First Results from Searches for Active to Sterile Neutrino Oscillations with NOvA

JOINT EXPERIMENTAL-THEORETICAL PHYSICS SEMINAR

FERMILAB

Gavin S. Davies, Indiana University

for the NOvA collaboration

JULY 29TH 2016

Outline

- NOvA Physics
- Sterile Neutrinos
- NOvA
  - Overview and detector capabilities
- Near and Far detector NC selection
- NC disappearance results
- Summary

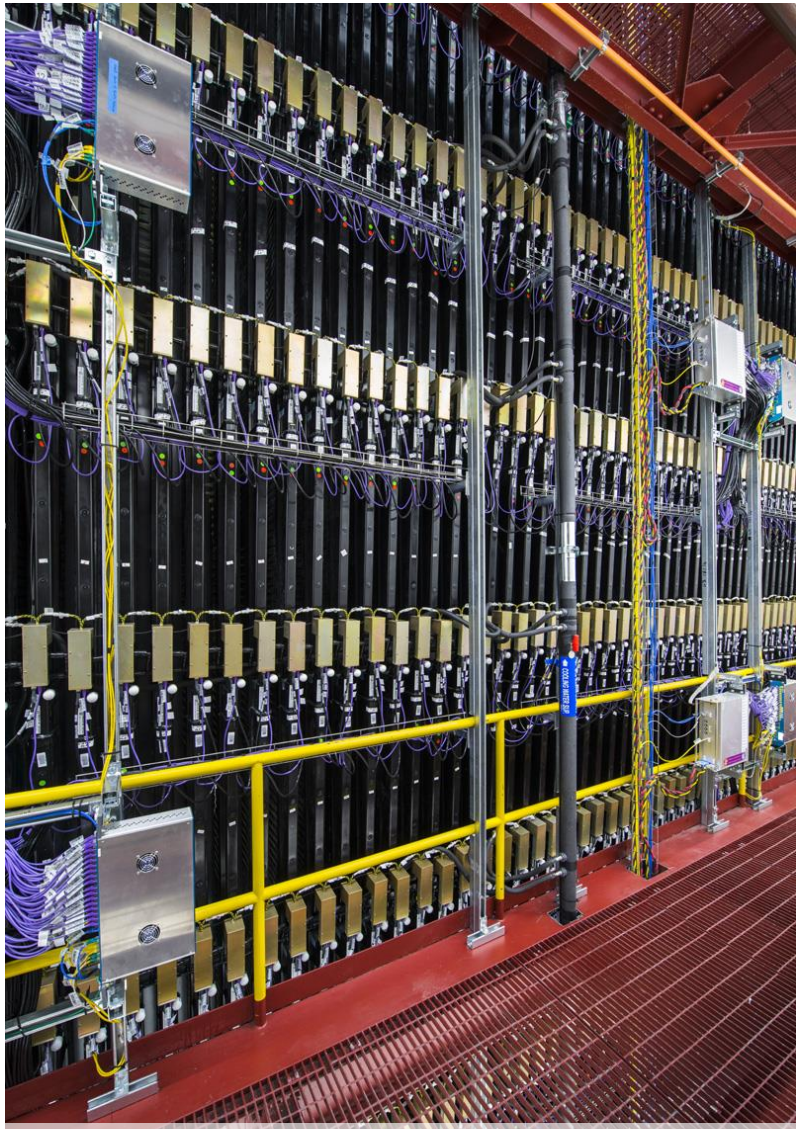
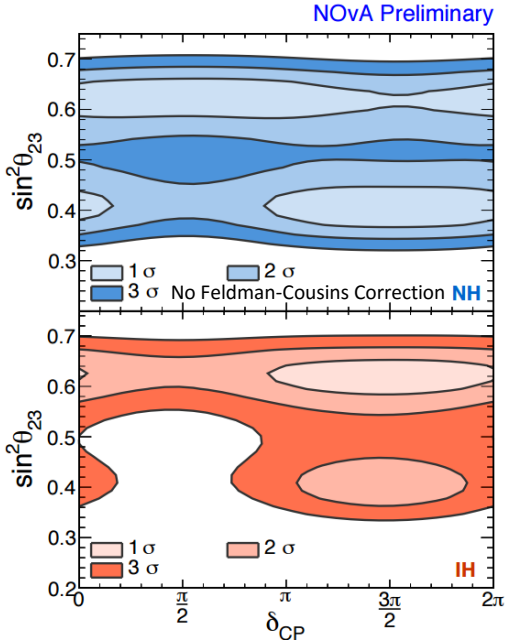


Photo Credit: Creative Services, Fermilab

NOvA Physics

Using $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Determine the mass hierarchy
- Determine the θ_{23} octant
- Constrain δ_{CP}
- See C. Backhouse (Caltech) JETP seminar 20/07/2016



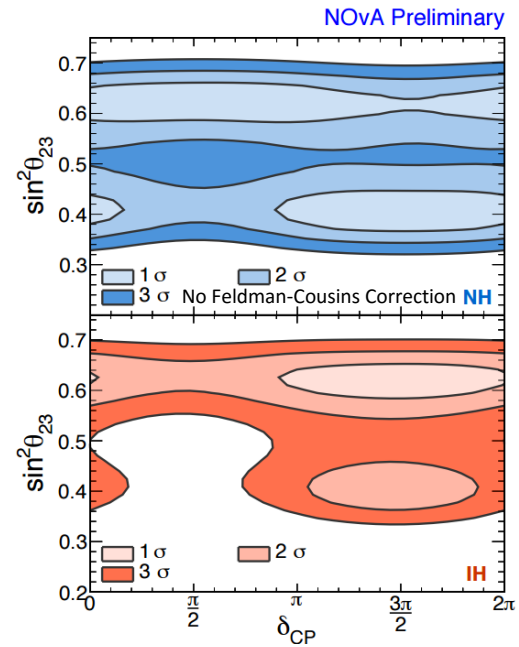
NOvA Physics

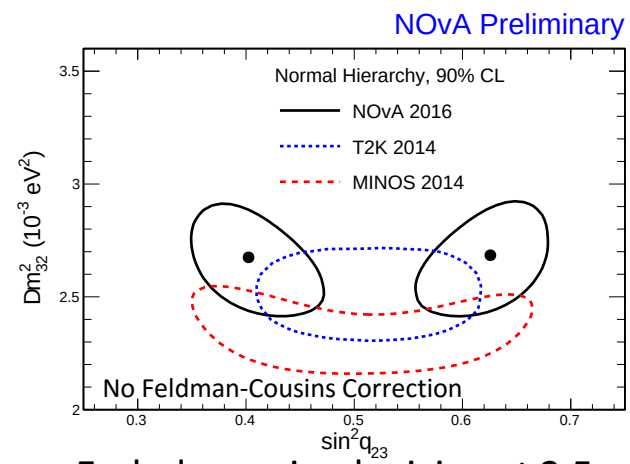
Using $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Determine the mass hierarchy
- Determine the θ_{23} octant
- Constrain δ_{CP}
- See C. Backhouse (Caltech) JETP seminar 20/07/2016

Using $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

- Precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{32}
- Over-constrain the atmospheric sector
- See C. Backhouse (Caltech) JETP seminar 20/07/2016





Exclude maximal mixing at 2.5σ

NOvA Physics

Using $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$

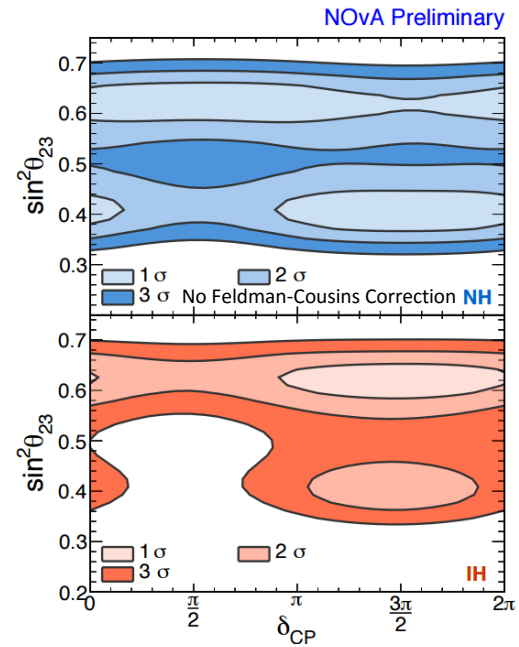
- Determine the mass hierarchy
- Determine the θ_{23} octant
- Constrain δ_{CP}
- See C. Backhouse (Caltech) JETP seminar 20/07/2016

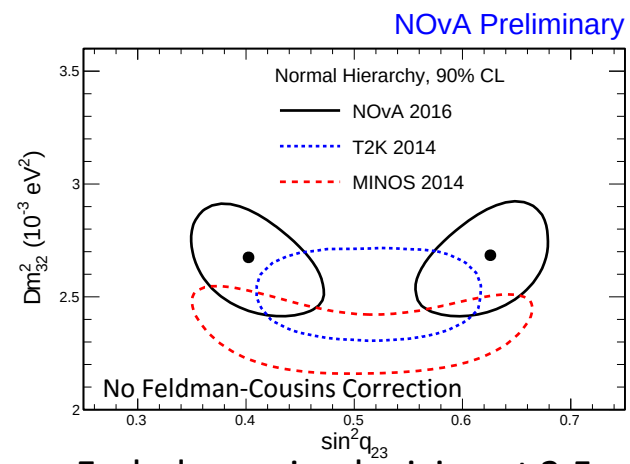
Using $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$

- Precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{32}
- Over-constrain the atmospheric sector
- See C. Backhouse (Caltech) JETP seminar 20/07/2016

Also:

- Neutrino cross-sections at the NOvA Near Detector
- Supernova neutrinos and other exotica
- **Search for sterile neutrinos**
  - Short-baseline ν_e and ν_τ appearance using NOvA ND
  - **Long-baseline NC disappearance in FD**



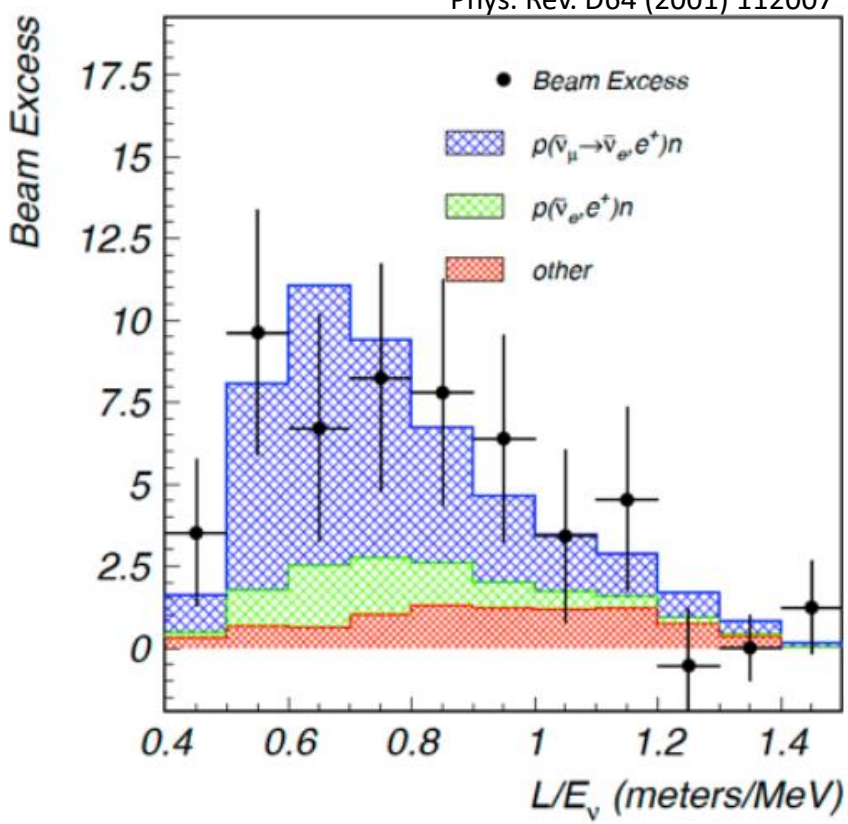


Exclude maximal mixing at 2.5σ

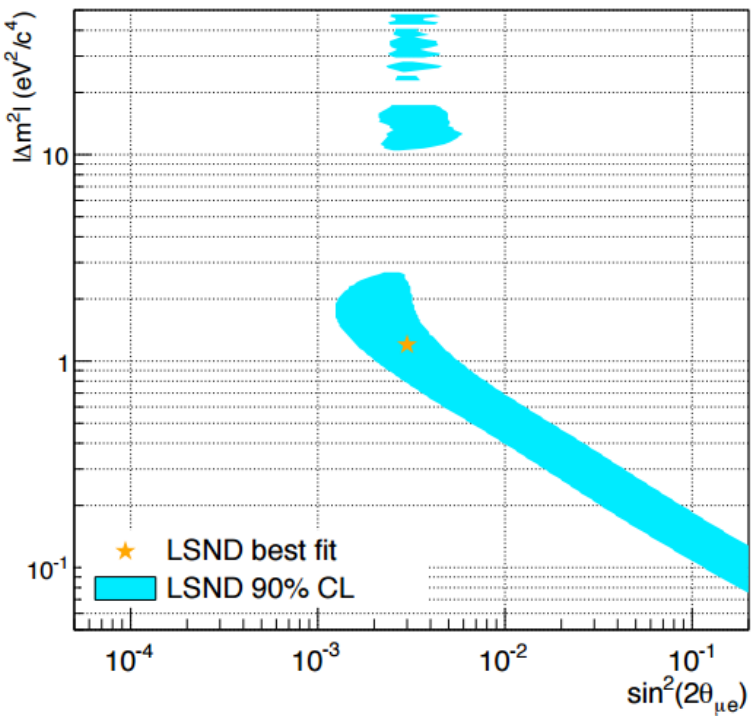
The LSND anomaly

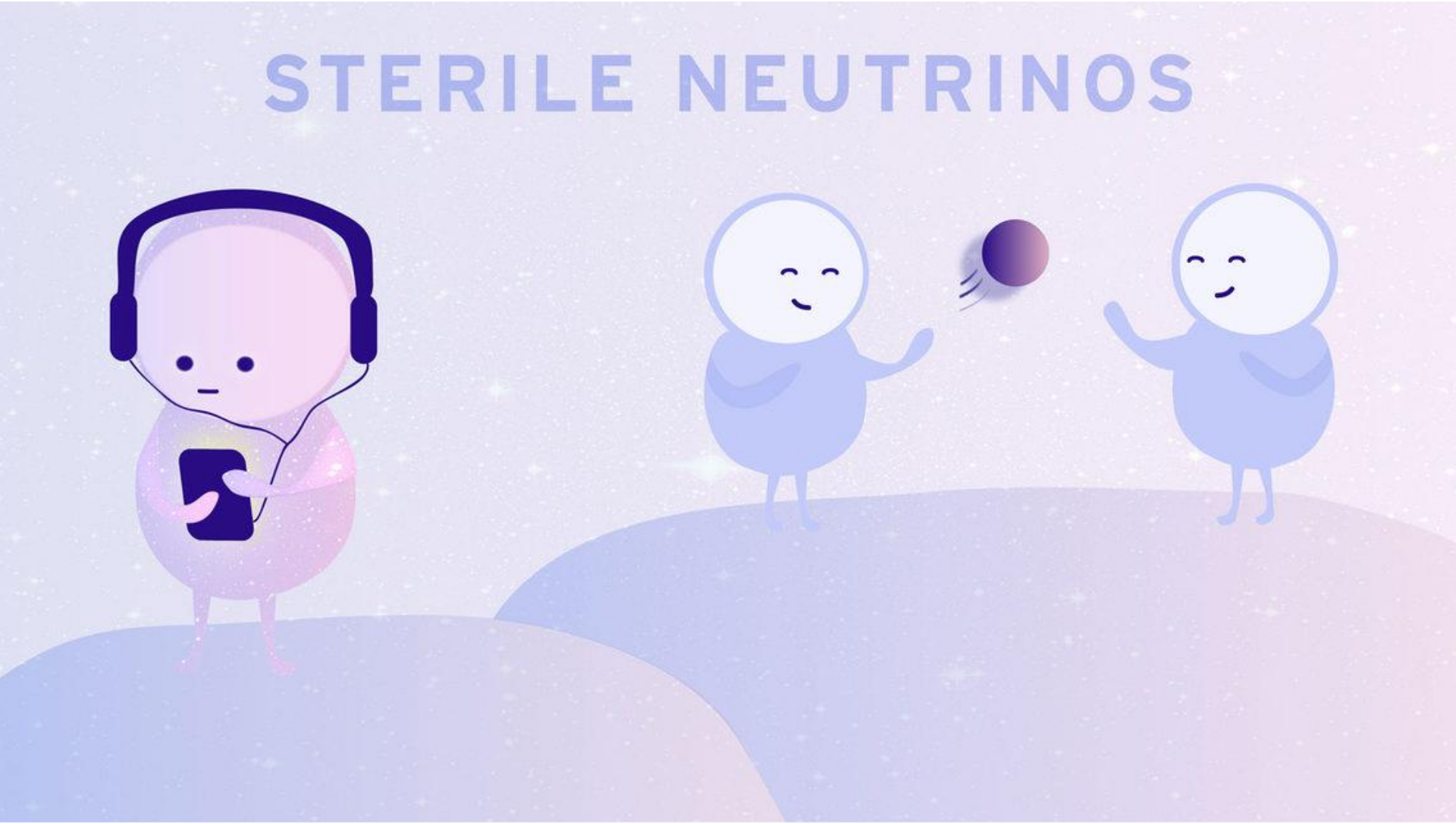
- Antineutrinos from an accelerator seem to appear
- LSND (1993-1998) observed a (~3.8σ) excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Phys. Rev. D64 (2001) 112007



- If due to oscillations:
  - L/E → high $\Delta m^2 \sim 1\ eV^2$
  - Can be accommodated by a NEW and STERILE neutrino
  - Oscillations into a sterile neutrino are one of the possible explanations, and one that we can test

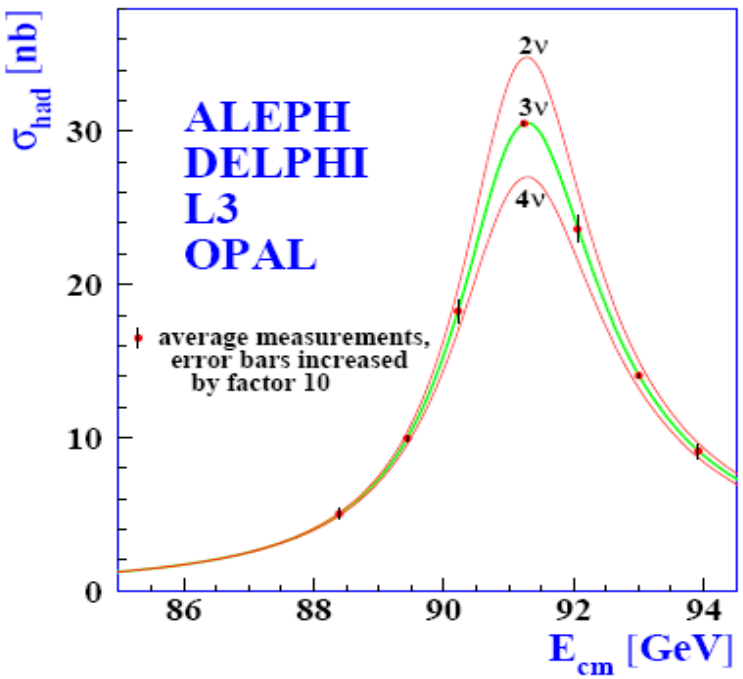




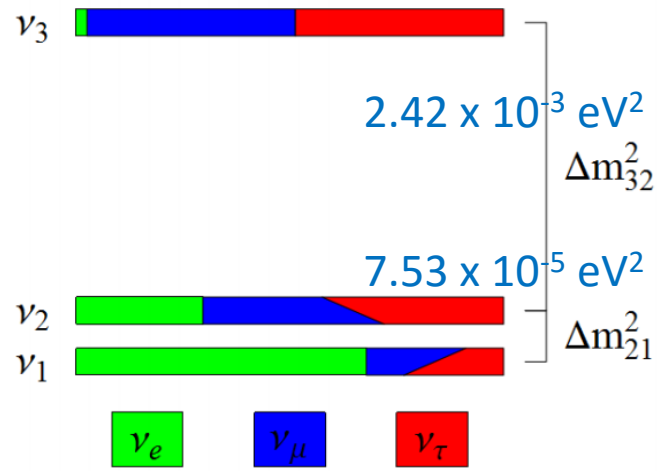
Source: symmetrymagazine.org
Artwork by Sandbox Studios, Chicago

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
  - $N_\nu = 3.011 \pm 0.077$
  - "light" means below ½ Z mass



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



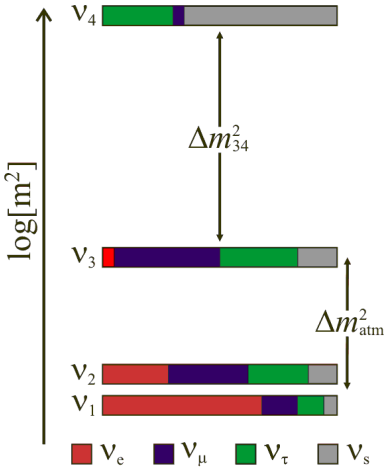
$\Delta m^2_{LSND} > 0.2$ eV^2 ($\gg \Delta m^2_{32} \gg \Delta m^2_{21}$)
Anomaly!

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

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}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



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

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

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

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

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

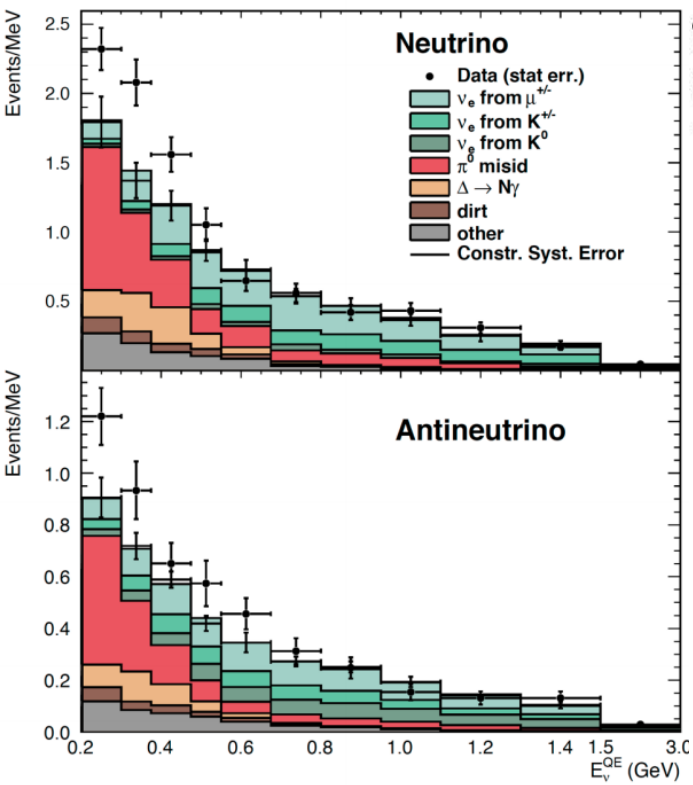
$\nu_\mu \to \nu_e$ at short baselines (LSND)

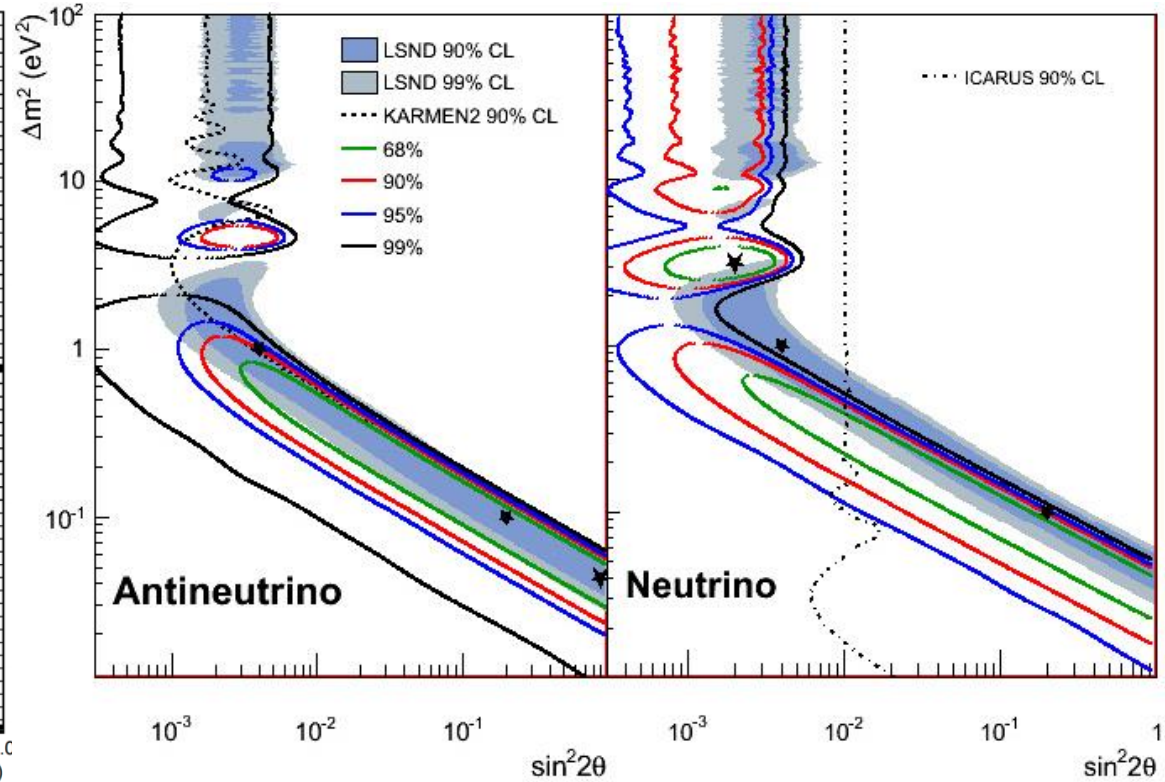
$\nu_\mu \to \nu_s$ at long baselines (NCs)

What 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

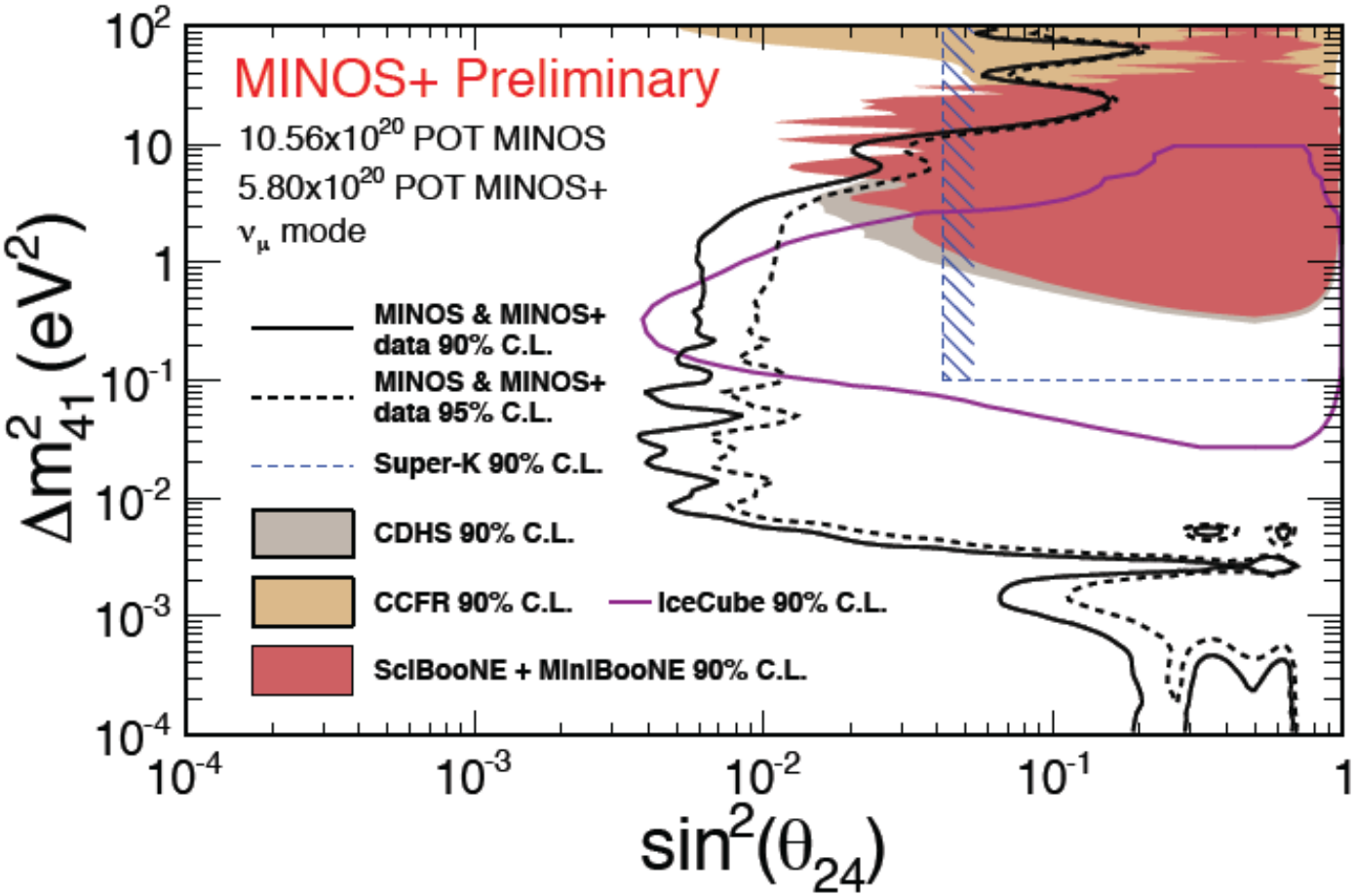




MiniBooNE Phys. Rev. Lett. 110, 161801 (2013)

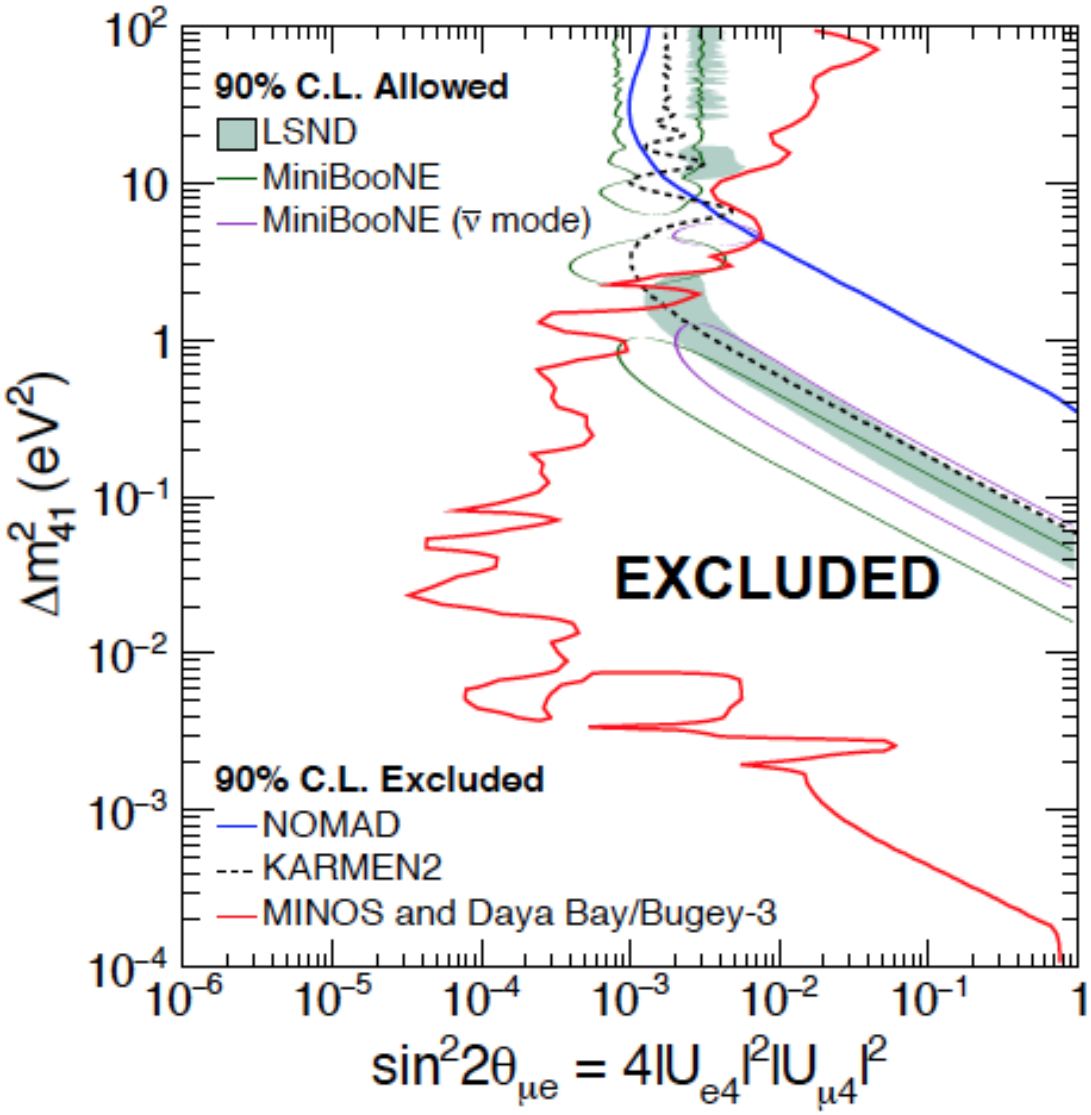
What about disappearance?

