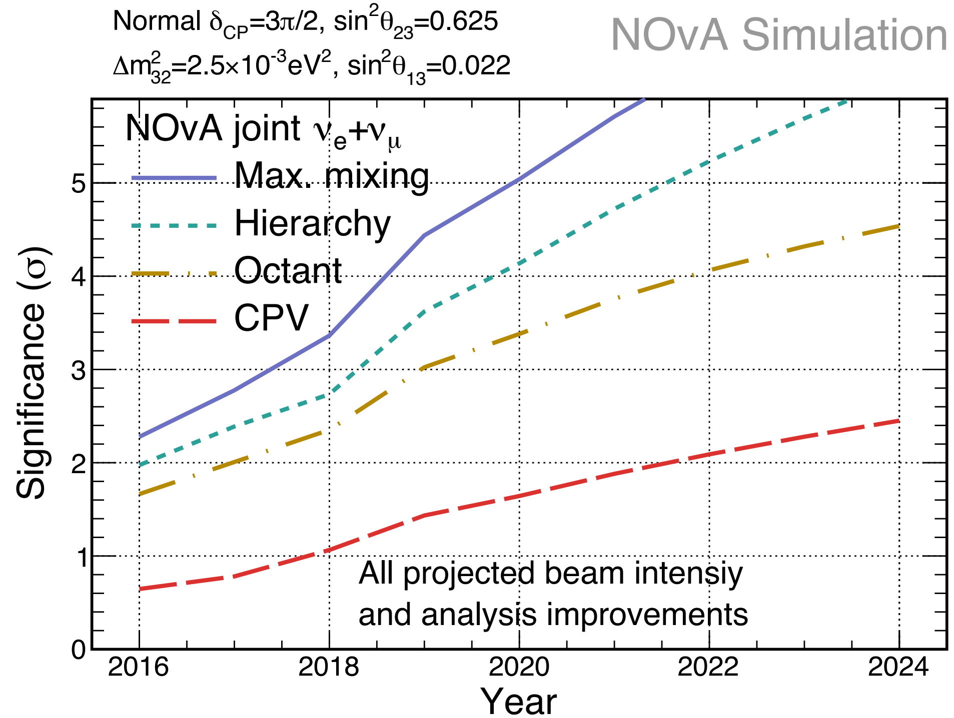


Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing.

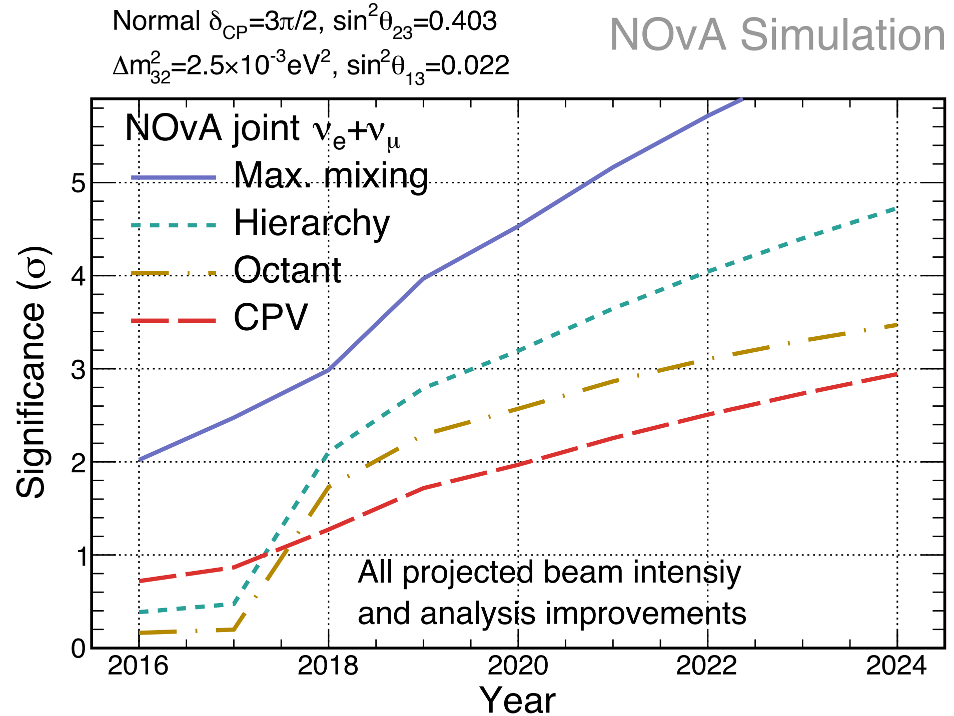
Results planned for summer 2018

Future Sensitivity

Upper Octant



Lower Octant



Conclusions

With 6.05×10^{20} POT, NOvA finds:

- Muon neutrinos disappear
  - Maximal mixing excluded at 2.6σ
- Electron neutrinos appear
  - Data prefers NH at low significance
  - IH, lower octant, $\delta_{CP}=\pi/2$ region excluded at 3σ

- 50% more neutrino data being analysed
  - Neutral current events show no evidence of steriles
  - New ν_e and ν_μ results very soon

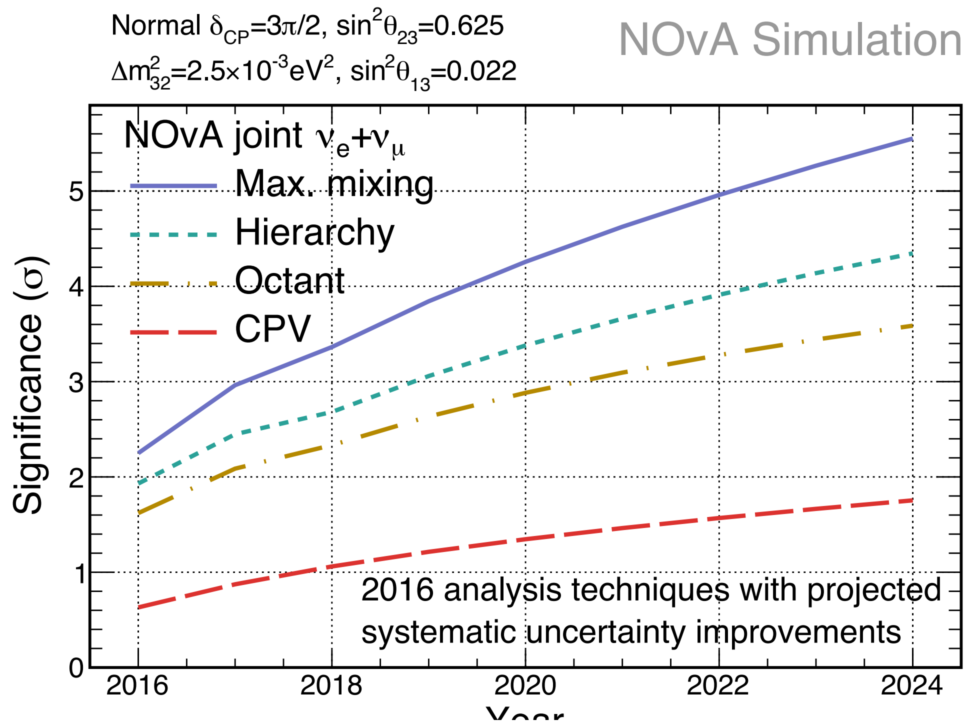
- Antineutrino run underway: results in summer 2018

- Stay tuned!

