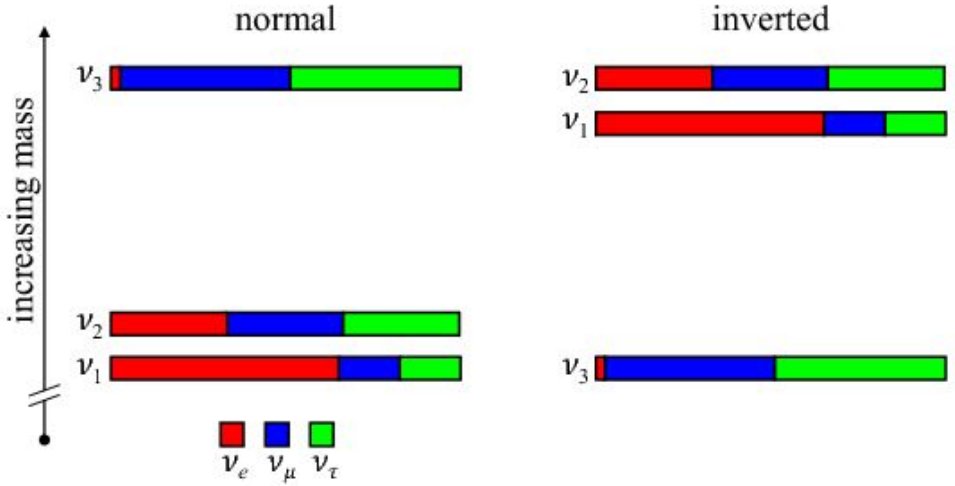
Recent Results from NOvA:
long-baseline neutrino and antineutrino flavor oscillation

Denver Whittington, Syracuse University
On behalf of the NOvA Collaboration

CIPANP 2022

NOvA : NuMI Off-axis ν_e Appearance

- Neutrino Mass Hierarchy
  - value and sign of the atmospheric mass splitting
- ν_3 Flavor Symmetry
- CP symmetry violation
- ν-nucleus interaction cross sections
- Other neutrinos beyond the three active flavors?
- Non-standard Interactions?



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$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric and long baseline	reactor and long baseline	reactor and solar
$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_\tau$	$\nu_\mu \rightarrow \nu_e$	$\nu_e \rightarrow \nu_\mu + \nu_\tau$

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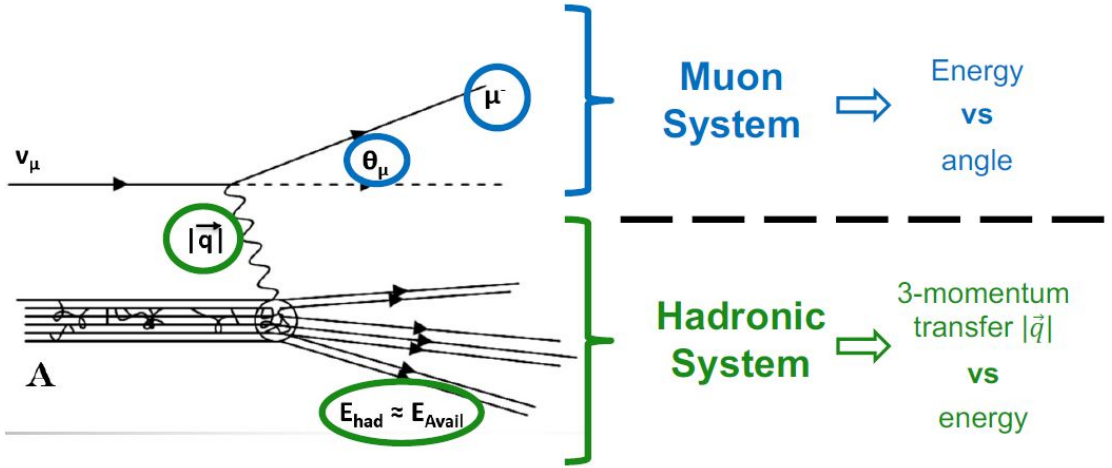

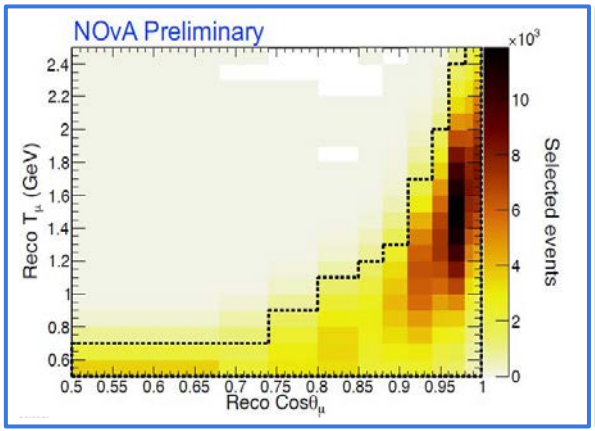

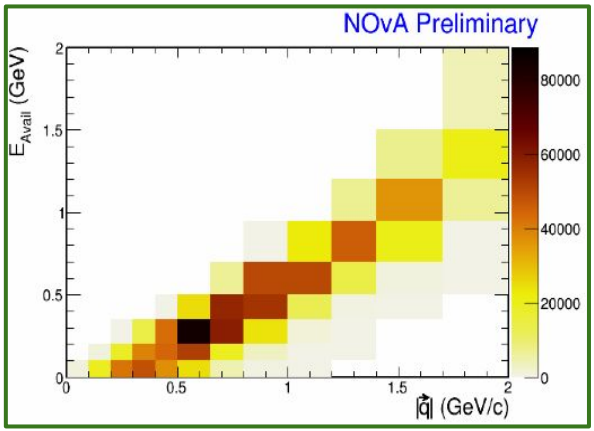

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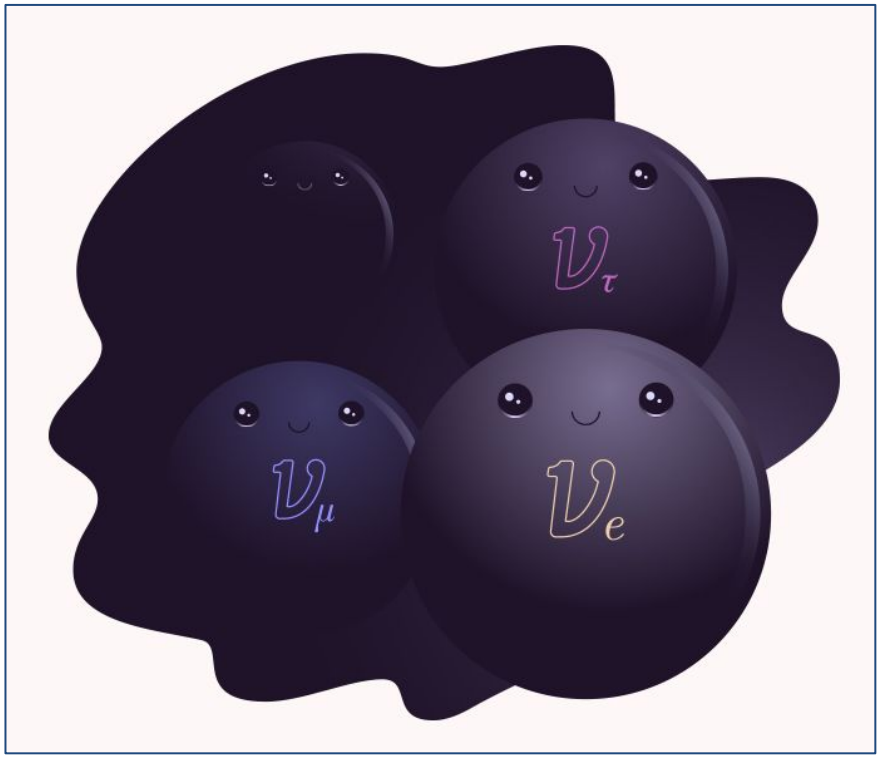

Symmetry Magazine
Illustration by Sandbox Studio, Chicago with Ana Kova

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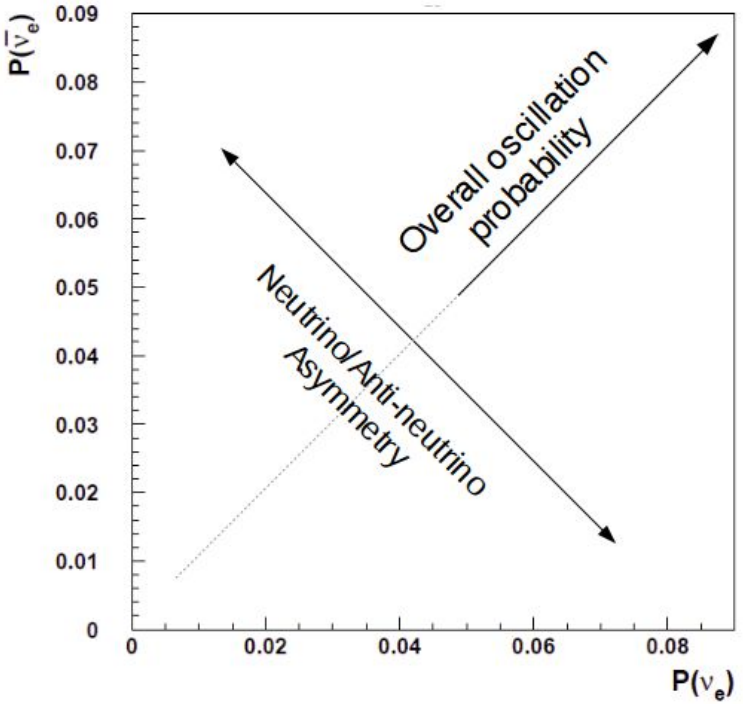

Muon neutrino and antineutrino disappearance: θ_{23} and the magnitude of Δm^2_{32}.

Electron neutrino and antineutrino appearance: ***sign*** of Δm^2_{32} and value of δ_{CP}

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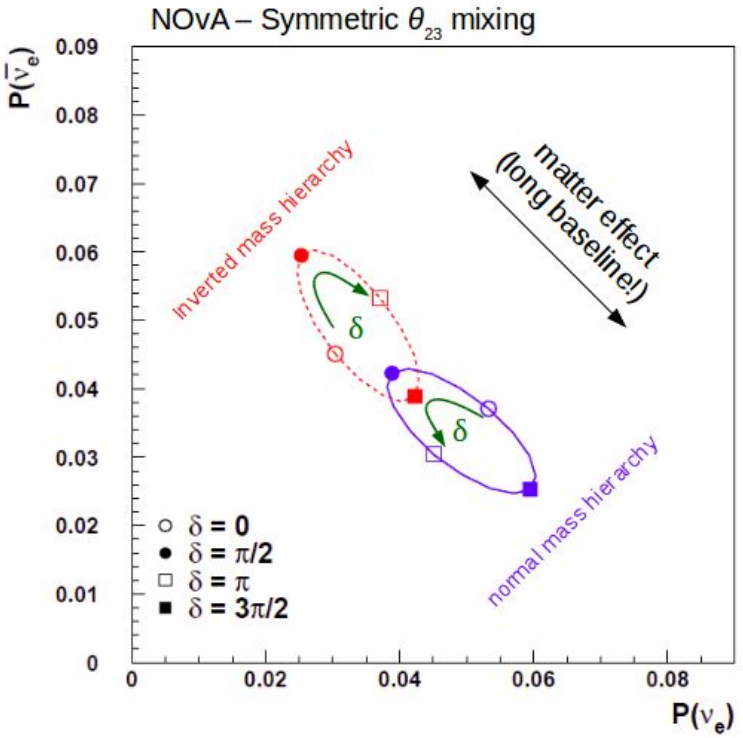

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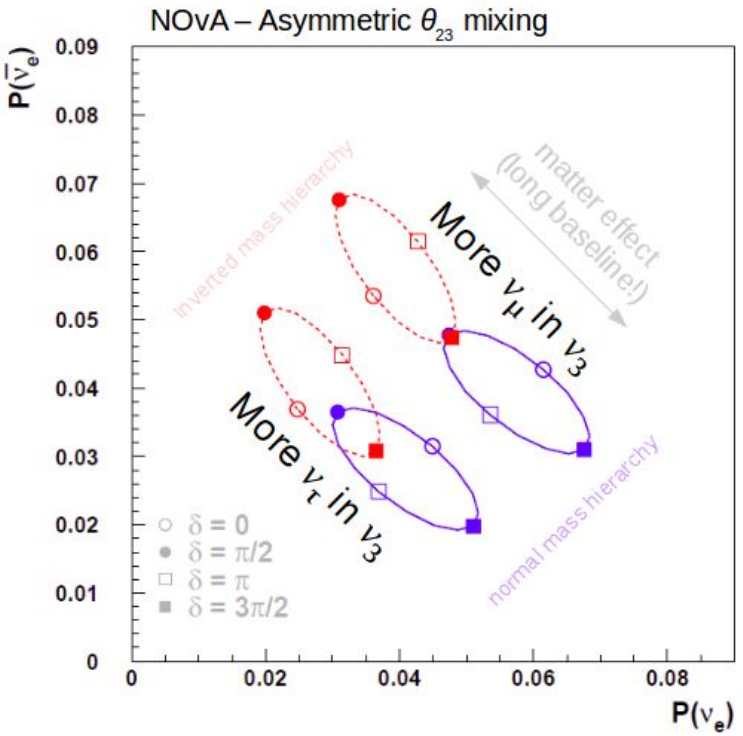

