First Active to Sterile Neutrino Search from NOvA using the Antineutrino Beam

Mike Wallbank, University of Cincinnati
for the NOvA collaboration

Joint Experimental-Theoretical Physics Seminar
October 18, 2019

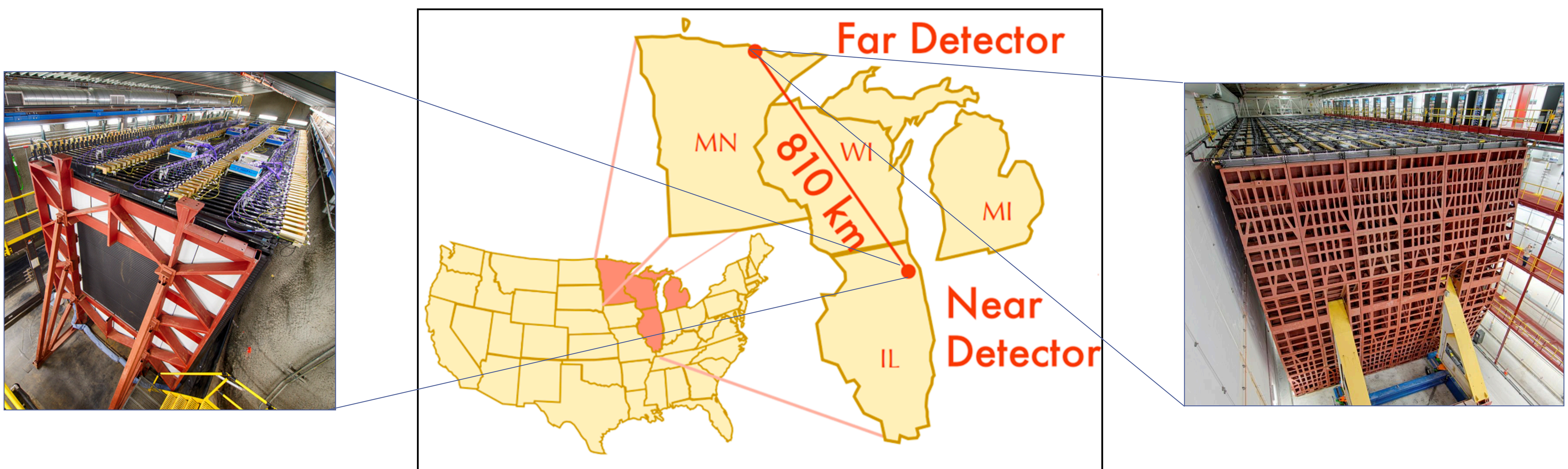
Outline

- NOvA
- NOvA Physics: Neutrino Oscillations
- Sterile Neutrinos, 3+1 Mixing
- Sterile Neutrino Searches
- NOvA Long-Baseline Neutral-Current Disappearance Analysis
- Results in Context

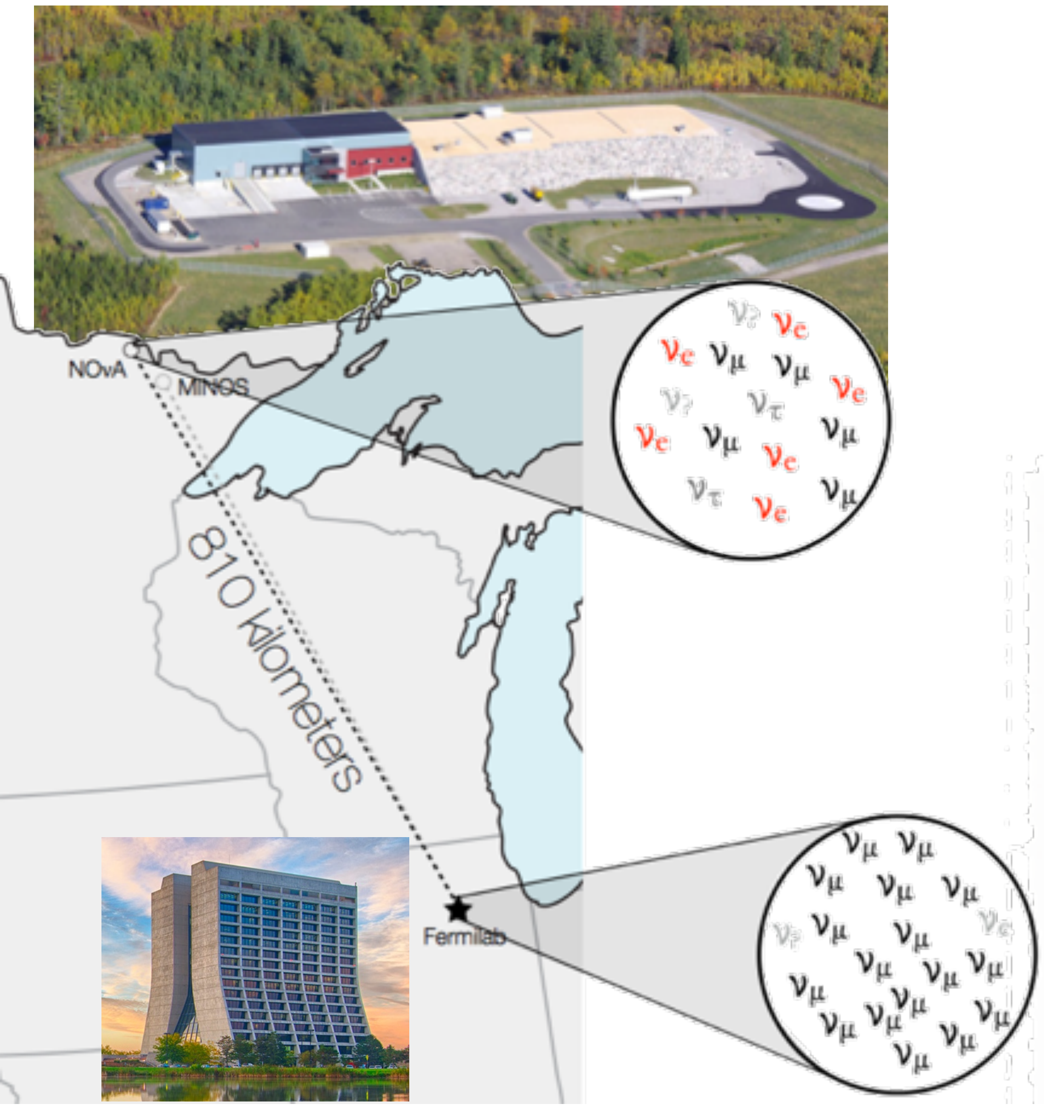
NOvA

NOvA

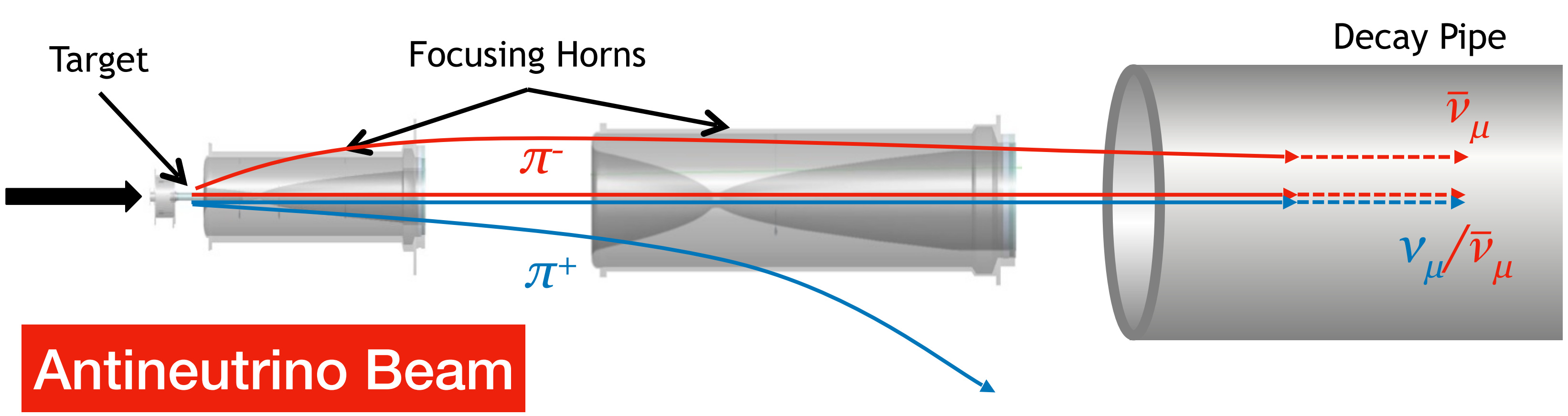
- The NOvA (NuMI Off-Axis ν_e Appearance) experiment is a long-baseline neutrino oscillation experiment based here at Fermilab.
- Rich physics program:
  - Precision Standard Model measurements, mass ordering, leptonic CPV: ν_μ, $\overline{\nu}_\mu$ disappearance, ν_e, $\overline{\nu}_e$ appearance.
  - Sterile neutrino searches: NC disappearance, short-baseline studies.
  - Other searches: supernovae, exotics, cross-sections.

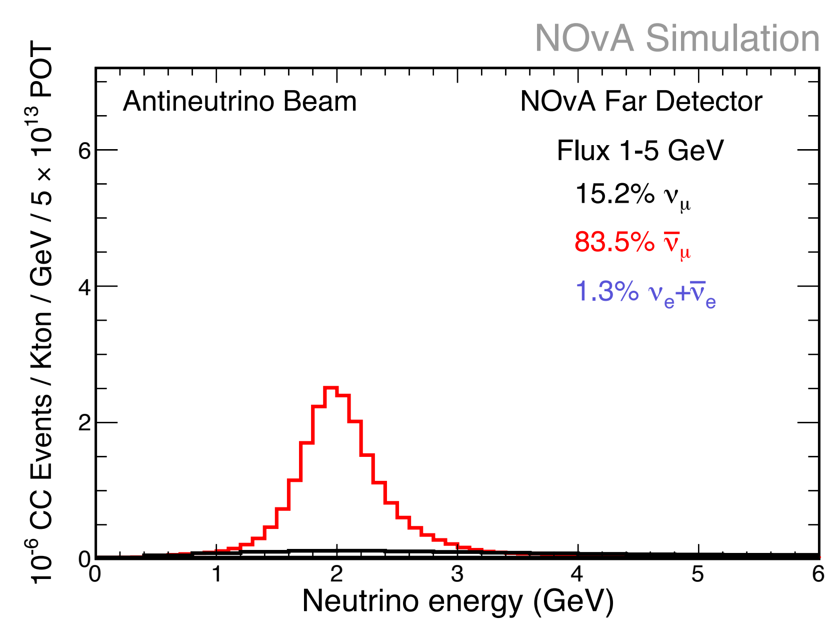


The NOvA Experiment



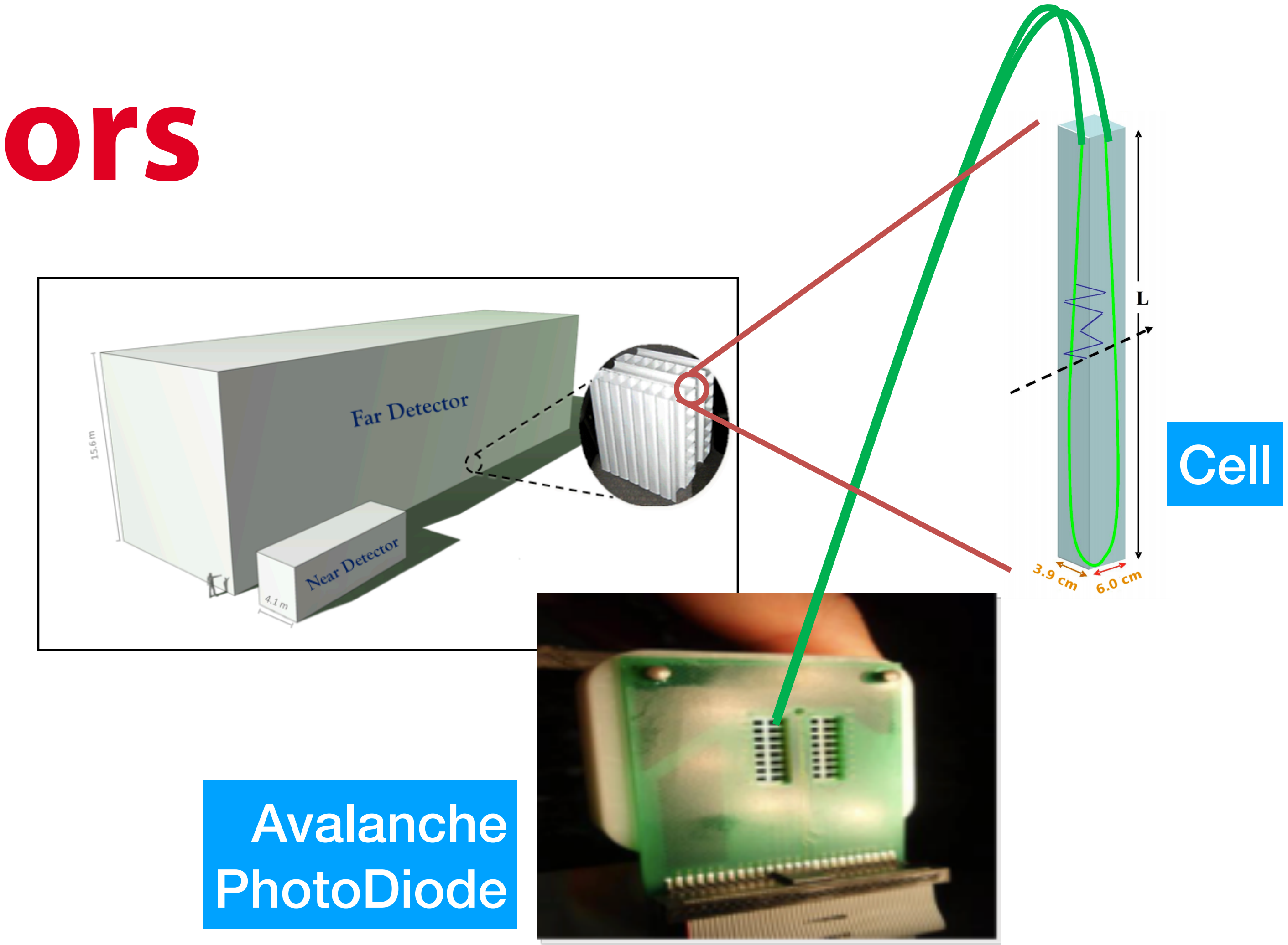
- Two functionally-identical detectors placed in an accelerator-produced neutrino beam, 1 km and 810 km from the source.
  - 14.6 mrad off-axis to produce a more monochromatic energy spectrum, peaked around 1-3 GeV.
- Use Fermilab's NuMI beam, dominated by $\overline{\nu}_{\mu}$.



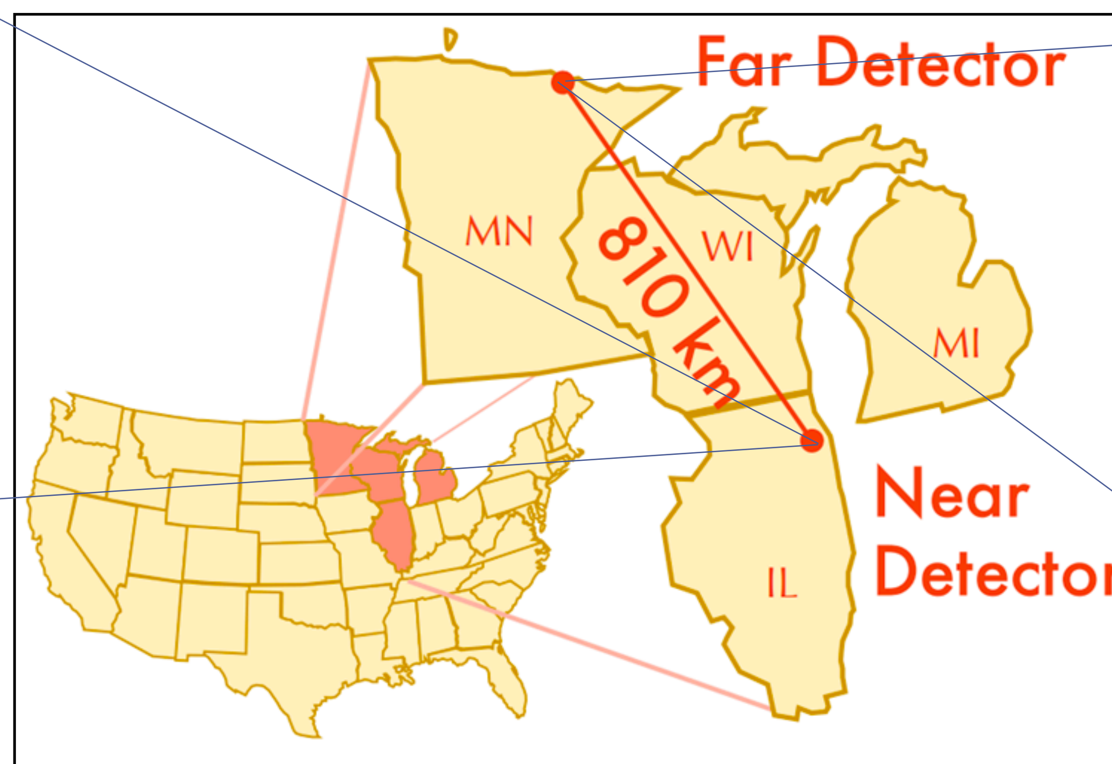


The NOvA Detectors

- Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid filled scintillator, read out out by photodiodes.
- Near Detector (ND) 100 m underground, Far Detector (FD) on surface of Earth.



Near Detector
300 tons
16 m x 4.1 m x 4.1 m
214 layers, ~20,000 channels



Far Detector
14 kton
60 m x 15.6 m x 15.6 m
896 layers, ~344,000 channels

200 collaborators, 7 countries, 33 theses (and counting!)

NOvA

Most recent paper published last week!
https://novaexperiment.fnal.gov/publications/

PHYSICAL REVIEW LETTERS **123,** 151803 (2019)

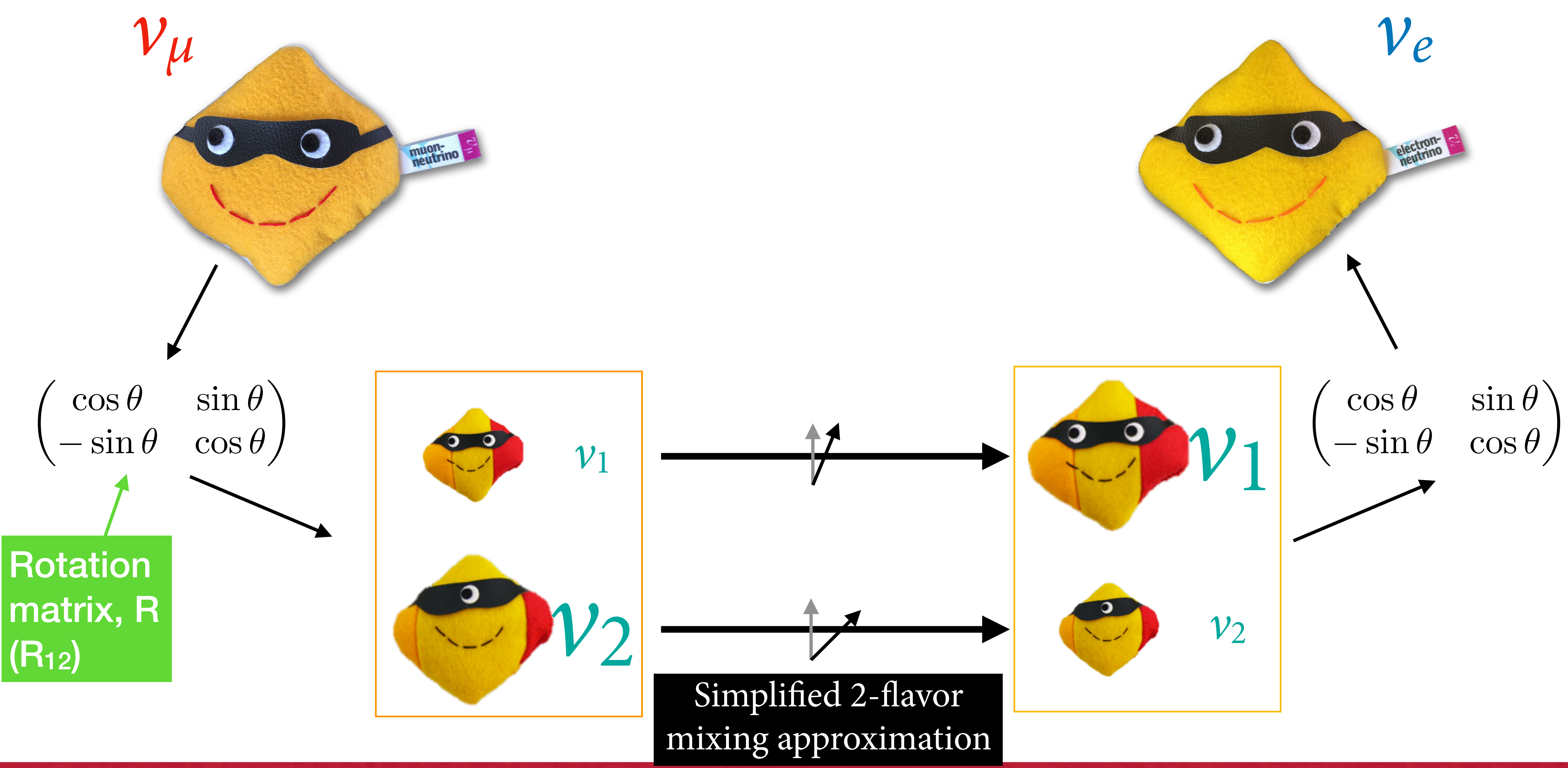
First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA

200 collaborators, 7 countries, 33 theses (and counting!)

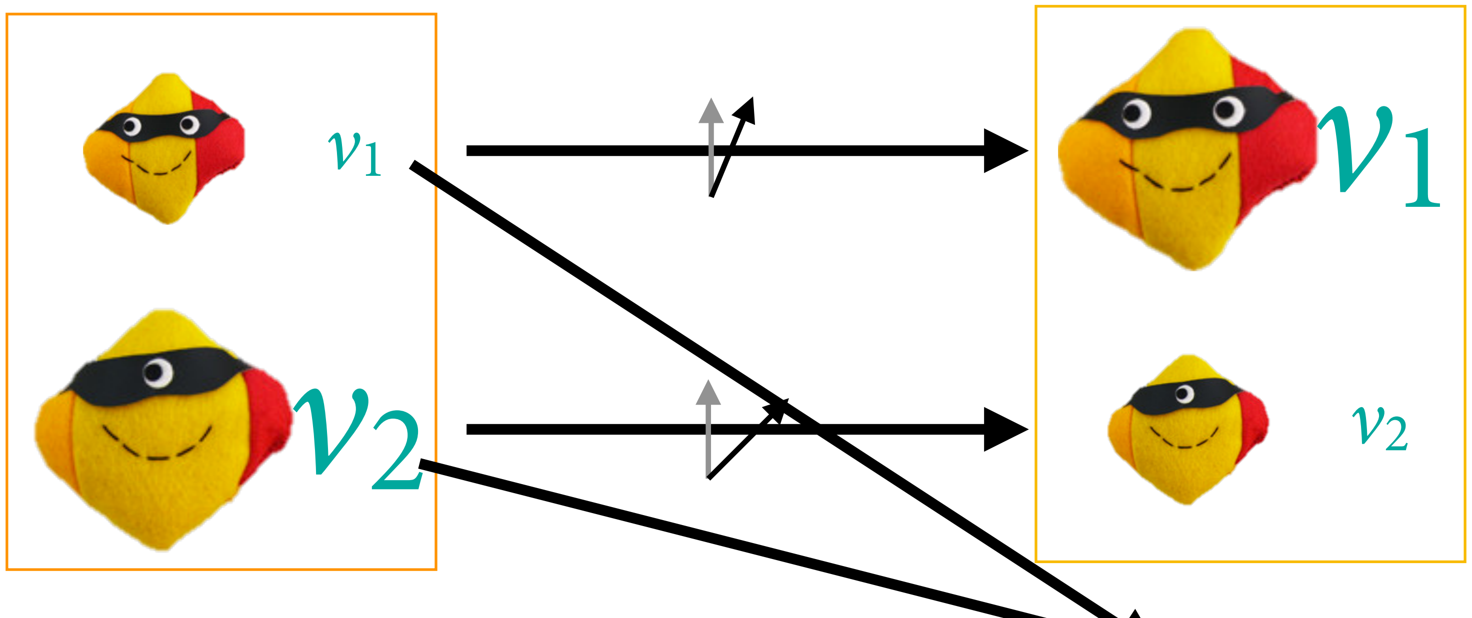
Neutrino Oscillations

Neutrino Oscillations

- Neutrino created in one flavor state (ν_μ) may be detected in another (ν_e).
- Flavor state isn't an eigenstate of the Hamiltonian, rather the mass states are.

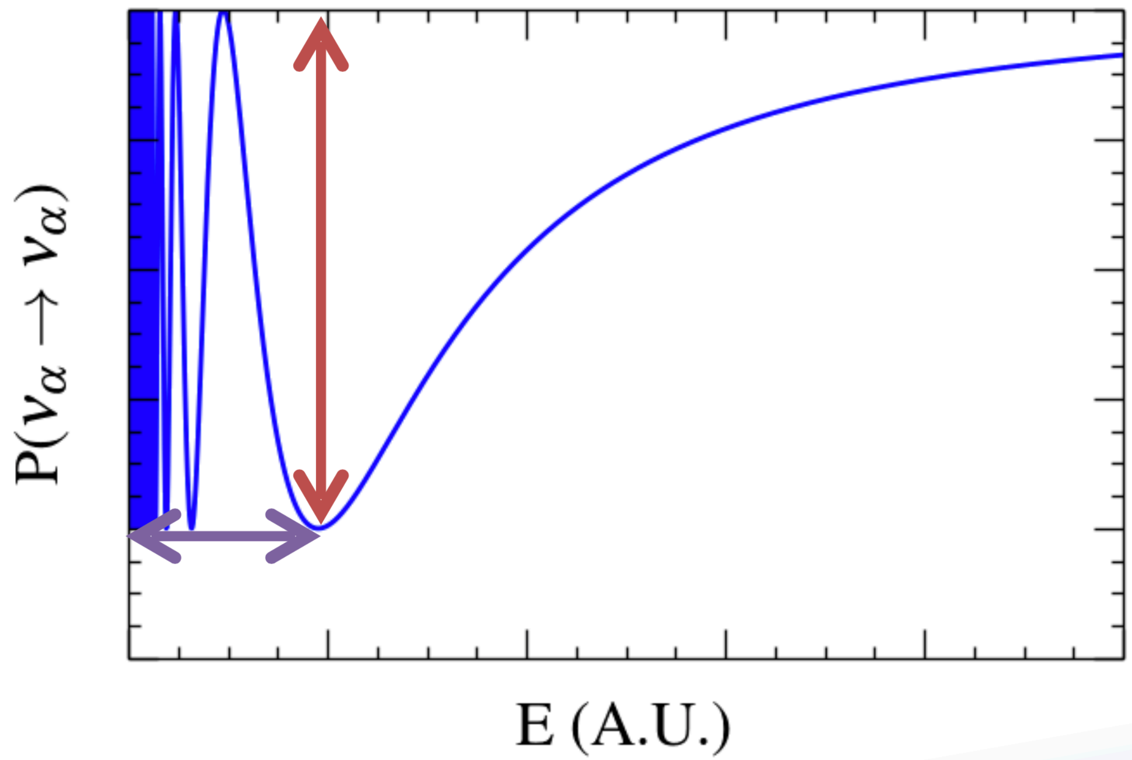


Neutrino Oscillations



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Simplified 2-flavor mixing approximation



- Neutrino oscillations are driven by the difference in mass between the neutrino mass eigenstates -> require neutrinos to have mass.
- Mass splitting drives the frequency of the oscillations, the mixing angle describes the magnitude.

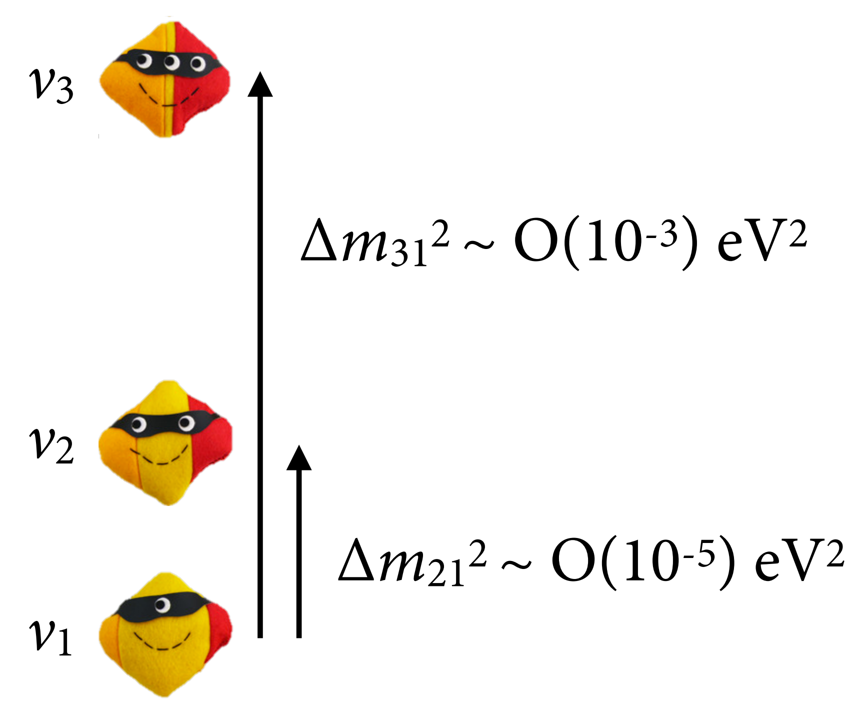
Standard 3-Flavor Neutrino Mixing

- Assume three neutrino flavor states and three neutrino mass states (standard picture):

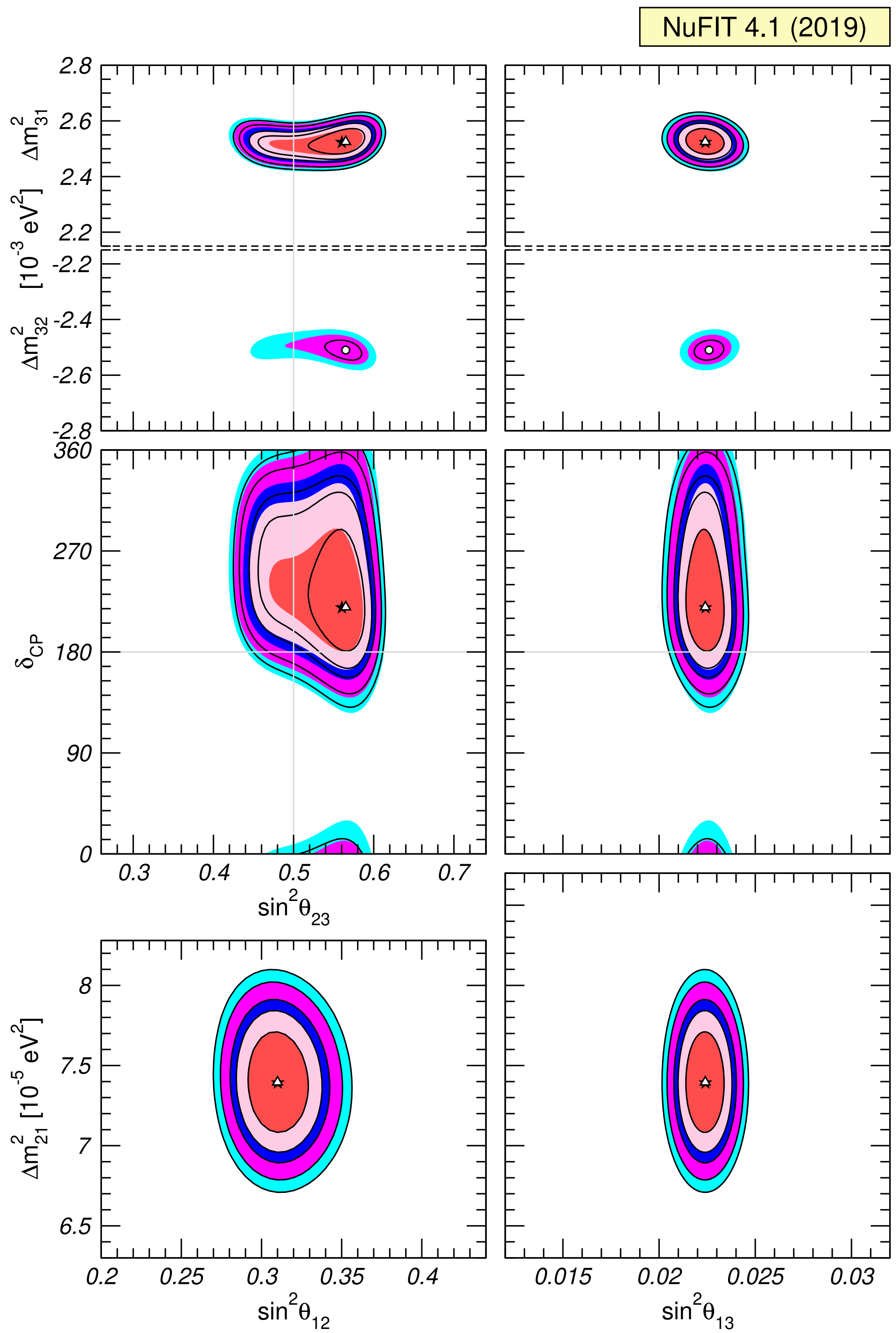
$$= R(\theta_{23})R(\theta_{13}, \delta_{13})R(\theta_{12})$$

- Parameterized by *mixing angles* θ_{13}, θ_{23}, θ_{12}, CP-violating *phase* δ_{13}.

- Oscillations additionally depends on the mass difference between the neutrino states.

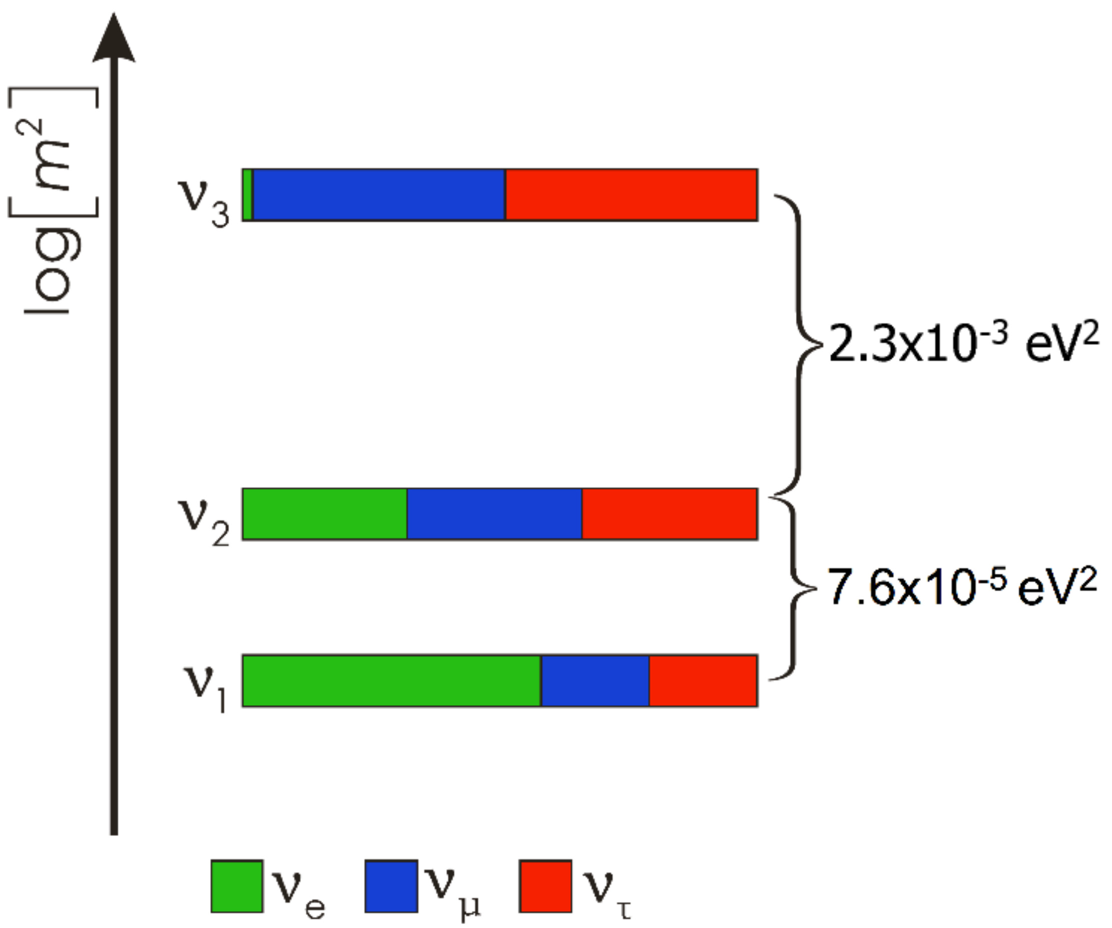


3-Flavor Neutrino Mixing

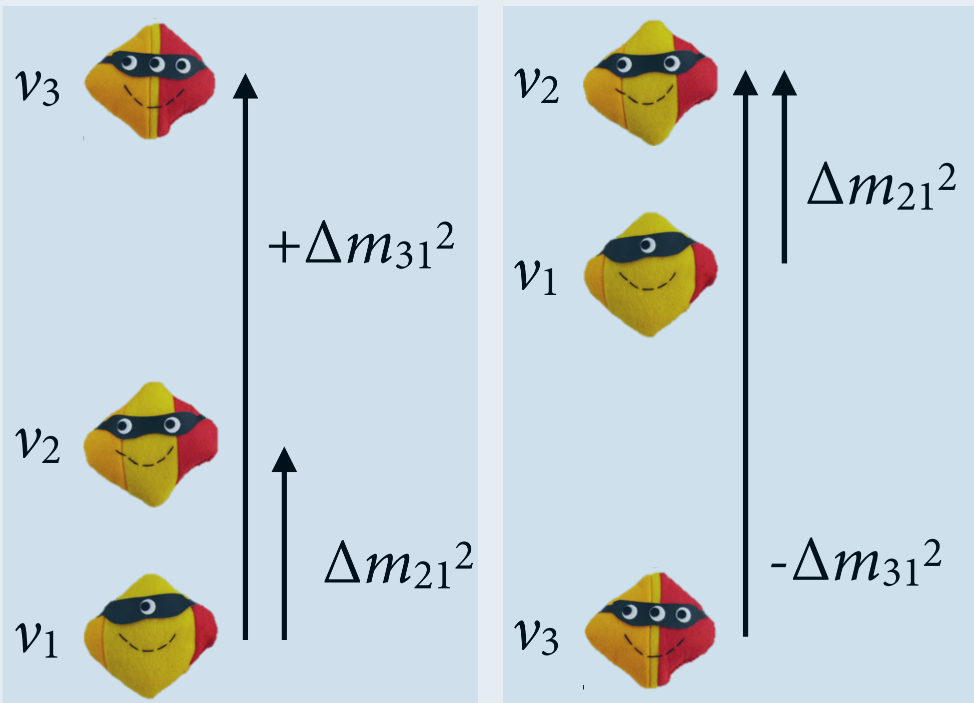


JHEP 01 (2019) 106 arXiv:1811.05487

- Increasingly precise measurements of the parameters governing 3-flavor oscillations over recent years.
- Relatively large mixing in the leptons!

