Sterile Neutrino Searches with NOvA

DPF 2017

FERMILAB

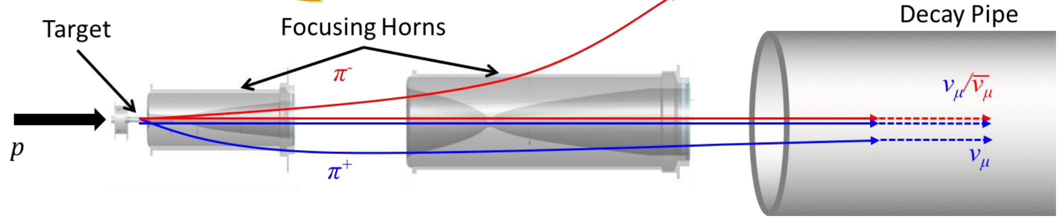
Gavin S. Davies, Indiana University

for the NOvA collaboration

JULY 31ST 2017

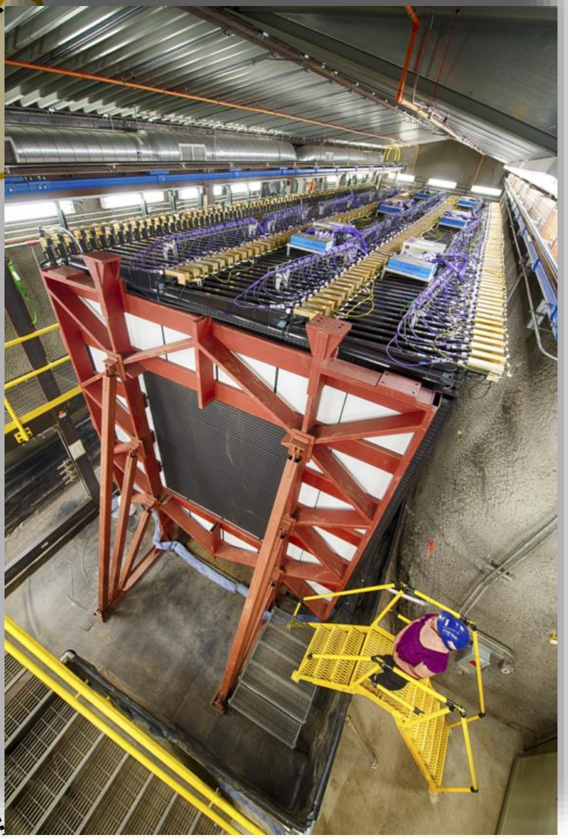
NuMI Off-axis ν_e Appearance

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

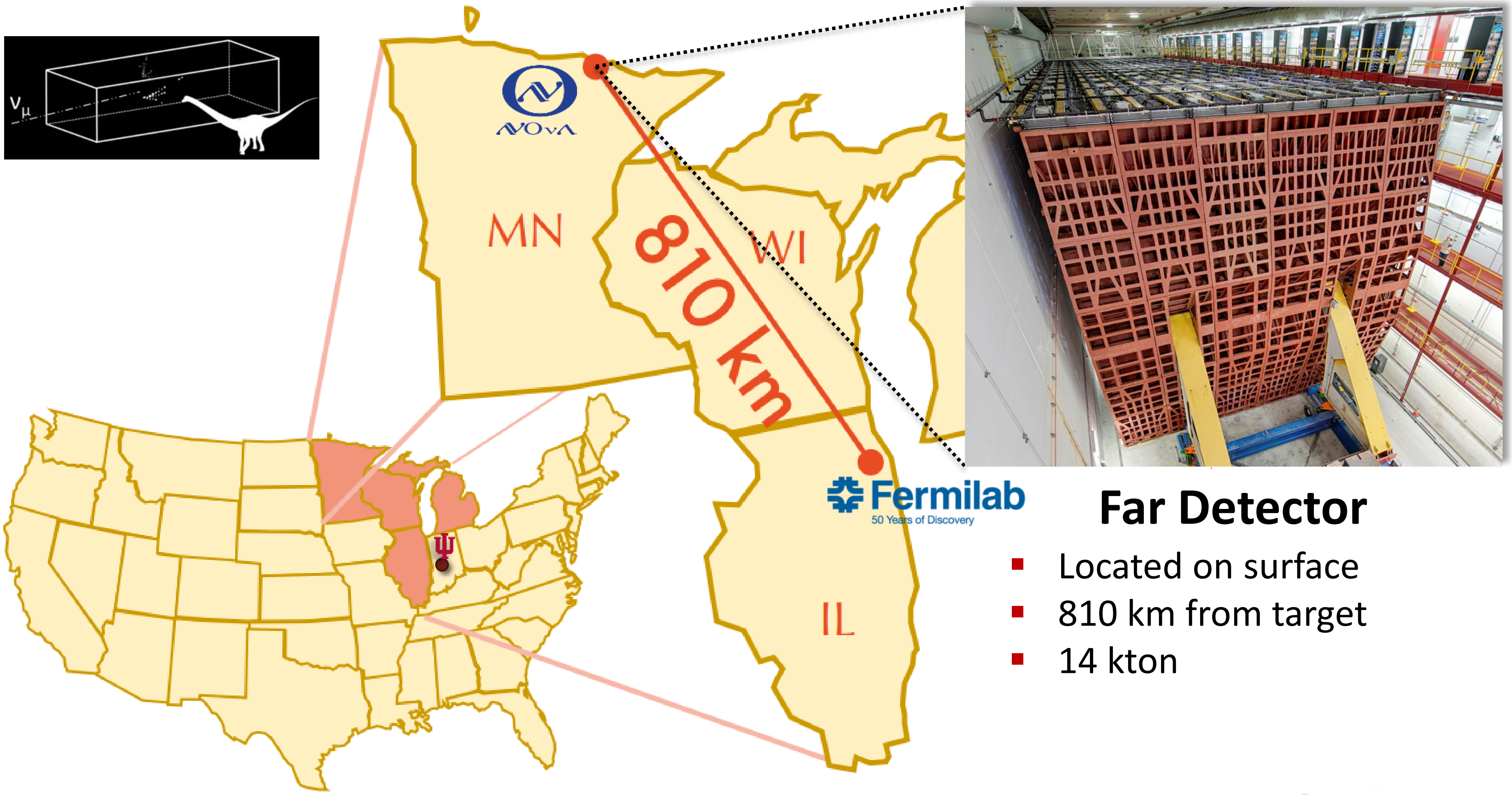


- 105 m underground
- 1 km from target
- 0.3 kton

Near Detector



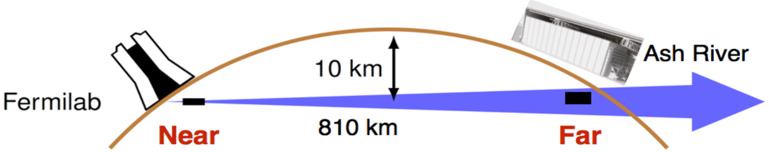
NuMI Off-axis ν_e Appearance



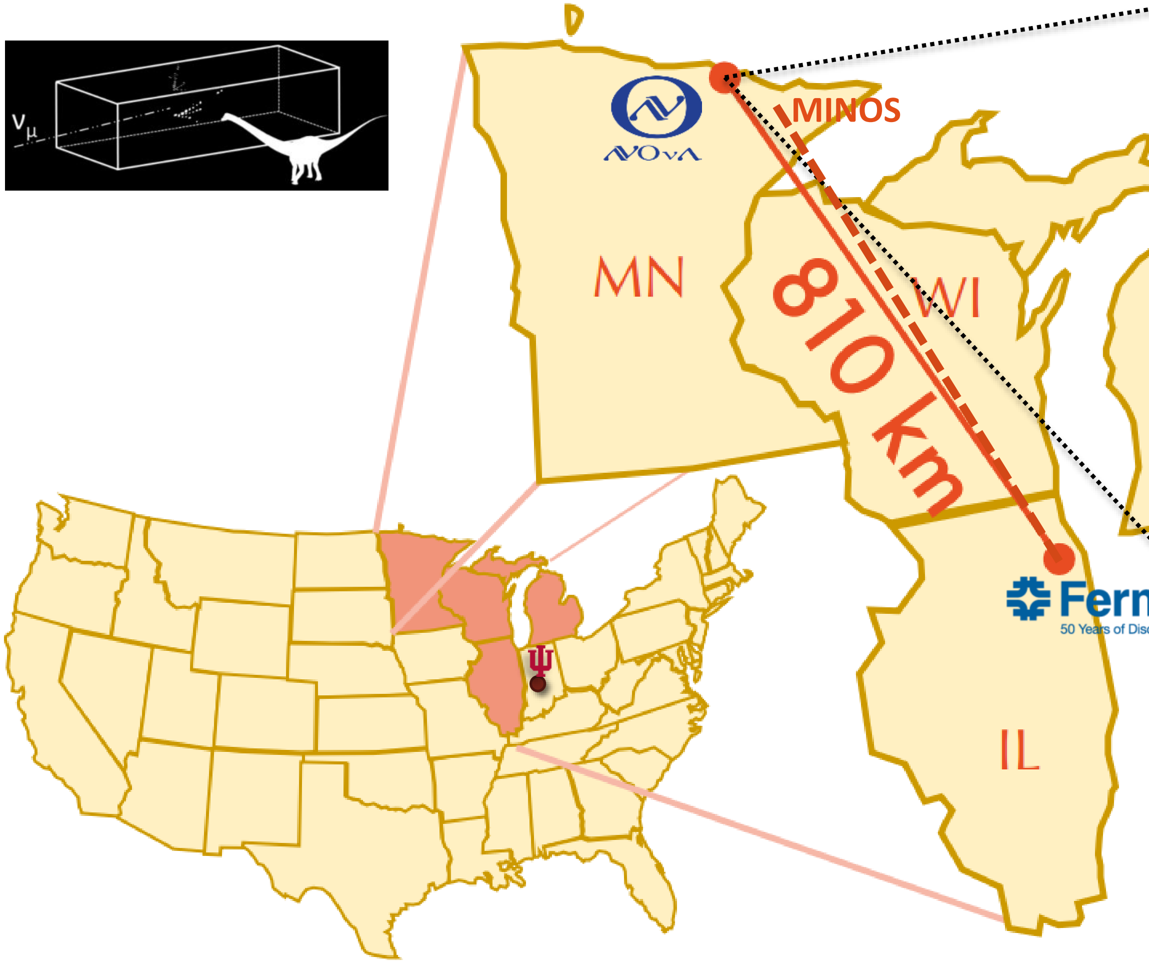
Far Detector

- Located on surface
- 810 km from target
- 14 kton

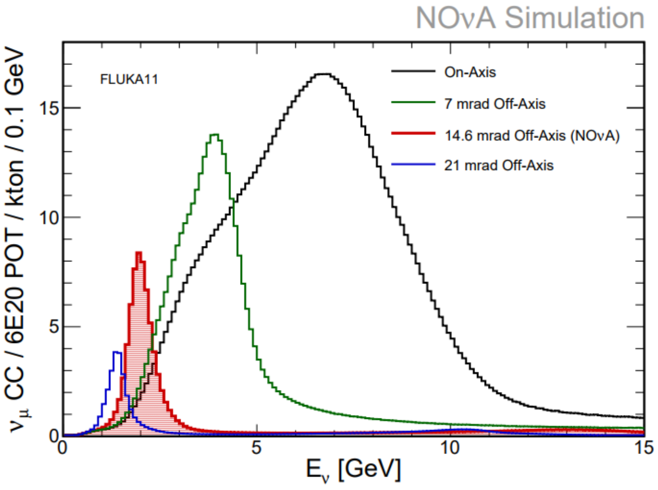
- Measure ν rates after oscillation
- Use of a ratio measurement allows for cancelation of most systematics



NuMI Off-axis ν_e Appearance

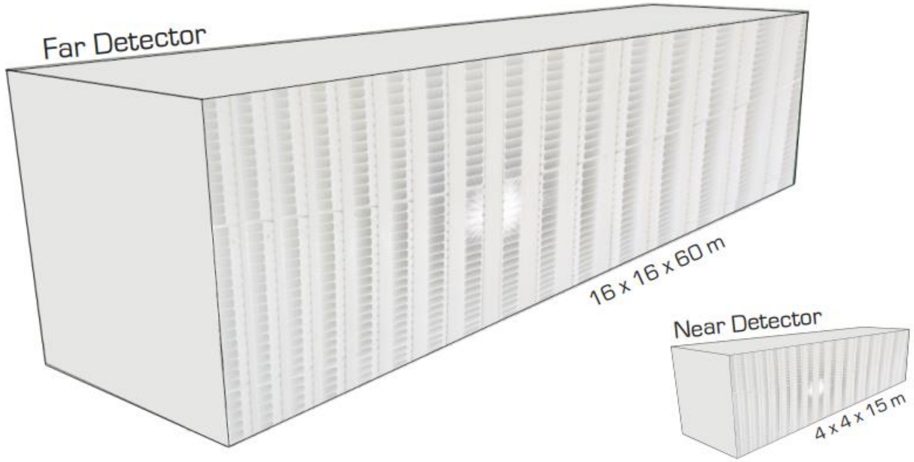


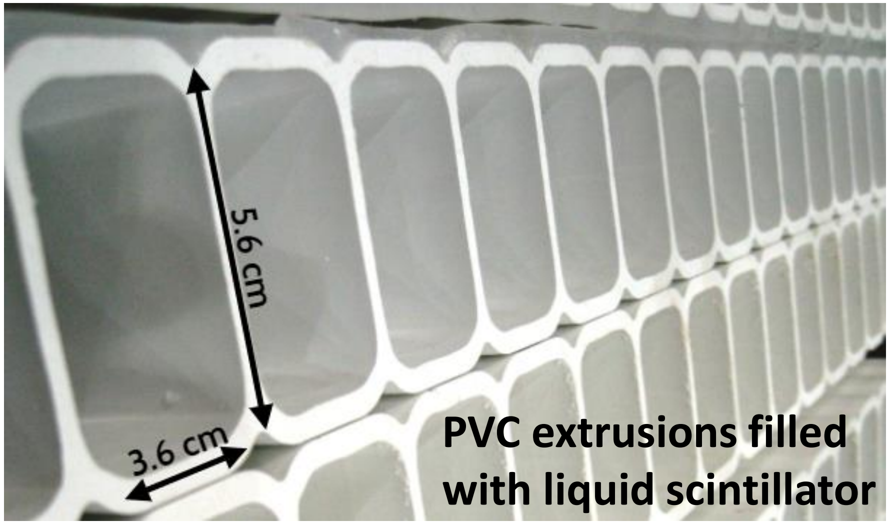
Far Detector



- Narrowly peaked ν flux centred at 2 GeV
- Detectors located 0.8° off NuMI beam axis
- Location optimized for ν_e appearance

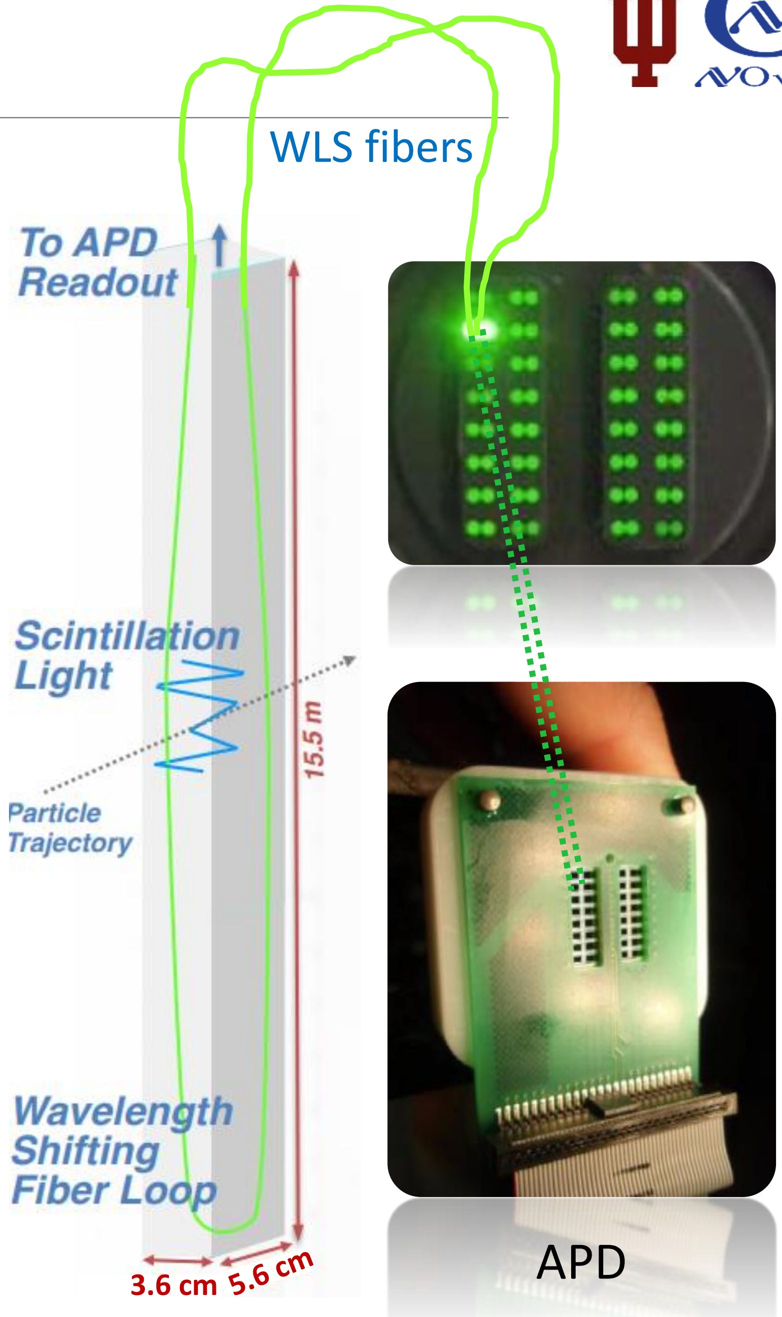
The NOvA detectors





PVC extrusions filled with liquid scintillator

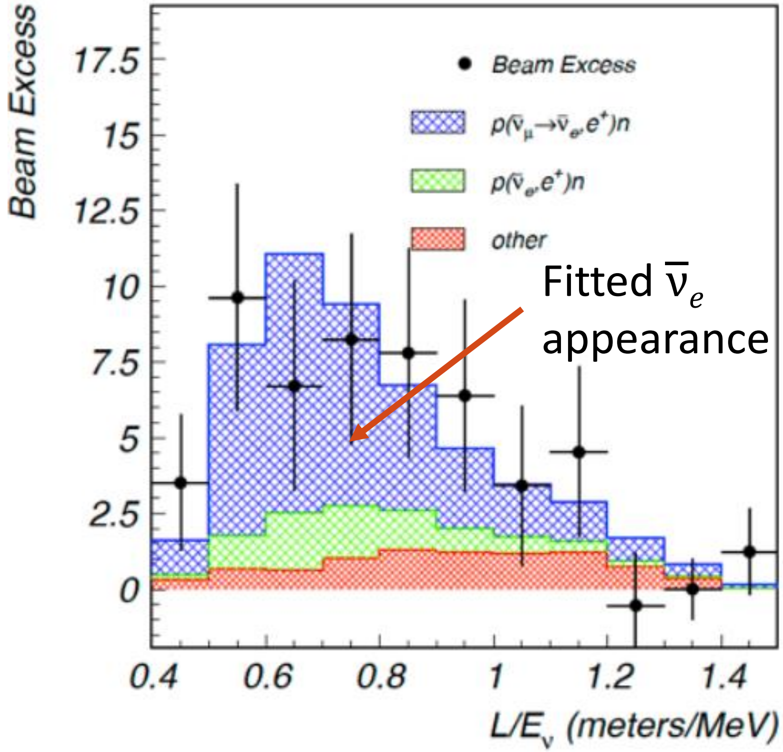
- ND: 20,000 channels
- FD: 344,000 channels



Searching for ν_S

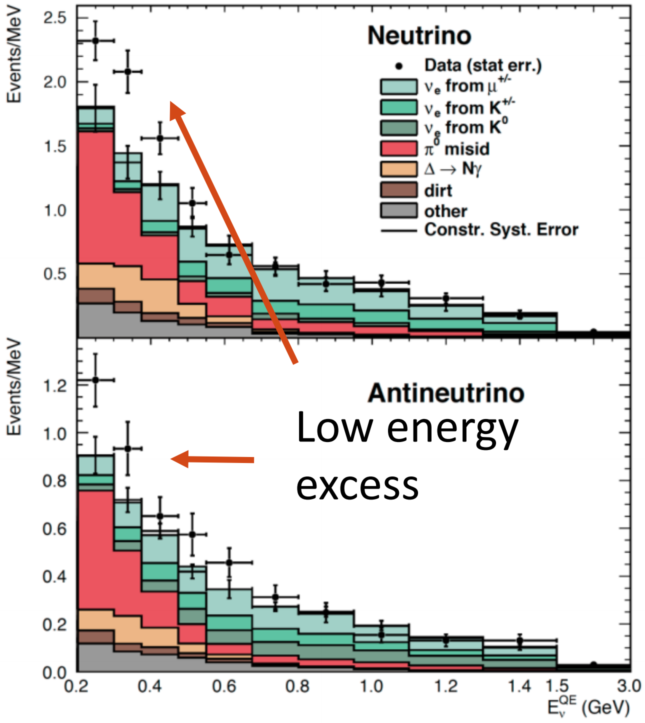
- Short-baseline experiments (LSND, MiniBooNE) have experimental results which could be interpreted as due to a new neutrino with a mass ~1 eV
  - Hints of **appearance** of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beam
  - LSND (1993-1998) observed a (~3.8σ) excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- 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)



