University of Sussex

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NOvA and DUNE: Neutrino Oscillations

Jeff Hartnell

University of Sussex

European Research Council

Established by the European Commission

NOvA

Birmingham Seminar

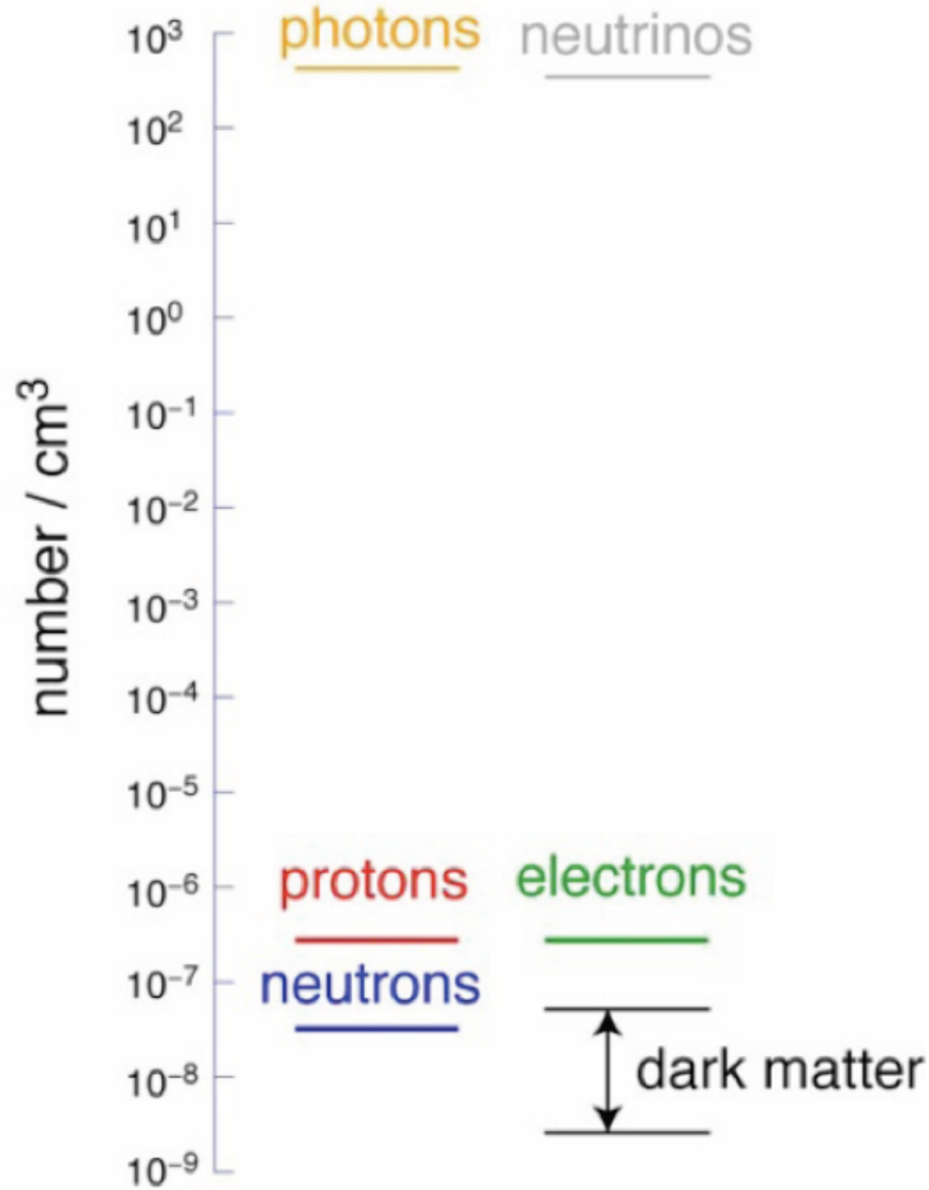
24th January 2018

Introduction

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

Why study neutrinos?

The Particle Universe

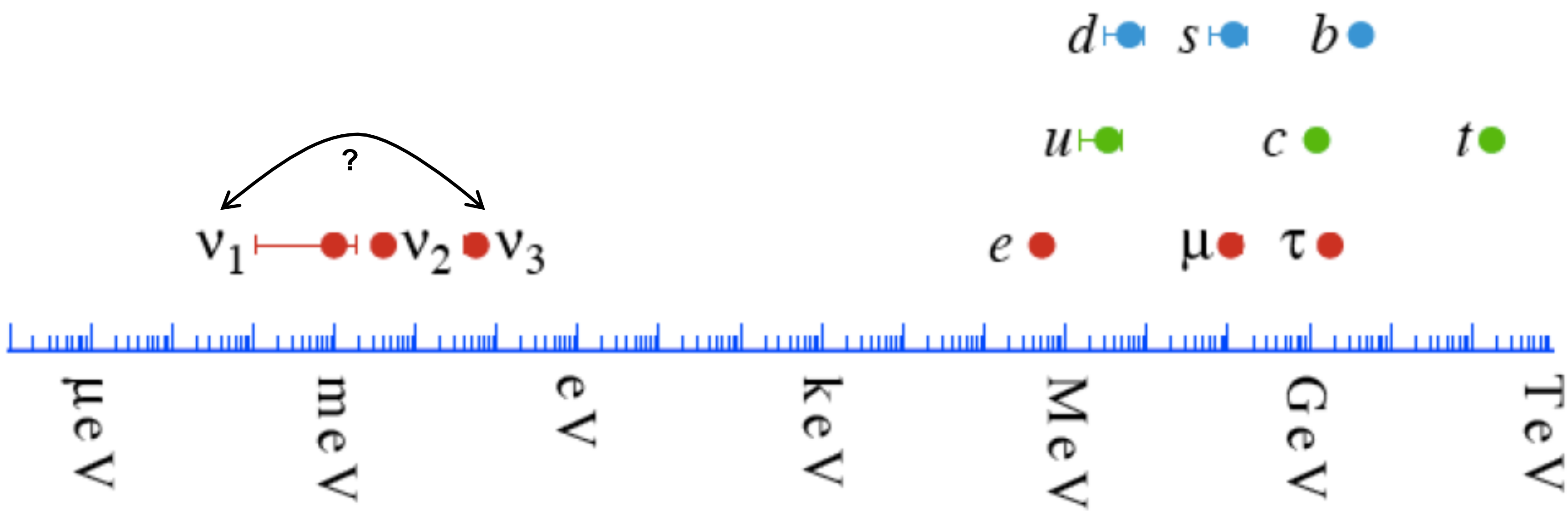


Two Major Questions

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

- Neutrinos ⟷ 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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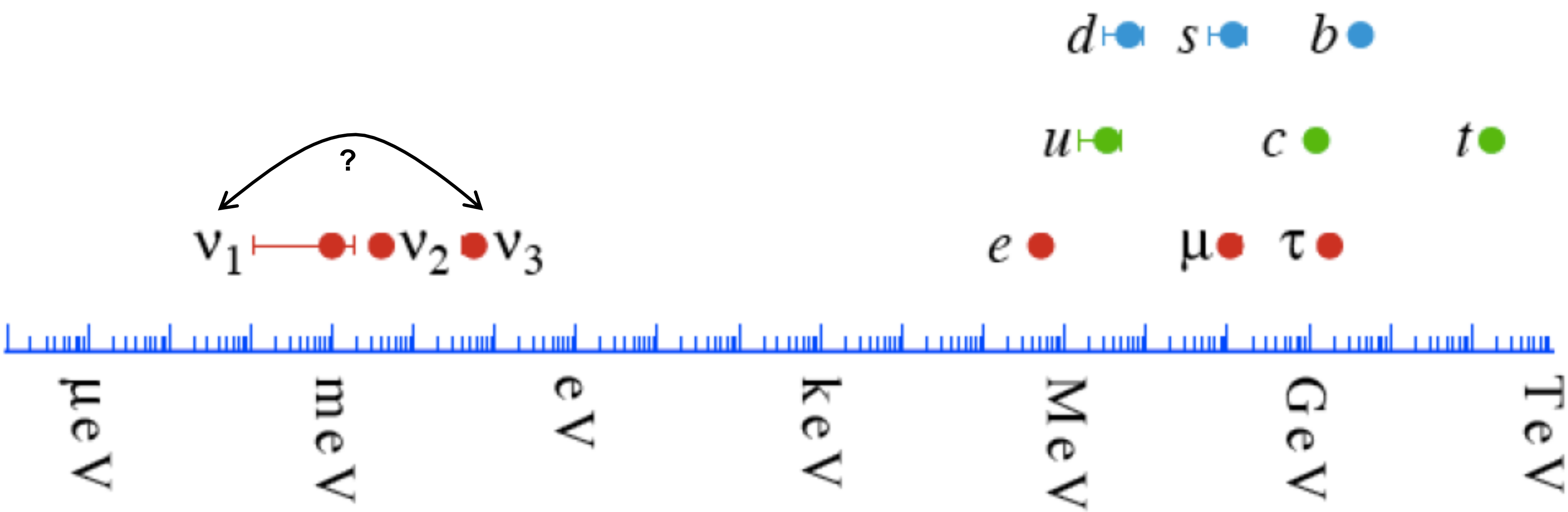
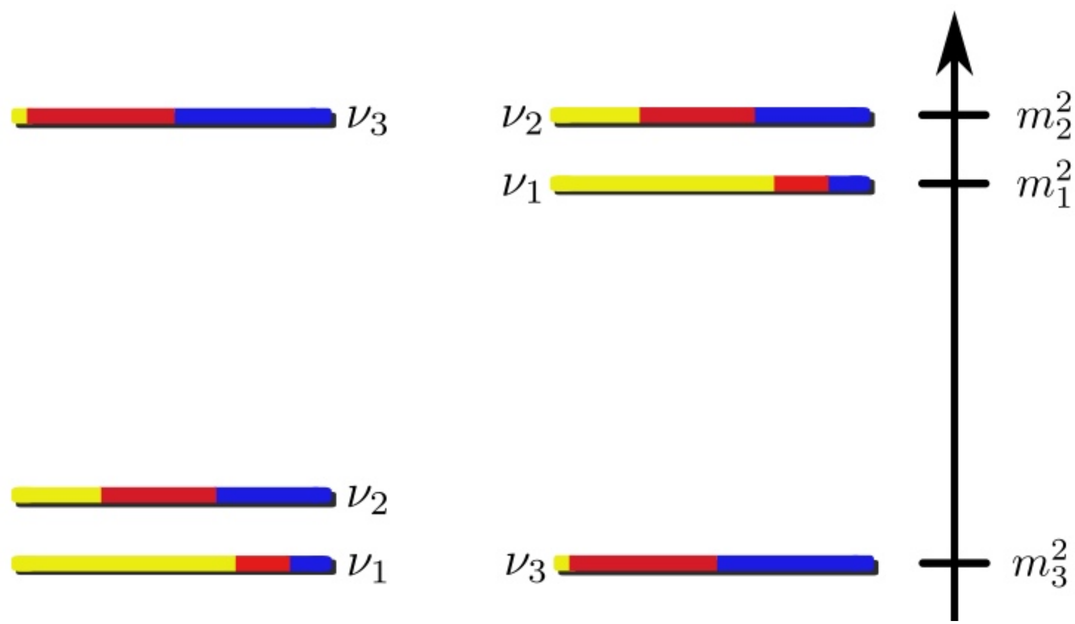


Two heavy and one light?

NOvA has sensitivity to the mass hierarchy

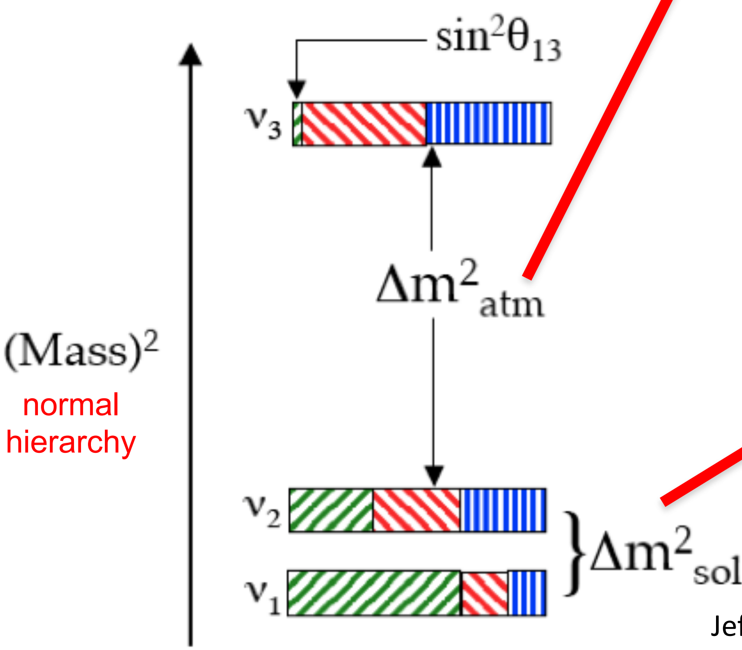


Theory Overview

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

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

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?

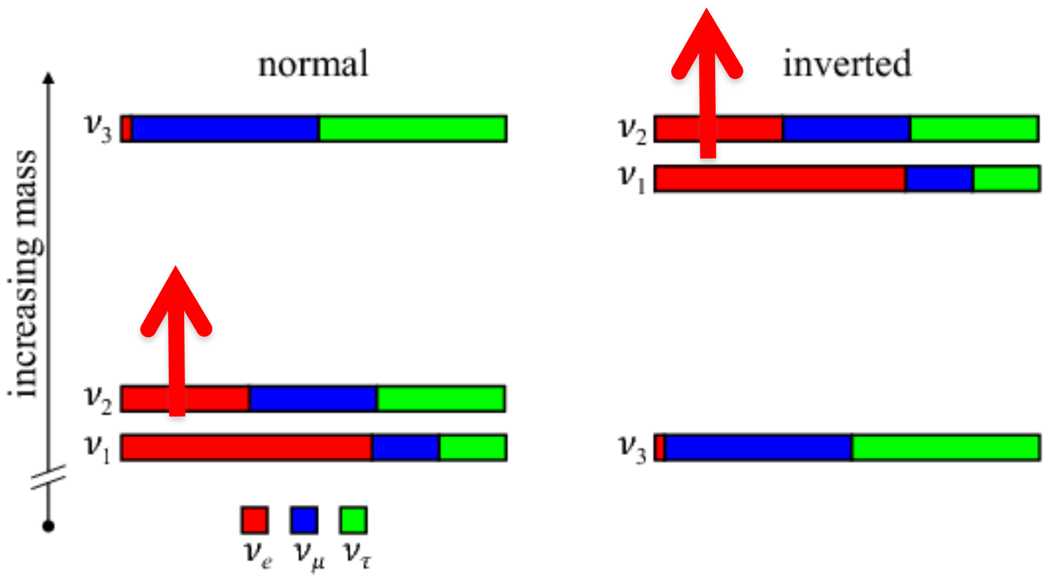
Δm^2_{31} and Δm^2_{32} differ by 3%

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?

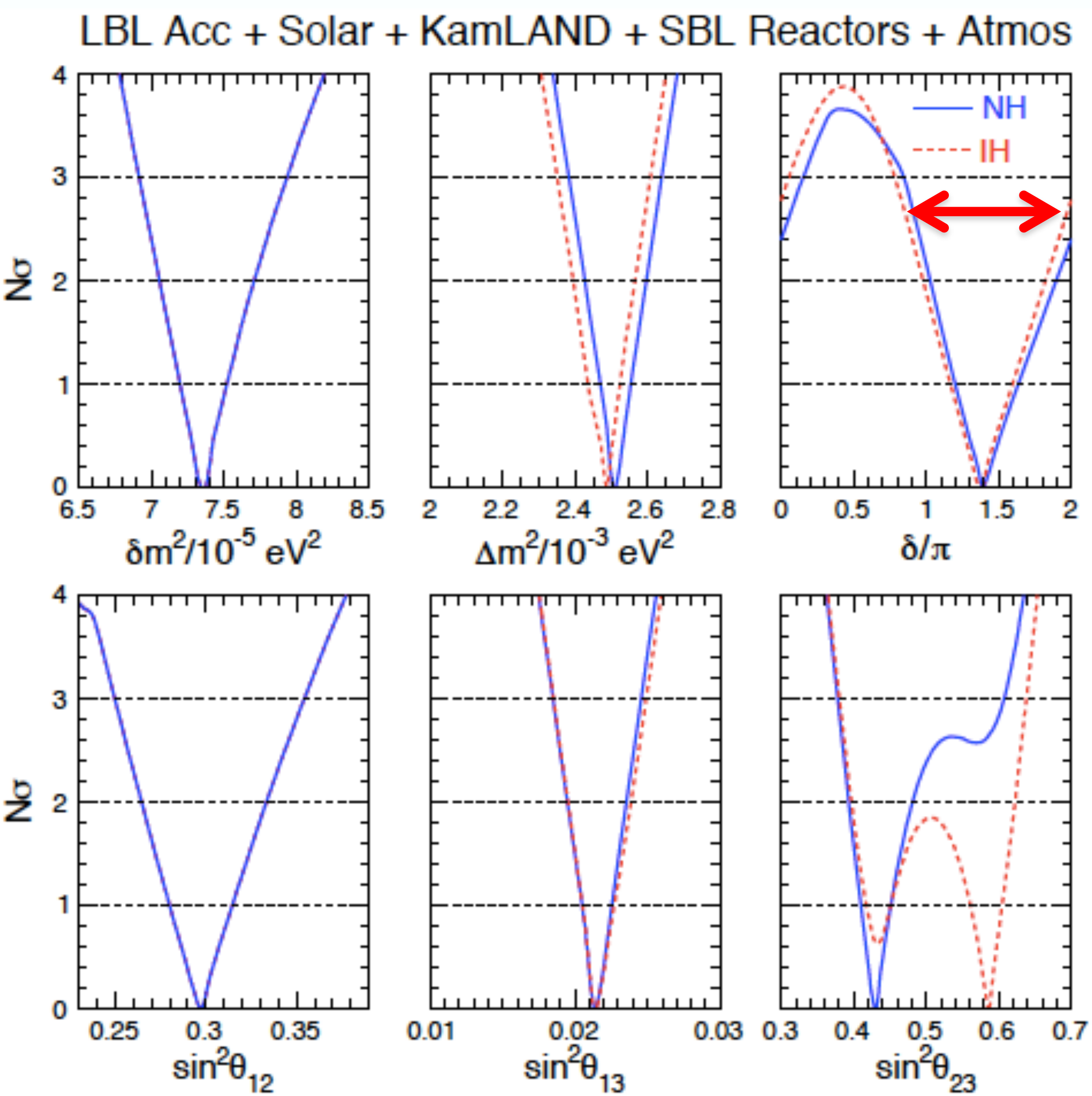
It's hard to overstate…

- The past ~5 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"

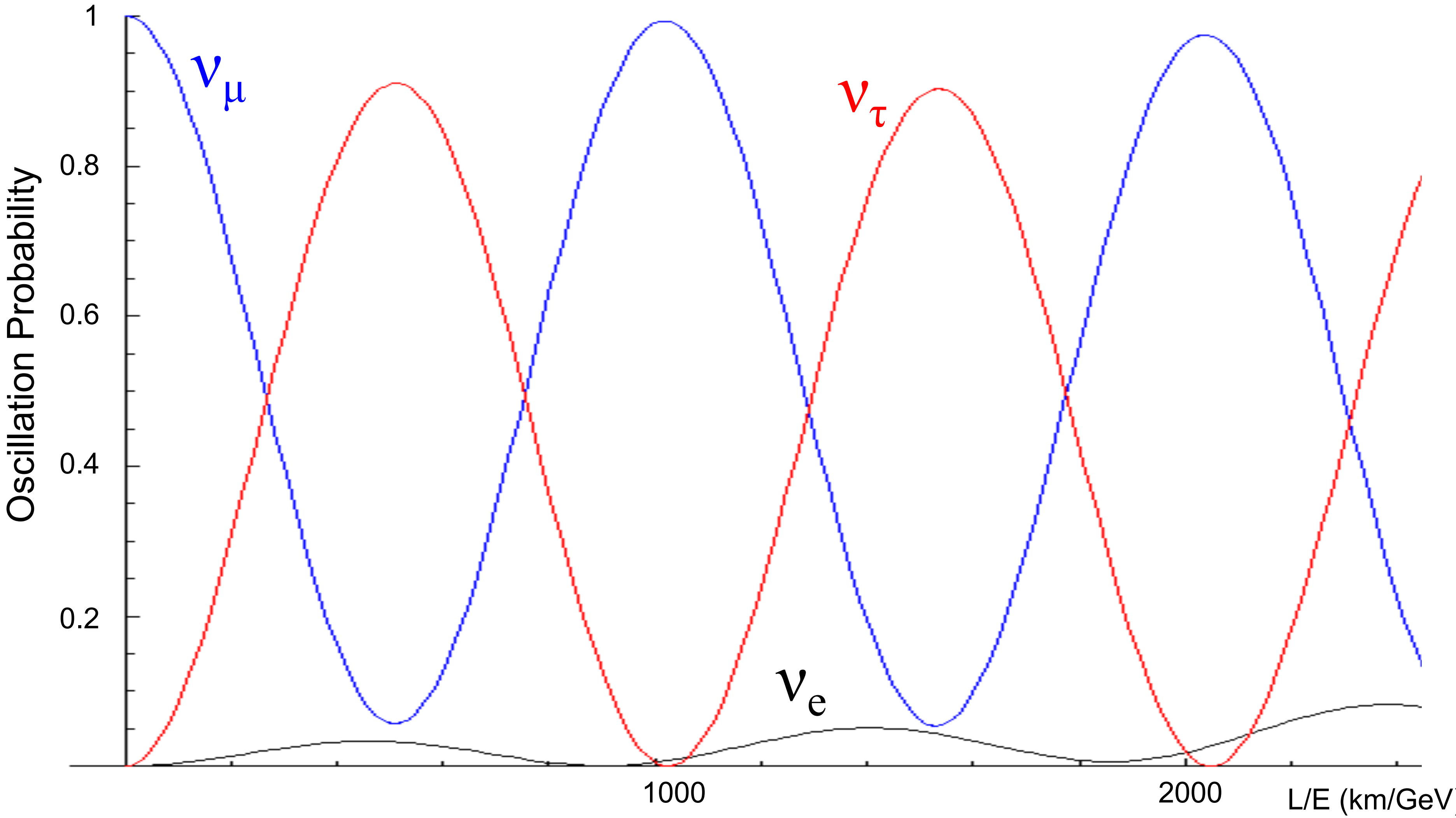
Wide range of δ_{CP} values possible (1)

