Recent results from NOvA

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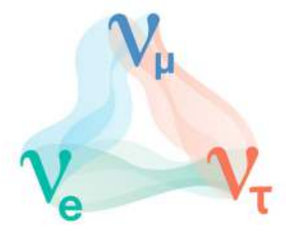
Rencontres de Moriond EW. La Thuile, Italy, March 16th 2022

3-flavor neutrino oscillations

- 3-flavor neutrino oscillations are transitions in-flight between the flavor neutrinos $\nu_e\ \nu_\mu\ \nu_\tau$
  - Caused by non-zero neutrino masses and neutrino mixing.



Flavor states (interaction)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Mixing matrix

Mass states (propagation)

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U^*_{\alpha i} e^{-i \frac{m_i^2 L}{2E}} U_{\beta i} \right|^2$$

- The oscillation probabilities depend on:
  - Neutrino energy (E_ν)
  - Distance between the source and the detector ("baseline" L)

  } Experimental "settings"

  - Squared mass differences (Δm^2_{21}, Δm^2_{32})
  - Parameters of the mixing matrix: 3 angles and 1 phase ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)

  } What we want to measure

Measurements of oscillation parameters

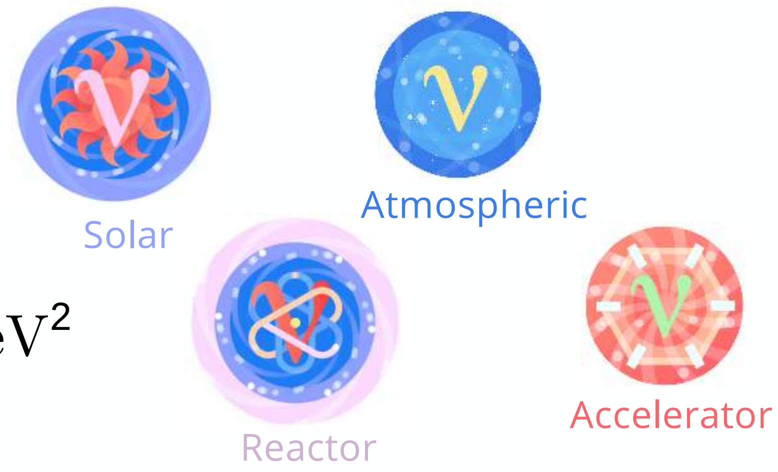
- Experiments contributing to the determination of the oscillation parameters:

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

PDG2020

- Our current knowledge:

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\sin^2(\theta_{13}) = 0.0220 \pm 0.0007$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{eV}^2$$



$$\sin^2(\theta_{23}) = 0.546 \pm 0.021$$
$$\Delta m^2_{32} = (+2.453 \pm 0.033) \times 10^{-3} \text{eV}^2 \ \text{(normal)}$$
$$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3} \text{eV}^2 \ \text{(inverted)}$$

Source: PDG, 2021 update

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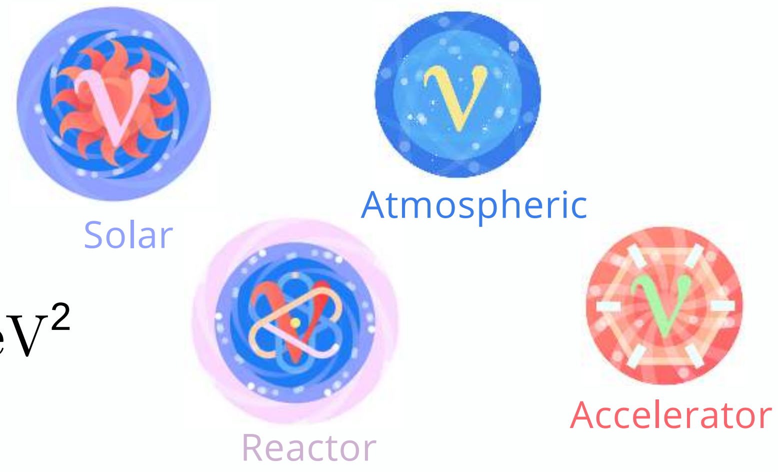