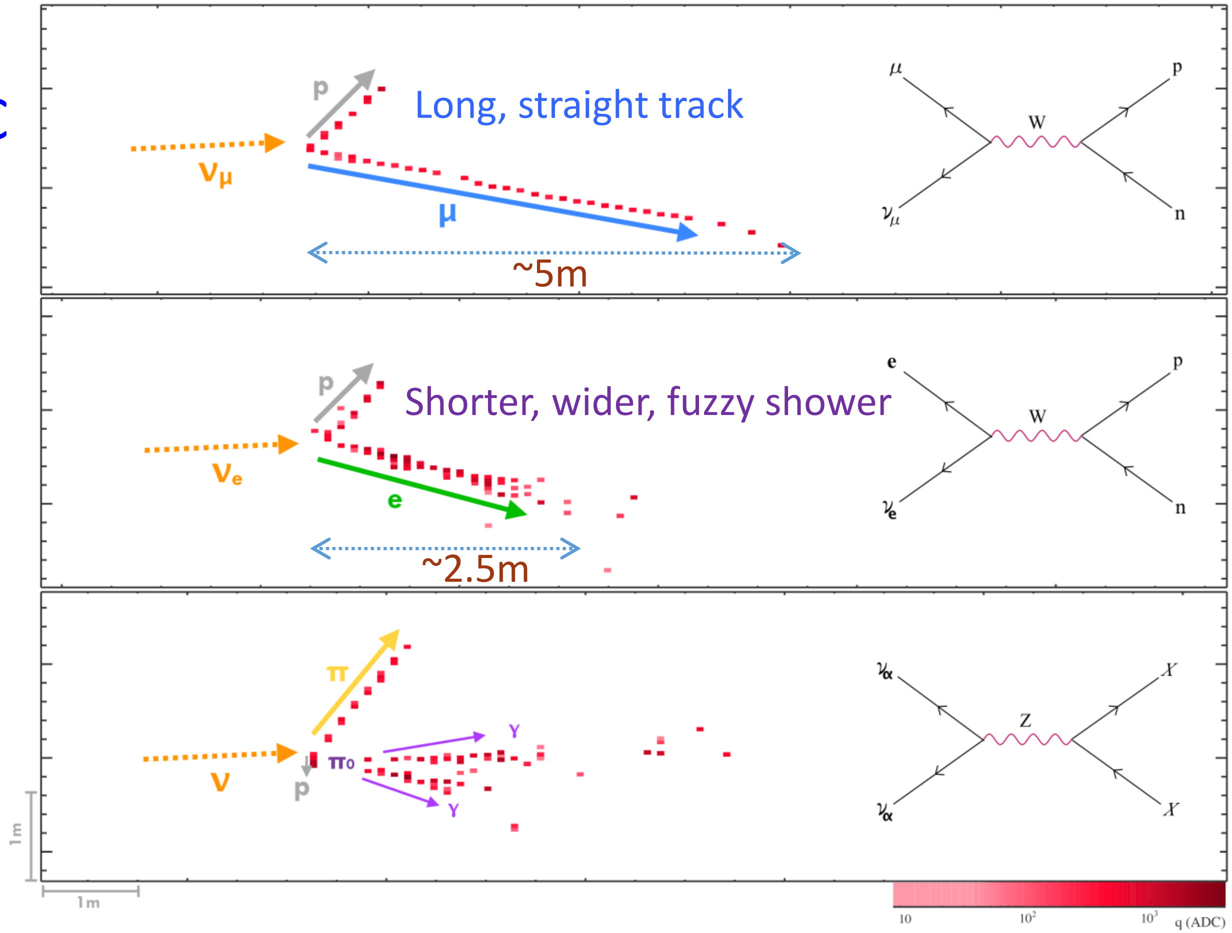
Fitted $\bar{\nu}_e$ appearance

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



Low energy excess

Neutrino Interactions at NOvA



ν_μ CC

Long, straight track

~5m

ν_e CC

Shorter, wider, fuzzy shower

~2.5m

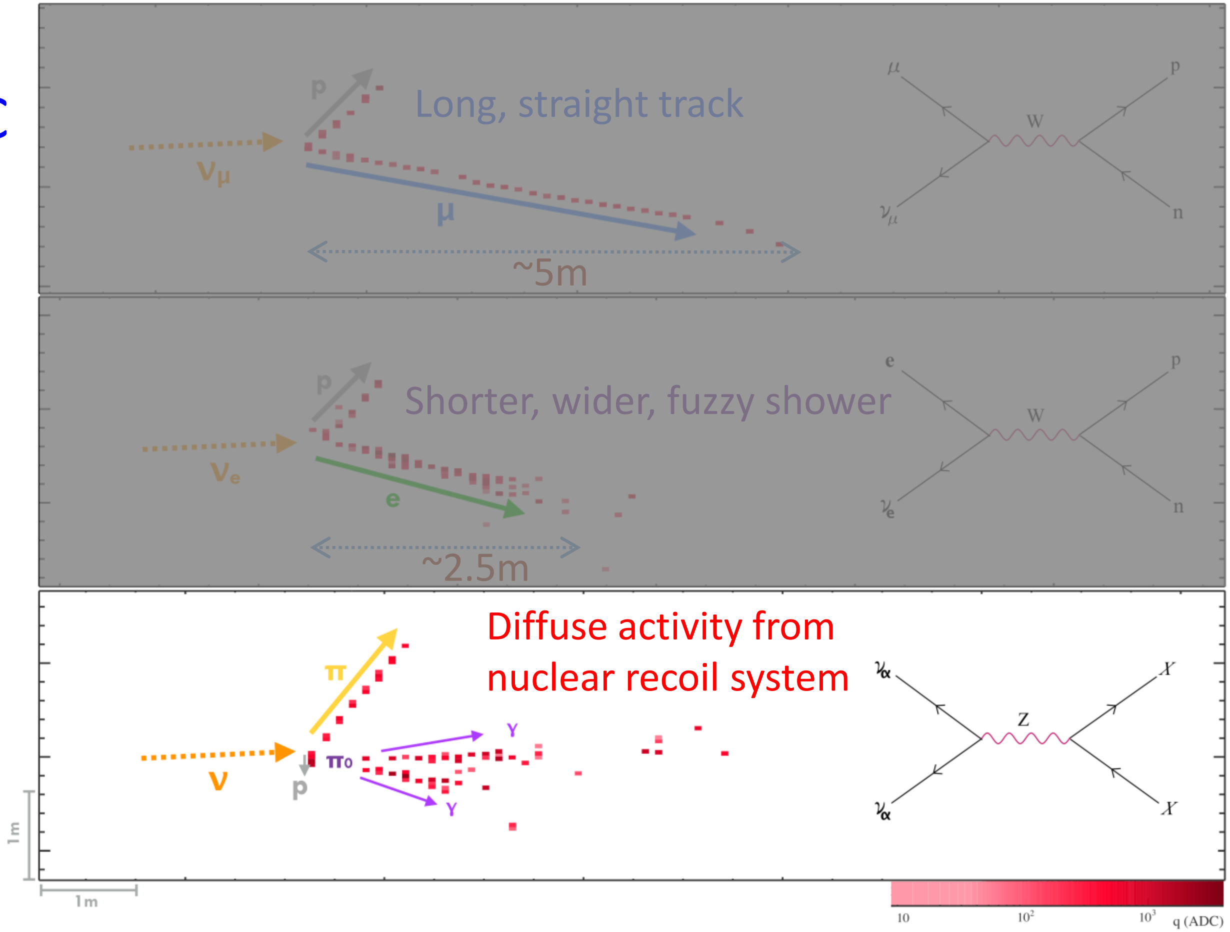
NC

Neutrino Interactions at NOvA

ν_μ CC

ν_e CC

NC



Long, straight track

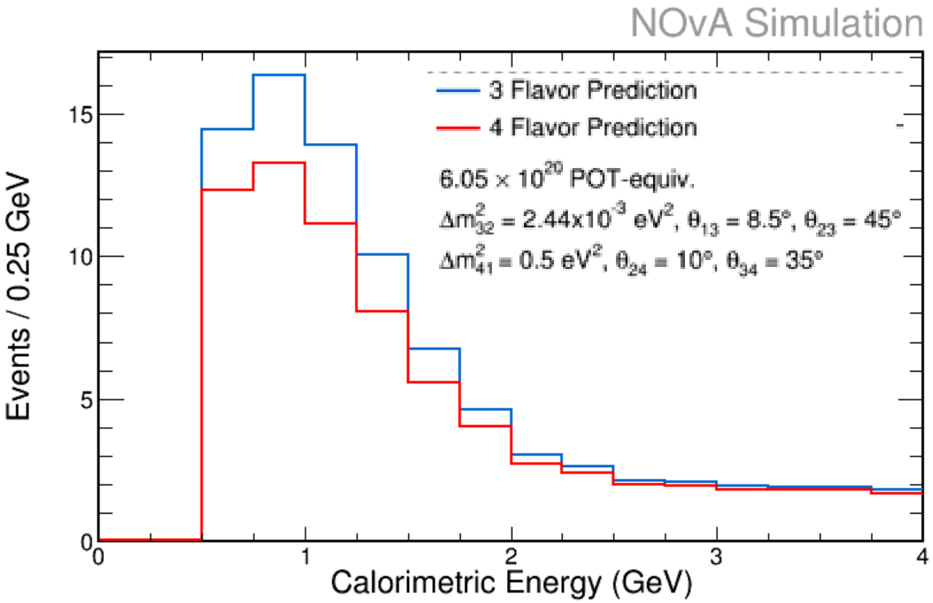
Shorter, wider, fuzzy shower

Diffuse activity from nuclear recoil system

- Neutral Current events are insensitive to oscillations between the active (electron, muon, tau) neutrinos.
- Thus, perfect to search for oscillations to non-active neutrinos

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



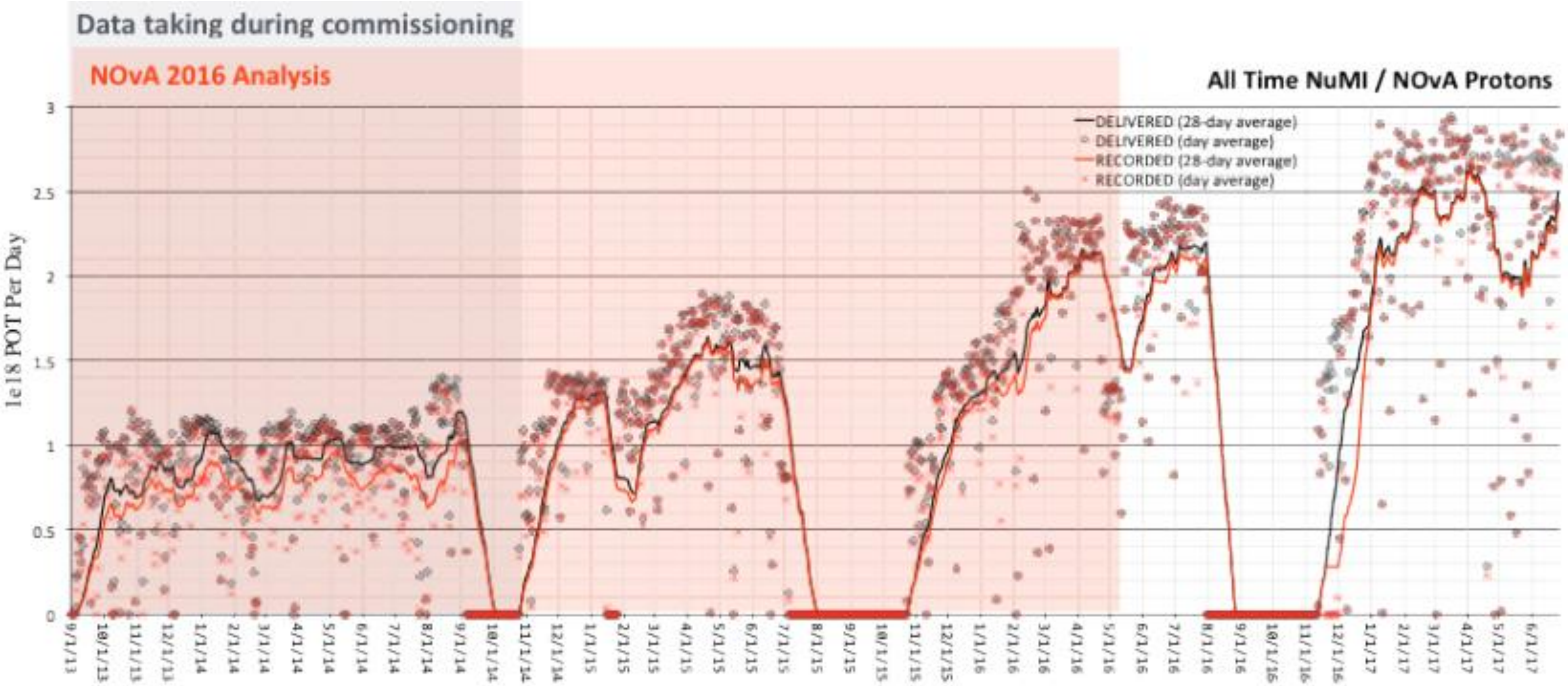
NC disappearance relative to 3-flavour predictions is model independent

Search for a depletion of NC events at the Far Detector

This is a rate-only analysis

2016 Analysis Dataset

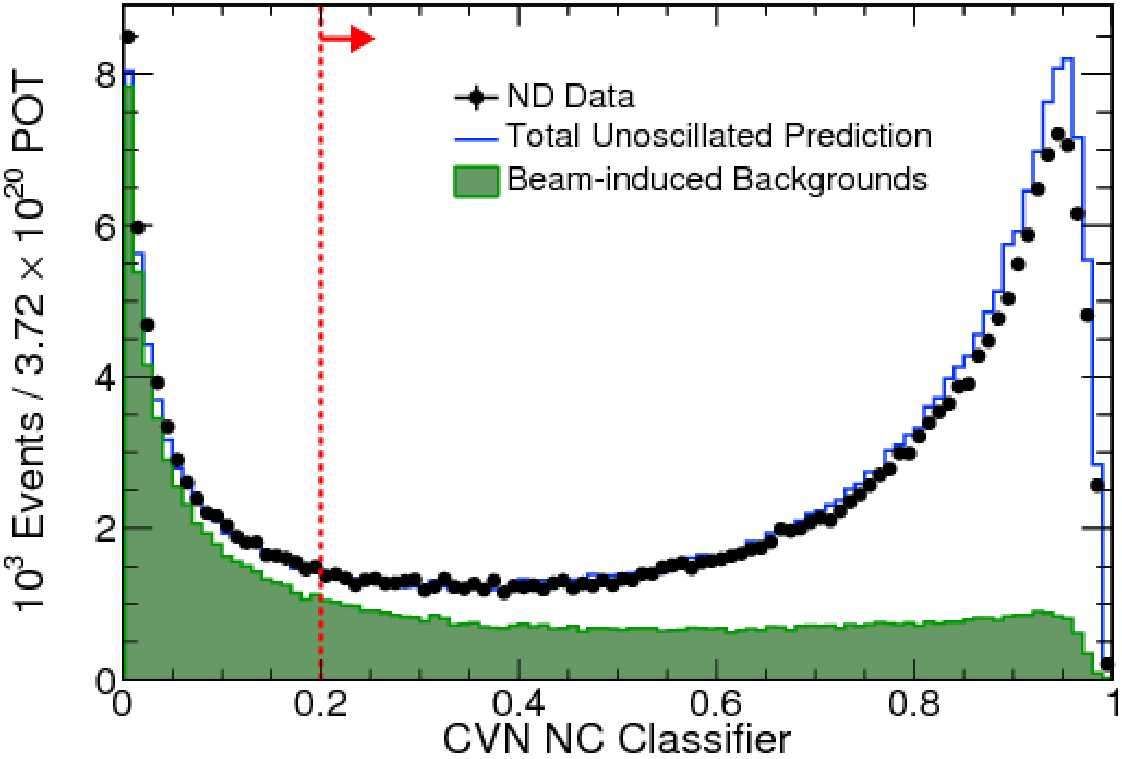
- Full detector equivalent exposure: **6.05×10^{20} POT**
- Excellent ν_μ beam delivered!
- Analysis uses data from *February 6th 2014 to May 2nd 2016*
- NuMI beam achieved 700 kW design goal
  - Ran routinely around 650 kW in recent anti-neutrino run pre-shutdown
  - **The most powerful neutrino beam in the world**



CVN neutral current classifier

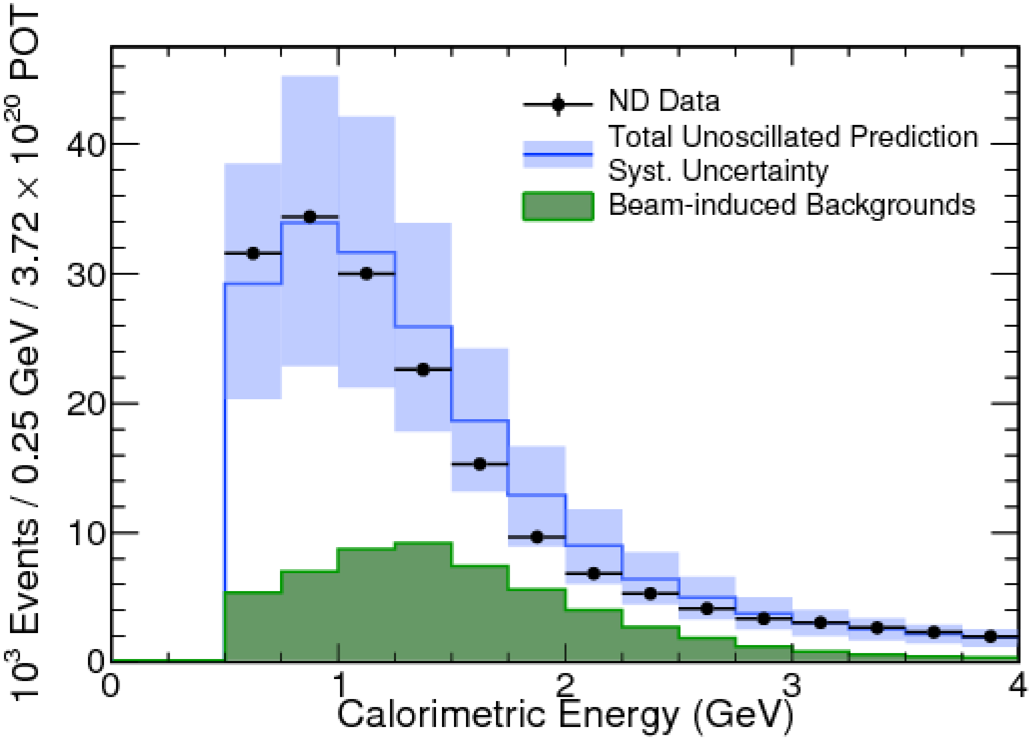
- At the ND, we achieve a 62% NC signal efficiency and 70% NC signal purity for contained events within the fiducial volume
  - At FD, we achieve 50% NC signal efficiency and 72% NC signal purity
  - FD training includes cosmic ray data sample to aid NC classification

- Excellent at separating NC events from beam backgrounds
  - Analysis cuts developed to separate NC from cosmic background in the Far Detector



See talk:
"Deep Learning Applications in the NOvA Experiment" **(Fernanda Psihas)**

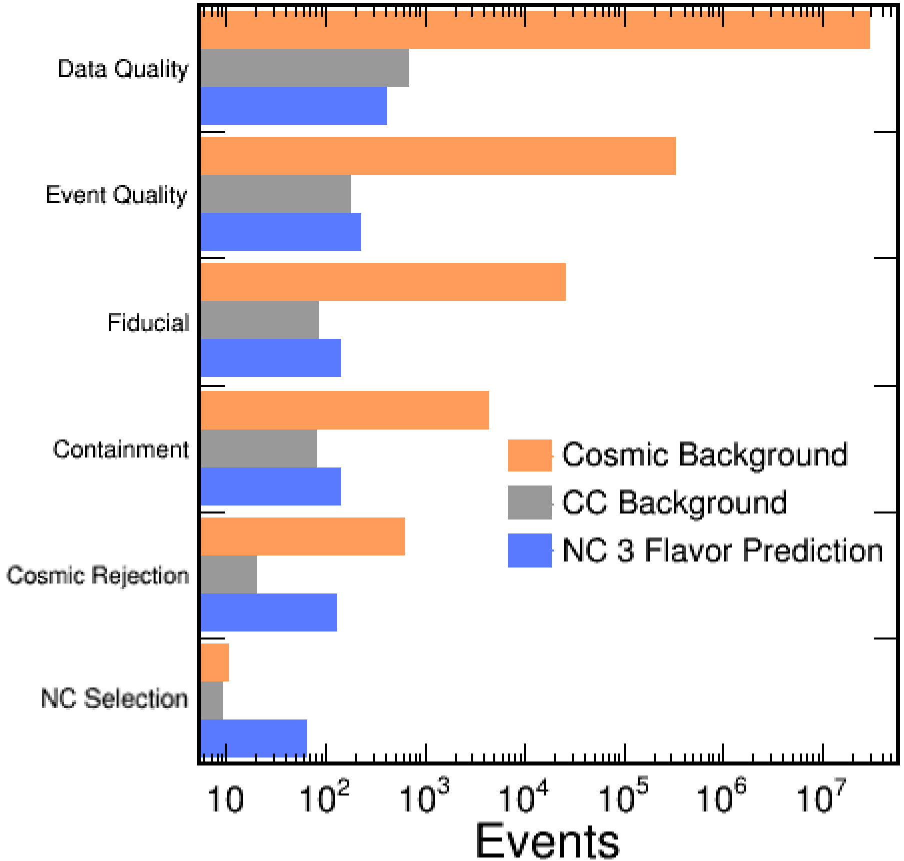
Near detector NC spectrum



- Normalisation agrees well
- Large uncertainties on NC cross-section

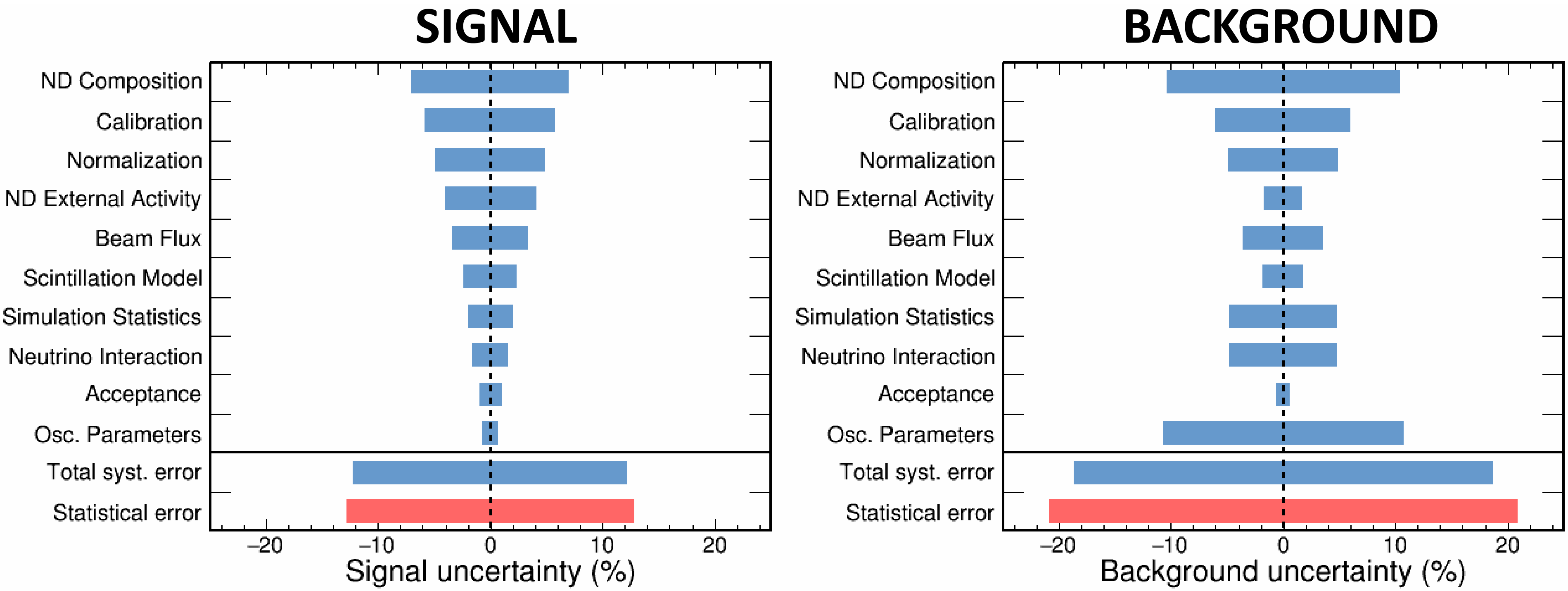
Cosmic ray rejection in FD

- Far Detector is on the surface
  - 148 kHz cosmic ray muon rate
- 10 μs spill window at ~ 1 Hz gives 10^5 rejection
- Improve cosmic rejection further with event topology cuts plus boosted decision tree based on
  - Track direction
  - Track start and end points
  - Track length
  - Energy
  - Number of hits
- Expect 1 from every 1.7 million cosmic rays selected as signal in NC analysis



See talk:
***"Exploring Computing Methods for Improved Cosmic Background Rejection in NOvA's Sterile Neutrino Searches"* (Shaokai Yang)**

Systematic uncertainties



- Two detector design cancels many systematics
- Propagate effect of each through extrapolation
- Include as pull terms in neutrino oscillation parameter fits

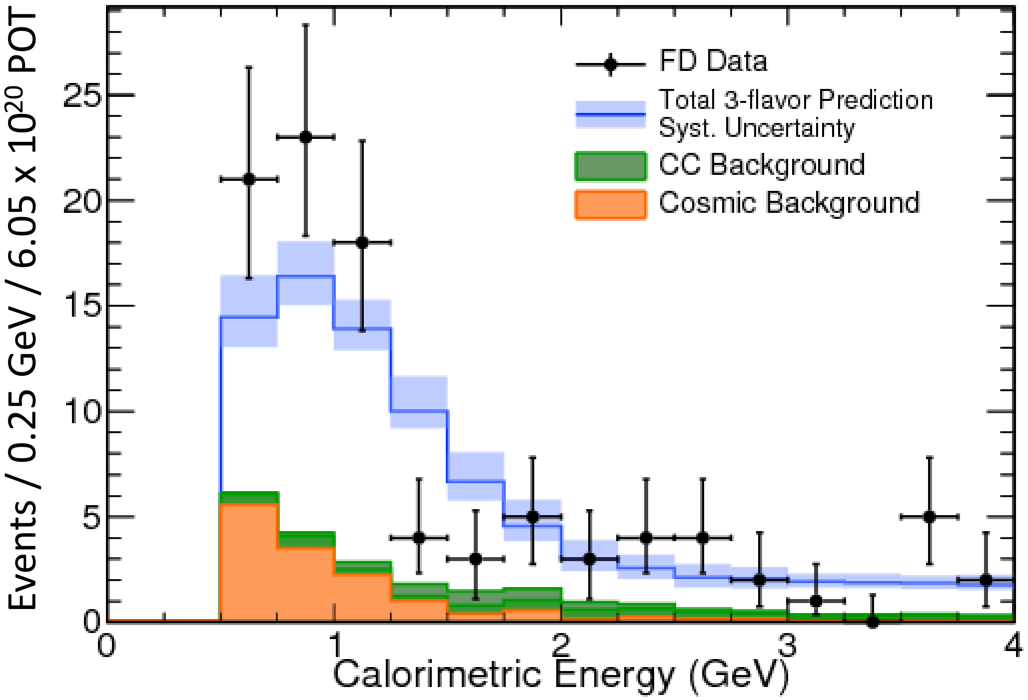
NC disappearance results

We observe 95 NC-like events in Far Detector

MC extrapolated prediction: 83.5 ± 9.7 (stat.) ± 9.4 (syst.)

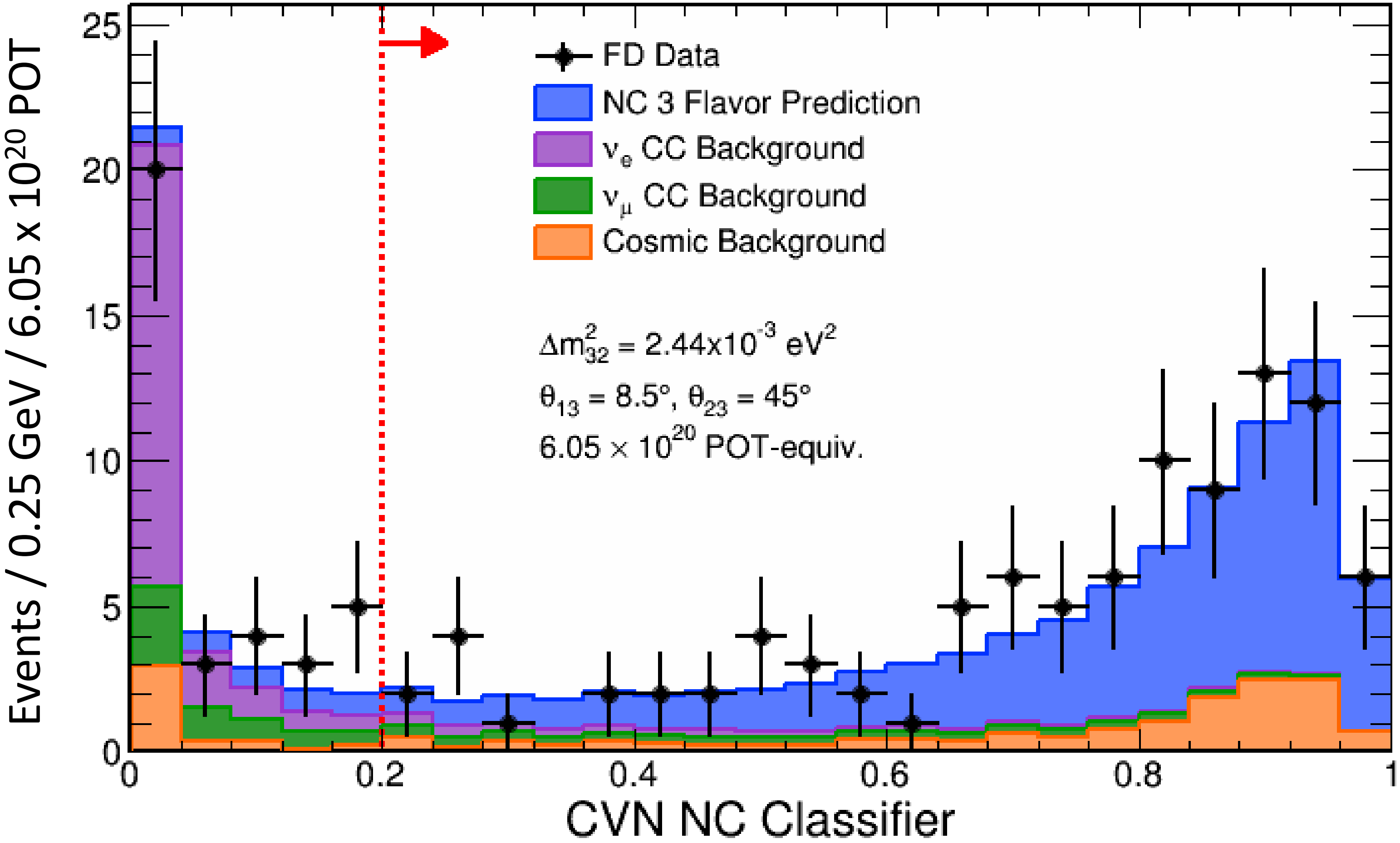
within 1σ of three-flavour prediction

NOvA sees no evidence for sterile neutrino mixing



Far detector NC selection

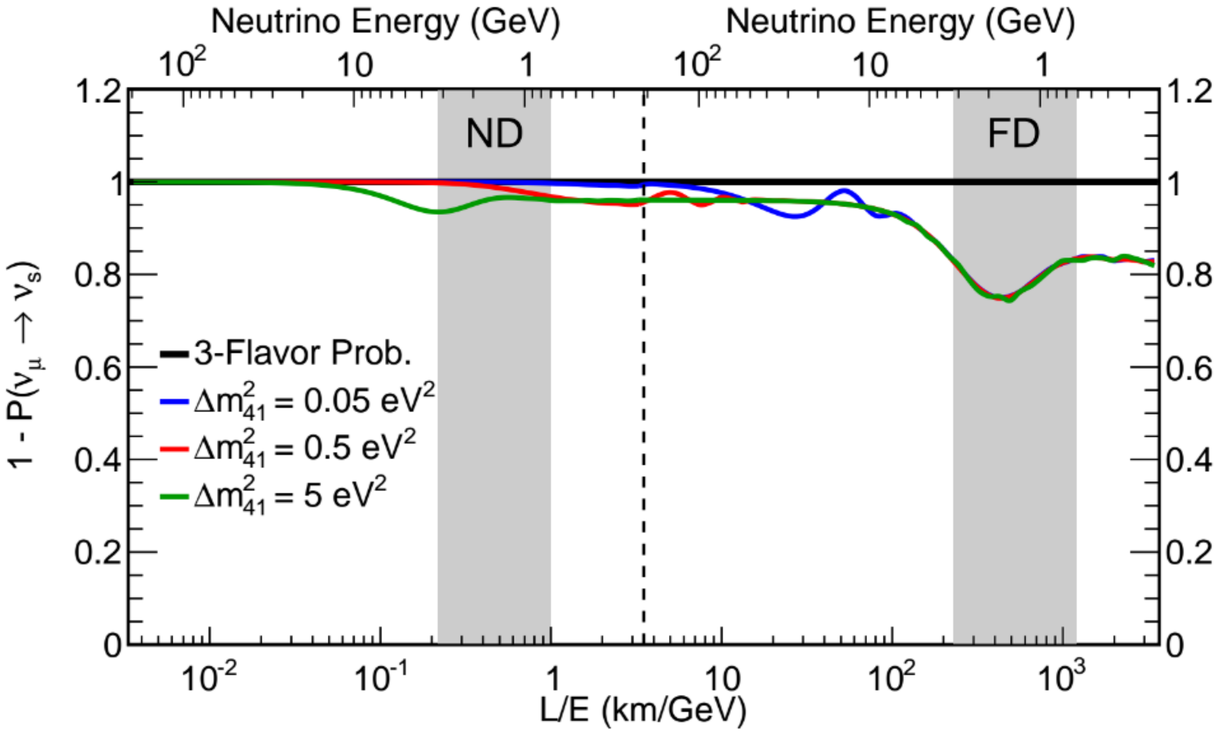
FD NC selection uses the same variables as the ND selection, with identical cut values