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!*

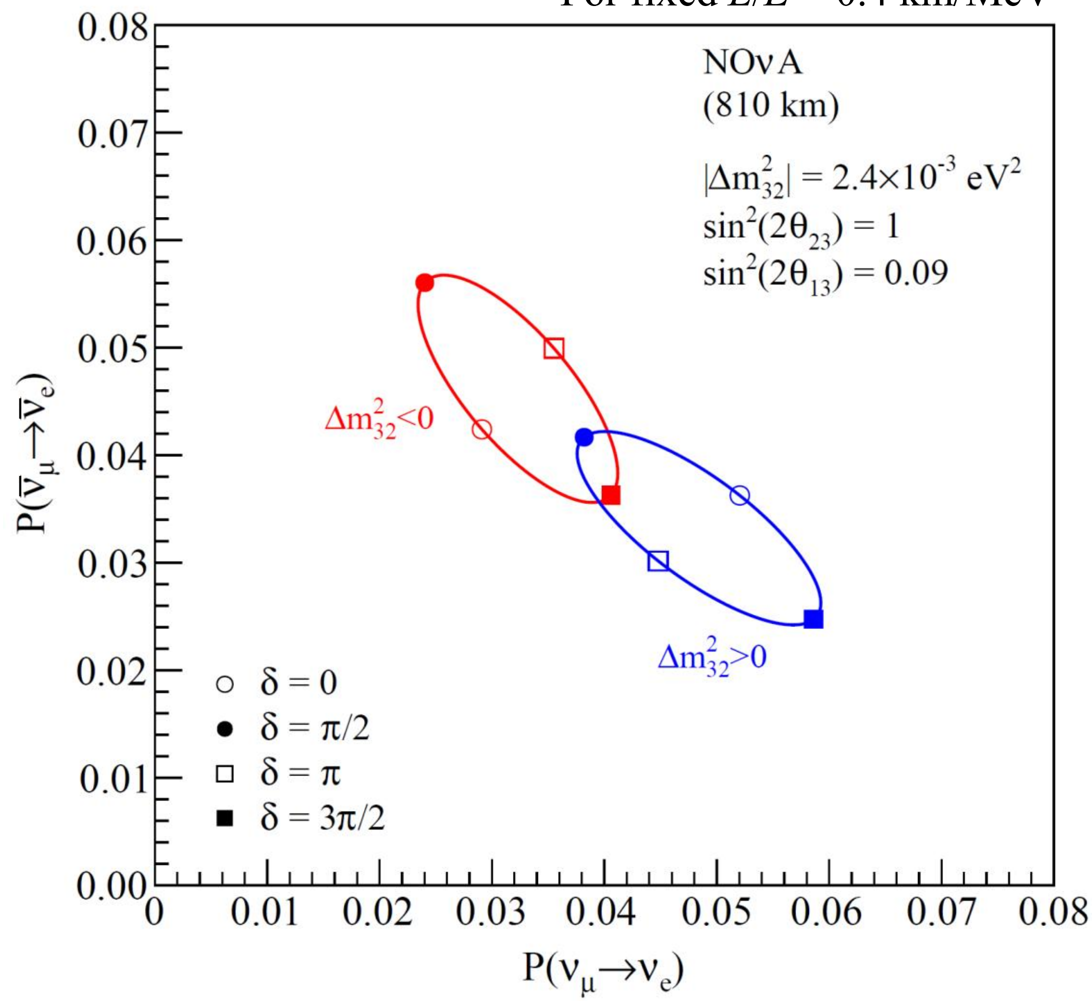
Long-baseline $\nu_\mu \rightarrow \nu_e$

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

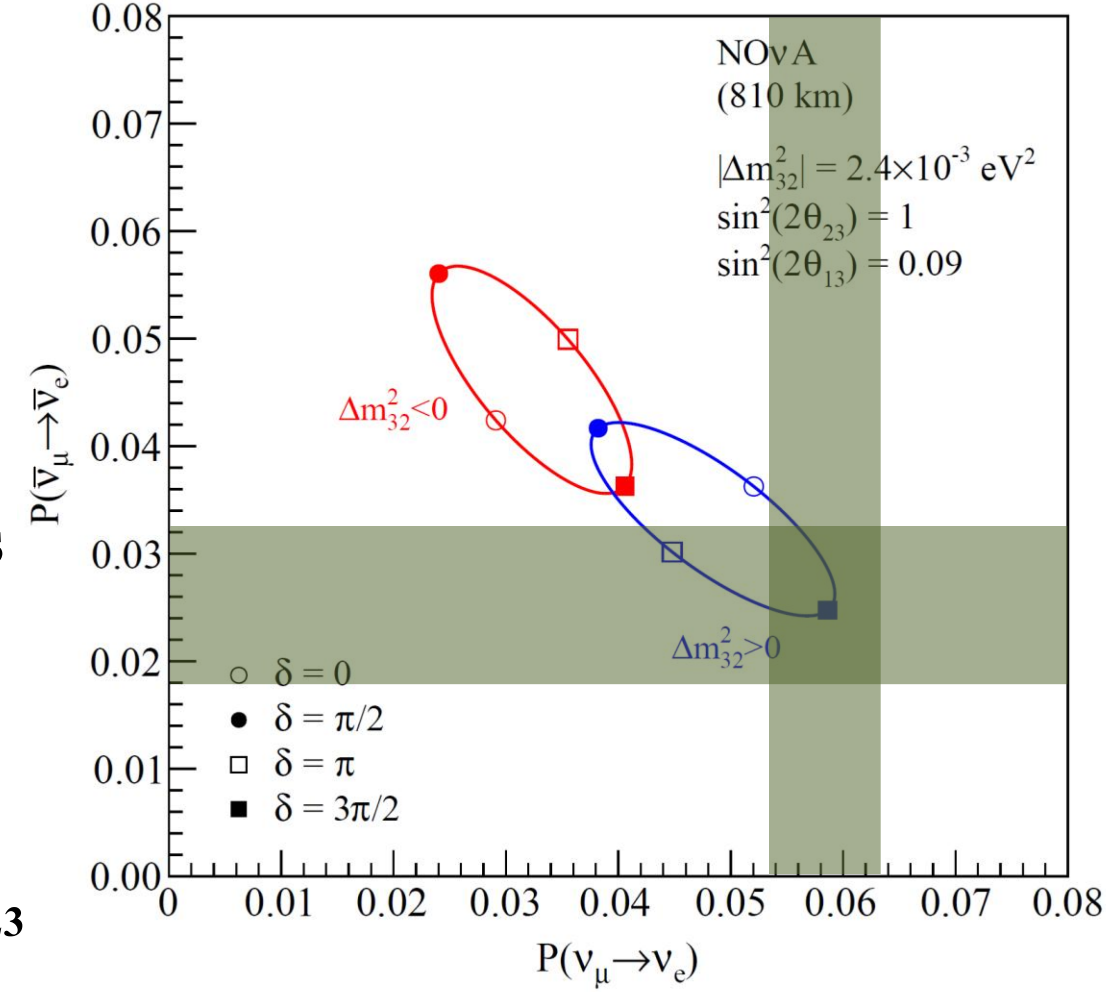
Measure these probabilities

(an example measurement of each shown)

Also:

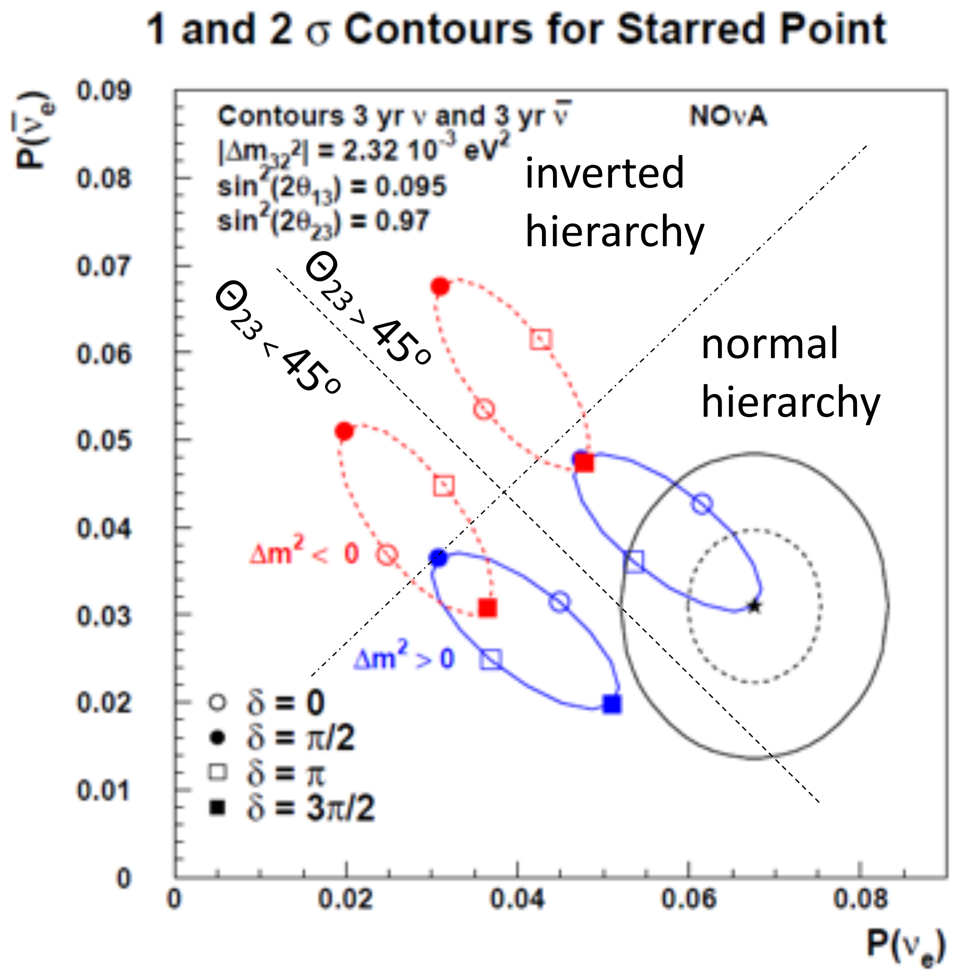
Both probabilities $\propto \sin^2\theta_{23}$

For fixed L/E = 0.4 km/MeV



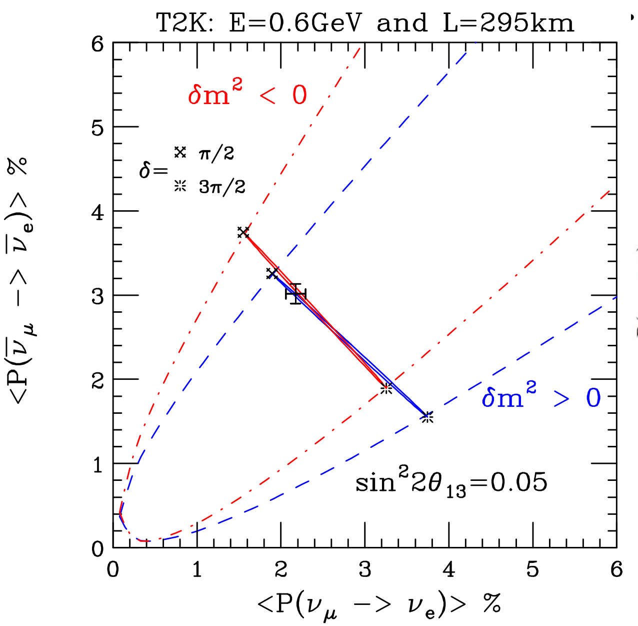
Non-maximal mixing scenario

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



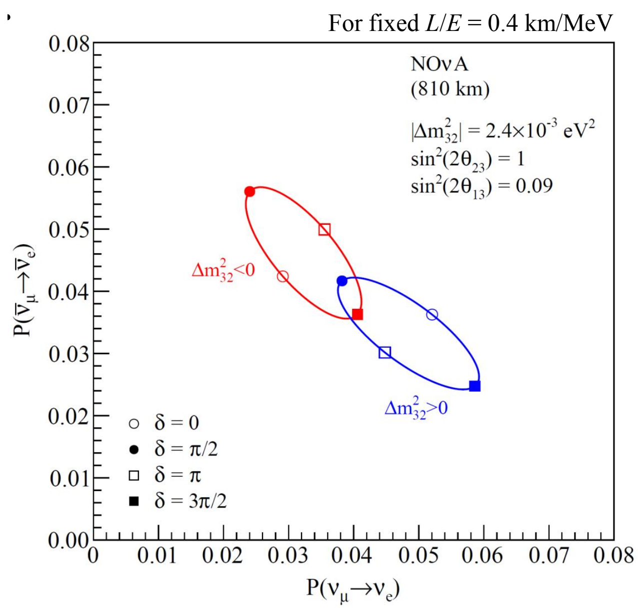
Effect of Increasing Energy

T2K



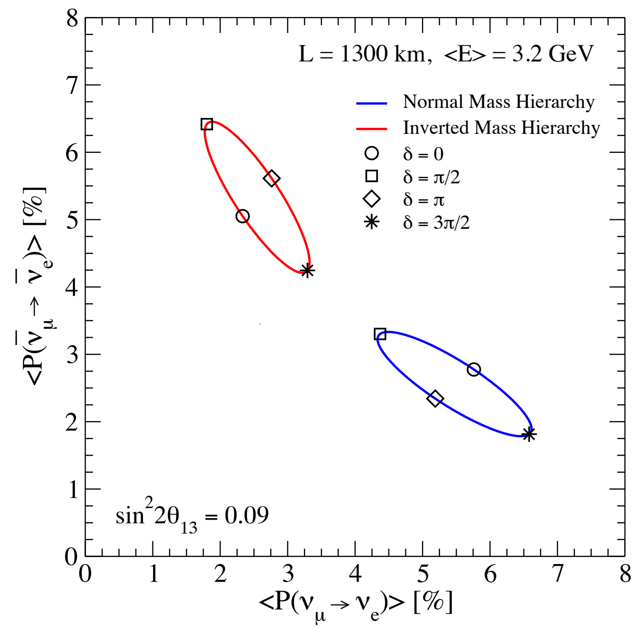
0.6 GeV

NOvA



2 GeV

DUNE



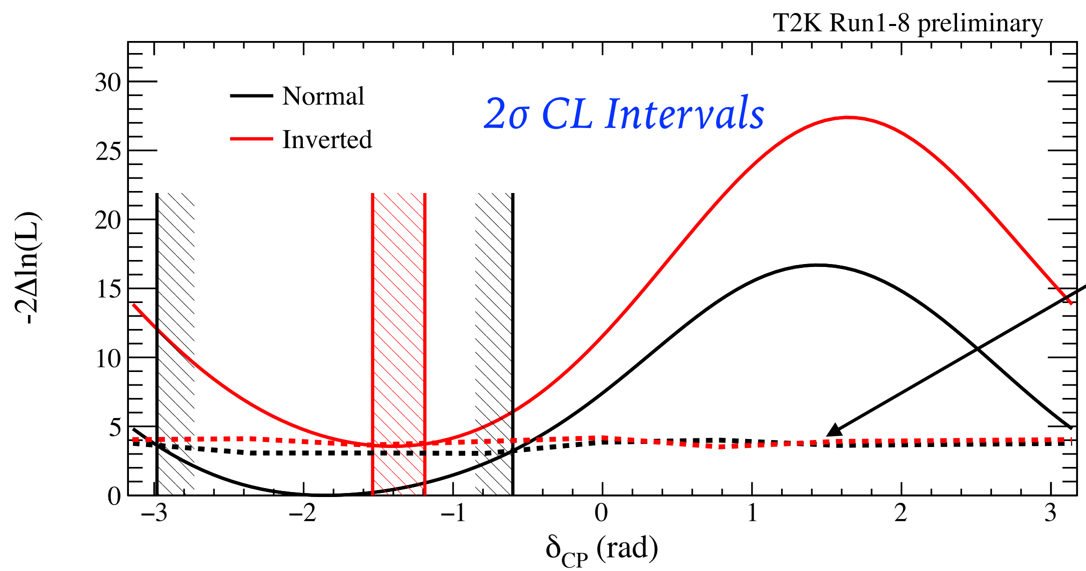
3 GeV

Increasing Energy

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

T2K ν_e Appearance

	Predicted Rates				Observed
Sample	δ_{cp}=-π/2	δ_{cp}=0	δ_{cp}=π/2	δ_{cp}=π	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68



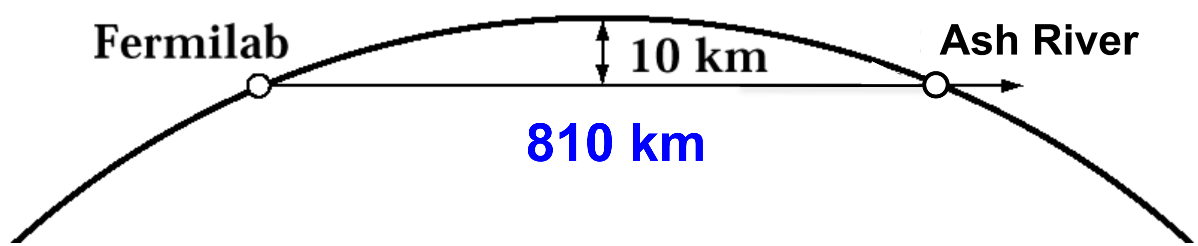
critical $\Delta\chi^2$ values for 2σ confidence level

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

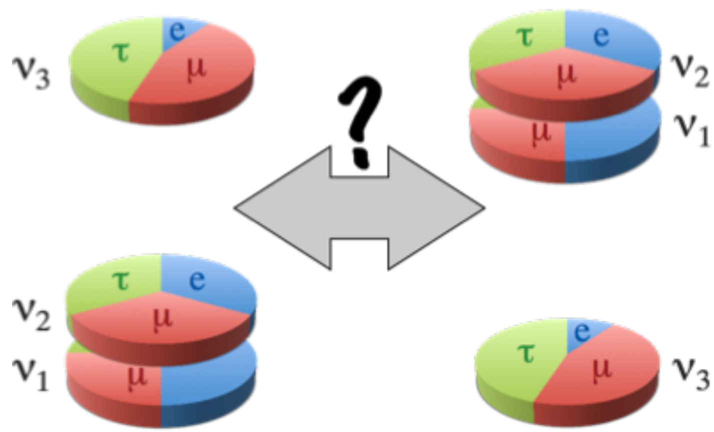
242 Collaborators
49 institutions
7 countries

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

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



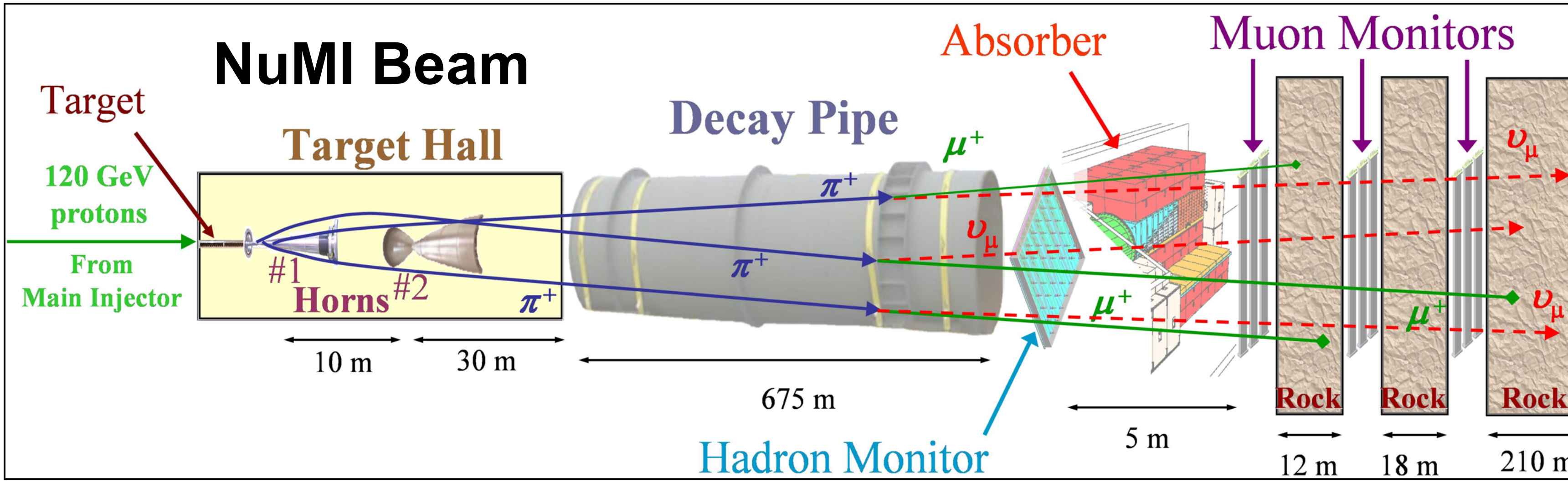
- Appearance of ν_e CC events

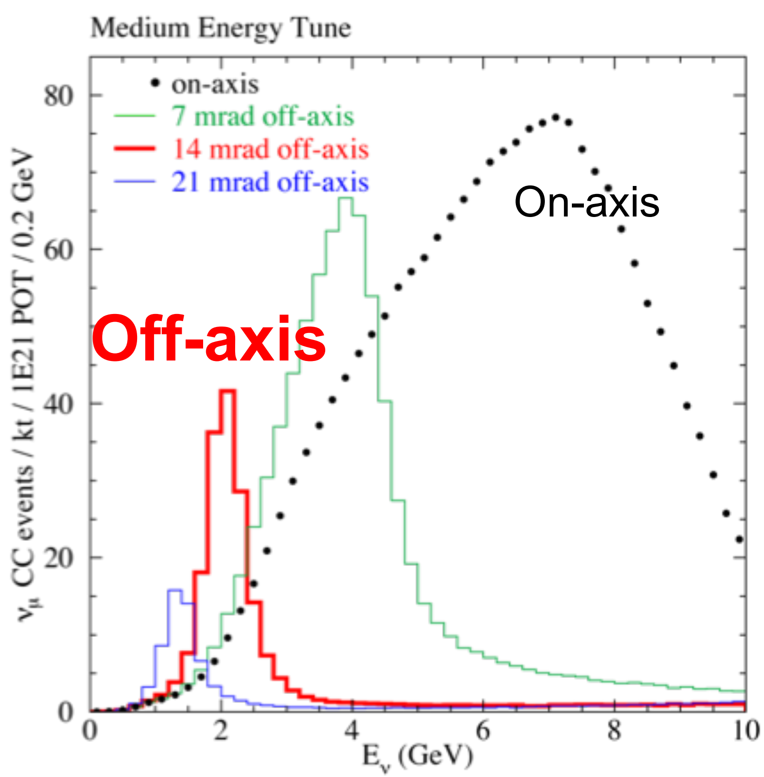
$$\theta_{13}, \theta_{23}, \delta_{CP},$$
and Mass Hierarchy

  - 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!

