University of Sussex

University of Sussex

NOvA Oscillation Results

Science & Technology Facilities Council

Jeff Hartnell

University of Sussex

European Research Council

Established by the European Commission

NOvA

LAL Seminar

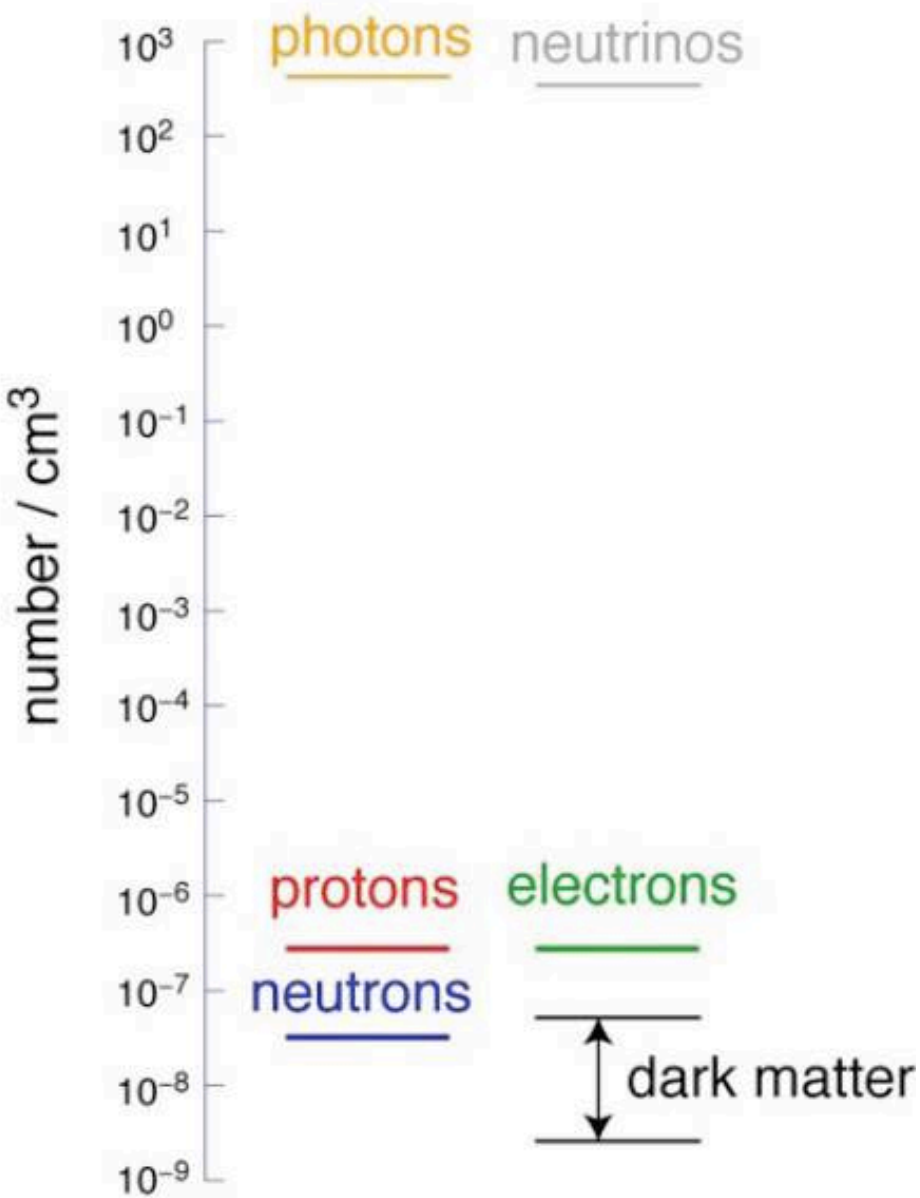
1st October 2019

Introduction

- Why study neutrinos?
- Neutrino oscillations
- NOvA experiment and physics goals
  - NuMI beam
  - NOvA detectors
- Muon neutrino disappearance
- Electron neutrino appearance
- NC analysis

Why study neutrinos?

The Particle Universe



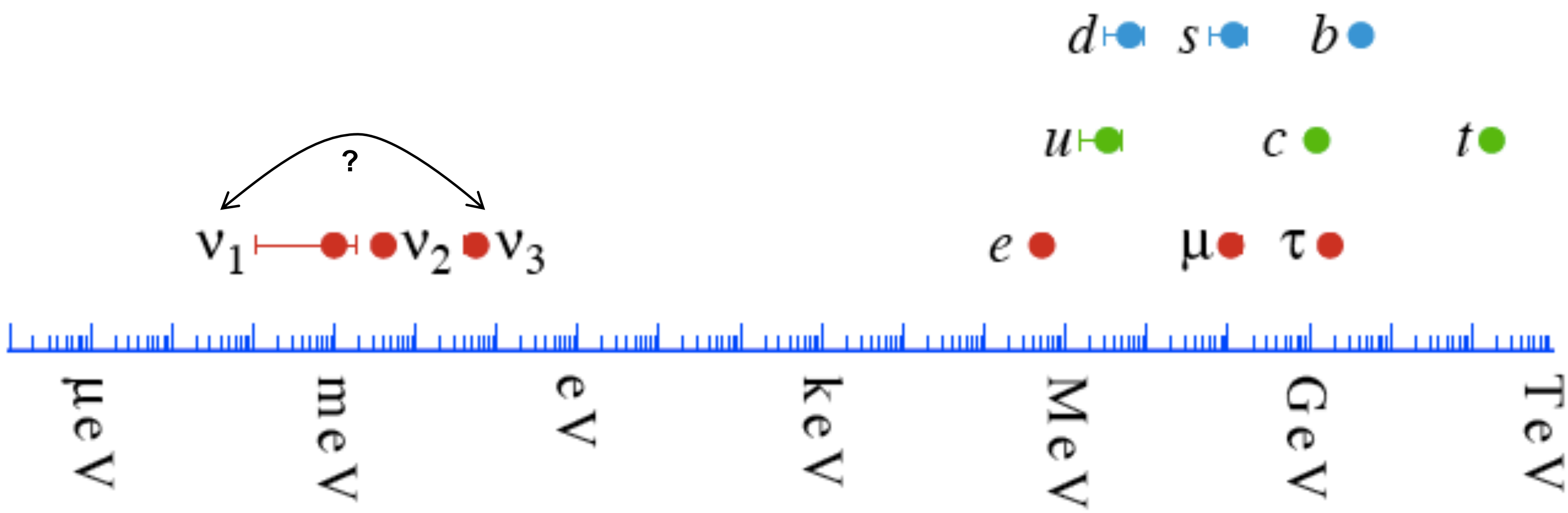
Two Major Questions

Why is the matter – antimatter asymmetry of the universe so large?

- Neutrinos $\longleftrightarrow$ leptogenesis

- Neutrino oscillations can test CP
  - NOvA has some sensitivity, DUNE/Hyper-K much more

Is there a pattern to the masses?



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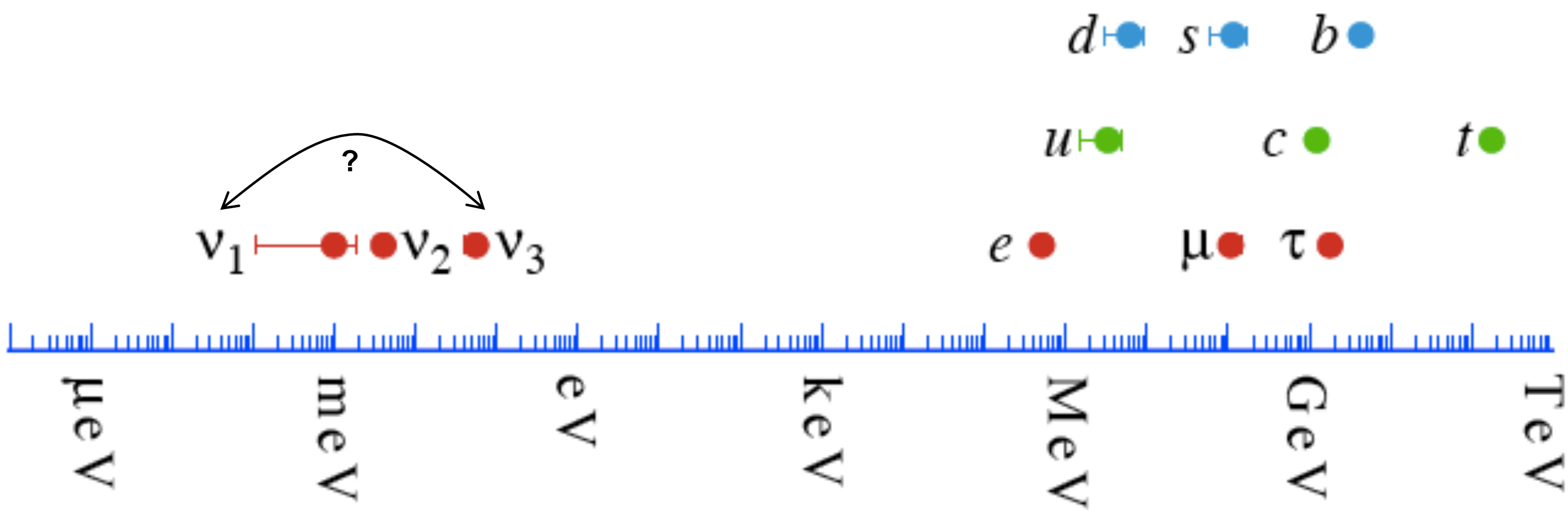
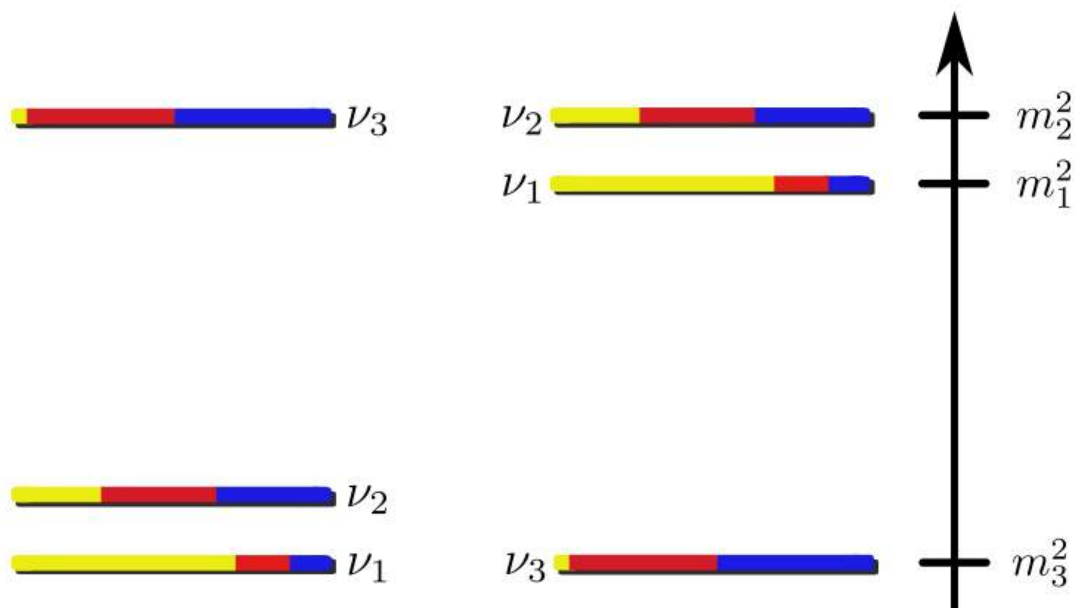


Two heavy and one light?

NOvA has sensitivity to the mass hierarchy

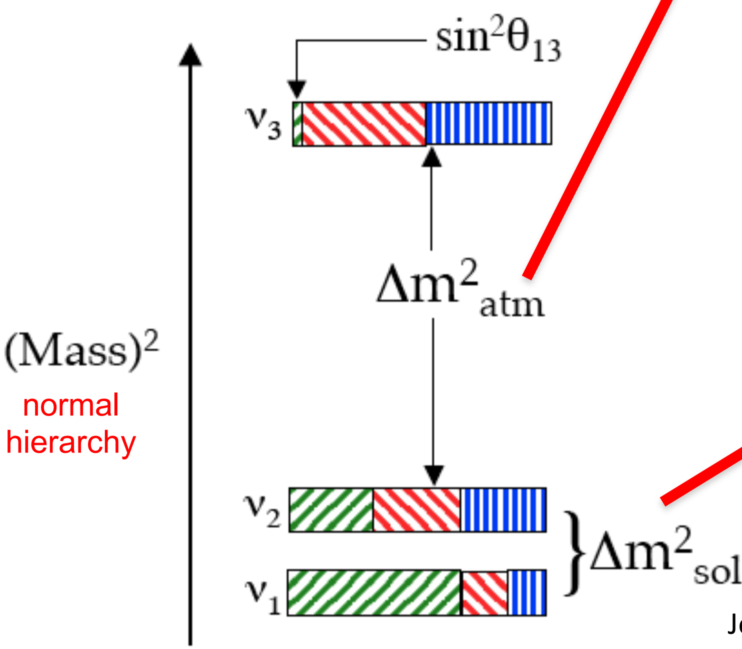


Theory Overview

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Subdominant term



$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

(≅0.5 km/MeV)

$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV

How does the mass hierarchy come into play?

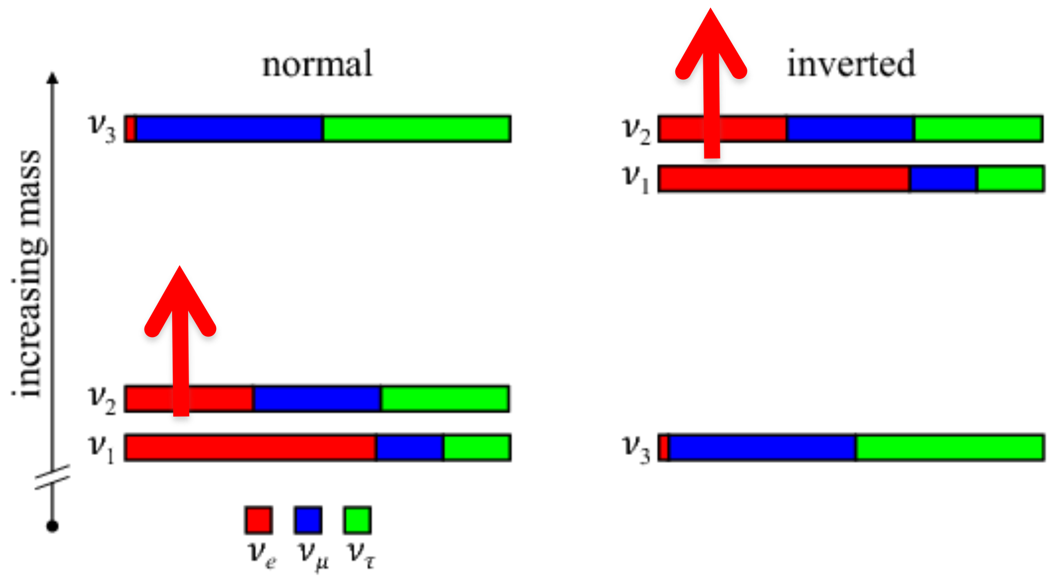
Δm^2_{31} and Δm^2_{32} differ by 3%

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

Where have we got to?