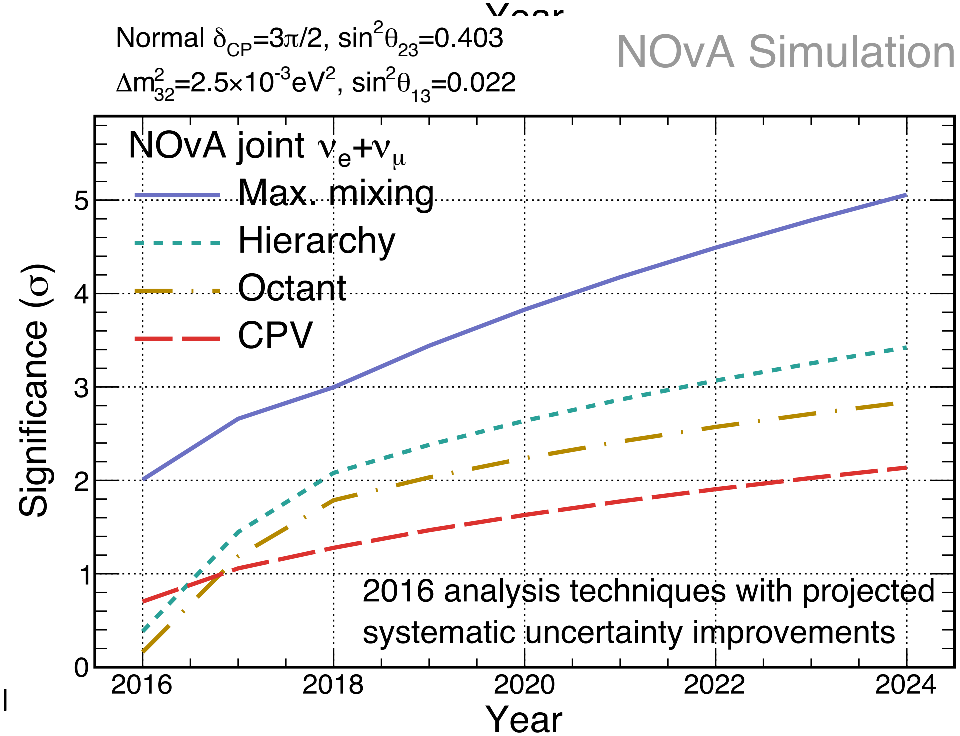
Backup slides

Future Sensitivity

Upper Octant



Lower Octant



$\nu_\mu \rightarrow \nu_e$ appearance probability

[PDG, 2014]

$$P_m^{3\nu\ man}(\nu_\mu \rightarrow \nu_e) \cong P_0 + P_{\sin\delta} + P_{\cos\delta} + P_3 \,.$$

Here

$$P_0 = \sin^2\theta_{23}\ \frac{\sin^2 2\theta_{13}}{(A-1)^2}\ \sin^2[(A-1)\Delta]$$

$$P_3 = \alpha^2\ \cos^2\theta_{23}\ \frac{\sin^2 2\theta_{12}}{A^2}\ \sin^2(A\Delta)\,,$$

$$P_{\sin\delta} = -\,\alpha\ \frac{8\,J_{CP}}{A(1-A)}\,(\sin\Delta)\,(\sin A\Delta)\ (\sin[(1-A)\Delta])\ ,$$

$$P_{\cos\delta} = \alpha\ \frac{8\,J_{CP}\ \cot\delta}{A(1-A)}\,(\cos\Delta)\,(\sin A\Delta)\ (\sin[(1-A)\Delta])\ ,$$

where

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\,,\ \ \Delta = \frac{\Delta m^2_{31}\,L}{4E}\,,\ \ A = \sqrt{2}G_{\rm F}N_e^{man}\,\frac{2E}{\Delta m^2_{31}}\,,$$

and $\cot\delta = J_{CP}^{-1}{\rm Re}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2}),\ \ J_{CP} = {\rm Im}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2})$.

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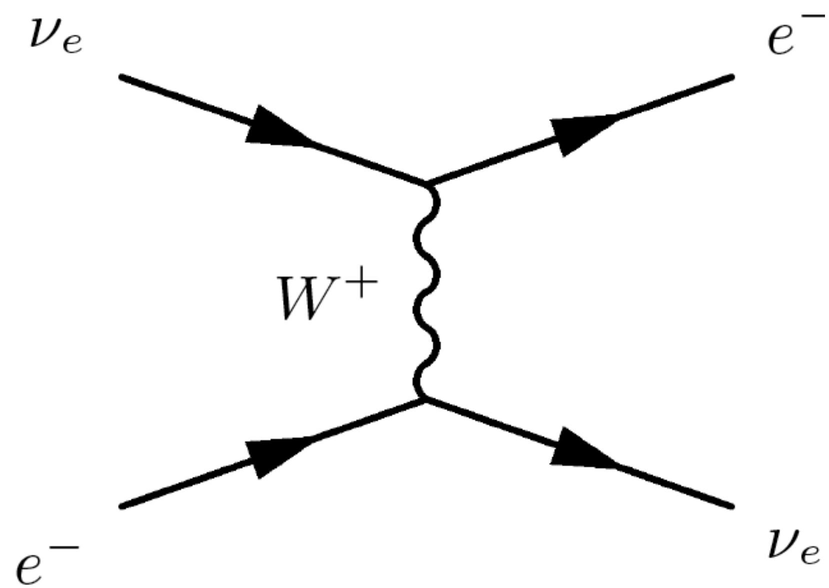
Matter Effect & Mass Hierarchy

- Coherent forward elastic scattering
- Neutrinos (and antineutrinos) travel through matter not antimatter
  - electron density causes the asymmetry
    - via specifically **CC** coherent forward elastic scattering
  - different Feynman diagrams for ν_e and $\bar{\nu}_e$ interactions with electrons...

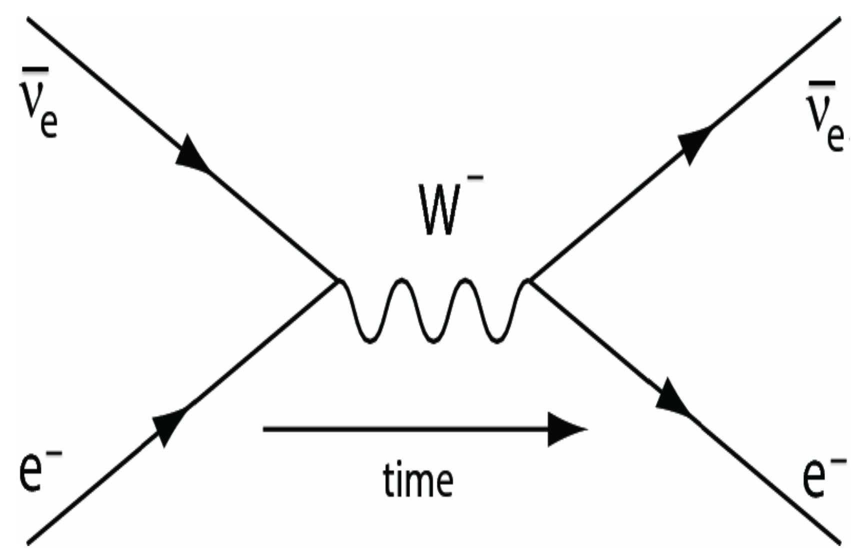
Different Feynman Diagrams

- Amplitude for electron **neutrino** interaction with an electron



- is not equal to...