3+1 model

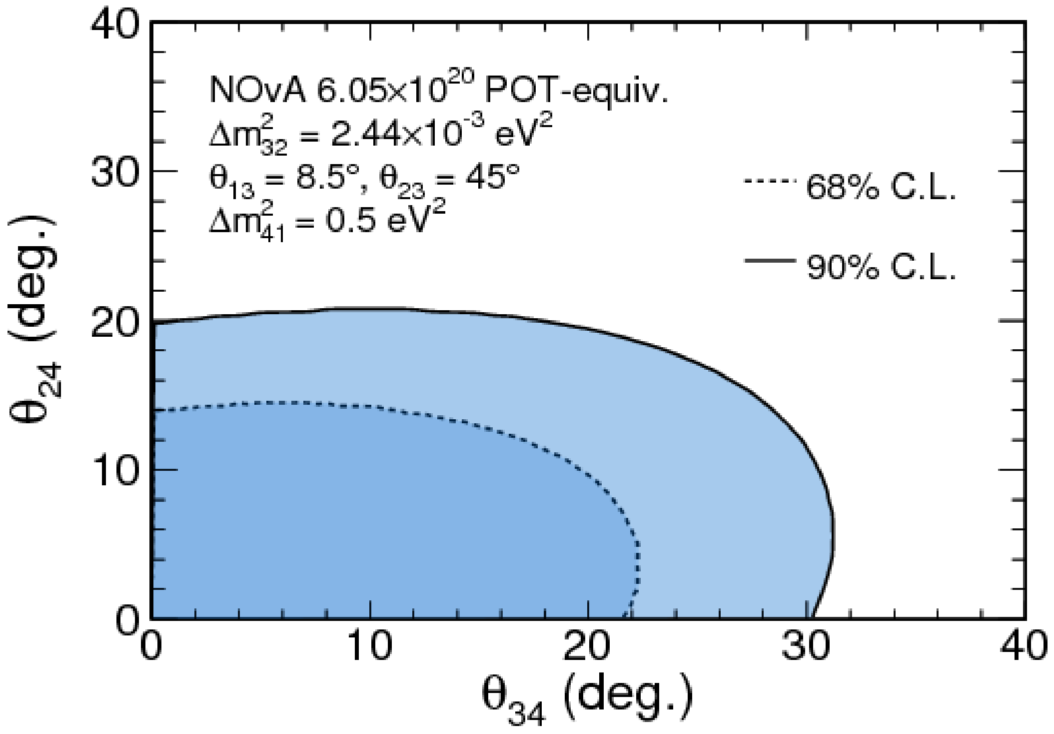
- ν_μ to ν_s mixing causes energy-dependent depletion of NC and ν_μ-CC events at Far Detector

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



- Solar and reactor neutrino data constrains $\sin^2\theta_{14} < 0.041$
  - Assume $\theta_{14} = 0$
- 0.05 eV^2 < Δm^2_{41} < 0.5 eV^2
  - no ND oscillations
- Constraint on θ_{23}
  - $\sin^2(\theta_{23}) = 0.514$
  - PDG 2016

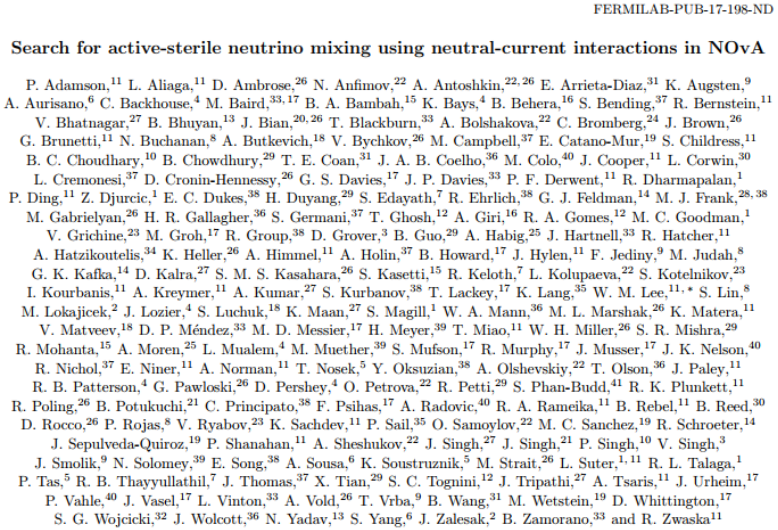
Sterile mixing angle limits



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.

Paper submitted, **arXiv:1706.04592**

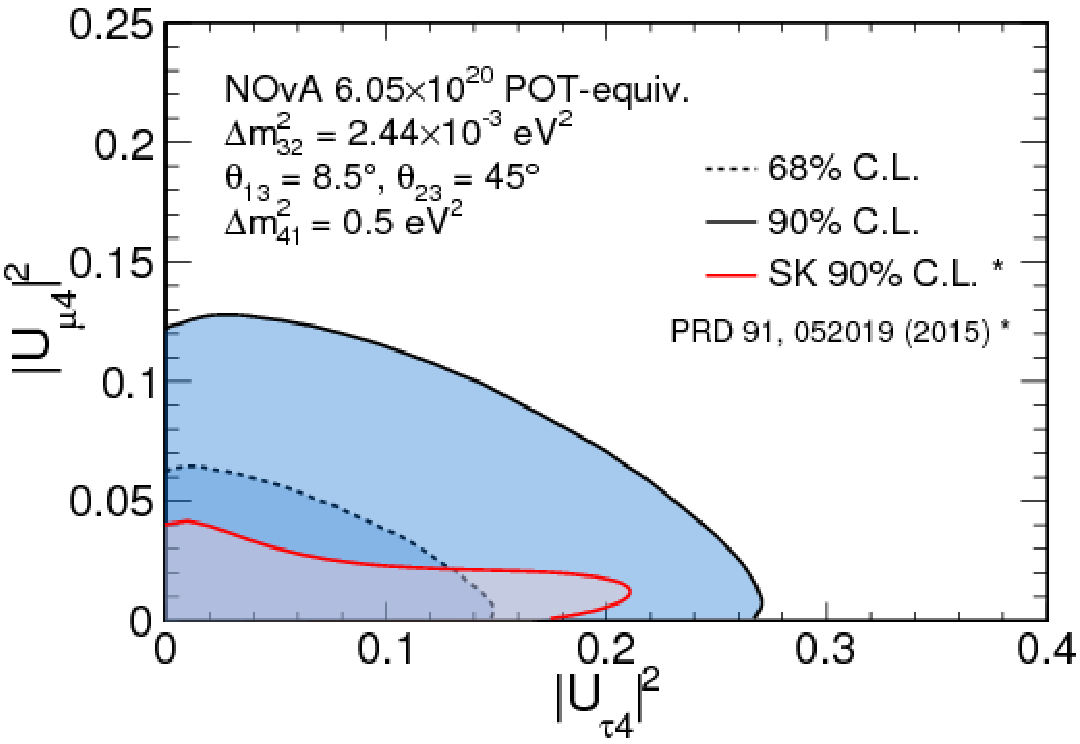

FERMILAB-PUB-17-198-ND

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]

See poster:
"Sterile neutrino search in the NOvA Far Detector"
(Sijith Edayath)

Sterile mixing angle limits



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

$|U_{\mu4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24}$
$|U_{\tau4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$

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

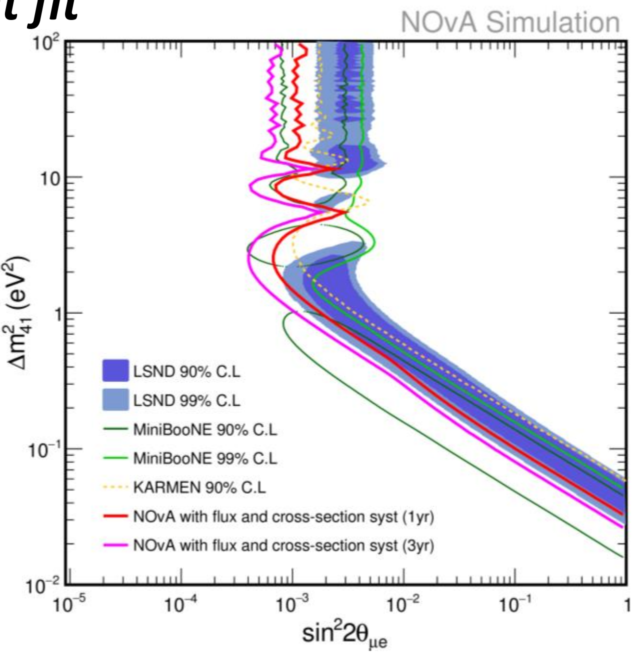
$|U_{\mu4}|^2 < 0.126$ at 90% C.L.
$|U_{\tau4}|^2 < 0.268$ at 90% C.L.

See poster:
“Sterile neutrino search in the NOvA Far Detector”
(Sijith Edayath)

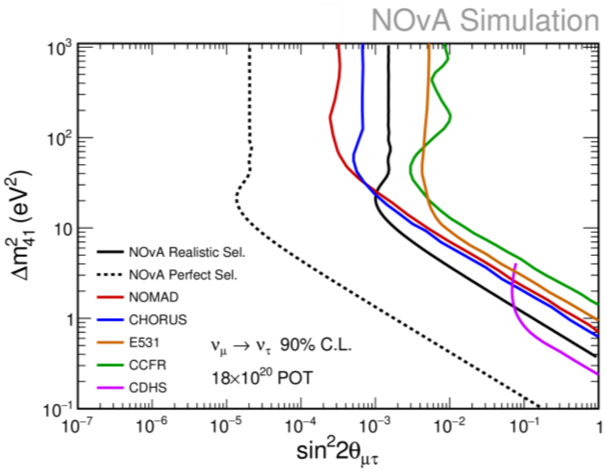
The future for NOvA ν_s searches

NOvA short-baseline ν_e appearance-ν_μ disappearance joint fit

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



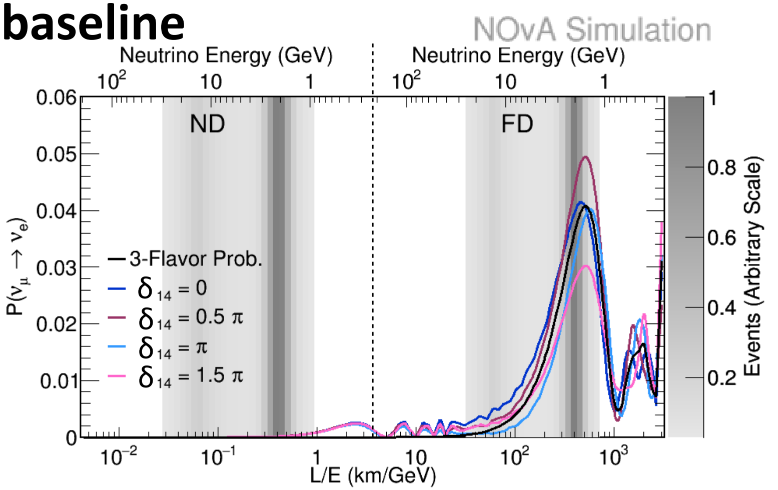
NOvA short-baseline ν_τ appearance



See poster:
"NOvA Short-Baseline Tau-Neutrino Appearance Search"
(Rijeesh Keloth)

- 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



Summary

- Performed the first NOvA NC disappearance analysis with **6.05 x 10^{20} POT**
- **95 observed events** compared to *83.5 ± 9.7 (stat.) ± 9.4 (syst.)* predicted
  - Within 1σ of three-flavour prediction
  - Consistent with 3-flavour oscillations
- **NOvA sees no evidence for sterile neutrino mixing**
- Competitive with world θ_{34} limits
- ND short-baseline searches underway
- Posters:
  - *"NOvA Short-Baseline Tau-Neutrino Appearance Search"* (Rijeesh Keloth)
  - *"Sterile neutrino search in the NOvA Far Detector"* (Sijith Edayath)
- Stay tuned for summer analysis update with 50% more data!

@novaexperiment

NOvA@DPF2017

18 Talks

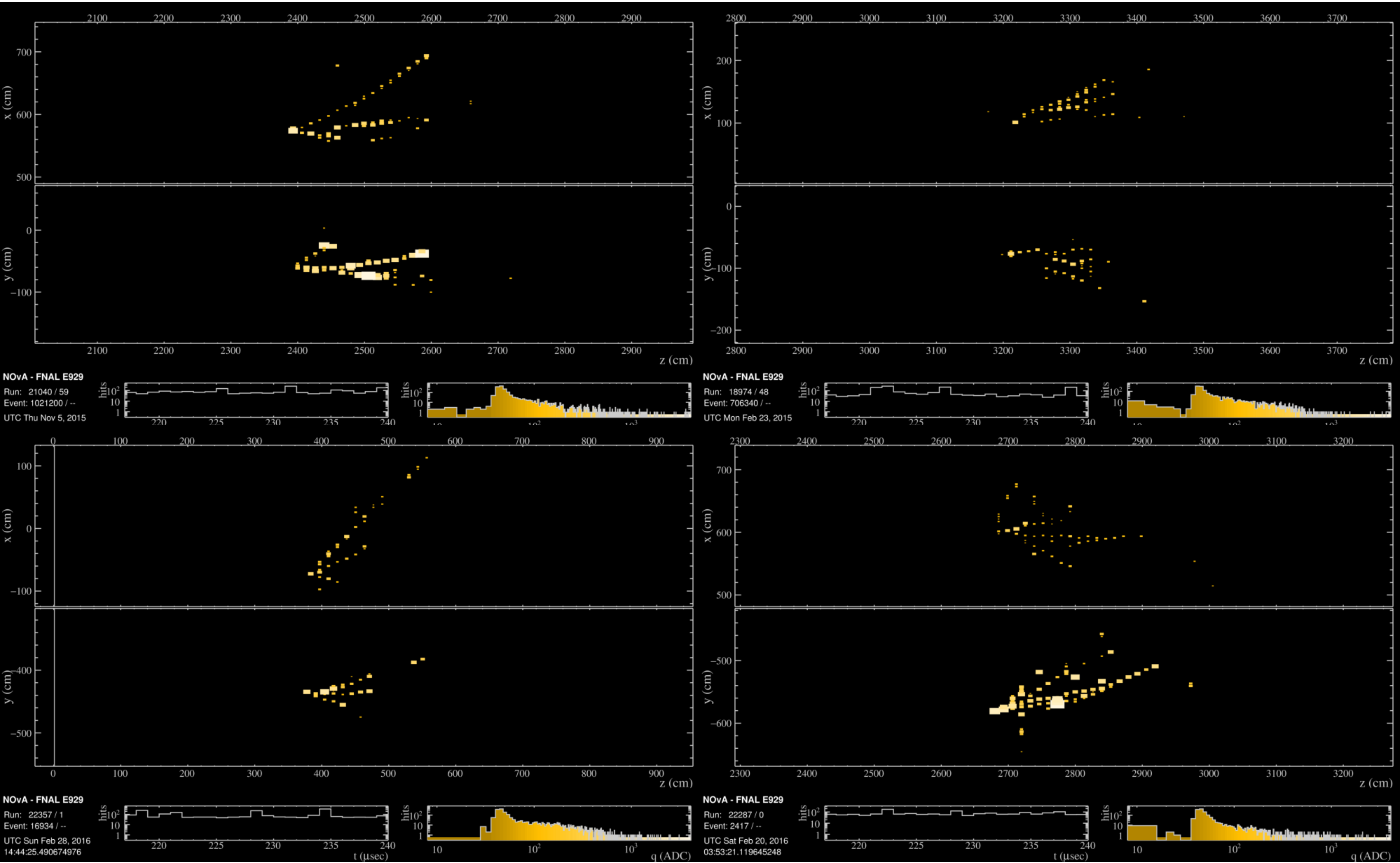
Large-scale Simulation and Data Processing in the NOvA Experiment – Adam Moren
Muon Neutrino Disappearance Analysis in NOvA: Improvements – Diana Patricia Méndez Méndez
Summary of the Second Numu Disappearance Results from the NOvA Experiment – Michael Baird
Extracting Neutrino Oscillation Parameters Using Simultaneous Fit of ν_e Appearance-ν_μ Disappearance Data in NOvA – Prabhjot Singh
Energy Reconstruction of NOvA Neutrino Events – Fernanda Psihas
Physics Reach of Electron Neutrino Appearance Measurements in NOvA – Erika Cataño Mur
Reconstruction in NOvA – Biswaranjan Behera
Deep Learning Application in the NOvA Detectors – Fernanda Psihas
A Search for WIMPs Using Upward-going Muons in NOvA – Cristiana Principato
A Neural Network Trigger for Magnetic Monopoles with the NOvA Far Detector – Enhao Song
Status of an Alternative Measurement of the Inclusive Muon Neutrino Charged-Current Cross Section in the NOvA ND – Biswaranjan Behera
Measurement of Neutrino-Electron Elastic Scattering at NOvA Near Detector – Jianming Bian
Status of the Charged Pion Semi-Inclusive Neutrino Charged-Current Cross Section in NOvA – Aristeidis Tsaris
Measurement of Neutral Current Coherent π^0 Production In The NOvA Near Detector – Hongyue Duyang
Current Analysis Status for the Inclusive Neutral Current π^0 Production Cross-Section Measurement with the NOvA ND – Daisy Kalra
Status of the Electron-Neutrino Charged-Current Inclusive Cross-Section Measurement in NOvA – Pengfei Ding
Exploring Computing Methods for Improved Cosmic Background Rejection in NOvA's Sterile Neutrino Searches – Shaokai Yang
Sterile Neutrino Searches with NOvA – Gavin Davies

11 Posters

Tracking Detector Performance and Data Quality in the NOvA Experiment – Biswaranjan Behera
A Particle Hypothesis-based Approach for Energy Estimation in Muon Neutrino Charged Current Events at NOvA – Erica Smith
NOvA Short-Baseline Tau-Neutrino Appearance Search – Rijeesh Keloth
Sterile Neutrino Search in the NOvA Far Detector – Sijith Edayath
The NOvA Data-Driven Trigger – Matthew Judah
Background Estimation for the Electron Neutrino Appearance Analysis in NOvA – Erika Cataño Mur
Search for a Large Muon Neutrino Magnetic Moment in the NOvA Near Detector – Biao Wang
Observing Neutrinos from the Next Galactic Supernova with the NOvA Detectors – Justin Vasel
Observation of BNB Neutrinos in the NOvA Near Detector – Ryan Murphy
NuMI Beam Simulations with Different Horn Configurations with a New NOvA Target Design – Jyoti Tripathi
Seasonal Variation of Multiple-Muon Events in NOvA – Philip Schreiner

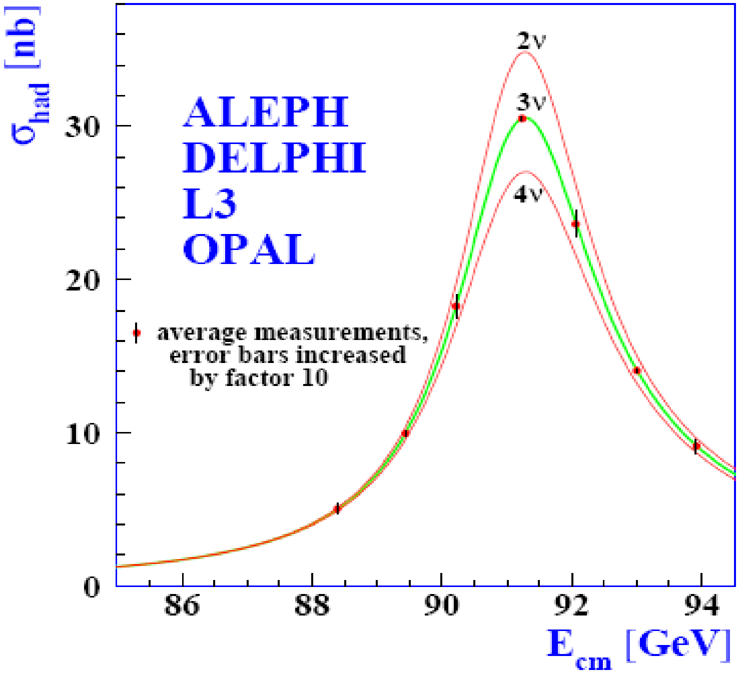
Backup

NC selected events in FD

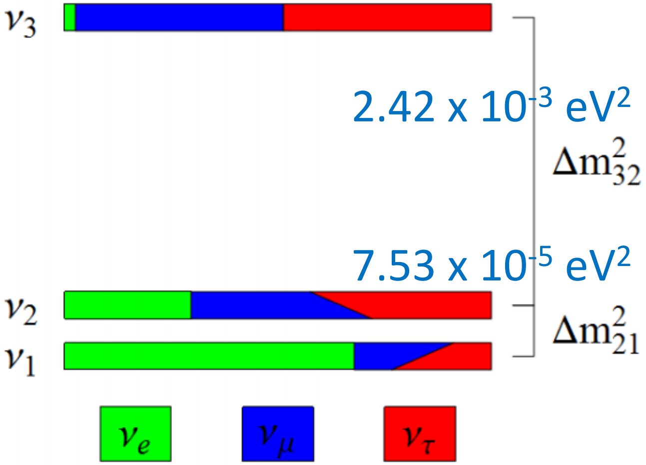


What is a sterile neutrino?

- 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



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



2.42×10^{-3} eV^2

7.53×10^{-5} eV^2

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

Anomaly!