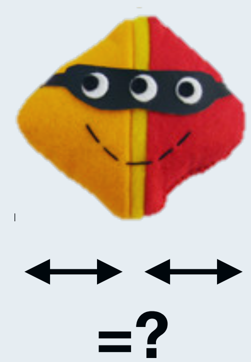


3-Flavor Neutrino Mixing



'Normal' 'Inverted'

Only know sign of one of the mass splitting: two possible 'hierarchies'



θ_{23} could be 45°, implying a deeper symmetry.

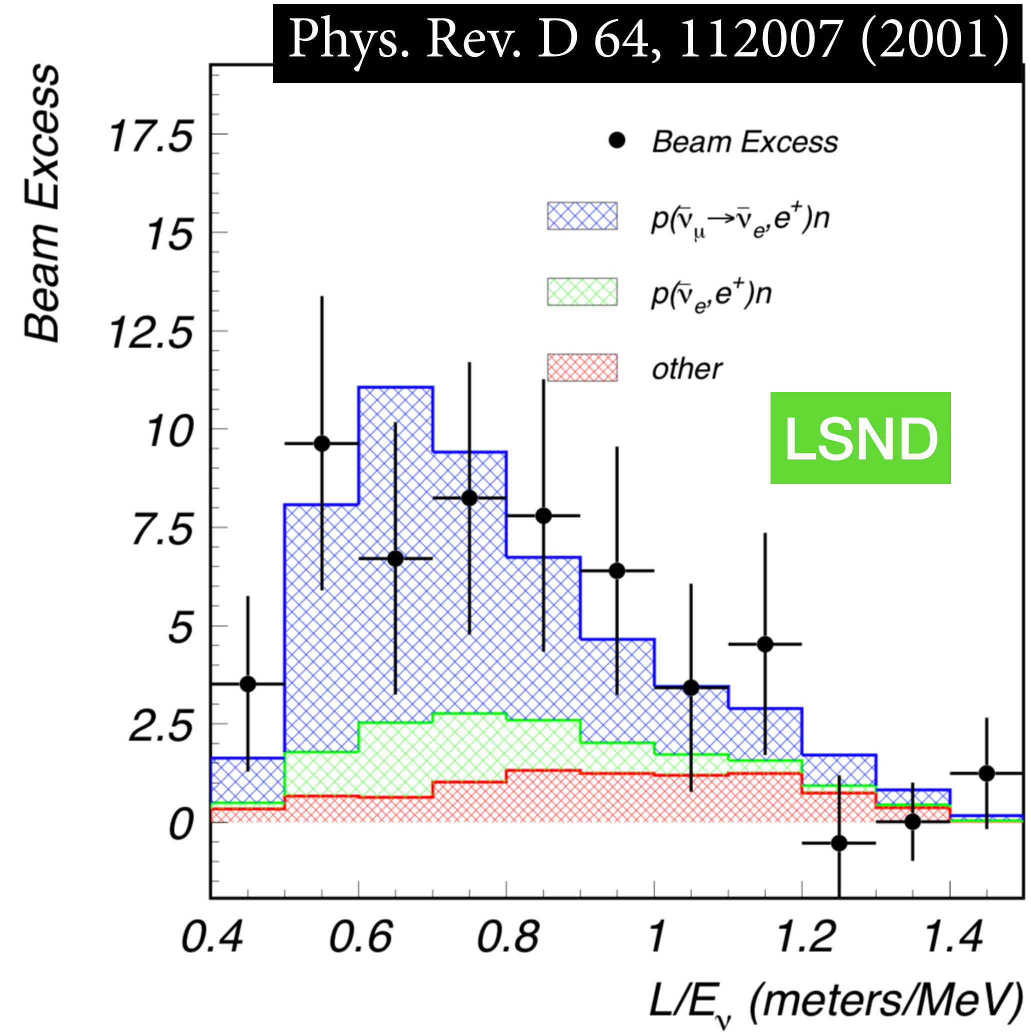
$$P(\nu \to \nu) \stackrel{?}{=} P(\bar{\nu} \to \bar{\nu})$$

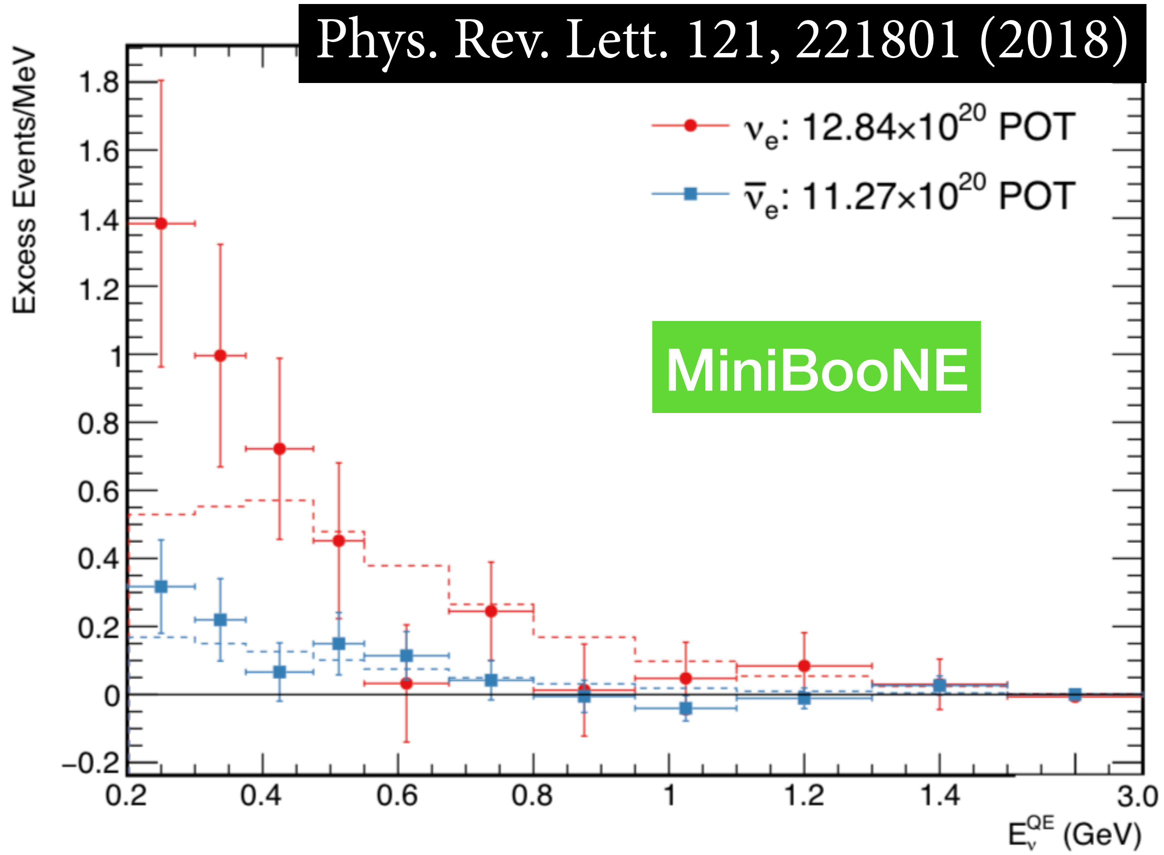
Possibility for CP violation in leptons.

- Other neutrino unknowns which can't be probed using oscillations:
  - absolute mass scale, Dirac or Majorana, mechanism of neutrino mass.

More Than 3 Flavors?

- Most results from neutrino oscillation experiments can be described by mixing in a 3-flavor framework.
- However, anomalous results from LSND and MiniBooNE have observed an excess of ν_e ($\overline{\nu}_e$) events in ν_μ ($\overline{\nu}_\mu$) beams.
- In order to describe these data using oscillations, require a mass splitting $\Delta m^2 \sim O(1)$ eV^2, much larger than the known values of the 3-flavor mass differences.
  - Need a fourth neutrino with the correct mass splitting.



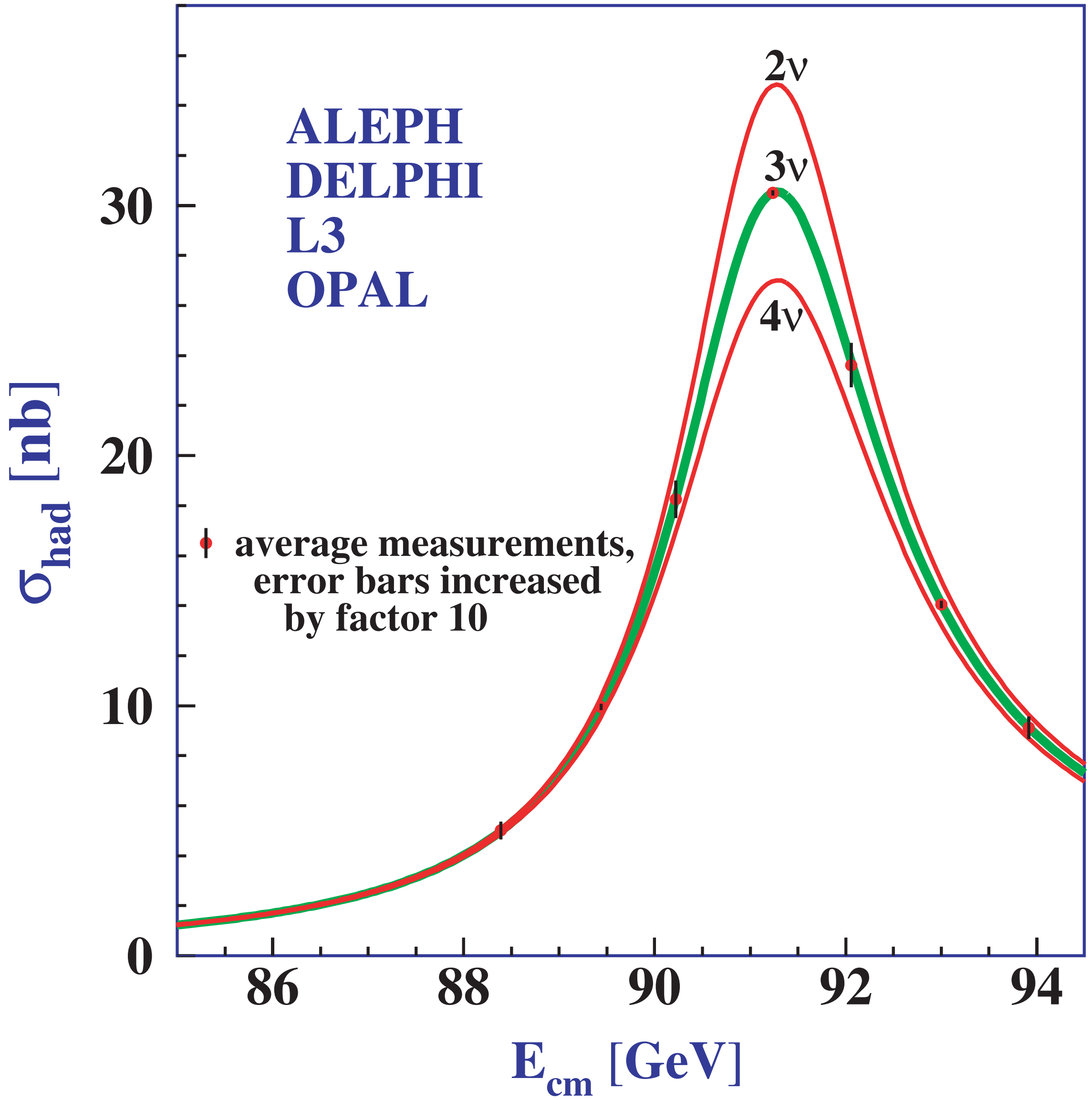


Sterile Neutrinos

- Measurements of the width of the Z decay from the LEP experiments constrained the number of light neutrinos ($M_\nu < M_Z/2$) participating in the weak interaction to be exactly 3.
- Any additional neutrinos must be *sterile*, and not couple to any Standard Model charge.

- Could participate in oscillations with active flavors: $\nu_e \rightarrow \nu_s$, $\nu_\mu \rightarrow \nu_s$, $\nu_\tau \rightarrow \nu_s$.

Phys. Rept. 427, 257-454 (2006)



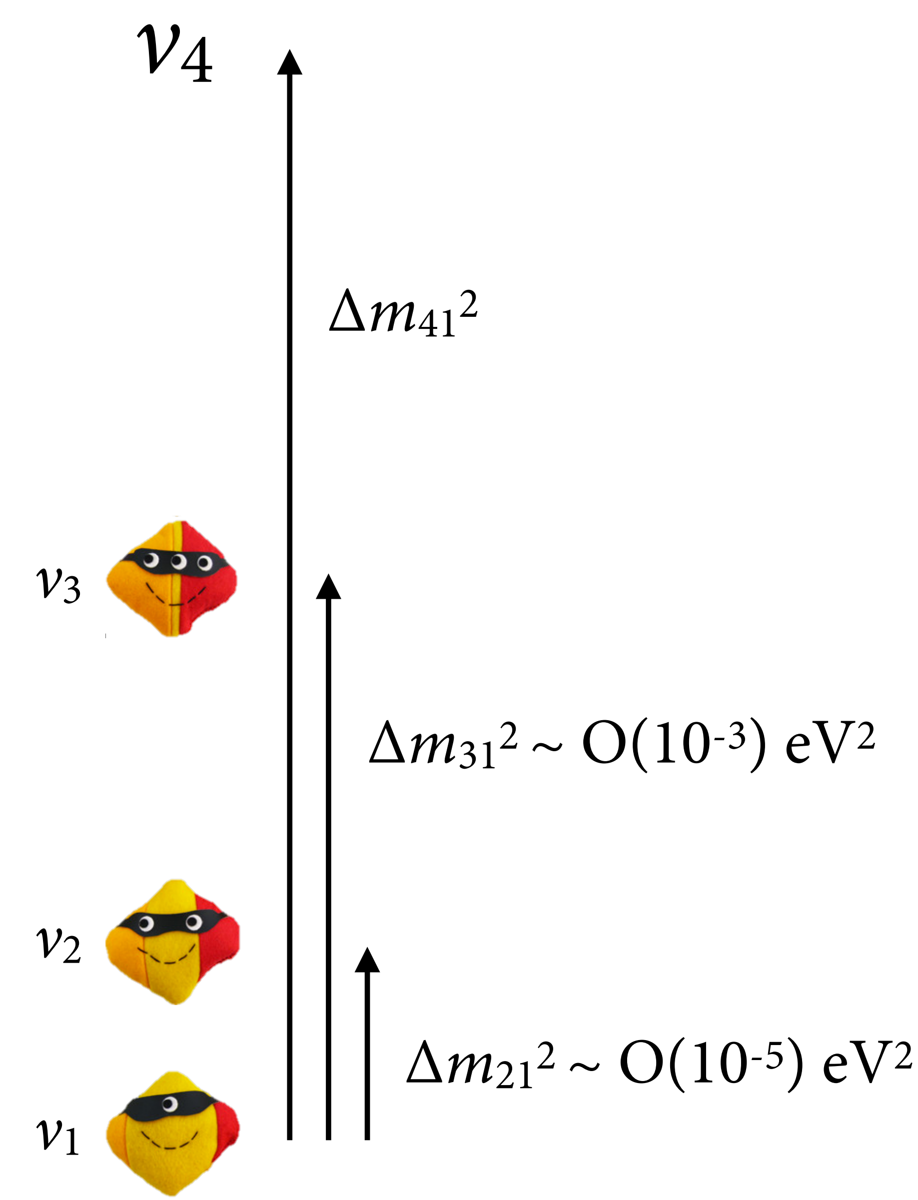
3+1 Neutrino Mixing

- Simplest model is to add a single new neutrino mass state with correct mass difference.

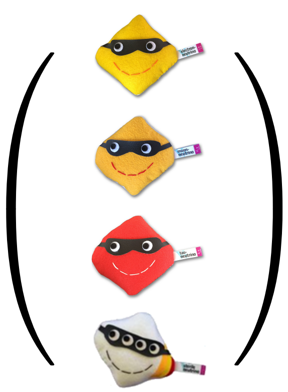
- PMNS mixing matrix increases from 3x3 to 4x4.

$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

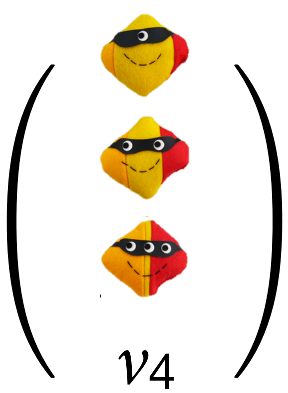
ν_4



3+1 Neutrino Mixing

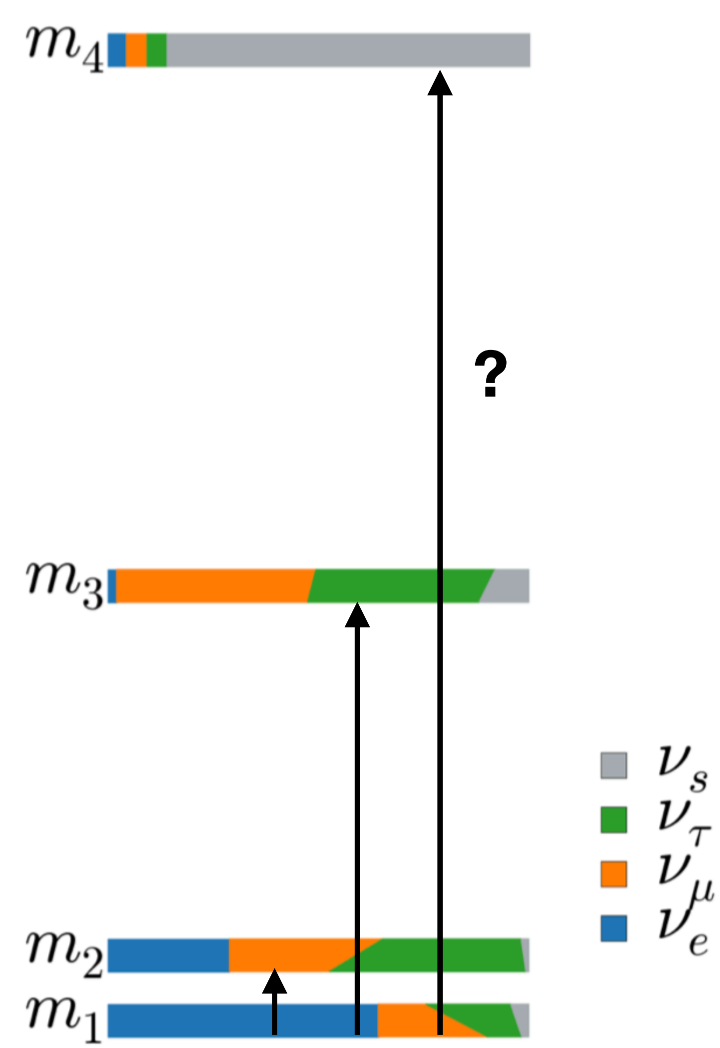


$$= R(\theta_{34})R(\theta_{24},\delta_{24})R(\theta_{14},\delta_{14})R(\theta_{23})R(\theta_{13},\delta_{13})R(\theta_{12})$$



ν_4

- When parameterized using rotation matrices, adds:
  - Three new mixing angles θ_{14}, θ_{24}, θ_{34};
  - Two new CP-violating phases δ_{14} and δ_{24};
- In addition to the new mass splitting $\Delta m_{41}{}^2$.
- In this parameterization, $U_{\mu 4} = \cos^2\theta_{14}\sin^2\theta_{24}$, $U_{\tau 4} = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$.

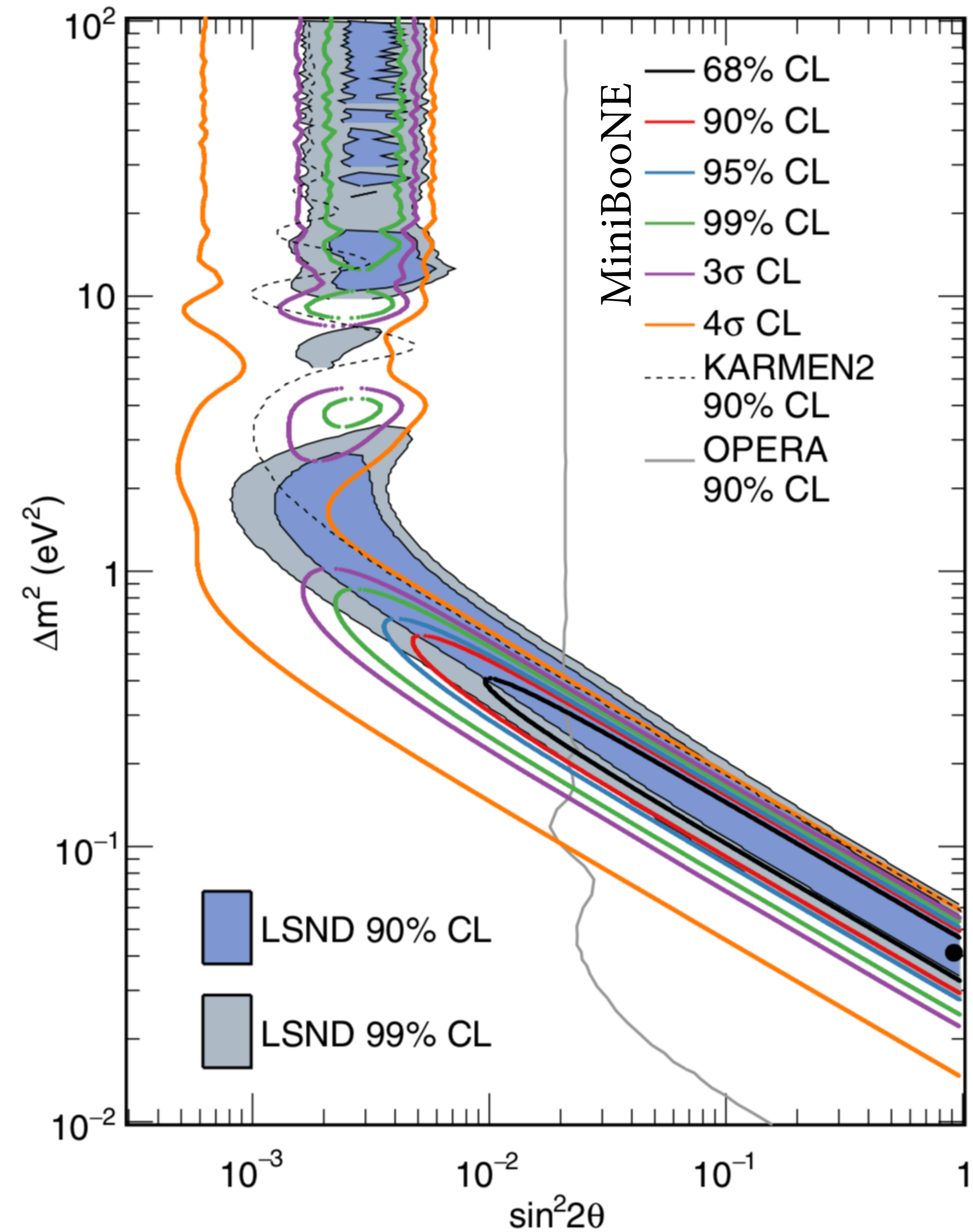


Sterile Neutrino Searches

Searches for Sterile Neutrinos

- Searching for $\nu_e/\overline{\nu}_e$ appearance, $\nu_\mu \rightarrow \nu_e$:
  - Sensitive to θ_{14}, θ_{24}.
- Allowed regions for short-baseline ν_e-appearance oscillations.
- LSND and MiniBooNE results require oscillations driven by a relatively large mass difference.
- These short-baseline observations will be probed further by the Short Baseline Neutrino (SBN) program at Fermilab.

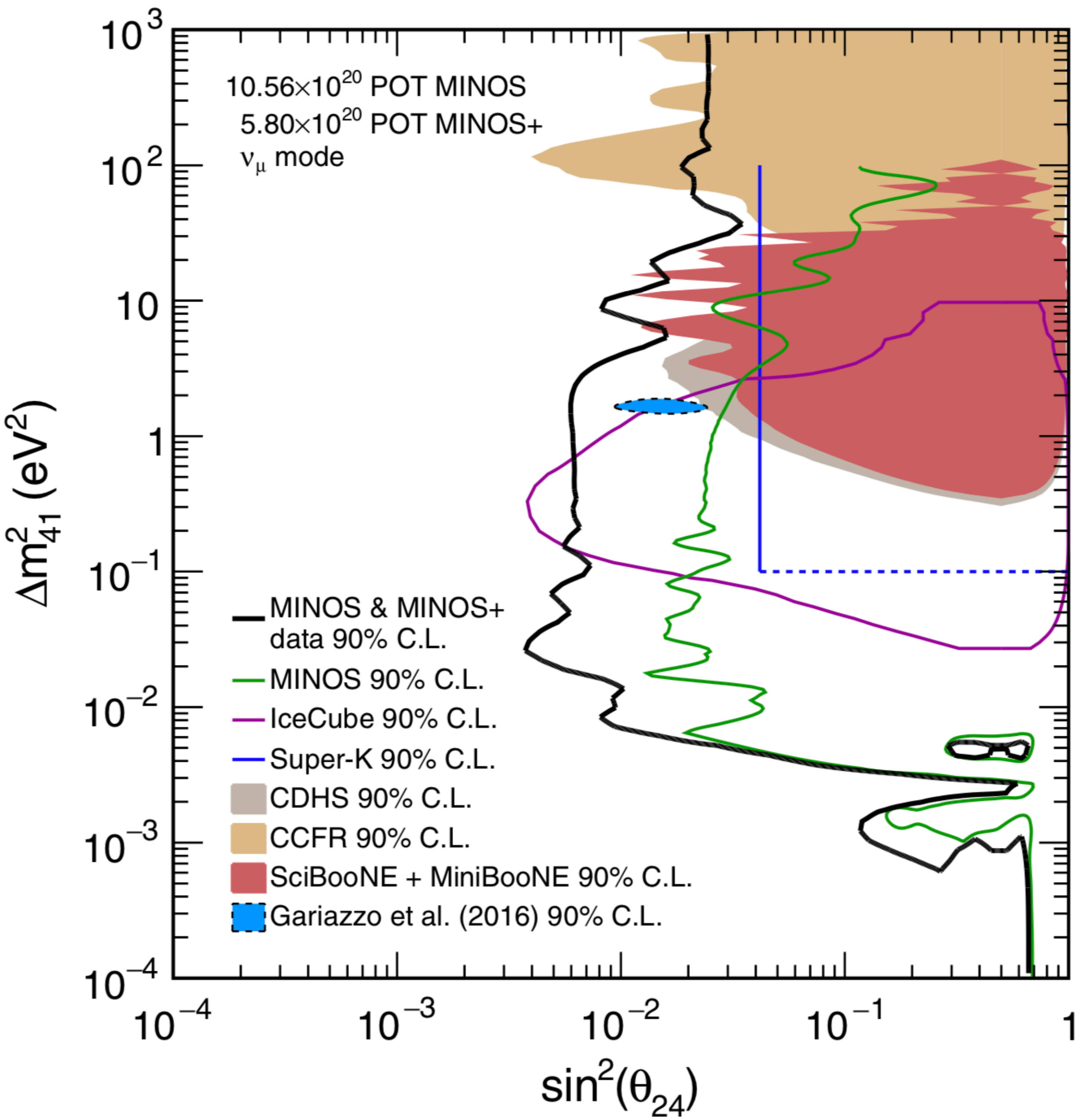
Phys. Rev. Lett. **121**, 221801 (2018)



Searches for Sterile Neutrinos

- Can also probe using disappearance of ν_μ/ $\bar{\nu}_\mu$ in accelerator-based experiments:
  - $\nu_\mu \rightarrow \nu_\mu$: θ_{14}, θ_{24};
  - $\nu_\mu \rightarrow \nu_s$ (NC disappearance): θ_{14}, θ_{24}, θ_{34}.
- Long-baseline disappearance searches have found no evidence of oscillations outside of a 3-flavor mixing framework.
  - Tension between these results and short-baseline appearance suggested by LSND and MiniBooNE.

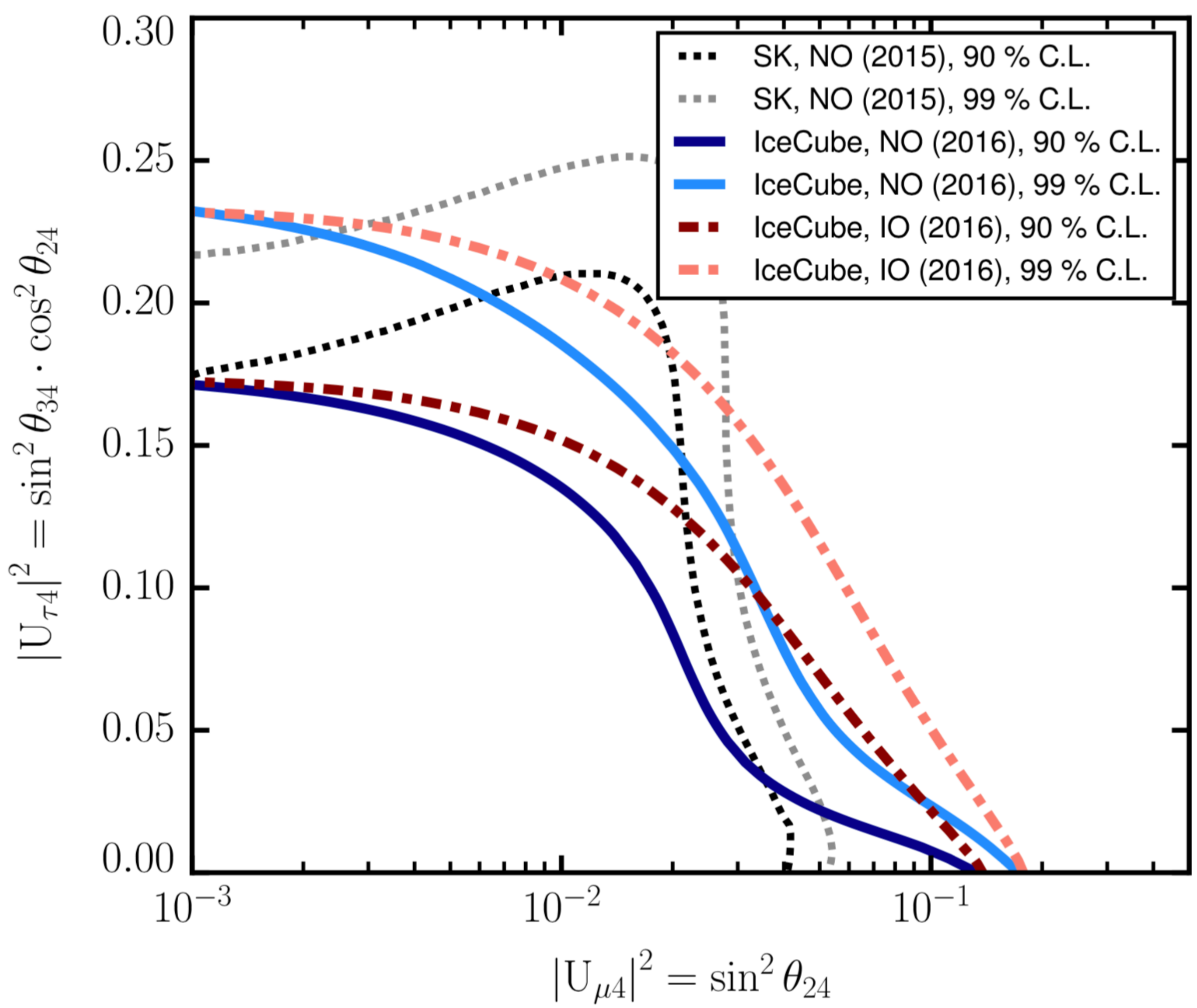
Phys. Rev. Lett. 122, 091803 (2019)



Searches for Sterile Neutrinos

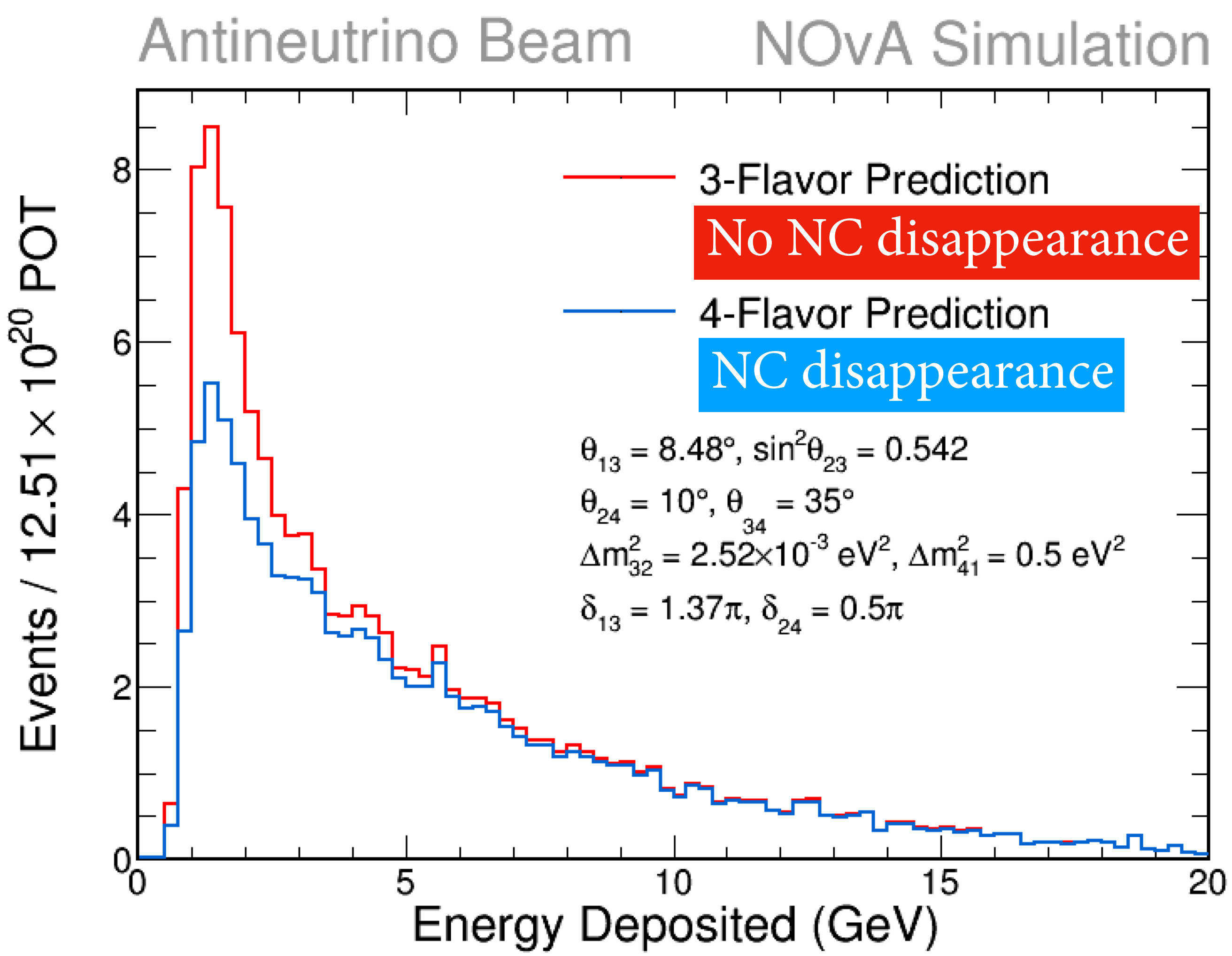
- Atmospheric neutrino experiments can use long-baseline ν_μ disappearance to search for evidence of oscillations outside of 3-flavor mixing.
  - $\nu_\mu \rightarrow \nu_\mu$: θ_{14}, θ_{24};
  - MSW effects θ_{34}.
- SuperKamiokande and IceCube have seen no evidence of sterile neutrino mixing and have set limits in the $|U_{\tau4}|^2$-$|U_{\mu4}|^2$ parameter space.
  - Directly comparable measurement to this analysis.