- Amplitude for electron **antineutrino** interaction with an electron

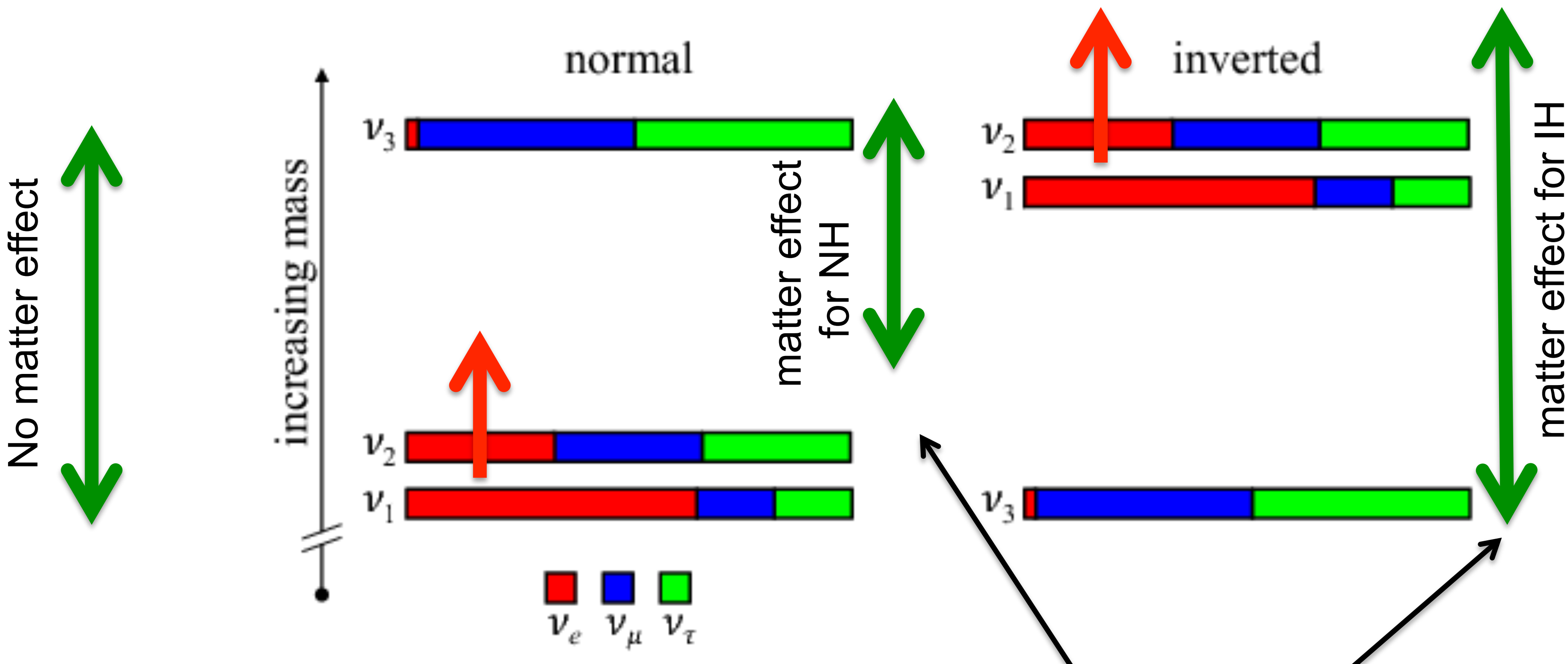


Electron neutrinos and antineutrinos are affected differently by interactions with matter → **fake** CP violation

Why does the mass hierarchy affect oscillations involving electron (anti)neutrinos?

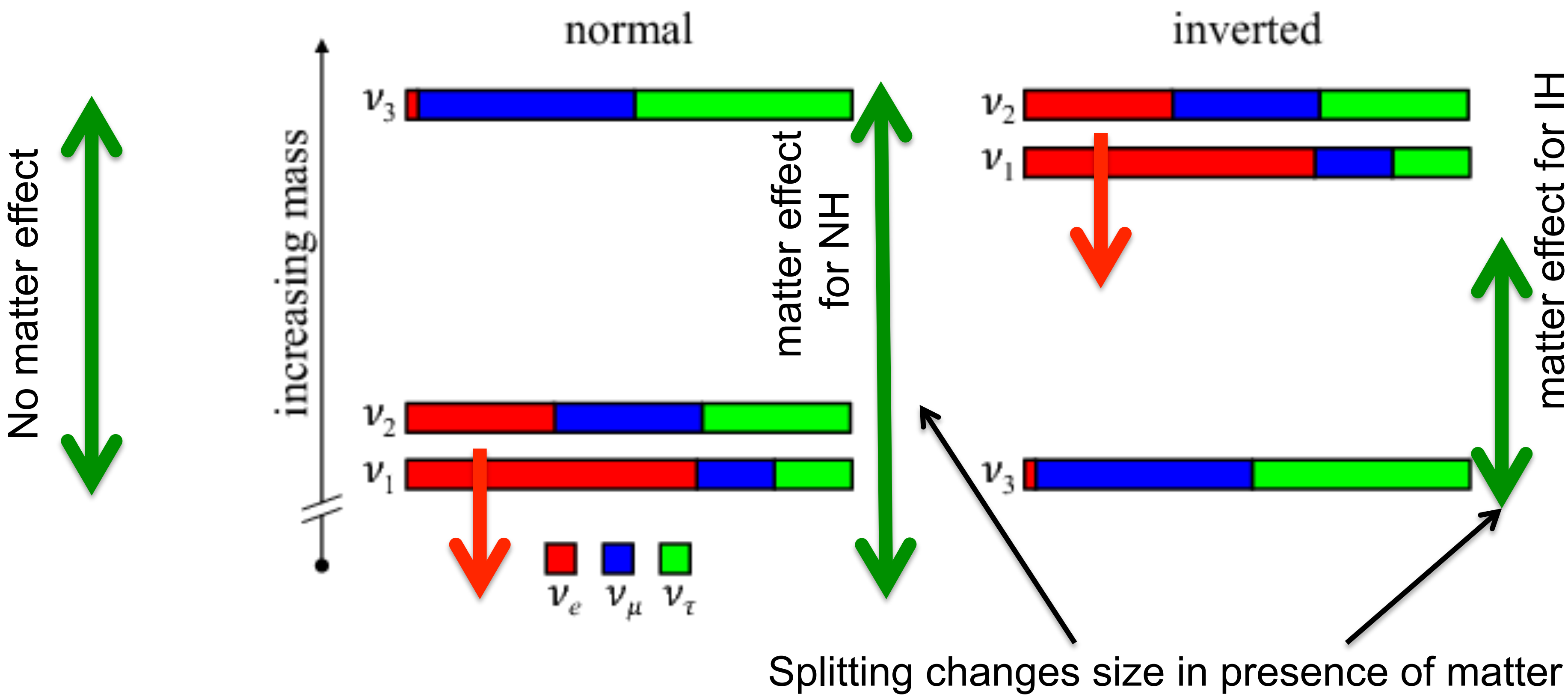
Matter effect (neutrino case)

- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



Antineutrino case

- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



Splittings **and** mixing angles affected

- Mixing angles in matter (θ_M) are modified by the mass squared splitting in matter (Δm^2_M)
  - e.g. simple 2-flavour case:

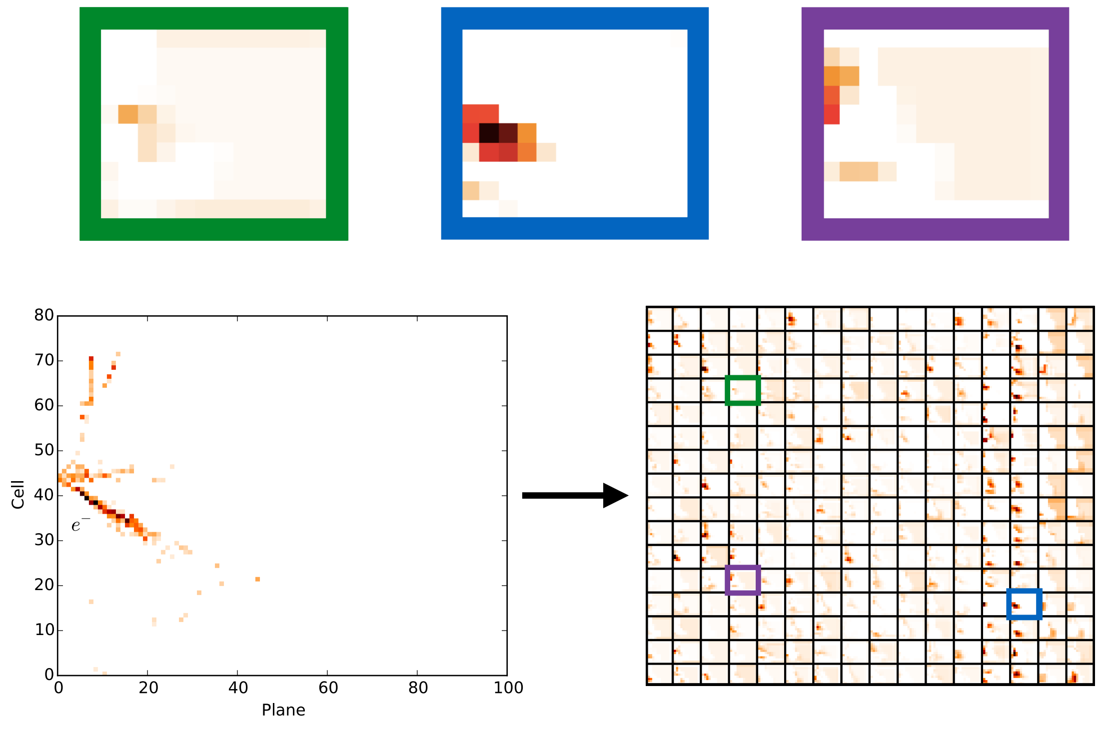
$$\sin 2\vartheta_{\mathrm{M}} = \frac{\Delta m^2 \sin 2\vartheta}{\Delta m^2_{\mathrm{M}}}$$

  - Also see it in full 3-flavour equations (a few slides back)

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



Improved Event Selection

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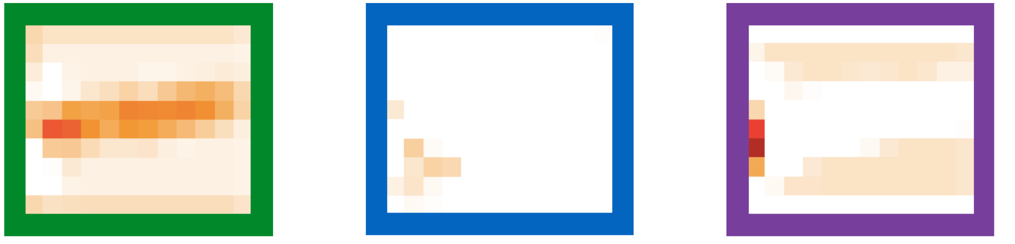
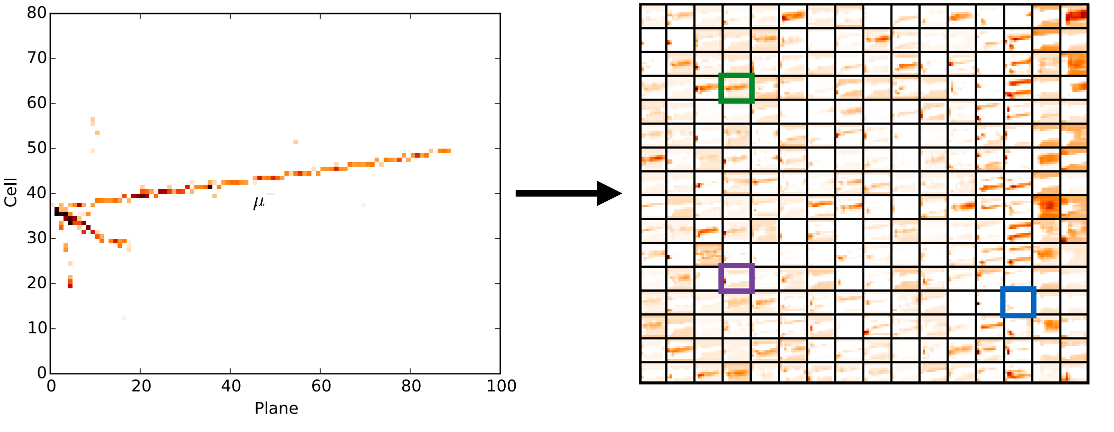
- □ Extracted features used as inputs to a conventional neural network to classify the event