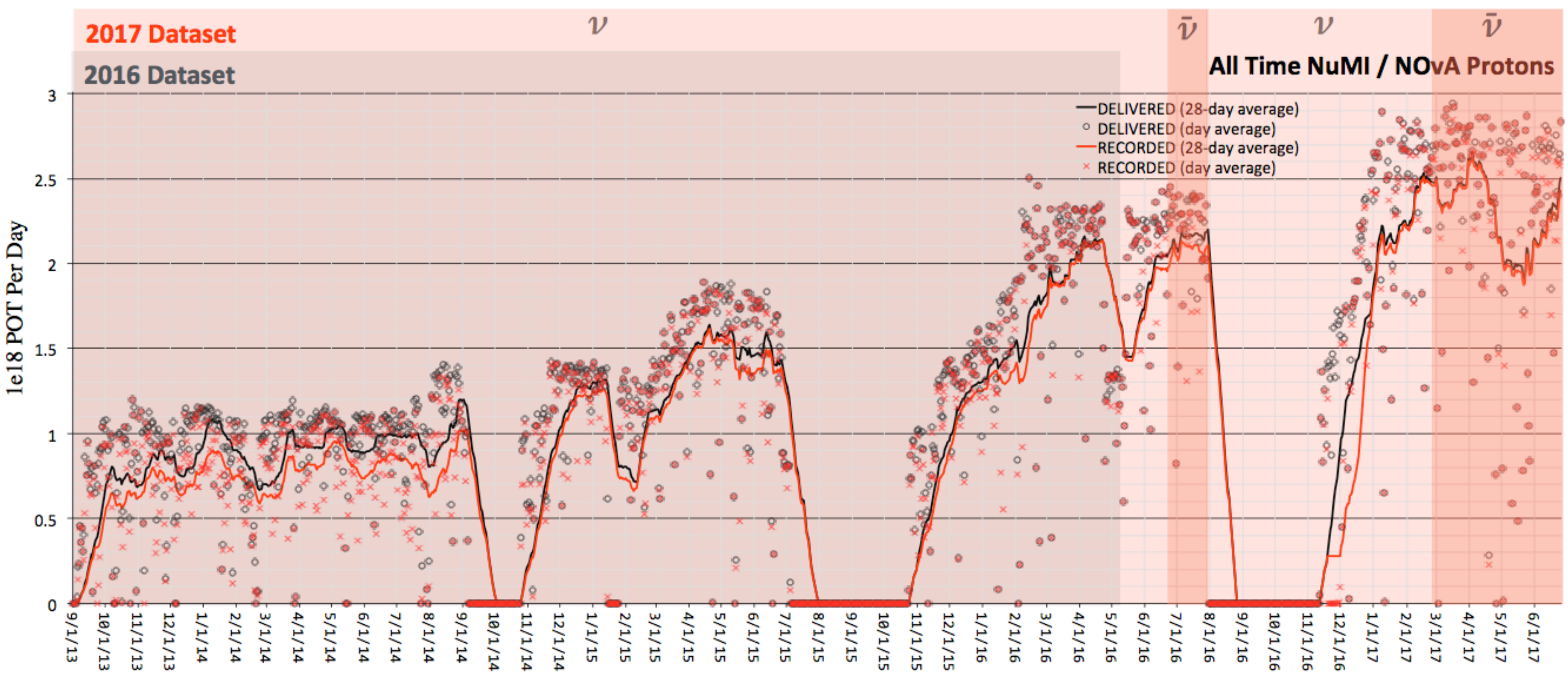
$$\Delta m^2_{41}, \theta_{34}, \theta_{24}$$


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

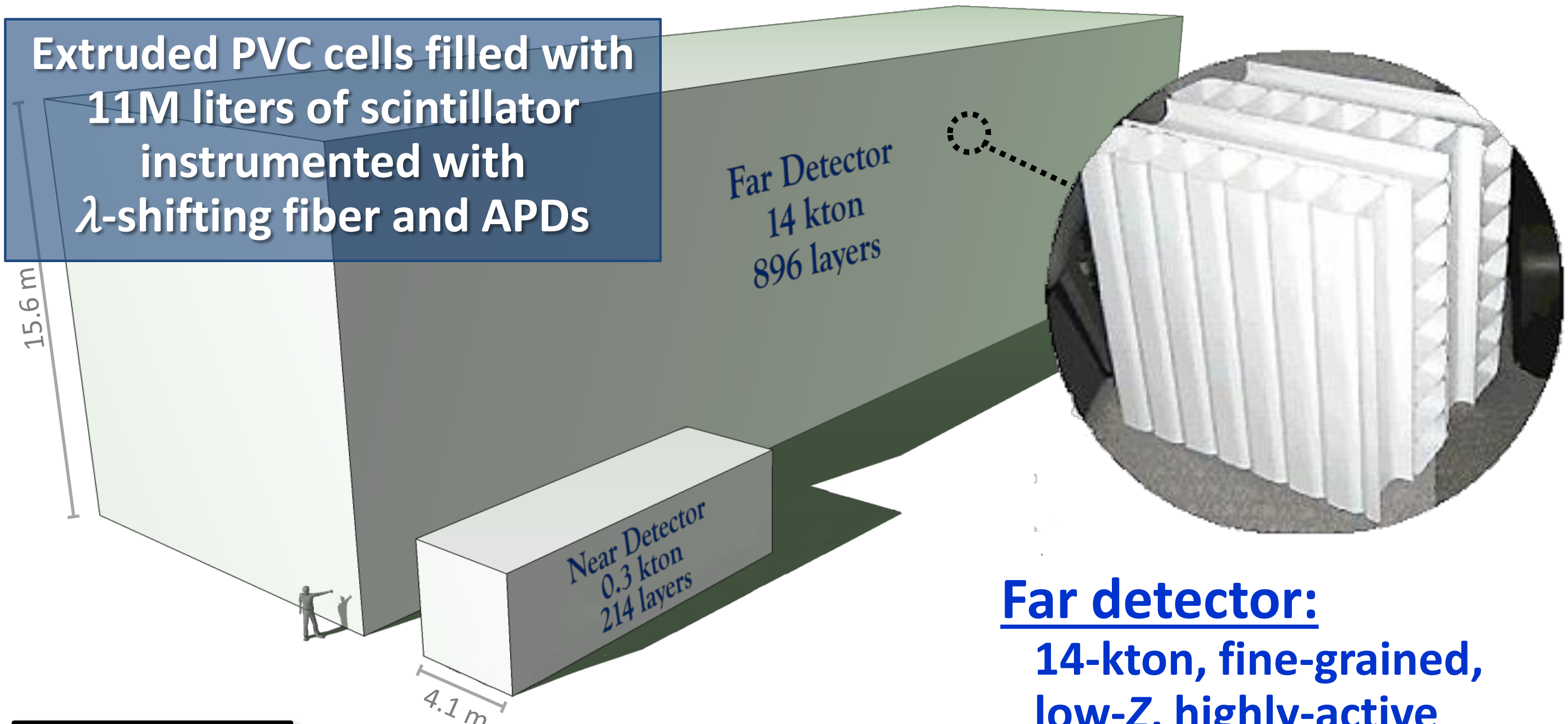

Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
On-axis
Off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)
0
20
40
60
80
0
2
4
6
8
10

Beam Performance

- 8.85×10^{20} POT in 14 kton equivalent detector
  - – 50% more than previous result
- Beam operating steadily at 700 kW for 1 year now
- 5×10^{20} POT antineutrinos so far (to be shown in June)

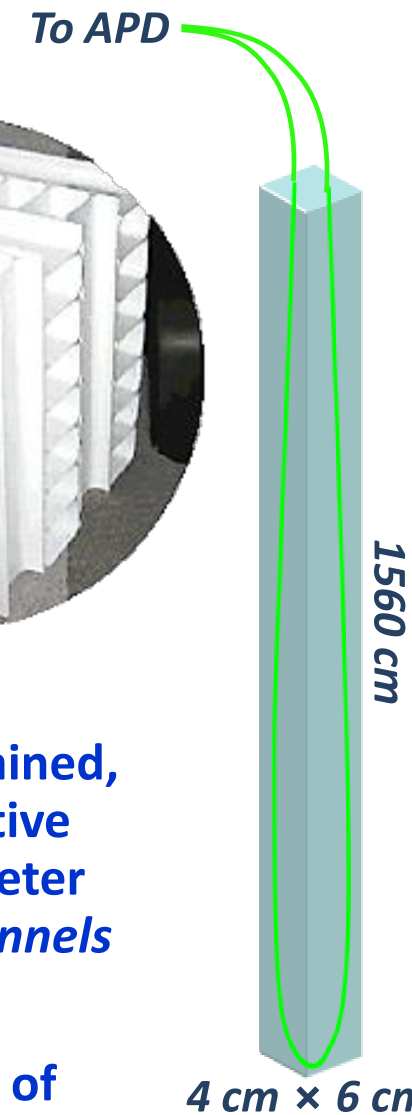


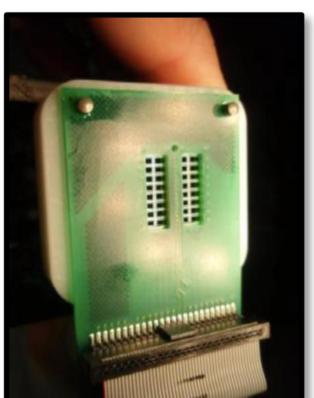
NOνA detectors



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 →

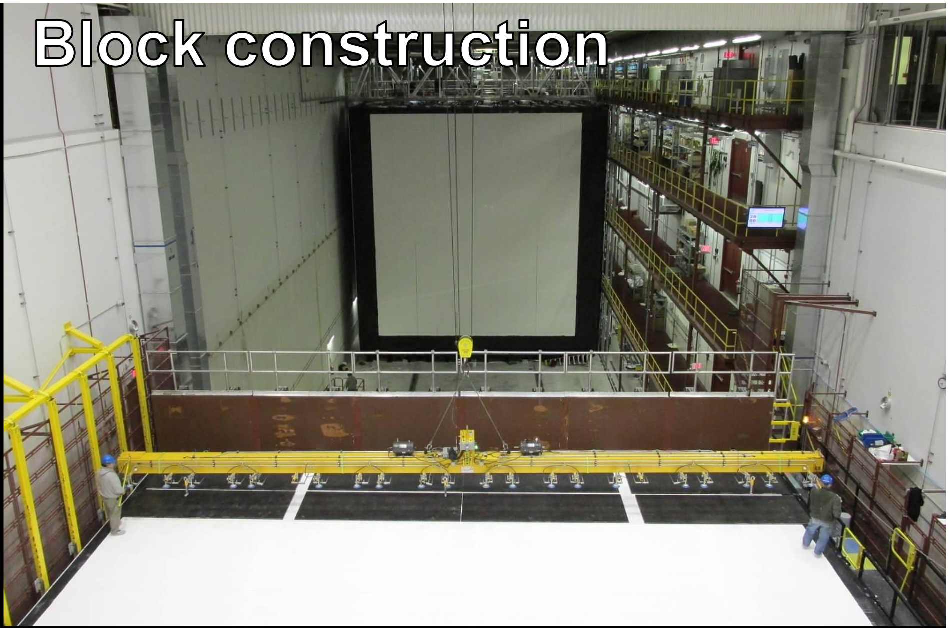
Far detector:

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*

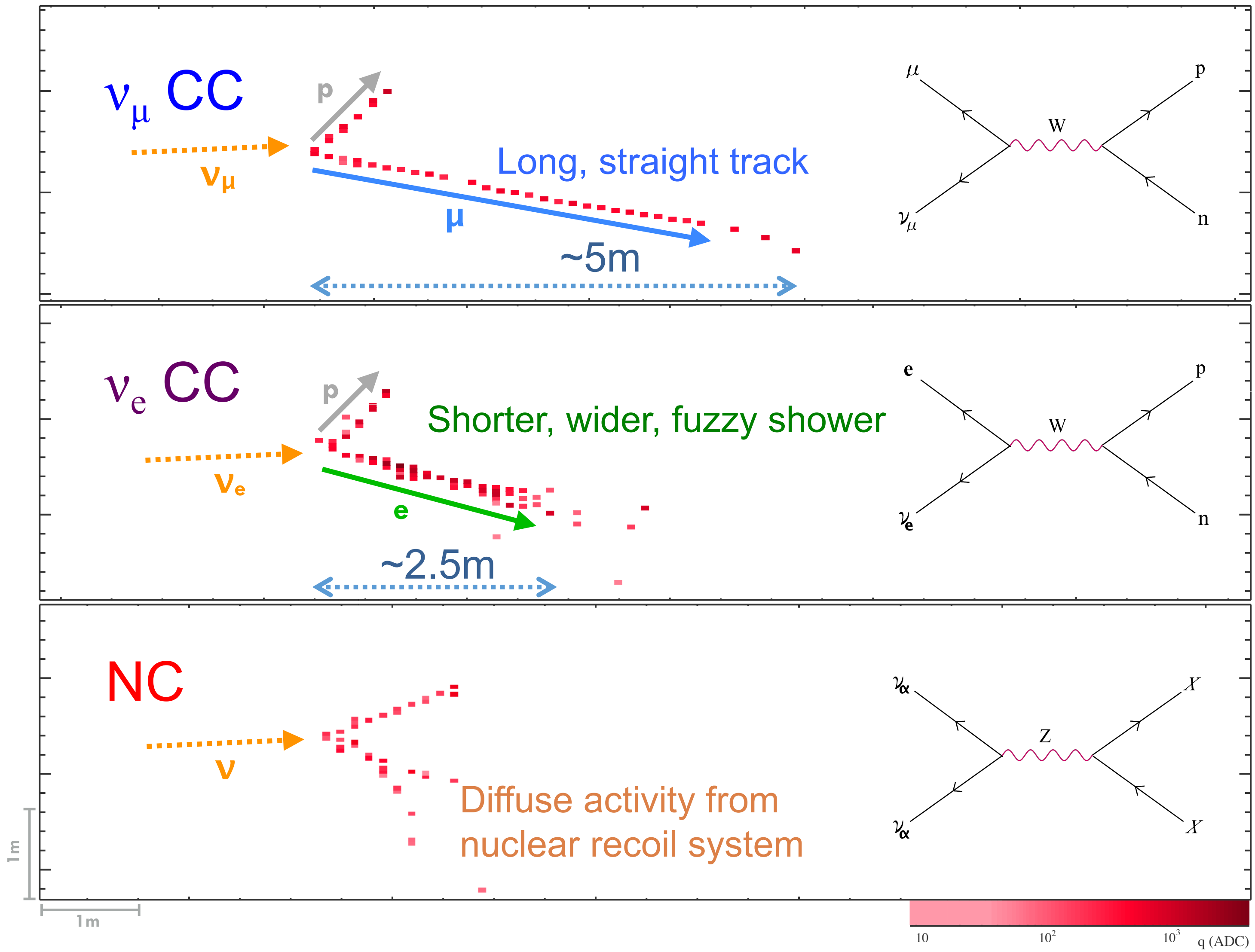

Far Detector site


Block construction


Outfitted Far Detector


Near Detector

Event Types



ν_μ CC
p
ν_μ
Long, straight track
μ
~5m
μ
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)

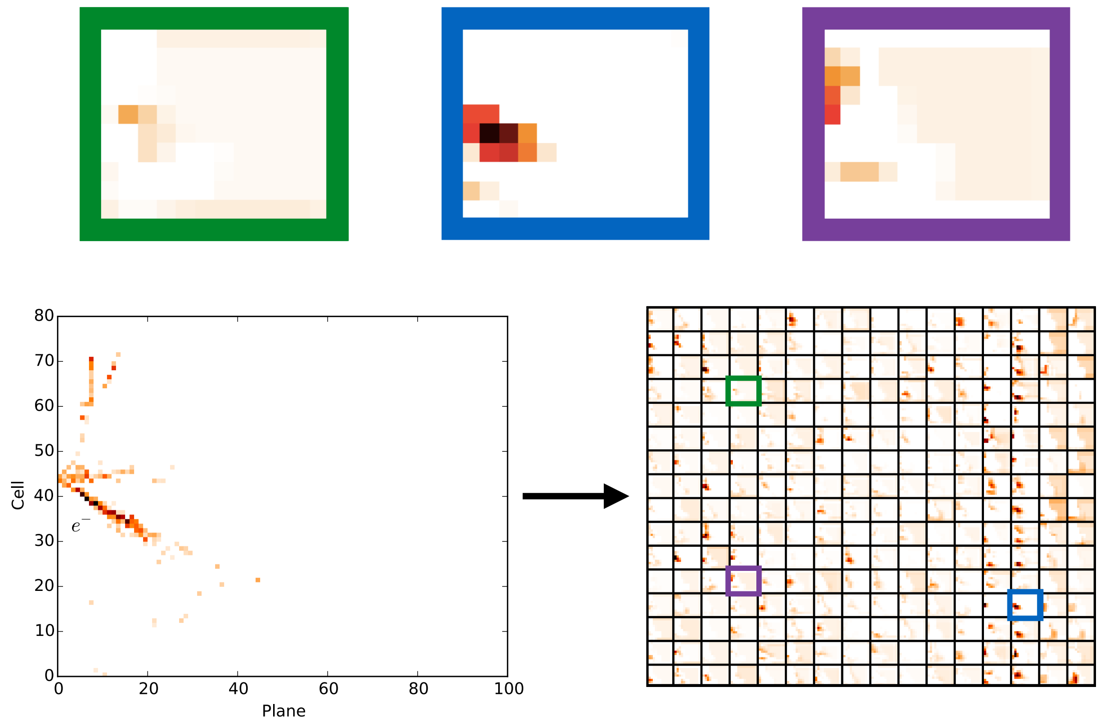
What's new?

- **More data:** 50%
- **Improved analysis**
  – continued use of deep learning tools: now also for disappearance measurements.
  – Bin in energy resolution
- **Retuned cross section model & systematics**
  – Includes empirical multi-nucleon model, QE RPA
- **Detector simulation improvements**
  – Substantially reduces associated systematic uncertainty
- **Data driven flux estimates:** PPFX

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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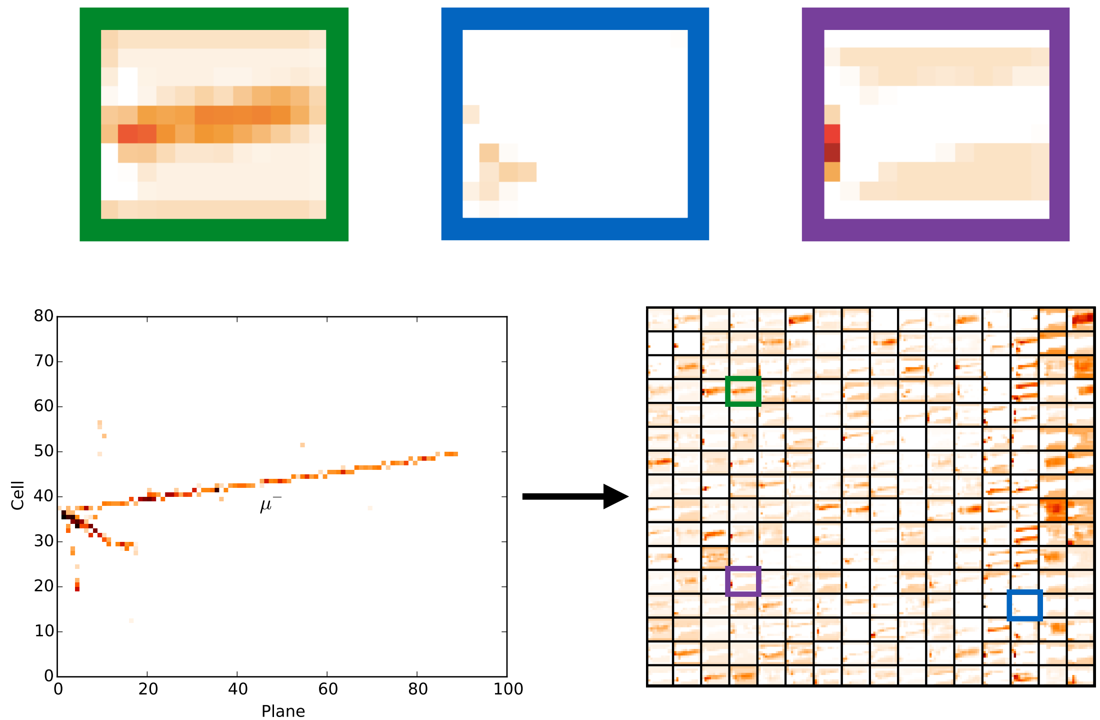
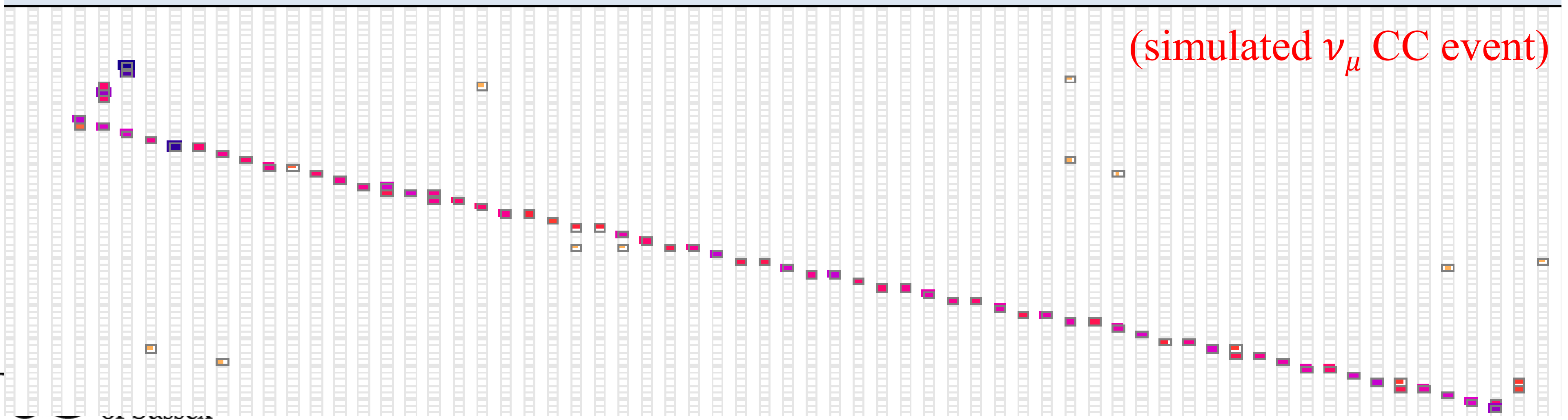


Improvement in ν_e sensitivity from CVN equivalent to 30% more exposure

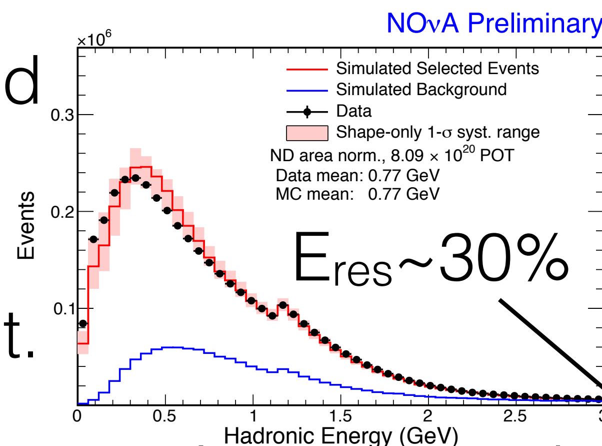
ν_μ disappearance

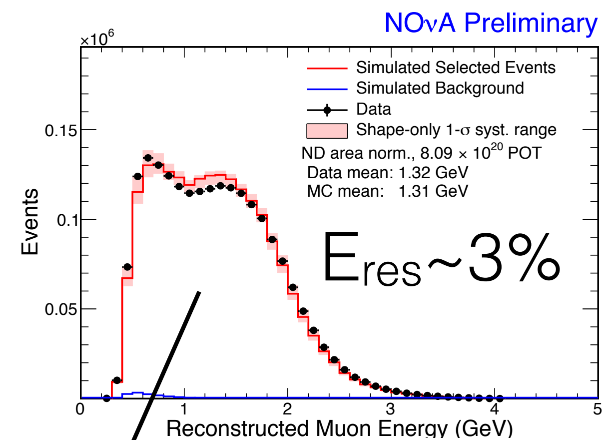
- Identify **contained ν_μ CC events** in each detector
- Measure their **energies**
- Extract oscillation information from differences between the **Far and Near energy spectra**



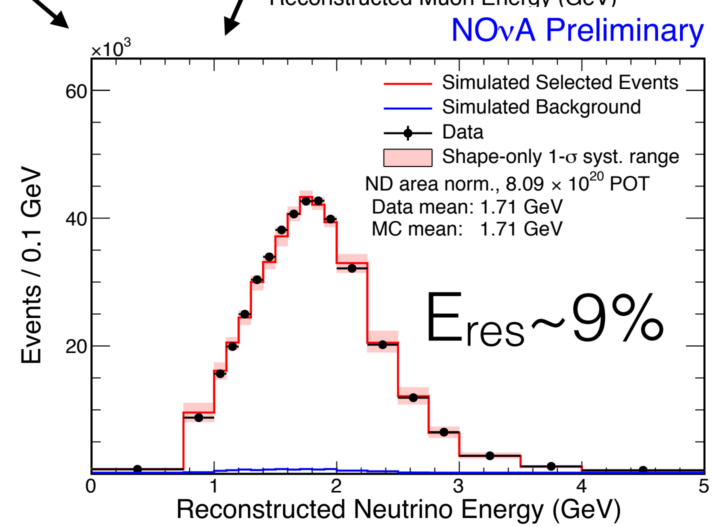
ν_μ Near Detector Data

- Final reconstructed energy combines E_{had} and E_μ via a piecewise linear fit.