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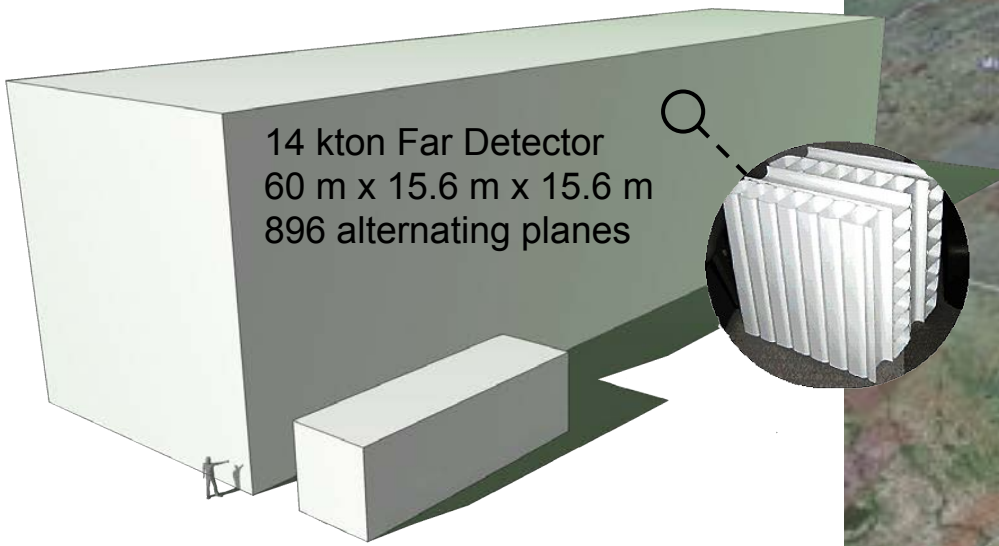
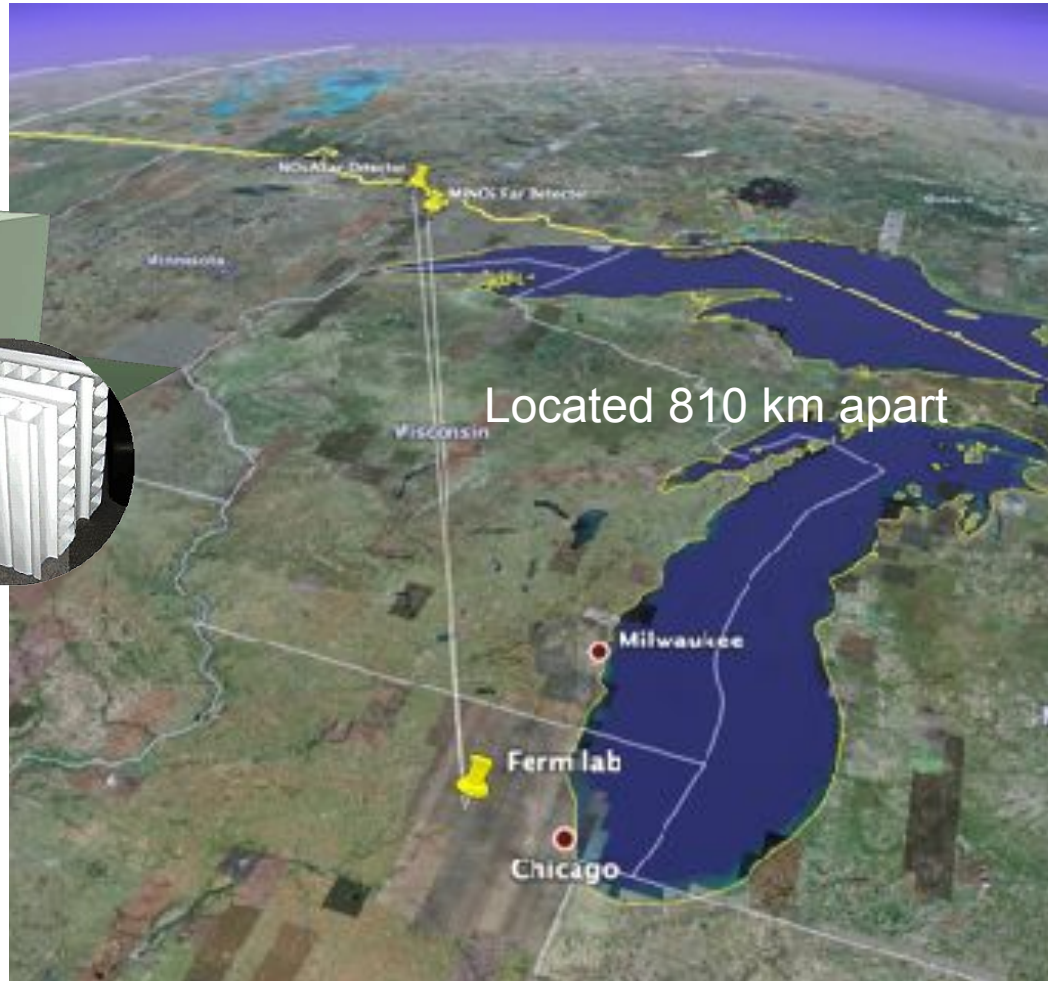
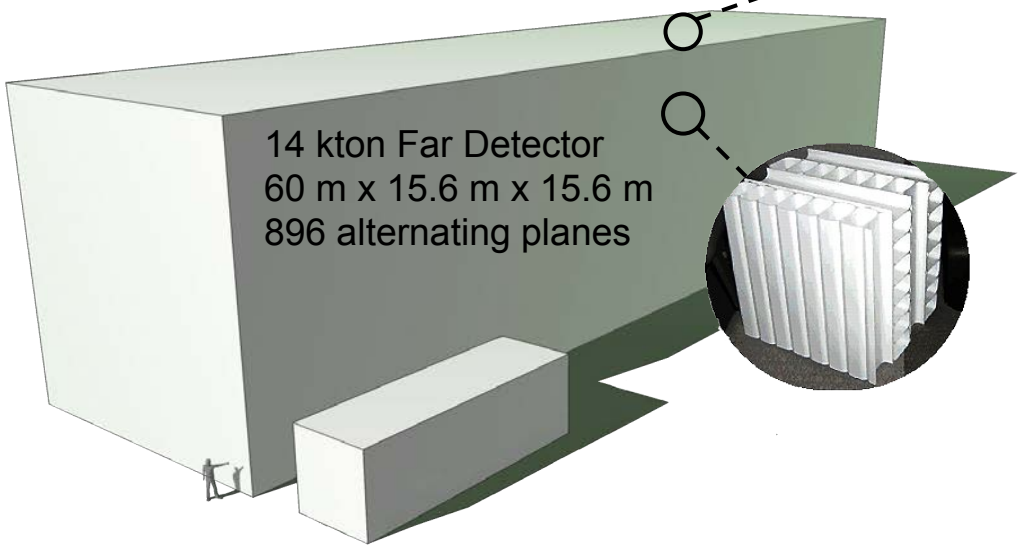
Functionally equivalent near and far segmented liquid scintillator detectors

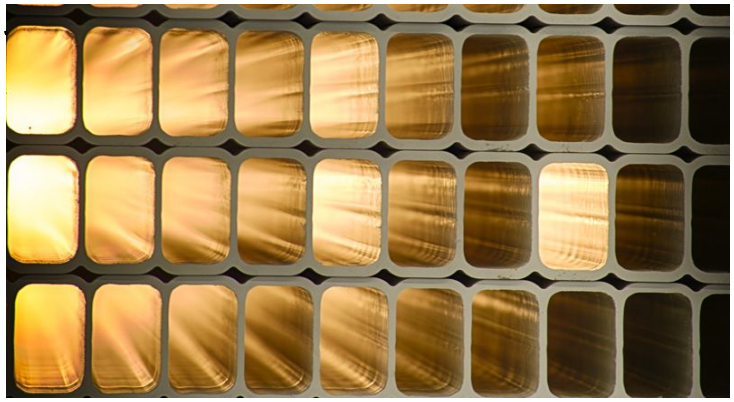


300 ton Near Detector underground at Fermilab
15.8 m x 4.2 m x 4.2 m, 214 alternating planes



Extruded PVC cells filled with 11 million liters of liquid scintillator





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Alternating layers for 3D event reconstruction

Each ~0.15 radiation lengths for e/pi separation

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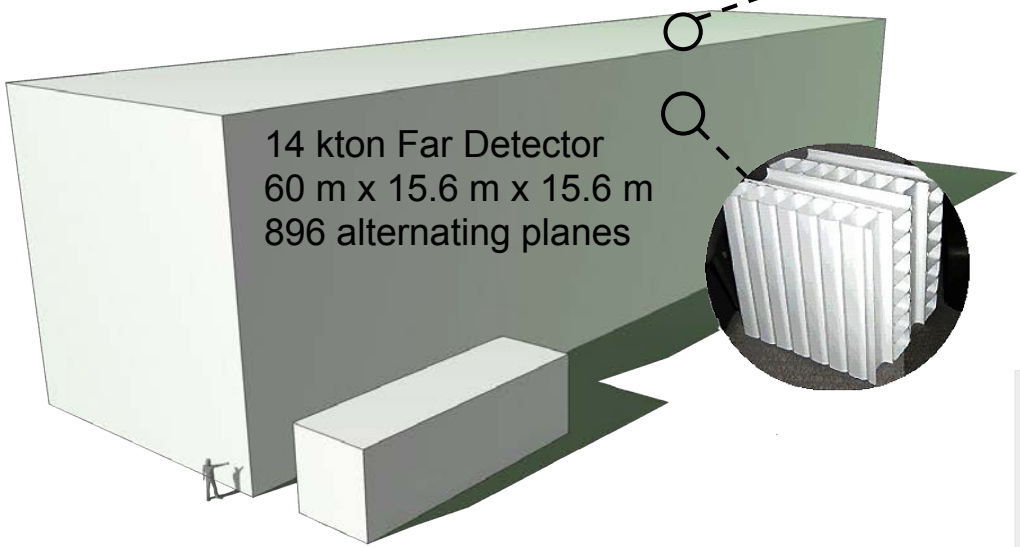

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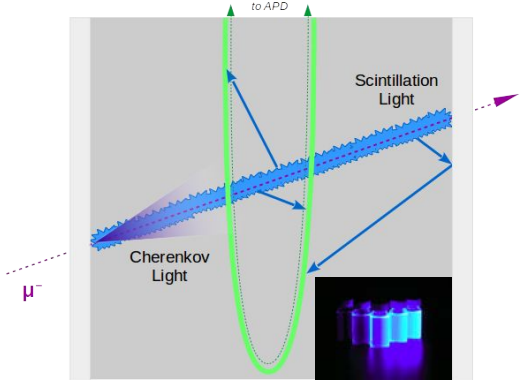
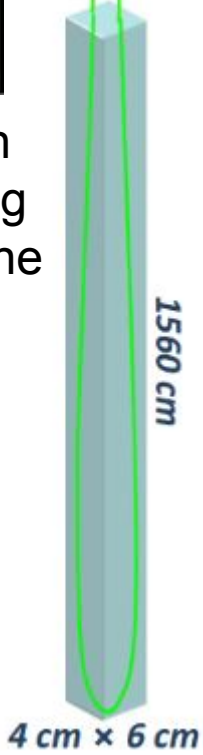
Instrumented with wavelength-shifting fibers and avalanche photodiodes

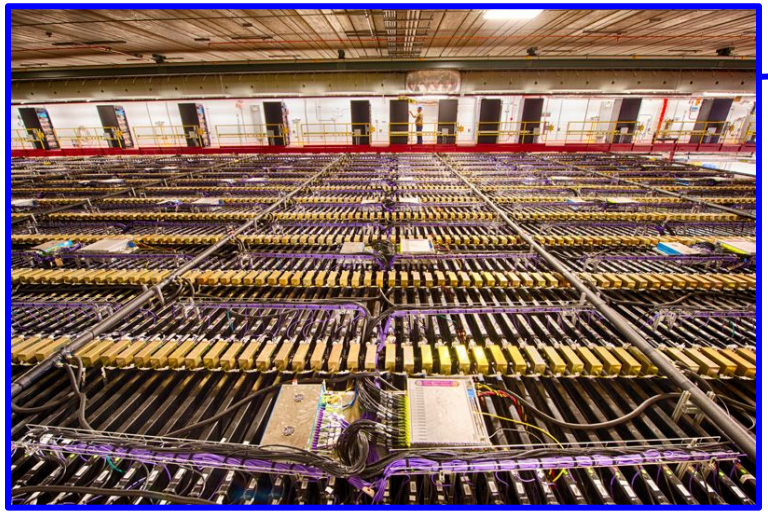


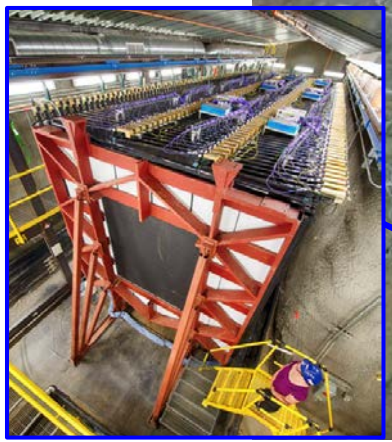


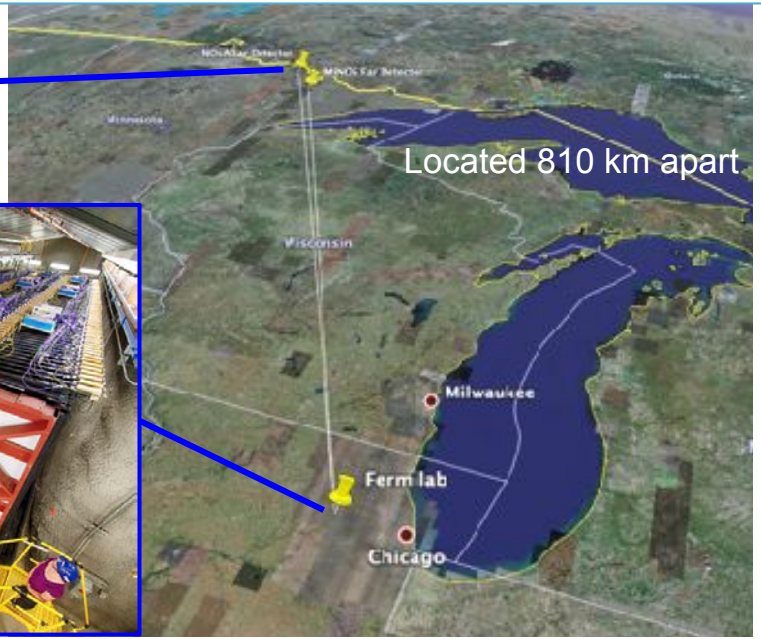
Leverage correlations in systematics between near & far detectors to better constrain the prediction at the far detector.

$$N_{near}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(...)$$

$$N_{far}(E_\nu^{reco}) = P_{osc}(E_\nu^{true}) \times \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(...)$$

