Results and Prospects from NOvA

NUFACT 2017

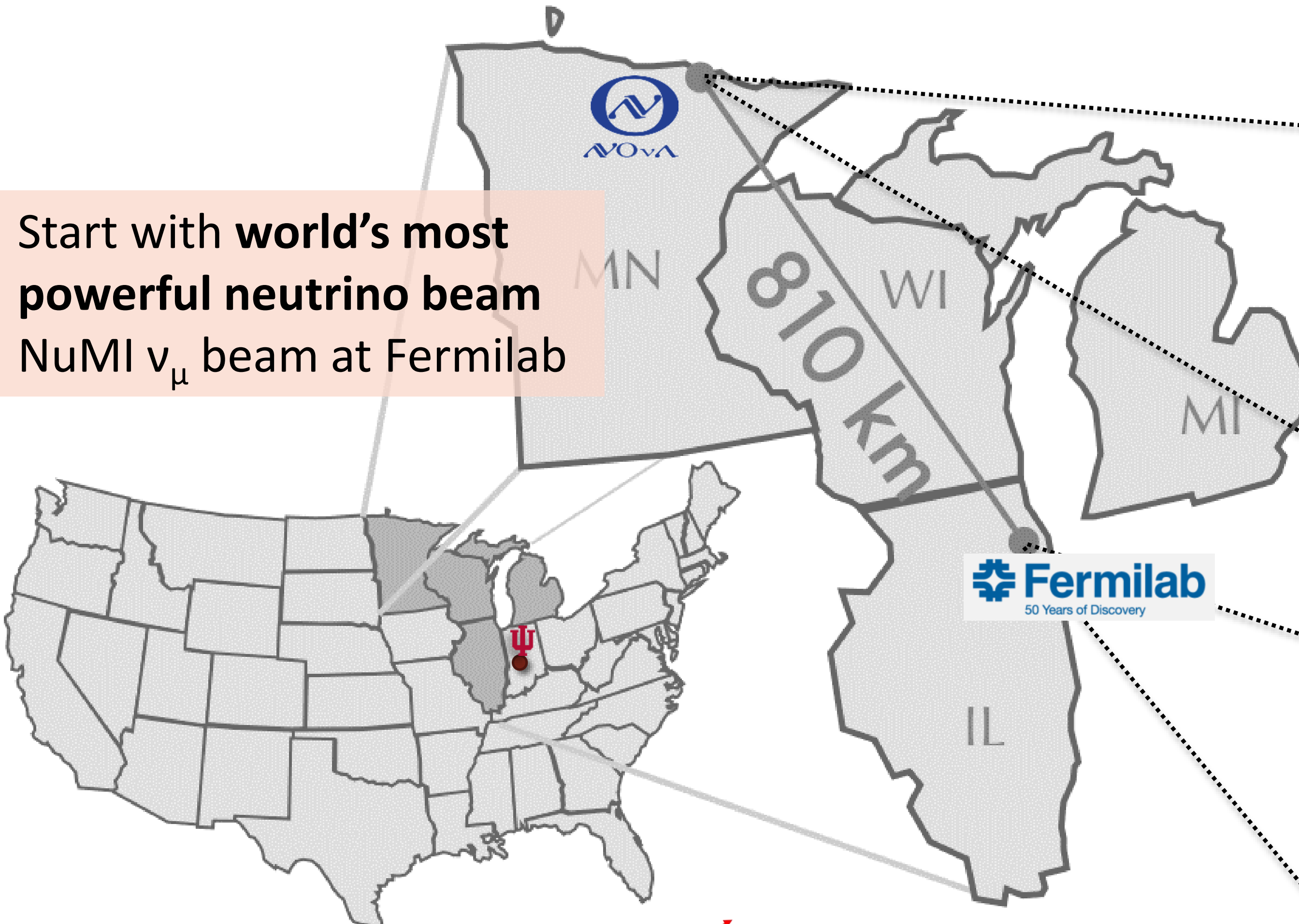
UPPSALA, SWEDEN

Gavin S. Davies
Indiana University
for the NOvA collaboration

SEPTEMBER 26TH 2017

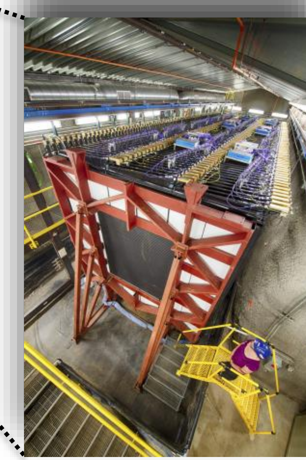
NuMI Off-axis ν_e Appearance

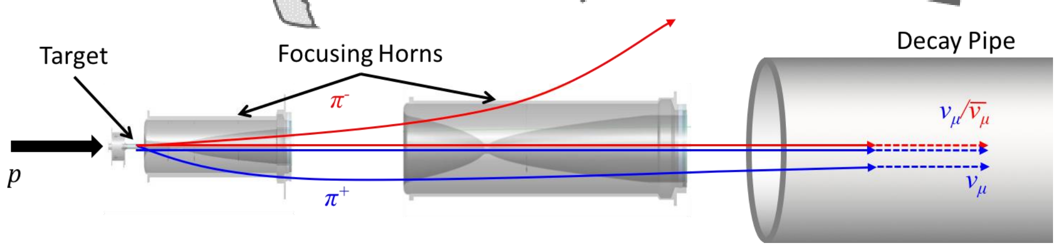
- Start with **world's most powerful neutrino beam**
- NuMI ν_μ beam at Fermilab



Far Detector

Near Detector

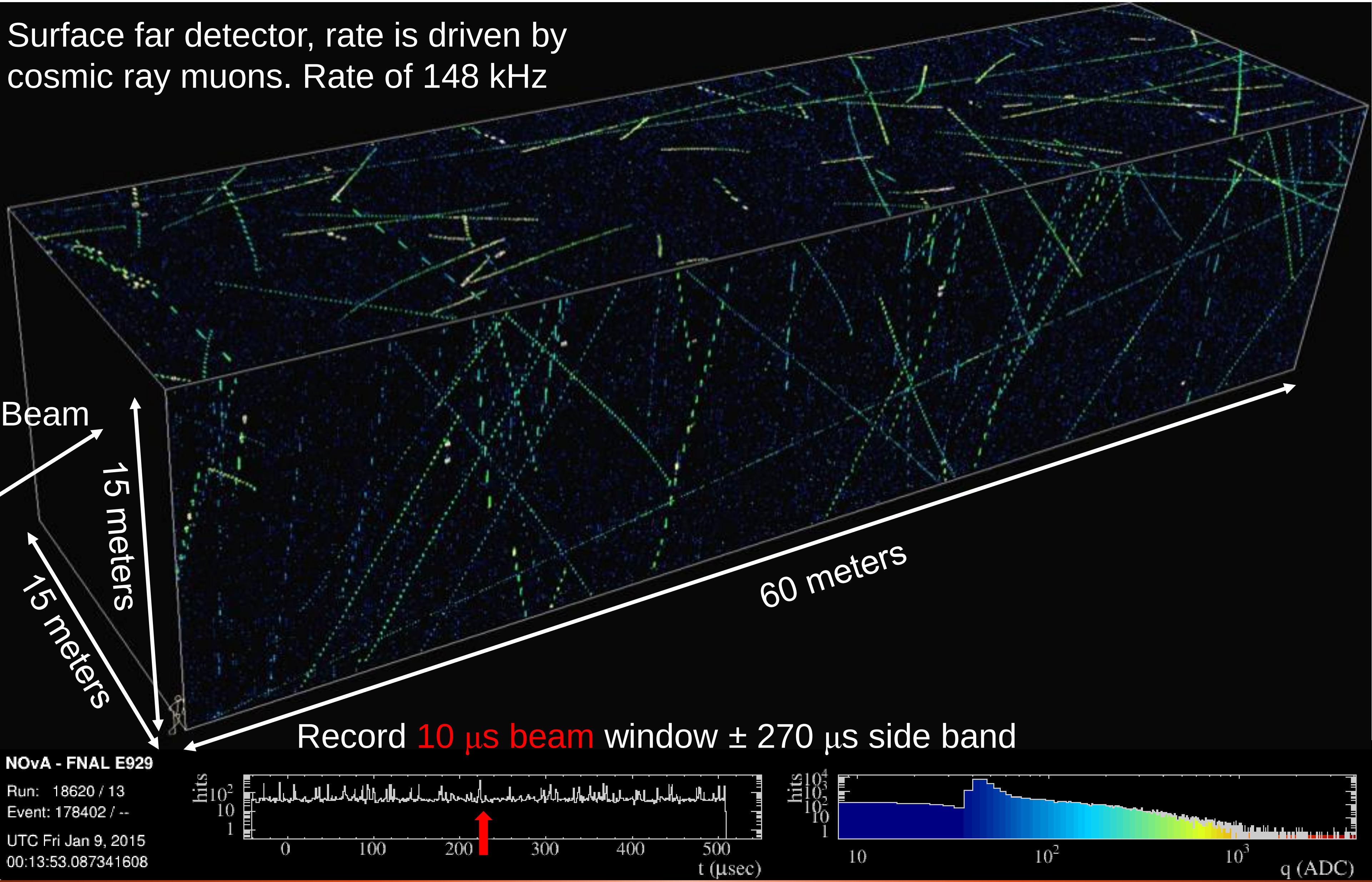




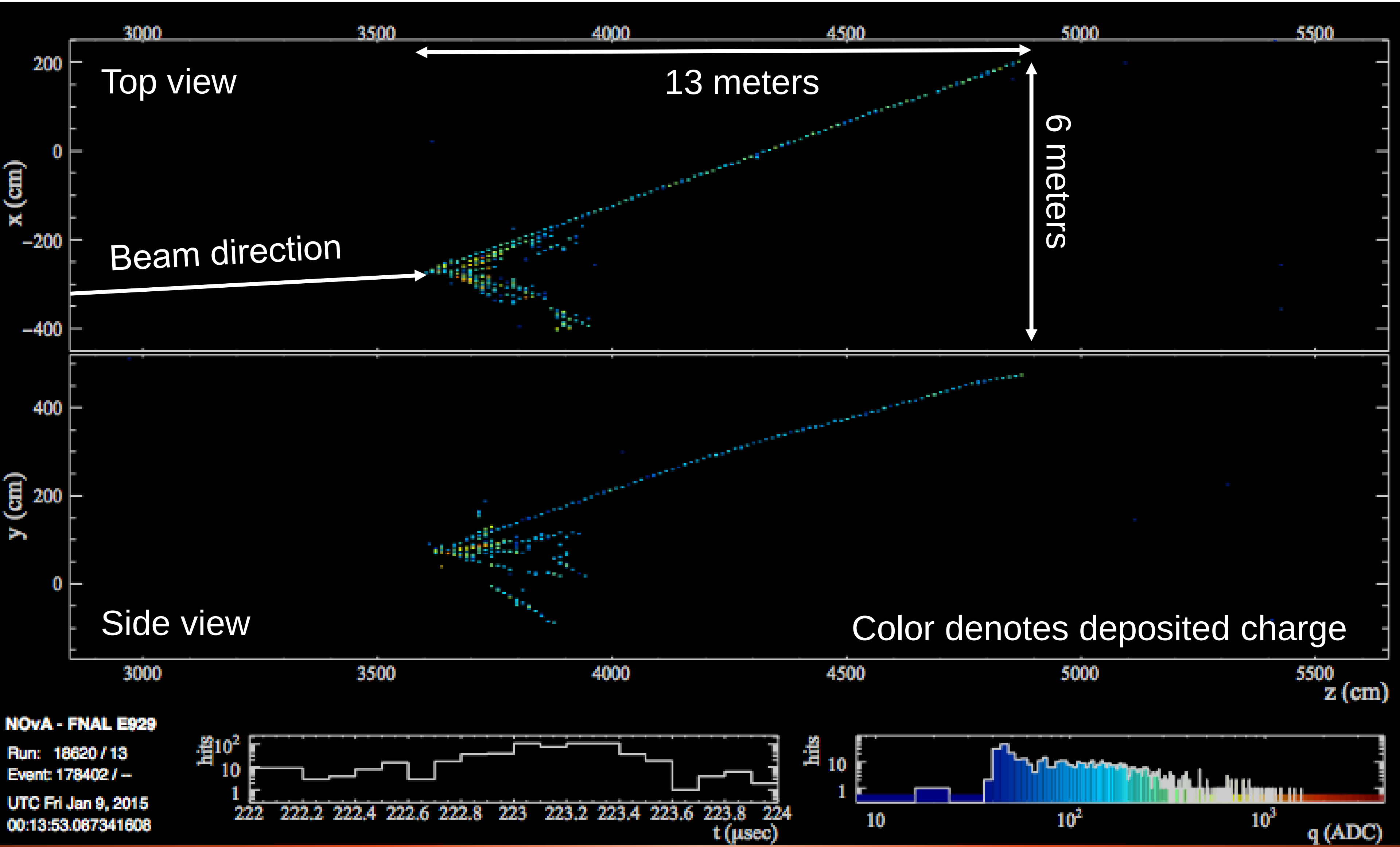
The NOvA detectors

NOvA FD on the surface

Surface far detector, rate is driven by cosmic ray muons. Rate of 148 kHz



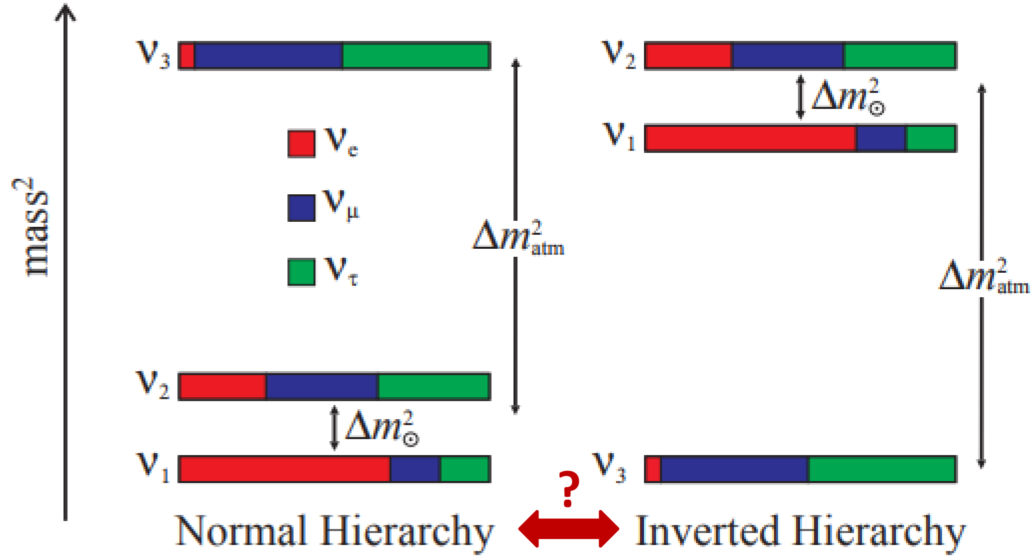
Zoomed NOvA FD 10μs spill



NOvA Physics Program

- Disappearance of ν_μ CC events
  - $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
  - Precision measurements of:

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



- Appearance of ν_e CC events
  - $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Determine mass hierarchy
  - Search for $\delta_{CP} \neq 0$

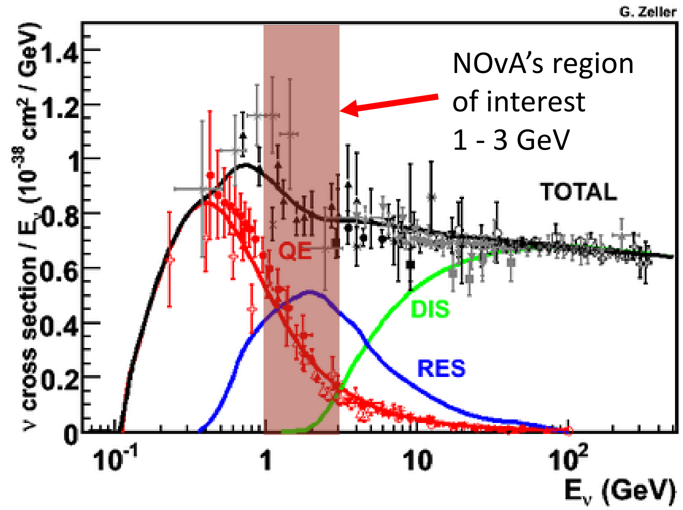
    θ_{13} & θ_{23} & δ_{CP}

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

    θ_{34} & θ_{24}
  - 2016 analysis: arXiv:1706.04592
  - **New 2017 result**!

NOvA Physics Program

Additionally, many cross section analyses, searches for exotic phenomena, and non-beam physics studies!



- ND cross-section measurements:
  - inclusive ν_e
  - inclusive ν_μ
  - inclusive π^0
  - coherent NC π^0
  - neutrino-on-electron scattering

WG2: Monday 25th, Linda Cremonesi (UCL)
"NOvA recent results of cross section measurements"

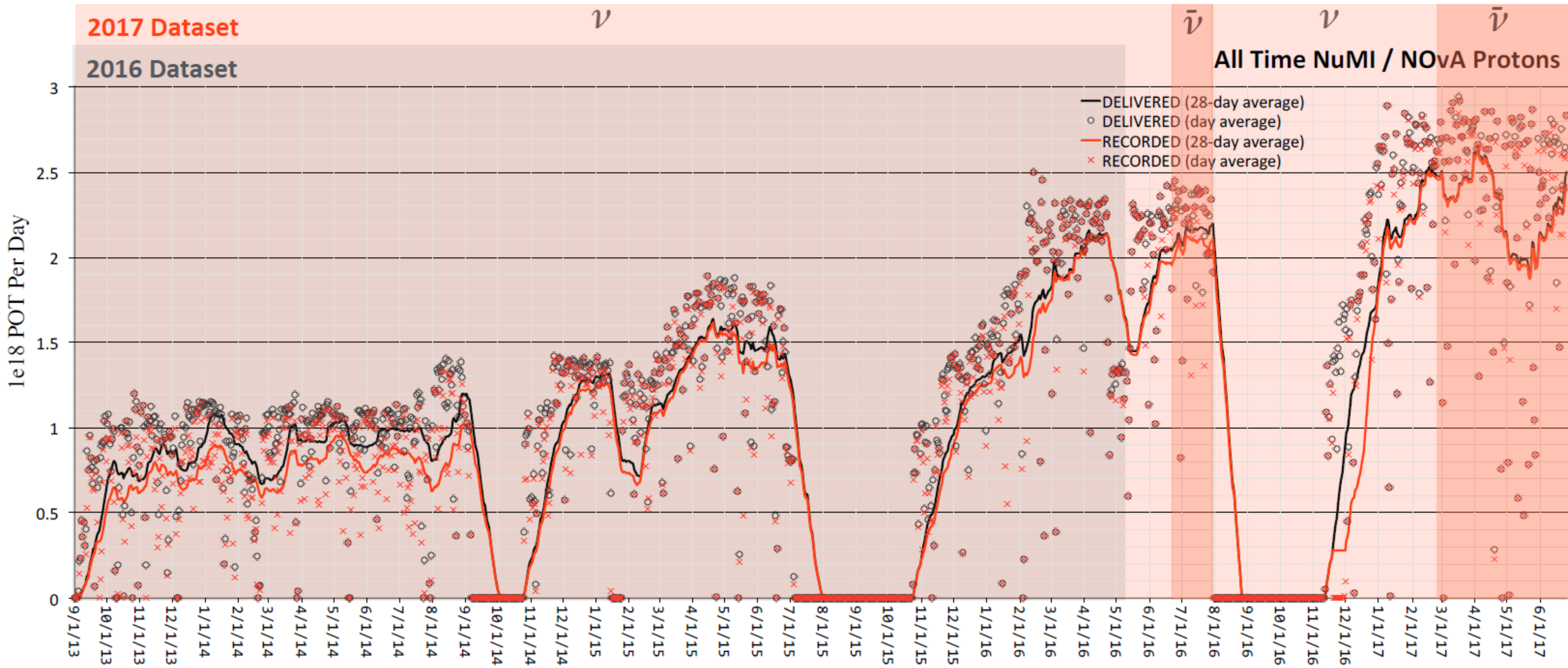
WG1+WG2: Tuesday 26th, Kirk Bays (Caltech)
"Cross Section Results from NOvA and their effect on oscillations"

- Exotic Physics:
  - multi-muon seasonal
  - neutrino magnetic moment
  - high energy cosmic ray air showers
  - magnetic monopole searches
  - dark matter searches
  - supernova neutrinos

Disclaimer: Non-exhaustive lists. NOvA has a very rich non-oscillations physics program

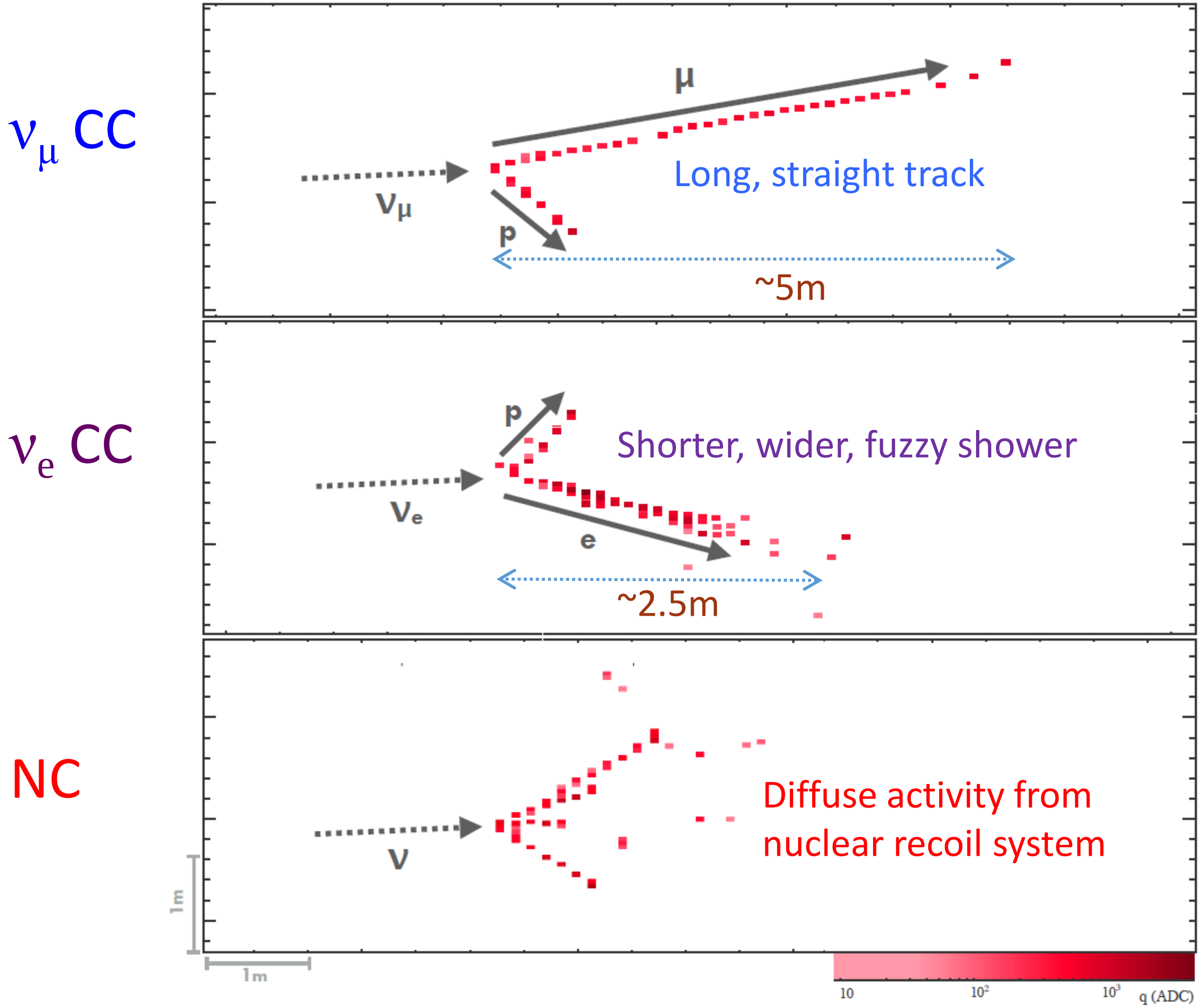
NOvA's Analysis Datasets

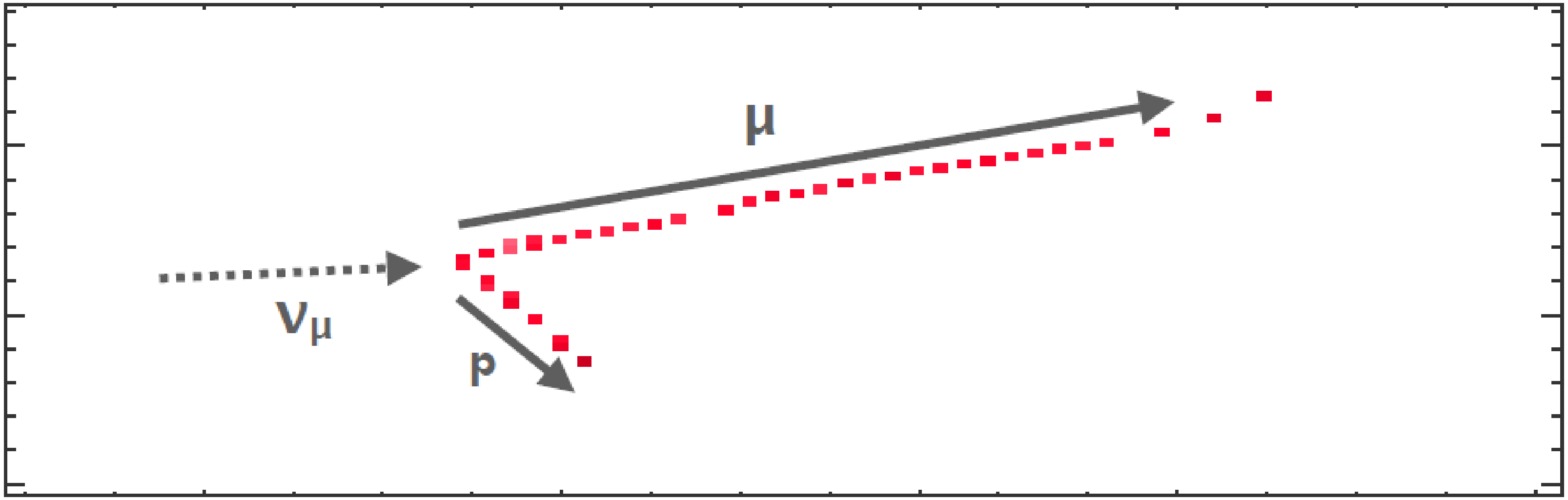
- **2016**: Full detector equivalent exposure: **6.05 x 10^{20} POT** (Feb. 6th 2014 to May 2nd 2016)
  - ν_μ disappearance and ν_e appearance analyses
- **2017**: Full detector equivalent exposure: **8.85 x 10^{20} POT** (Feb. 6th 2014 to Feb 20th 2017)
  - NC disappearance analysis
- Excellent ν_μ beam delivered; NuMI beam achieved 700 kW design goal
  - Routinely running above 650 kW during latest $\bar{\nu}$ running (Feb. 2017 onwards)



Neutrino Interactions at NOvA

Low-Z to enhance electron photon separation, each plane is ~0.18 X_0
Molière radius is ~10 cm, 2.5 NOvA cells



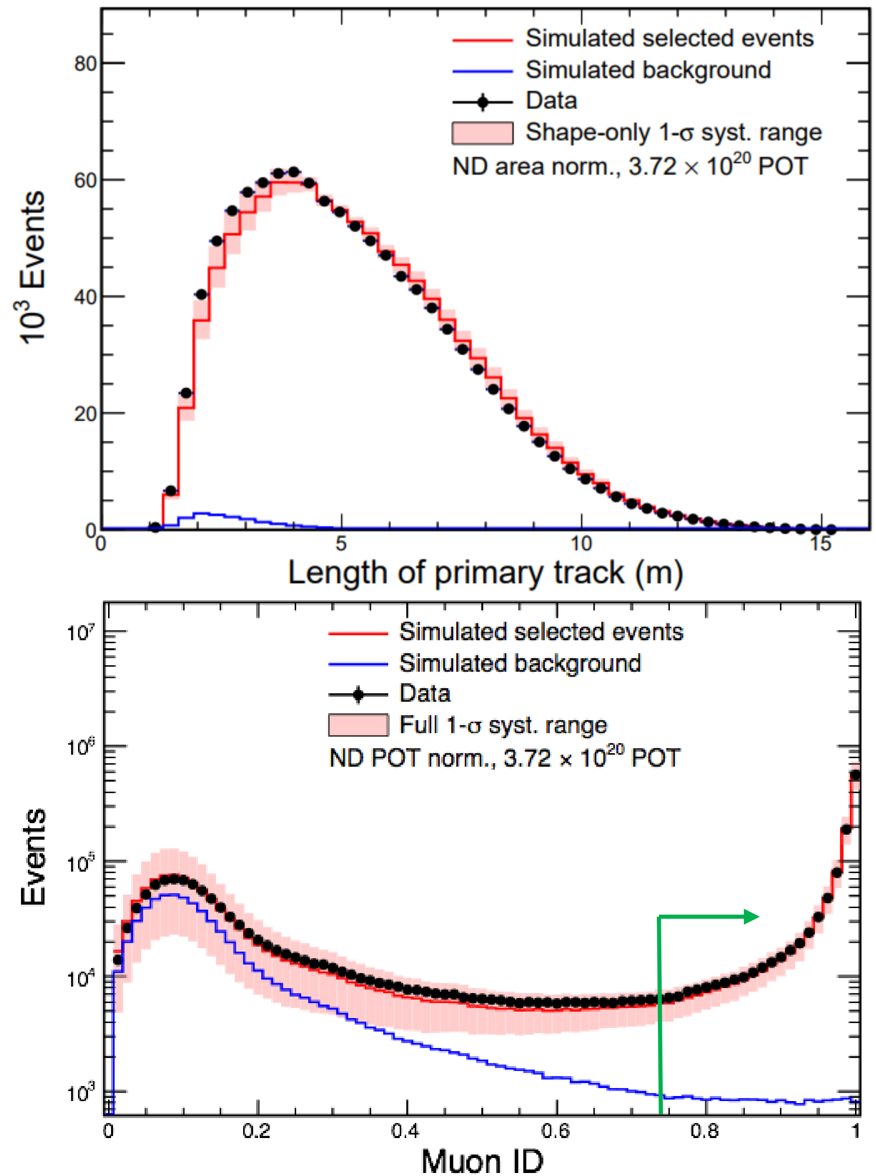


1. ν_μ Disappearance

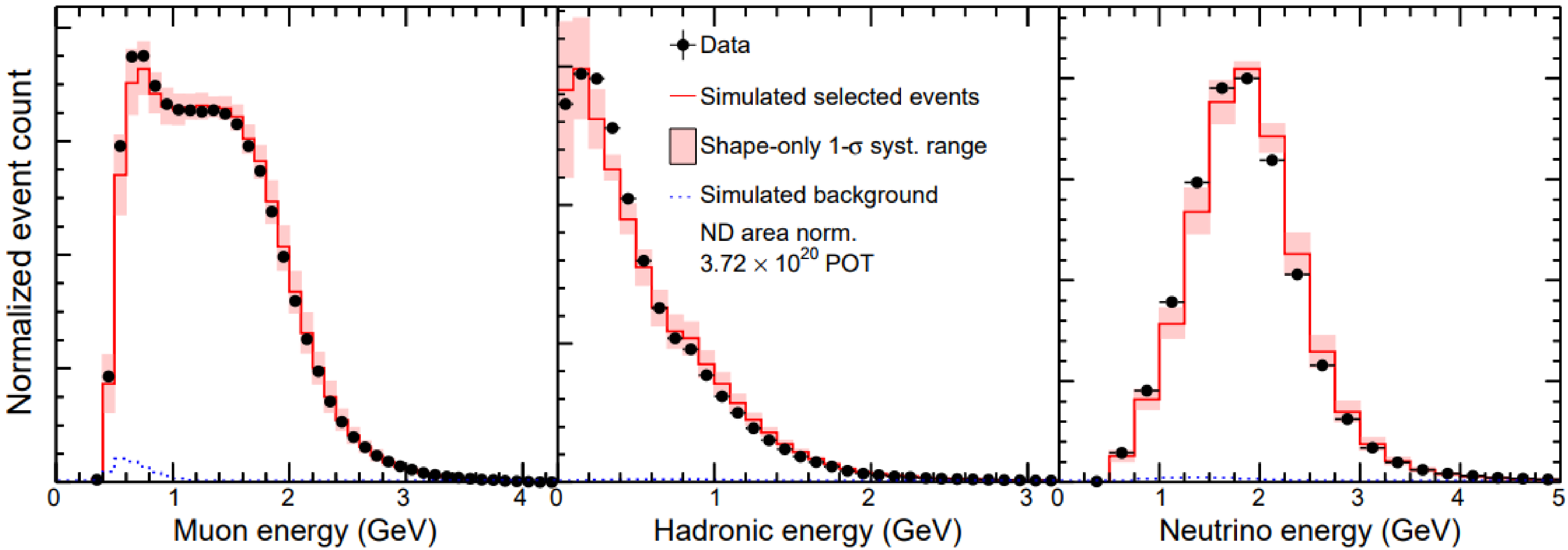
2016 DATASET

ν_μ selection

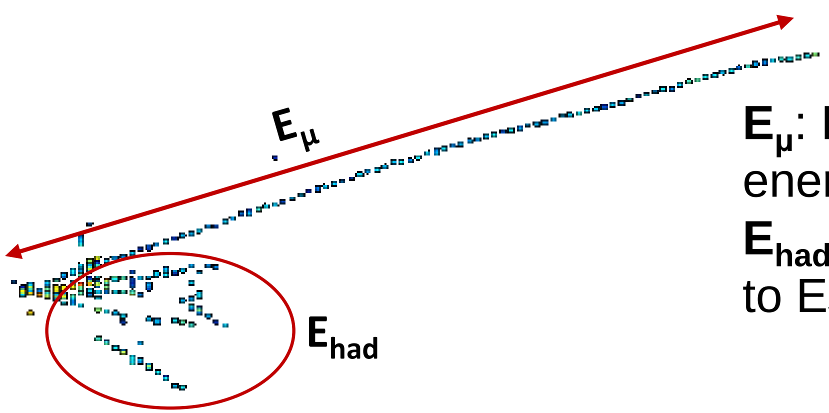
- Select ν_μ CC from NC background
- Combine input variables in a k-Nearest Neighbour algorithm, 4 inputs:
  - Track length
  - dE/dx
  - Scattering
  - Fraction of planes that have track-only
- ν_μ selection purity of **95%** and efficiency of **81%**