Phys. Rev. D 95, 112002 (2017)



Long-Baseline Neutral-Current Disappearance

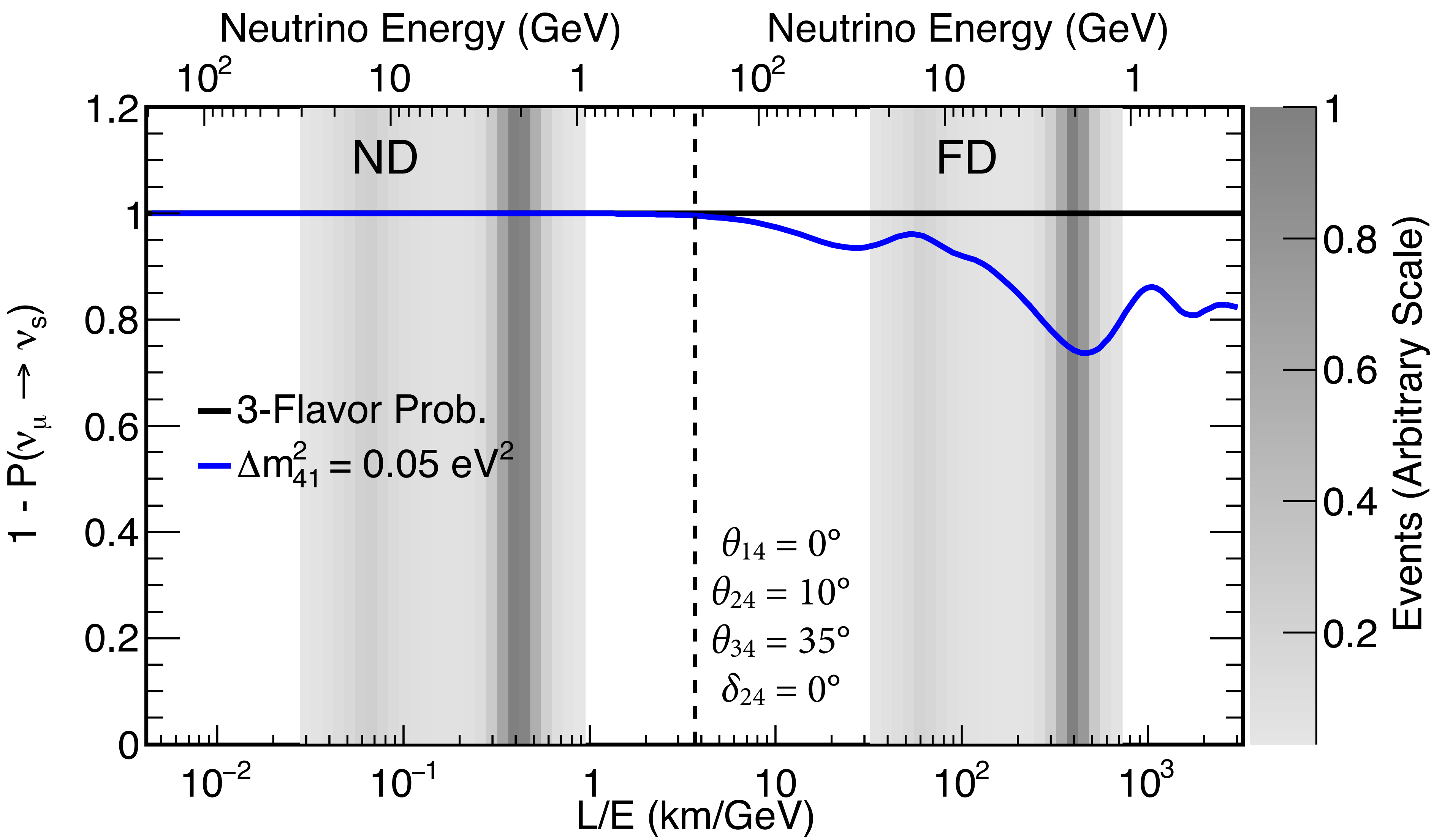
- Neutral Current (NC) interaction rate is the same for the 3 active neutrino flavors — insensitive to 3-flavor oscillations.
- Oscillations to sterile neutrino states will result in deficit in the NC interaction rate.
- Interpreting in 3+1 framework, sensitive to mixing parameters θ_{24}, θ_{34}, Δm^2_{41}, δ_{24} (assuming small θ_{14}, δ_{14}).



$$1 - P^{3+1}_{LBL}(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41} - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin 2\Delta_{31}$$

Approximate disappearance probability
(Exact formalism used in the fit)

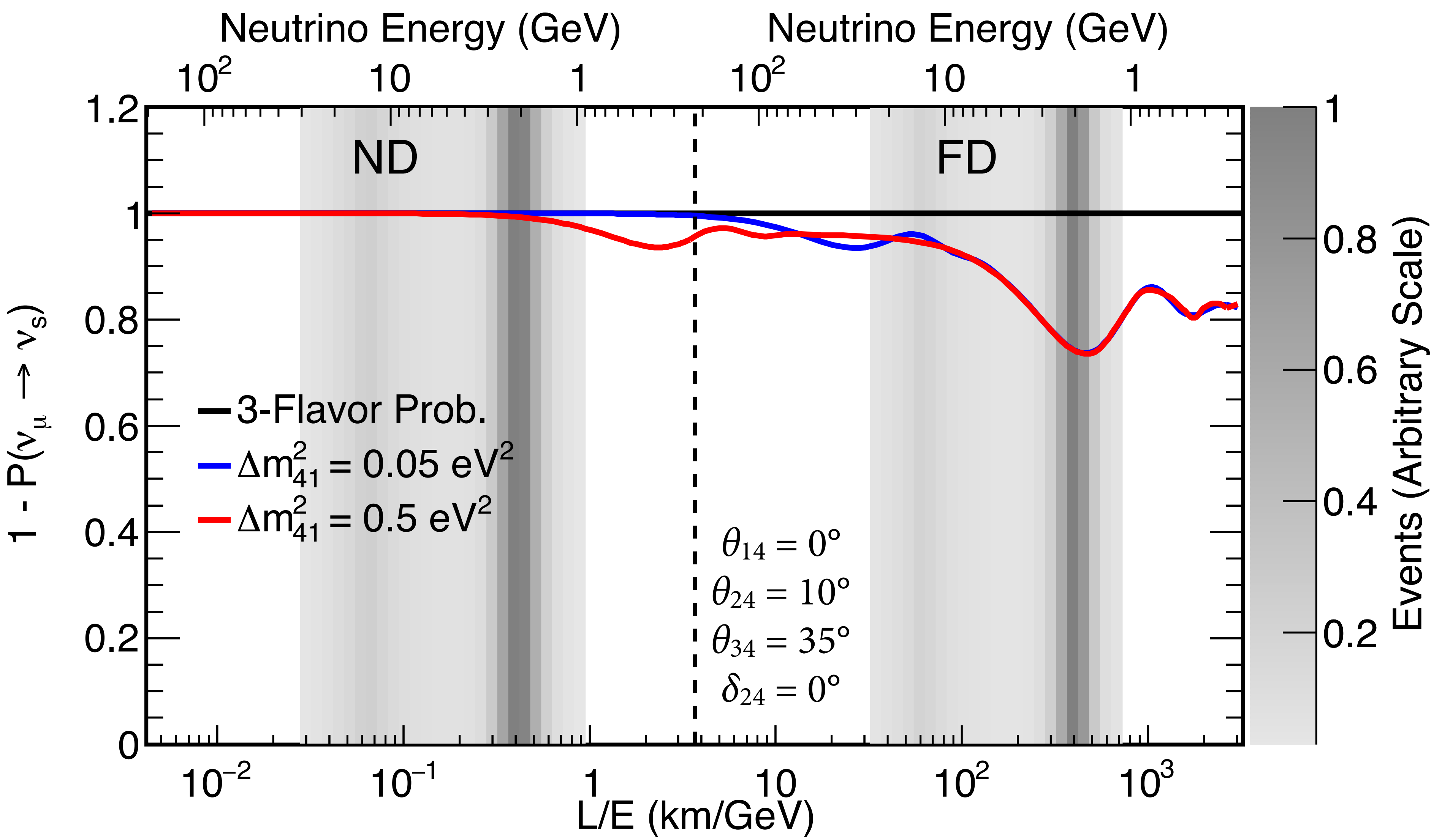
NOvA Oscillation Probabilities



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

- Region $0.05 < \Delta m^2_{41}$ (eV^2) < 0.5;
  - No significant ND oscillations,
  - Rapid oscillations in FD — independent of Δm^2_{41}.

NOvA Oscillation Probabilities



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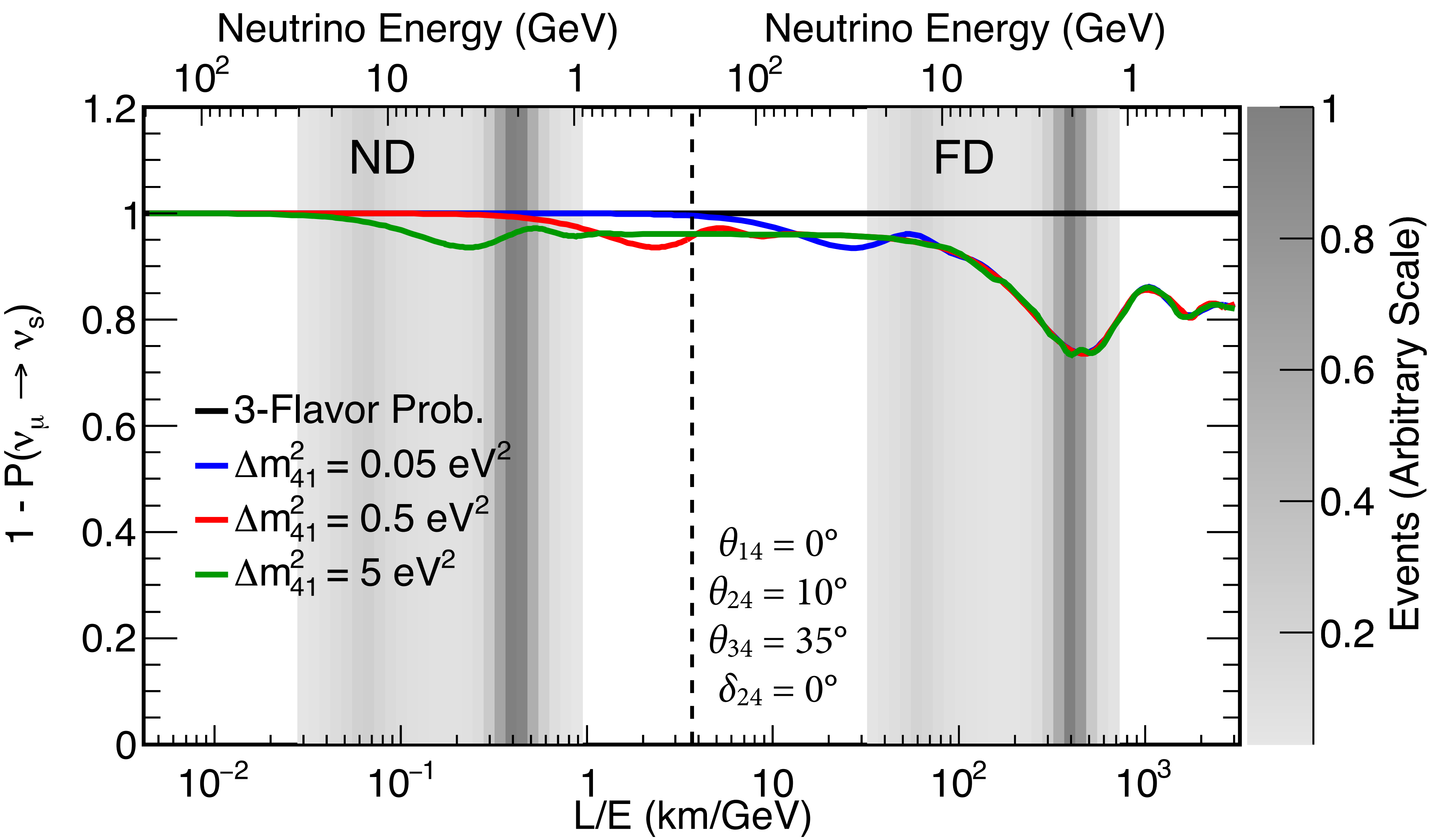

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  - Rapid oscillations in FD — independent of Δm^2_{41}.

$\Delta m^2_{41} > 0.5$ eV^2

- $\Delta m^2_{41} > 0.5$ eV^2;
  - ND oscillations become significant,
  - Dependence on Δm^2_{41}.

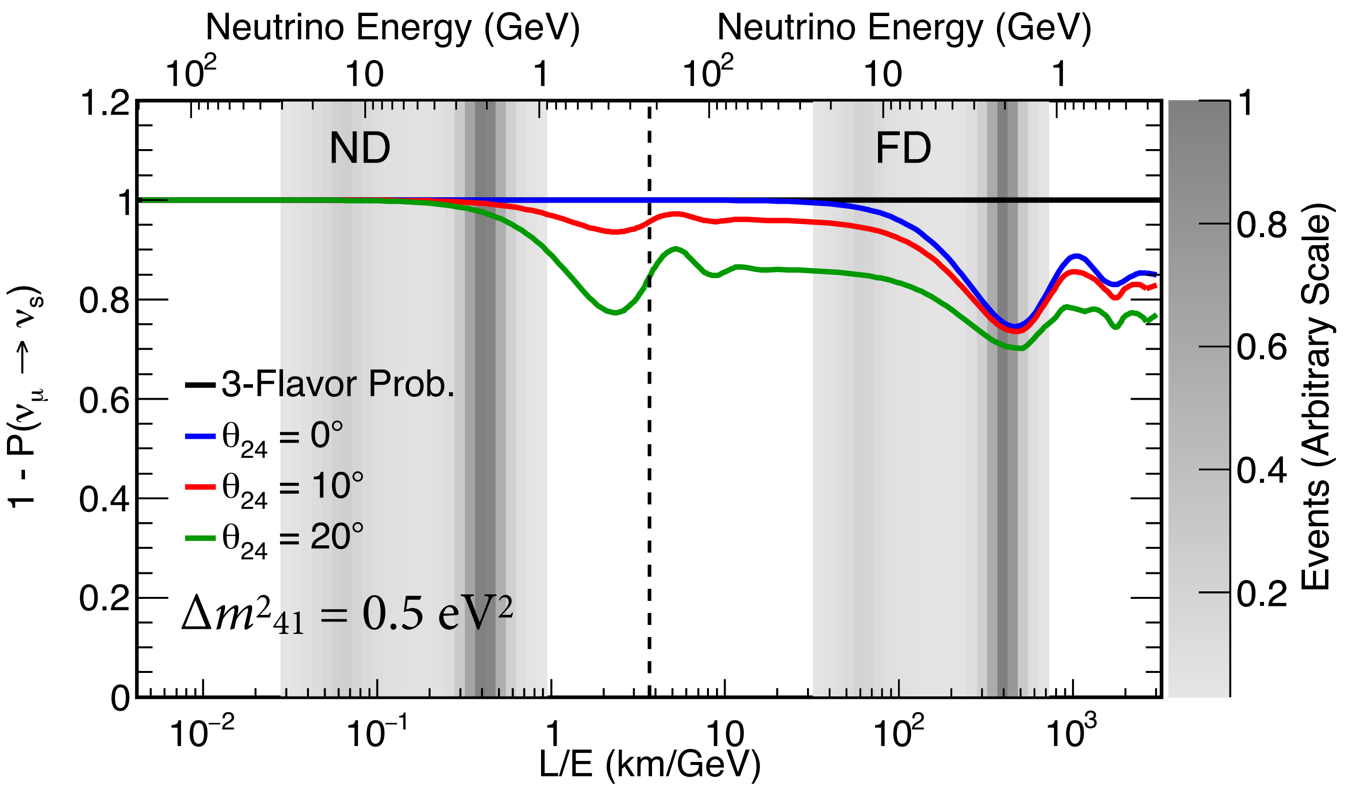
- In this analysis, we don't consider the possibility of oscillations in the Near Detector — limit parameter space to smaller values of the mass splitting Δm^2_{41}.

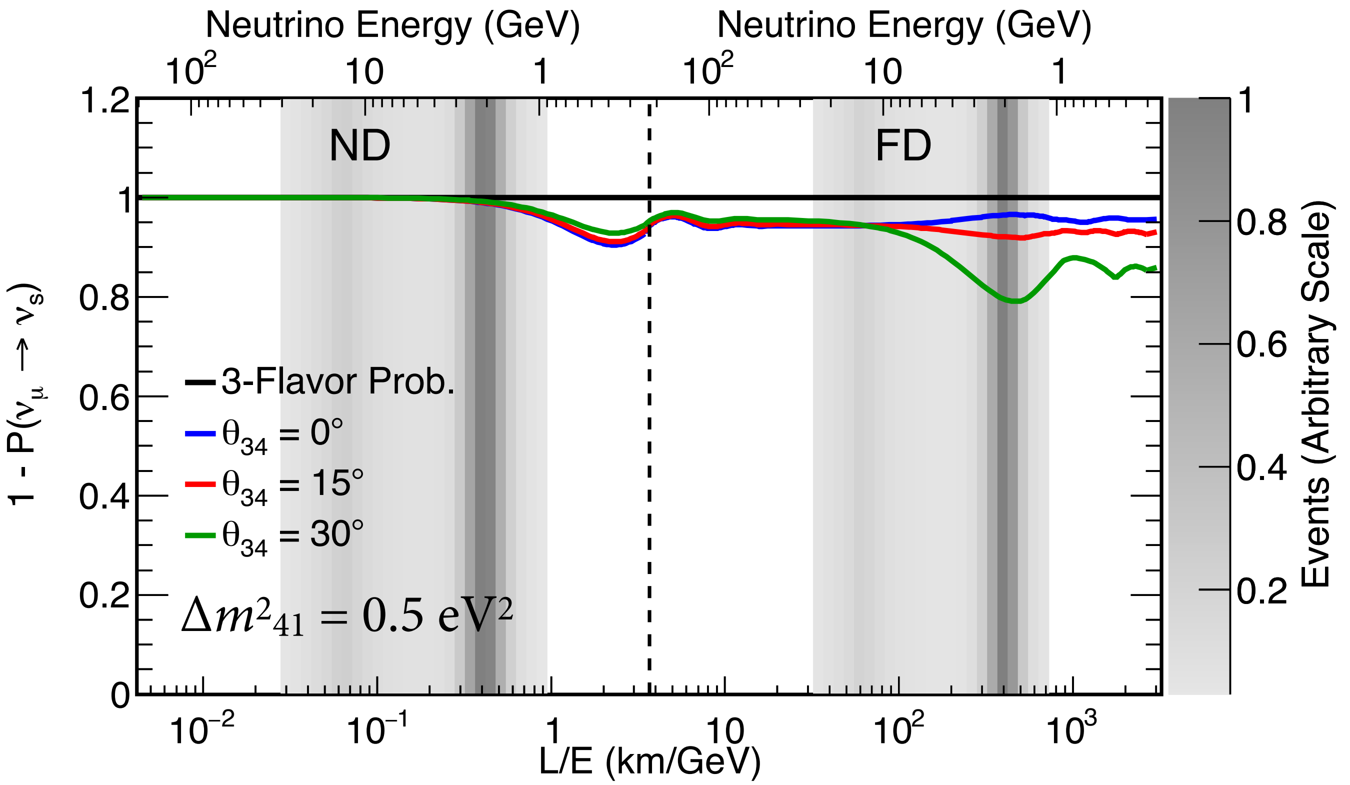
NOvA Oscillation Probabilities

- NOvA has sensitivity to the 3+1 θ_{24} and θ_{34} mixing parameters through changes to the observable interactions following 4-flavor oscillations.

- θ_{24} mostly affects the rate of events in the far detector compared to the near detector, especially in the high energy tail (>2 GeV) of the neutrino spectrum.

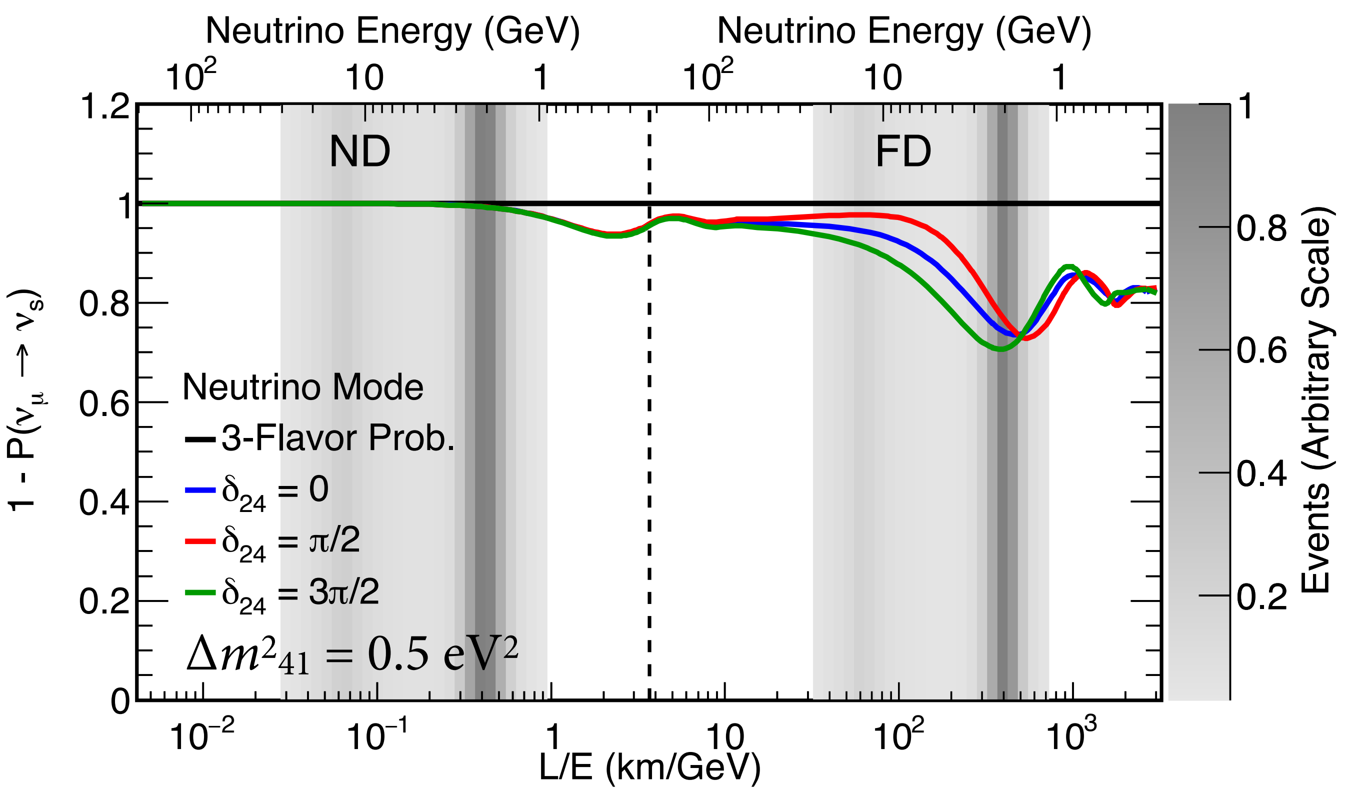
- θ_{34} drastically alters the shape of the energy spectrum of observable events in the far detector.

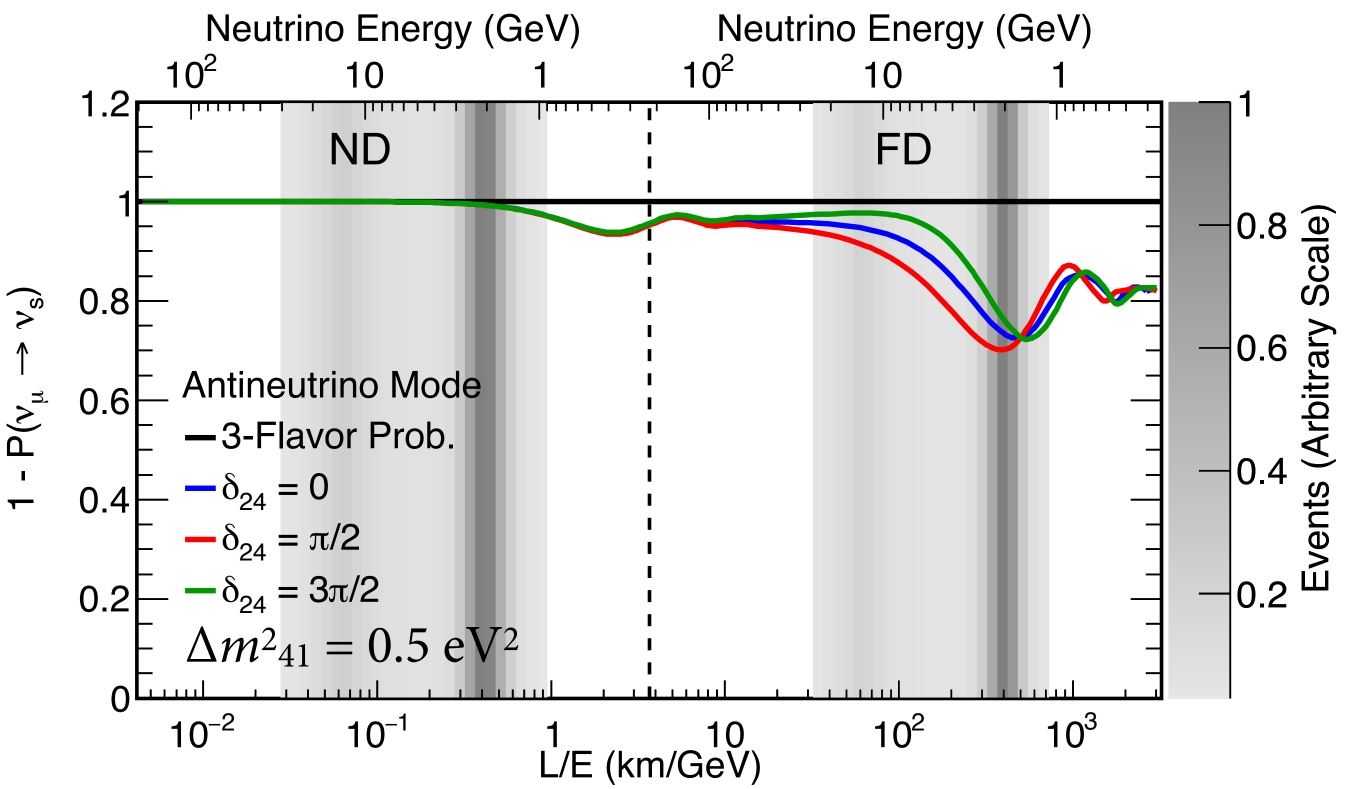




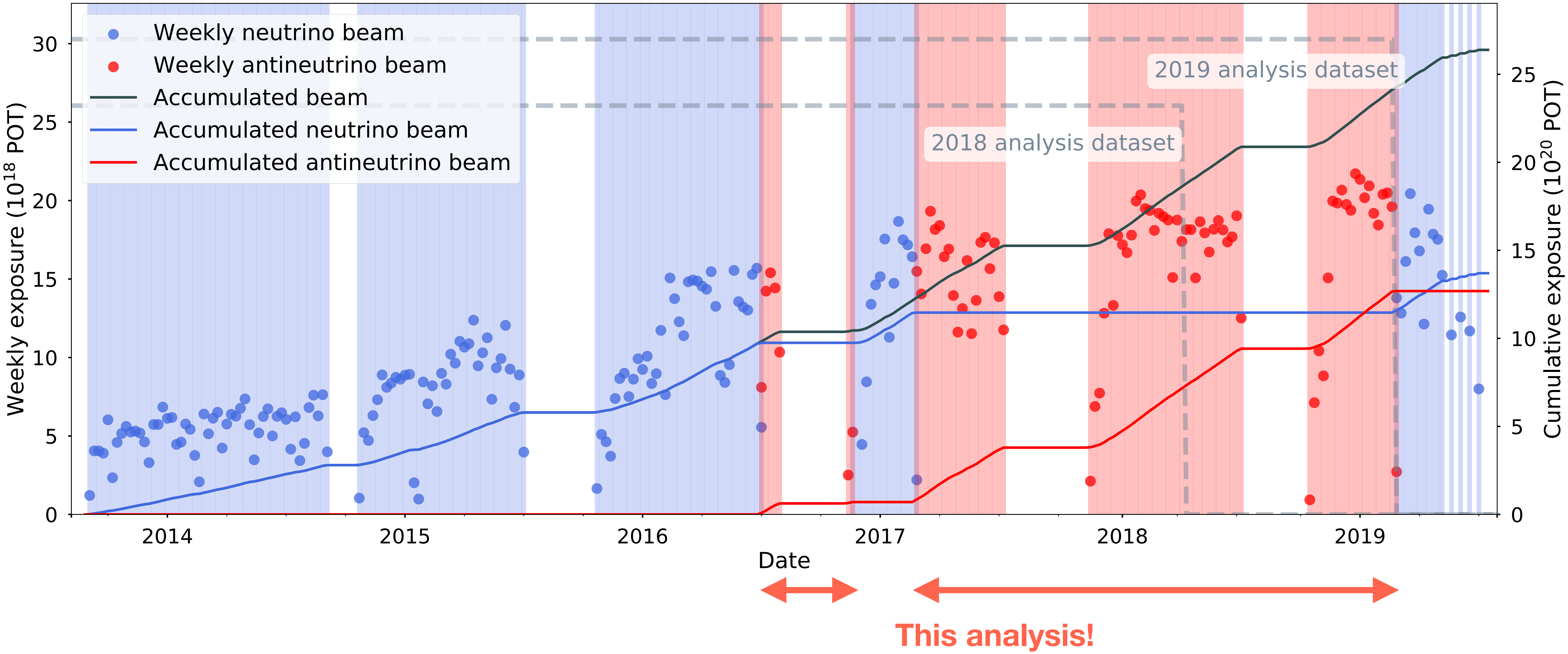
NOvA Oscillation Probabilities

- The CP-violating phase δ_{24} shifts the disappearance maximum, compensating for θ_{24} and θ_{34} effects.
- Shifts are reversed between neutrinos and antineutrinos.
  - Analyzing both can provide additional constraints and help disentangle oscillations from systematics.





NOvA Antineutrino Dataset

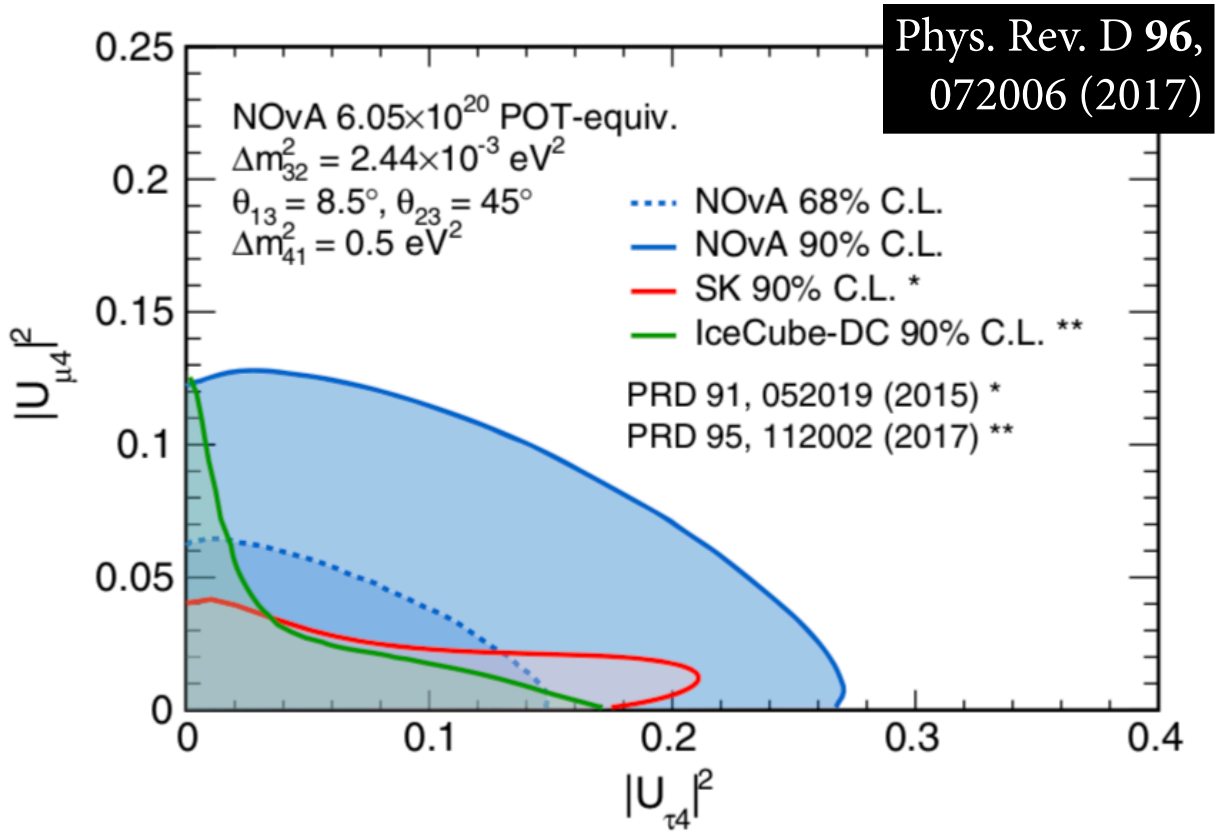


- Thanks to Fermilab for fantastic beam!
- Previous analysis using the **neutrino** dataset.
- This analysis uses the full 12.5×10^{20} POT **antineutrino** dataset.

NOvA Long-Baseline Sterile Searches

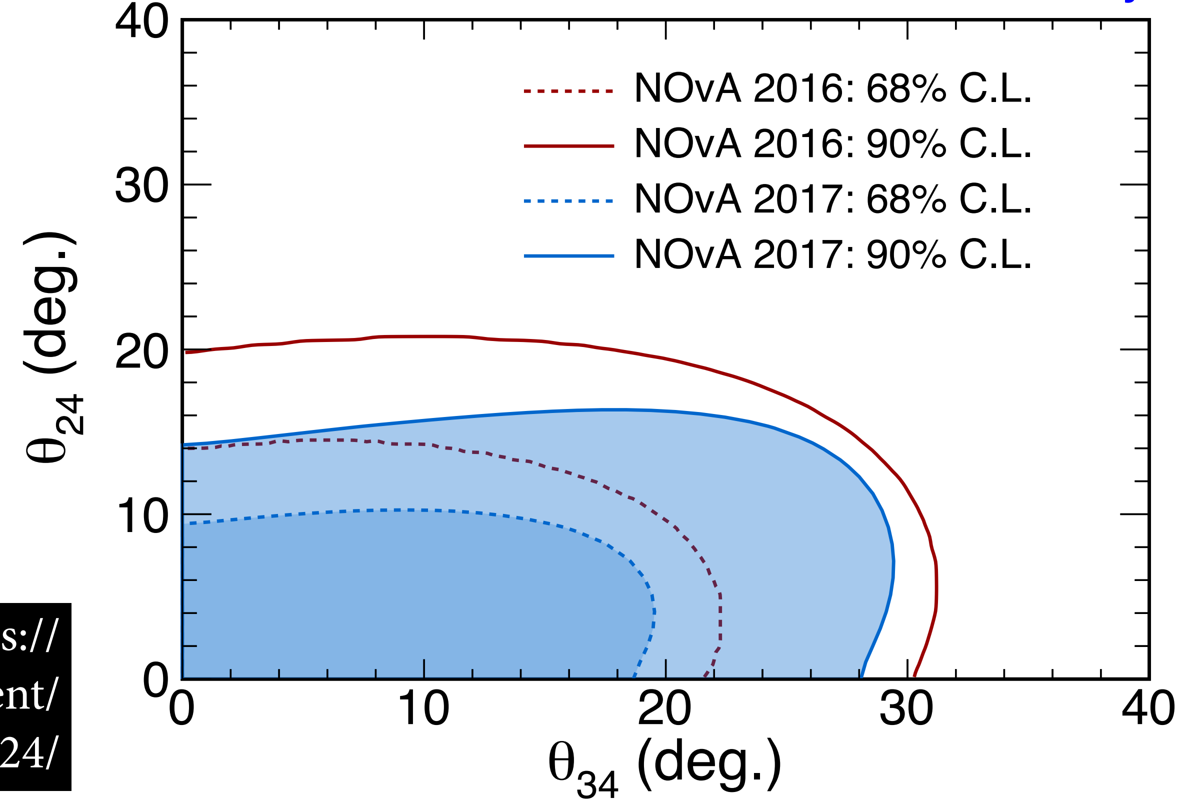
Neutrino Mode

- Previously NOvA has searched for disappearance of NC events using a neutrino-dominated beam.
  - Similar selection and analysis technique to this analysis.
- No evidence for neutrino oscillations outside of 3-flavor framework.
- Set limits in θ_{34}-θ_{24} parameter space.