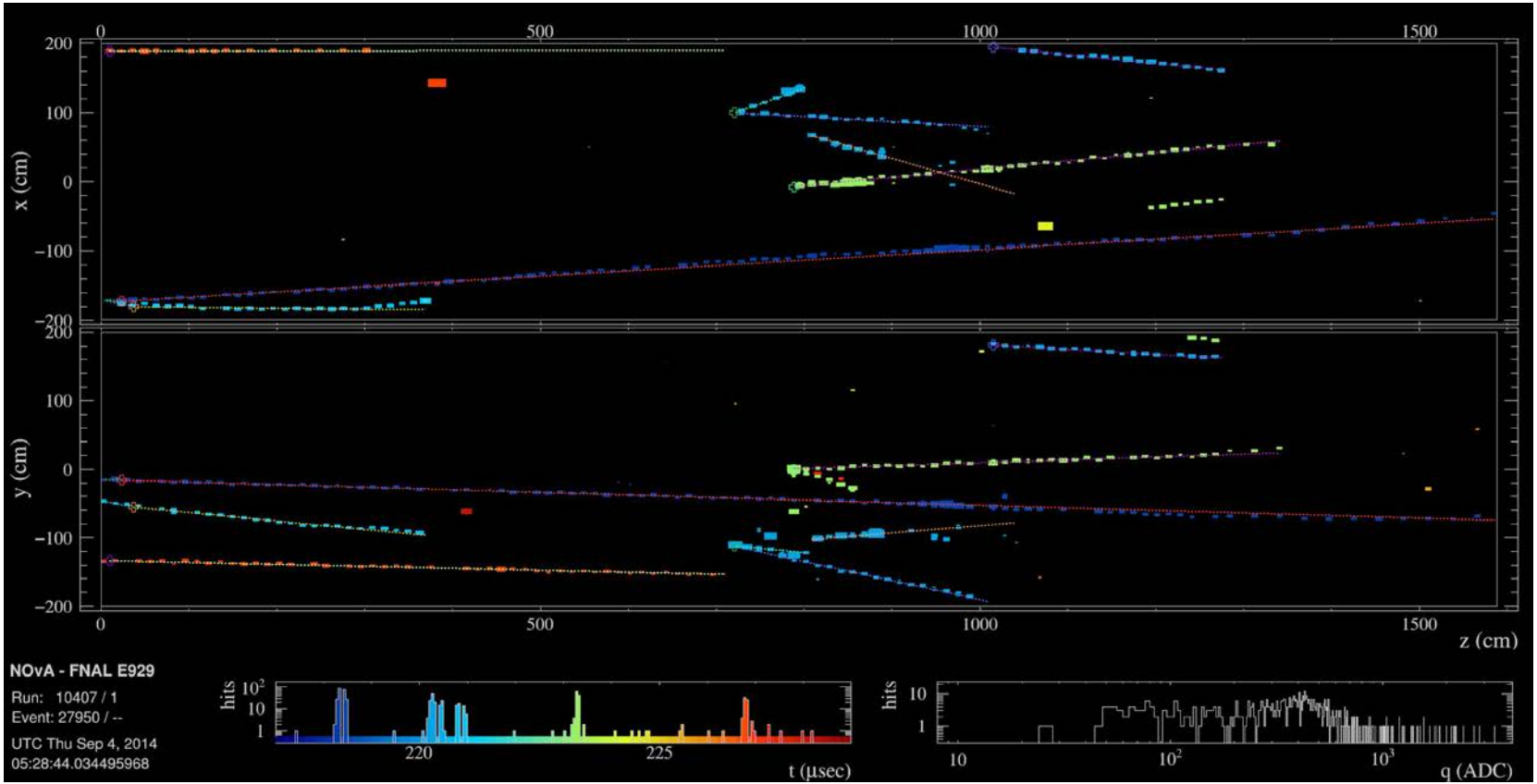






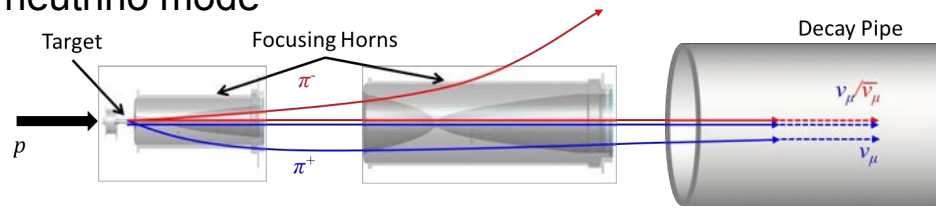
Top View

Side View

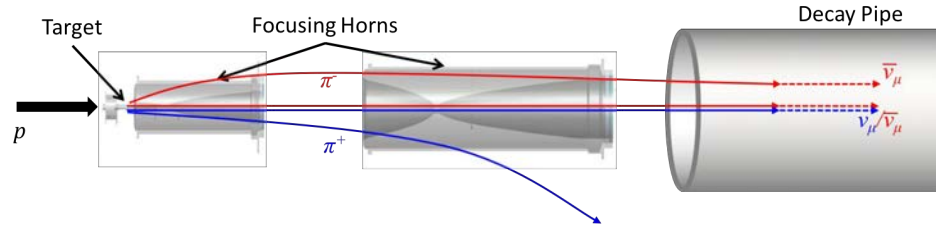


NuMI Off-Axis → narrowed, 2 GeV neutrino beam

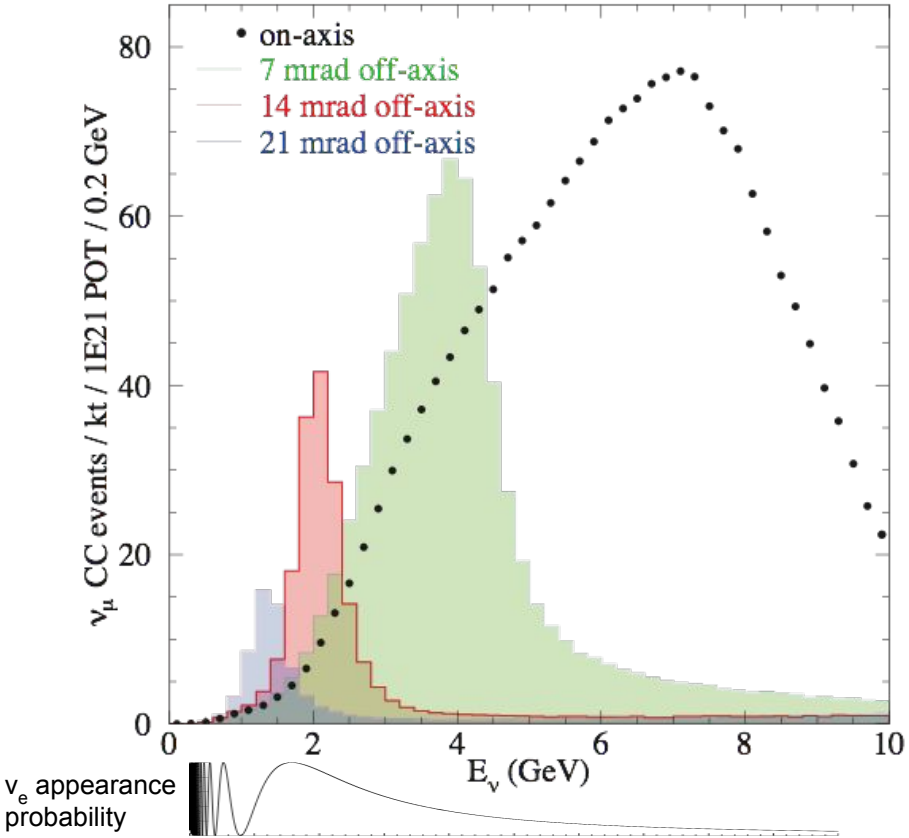
neutrino mode



antineutrino mode

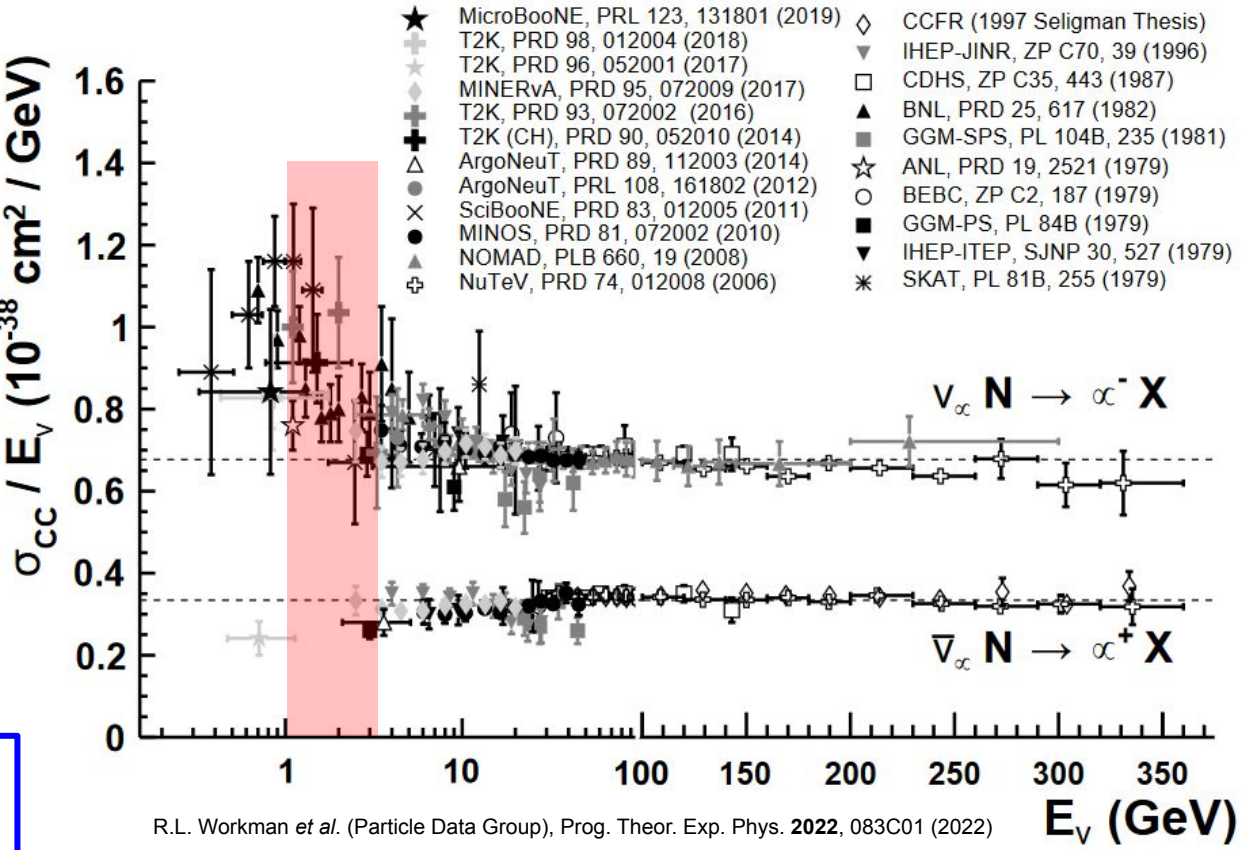


$\pi \rightarrow \nu_\mu + \mu$ back-to-back in COM frame
boosted to the lab frame



NOvA is exploring neutrino interactions at an important low-energy region.

- High-statistics data from NOvA near detector
- Overlap with MiniBooNE, T2K, & MINERvA measurements
- Measurements of both neutrino and antineutrino interactions
- Combination of quasi-elastic, resonance, *and more complex* interactions

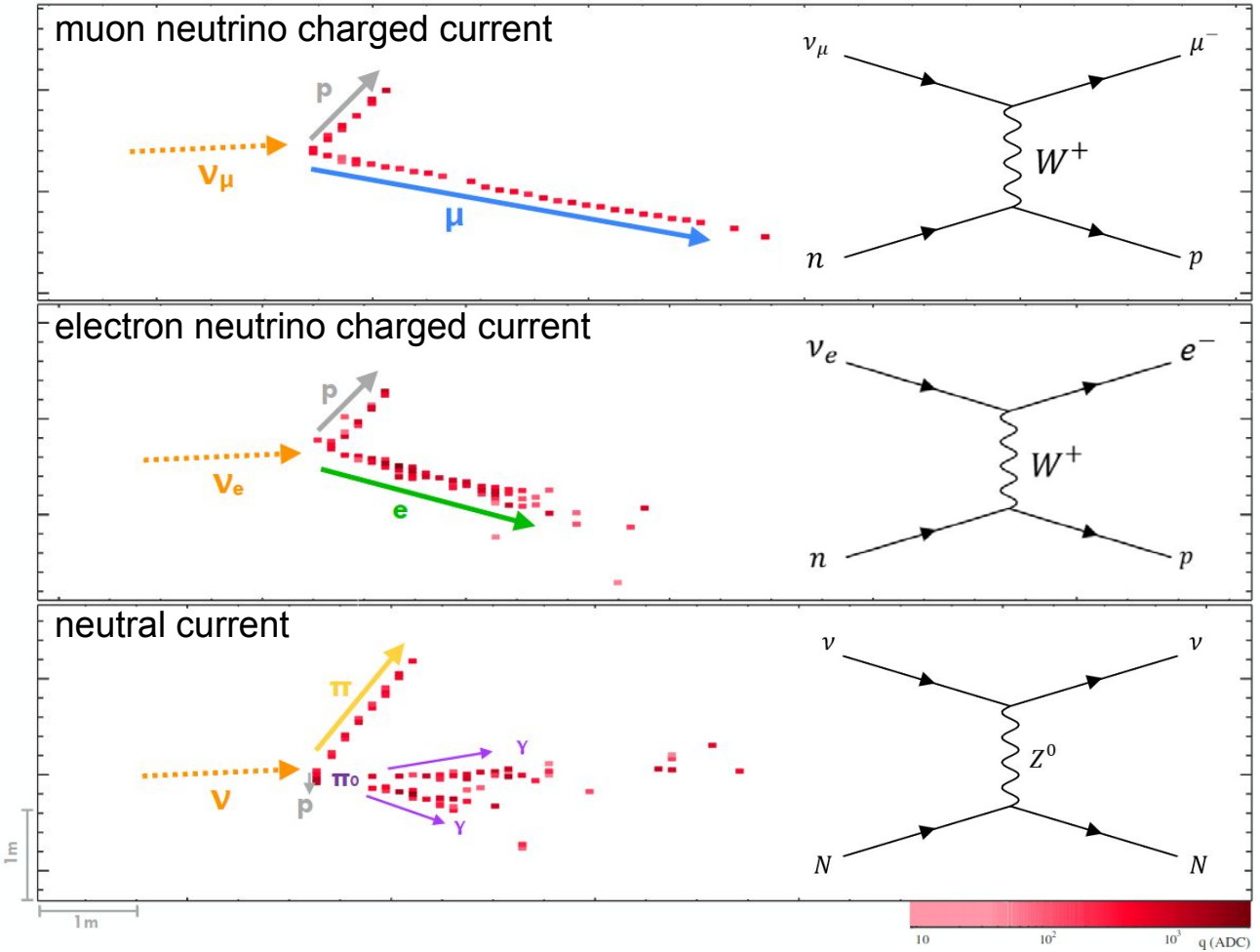


R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

see tomorrow's talk from Maria Martinez-Casales!

Inside Neutrino Events

- Identify components
  - tracks, showers, vertex, hadronic activity
- Reject cosmic rays and associated activity
  - muons, neutrons, etc.
- Convolutional neural network (CNN) distinguishes between interaction processes
  - ν_e charged current,
  - ν_μ charged current,
  - neutral current



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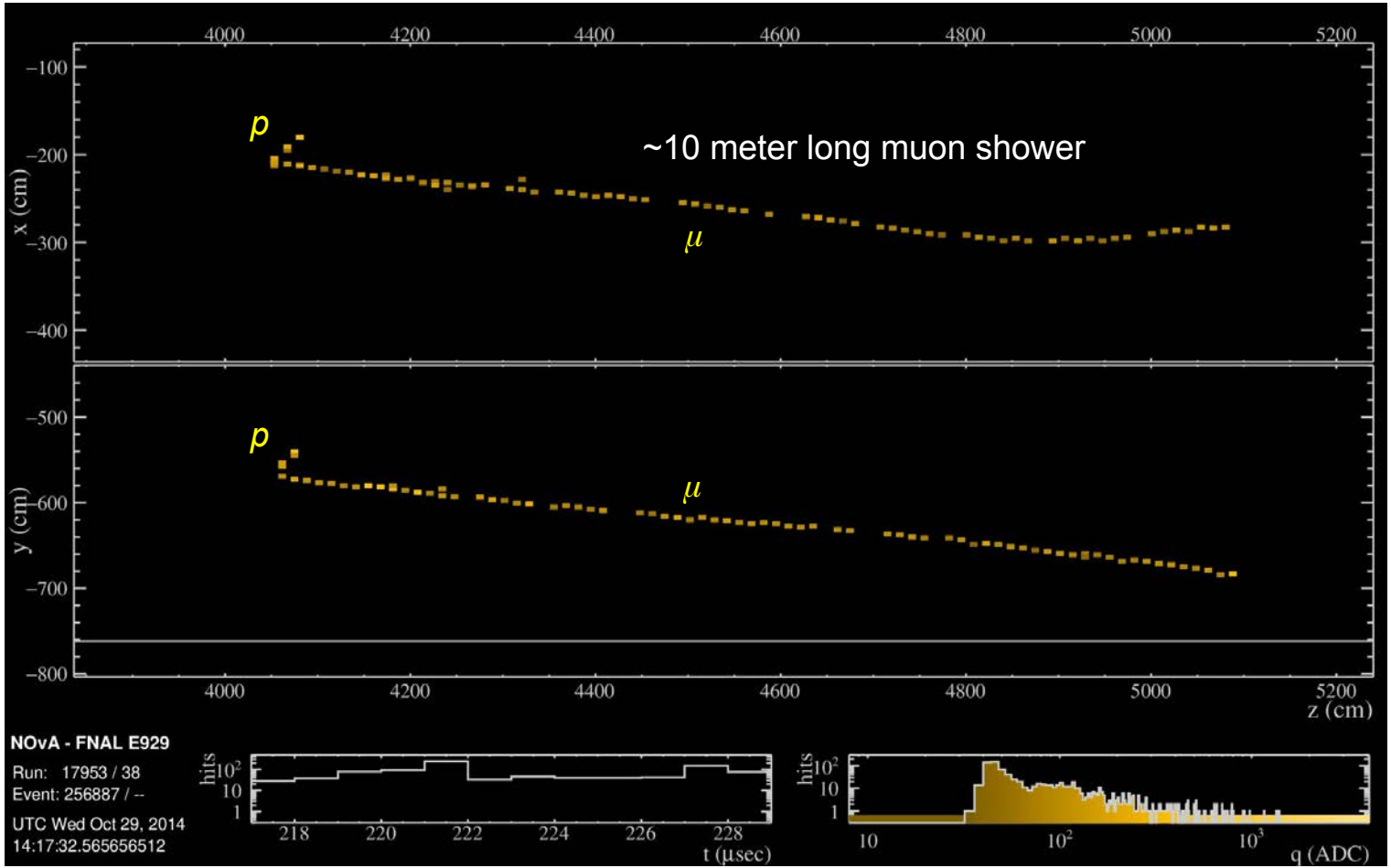