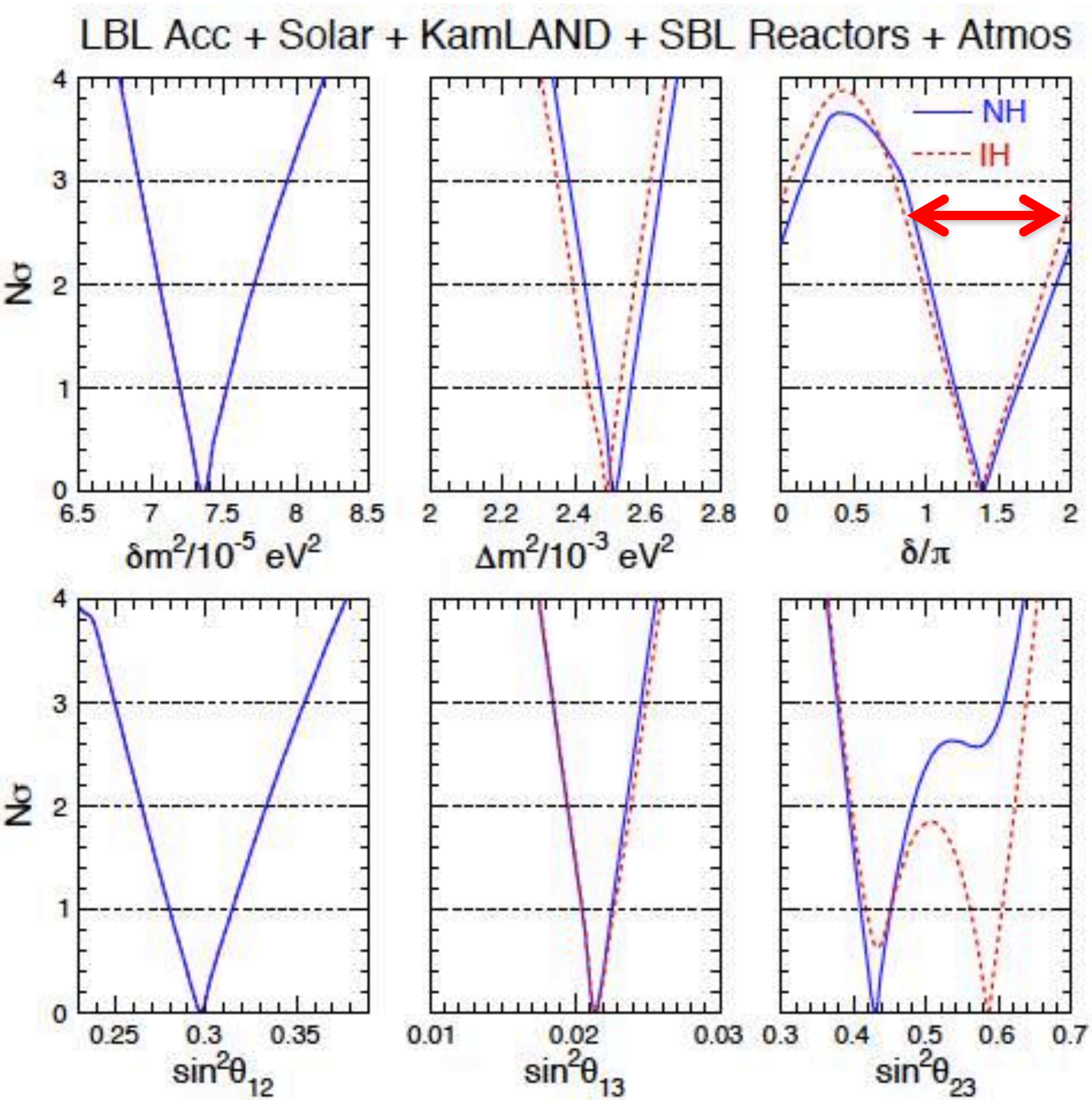
It's hard to overstate…

- The past ~7 years saw a major breakthrough in neutrino physics
  - Measurement of θ_{13} has gone from just an upper limit to one of the best measured angles
- A new door has been opened to probing CP violation, mass hierarchy and octant of θ_{23}

Reactor Experiments Provided Breakthrough on θ_{13}

- Daya Bay, RENO and Double Chooz

What we know and don't know



Three "Unknowns"

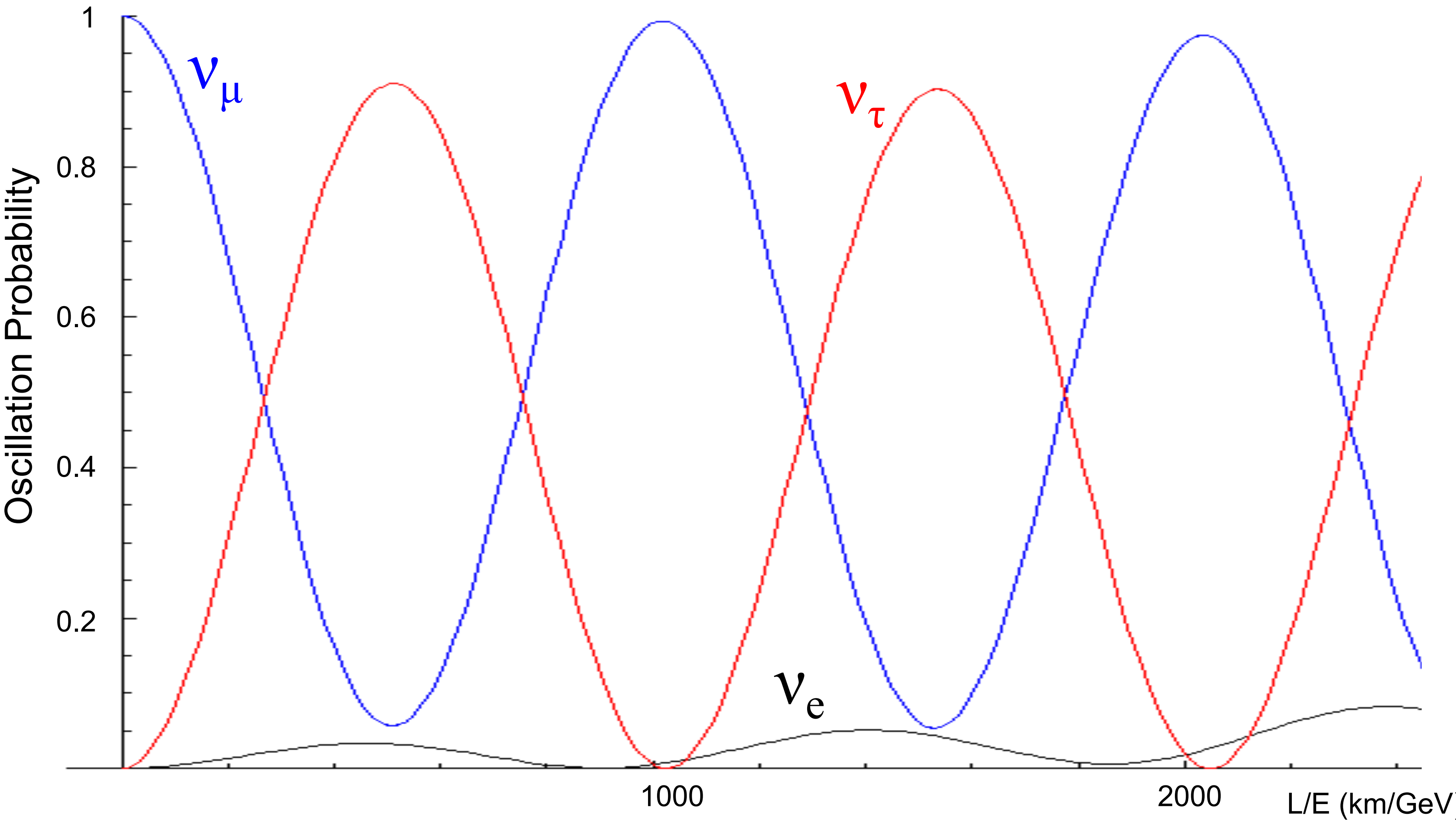
Wide range of δ_{CP} values possible (1)

Slight preference for **NH** (suppressed in plot) (2)

Non-maximal θ_{23} mixing a possibility. Octant largely unknown. (3)

[Ferruccio Feruglio, NOW]

Starting with ν_μ



Long-baseline neutrino oscillations

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \underbrace{\sin^2 2\theta_{23}}\, \sin^2(\Delta m^2_{32} L/4E)$$

...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:

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

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

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

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

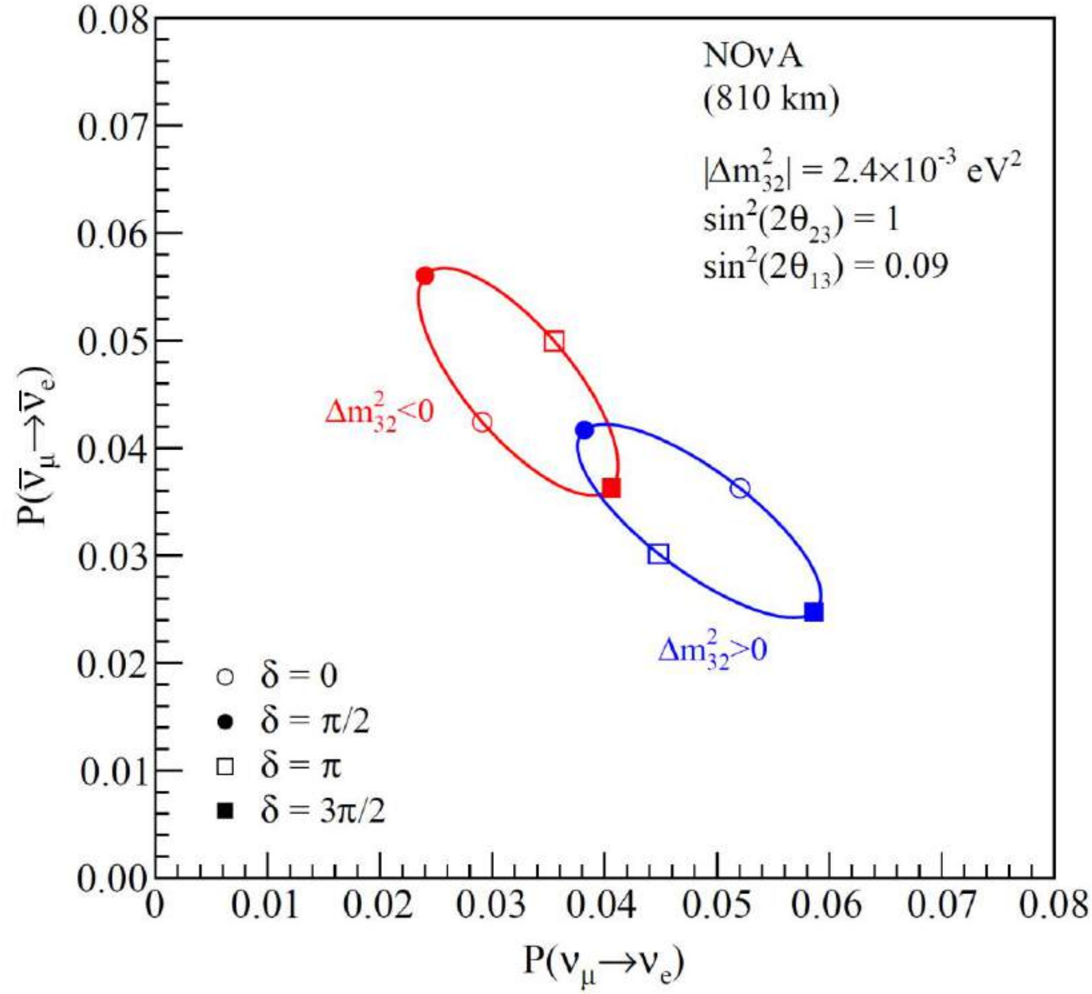
A more quantitative sketch…

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

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. $P(\nu_\mu \rightarrow \nu_e)$

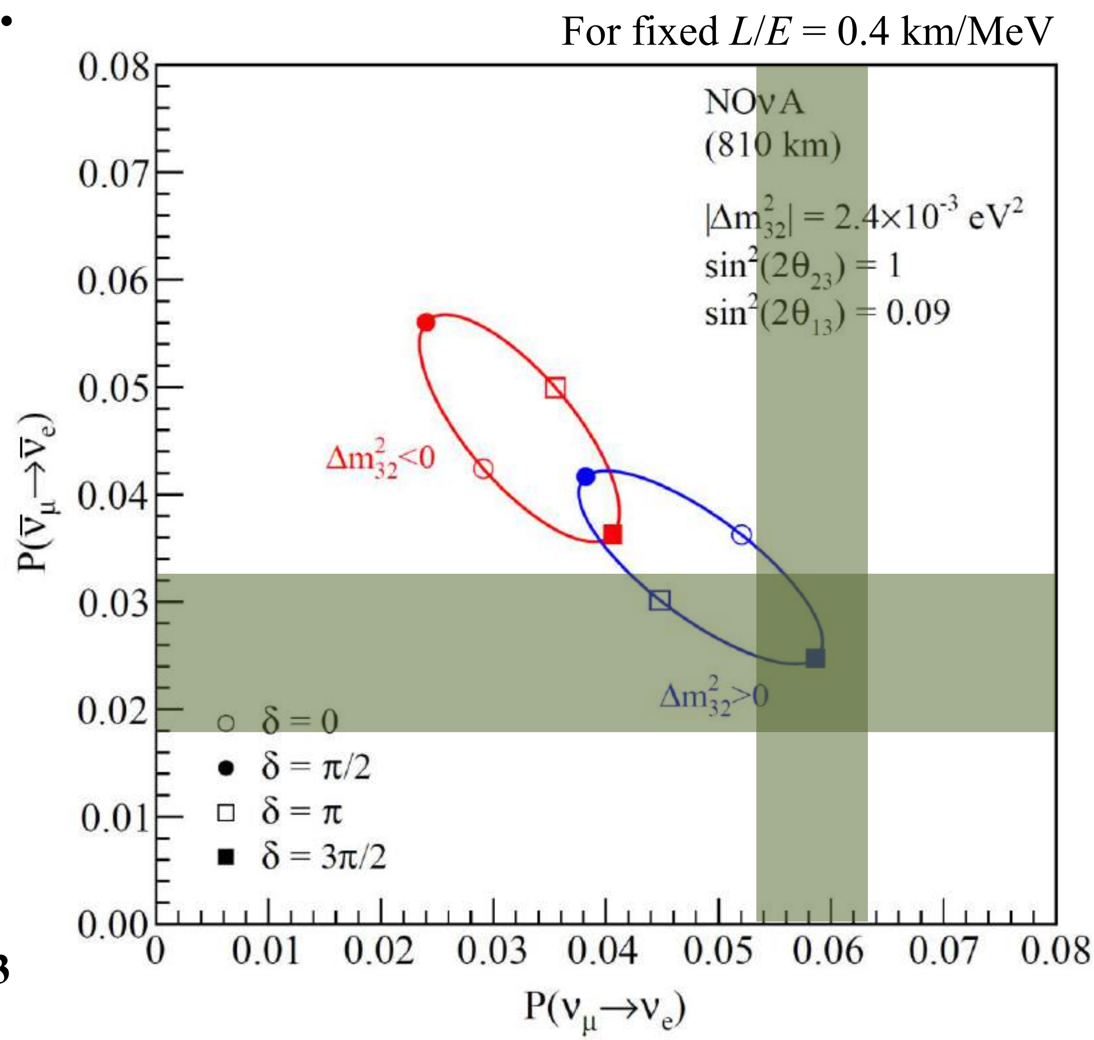
plotted for a single neutrino energy and baseline

Measure these probabilities

(an example measurement of each shown)

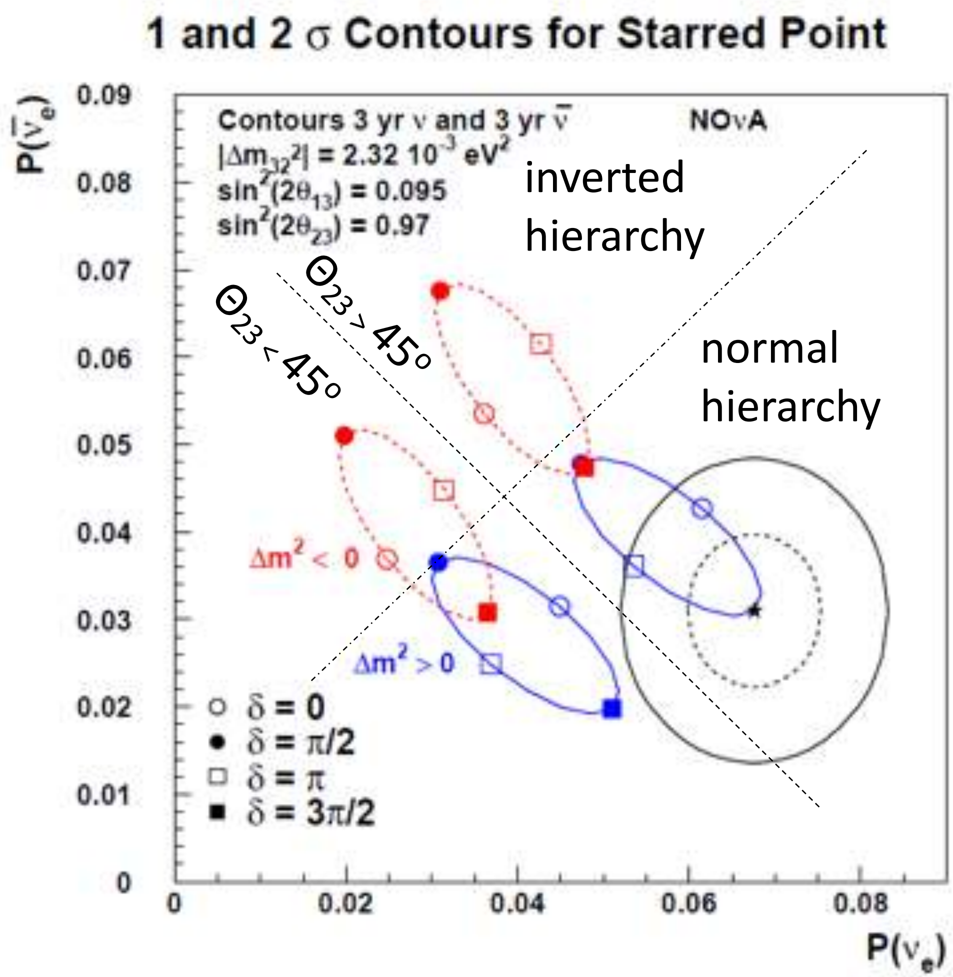
Also:

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



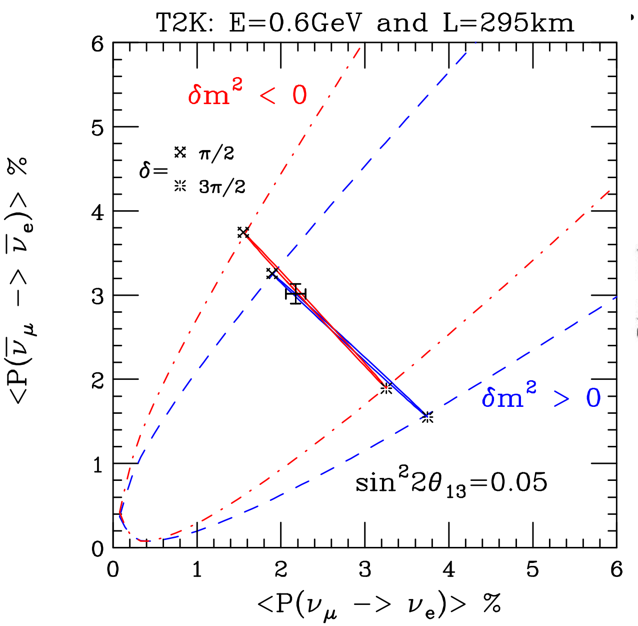
Non-maximal mixing scenario

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



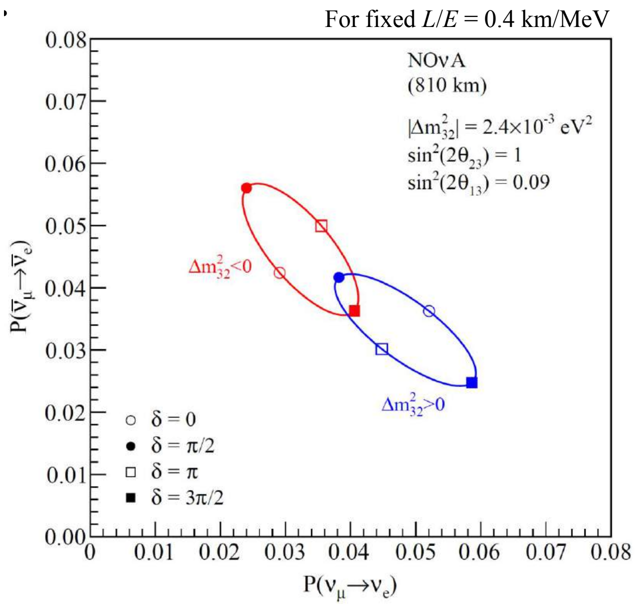
Effect of Increasing Energy

T2K



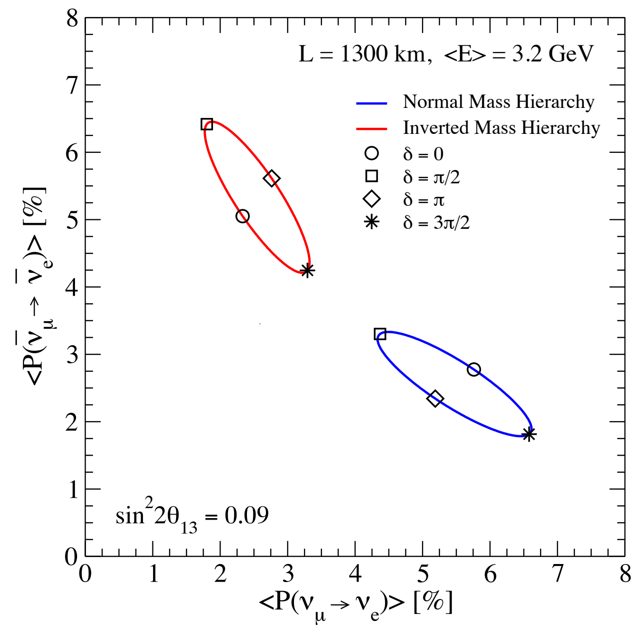
0.6 GeV

NOvA



2 GeV

DUNE



3 GeV

Increasing Energy →

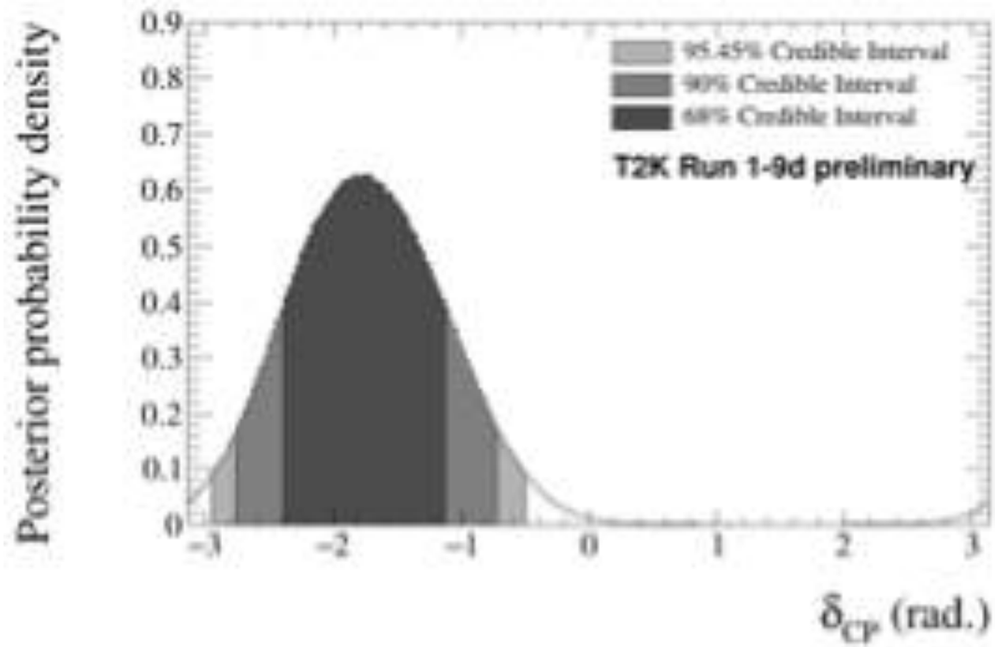
[→ bigger matter effect and hence bigger fake CP violation]

T2K ν_e Appearance

T2K (NO)		$-\pi/2$	0	$+\pi/2$	π	OBS
ν mode	1Re 0 d.e.	74.5	62.3	50.6	62.8	75
	1Re 1 d.e.	7.0	6.1	4.9	5.9	15
$\bar{\nu}$ mode	1Re 0 d.e.	17.1	19.6	21.7	19.3	15

For T2K:

- credible intervals favor $\delta_{CP} \sim -\pi/2$
- disfavor $\delta_{CP} = 0,\pi$ ($\sin \delta_{CP} = 0$) at >2 σ in Bayesian analysis
- Some preference for NO

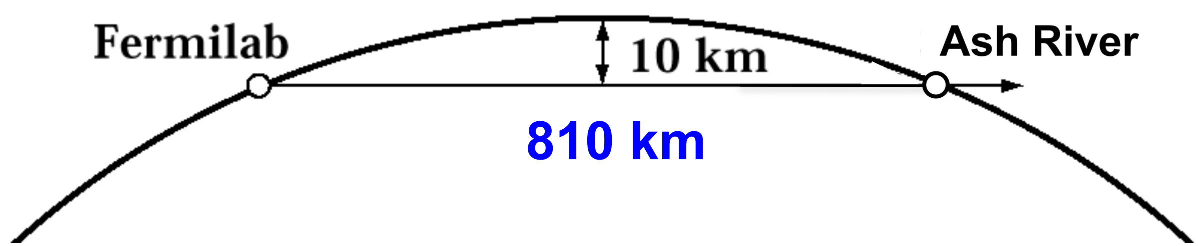


NOvA Overview

- “Conventional” beam
- Two-detector experiment:

- Near detector
  - measure beam composition
  - energy spectrum

- Far detector
  - measure oscillations and search for new physics



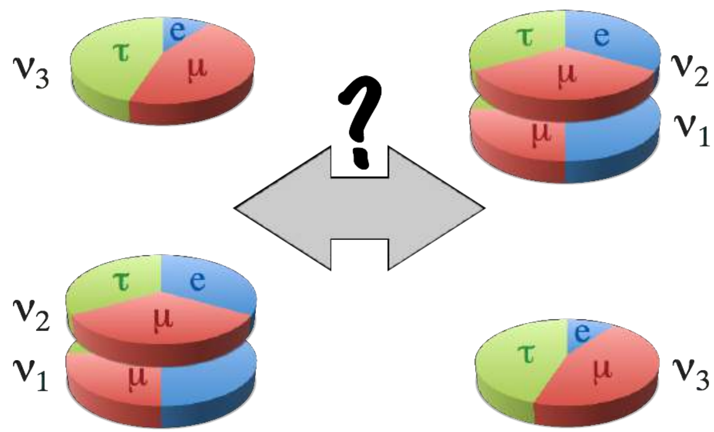
[June 2019 meeting @ Sussex University, Brighton, UK]

Physics Goals

Results from 3 different oscillation analyses

- Disappearance of ν_μ CC events
  - clear suppression as a function of energy

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



- Appearance of ν_e CC events

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

  - 2 GeV neutrinos enhances matter effects
  - ±30% effect

- Deficit of NC events?
  - suppression of NCs could be evidence of oscillations involving a sterile neutrino

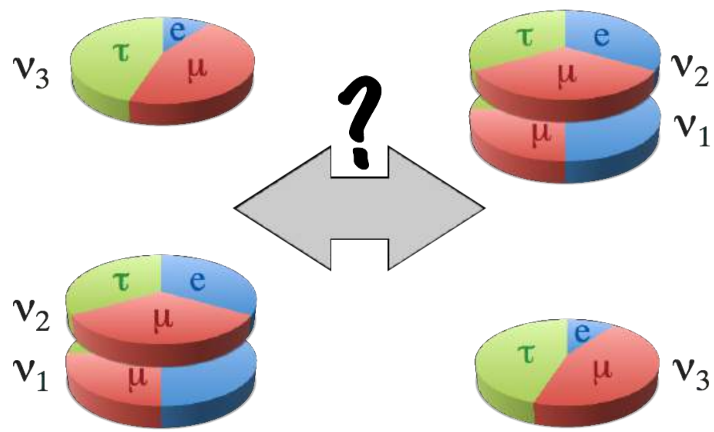
$$\Delta m^2_{41}, \theta_{34}, \theta_{24}$$

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

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



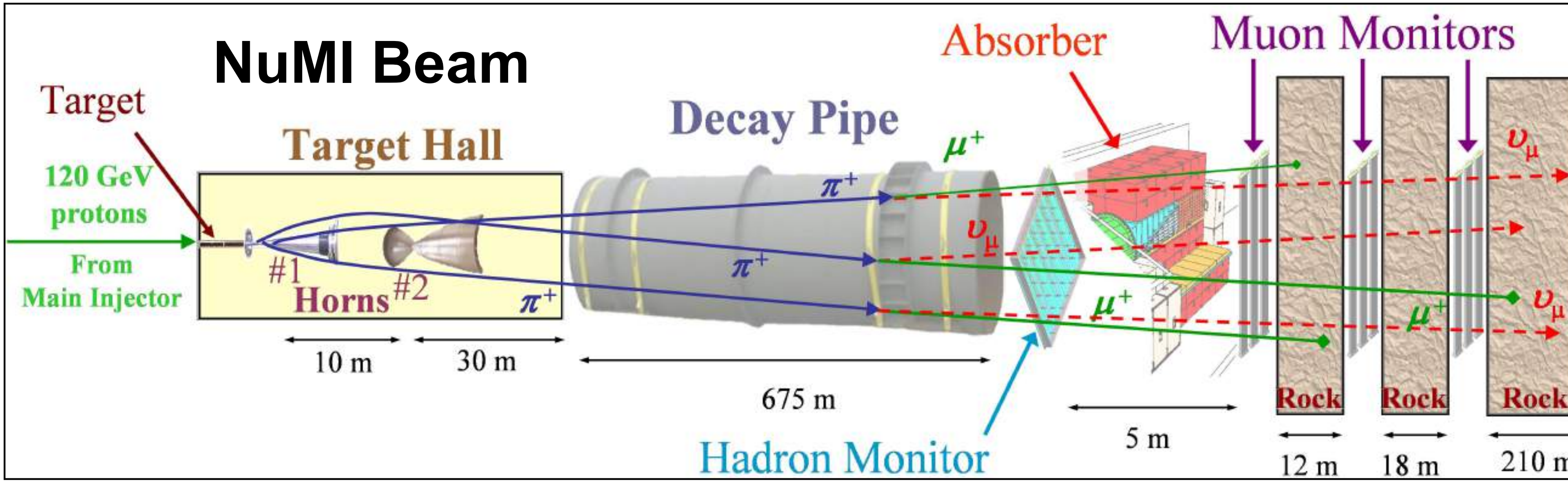
- Appearance of ν_e CC events

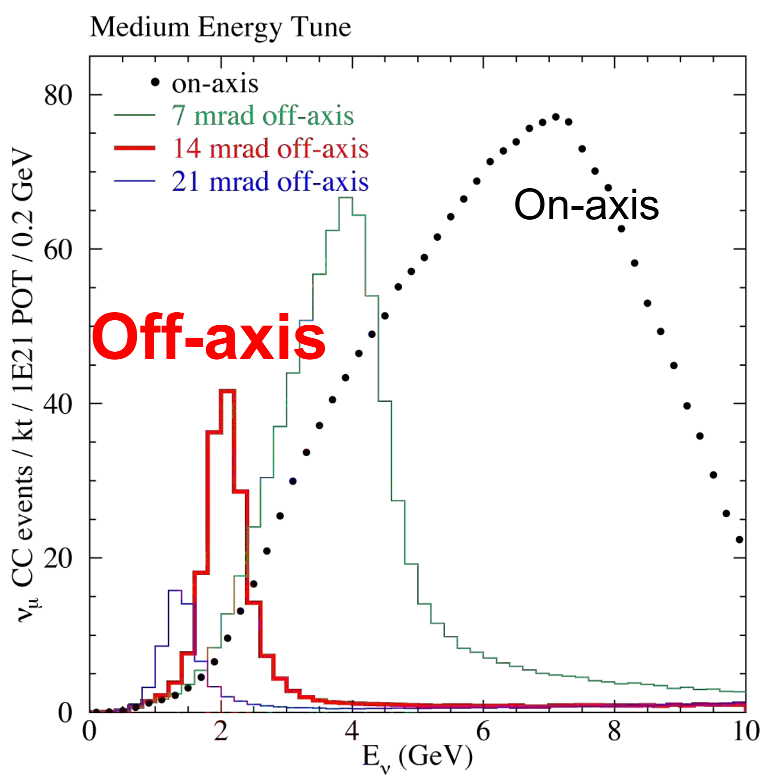
$$\theta_{13}, \theta_{23}, \delta_{CP},$$
and Mass Hierarchy

  - 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!

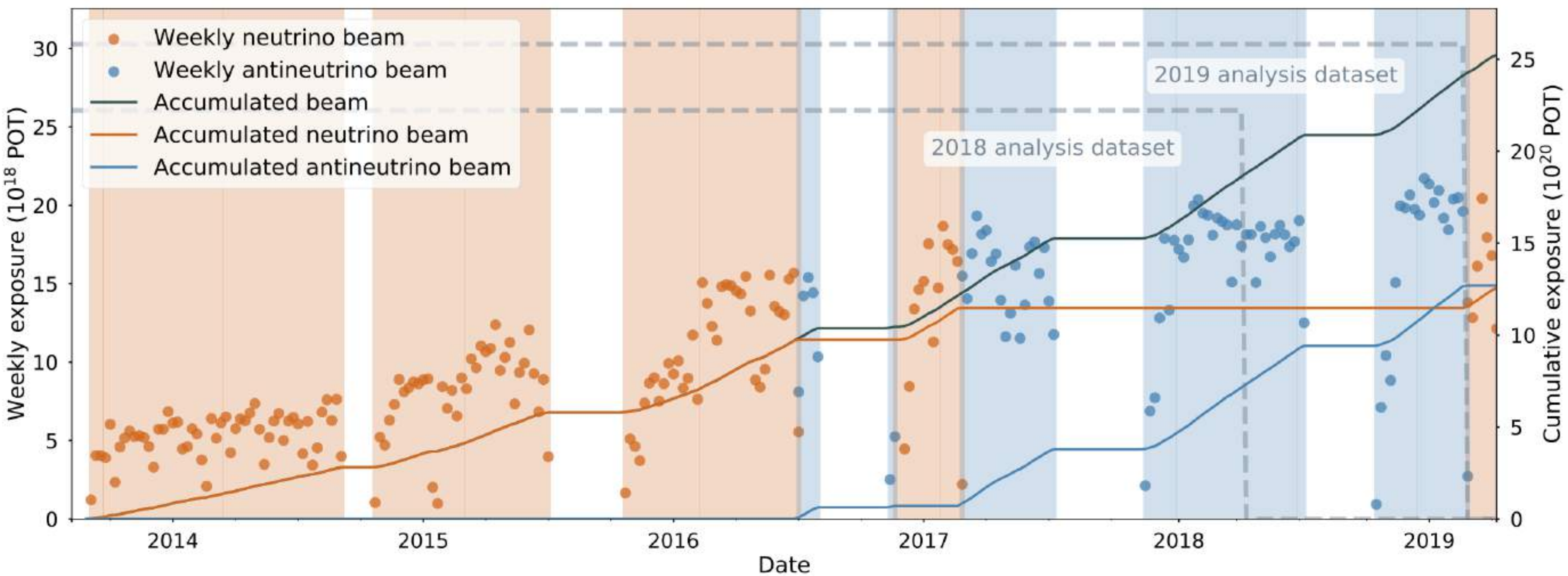
$$\Delta m^2_{41}, \theta_{34}, \theta_{24}$$


NuMI Beam
Target
Target Hall
120 GeV protons
From Main Injector
#1
Horns
#2
Decay Pipe
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
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)