- 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

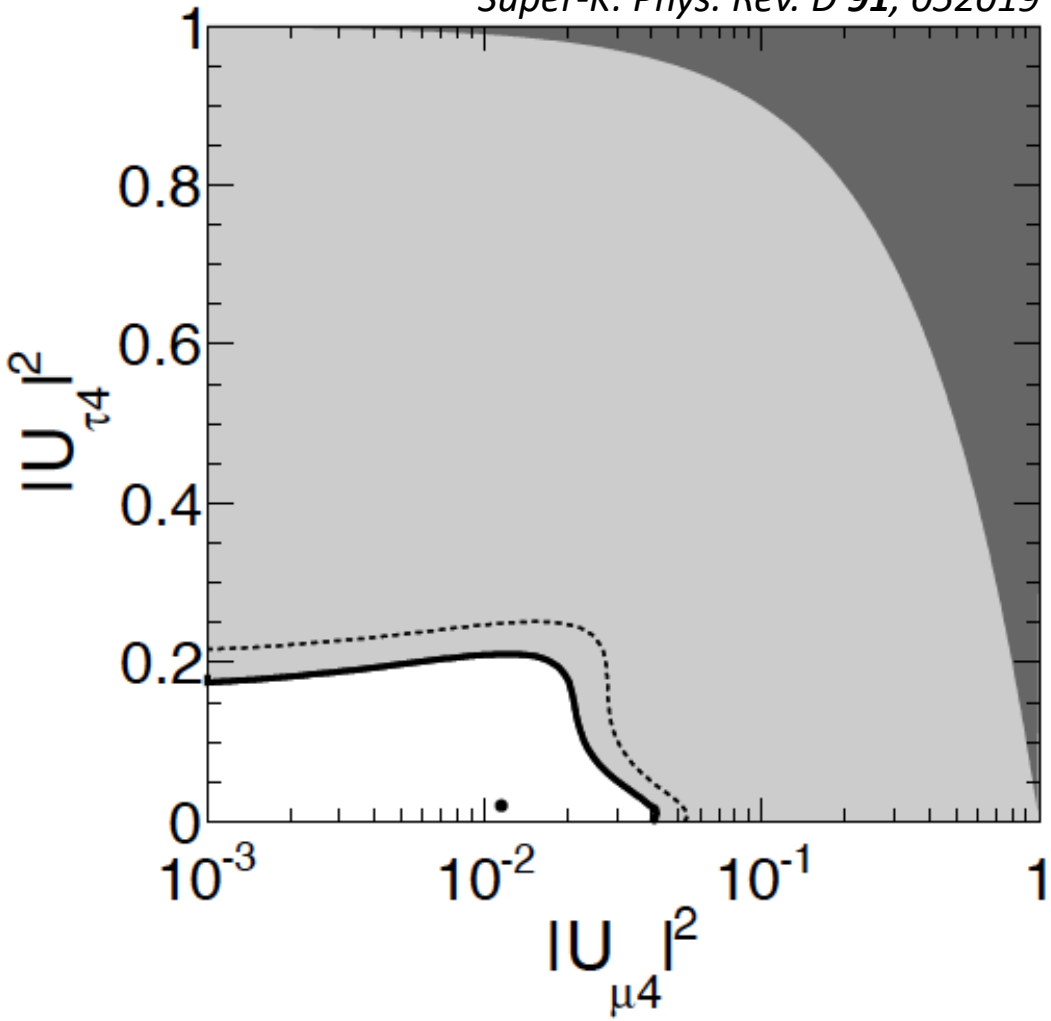
  $|U_{\mu 4}|^2 < 0.041$ for $\Delta m^2_{41} > 0.1$ eV^2

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

- Super-K only experiment with measurement on $|U_{\tau 4}|^2$ directly comparable to NOvA

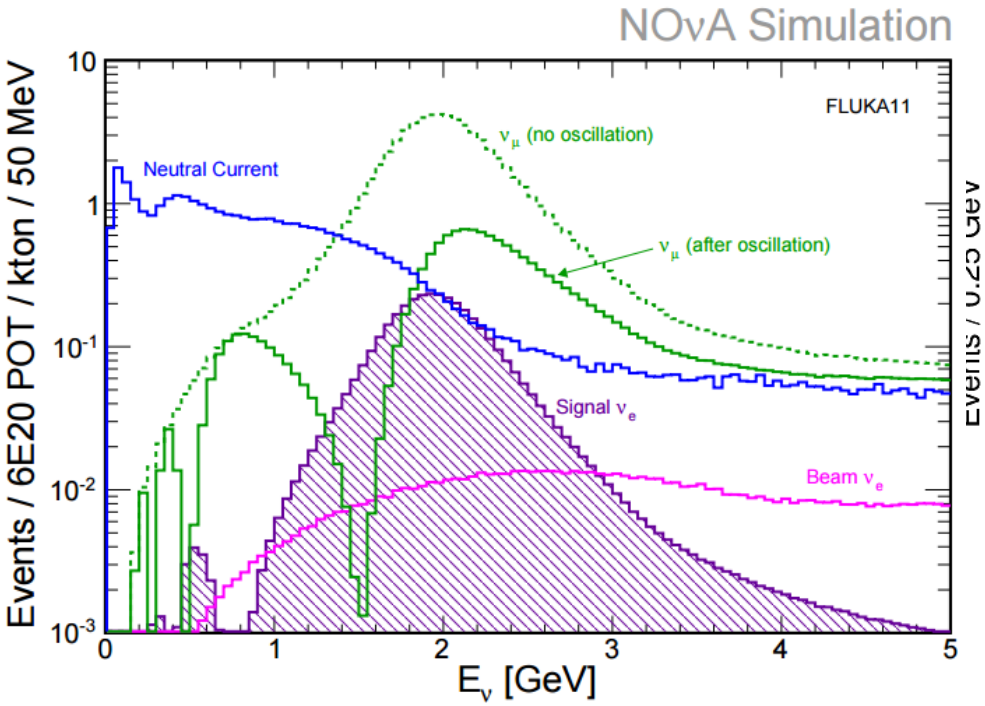
- Note also there are unresolved discrepancies in short-baseline reactor experiments and gallium-based radiochemical experiments

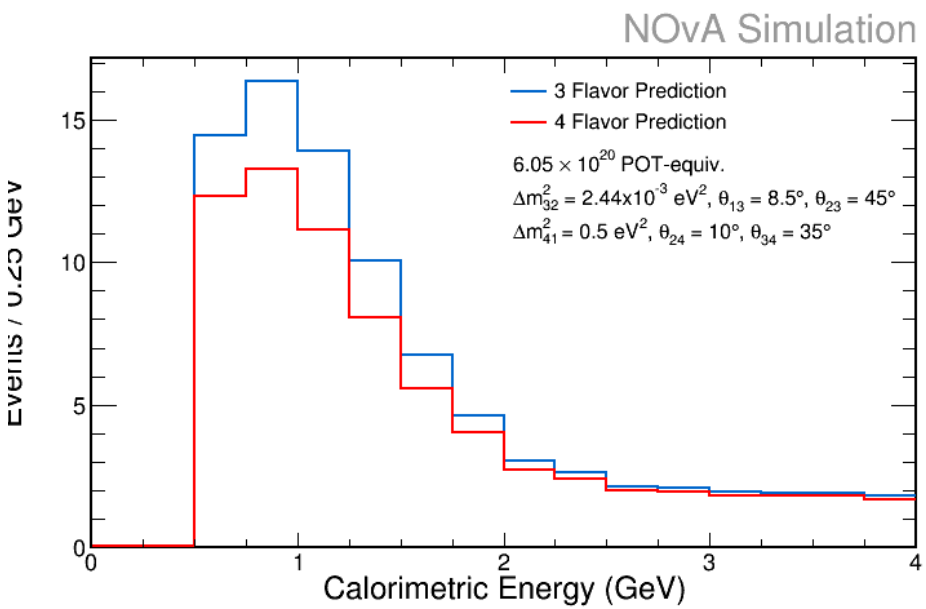
*Super-K: Phys. Rev. D **91**, 052019*



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
- Null results allows NOvA to set limits on sterile mixing angles and further increase the exclusion region





NC disappearance relative to 3-flavour predictions is model independent

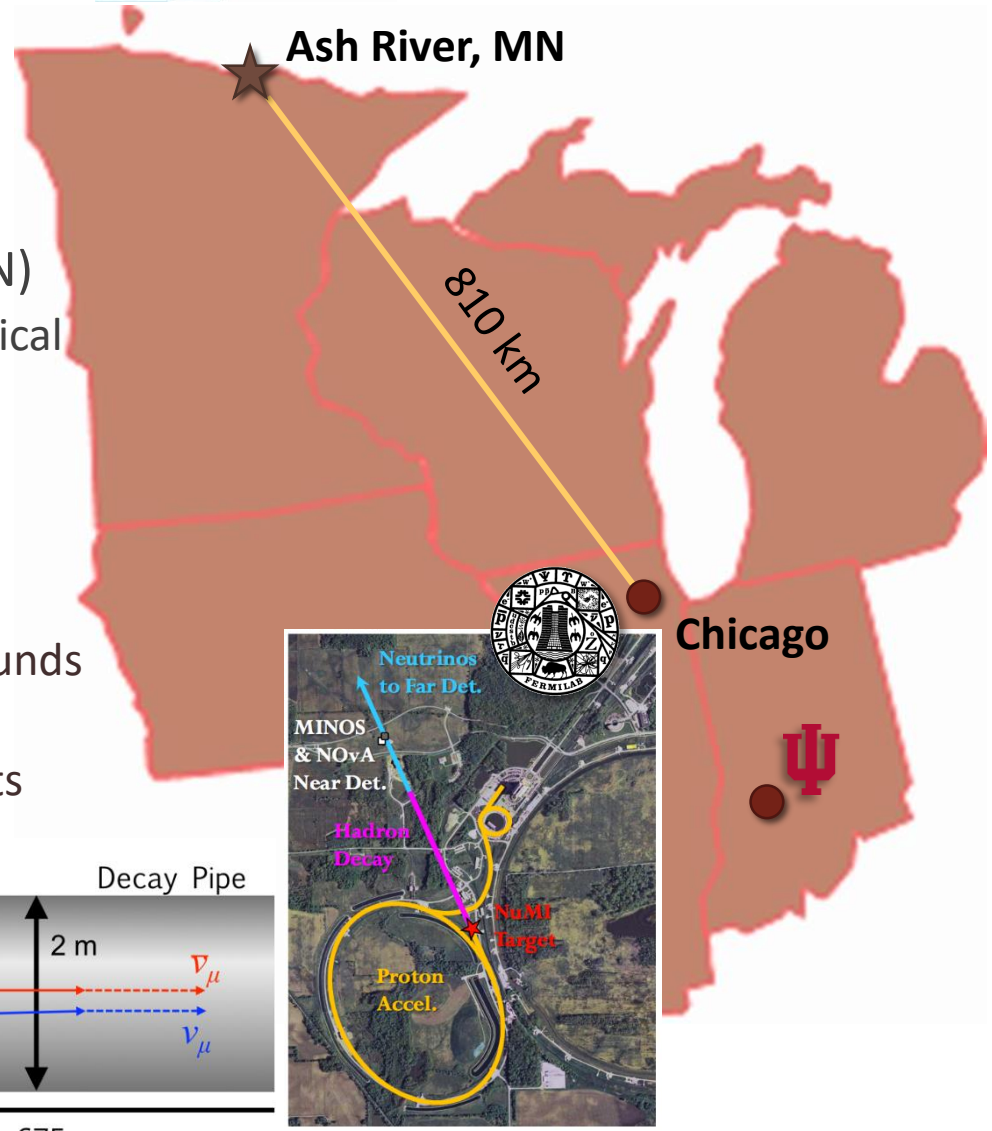
The NOvA collaboration

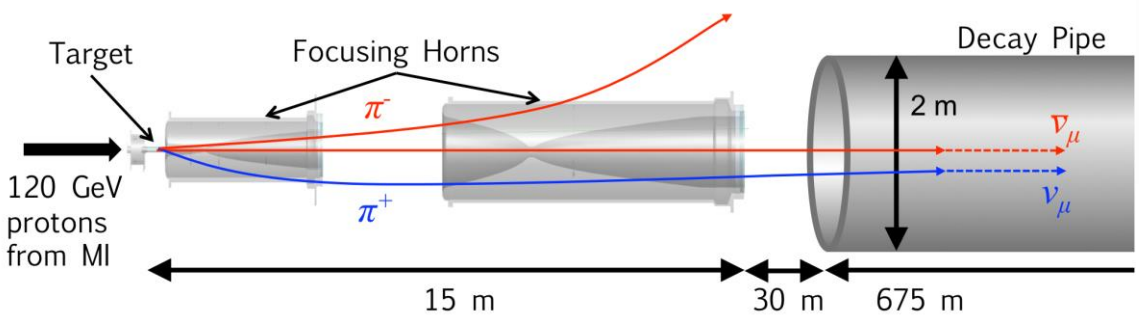
234 Collaborators
41 institutions
7 countries

Argonne, Atlantico, Banaras Hindu University, Caltech, Cochin, Institute of Physics and Computer science of the Czech Academy of Sciences, Charles University, Cincinnati, Colorado State, Czech Technical University, Delhi, JINR, Fermilab, Goiás, IIT Guwahati, Harvard, IIT Hyderabad, U. Hyderabad, Indiana, Iowa State, Jammu, Lebedev, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Panjab, South Carolina, SD School of Mines, SMU, Stanford, Sussex, Tennessee, Texas-Austin, Tufts, UCL, Virginia, Wichita State, William and Mary, Winona State

NOvA

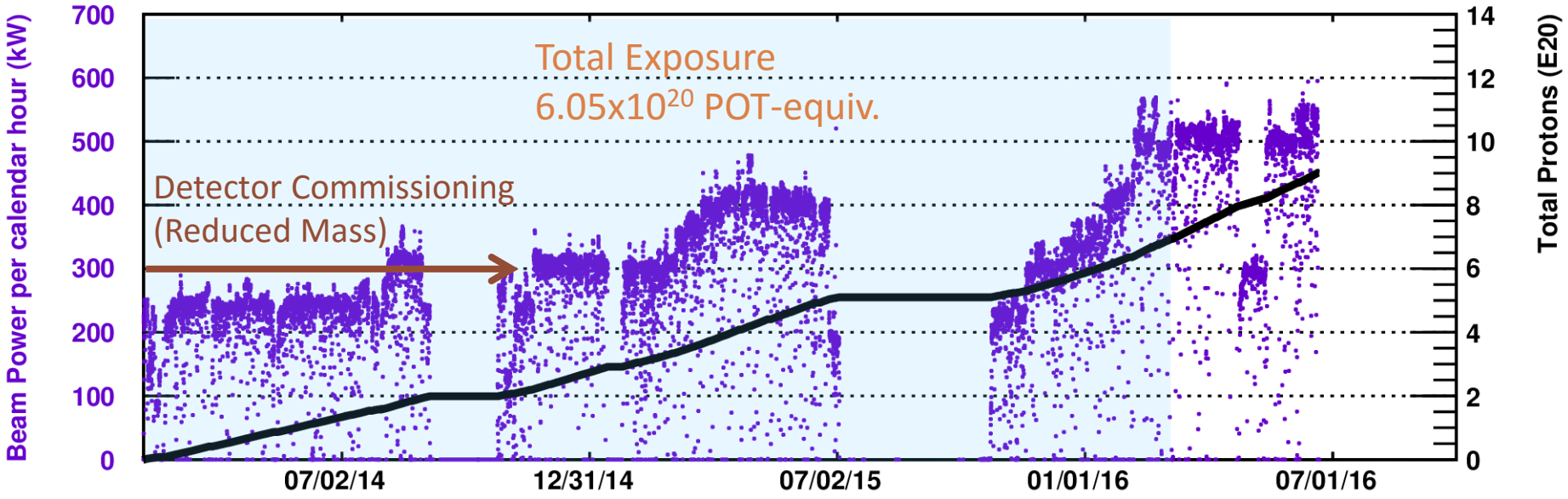
- Long-baseline, off-axis neutrino oscillation experiment
- NuMI ν_μ beam from Fermilab
- ND (Fermilab) and FD (Ash River, MN)
  - 14.6 mrad off-axis, functionally identical
  - ND measurement predicts FD
- Beam peak from 1-3 GeV
- Near oscillation maximum
  - Few high energy NC events (backgrounds to standard oscillation analyses)
  - NCs largest sample of available events





NuMI beam performance

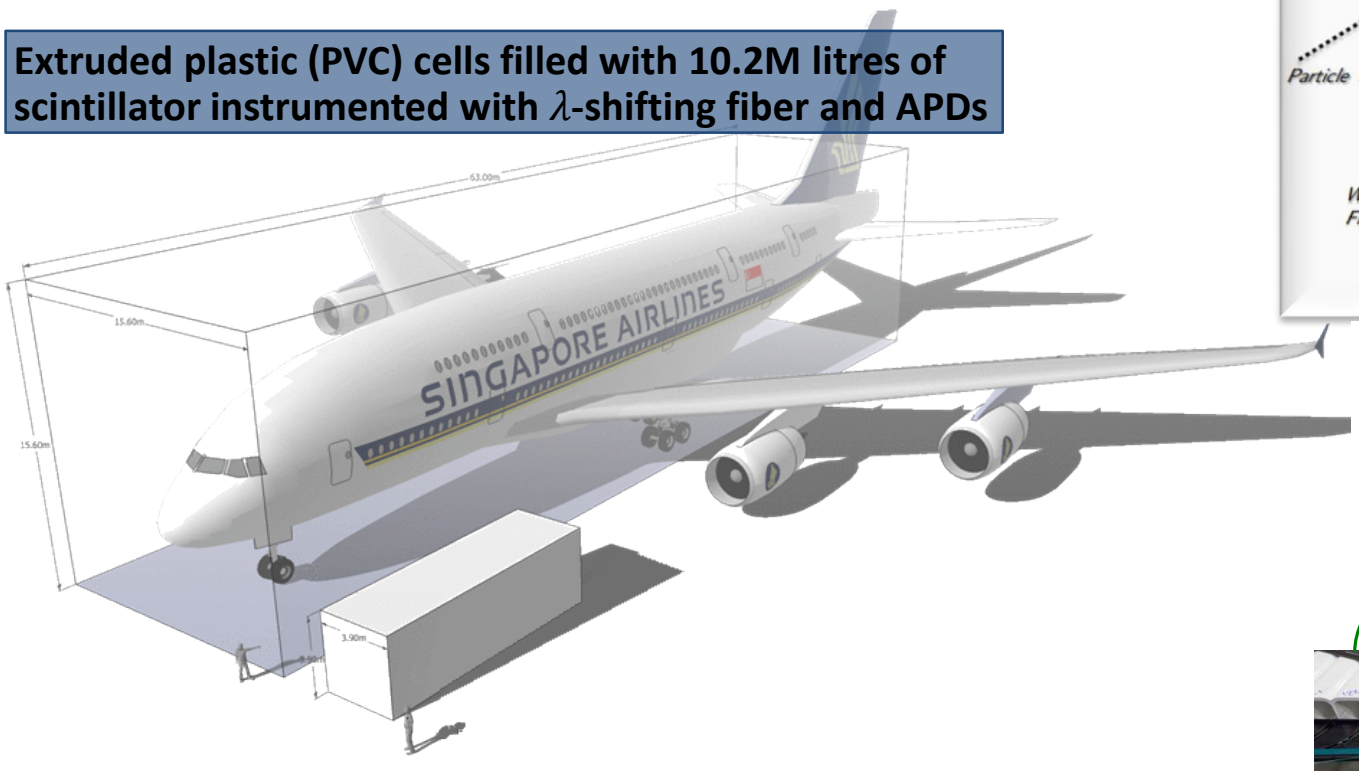
- Marvellous beam performance
- Currently running at 560 kW (anti-neutrino mode)
- Achieved 700 kW design goal in tests on June 13th 2016
- Analysis uses data from February 6th 2014 to May 2nd 2016
- **6.05 x 10^{20} POT** in full 14 kton equivalent detector (1 TDR year)

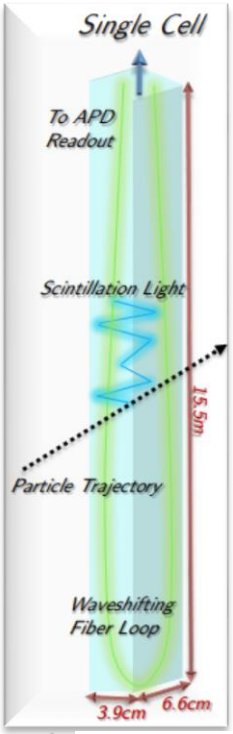


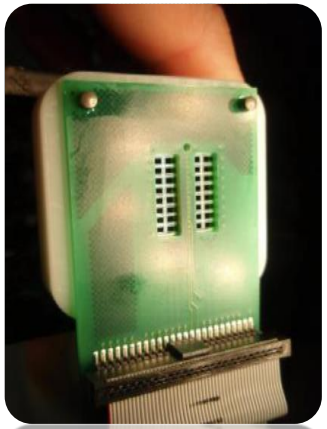
NOvA detector technology

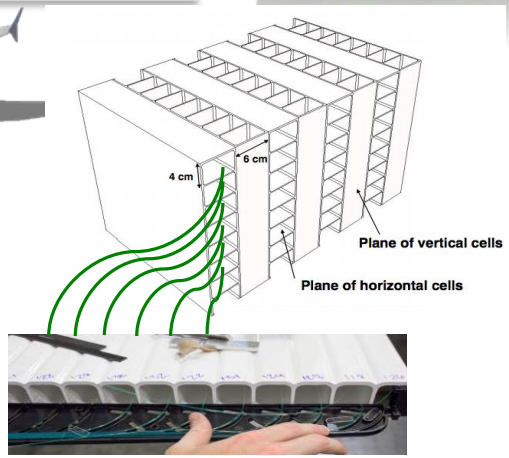
- Fine-grained low-Z, highly active, tracking calorimeter
- 64% liquid scintillator by mass
  - 300 ton ND: 20,000 channels
    - 4.2 m x 4.2 m x 15.8 m
  - 14 kton FD: 344,000 channels
    - 15.6 m x 15.6 m x 60 m

Extruded plastic (PVC) cells filled with 10.2M litres of scintillator instrumented with λ-shifting fiber and APDs

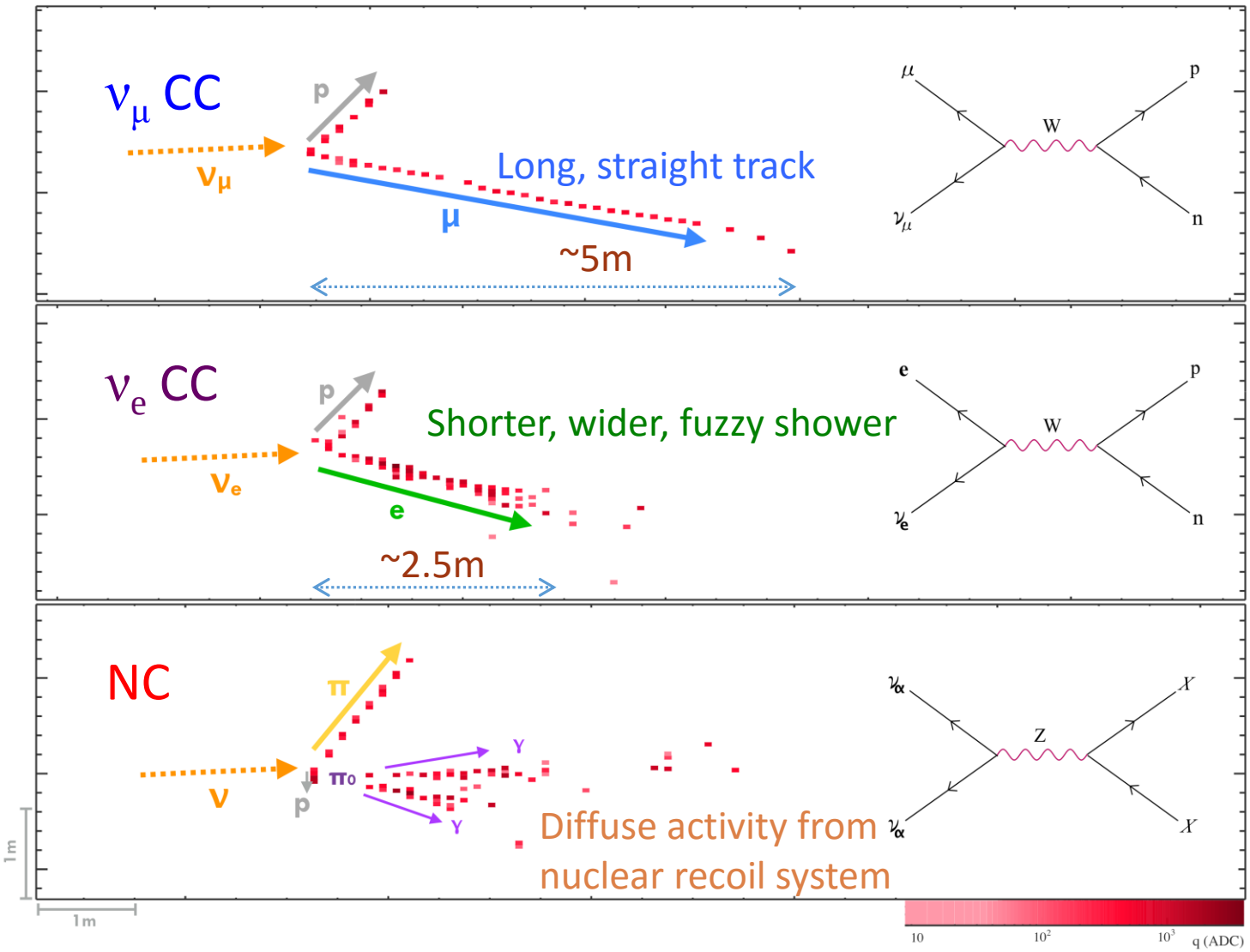






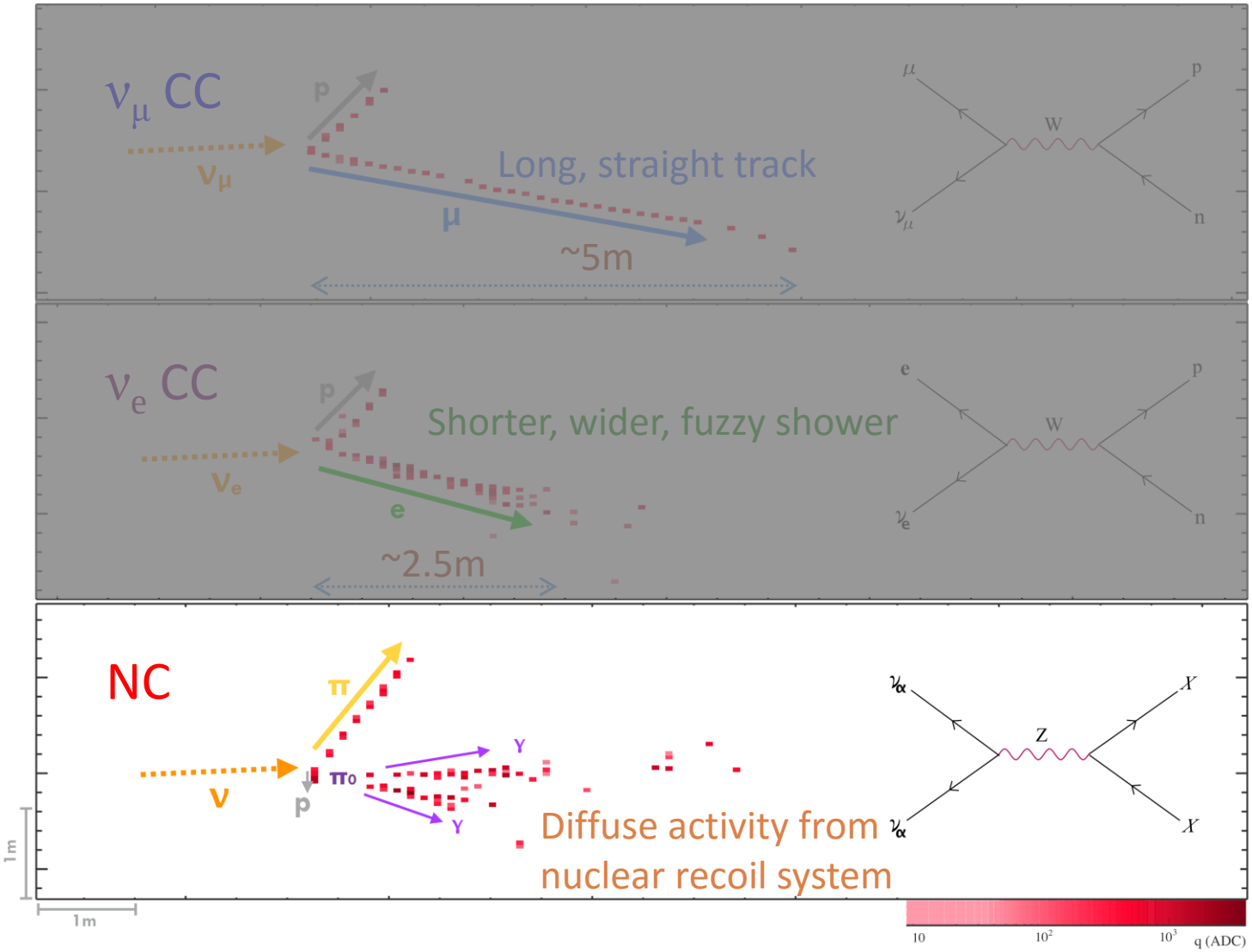


NOvA event topologies



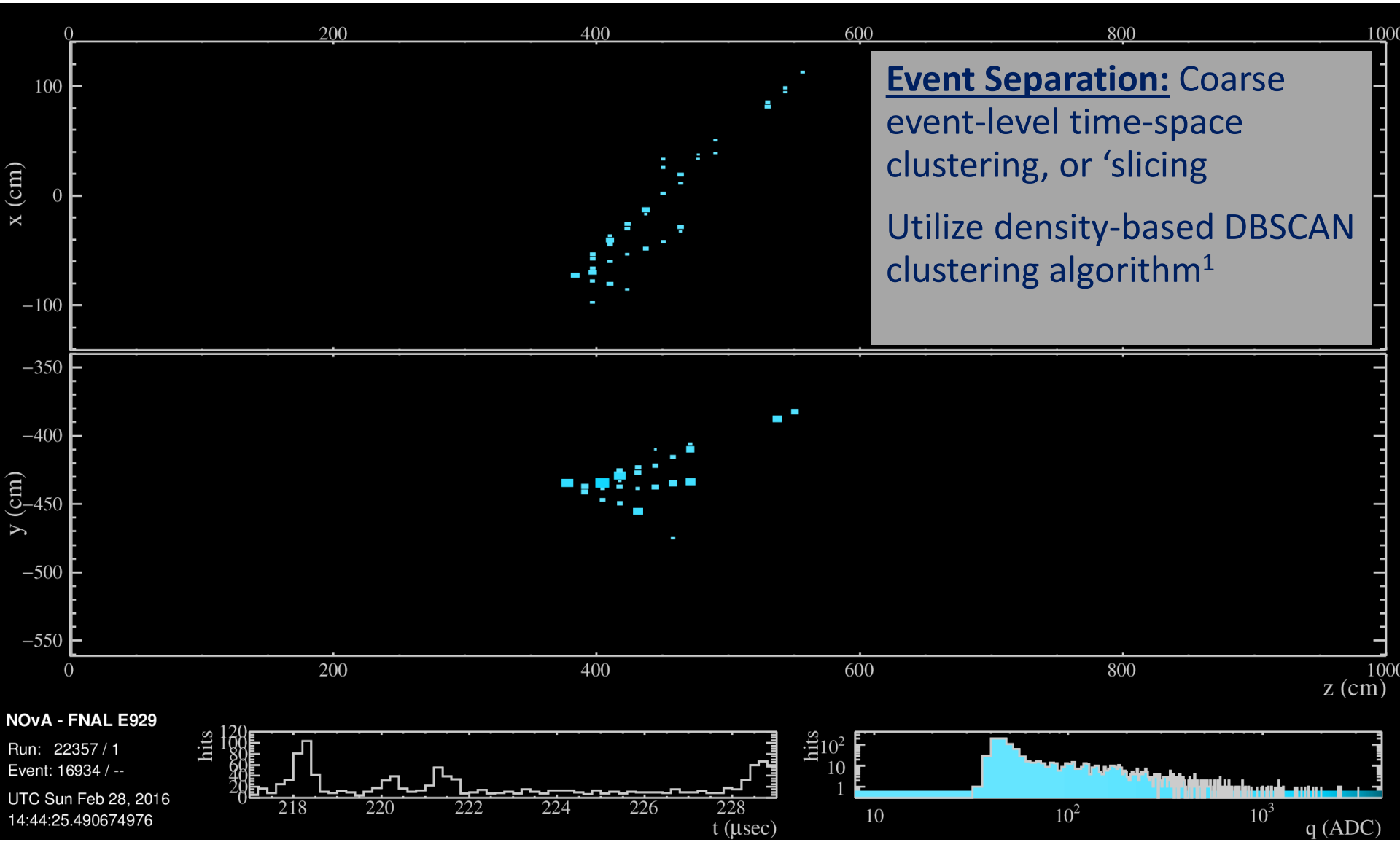
Excellent granularity; X_0 = 38cm (6 cell depths, 10 cell widths)

NOvA event topologies



Excellent granularity; X_0 = 38cm (6 cell depths, 10 cell widths)

Reconstruction

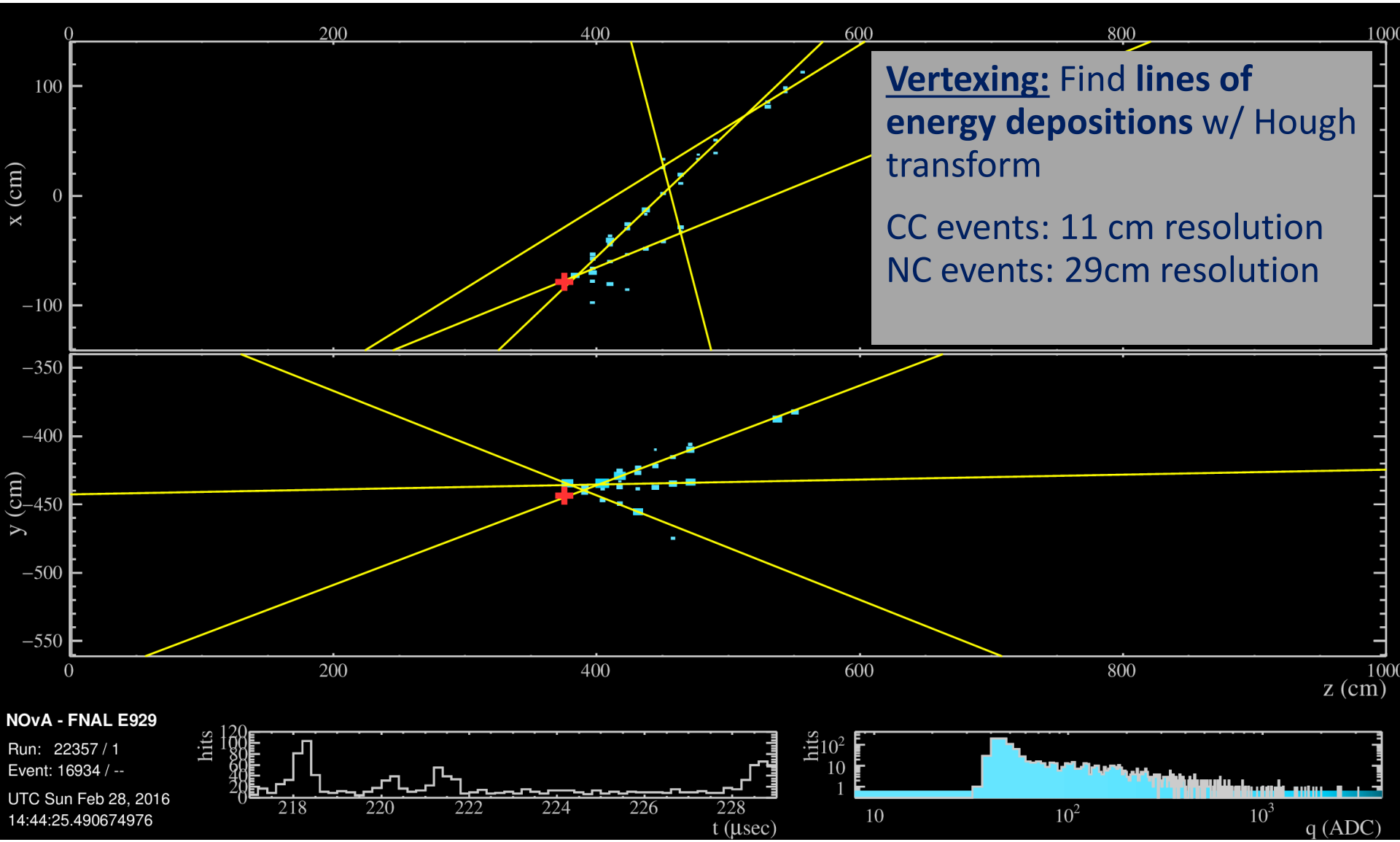


Event Separation: Coarse event-level time-space clustering, or 'slicing

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)