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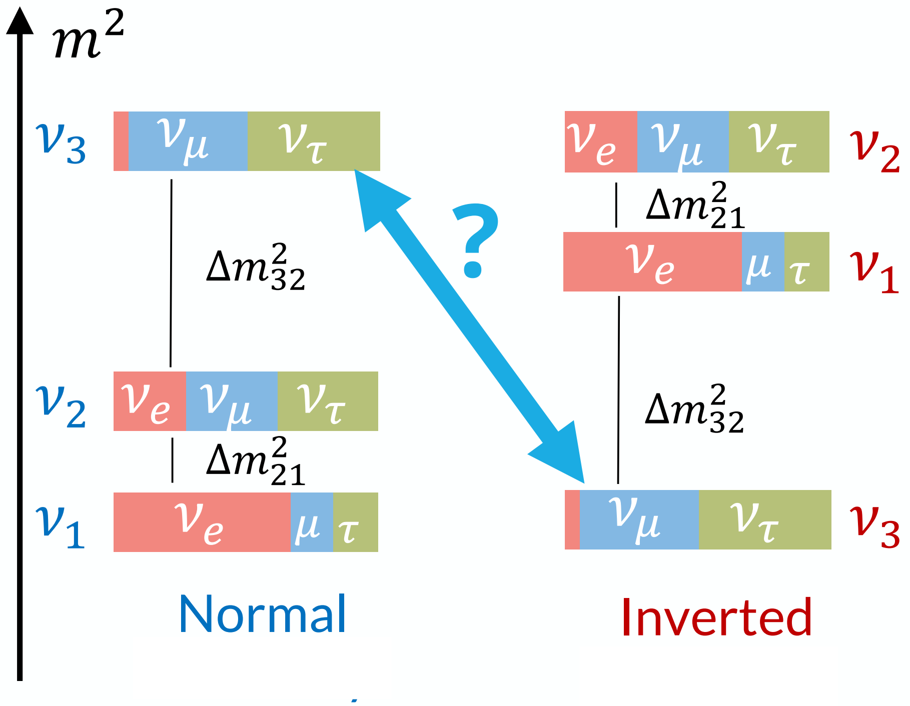
Known unknowns

Is the neutrino mass ordering normal or inverted?

$\mathbf{sgn}(\Delta m^2_{32}) = ?$



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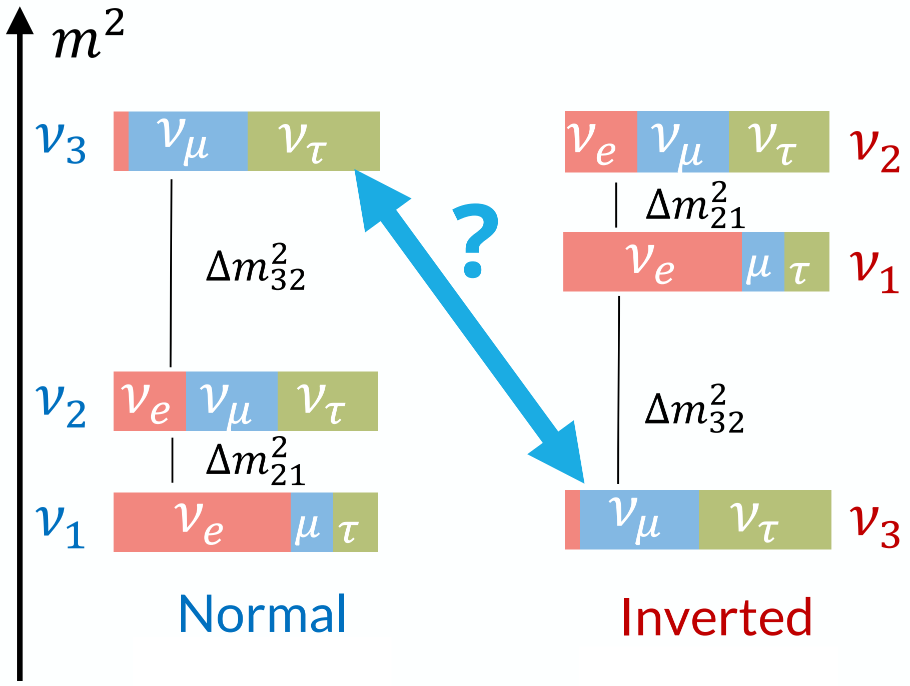
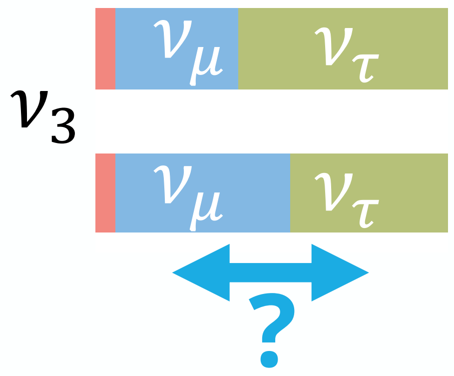


Is θ_{23} mixing maximal?
($\theta_{23} = \pi/4$: ν_μ-ν_τ symmetry)

If not, what is the octant of θ_{23}?

$\boldsymbol{\theta_{23} \gtreqless \pi/4}$?