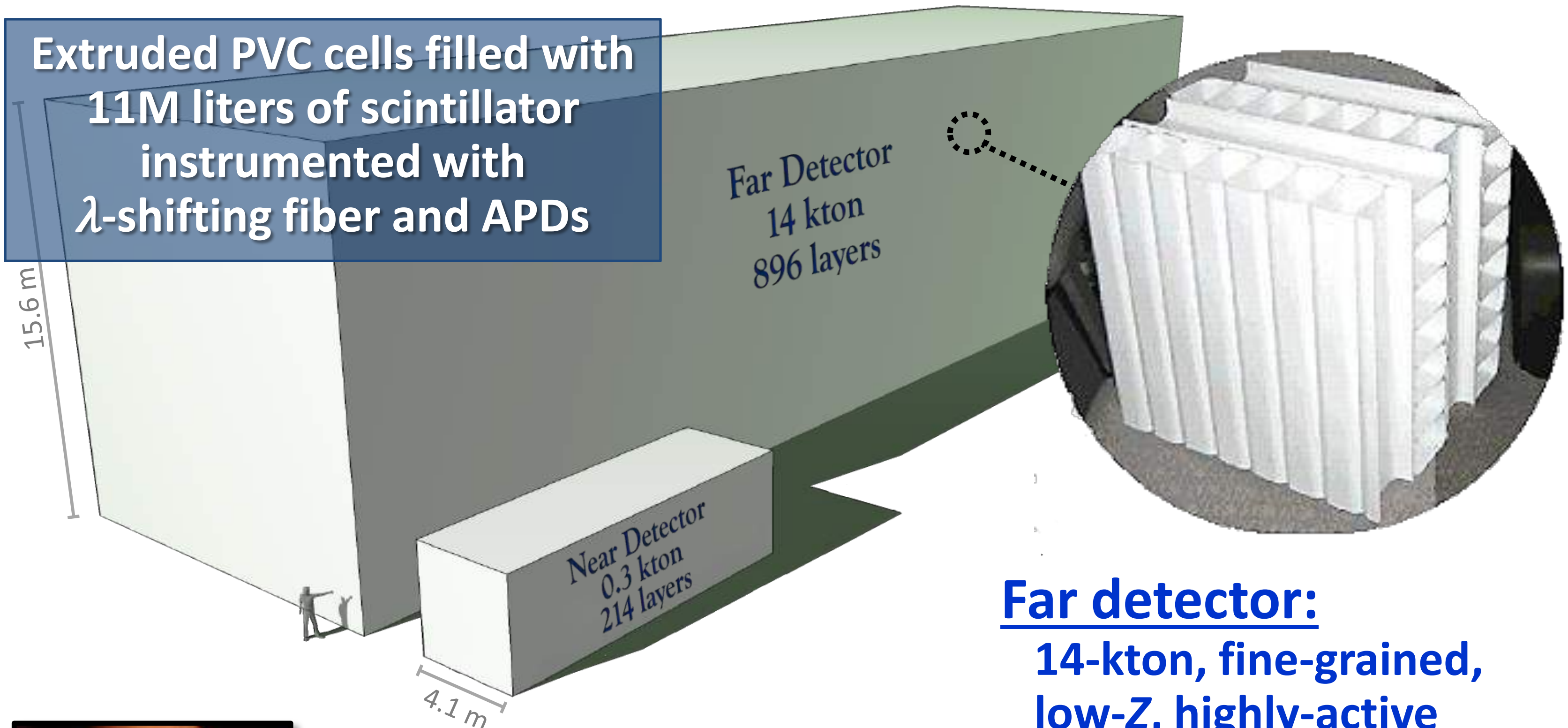
Beam Performance

- Neutrino beam: 8.9×10^{20} POT
- Antineutrino beam: 12.3×10^{20} POT
  - Updated from 6.9×10^{20} POT (summer 2018)
- Beam operating steadily at 750 kW

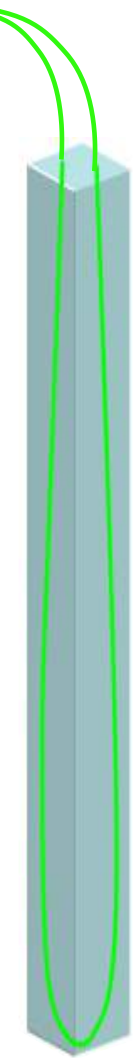


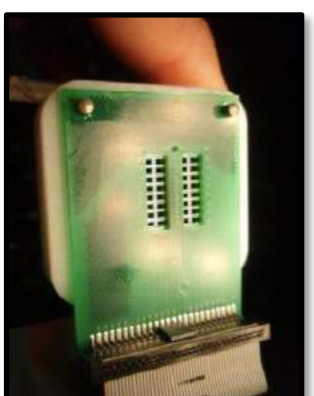
NOνA detectors

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



A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

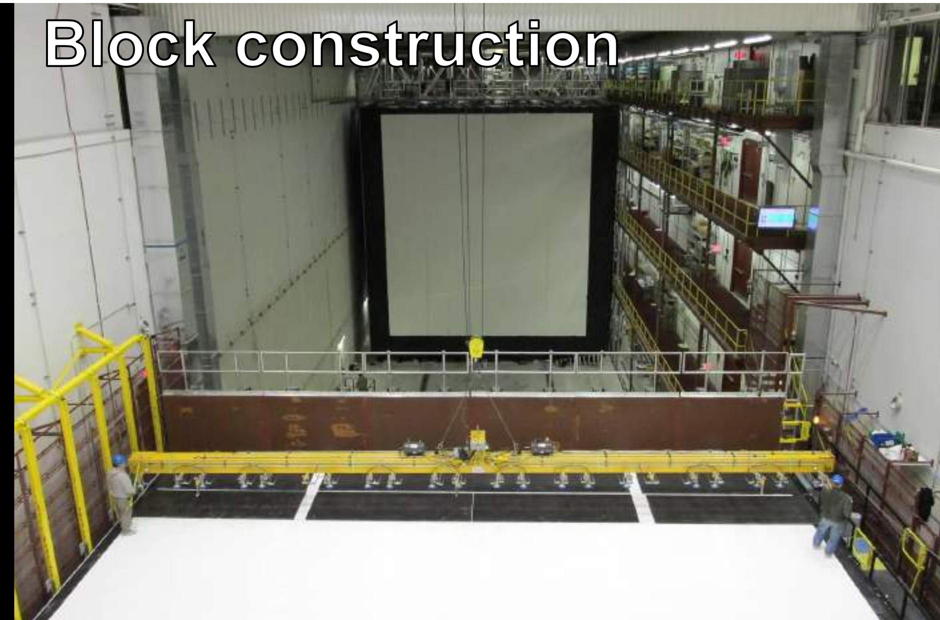
Far detector:

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*

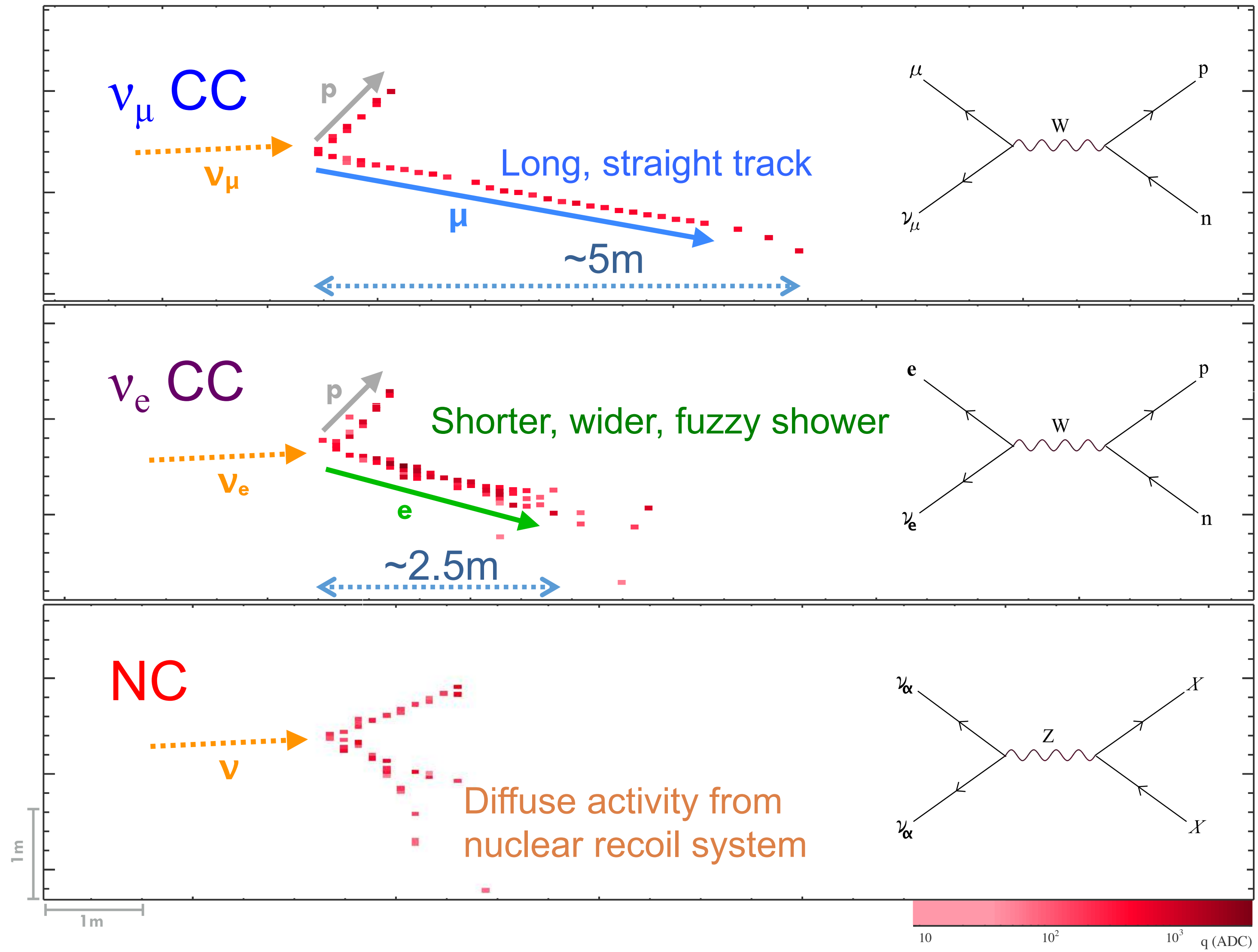

Far Detector site


Block construction


Outfitted Far Detector


Near Detector

Event Types

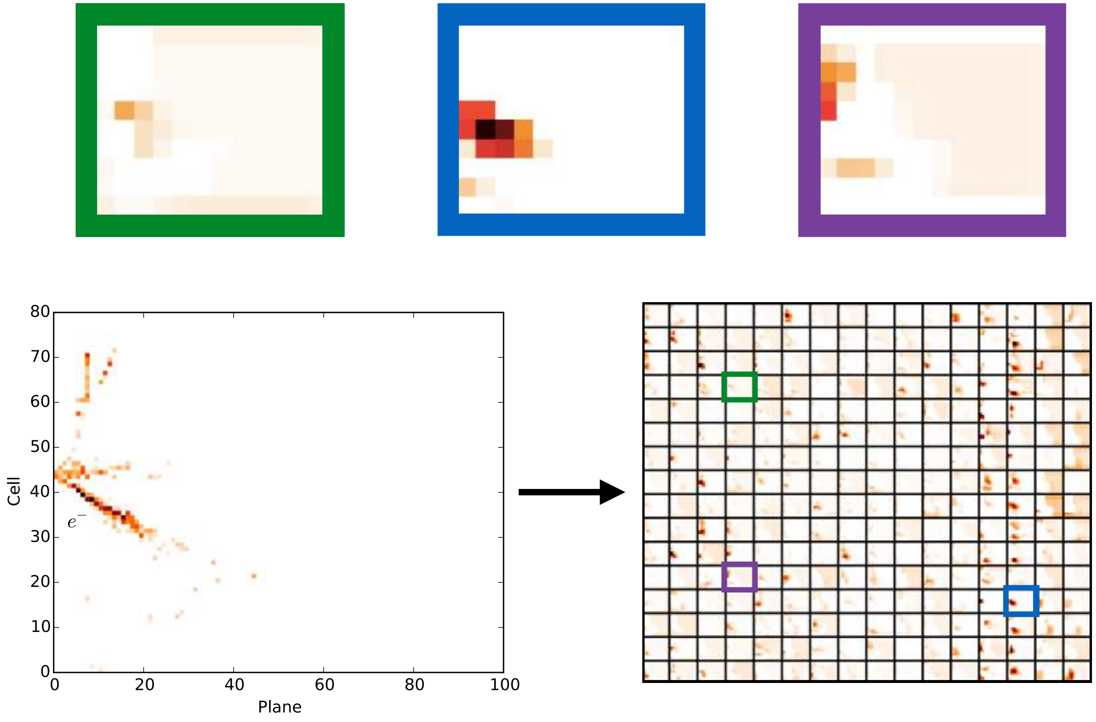


ν_μ CC
p
ν_μ
Long, straight track
μ
~5m
μ
W
p
ν_μ
n
ν_e CC
p
ν_e
Shorter, wider, fuzzy shower
e
~2.5m
e
W
p
ν_e
n
NC
ν
Diffuse activity from
nuclear recoil system
ν_α
Z
X
ν_α
X
1 m
1 m
10
10^2
10^3
q (ADC)

Event Classification

- This analysis features an 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



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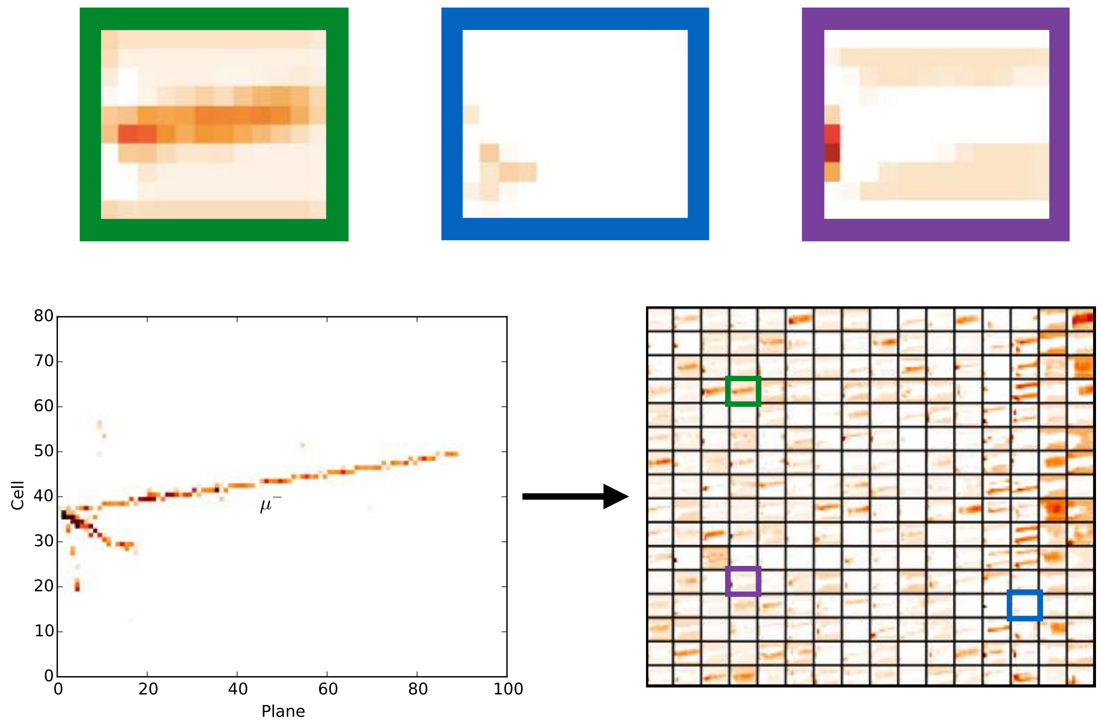

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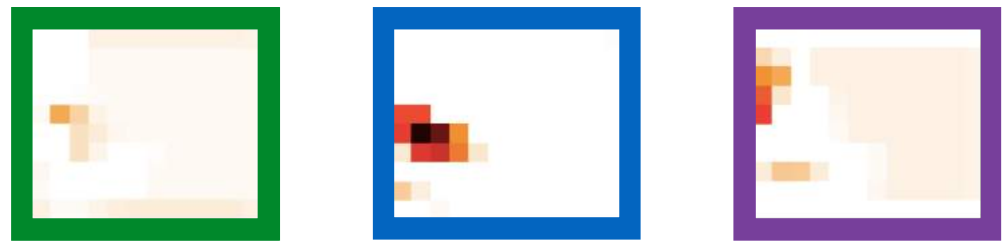
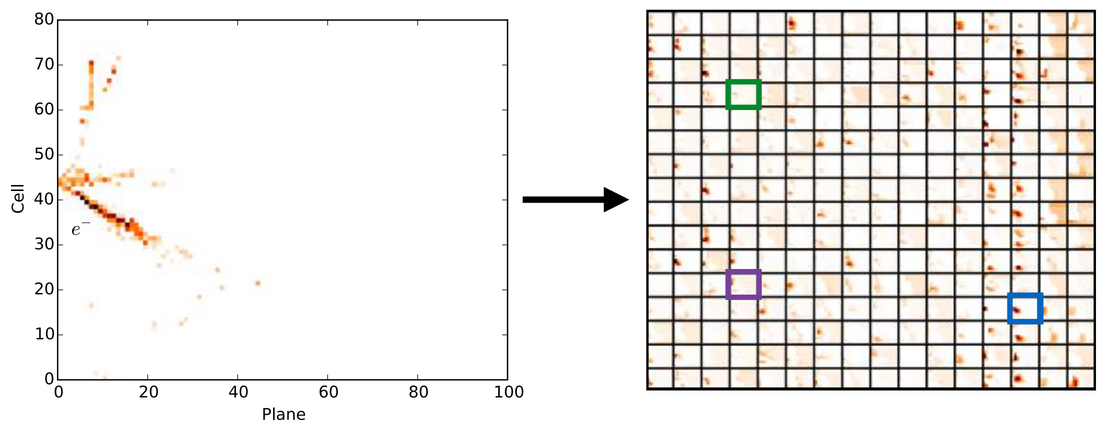