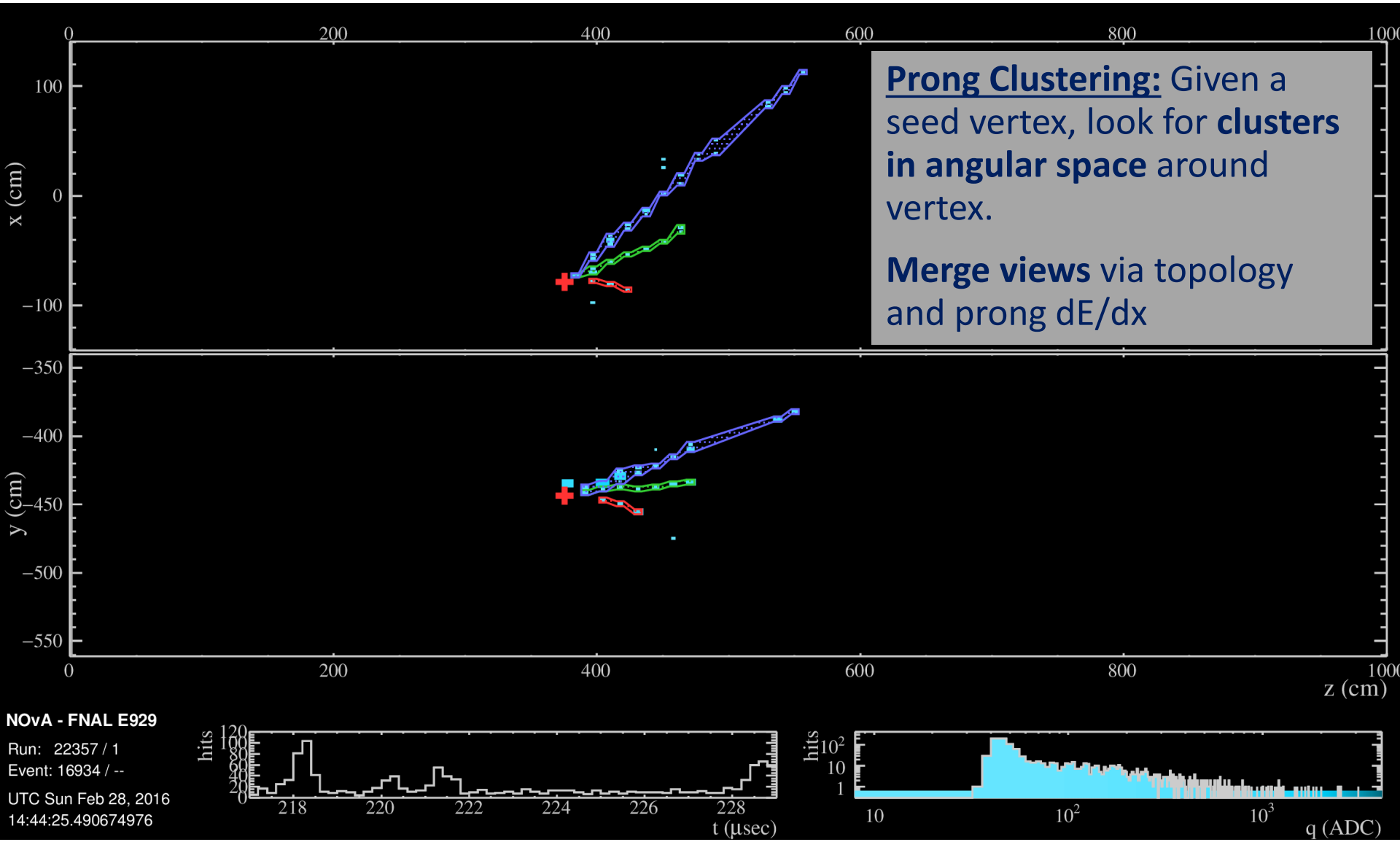
Reconstruction



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

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

Reconstruction



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

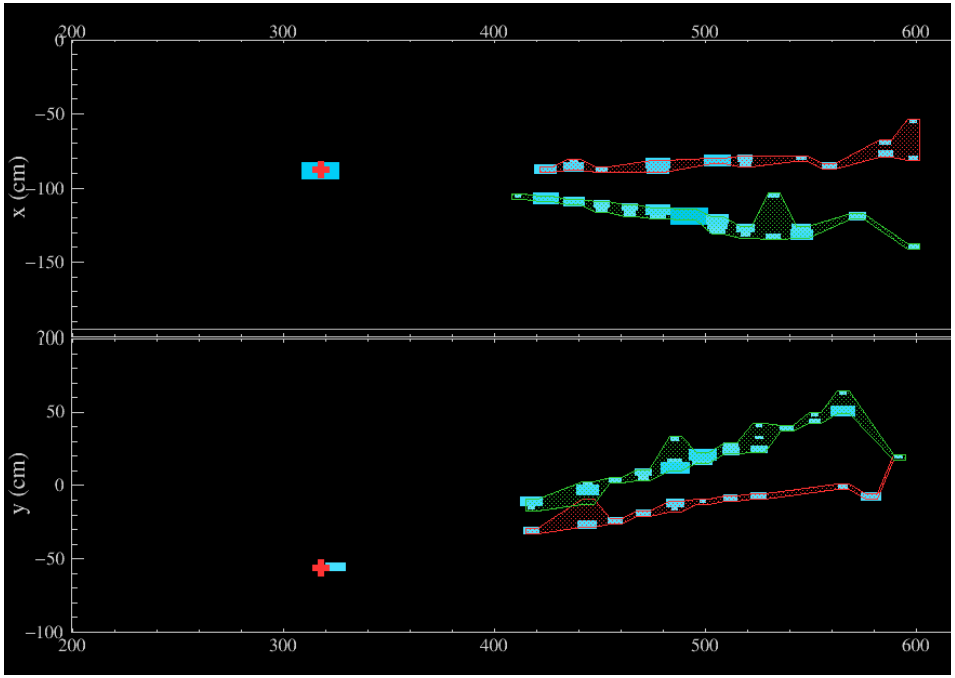
Merge views via topology and prong dE/dx

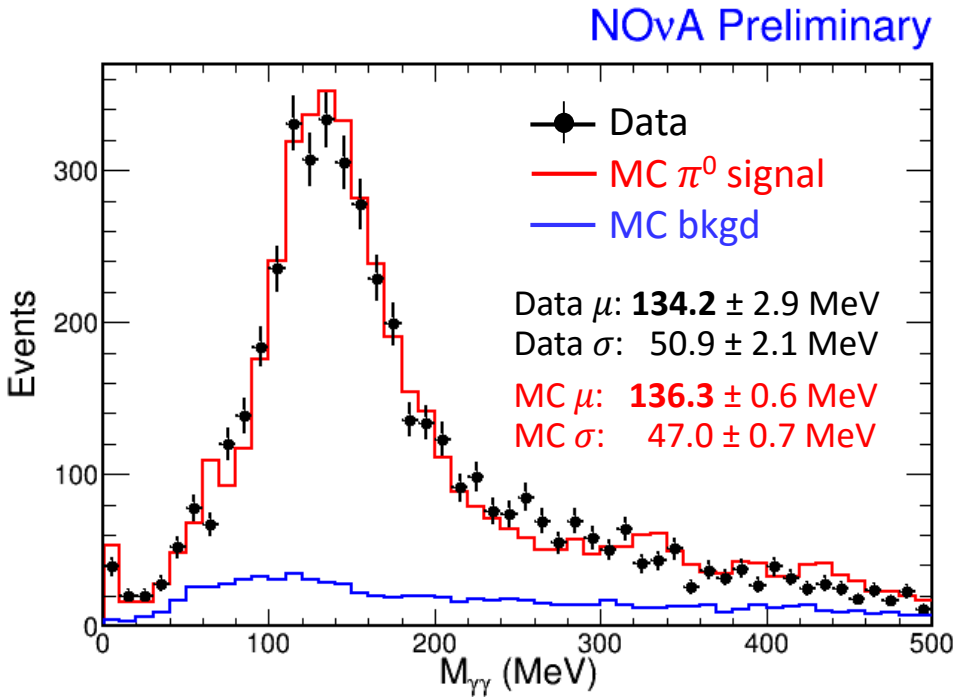
Reconstruction

Excellent reconstruction capabilities

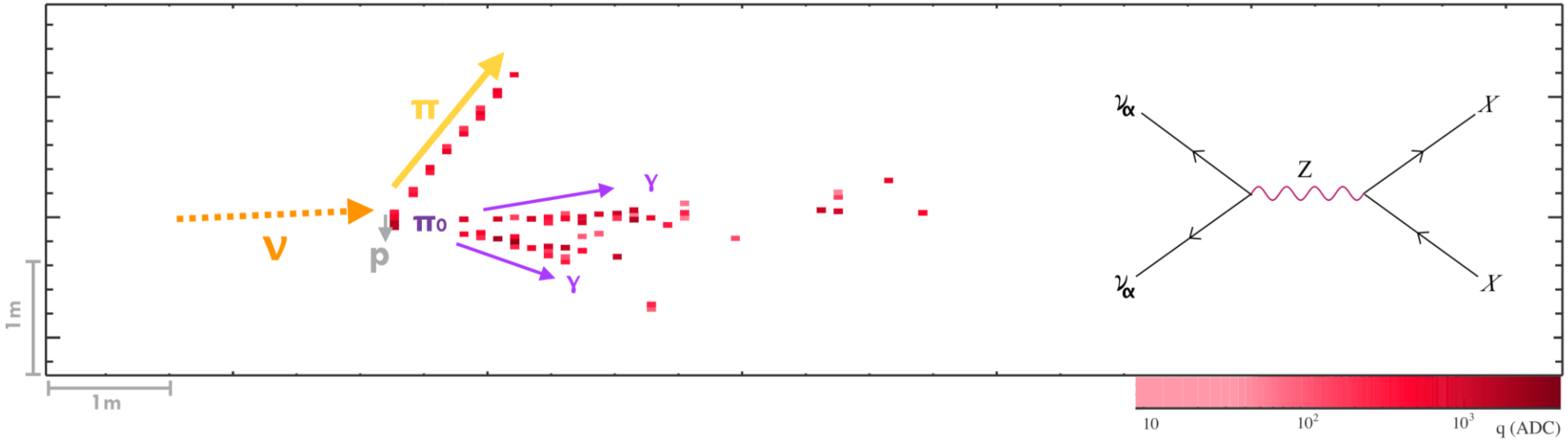
Reconstruct π^0 peak – used as a calibration cross-check

- Demonstrates ability to reconstruct NC events

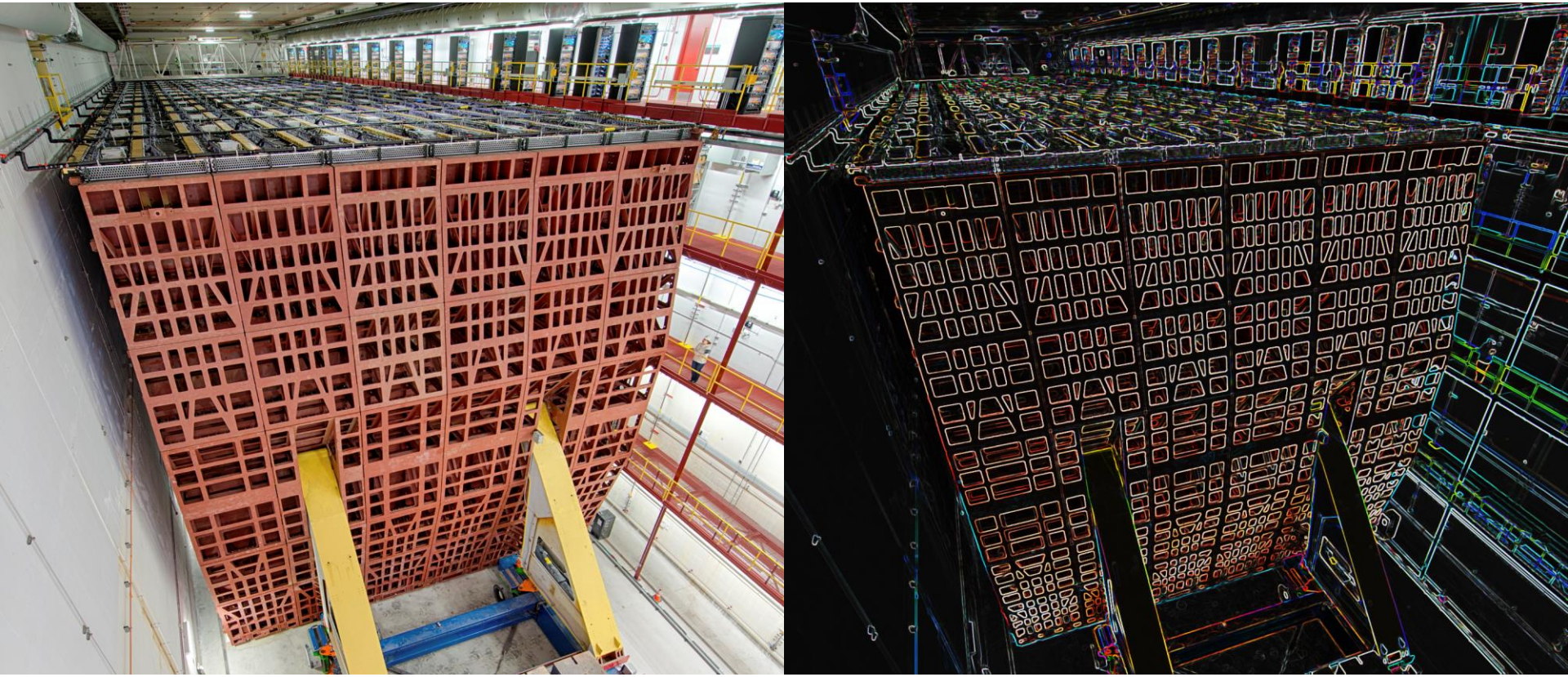




Event identification



Convolution Neural Networks



Take advantage of recent advances in machine learning/computer vision

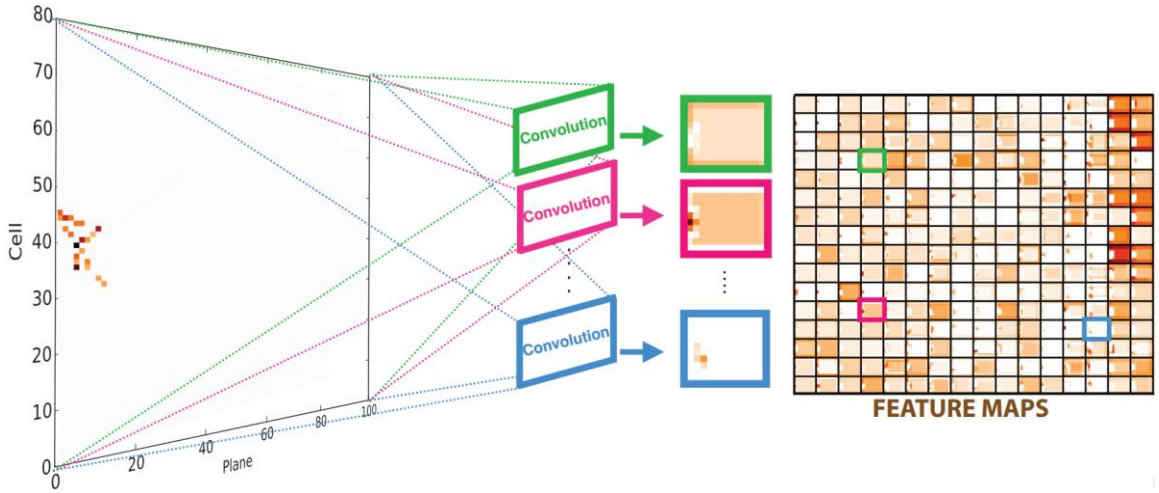
- Classify event-displays!

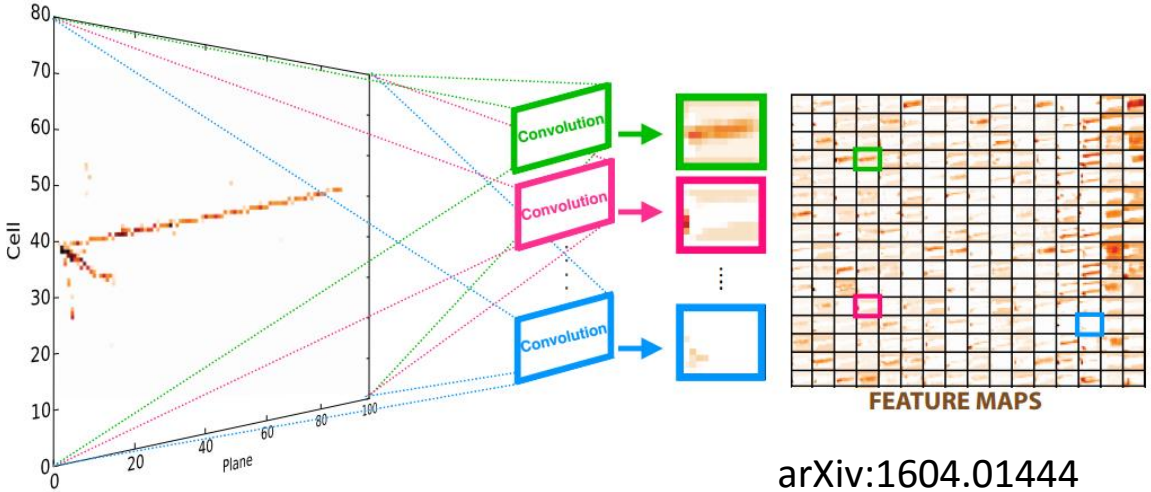
CNN – deep neural network, inputs are the pixels of the image

CVN

This analysis uses same event classifier as the ν_e analysis

- 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
- Trained using FNAL's Wilson Cluster GPUs

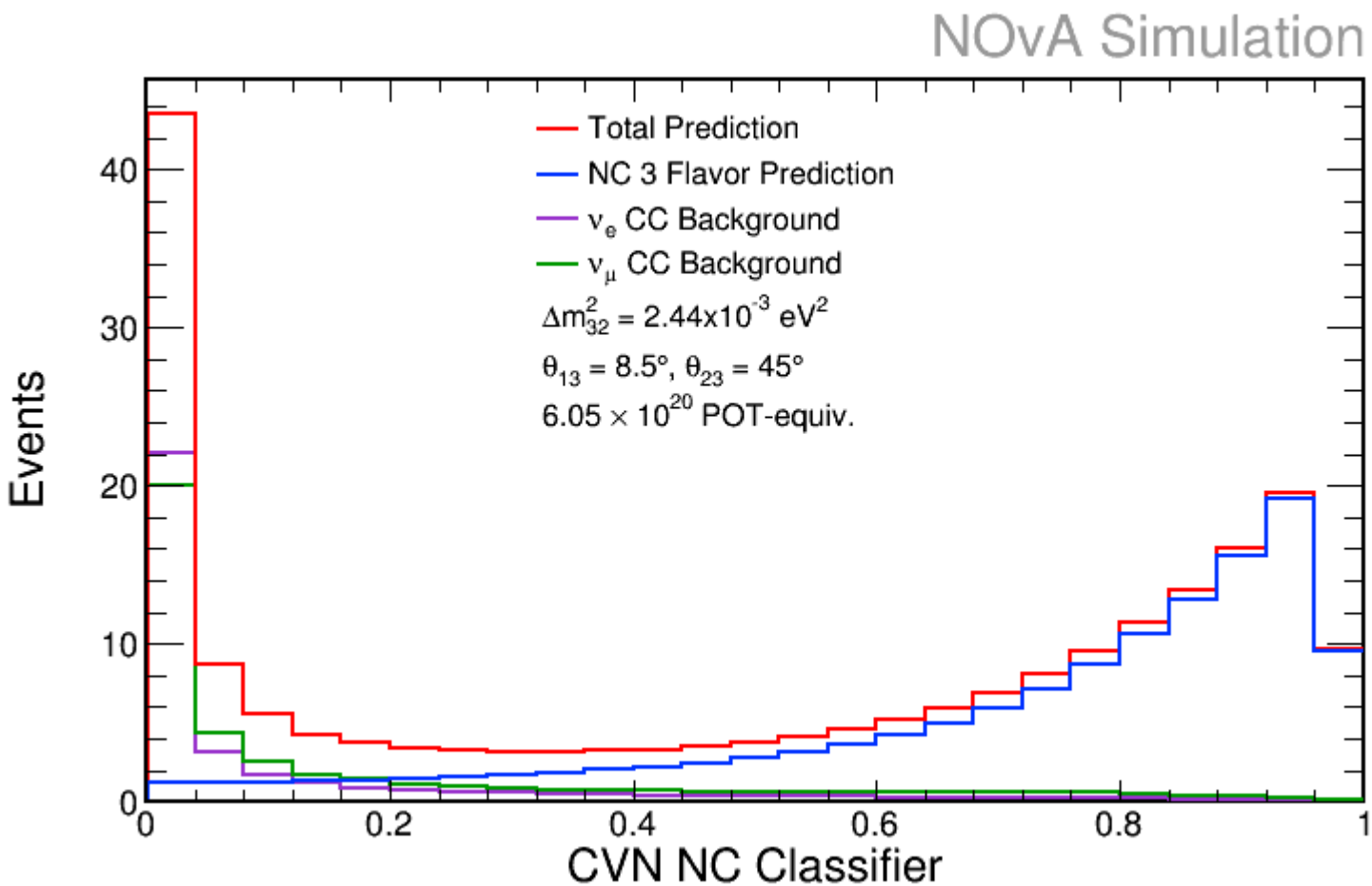




arXiv:1604.01444

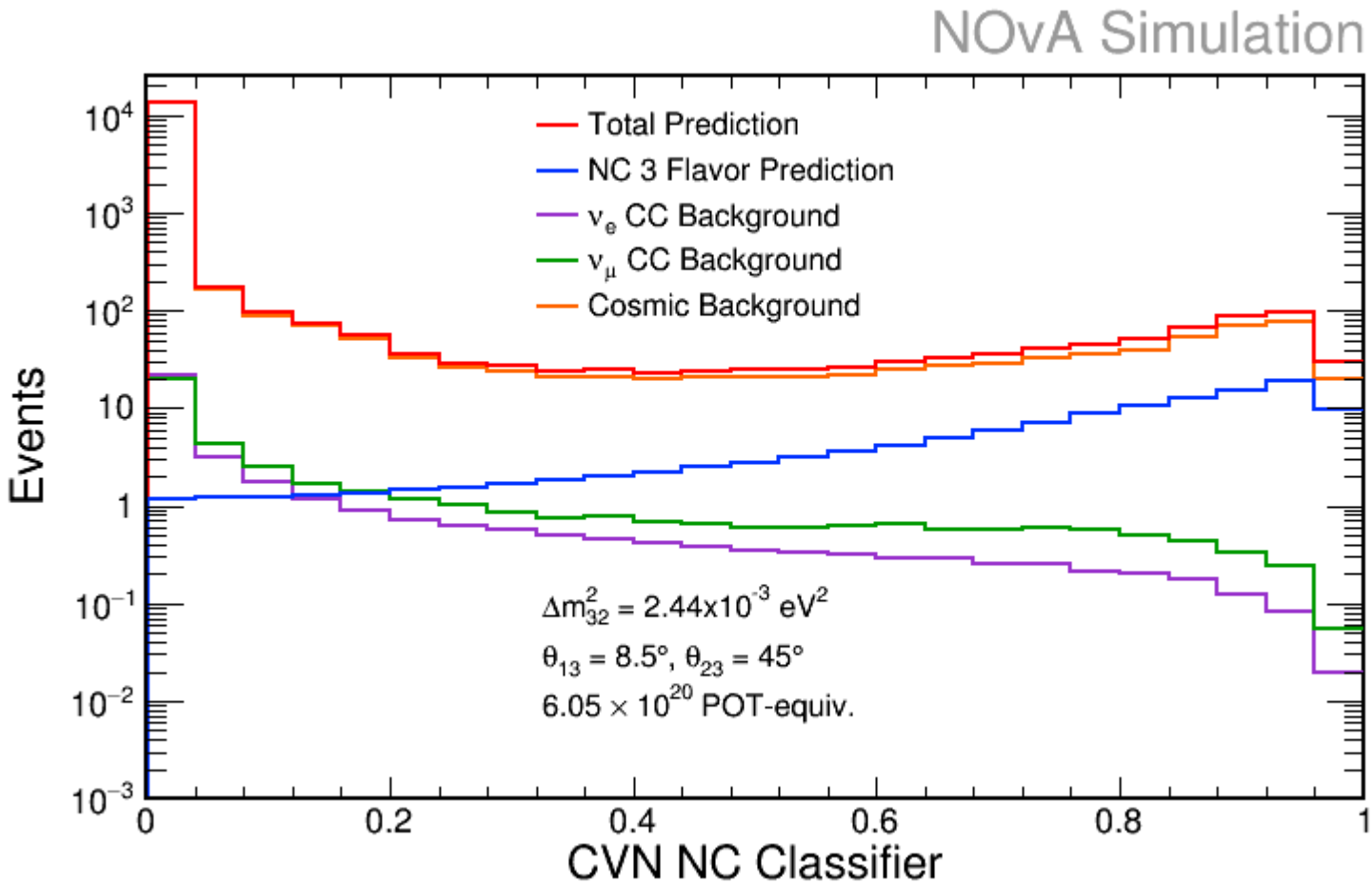
CVN neutral current classifier

- Training includes cosmic ray data sample to aid NC classification
- 94% efficiency, 88% purity when considering beam backgrounds only

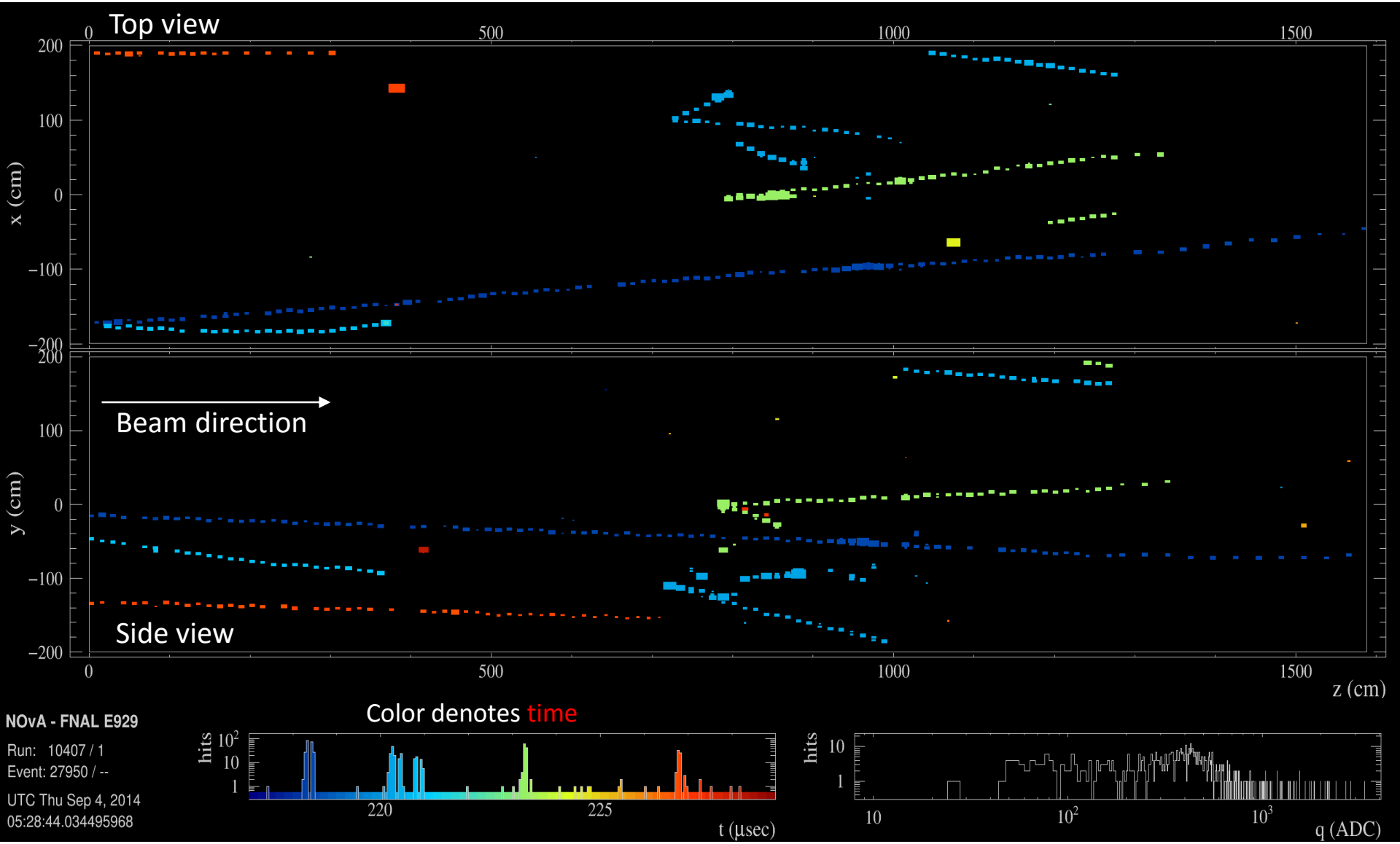


CVN neutral current classifier

- Trained with cosmic ray data sample to aid NC classifier
- Excellent at separating NC events from beam backgrounds
  - Analysis cuts developed to separate NC from cosmic background

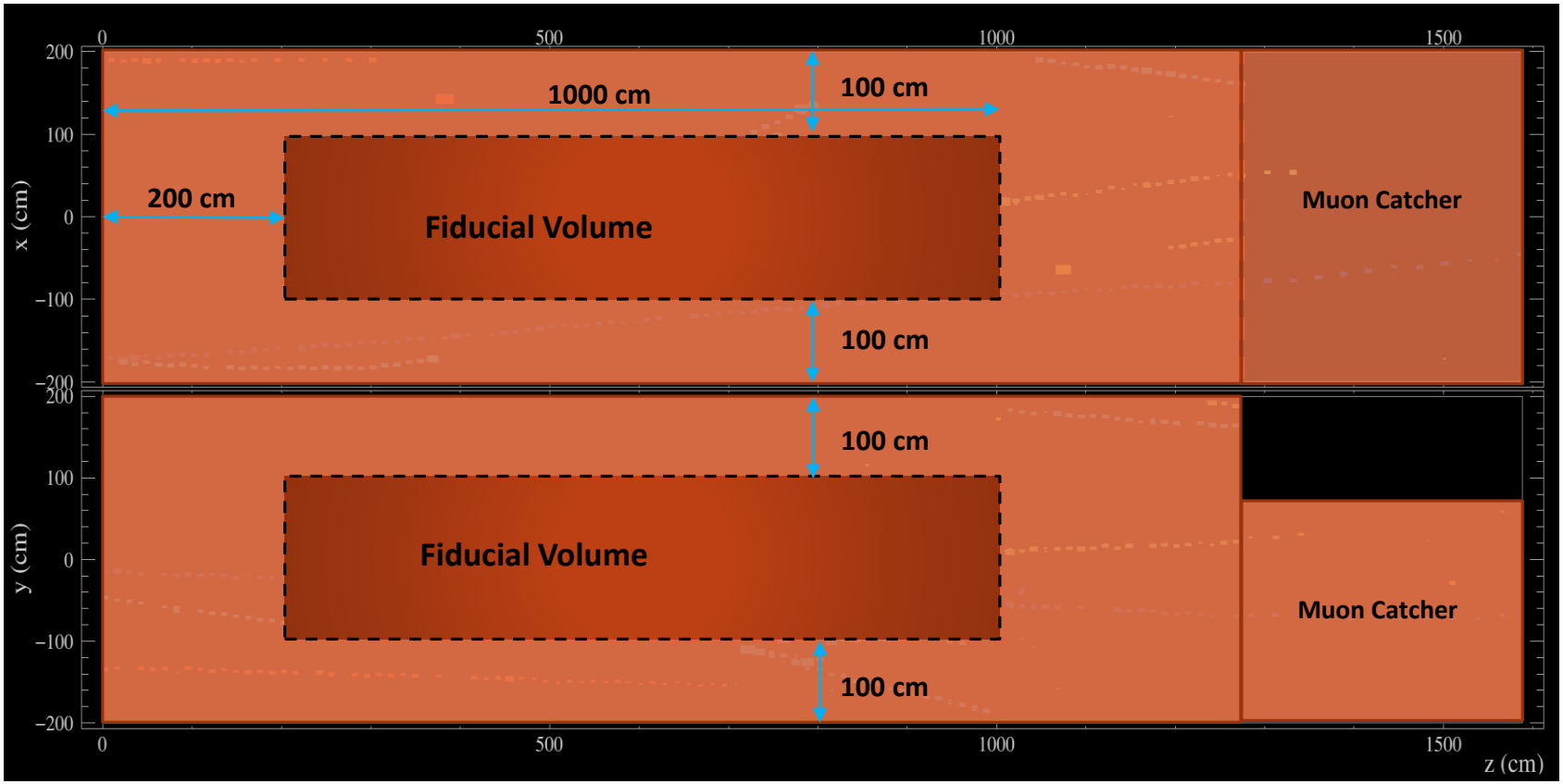


Near detector spills



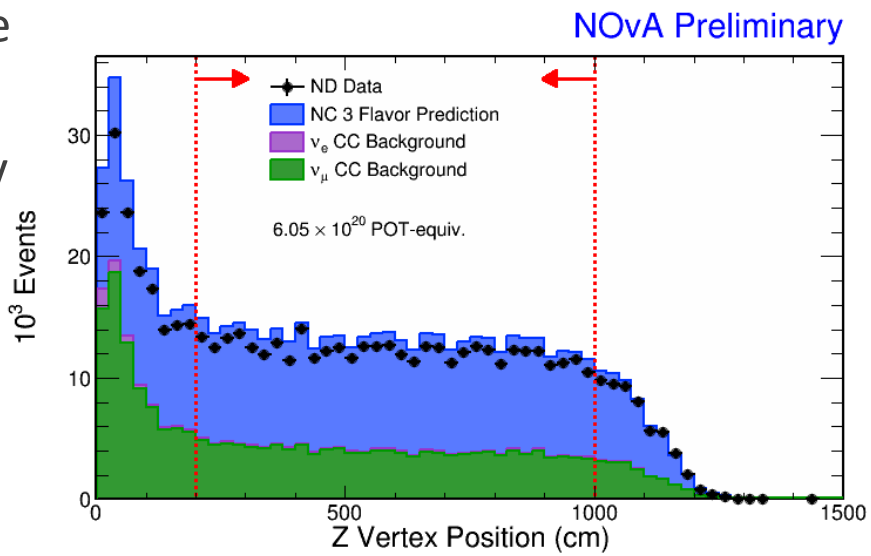
Near detector event preselection

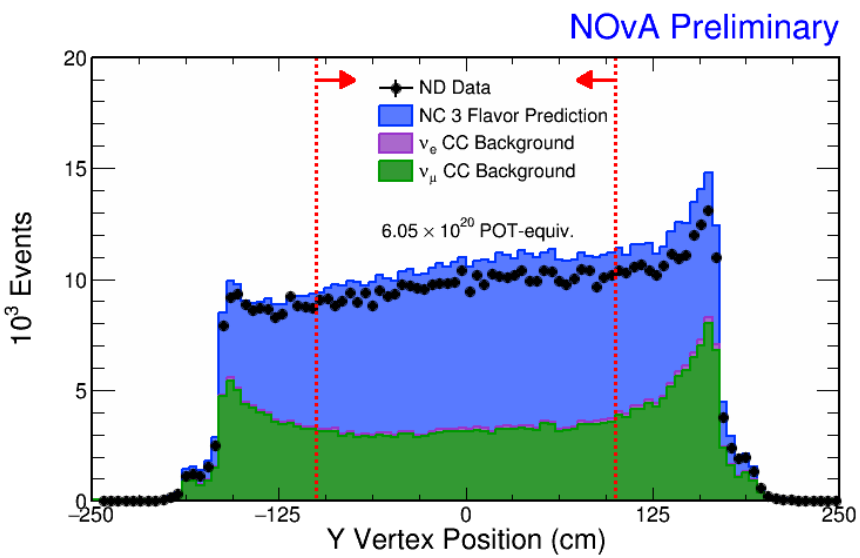
- Beam spill quality, detector and event quality cuts
  - Beam positioning, horn current range, minimum spill POT, maximum time to nearest spill
- Reconstructed event vertex within the fiducial volume
- Reconstructed track start/stop positions > 25 cm from each detector face