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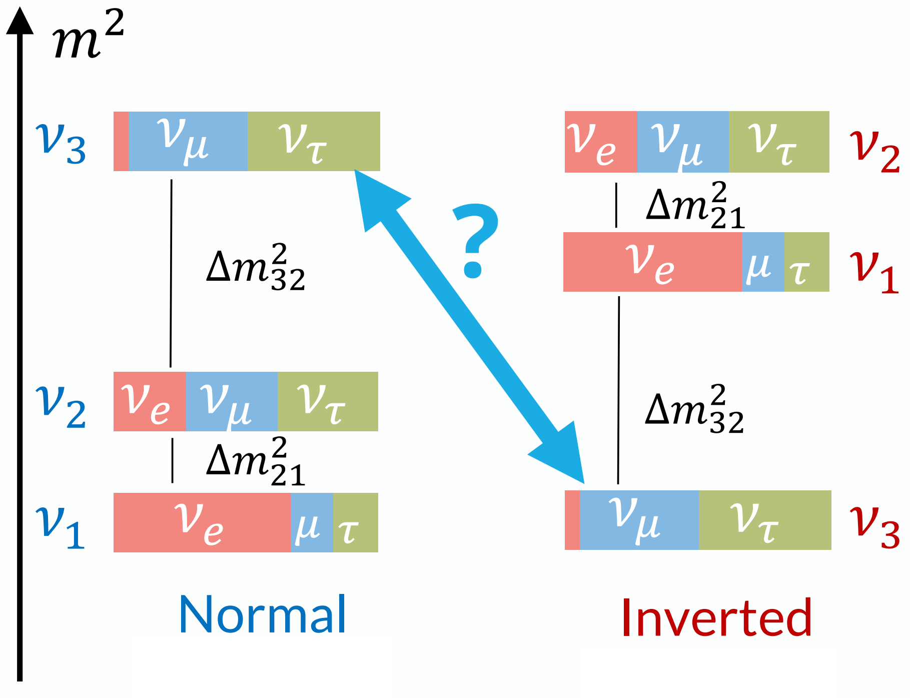

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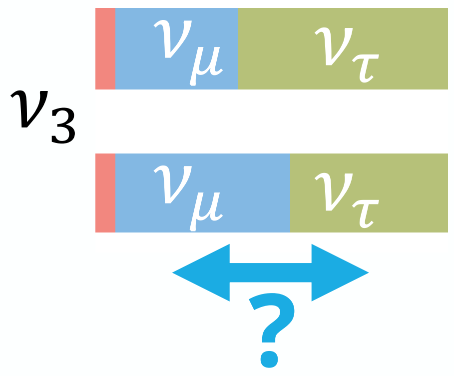
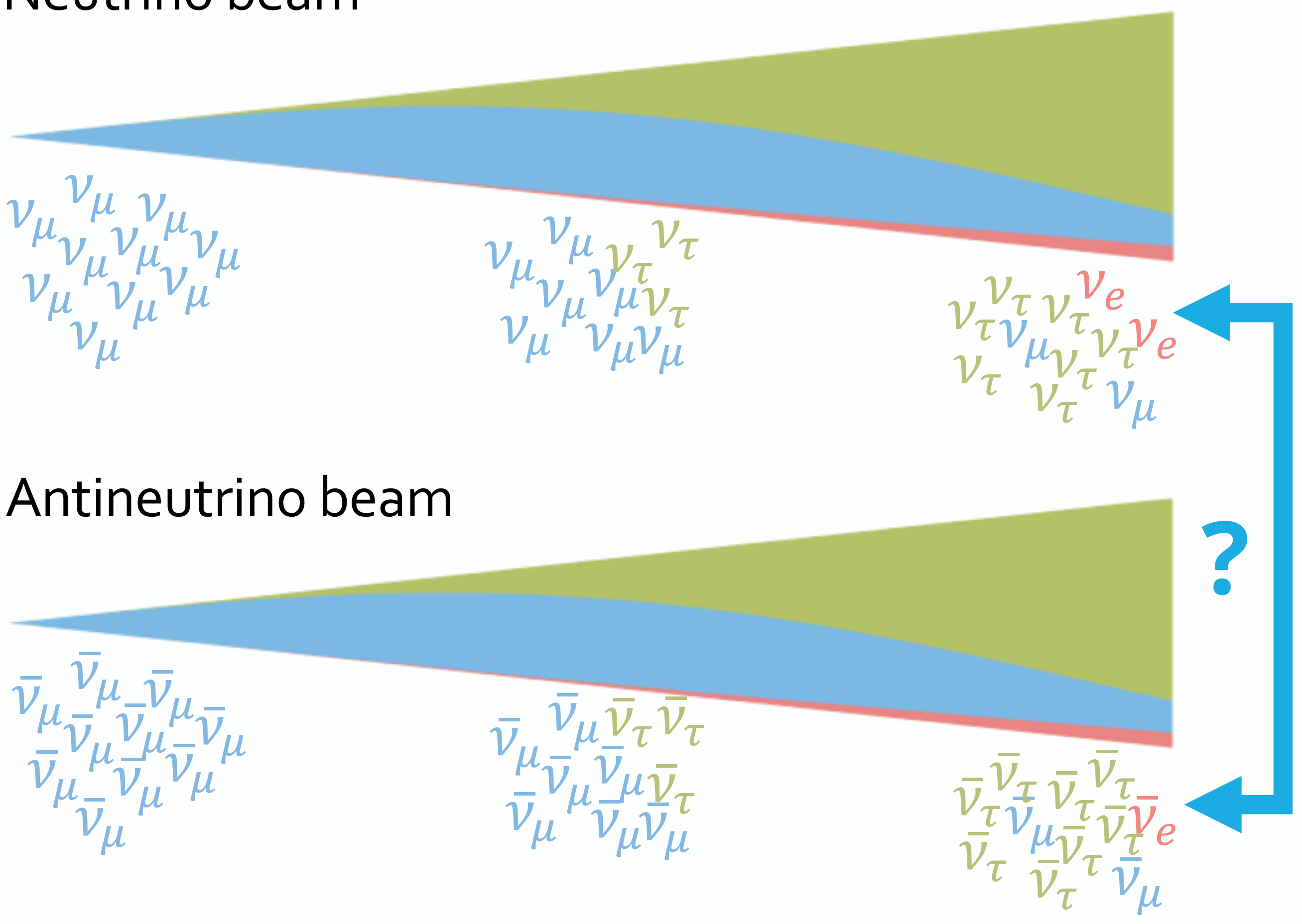