Phys. Rev. D **96**, 072006 (2017)

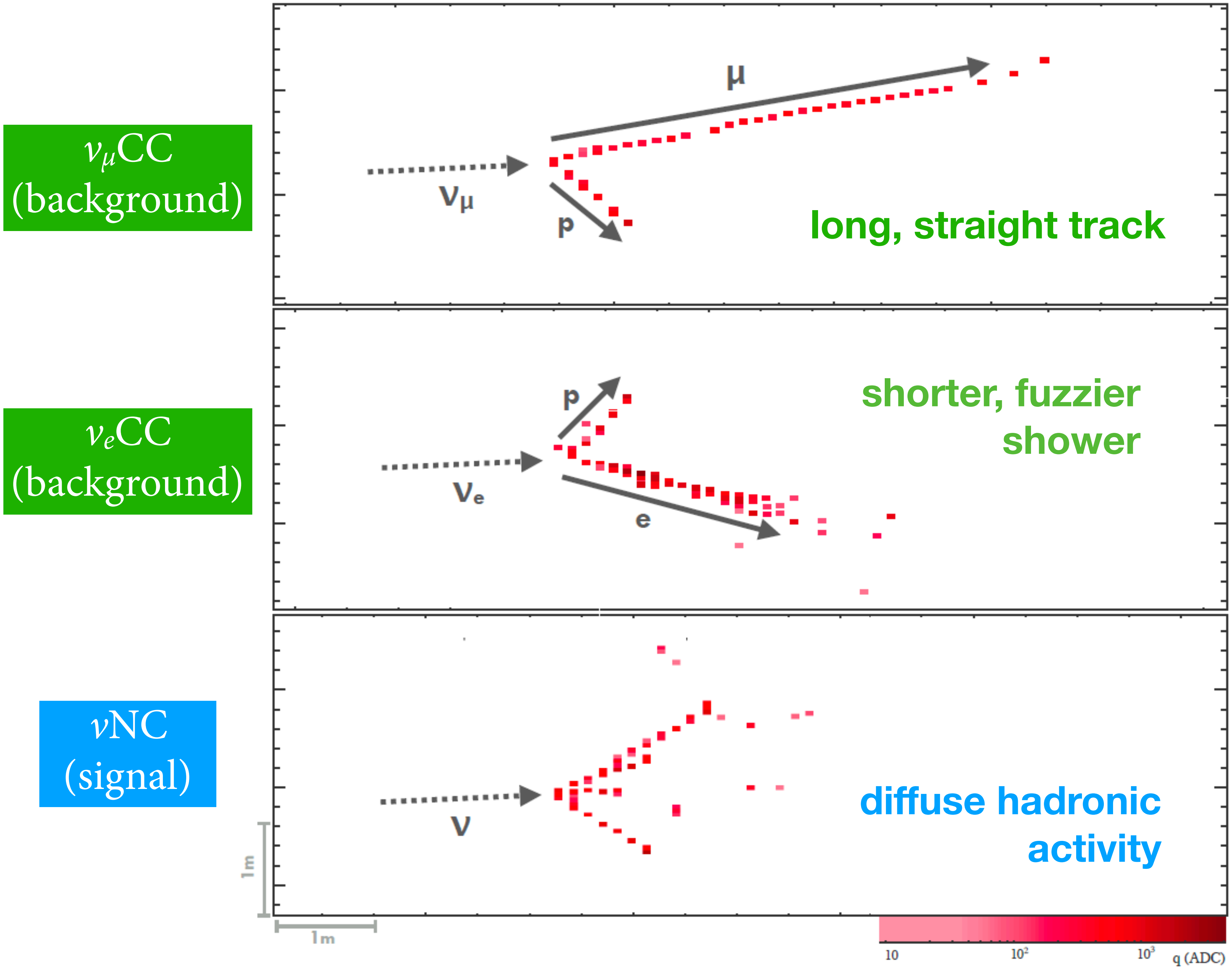
NOvA Preliminary



NuFact 2017: https://indico.uu.se/event/324/contributions/324/

NOvA Antineutrino Sterile Search

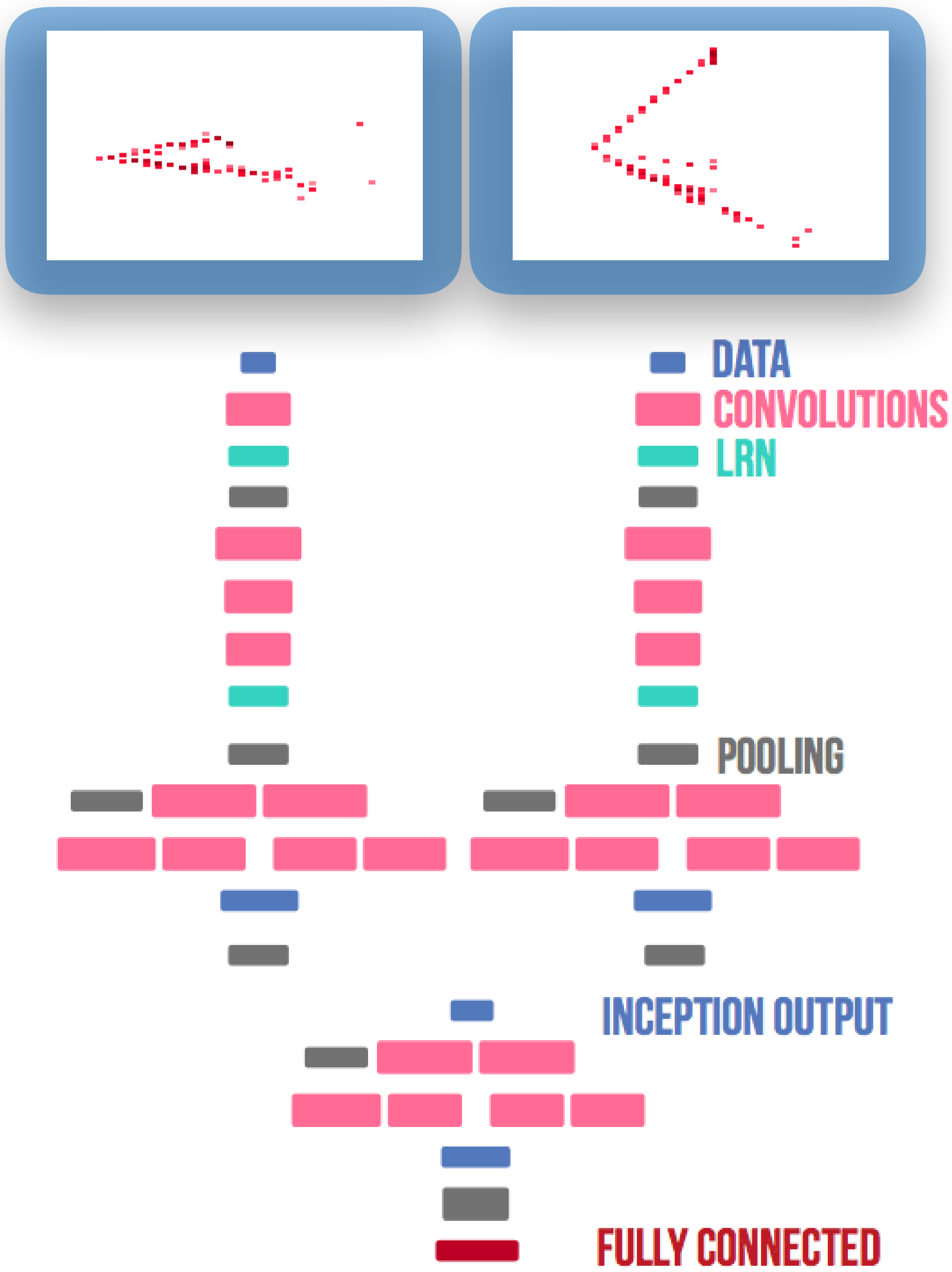
Event Topologies



Event Classification

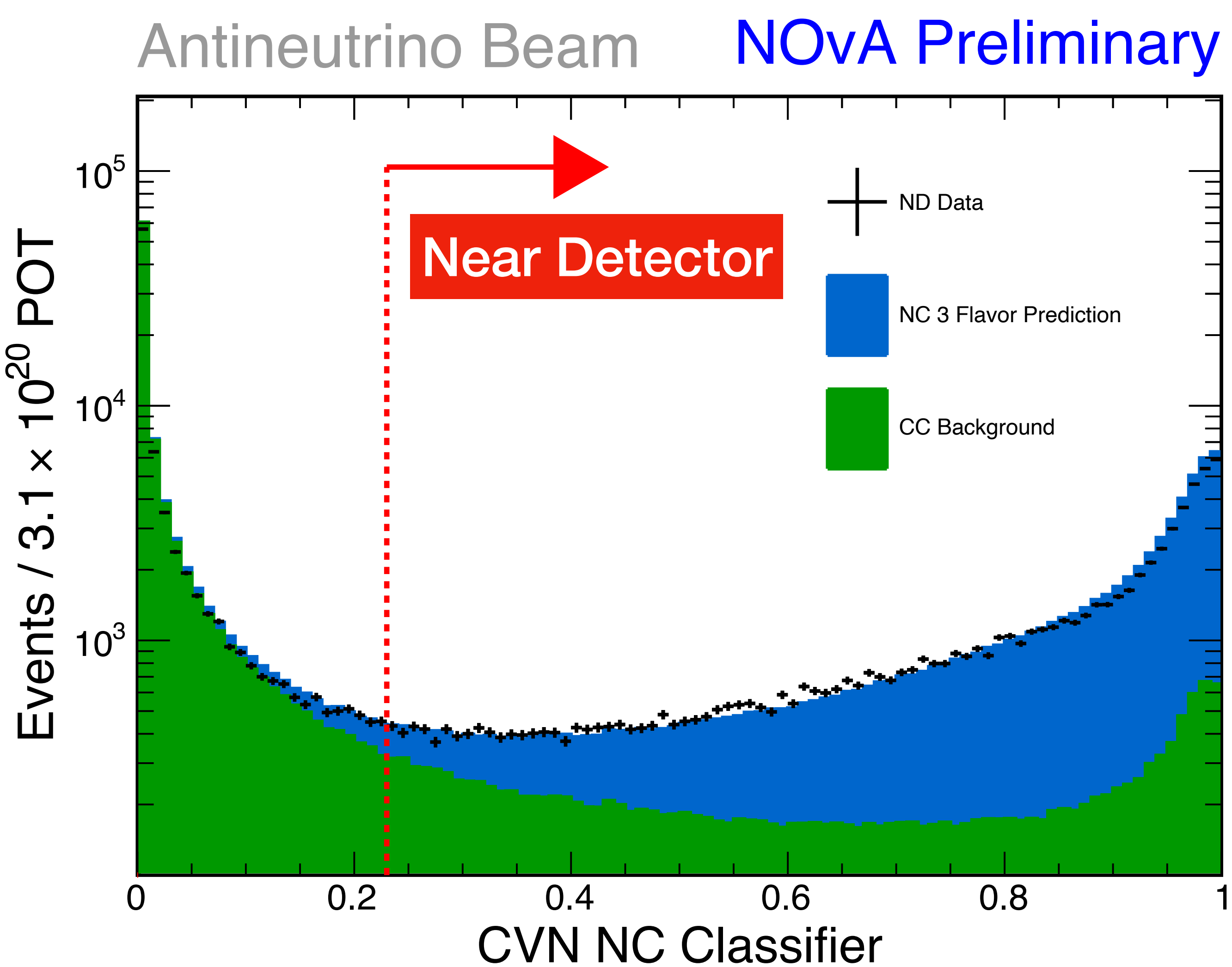
Aurisano *et al.*, JINST **11**, P09001 (2016)

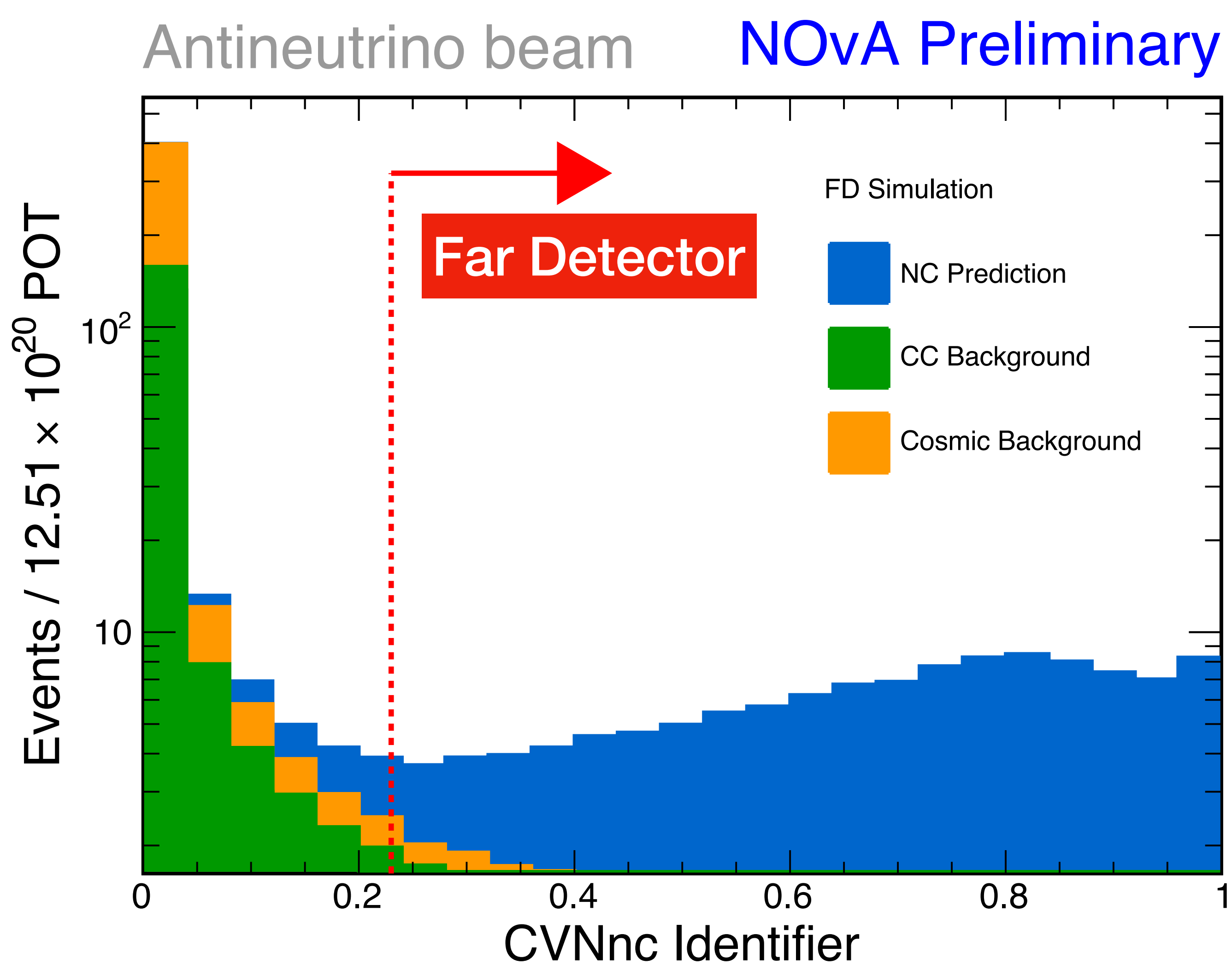
- Utilize deep-learning techniques to perform event classification — NOvA's **Convolutional Visual Network (CVN)**.
    - Multipurpose classifier used to identify ν_μ CC, ν_e CC, ν_τ CC, NC and cosmic-induced events.
- Two tower Convolutional Neural Network architecture learns from the detector top and side views of each event independently first.
- First implementation of CNN on a HEP result.
- New this analysis:
    - Updated simulation, network optimizations.
    - Classify events using final states.
    - Separate neutrino and antineutrino training.



F. Psihas, Ph.D. thesis, Indiana University, 2018, doi:10.2172/1437288.

Particle Identification





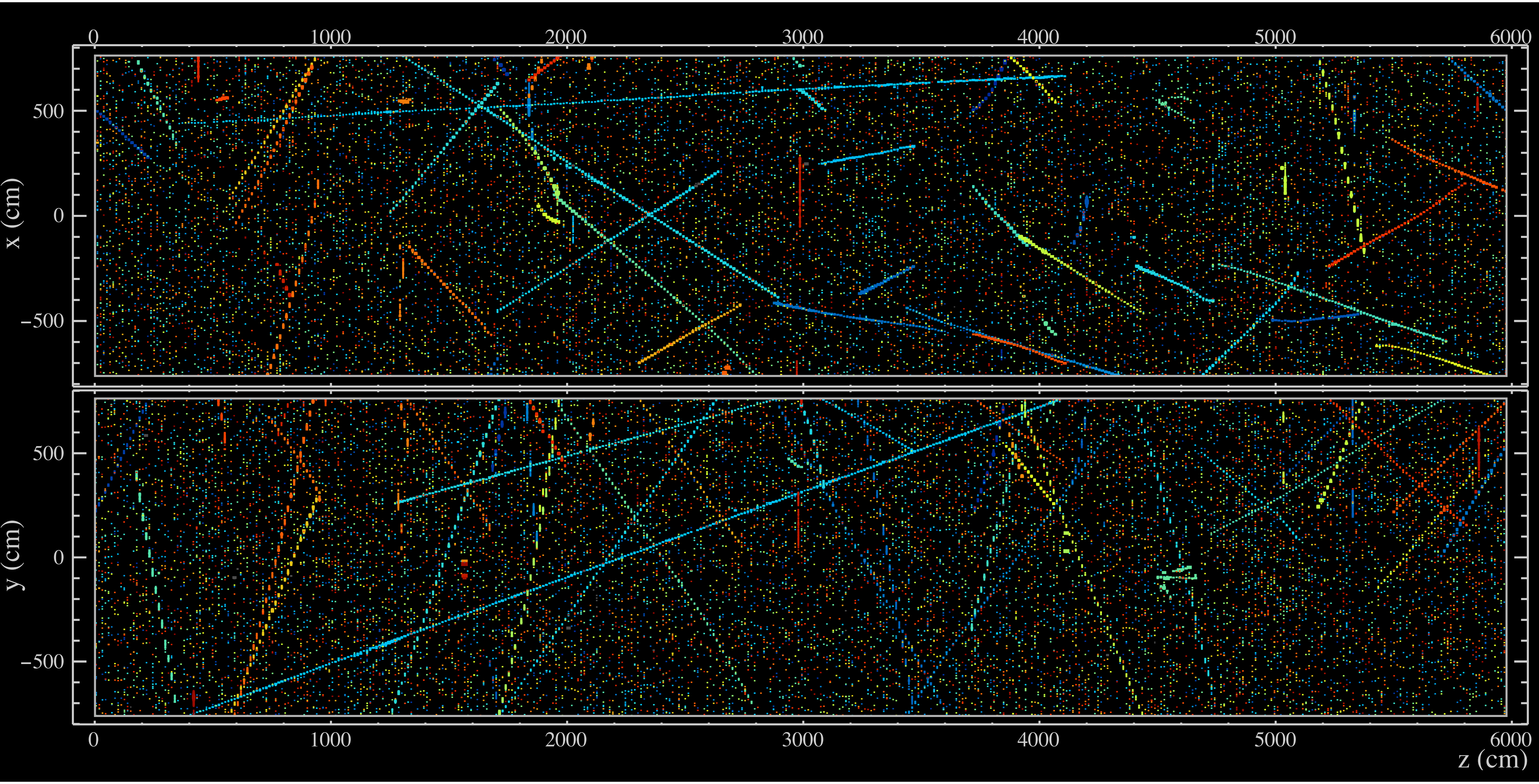
- CVN gives very good separation between NC signal and CC/cosmic backgrounds.
- Main particle identification used in this analysis.

Cosmic Rejection

- Far Detector on surface, exposed to around 11 billion cosmic rays every day.

550 μs event window

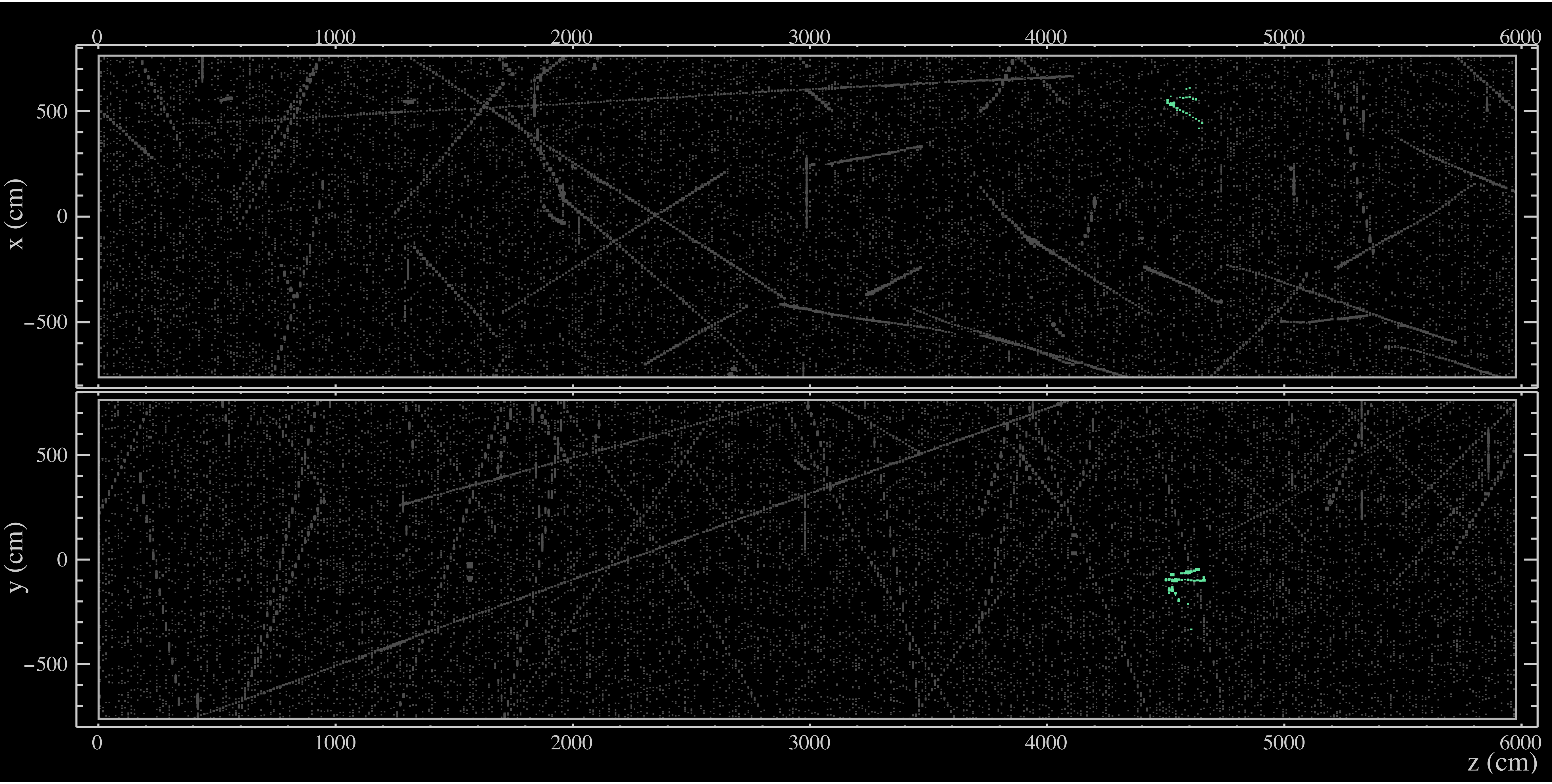
Color represents time



Cosmic Rejection

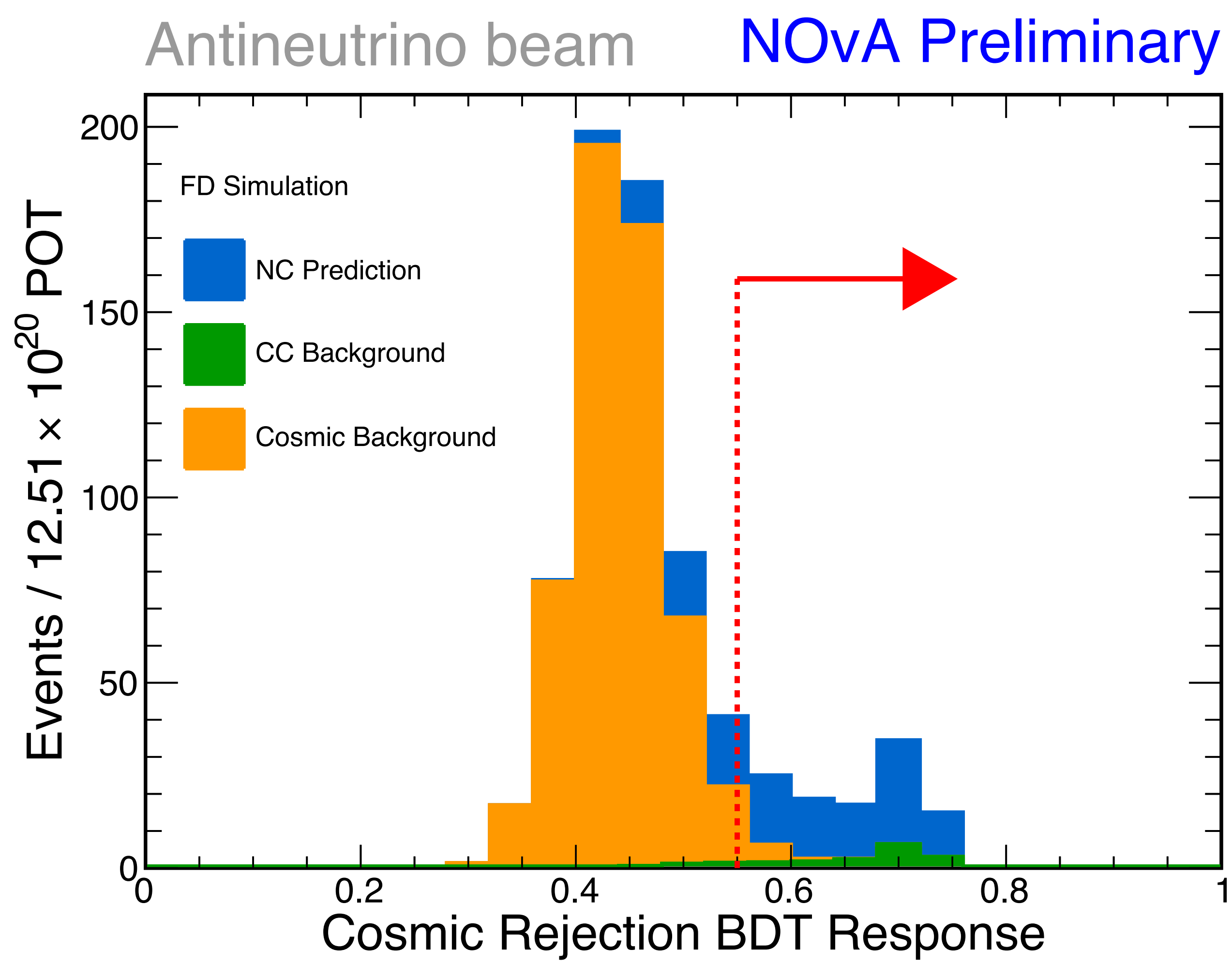
- Use high timing resolution to split the event into sections of correlated activity.

550 μs event window



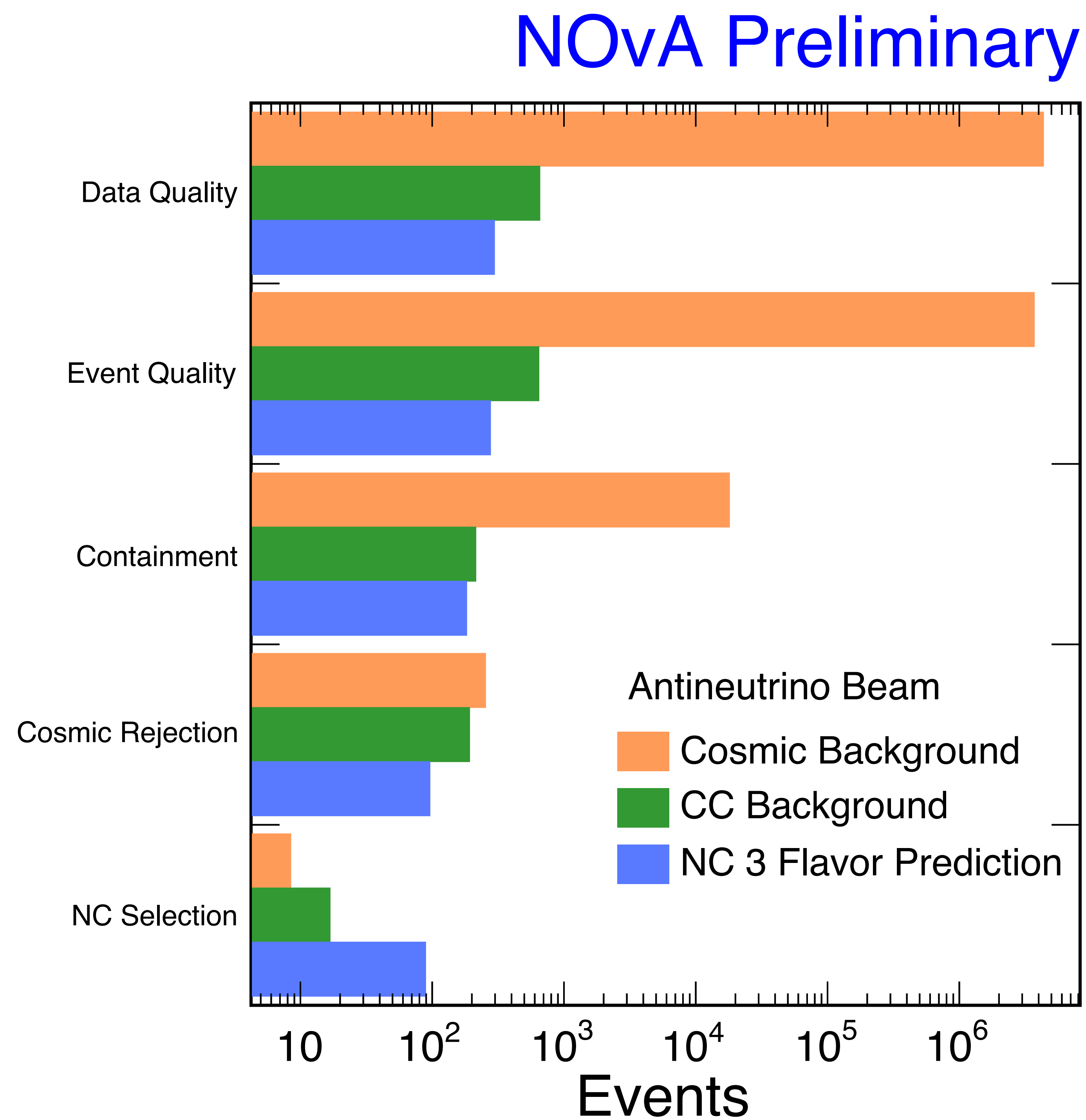
Cosmic Rejection

- Remove cosmic events by considering:
  - direction of showering particles in detector;
  - component of transverse momentum in the event;
  - activity in events close in space and time to candidate NC interactions.
- Also train a Boosted Decision Tree (BDT) on 13 shower variables which provide separation between signal beam events and cosmic backgrounds.
  - Good separation observed between signal prediction and cosmic-induced events.

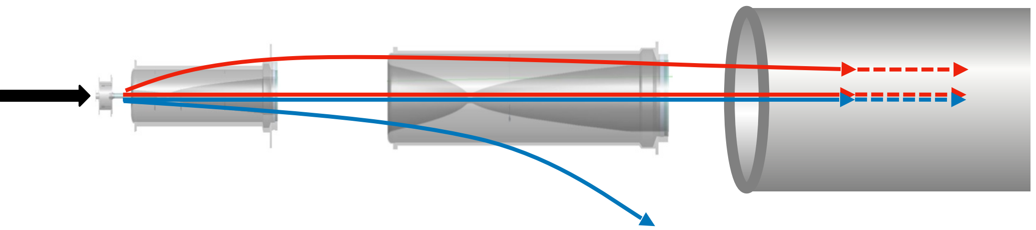


Event Selection

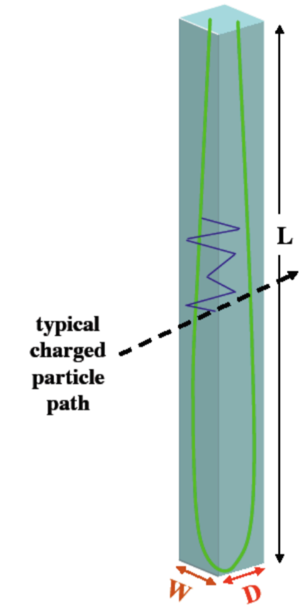
- Selection provides a sample of Neutral Current events with 78% purity.
- Impressive rejection of cosmics events of six orders of magnitude.



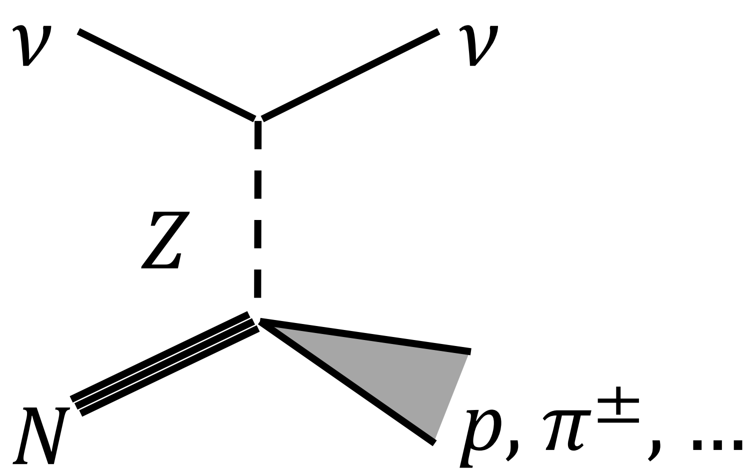
Near Detector Prediction



Full beam simulation with external target data input.



Neutrino flux → Neutrino interactions → Detector simulation



GENIE 2.12.2 event generator with additional tuning.

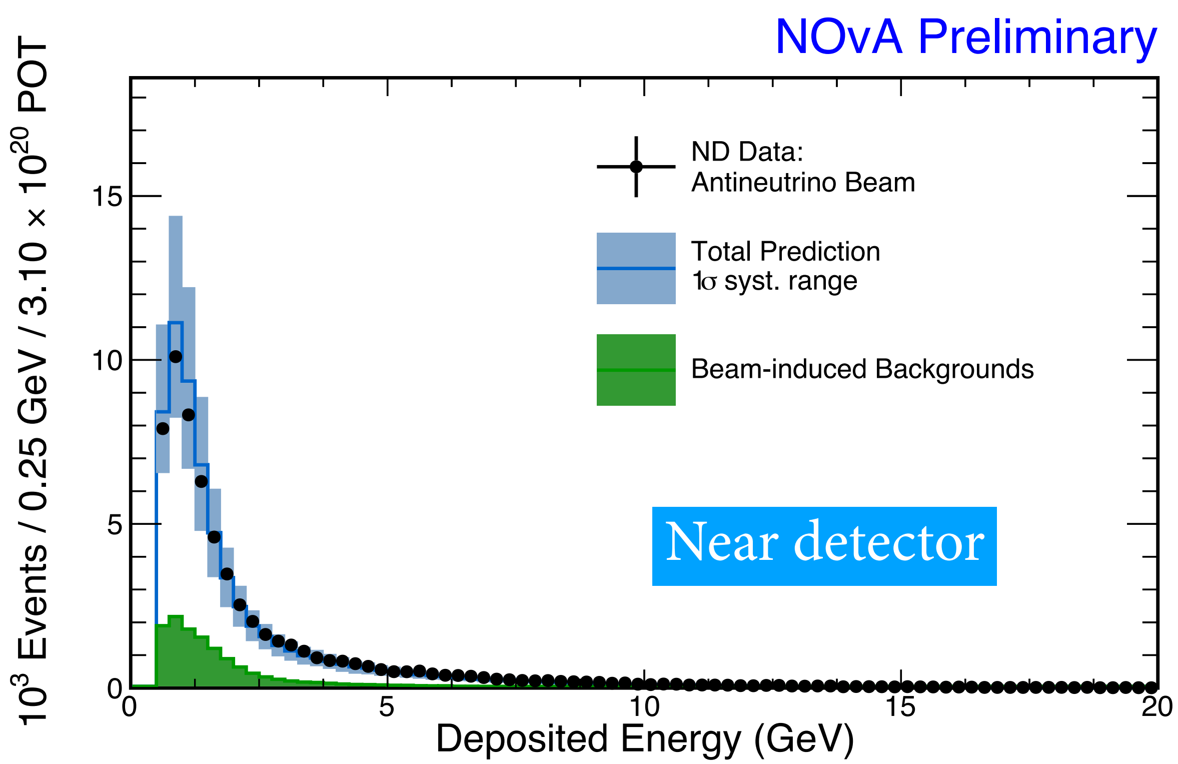
GEANT4 and custom software to simulate the response of the NOvA detectors to simulated charge deposits.

Nucl. Instrum. Meth. A 614, 87-104 (2010)

Nucl. Instrum. Meth. A 506 250-303 (2003)

Far Detector Prediction

- Assuming a mass-splitting such that there are no ND oscillations ($0.05 < \Delta m^2_{41}$ (eV^2) < 0.5), can produce a FD 'prediction' using ND data.
- Constrain the ND simulation with data and convolve with the predicted ratio of the FD and ND distributions.
    - Take into account geometrical differences, beam dispersion and the effect of oscillations.
    - Partially cancels correlated systematic uncertainties between two detectors.

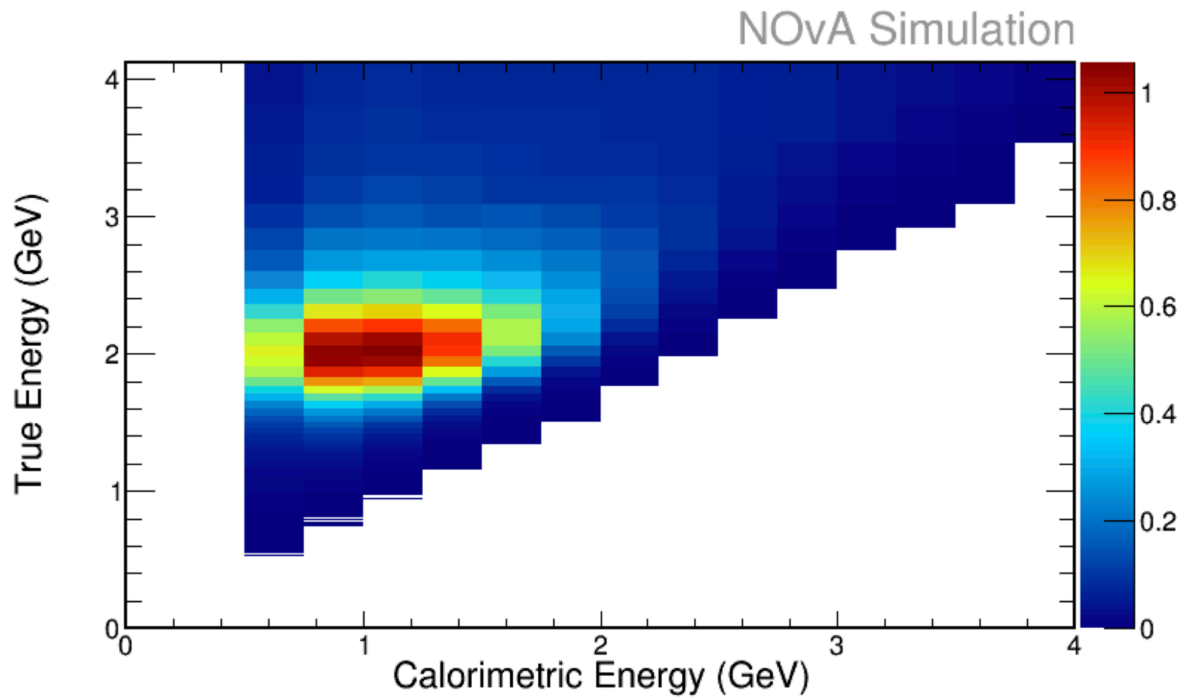


Far Detector Prediction

- Assuming a mass-splitting such that there are no ND oscillations ($0.05 < \Delta m^2_{41}$ (eV^2) < 0.5), can produce a FD 'prediction' using ND data.