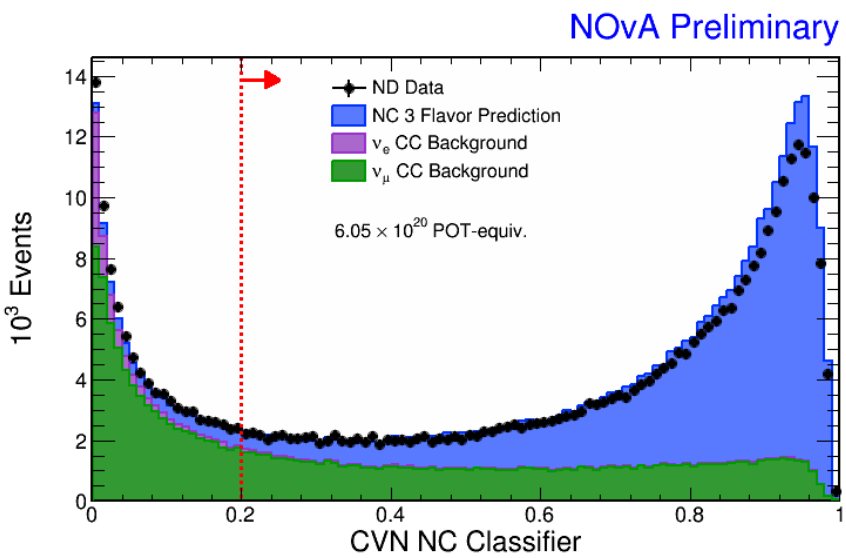


Near detector NC event selection

- 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

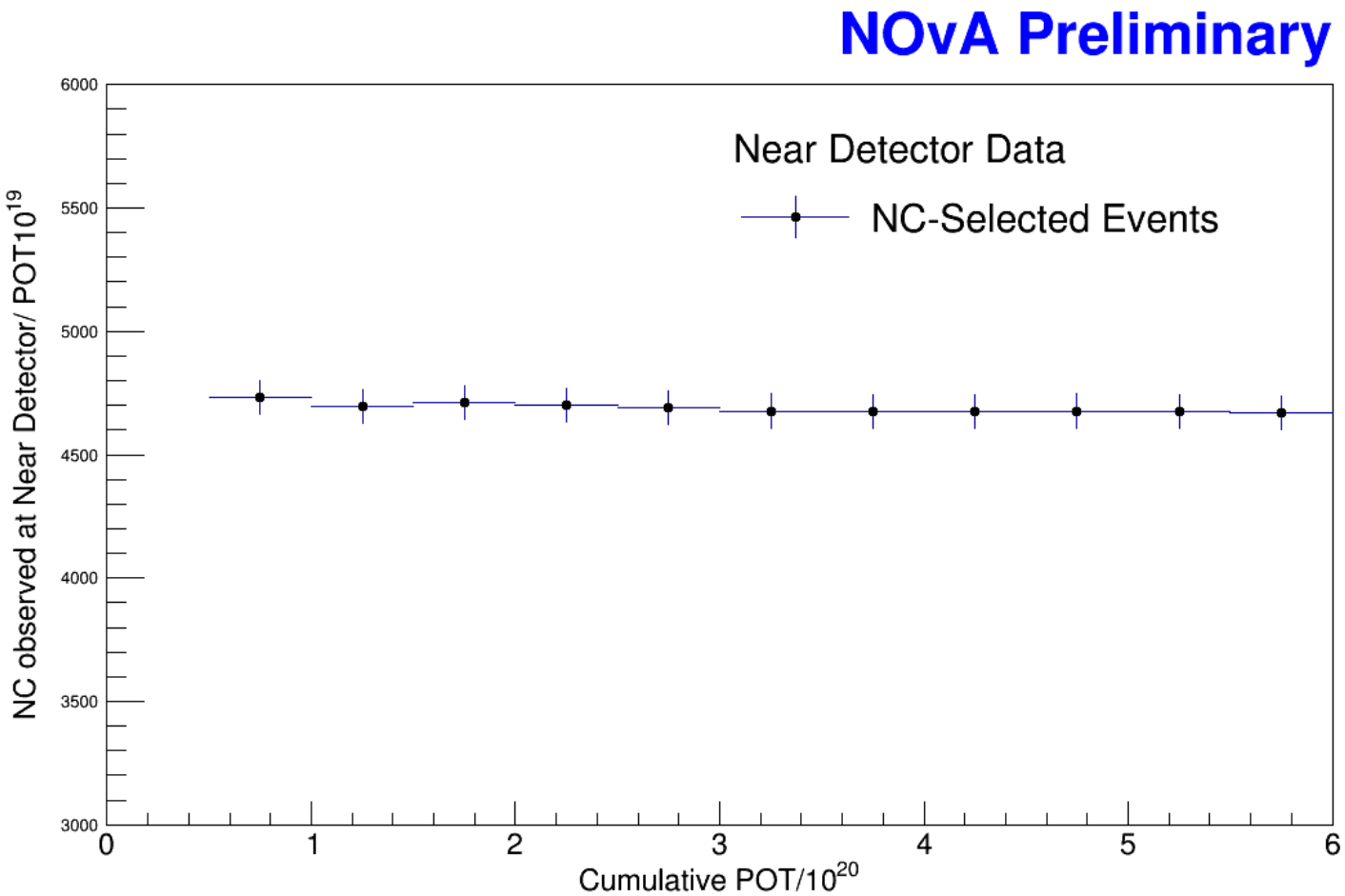






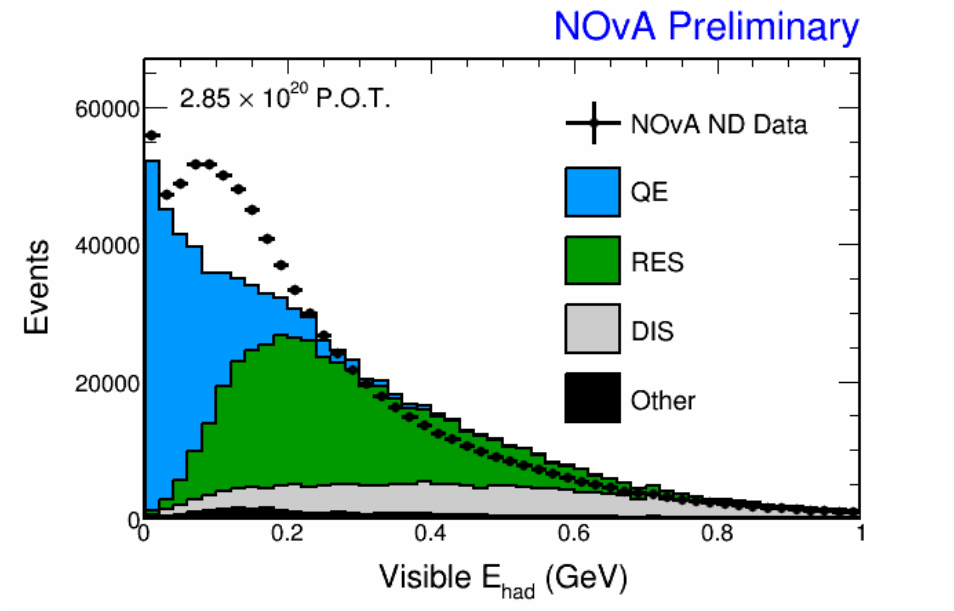
Near detector data stability

- Checked ND data stability of observed NC events across cumulative POT
  - Good agreement between data and MC

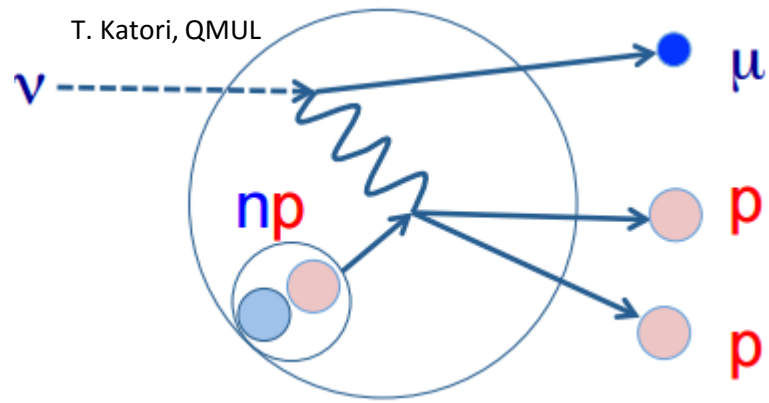


Nuclear correlations

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



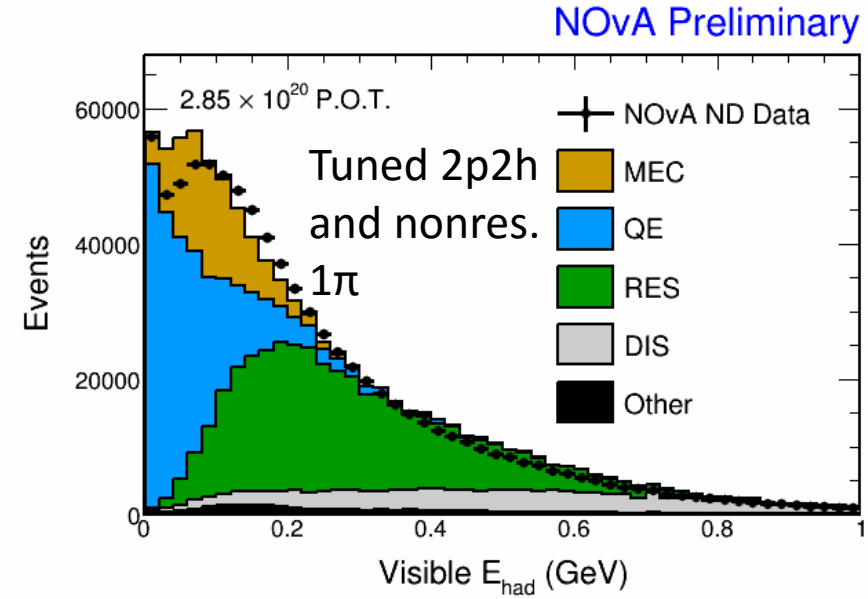
Multi-nucleon 2p2h interaction



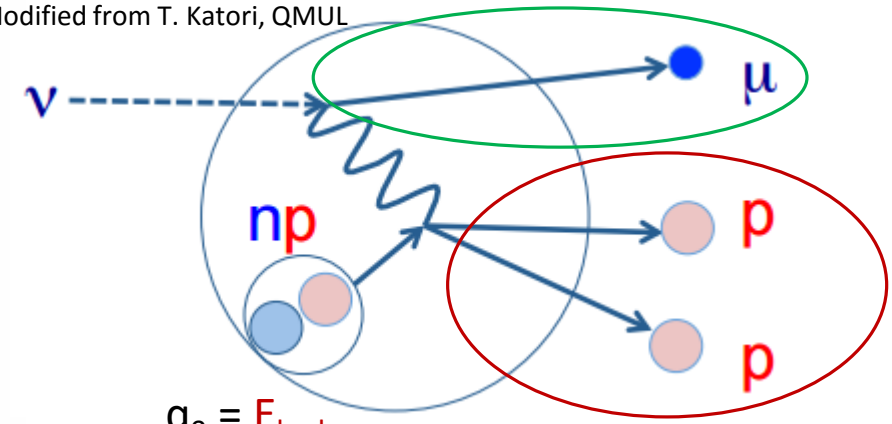
[1]P.A. Rodrigues et al., PRL 116 (2016) 071802 (arXiv:1511.05944)
[2]S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
[3]P.A. Rodrigues et al., arXiv:1601.01888

Nuclear correlations

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



Modified from T. Katori, QMUL



$$q_0 = E_{had}$$

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

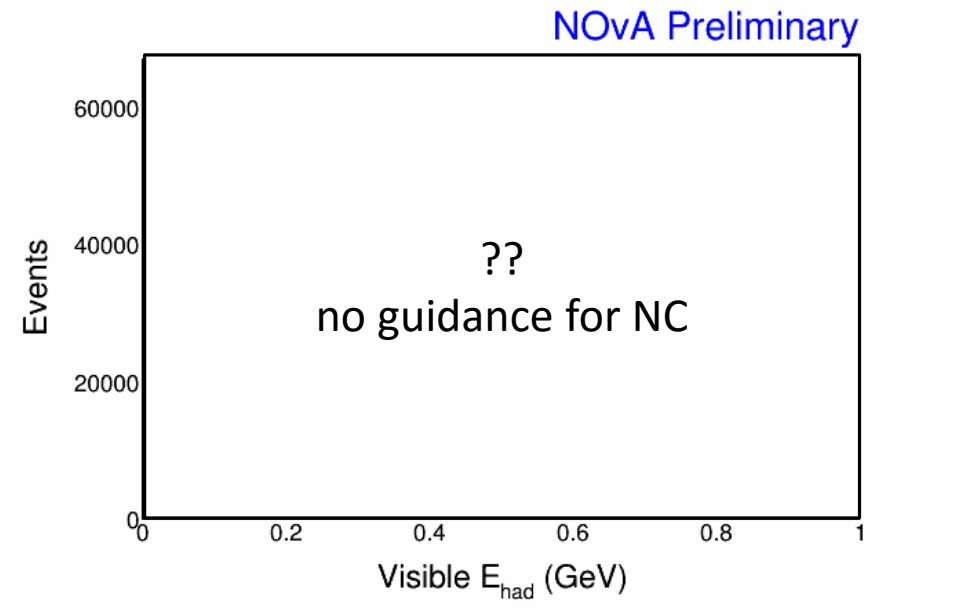
$$Q^2 = 2E_\nu(E_\mu - p_\mu\cos(\theta_\mu) - M^2_\mu)$$

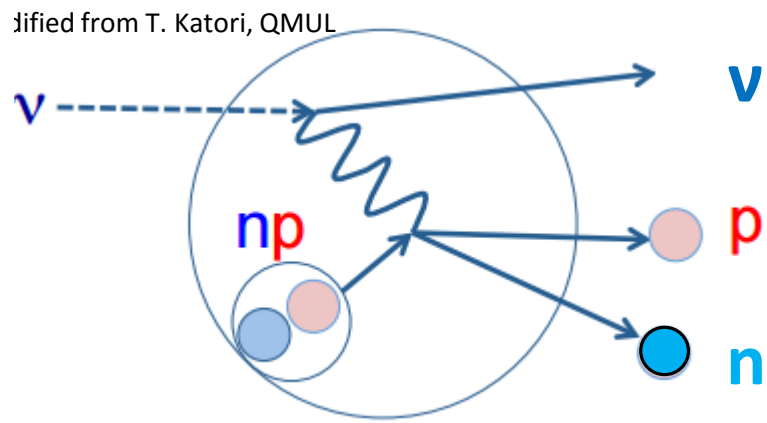
$$|\vec{q}| = Q^2 + q_0$$

- 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

[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

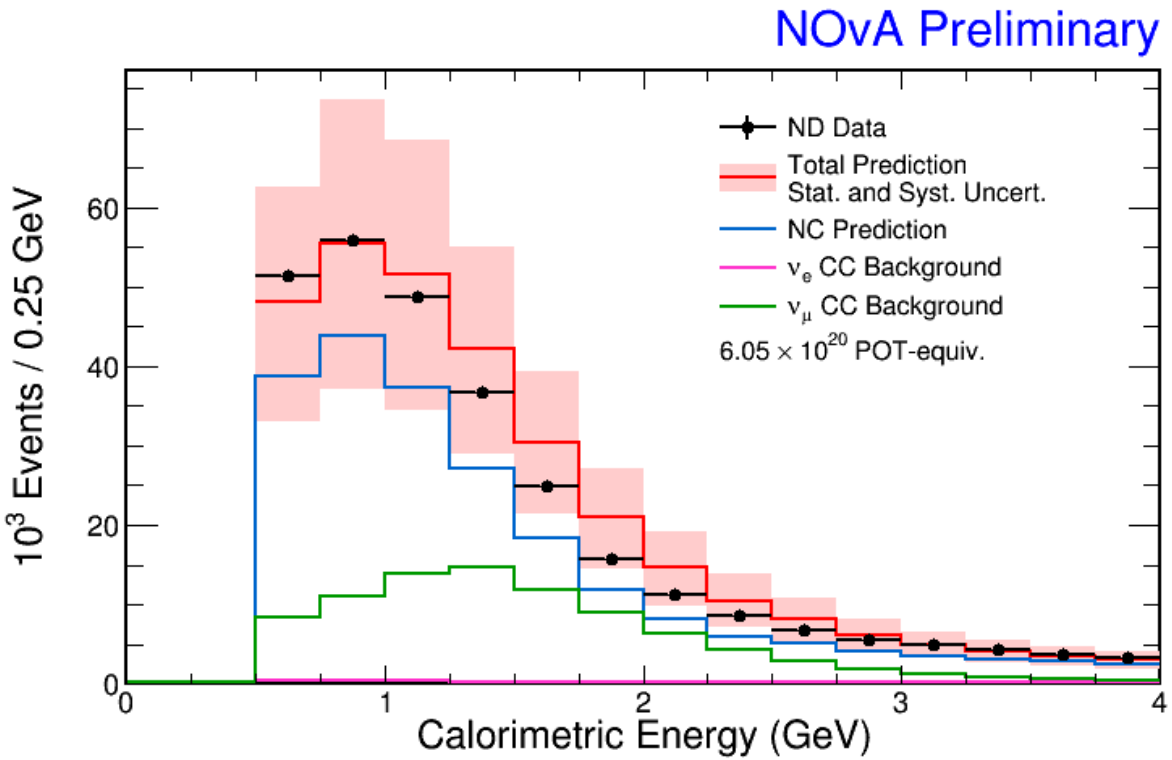
Nuclear correlations





- "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

Near detector NC spectrum



- Normalisation agrees well

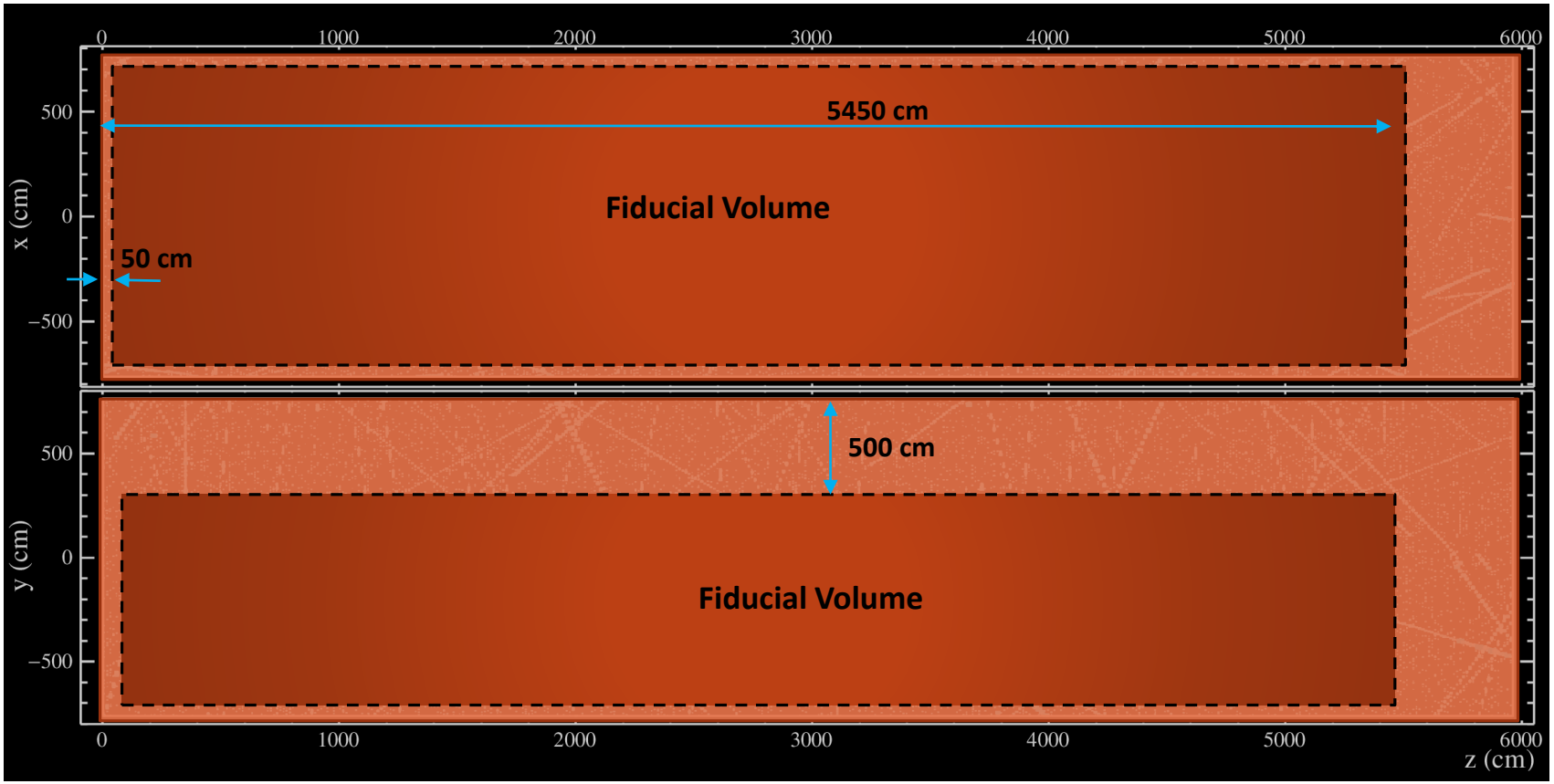
- Large uncertainties on NC cross-section
- No GENIE "Empirical MEC" corrections for NC events

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

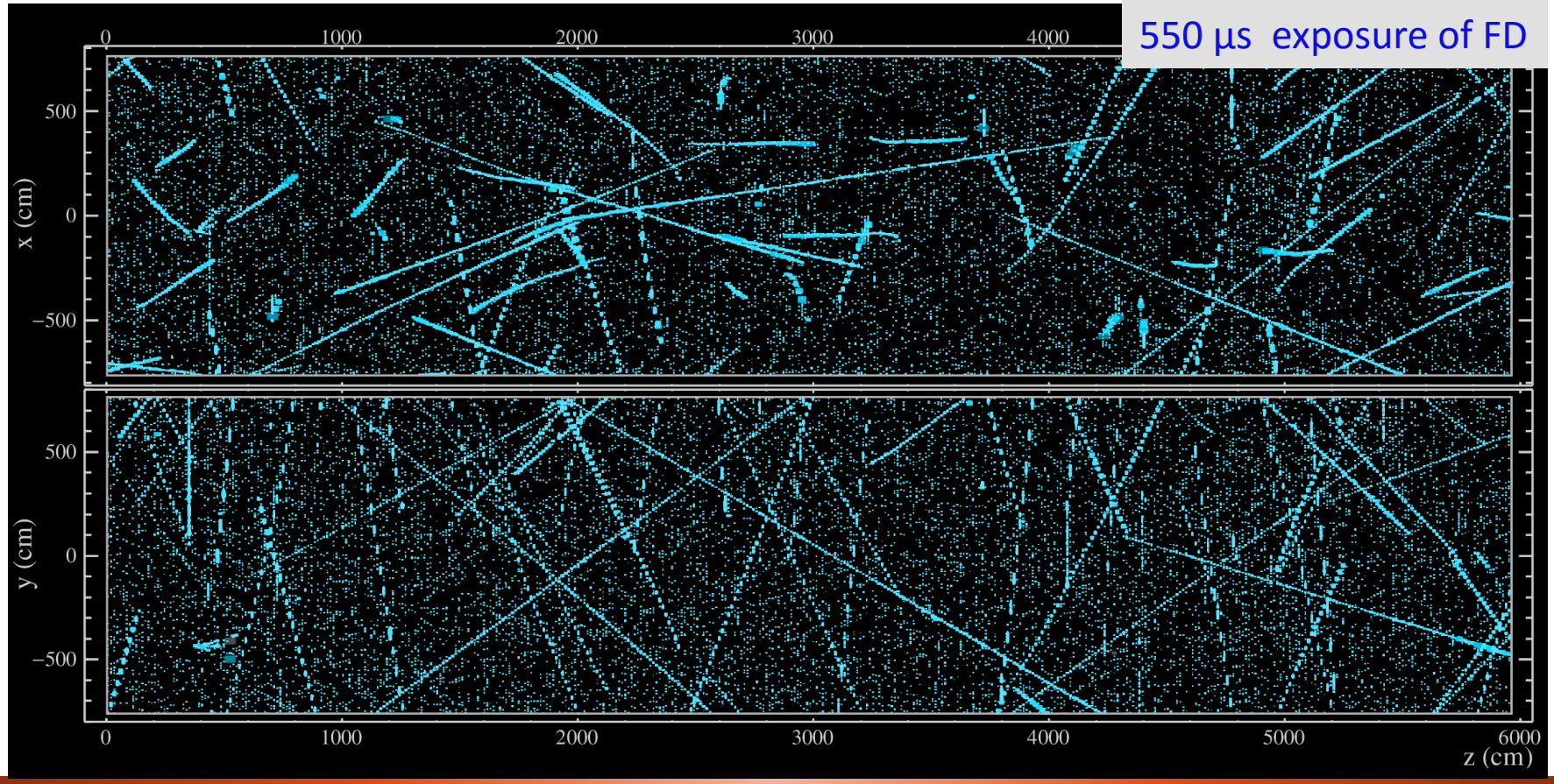
Top

Side

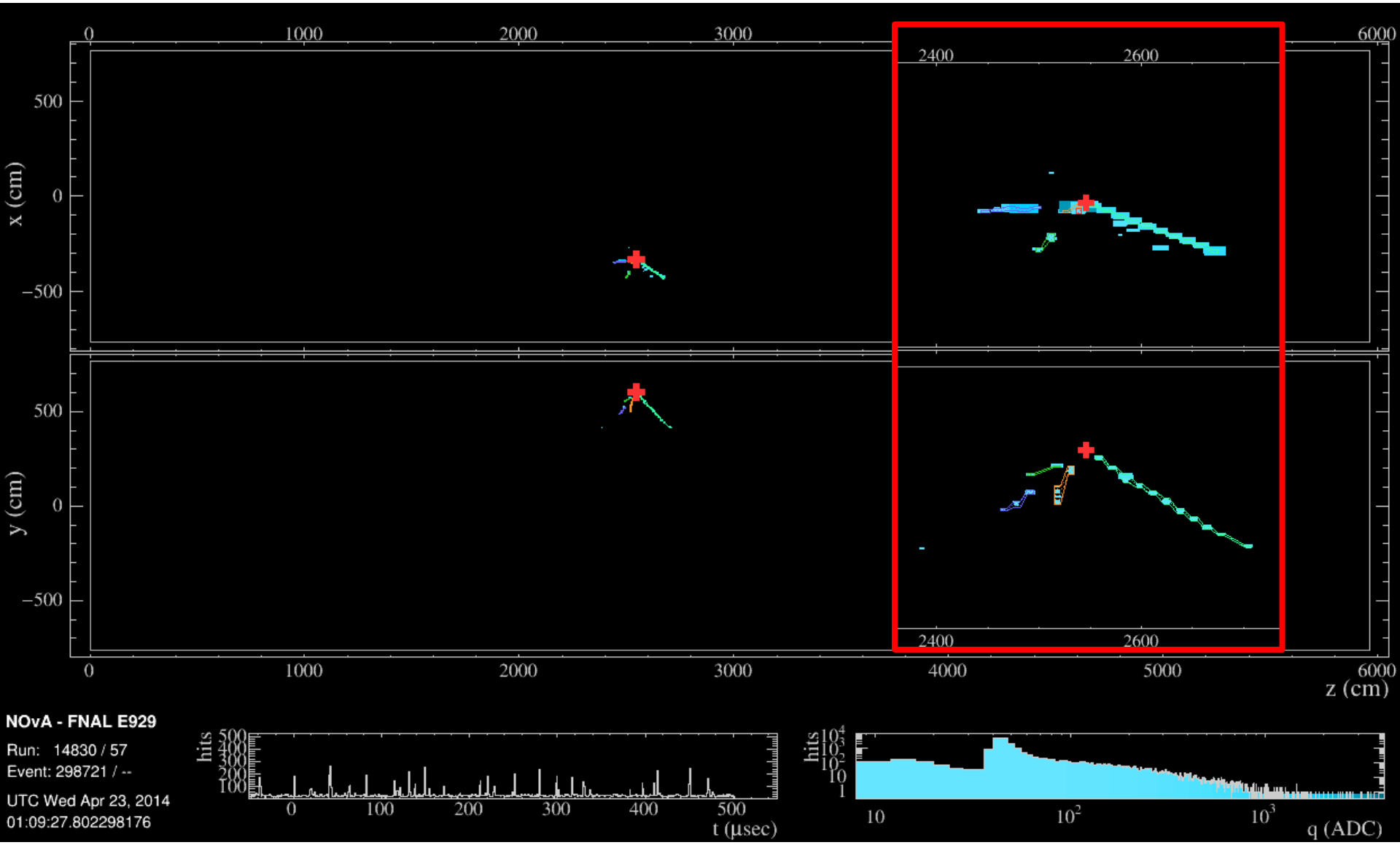


Cosmic ray rejection

- 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

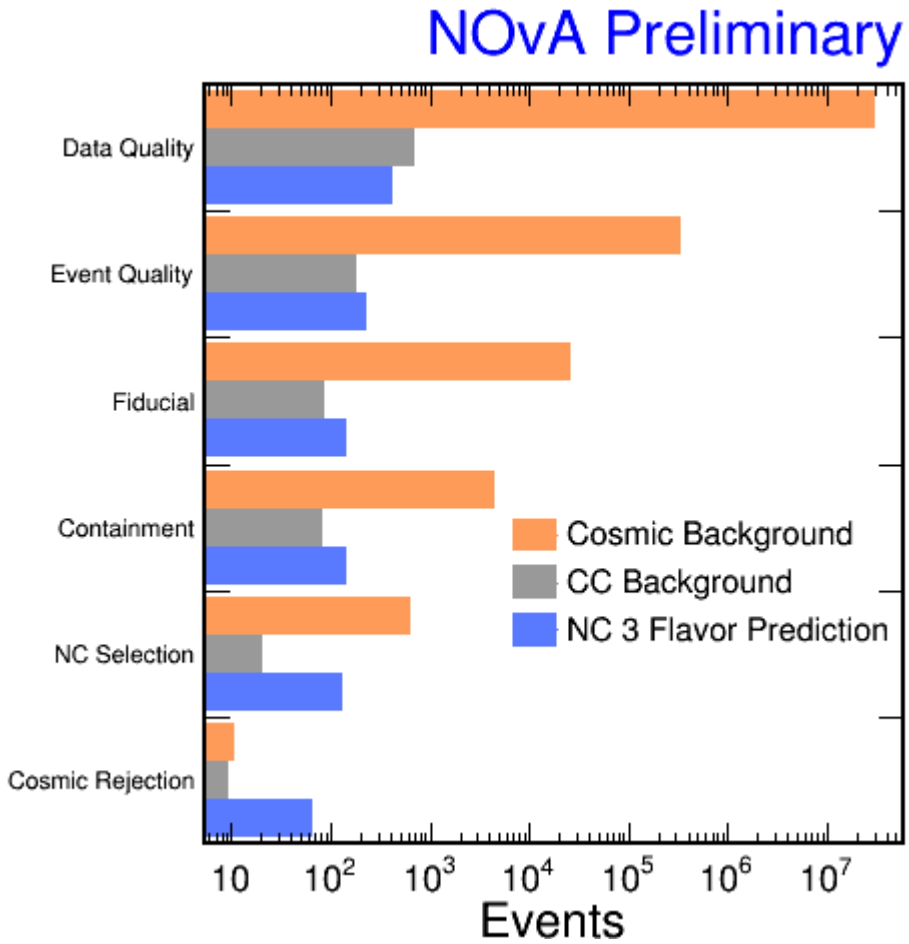


Cosmic ray rejection



Cosmic ray rejection

- 10 µs spill window at ~ 1 Hz gives 10^5 rejection
- Remaining factor from event topology 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



Extrapolation

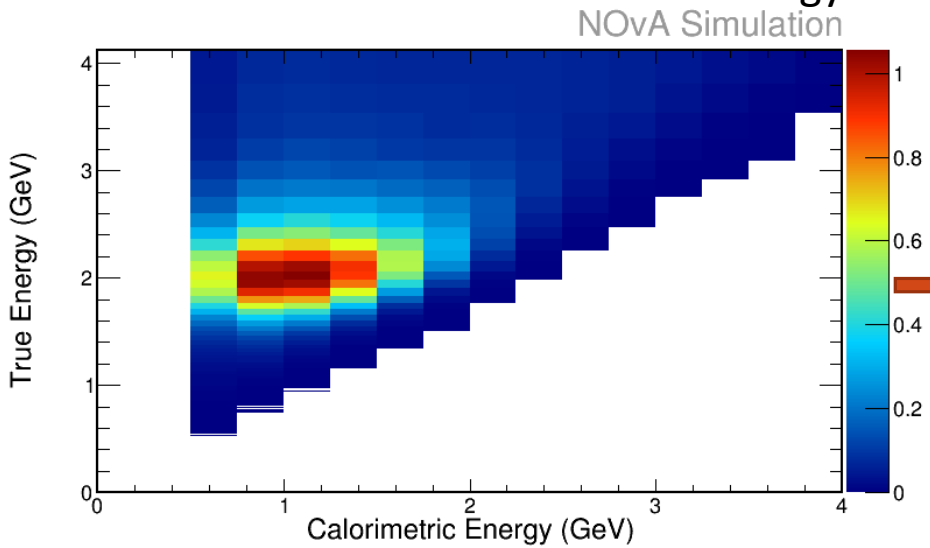
- We use the measured ND energy spectrum to predict the unoscillated FD spectrum

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

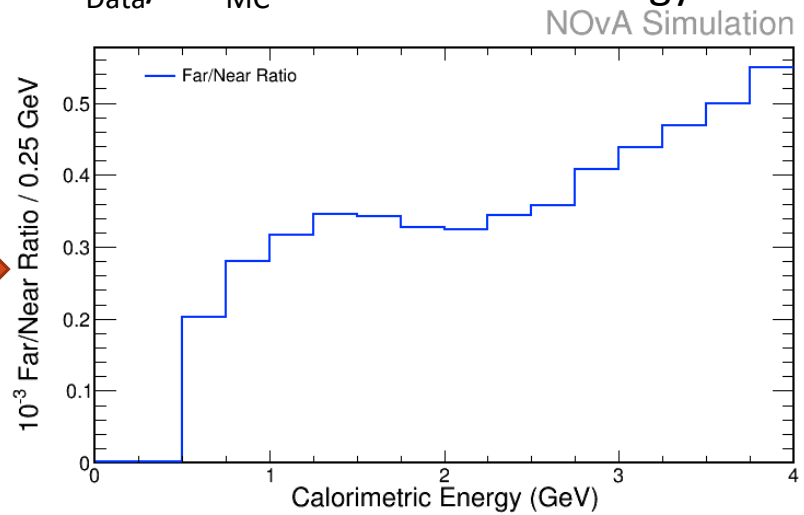
FD MC extrapolated prediction (3-flavour):

83.71 ± 9.15 (stat.) ± 8.28 (syst.)

FD Migration matrix
Maps the FD reconstructed energy spectrum to an estimate for true neutrino energy



FD/ND ratio equivalent to reweighting migration matrix with ND_{Data}/ND_{MC} reconstructed energy



Apply oscillation weights and unfold migration matrix back to reconstructed Energy

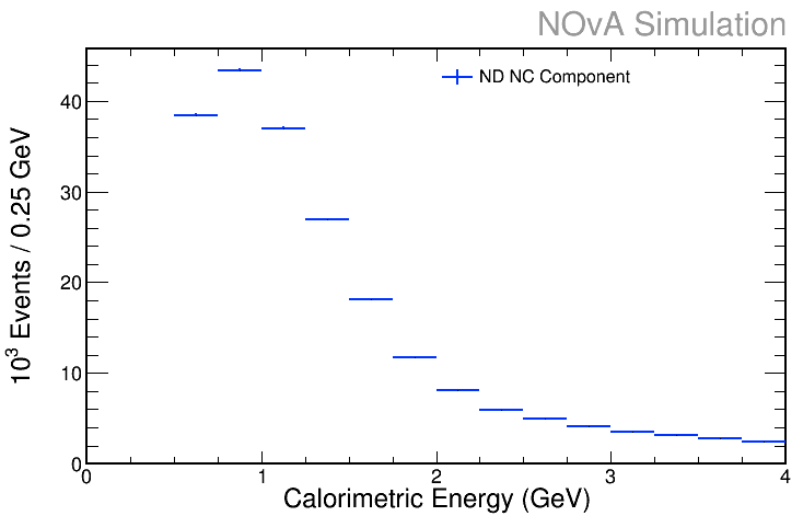
Extrapolation

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

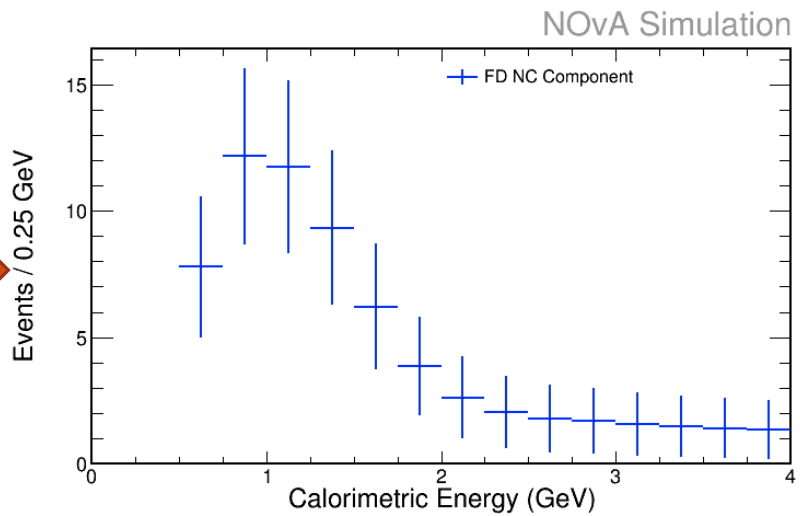
$$FD^{Predicted} = \frac{FD^{MC}}{ND^{MC}} ND^{Data}$$

FD MC extrapolated prediction (3-flavour):
83.71 ± 9.15 (stat.) ± 8.28 (syst.)