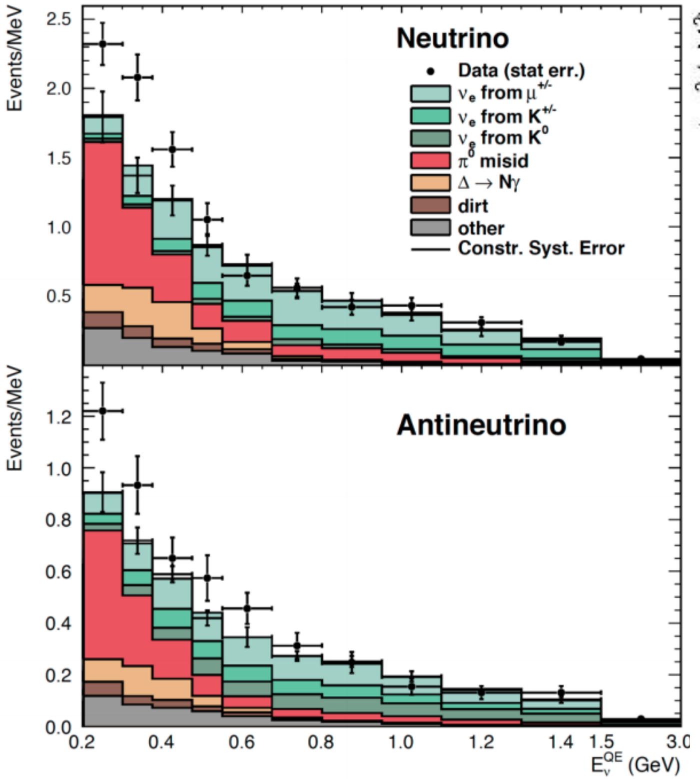
- Sterile neutrinos can participate in oscillations with active flavours
  - ○ $\nu_\mu \rightarrow \nu_s, \nu_e \rightarrow \nu_s, \nu_\tau \rightarrow \nu_s$

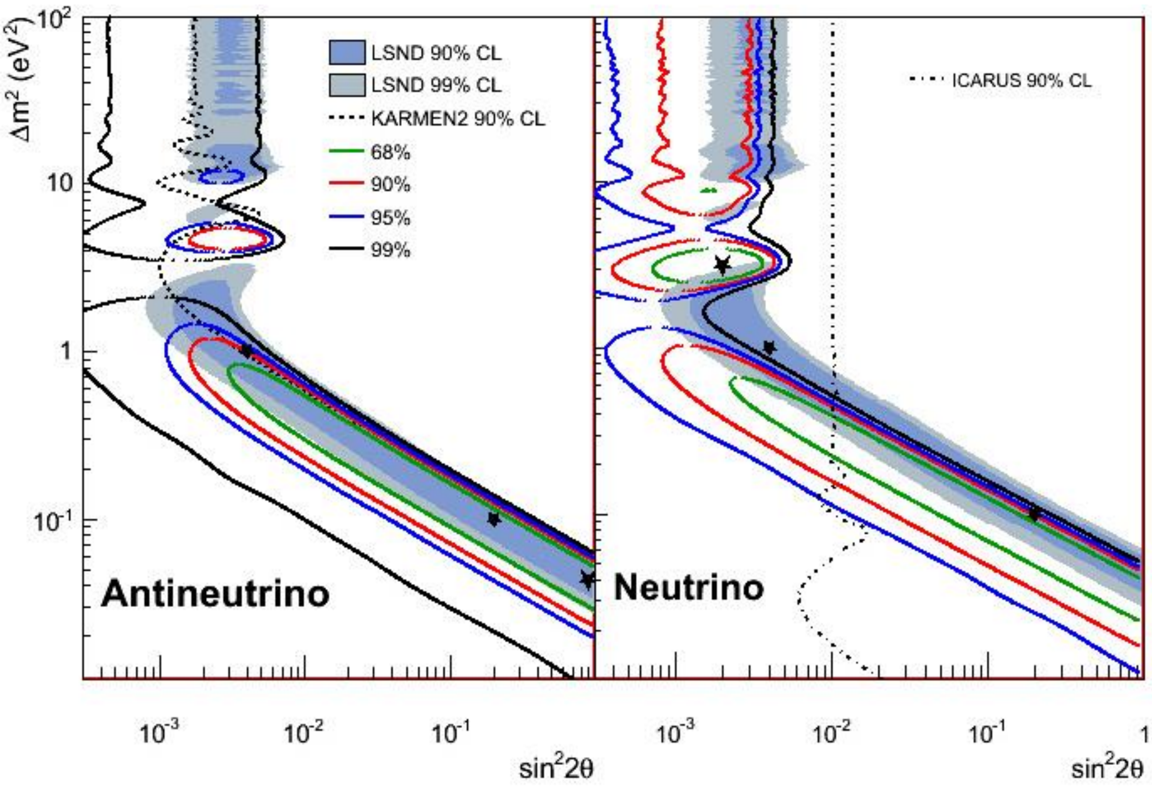
ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and LEP Electroweak Working Group, and SLD Electroweak Group, and SLD Heavy Flavour Group, Phys. Report 427, 257 (2006)

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

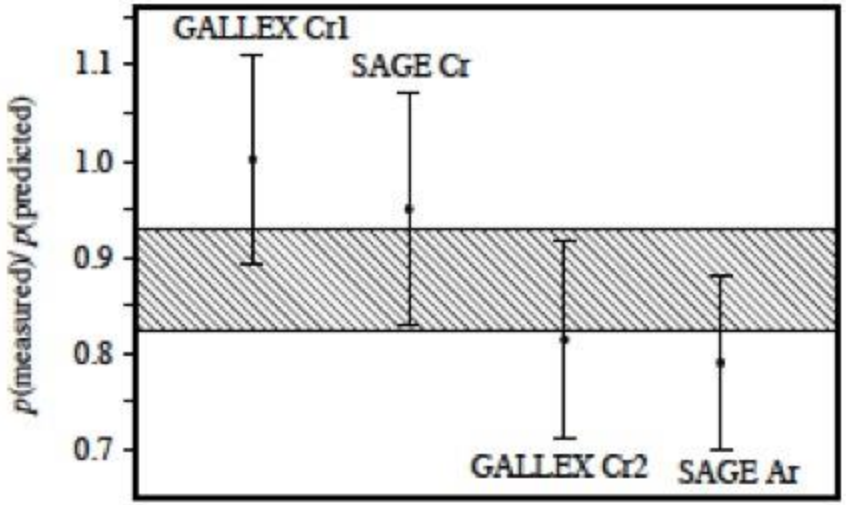




MiniBooNE Phys. Rev. Lett. 110, 161801 (2013)

The Gallium anomaly

- SAGE and GALLEX were both solar neutrino experiments
  - Neutrino detection via ${}^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- Both measured lower than expected cross-section:
  - R = 0.76 ± 0.09 (2.8σ low)
- Ended in 1992; in light of other results, possibility due to large-mass sterile neutrinos suggested



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:

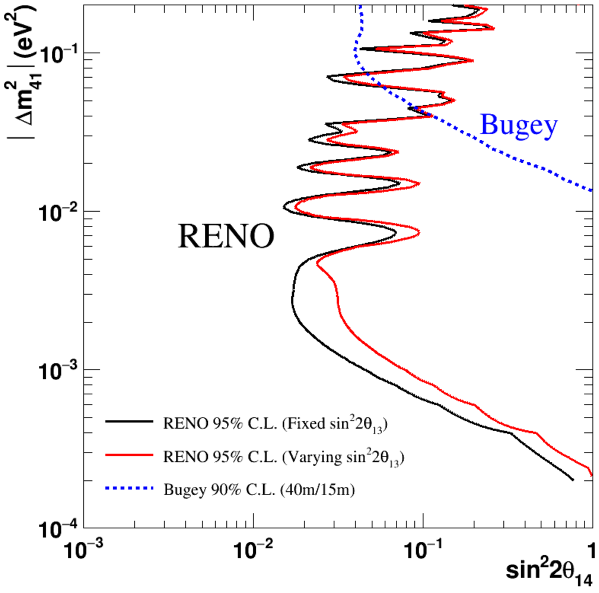
$\Delta m^2_{41} < 0.8$ eV^2 at 95% C.L

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

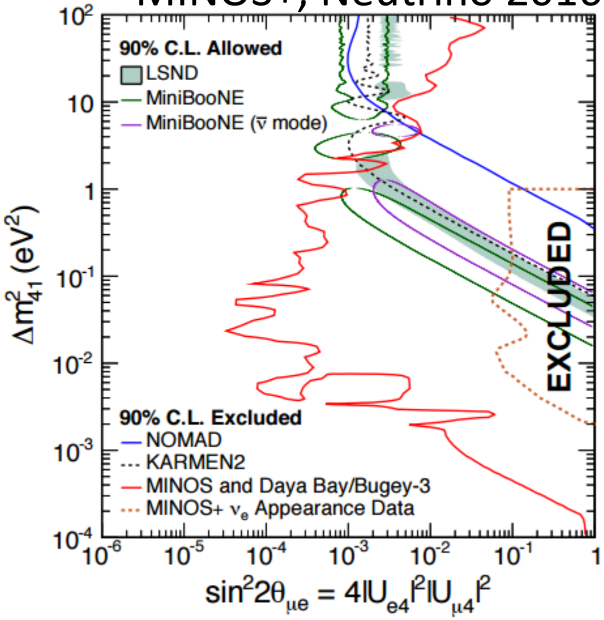
IceCube expect a resonant matter effect in the disappearance of atmospheric anti-numu

No evidence; strong limits on θ_{24}

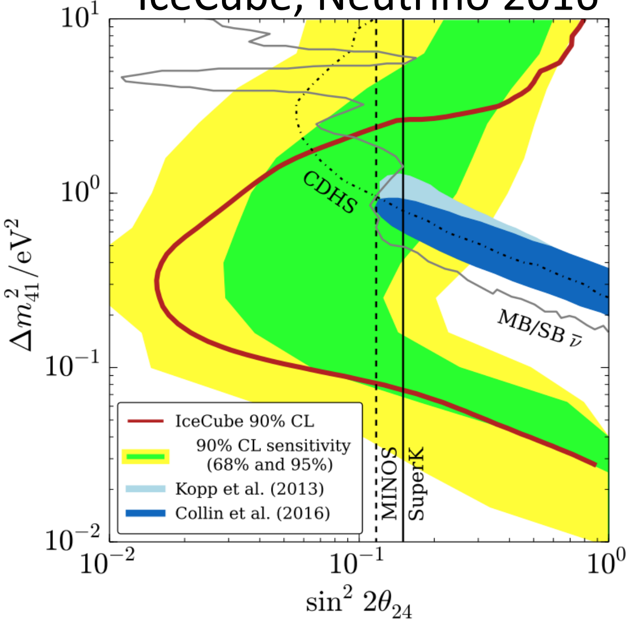
RENO, Neutrino 2016



MINOS+, Neutrino 2016

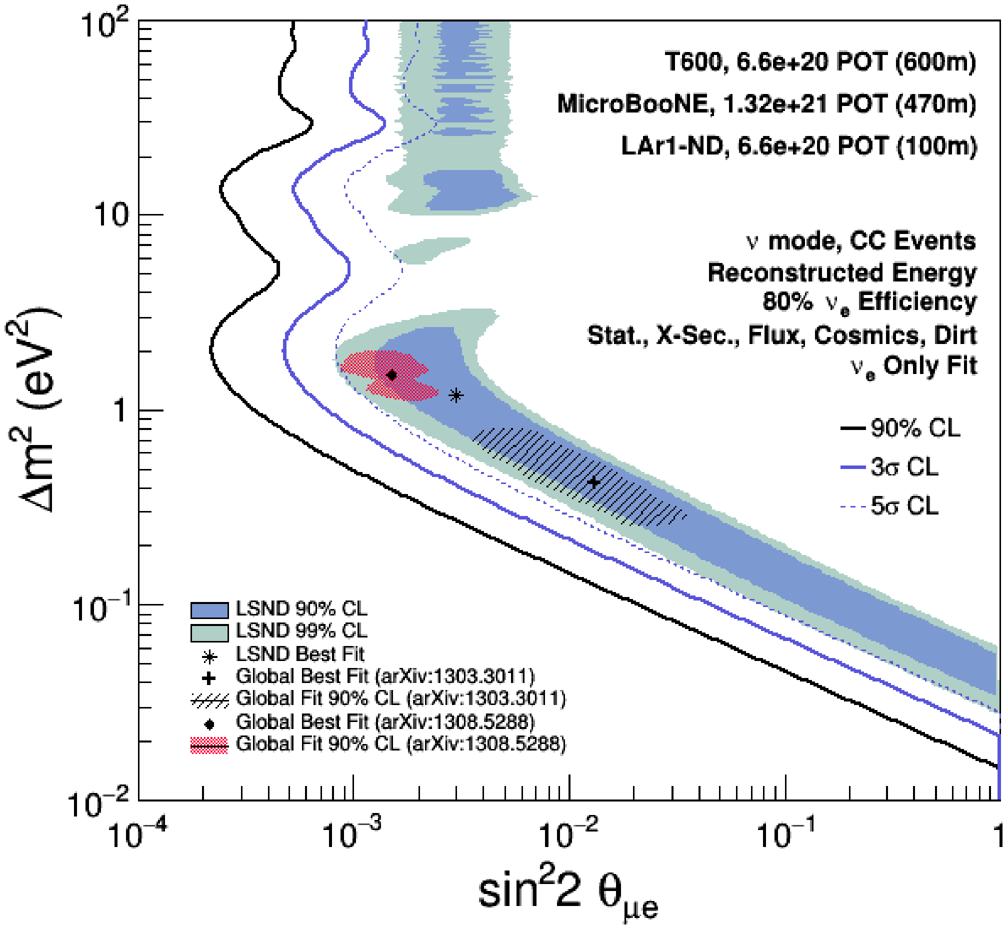


IceCube, Neutrino 2016



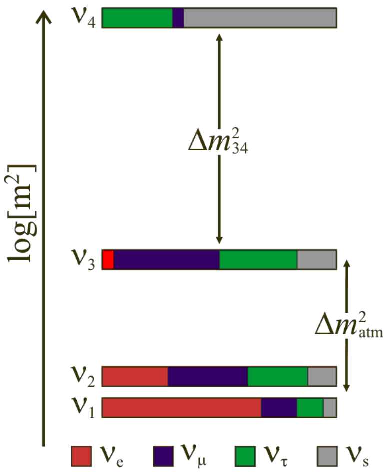
Fermilab SBL program

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



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

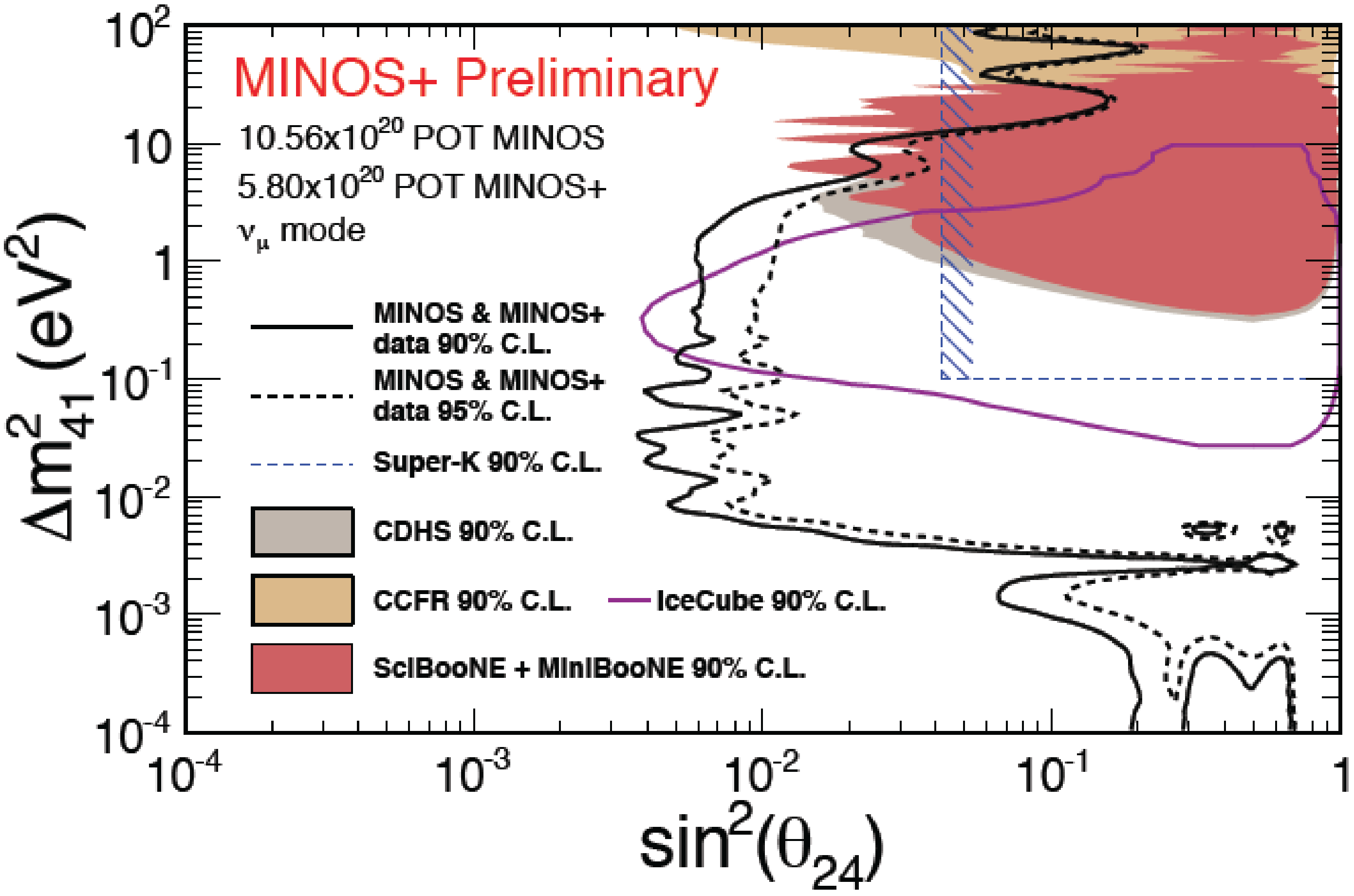
$$|U_{e4}|^2 = \sin^2\theta_{14}$$
$$|U_{\mu4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24}$$
$$4\,|U_{e4}|^2\,|U_{\mu4}|^2 = \sin^2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$$
$$|U_{\tau4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$$

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

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

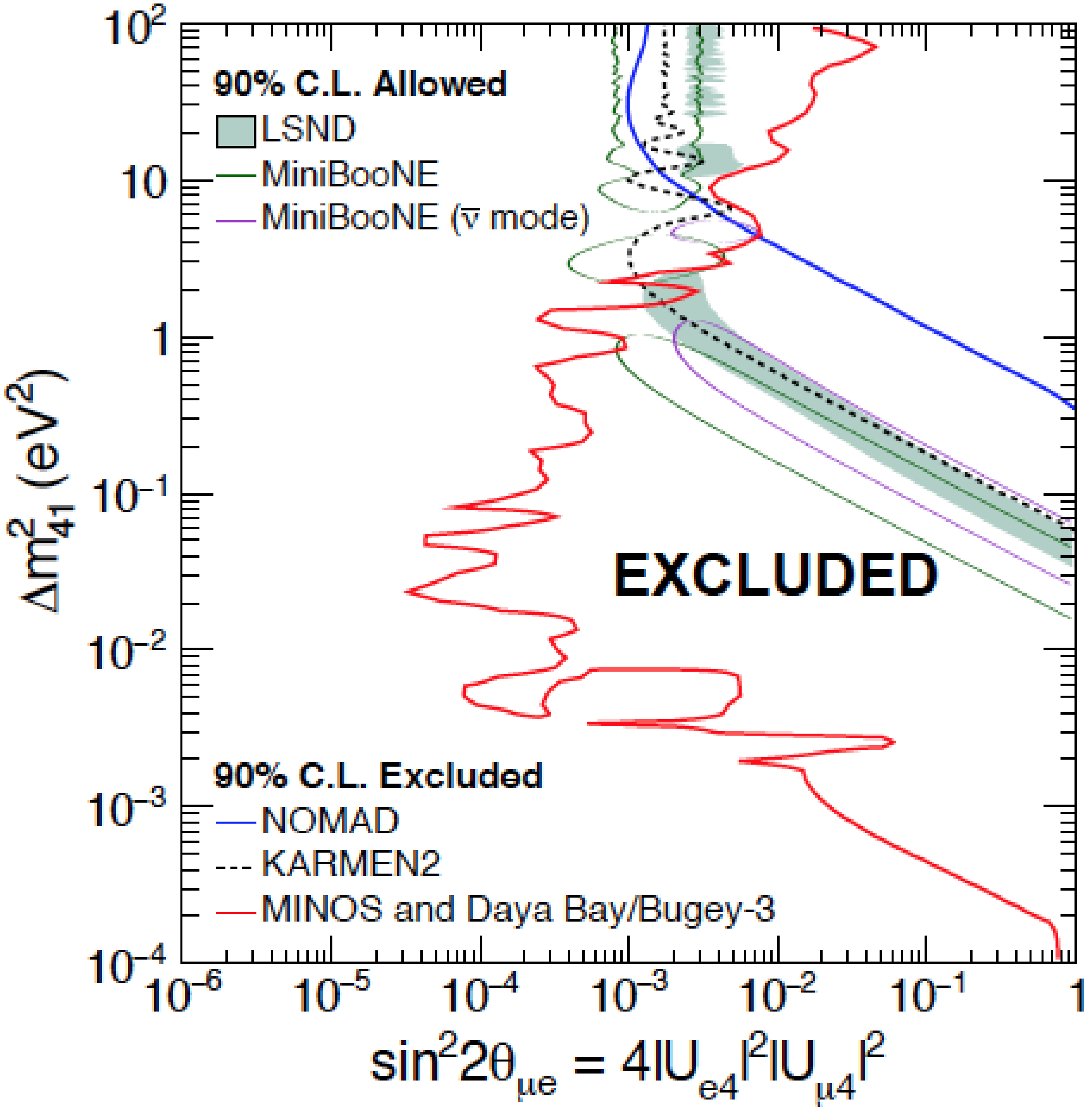
What about disappearance?

- 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?

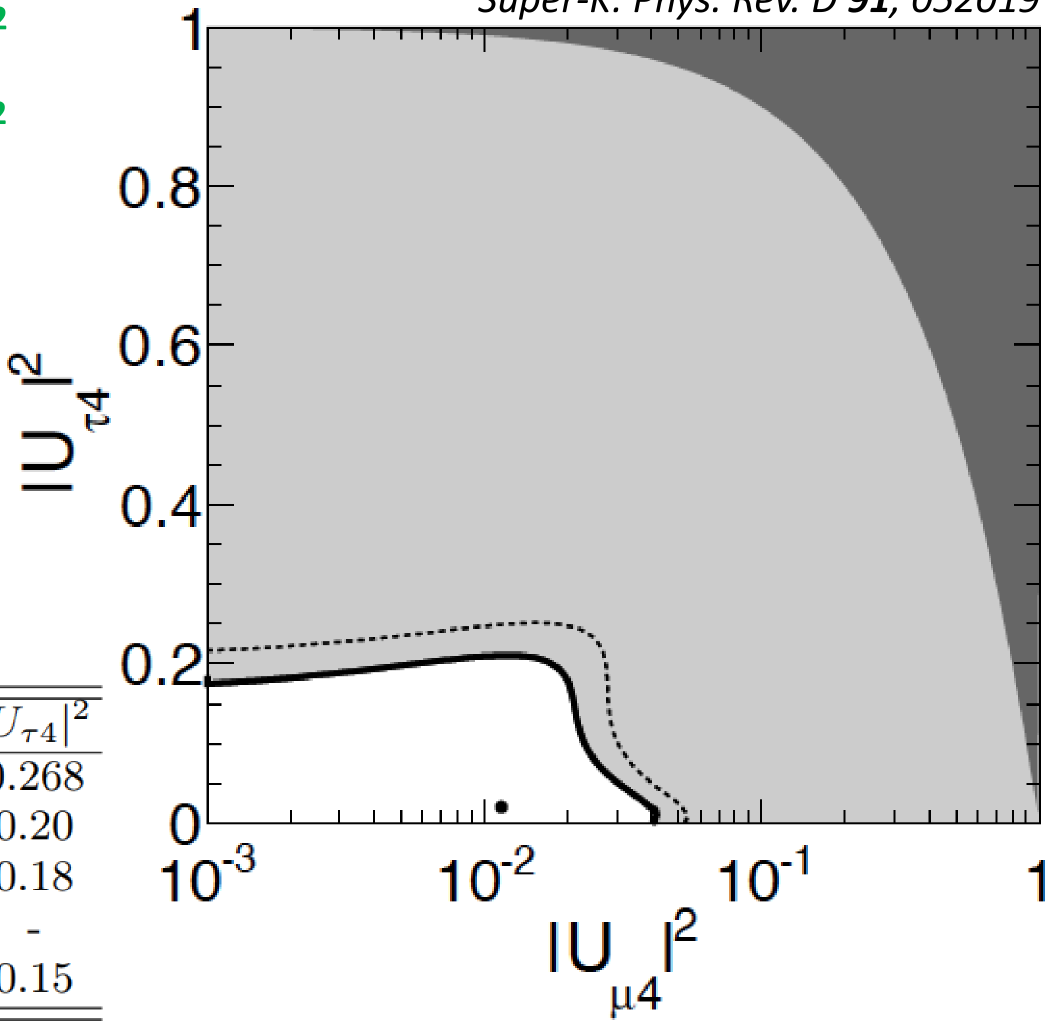
- Super-K exclusion in $|U_{\mu 4}|^2$, $|U_{\tau 4}|^2$ parameter space

  $|U_{\mu 4}|^2 < 0.041$ for $\Delta m^2_{41} > 0.1$ eV^2

  $|U_{\tau 4}|^2 < 0.18$ for $\Delta m^2_{41} > 0.1$ eV^2

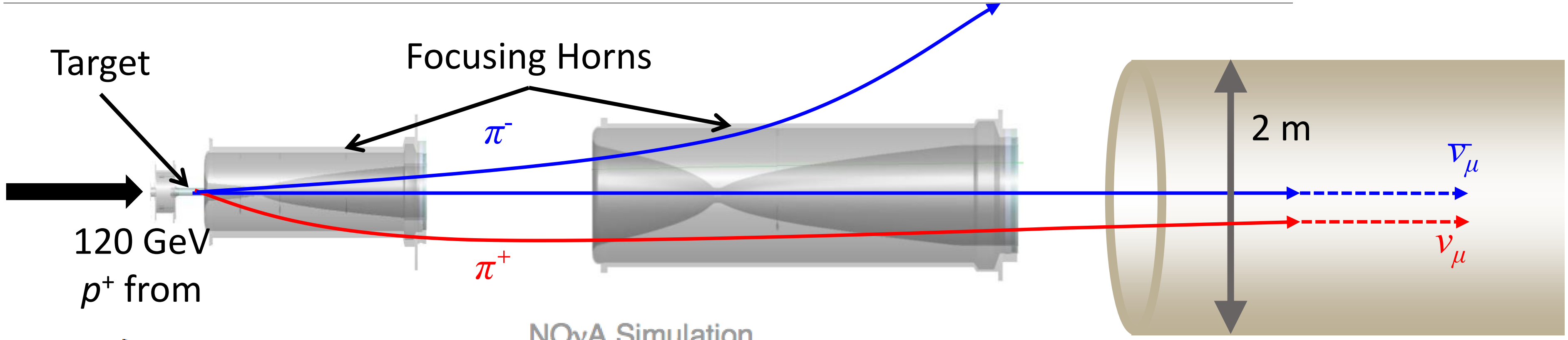
- Super-K only experiment with measurement on $|U_{\tau 4}|^2$ directly comparable to NOvA
- Note also there are unresolved discrepancies in short-baseline reactor experiments and gallium-based radiochemical experiments

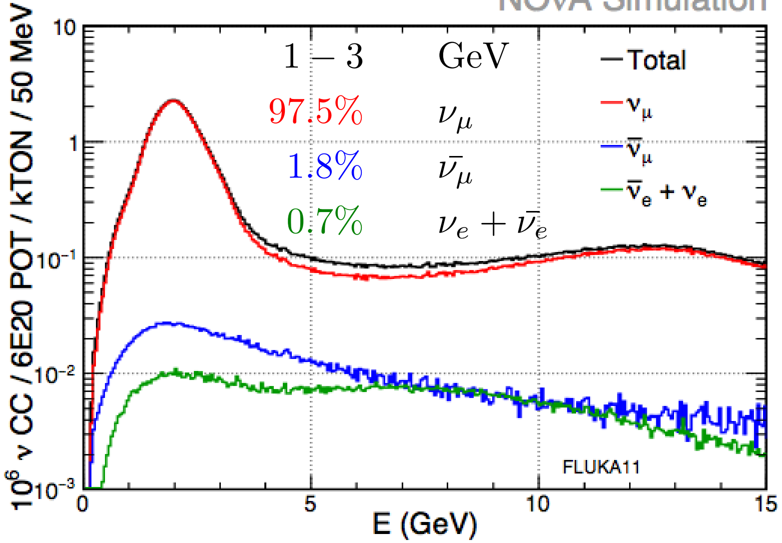
*Super-K: Phys. Rev. D **91**, 052019*

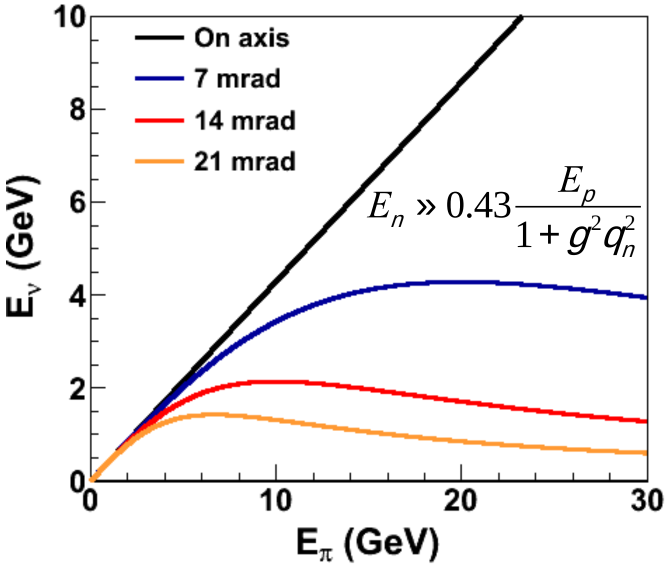


	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
NOvA	20.8°	31.2°	0.126	0.268
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