ν_μ Energy Reconstruction



$$E_\mu + E_{had} = E_\nu$$



E_μ: Fit splines of muon track length to muon energy

E_{had}:Fit splines of non-track calorimetric energy to E_ν (true)–E_μ(reco)

~7% energy resolution

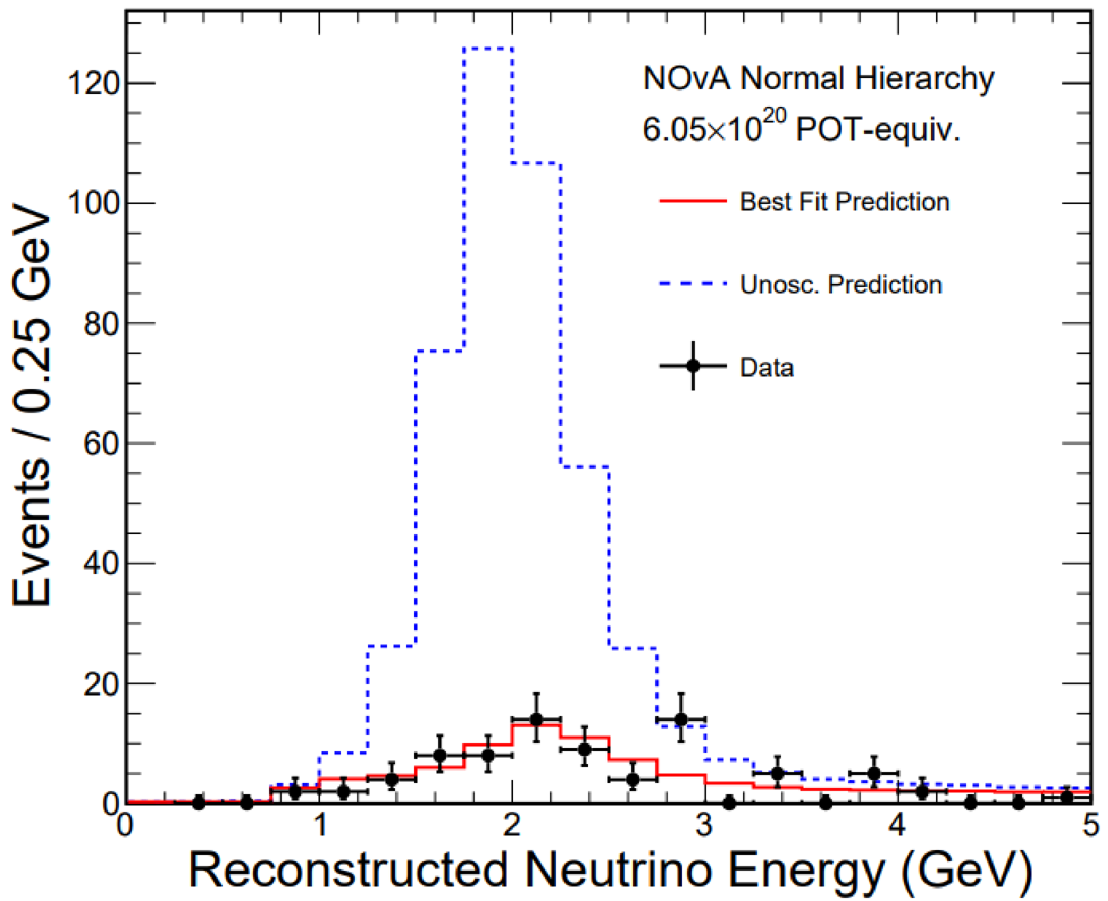
Use ND data to predict FD spectrum

ν_μ Disappearance Results

- Far/Near extrapolation predicts, in the absence of oscillations:
  - **473 ± 30** events

- Observed **78** ν_μ CC candidates
- Estimated background of 3.9 events from beam and 2.7 from cosmics

- Fit for $\mathbf{sin^2(\theta_{23})}$ and $\boldsymbol{\Delta m^2_{32}}$



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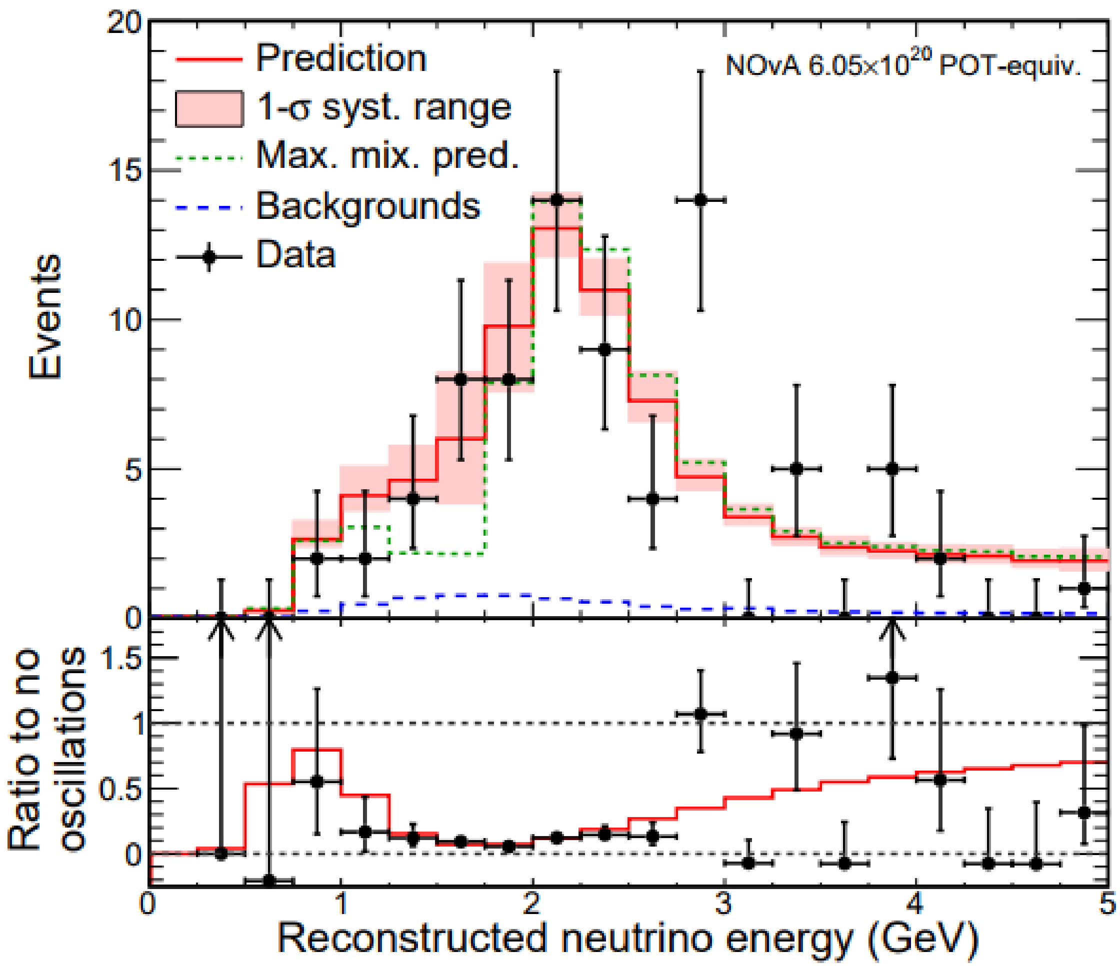
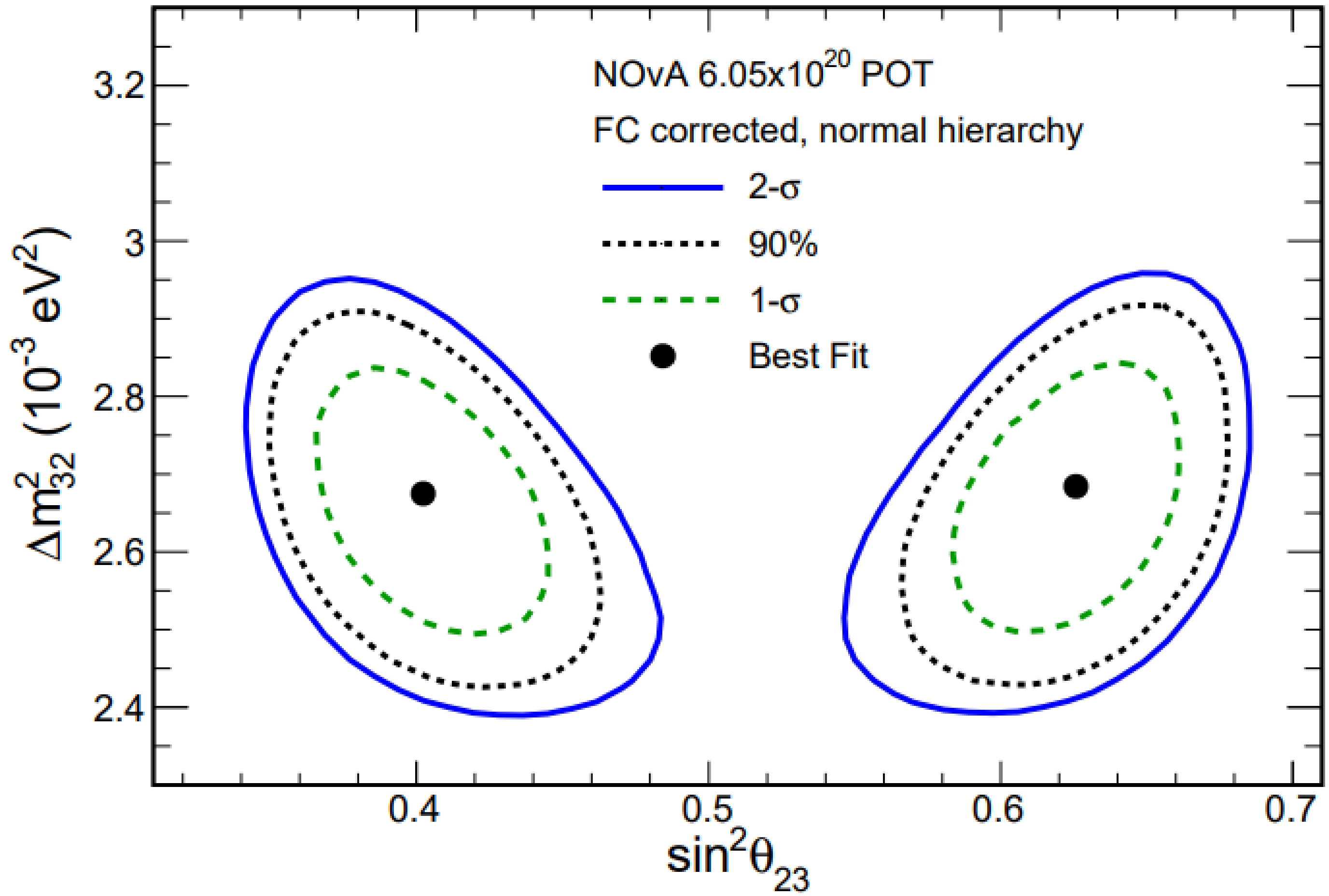
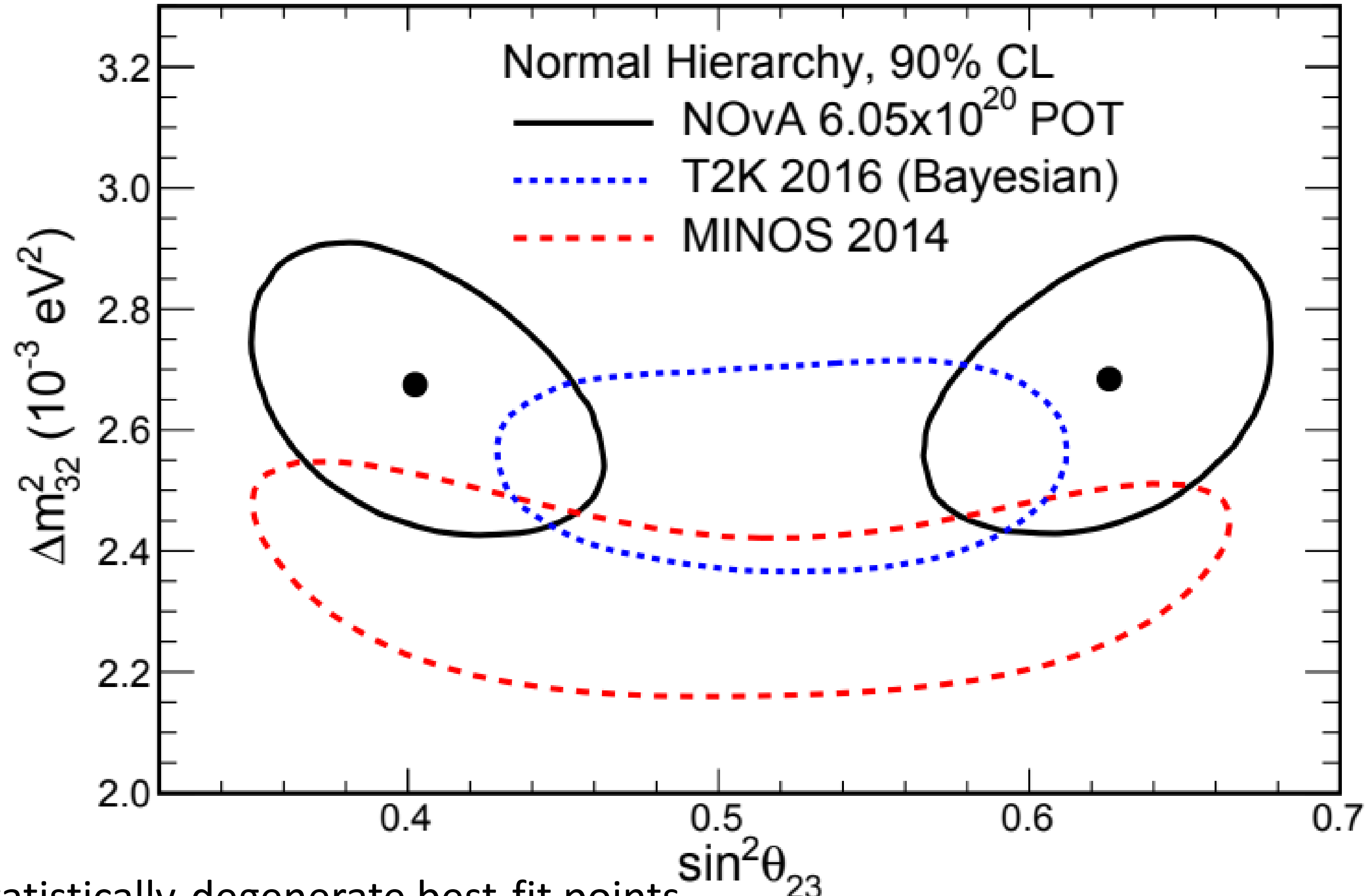


ν_μ Disappearance Results



- Two statistically-degenerate best-fit points
  - **$\sin^2(\theta_{23})$ = $\mathbf{0.404^{+0.030}_{-0.022}}$ and $\mathbf{0.624^{+0.022}_{-0.030}}$** (68% C.L., NH)
  - **Δm^2_{32} = (+2.67 ± 0.12) x 10^{-3} eV^2**
- Maximal mixing disfavoured at 2.6σ (FC-corrections applied)

ν_μ Disappearance Results



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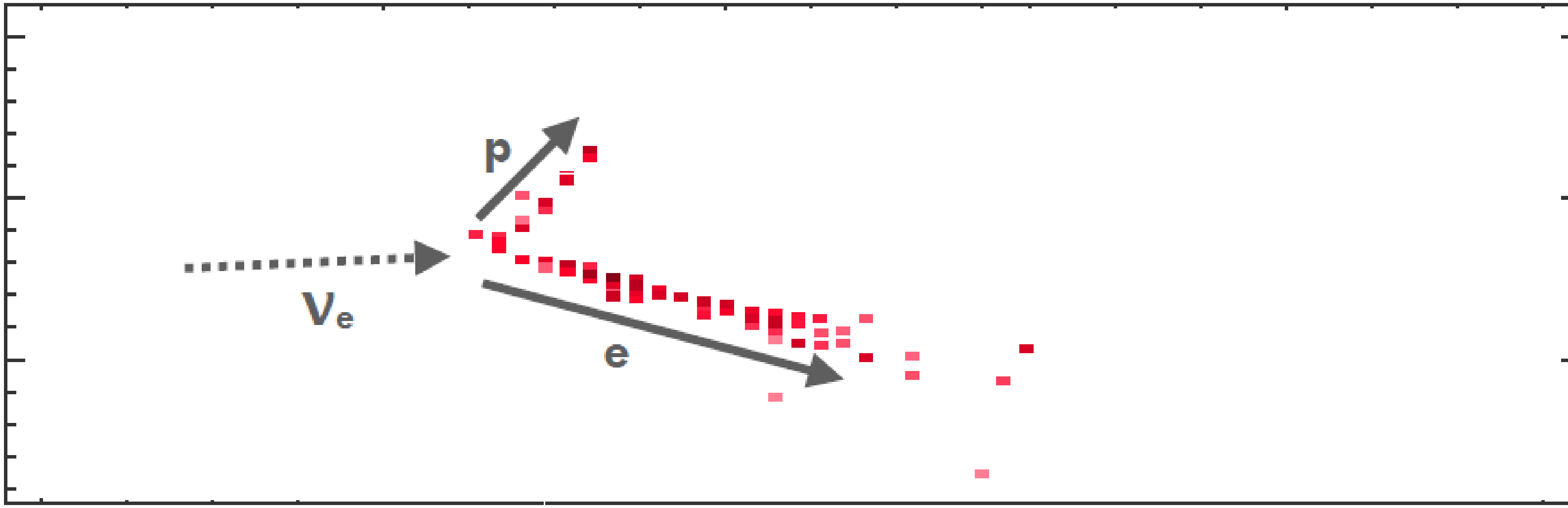
- Maximal mixing disfavoured at 2.6σ
- Updating this coming fall with 50% increased exposure

Phys. Rev. Lett. 118, 151802 (2017)
Published 10th April 2017

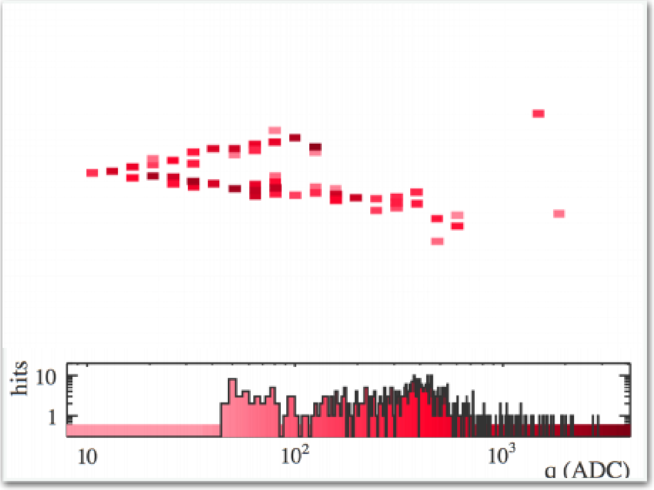


2. ν_e Appearance

2016 DATASET

ν_e Event Selection

- CVN: Convolutional Visual Network, a deep neural network implementation of a CNN
- Input is **NOvA**'s 2D event display (pixel map) "images" of calibrated hits

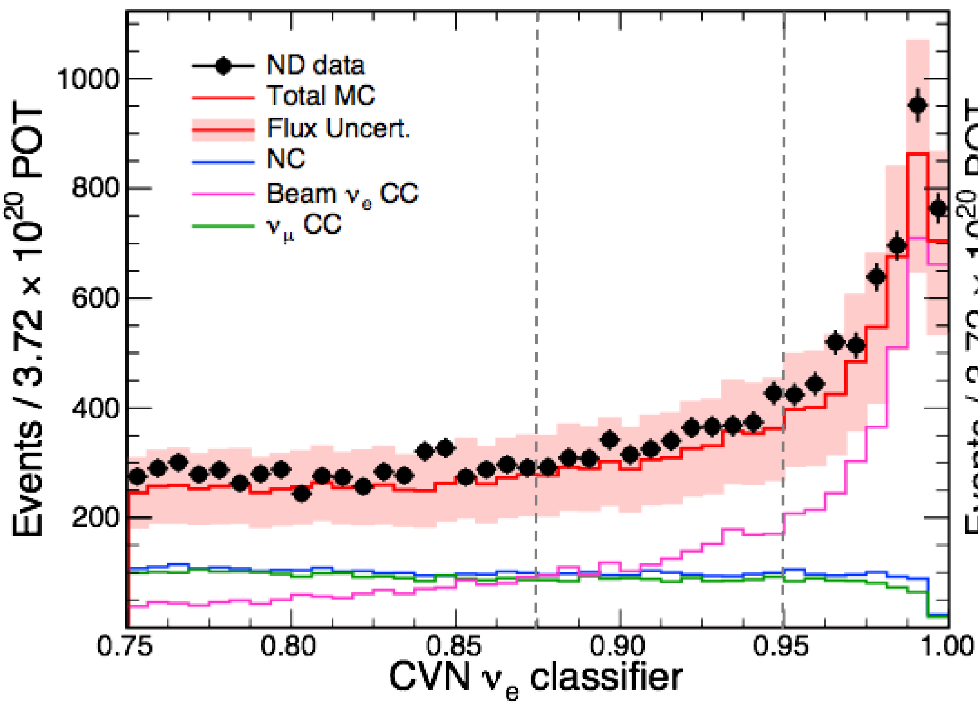


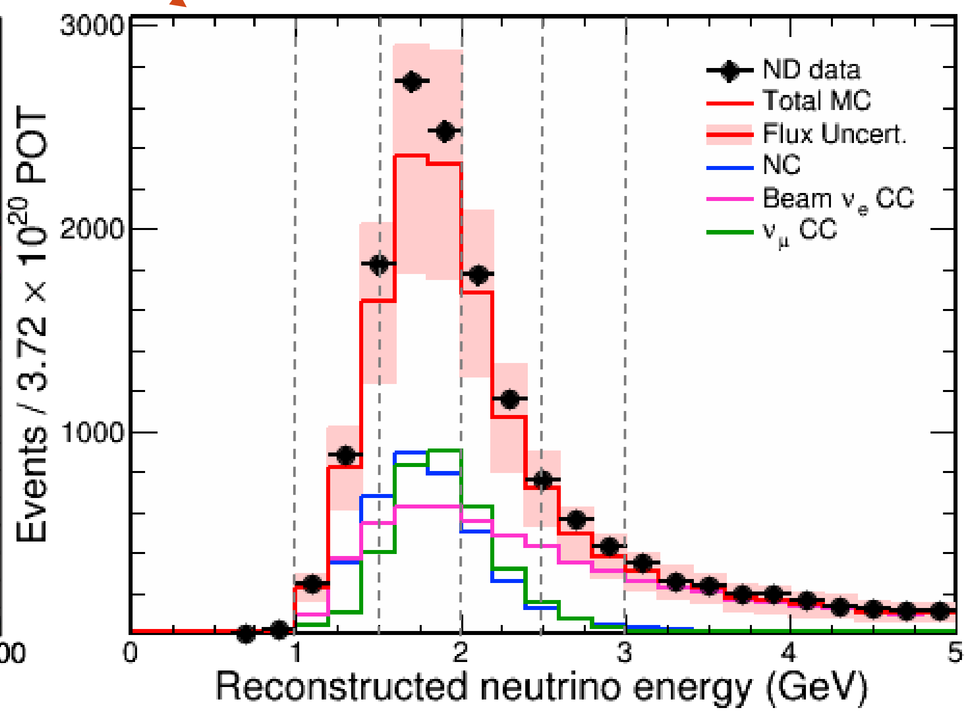
- Each layer performs convolutions to extract features and draw correlations to identify neutrino flavour
- Current version classifies events as NC, ν_μCC, ν_eCC, ν_tCC and cosmics

A Convolutional Neural Network Neutrino Event Classifier
A. Aurisano, A. Radovic, D. Rocco et.al: JINST 11 (2016) no.09, P09001

ν_e Event Selection

- Select ν_e CC interactions with 73% efficiency and 76% purity
- Equivalent to 30% increase in exposure compared to more conventional IDs
- Maximise $s/\sqrt{s+b}$
- Exhibits good data-MC agreement in Near Detector
- Analyze in 3 PID x 4 energy bins





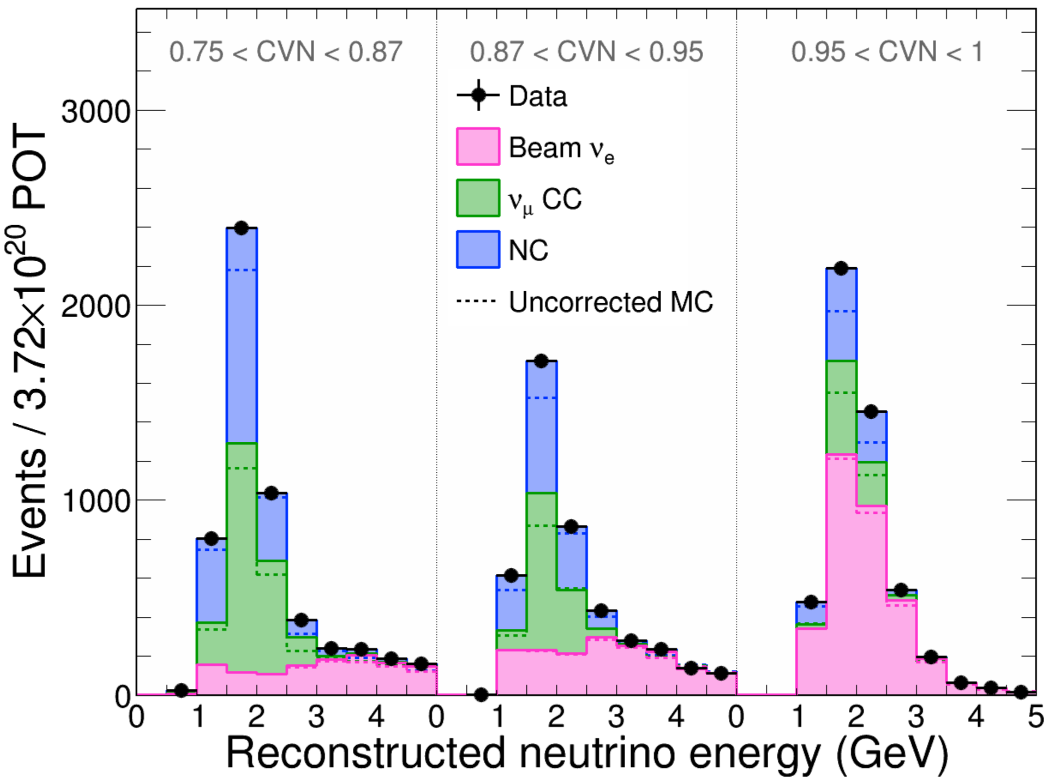
ND Background estimate

- ν_e CC selection selects 10% more events in ND data than in simulation
- Data-driven methods estimate what fraction in data is NC, beam ν_e CC and ν_μ CC

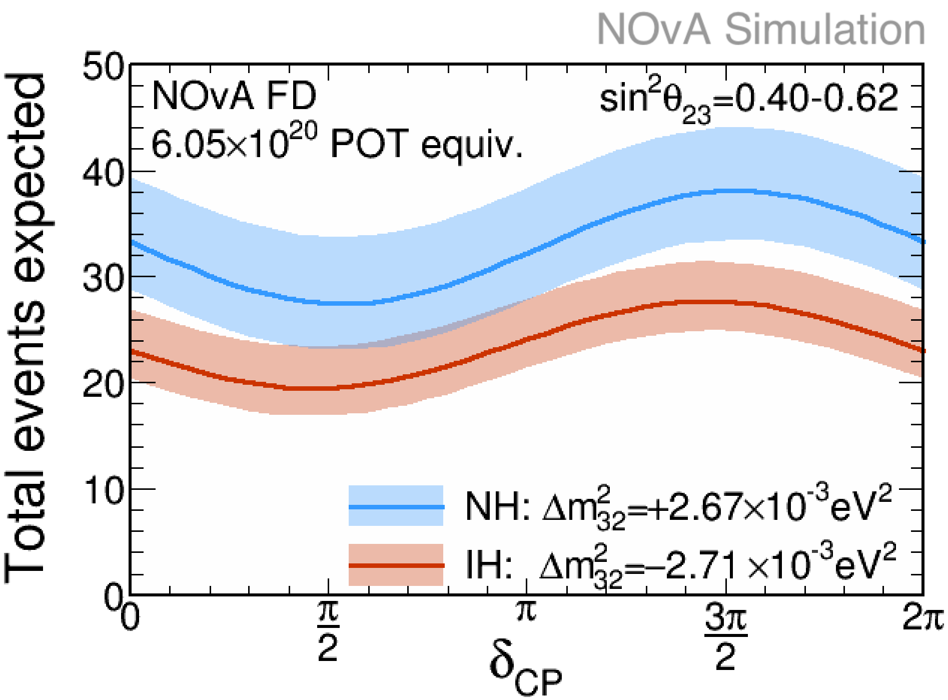
- Beam ν_e :
  - Weight ν_e with K^+ parents up 17%
  - Decrease ν_e with π^+ parent 3-4%
  - Overall 3% increase in 1-3 GeV

- Michel electrons:
  - Fit observed N_{michel} spectrum
  - Data excess assigned between NC (+17%) and ν_μ CC (+10%)

- Extrapolate adjustments to the FD for more realistic background estimates



ν_e Appearance Prediction



Background	Estimate
Total Bkgd	8.2
NC	3.7
Beam ν_e CC	3.1
ν_μ CC	0.7
ν_τ CC	0.1
Cosmic	0.5

± 10% syst.