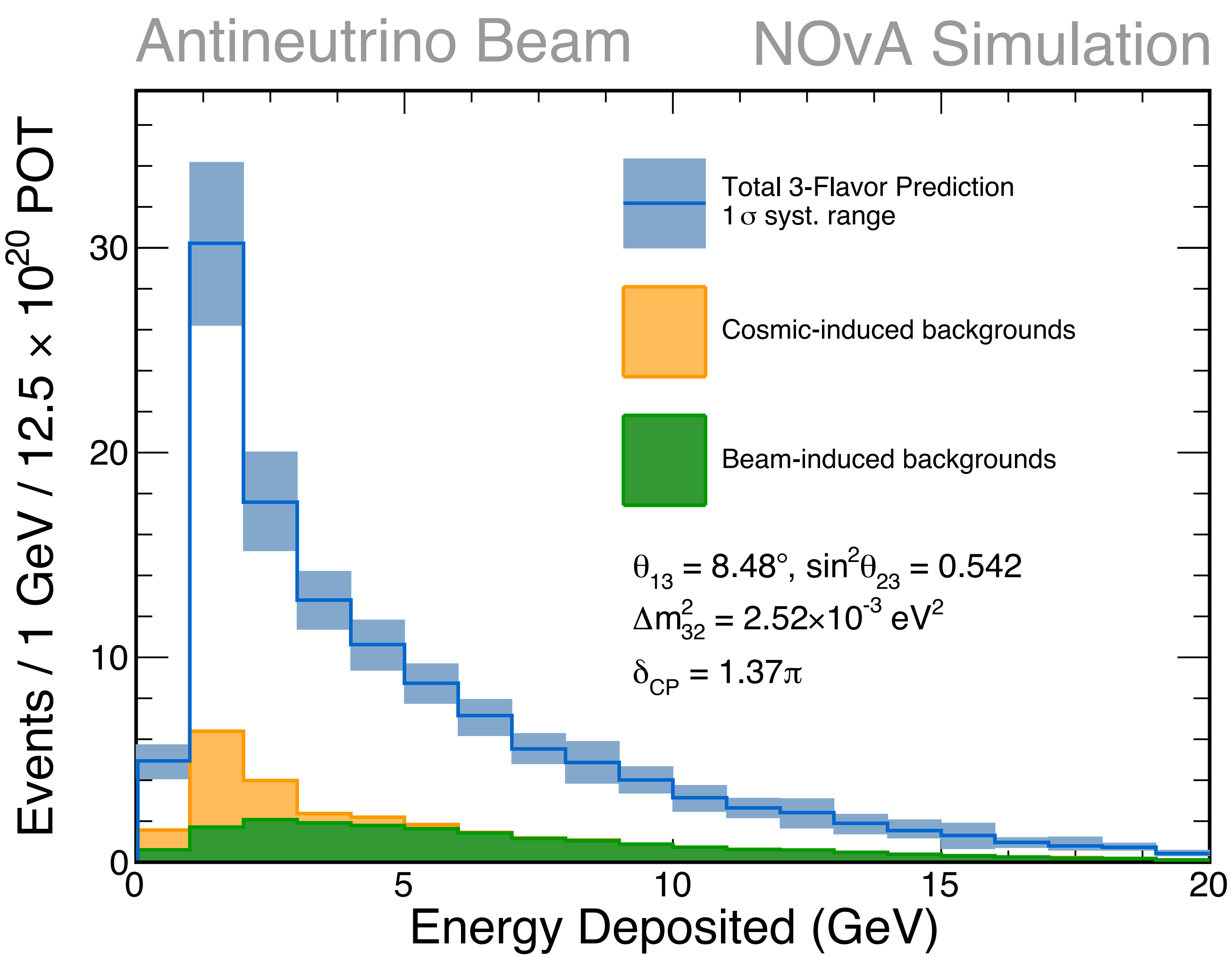
- Constrain the ND simulation with data and convolve with the predicted ratio of the FD and ND distributions.

  - Use migration matrix to convert reconstructed energy to true energy, apply oscillations and migrate back to reconstructed energy.



Far Detector Prediction

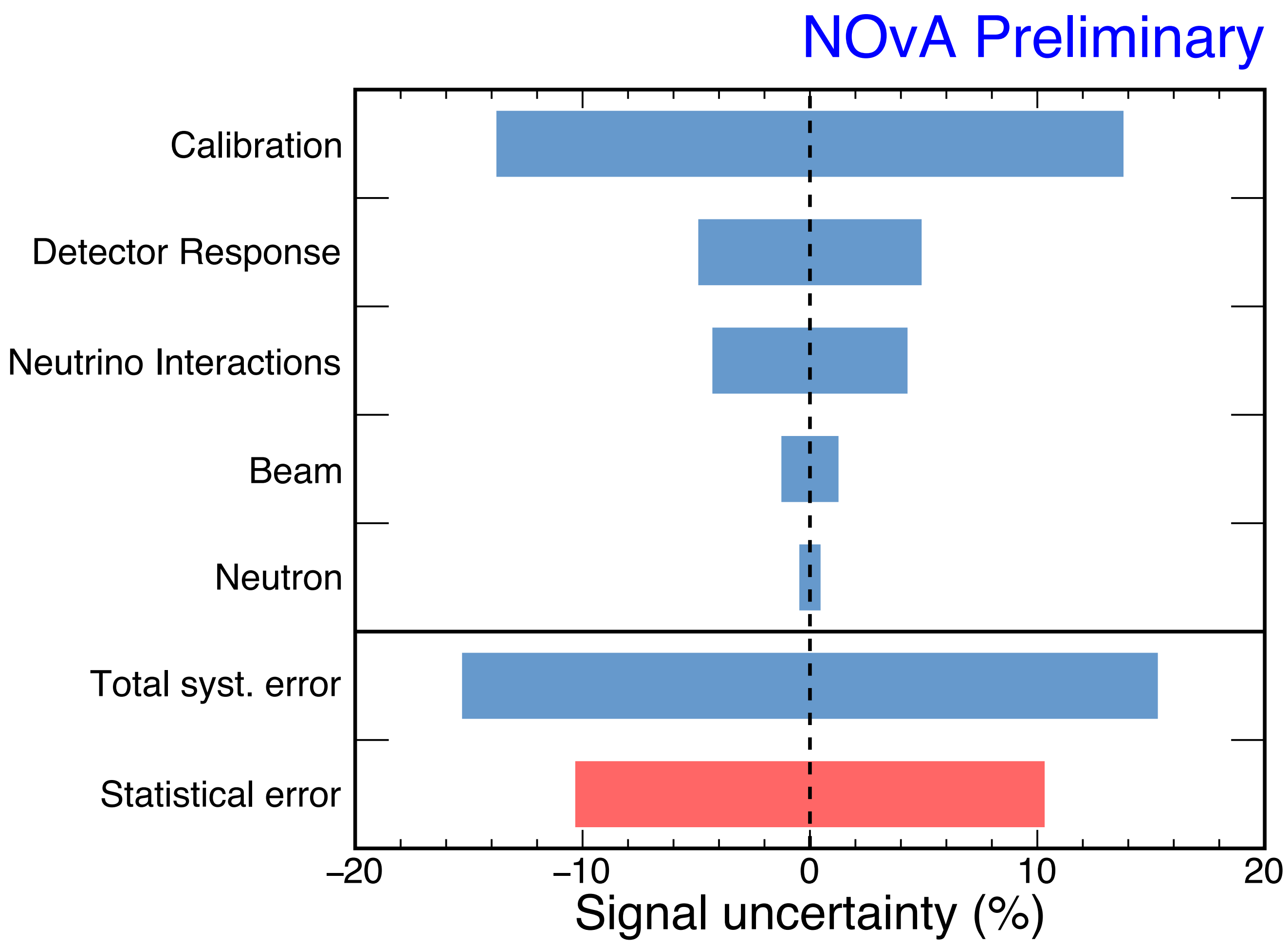
- Predict 122 events from the simulation and external background samples (78% purity).
  - 95 NC signal events, 18 CC beam backgrounds (12 ν_μ, 4 ν_e, 2ν_τ), and 9 cosmics backgrounds.
- Produce 3-flavor prediction at the NOvA Far Detector using global best-fit values taken from the PDG:
  - $\theta_{13} = 8.48°$, $\theta_{12} = 33.6°$, $\delta_{13} = 1.37\pi$.
  - Assume normal mass ordering, upper octant (most conservative): $\sin^2\theta_{23} = 0.542$, $\Delta m^2_{32} = +2.52 \times 10^{-3}$ eV^2.

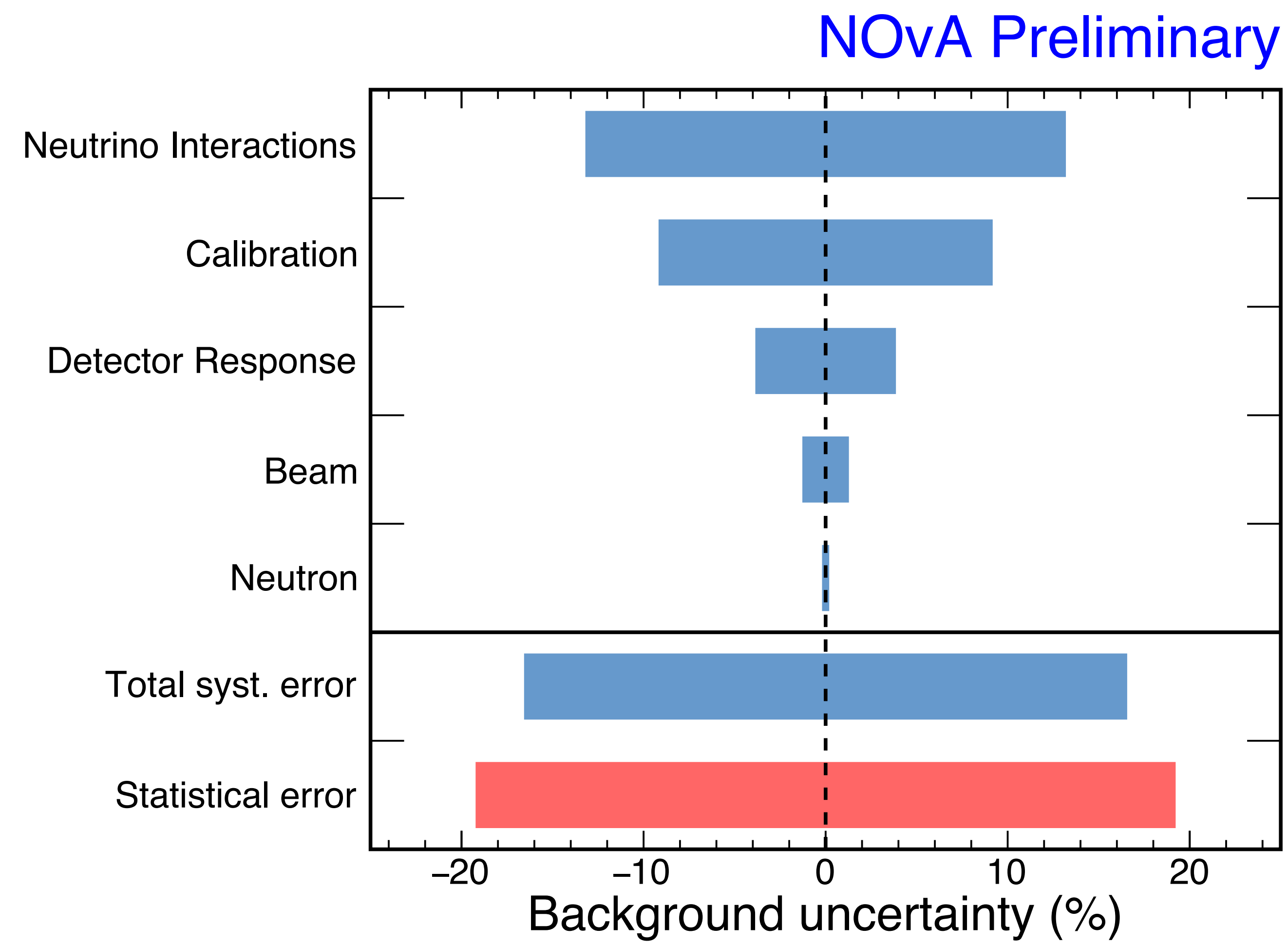


Phys. Rev. D 98, 030001 (2018)

Systematic Uncertainties

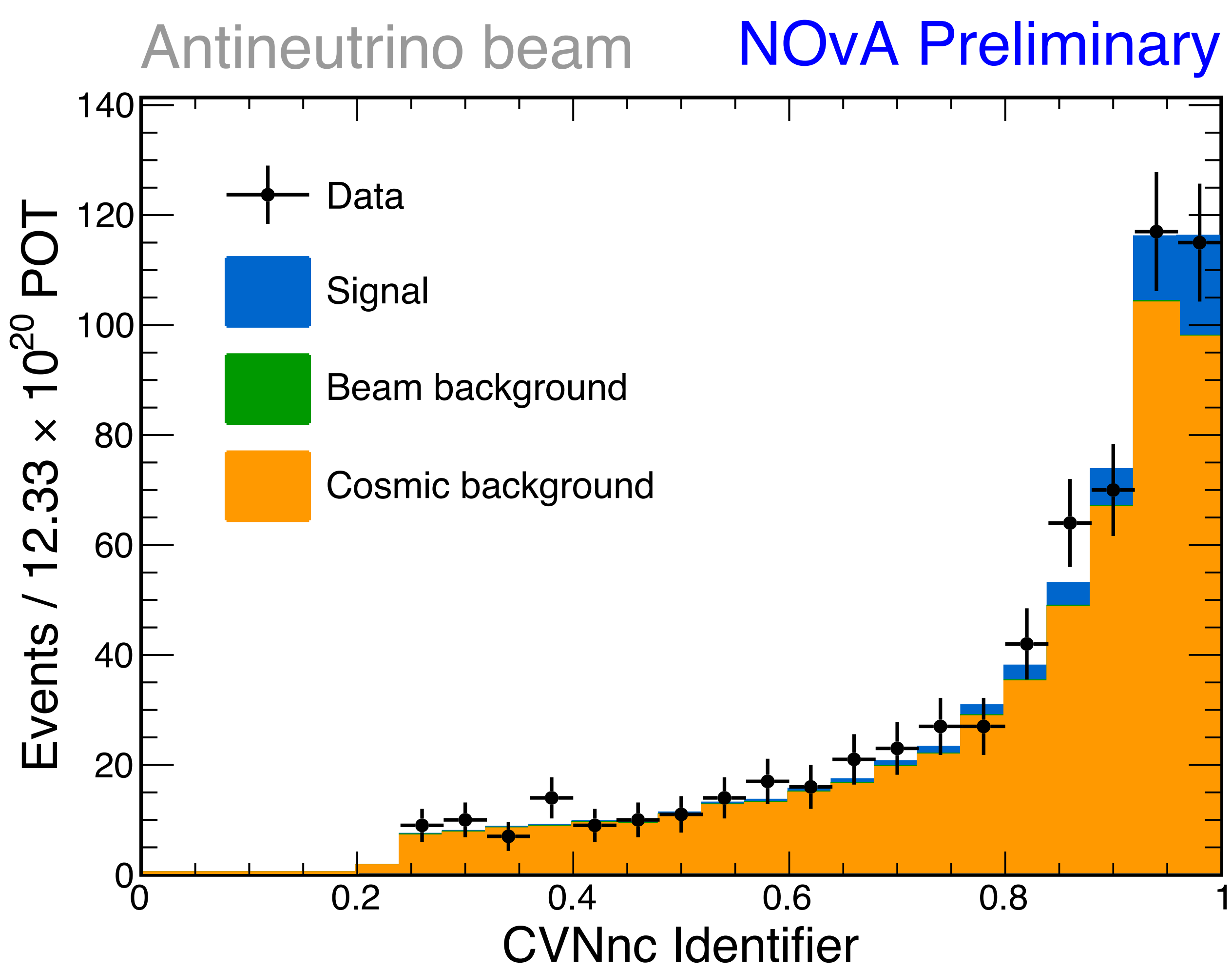
- Residual uncertainties following the data-driven extrapolation procedure and partial cancellation of correlated systematics.
- Even with low statistics, the analysis is already limited by the large experimental uncertainties. Reducing these is a focus for improvements going forward.

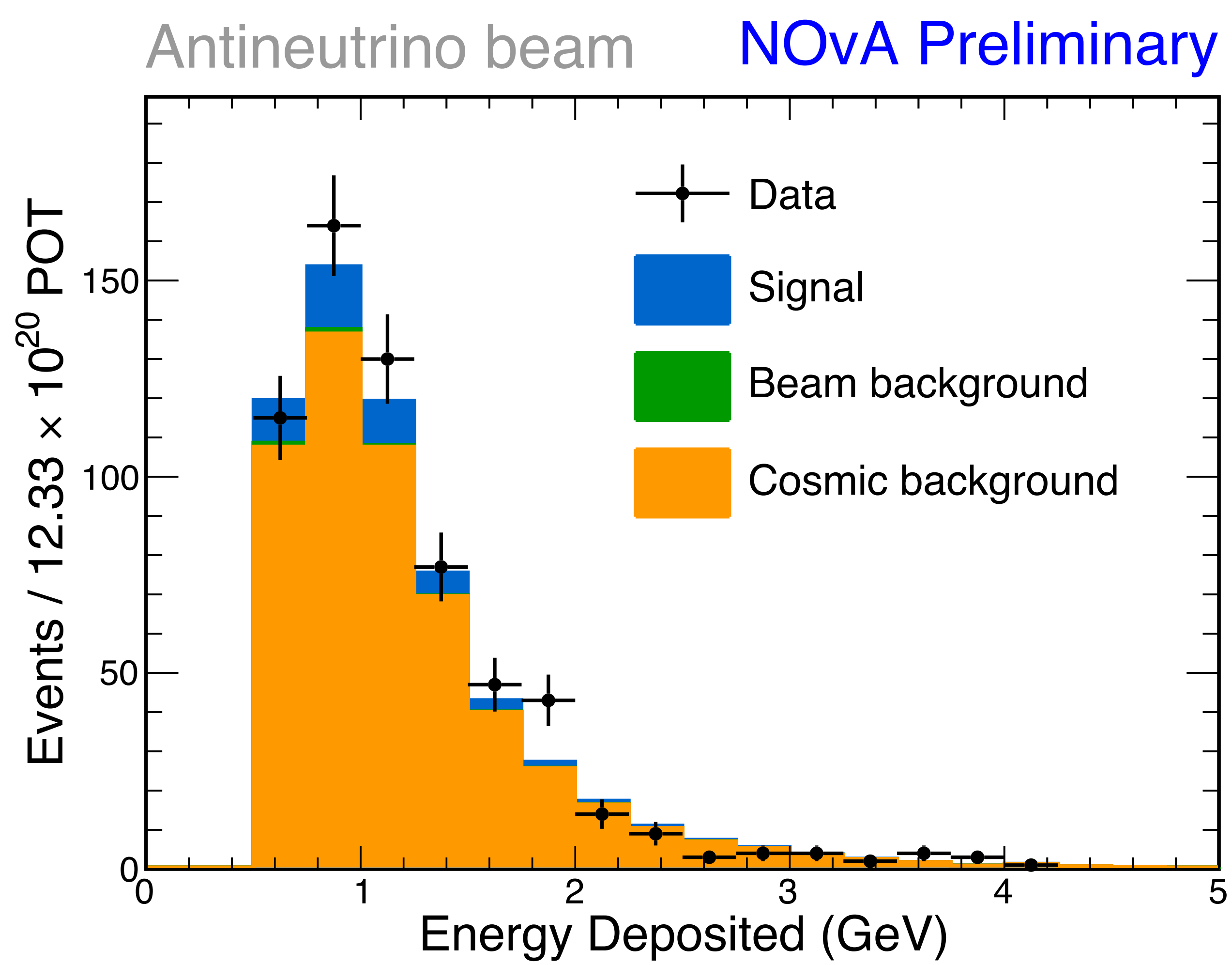




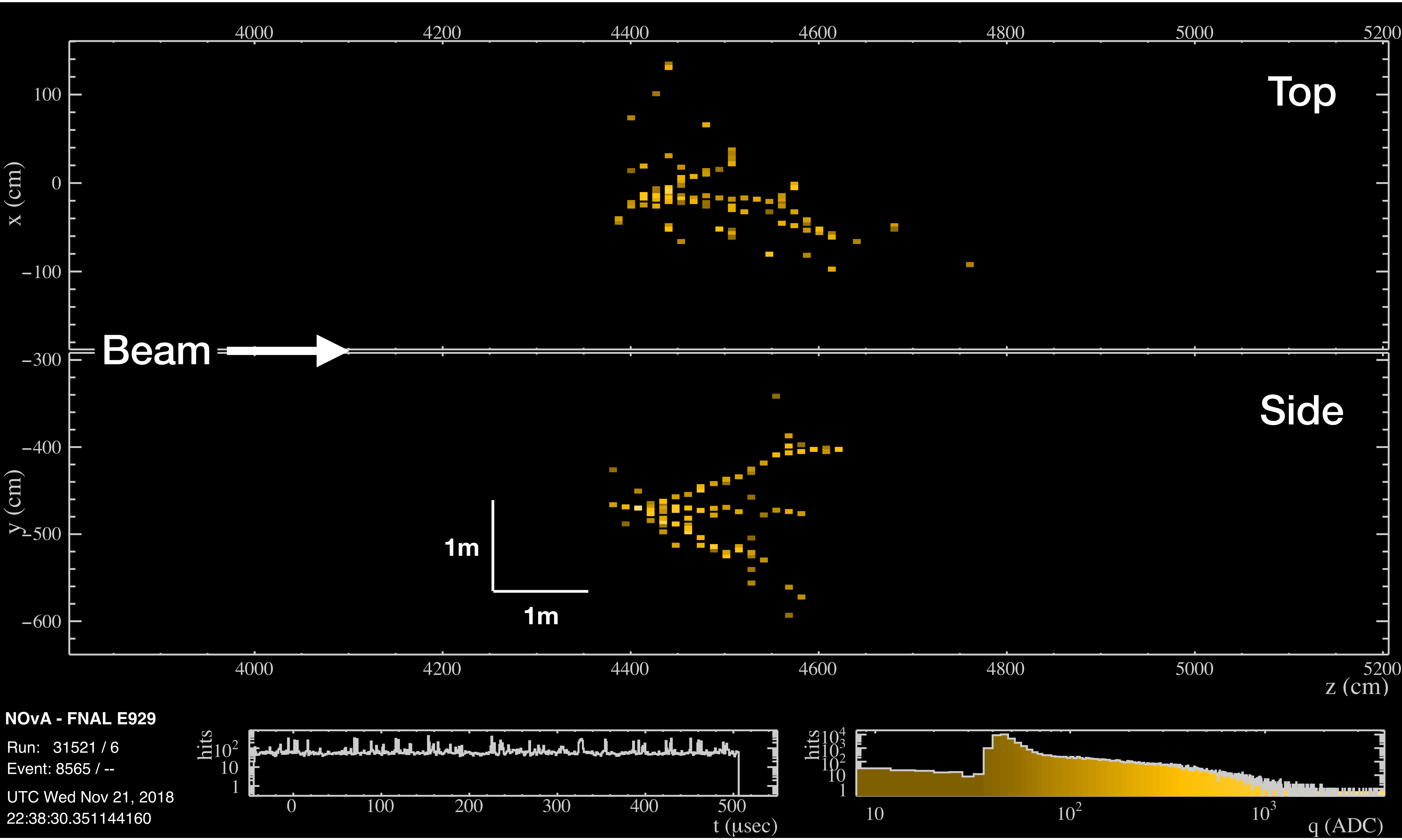
Sideband Studies

- Before examining the Far Detector data, use Near Detector data to produce data-driven predictions to compare to sideband regions.
- Choose region of low BDT response (< 0.55), which would fail cosmic rejection cuts.



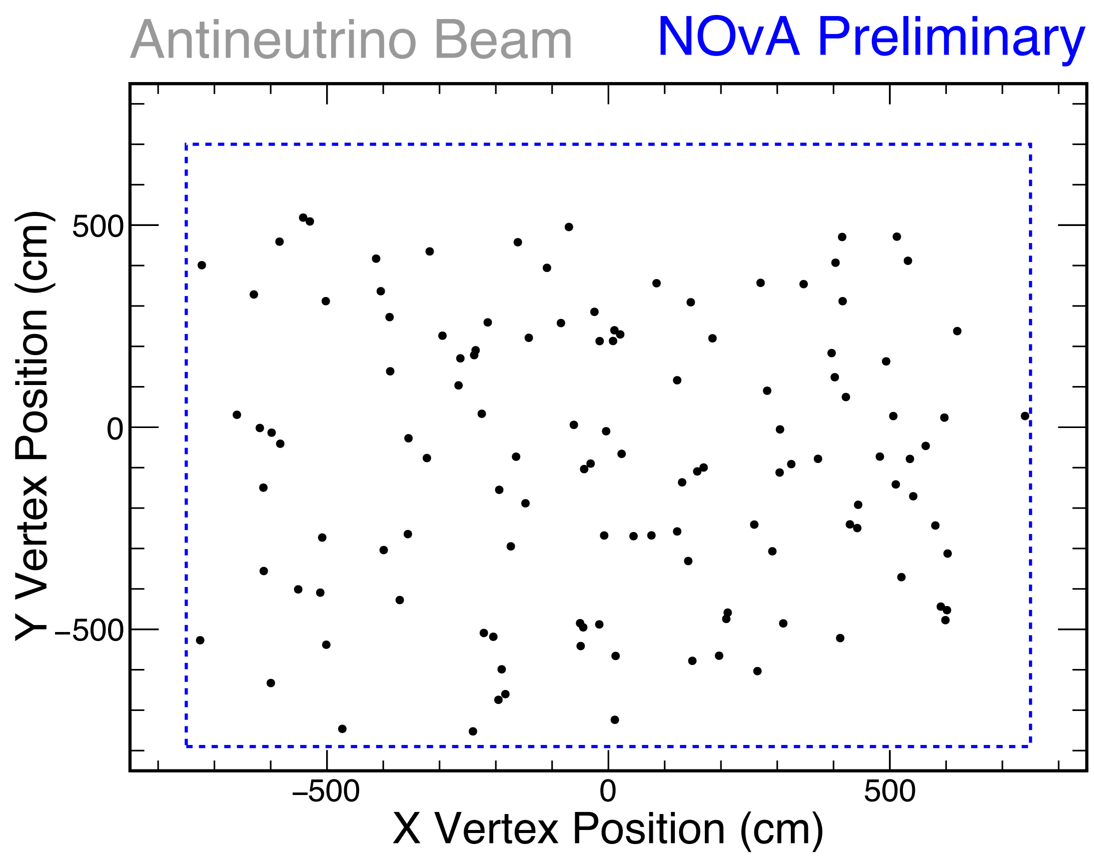


Candidate Selected Beam Event

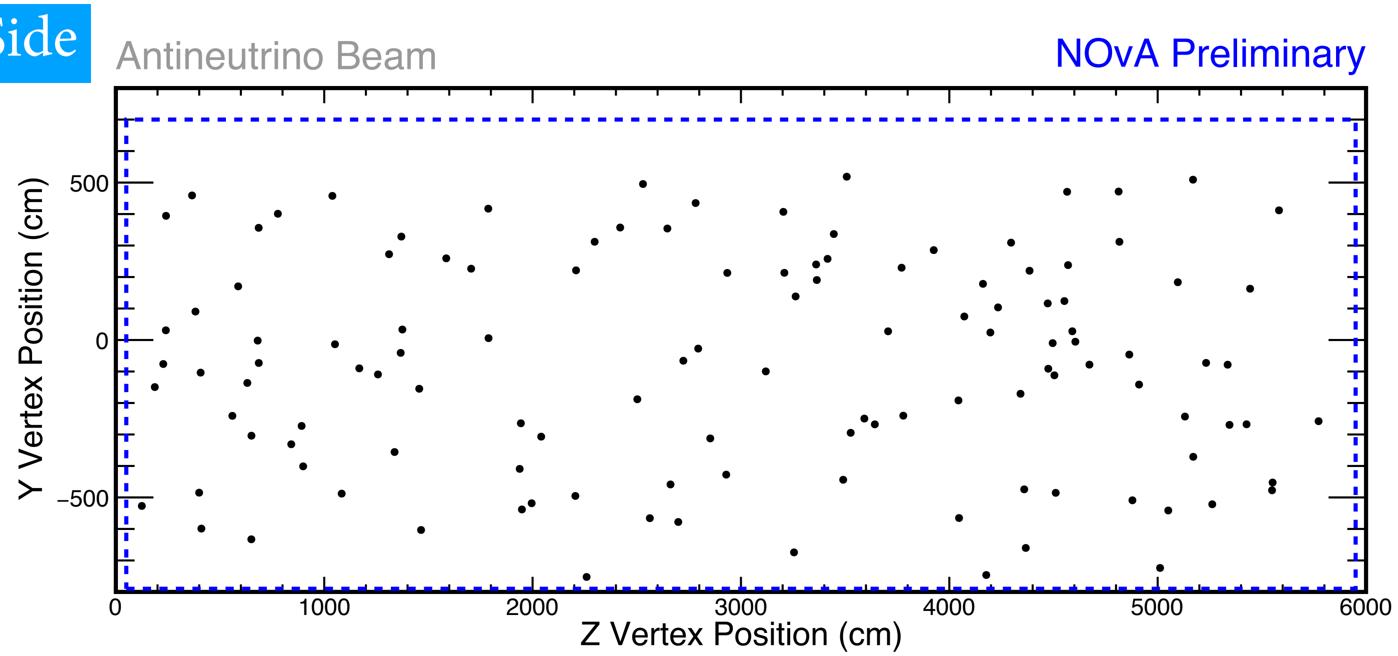


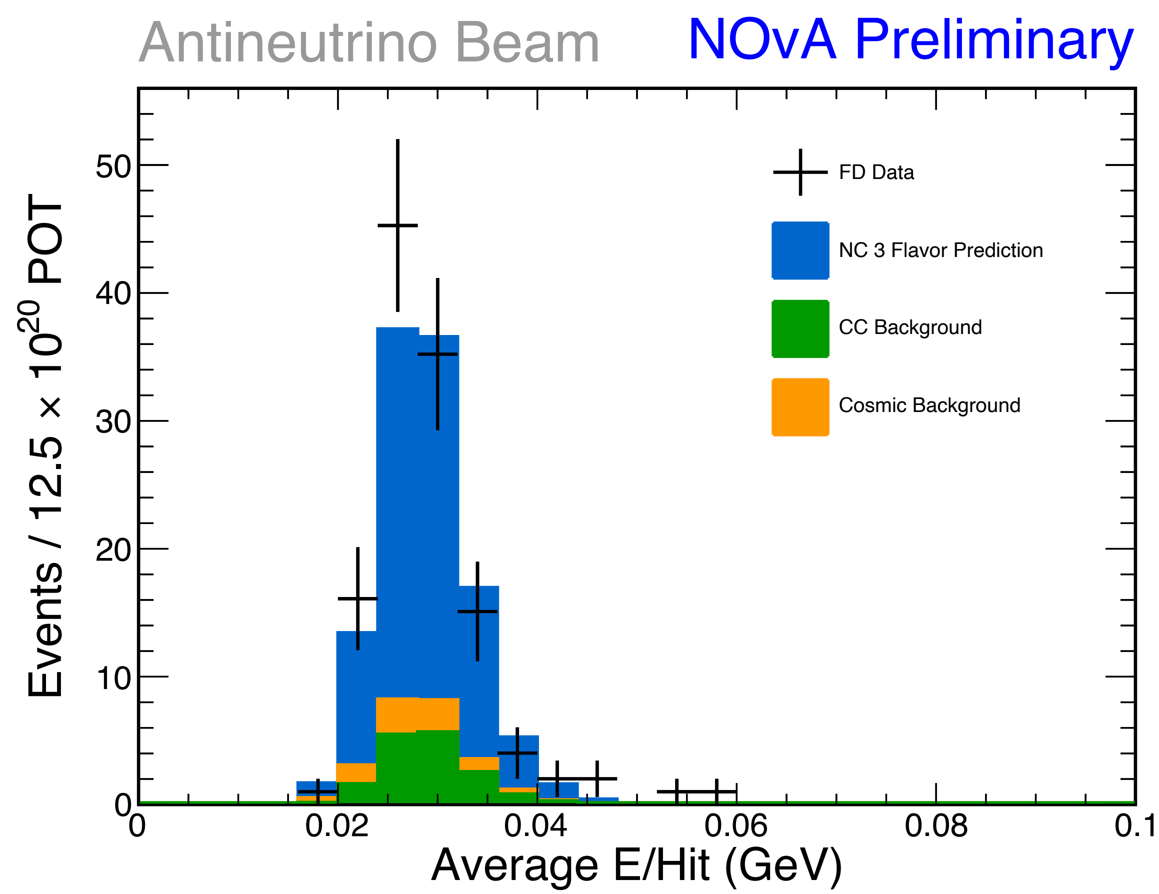
Far Detector Data

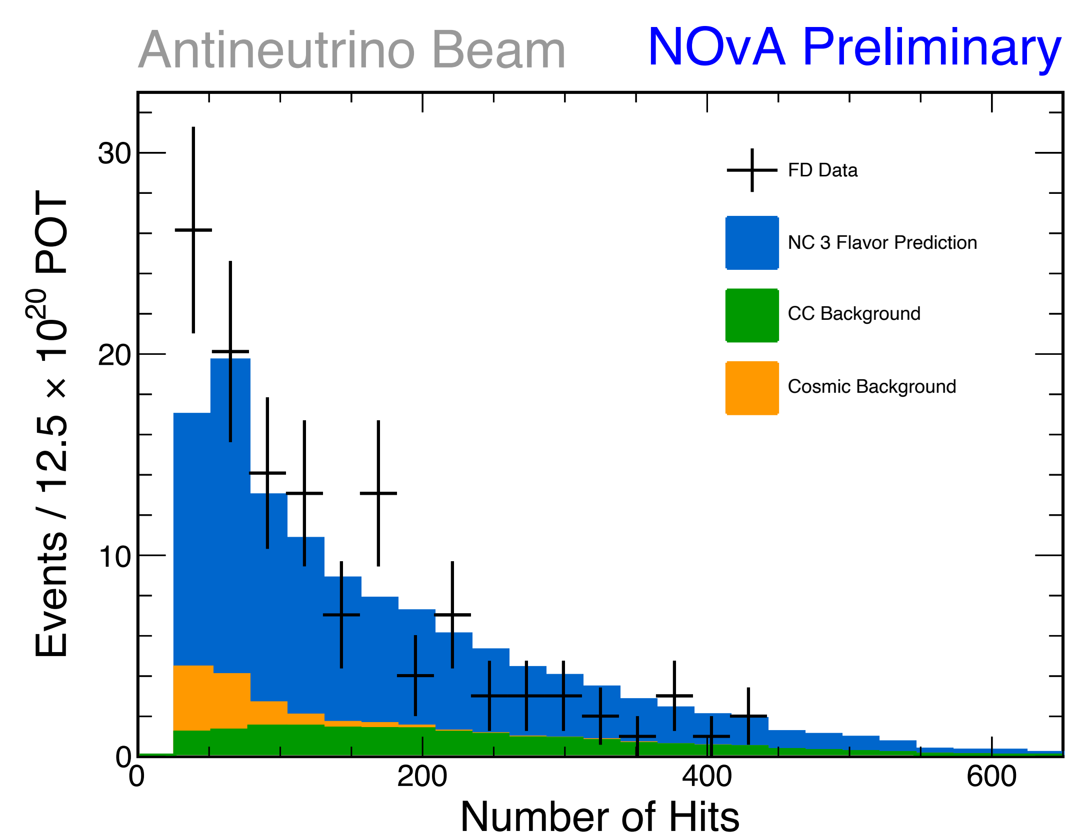
Along beam



Side

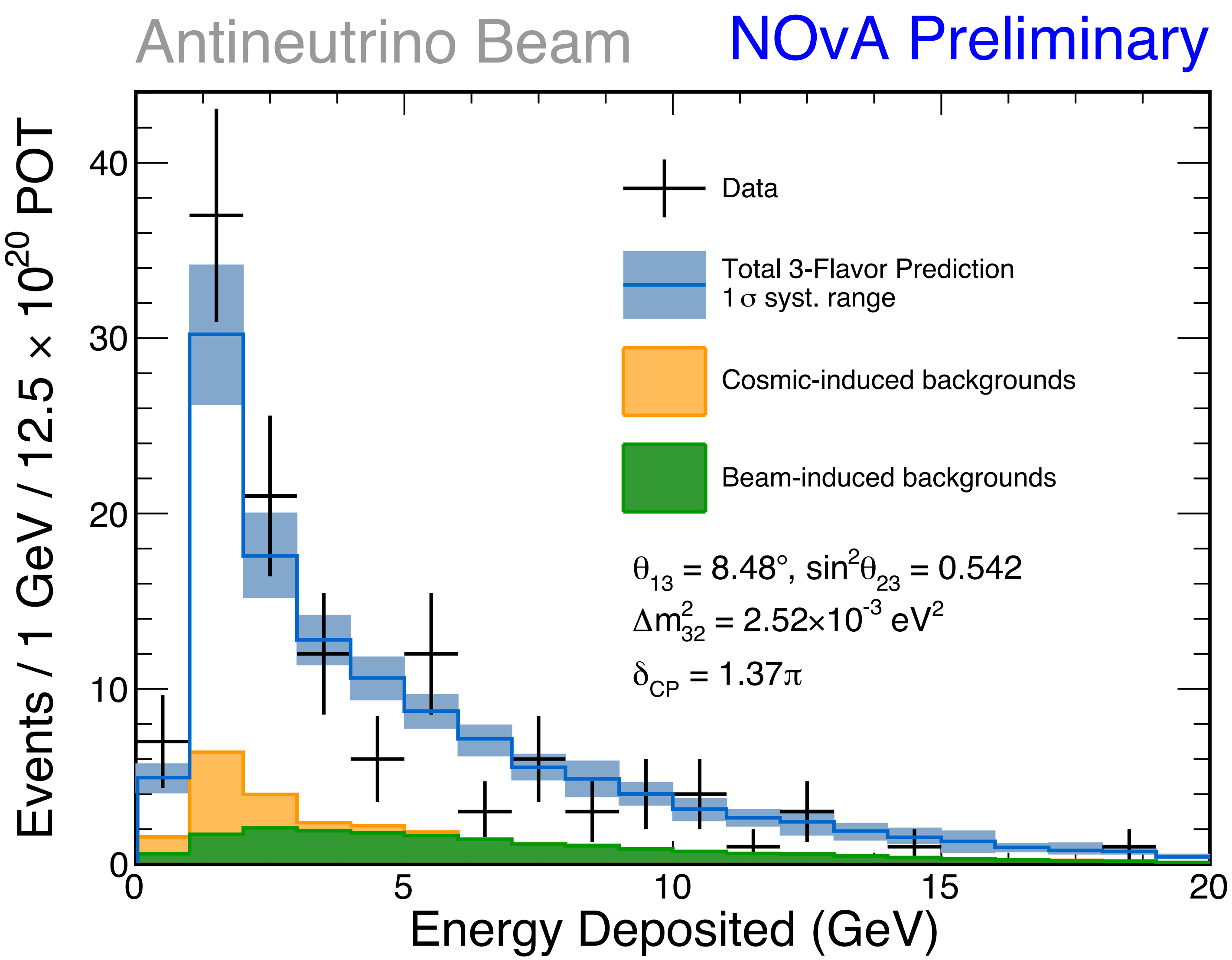






Far Detector Data

- Observe **121** events NC-like events in the Far Detector.
- Simulated 3-flavor prediction **122 ± 11 (stat.) ± 18 (syst.)**.