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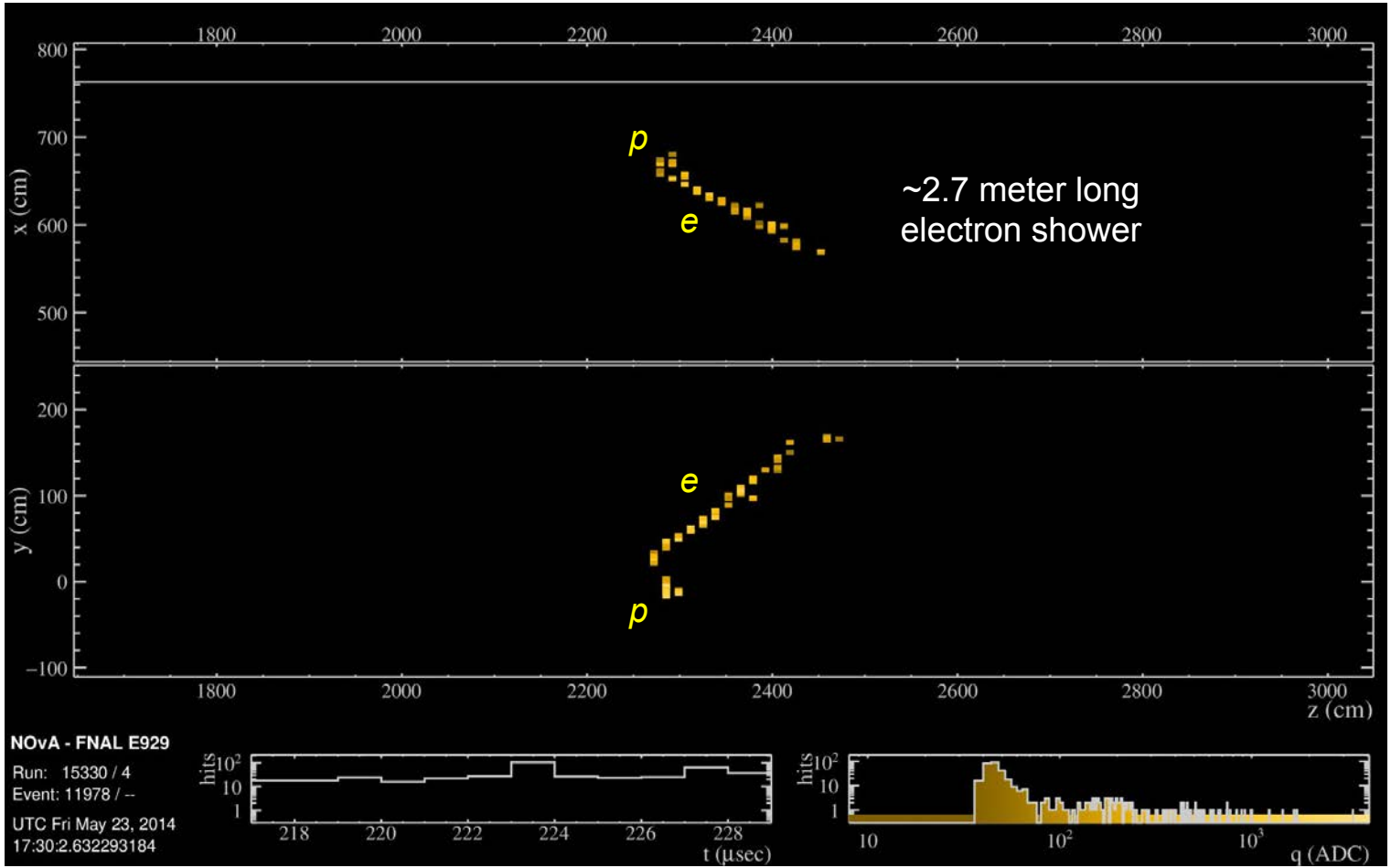
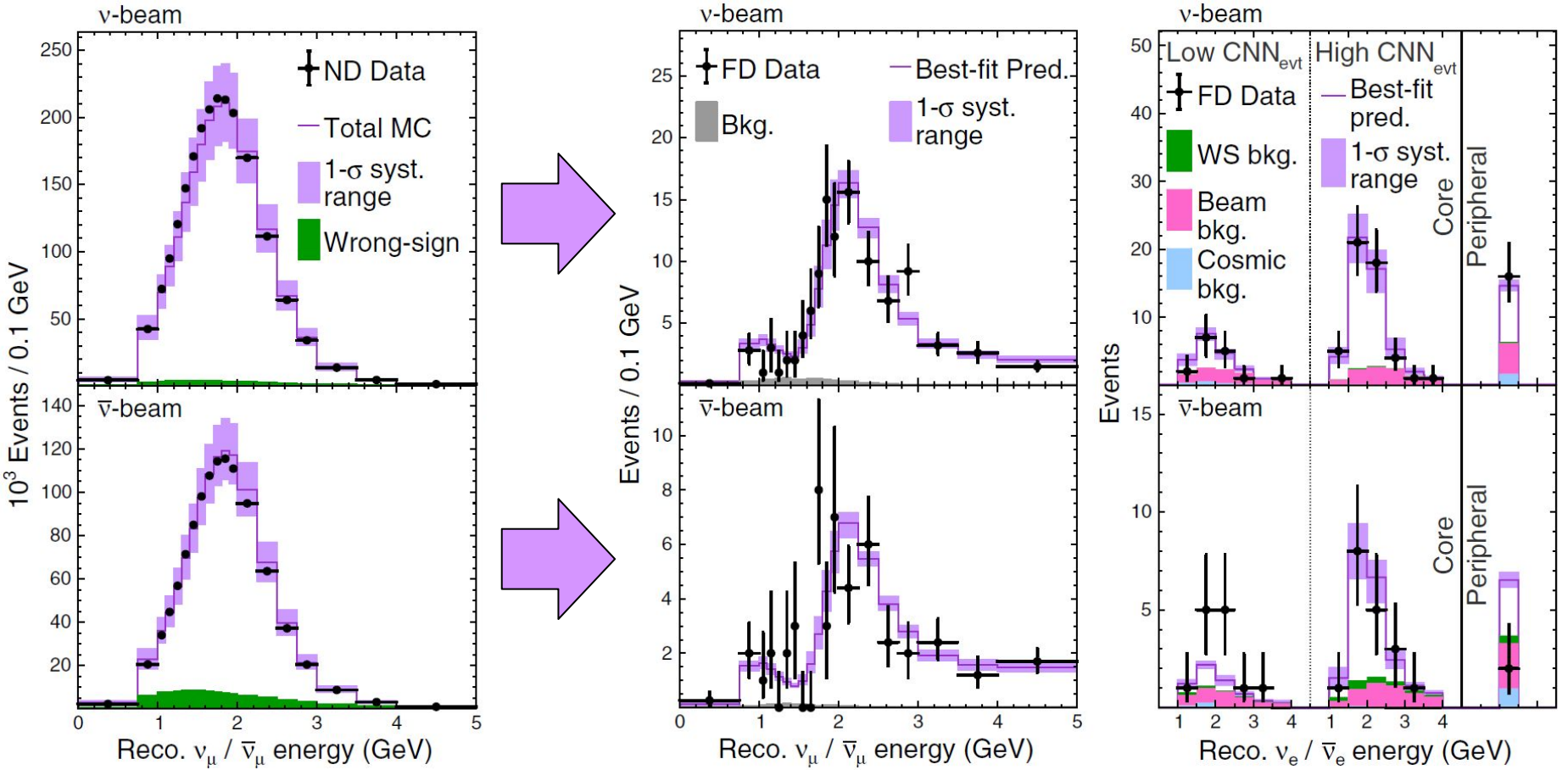


Phys.Rev.D 106 (2022) 3, 032004

Measured rates at the ND …… extrapolated to FD and compared to measured rates.



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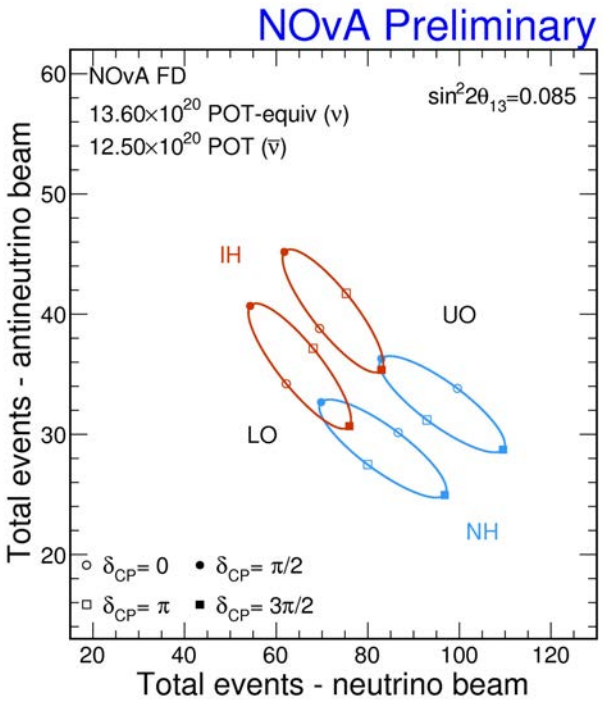
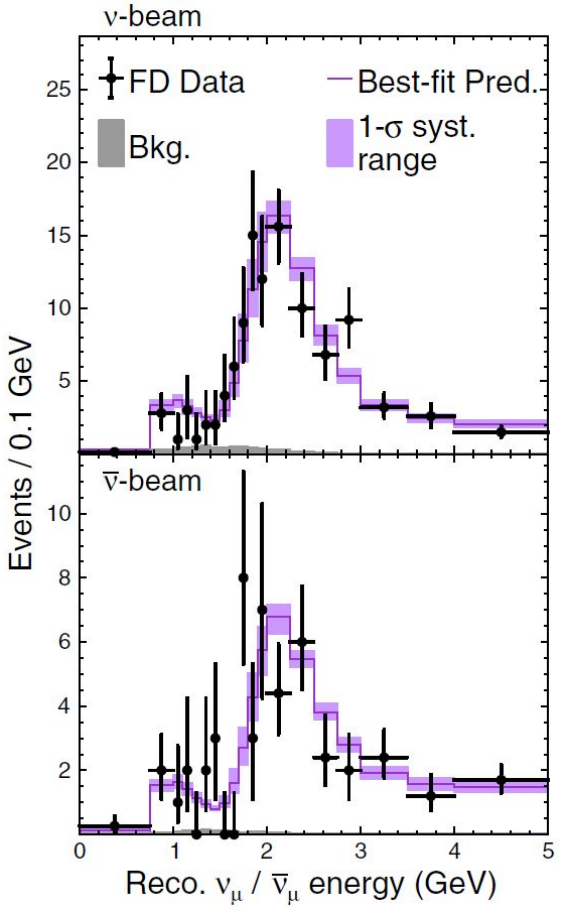
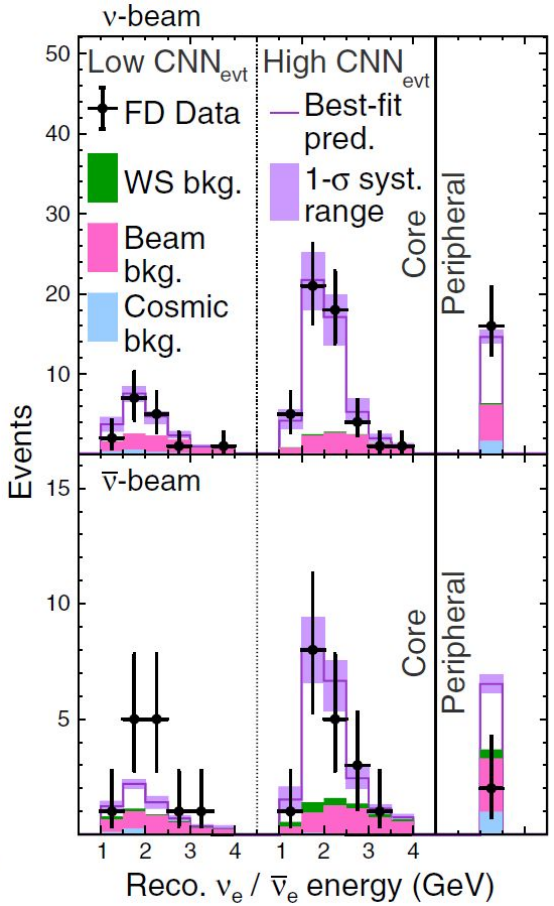
Comparing Neutrino vs Antineutrino Appearance Probabilities







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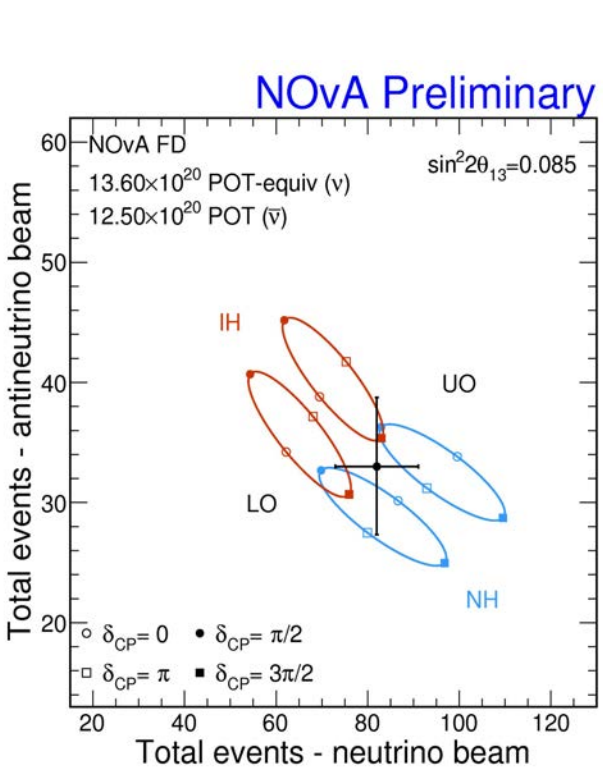