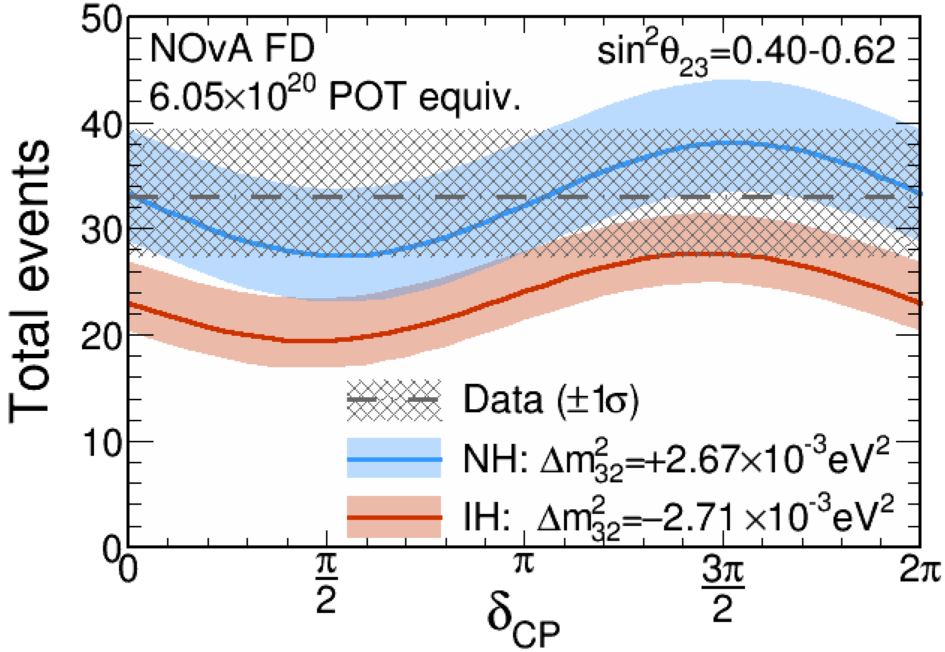
Predicted Signal

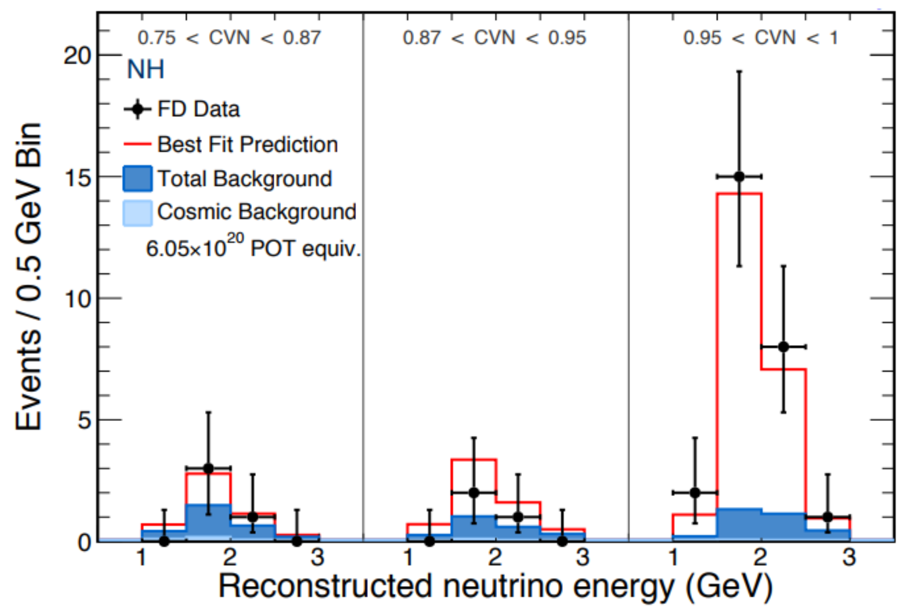
NH, $\delta_{CP} = \frac{3\pi}{2}$	IH, $\delta_{CP} = \frac{\pi}{2}$
36.4	19.4

Signal ± 5% syst.

Signal prediction depends on hierarchy, δ_{CP} and $\sin^2(\theta_{23})$
Width of band governed by $\sin^2(\theta_{23})$
Prediction values quoted for $\sin^2(\theta_{23})$ = 0.5 (maximal mixing).

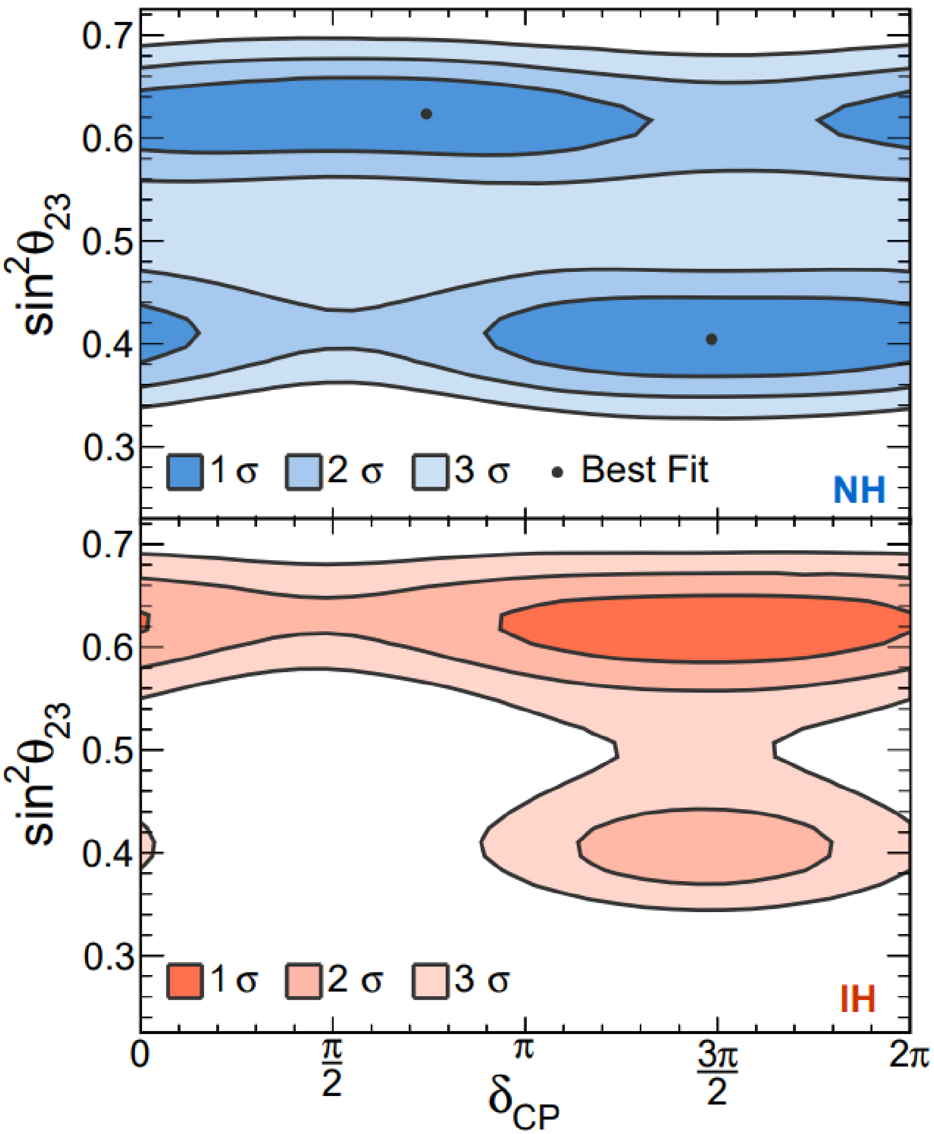
ν_e Appearance Result





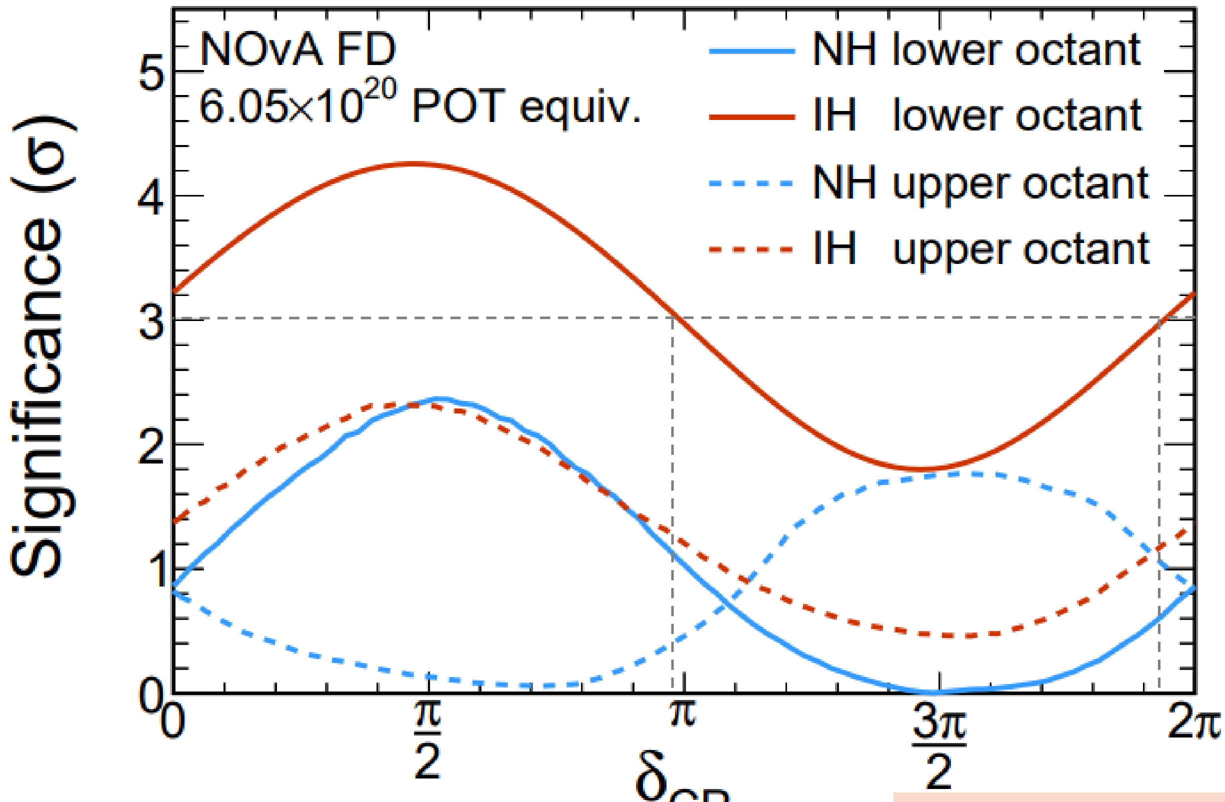
Observe **33** ν_e candidates, 8.2 ± 0.8 (syst.) predicted background

Joint Fit Result



- Joint fit of **NOvA**'s ν_e appearance and ν_μ disappearance data
- Constrain $\sin^2(2\theta_{13})$ = 0.085 ± 0.005, reactor average value
- Two statistically degenerate best fit points in Normal Hierarchy :
  - $\sin^2(\theta_{23}) = \mathbf{0.404}$, δ_{CP} = **1.48π**, and
  - $\sin^2(\theta_{23}) = \mathbf{0.623}$, δ_{CP} = **0.74π**
- The best-fit point in the Inverted Hierarchy near $\delta_{CP} = \frac{3\pi}{2}$
  - 0.46σ from the global best-fit points

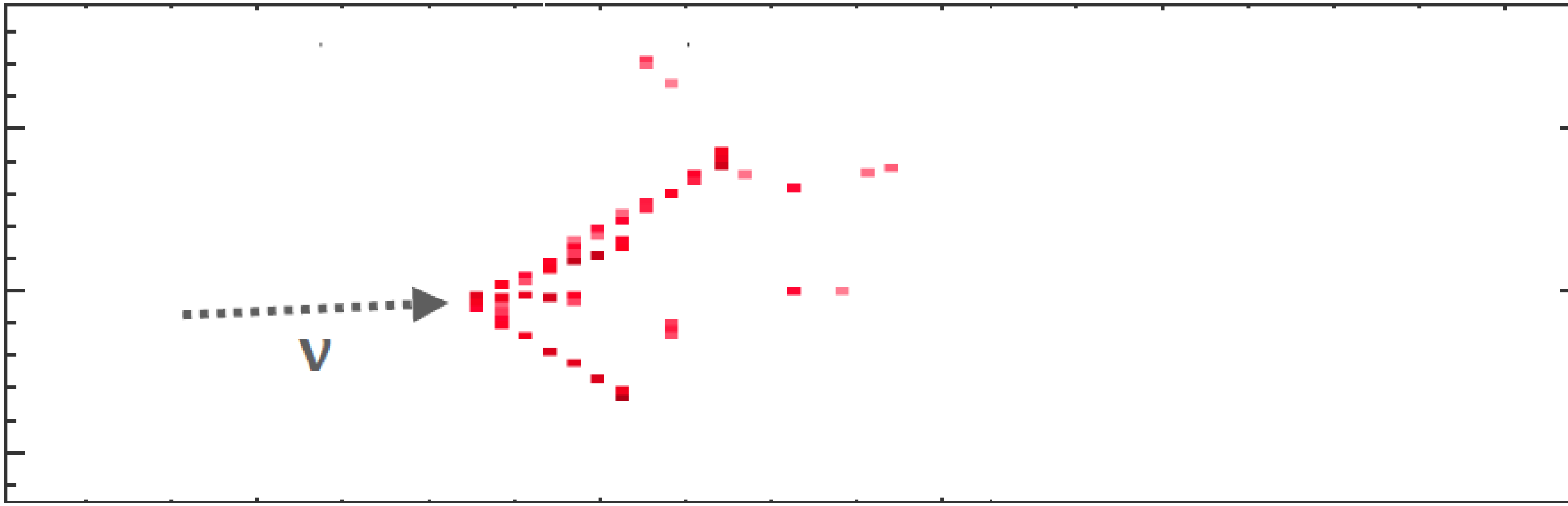
Joint Fit Result



- Inverted Hierarchy in lower octant is disfavoured at > 93% C.L. for all values of δ_{CP}
  - **Excluded > 3σ outside the range $0.97\pi < \delta_{CP} < 1.94\pi$**
  - Updating this coming fall with 50% more data; antineutrinos (2018) to break degeneracies

Phys. Rev. Lett. 118, 231801 (2017)
Published 5th June 2017

WG1: Wednesday 27th, Linda Cremonesi (UCL)
"Details of the NOvA oscillation analyses and systematic uncertainties"



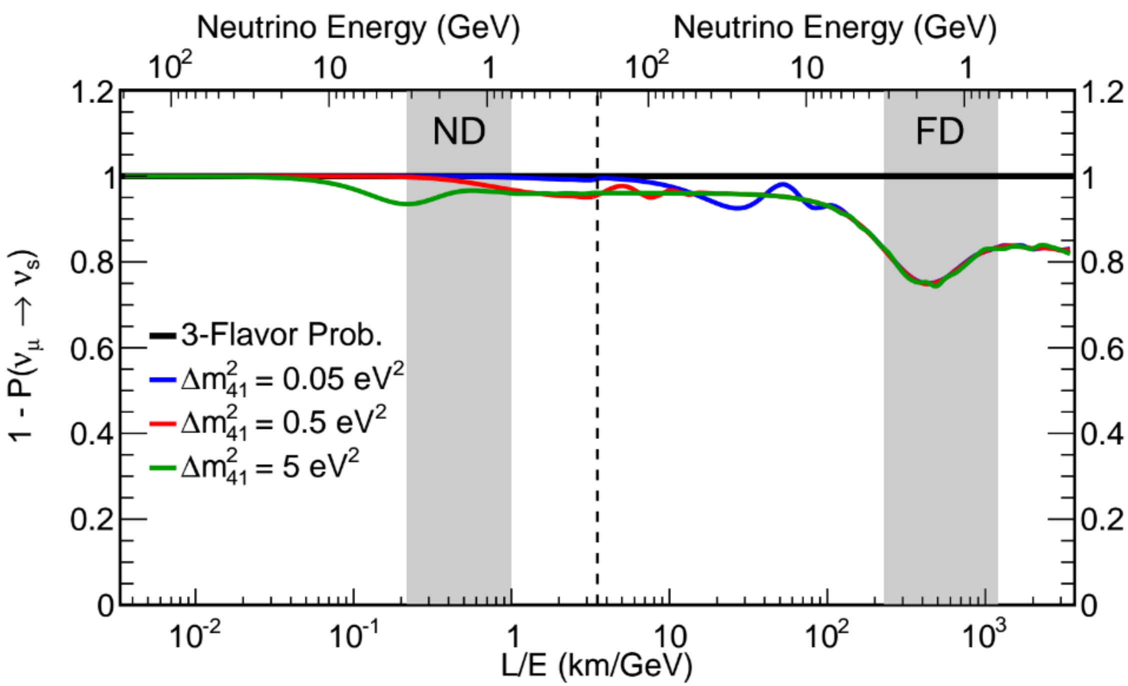
3. NC Disappearance

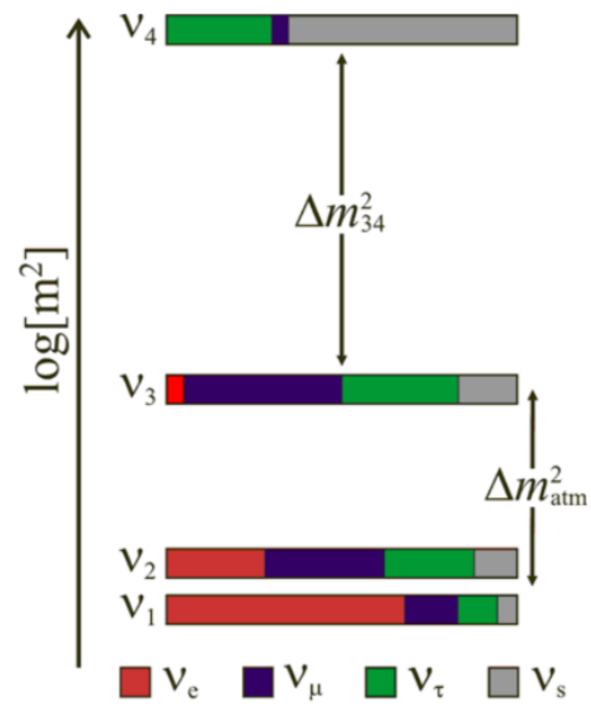
NEW!

NOVA'S FIRST 2017 DATASET RESULT

Why NC's?

- Do any ν_μ's oscillate to a sterile state?
  - ν_μ to ν_s mixing causes energy-dependent depletion of NC
- NC spectrum unaffected by oscillations among active flavours
  - Select NC events in ND, extrapolate to FD prediction
  - Count NC events in FD, compare to prediction and fit shape
  - Extend to 3+1 model
    - Fix Δm^2_{41} = 0.5 eV^2 rapid oscillations in FD, minimal in ND



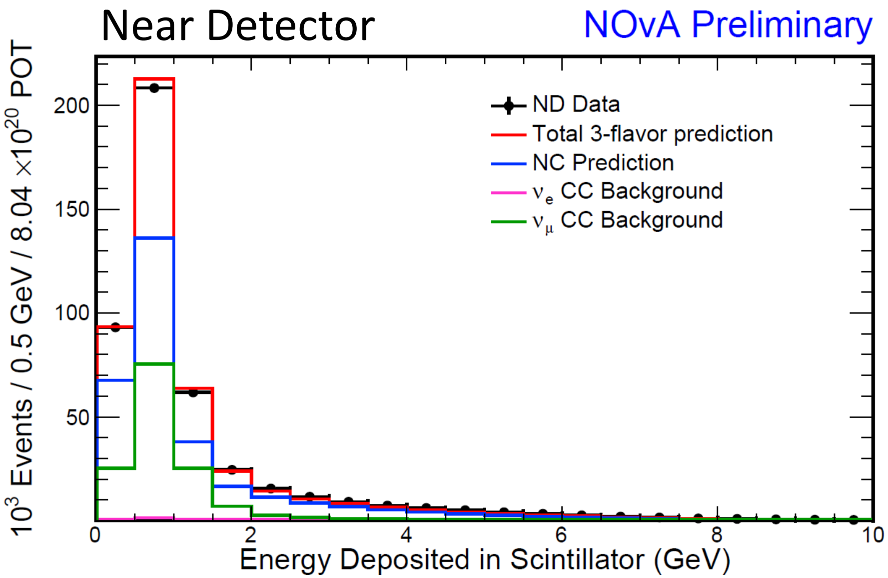


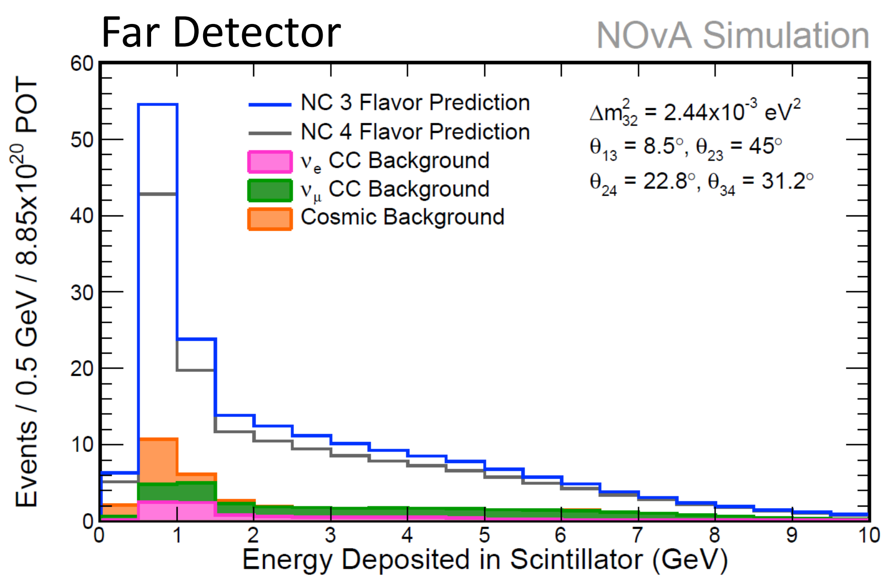
2017 NC Analysis

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

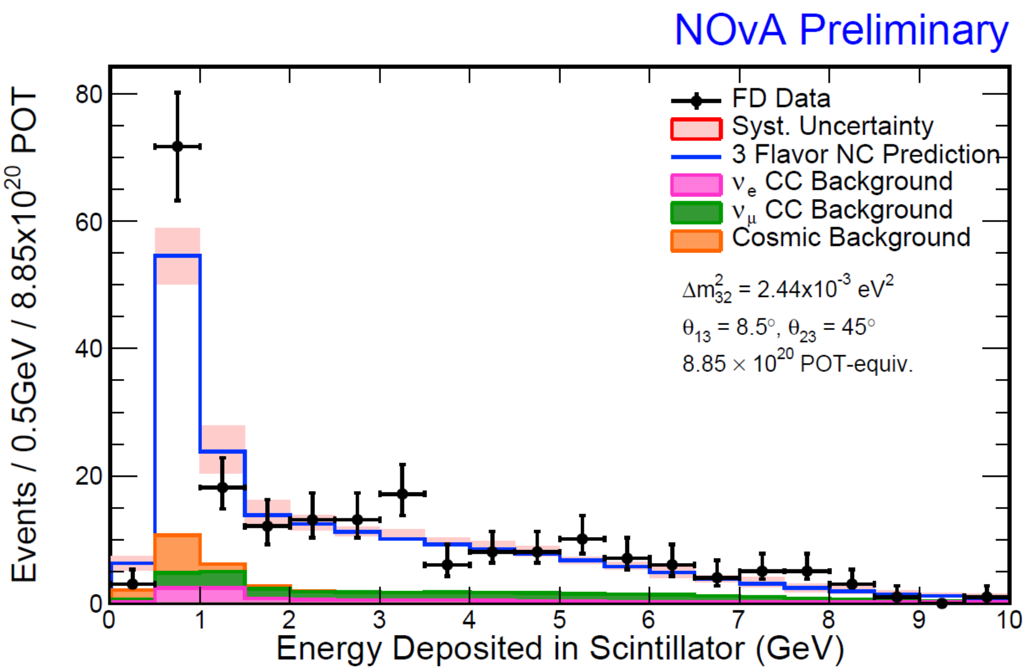
Background	Estimate
Total Bkgd	42.8
ν_μ CC	22.2
ν_e CC	9.9
ν_τ CC	2.8
Cosmic	7.9

Total Signal Prediction: **148.3**





NC Disappearance 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

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

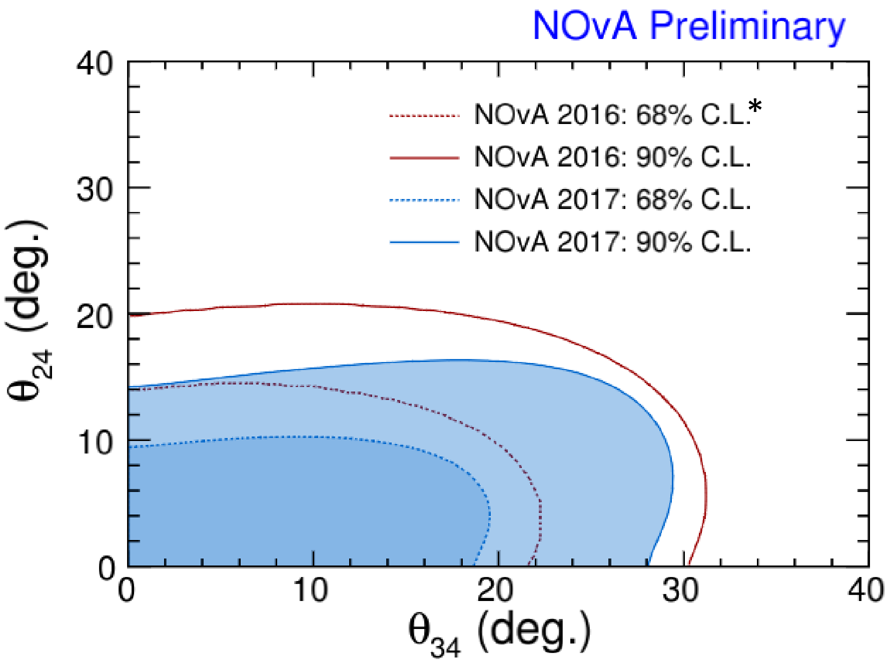
No NC disappearance → R = 1

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

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

NC Disappearance Results

- Constrain **NOvA**'s degenerate best fit points for $\sin^2(\theta_{23})$, $|\Delta m^2_{32}|$, and δ_{CP} (NH)
- Profile $\sin^2(\theta_{23})$, δ_{24}
- Perform a shape-based fit for θ_{24} and θ_{34}



*: 2016 applies constraints for maximal mixing; rate-only fit

	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

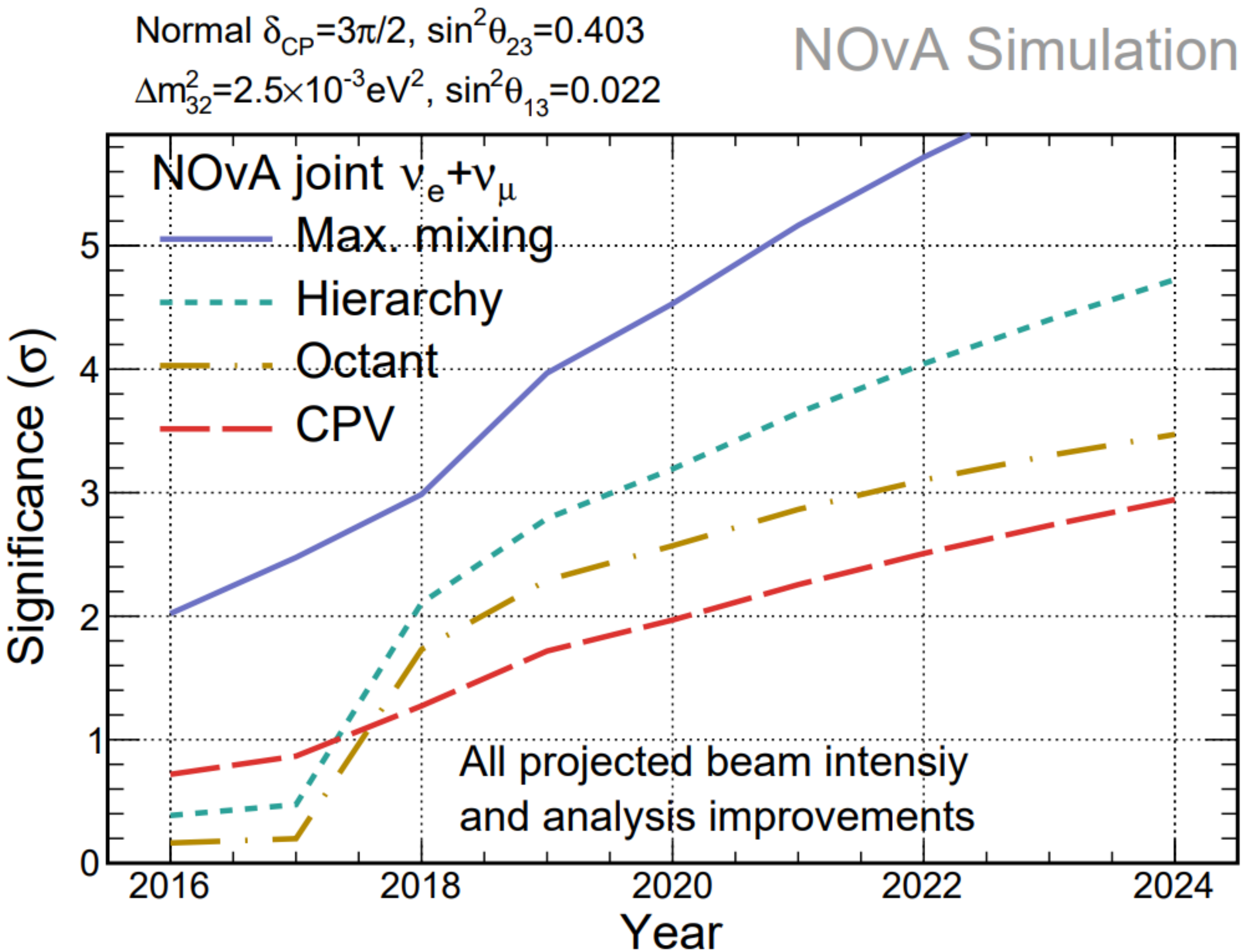
In a 3+1 analysis, for Δm^2_{41} = 0.5 eV^2:
θ_{24} < 16.2 at 90% C.L.
θ_{34} < 29.8 at 90% C.L.