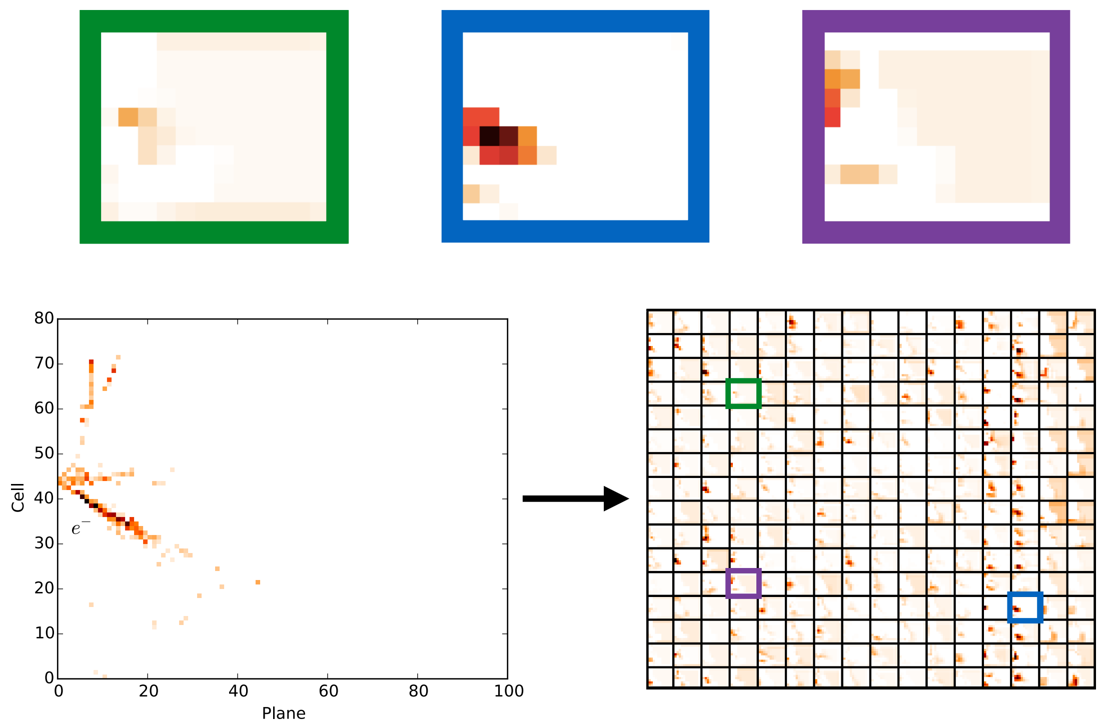




Improved Event Selection

- 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



Improvement in sensitivity from CVN equivalent to 30% more exposure

[A. Aurisano et al., arXiv:1604.01444]

We consider multiple possible sources of systematic error

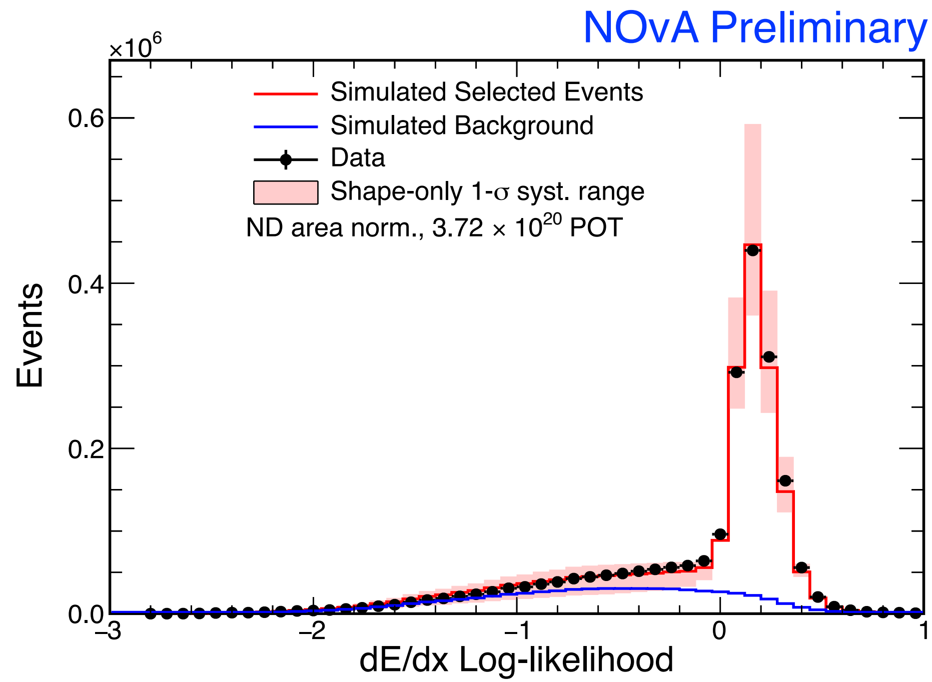
Systematic	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model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

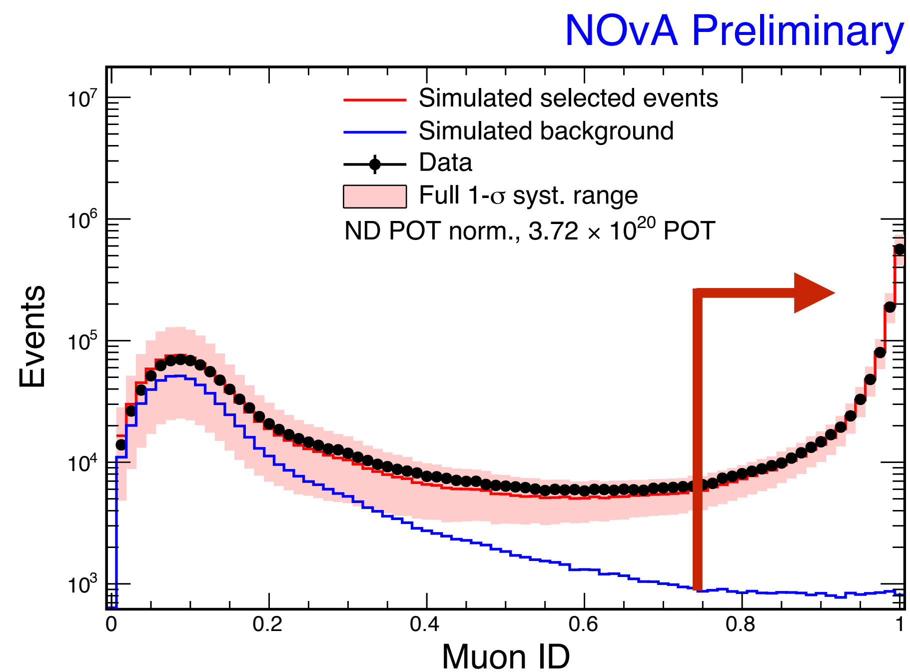
In each case:

- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the parameter measurement error is recorded