- Observed ND spectrum is converted to true energy using MC expectation, extrapolated to FD using a Far/Near flux ratio, and then converted to an expected reconstructed energy spectra.

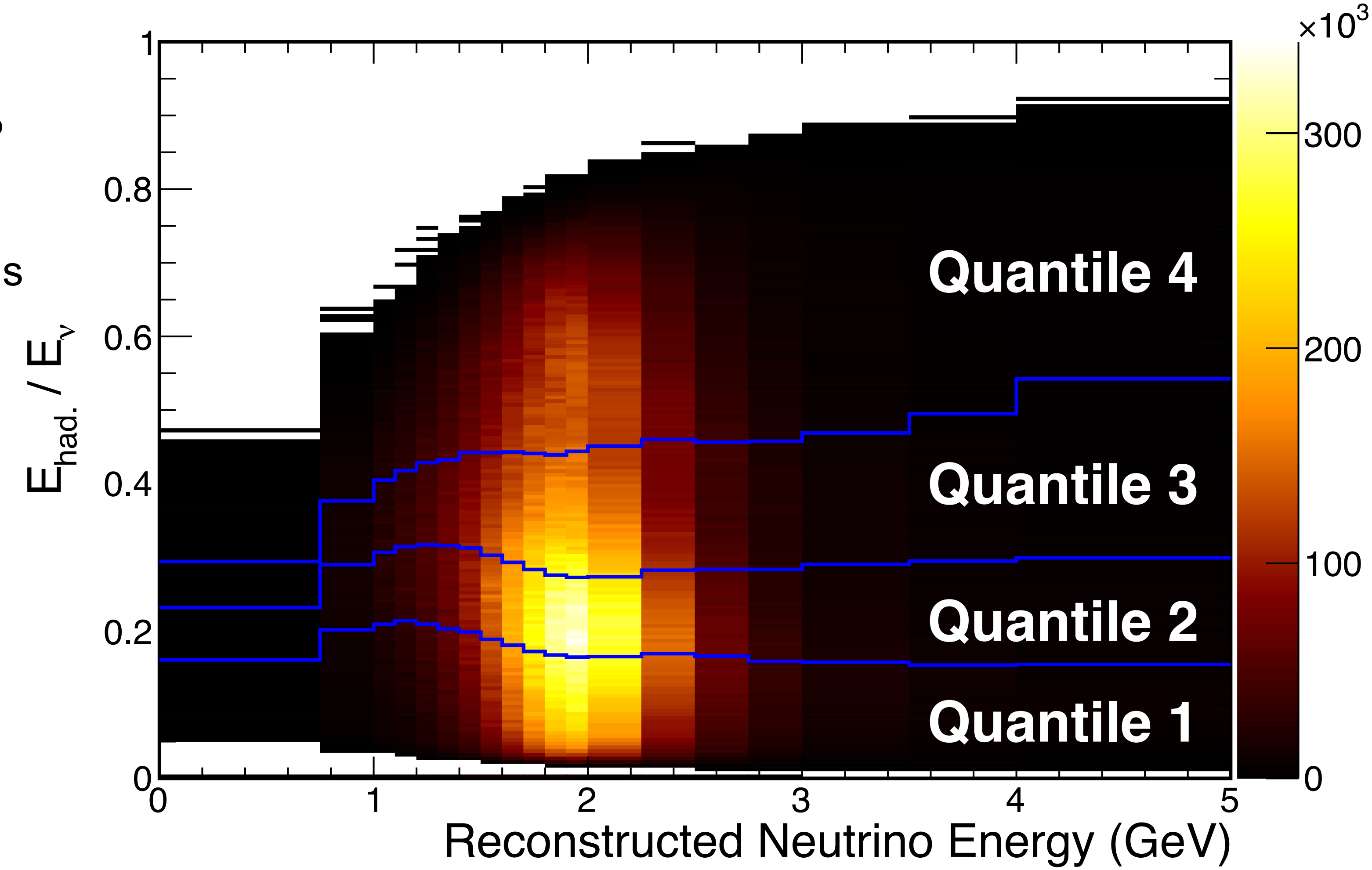


[A. Radovic, JTEP seminar 12th January 2018]

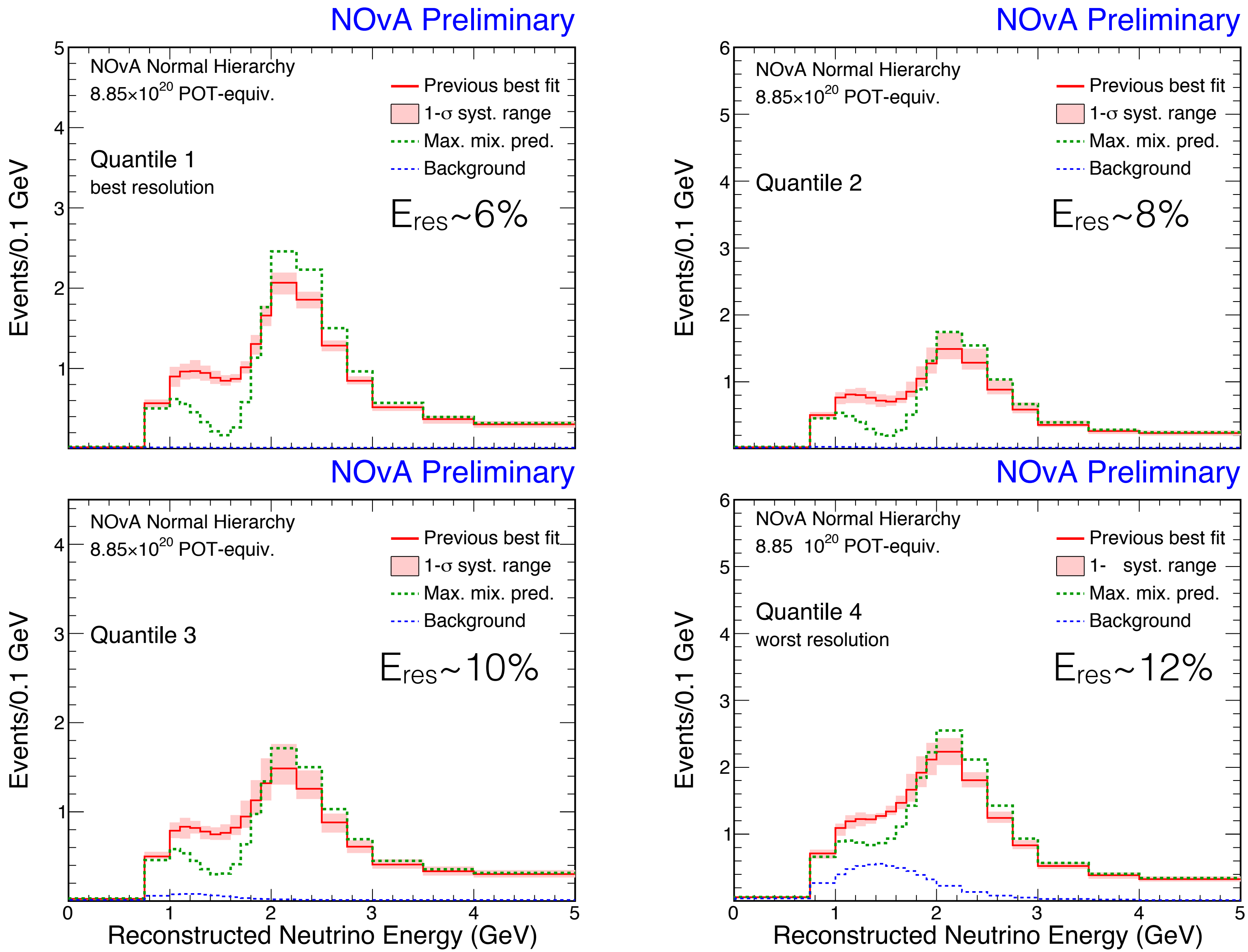
Resolution Bins

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

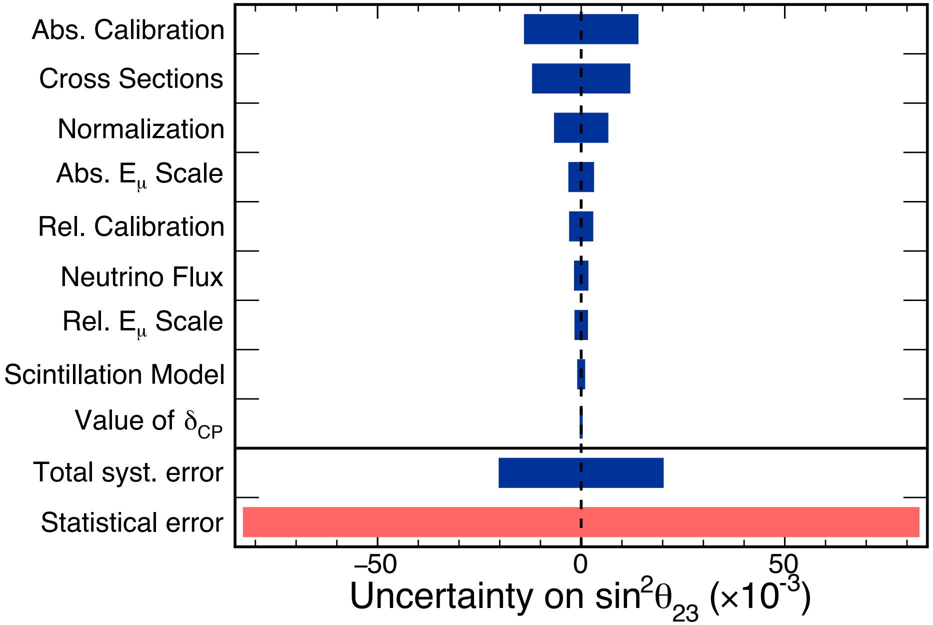
Resolution varies from ~6% to ~12% from the best to worst resolution bins

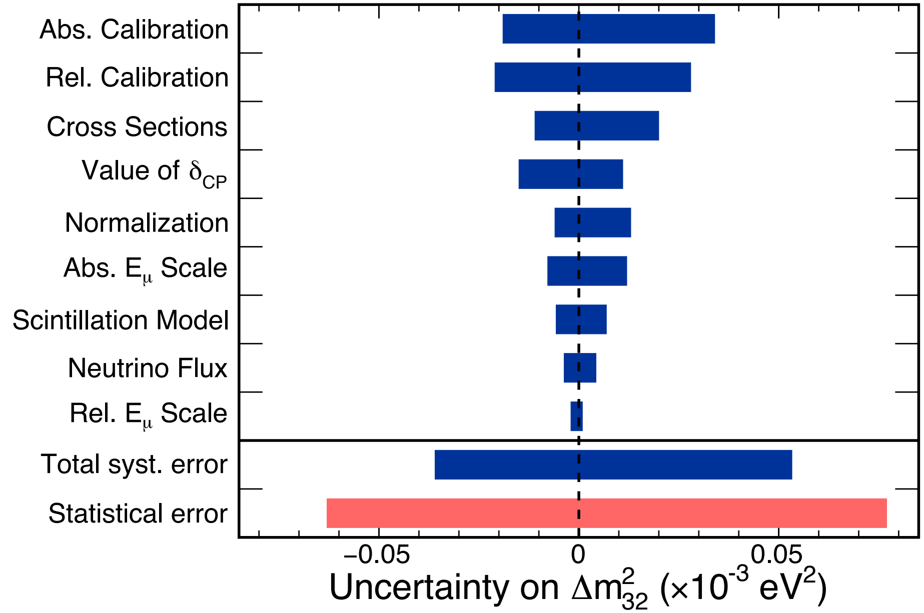


Resolution Bins



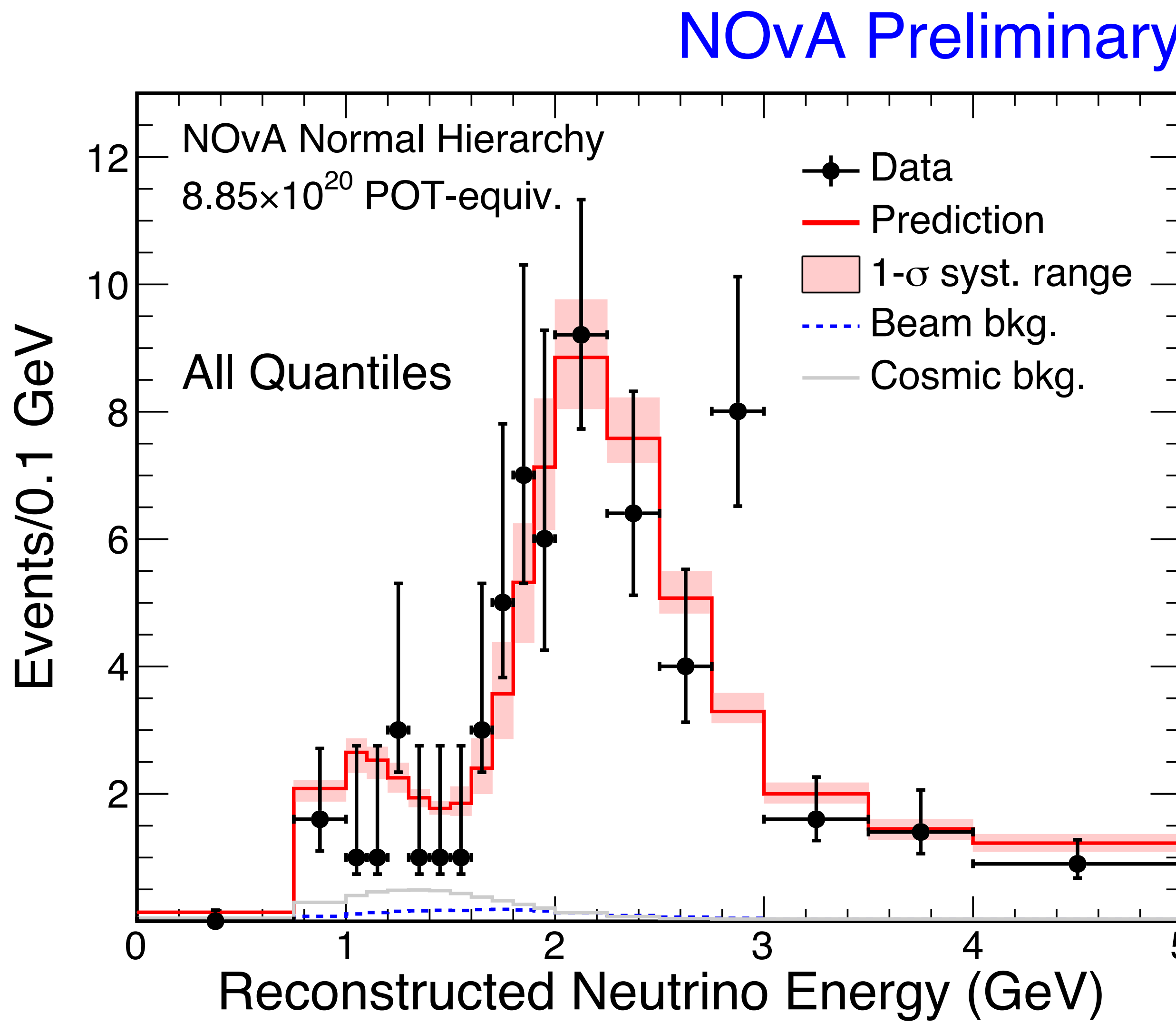
υ_μ Systematics



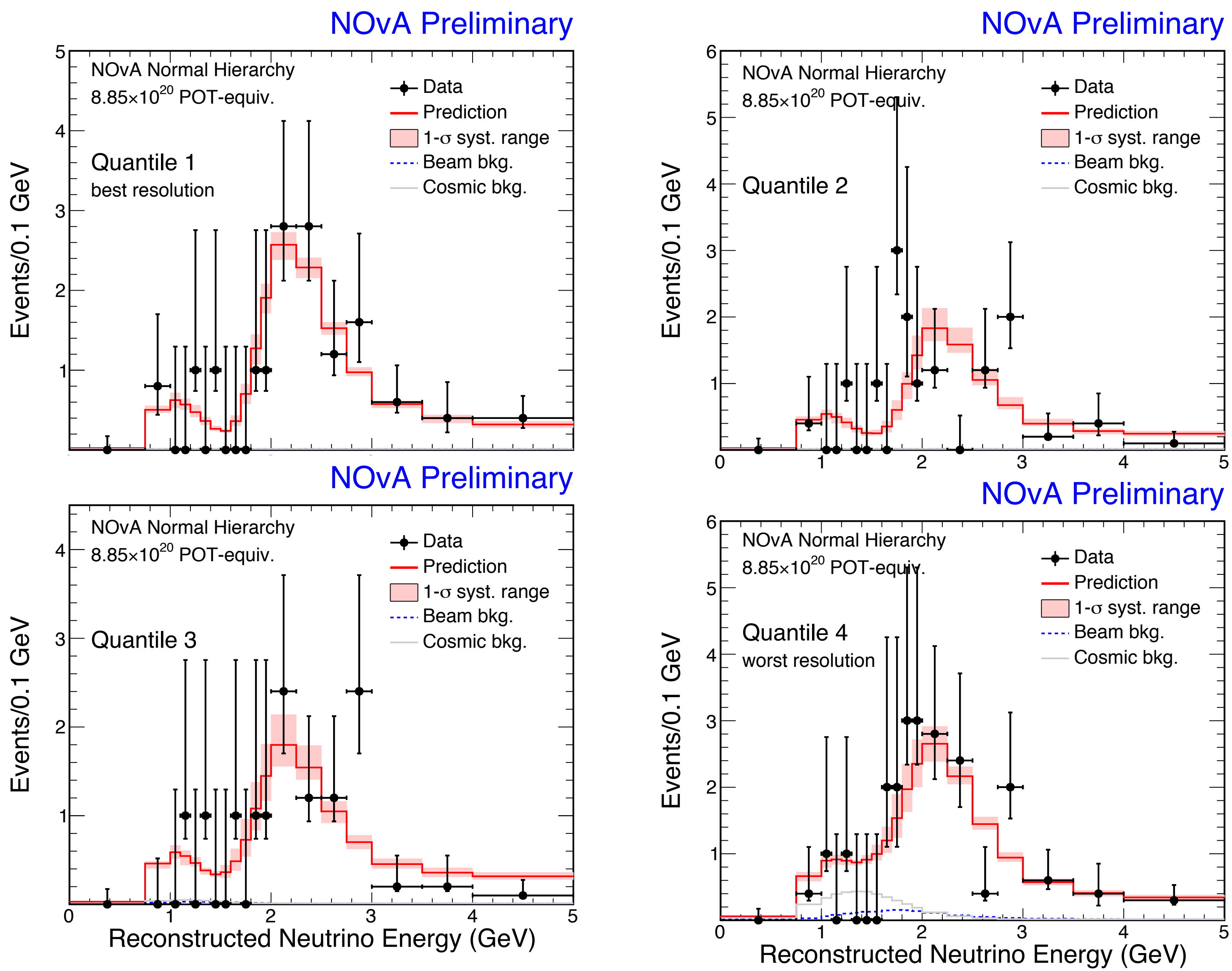


ν_μ Far Detector Data

- **126 events** observed in FD
  - **763±30 with no oscillation**
  - 129 at best oscillation fit
  - 3.5 beam BG + 5.8 cosmic