WG1+WG5: Tuesday 26th, Adam Aurisano (U. Cincinnati) Today: 11:30am
"Looking for Sterile Neutrinos via Neutral-Current Disappearance with NOvA"

2017 & Beyond

Future Sensitivities

Projected significance of rejecting maximal mixing, wrong hierarchy, wrong octant and CP conservation



- Improvements in **suppressing systematics**
- 25% gain in exposure from **improved analysis**
- **40 weeks of beam** starting 2018
- **PIP 1+**: 800 kW in 2019, 900 kW in 2021 + target improvements

Future Sensitivities

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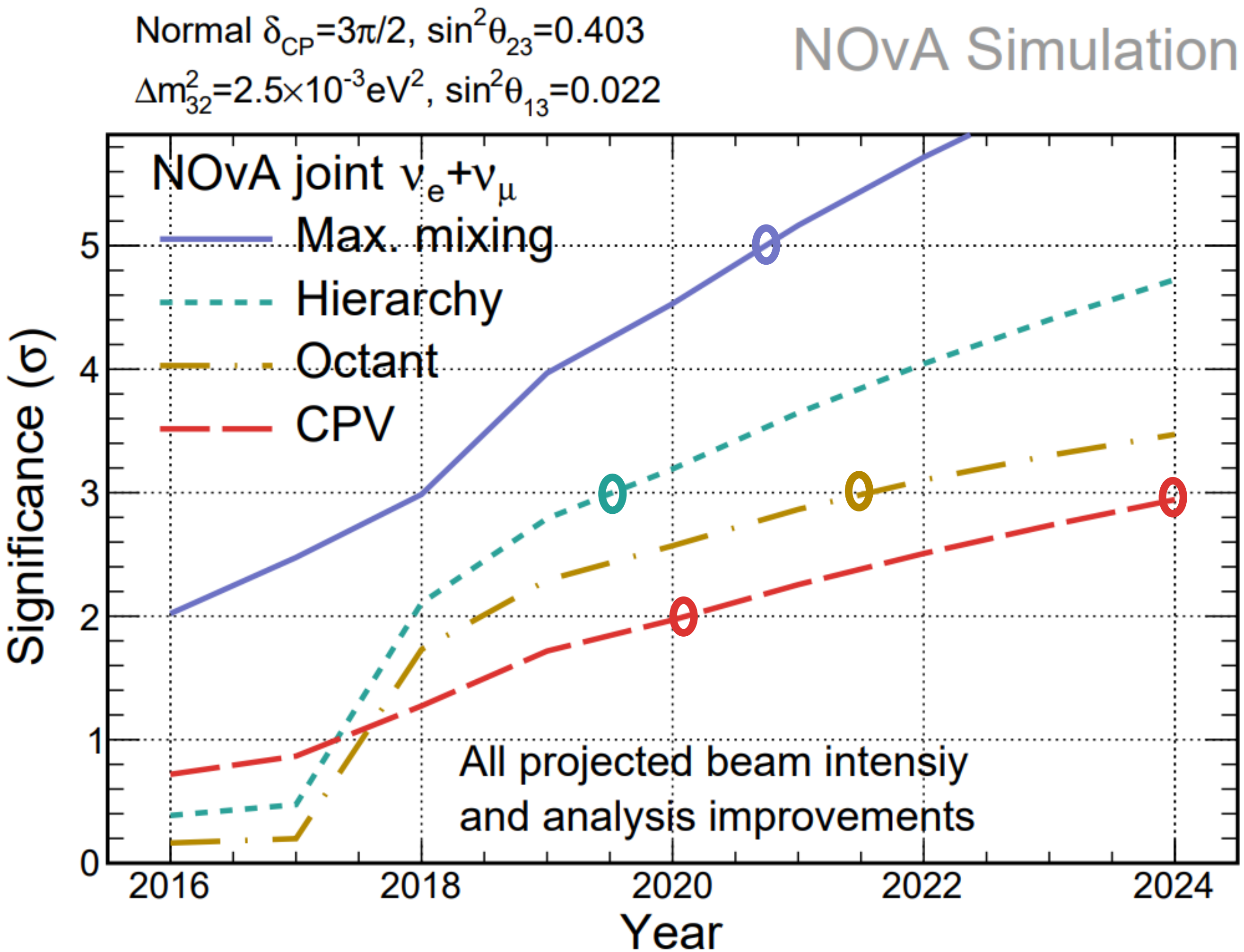

- Improvements in **suppressing systematics**
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Summary

- **NOvA** has a rich physics program
- Muon neutrinos disappear
  - **NOvA** disfavours maximal mixing at 2.6σ
- Electron neutrinos appear
  - Slight preference for NH; IH, lower octant, π/2 ruled out (>3σ)
- Updated NC disappearance analysis with **8.85 x 10^{20} POT-equiv.**
  - **NOvA** sees no evidence for sterile neutrino mixing
  - Competitive limits; ND short-baseline searches underway
- Updated ν_μ - ν_e joint fit and ν_μ-only results will be presented this Fall
- First anti-neutrino results to be released Summer 2018

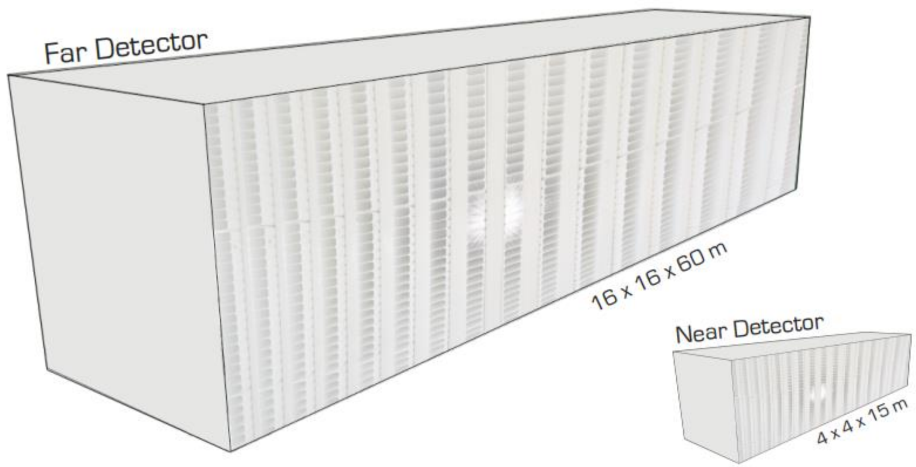
@novaexperiment

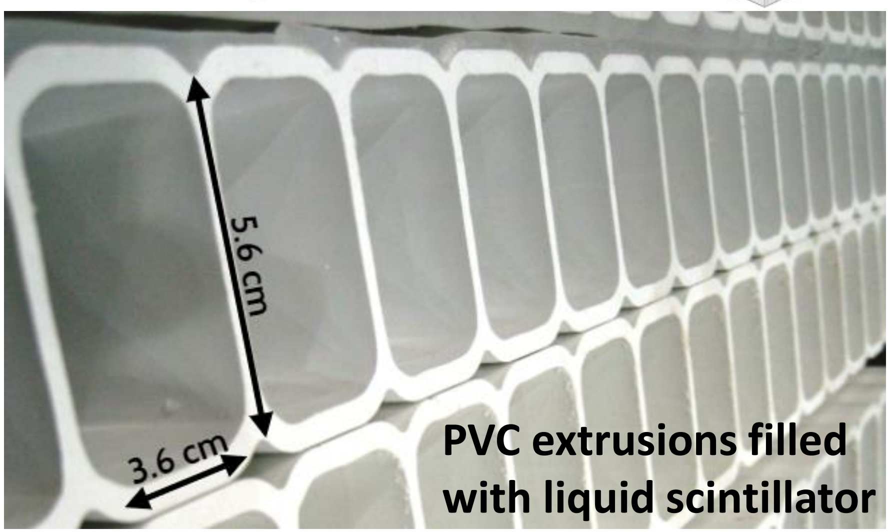
Tack så mycket!

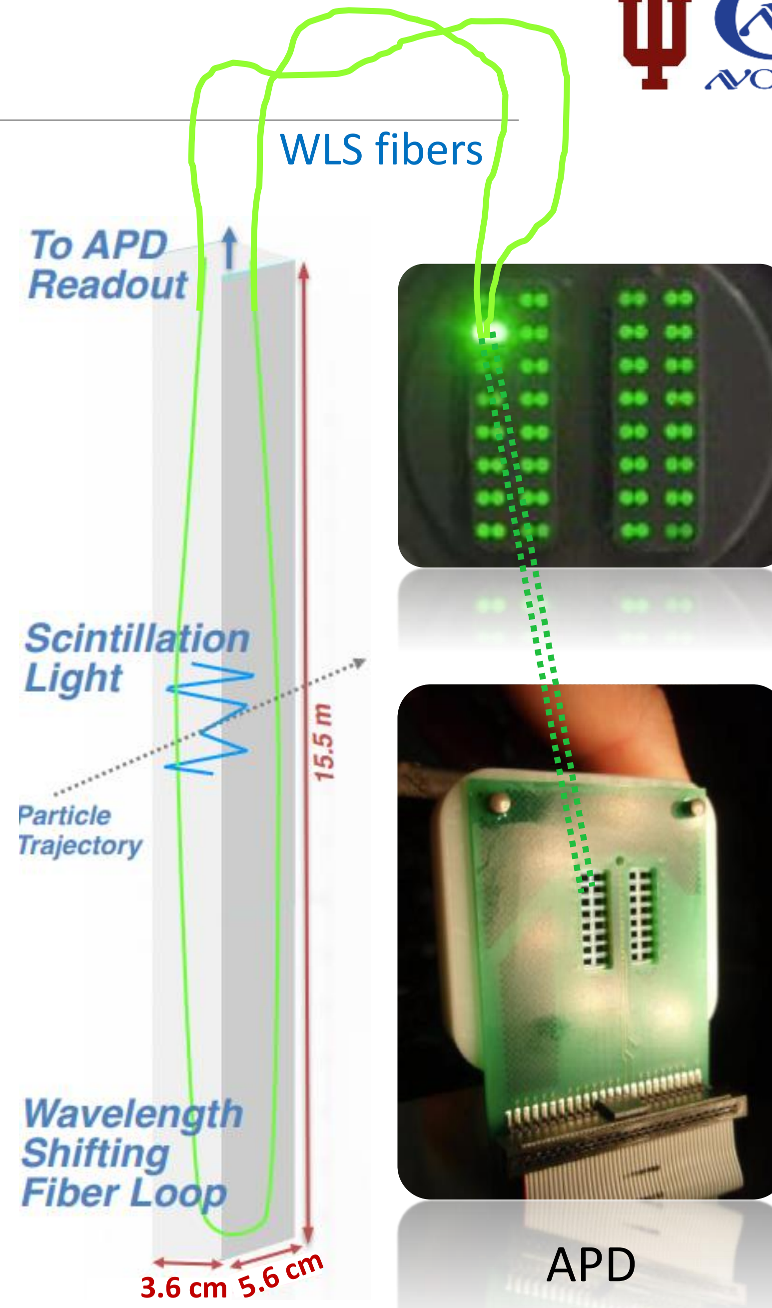
@novaexperiment

Backup

The NOvA detectors



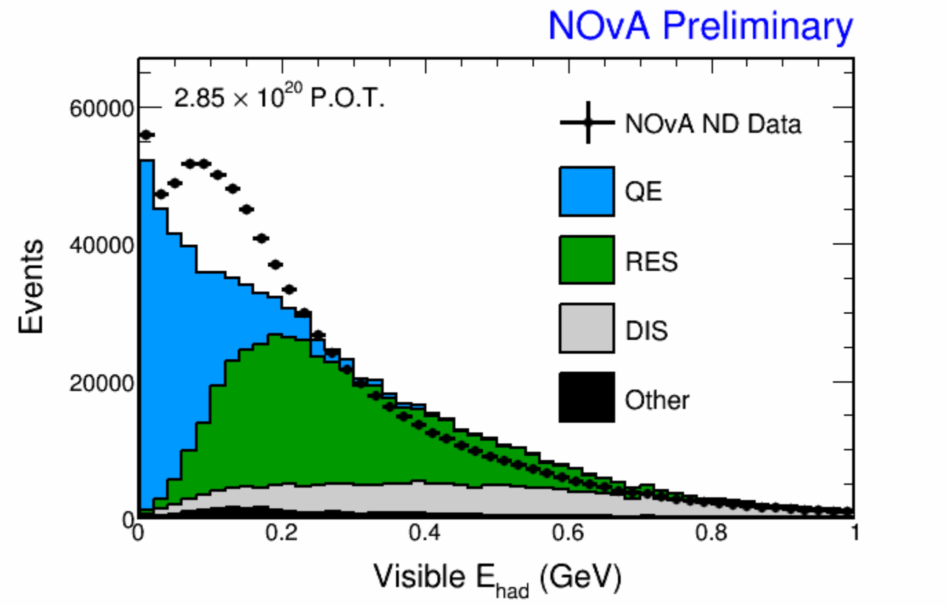




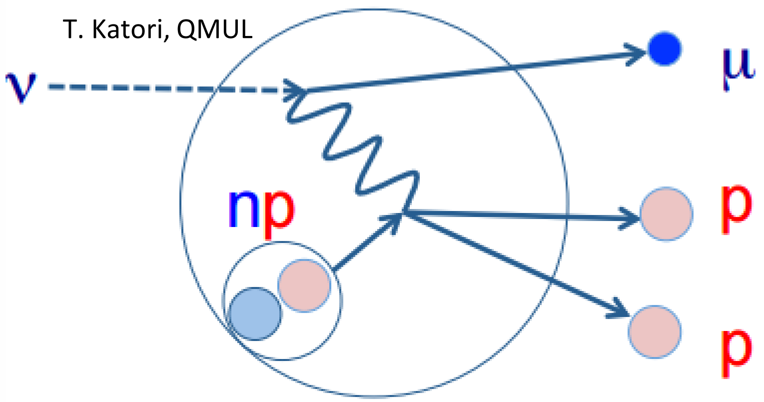
- ND: 20,000 channels
- FD: 344,000 channels

Nuclear correlations

- ND hadronic energy (**ν_μ CC**) suggests extra process between QE and Δ production
- MINERVA report similar excess in their data[1]



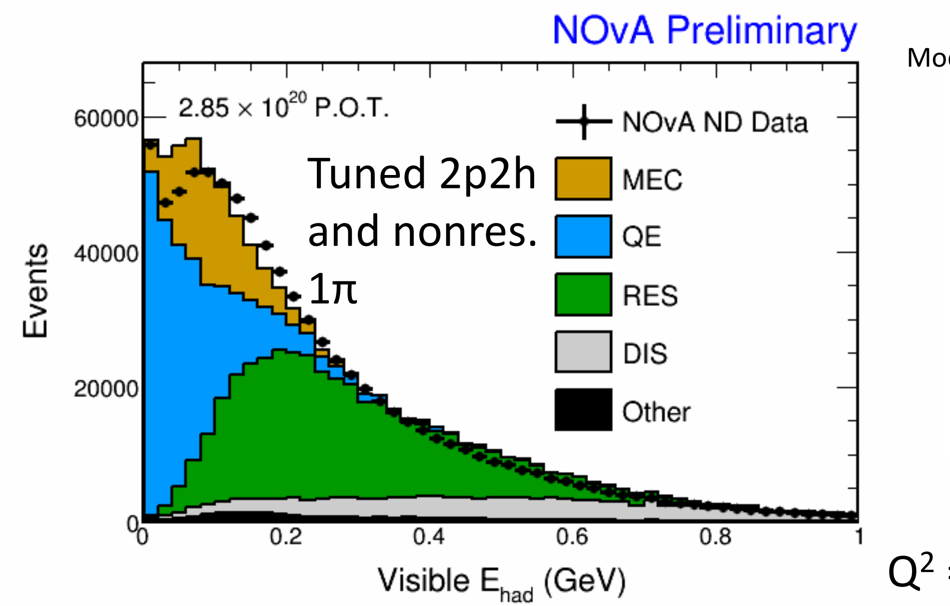
Multi-nucleon 2p2h interaction

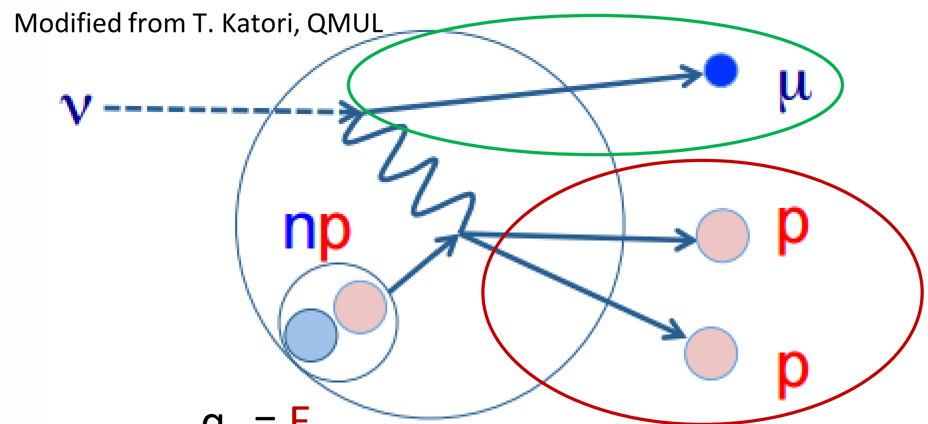


[1]P.A. Rodrigues et al., PRL 116 (2016) 071802 (arXiv:1511.05944)
[2]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
[3]P.A. Rodrigues et al., arXiv:1601.01888

Nuclear correlations

- ND hadronic energy (**ν_μ CC**) suggests extra process between QE and Δ production
- MINERVA report similar excess in their data[1]



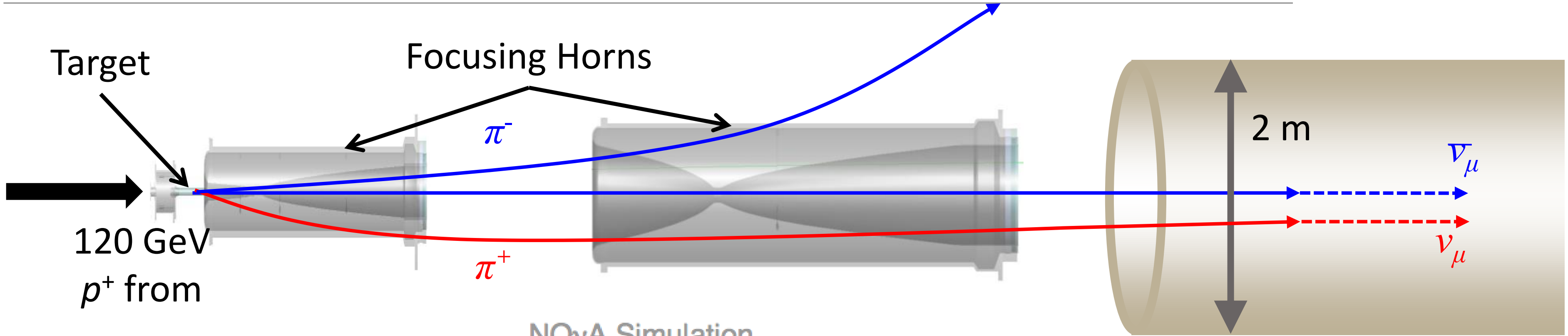


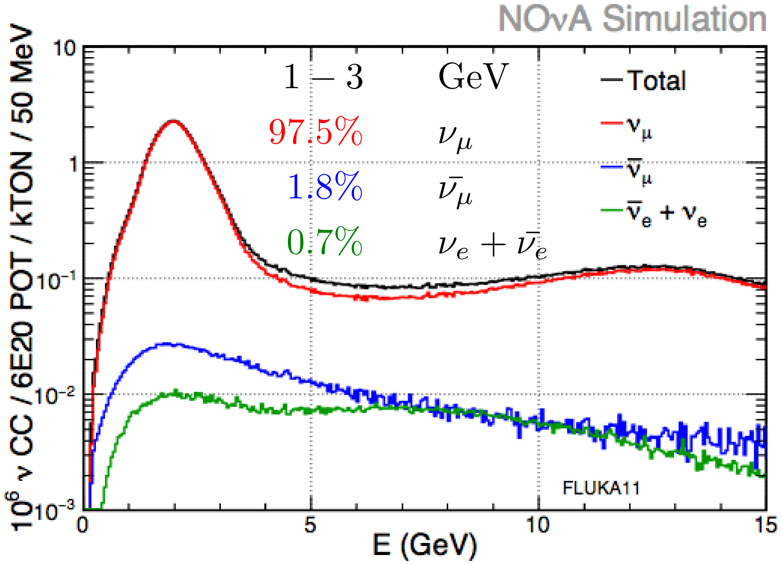
$$q_0 = E_{had}$$
$$E_\nu = E_\mu + E_{had}$$
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_\mu) - M^2_\mu)$$
$$|\vec{q}| = Q^2 + q_0$$

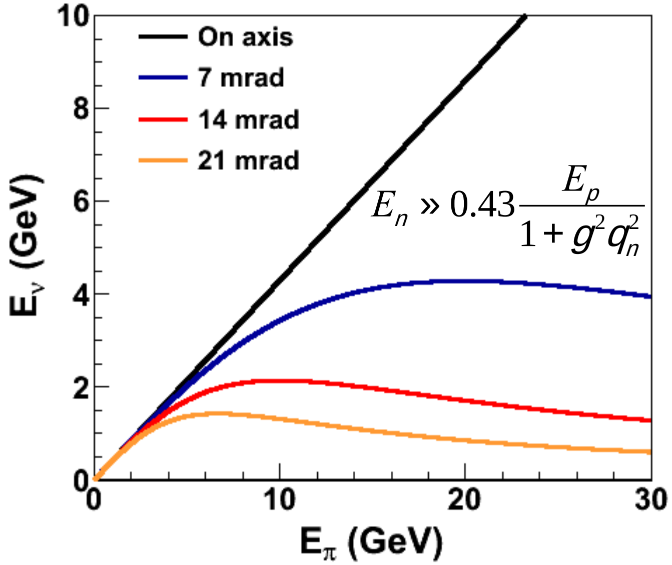
- Enable GENIE's empirical Meson Exchange Current (MEC) model[2]
  - Also reduce single non-resonant pion production by 50%[3]
  - Reweight to match observed excess as a function of $|\vec{q}|$ transfer

[1] P.A. Rodrigues et al., PRL 116 (2016) 071802 (arXiv:1511.05944)
[2] S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
[3] P.A. Rodrigues et al., arXiv:1601.01888

Making an off-axis neutrino beam

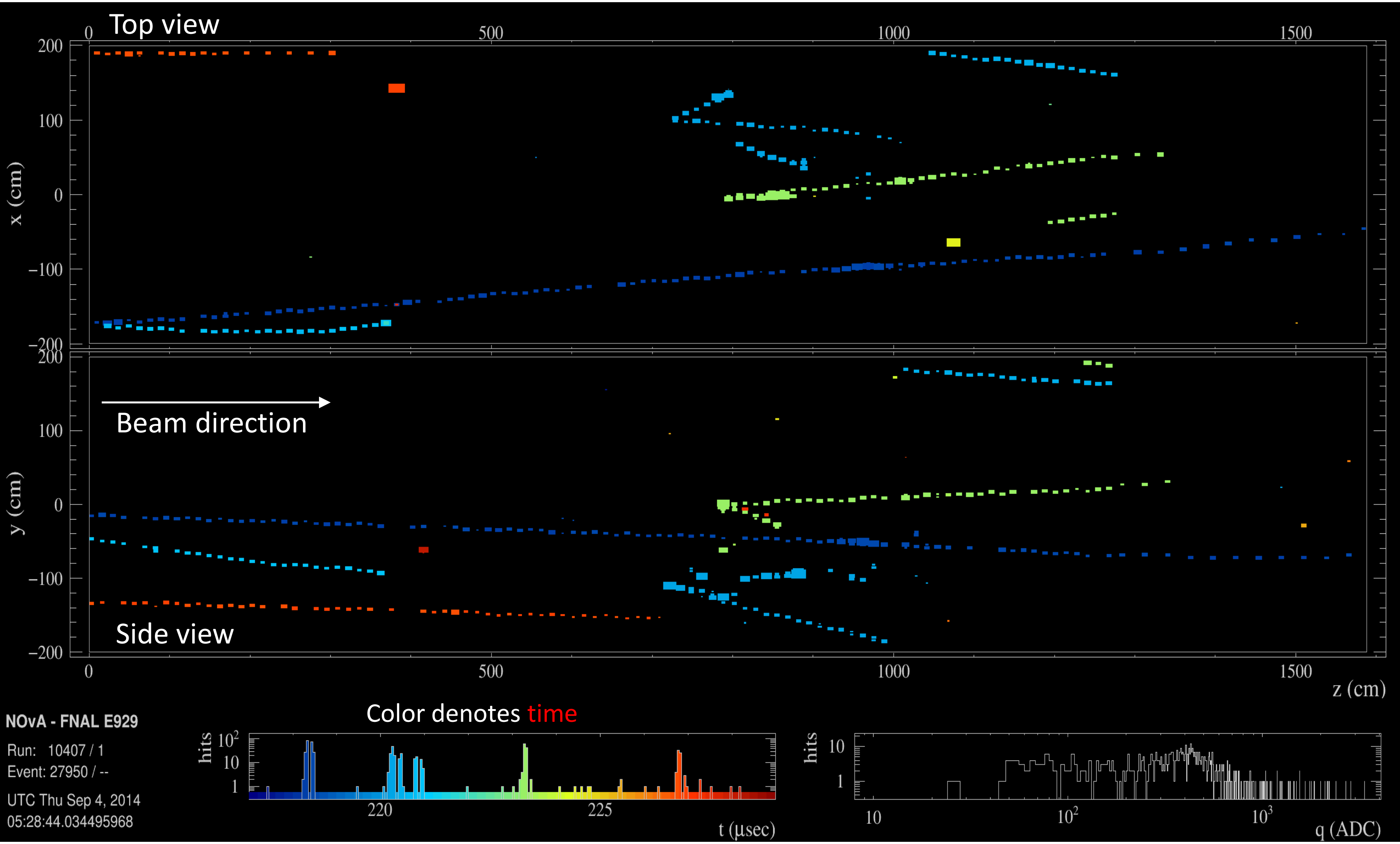






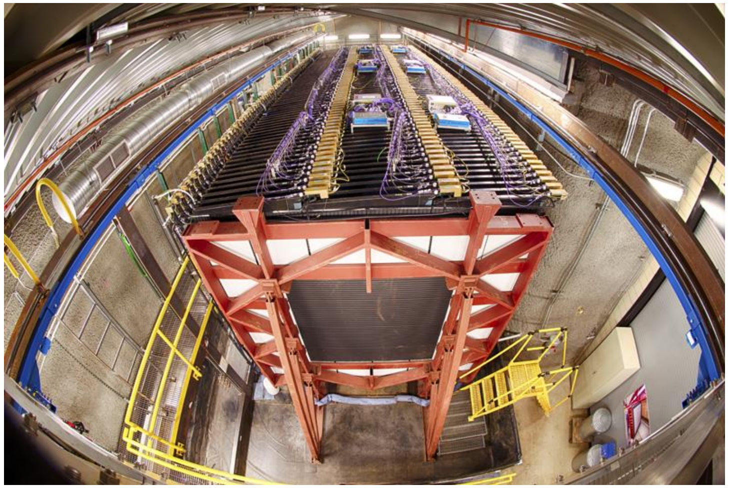
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events