Original ND NC component
All flavours decomposed proportionally



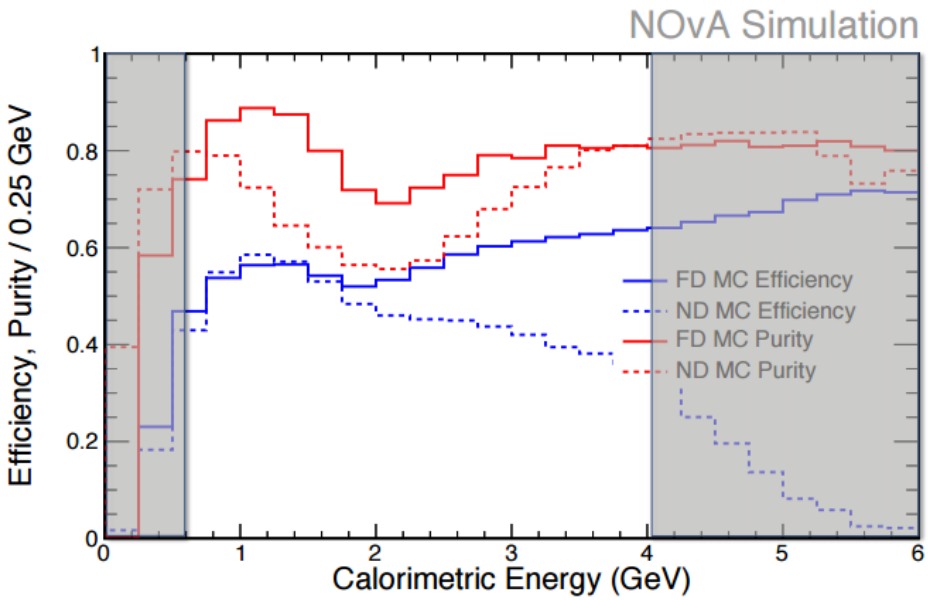
Final FD reconstructed energy spectrum



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

Systematic uncertainties

Systematic	NC (%)	bkgd. (%)
Hadron production	3.4	3.6
Scintillator saturation	2.4	1.8
Calibration	5.8	6.0
GENIE	1.6	4.8
ND containment	1.0	0.6
ND rock contamination	4.1	1.7
NC mis-modeling	7.0	10.4
MC statistics	2.0	4.8
Normalisation	4.9	4.9
Total	**12.2**	**15.3**

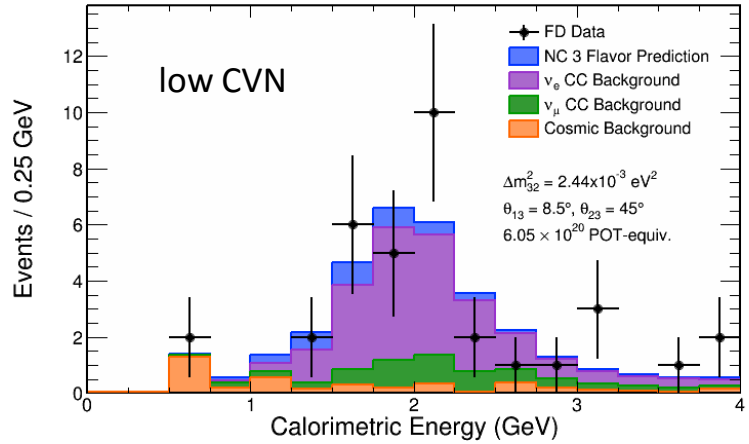
- Propagate effect of each through extrapolation
- Include as pull terms in neutrino oscillation parameter fits

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

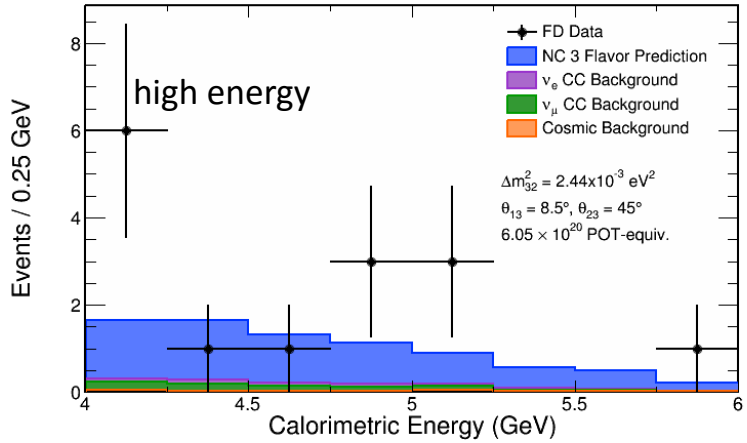
Observed	Predicted
34	**33.0** ± 5.8 (stat.)± 4.1 (syst.)

NOvA Preliminary



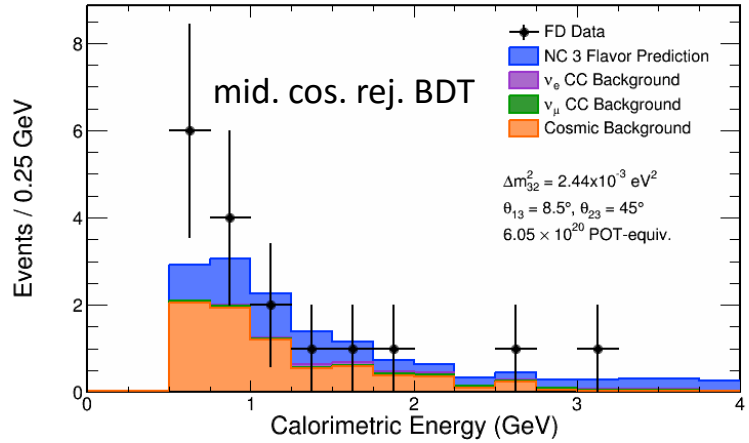
Observed	Predicted
15	**8.1** ± 3.8 (stat.)± 4.4 (syst.)

NOvA Preliminary

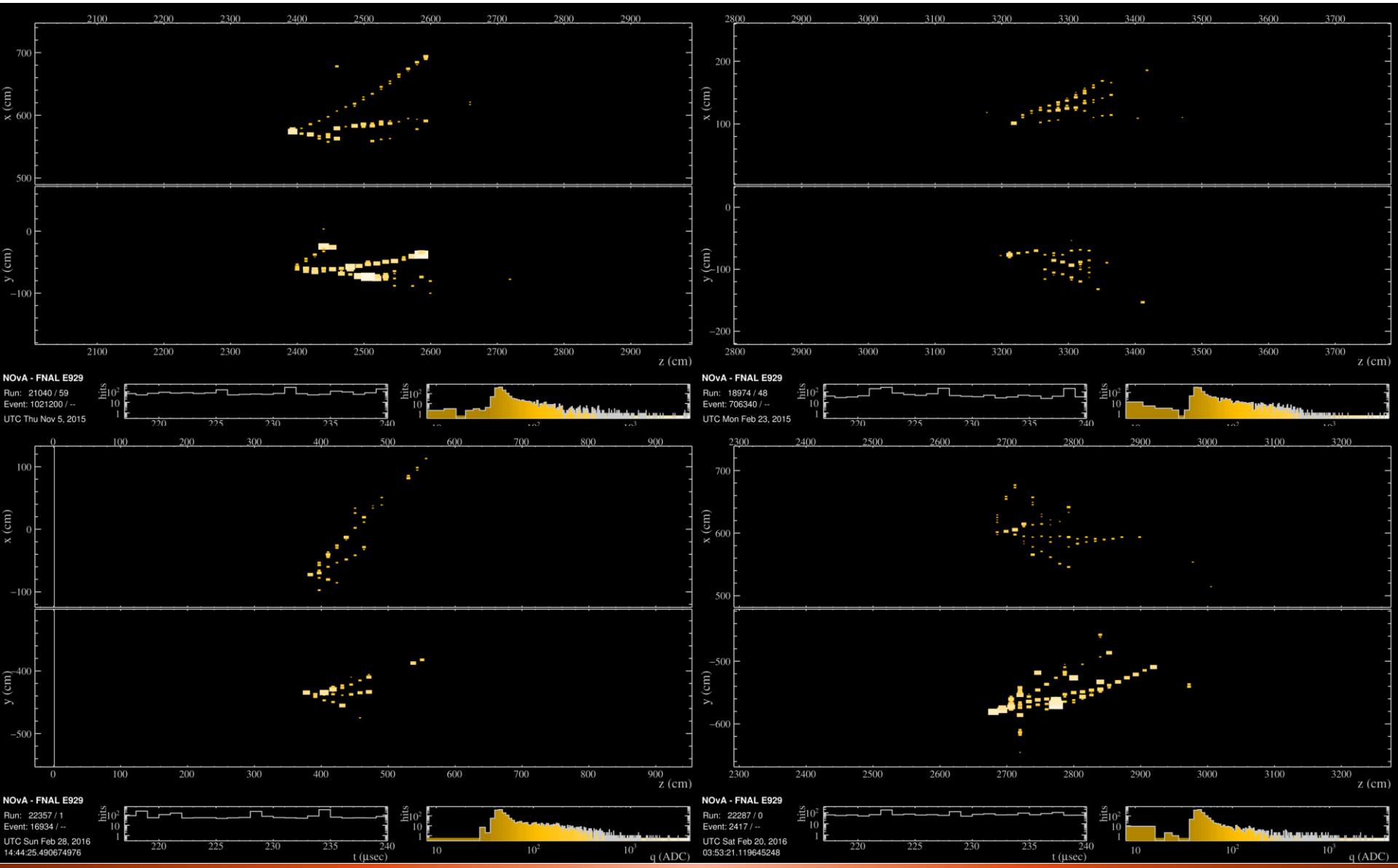


Observed	Predicted
17	**14.3** ± 4.1 (stat.)± 1.8 (syst.)

NOvA Preliminary



NC selected events in FD



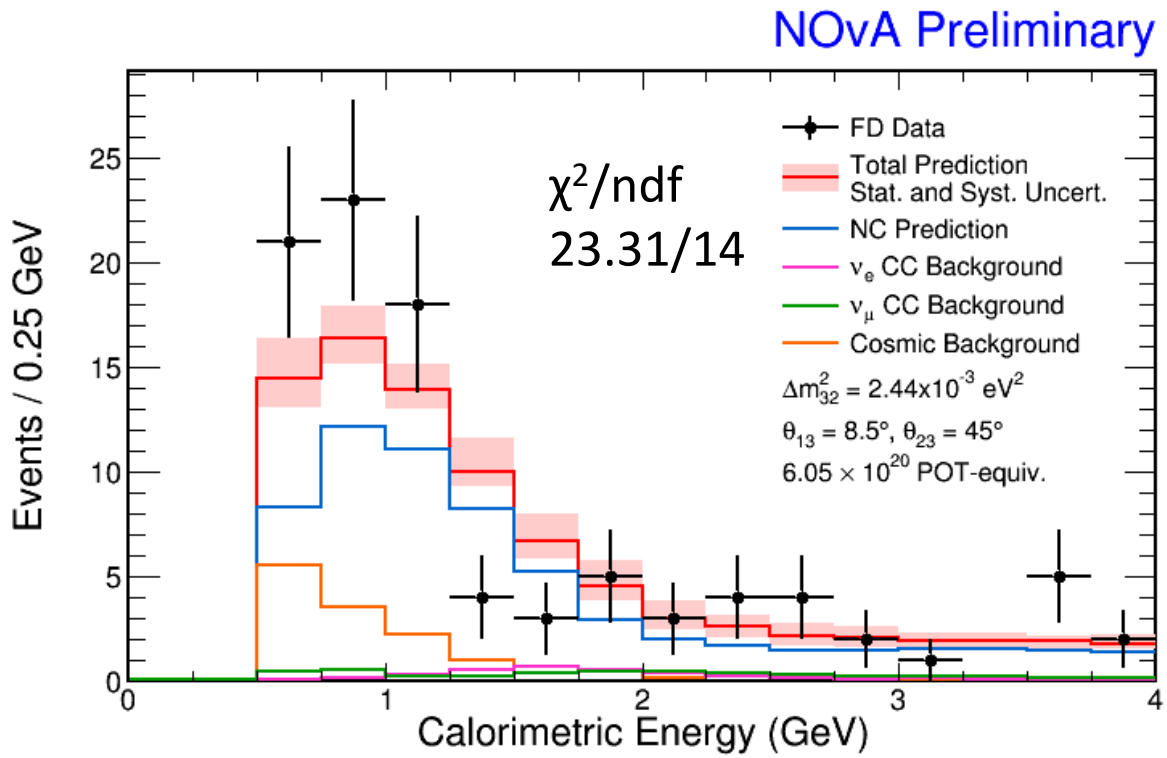
NC disappearance results

Observe 95 NC-like event in Far Detector

MC extrapolated prediction: 83.71 ± 9.15 (stat.) ± 8.28 (syst.)

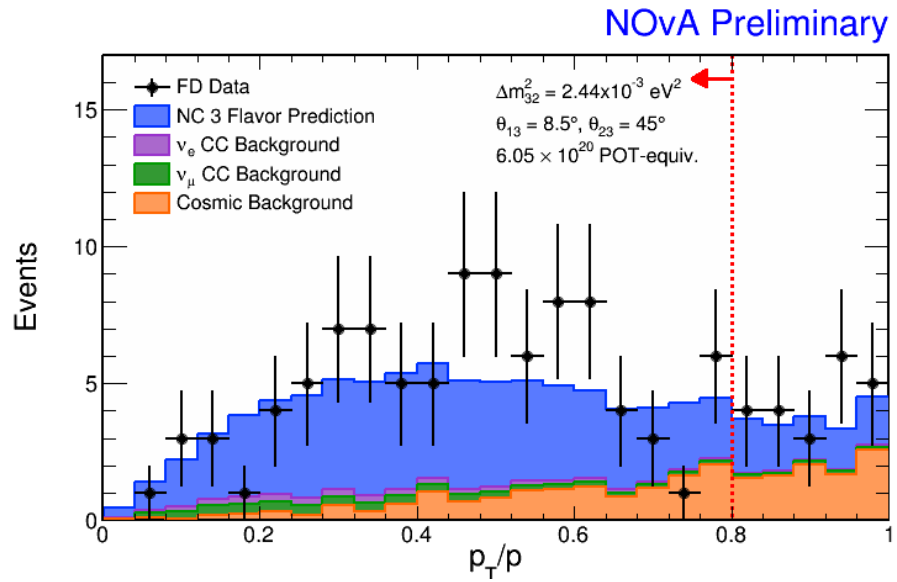
within 1σ of three-flavour prediction

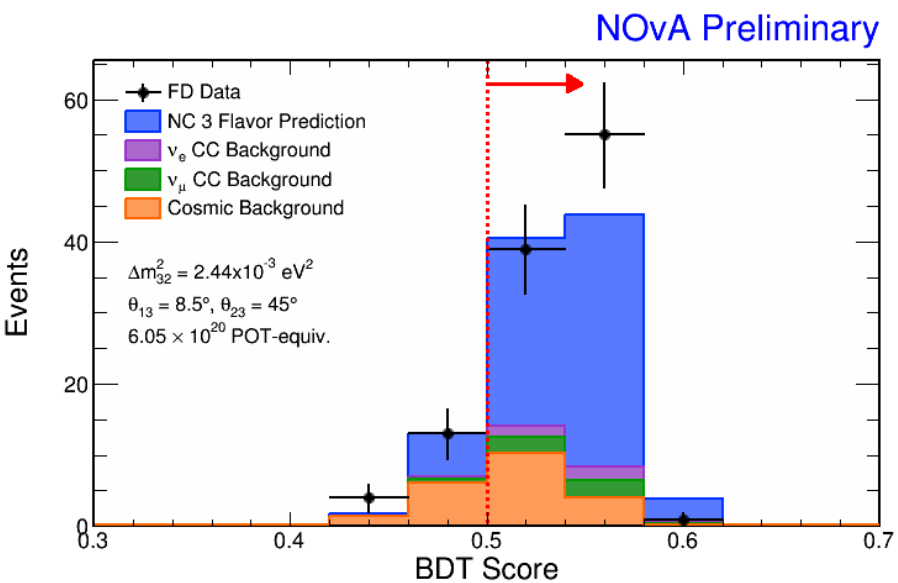
NOvA sees no evidence for sterile neutrino mixing

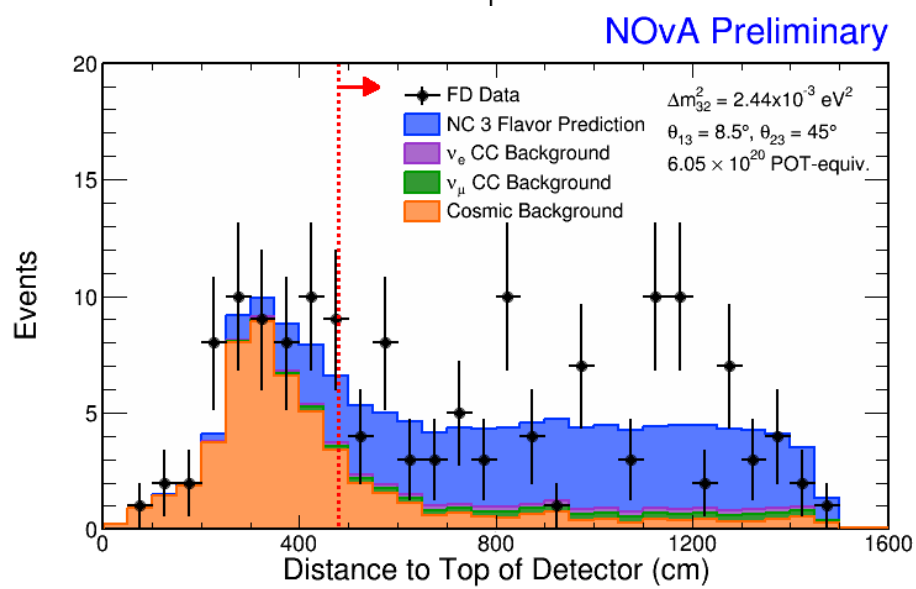


Far detector NC selection

Good data/MC agreement among the cosmic rejection variables

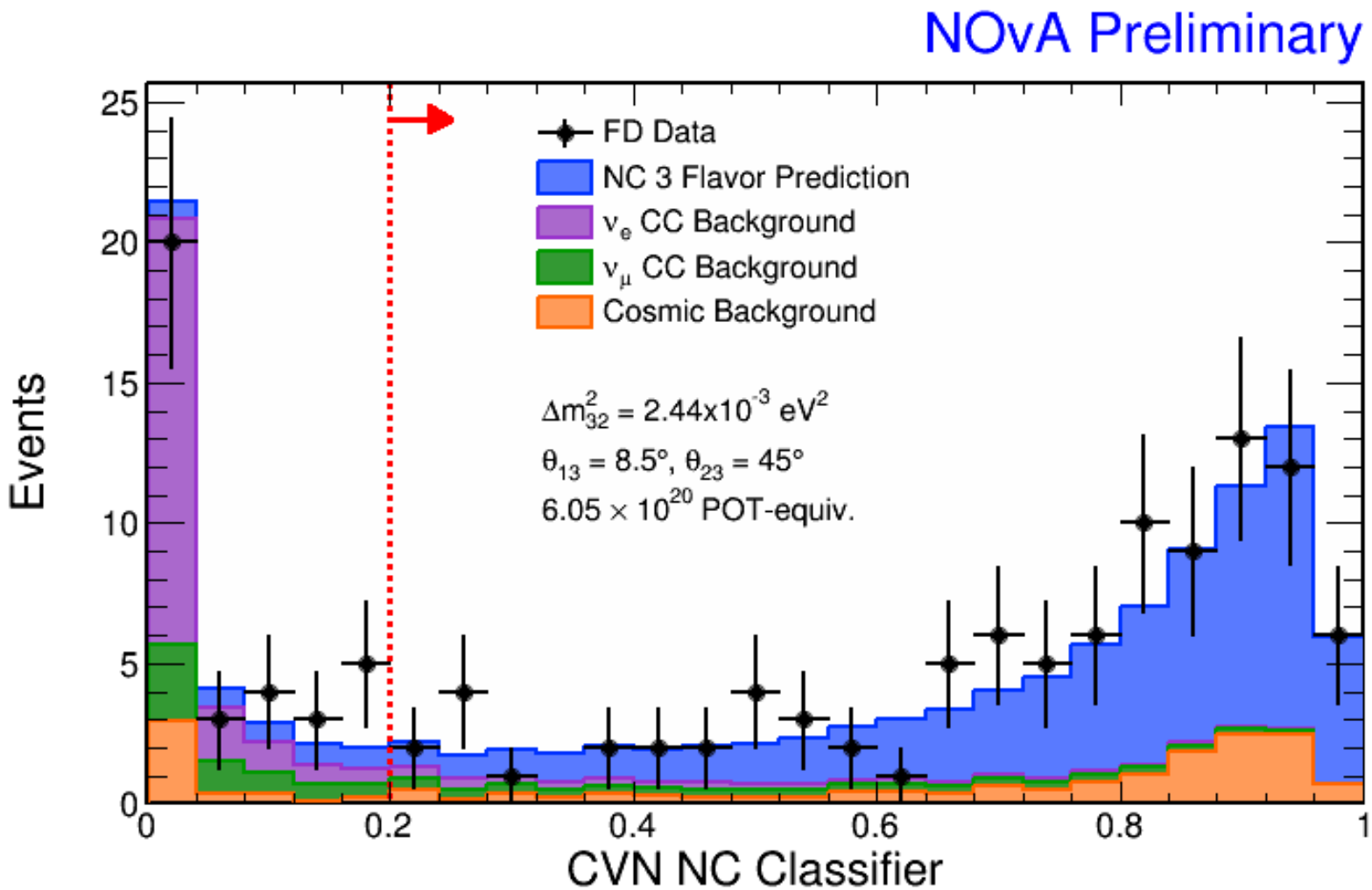




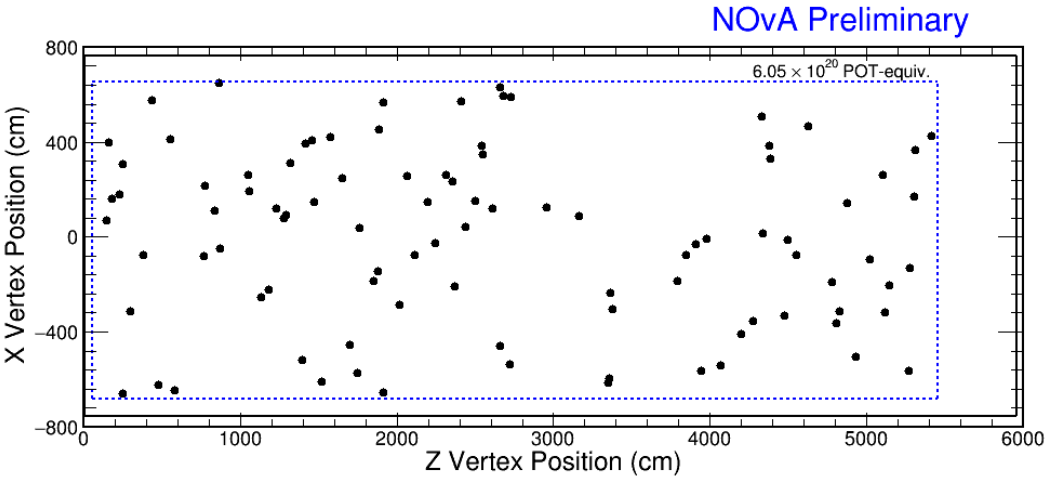


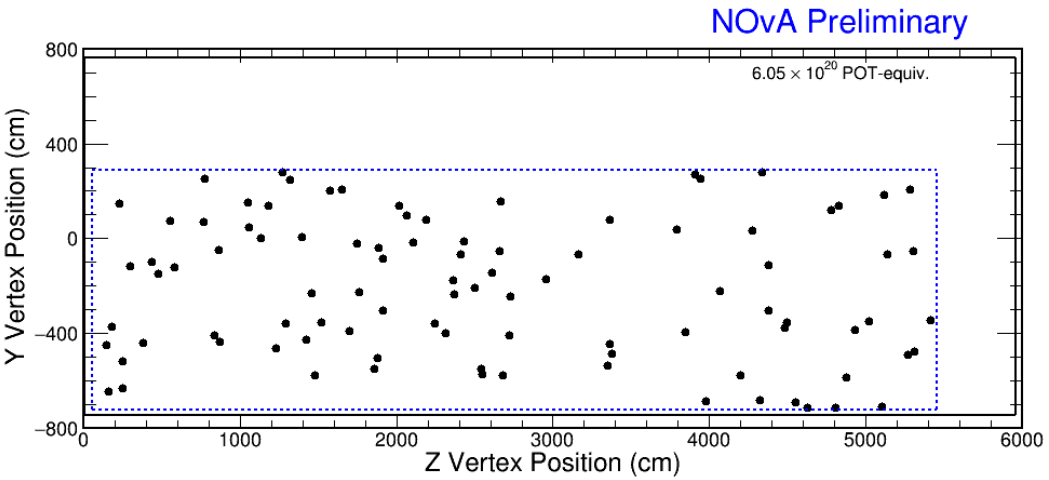
Far detector NC selection

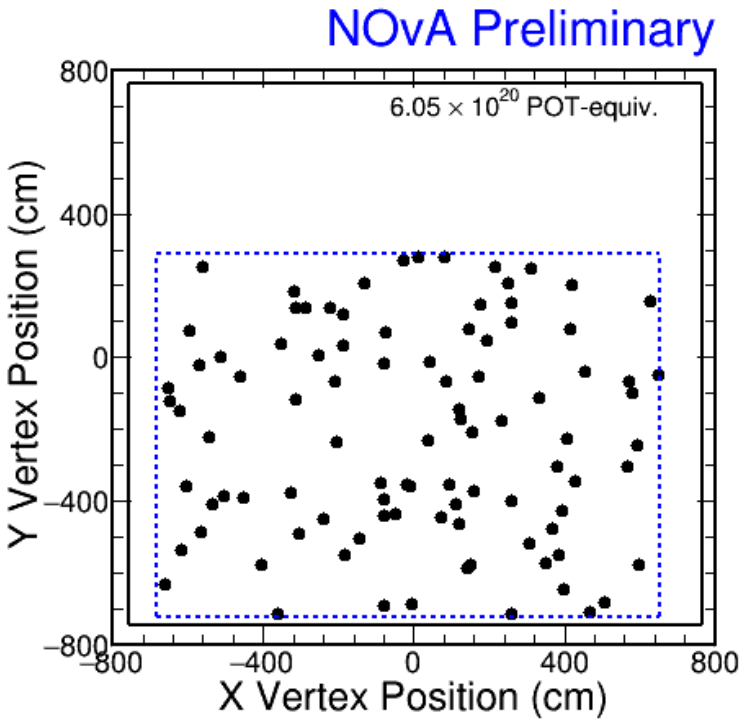
FD NC selection uses the same variables as the ND selection, with identical cut values



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

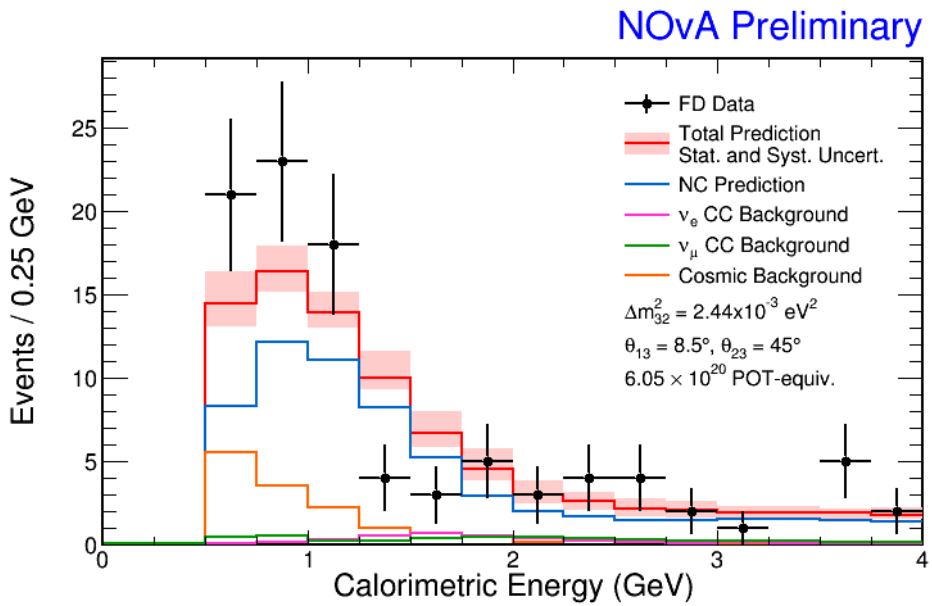
FD Data NC-like: **95**

MC prediction: **83.71 ± 9.15 (stat.) ± 8.28 (syst.)**

For 0.5 GeV < Calorimetric energy < 4.0 GeV

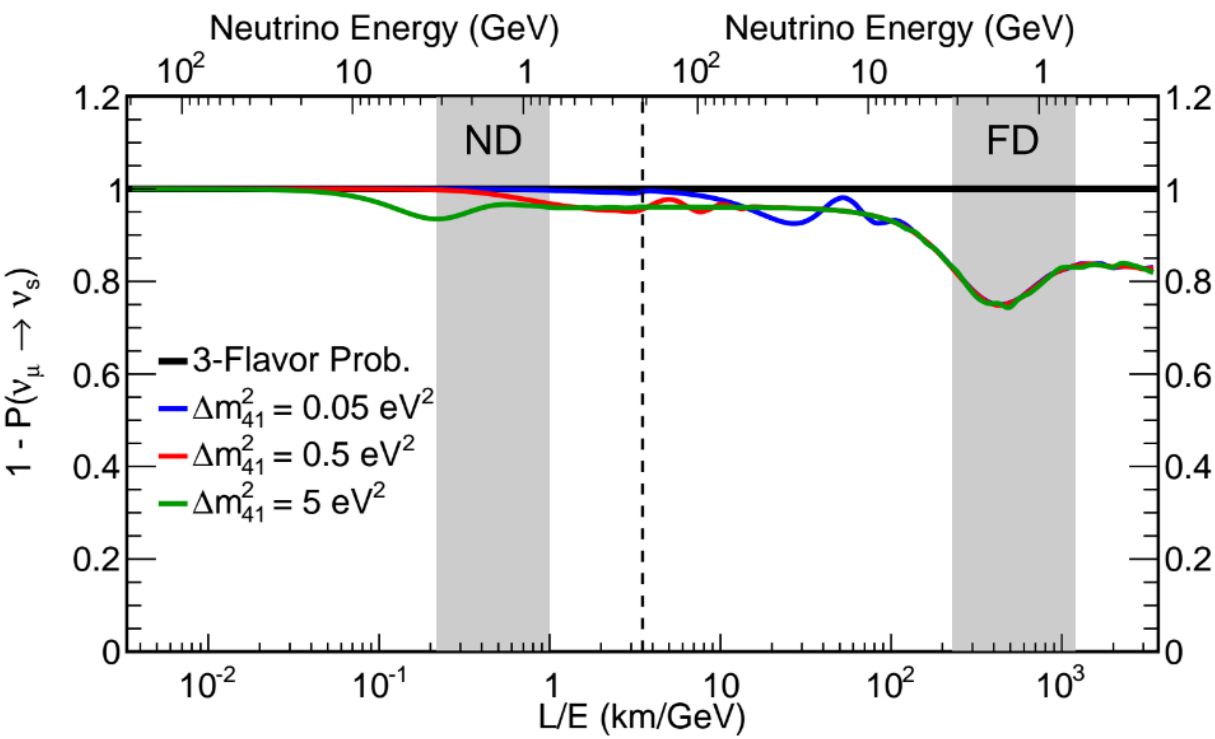
$$R = 1.19 \pm 0.16\ (stat.)^{+0.08}_{-0.13}\ (syst.)$$

Consistent with 3-flavour oscillations (R = 1.0)



3+1 model

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



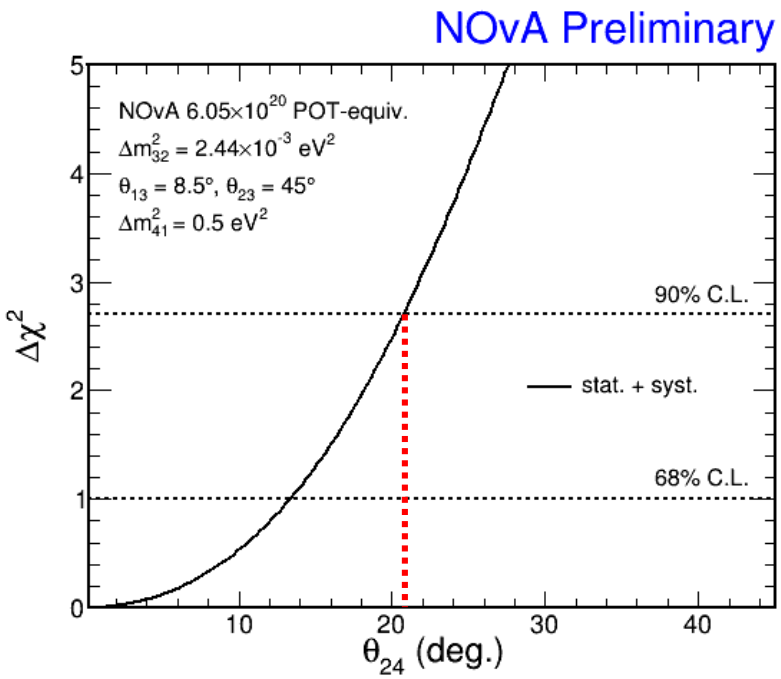
- Solar and reactor neutrino data constrains $\sin^2\theta_{14} < 0.041$
  - Assume $\theta_{14} = 0$
- $0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$
  - no ND oscillations
- Constraint on θ_{23}
  - $\sin^2(\theta_{23}) = 0.514$
  - Particle Data Group

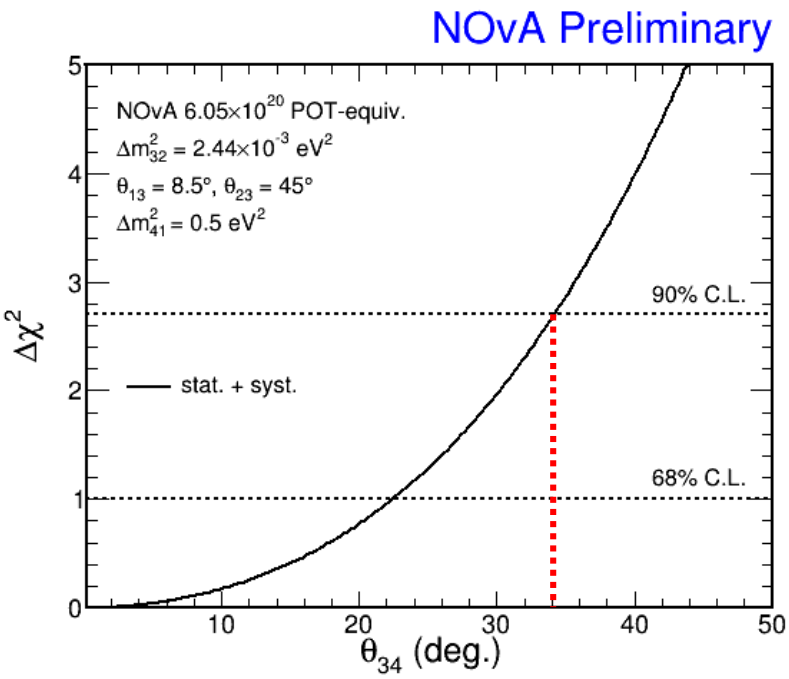
$|U_{e4}|^2 = \sin^2\theta_{14} = 0,\ \cos^2\theta_{14} = 1$

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

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

3+1 1D limits



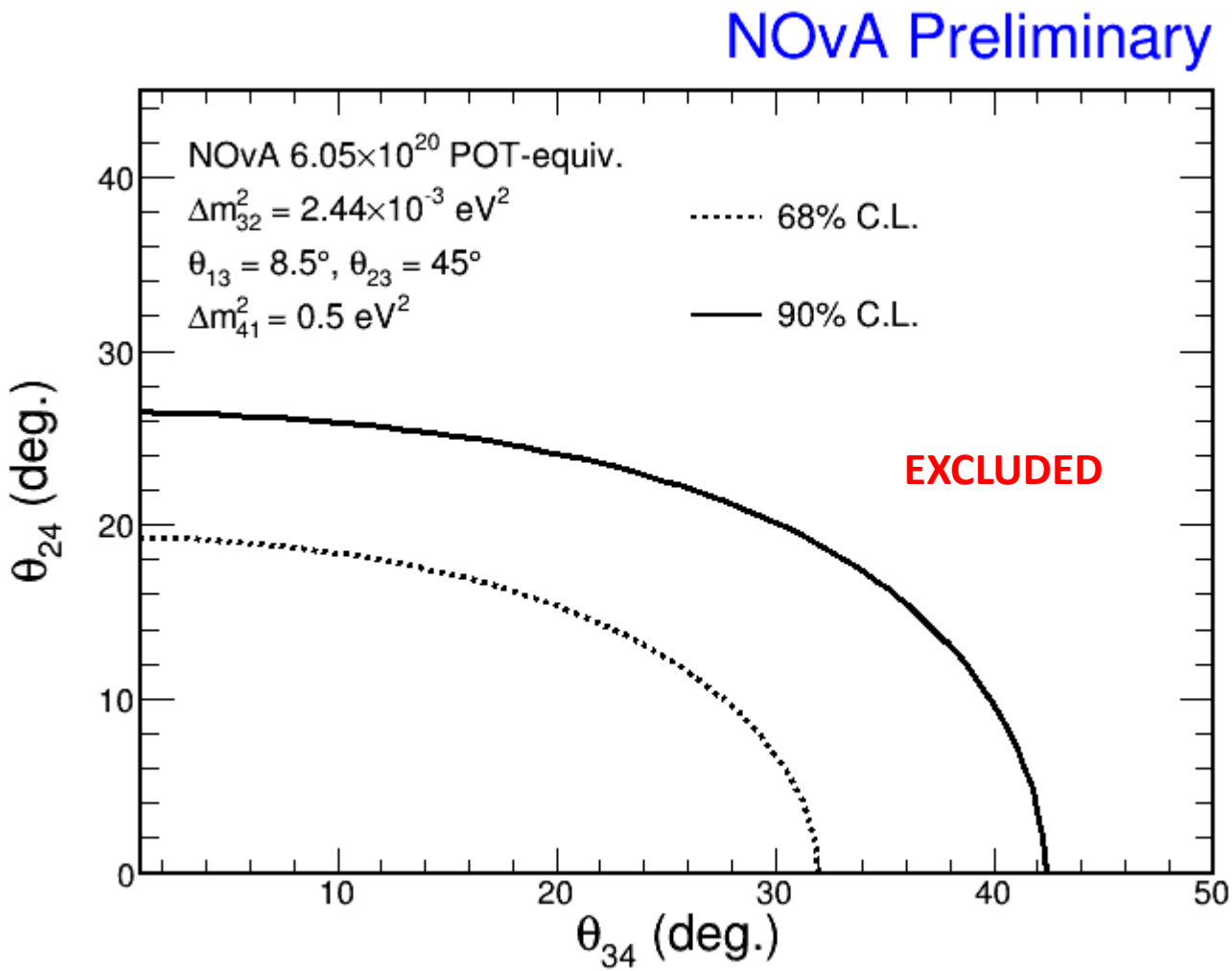


For $0.05\ eV^2 < \Delta m^2_{41} < 0.5\ eV^2$:

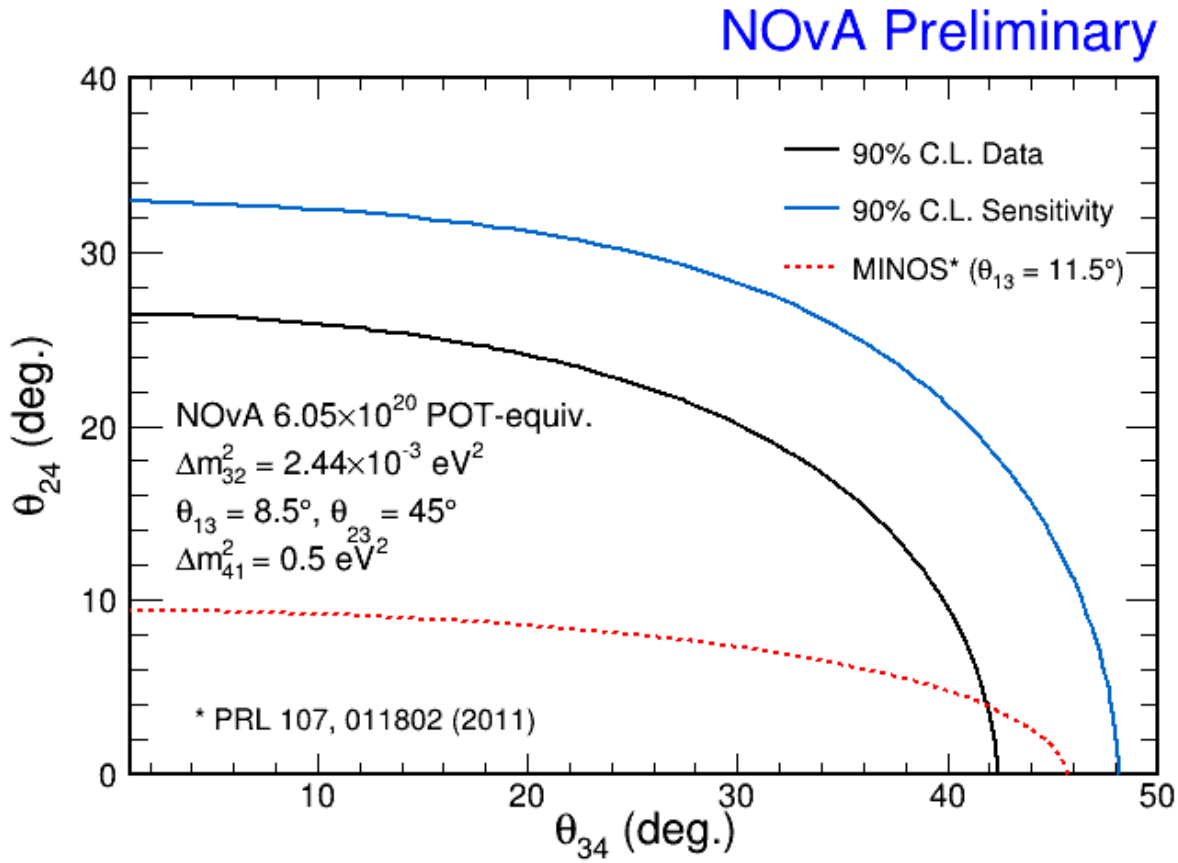
$\theta_{24} < 21°$ at 90% C.L. **$|U_{\mu 4}|^2 < 0.14$ at 90% C.L.**

$\theta_{34} < 35°$ at 90% C.L. **$|U_{\tau 4}|^2 < 0.33$ at 90% C.L.**

2D exclusion region



Comparison with other expts.