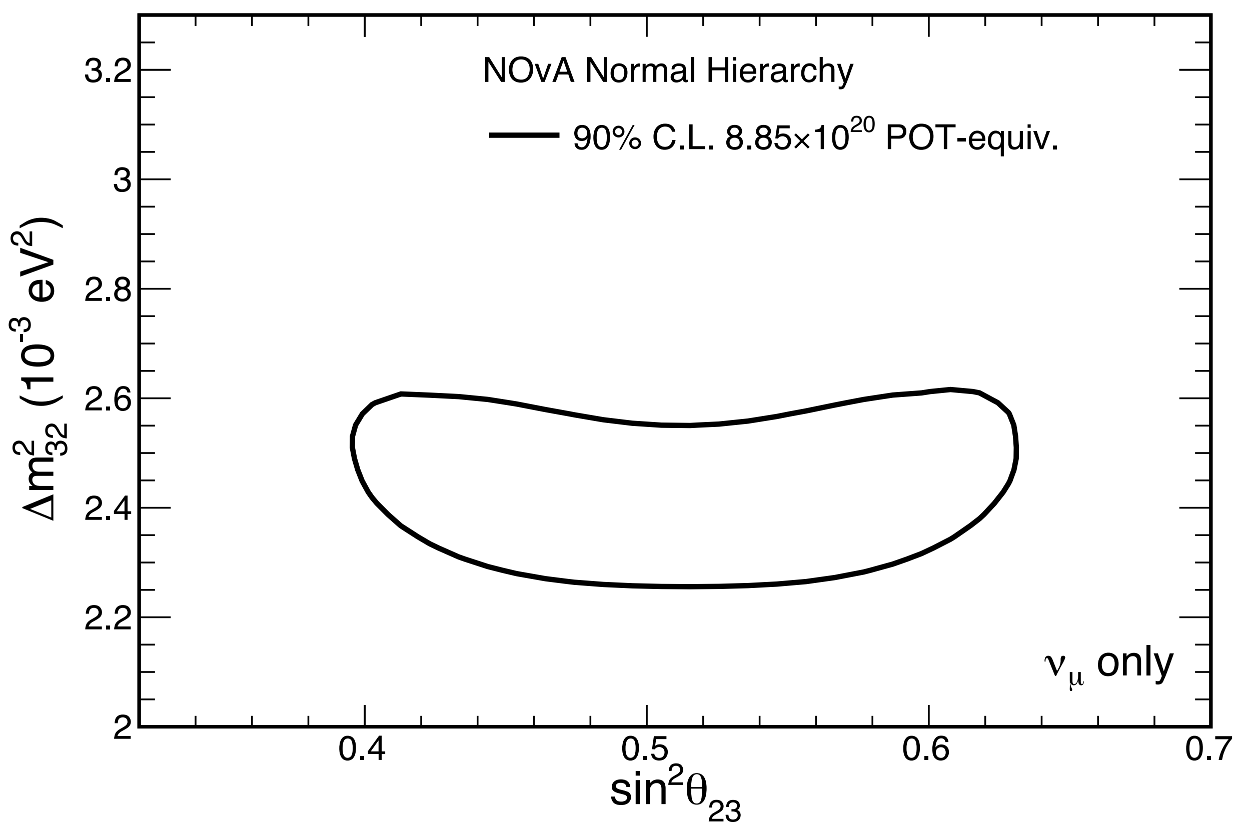


Best --> Worst Energy Resolution



υ_μ Result

- Full joint fit with appearance analysis
- Feldman-Cousins corrections in 2D and 1D limits
- All systematics & pull terms shared
- Constrain θ_{13} using PDG world average: $\sin^2 2\theta_{13}$=0.082



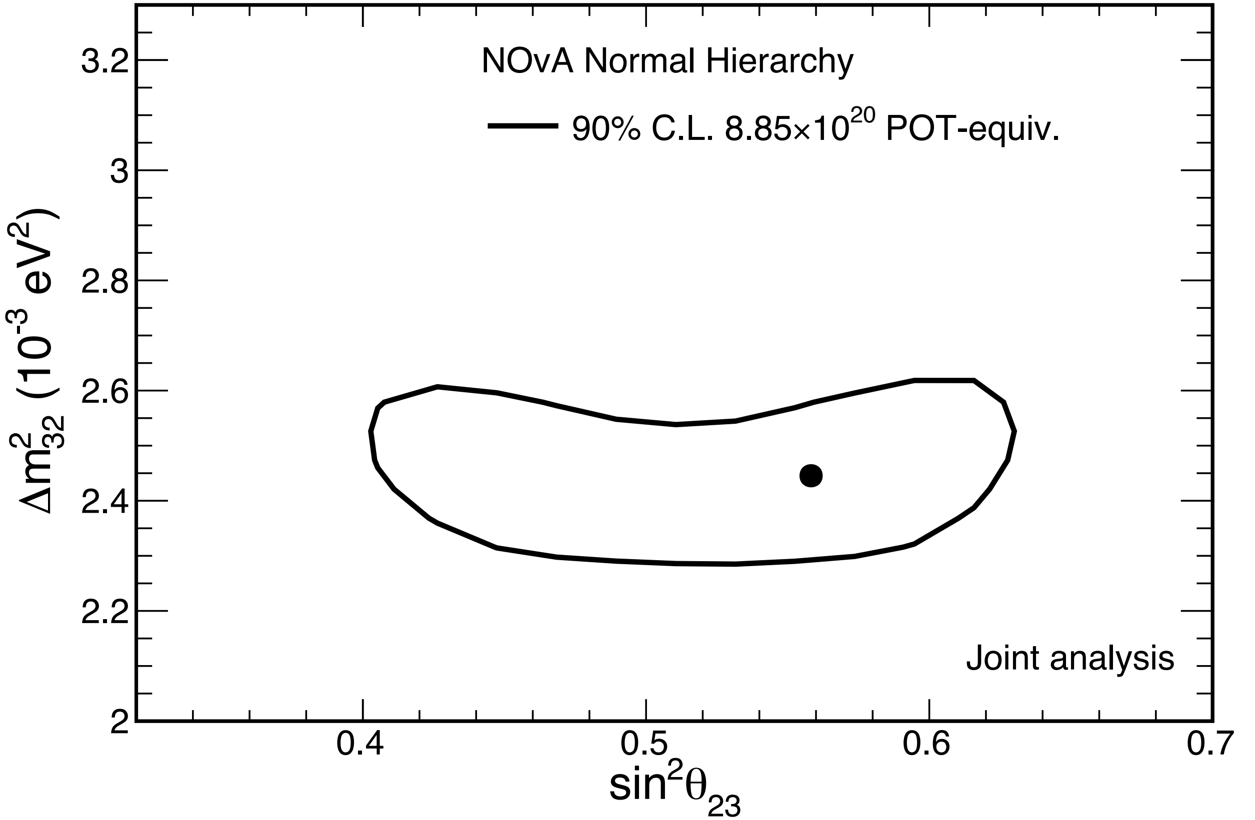
υ_μ Result

Best fit:

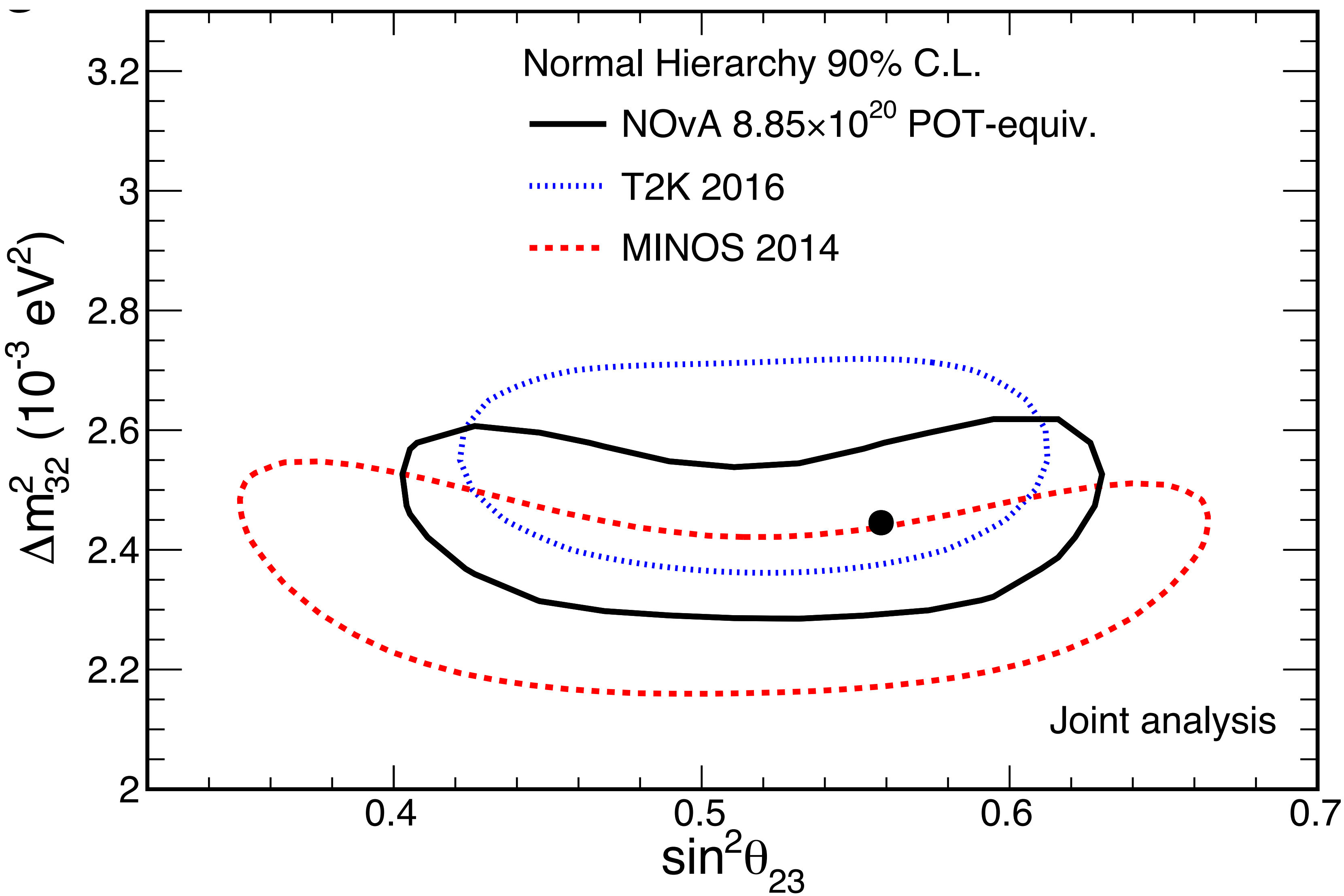
Δm^2_{32} =
$2.444^{+0.079}_{-0.077}$ x 10^{-3} eV^2

UO preferred at 0.2σ

$\sin^2\theta_{23}$ =
UO: $0.558^{+0.041}_{-0.033}$
LO: $0.475^{+0.036}_{-0.044}$



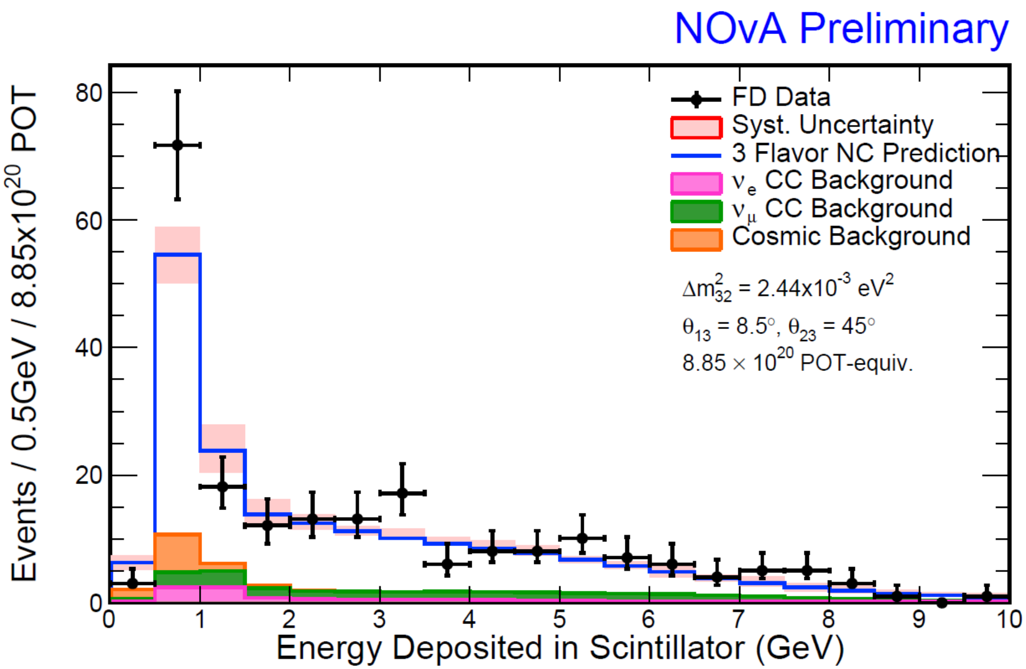
Comparison to other experiments



Neutral Current & ν_e Results

Neutral Current Result

NC Far Detector Data & Results



Observed **214** NC candidates

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

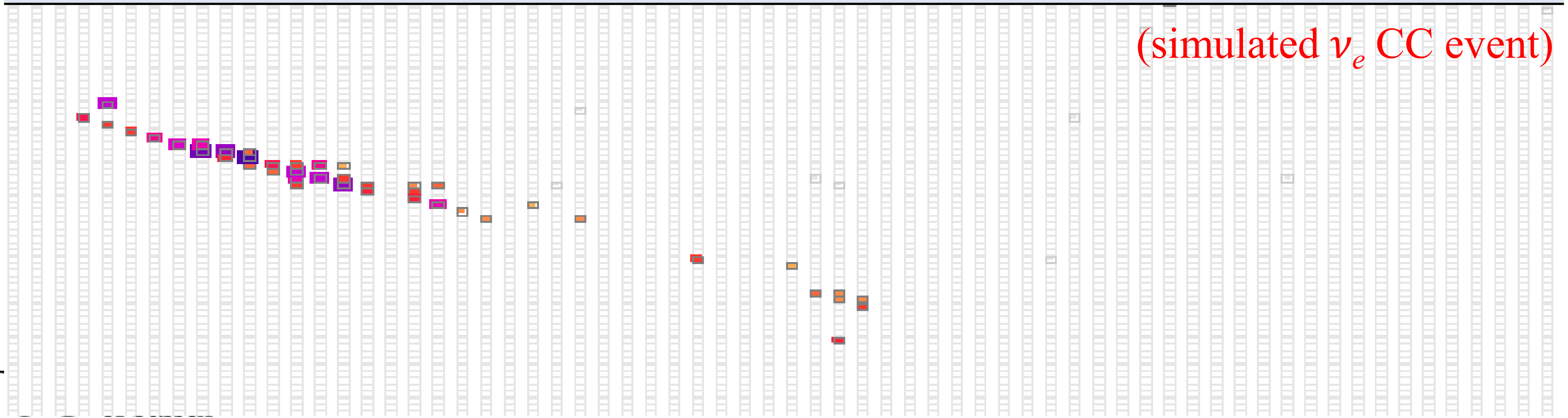
No depletion of NC events observed

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

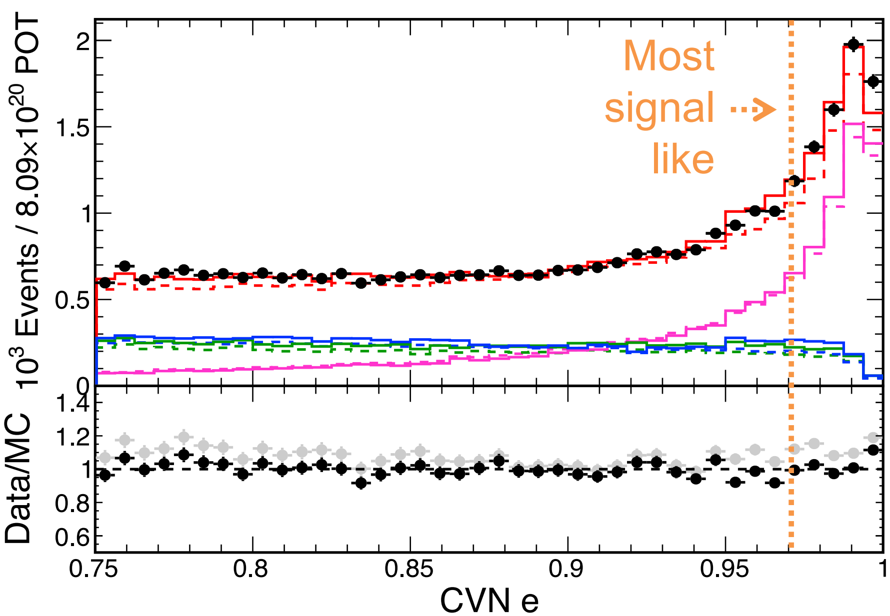
- Identify **contained ν_e CC candidates** in each detector
- Use Near Det. candidates to **predict beam backgrounds** in the Far Detector
- Interpret any **Far Det. excess** over predicted backgrounds as ν_e appearance

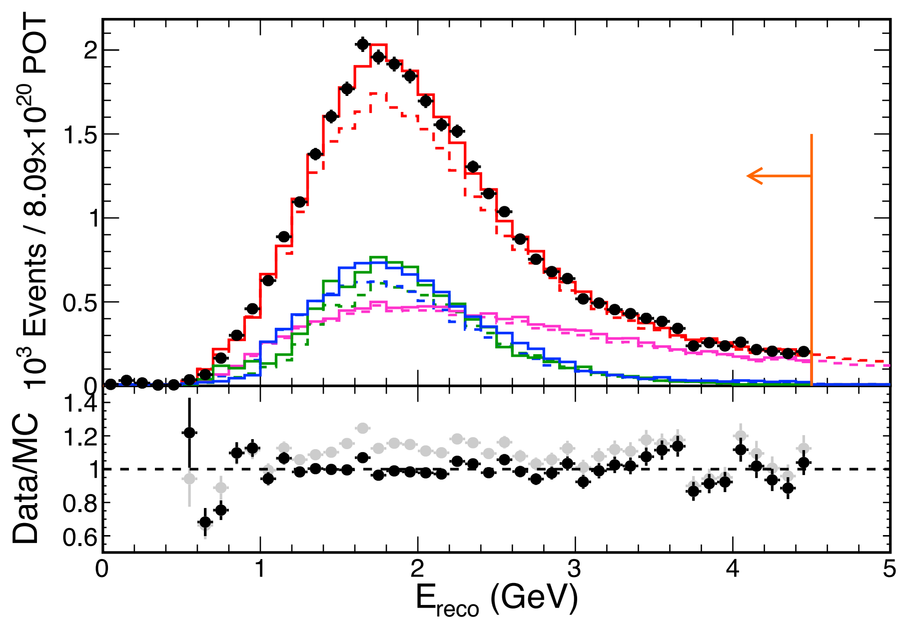


ν_e Near Detector Data

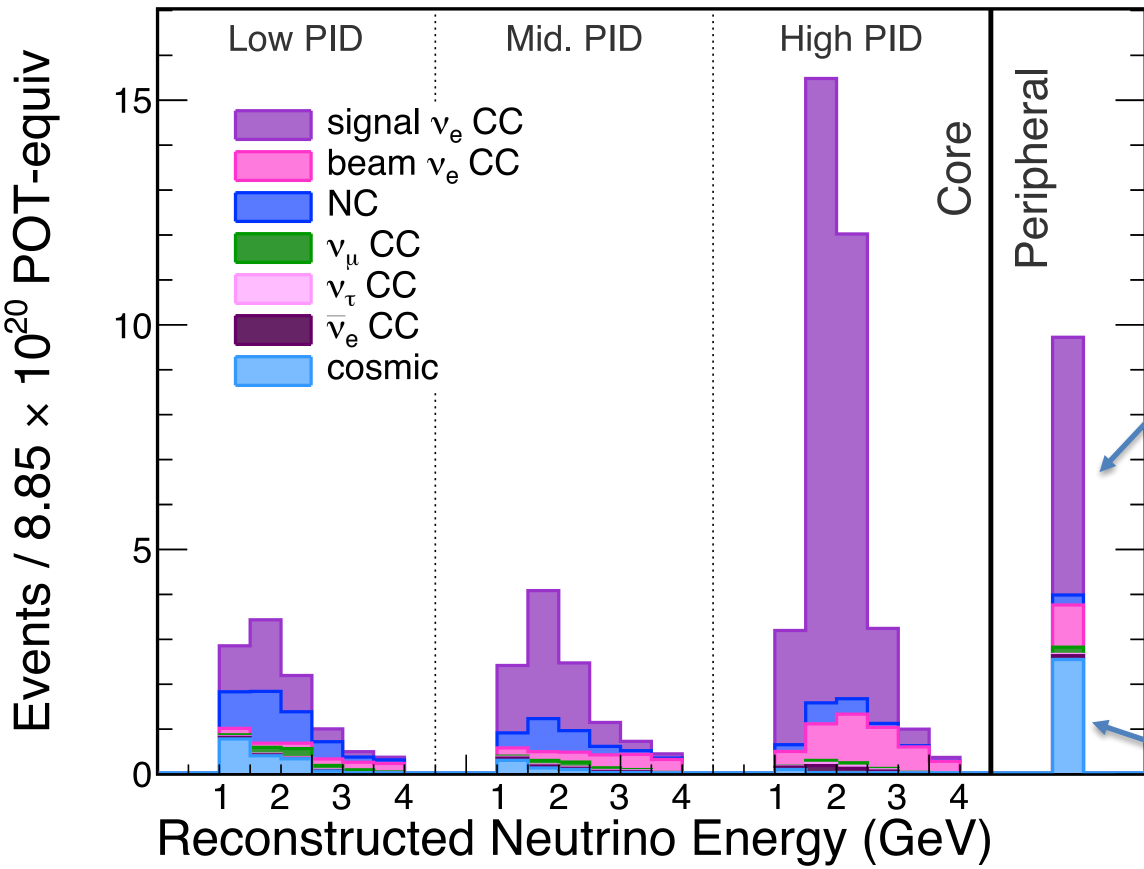
- Use ND data to predict background in FD
  - NC, ν_μ CC, beam ν_e each propagate differently
  - constrain beam ν_e using selected ν_μ CC spectrum
  - constrain ν_μ CC using Michel Electron distribution

beam ν_e up by 1%
NC up by 20%
ν_μ CC up by 10%





FD Predicted Events



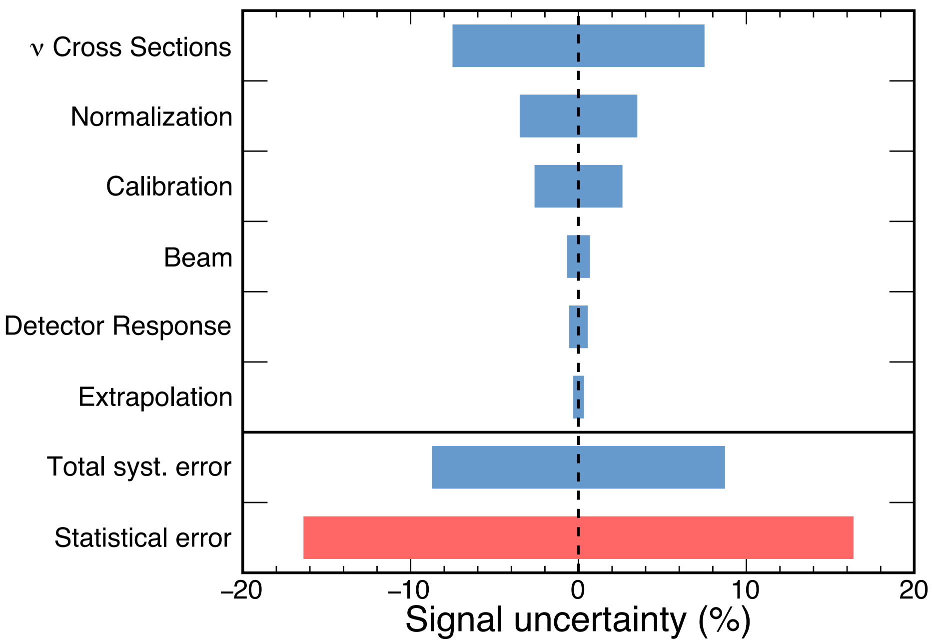
New "peripheral" sample

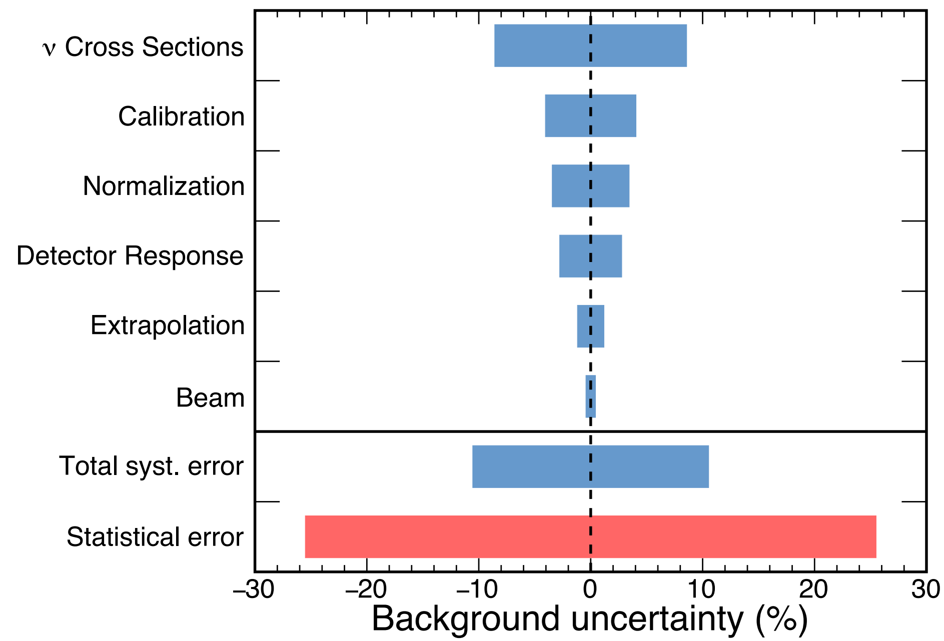
Events that fail standard pre-selection or cosmic cuts but are very electron-like

New BDT to reject cosmics in the peripheral sample (still the largest background but measured in beam-off)

Systematics

- As in ν_μ systematics were assessed by generating sets of shifted MC.
- Those shifted datasets were used instead of our nominal MC to assess the impact on our final result.