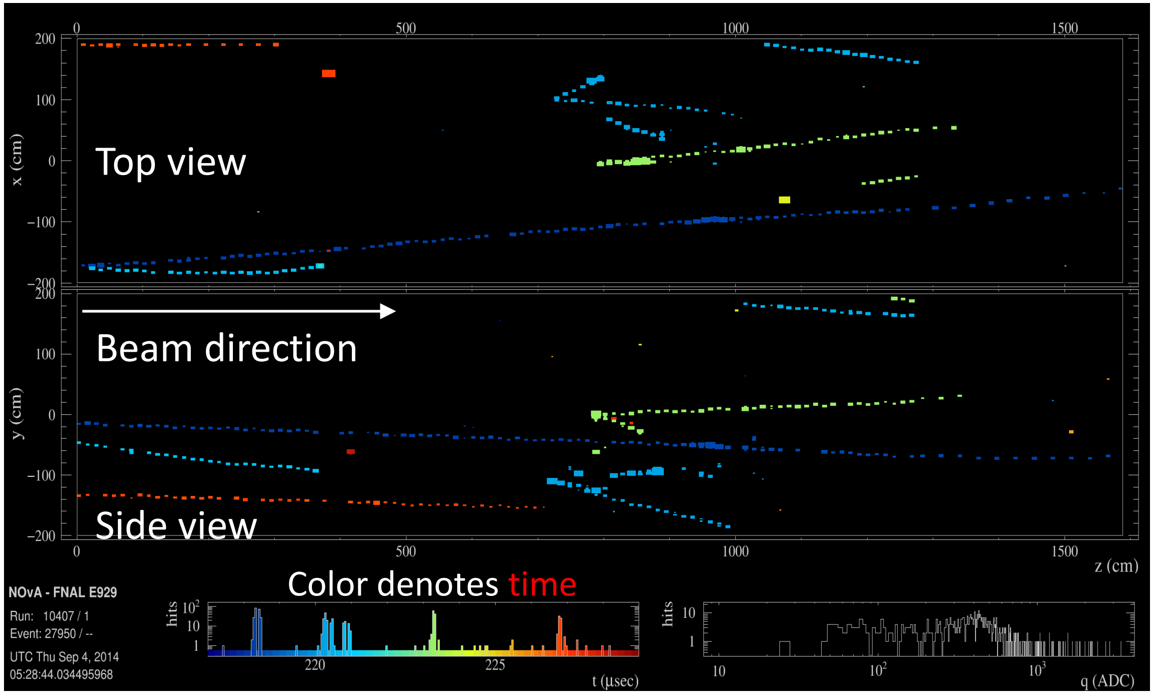
Near detector spills



Near detector spills

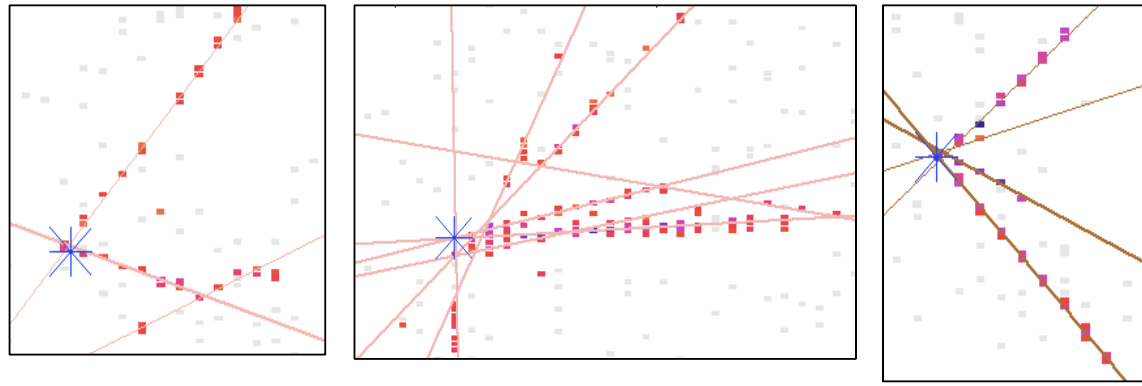
- Multiple events in ND per NuMI spill
  - Over 2 million/year fiducial events collected
- Events separated using topology and timing
  - Color in display denotes time
  - Blue hits are early in spill, red are late



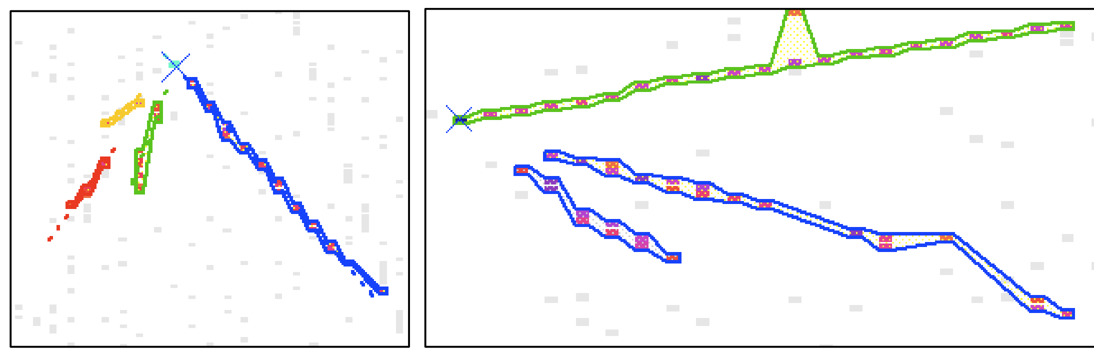


Reconstruction

Vertexing: Find **lines of energy depositions** w/ Hough transform CC events: 11 cm resolution



Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong dE/dx

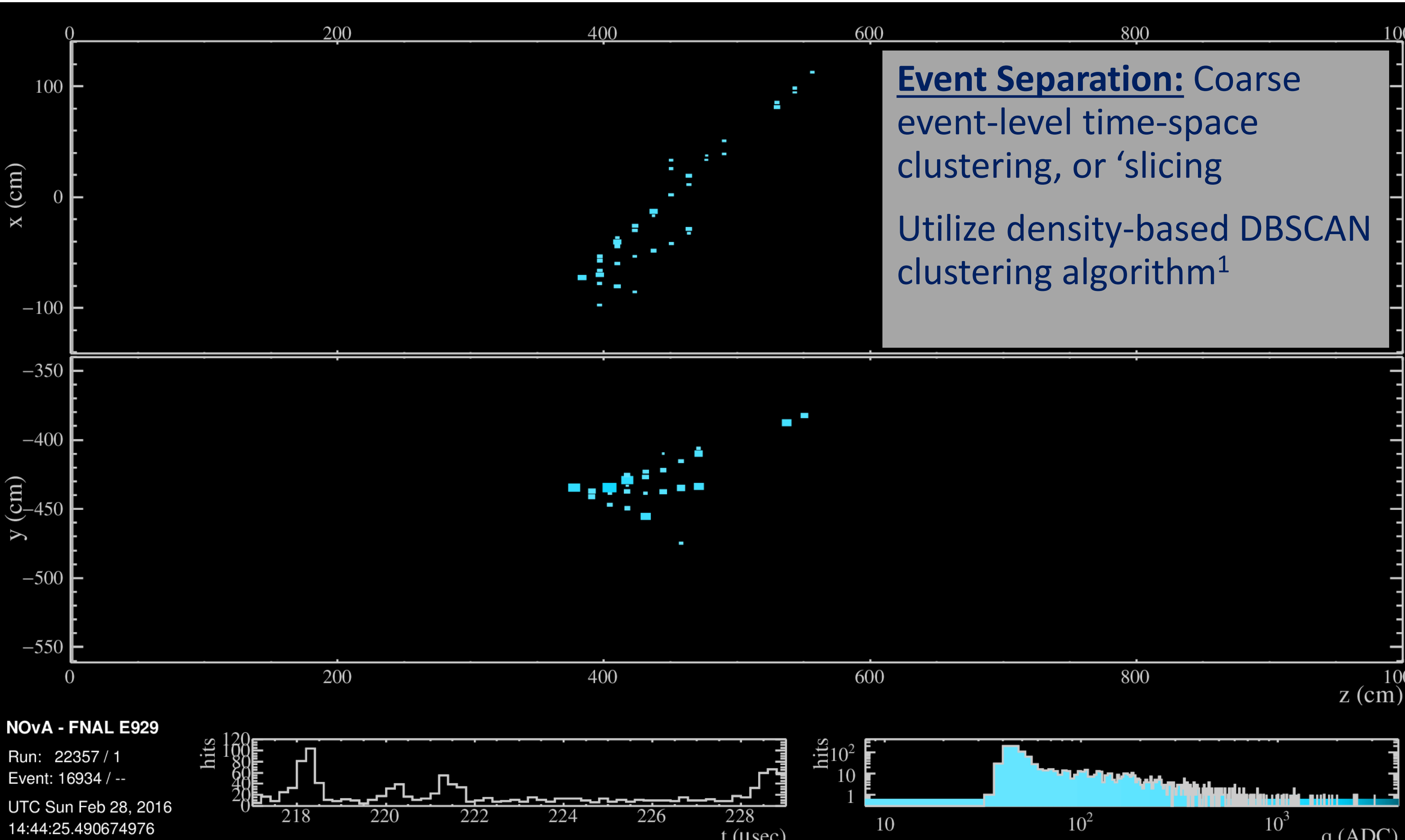


Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.

Reconstruction

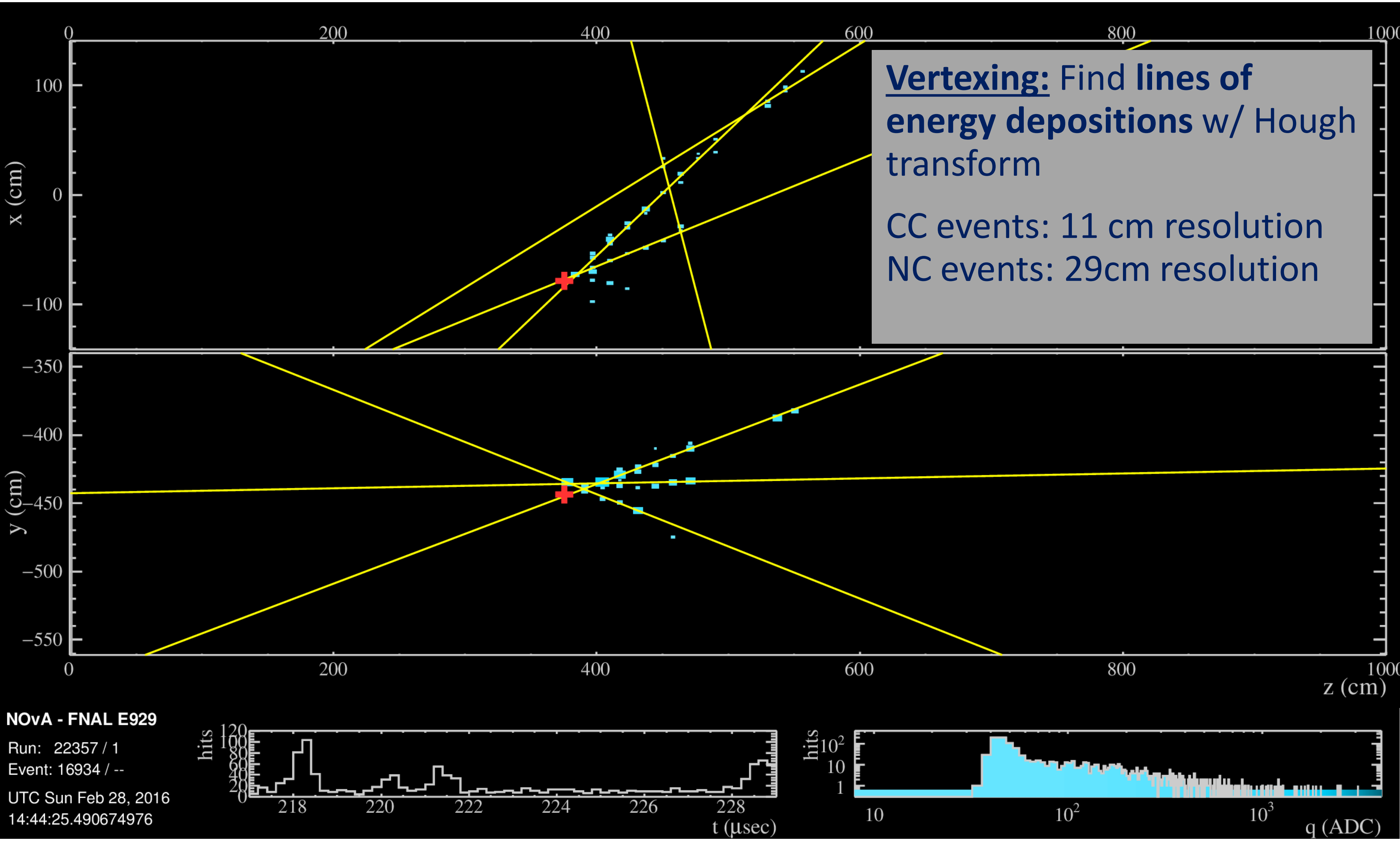
Event Separation: Coarse event-level time-space clustering, or ‘slicing

Utilize density-based DBSCAN clustering algorithm[1]



1. M. Ester, et. al., A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise (1996)

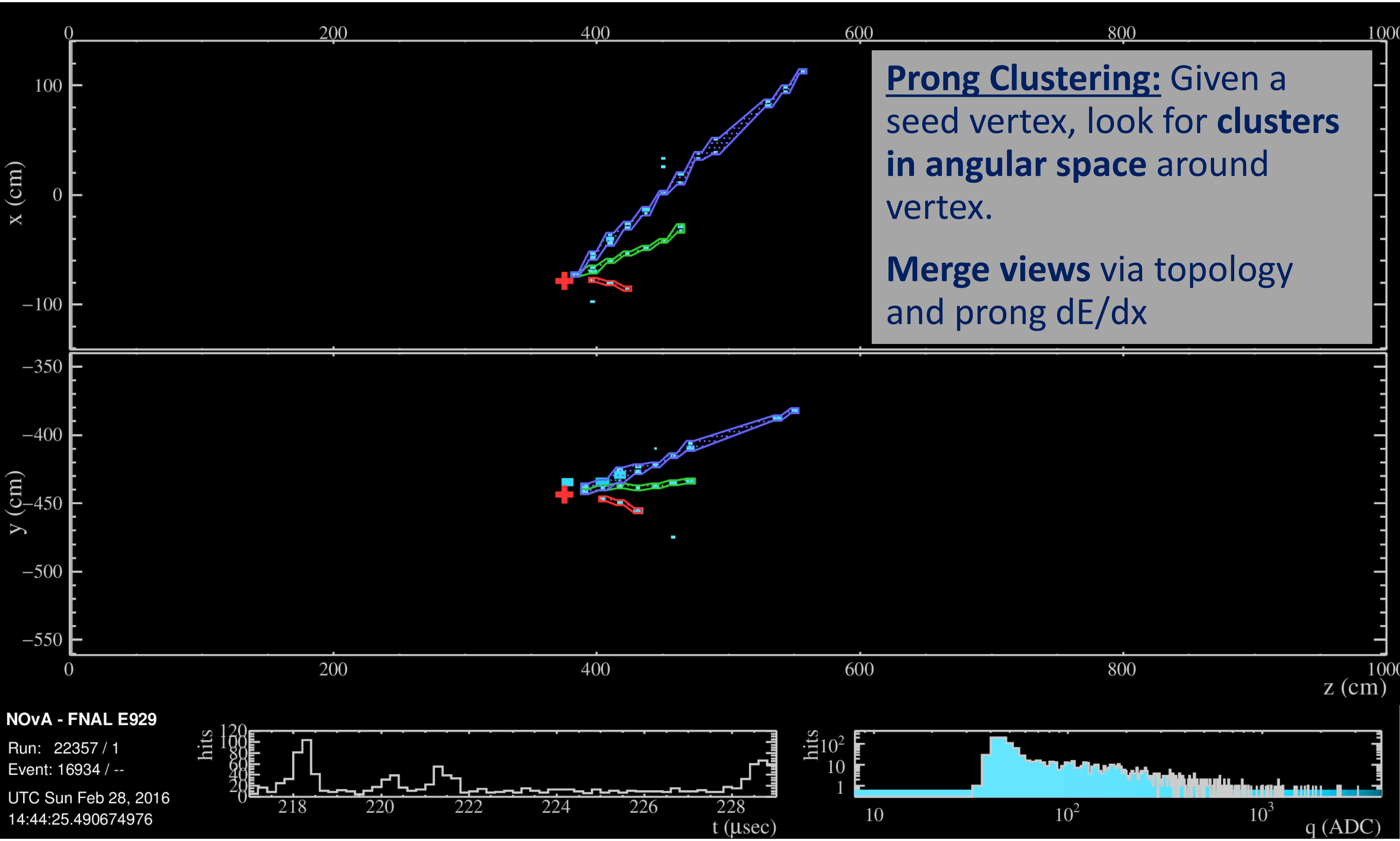
Reconstruction



<u>Vertexing:</u> Find **lines of energy depositions** w/ Hough transform

CC events: 11 cm resolution
NC events: 29cm resolution

Reconstruction



<u>Prong Clustering:</u> Given a seed vertex, look for **clusters in angular space** around vertex.

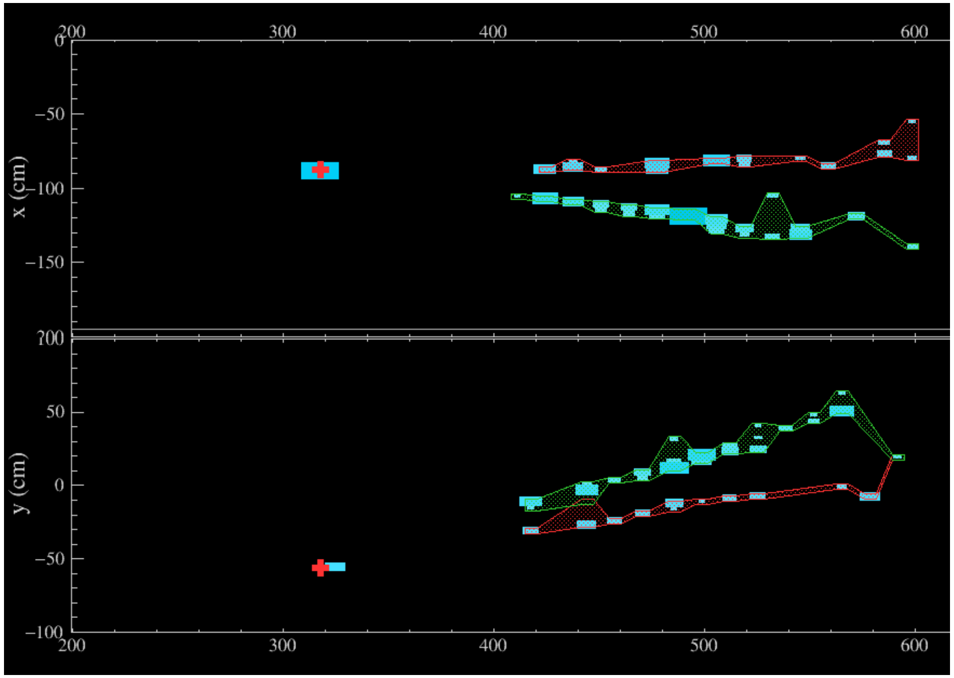
Merge views via topology and prong dE/dx

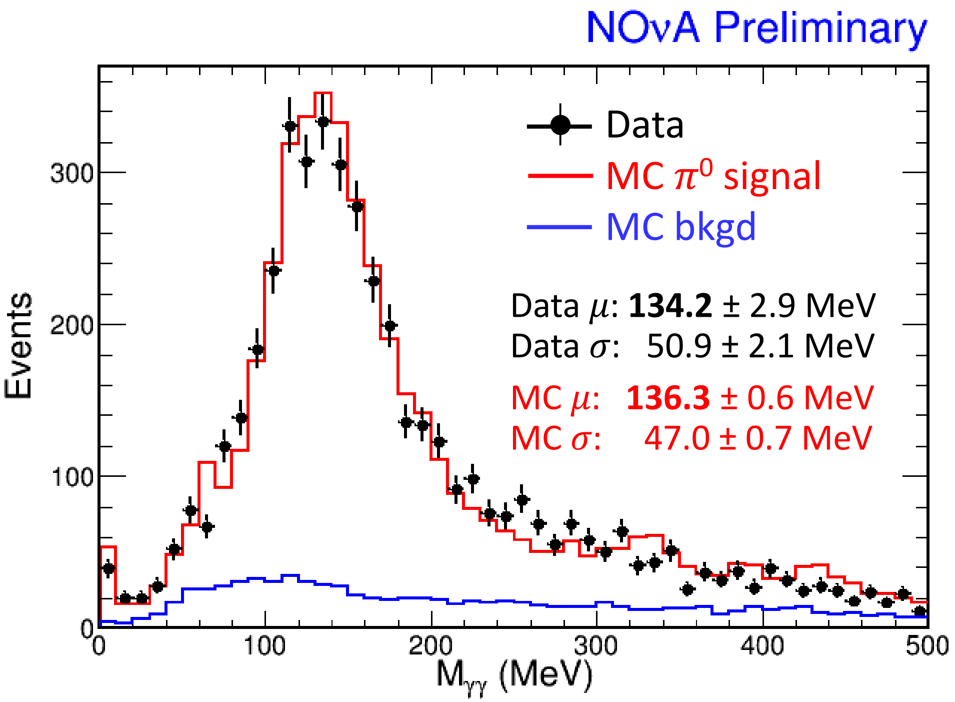
Reconstruction

Excellent reconstruction capabilities

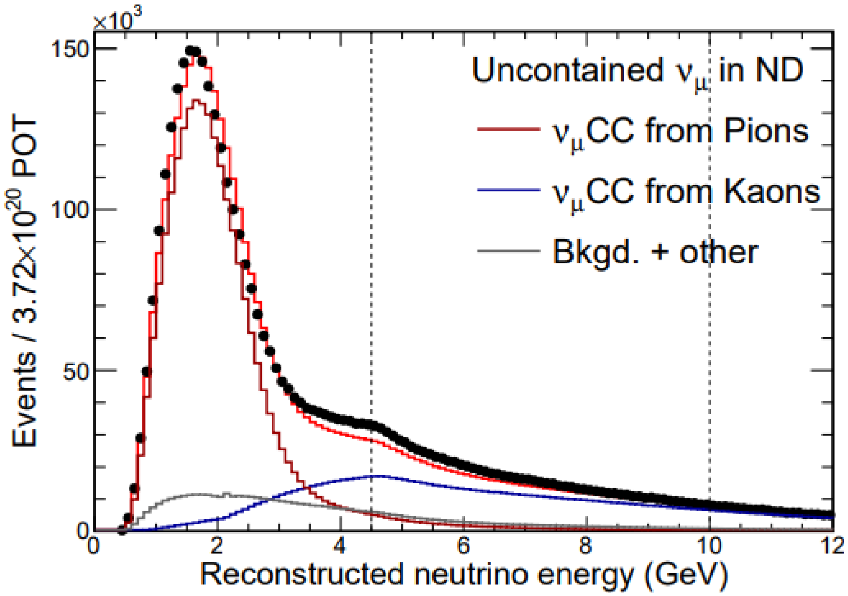
Reconstruct π^0 peak – used as a calibration cross-check

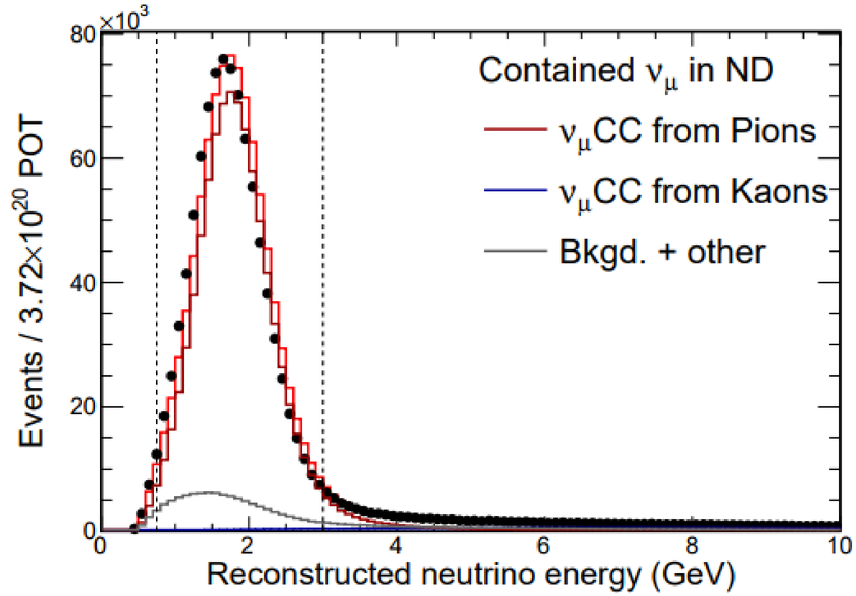
- Demonstrates ability to reconstruct NC events





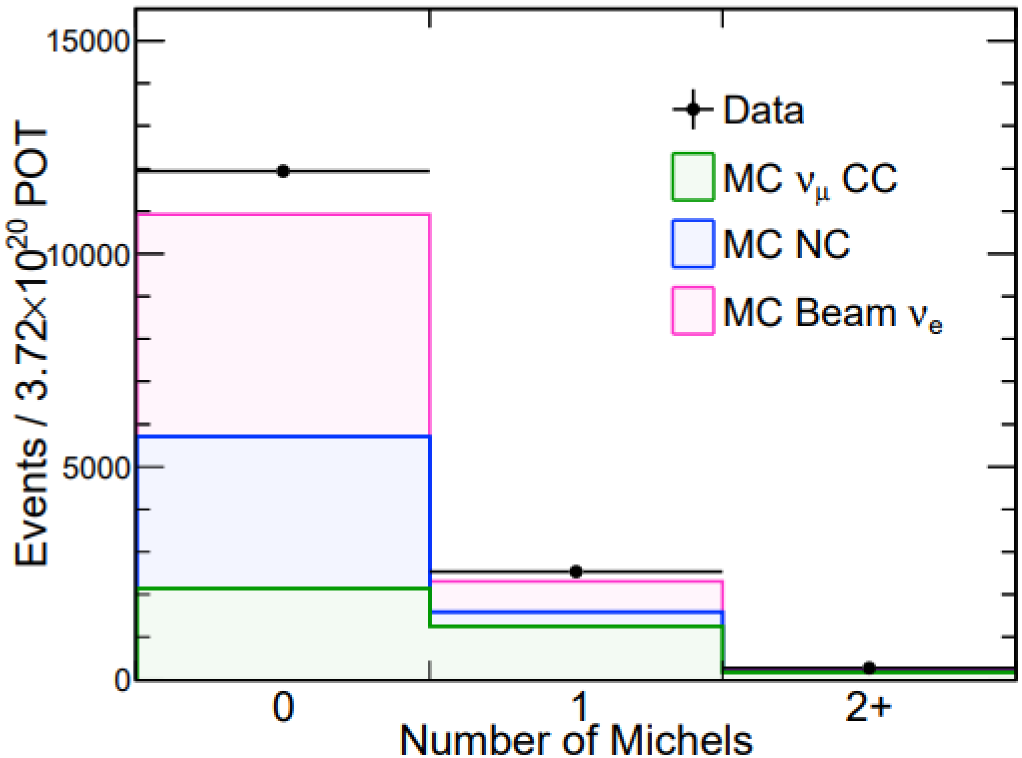
Beam ν_e Background Estimate





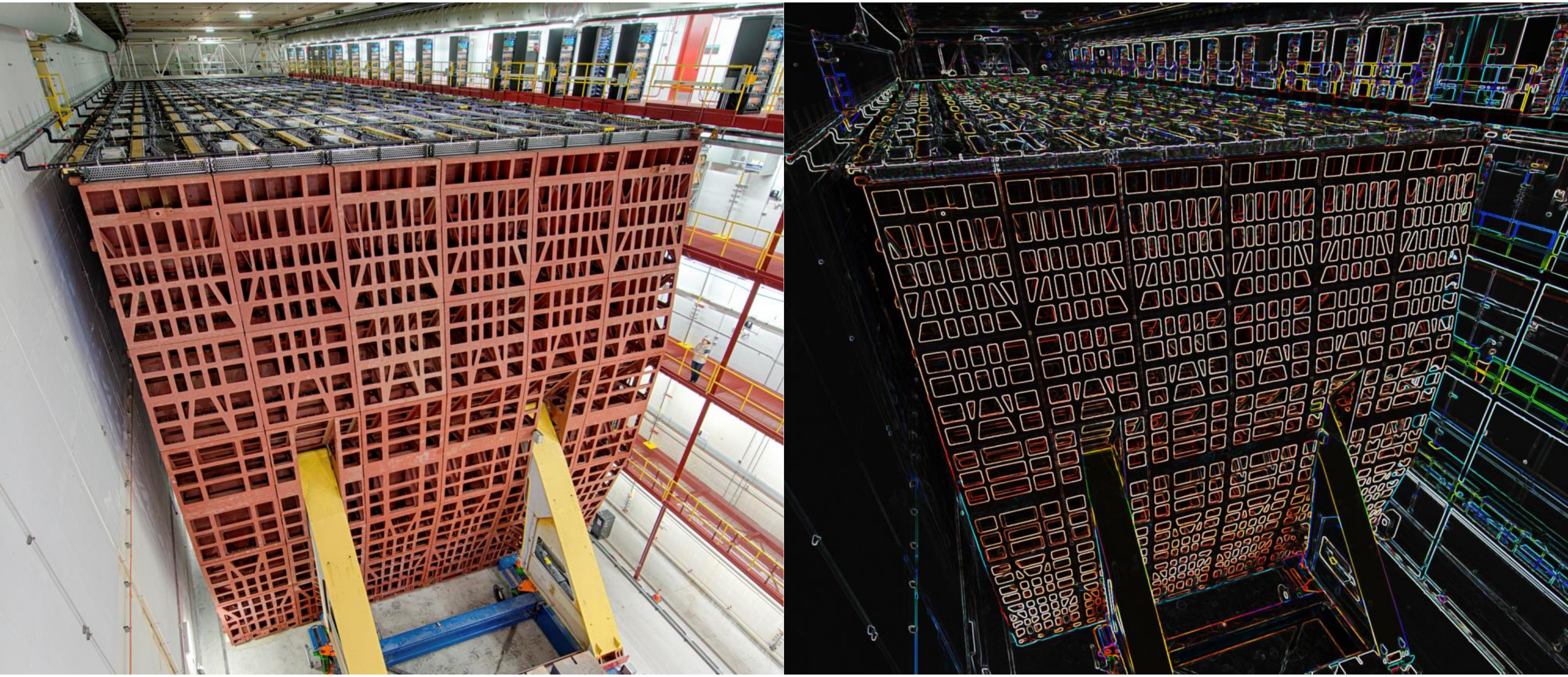
- Beam ν_e's at **NOvA**'s location mostly arise from muon decay in beamline
- At low energy, ν_μ's and beam ν_e's come from common pion parents; at higher energy, the parents are Kaons
- Pion and Kaon yields are derived from the observed low and high energy ν_μ data
- Infer that Kaon yield is higher by 17% and Pion yield lower by 3%
- Leads to 1% increase in Beam ν_e background between 1-3 GeV in ND

ν_μ CC Background Estimate



- Look for Michel electron associated with interactions selected with ν_e criteria
- ν_μ CC's should have 1 additional Michel electron than NC and ν_e CC's
- Fitting the number of Michels distribution suggests an integrated increase of 17.4% in ν_μ CC and 10.4% in NC backgrounds

Event Identification in NOvA

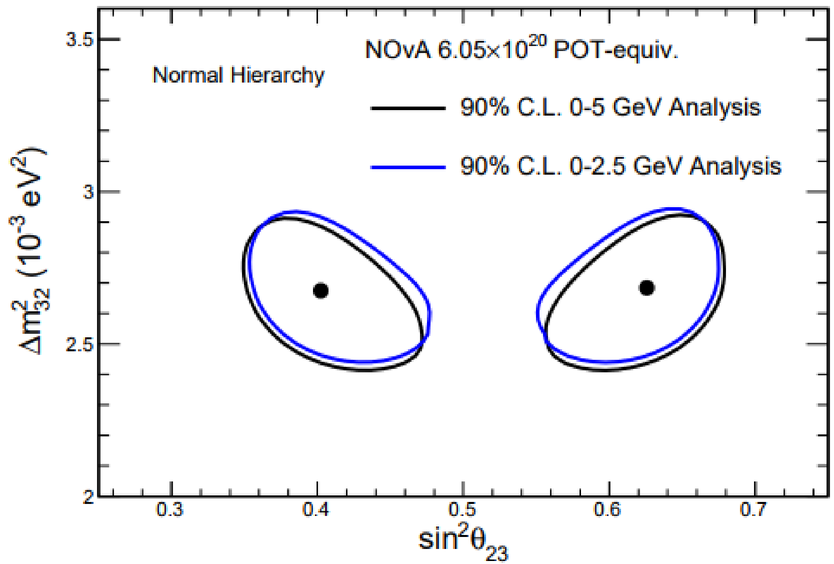


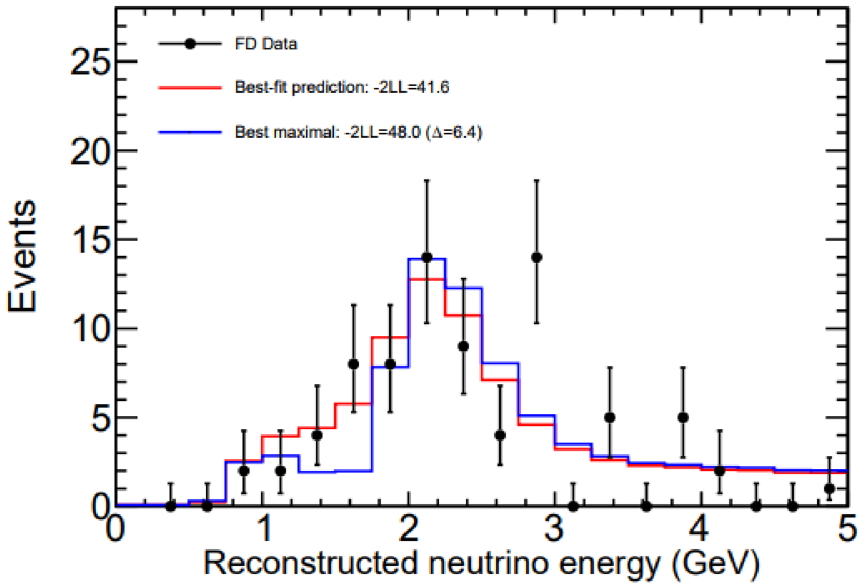
Take advantage of recent advances in machine learning/computer vision

- Classify event-displays!