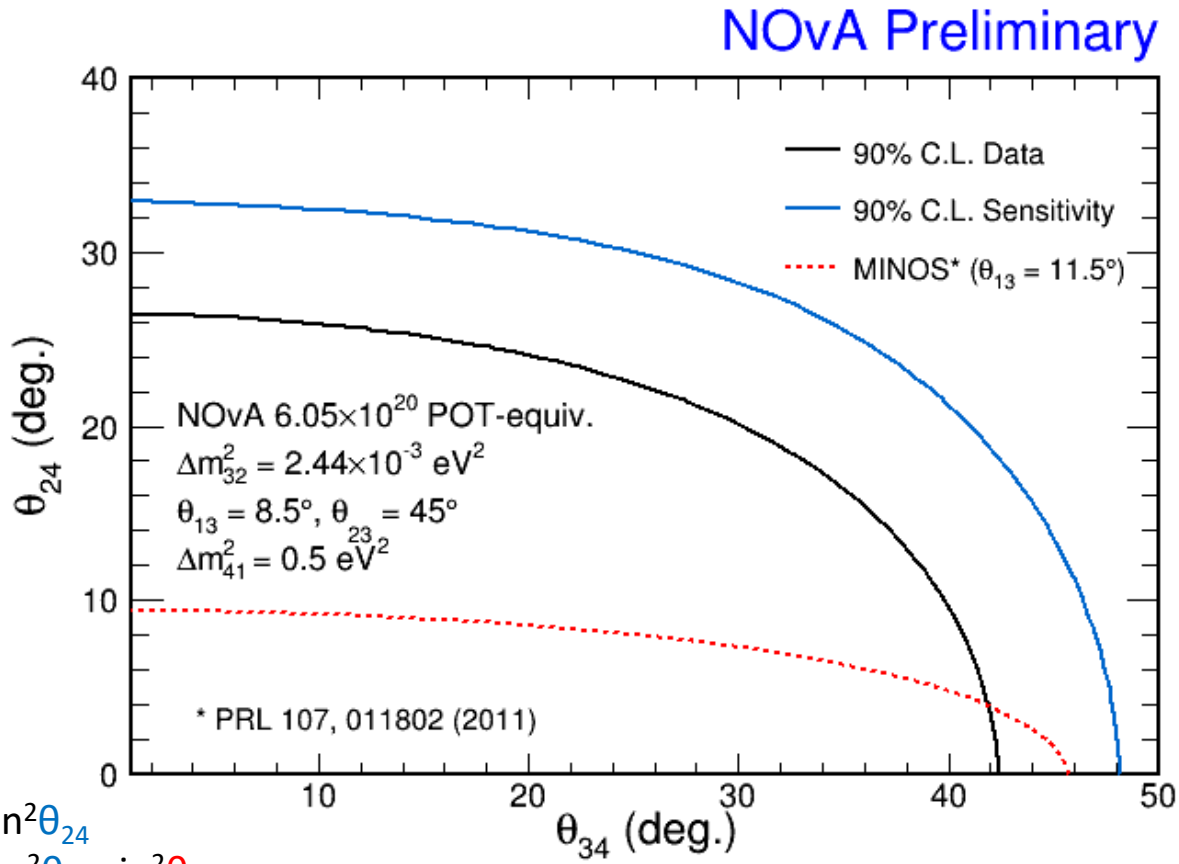
θ_{24} < 21° at 90% C.L.
θ_{34} < 35° at 90% C.L.

MINOS: θ_{24} < 8° for Δm^2_{41} < 0.5 eV^2
MINOS: θ_{34} < 38° for Δm^2_{41} < 0.5 eV^2

SuperK: θ_{24} < 12° for Δm^2_{41} > 0.1 eV^2
SuperK: θ_{34} < 25° for Δm^2_{41} > 0.1 eV^2

Due to overall excess observed in data, we obtain stronger limits than our sensitivity

Comparison with other expts.



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

MINOS: $|U_{\mu 4}|^2 < 0.020$ for $\Delta m^2_{41} < 0.5$ eV^2
MINOS: $|U_{\tau 4}|^2 < 0.38$ for $\Delta m^2_{41} < 0.5$ eV^2

SuperK: $|U_{\mu 4}|^2 < 0.041$ for $\Delta m^2_{41} > 0.1$ eV^2
SuperK: $|U_{\tau 4}|^2 < 0.18$ for $\Delta m^2_{41} > 0.1$ eV^2

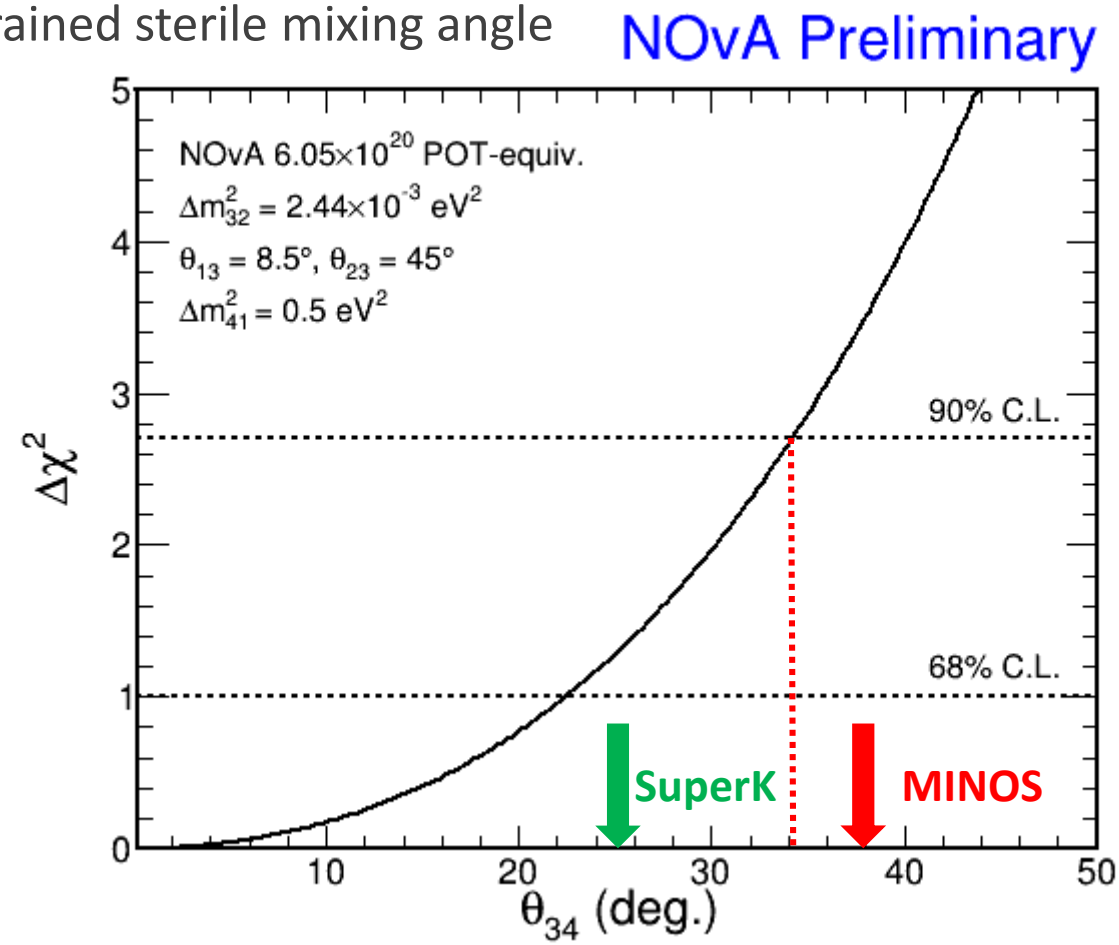
$|U_{\mu 4}|^2 < 0.14$ at 90% C.L.
$|U_{\tau 4}|^2 < 0.33$ at 90% C.L.

Due to overall excess observed in data, we obtain stronger limits than our sensitivity

The future for NOvA ν_s searches

A reminder: θ_{34} 1D limit (this result!)

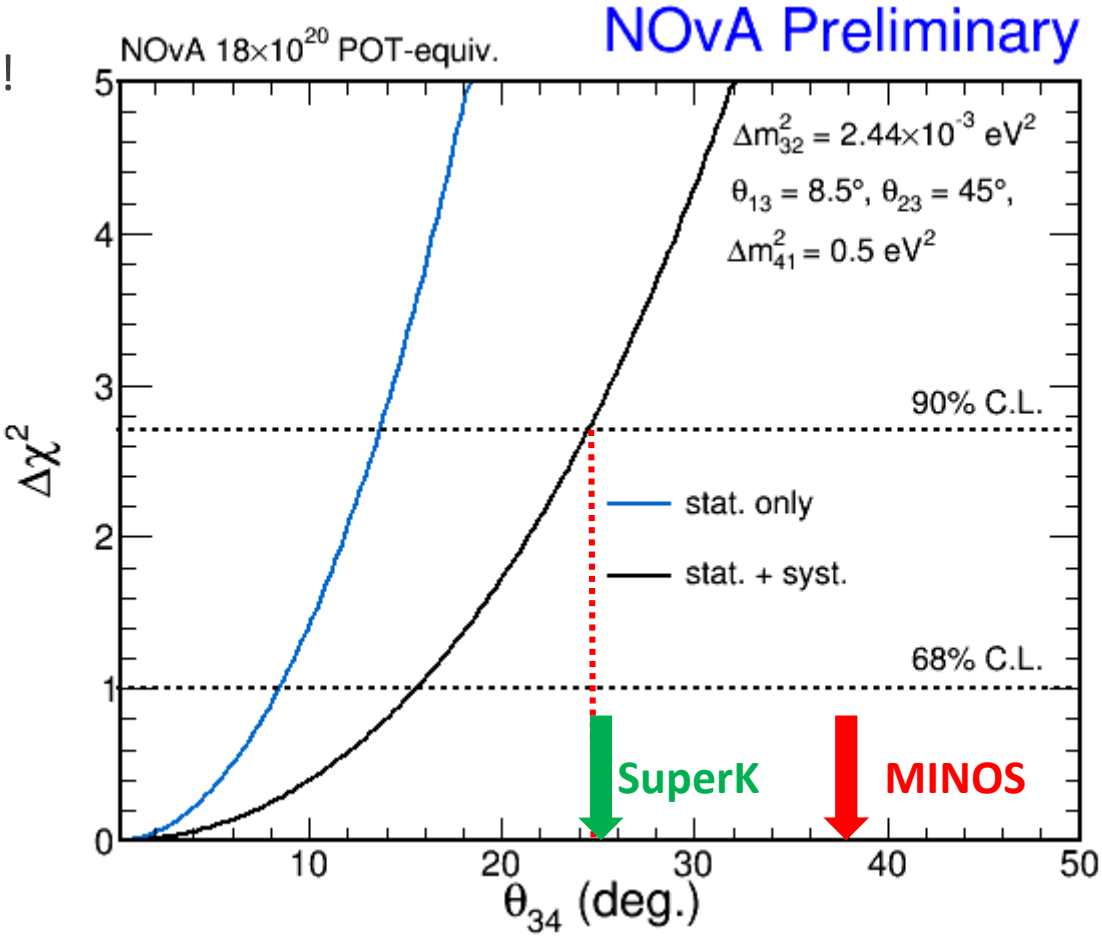
Least constrained sterile mixing angle



The future for NOvA ν_s searches

NOvAs 3yr projected sensitivities with current systematics and assumed cosmic background reduction of ~50%

More to come!

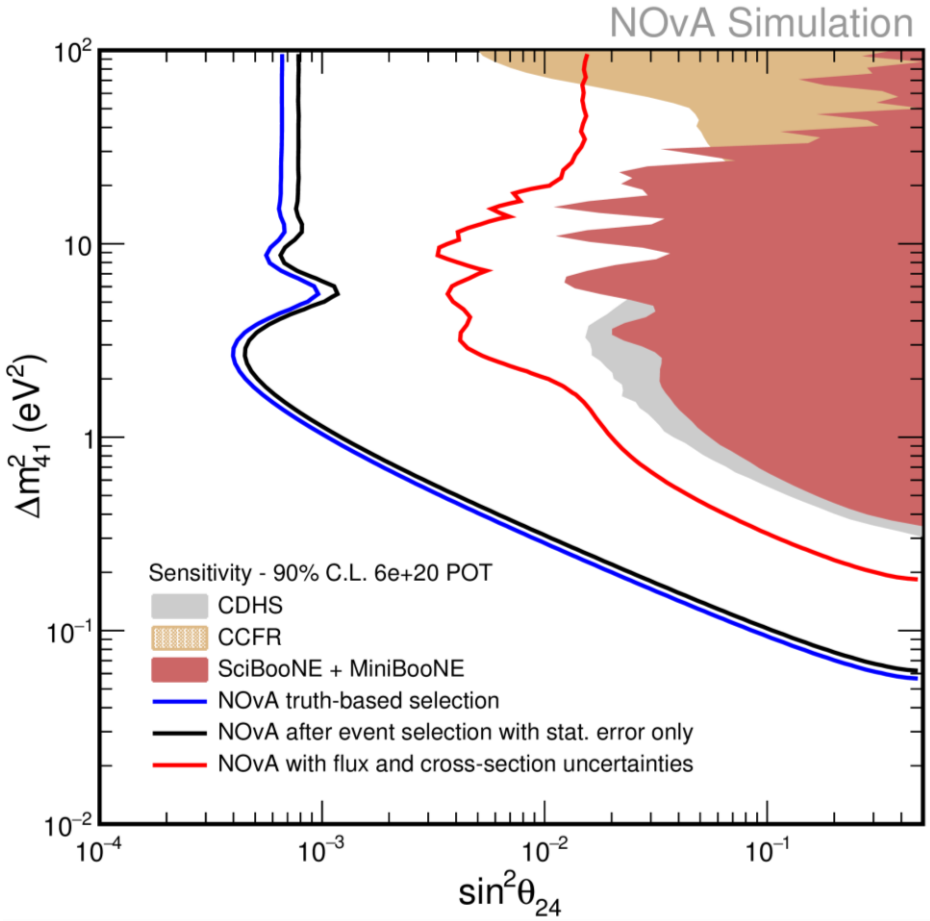


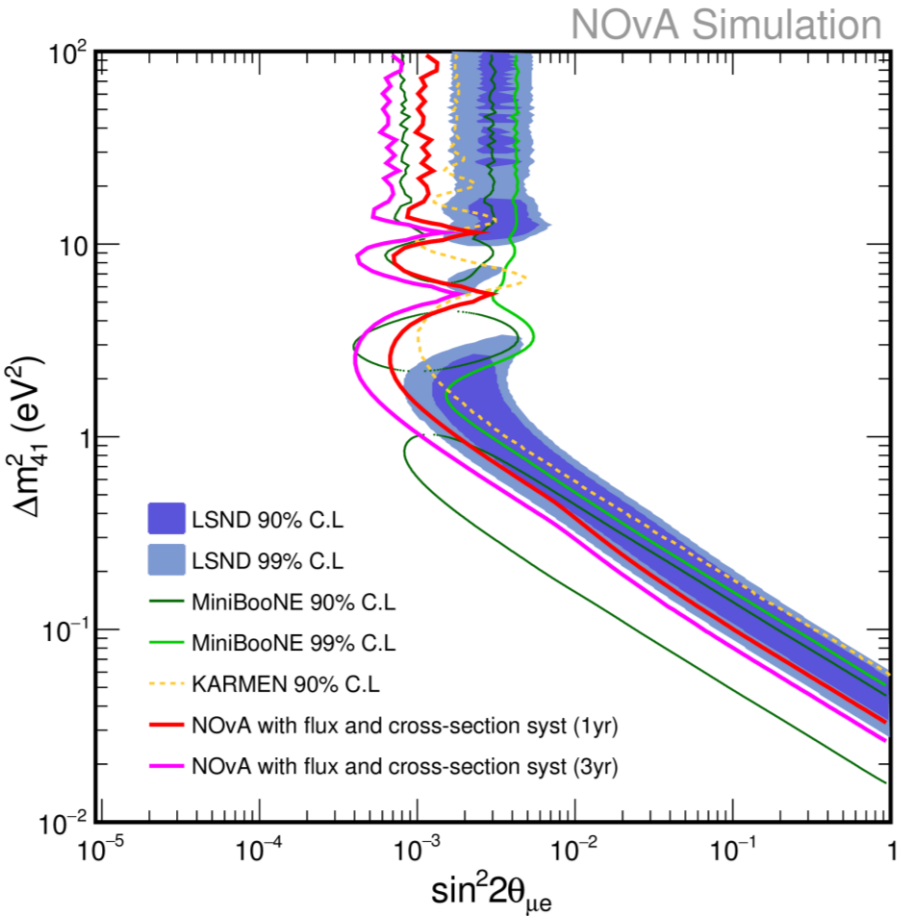
Competitive with current best θ_{34} limits (Super-K)

The future for NOvA ν_s searches

- NOvA short-baseline $\nu_\mu \rightarrow \nu_e$ search in ND; complementary to long-baseline search
  - L/E ~0.5, sensitive to oscillations due to light sterile neutrinos ~1 eV^2
  - Probing the LSND and MiniBooNE allowed

$\sin^2\theta_{14}\sin^2\theta_{24} \equiv \sin^2 2\theta_{\mu e}$

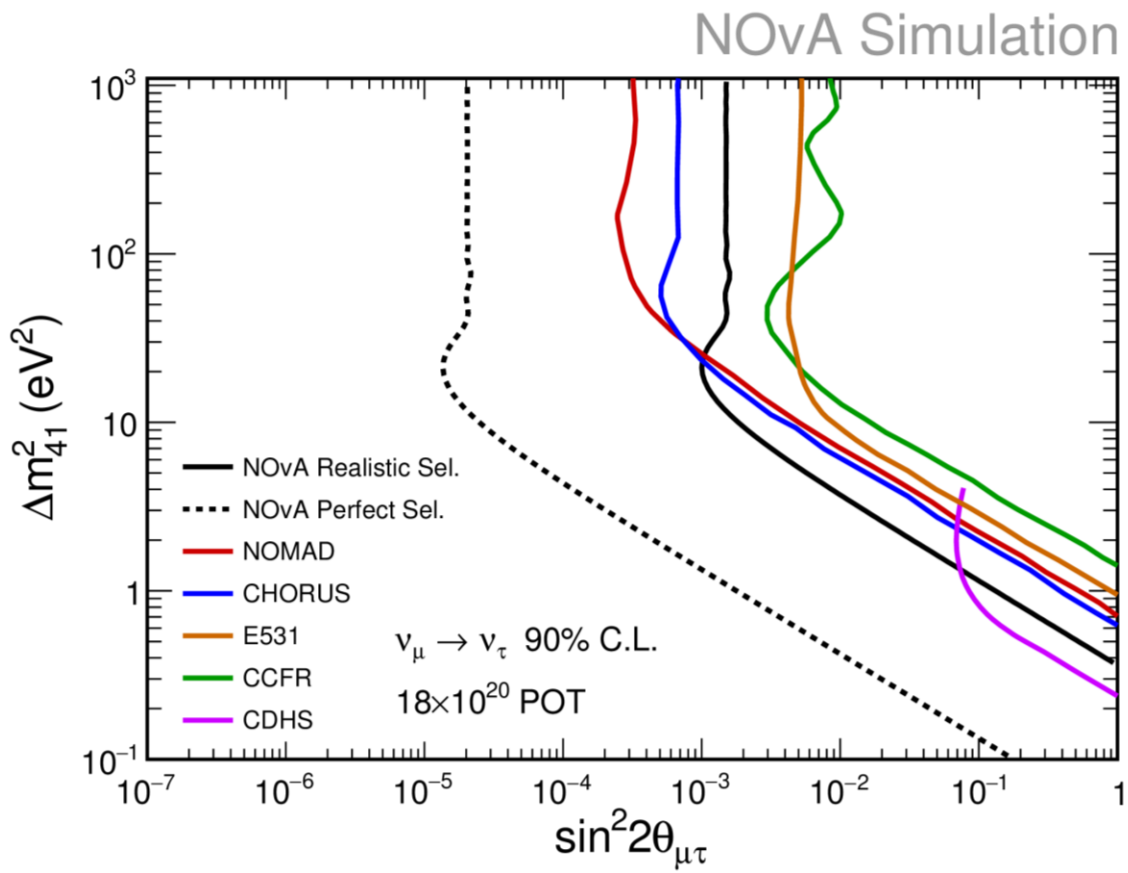




The future for NOvA ν_s searches

- NOvA short-baseline $\nu_\mu \rightarrow \nu_\tau$ search in ND
  - Potential ν_τ appearance from high energy kaon-induced flux
- Competitive with previous experiments after 3 years running

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



Summary

- Performed the first NOvA NC disappearance analysis with **6.05 x 10^{20} POT**
- **95 observed events** compared to 83.71 ± 9.15 (stat.) ± 8.28 (syst.) predicted
  - **within 1σ of three-flavour prediction**

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

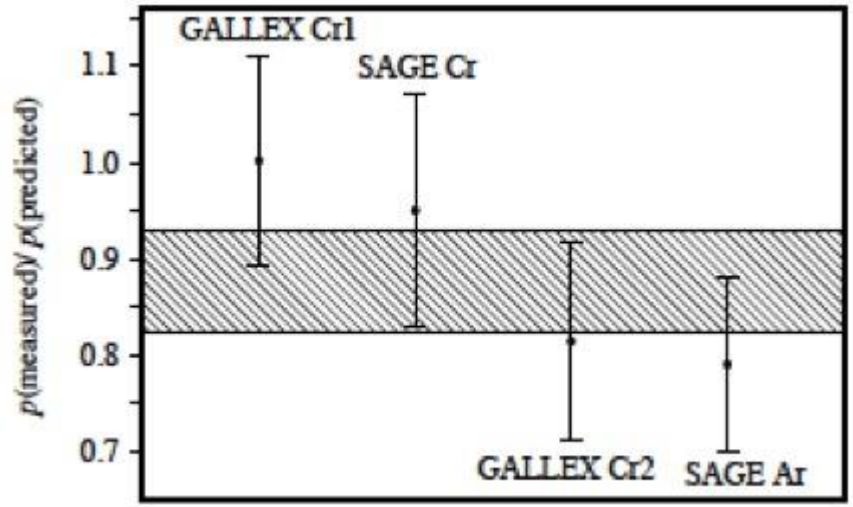
  - Consistent with 3-flavour oscillations (R = 1.0)
- **NOvA sees no evidence for sterile neutrino mixing**
- In 3+1 analysis, for 0.05 $eV^2 < \Delta m^2_{41} < 0.5\ eV^2$:
  - **$\theta_{24} < 21°$ at 90% C.L.** **$|U_{\mu 4}|^2 < 0.14$ at 90% C.L.**
  - **$\theta_{34} < 35°$ at 90% C.L.** **$|U_{\tau 4}|^2 < 0.33$ at 90% C.L.**
- **Competitive with MINOS θ_{34} limits**
- **Future limits on θ_{34} competitive with Super-K;**
- **ND short-baseline searches underway**
- Thank you!

@novaexperiment

Backup

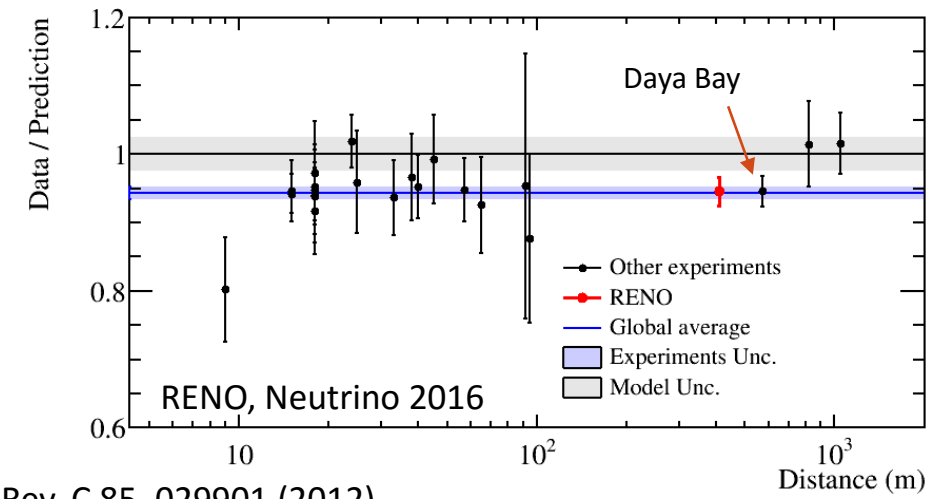
The Gallium and reactor anomalies

- 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:
  - $R = 0.76 \pm 0.09$ (2.8σ low)
- Ended in 1992; in light of other results, possibility due to large-mass sterile neutrinos suggested



Have short-baseline reactor experiments observed a $\bar{\nu}_e$ deficit?

- Reactor neutrino flux calculation increased expected flux by +3% (2% uncertainty; all experiments appear low
  - 5 MeV bump
- Discrepancies to the Huber+Mueller[1,2] model indicate:
  - Over estimated flux and/or underestimated flux uncertainty
  - Or the existence of a sterile neutrino



[1]Phys. Rev. C 85, 029901 (2012)
[2]Phys. Rev. C 83, 054615 (2011)

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:

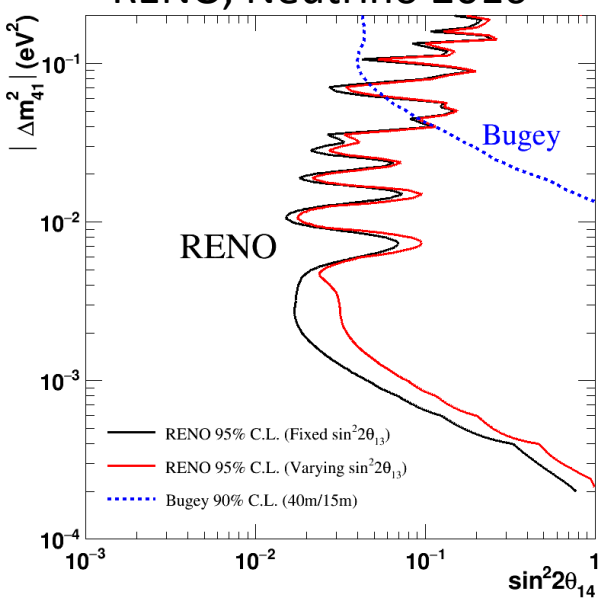
$\Delta m^2_{41} < 0.8\ eV^2$ at 95% C.L

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

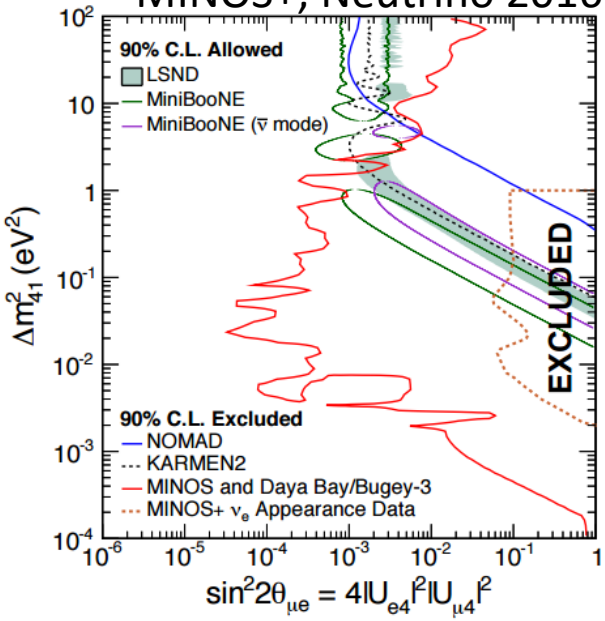
IceCube expect a resonant matter effect in the disappearance of atmospheric anti-numu