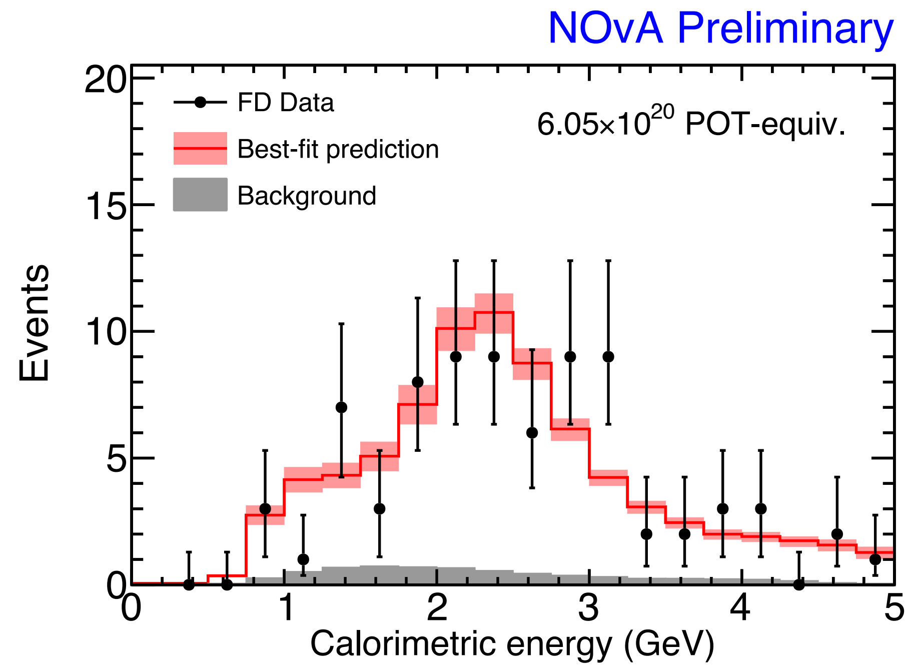
ν_μ Event Selection

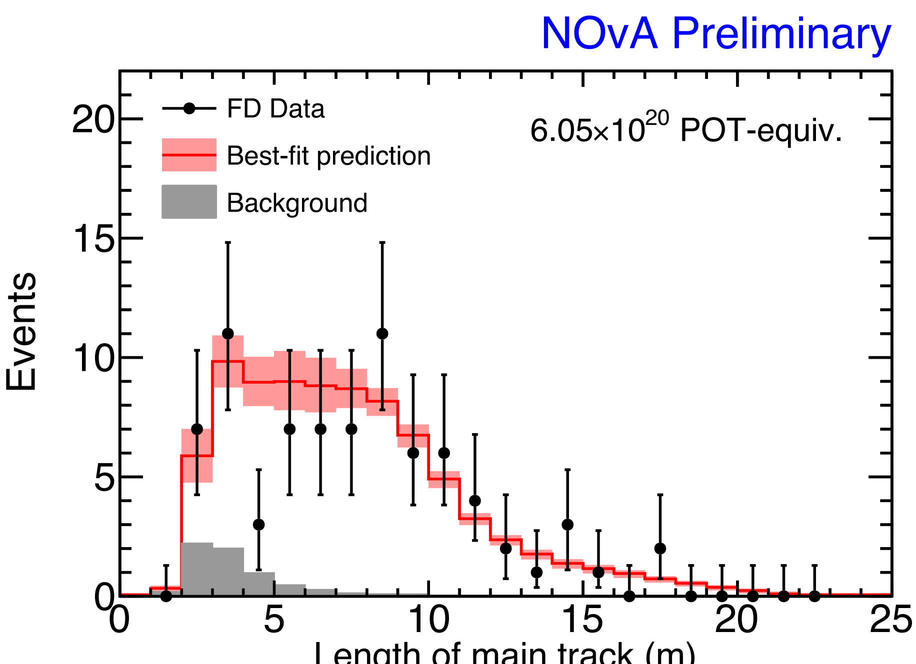
- Goal: Isolate a pure sample of ν_μCC events less than 5GeV
  - Select events with long tracks
  - Suppress NC and cosmic backgrounds
- 4-variable kNN used to identify muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- ND data matches simulation well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

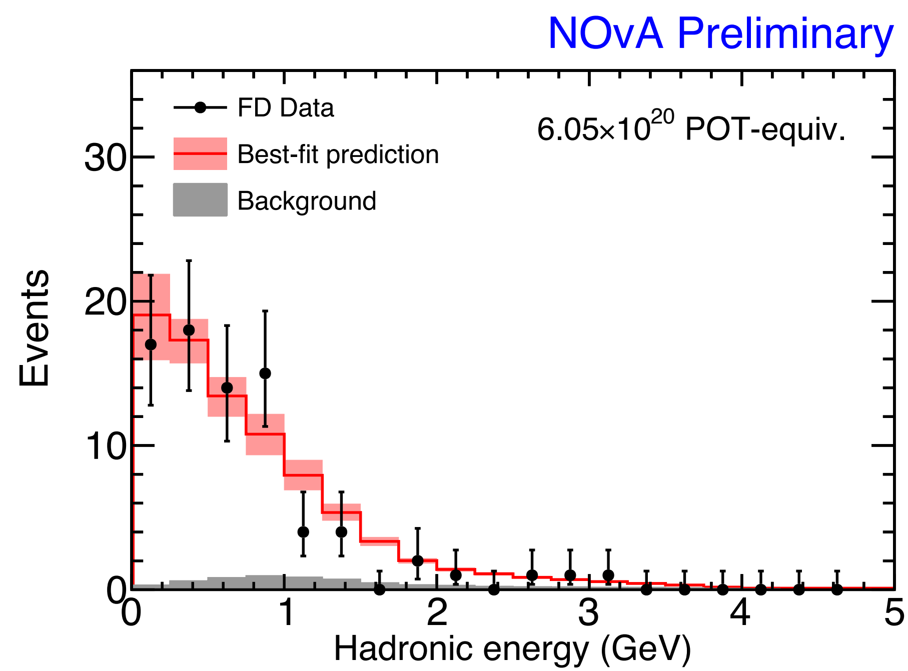




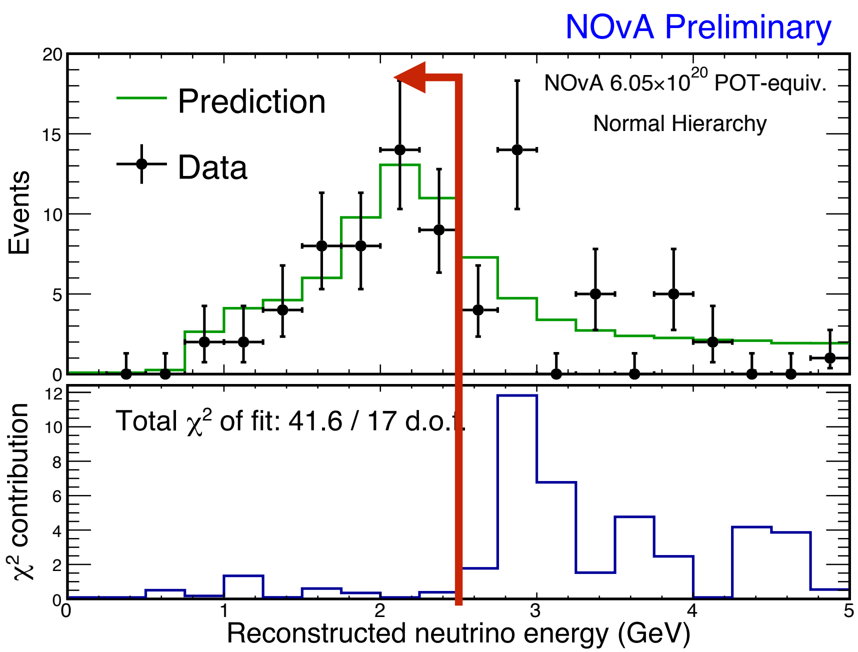
Our best fit oscillation prediction matches other distributions well