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

Simulation

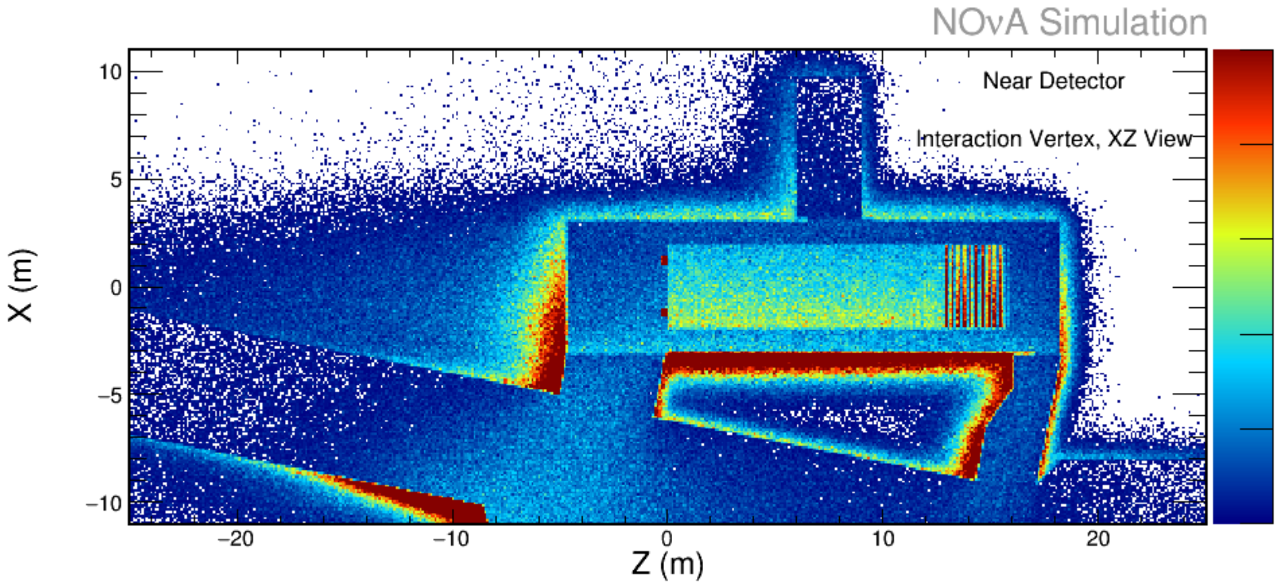
Beam line production, propagation and neutrino flux: FLUKA/Flugg

Cosmic Ray flux: CRY

Neutrino interaction and FSI: GENIE

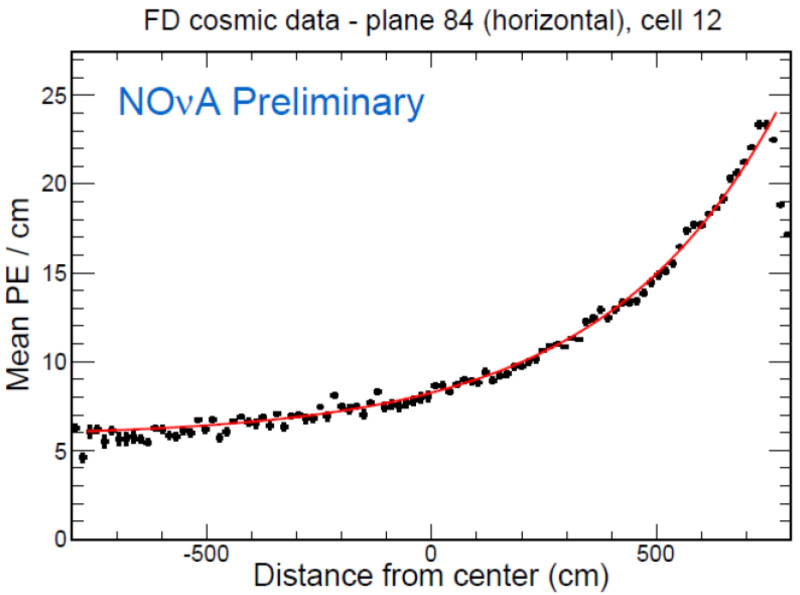
Detector: Simulation: Geant4

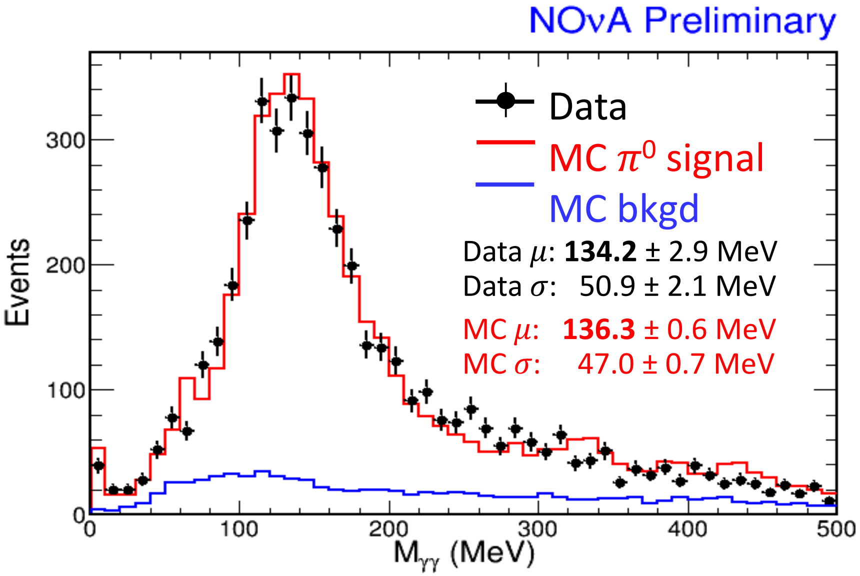
Detector response: Custom simulation Routines



Calibration

- Response varies substantially along cell due to light attenuation
- Use cosmic ray muons as a standard candle to calibrate every channel individually
- Use dE/dx near the end of stopping muon to set absolute scale
- Multiple calibration cross-checks
  - Beam muon dE/dx
  - Michel energy spectrum
  - π^0 mass peak
- Take 5% absolute and relative errors on energy scale



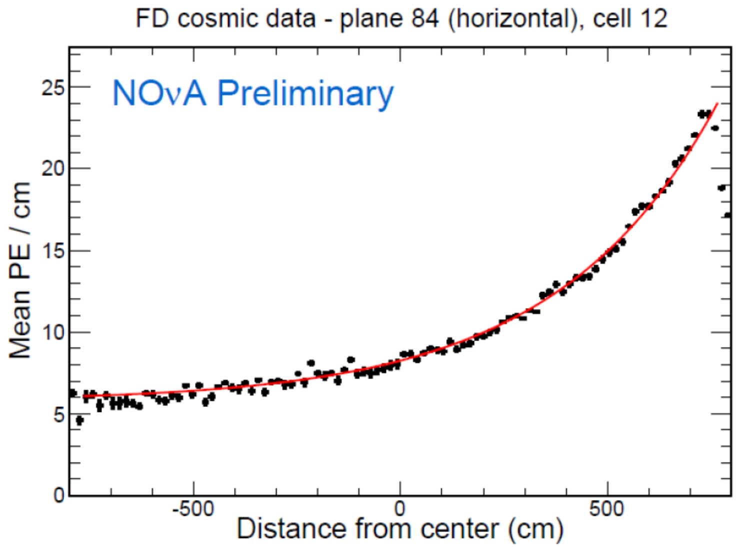


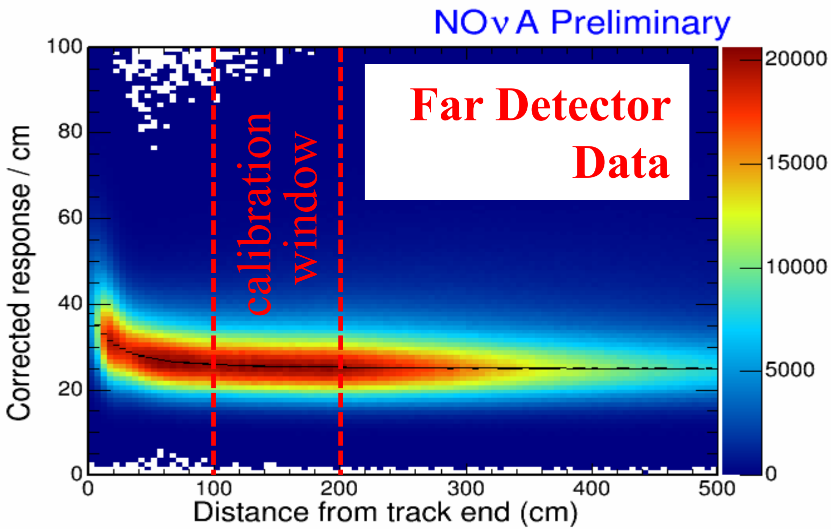
Calibration

Calibration achieved using cosmic rays

Light levels drop by a factor of 8 across a FD cell

Stopping muons provide a standard candle





Energy Scale

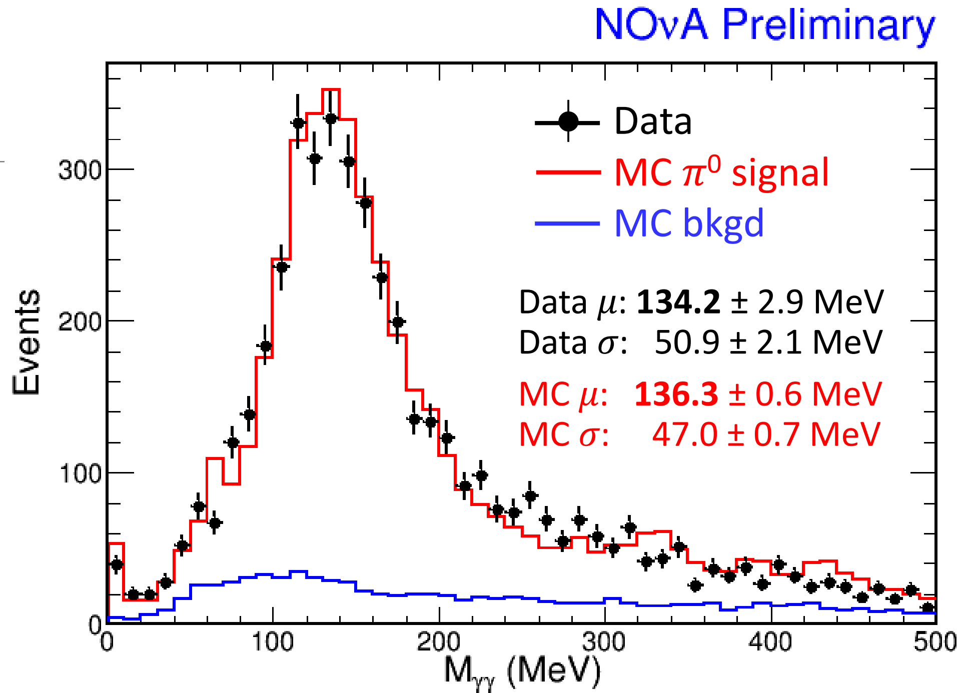
Near Detector

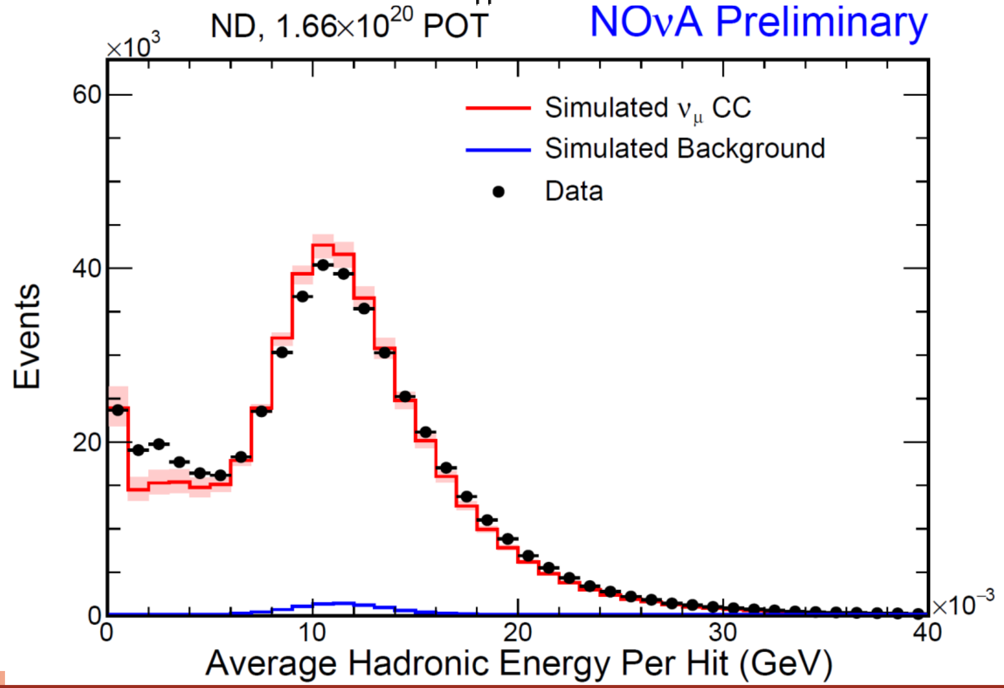
- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum
- π^0 mass
- hadronic shower *E*-per-hit

Far Detector

- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum

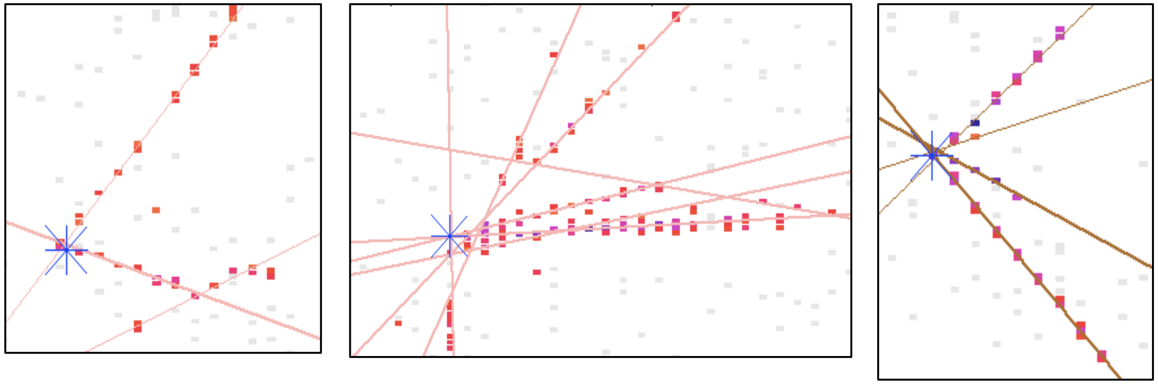
All agree to 5%



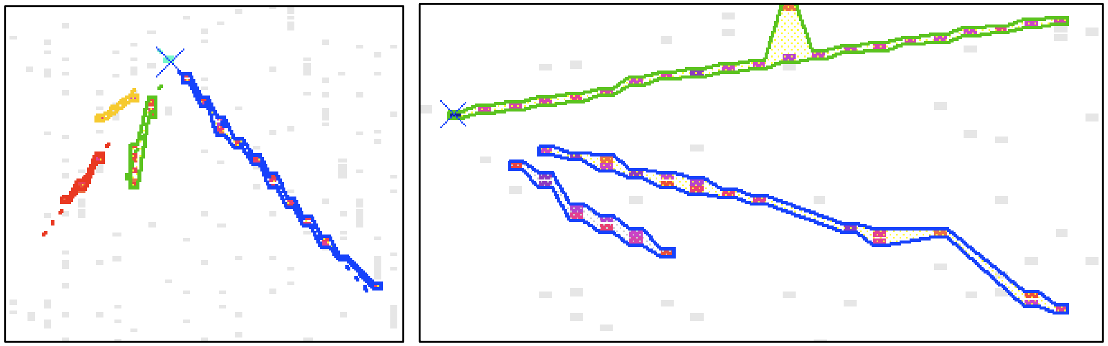


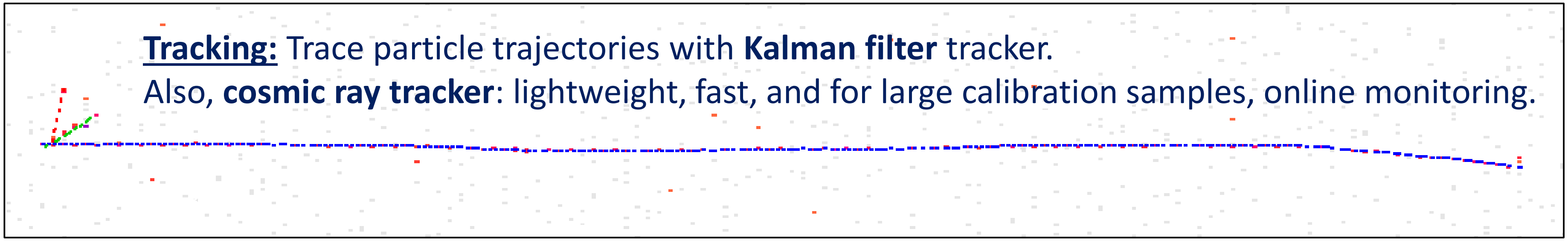
Reconstruction

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



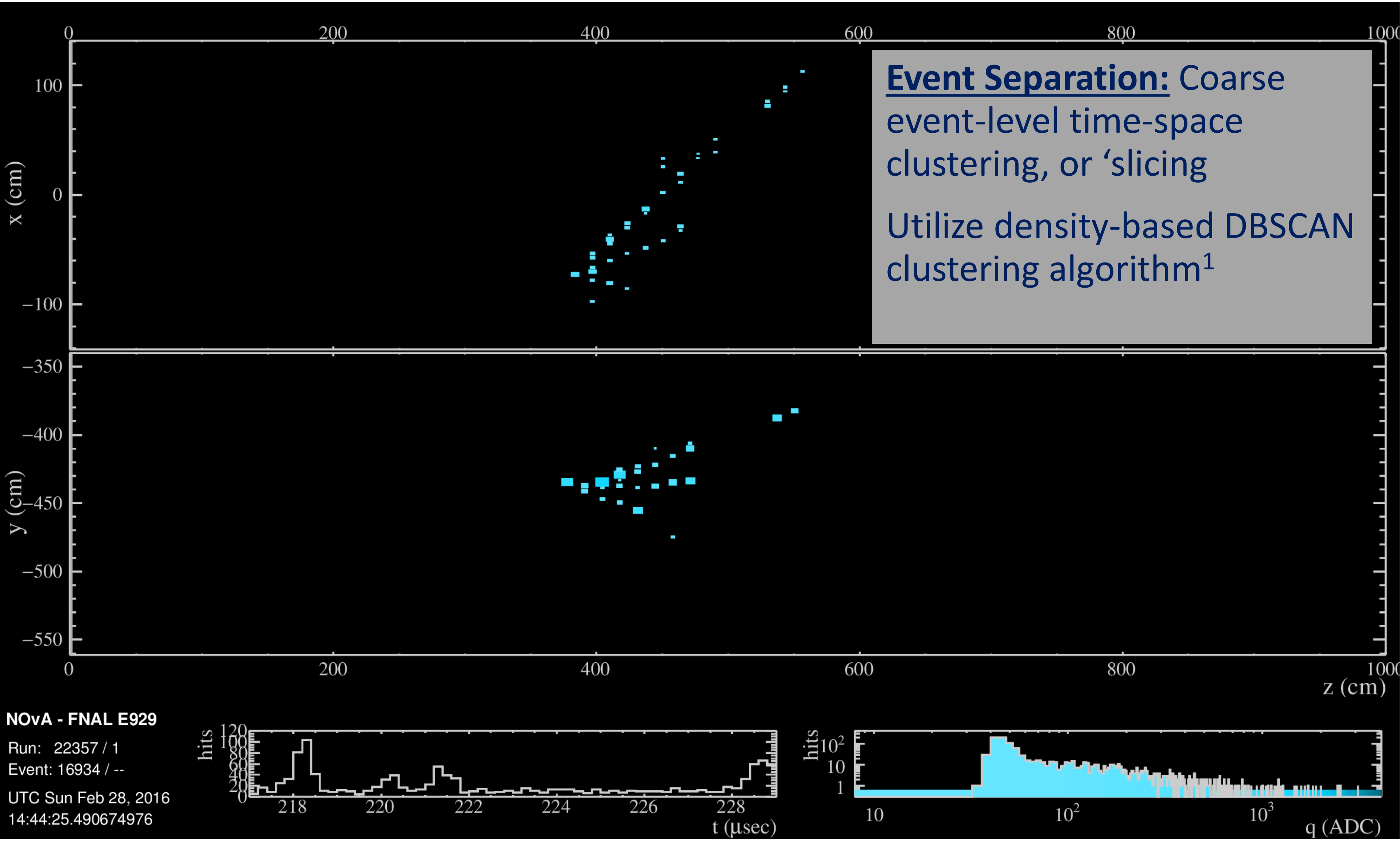
Clustering: Find **clusters in angular space** around vertex. **Merge views** via topology and prong dE/dx





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]

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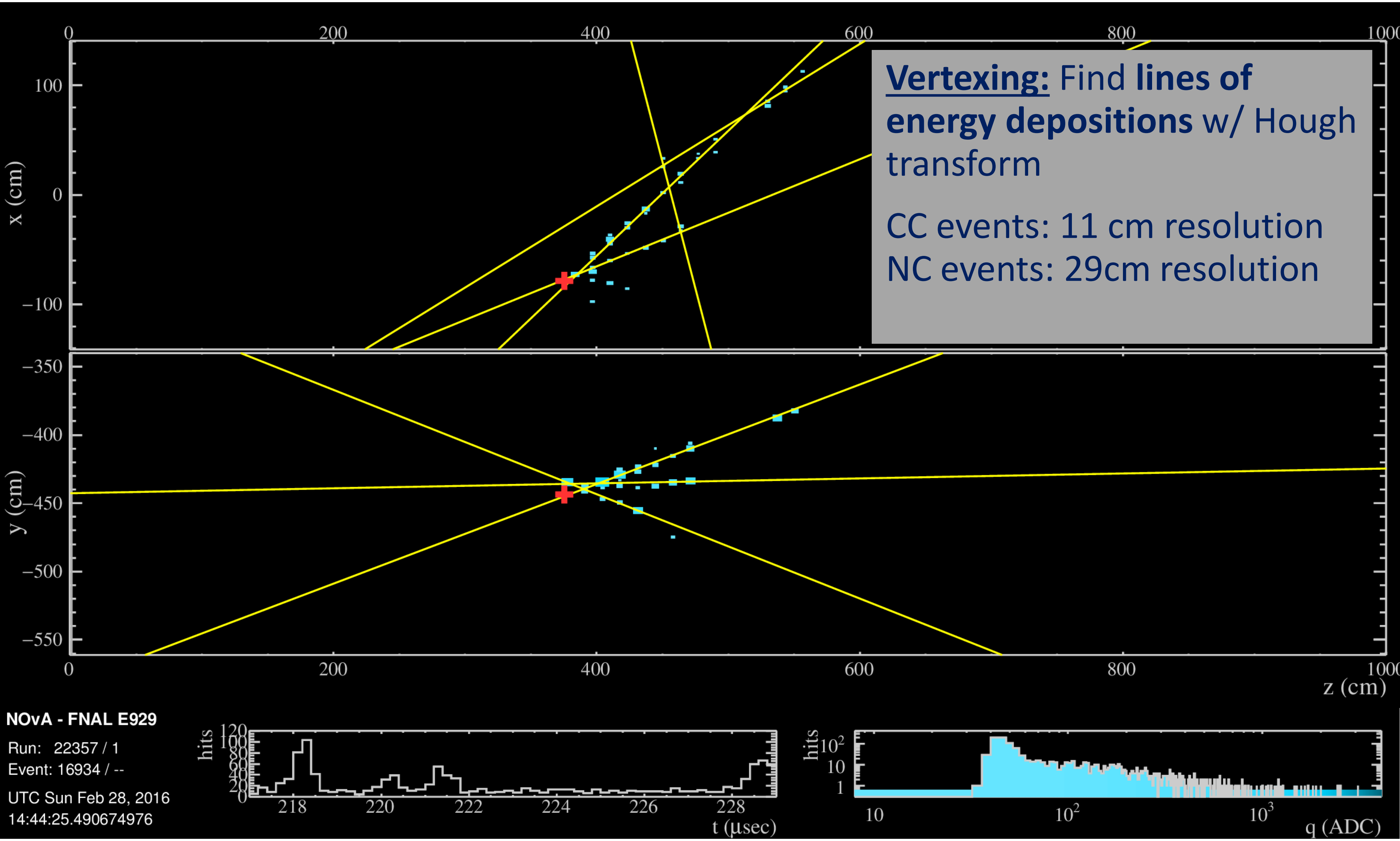
[1] M. Ester, et. al., A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise (1996)

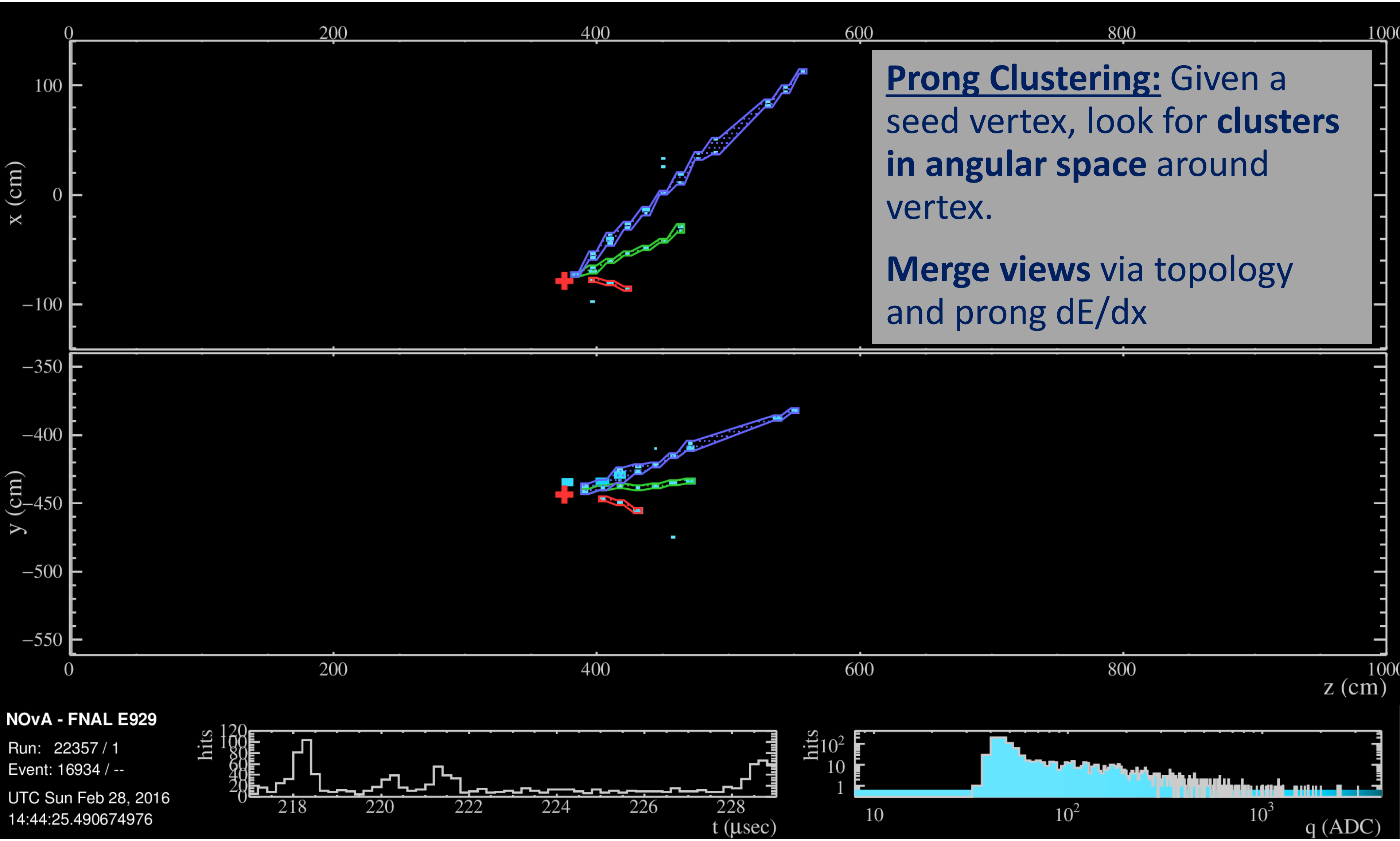
Reconstruction



Vertexing: 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.