No evidence; strong limits on θ_{24}

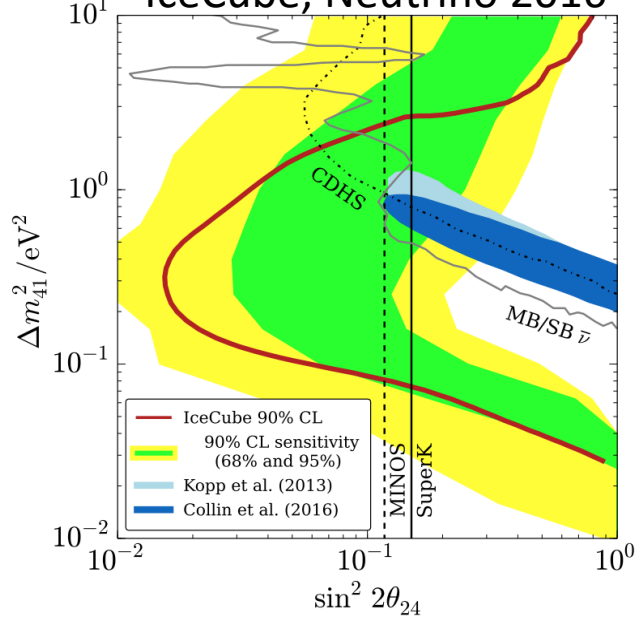
RENO, Neutrino 2016



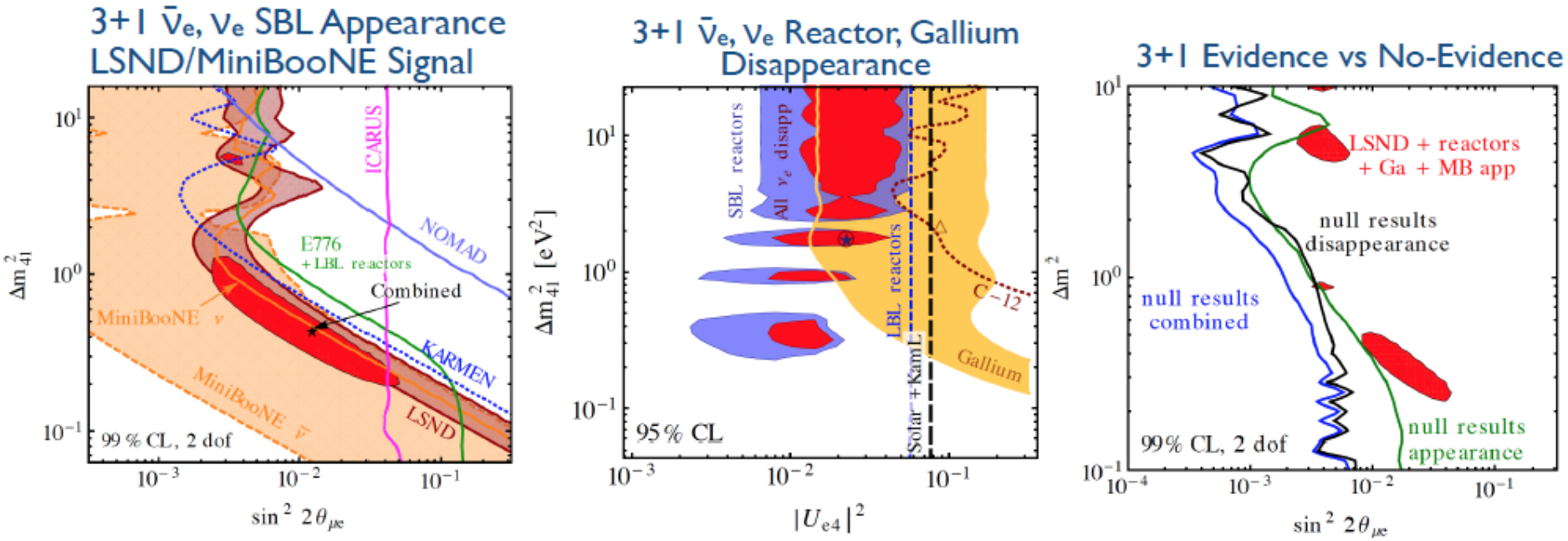
MINOS+, Neutrino 2016



IceCube, Neutrino 2016



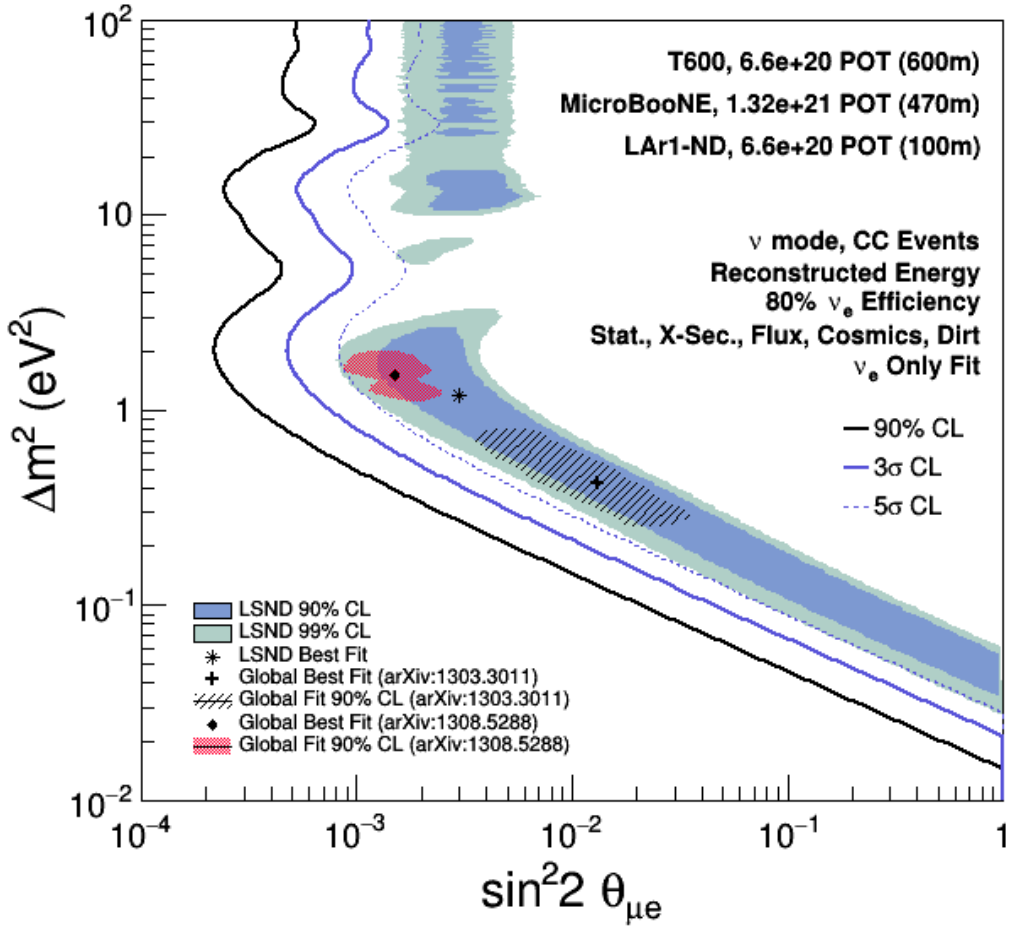
2013 global fits



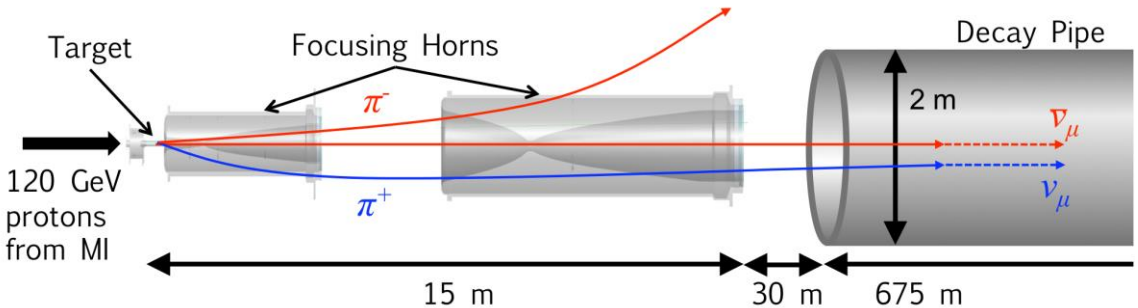
Kopp, Machado, Maltoni, Schwetz, arXiv:1303.3011

Fermilab SBL program

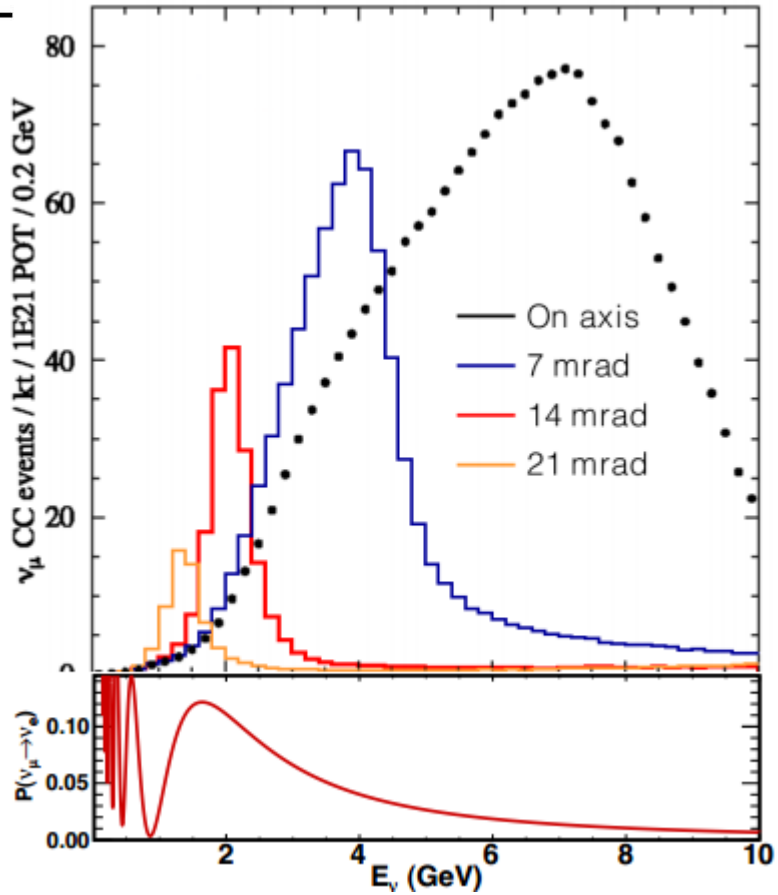
Fermilab Short-Baseline Neutrino program
LAr1-ND + MicroBooNE + ICARUS T600



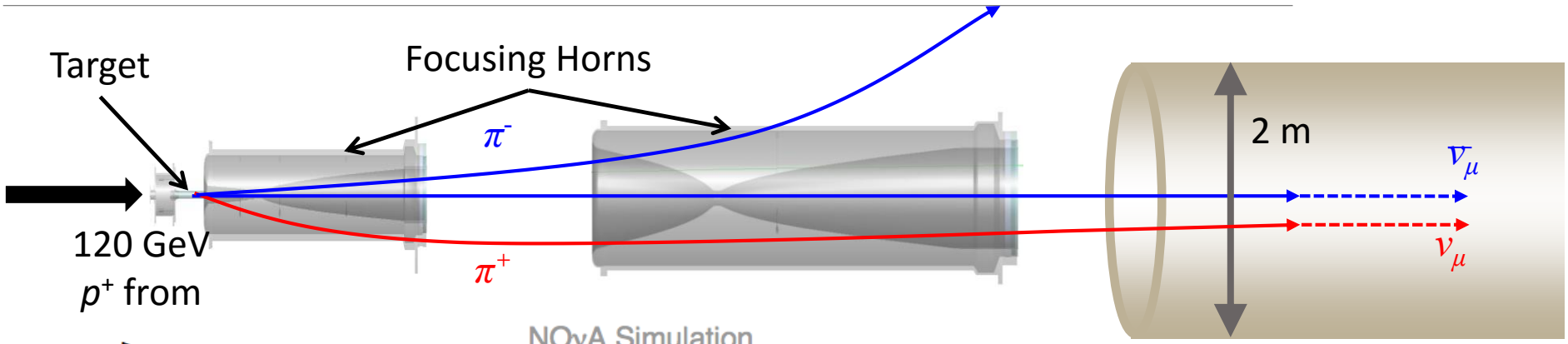
NuMI beam

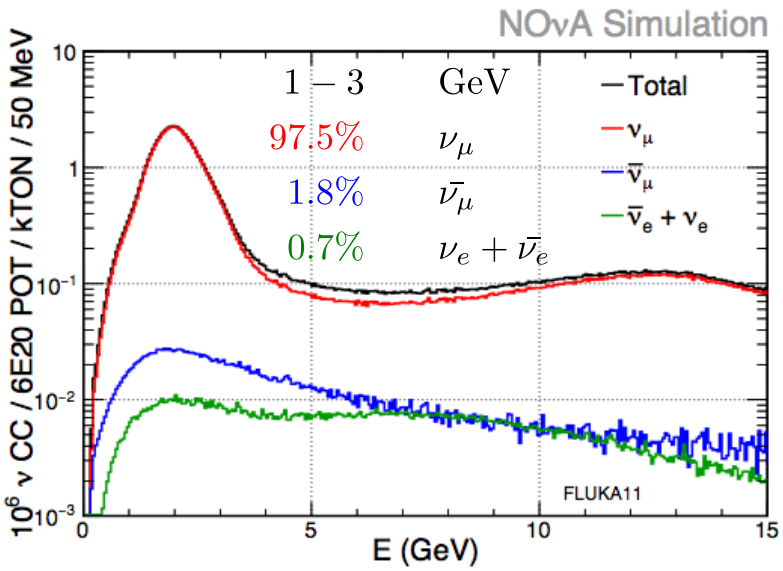


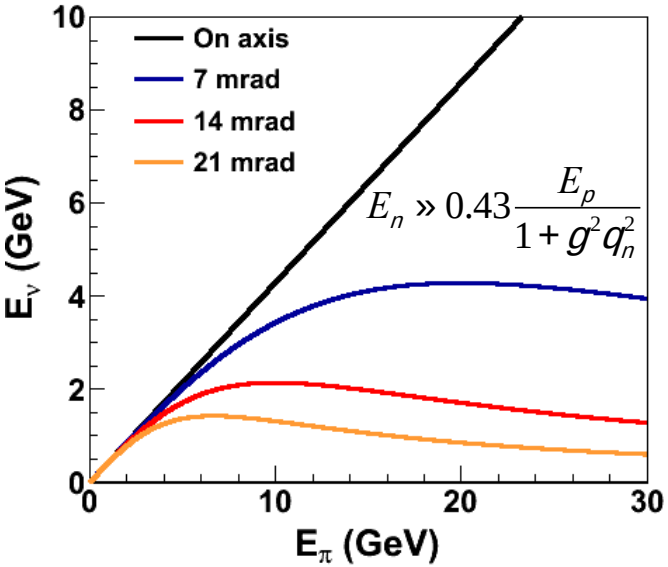
- 120 GeV protons from Main Injector
- Produce mainly pi and K
- Focused by two magnetic horns
- Select neutrino or antineutrino beam



Making an off-axis neutrino beam



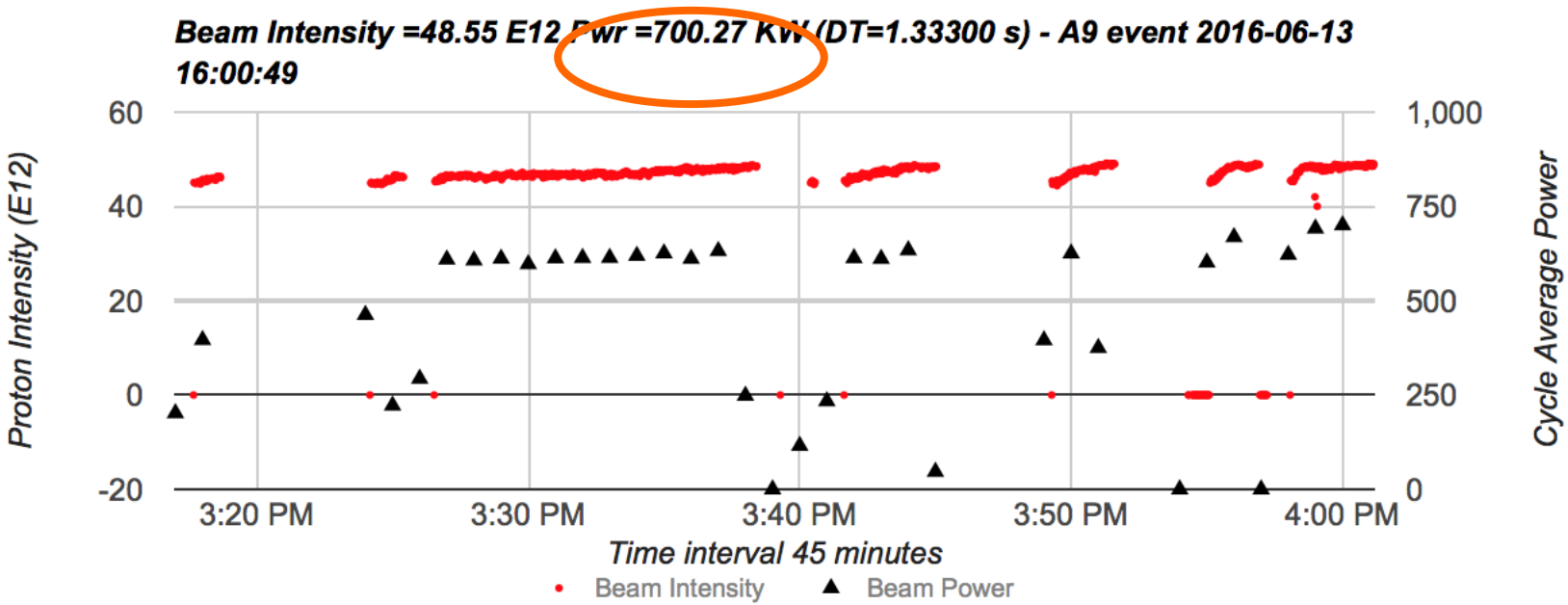




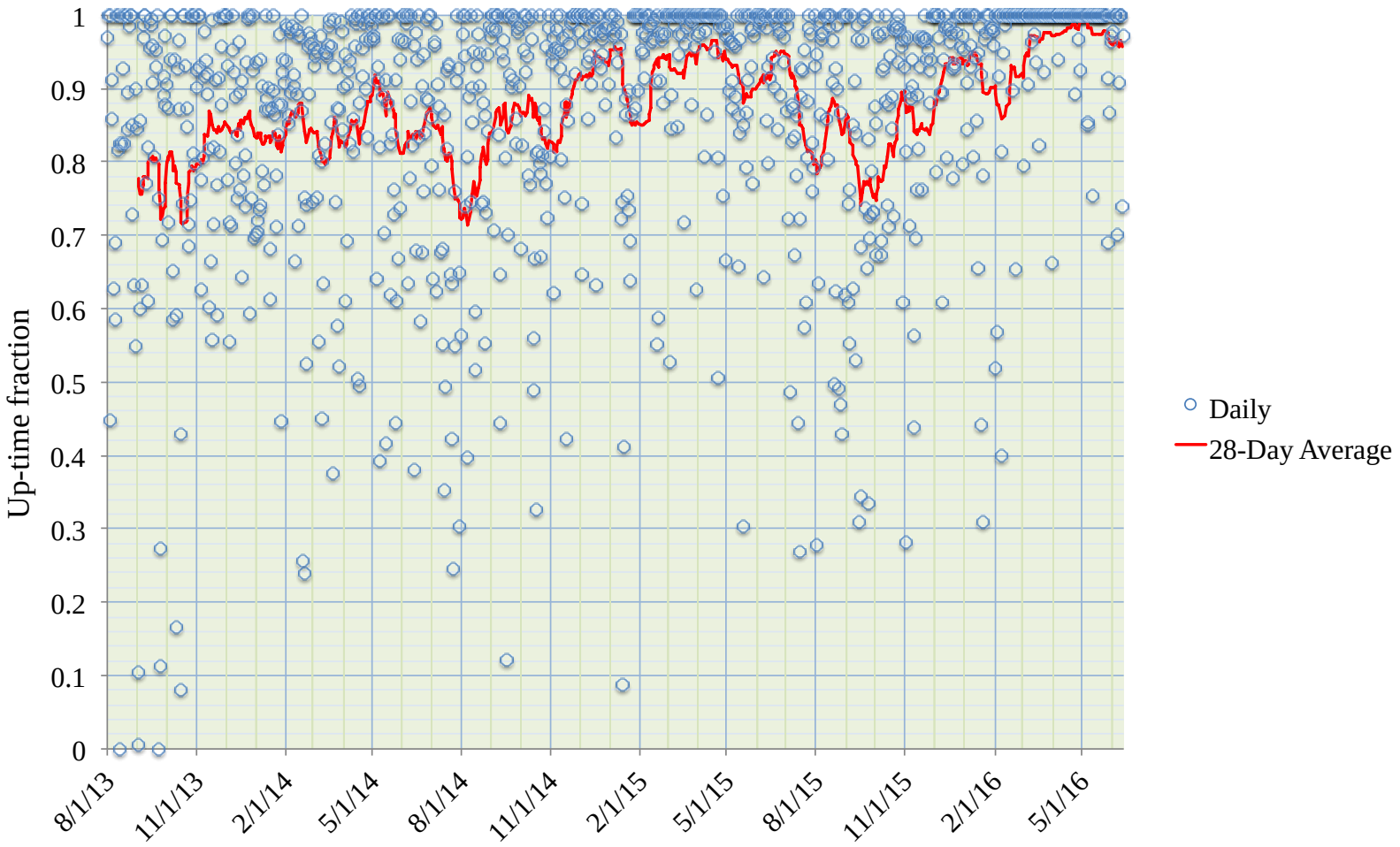
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events

Beam Performance

Achieved design power 700kW!



Detector Performance



Simulation

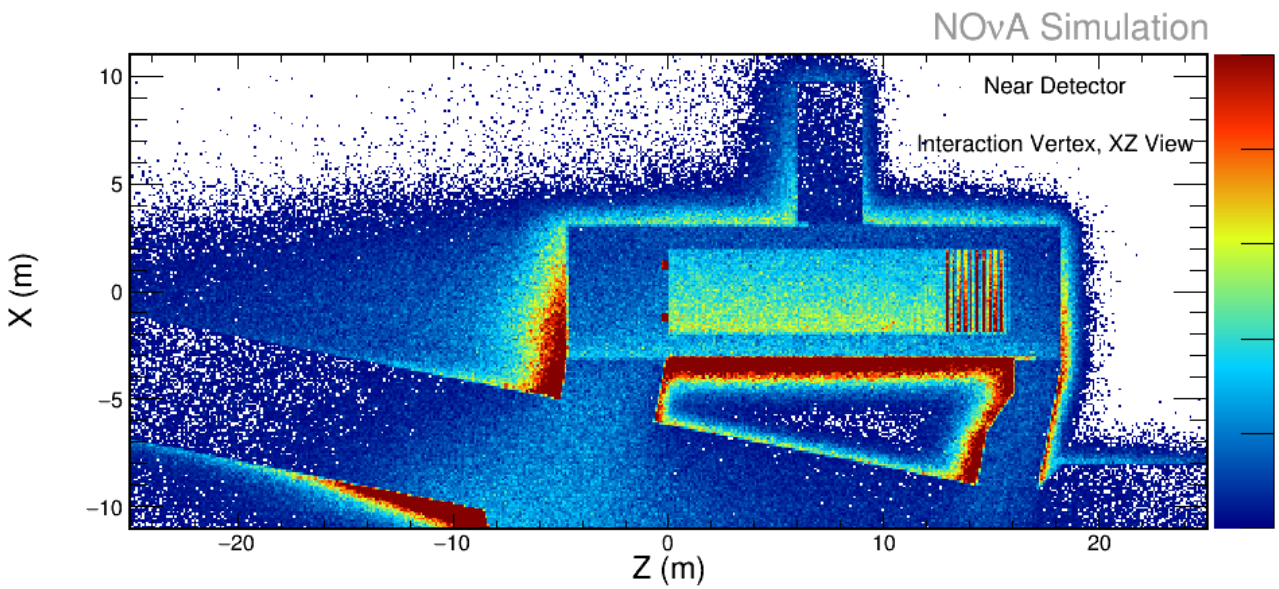
Beam line production, propagation and neutrino flux: FLUKA/Flugg

Cosmic Ray flux: CRY

Neutrino interaction and FSI: GENIE

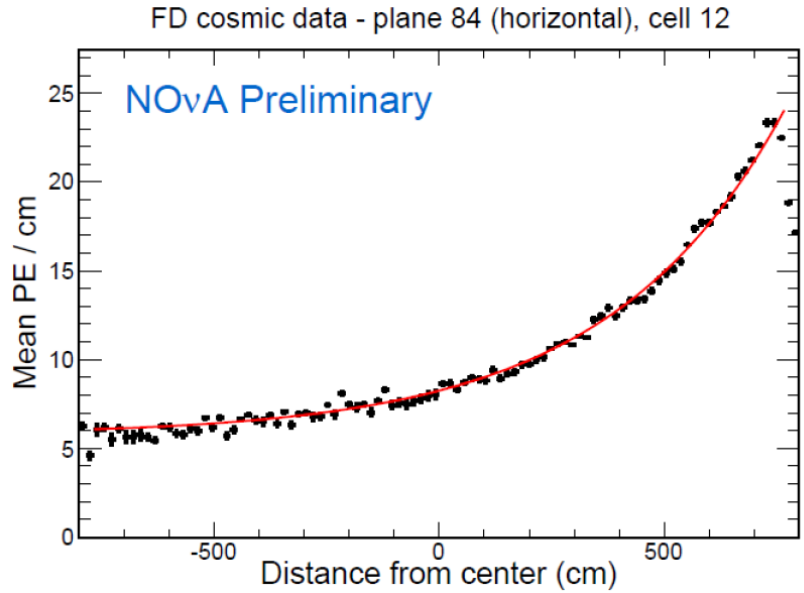
Detector: Simulation: Geant4

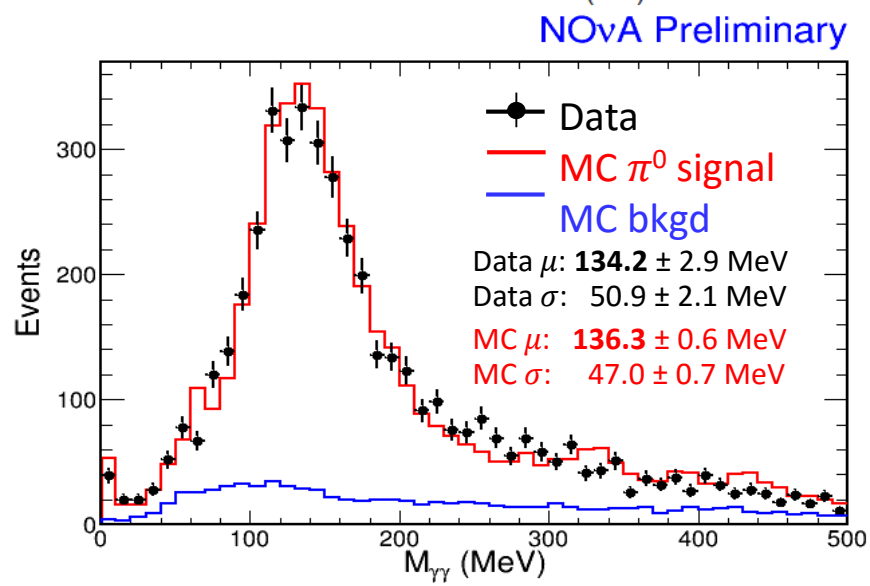
Detector response: Custom simulation Routines



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



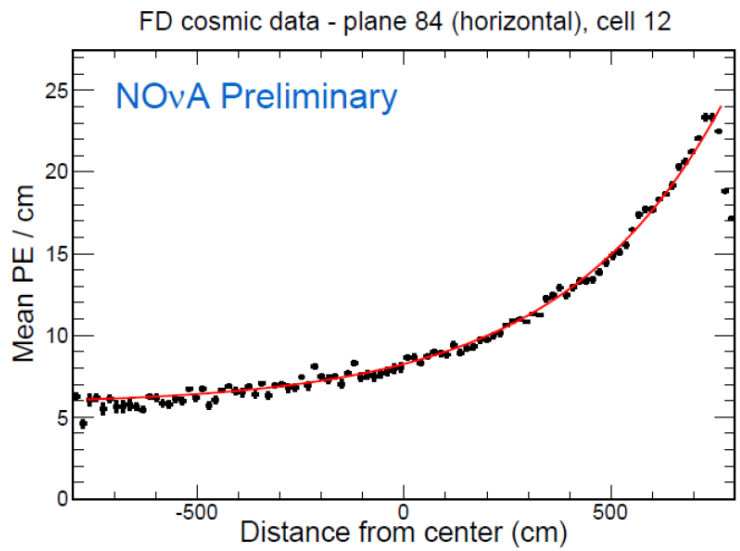


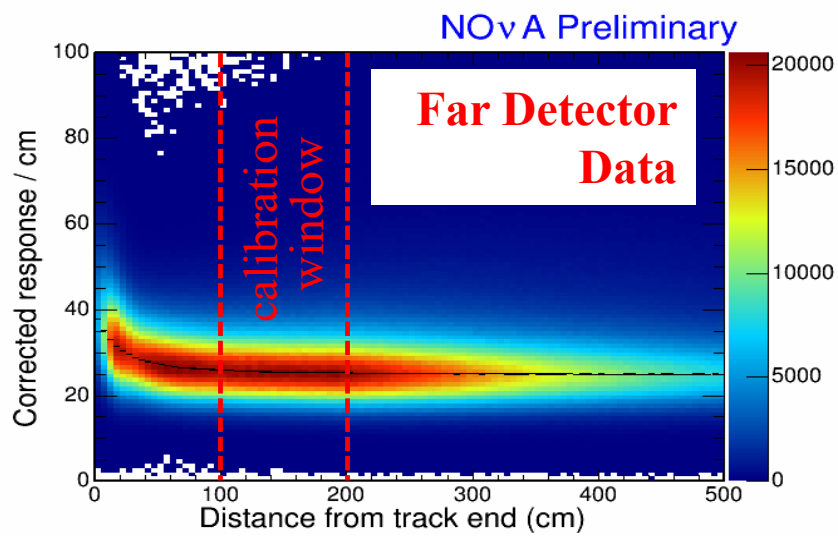
Calibration

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

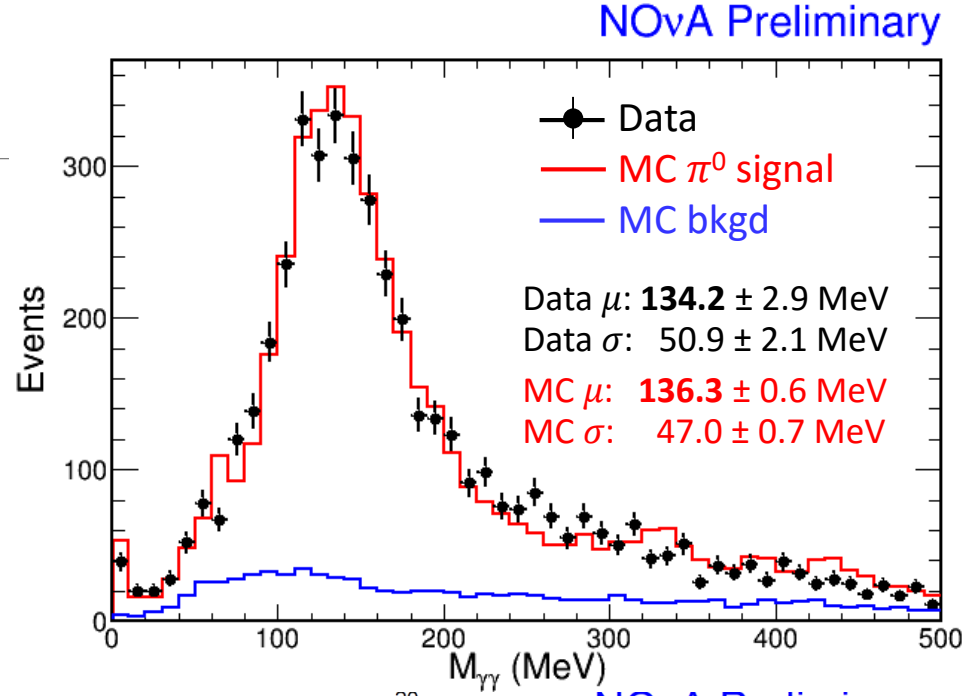
Near Detector

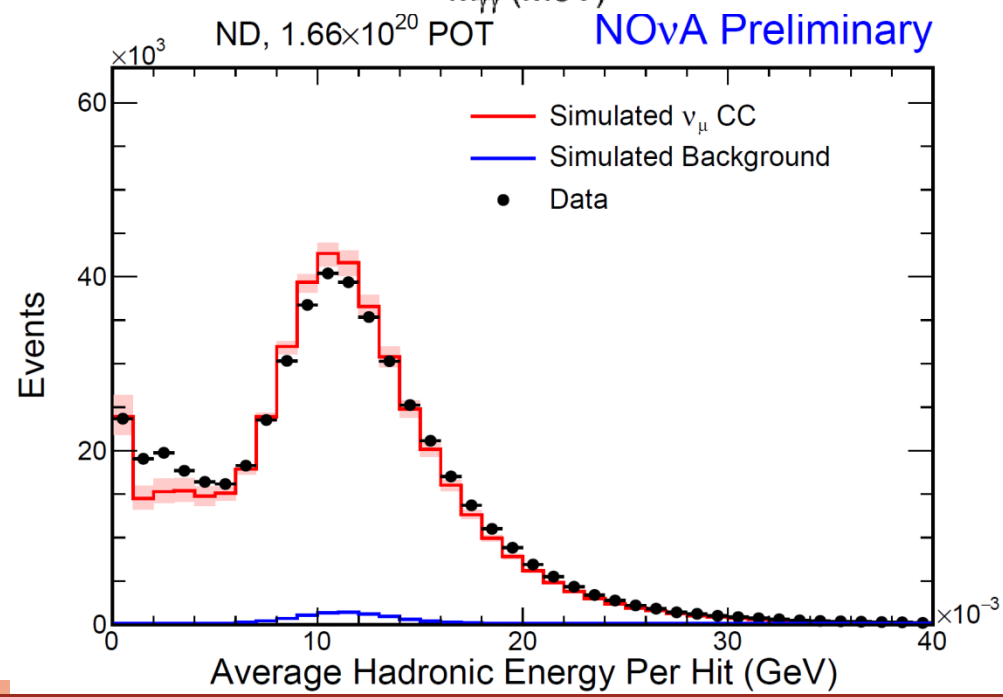
- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum
- π^0 mass
- hadronic shower *E*-per-hit

Far Detector

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

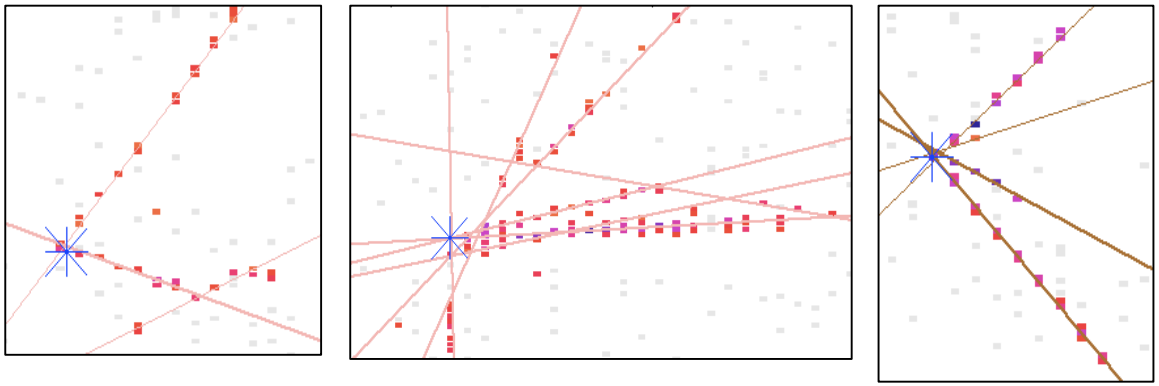
All agree to 5%



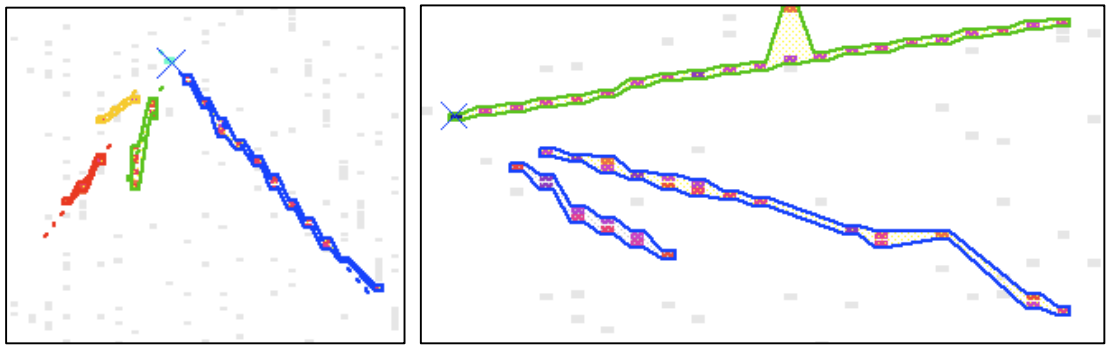


Reconstruction

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.