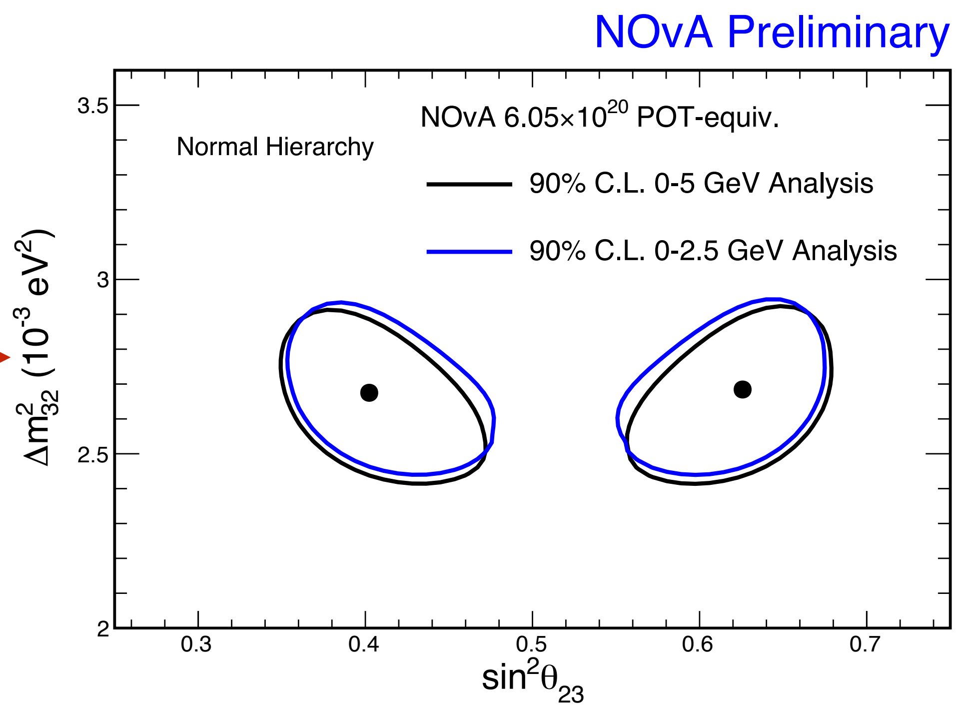




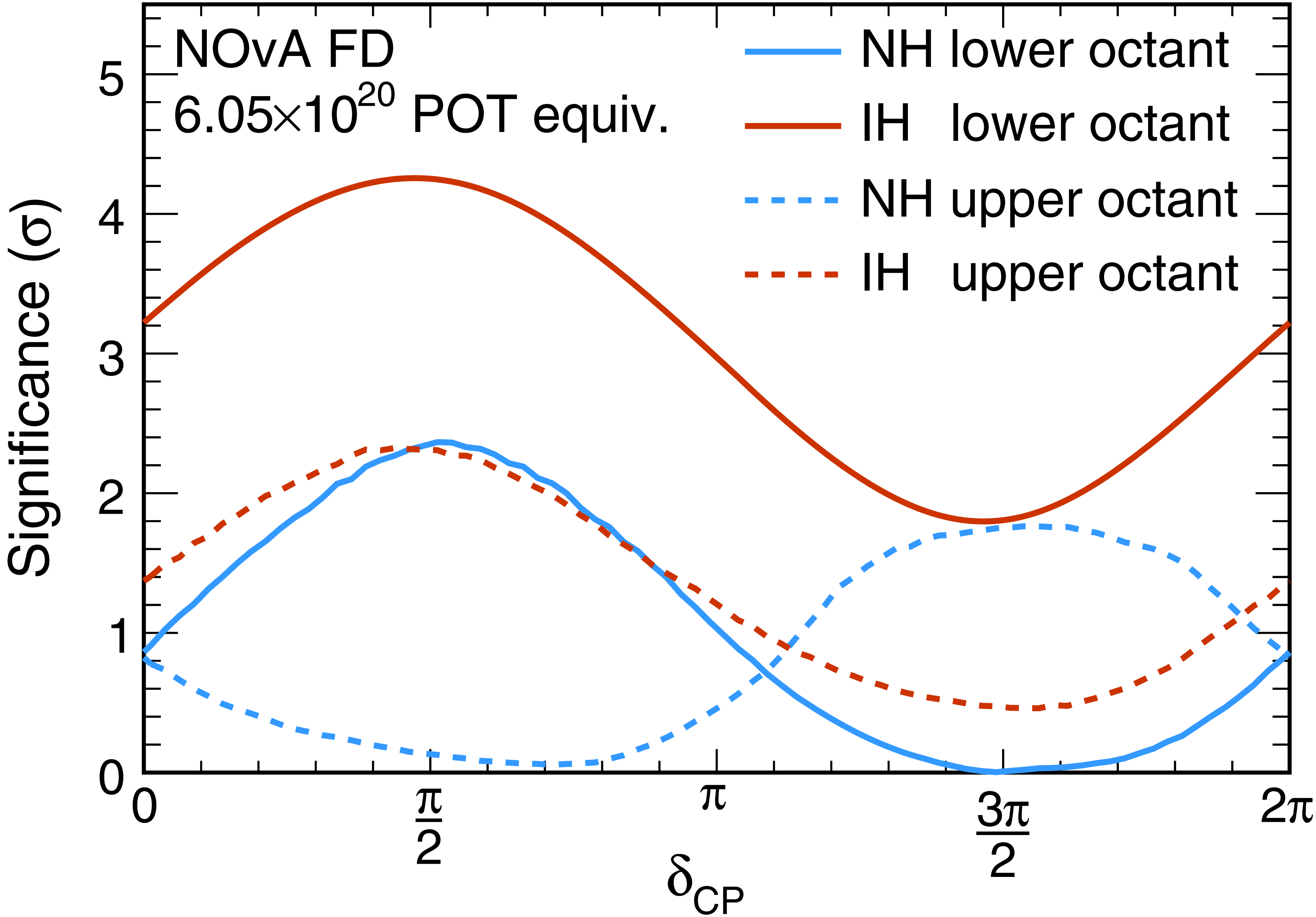


Goodness of fit





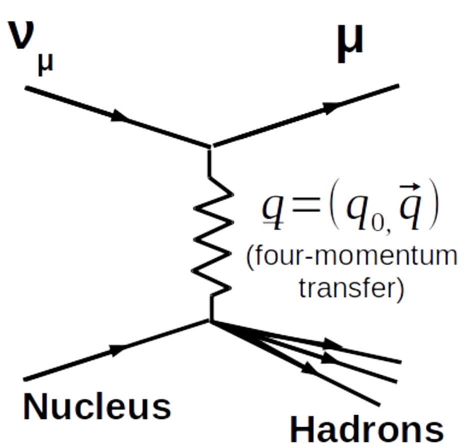
There is no significant pull in the oscillation fit from bins in the tail