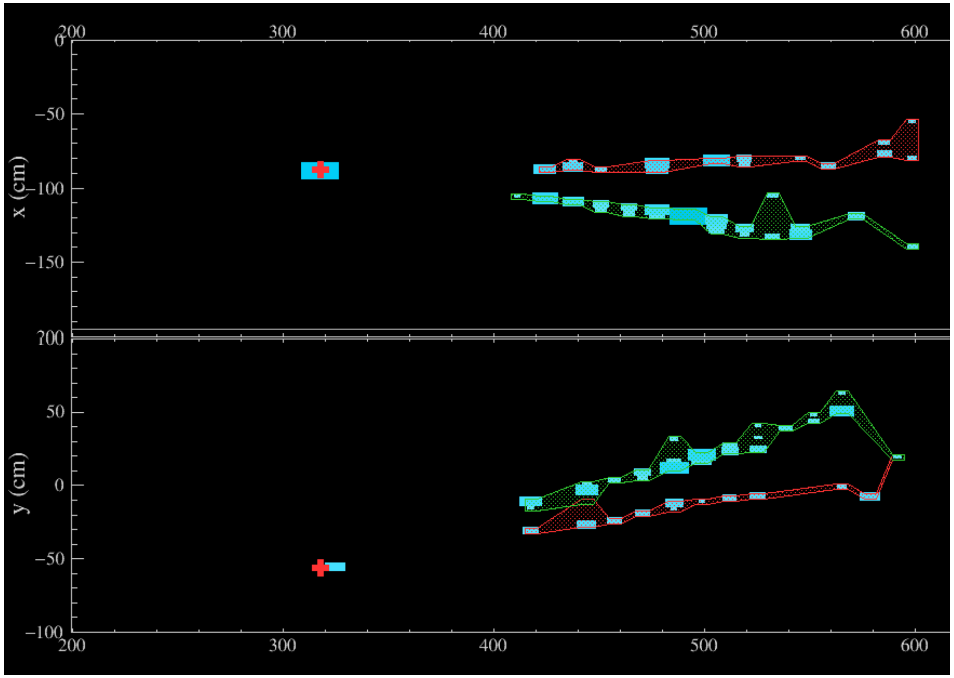
Merge views via topology and prong dE/dx

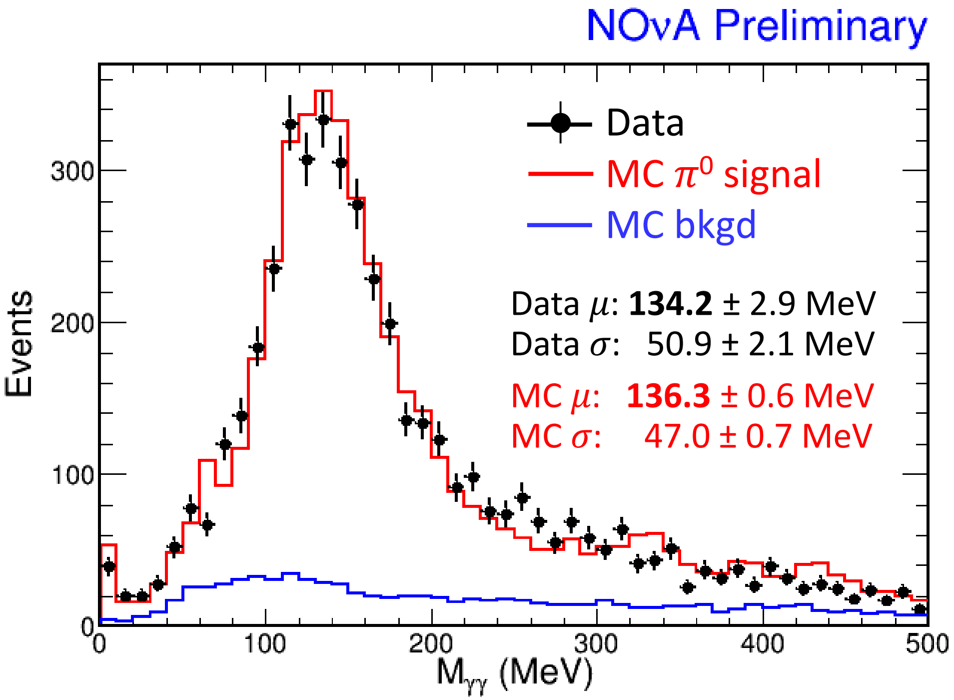
Reconstruction

Excellent reconstruction capabilities

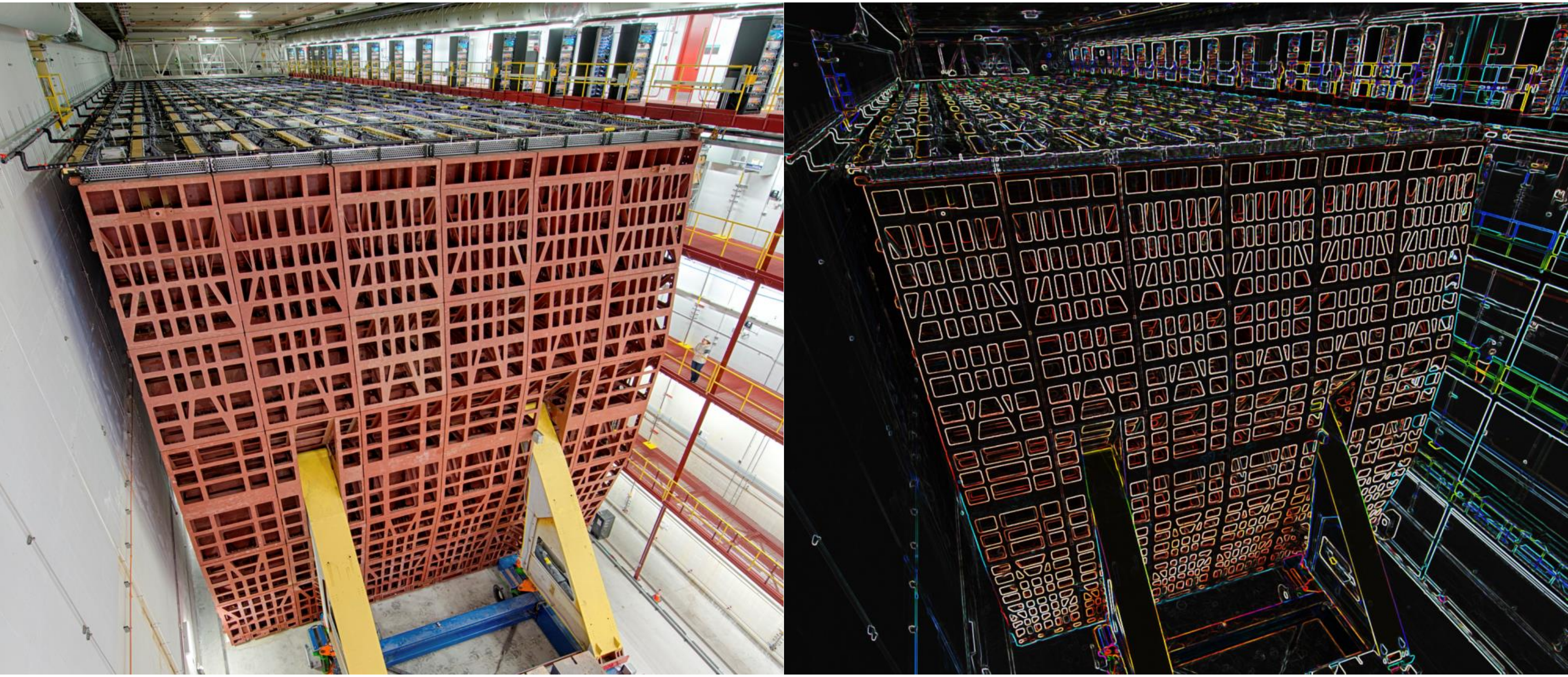
Reconstruct π^0 peak – used as a calibration cross-check

- Demonstrates ability to reconstruct NC events





Event Identification in NOvA



Take advantage of recent advances in machine learning/computer vision

- Classify event-displays!

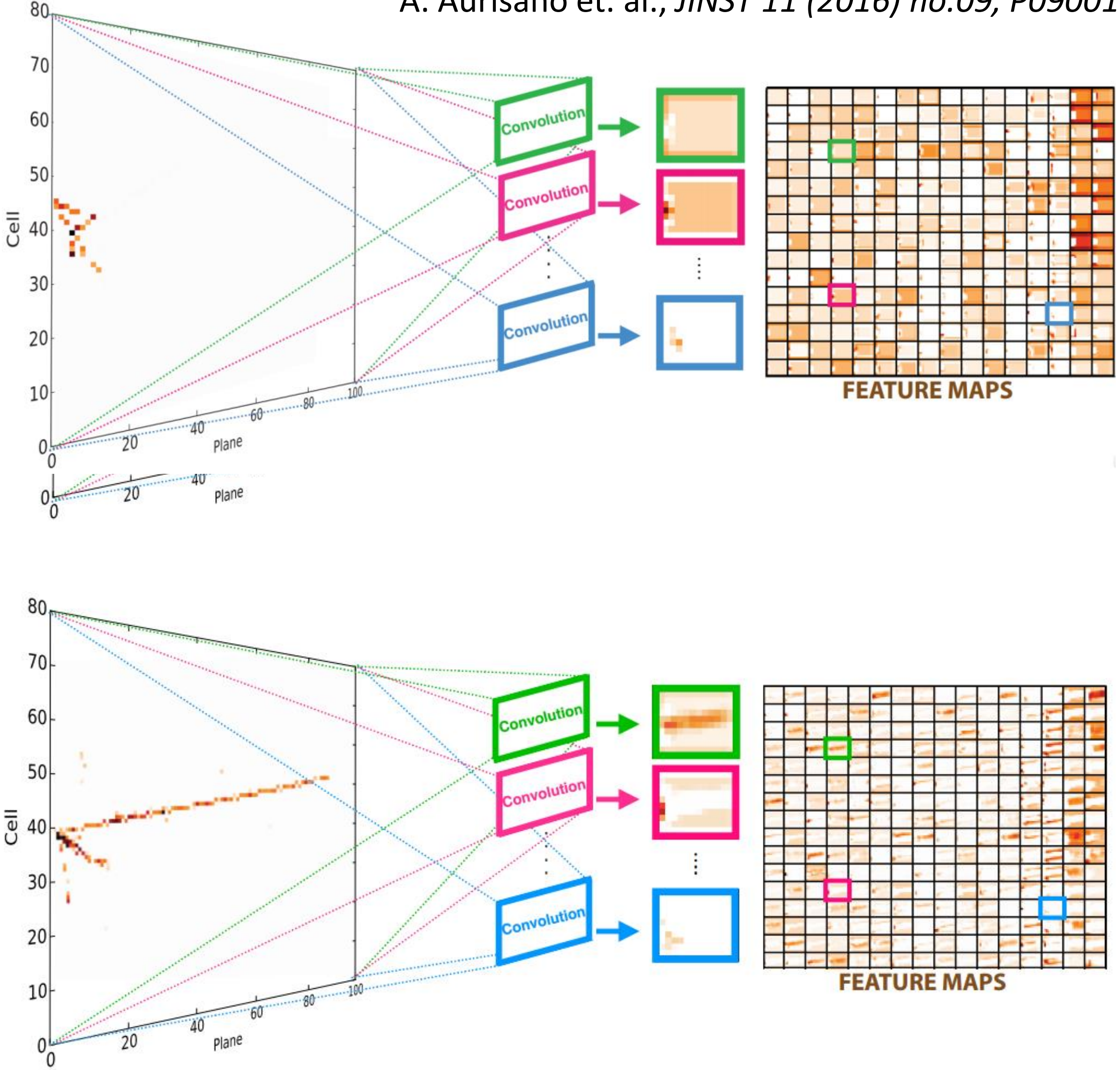
CNN – deep neural network, inputs are the pixels of the image

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)

"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano et. al., *JINST 11 (2016) no.09, P09001*

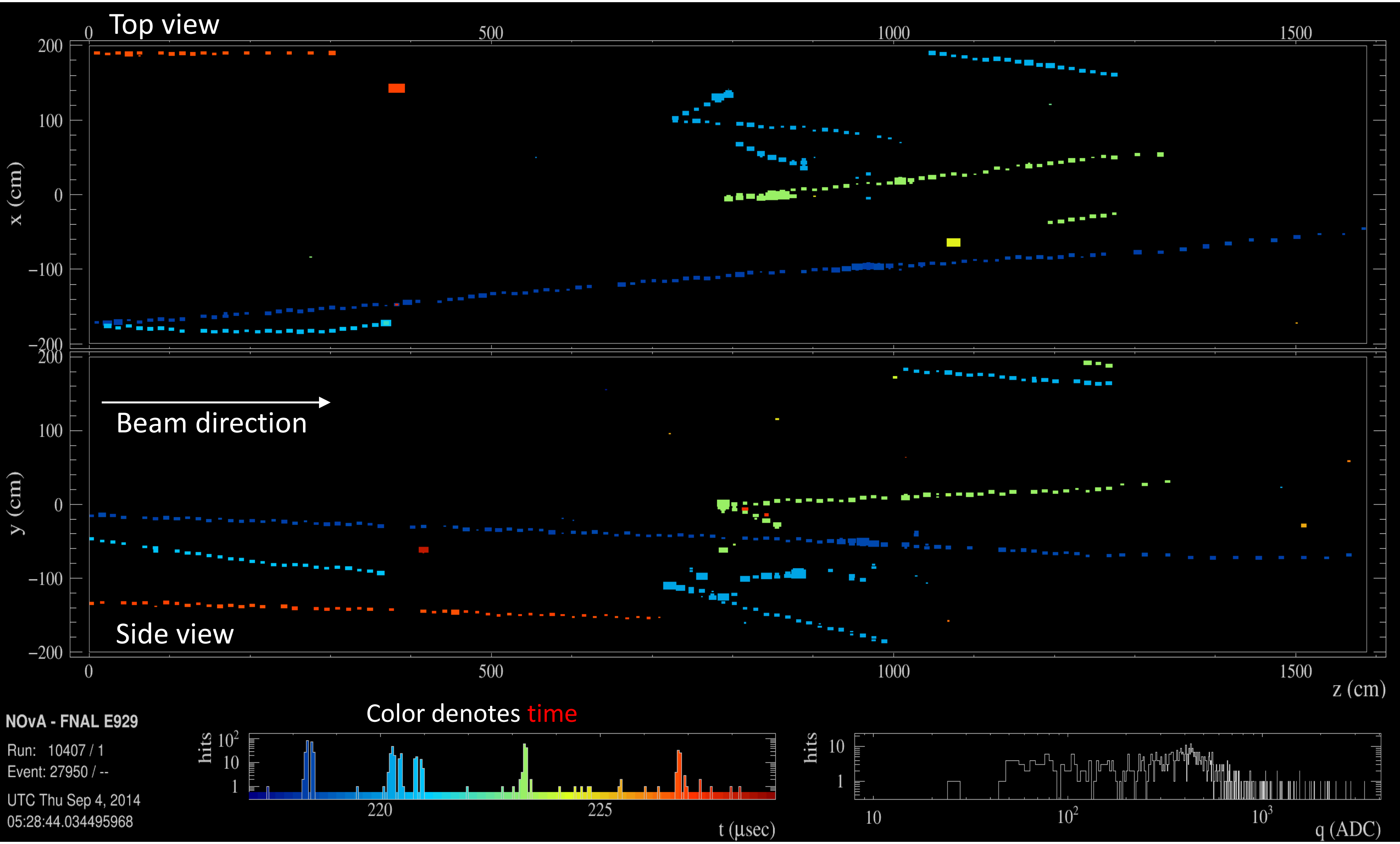


- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event
- Effectively increases our exposure by 30% compared to traditional ID methods

Near detector MC event counts

Cut	Total	NC (%)	ν_μ (%)	beam ν_e (%)
Data quality	95.5×10^6	12.46	86.49	1.05
Event quality	53.1×10^6	13.56	85.33	1.11
Fiducial	1.9×10^6	28.64	70.35	1.01
Containment	71.8×10^4	45.68	52.79	1.53
NC selection	**27.8×10^4**	**71.22**	**27.87**	**1.00**

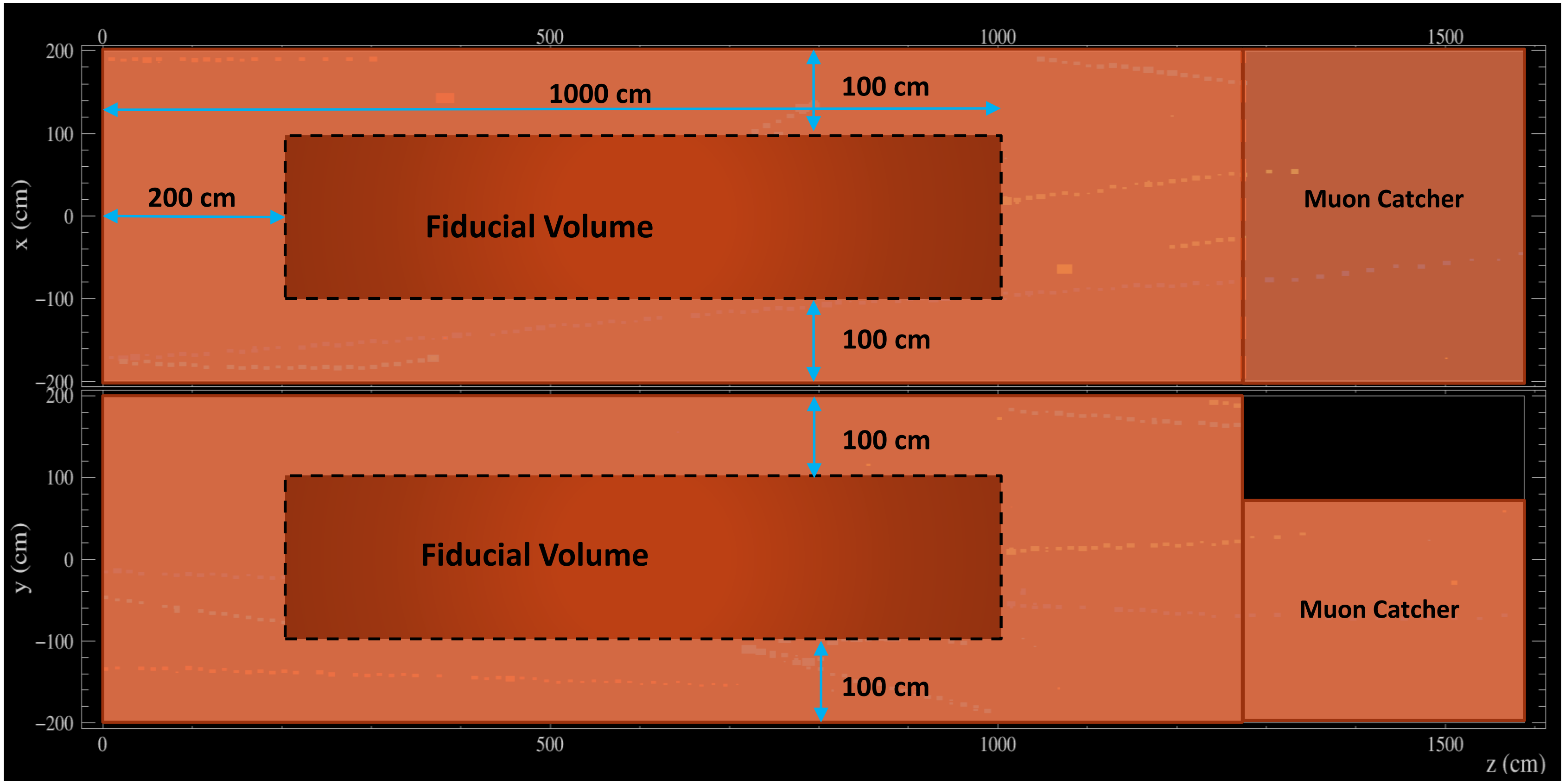
Near detector spills



Color denotes time

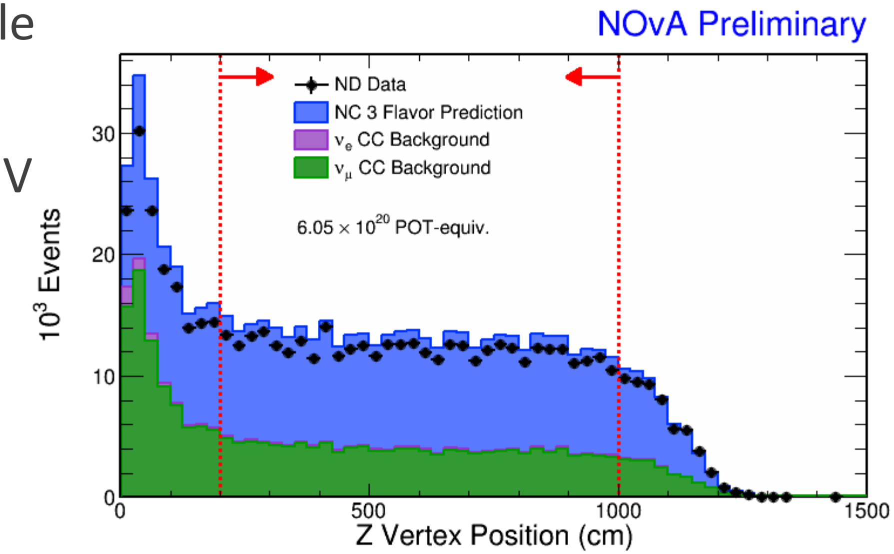
Near detector event preselection

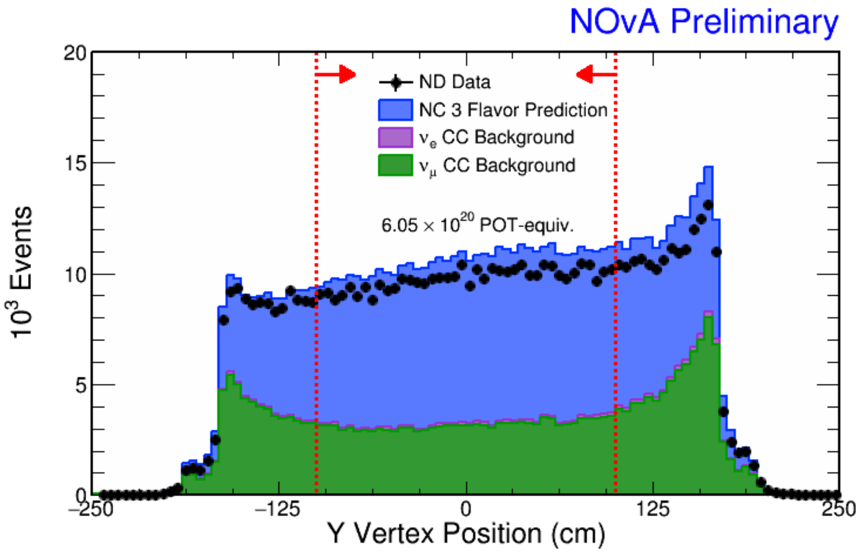
- Beam spill quality, detector and event quality cuts
  - Beam positioning, horn current range, minimum spill POT, maximum time to nearest spill
- Reconstructed event vertex within the fiducial volume
- Reconstructed track start/stop positions > 25 cm from each detector face

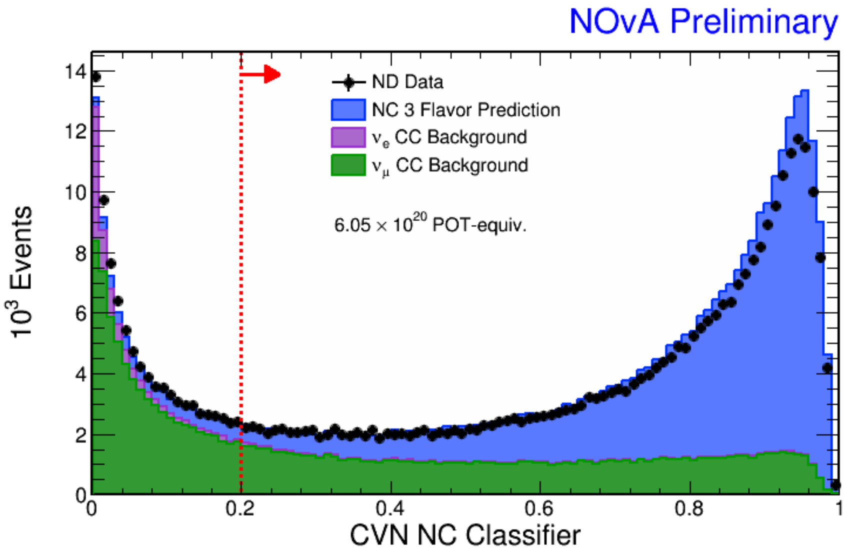


Near detector NC event selection

- Keep selection cuts as similar as possible in both detectors
- Average calorimetric energy/hit > 9 MeV
- 20 < Number of hits < 200
- Transverse momentum fraction < 0.8
- CVN NC classifier value > 0.2