GAVIN S. DAVIES, PASCOS 2016

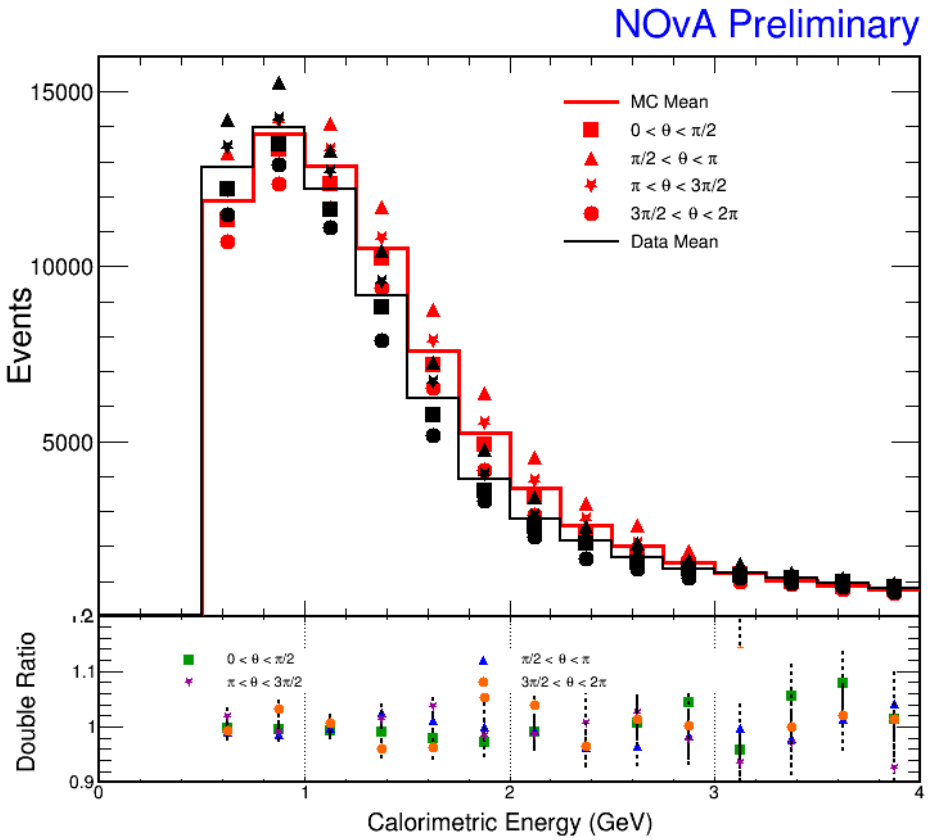
76

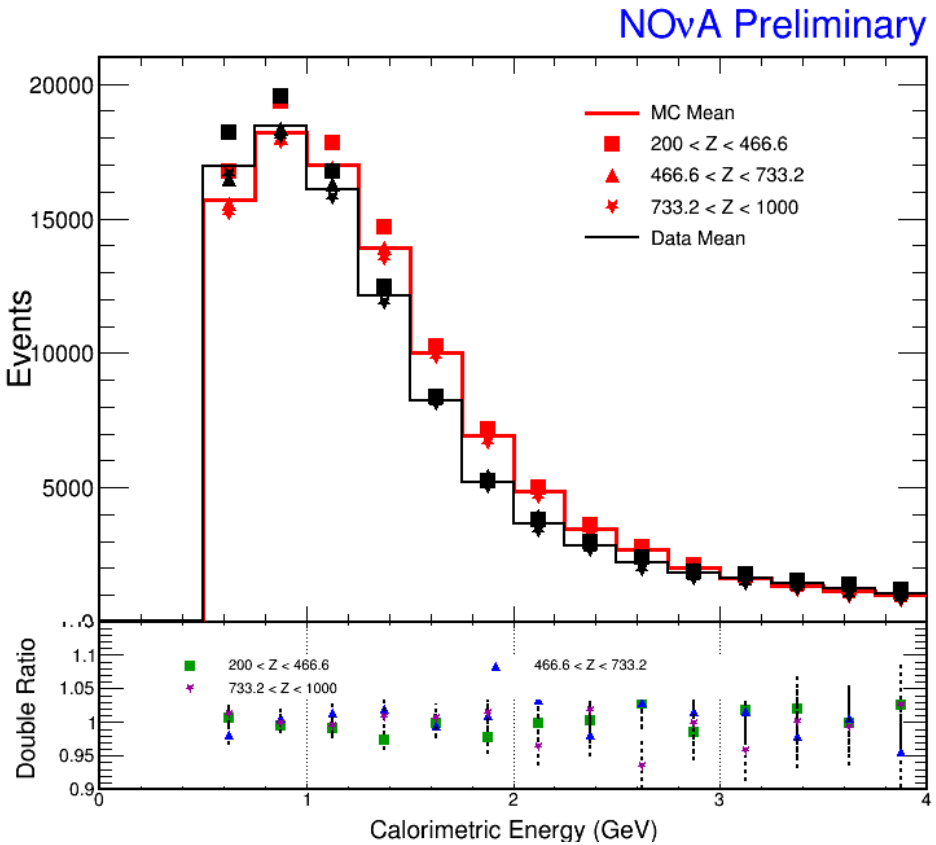
Near detector MC event counts

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**

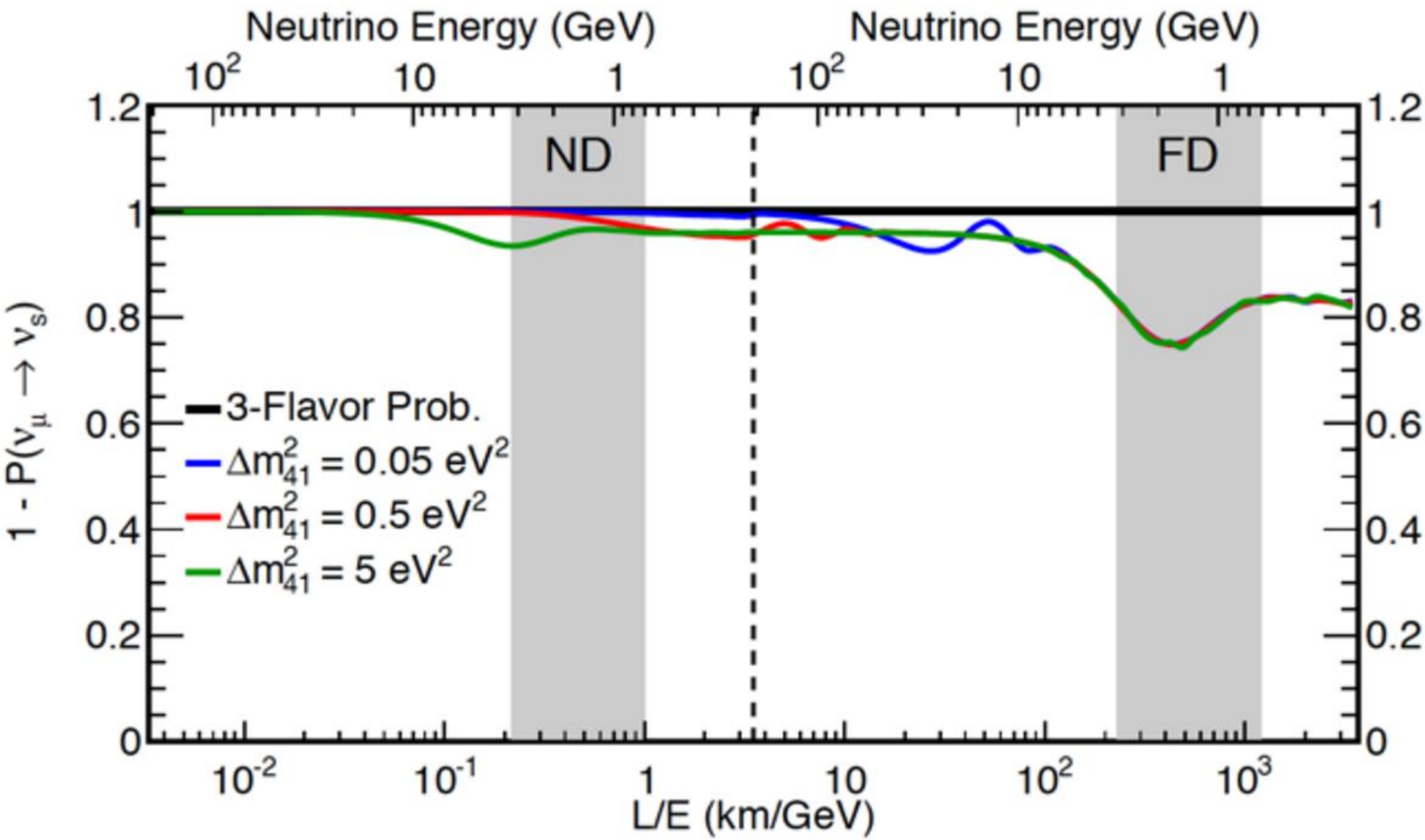
Near detector data stability

- Checked ND data stability by observing event distributions in ND quadrants and slices in Z-coordinate
  - Good agreement between data and MC





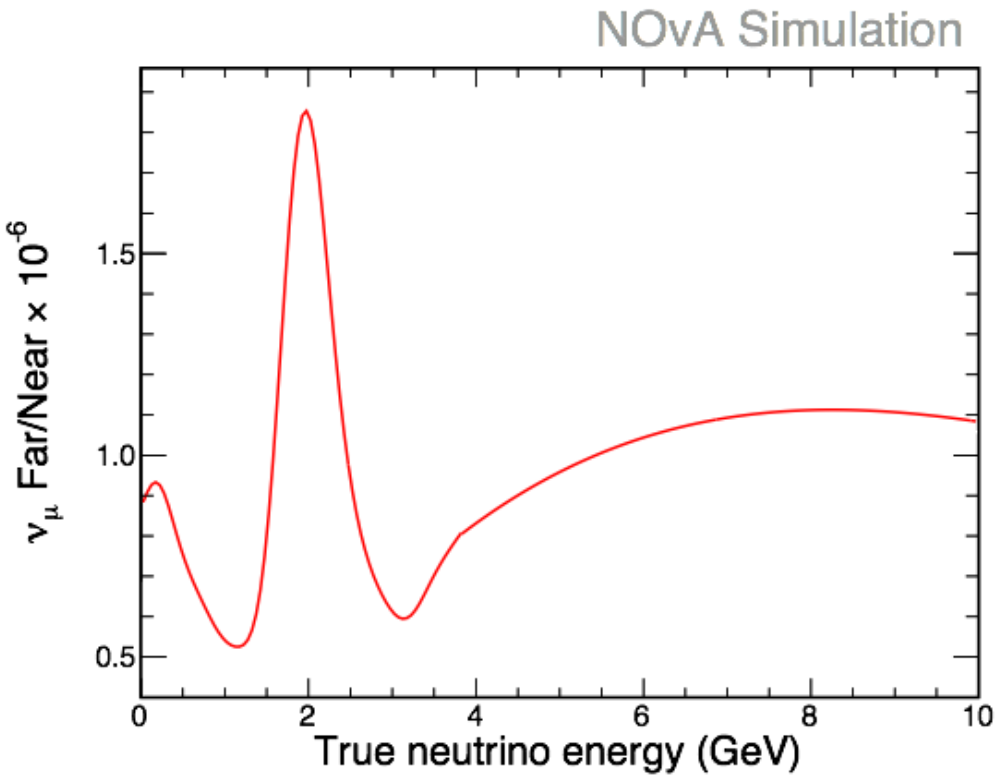
Sterile Oscillations



Extrapolation

All NOvA analyses use ND data to predict the FD spectrum

- Muon Neutrino analyses: unfold reco energy, use true F/N ratio for FD prediction of track events
- Electron Neutrino signal: use Muon-neutrino FD prediction
- NC and Electron Neutrino background analyses: Far to Near spectrum in reconstructed energy ratio for FD prediction of shower events

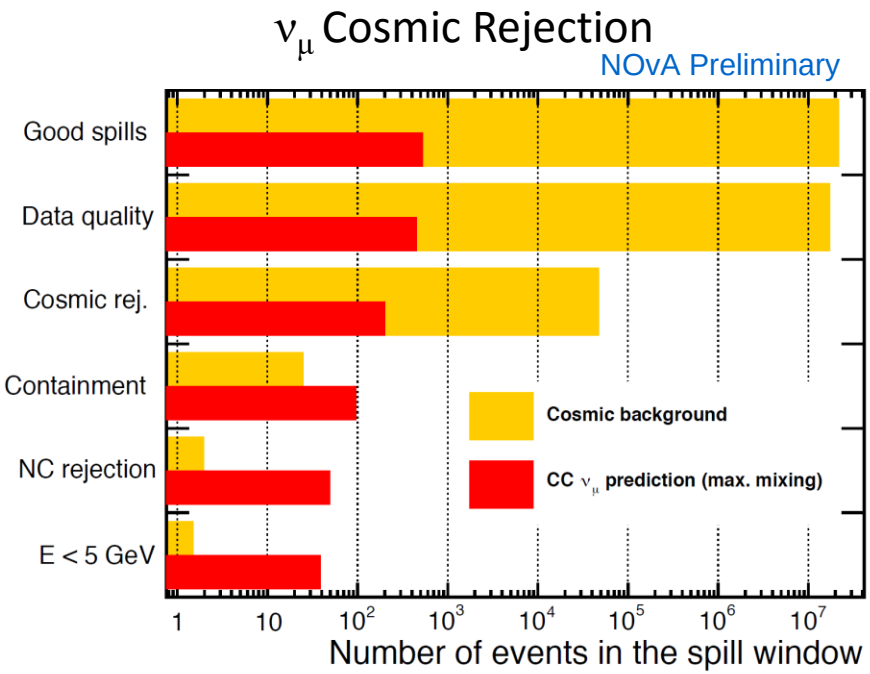


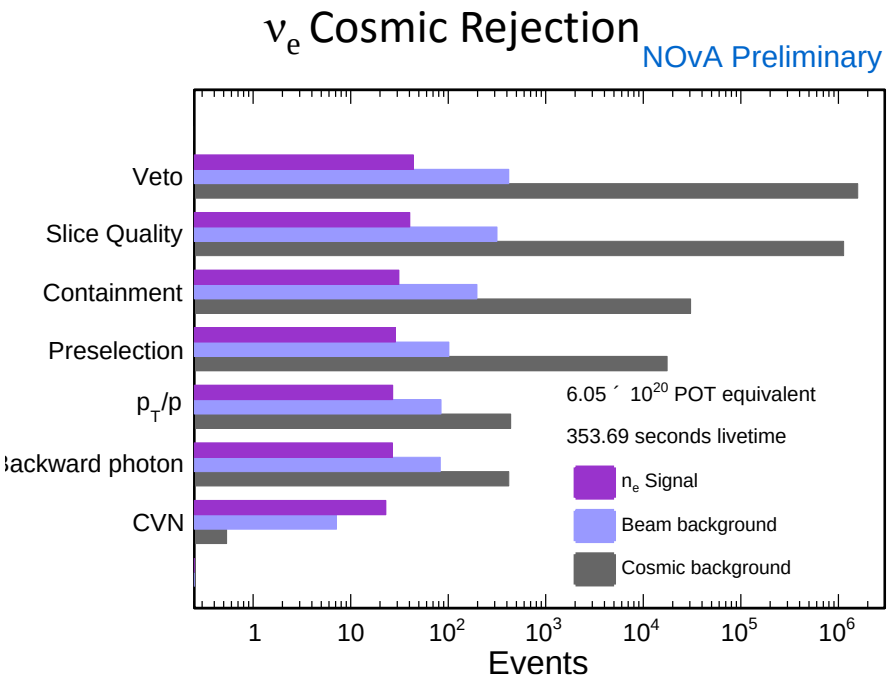
Cosmic Rejection

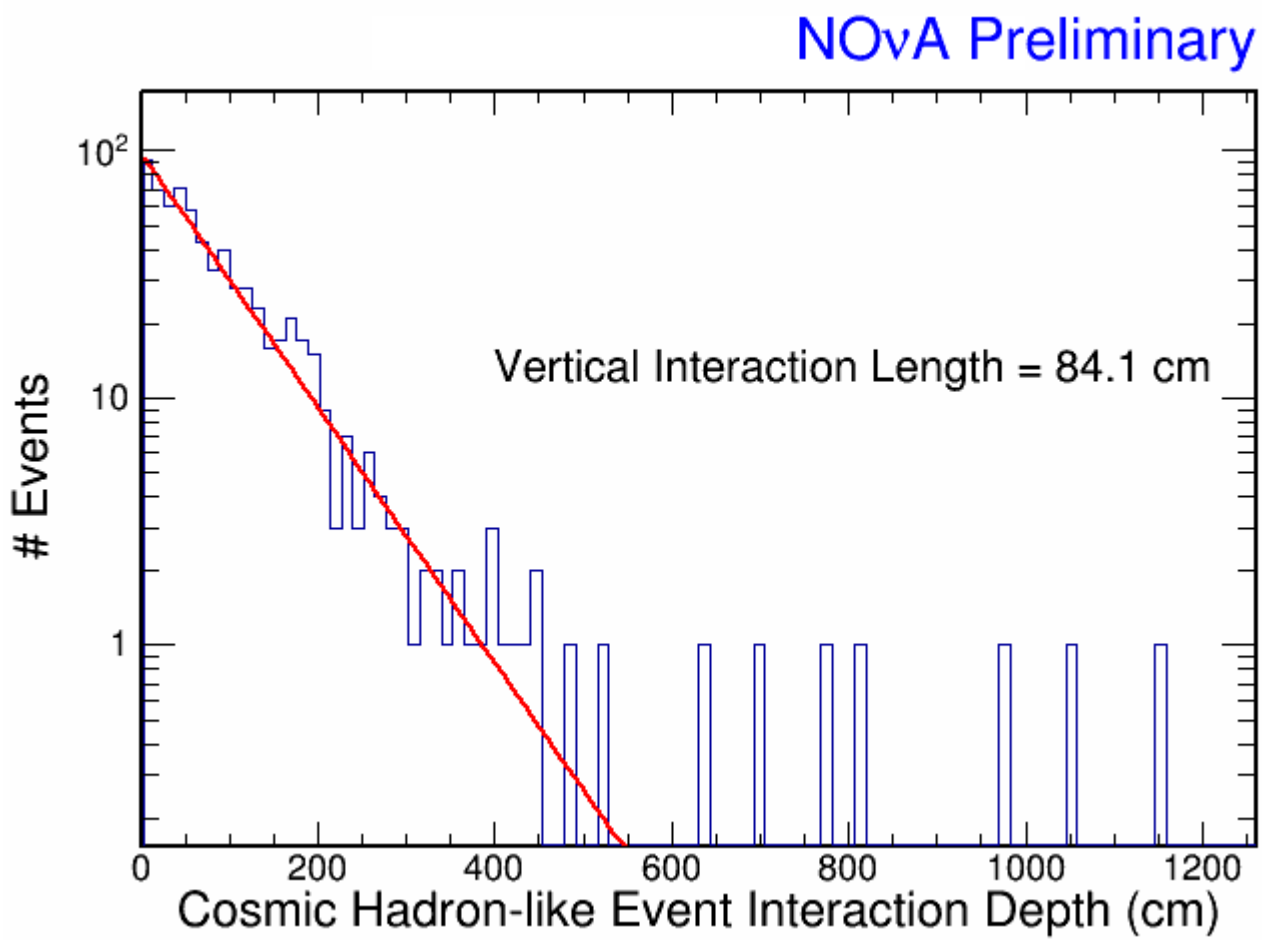
NOvA FD sees 150kHz of cosmic induced events

Beam timing gives 10^5 rejection factor

Combination of containment and event topology gives another ~10^7 in rejection

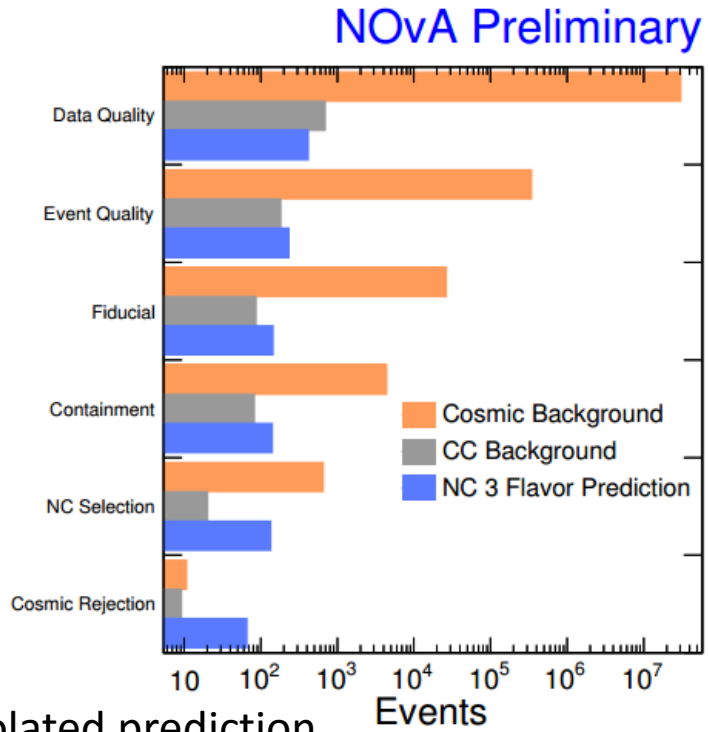





NOvA Preliminary
Vertical Interaction Length = 84.1 cm
Events
10^2
10
1
0
200
400
600
800
1000
1200
Cosmic Hadron-like Event Interaction Depth (cm)

Neutral Current FD Selection

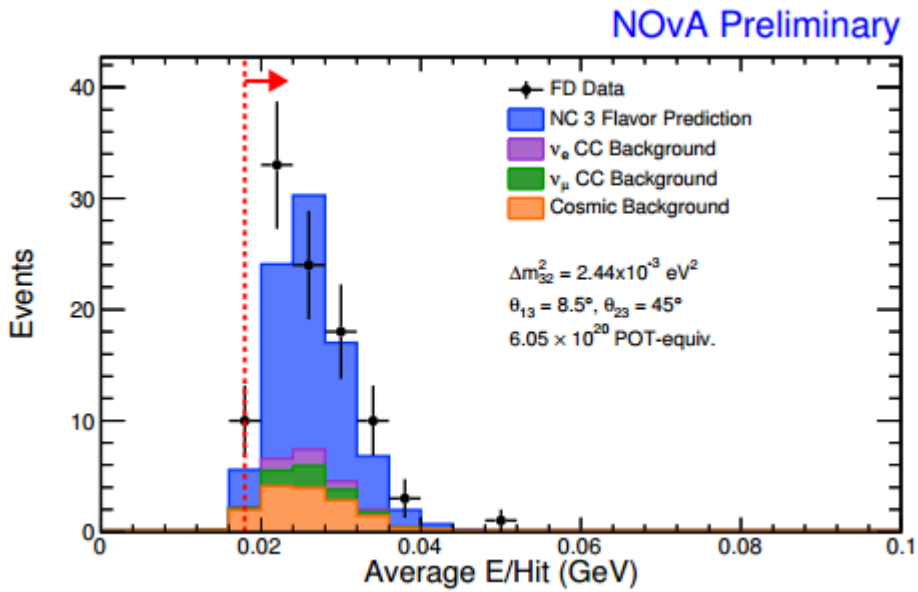
Cut	Total	NC	ν_μ	ν_e	ν_τ	cosmic
Data Quality	23.4×10^6	337.0	230.6	58.5	?	23.4×10^6
Cosmic Rejection	88.3	65.0	5.3	3.7	?	14.3



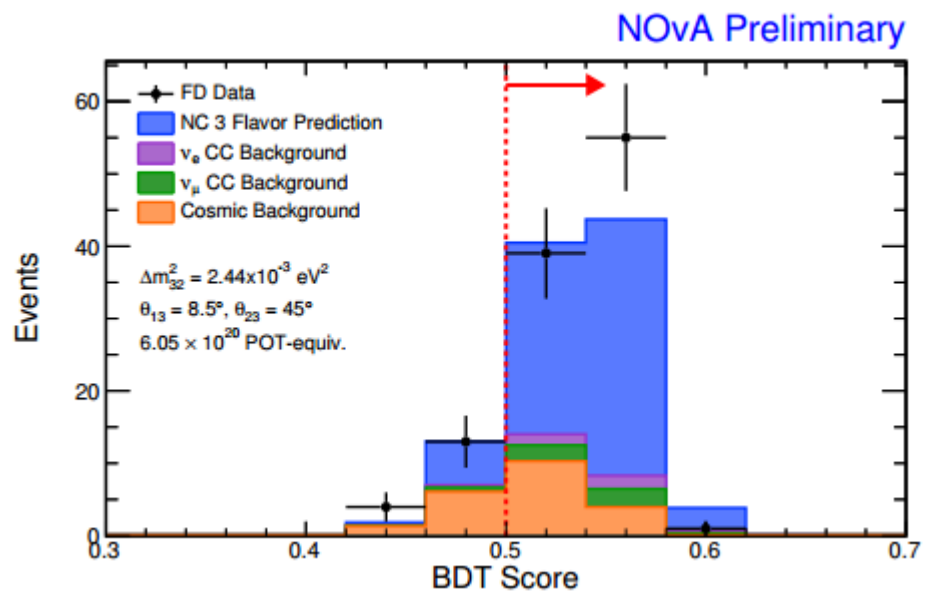
Three-flavour Far Detector extrapolated prediction

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

NC FD Cosmic Rejection



Distribution of average calorimetric energy per hit deposition in a cell

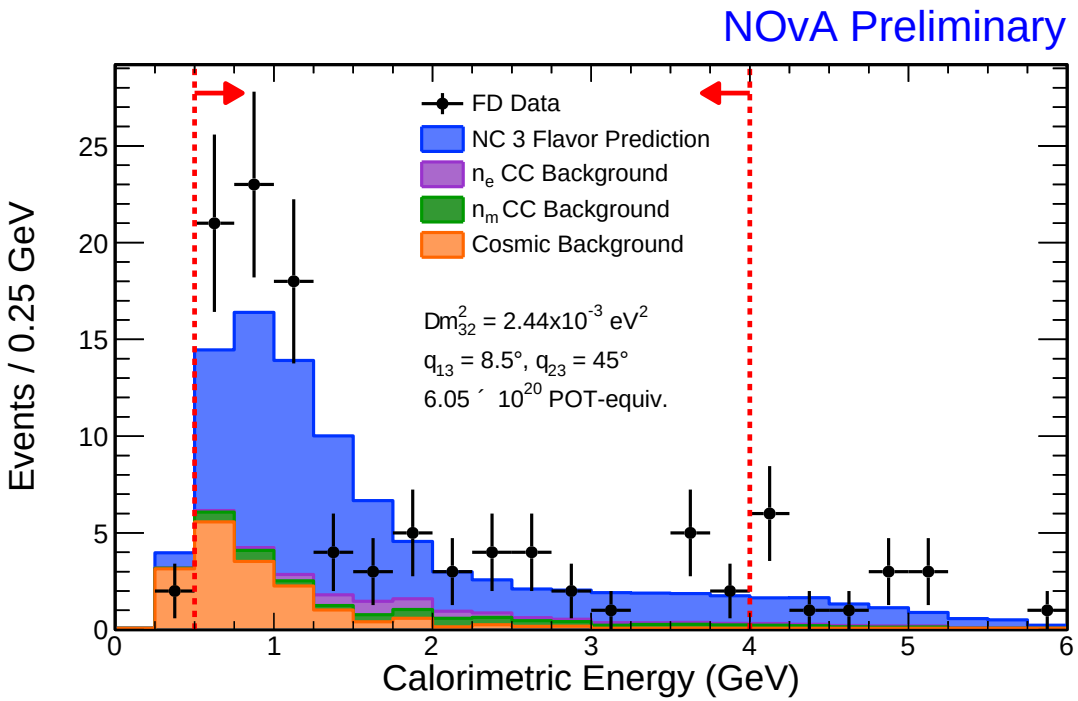


Cosmic PID based on Boosted Decision Tree algorithm sourced from the Numu disappearance analysis used in rejection of cosmic backgrounds. Events with cut> 0.5 are accepted by the selection

Neutral Current FD Data

Observe 95 events

No evidence of oscillations involving steriles



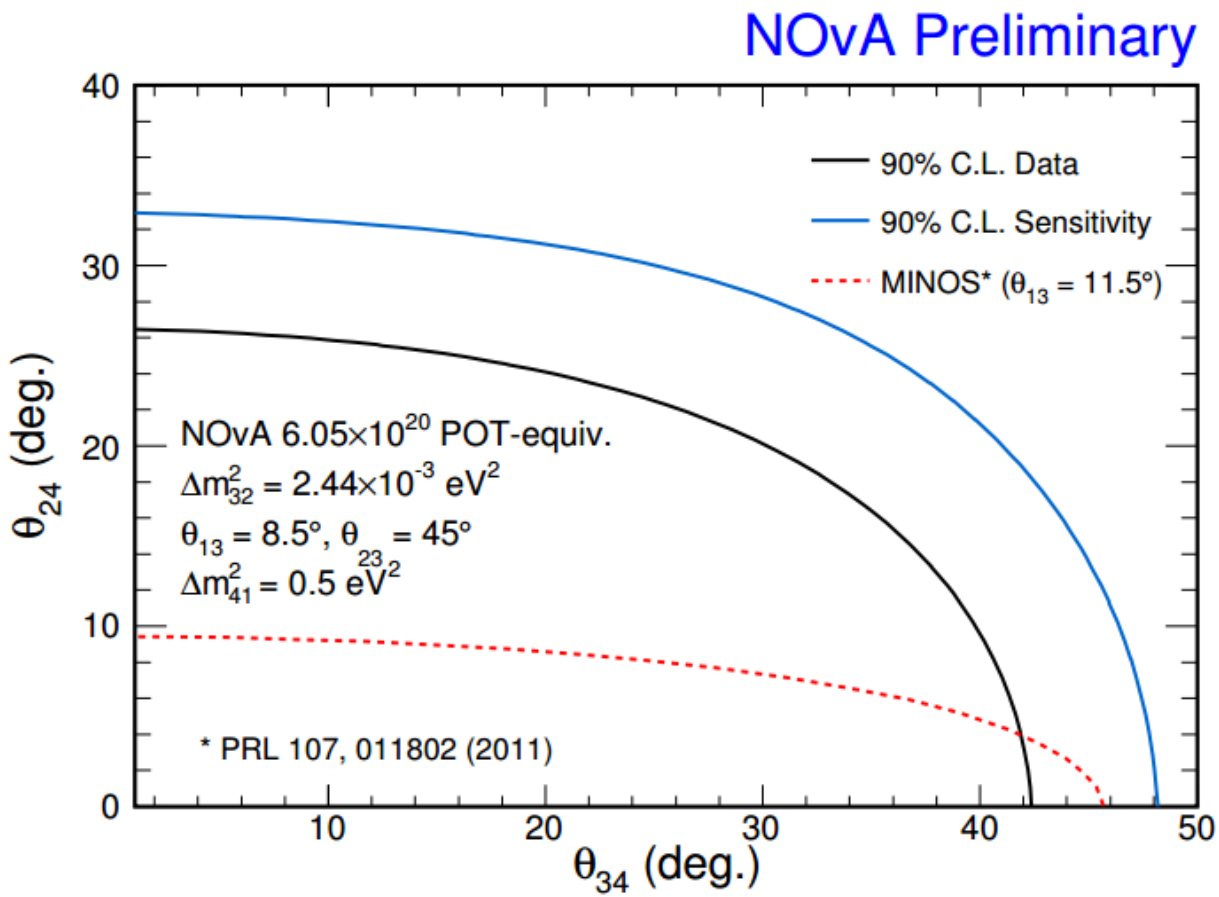
$$R = \frac{N_{data} - BG}{S_{NC}} = 1.19 \pm 0.16(\text{stat.}) \pm 0.11(\text{syst.})$$

$$\text{For } 0.05 \text{ eV}^2 < \Delta m^2_{41} < 0.5 \text{ eV}^2$$

$$\theta_{34} < 35^\circ,\ \theta_{24} < 21^\circ \ (90\%\text{C.L.})$$

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

NC Disappearance 2D limits

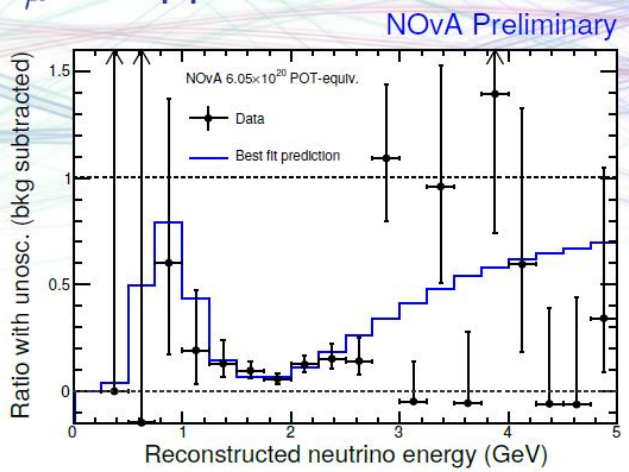


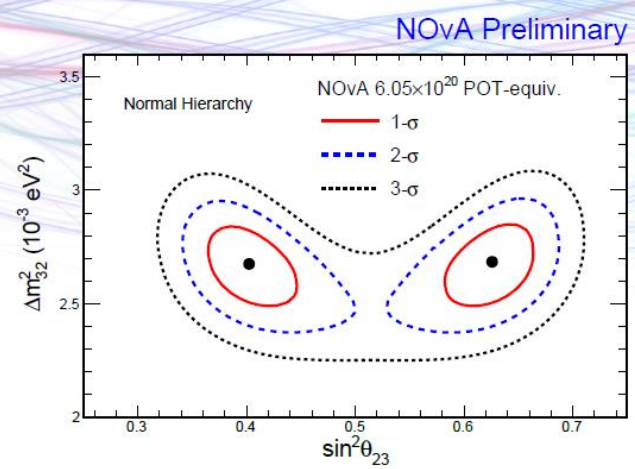
90% C.L. curves obtained by fitting a 3+1-flavor hypothesis with the predicted FD NC spectrum in data. These sensitivities are valid in the range with Δm^2 41 > 0.05 eV^2 and with Δm2 41 < 0.5 eV^2

A word on standard oscillations…

C. Backhouse, JETP seminar 20th July

ν_μ disappearance results





- Expect 473 FD ν_μ CC events with no oscillation
- Observe 82 (inc. 3.7 beam bkg. and 2.9 cosmic)

$$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3}\text{eV}^2 \text{ (NH)}$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}\ (0.63^{+0.02}_{-0.03})$$

- Maximal mixing excluded at 2.5σ (FC corrections in progress)

C. Backhouse (Caltech) NOvA 26 / 43

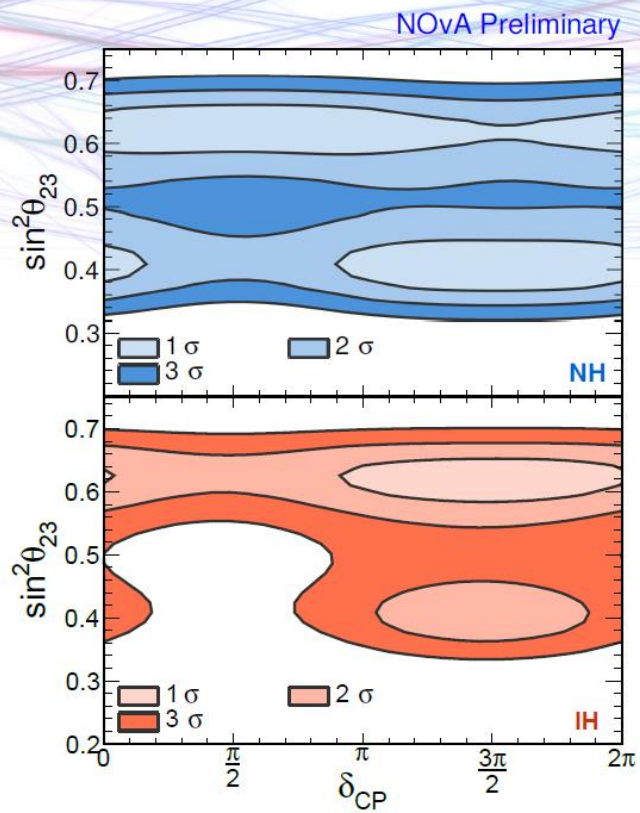
A word on standard oscillations…

C. Backhouse, JETP seminar 20th July

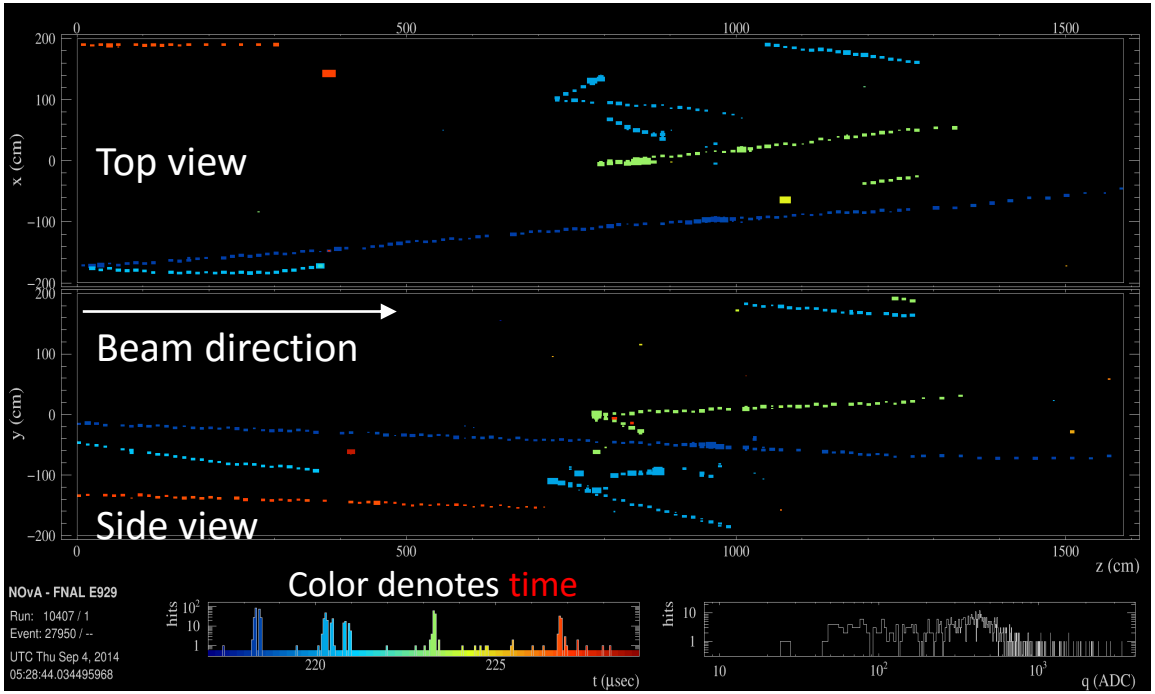
ν_e fit results

- Constrain θ_{13} to reactor average $\sin^2 2\theta_{13} = 0.085 \pm 0.005$
- Add $\Delta m^2_{32}/\theta_{23}$ results from ν_μ analysis
- Not a full joint fit. No syst./osc. param correlations. No FC.

- Prefer NH, not statistically significant $\Delta\chi^2 = 0.46$
- Exclude region in IH, lower octant, around $\delta_{CP} = \pi/2$ at 3σ



C. Backhouse (Caltech) NOvA 42 / 43

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