CNN – deep neural network, inputs are the pixels of the image

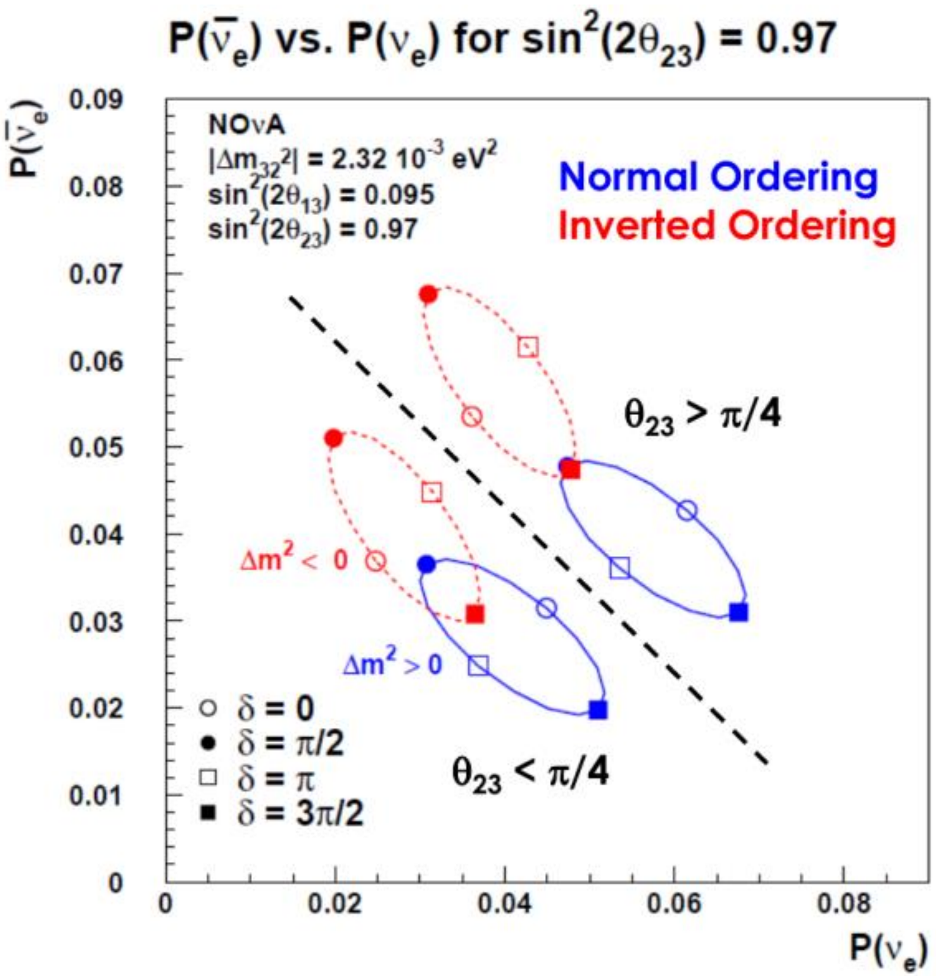
ν_μ Disappearance Results





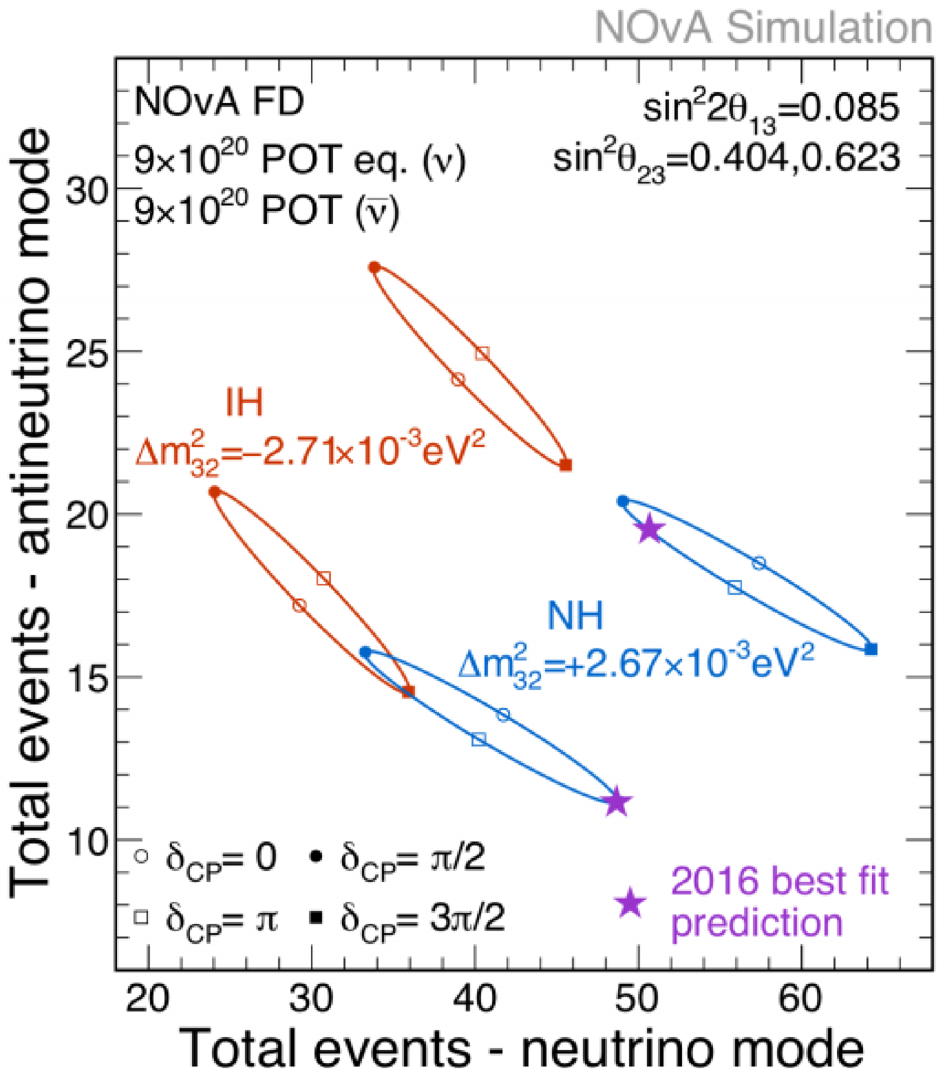
- $\chi^2 = 41.6/17$ driven by fluctuations in the tail
- Restricting the fit up to 2.5 GeV causes minimal change in the result

Why Anti-neutrinos?



- Currently there is no information about the vertical axis
- NuMI switched to anti-neutrino mode in February 2017
- Plan to run 50% in neutrino and 50% in anti-neutrino mode in 2018
- Will help resolve some of the degeneracies

Why Anti-neutrinos?



- Currently there is no information about the vertical axis
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- Will help resolve some of the degeneracies

Recap 2016 NC Analysis

MC extrapolated prediction:

- 83.5 ± 9.7 (stat.) ± 9.4 (syst.)

- Observe **95** NC-like events in FD
  - within 1σ of three-flavour prediction

- **NOvA** sees no evidence for ν_s mixing

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

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

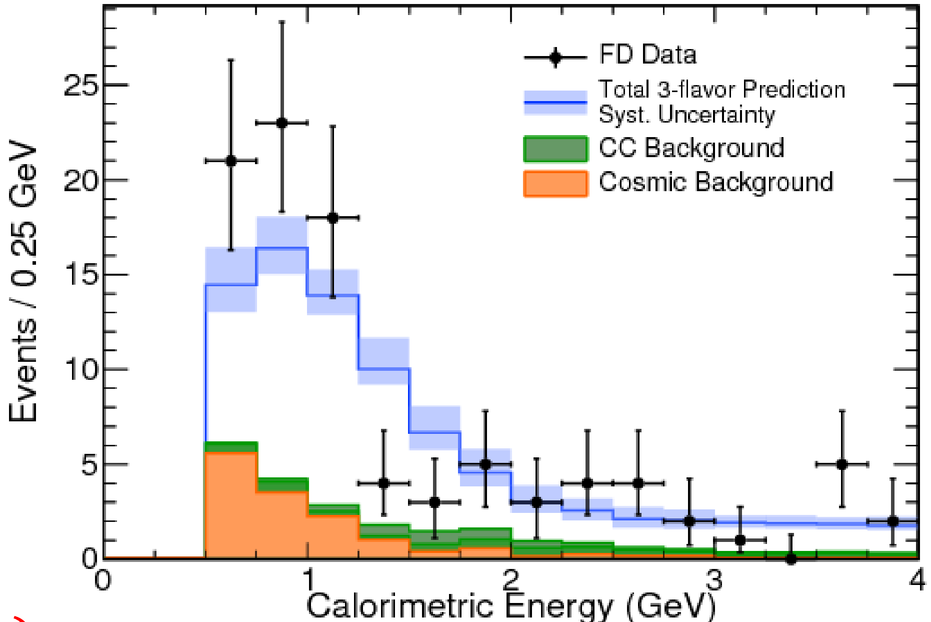
Consistent with three-flavour oscillations

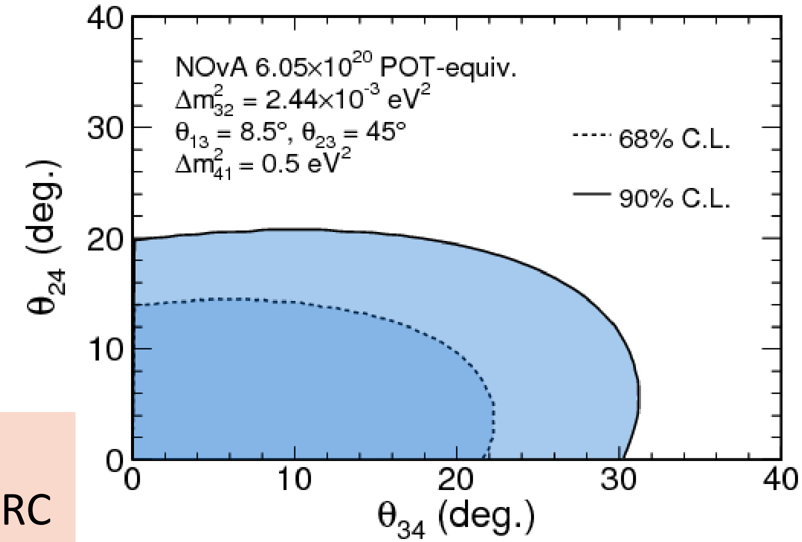
Rate analysis-only (Feldman-Cousins corrected):

In 3+1 analysis, for $\Delta m^2_{41} = 0.5\ eV^2$

$\theta_{24} < 20.8°$ at 90% C.L.
$\theta_{34} < 31.2°$ at 90% C.L.

arxiv:1706.04592
Submitted to PRD-RC

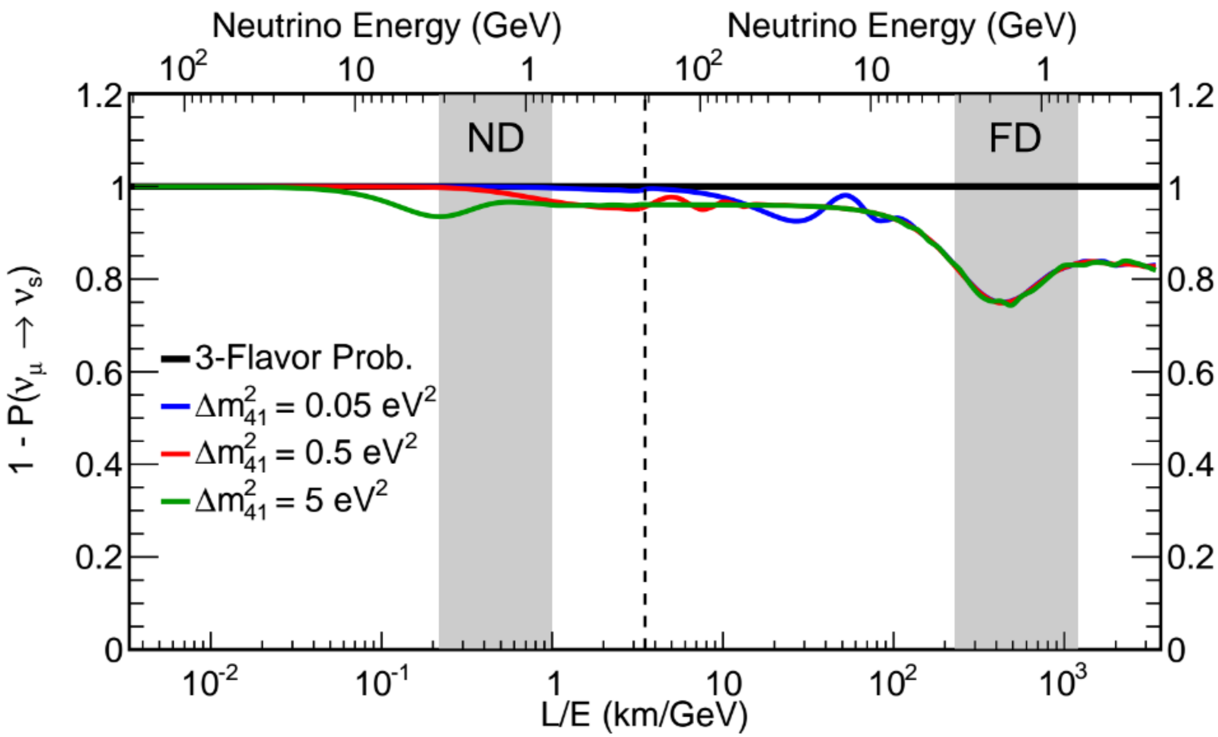




3+1 model

- ν_μ to ν_s mixing causes energy-dependent depletion of NC and ν_μ-CC events at Far Detector

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



- 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}
  - $\sin^2(\theta_{23}) = 0.514$
  - PDG 2016

2017 NC Disappearance Results

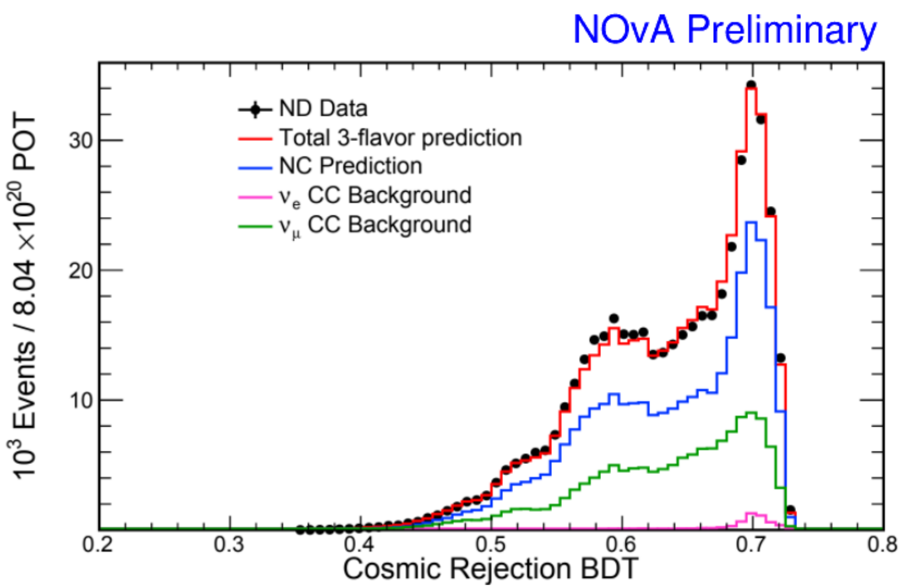
$$R_{\rm NC} \equiv \frac{F^{\rm data} - \sum F^{\rm pred}({\rm bkg})}{F^{\rm pred}({\rm NC})}$$

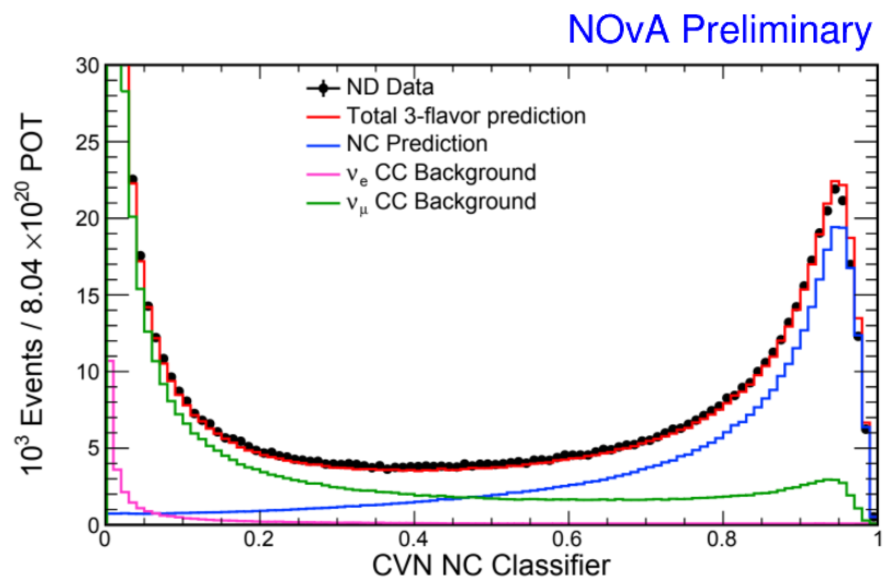
Consistent with three-flavour oscillations

	0 – 2.5 GeV	2.5 – 10 GeV
θ_{23} = 45 (2016)	$\mathbf{1.190} \pm 0.160\,(stat.)^{+0.080}_{-0.130}\,(syst.)$	n/a
θ_{23} = 45 (2017)	$\mathbf{1.190} \pm 0.123\,(stat.)^{+0.143}_{-0.124}\,(syst.)$	$1.076 \pm 0.123\,(stat.)^{+0.125}_{-0.136}\,(syst.)$
θ_{23} < 45	$\mathbf{1.179} \pm 0.123\,(stat.)^{+0.142}_{-0.124}\,(syst.)$	$1.076 \pm 0.123\,(stat.)^{+0.125}_{-0.135}\,(syst.)$
θ_{23} > 45	$\mathbf{1.176} \pm 0.123\,(stat.)^{+0.142}_{-0.124}\,(syst.)$	$1.074 \pm 0.123\,(stat.)^{+0.125}_{-0.137}\,(syst.)$

NC Disappearance Results

Near Detector data/mc comparisons

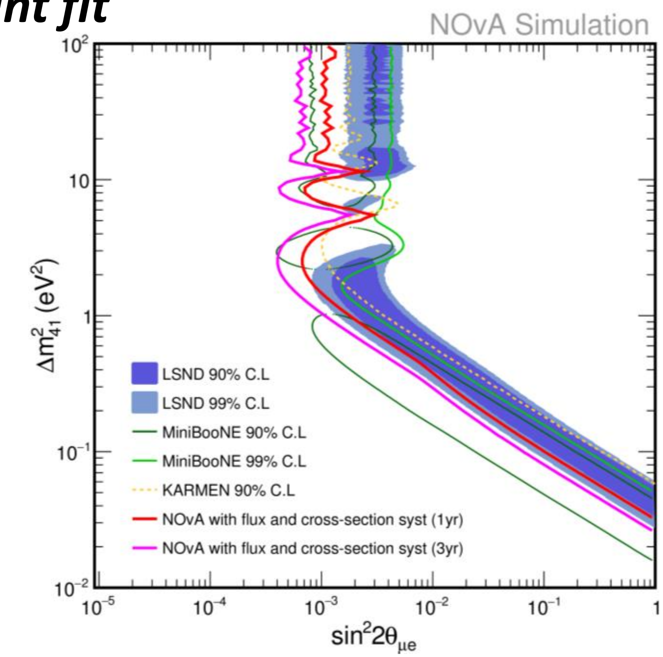




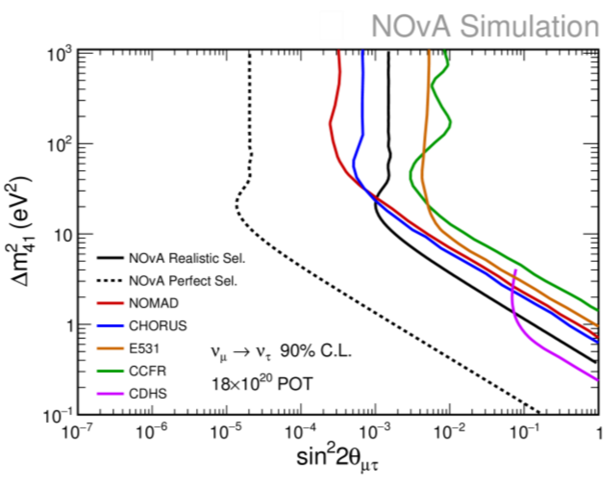
The future for NOvA ν_s searches

NOvA short-baseline ν_e appearance-ν_μ disappearance joint fit

- Probe LSND and MiniBooNE allowed regions with one NOvA year of NOvA data

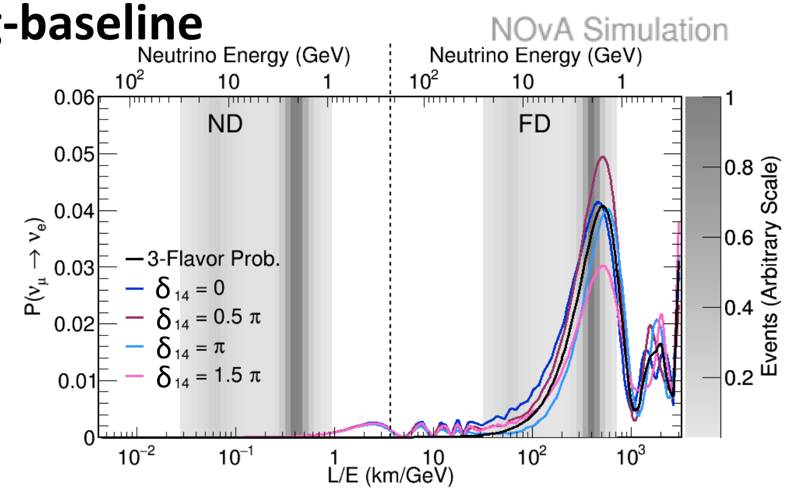


NOvA short-baseline ν_τ appearance



- Black line shows NOvA sensitivity to ν_τ appearance; rate-only fit to two flavour model
- NOvA will be competitive with previous experiments after 3 years of running

Probing δ_{14} & δ_{13} with ν_e long-baseline



2016 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

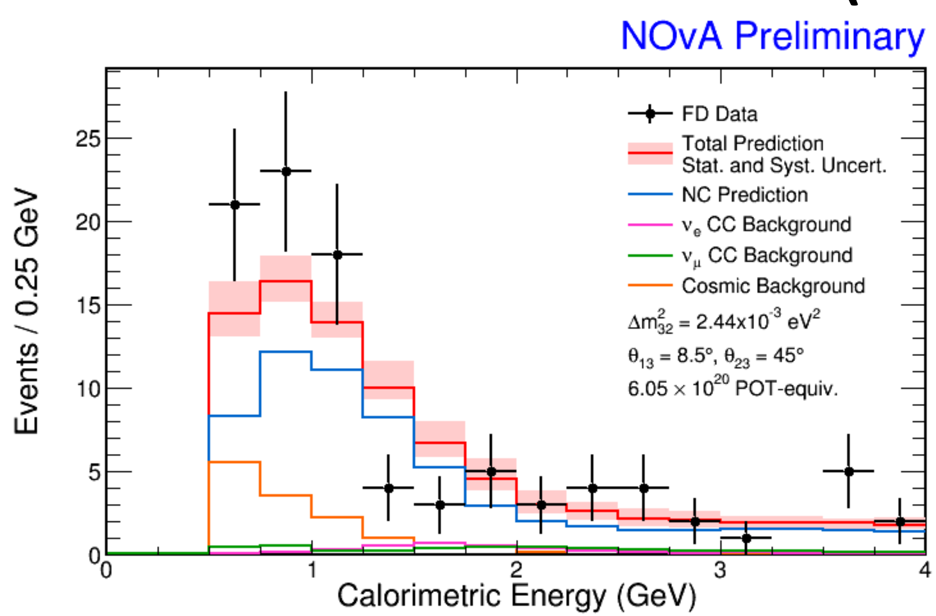
FD Data NC-like: **95**

MC prediction: **83.5 ± 9.7 (stat.) ± 9.4 (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)



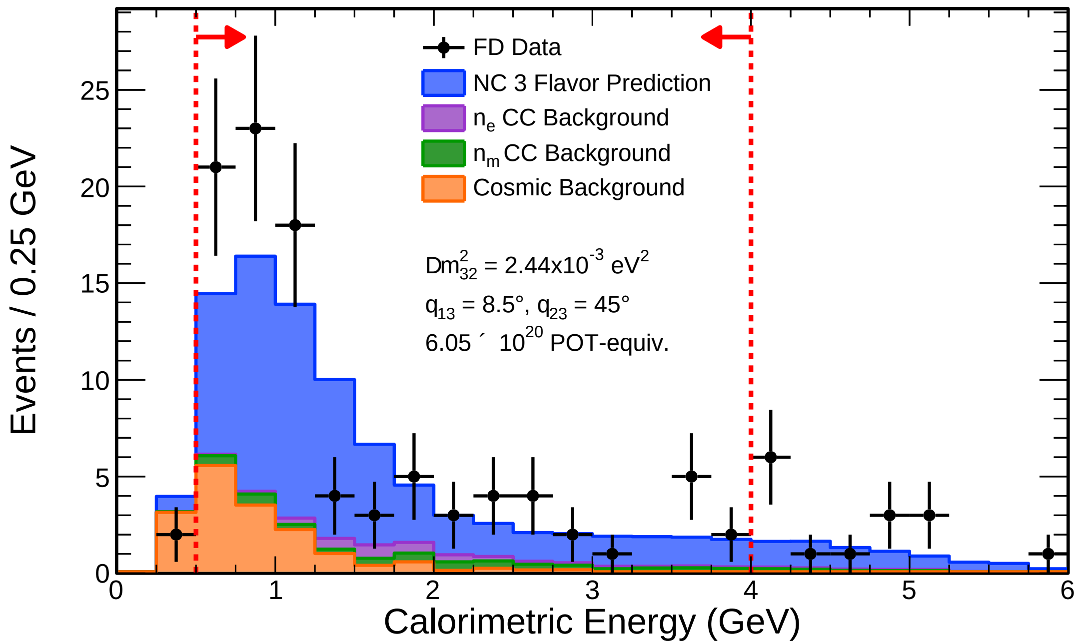
2016 Neutral Current FD Data

Observe 95 events

No evidence of oscillations involving steriles

$$R = \frac{N_{data} - BG}{S_{NC}} = 1.19 \pm 0.16(\text{stat.}) \pm 0.11(\text{syst.})$$

NOvA Preliminary

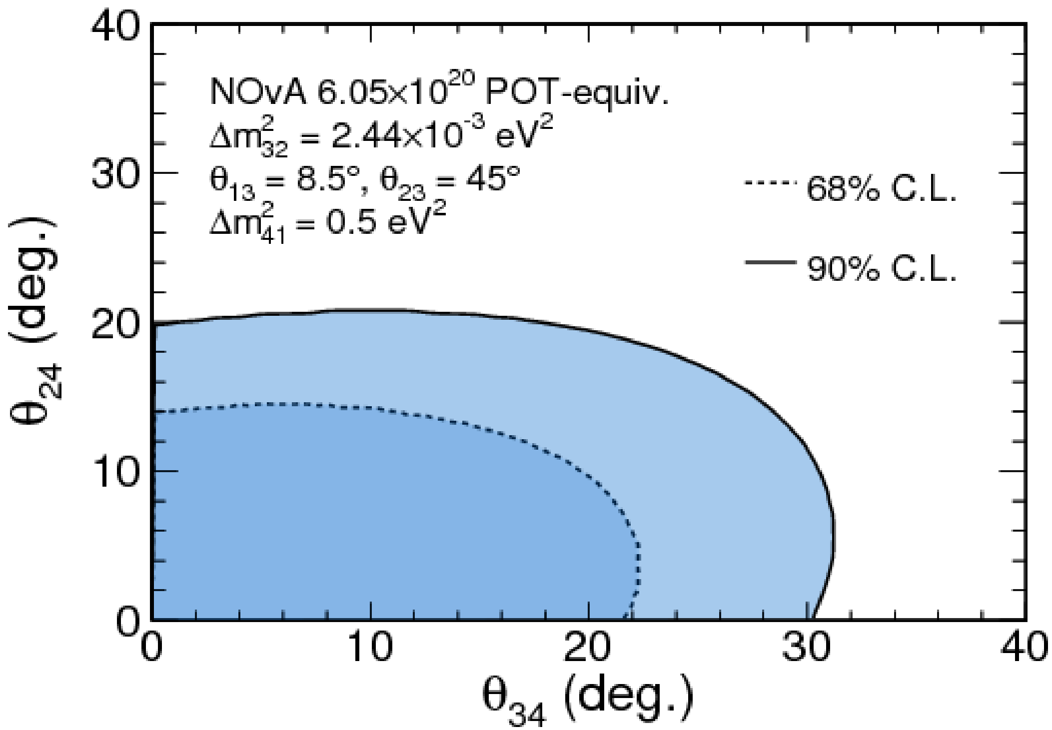


In 3+1 analysis, for $\Delta m^2_{41} = 0.5\ \text{eV}^2$

$\theta_{24} < 20.8°$ at 90% C.L.
$\theta_{34} < 31.2°$ at 90% C.L.