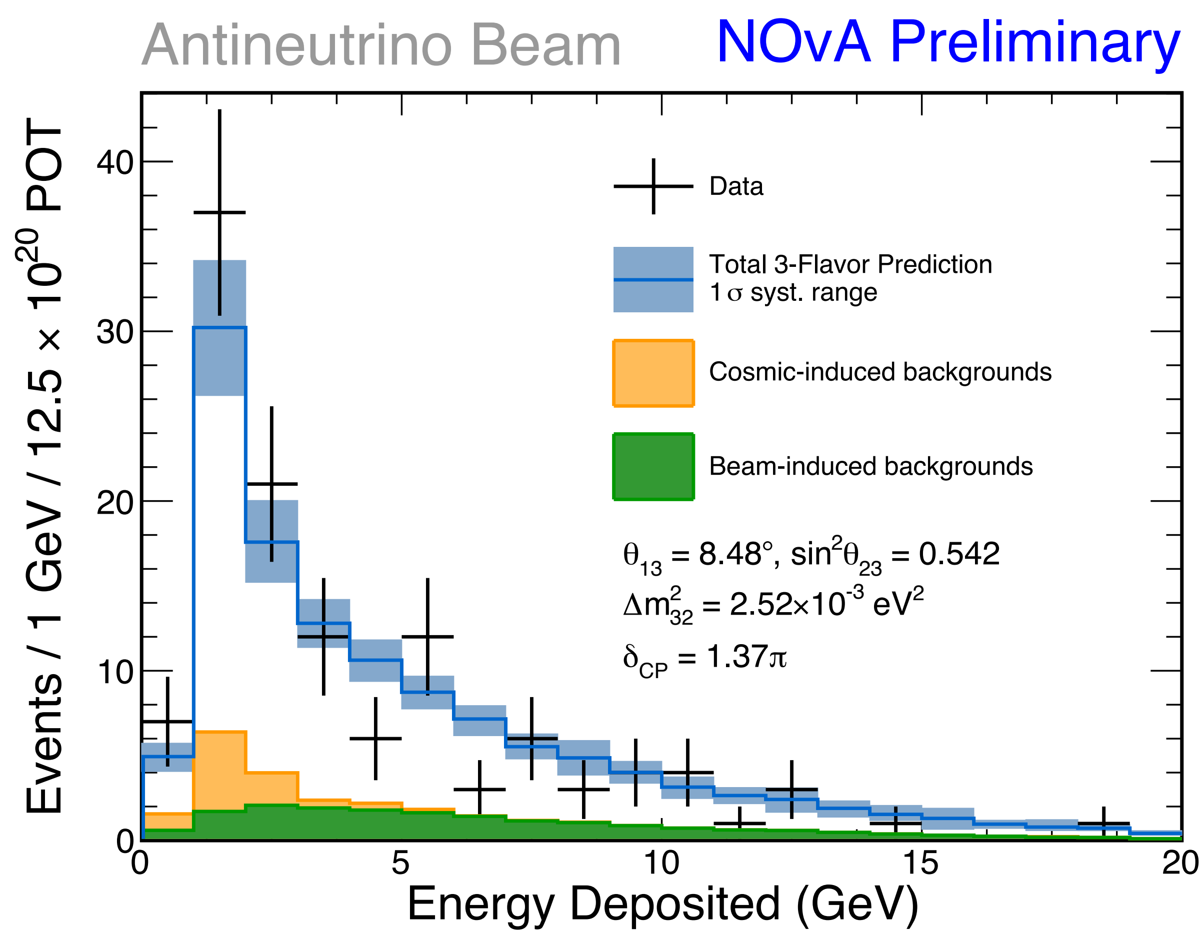


Far Detector Data

- Define model-independent 'R-ratio' to quantify the level of agreement between data and 3-flavor simulated prediction.

$$R_{NC} \equiv \frac{N_{Data} - \sum N_{Bkg}^{Pred}}{N_{NC}^{Pred}} = 0.99 \pm 0.12(\text{stat.})^{+0.14}_{-0.16}(\text{syst.})$$

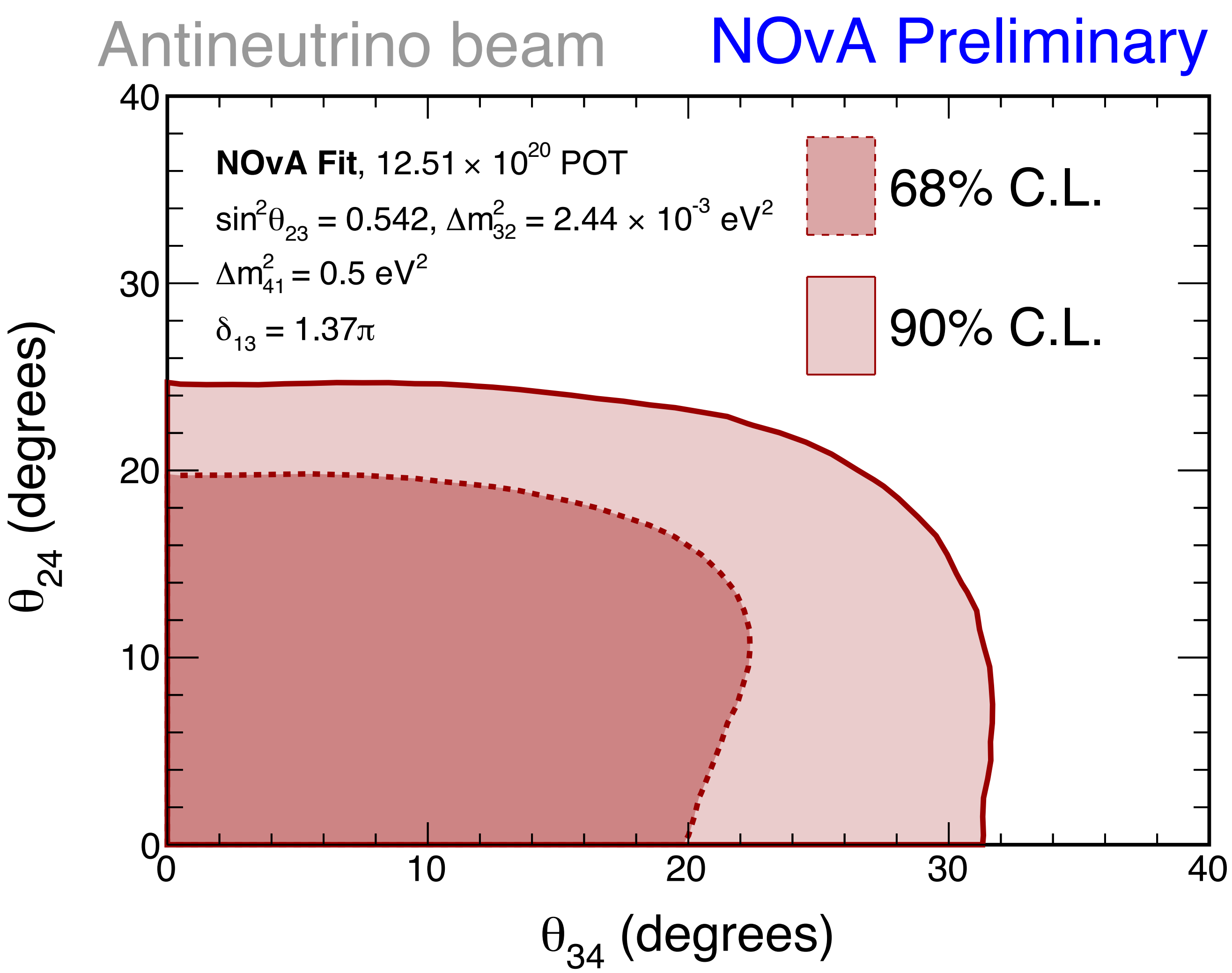
Consistent with oscillations in 3-flavor framework.



$\chi^2/\text{DOF} = 79.1/79 = 1.04$

3+1 Model Limits

- Perform rate and shape-based fits to the 3+1 model to set limits on the allowed values of the mixing parameters using Feldman-Cousins approach:
  - Valid for $0.05 < \Delta m^2_{41}$ (eV^2) < 0.5;
  - Profile over θ_{23} ($0.520 < \theta_{23} < 0.561$; PDG constraint) and δ_{24}.
  - Assume $\theta_{14} = 0$ and $\delta_{14} = 0$ (solar and reactor constrains $\sin^2\theta_{41} < 0.04$).
- 1D limits (90% C.L.):
  - $\theta_{24} < 24.7°$;
  - $\theta_{34} < 31.7°$.



J. High Energ. Phys. (2018) 2018: 10

Phys. Rev. Lett. **117**, 151802 (2016)

3+1 Model Limits

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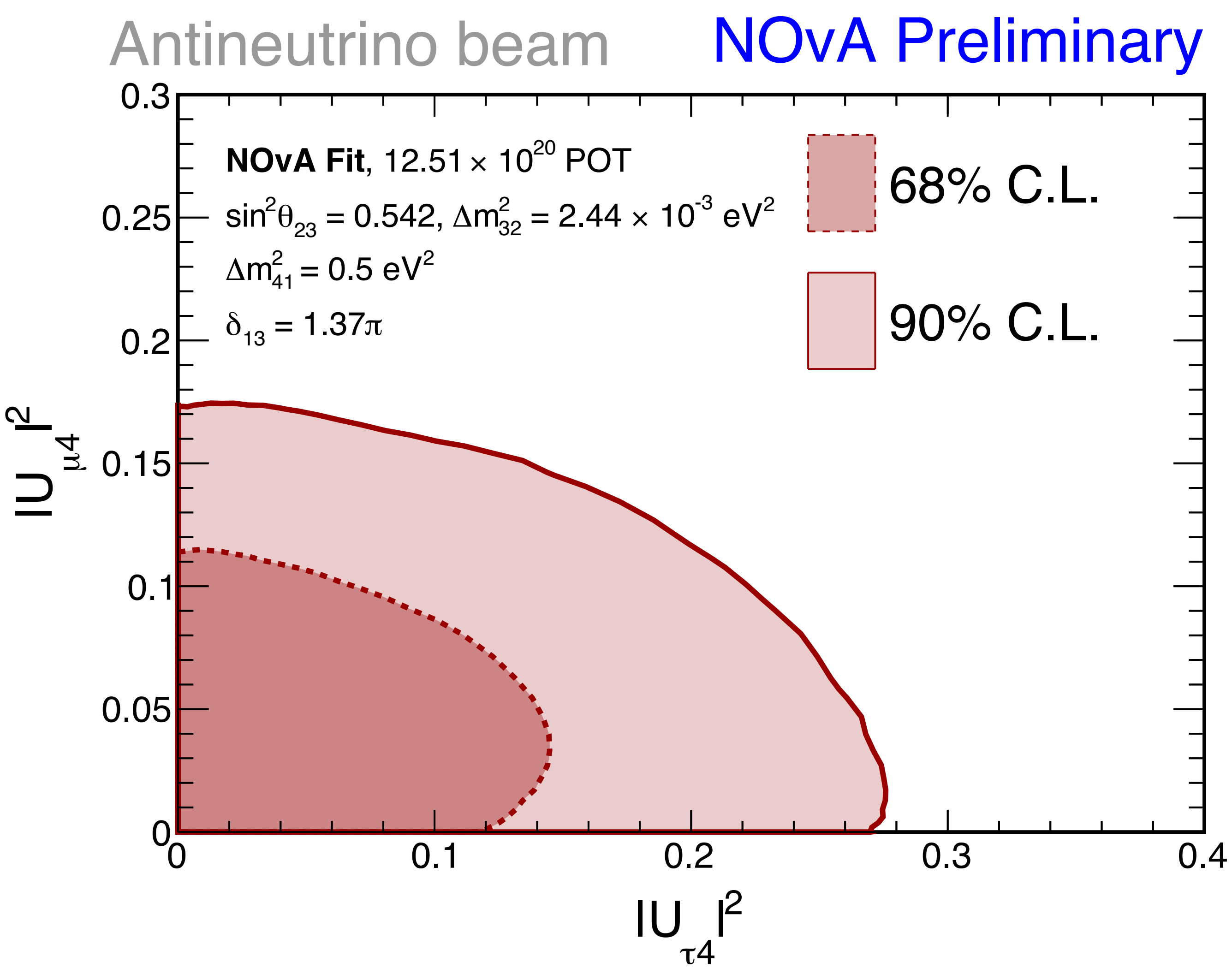
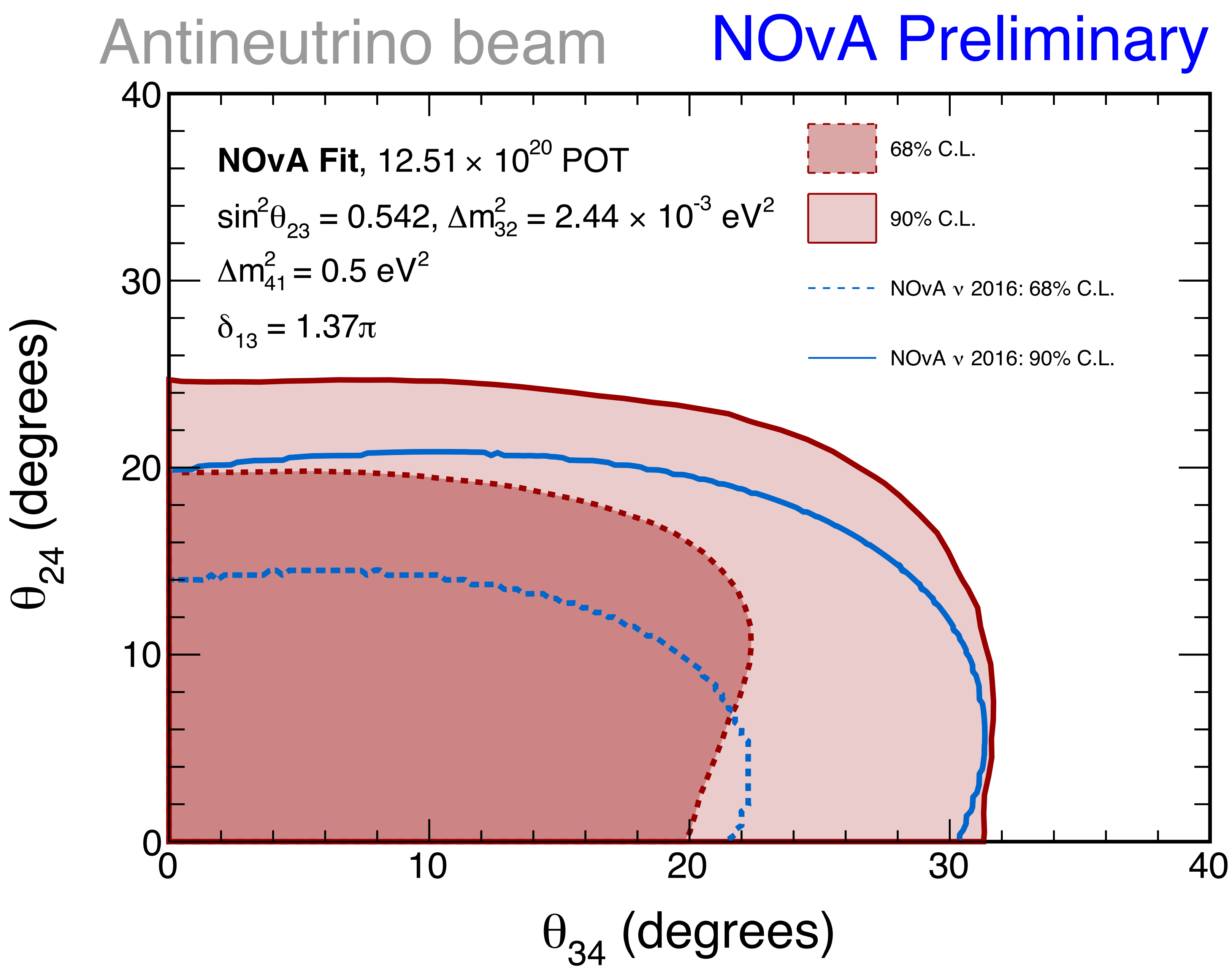


Limits in Context

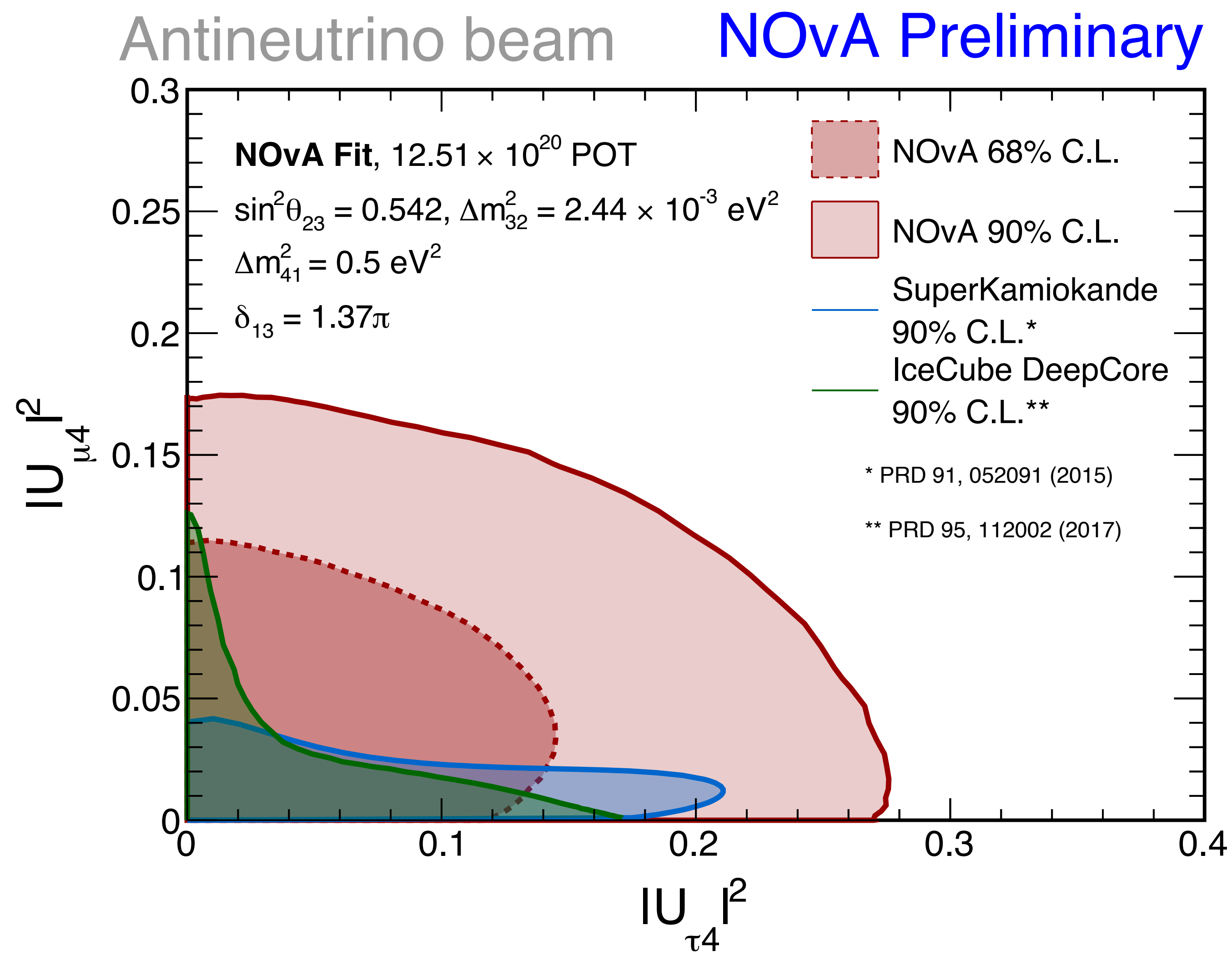
- Previous NOvA limits from the neutrino-dominated beam. The first analysis (2016) is very comparable to this result.



Phys. Rev. D **96**, 072006 (2017)

Limits in Context

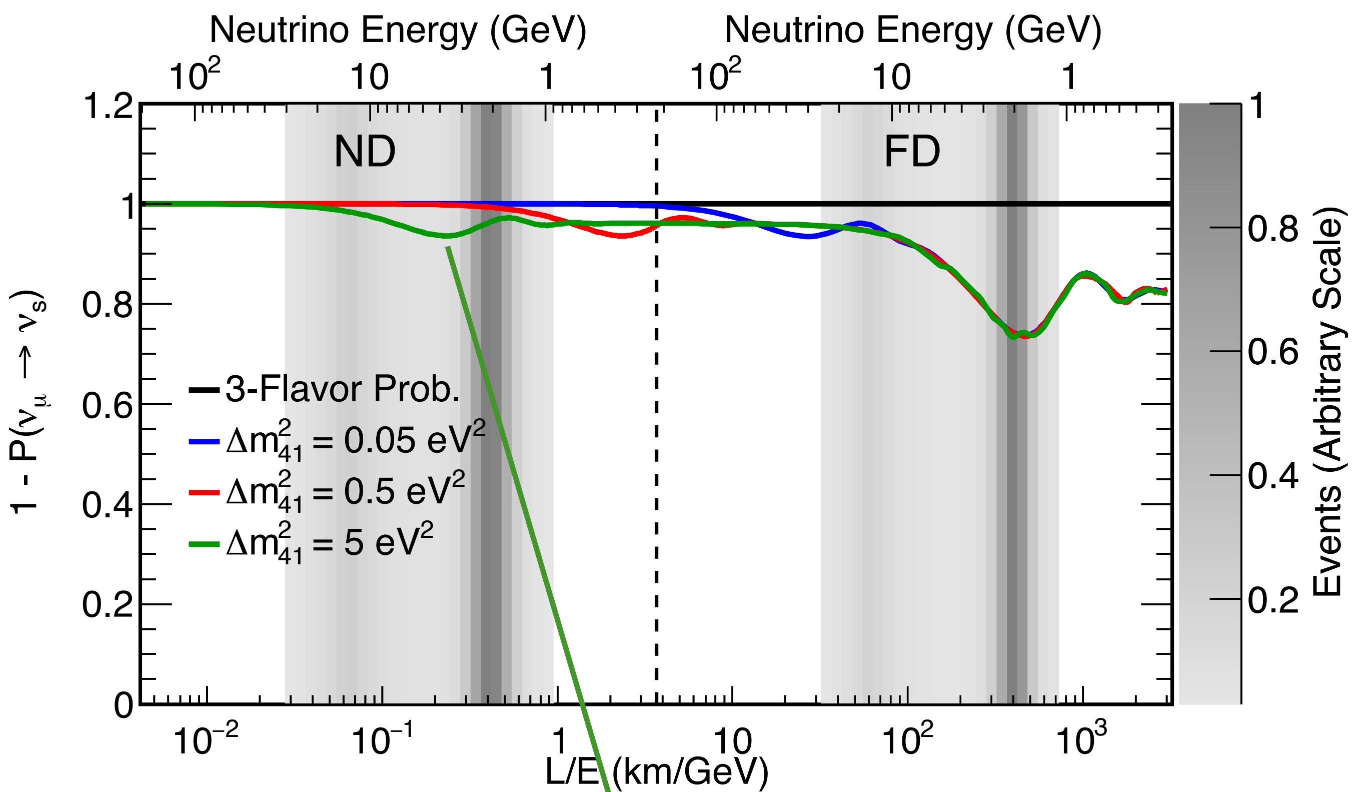
- Limits at fixed Δm^2_{41}.
  - NOvA, MINOS/MINOS+: 0.5 eV², IceCube 0.3 eV², SuperK, T2K 0.1 eV², DeepCore 1.0 eV².

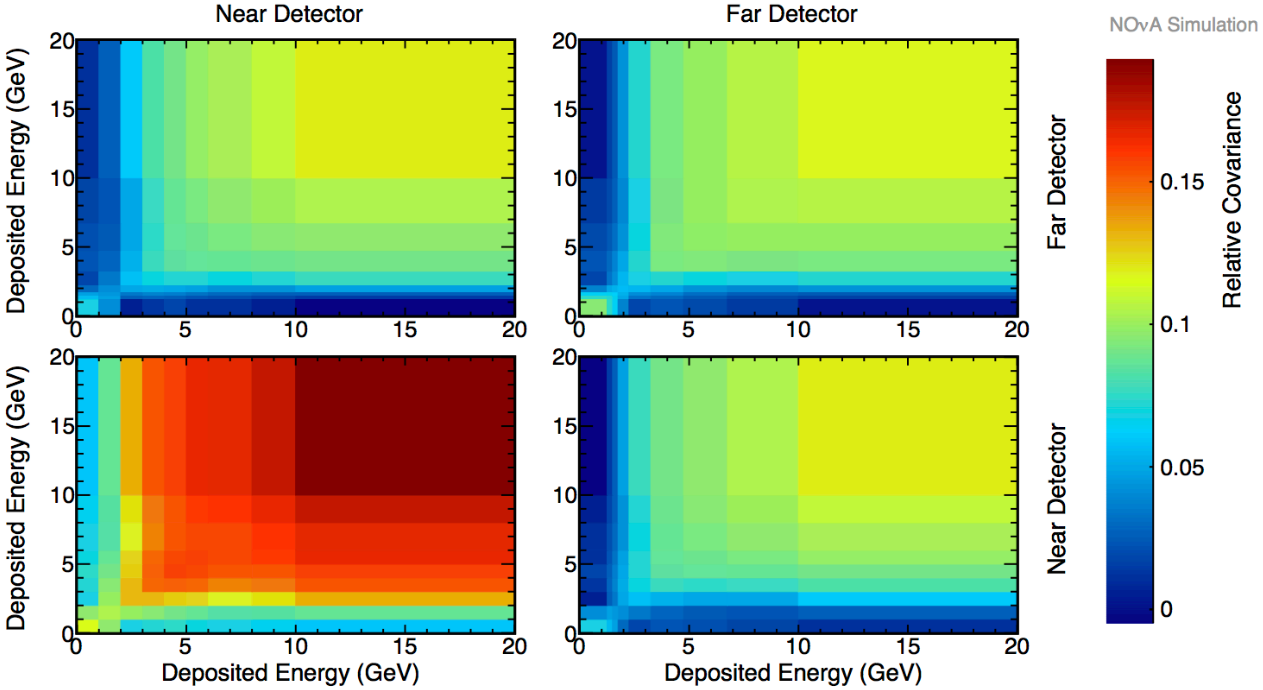


		θ_{24}	θ_{34}	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
Accelerator $\bar{\nu}$	NOvA 2019 ($\bar{\nu}$)	24.7°	31.7°	0.175	0.276
Accelerator ν	NOvA 2017 (ν)	16.2°	29.8°	0.078	0.247
	NOvA 2016 (ν)	20.8°	31.2°	0.126	0.268
	MINOS/MINOS+	4.4°	23.6°	0.006	0.160
Accelerator $\nu/\bar{\nu}$	T2K	18.4°	45.0°	0.1	0.5
Atmospherics	SuperK	11.7°	25.1°	0.041	0.180
	IceCube	4.1°	-	0.005	-
	IceCube-DeepCore	19.4°	22.8°	0.11	0.150

Outlook

Two Detector Fit





$\Delta m^2_{41} > 0.5$ eV^2

- Oscillations in both ND and FD, can no longer treat Δm^2_{41} as constant.
- Must perform joint fit in both ND and FD to properly account for these effects.

- Use covariance matrix to track correlated systematics between two detectors, maintaining the cancellation of uncertainties.
- First analysis with neutrino dataset, before a joint analysis with antineutrinos.
- Also plan to fit additional samples, ν_μ CC disappearance.

NOvA Test Beam Program

- Six-month test beam run scheduled December 2019 — June 2020, currently commissioning at Fermilab Test Beam Facility.

- Use a scaled-down (30 ton) NOvA detector to sample beams of tagged electrons, muons, pions, and protons in the momentum range of 0.3 to 2 GeV and will further the NOvA physics reach by precisely measuring the detector's muon energy scale and electromagnetic and hadronic response.

Summary

http://novaexperiment.fnal.gov

- Performed first long-baseline sterile search using NC-disappearance with NOvA's antineutrino data sample.
- Using full NOvA antineutrino dataset, 12.5×10^{20} POT, **found no evidence of neutrino oscillations outside of a 3-flavor mixing framework** for $\Delta m^2_{41} < 0.5$ eV^2.
  - R ratio 0.99 ± 0.12(stat.) ± 0.16(syst.).
- Interpreting in a 3+1 model, set limits on the mixing angles:
  - $\theta_{24} < 24.7°$, $\theta_{34} < 31.7°$.
- Paper in preparation.
- Look out for exciting updates and new sterile neutrino searches from NOvA very soon!

Thank You!

http://novaexperiment.fnal.gov

Backups

3-Flavor Oscillations

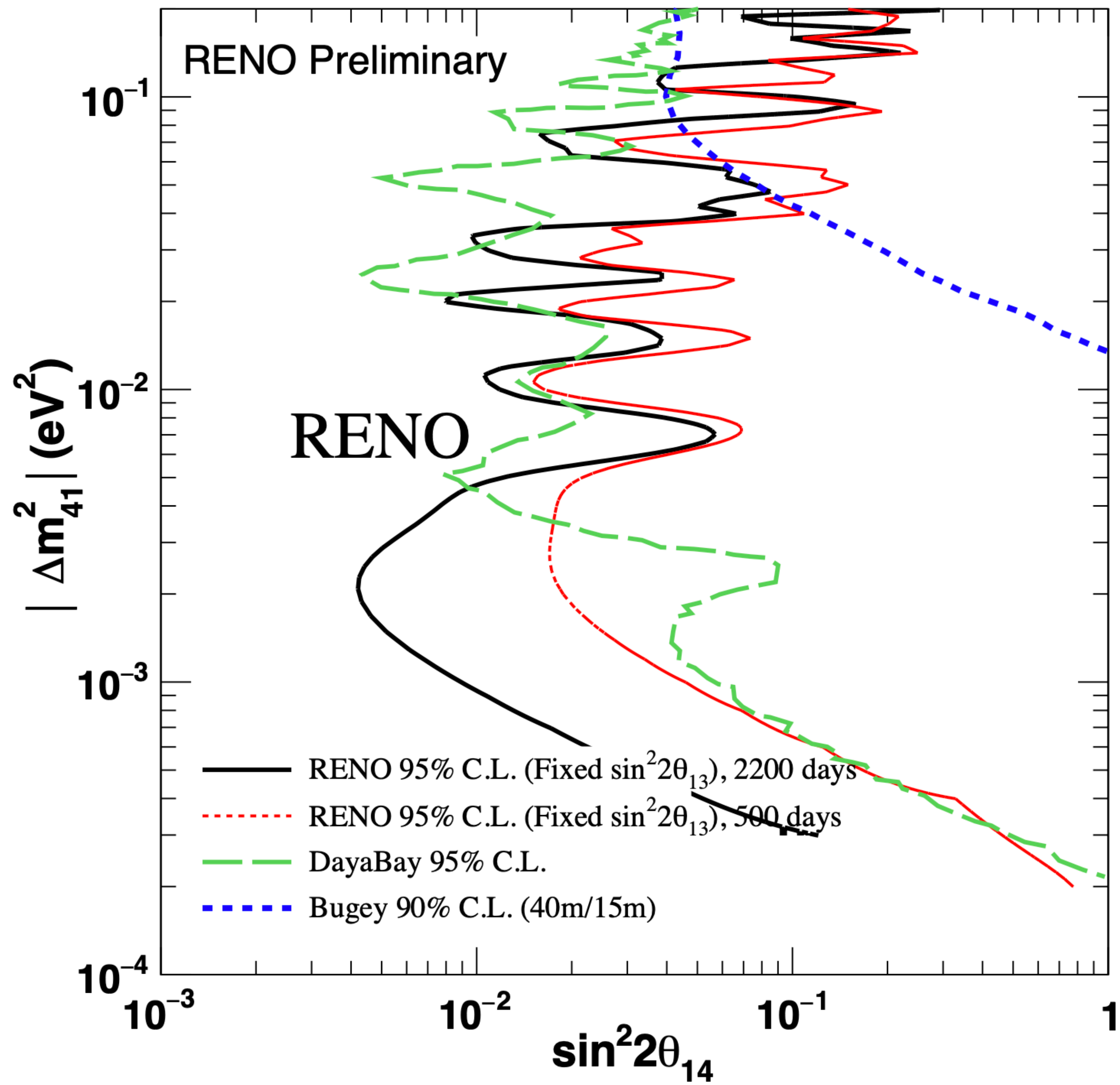
$$\left(\ \right) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \left(\ \right)$$

Searches for Sterile Neutrinos: Reactors

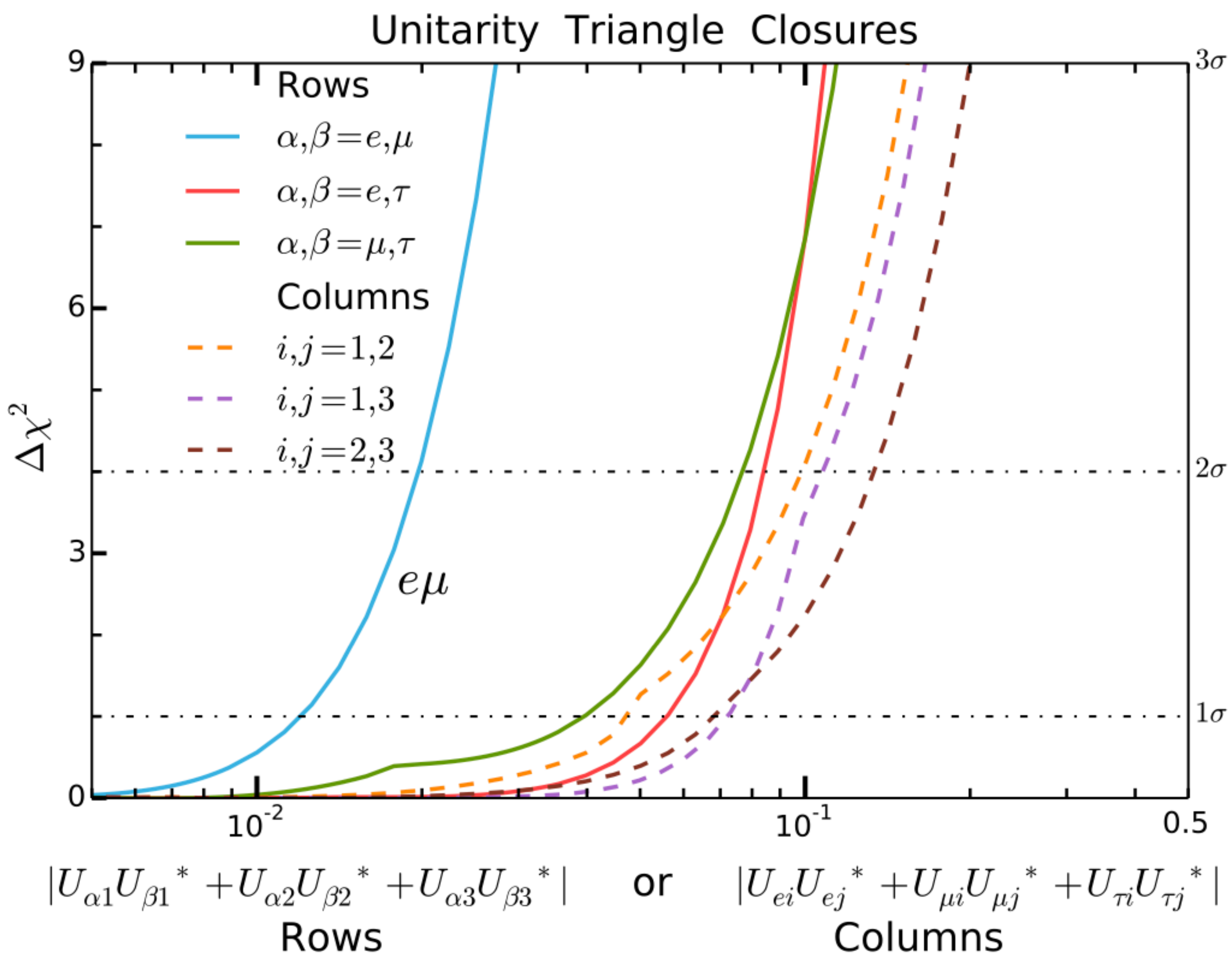
- Reactor experiments have studied oscillations involving $\overline{\nu}_e$ to search for evidence of sterile mixing.
- Looking for $\nu_e/\overline{\nu}_e$ disappearance:
  - Sensitive to θ_{14}.
- No evidence observed has set strong limits on the θ_{14} mixing angle.

Phys. Rev. Lett. **117**, 151802 (2016) (Daya Bay)

PoS ICHEP 2018 Proceedings, Page 879 (2018)



Unitarity Considerations



S Parke, M Ross-Lonergan, Phys. Rev. D **93**, 113009 (2016)

- Constraints from unitarity considerations of the PNMS matrix, with current understanding of the mixing angles.
- Current bounds on normalization of rows and columns.
- 'e' row gives strong bounds on $|U_{e4}|^2$.

Flux Prediction

- FLUGG/FLUKA Monte Carlo simulation using GEANT4 beamline to simulate hadron production at targets. Technical Report CERN-2005-010 (2005)

- PPFX (Package to Predict the FluX) reweighing framework developed for MINERvA and applicable to the NuMI beamline.

    - Accounts for attenuation of particles passing through al NuMI materials, uses external data to constrain particle production.