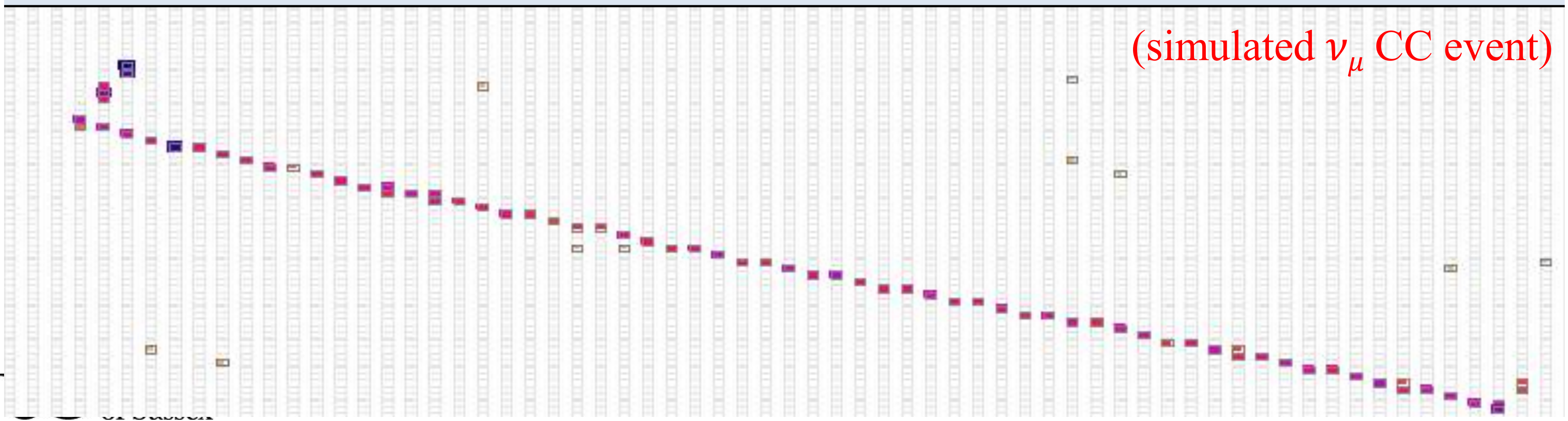


Improvement in sensitivity from CVN equivalent to 30% more exposure

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

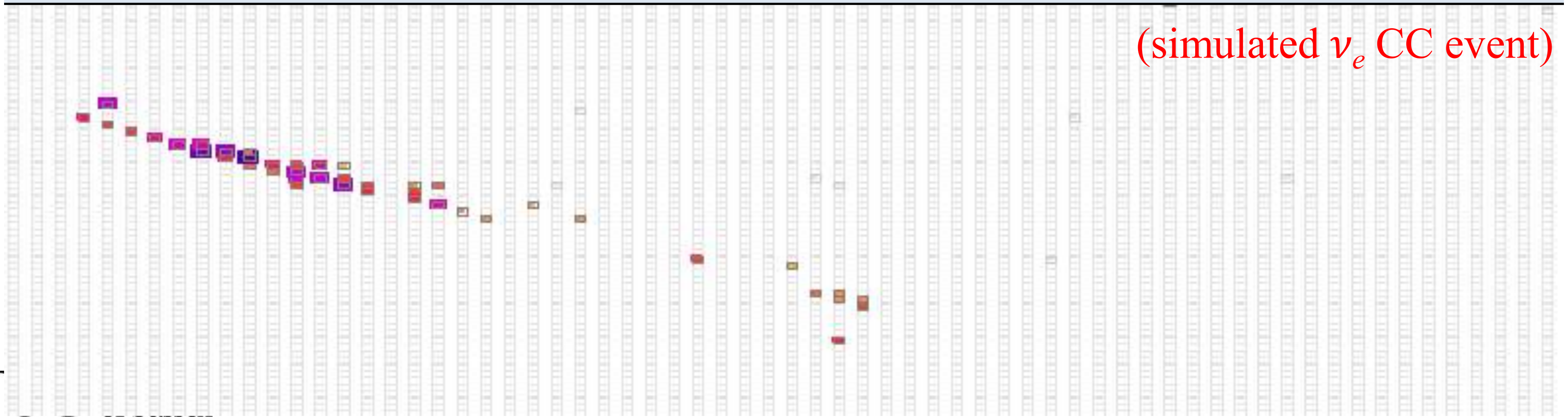
ν_μ disappearance

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



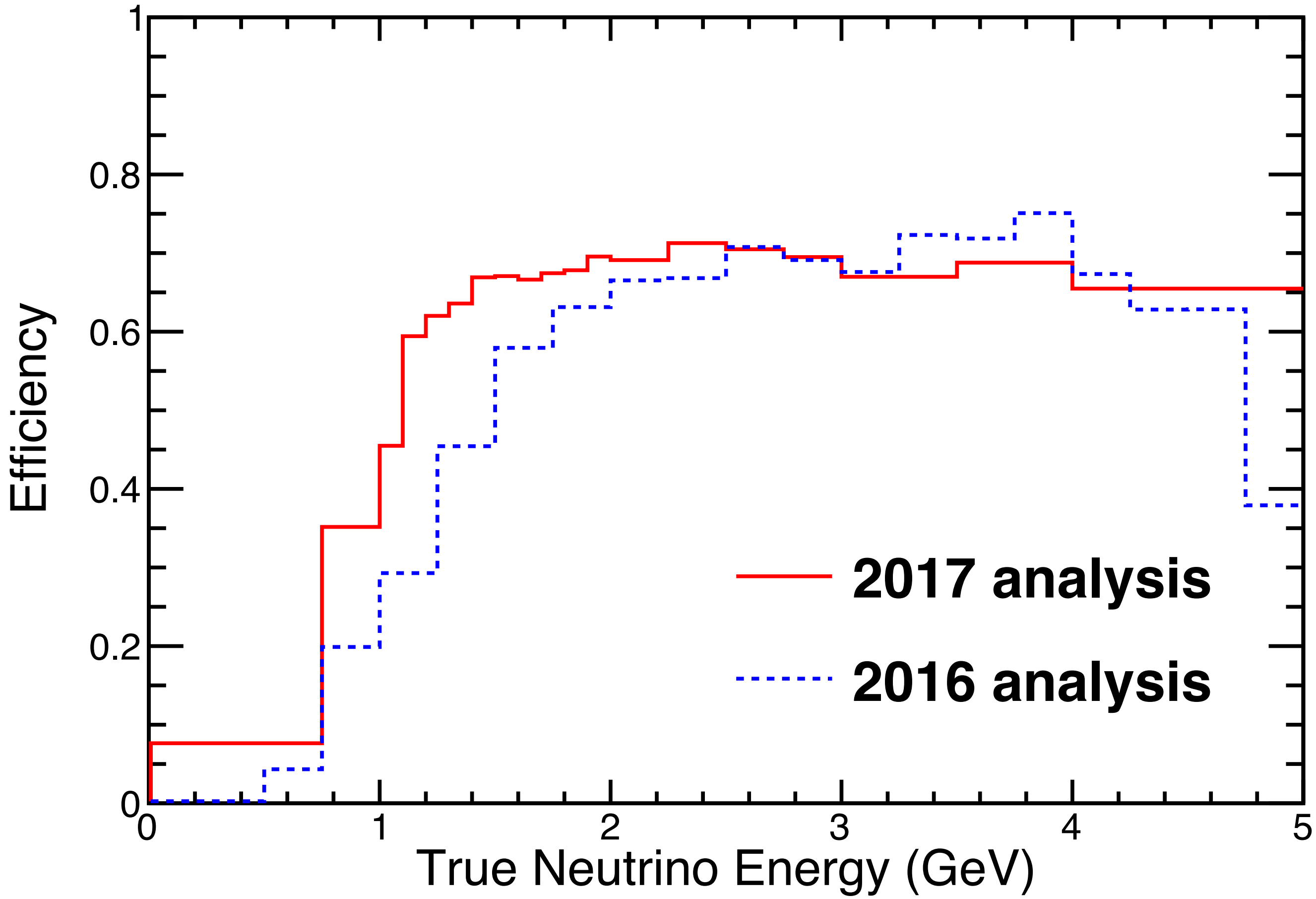
ν_e appearance

- 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

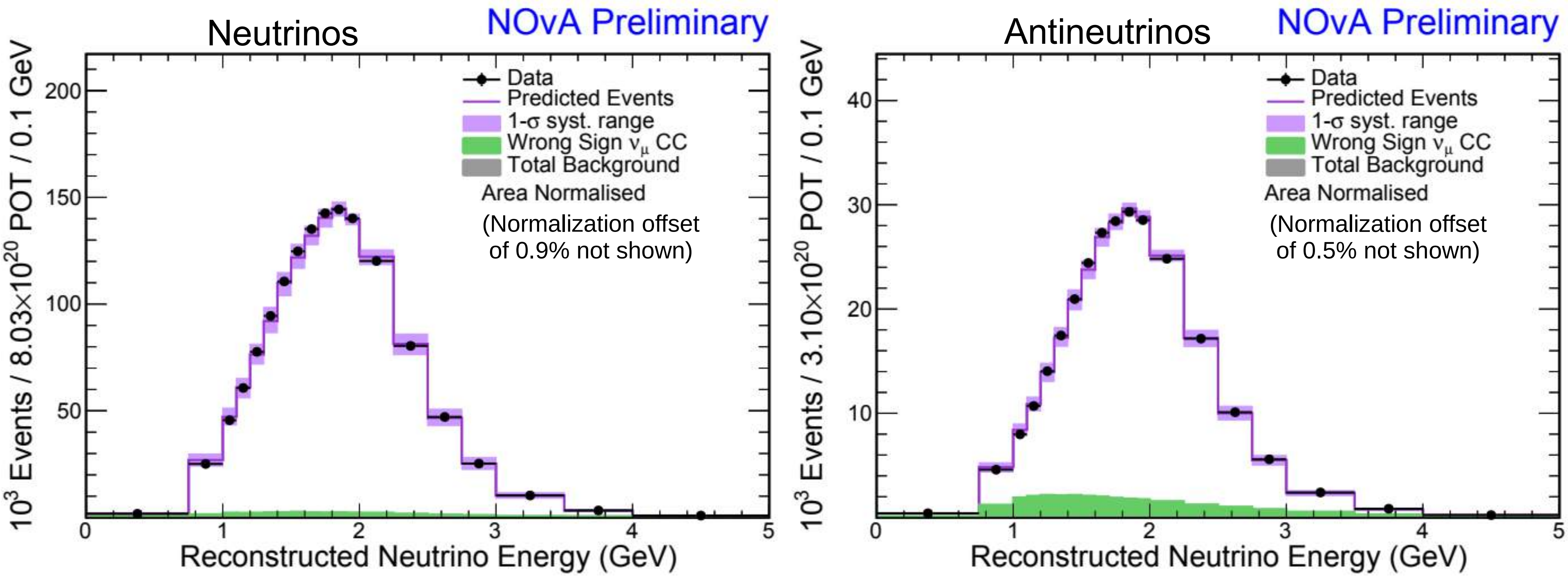


ν_μ Event Selection

- Goal: Isolate a pure sample of ν_μ CC events less than 5 GeV
- Use CVN in 2 ways:
  - muon event PID, also cosmic event PID used in BDT to reject cosmics



ND Data - ν_μ

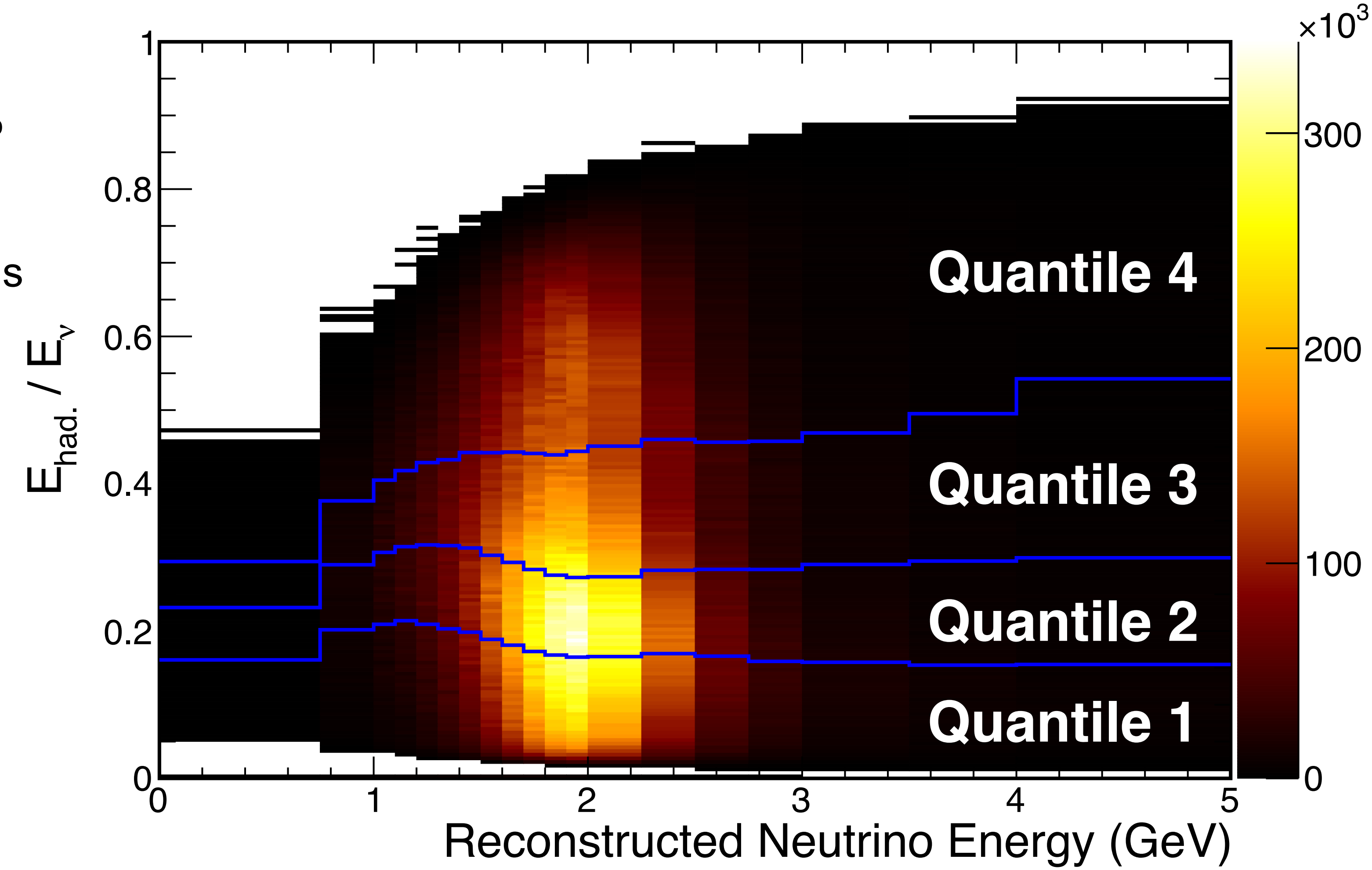


Neutrinos
NOvA Preliminary
Data
Predicted Events
1-σ syst. range
Wrong Sign νμ CC
Total Background
Area Normalised
(Normalization offset of 0.9% not shown)
10³ Events / 8.03×10²⁰ POT / 0.1 GeV
Reconstructed Neutrino Energy (GeV)
Antineutrinos
NOvA Preliminary
Data
Predicted Events
1-σ syst. range
Wrong Sign νμ CC
Total Background
Area Normalised
(Normalization offset of 0.5% not shown)
10³ Events / 3.10×10²⁰ POT / 0.1 GeV
Reconstructed Neutrino Energy (GeV)

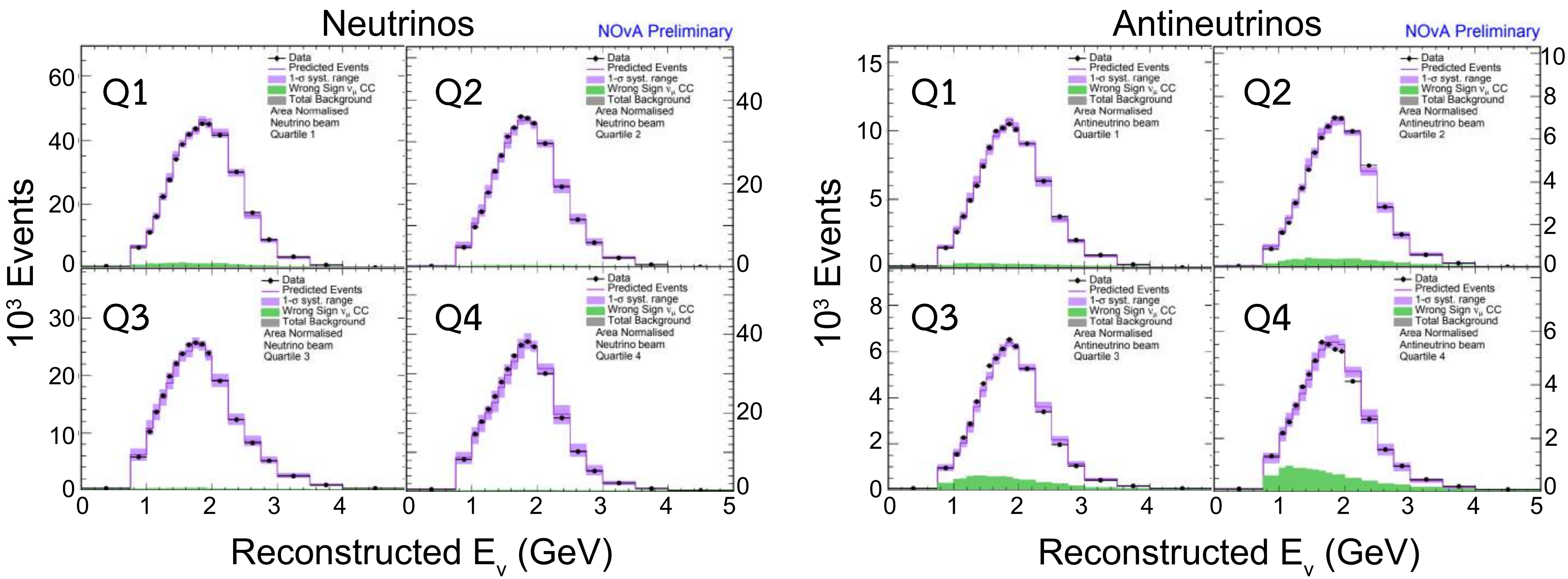
Resolution Bins

Four bins of equal populations in FD, split in hadronic energy fraction as a function of reconstructed neutrino energy.