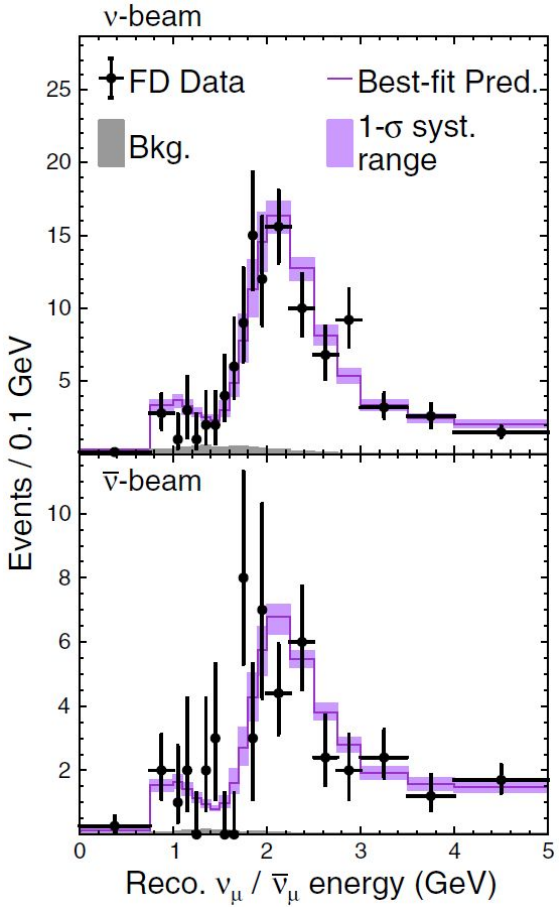

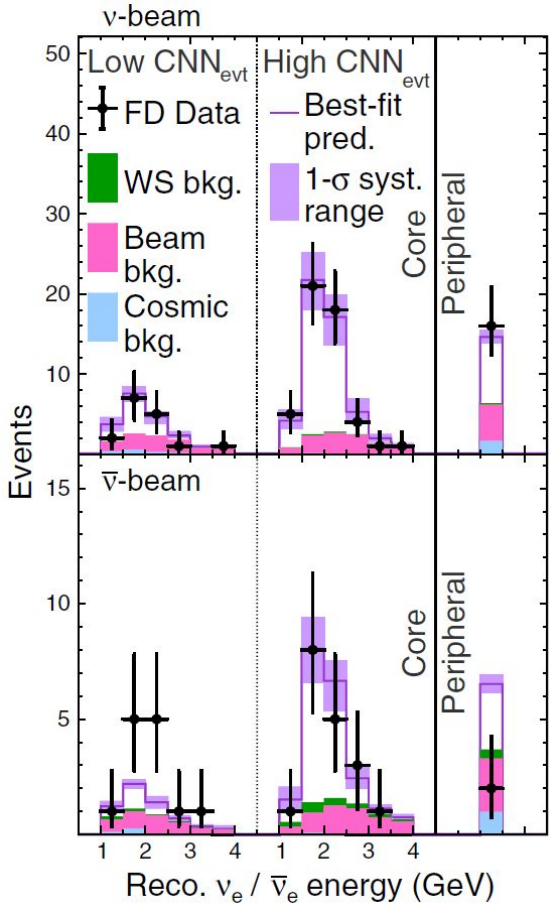

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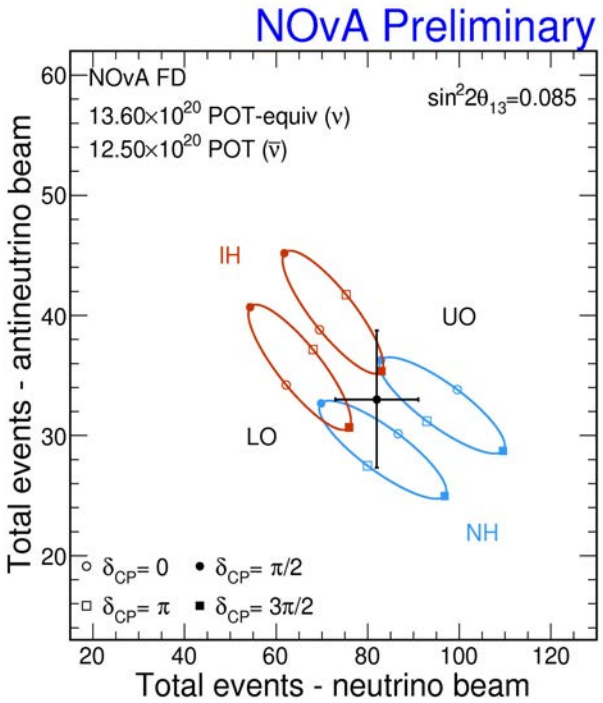
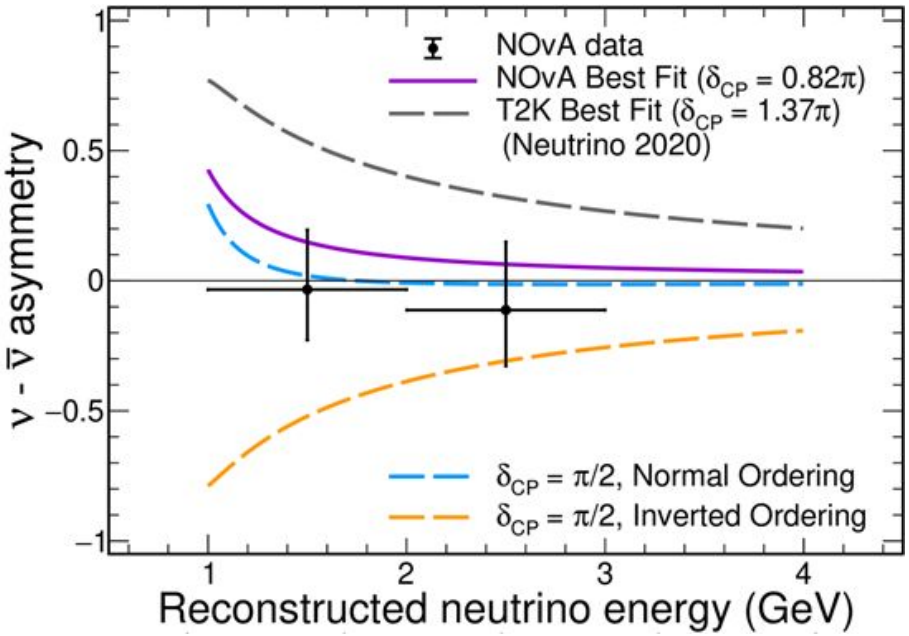


Appearance Asymmetry: $\frac{P(\nu_e) - P(\bar{\nu}_e)}{P(\nu_e) + P(\bar{\nu}_e)}$



Markov Chain MC Bayesian Analysis

alternative statistical approach to previous frequentist analyses

- Allows results to be examined in new ways
- Conclusions the same as frequentist results
- Exclude (Inverted Ordering, $\delta = \pi/2$) at > 3σ

Best Fit

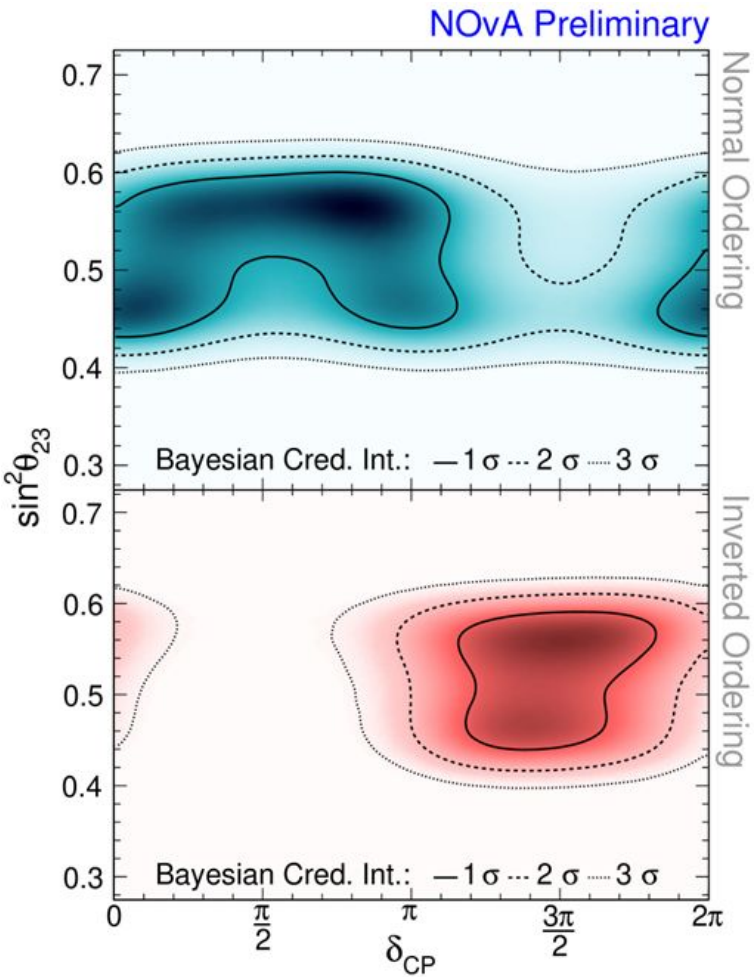
Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$

(frequentist results)



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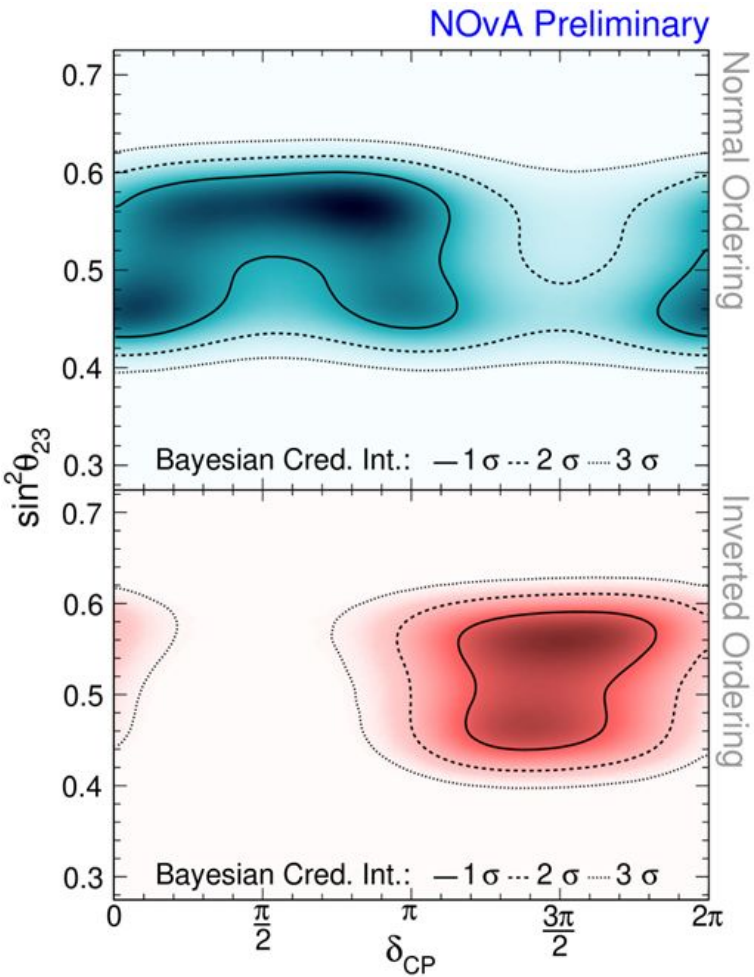
More power through a joint fit combining **NOvA and T2K data** is in the works!

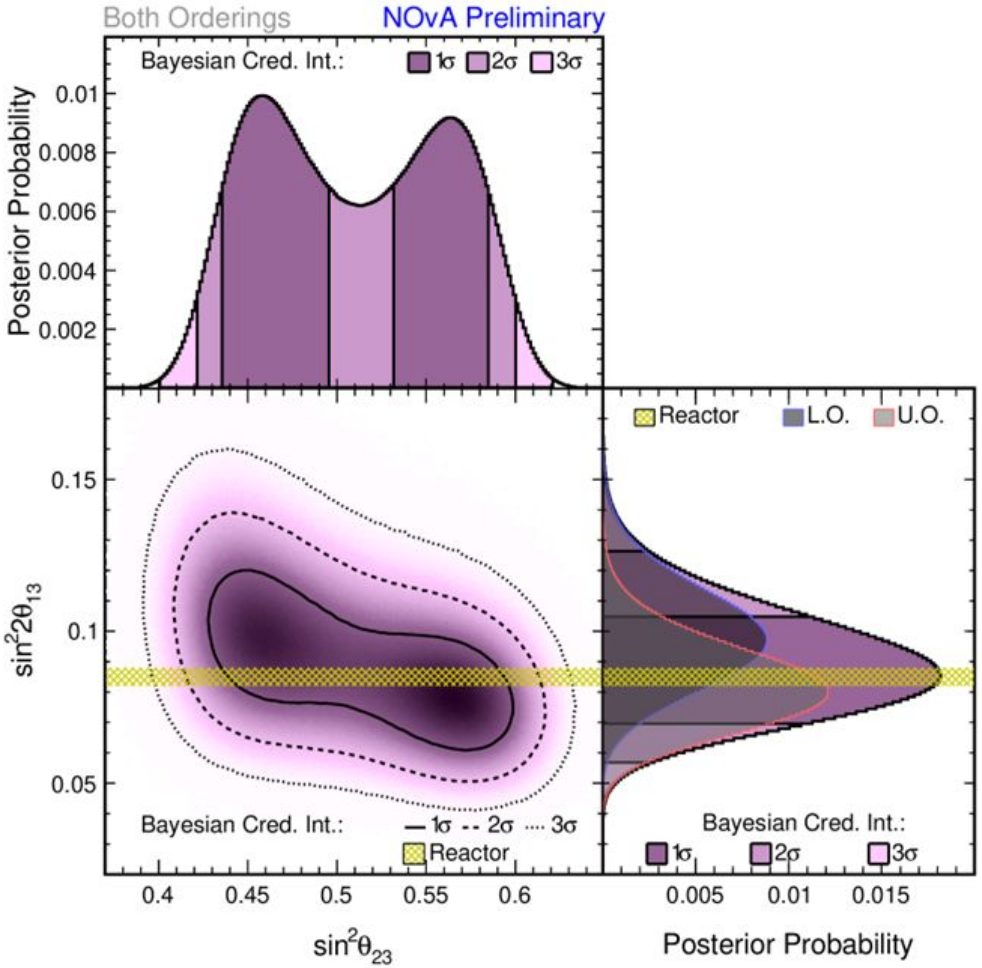


NOvA-Only θ_{13} & θ_{23} results

- Previously, θ_{13} constrained by PDG global average
- Here θ_{13} is measured by NOvA

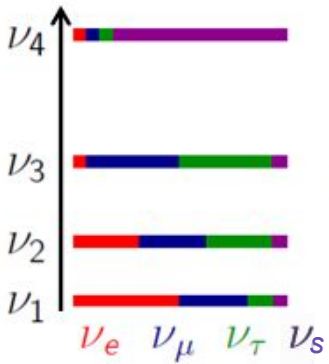
$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

- Completely different approach to the measurement of θ_{13}!
  - long-baseline ν_μ to ν_e appearance vs reactor neutrino ν_e disappearance



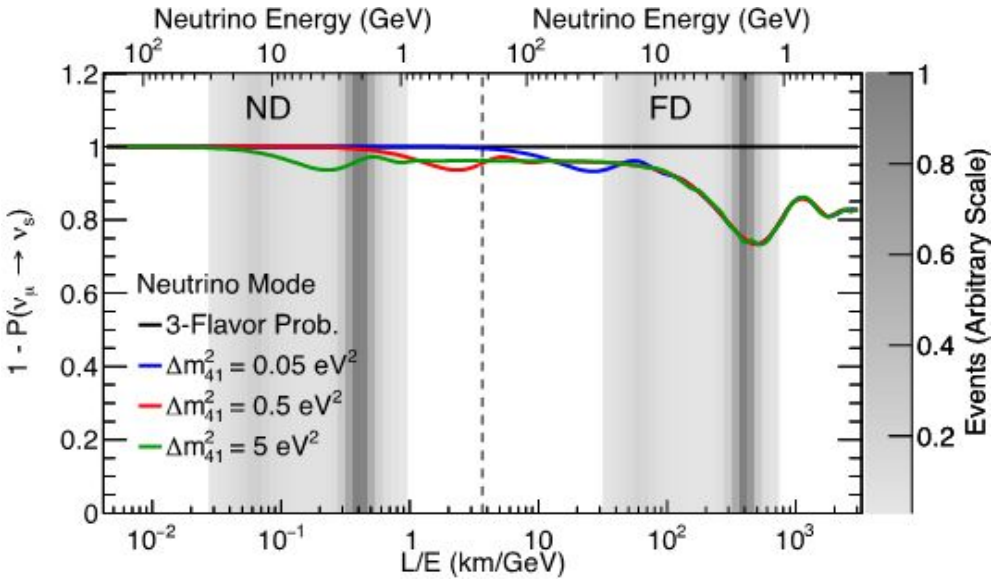
Sterile neutrino oscillations(?) at NOvA

- Some compelling short-baseline neutrino rate anomalies (<1 km, few MeV to ~1 GeV)
  - Deficits in neutrino detection rates at electron-flavor sources (e.g. fission reactors)
  - Excesses of electron-like events in ~muon-flavor sources (e.g. LSND, MiniBooNE)
- Could be explained with addition of a non-interacting fourth flavor state ("3+1 model")
  - Dark matter candidate?
  - See-saw mechanism participant?