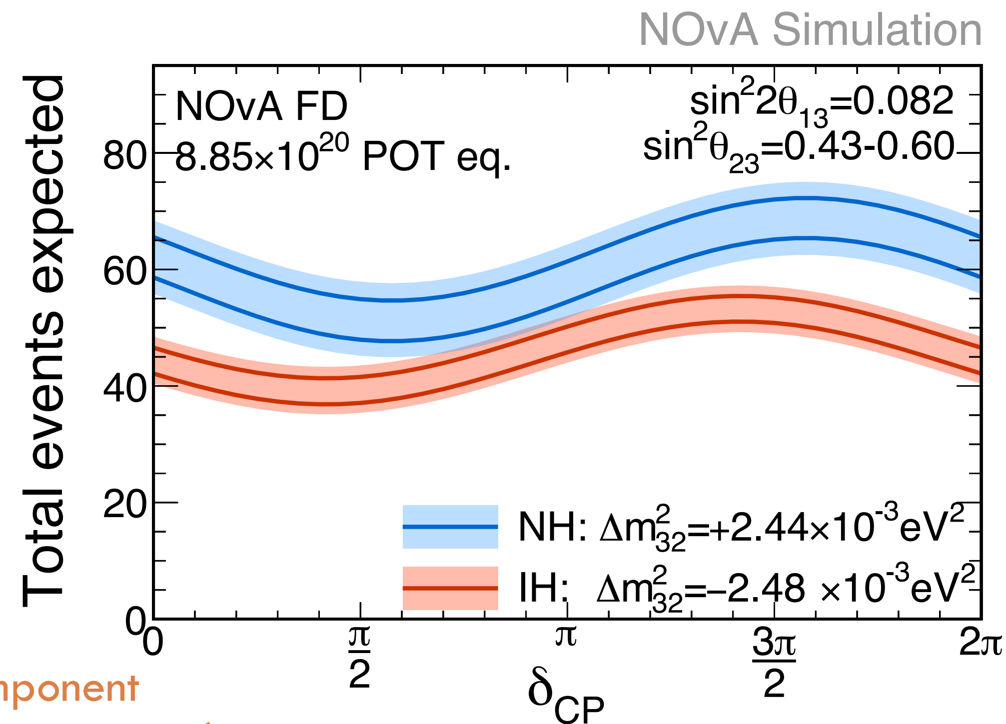


Predicted events

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

Signal events
($\pm$9% systematic uncertainty):

NH, $3\pi/2$,	IH, $\pi/2$,
48	20

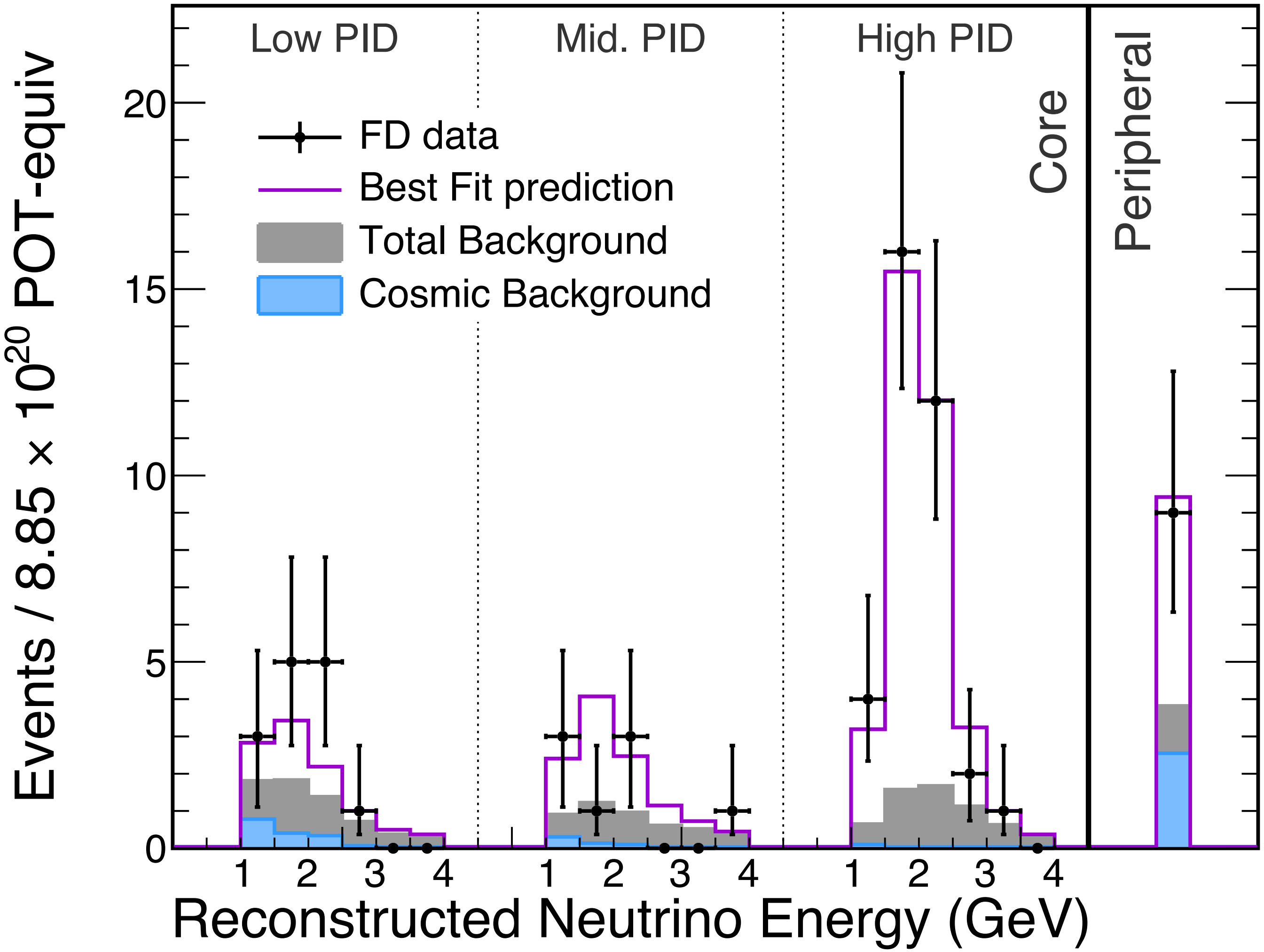


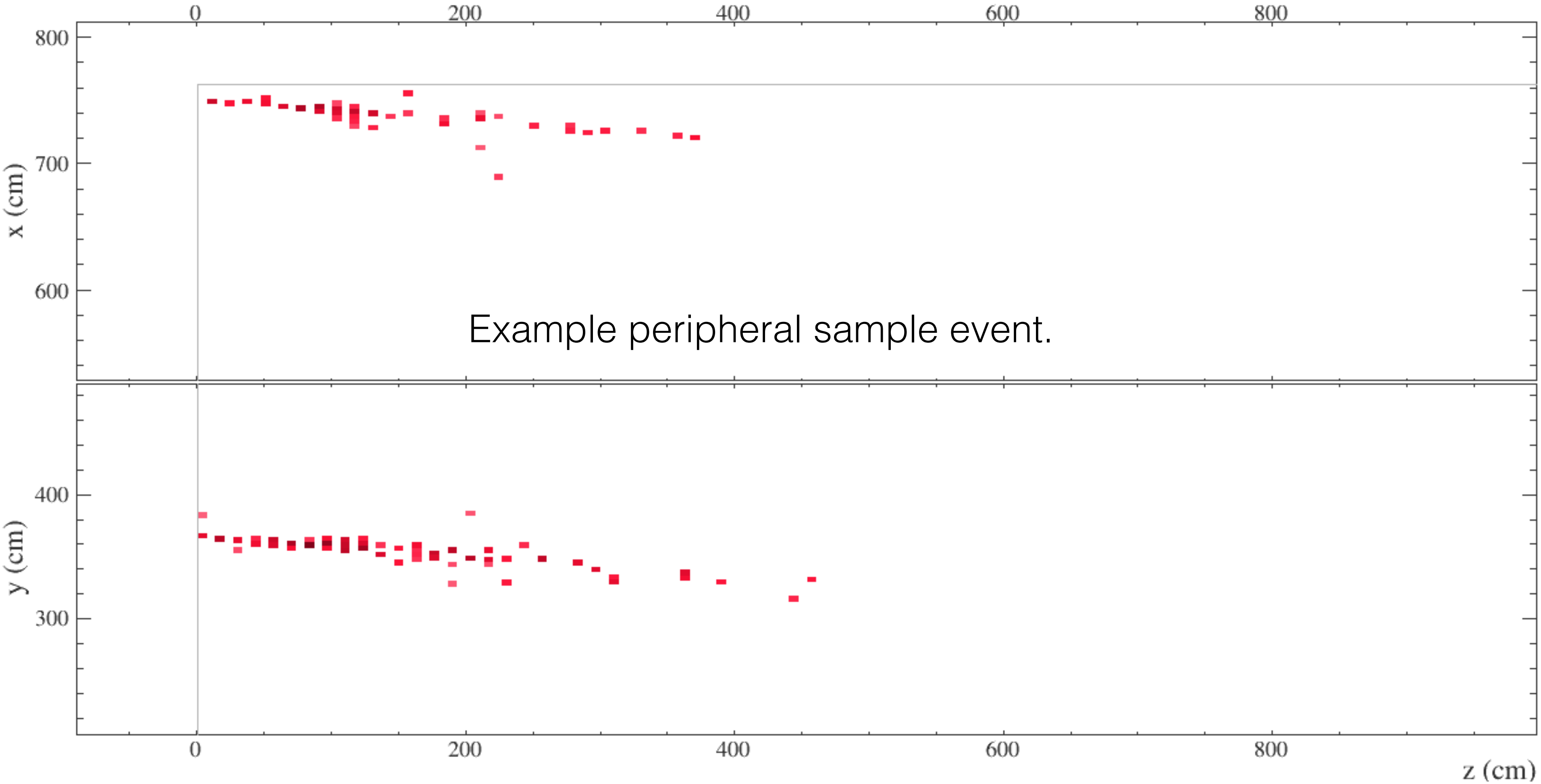
Background by component
($\pm$10% systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
20.5	6.6	7.1	1.1	0.3	4.9

ν_e Far Detector Data

- Observe 66 events in FD
  - background 20.5±2.5



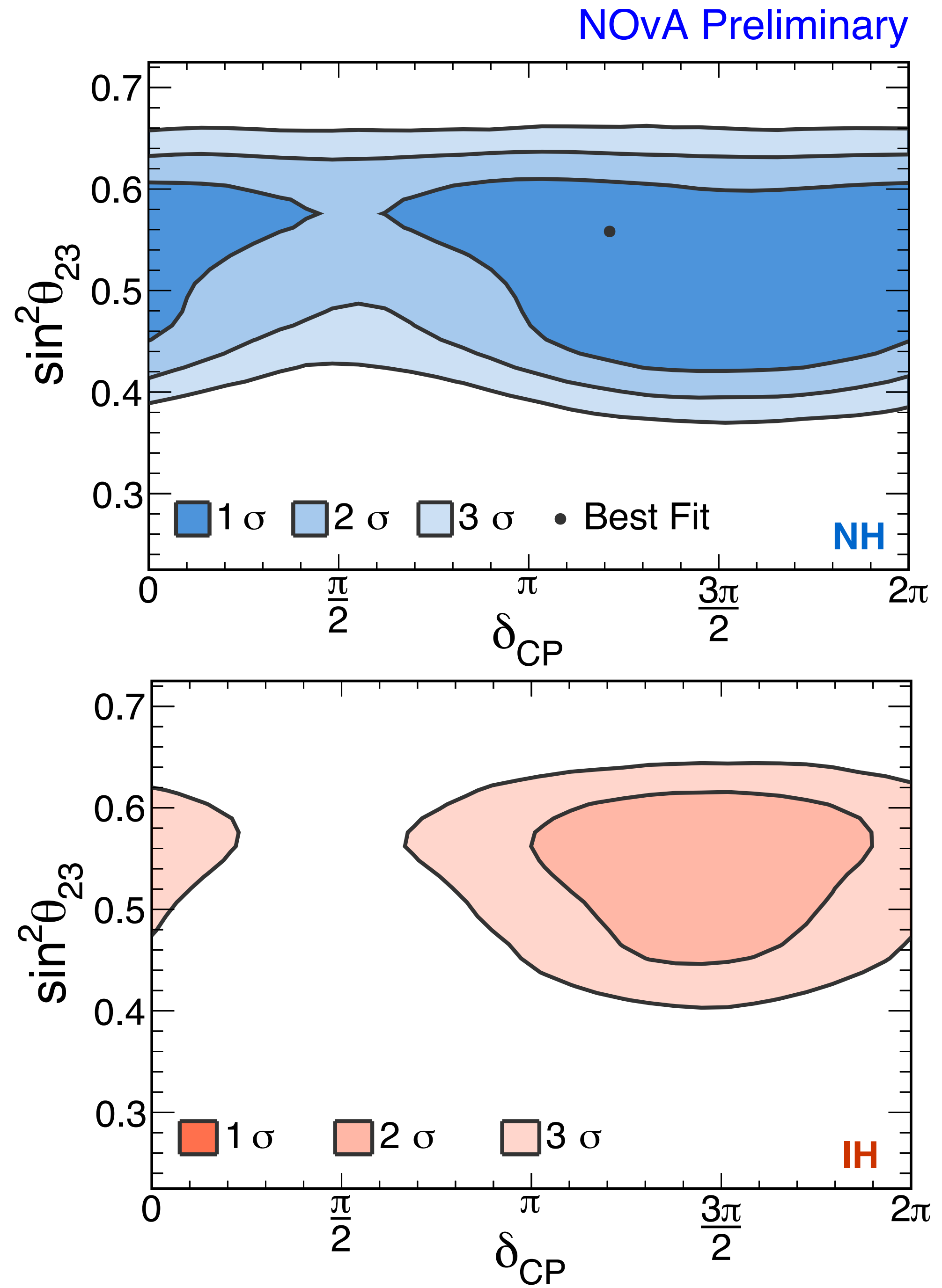


0
200
400
600
800
800
700
600
x (cm)
Example peripheral sample event.
400
300
y (cm)
0
200
400
600
800
z (cm)

$\nu_e + \nu_\mu$ Results

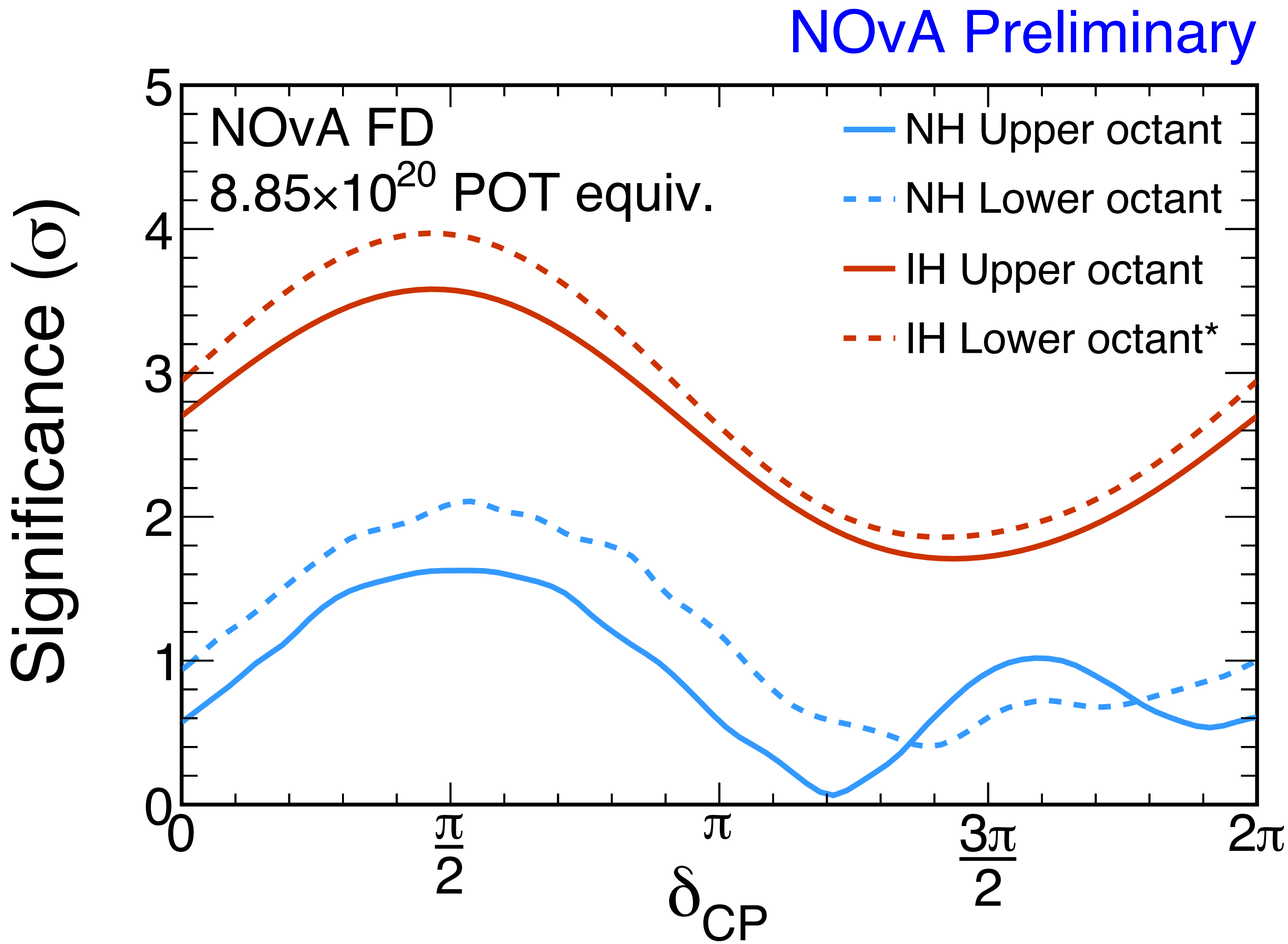
- Full joint fit of $\nu_e + \nu_\mu$
- Feldman-Cousins corrections in 2D and 1D limits
- All systematics & pull terms shared
- Constrain θ_{13} using PDG world average: $\sin^2 2\theta_{13}$=0.082