Resolution varies from ~6% to ~12% from the best to worst resolution bins



ND Data - ν_μ



Muon neutrino candidate sample divided into four "quartiles" based on E_{had} / E_ν:

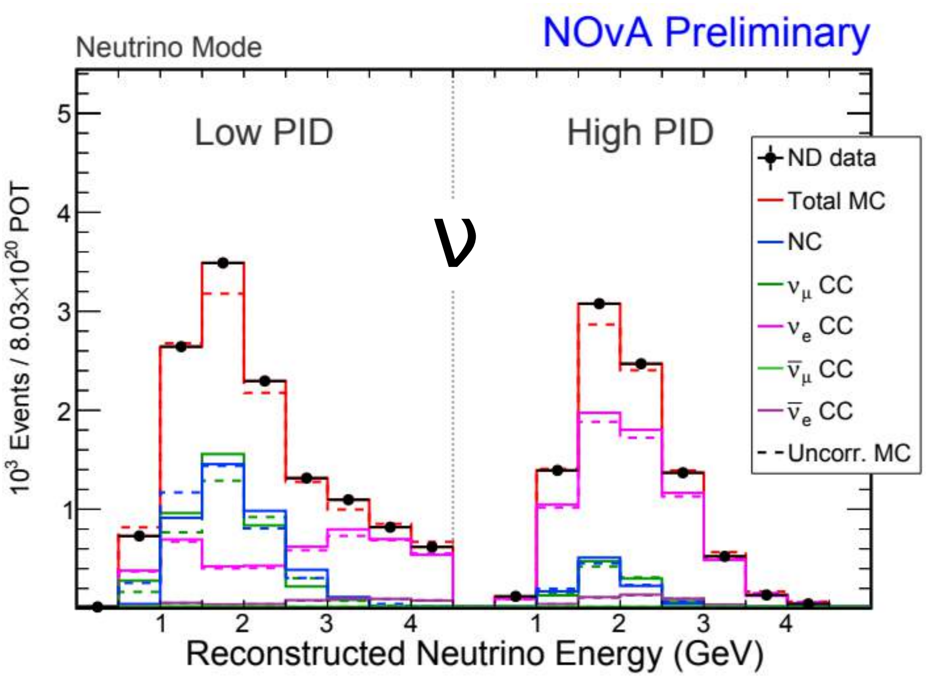
Q1 → Q4

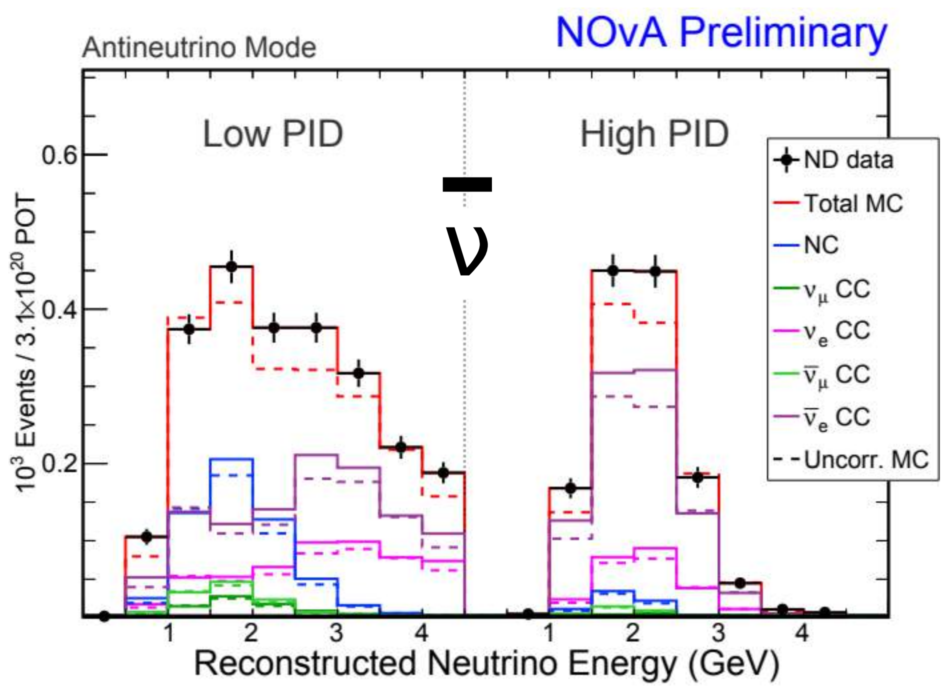
smallest E_{had}/E_ν
~6% E_ν resolution

(each quartile extrapolated separately)

largest E_{had}/E_ν
~12% E_ν resolution

ND Data - ν_e





More ν_e-like

More ν_e-like

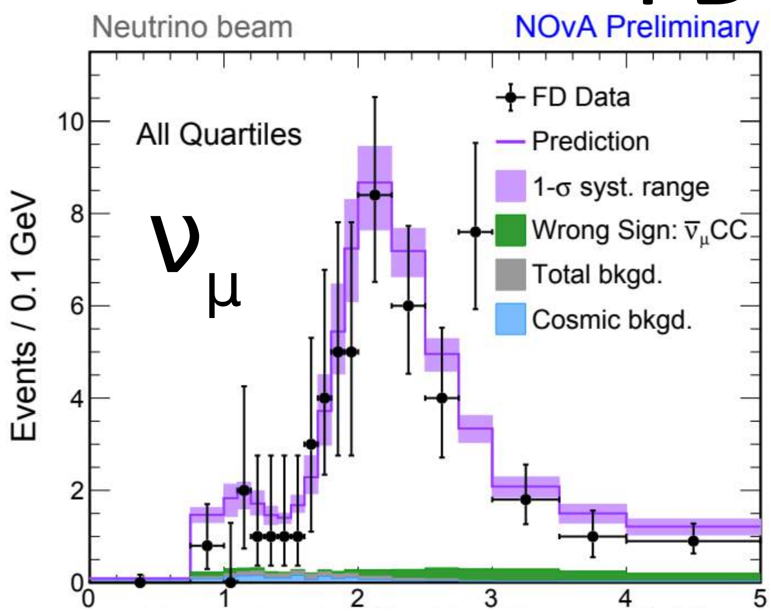
ND ν_e candidates are all background (no oscillations yet):

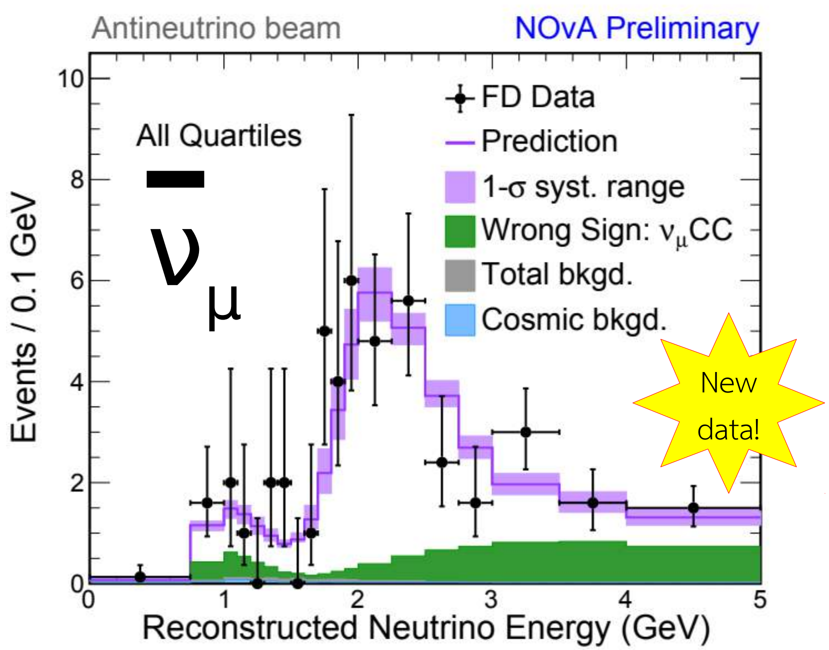
correct & extrapolate each category separately;

use corrected ND ν_μ prediction for ν_e appearance signal correction

FD Data - ν_μ

arXiv:1906.04907





Data neutrino candidates	113
Best fit total prediction	**124**
total bkgd.:	4.2
↳ cosmic bkgd.	2.1
↳ beam bkgd.	2.1

3-flavor oscillations describe data well
(goodness-of-fit p = 0.91)

Data antineutrino candidates	102
Best fit total prediction	**96**
total bkgd.:	2.2
↳ cosmic bkgd.	0.8
↳ beam bkgd.	1.4

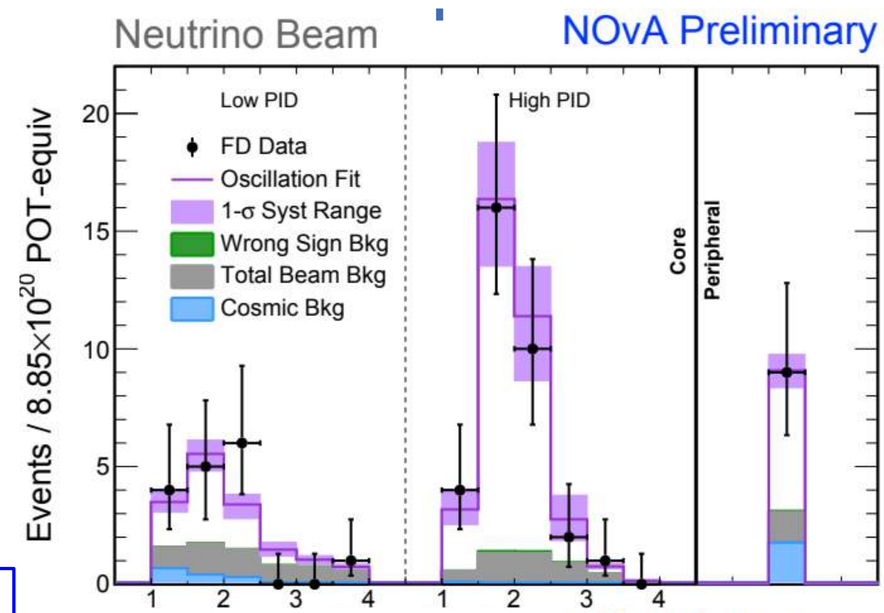
FD Data - ν_e

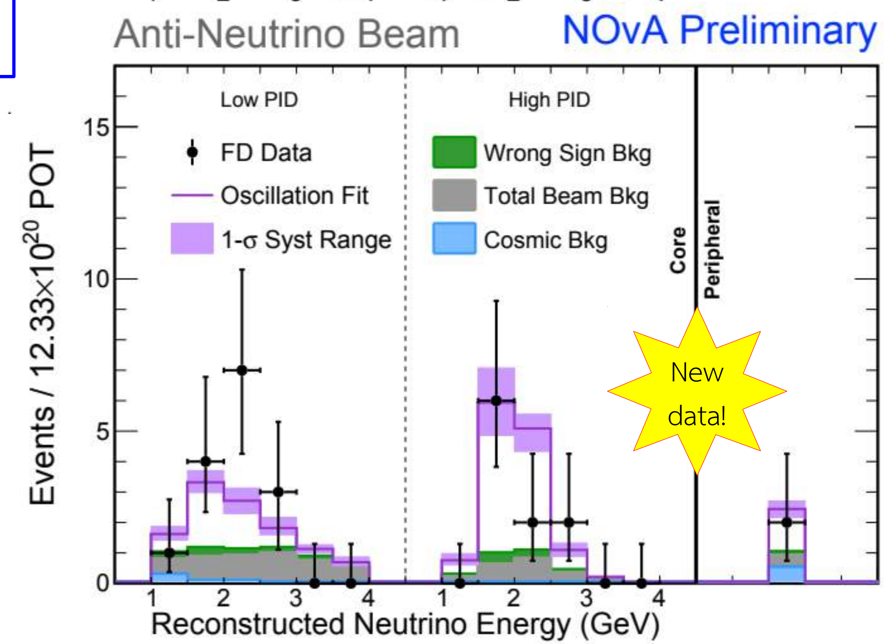
arXiv:1906.04907

Data neutrino candidates	58
Best fit total prediction	**59**
total bkgd.:	15.0
↳ cosmic bkgd.	3.3
↳ beam bkgd.	11.1
↳ wrong-sign (app. $\bar{\nu}_e$)	0.7

Evidence for $\bar{\boldsymbol{\nu}}_e$ appearance at 4.4$\boldsymbol{\sigma}$

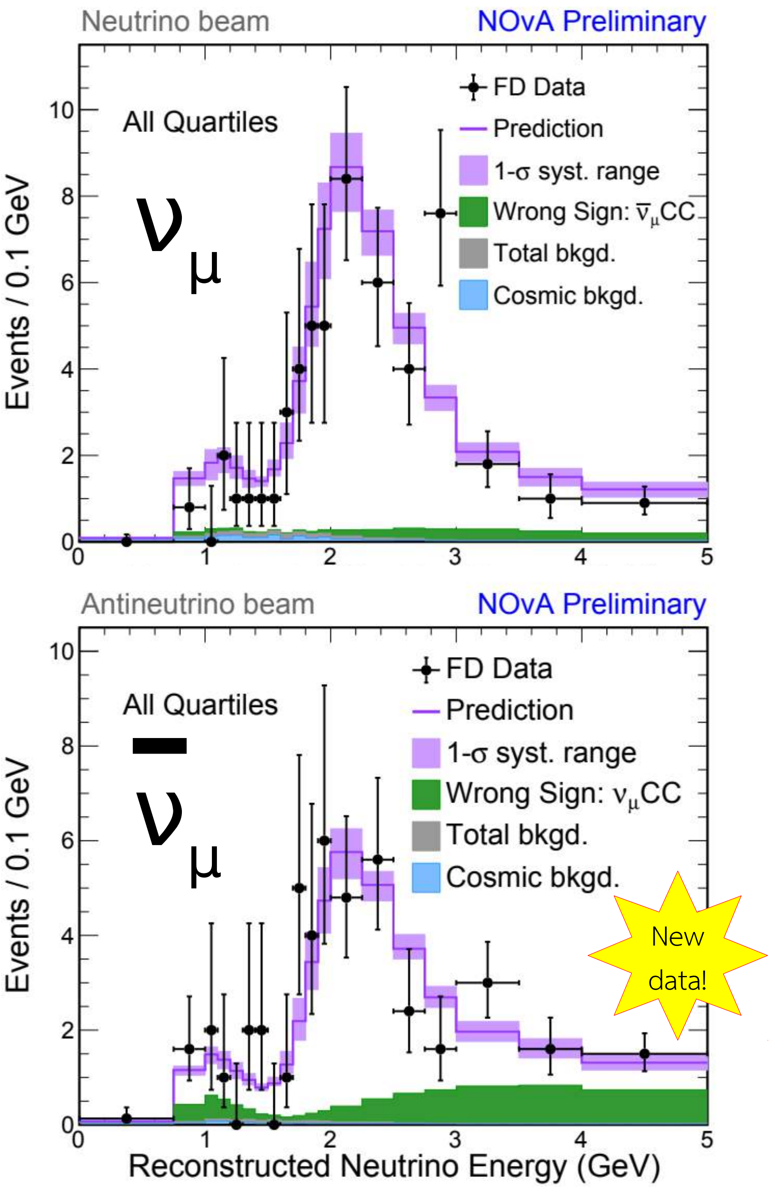
Data antineutrino candidates	27
Best fit total prediction	**27**
total bkgd.:	10.3
↳ cosmic bkgd.	1.1
↳ beam bkgd.	7.0
↳ wrong-sign (app. ν_e)	2.2