3+1 model

Add 4th mass eigenstate



Phys.Rev.Lett. 127 (2021) 20, 201801

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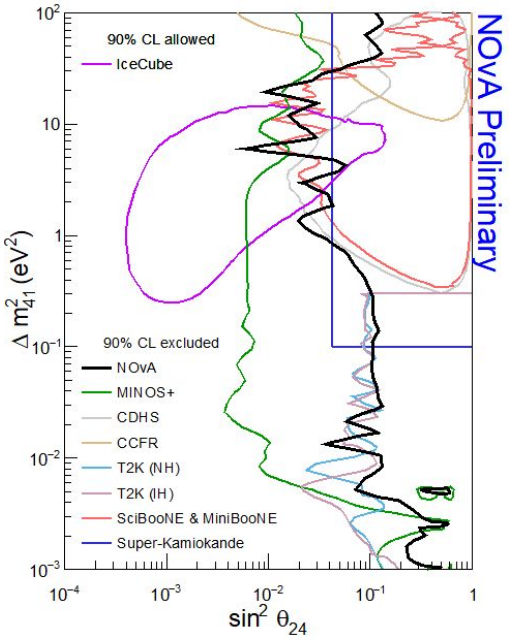

Data shows no evidence for sterile neutrinos

Competitive limits on θ_{24} for Δm_{41}^2 = ~10 eV^2

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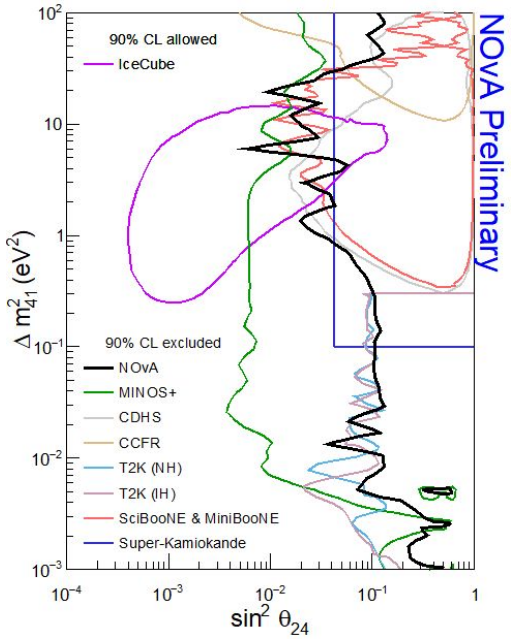

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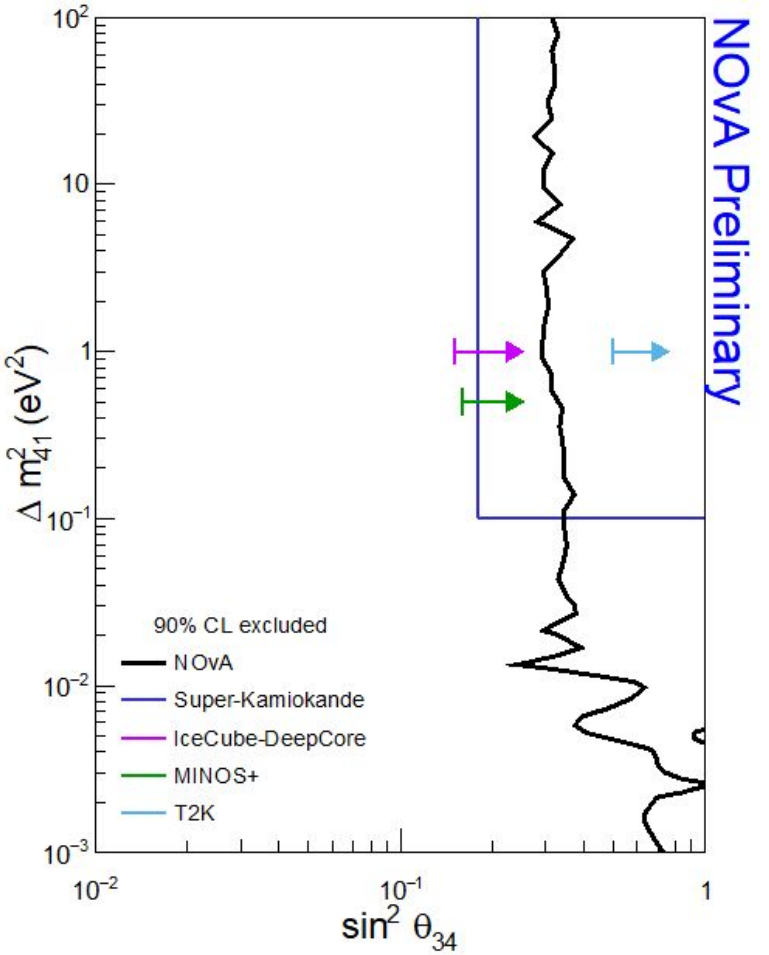
Competitive limits on θ_{24} for Δm_{41}^2 = ~10 eV^2

New constraints on θ_{34}!

- measure of mixing between ν_τ and a sterile ν_s
- long-baseline provides sensitivity at small Δm_{41}^2
- NOvA's high resolution on the hadronic system provides access to the *NC disappearance* signal



Non-Standard Interactions - anomalous interactions between ν & $\overline{\nu}$ and matter

$$\mathcal{H} = U\mathcal{H}_0 U^\dagger + \mathcal{H}_{matter} + \mathcal{H}_{NSI}$$

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NSI can add new flavor-changing and flavor-conserving contributions to forward scattering in matter

- On-diagonal similar to effective mass-squared differences
- Off-diagonal induce effects similar to mixing angles (may include complex phases!)

Take the standard 3-flavor dataset/extrapolation and refit in an NSI scenario…

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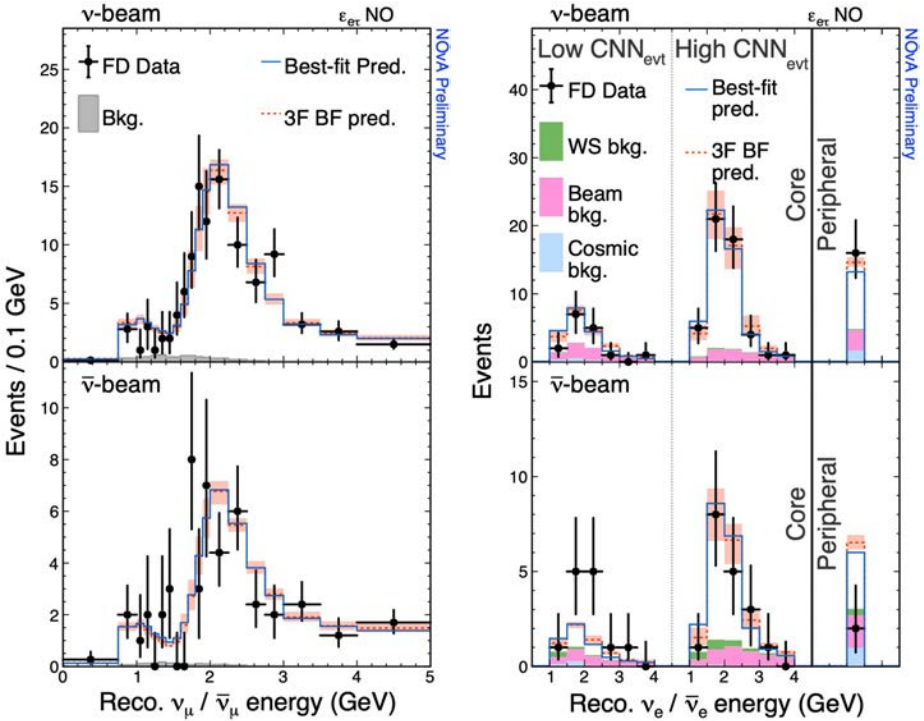

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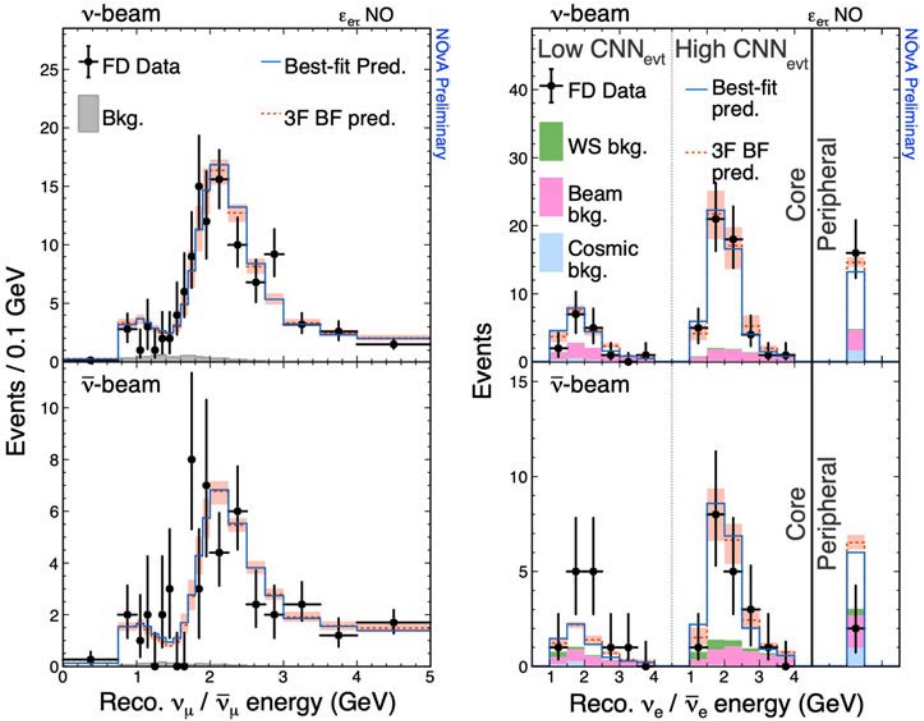

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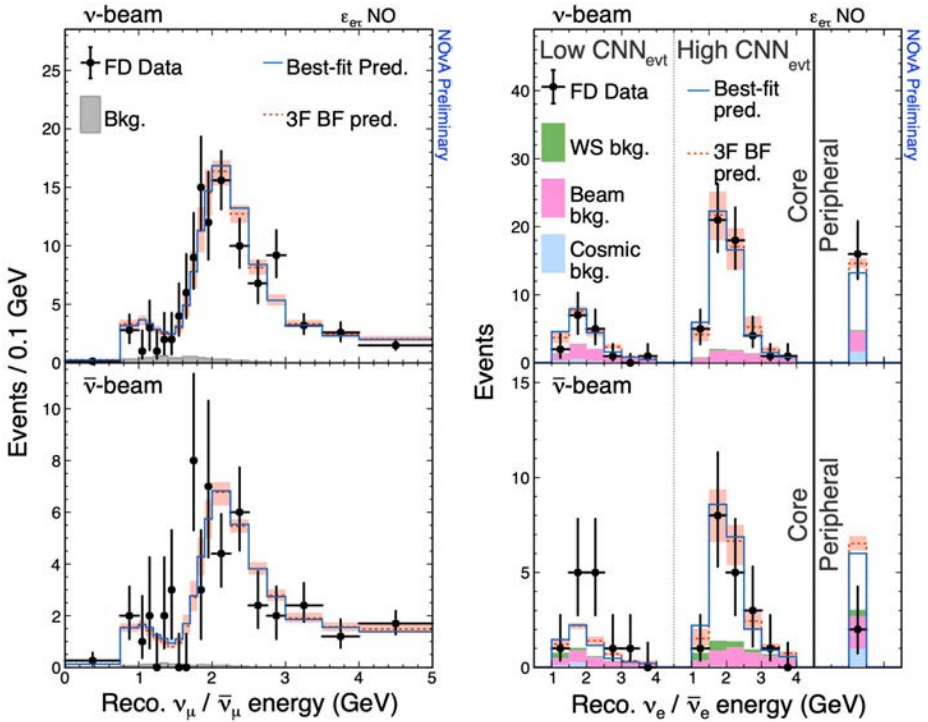

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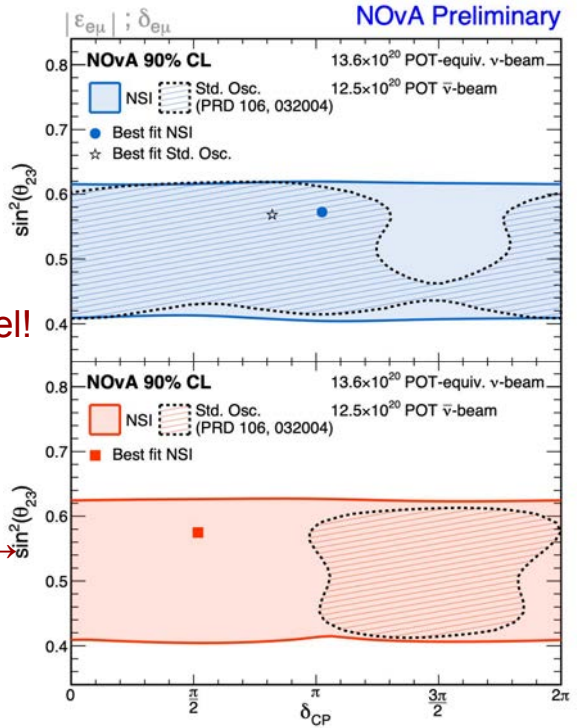
But… NSI would lead to major reinterpretations of those results. →



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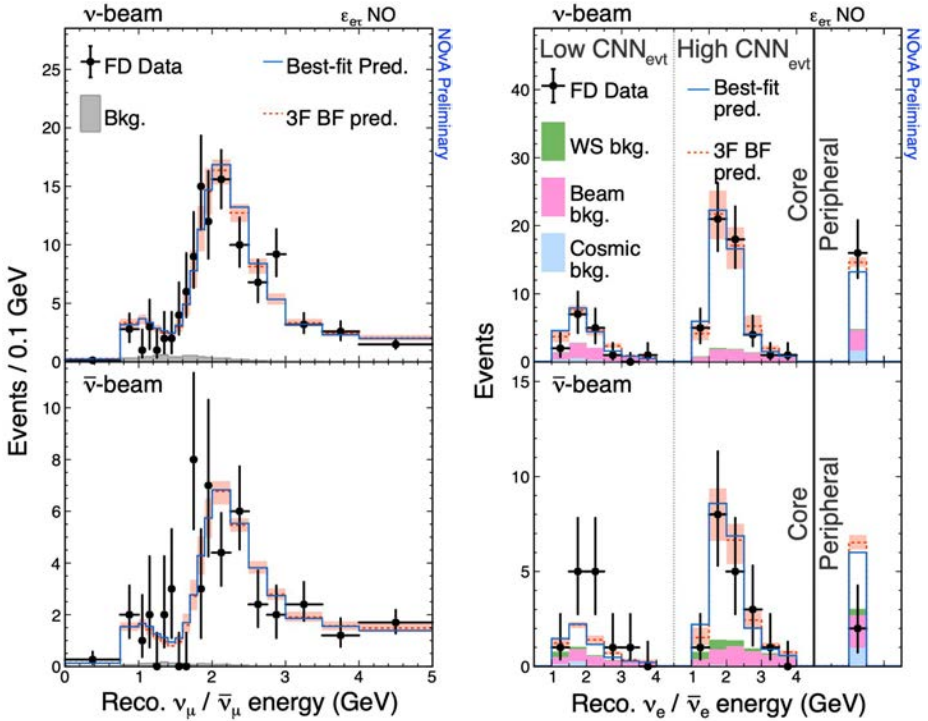

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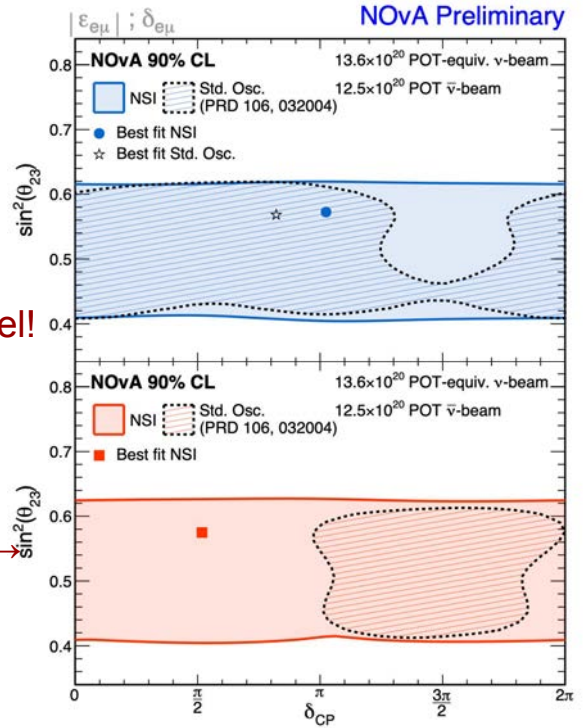
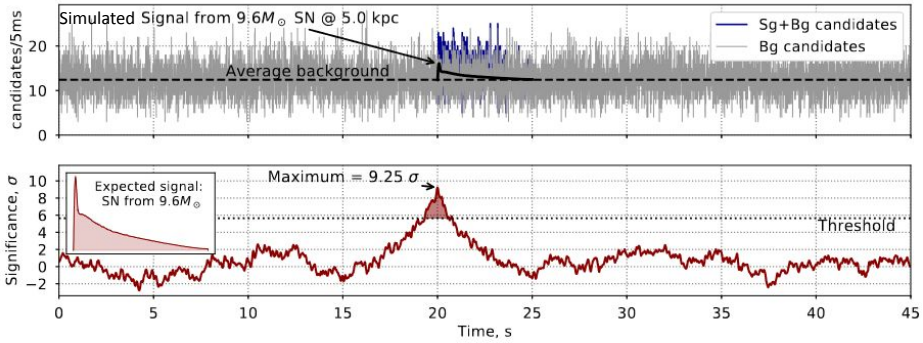


Check out the Fermilab Wine & Cheese talk by Jeffrey Kleykamp, this Friday!