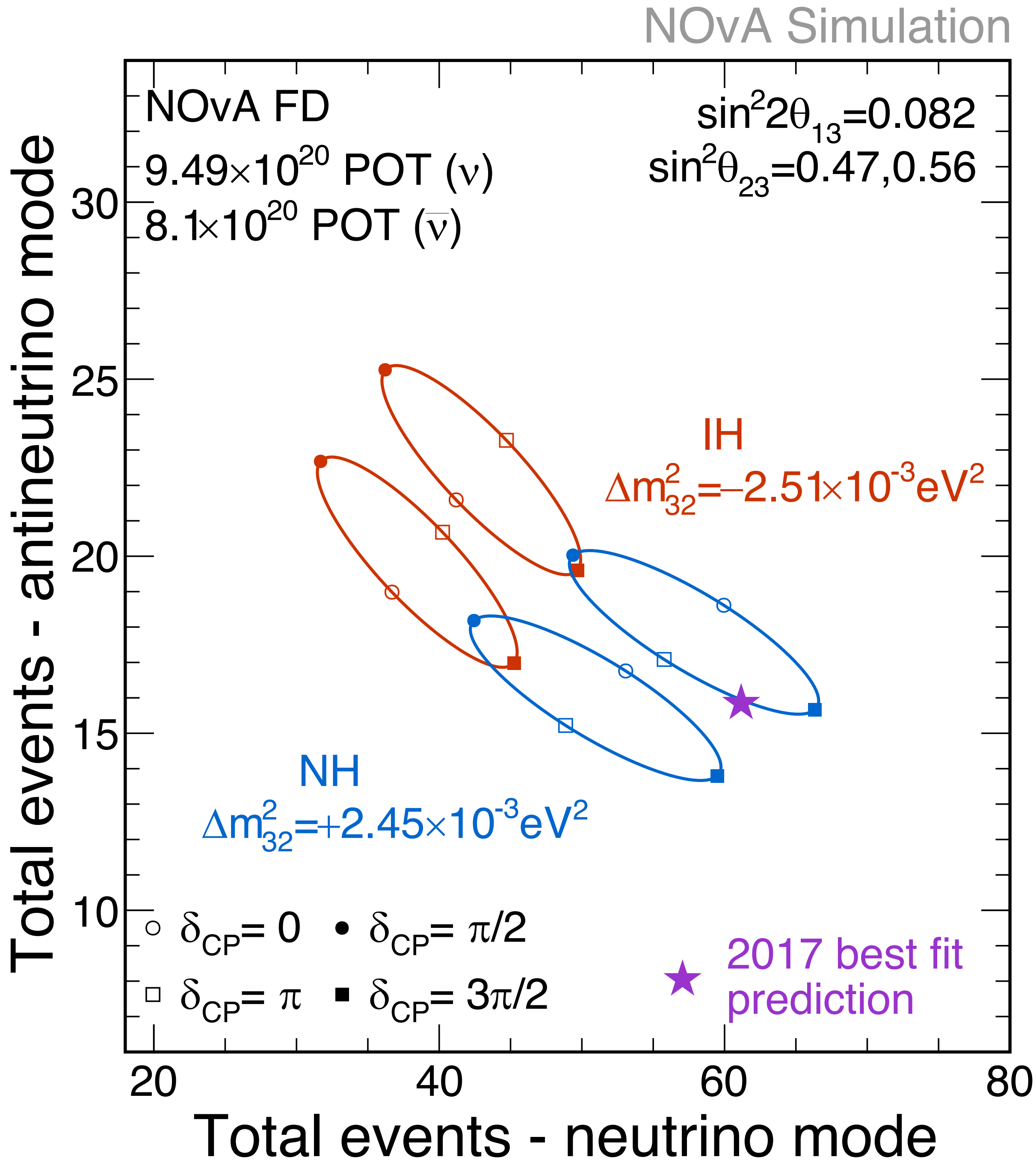
- Inverted hierarchy at $\delta_{CP}=\pi/2$ disfavoured at >3σ



$\nu_e + \nu_\mu$ Results

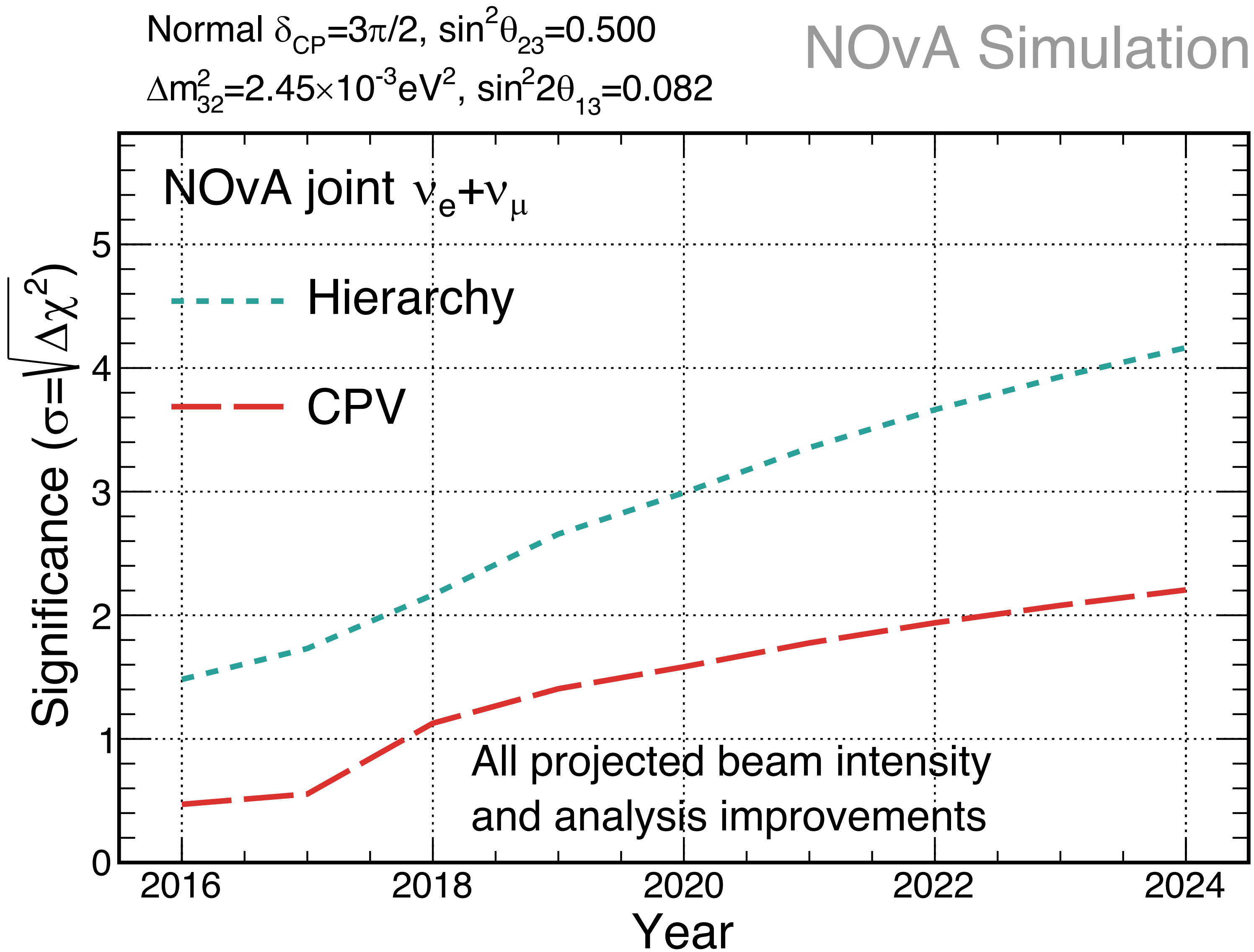
Approaching inverted hierarchy rejection at 2σ





University of Sussex

Future Sensitivity



NOvA Summary

With 8.85×10^{20} POT, NOvA finds:

- Muon neutrinos disappear
  - Competitive measurement of Δm^2_{32}
  - Best fit is near maximal
- Neutral current event rate shows no evidence of steriles
  - With more data, expect strong limits on θ_{34}
- Electron neutrinos appear
  - At the upper end of expectations
  - Approaching 2 σ inverted hierarchy rejection
  - IH at $\delta_{CP} = \pi/2$ region excluded at >3 σ
- Antineutrino run well underway
  - Results expected this summer

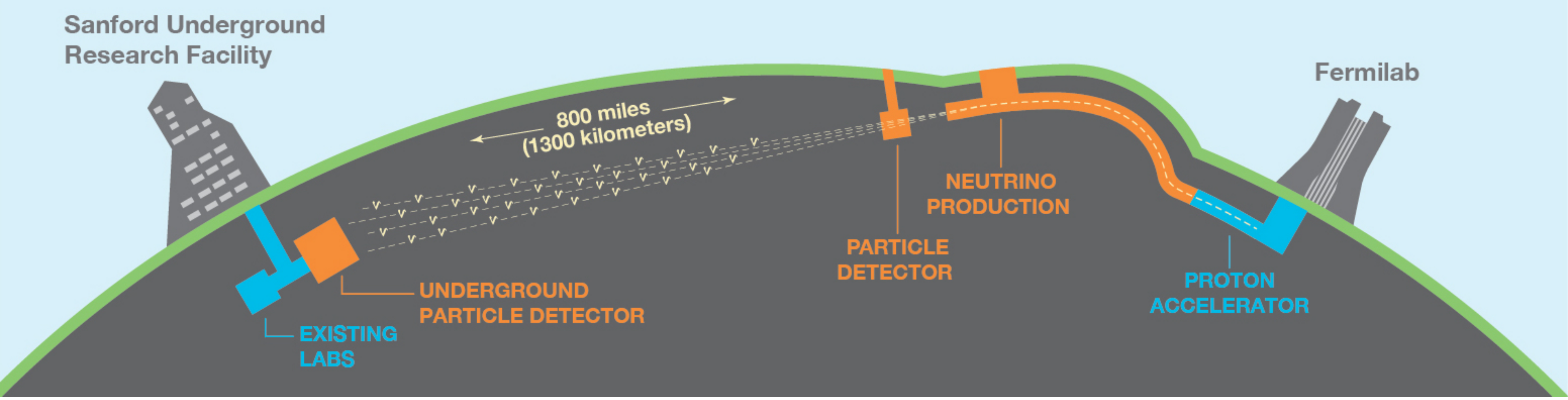
DUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

DUNE Overview

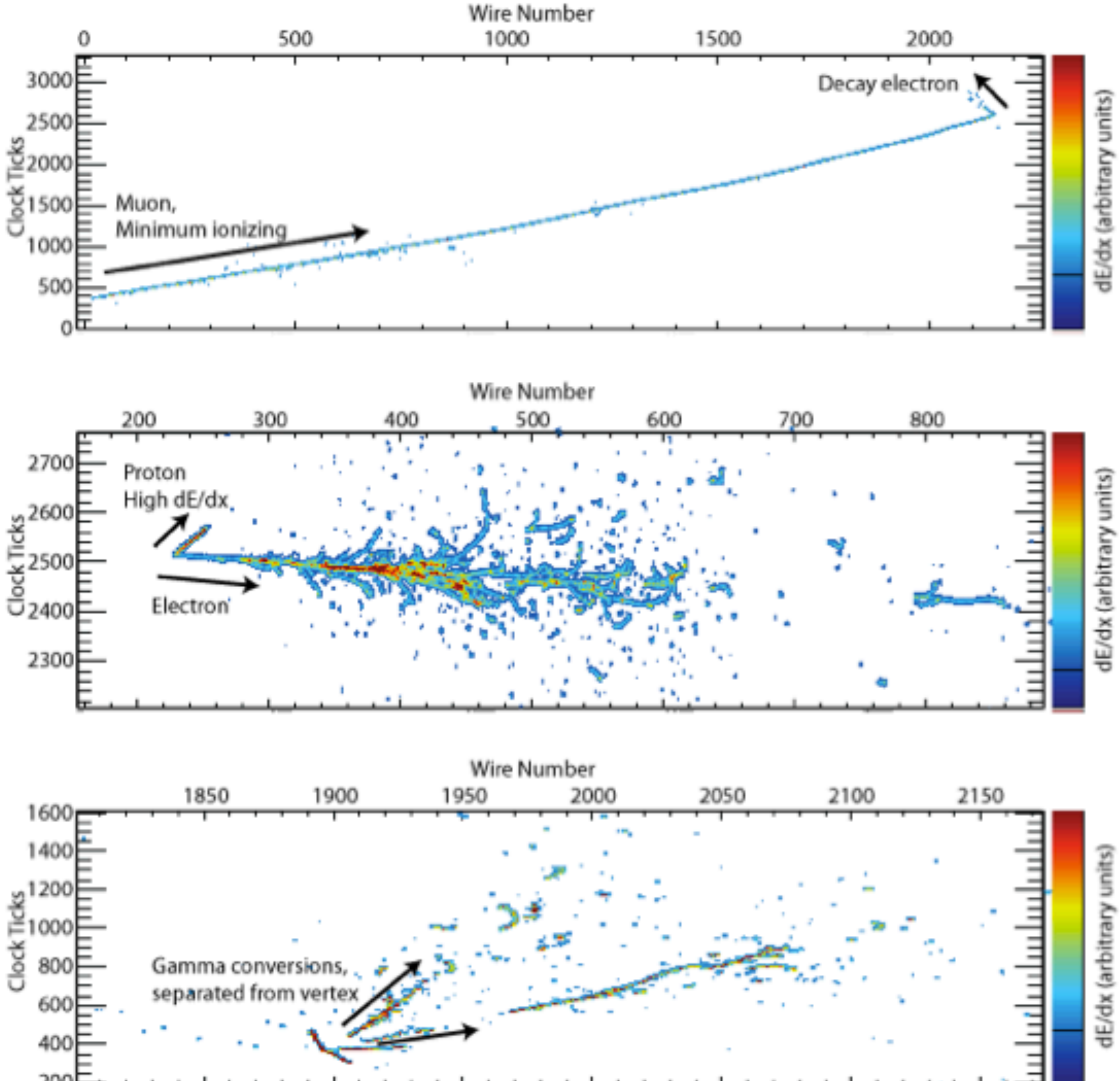
- Approved expt., under construction ($50M in FY17)
- UK commitment of £65M for detectors and beam
- Due to take beam data in 2026 with
  - new MW-scale neutrino beamline (LBNF)
  - 4x10-kilotonne (fiducial) liquid argon far detector
  - high-resolution, high-rate near detector

– CERN providing cryostat for first 1x10kt

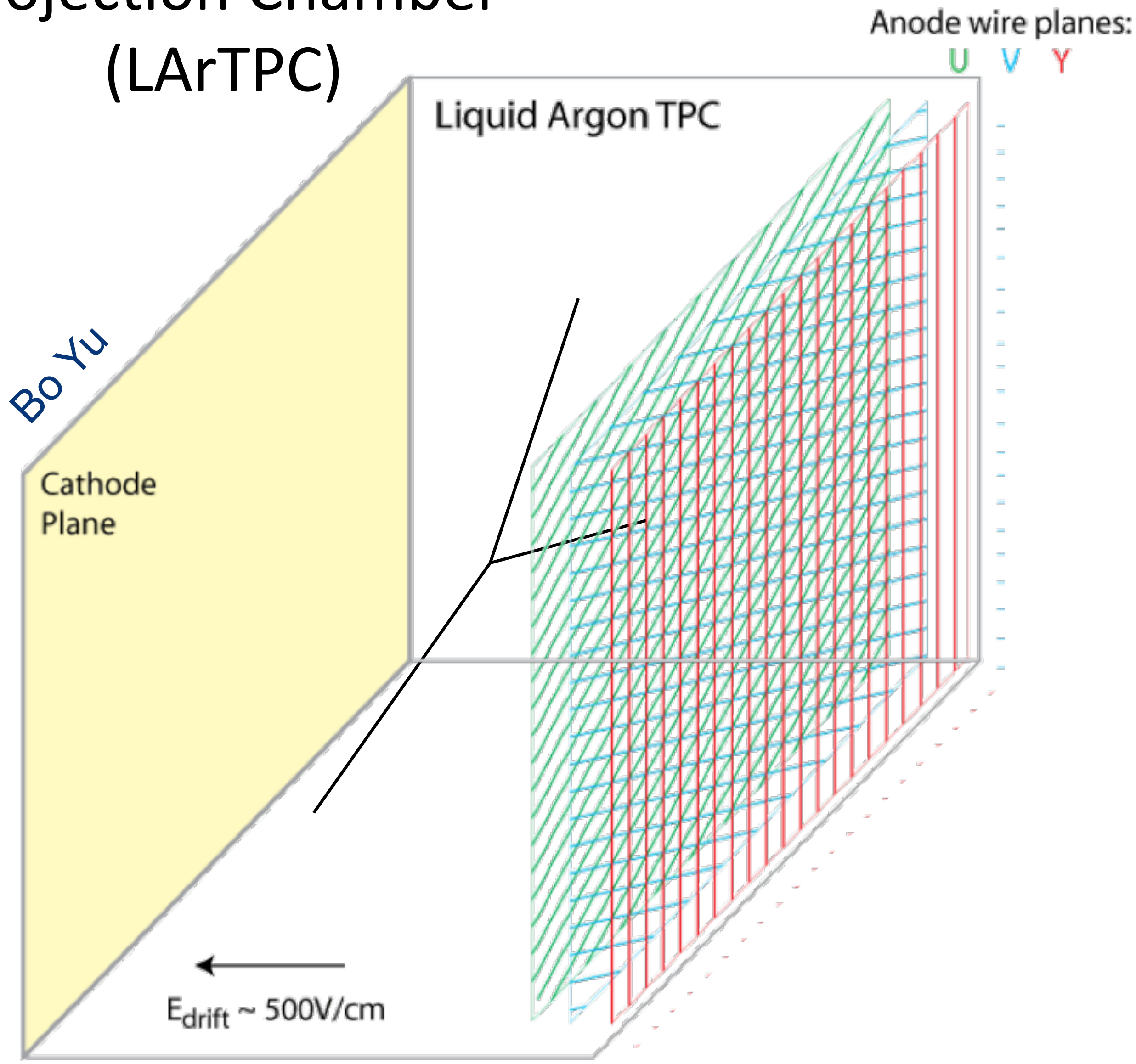


Liquid Argon Time Projection Chamber

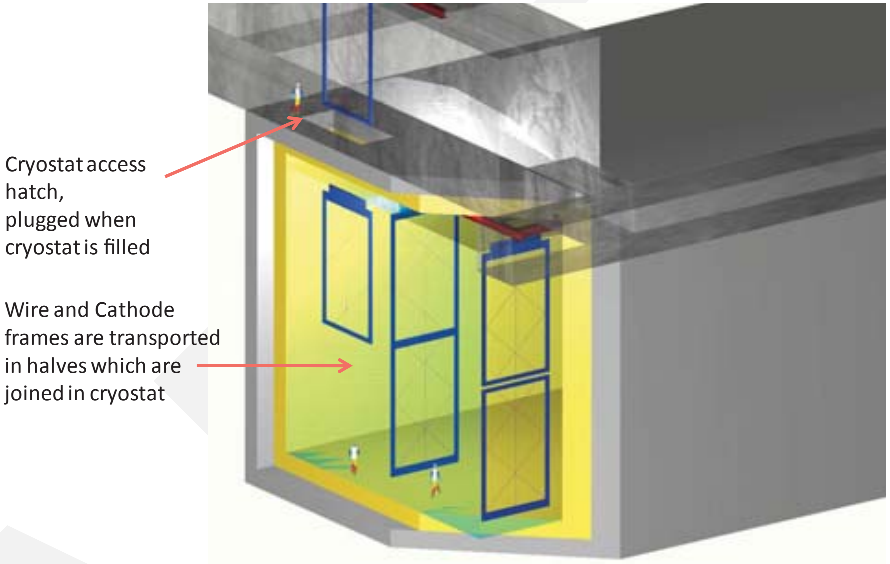
Exquisite imaging

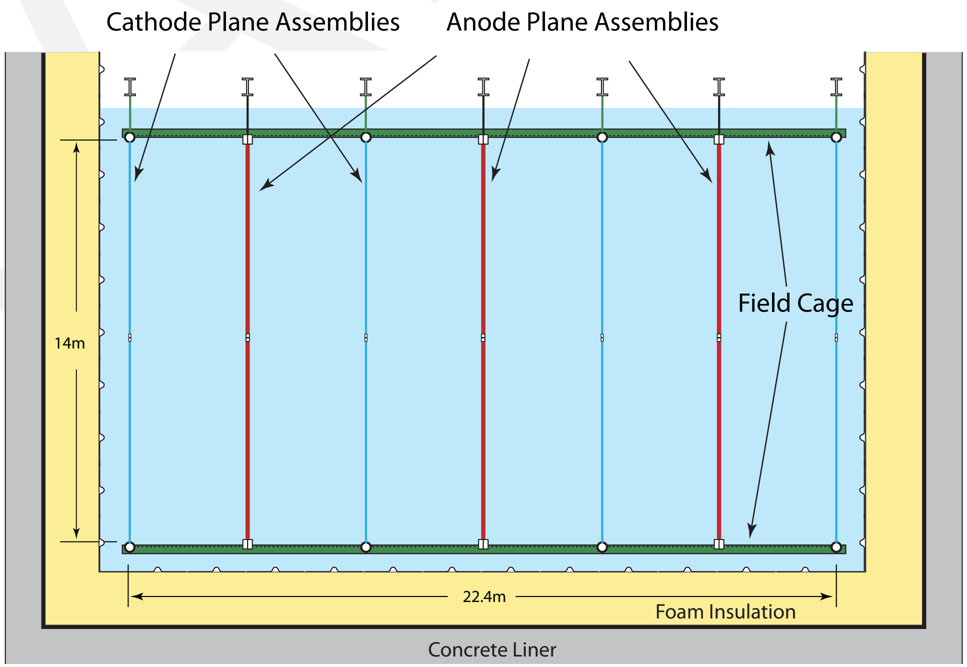


Liquid Argon Time Projection Chamber (LArTPC)

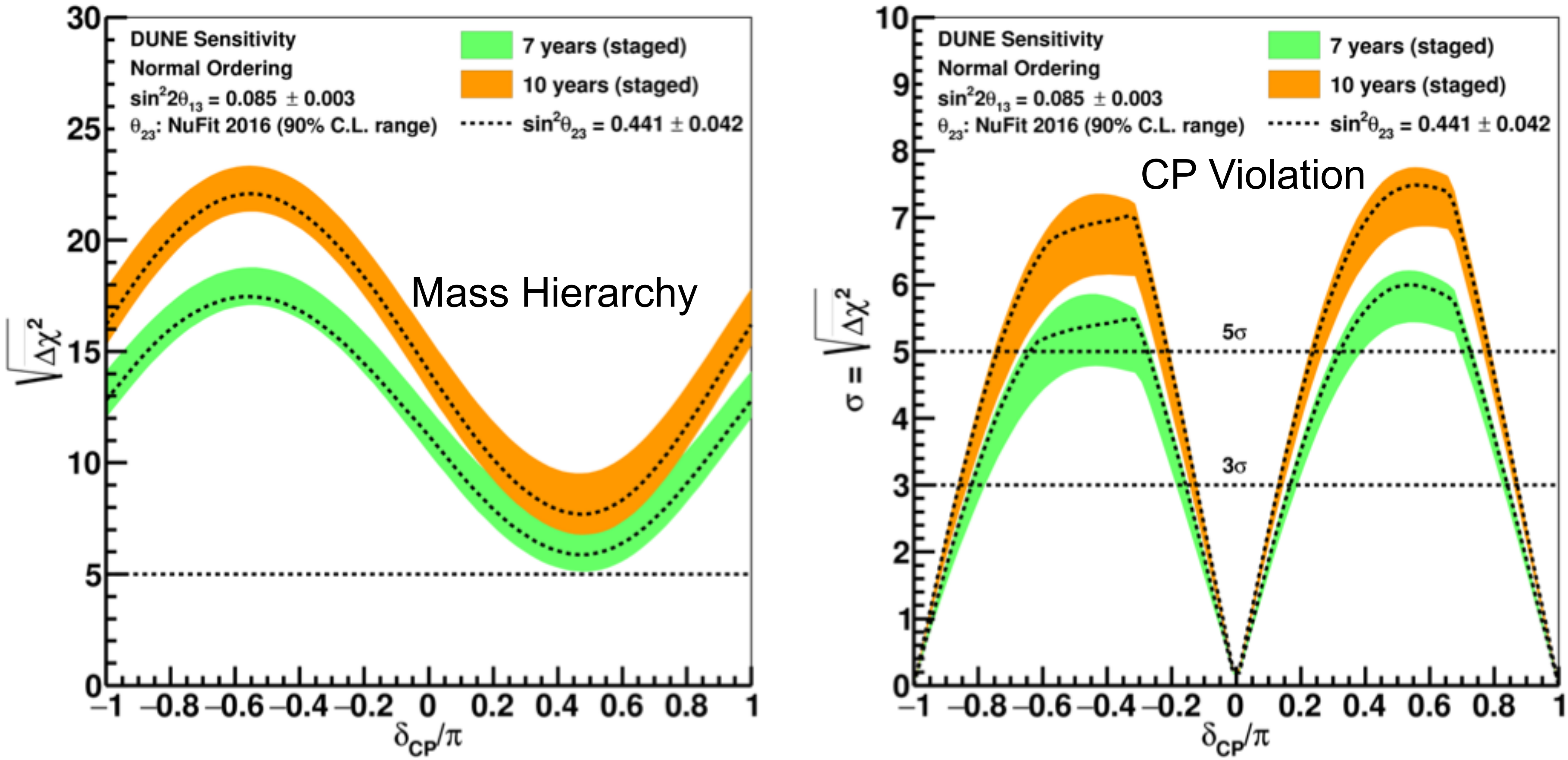


Detector schematics





DUNE Sensitivity



Wide-band and higher energy beam: => CP, MH, BSM physics in a single expt.