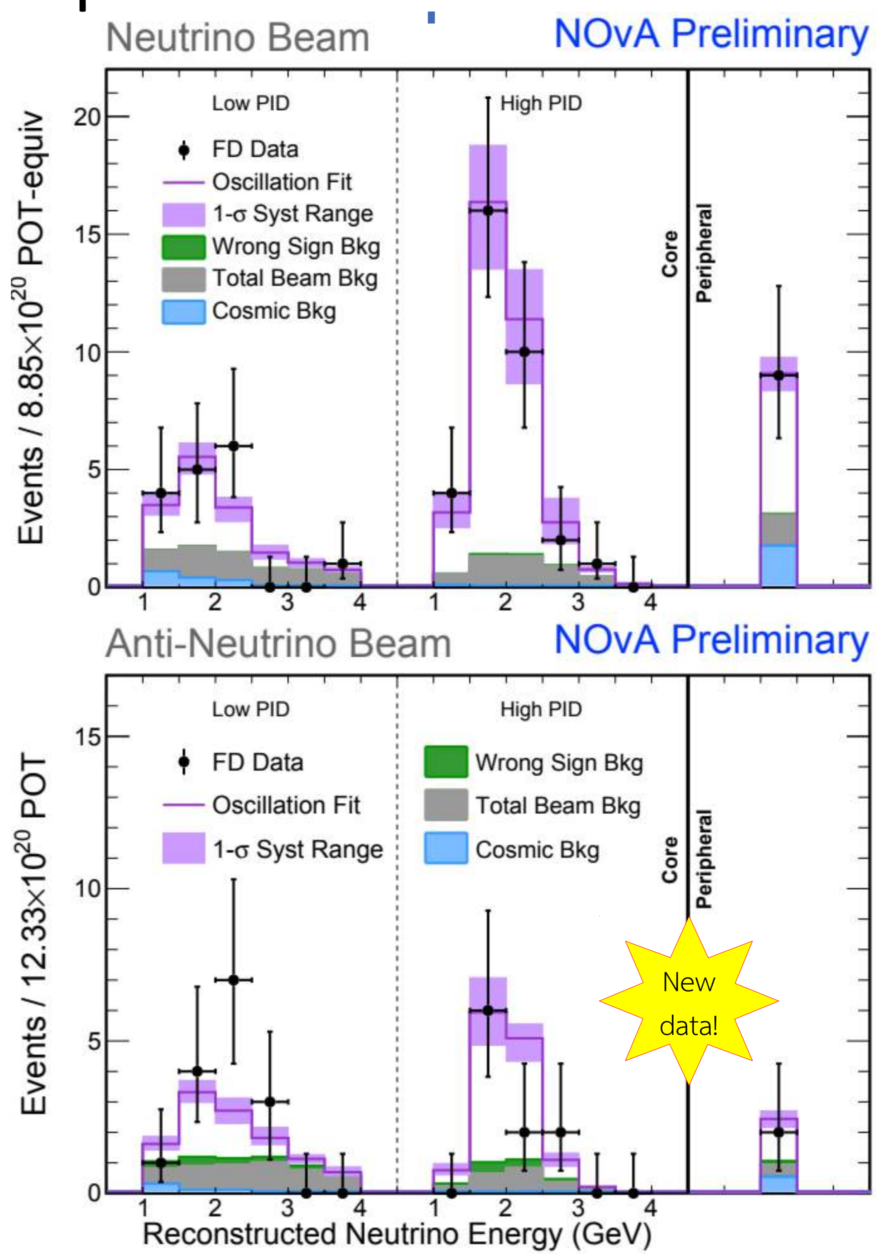


FD Data - $\nu_\mu + \nu_e$

arXiv:1906.04907

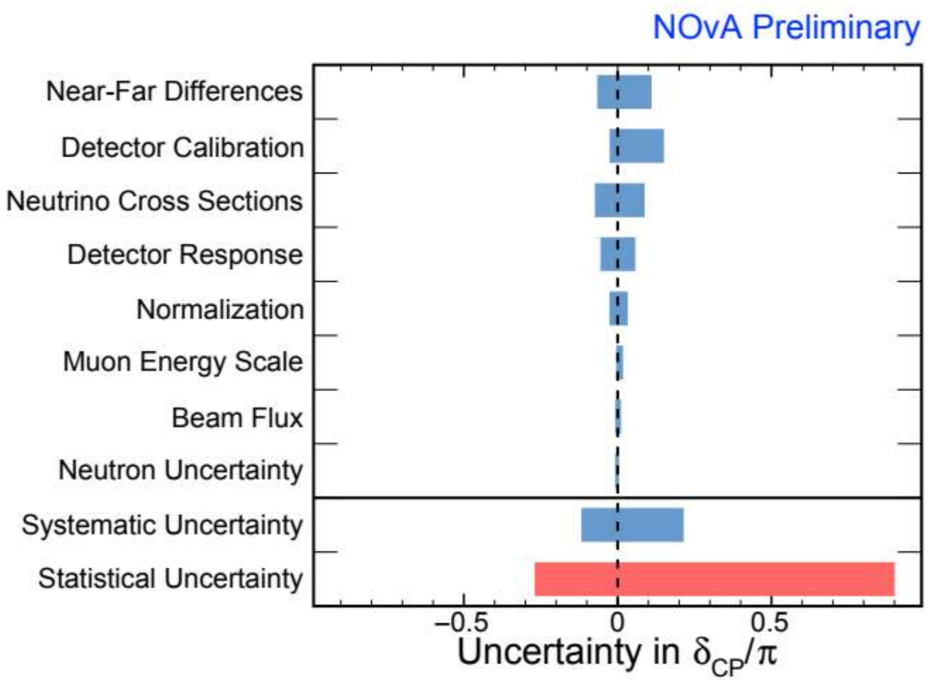


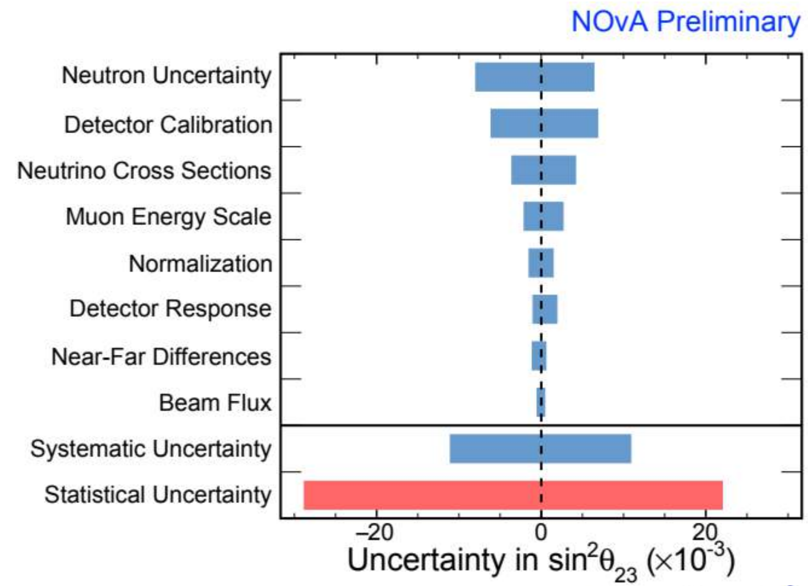
Joint Fit

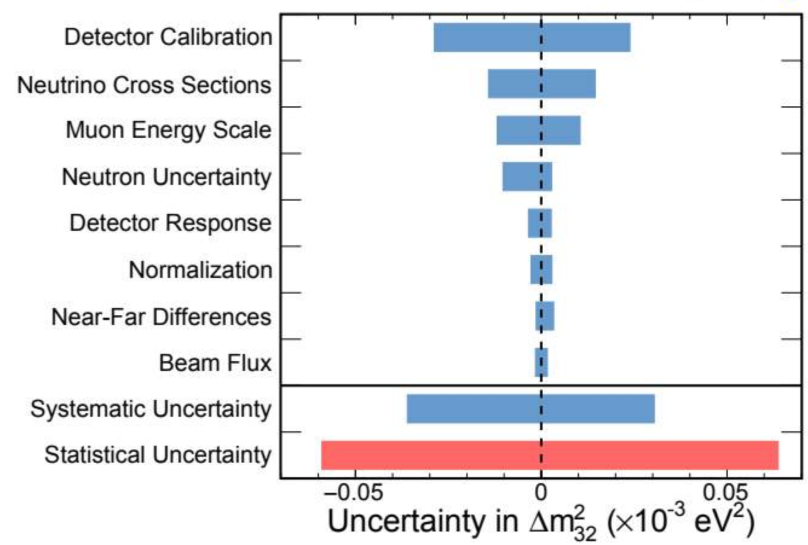


Systematics

Uncertainties dominated by statistics,
but
detector calibration
and neutrino interactions
growing in importance

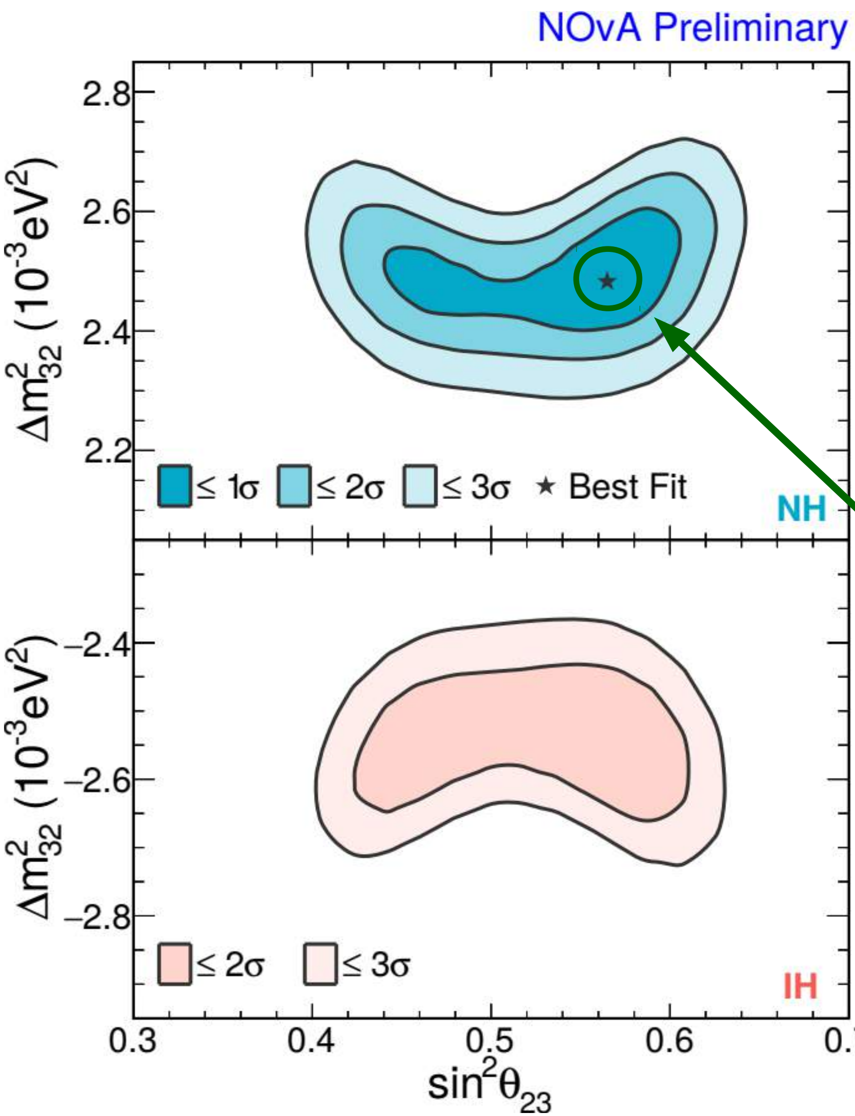


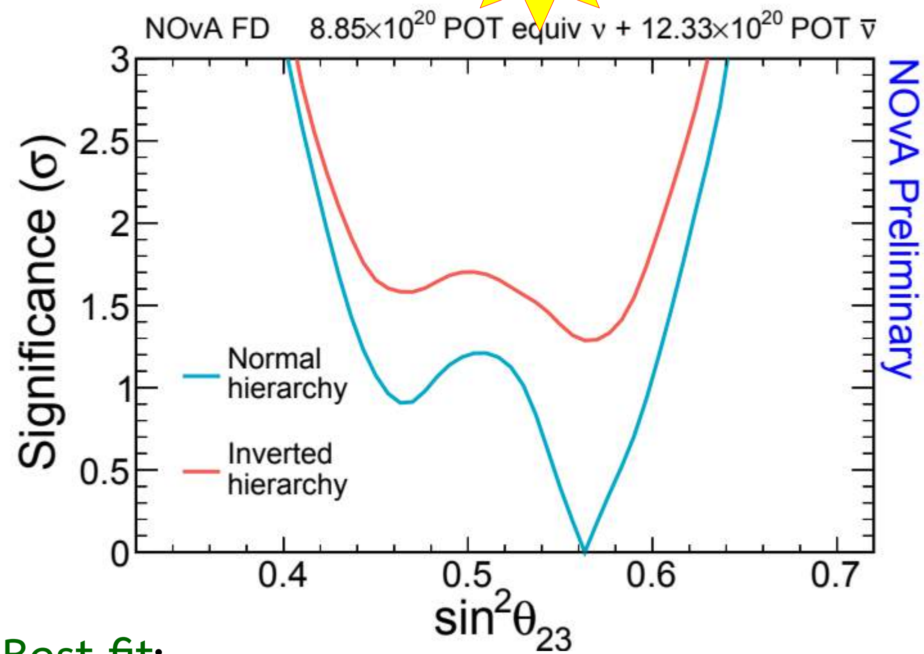




Oscillation results

New data!





Best fit:

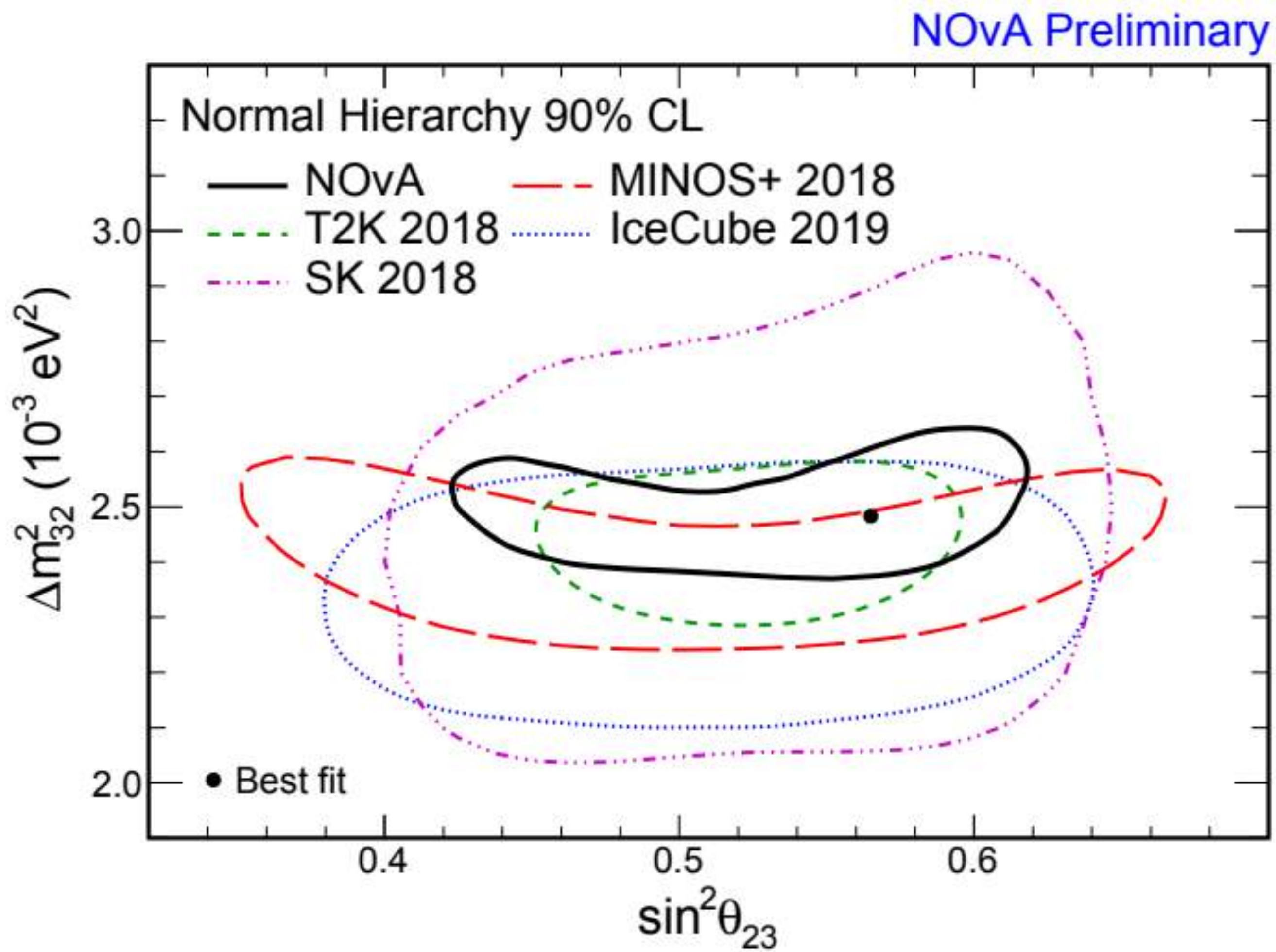
- $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$
- $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\,\mathrm{eV}^2/c^4\,(\mathrm{NH})$