Supernova neutrino detection in NOvA

Prospects for NOvA's sensitivity to a core-collapse supernova in the Milky Way

JCAP 10 (2020) 014



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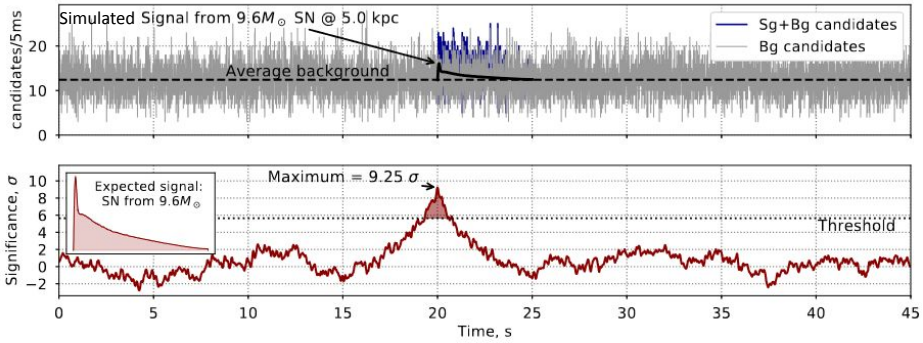
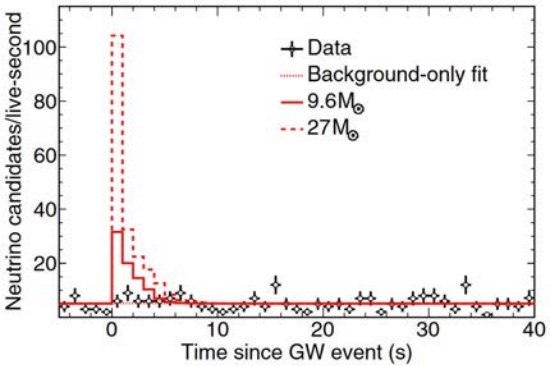


Extended search for supernovalike neutrinos in NOvA coincident with LIGO/Virgo detections

Phys.Rev.D 104 (2021) 6, 063024



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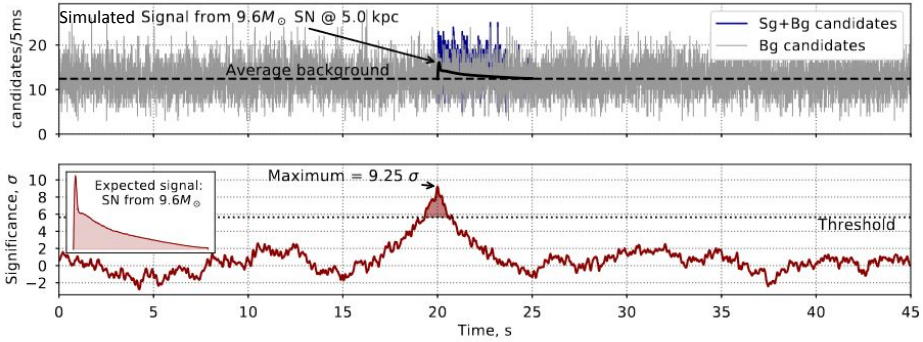

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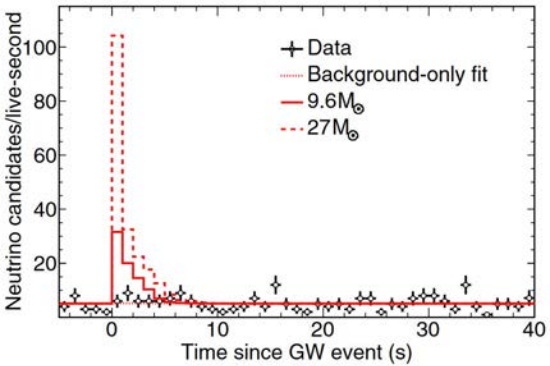

Seasonal variation of multiple-muon cosmic ray air showers observed in the NOvA detector on the surface

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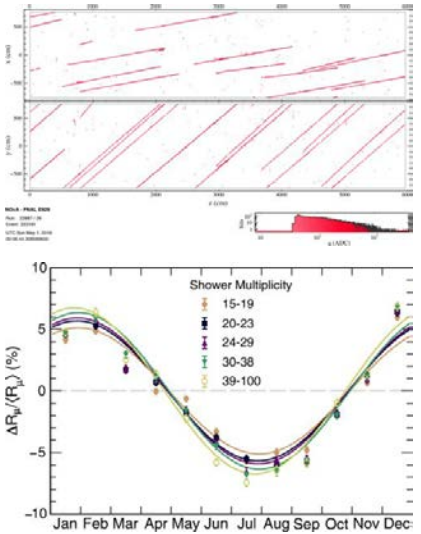

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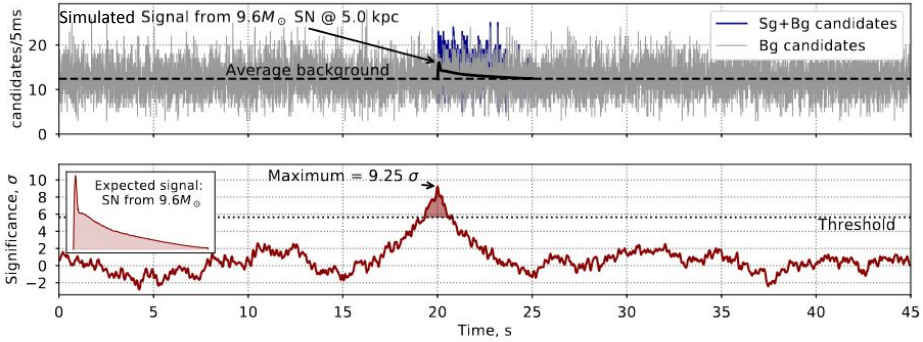

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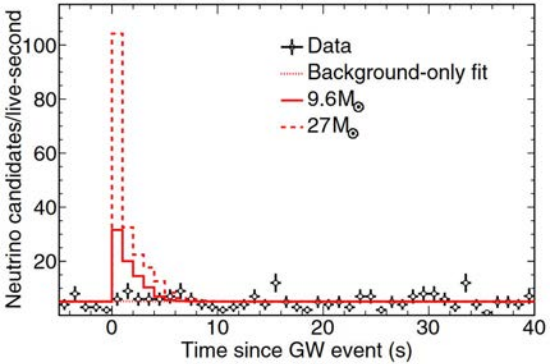

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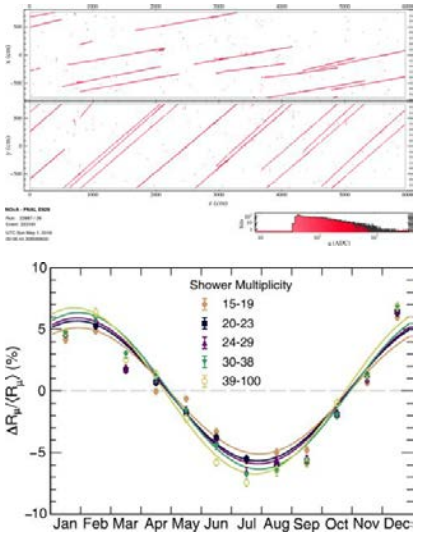
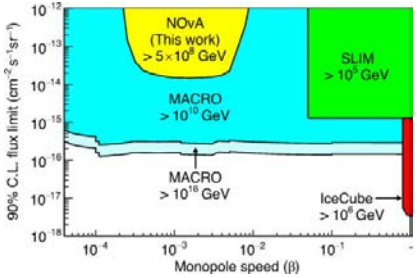




Search for slow magnetic monopoles with the NOvA detector on the surface

Phys.Rev.D 103 (2021) 1, 012007

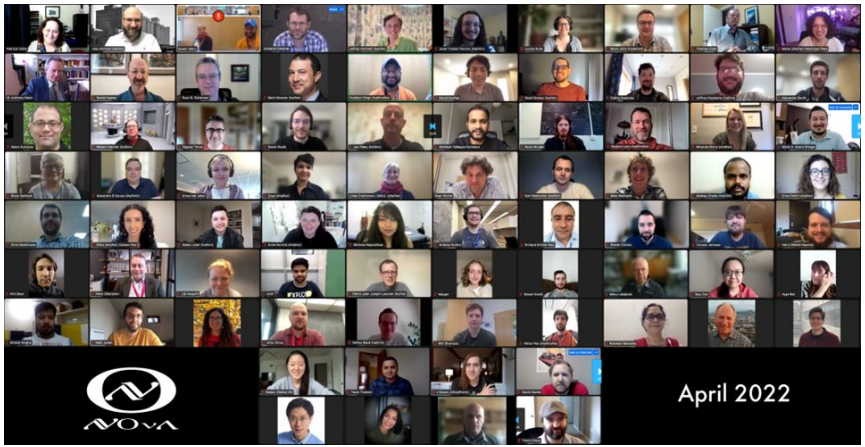
- NuMI beam power continues to improve and NOvA data continues to grow!
- Asymmetry in $\nu_e - \bar{\nu}_e$ appearance consistent with zero to 25% precision.
- Measure $\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$ … consistent with global average, new approach
- Data shows no evidence of a sterile ν

And more to come!

- Expect ***doubling* of data** over next few years
- **Joint fit with T2K** collaboration in the works
- Antineutrino **cross-section** results forthcoming
- Investigating complications in neutrino scattering (e.g. **meson exchange currents**)

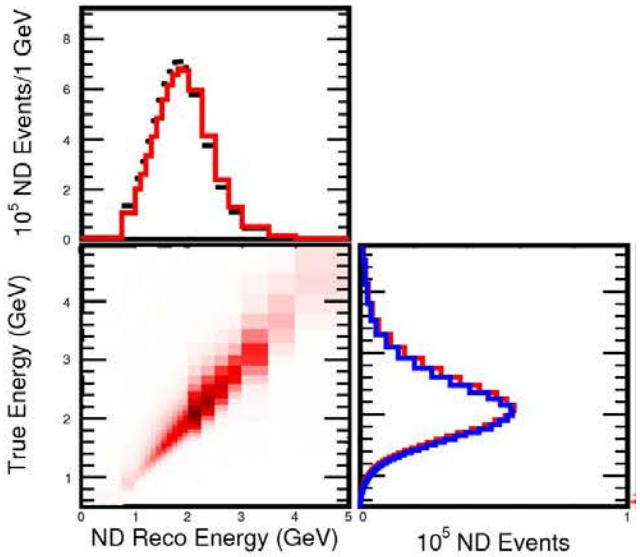
see tomorrow's talk from Maria Martinez-Casales!

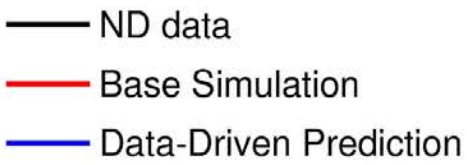
- More analyses **extending** the 3-flavor paradigm and **beyond**



Thanks!

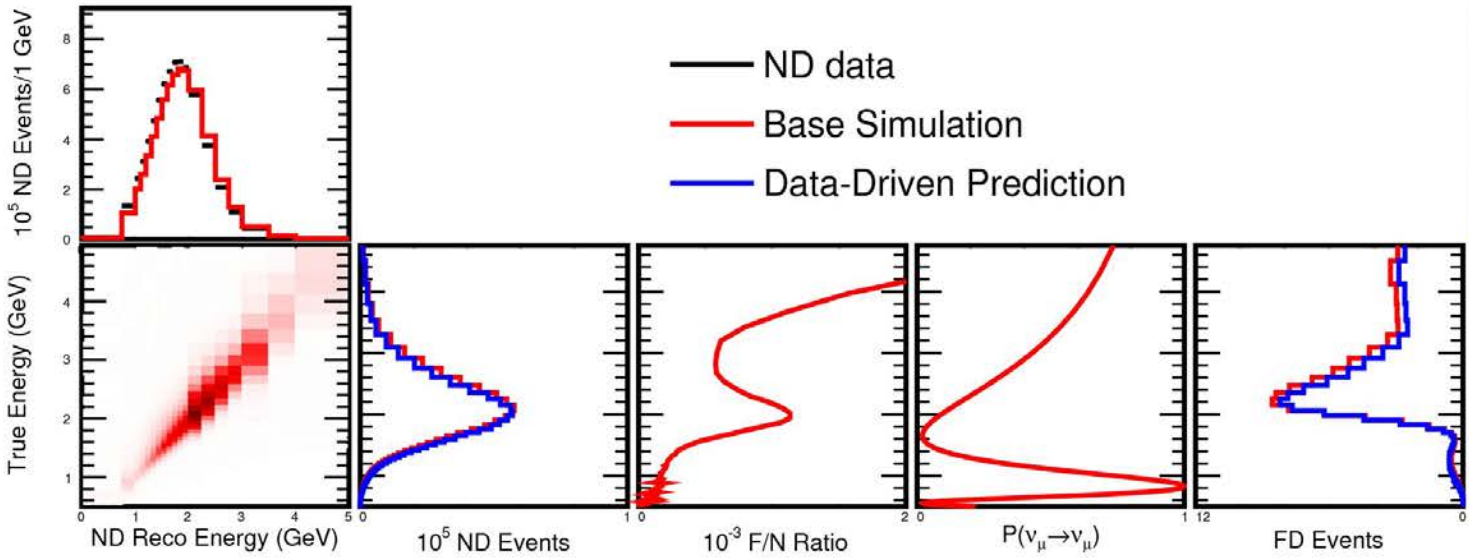
Backup



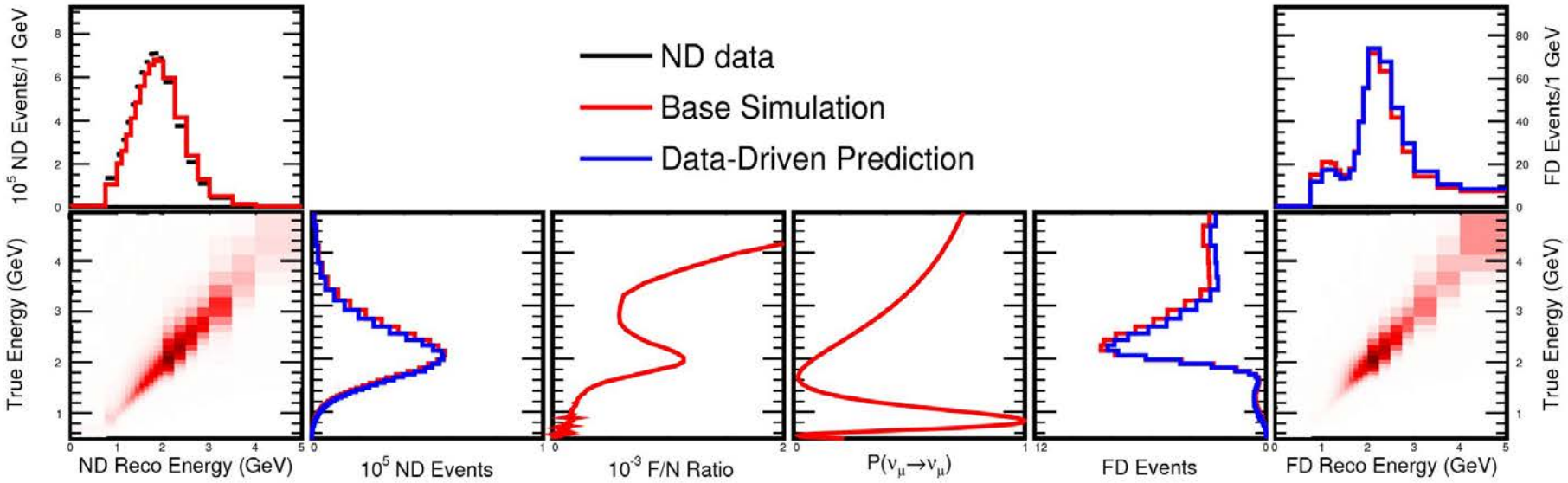


Data-Driven Prediction:
Reweight the underlying simulated neutrino energy spectrum using high-statistics near detector data.