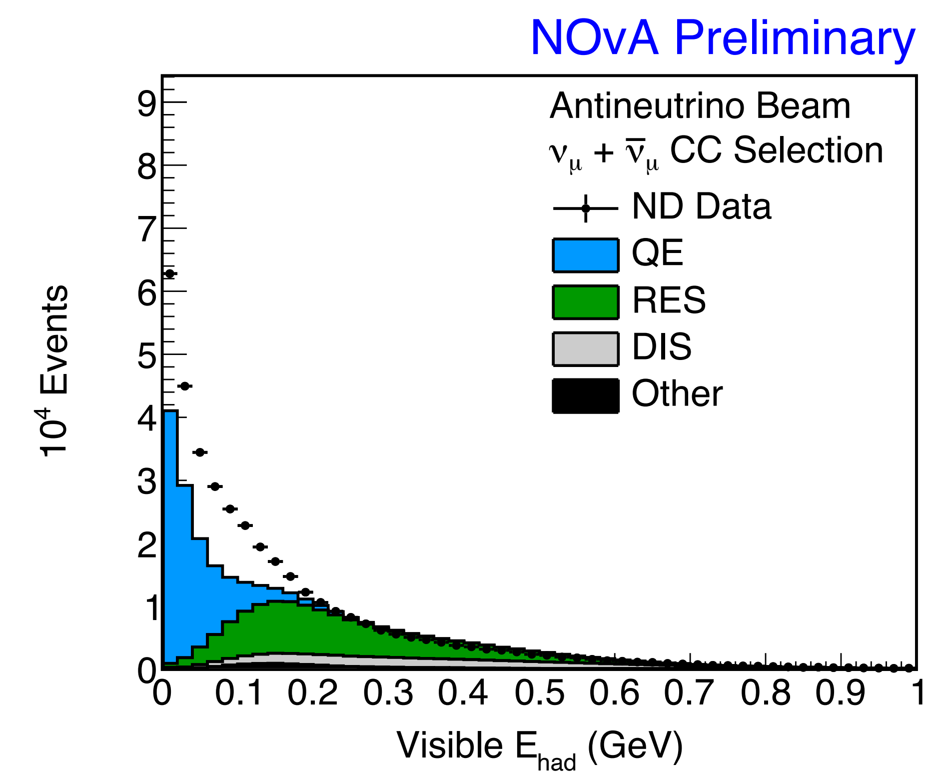
    - Provides reweighing framework to handle systematic uncertainties in a multi-universe approach.

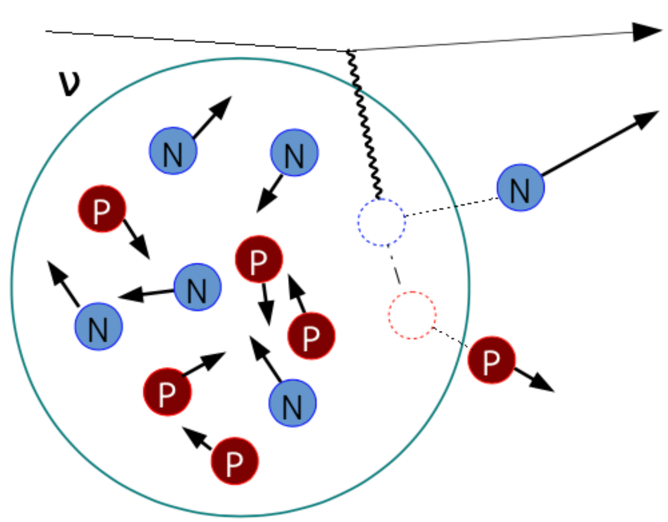
Neutrino Flux Prediction for the NuMI Beamline, Leonidas Aliaga Soplin Thesis, William & Mary (2016)

NOvA paper in preparation

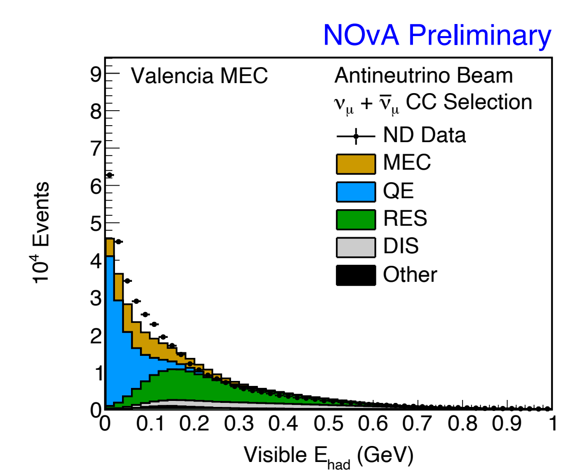
Near Detector Prediction

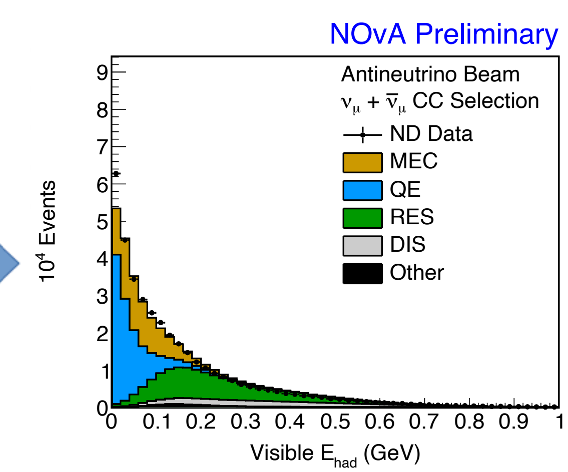
- Use GENIE 2.12.2 and add some additional effects to account for discrepancies seen in the hadronic energy at the ND.
- 'NOvA tune' used in the 3-flavor oscillation analyses. Tuned on ν_μ, not NCs.
- Most reweighing affects CC or neutrinos only, so not relevant.
- Full MEC tune of Empirical MEC events based on NOvA data to account for extra processes between QE and Δ production. Fewer than one MEC event selected in our NC sample.



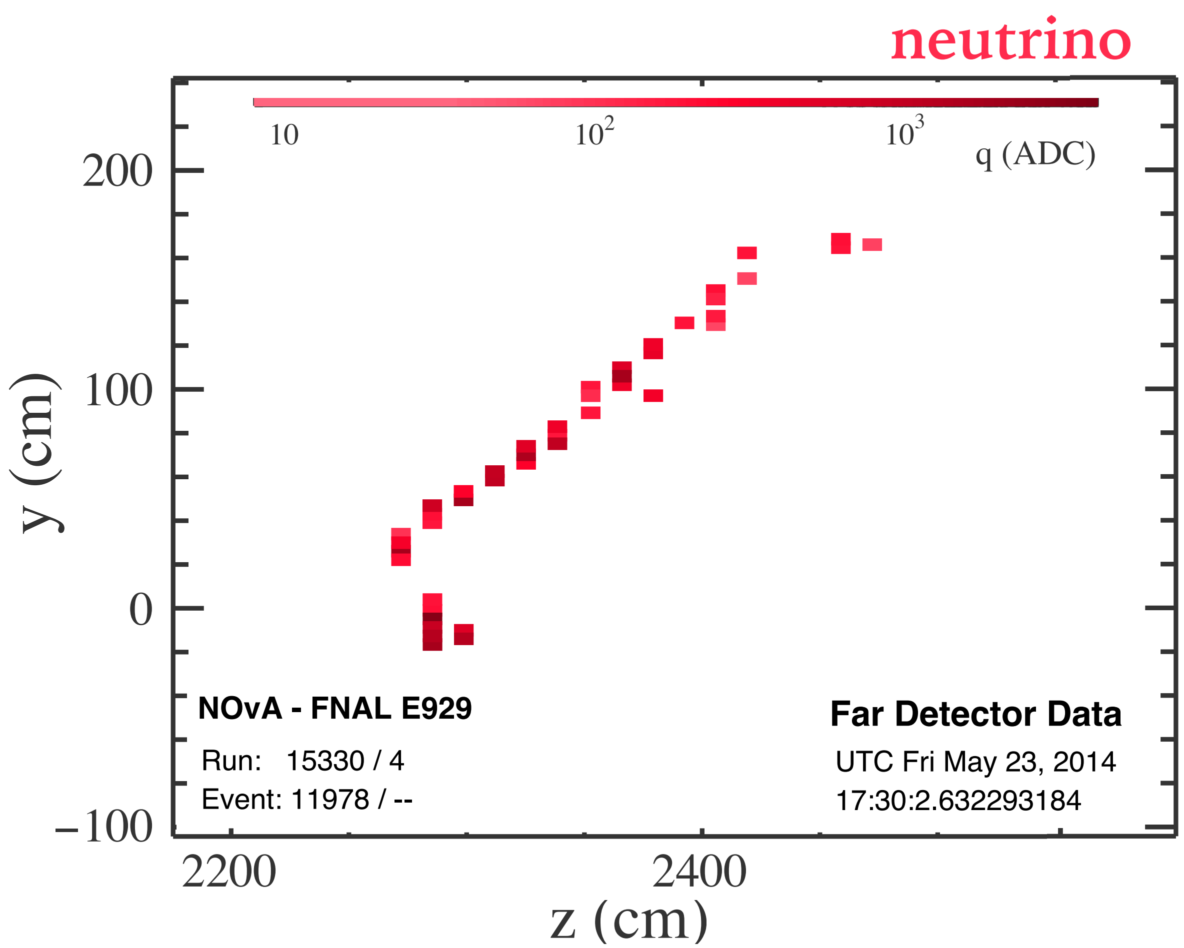


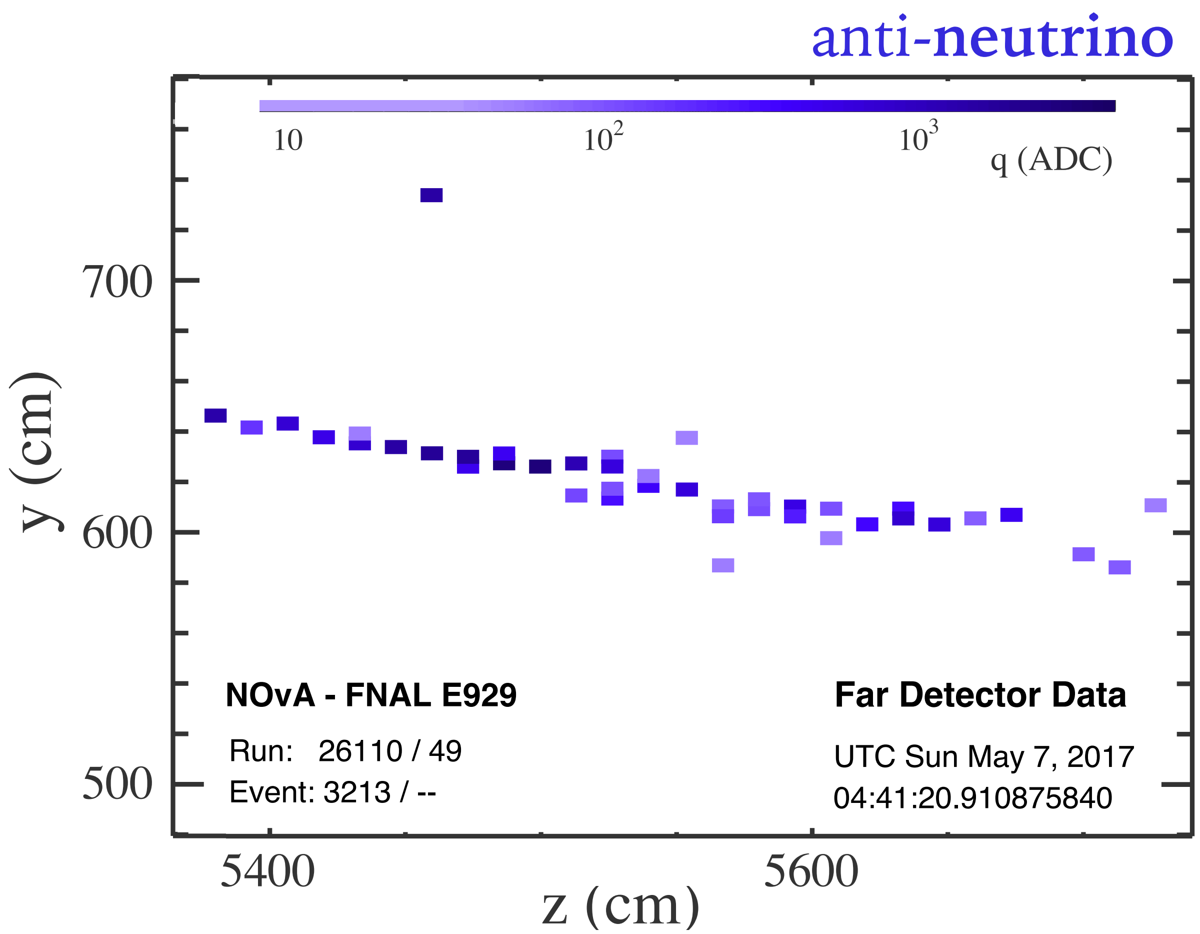
'2p2h'





Event Classification





The topology of neutrino and anti-neutrino interactions is different on average.

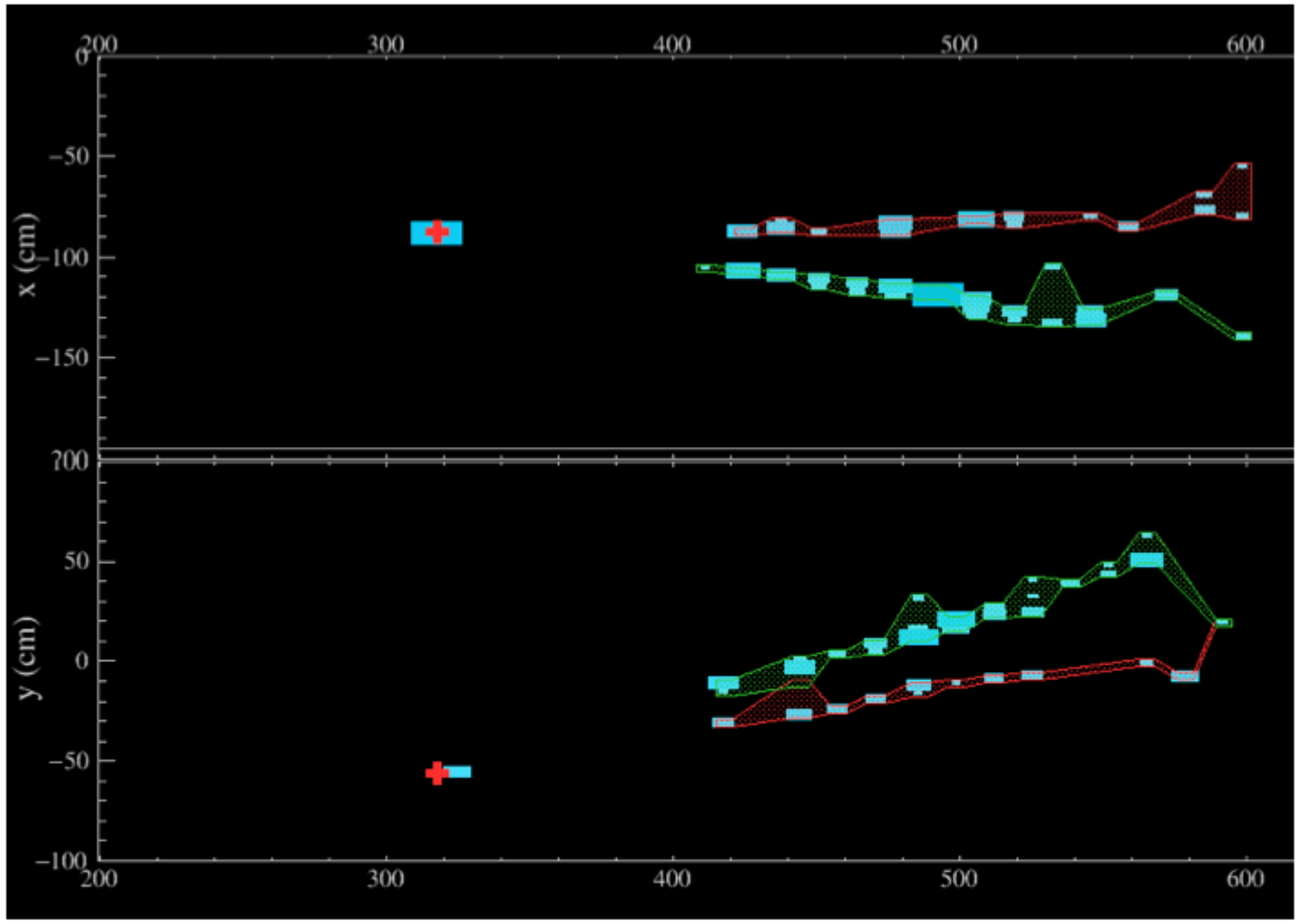
Train on **neutrino** beam and **anti-neutrino** beam simulations separately.

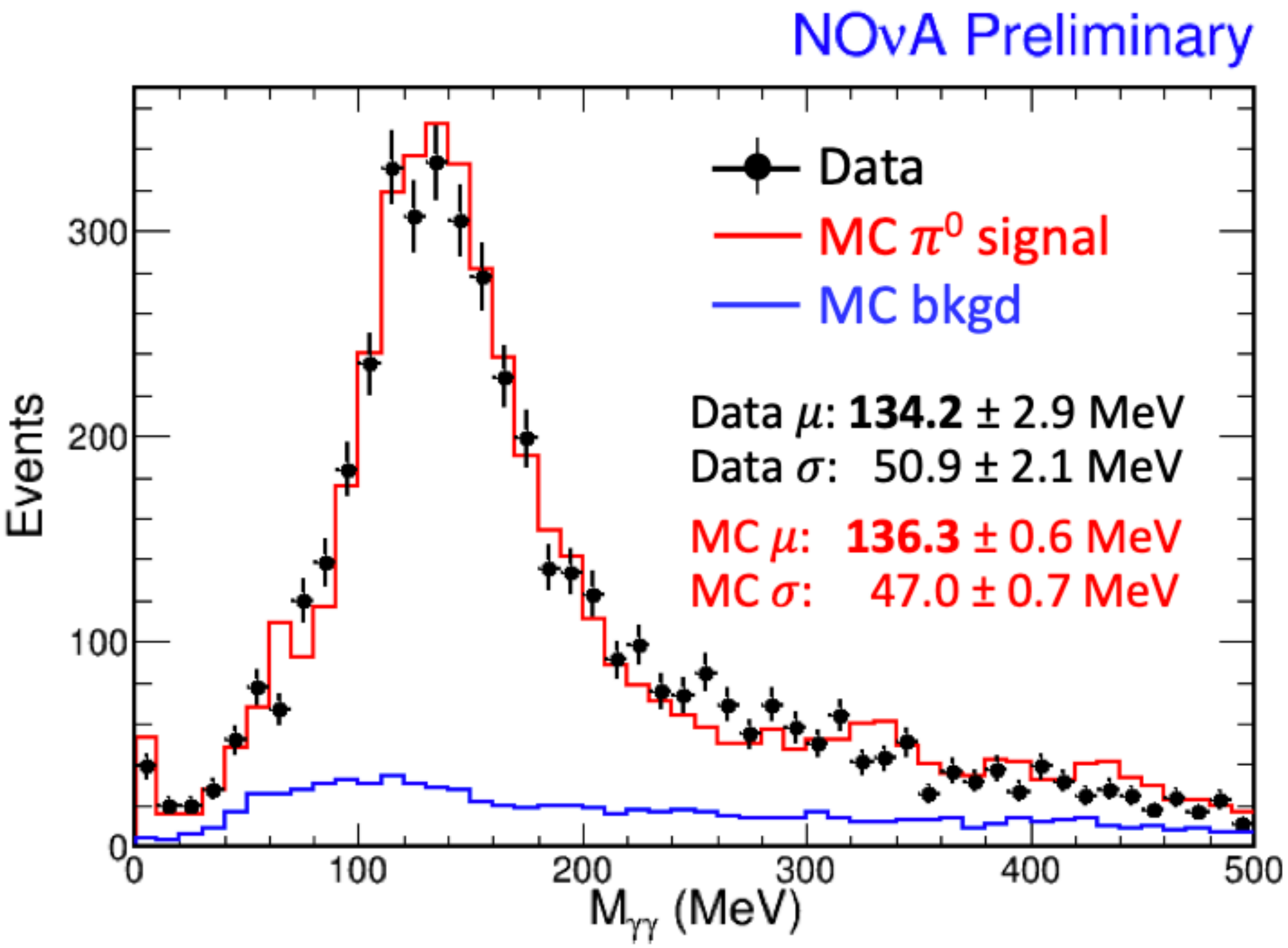
Utilize differences in event topology.

$\bar{\nu}$ **Efficiency Improvement** Training Sample (ID > 0.9)		
$\bar{\nu}_e$ CC Signal	$\bar{\nu}_\mu$ CC Signal	$\bar{\nu}$ NC Signal
14%	6%	10%

Reconstruction Capabilities

- Nicely reconstructed π^0 mass peak, demonstrates ability to reconstruct NC events.
- Used as calibration cross-check.





Cosmic Rejection BDT

- Variables:
  - CVN cosmic,
  - Number of showers,
  - Leading shower direction,
  - Leading shower length,
  - Transverse momentum fraction,
  - Leading shower number of hits [4] (each view separately, sum and difference),
  - Leading shower number of hits (X-Y)/(X+Y) view,
  - Leading shower width,
  - Leading shower gap,
  - Number of MIP hits in slice,
  - 'Calorimetric energy' for leading shower.

Far Detector Prediction

Total	NC	ν_μ	ν_e	ν_τ	Cosmics
132.16	95.50	25.52	2.40	0	8.73

No oscillations

Total	NC	ν_μ	ν_e	ν_τ	Cosmics
122.29	95.50	12.20	3.63	2.23	8.73

With oscillations

Systematics

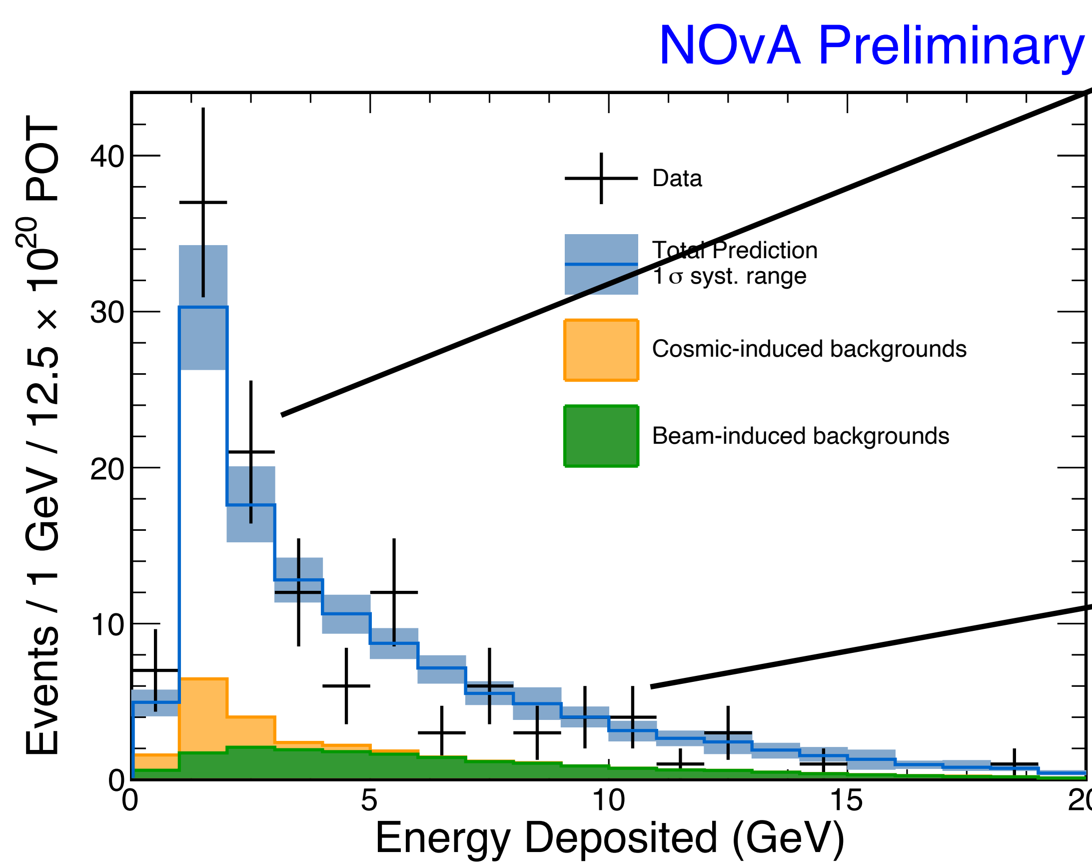
- Calibration:
  - Shift calibration normalization by 5% to account for level of agreement with the dE/dx distributions and π^0 mass peak.
  - Shape calibrations from the discrepancy of number of calibrated PEs/cm with dE/dx from simulation.
- Detector response:
  - Scintillation light level normalization; 10% to account for differences between MC/data for the number of photoelectrons/cm detected in through-going cosmics (shift absolute calibration in the opposite direction to avoid canceling effects);
  - Scale the parameters describing the production of Cherenkov light to the extremes where no change is observed in muons but would improve agreement in dE/dx distributions in QE-like ND events between data and MC.

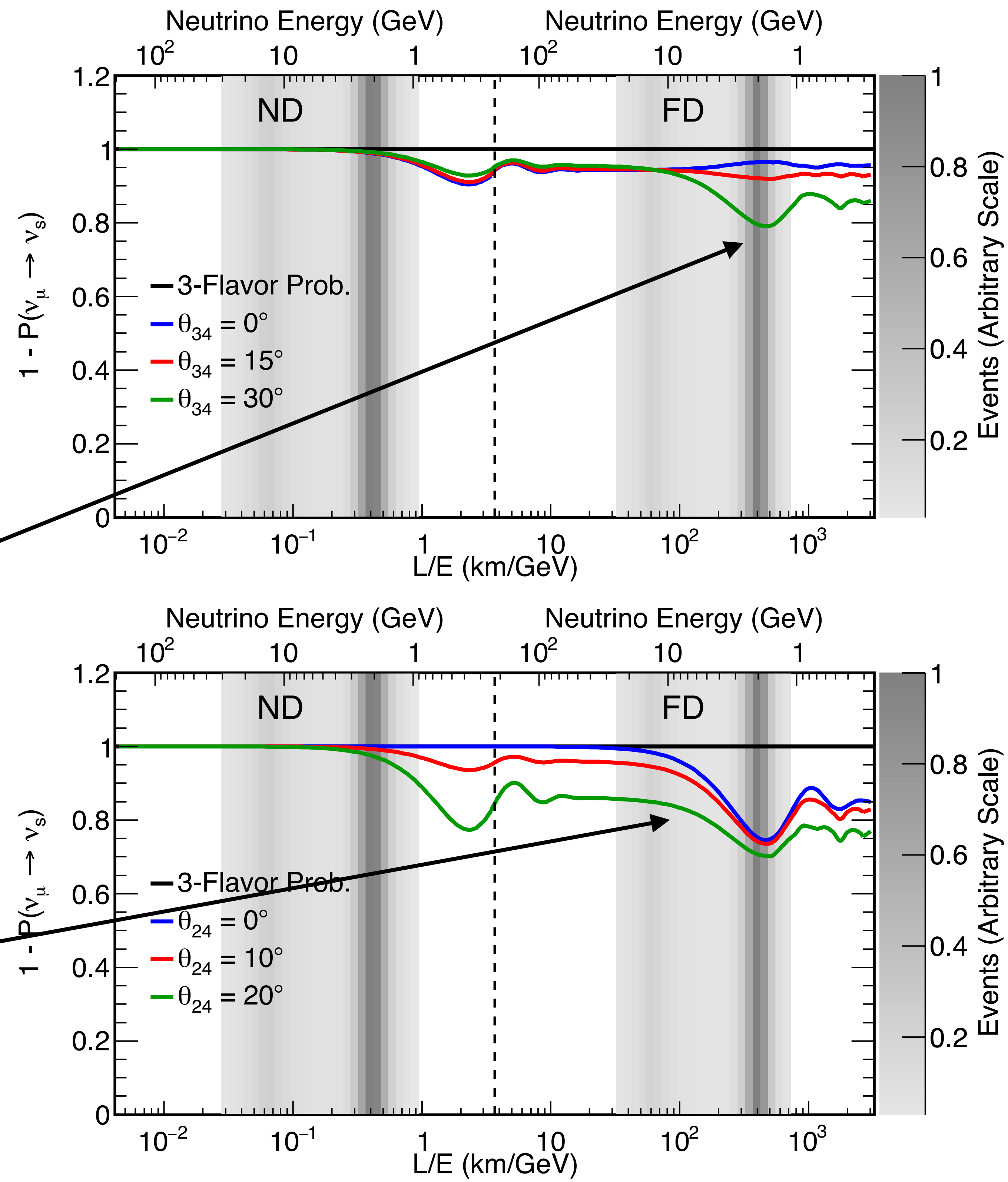
Systematics

- Neutrino interactions:
  - GENIE reweighting;
  - 60% ν_τ interaction uncertainty;
  - effect of removing the 'NOvA tune' cross-section central values.
- Beam:
  - Beam transport uncertainties, including all parts of modeling the target, decay volume, etc.
  - Uncertainties in modeling the flux using the reweighting framework included in PPFX.
  - Additional 30% uncertainty on neutrinos from kaon decay in the high energy tail of beam.
- Neutron: systematic variation accounting for differences in reconstructed energy between data and simulation for CCQE events with one muon and a single additional object identified as coming from neutron interactions. Low energy neutron depositions scaled up to higher energies.

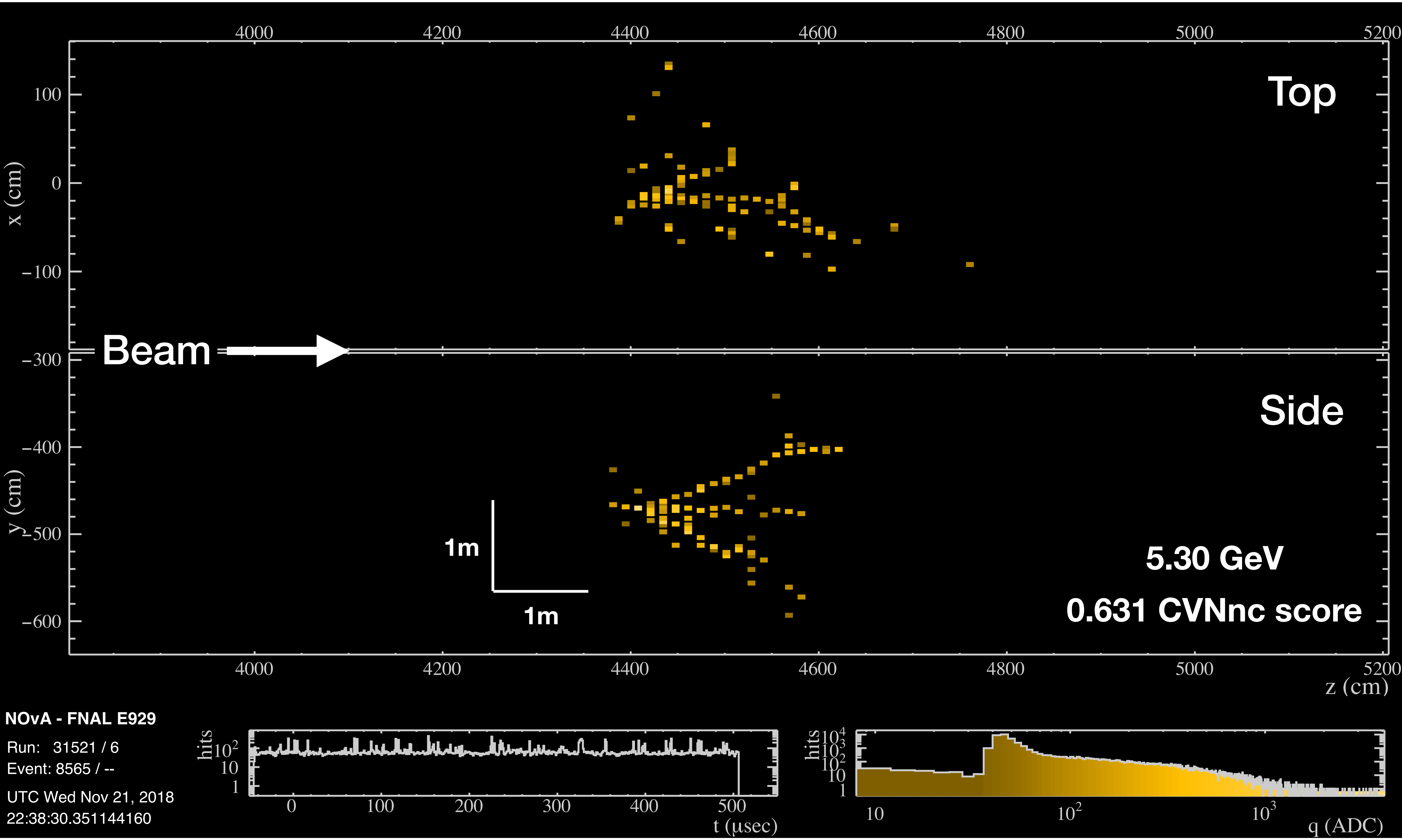
Limits

- Oscillations driven by θ_{34} at the peak of the spectrum and by θ_{24} in the tail.
- Strong limits in θ_{34} from the excess in the bins at the peak; weaker limit in θ_{24} from the overall deficits in the tail.