Excellent NC efficiency (50%) and purity (72%) promise strong future limits on θ_{34}

2016 Sterile mixing angle limits



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$\theta_{24} < 20.8°$ at 90% C.L.
$\theta_{34} < 31.2°$ at 90% C.L.

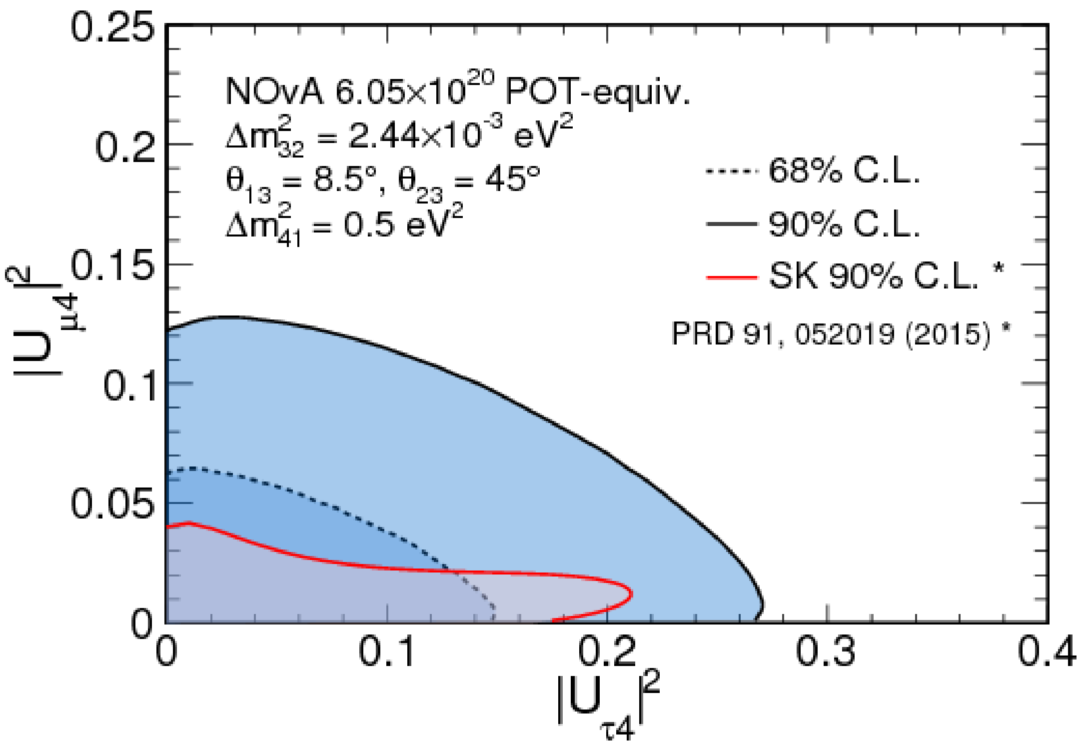
Paper submitted, **arXiv:1706.04592**

FERMILAB-PUB-17-198-ND

Search for active-sterile neutrino mixing using neutral-current interactions in NOvA

P. Adamson,[11] L. Aliaga,[11] D. Ambrose,[26] N. Anfimov,[22] A. Antoshkin,[22,26] E. Arrieta-Diaz,[31] K. Augsten,[9] A. Aurisano,[6] C. Backhouse,[4] M. Baird,[33,17] B. A. Bambah,[15] K. Bays,[4] B. Behera,[16] S. Bending,[37] R. Bernstein,[11] V. Bhatnagar,[27] B. Bhuyan,[13] J. Bian,[20,26] T. Blackburn,[33] A. Bolshakova,[22] C. Bromberg,[24] J. Brown,[26] G. Brunetti,[11] N. Buchanan,[8] A. Butkevich,[18] V. Bychkov,[26] M. Campbell,[37] E. Catano-Mur,[19] S. Childress,[11] B. C. Choudhary,[10] B. Chowdhury,[29] T. E. Coan,[31] J. A. B. Coelho,[36] M. Colo,[40] J. Cooper,[11] L. Corwin,[30] L. Cremonesi,[37] D. Cronin-Hennessy,[26] G. S. Davies,[17] J. P. Davies,[33] P. F. Derwent,[11] R. Dharmapalan,[1] P. Ding,[11] Z. Djurcic,[1] E. C. Dukes,[38] H. Duyang,[29] S. Edayath,[7] R. Ehrlich,[38] G. J. Feldman,[14] M. J. Frank,[28,38] M. Gabrielyan,[26] H. R. Gallagher,[36] S. Germani,[37] T. Ghosh,[12] A. Giri,[16] R. A. Gomes,[12] M. C. Goodman,[1] V. Grichine,[23] M. Groh,[17] R. Group,[38] D. Grover,[3] B. Guo,[29] A. Habig,[25] J. Hartnell,[33] R. Hatcher,[11] A. Hatzikoutelis,[34] K. Heller,[26] A. Himmel,[11] A. Holin,[37] B. Howard,[17] J. Hylen,[11] F. Jediny,[9] M. Judah,[8] G. K. Kafka,[14] D. Kalra,[27] S. M. S. Kasahara,[26] S. Kasetti,[15] R. Keloth,[7] L. Kolupaeva,[22] S. Kotelnikov,[23] I. Kourbanis,[11] A. Kreymer,[11] A. Kumar,[27] S. Kurbanov,[38] T. Lackey,[17] K. Lang,[35] W. M. Lee,[11,*] S. Lin,[8] M. Lokajicek,[2] J. Lozier,[4] S. Luchuk,[18] K. Maan,[27] S. Magill,[1] W. A. Mann,[36] M. L. Marshak,[26] K. Matera,[11] V. Matveev,[18] D. P. Méndez,[33] M. D. Messier,[17] H. Meyer,[39] T. Miao,[11] W. H. Miller,[26] S. R. Mishra,[29] R. Mohanta,[15] A. Moren,[25] L. Mualem,[4] M. Muether,[39] S. Mufson,[17] R. Murphy,[17] J. Musser,[17] J. K. Nelson,[40] R. Nichol,[37] E. Niner,[11] A. Norman,[11] T. Nosek,[5] Y. Oksuzian,[38] A. Olshevskiy,[22] T. Olson,[36] J. Paley,[11] R. B. Patterson,[4] G. Pawloski,[26] D. Pershey,[4] O. Petrova,[22] R. Petti,[29] S. Phan-Budd,[41] R. K. Plunkett,[11] R. Poling,[26] B. Potukuchi,[21] C. Principato,[38] F. Psihas,[17] A. Radovic,[40] R. A. Rameika,[11] B. Rebel,[11] B. Reed,[30] D. Rocco,[26] P. Rojas,[8] V. Ryabov,[23] K. Sachdev,[11] P. Sail,[35] O. Samoylov,[22] M. C. Sanchez,[19] R. Schroeter,[14] J. Sepulveda-Quiroz,[19] P. Shanahan,[11] A. Sheshukov,[22] J. Singh,[27] J. Singh,[21] P. Singh,[10] V. Singh,[3] J. Smolik,[9] N. Solomey,[39] E. Song,[38] A. Sousa,[6] K. Soustruznik,[5] M. Strait,[26] L. Suter,[1,11] R. L. Talaga,[1] P. Tas,[5] R. B. Thayyullathil,[7] J. Thomas,[37] X. Tian,[29] S. C. Tognini,[12] J. Tripathi,[27] A. Tsaris,[11] J. Urheim,[17] P. Vahle,[40] J. Vasel,[17] L. Vinton,[33] A. Vold,[26] T. Vrba,[9] B. Wang,[31] M. Wetstein,[19] D. Whittington,[17] S. G. Wojcicki,[32] J. Wolcott,[36] N. Yadav,[13] S. Yang,[6] J. Zalesak,[2] B. Zamorano,[33] and R. Zwaska[11]

2016 Sterile mixing angle limits



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

$|U_{\mu 4}|^2 = \cos^2\theta_{14} \sin^2\theta_{24}$

$|U_{\tau 4}|^2 = \cos^2\theta_{14} \cos^2\theta_{24} \sin^2\theta_{34}$

In 3+1 analysis, for $\Delta m^2_{41} = 0.5$ eV^2

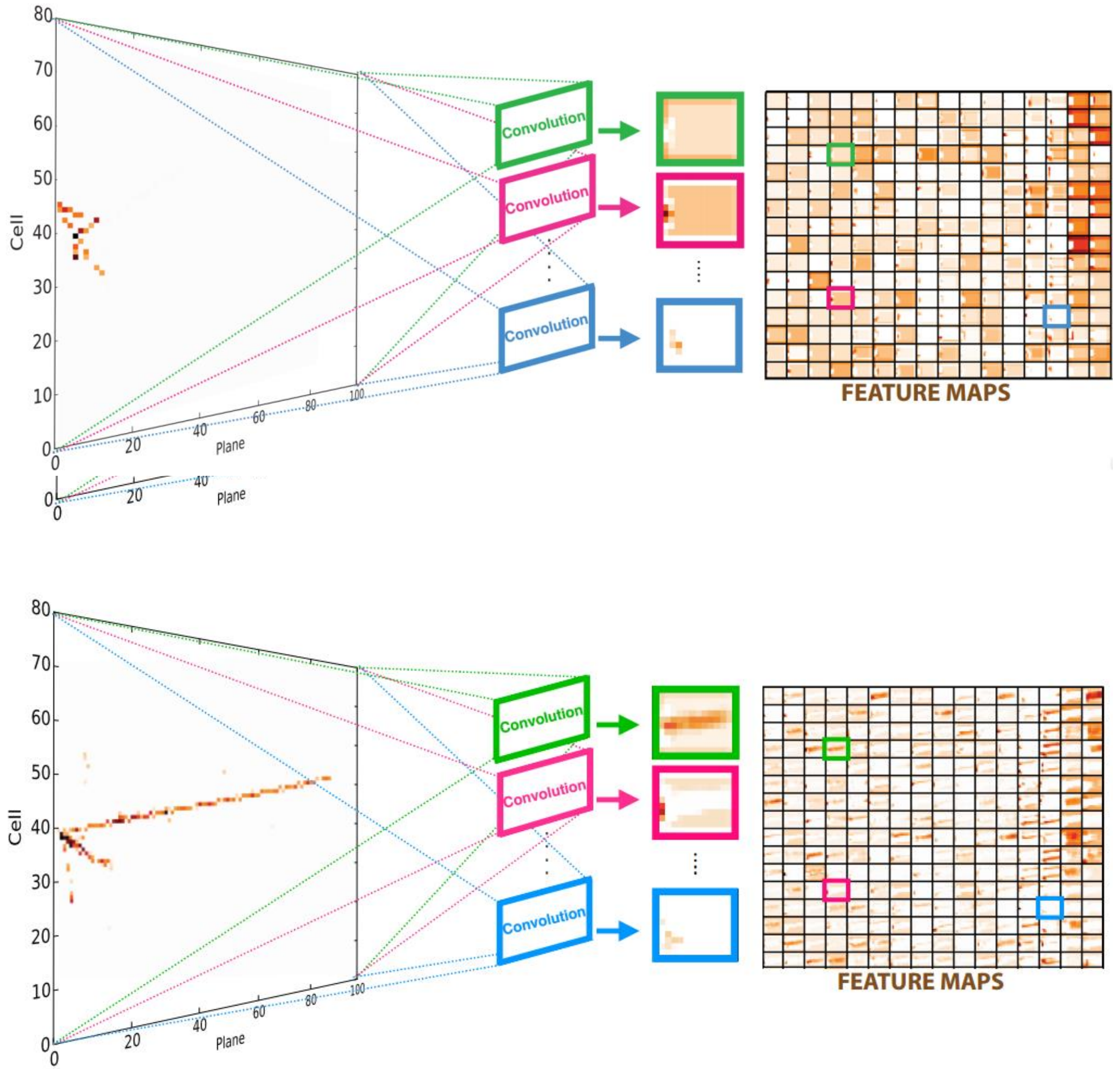
$|U_{\mu 4}|^2 < 0.126$ at 90% C.L.
$|U_{\tau 4}|^2 < 0.268$ at 90% C.L.

CVN

This analysis uses same event classifier as the ν_e analysis

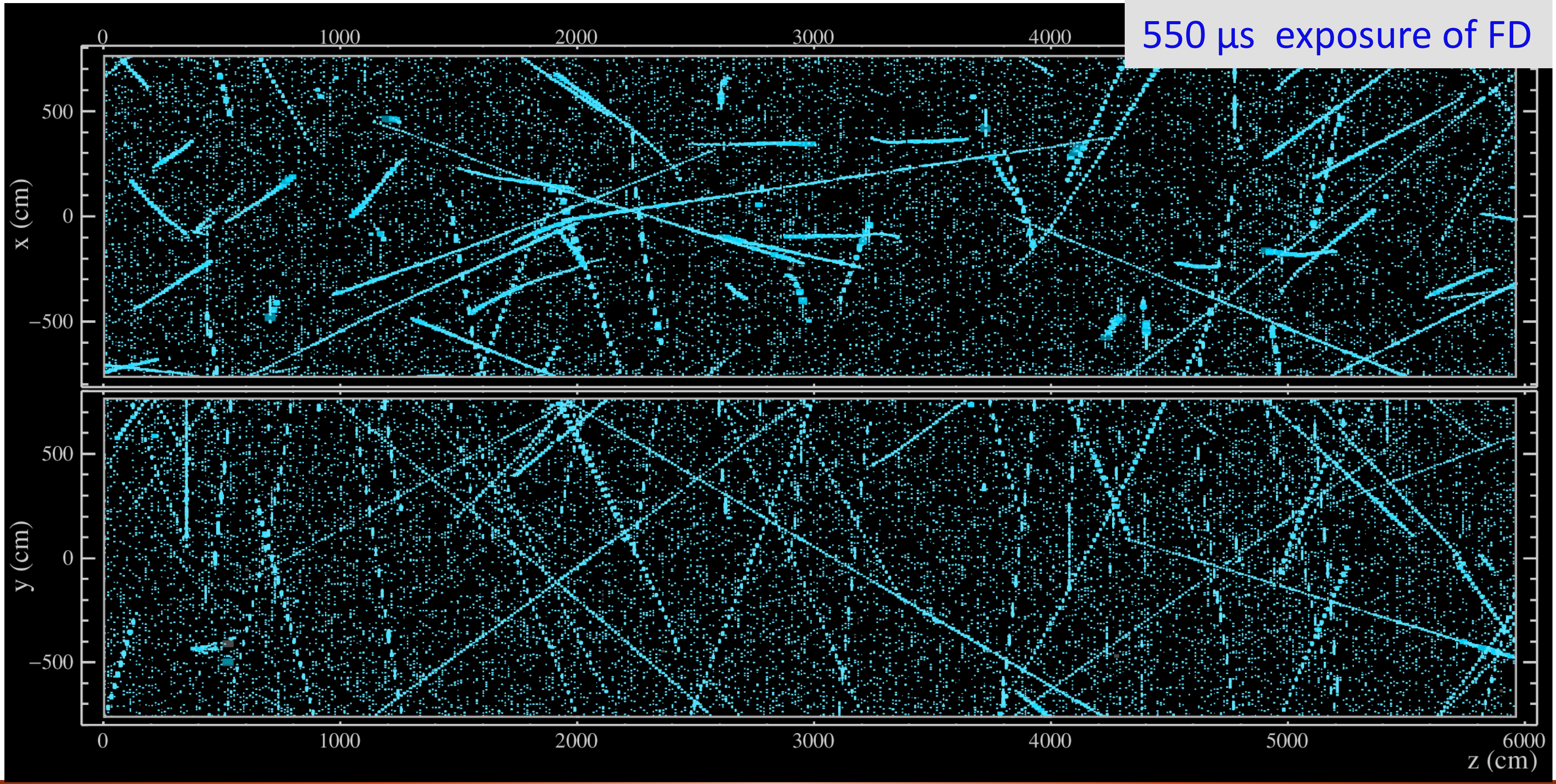
- **First implementation of a CNN in a HEP result**
  "Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA"
  P. Adamson *et al.*, PRL **118**, 231801 (2017)

- 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
- Effectively increases our exposure by 30% compared to traditional ID methods

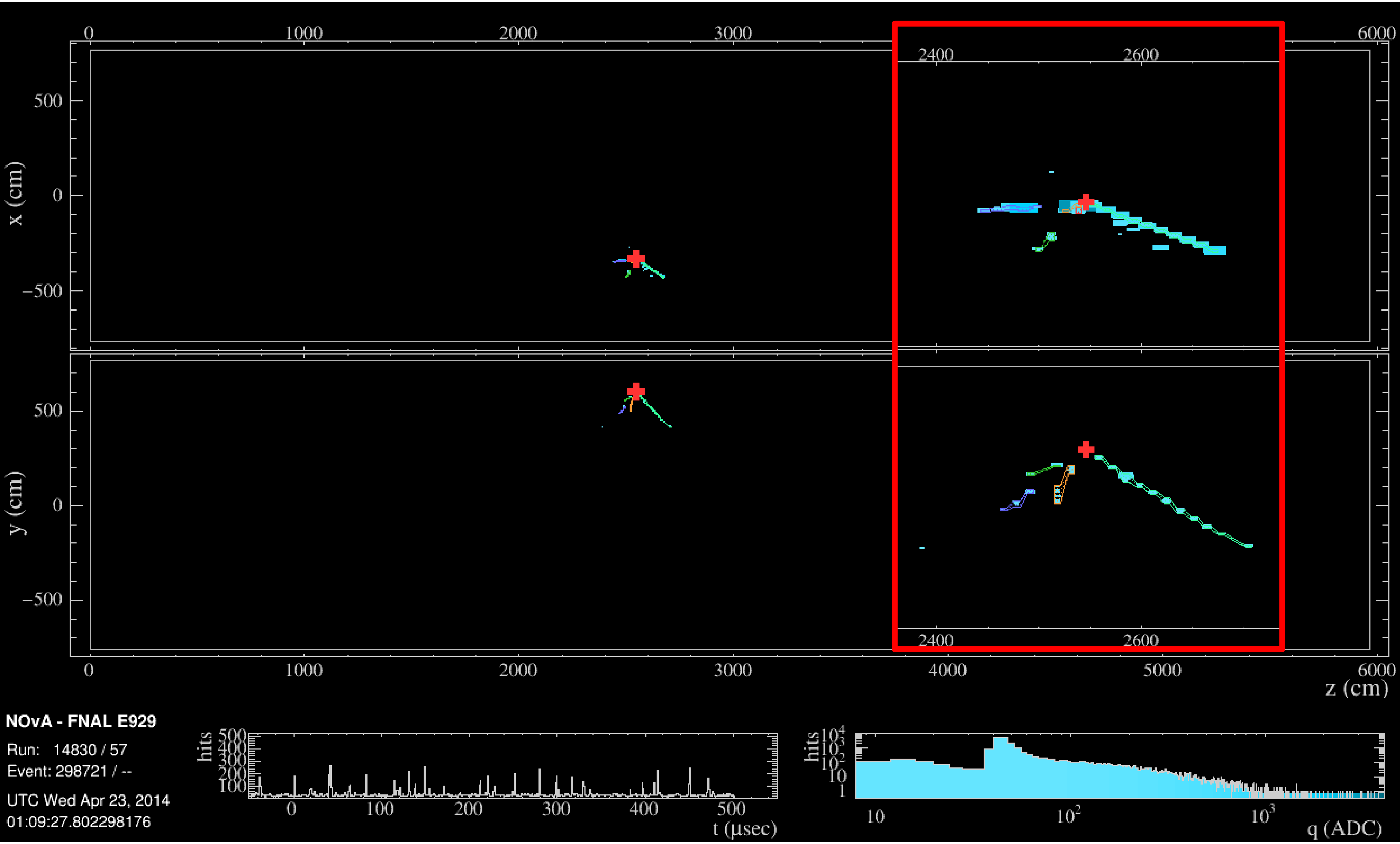


Cosmic ray rejection

- FD is on the surface; exposed to 150 kHz of cosmic rays
- 10 μs spill window at ~ 1 Hz gives 10^5 rejection
- Cosmic background rate measured from data adjacent in time to the beam spill window



Cosmic ray rejection

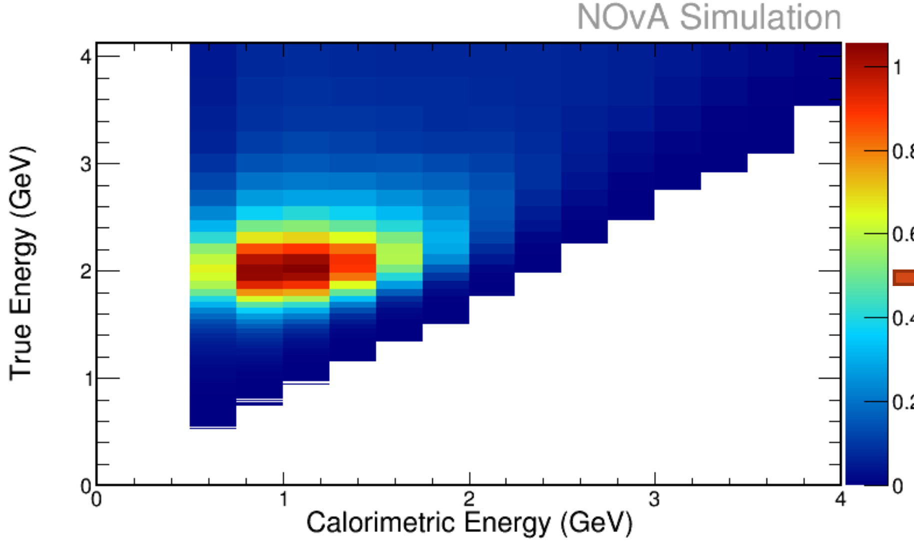


Extrapolation

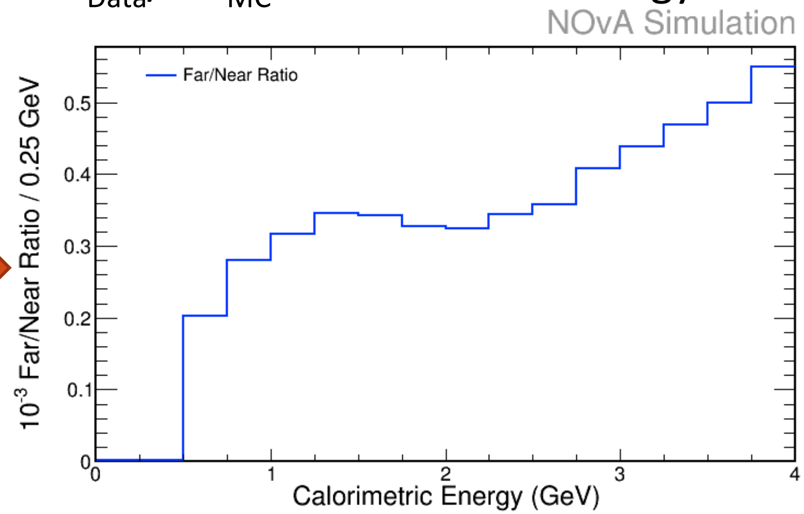
- We use the measured ND energy spectrum to predict the unoscillated FD spectrum

$$FD^{Predicted} = \frac{FD^{MC}}{ND^{MC}} ND^{Data}$$

FD reco. E. vs. true E. matrix
Maps the FD reconstructed energy spectrum to an estimate for true neutrino energy



FD/ND ratio equivalent to reweighting reco. E vs. true E. matrix with ND_{Data}/ND_{MC} reconstructed energy



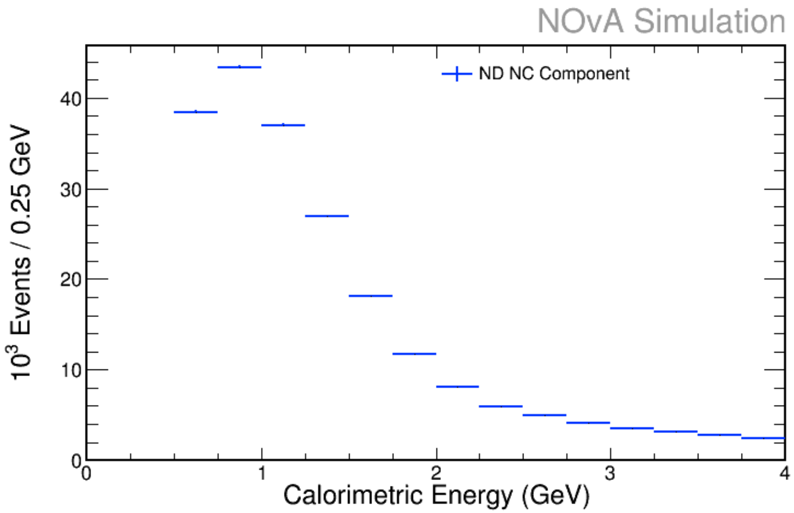
Apply oscillation weights and unfold reco. E. vs. true E. matrix back to reconstructed energy

Extrapolation

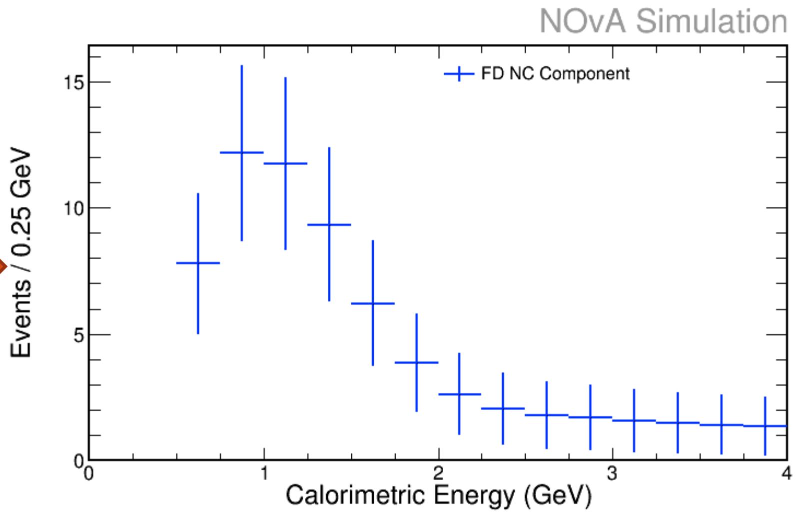
- We use the measured ND energy spectrum to predict the unoscillated FD spectrum

$$FD^{Predicted} = \frac{FD^{MC}}{ND^{MC}} ND^{Data}$$

Original ND NC component
All flavours decomposed proportionally

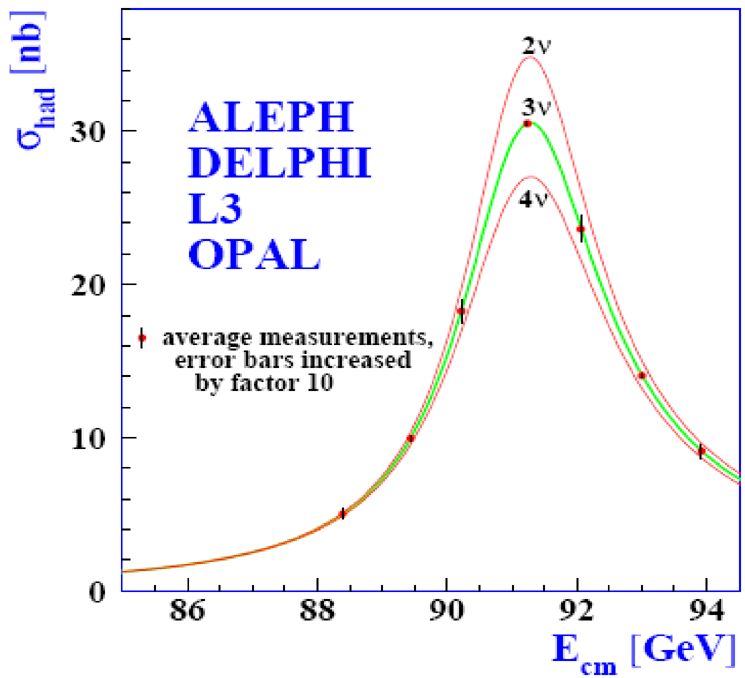


Final FD reconstructed energy spectrum

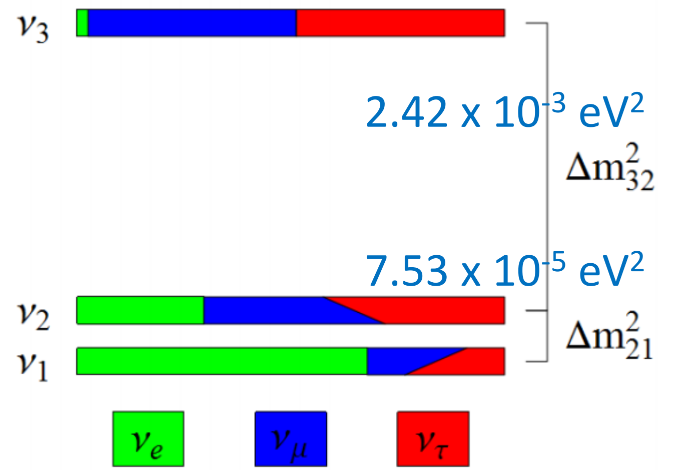


What is a sterile neutrino?

- A sterile neutrino is a lepton with no Standard Model charges; no SM interactions
- We know the Z boson decays into three light neutrinos
  - $N_\nu = 2.984 \pm 0.008$
  - "light" means below ½ Z mass



$\Delta m^2_{32} + \Delta m^2_{21} + \Delta m^2_{13} = 0$



$\Delta m^2_{LSND} > 0.2\ eV^2$ ($\gg \Delta m^2_{32} \gg \Delta m^2_{21}$)
Anomaly!