Sample the neutrino spectrum in the event selection at the near detector and extrapolate to predict the spectrum at the far detector...



Multiply by the far-to-near flux ratio (shape of beam at far vs near detectors) and the oscillation probability to predict the true spectrum at the far detector.



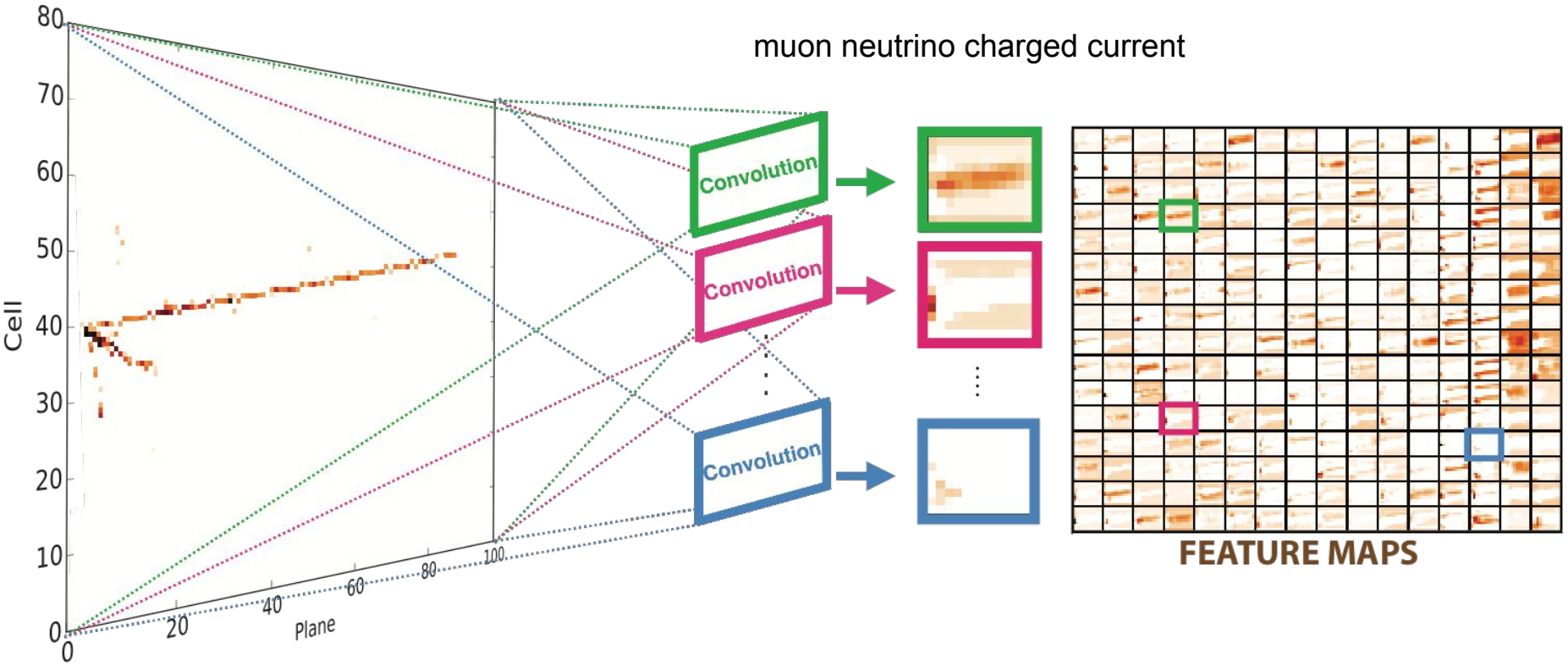
Convert back to reconstructed energy to compare to far detector data.

Leverage correlations in systematics between near & far detectors to better constrain the prediction at the far detector.

$$N_{near}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(...)$$

$$N_{far}(E_\nu^{reco}) = P_{osc}(E_\nu^{true}) \times \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(...)$$

Events are classified using a Convolutional Neural Network



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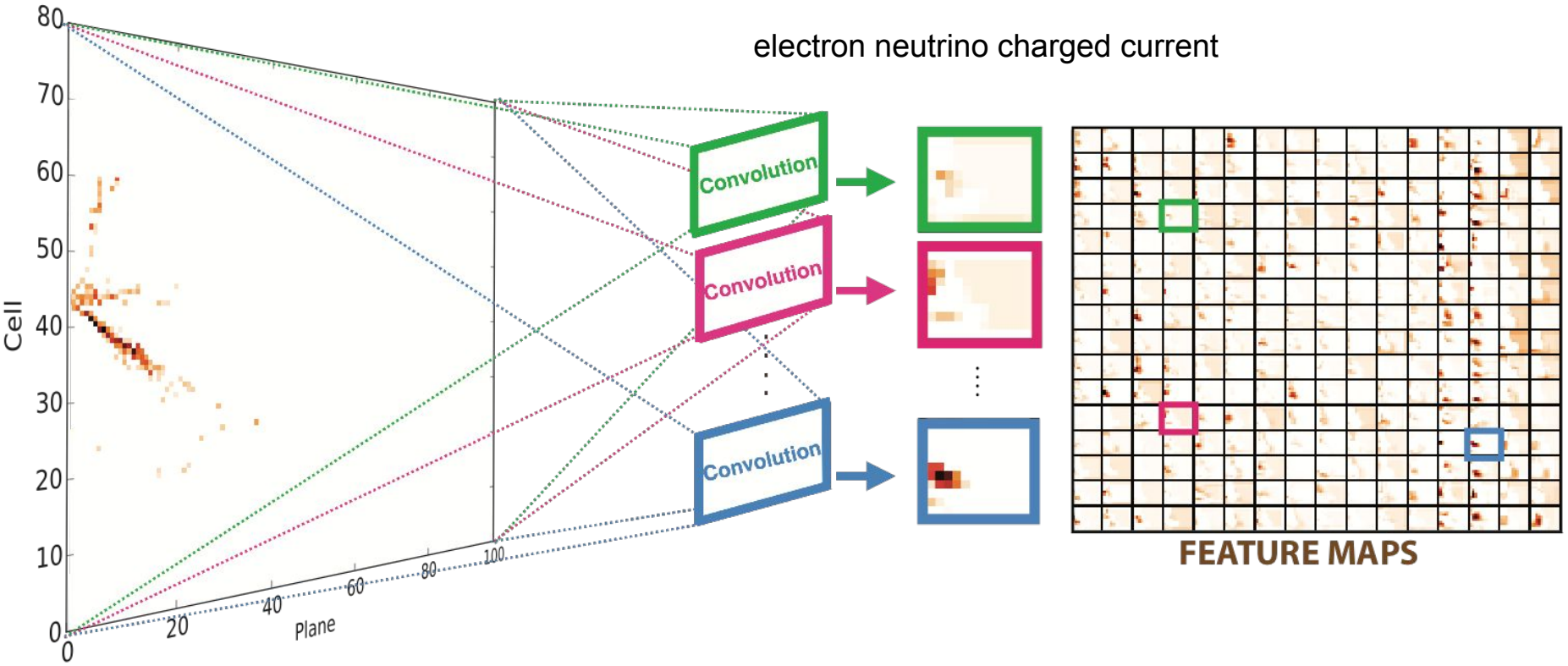

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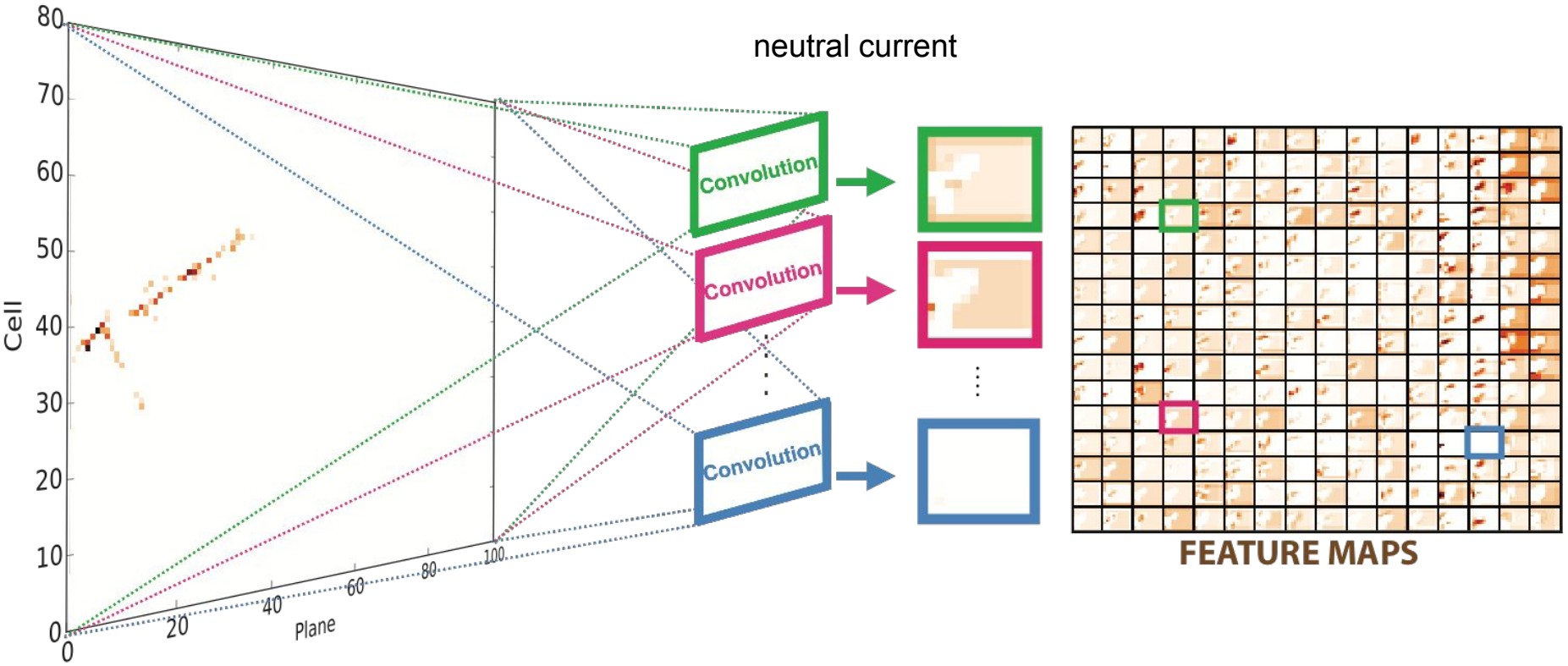

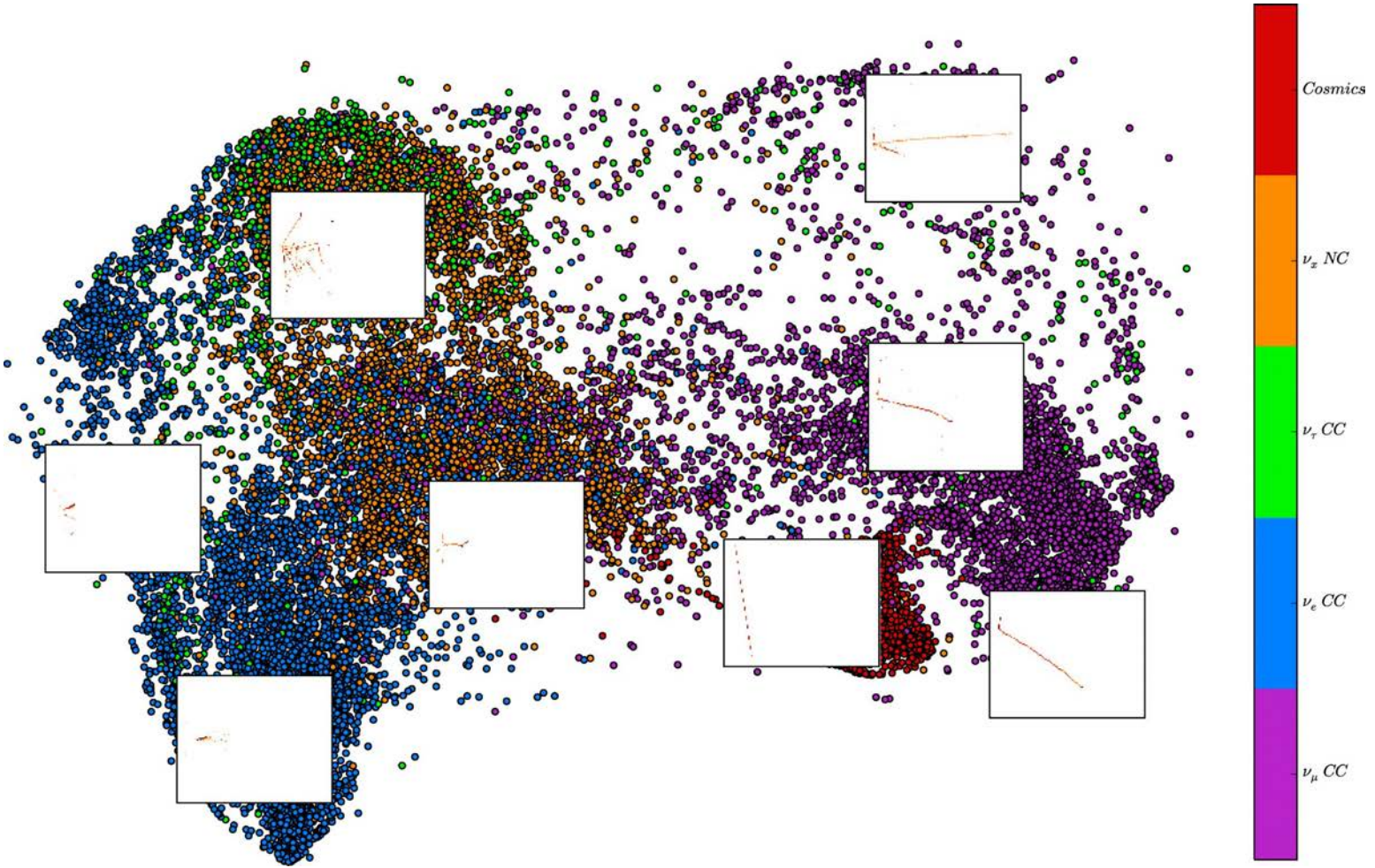
Cosmics
ν_x NC
ν_τ CC
ν_e CC
ν_μ CC

Frequentist Analysis

Exclude
IO, $\delta = \pi/2$
at > 3σ

Best Fit

Normal hierarchy

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$