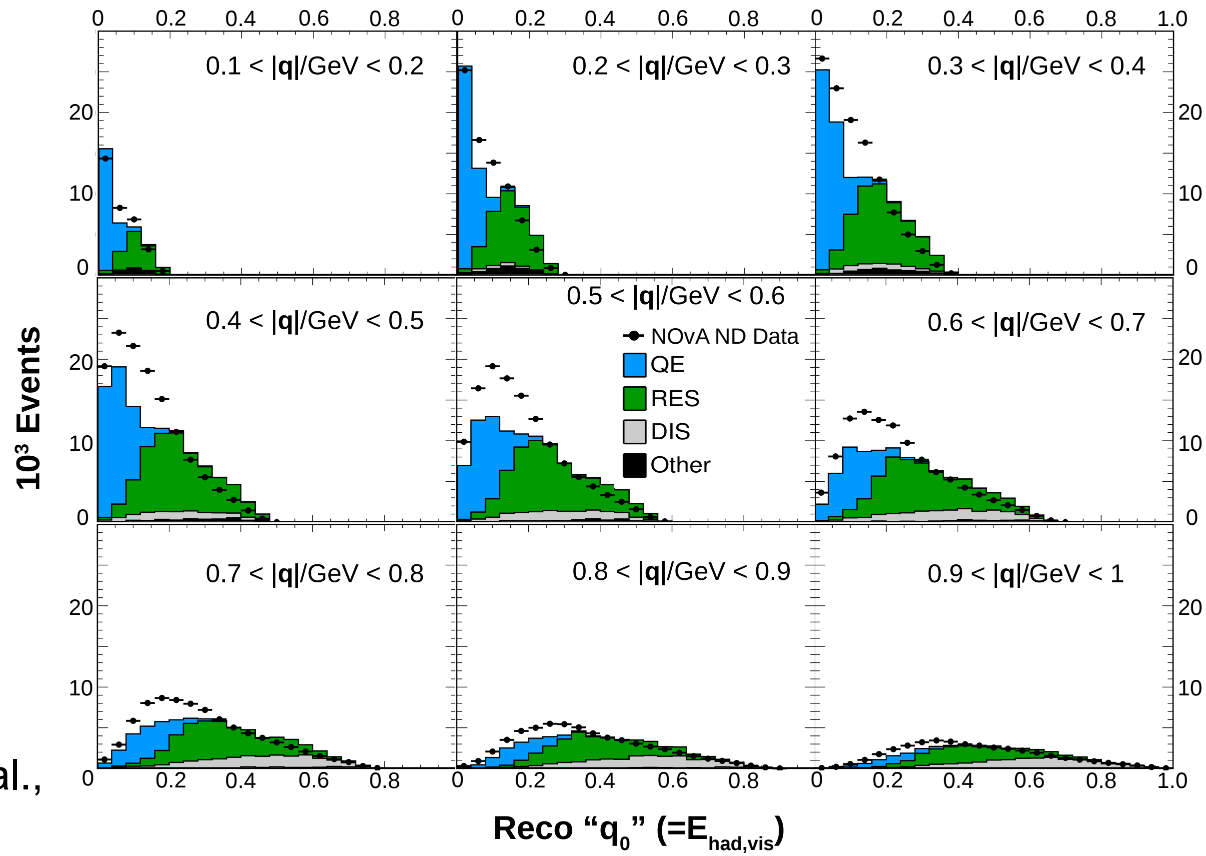

NOvA FD
6.05×10^20 POT equiv.
NH lower octant
IH lower octant
NH upper octant
IH upper octant
Significance (σ)
5
4
3
2
1
0
0
π/2
π
3π/2
2π
δCP

Scattering in a Nuclear Environment

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

NOvA Preliminary



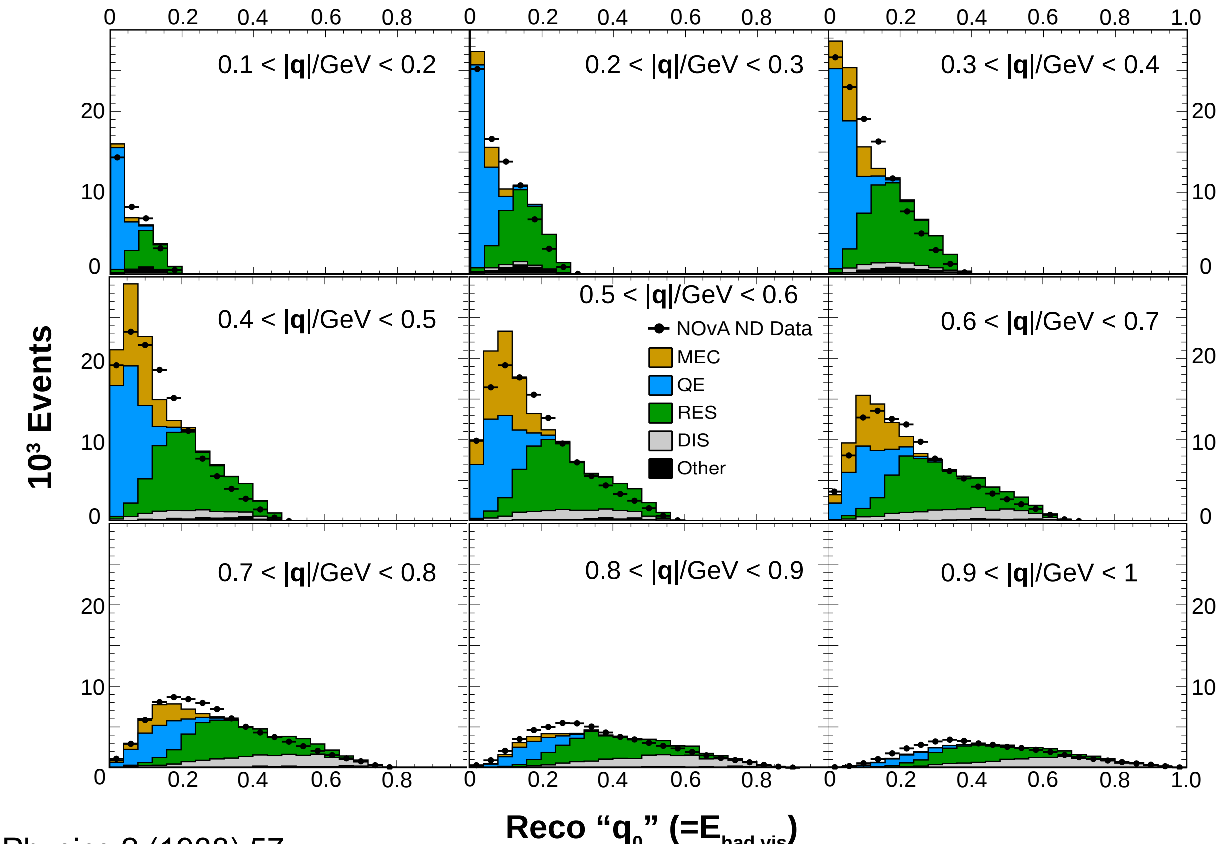


Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

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.