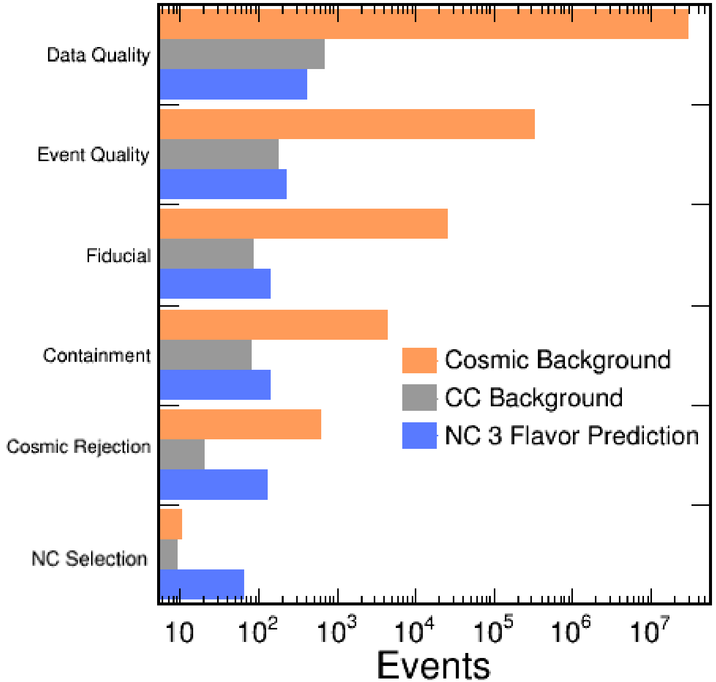






Neutral Current FD Selection

Cut	Total	NC	ν_μ	ν_e	ν_τ	cosmic
Data Quality	23.4 x 10^6	337.0	230.6	58.5	~0	23.4 x 10^6
Cosmic Rejection	88.3	65.0	5.3	3.7	~0	14.3



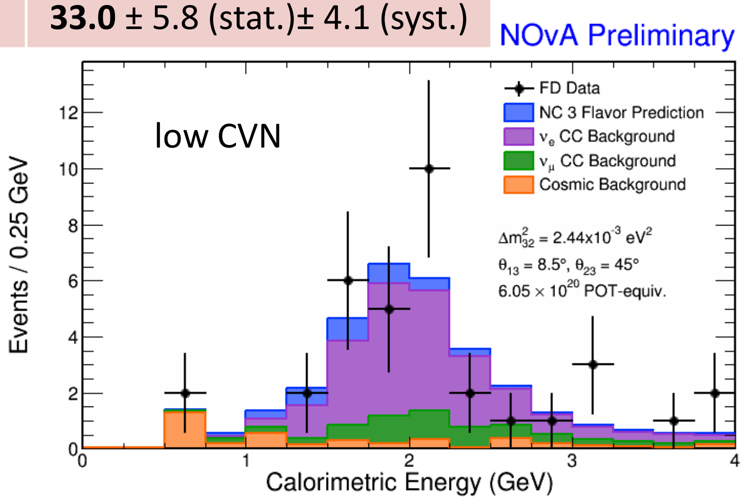
Three-flavour Far Detector extrapolated prediction

Total	NC	ν_μ CC	ν_e CC	ν_τ CC	cosmics
83.7 ± 8.3	60.6	4.8	3.6	0.4	14.3

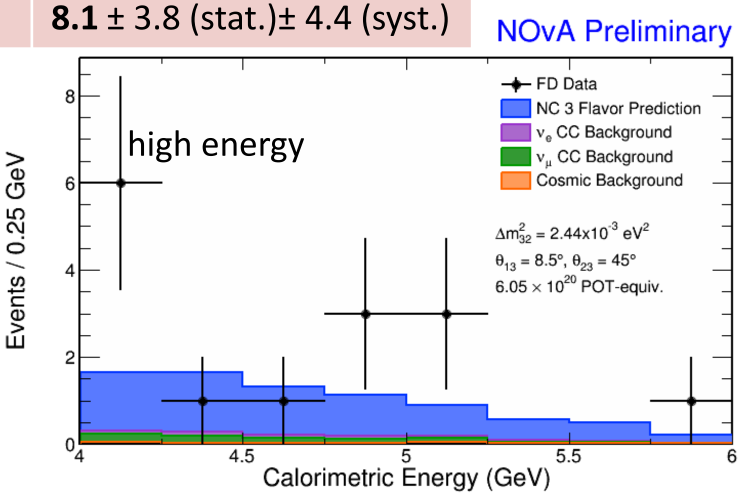
Sideband studies

- Looked at 3 sideband regions
  - Low CVN (CVN < 0.2)
  - Mid-cosmic rejection BDT region (0.42 – 0.5)
  - High energy region (4 – 6 GeV)
- Good agreement with observed data to extrapolated predictions
- Including systematics, all within < 1.6σ

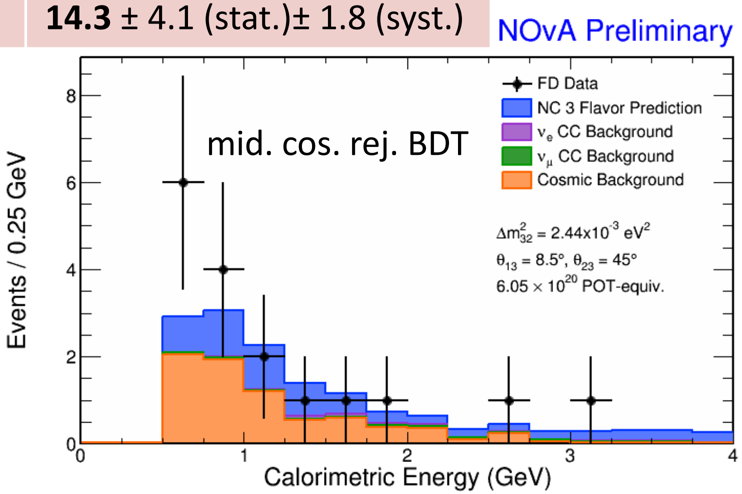
Observed	Predicted
34	**33.0** ± 5.8 (stat.)± 4.1 (syst.)



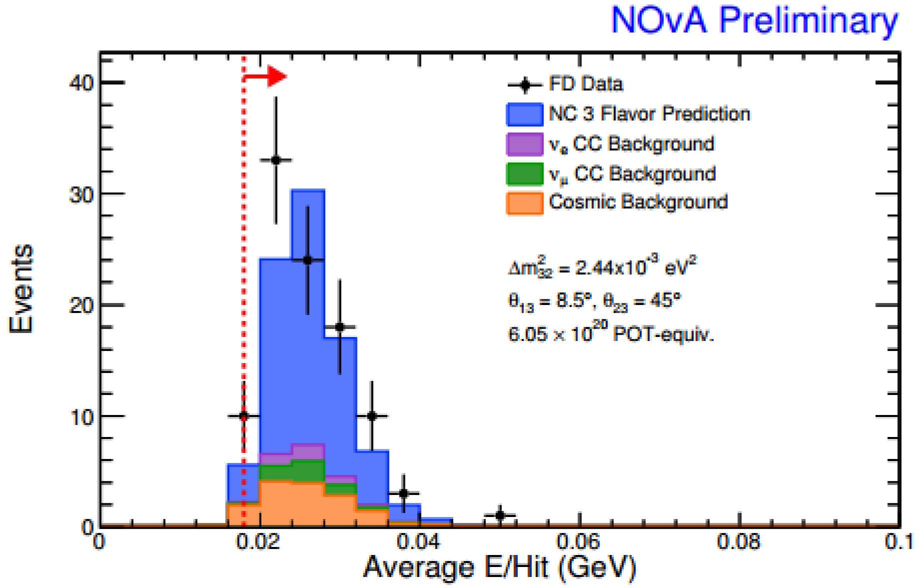
Observed	Predicted
15	**8.1** ± 3.8 (stat.)± 4.4 (syst.)



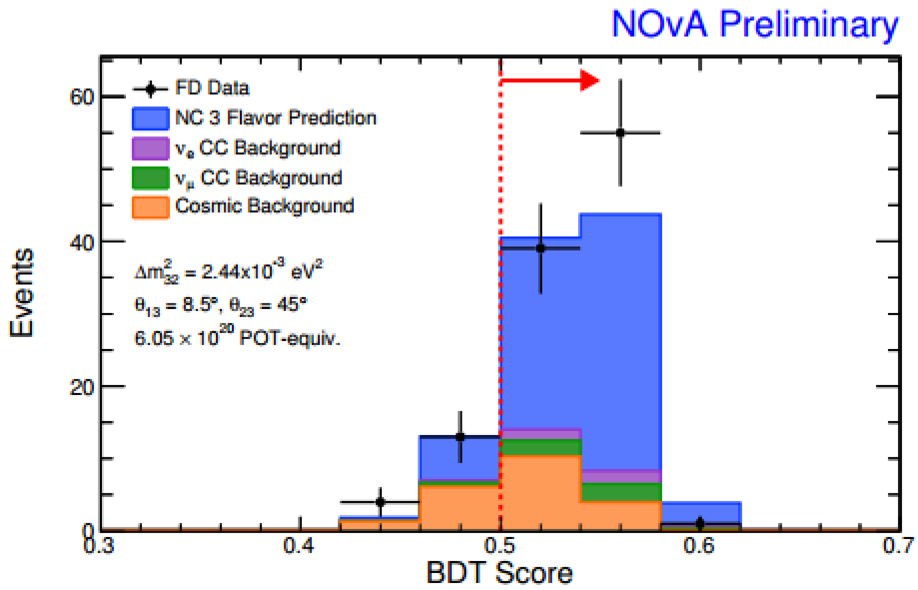
Observed	Predicted
17	**14.3** ± 4.1 (stat.)± 1.8 (syst.)



NC FD Cosmic Rejection



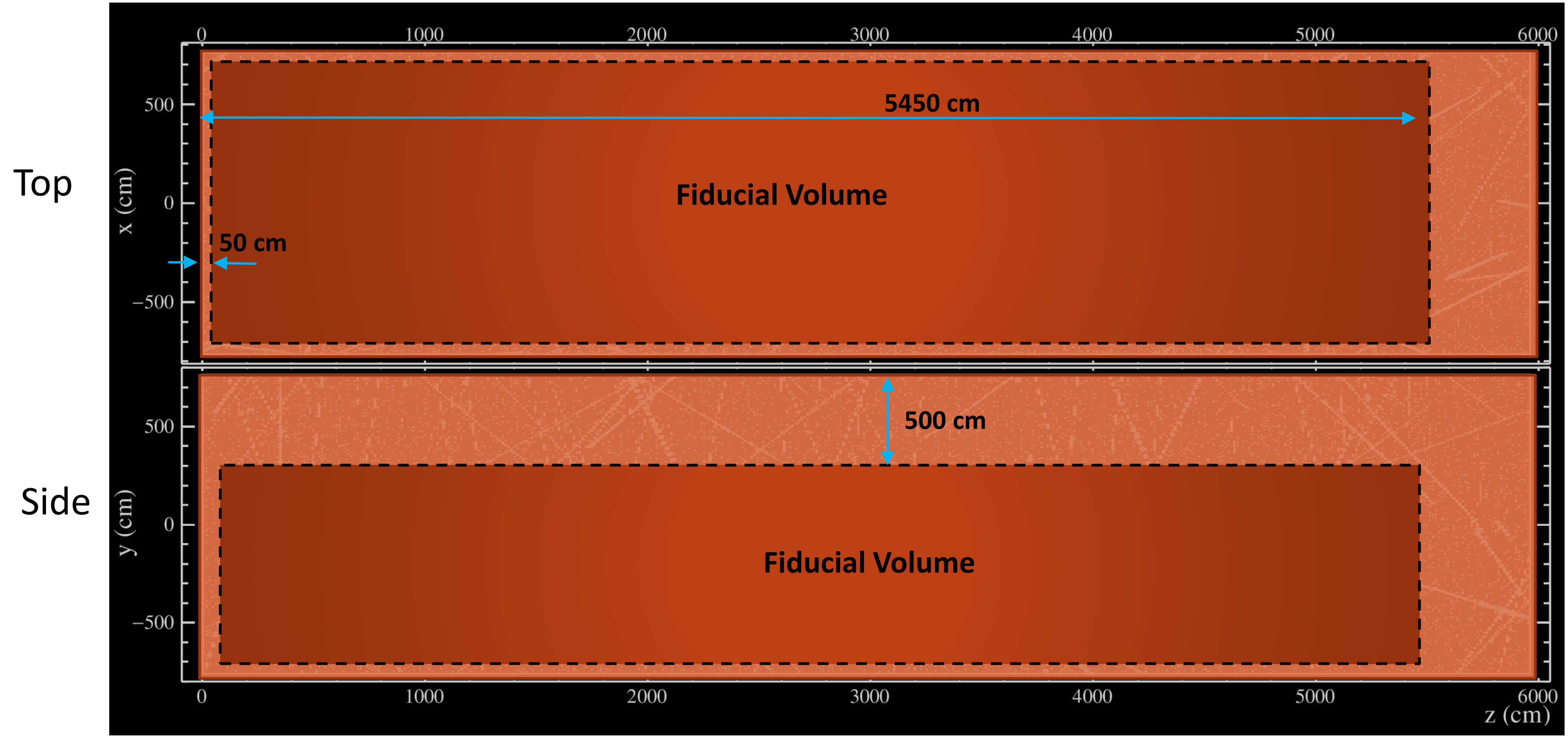
Distribution of average calorimetric energy per hit deposition in a cell



Cosmic PID based on Boosted Decision Tree algorithm sourced from the Numu disappearance analysis used in rejection of cosmic backgrounds. Events with cut> 0.5 are accepted by the selection

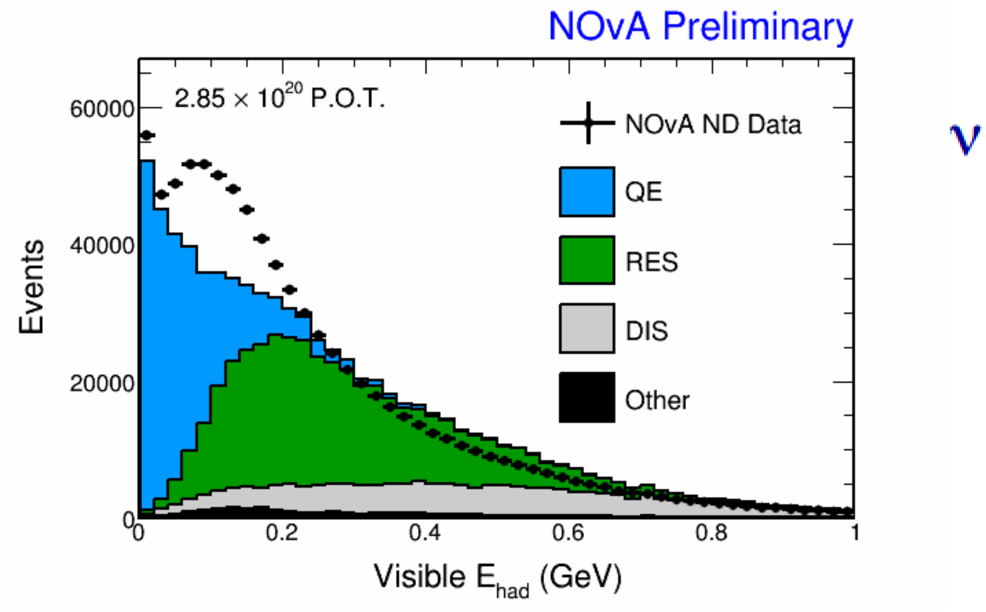
Far detector preselection

- Beam spill quality and detector quality cuts
  - Beam positioning, horn current range, minimum spill POT, maximum time to nearest spill
- Reconstructed event vertex within the fiducial volume
- Reconstructed track start/stop positions > 10 cm from each detector face

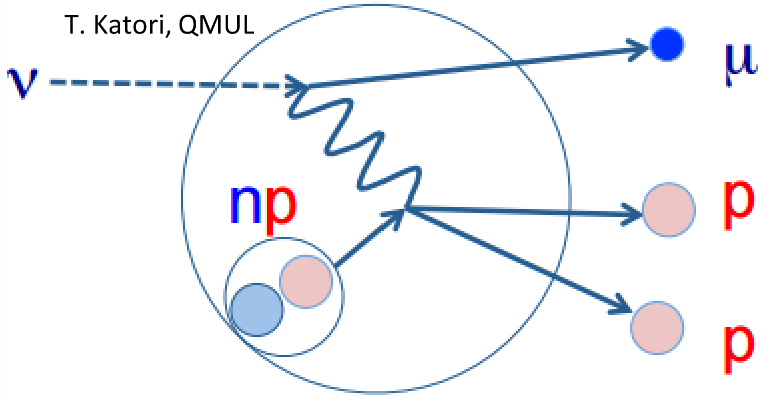


Nuclear correlations

- 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



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[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

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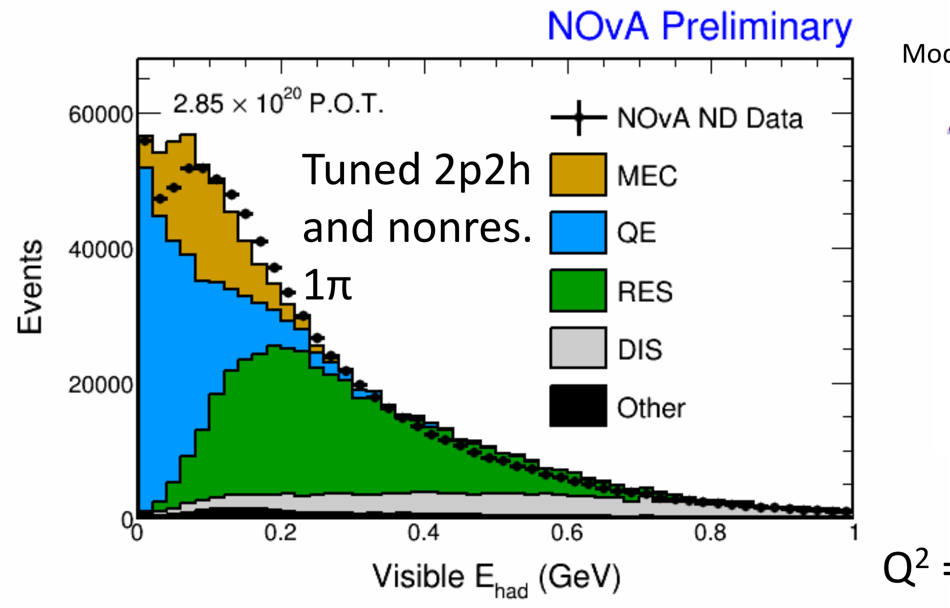
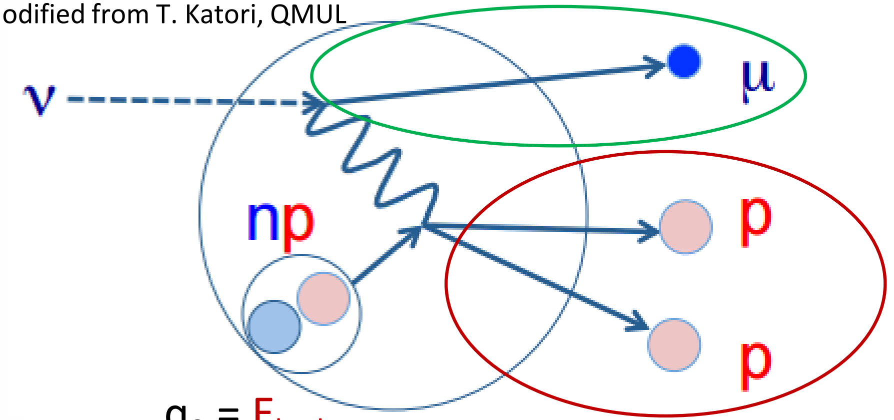


Modified from T. Katori, QMUL



$$q_0 = E_{had}$$

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

$$Q^2 = 2E_\nu(E_\mu - p_\mu\cos(\theta_\mu) - M^2_\mu)$$

$$|\vec{q}| = Q^2 + q_0$$

- 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

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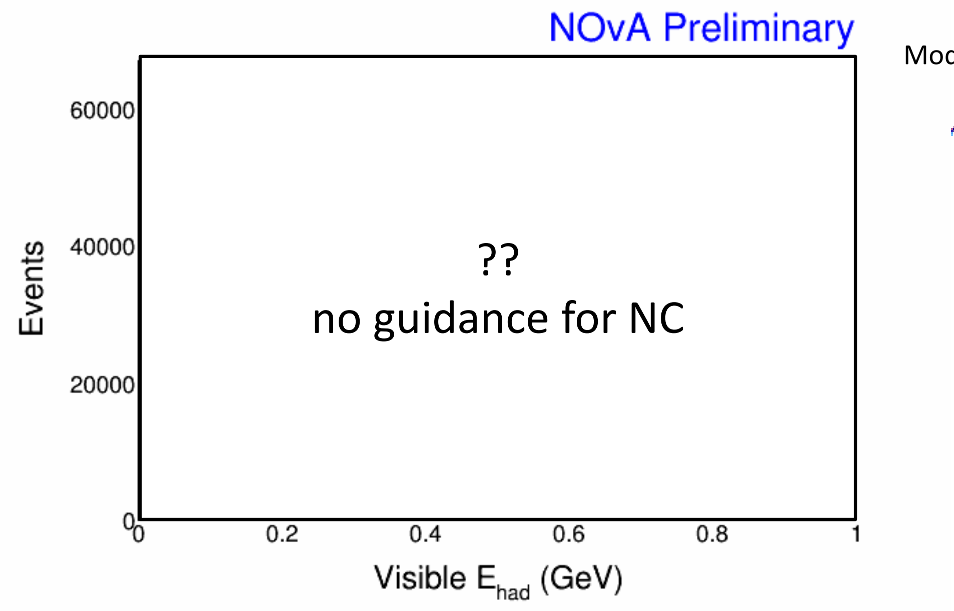
[1] P.A. Rodrigues et al., PRL 116 (2016) 071802 (arXiv:1511.05944)

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

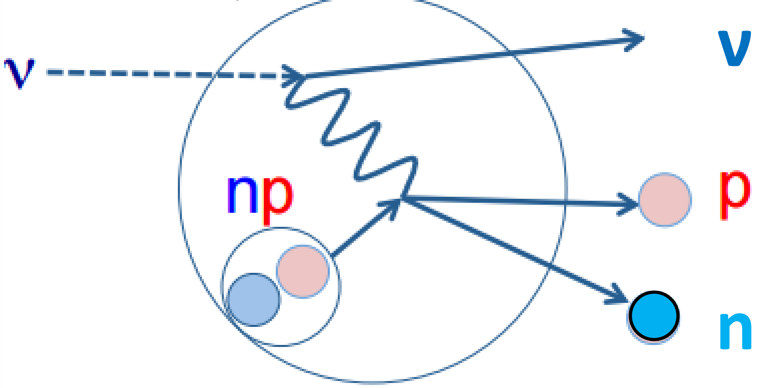
[3] P.A. Rodrigues et al., arXiv:1601.01888