$\sin^2\theta_{23} < 0.5$ **(lower octant) disfavored at 1.6σ**

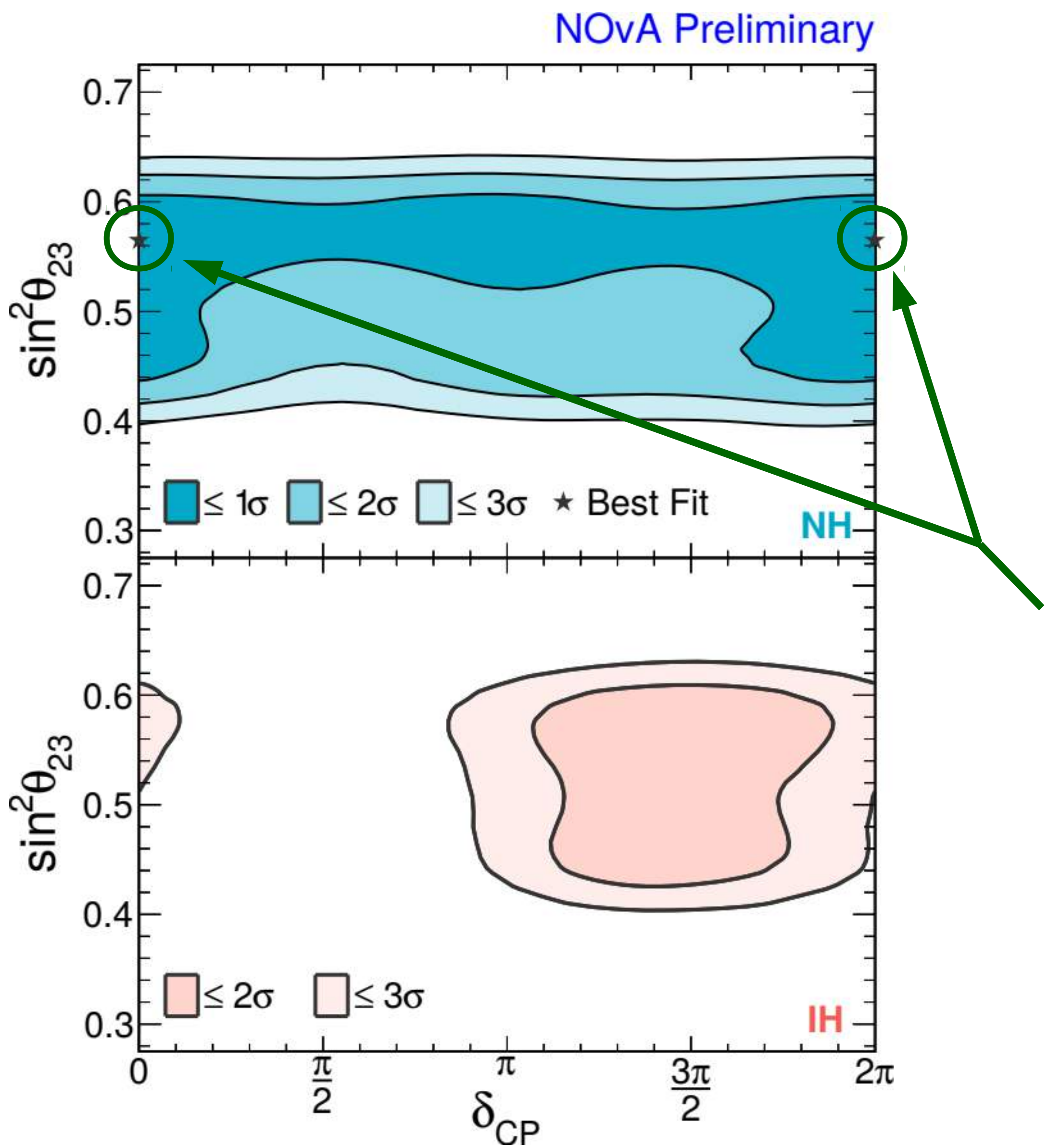
$\sin^2\theta_{23} = 0.5$ disfavored at 1.2σ

[All contours and significances calculated using Feldman-Cousins method thanks to NERSC] arXiv:1906.04907

Oscillation Results



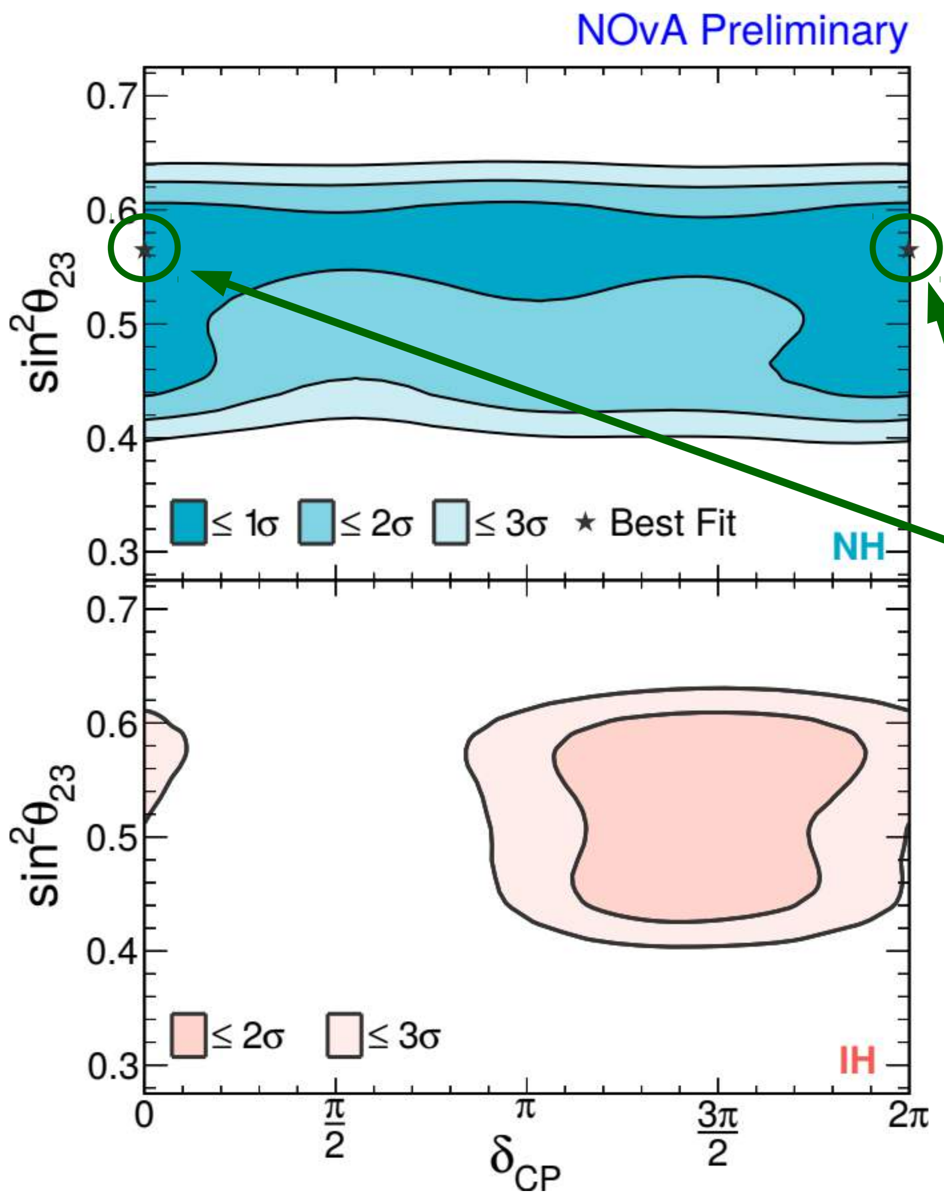
Precision measurement of atmospheric parameters

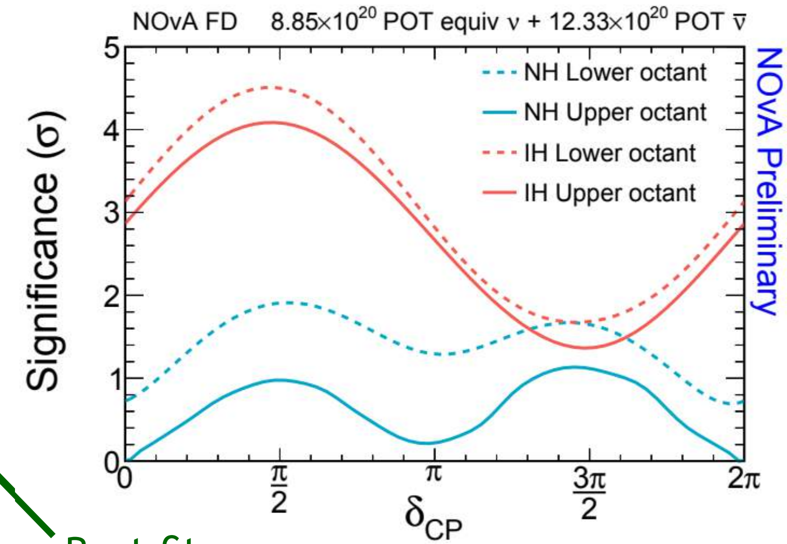


Best fit:

- $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$
- $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\,\mathrm{eV}^2/c^4\,(\mathrm{NH})$
- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

[All contours and significances calculated using Feldman-Cousins method thanks to NERSC]





Best fit:

- $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$
- $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\,\mathrm{eV}^2/c^4\,(\mathrm{NH})$
- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

NHUO: All values of **δ** allowed at 1.1**σ**

IH: **δ**= **π**/2 ruled out > 4**σ**

Hierarchy / Octant

NH UO Best fit	**IH UO** Disfavored 1.8σ
NH LO Disfavored 1.6σ	**IH LO** Disfavored 2.0σ

LO
Disfavored
1.6σ

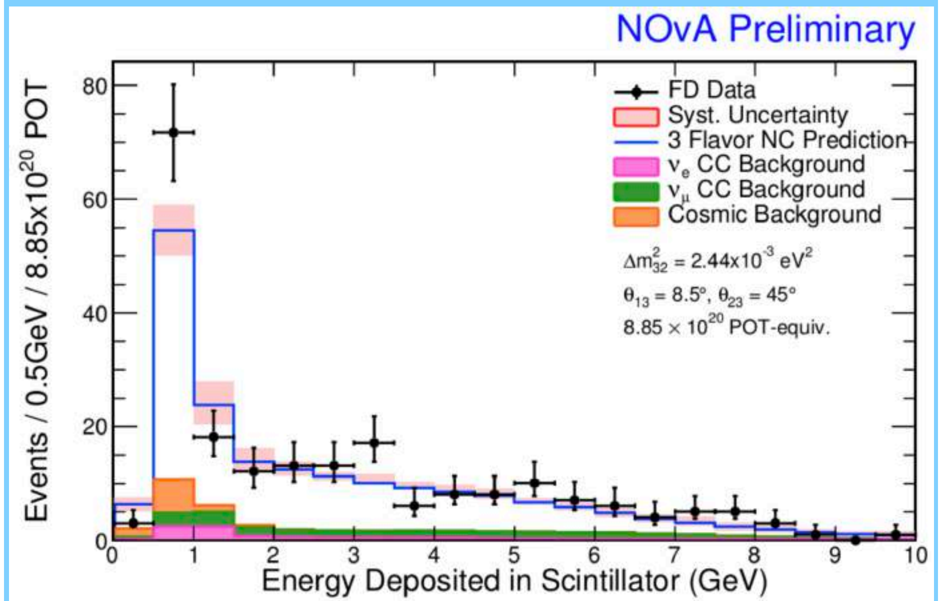
IH
Disfavored
1.9σ

Neutral Current Events

Neutral Current FD Data

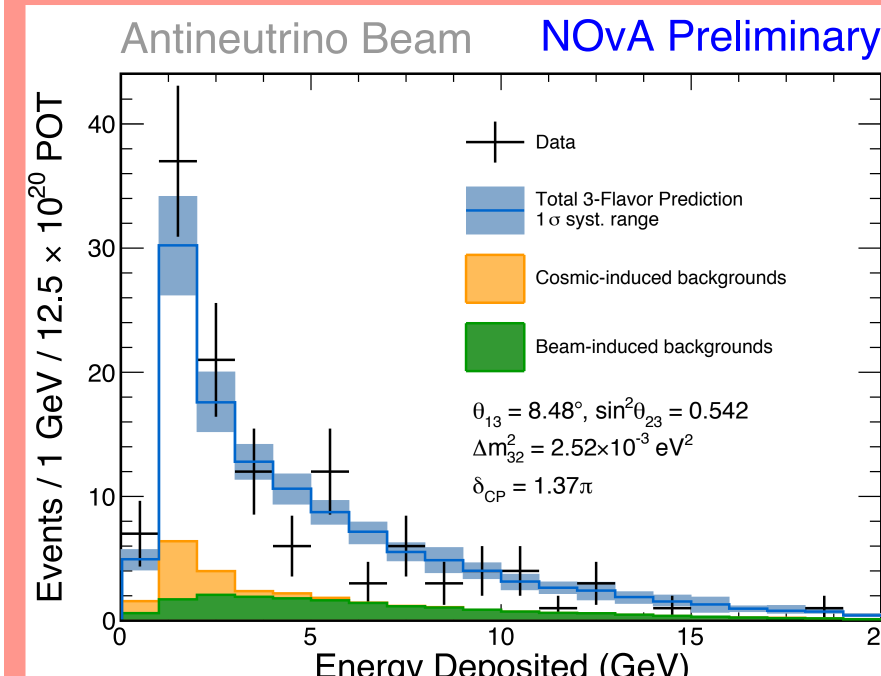
Neutrino Data

- Observed **214** events, with prediction of **191.2 ± 13.8 (stat) ± 22.0 (syst)**.



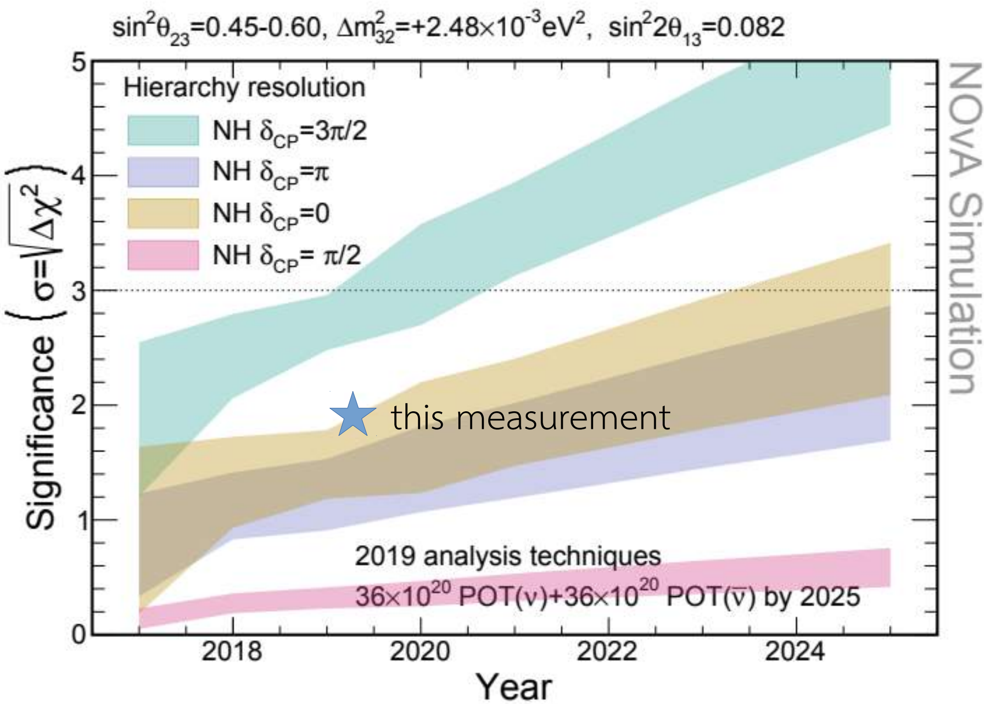
Antineutrino Data

- Observed **121** events, with 3-flavor prediction of **122 ± 11 (stat.) ± 18 (syst.)**.



Future

- Currently running in neutrino mode
  - Run plan: 50:50 $\nu:\bar{\nu}$
  - NOvA is expected to run until 2025
  - Beam improvements an important part of story!
- With current analysis, expect:
  - **Potential 3-5σ sensitivity to hierarchy** with favorable parameters
  - **Possible >2σ sensitivity to CP violation**
- Anticipating improvements in simulations that should improve analysis robustness
  - Test Beam / improved det. response model
  - GENIE 3.0 / improved cross section models



Conclusions

- With 8.85×10^{20} POT neutrino + 12.33×10^{20} POT antineutrino beam exposure, NOvA finds:
  - **4.4σ evidence for electron antineutrino appearance** in a muon antineutrino beam
  - **1.9σ preference for the Normal neutrino mass hierarchy**
  - **1.6σ preference for θ_{23} residing in the Upper Octant** (maximal mixing disfavored at 1.2σ)
- With continued running through 2025, NOvA anticipates:
  - **Possible 3-5σ sensitivity to the mass hierarchy**
  - **Potential sensitivity to CP violation** >2σ
  - Input from NOvA Test Beam program, neutrino interactions community to **further improve robustness** to systematics

Paper reference arXiv:1906.04907