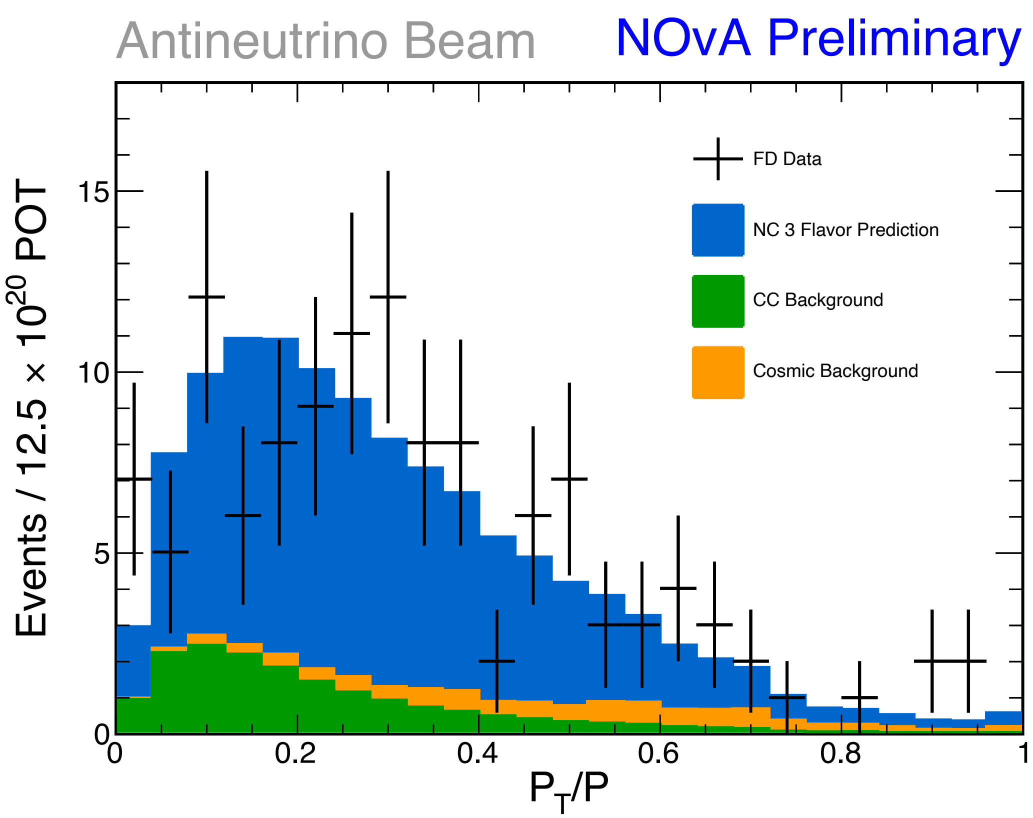


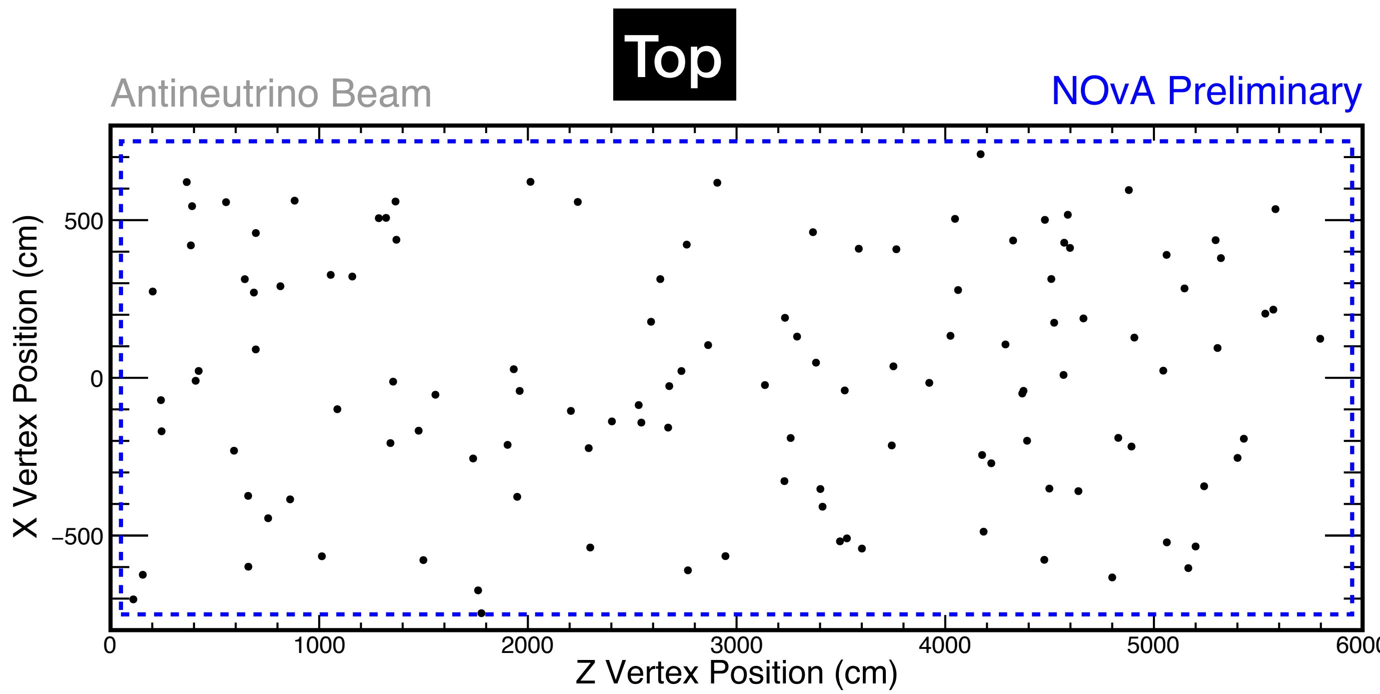


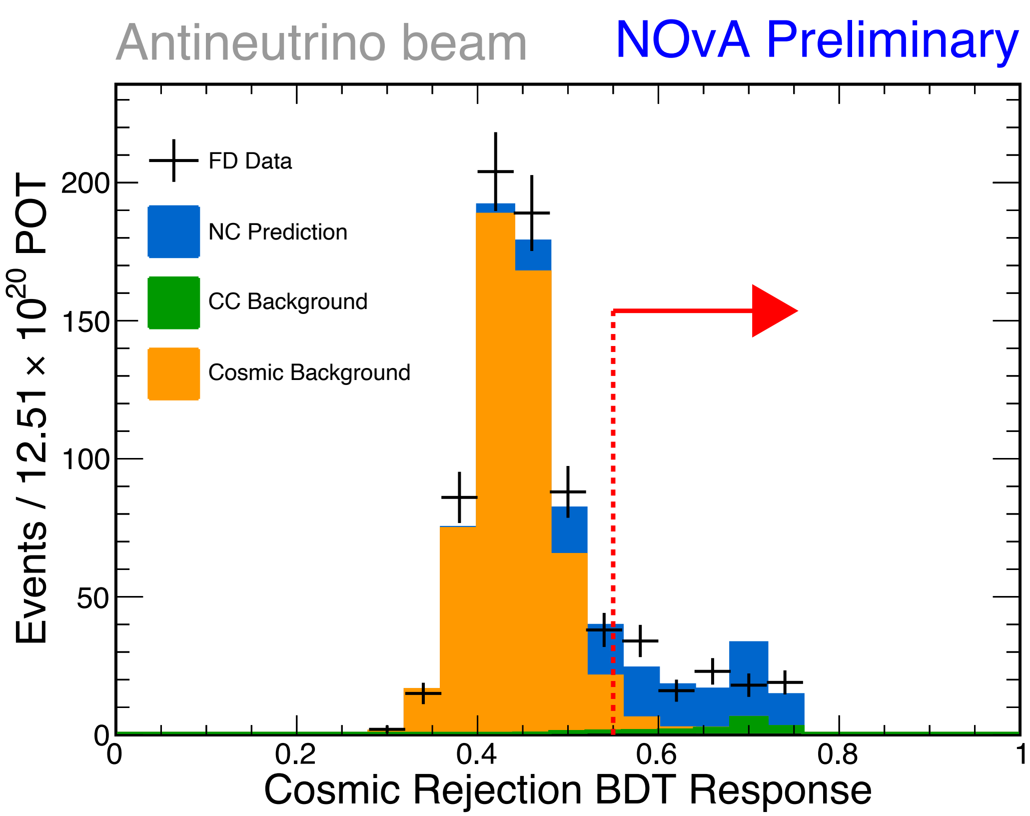
Candidate Selected Event

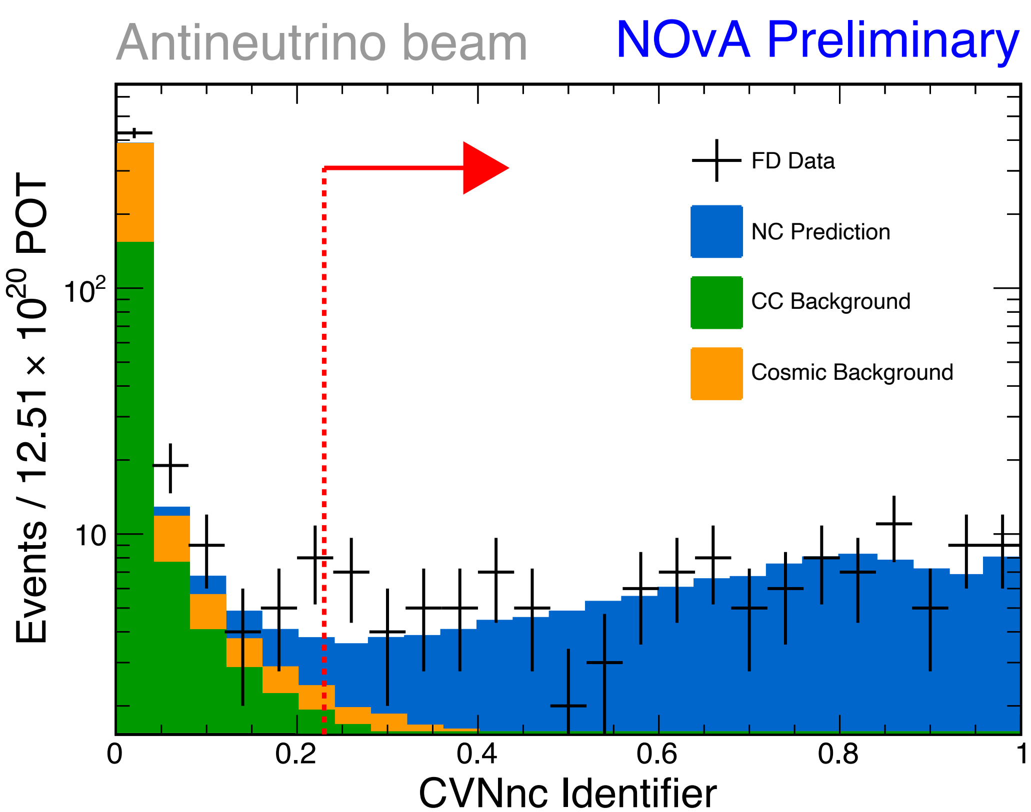


(More) Far Detector Distributions

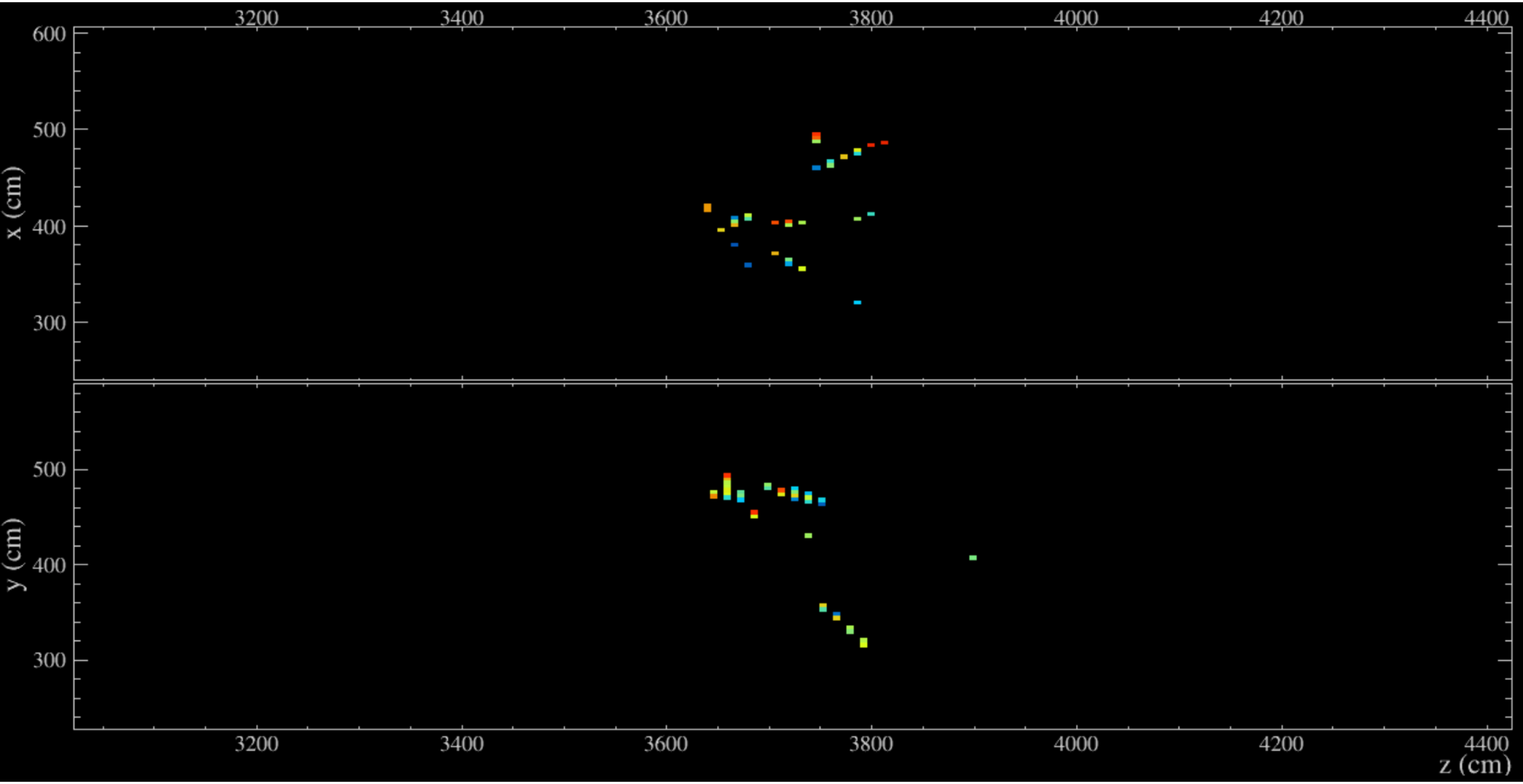




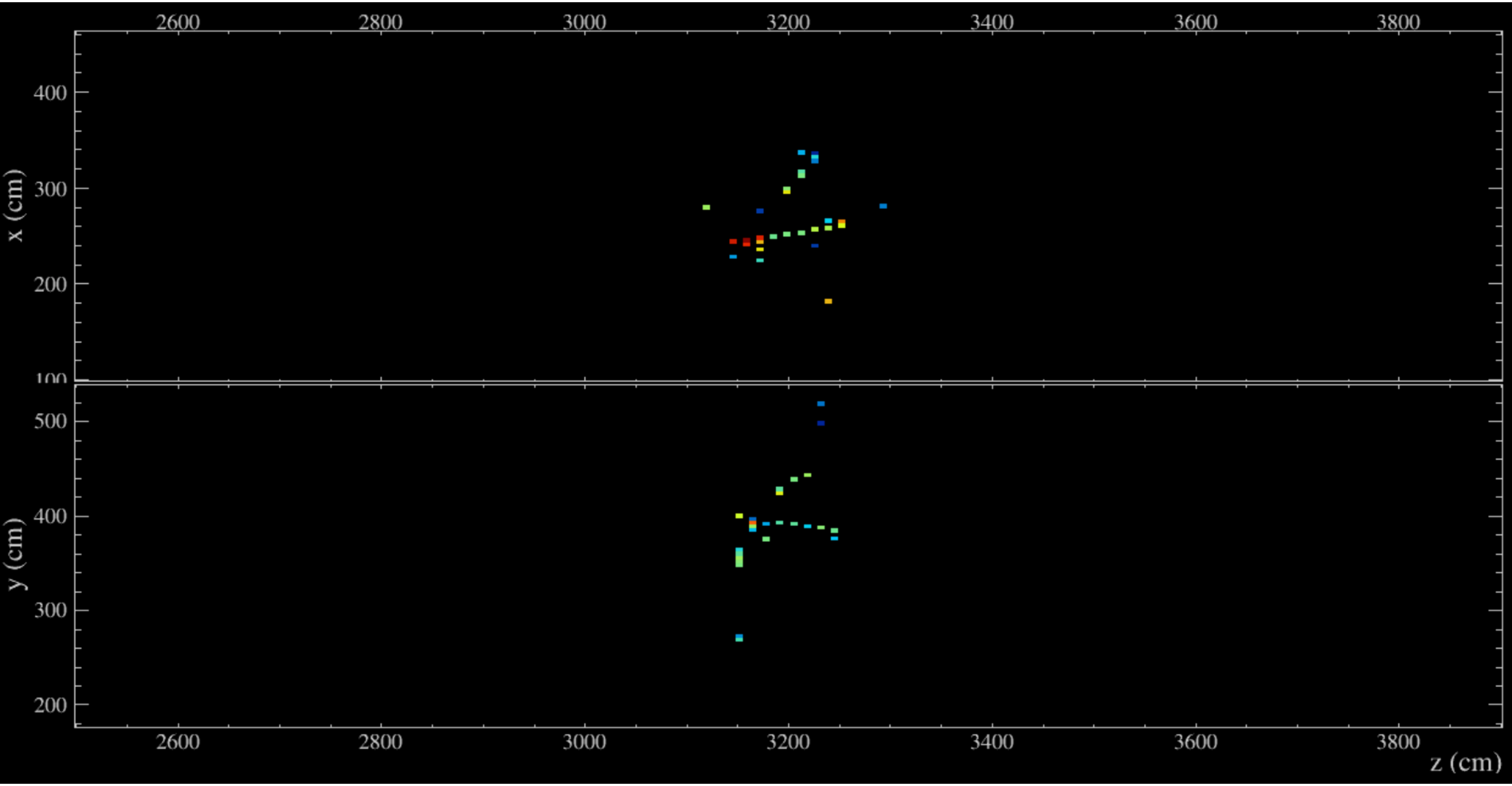




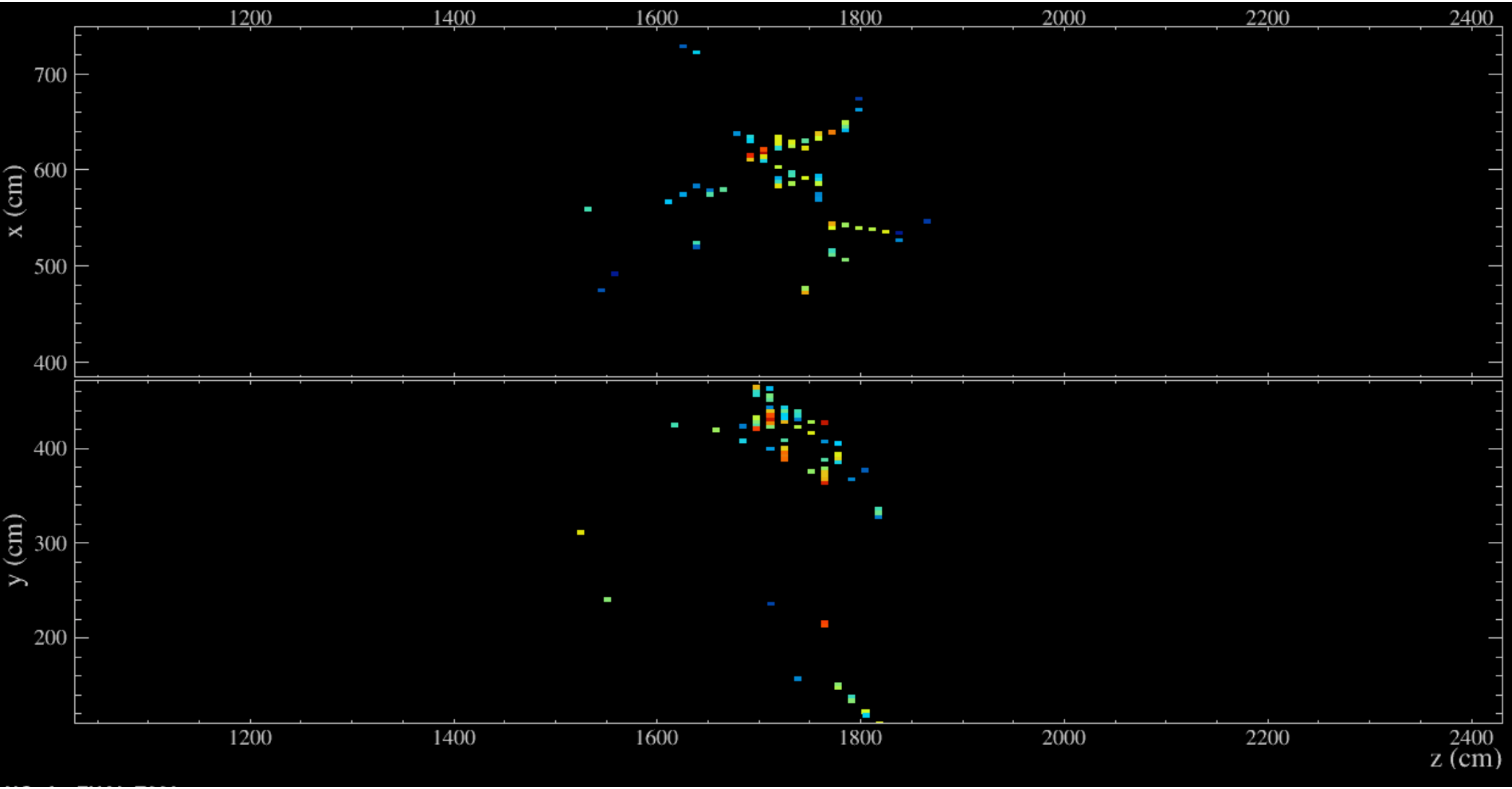
Cosmic Events



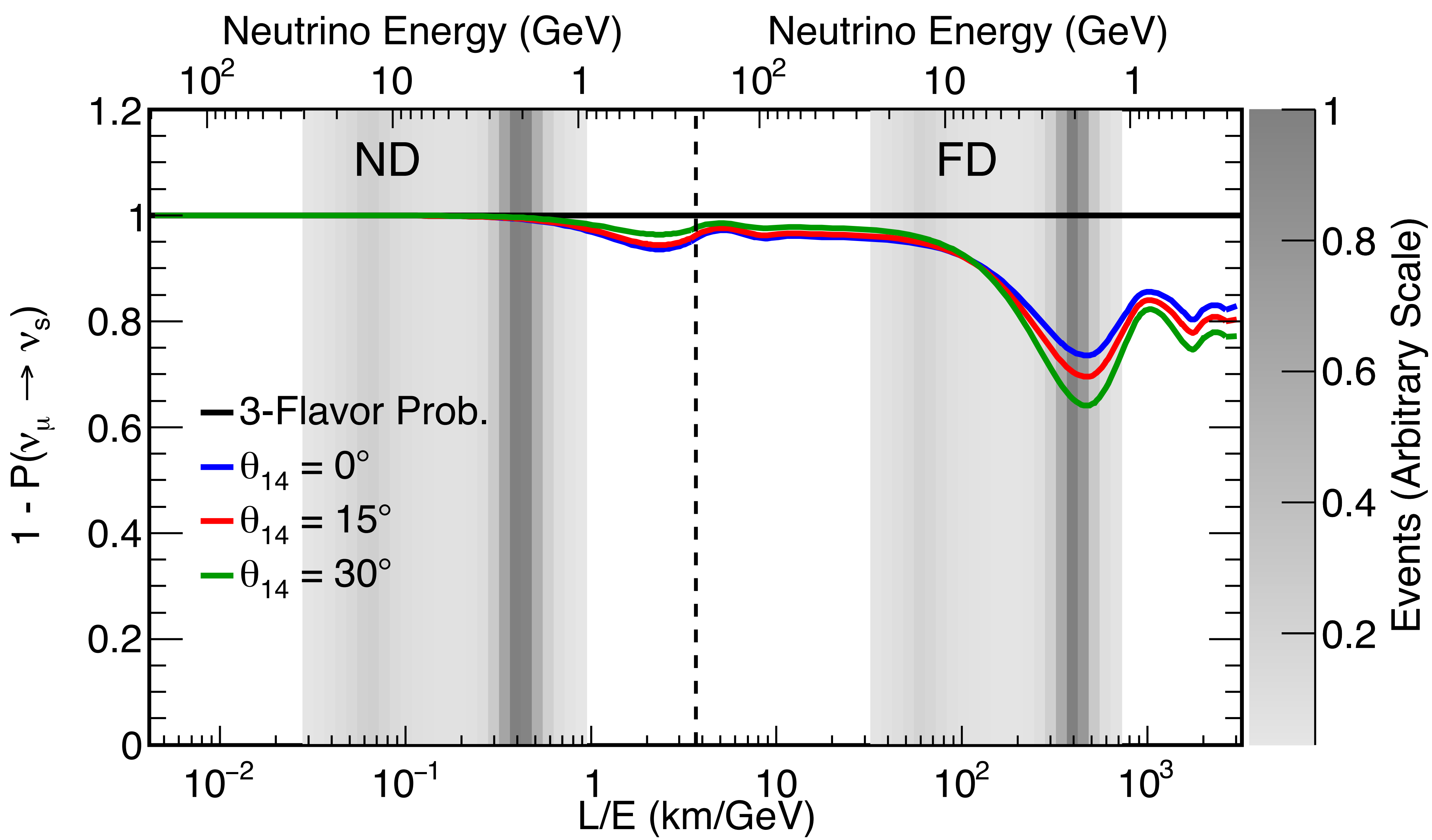
Cosmic Events



Cosmic Events

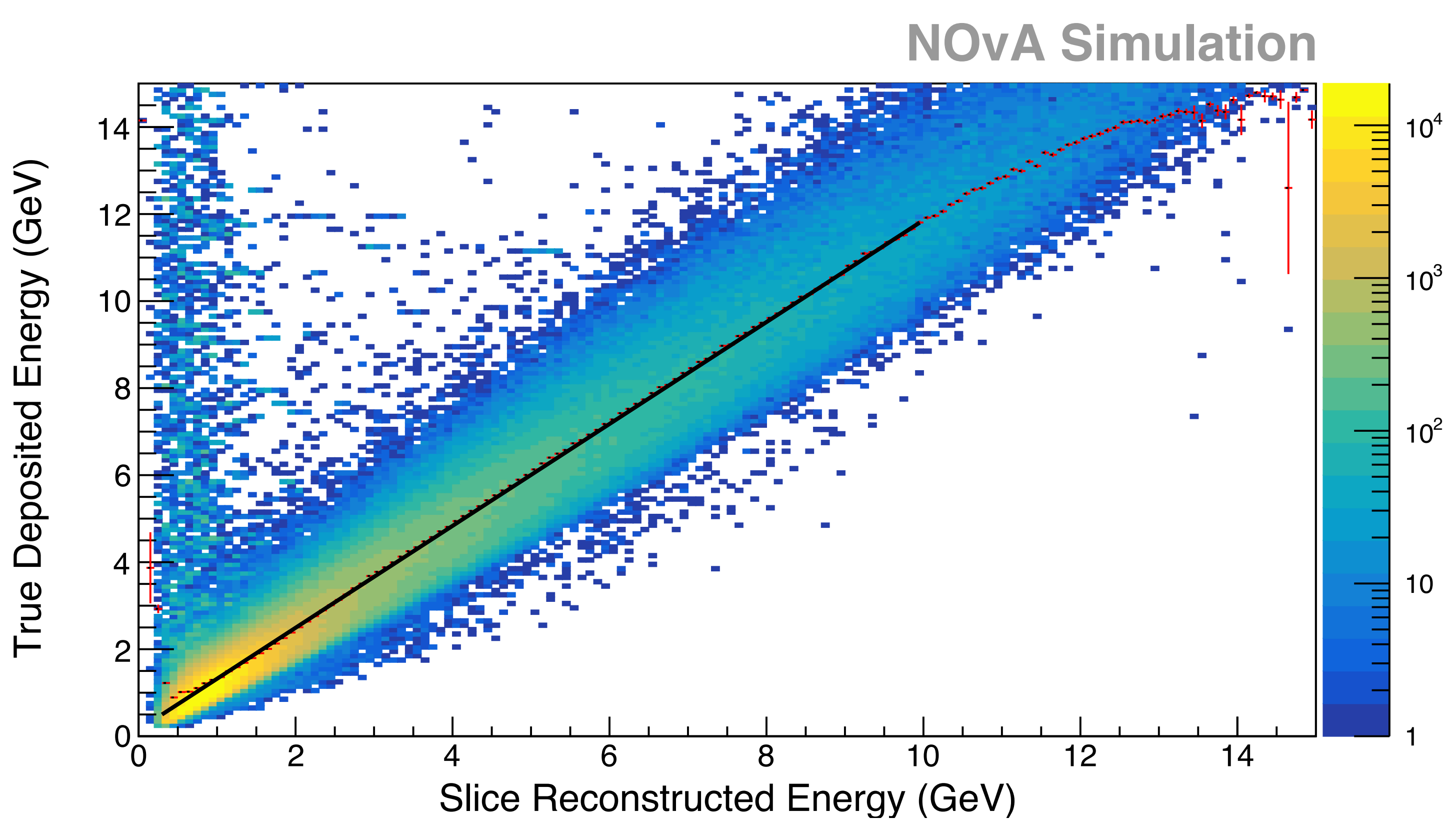


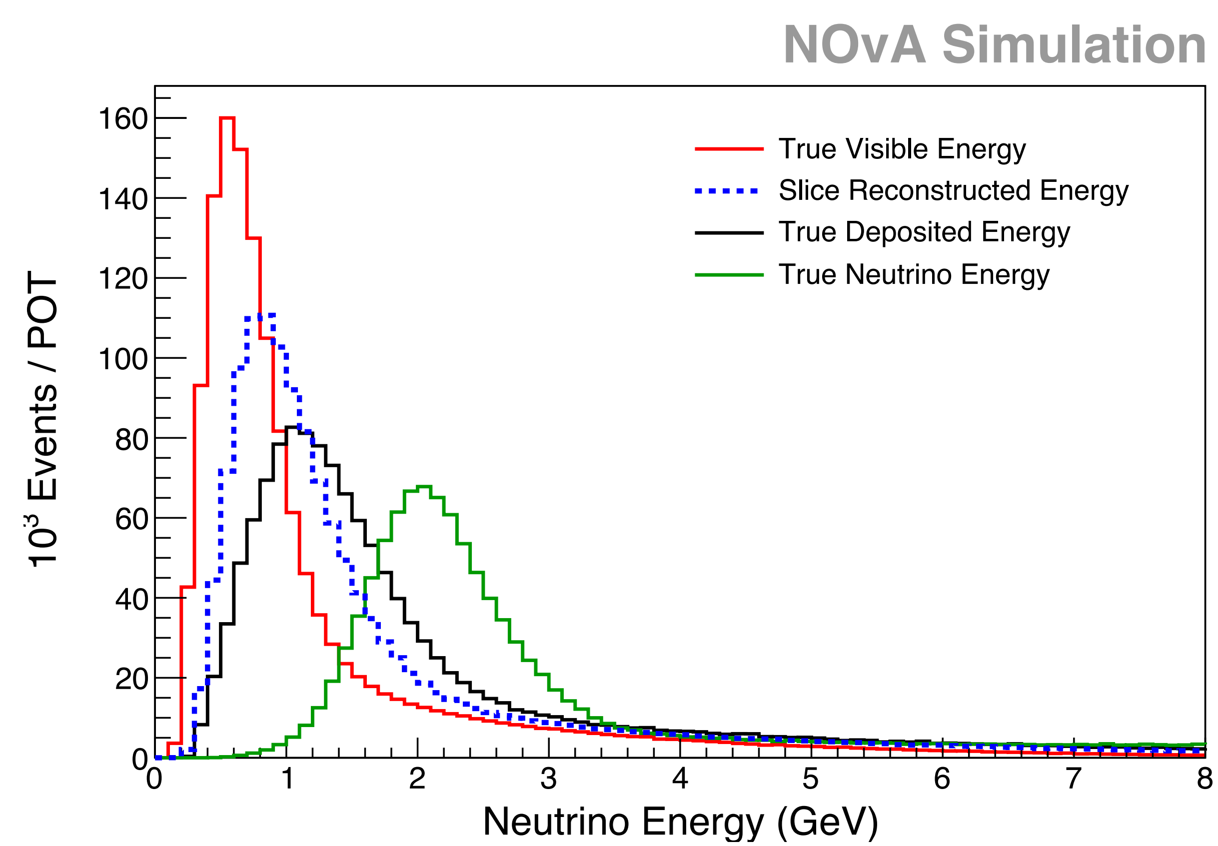
Effect of θ_{14}



Energy Reconstruction

- Determine 'calorimetric energy' based on calibrated charge collected in detector.
- Use simulation to convert reconstructed energy into 'true deposited energy' in the event.
- Final energy resolution ~25%.





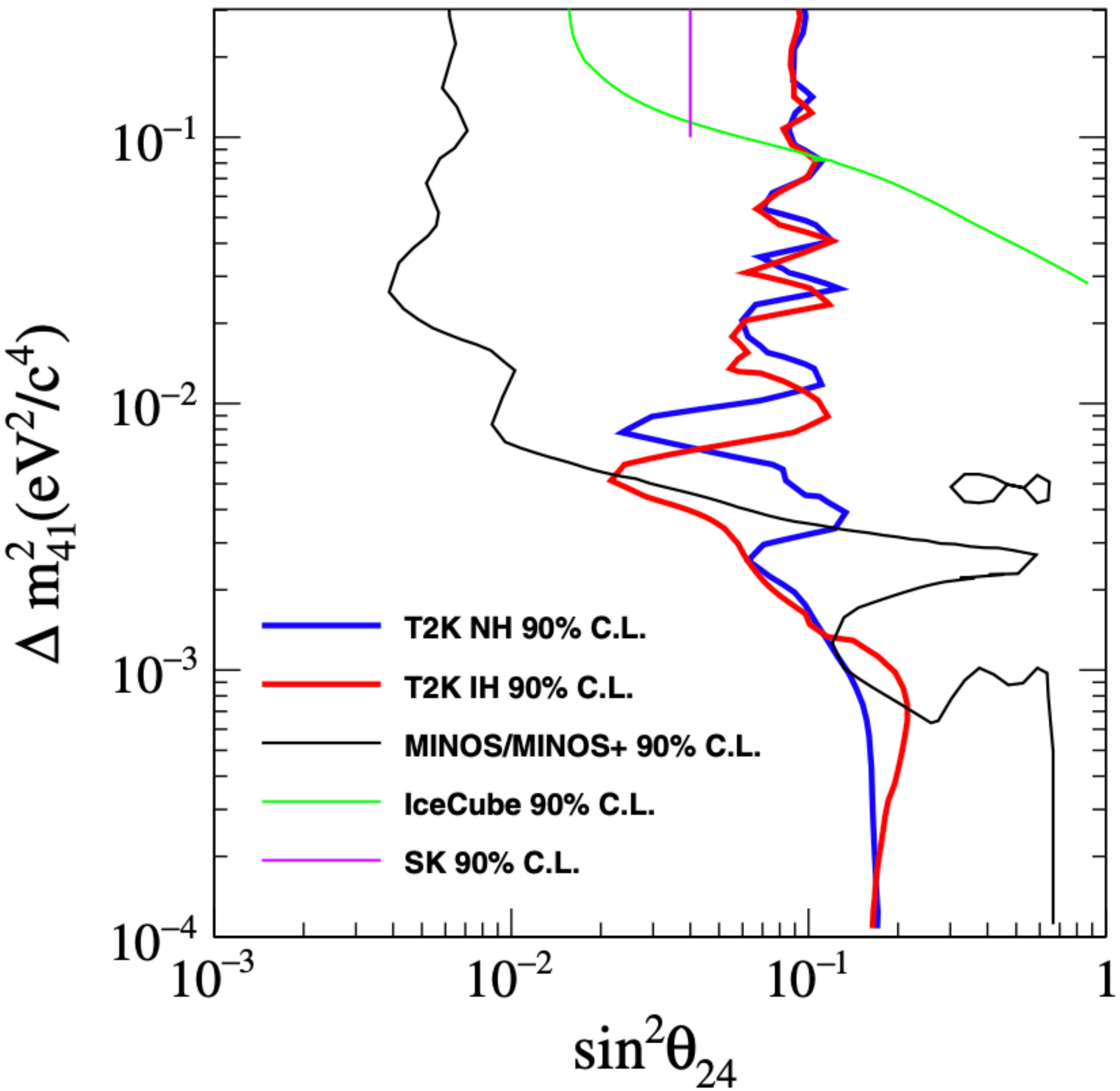
90% World Limits

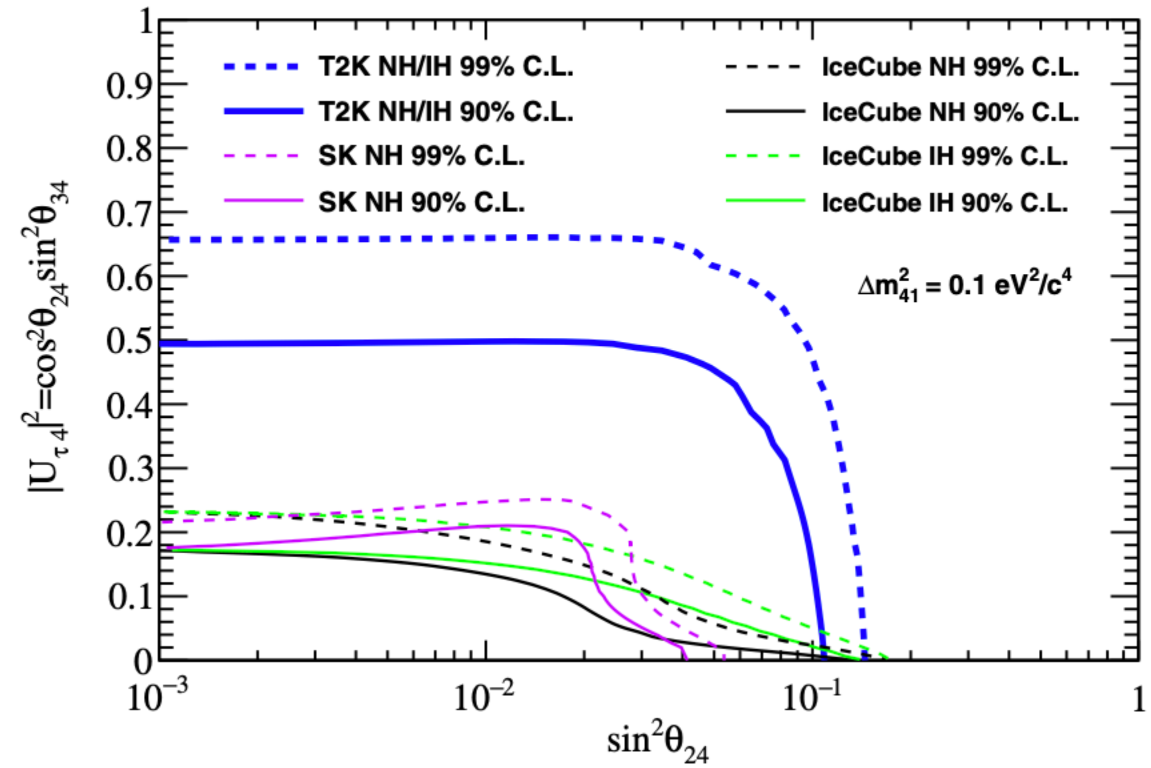
	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
NOvA 2019 ($\bar{\nu}$)	24.7°	31.7°	0.175	0.276
NOvA 2017 (ν)	16.2°	29.8°	0.078	0.247
NOvA 2016 (ν)	20.8°	31.2°	0.126	0.268
MINOS/MINOS+	4.4°	23.6°	0.006	0.160
T2K	18.4°	45.0°	0.1	0.5
SuperK	11.7°	25.1°	0.041	0.180
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.150

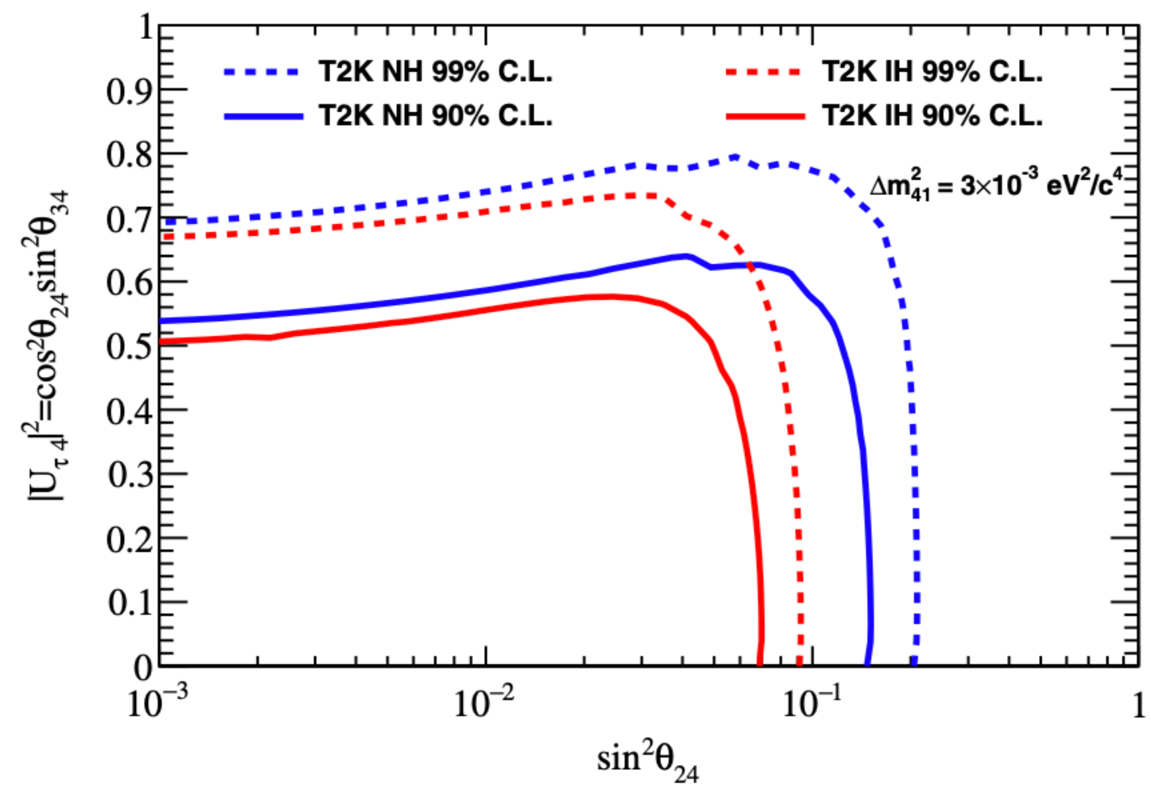
- NOvA 2017: unpublished, e.g. DPF 2017 proceedings (https://arxiv.org/abs/1710.01280)
- NOvA 2016: Phys. Rev. D **96**, 072006 (2017)
- MINOS/MINOS+: Phys. Rev. Lett. **122**, 091803 (2019)
- T2K: Phys. Rev. D **99**, 071103 (2019)
- SuperK: Phys. Rev. D **91**, 052019 (2015)
- IceCube: Phys. Rev. Lett. **117**, 071801 (2016)
- IceCube-DeepCore: Phys. Rev. D **95**, 112002 (2017)

T2K 2019

Phys. Rev. D **99**, 071103 (2019)







NOvA Short-Baseline Sterile Searches

- Two short-baseline analyses using the NOvA Near Detector.
- With sterile neutrino oscillations, electron neutrino and tau neutrino appearance must be consistent with muon neutrino disappearance.
- Joint analysis of ν_e, ν_τ appearance with ν_μ disappearance allows partial cancellation of systematics.
- Short-baseline oscillations at the NOvA near detector covers L/E range of LSND and allows searching for high-energy ν_τs in the tail above the beam peak.