Nuclear correlations



??
no guidance for NC

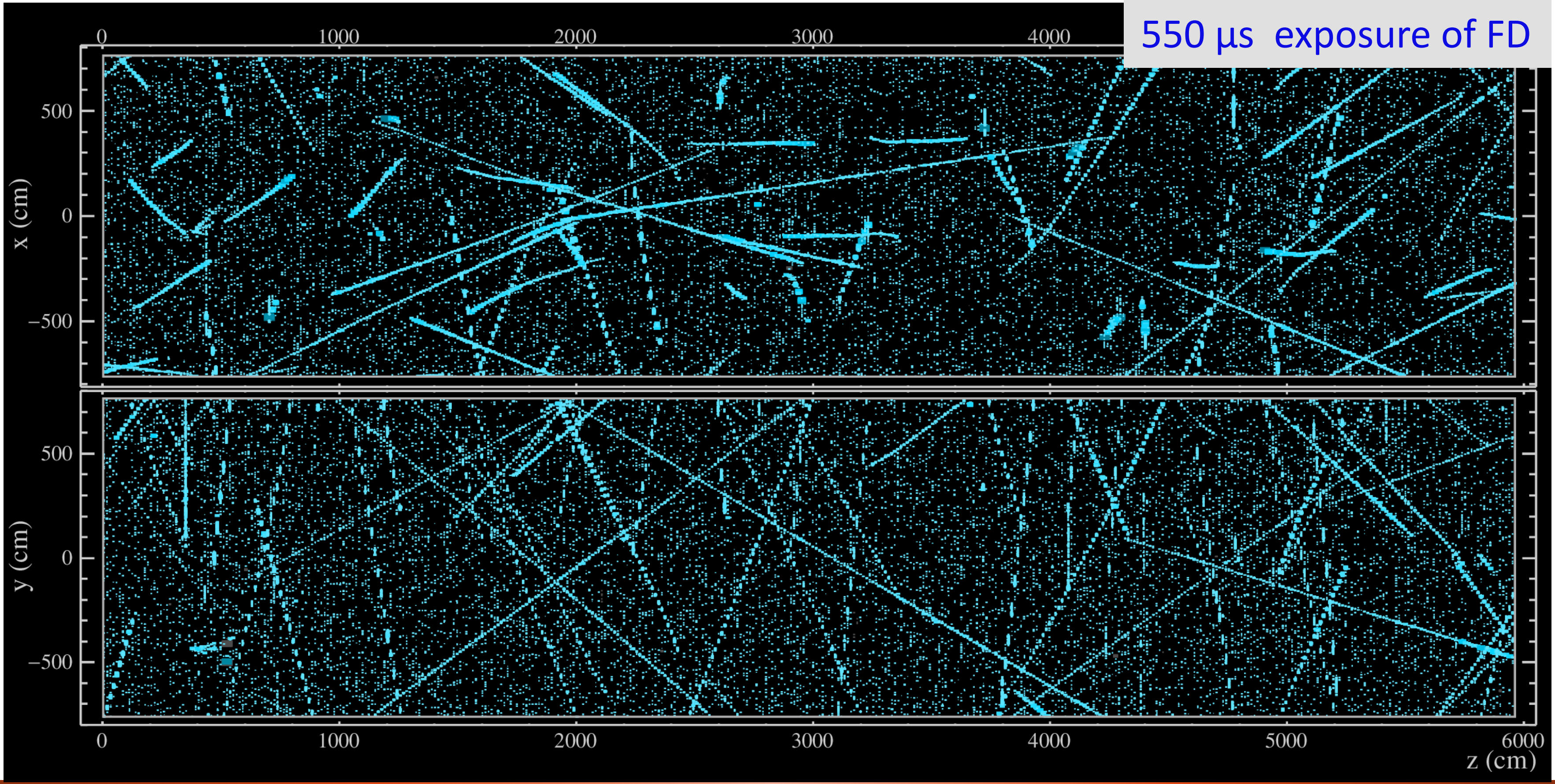
Modified from T. Katori, QMUL



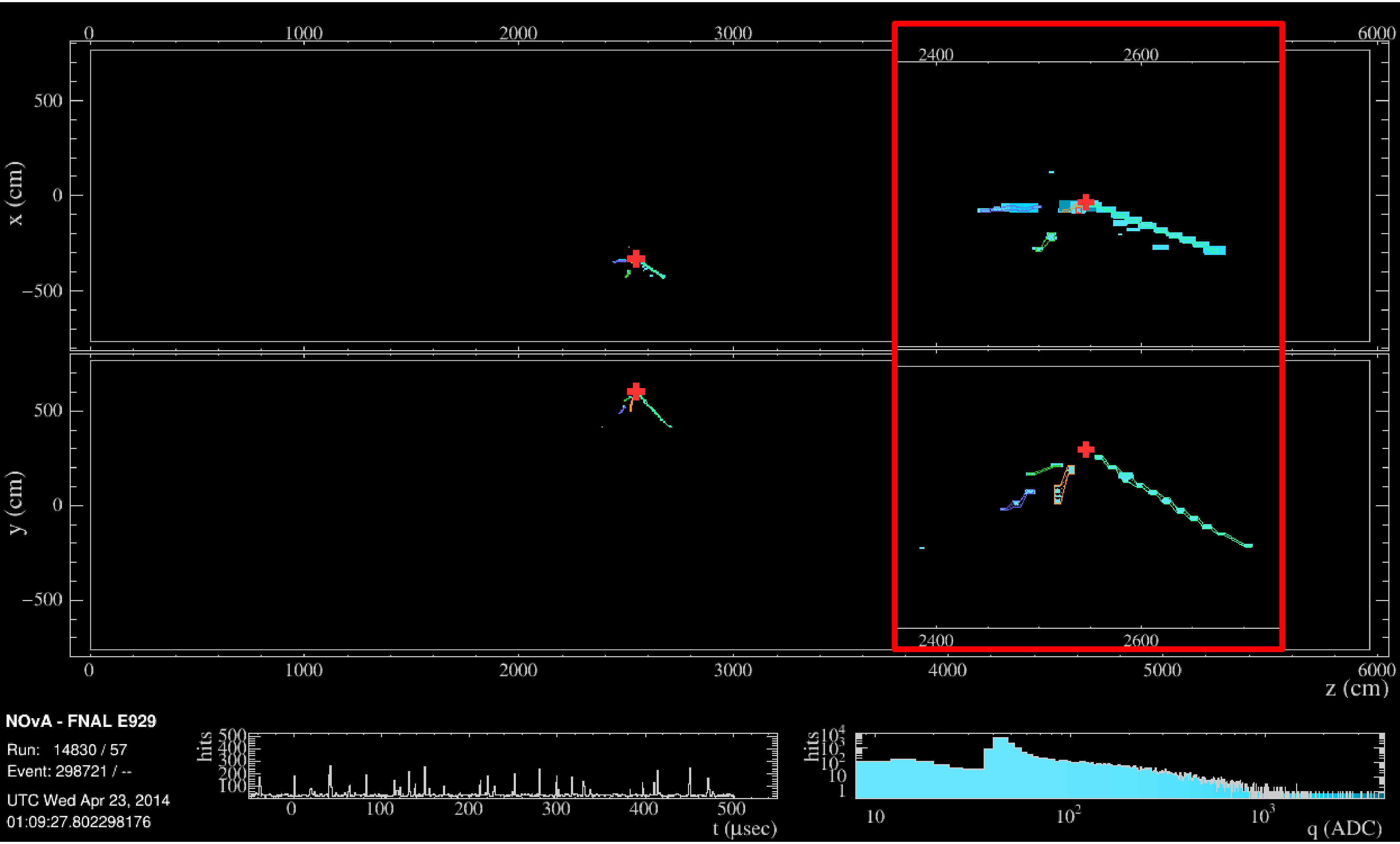
- “Empirical MEC” doesn’t do NC; also can’t retune in same way
  - no lepton to reconstruct all $|\vec{q}|$
  - Take 50% systematic on the applied MEC
  - Additional cross-section uncertainty on NCs taken to be equivalent to data/MC discrepancy observed

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

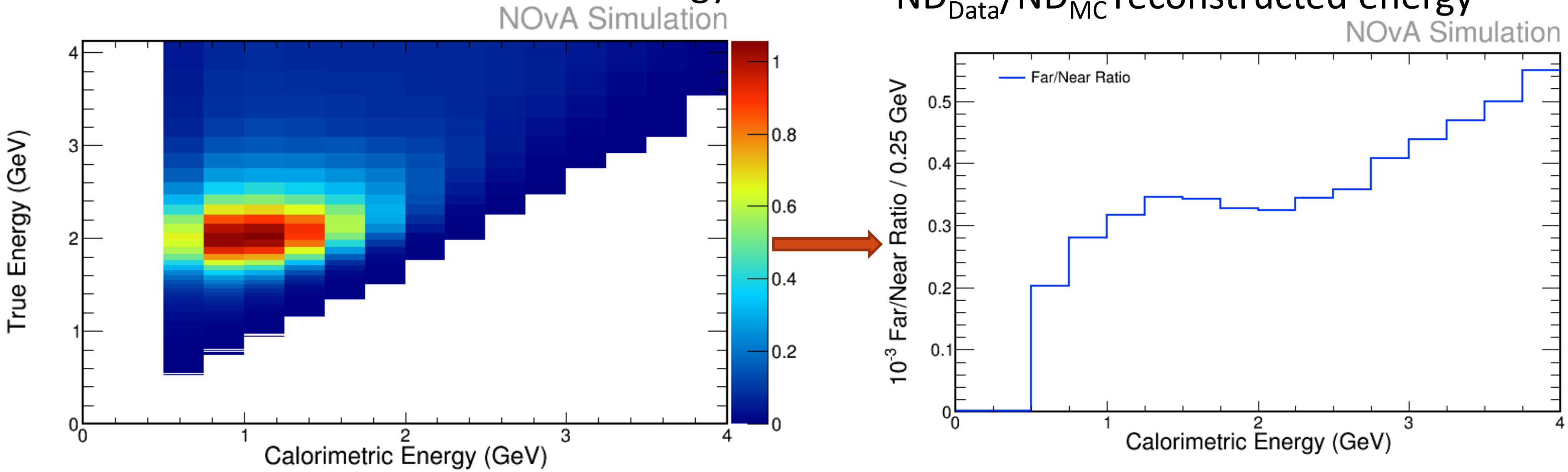
- We use the measured ND energy spectrum to predict the unoscillated FD spectrum

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

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

FD MC extrapolated prediction (3-flavour):

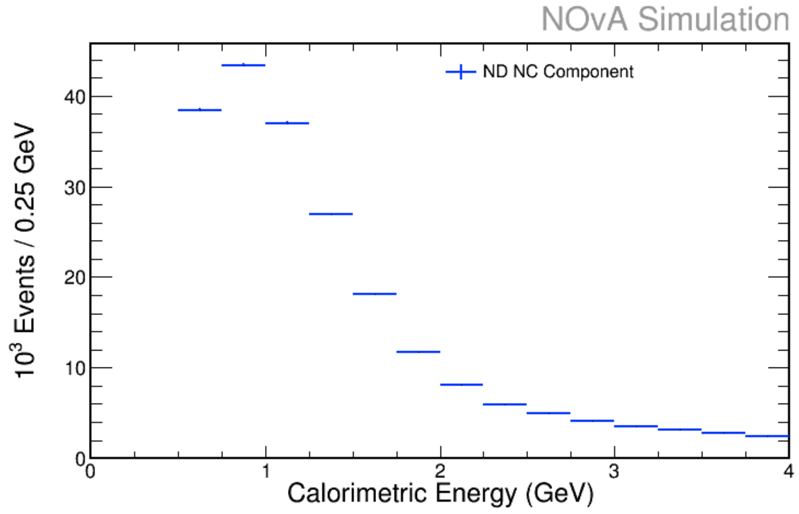
83.71 ± 9.15 (stat.) ± 8.28 (syst.)

Extrapolation

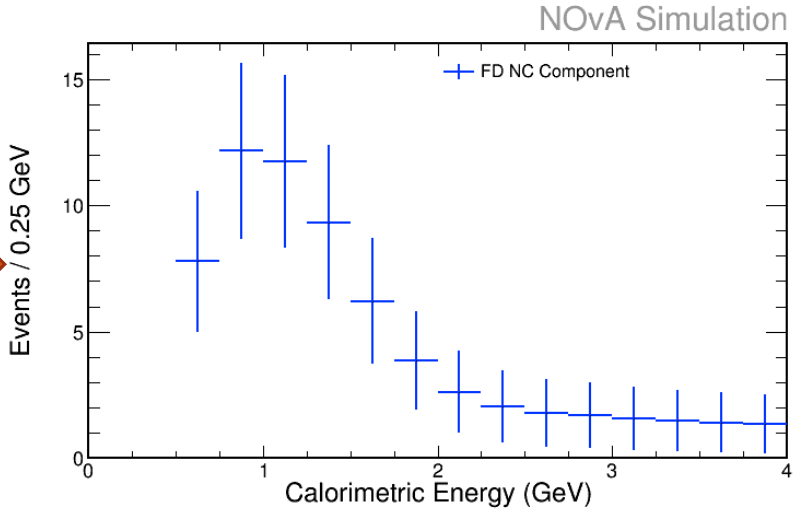
- We use the measured ND energy spectrum to predict the unoscillated FD spectrum

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

Original ND NC component
All flavours decomposed proportionally



Final FD reconstructed energy spectrum

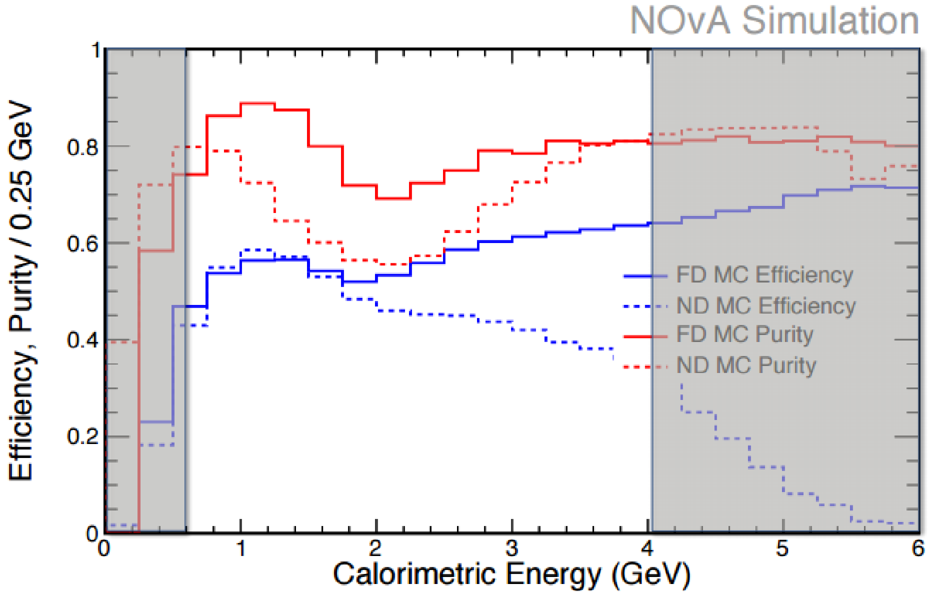


FD MC extrapolated prediction (3-flavour):
83.5 ± 9.7 (stat.) ± 9.4 (syst.)

Analysis approach

- Look for deficit of NCs; active-sterile neutrino oscillation signature
- Compare the NC rate with the expectation of standard 3-flavour oscillations
  - Cut and count analysis

Osc. Parameter	Value
ρ	2.84 g/cm^3
Δm^2_{21}	7.53 x 10^{-5} eV^2
$\sin^2 2\theta_{12}$	0.846
Δm^2_{32}	2.44 x 10^{-3} eV^2
θ_{23}	$\pi/4$
$\sin^2 2\theta_{13}$	0.085
δ	0



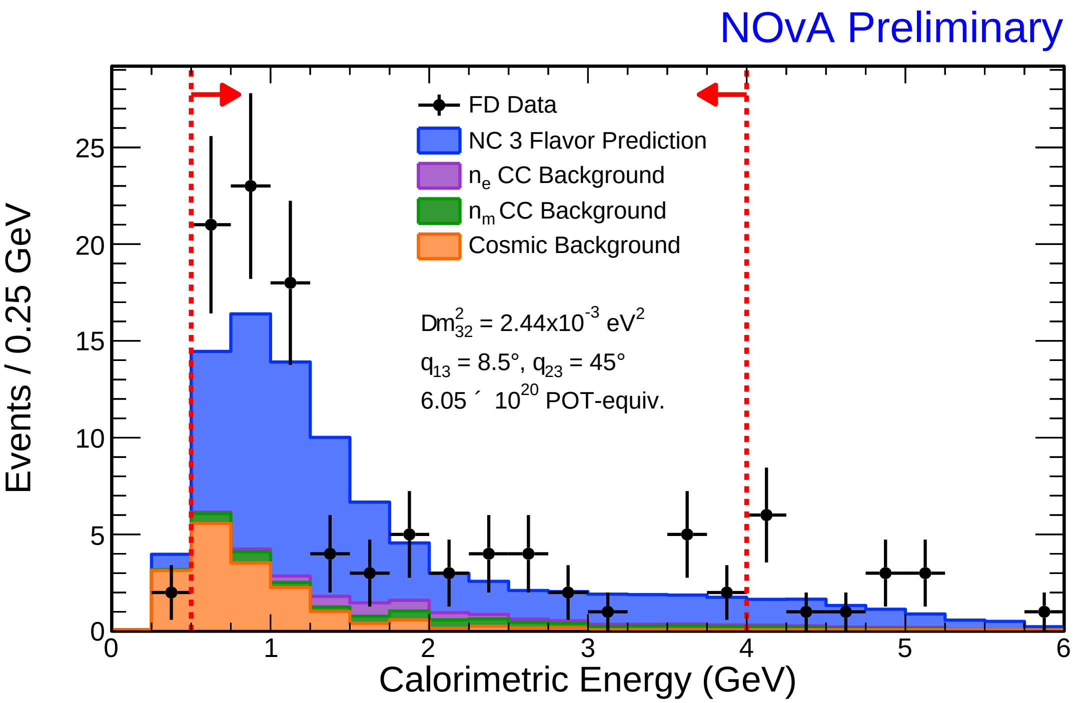
Restrict energy range from 0.5 to 4.0 GeV to remove low efficiency ND regions

Neutral Current FD Data

Observe 95 events

No evidence of oscillations involving steriles

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



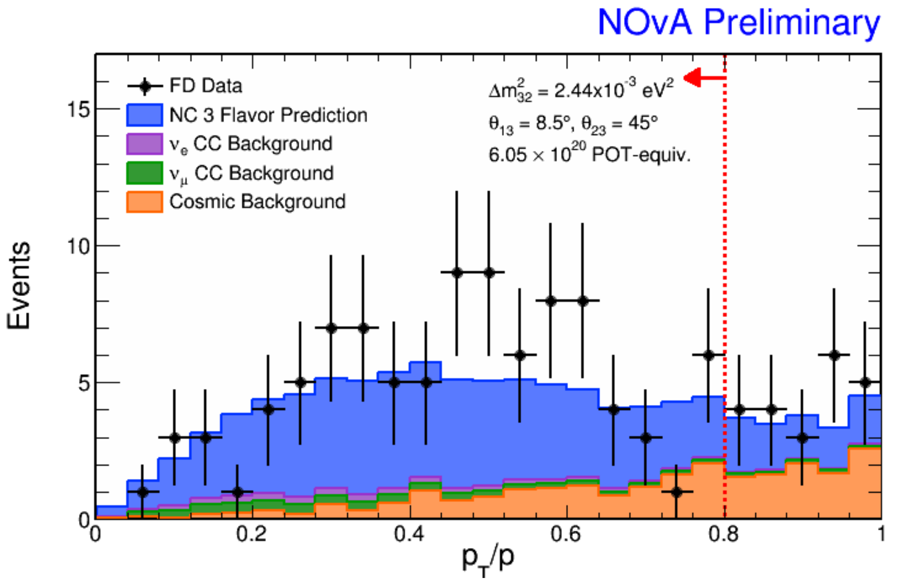
In 3+1 analysis, for $\Delta m^2_{41} = 0.5$ eV^2

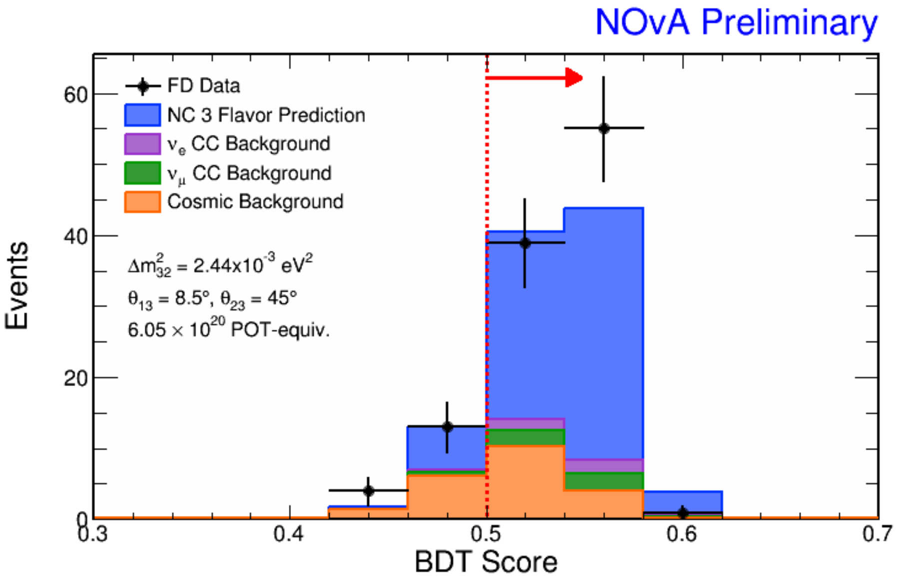
$\theta_{24} < 20.8°$ at 90% C.L.
$\theta_{34} < 31.2°$ at 90% C.L.

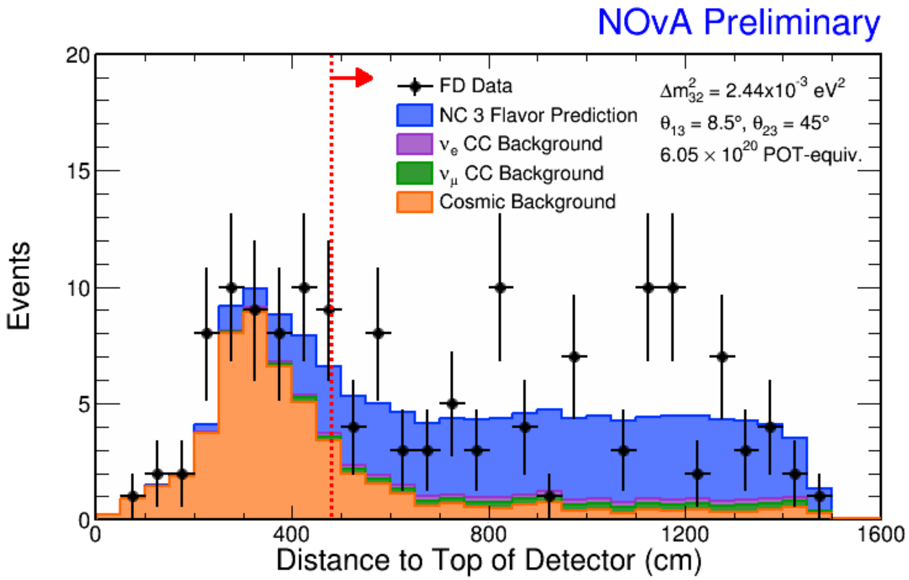
Excellent NC efficiency (50%) and purity (72%) promise strong future limits on θ_{34}

Far detector NC selection

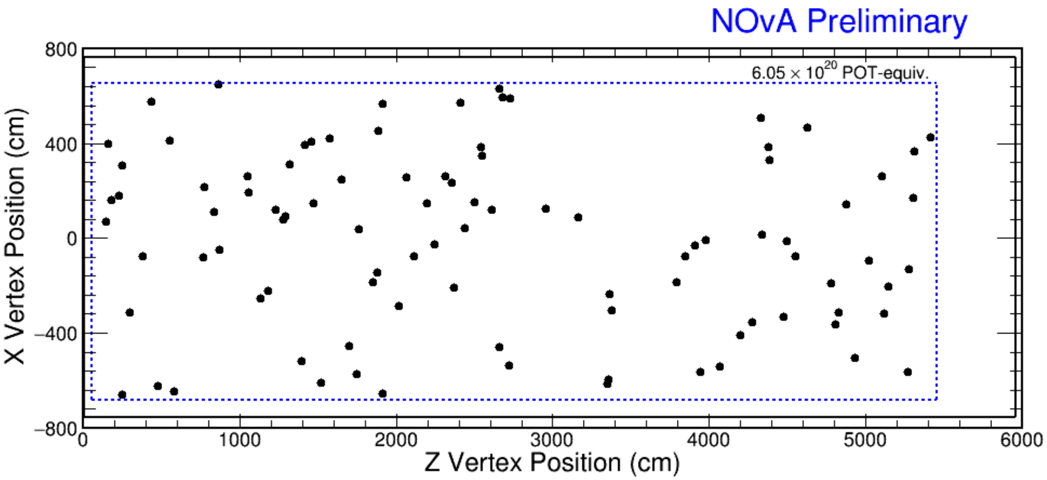
Good data/MC agreement among the cosmic rejection variables

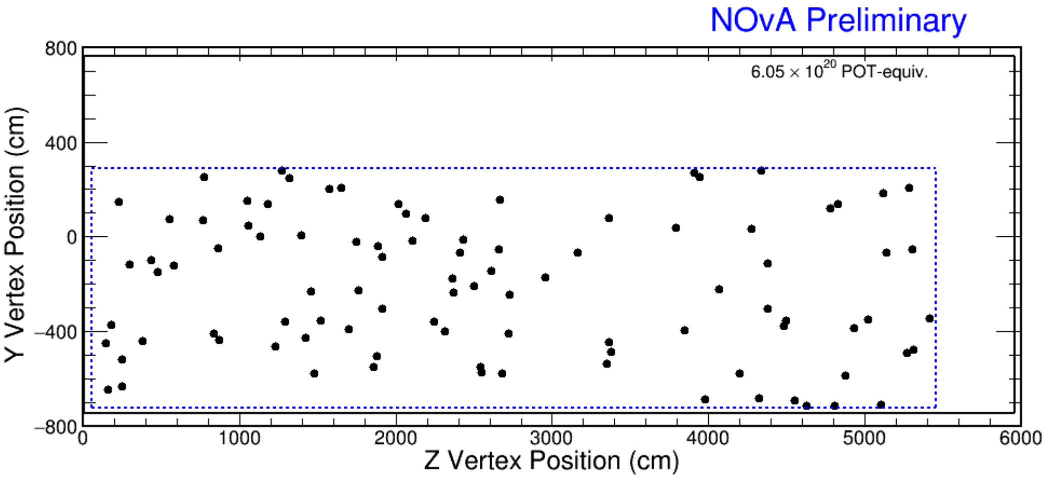


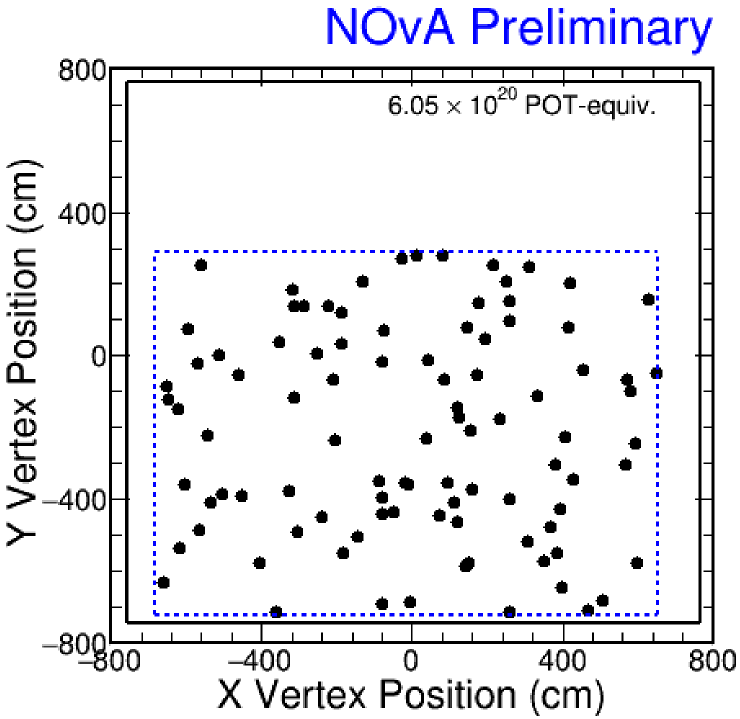




Event distributions







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

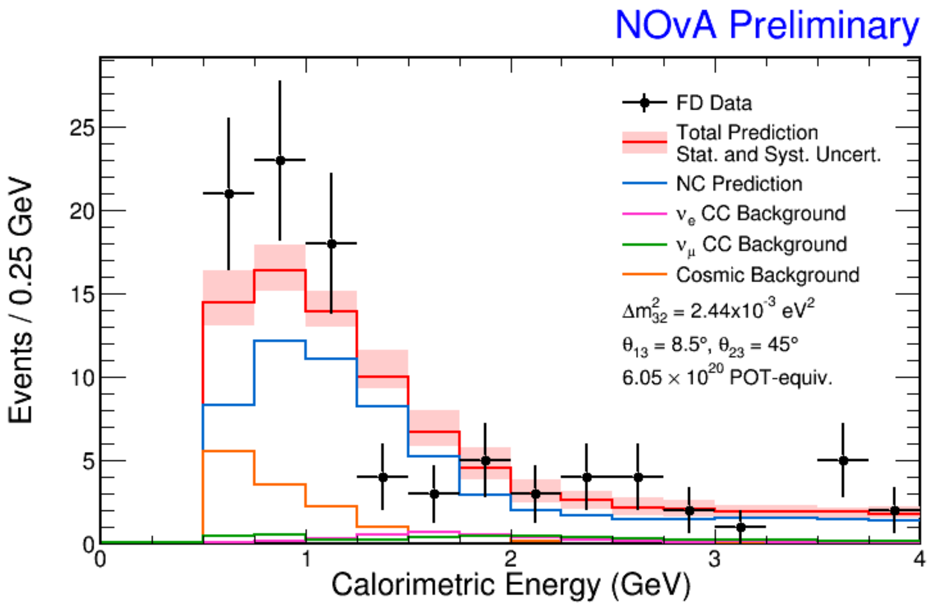
FD Data NC-like: **95**

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)



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