Furthermore, huge, deep, high precision detectors provide abundant non-accelerator physics: proton-decay, supernova neutrinos, ...

ProtoDUNE-SP

- CERN Neutrino Platform
- Large-scale prototyping/calibration
- UK building 3 (of 6) anode wire planes
  - 6 m tall x 2.3 m wide
- Data taking this year

DUNE UK Long-term Objectives

- **Leading partner in DUNE far detector construction**
  - ~15% UK core contribution to DUNE
  - TPC readout wire planes (APAs) and the DAQ
- **Construction phase objectives**
  - Construction of 150 of the 300 APAs for the first for 1^{st} 2x10kt
  - UK leadership of the FD DAQ, with UK providing the majority of the back-end DAQ for 1^{st} 2x10kt
  - Continued UK leadership in software/reconstruction
  - Cement leading UK role in preparation for physics exploitation
- **Plan to secure long-term UK leadership in DUNE**
  - Ionization collection → data readout → reconstruction → physics

Conclusions

Measurement of θ_{13} has opened a door to probing CP violation, mass hierarchy and octant of θ_{23}

NOvA and T2K both see electron neutrino appearance at the upper end of expectations

- NOvA is approaching 2 σ inverted hierarchy rejection
- $\delta_{CP} = \pi/2$ region is strongly disfavoured by T2K

Antineutrino results expected this summer

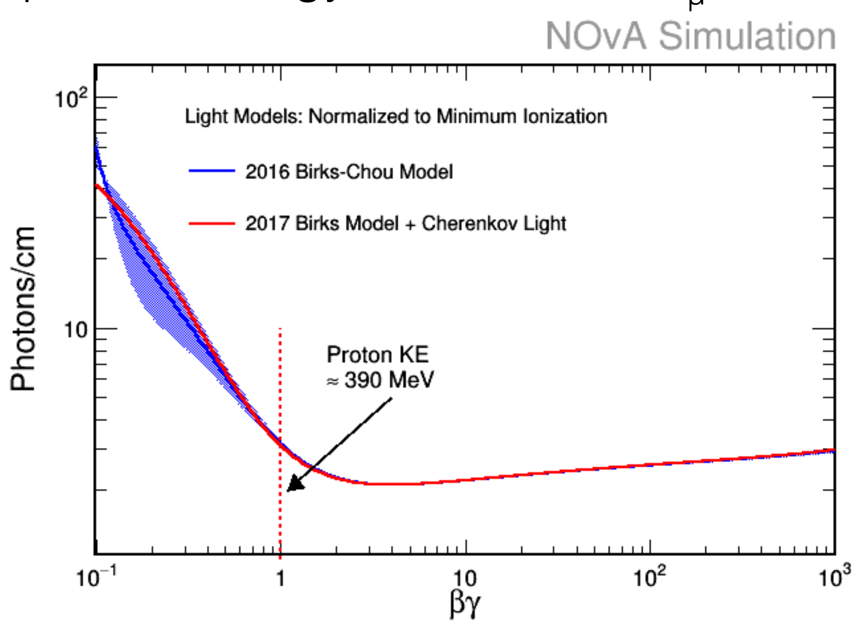
Stay tuned!

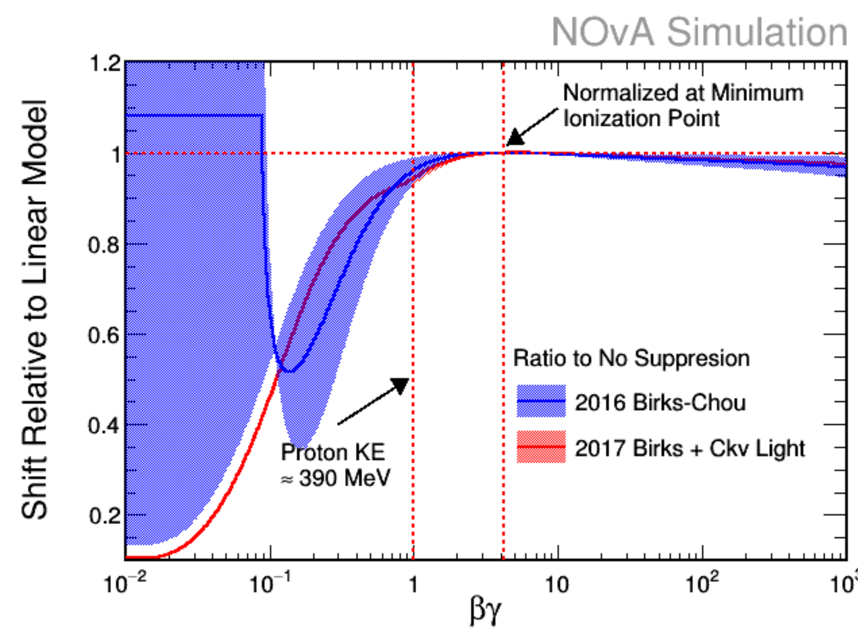
- Real possibility of a breakthrough on mass hierarchy soon
- Exciting times ahead, multiple discoveries to be made

Backup slides

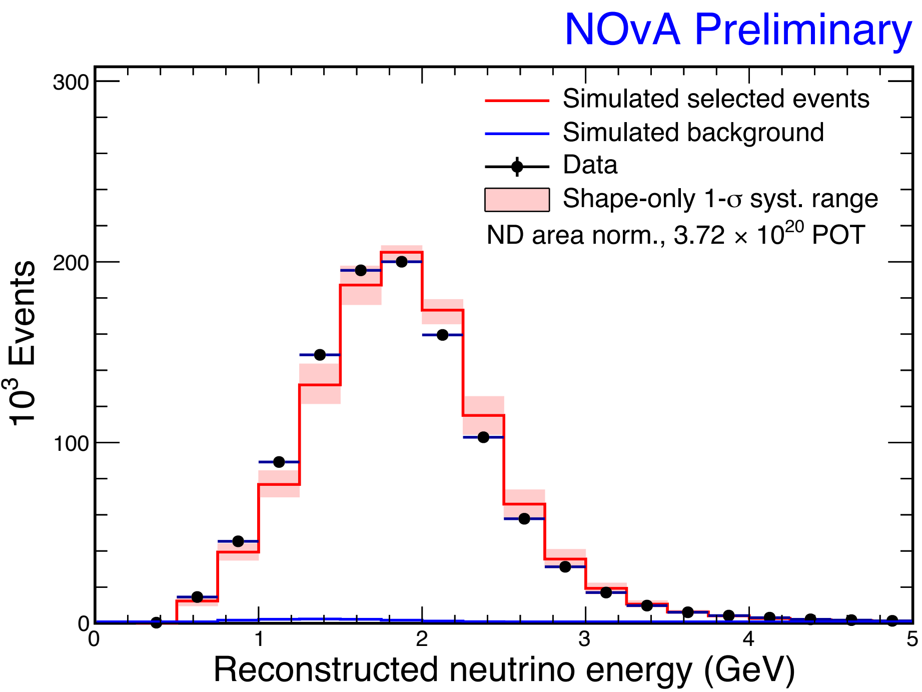
Improved Detector Simulation

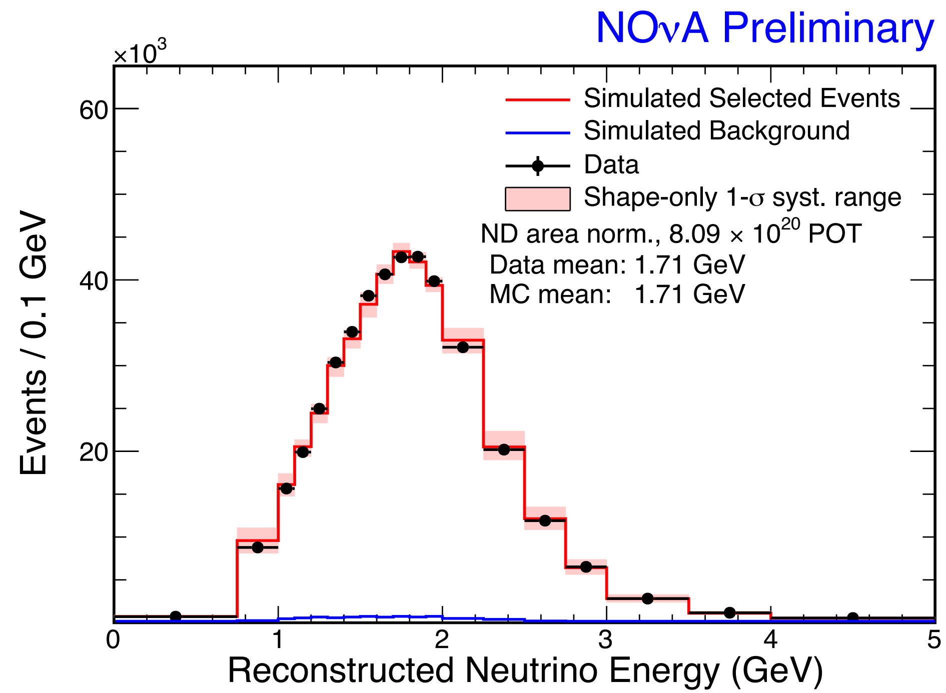
- Previously detector response uncertainties were some of our largest. Reduced by an order of magnitude in new detector simulation, driven by addition of cherenkov light.
- Absorbed and re-emitted Cherenkov light is a small but important in modeling the detector response to hadronic activity.
- Expected energy resolution for ν_μ CC events moves from 7% to 9%.





New simulation

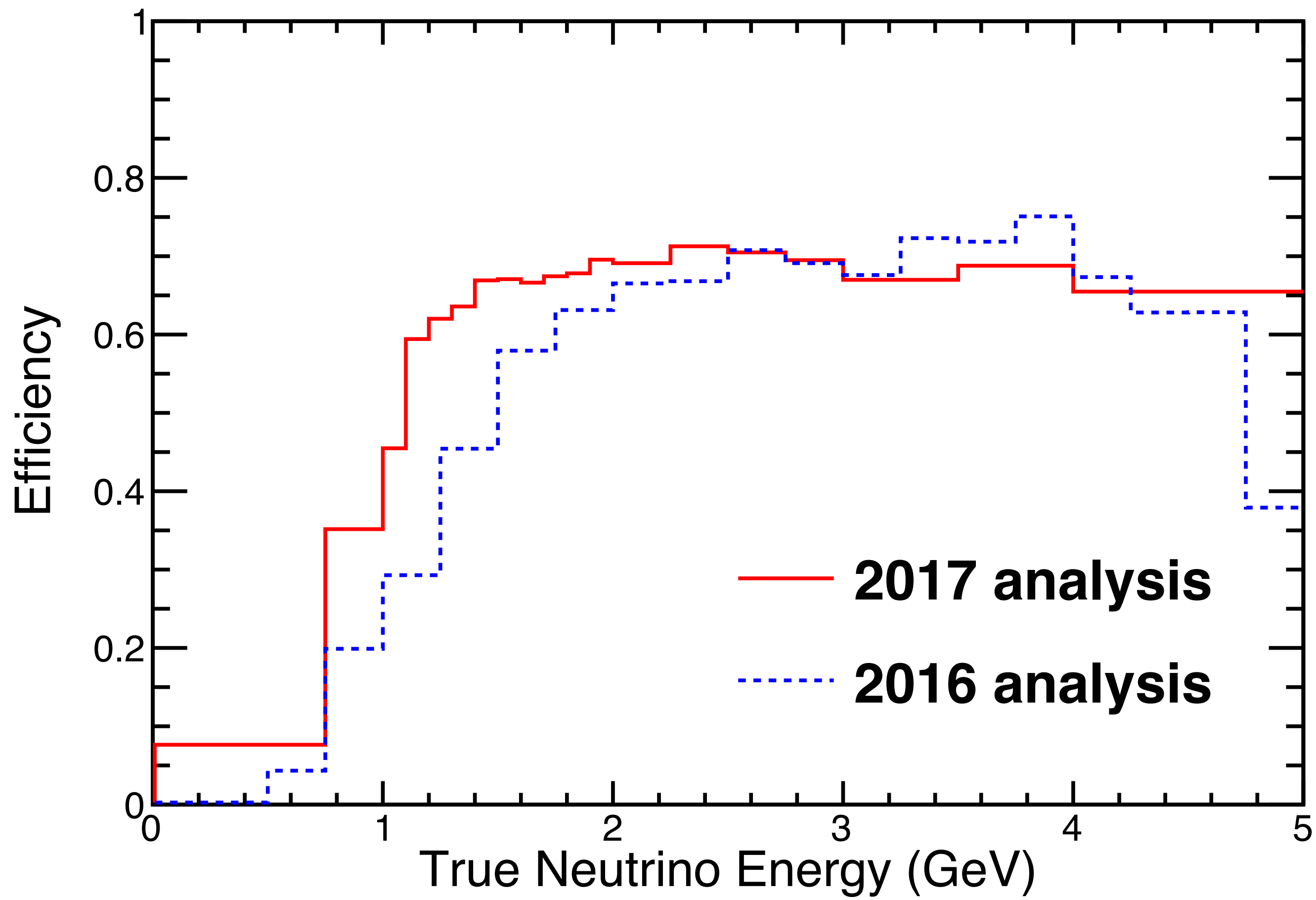




Old → New

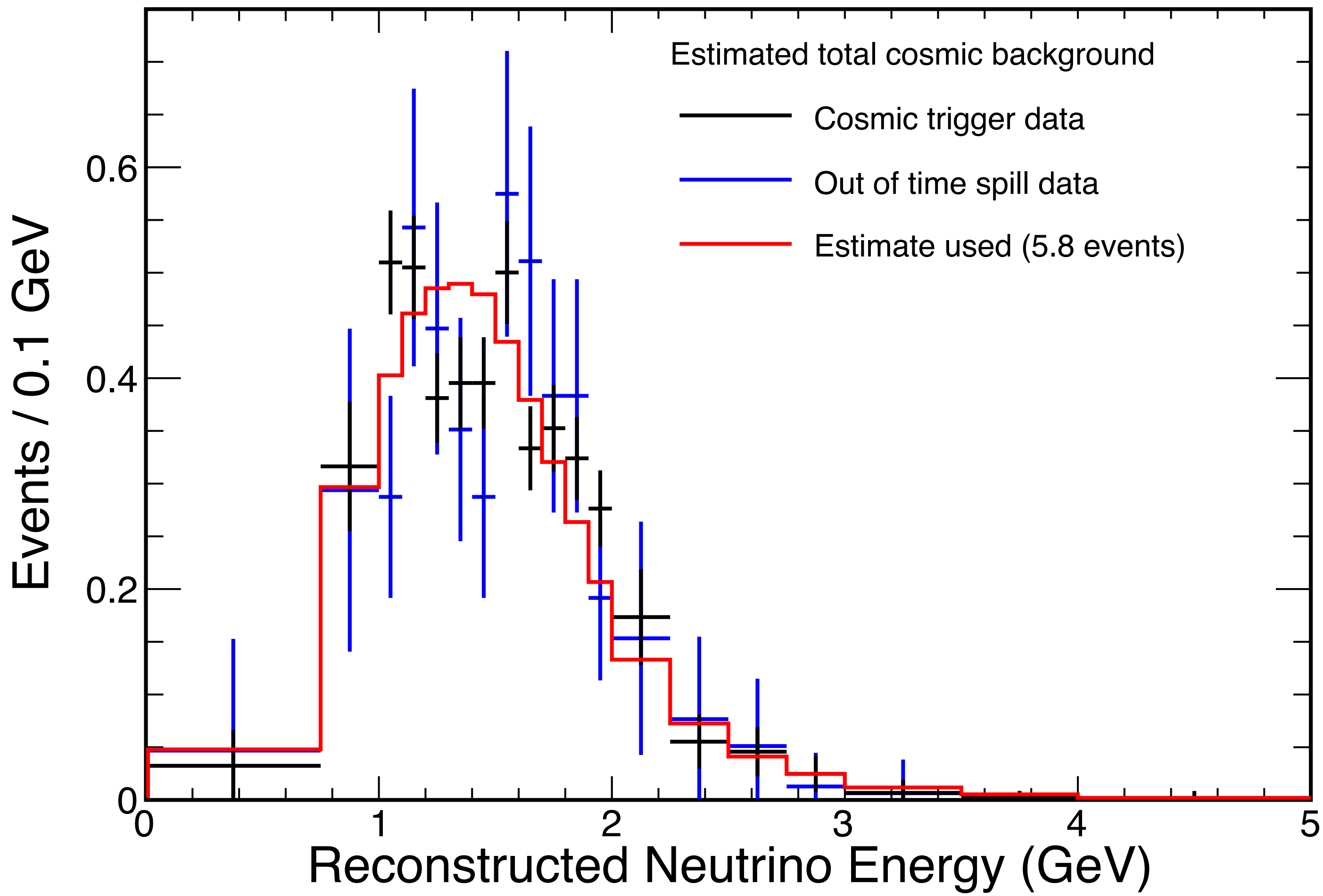
ν_μ Event Selection

- 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

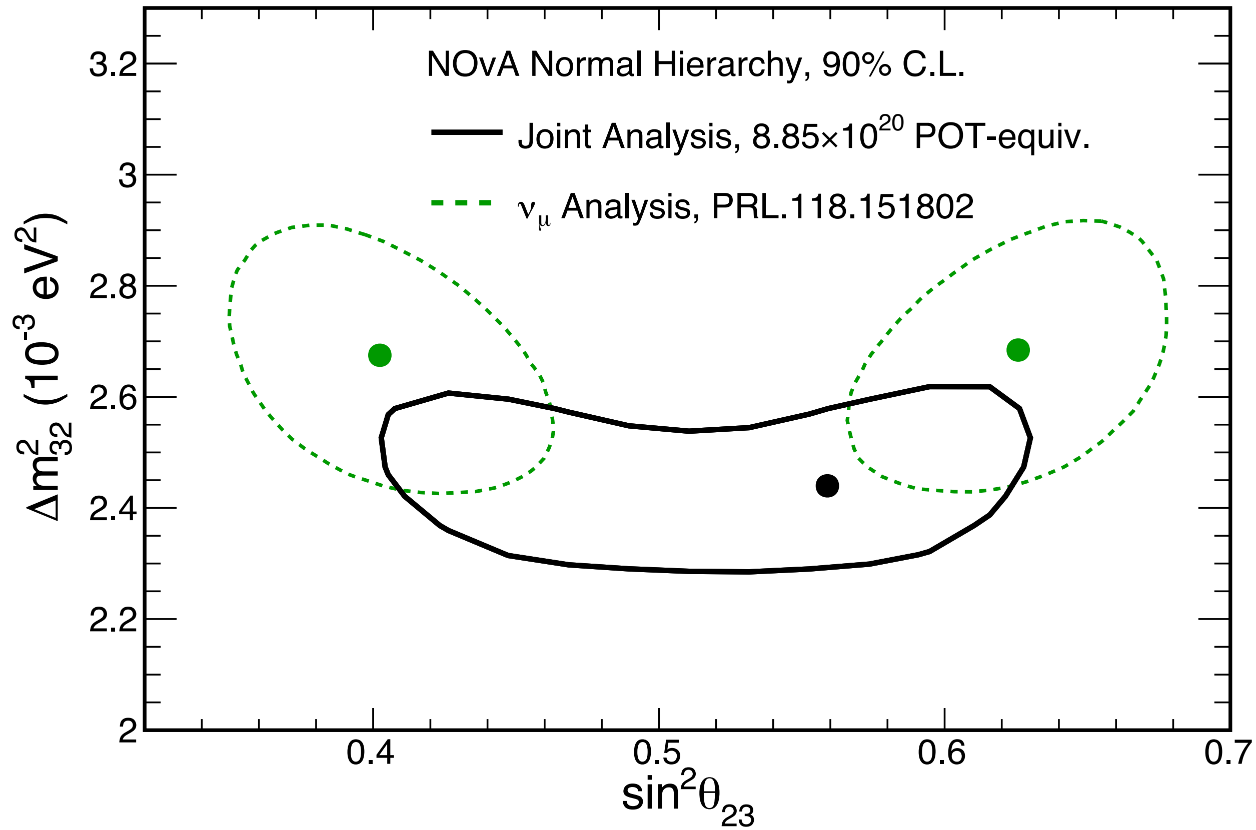


Far Detector Cosmic Background

Measure cosmic background using beam-off data



Comparison to previous result



Comparison to previous result

Our previous result*:
2.6σ

Our rejection of maximal mixing has moved from 2.6σ to 0.8σ. This change in the character of our result comes from a few key changes which I'll break down below.

↓

New simulation & Calibration:
~1.8σ

Driven by updates to energy response model. Drop to 2.3σ expected due to new energy resolution. Additionally we have a <70 MeV> shift in our hadronic energy response. This energy shift would be expected to move 0.5 events out of the "dip" region. However it instead pushes 3 "dip" events past a bin boundary.

↓

New selection and analysis:
~0.5σ

For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

↓

Full dataset:
~0.4σ

→

Full dataset*:
0.8σ

New, $3x10^{20}$ POT, data prefers maximal mixing.

*Feldman-cousins corrected significance.