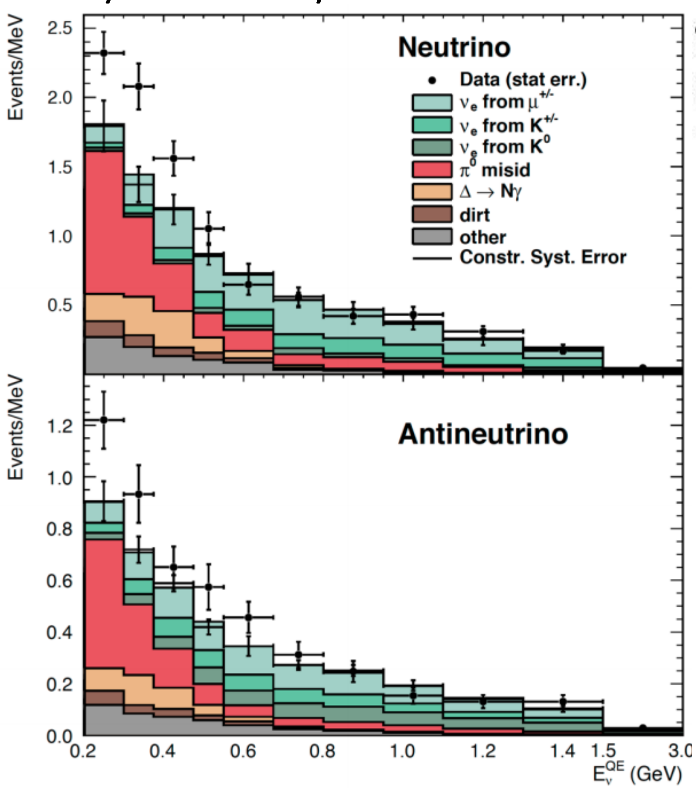
- Sterile neutrinos can participate in oscillations with active flavours
  - $\nu_\mu \rightarrow \nu_s, \nu_e \rightarrow \nu_s, \nu_\tau \rightarrow \nu_s$

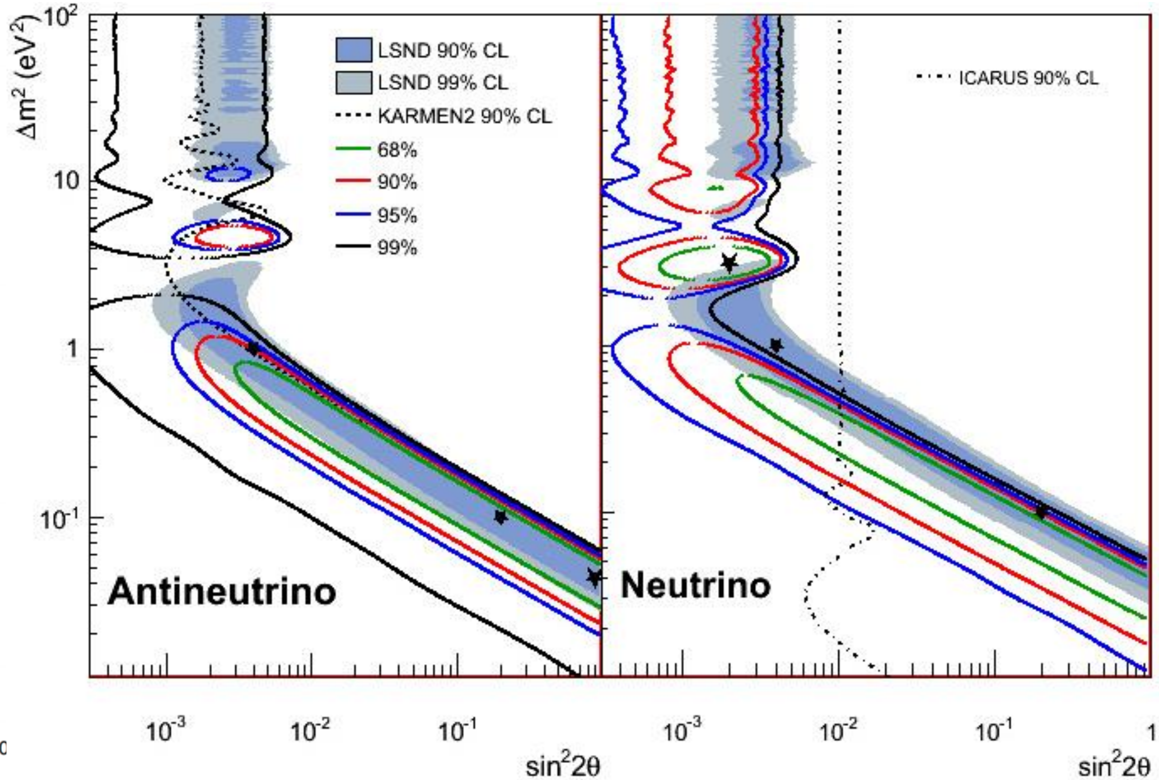
ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and LEP Electroweak Working Group, and SLD Electroweak Group, and SLD Heavy Flavour Group, Phys. Reports 427, 257 (2006)

What did MiniBooNE say?

- Neutrinos and antineutrinos from an accelerator seem to appear
- Data consistent with antineutrino oscillations for $0.01 < \Delta m^2 < 1.0\ eV^2$
- Some overlap with the evidence for antineutrino oscillations from the LSND

L/E ~ 450 m/450 MeV ~ 1 eV^2



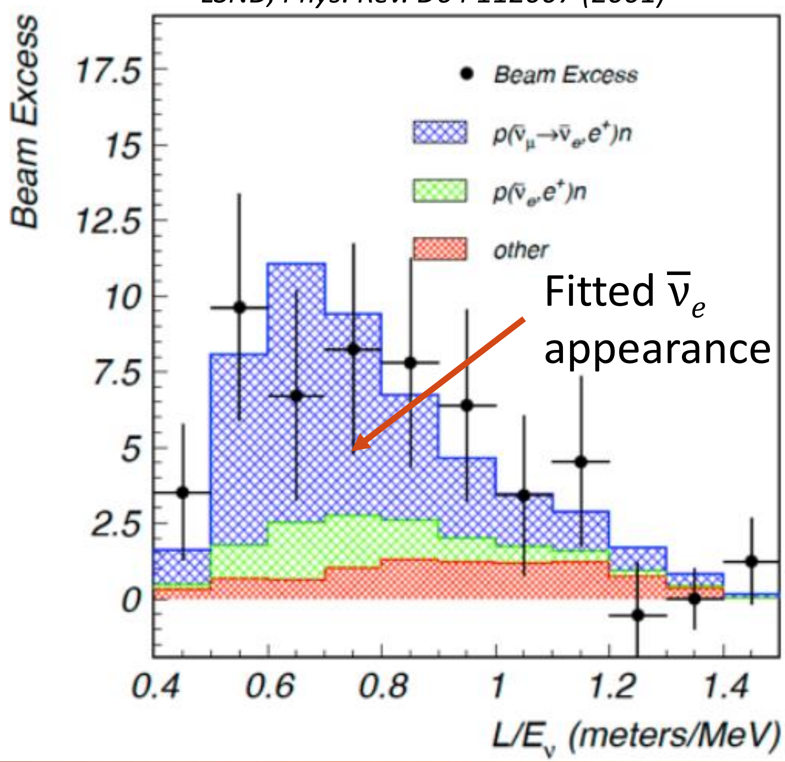


MiniBooNE Phys. Rev. Lett. 110, 161801 (2013)

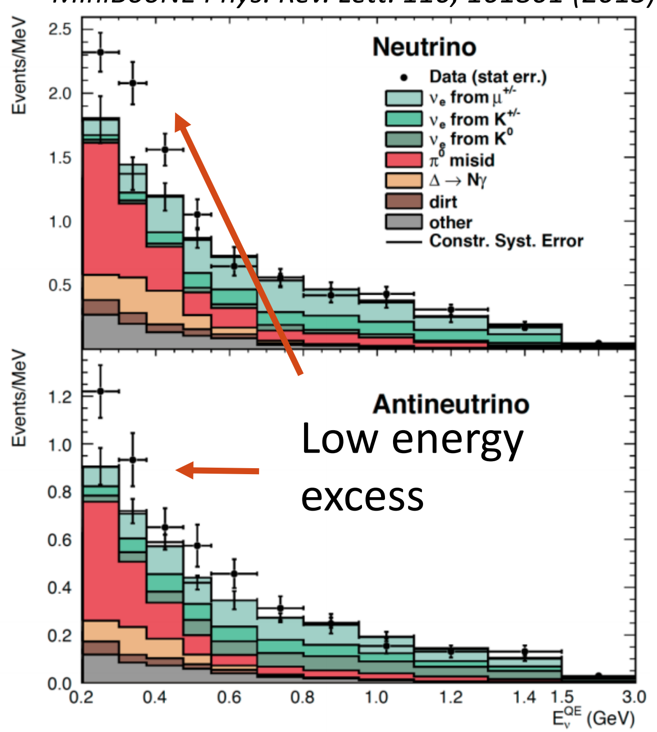
Searching for ν_s

- Short-baseline experiments (LSND, MiniBooNE) have experimental results which could be interpreted as due to a new neutrino with a mass ~1 eV
  - Hints of **appearance** of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beam
  - LSND (1993-1998) observed a (~3.8σ) excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Gallium anomaly in solar neutrino experiment (SAGE, GALLEX) results
  - Lower than expected cross-sections possibly due to large-mass sterile neutrino
- Null results from long-baseline appearance and disappearance searches

LSND, Phys. Rev. D64 112007 (2001)



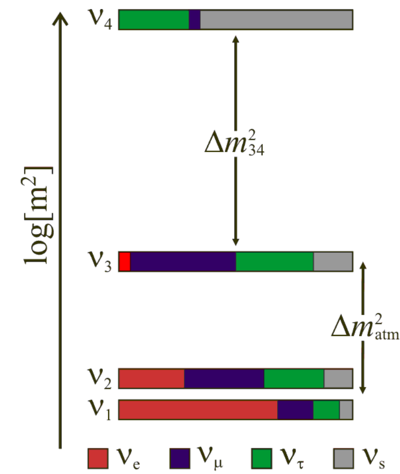
MiniBooNE Phys. Rev. Lett. 110, 161801 (2013)



3+1 model analysis

- Assume there is an additional sterile neutrino (ν_s) and an additional mass scale (Δm^2_{34}); θ_{14}, θ_{24}, θ_{34} and CP phases δ_{14}, δ_{24}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



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

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ji} L}{4E}$$

$\nu_\mu \to \nu_e$ at short baselines (reactor)

$\nu_\mu \to \nu_\mu$ at short/long baselines

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

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

$$4\,|U_{e4}|^2\,|U_{\mu4}|^2 = \sin^2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$

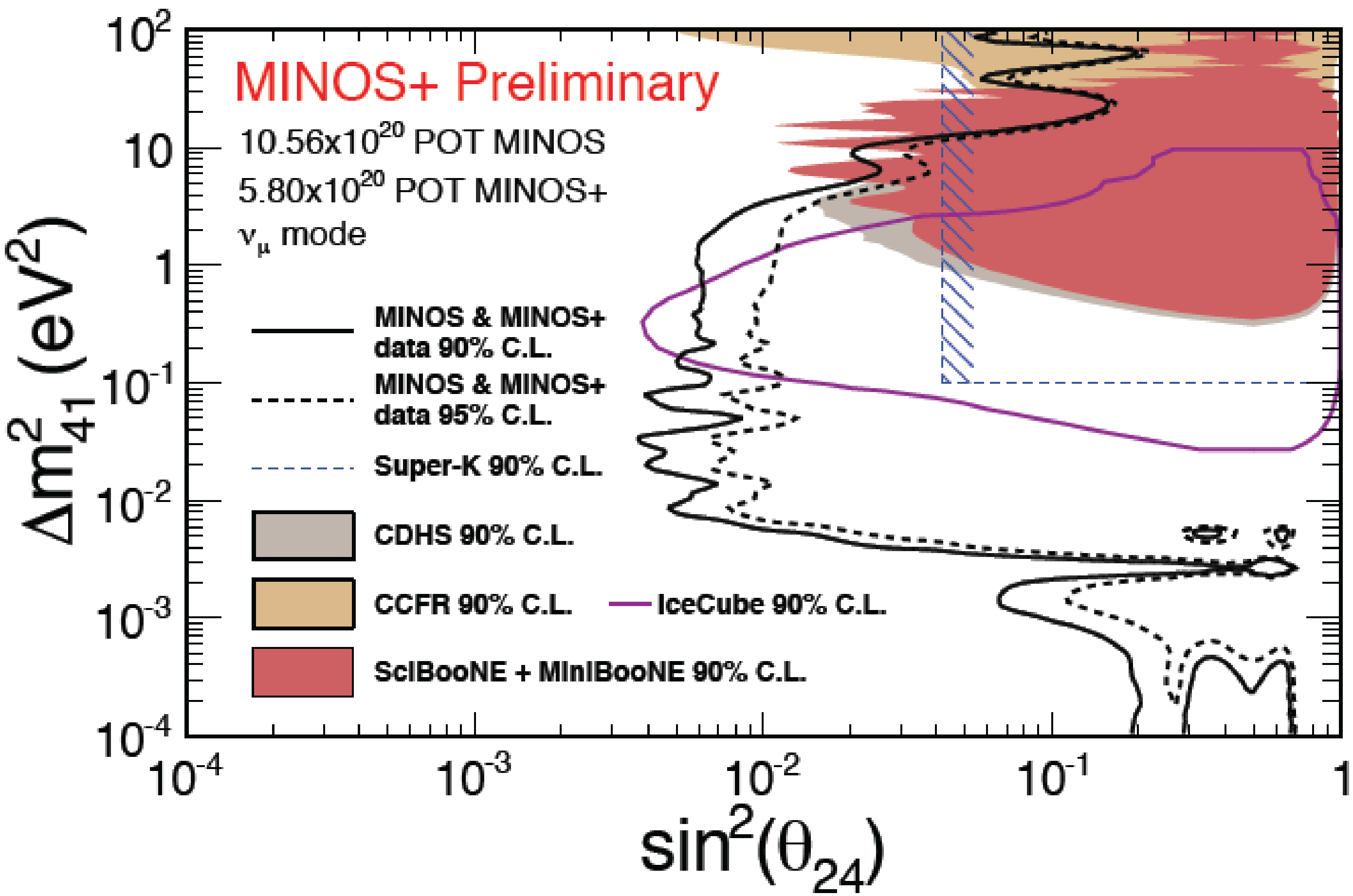
$$|U_{\tau4}|^2 = \cos^2\theta_{14}\,\cos^2\theta_{24}\,\sin^2\theta_{34}$$

$\nu_\mu \to \nu_e$ at short baselines (LSND)

$\nu_\mu \to \nu_s$ at long baselines (NCs)

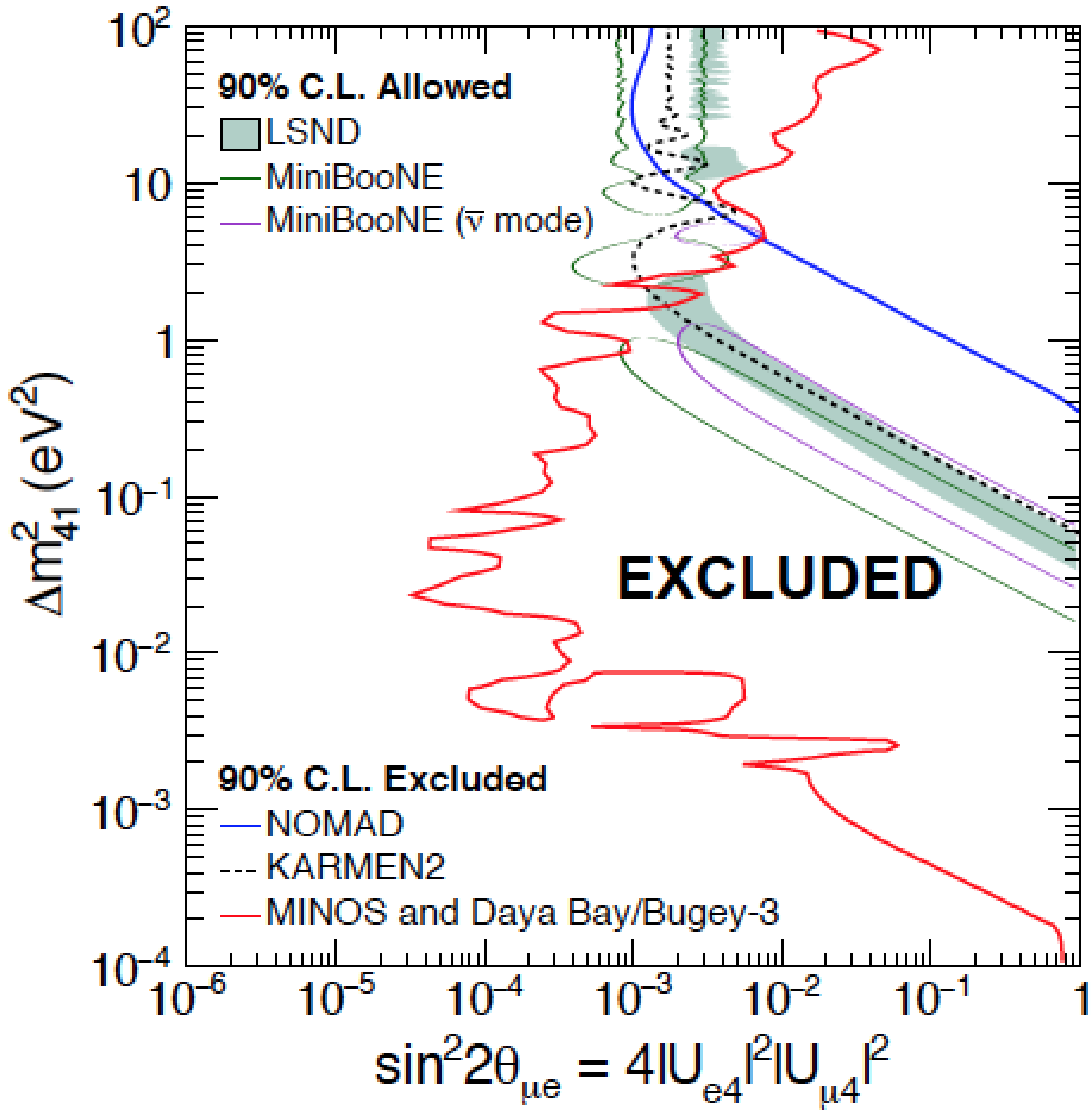
What about disappearance?

- MINOS+ results comparing MiniBooNE disappearance, IceCube, and Super-K
  - Constraint on θ_{24}; measures mixing between ν_μ and ν_s



What about disappearance?

- MINOS/Bugey/Daya Bay combined (*arxiv: 1607.01177*)
- Tension between disappearance results and allowed regions in $\theta_{\mu e}$ from LSND and MiniBooNE



What about disappearance?

Electron antineutrino disappearance limits on θ_{14} by reactor neutrino experiments such as Daya Bay and RENO

No evidence for steriles

MINOS-Daya Bay-Bugey exclude parameter space allowed by LSND and MiniBooNE for:

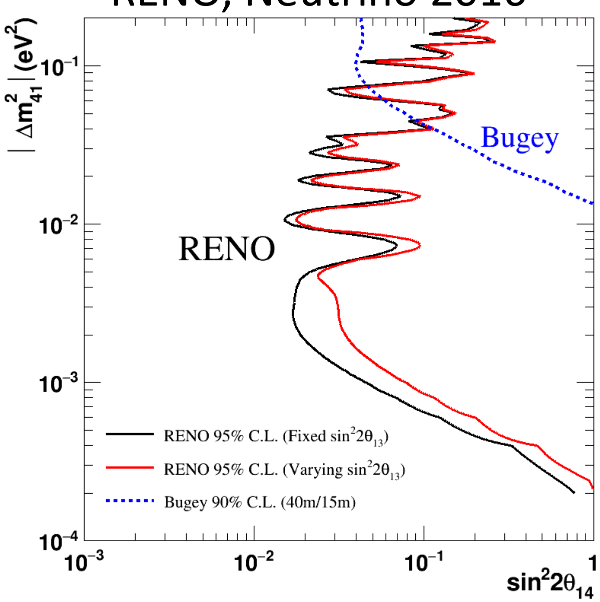
$\Delta m^2_{41} < 0.8\ eV^2$ at 95% C.L

MINOS+ 3x more data to analyse; consistent with null

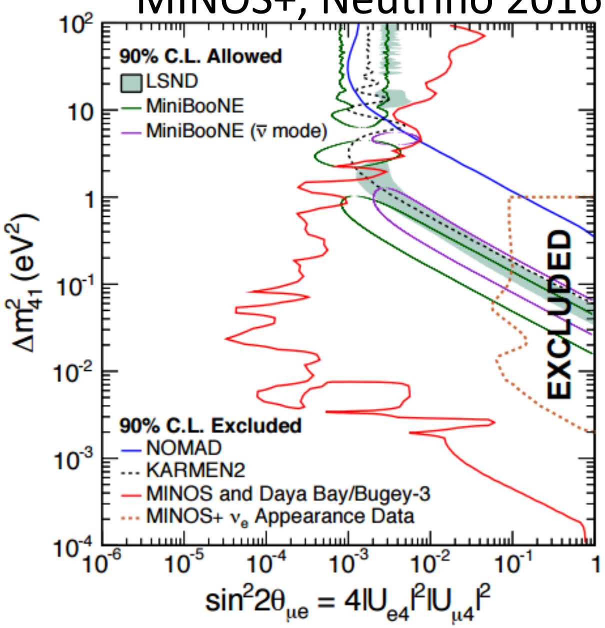
IceCube expect a resonant matter effect in the disappearance of atmospheric anti-numu

No evidence; strong limits on θ_{24}

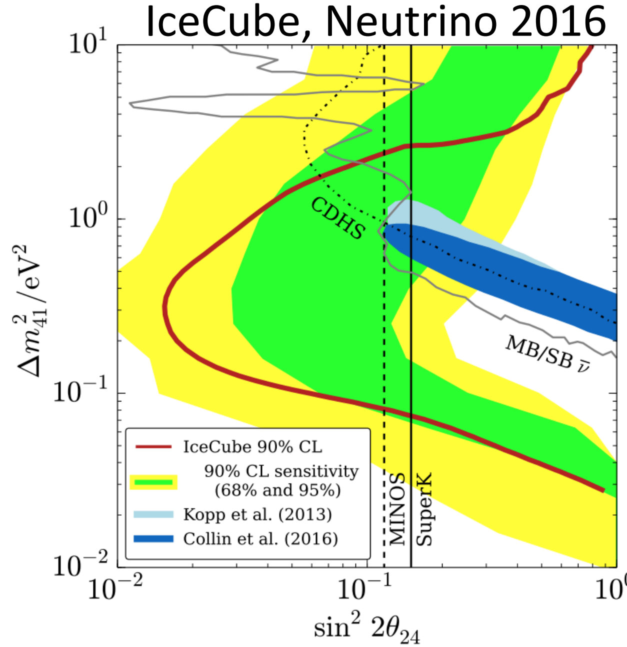
RENO, Neutrino 2016



MINOS+, Neutrino 2016

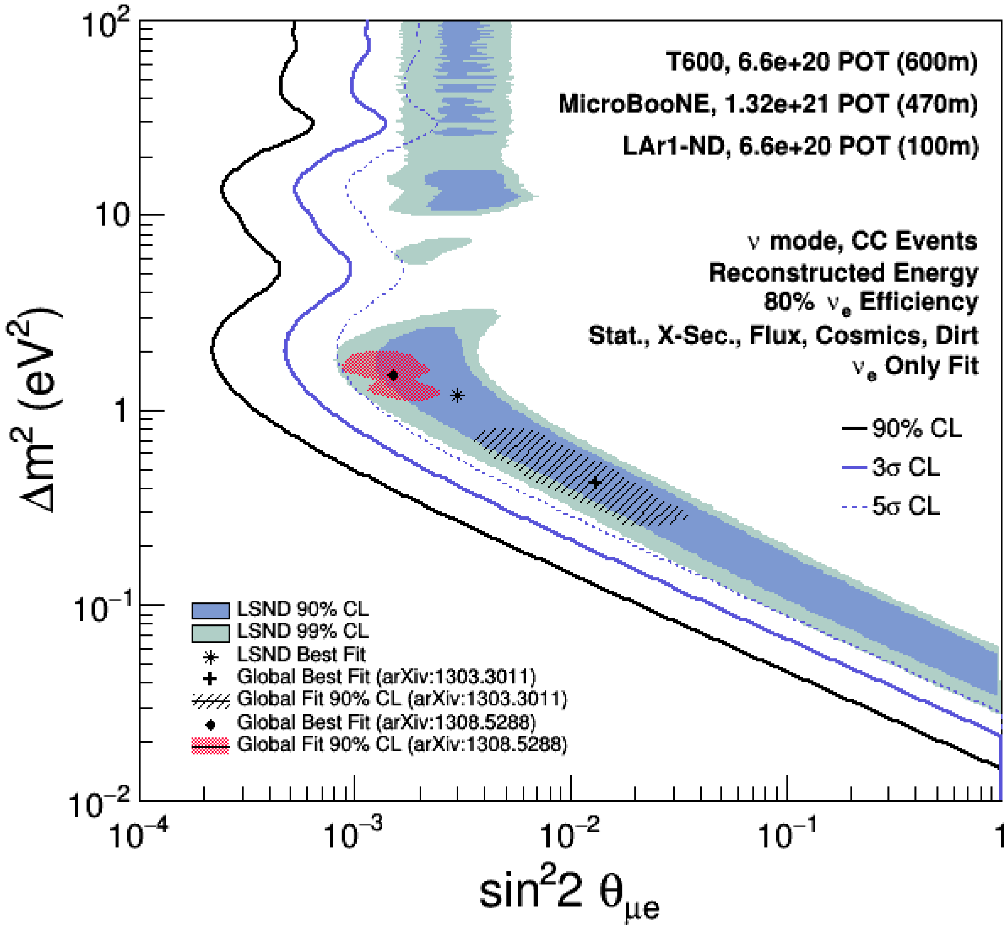


IceCube, Neutrino 2016



Fermilab SBL program

Fermilab Short-Baseline Neutrino program
LAr1-ND + MicroBooNE + ICARUS T600



What about disappearance?

- Super-K exclusion in $|U_{\mu4}|^2$, $|U_{\tau4}|^2$ parameter space

  $|U_{\mu4}|^2 < 0.041$ for $\Delta m^2_{41} > 0.1$ eV^2

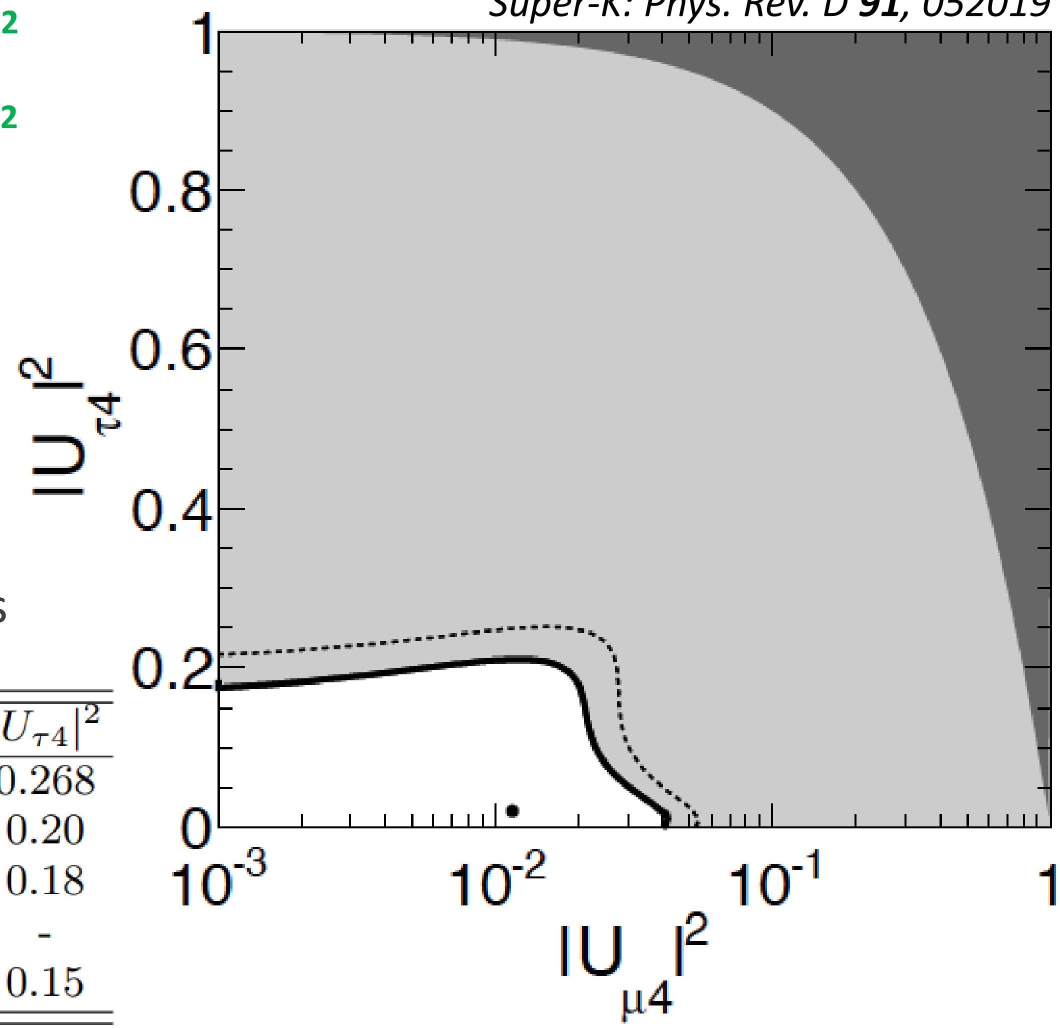
  $|U_{\tau4}|^2 < 0.18$ for $\Delta m^2_{41} > 0.1$ eV^2

- Super-K only experiment with measurement on $|U_{\tau4}|^2$ directly comparable to NOvA

- Note also there are unresolved discrepancies in short-baseline reactor experiments and gallium-based radiochemical experiments

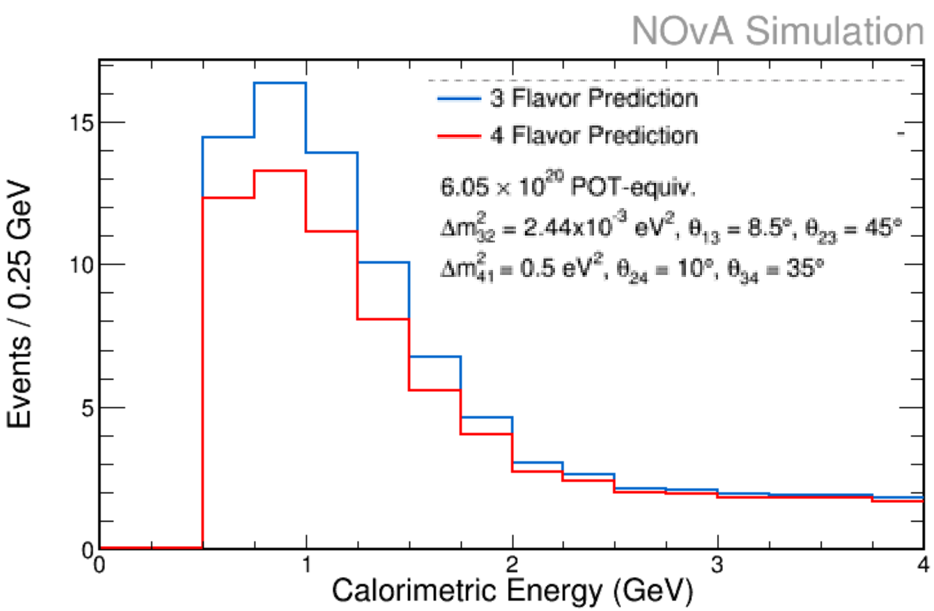
	θ_{24}	θ_{34}	$\lvert U_{\mu4}\rvert^2$	$\lvert U_{\tau4}\rvert^2$
NOvA	20.8°	31.2°	0.126	0.268
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

*Super-K: Phys. Rev. D **91**, 052019*



Searching for ν_s in NOvA

- NC interactions unaffected by 3-flavour oscillations but mixing between active and sterile neutrinos reduces the rate of NC events
  - NC rate is the same for all 3 active flavours
- Compare number of Neutral Current events between Near and Far Detectors
  - Select high statistics ND sample to predict expected rate at the FD
  - Select FD events to search for reduced rate due to sterile oscillations
- Null result would allow NOvA to set limits on sterile mixing angles and further increase the exclusion region



NC disappearance relative to 3-flavour predictions is model independent

Search for a depletion of NC events at the Far Detector

This is a rate-only analysis

NC selected events in FD