Is CP violated in the neutrino sector? $\delta_{CP} \neq 0, \pi$?

Charge-Parity symmetry: $\nu_\mu \rightarrow \nu_e \overset{CP}{\Longleftrightarrow} \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

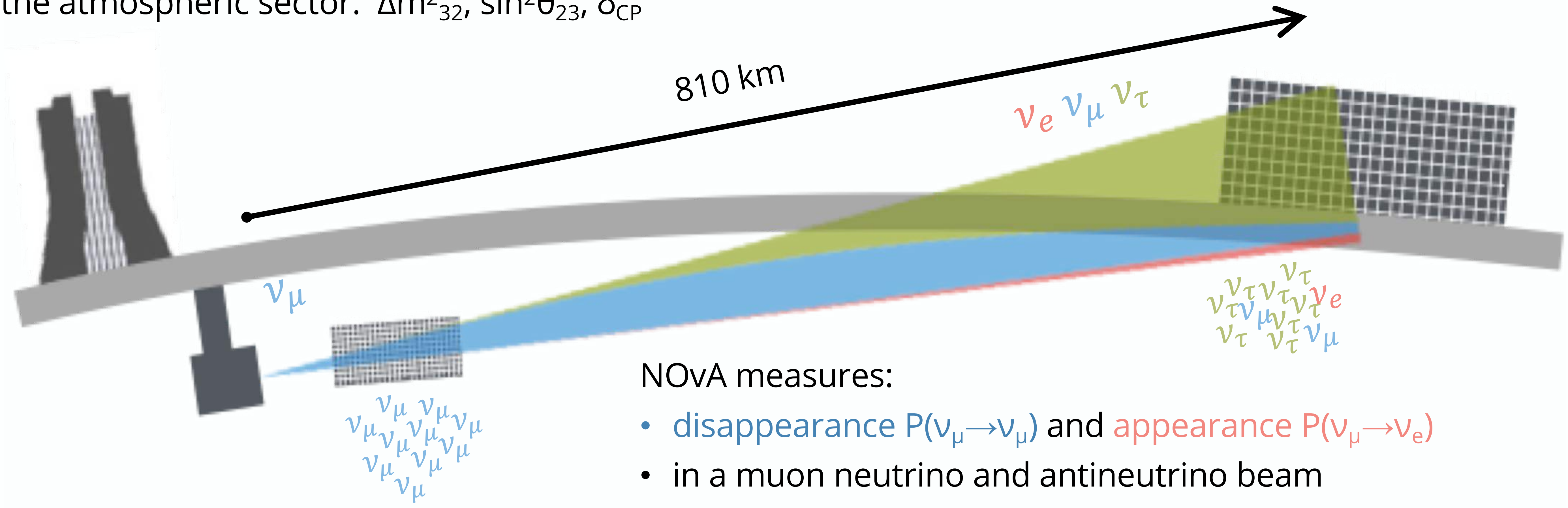
Neutrino beam

Antineutrino beam



The NOvA Experiment

NOvA is a long-baseline accelerator neutrino experiment.
It’s primary goal is the estimation of 3-flavor oscillation parameters in the atmospheric sector: Δm^2_{32}, $\sin^2\theta_{23}$, δ_{CP}

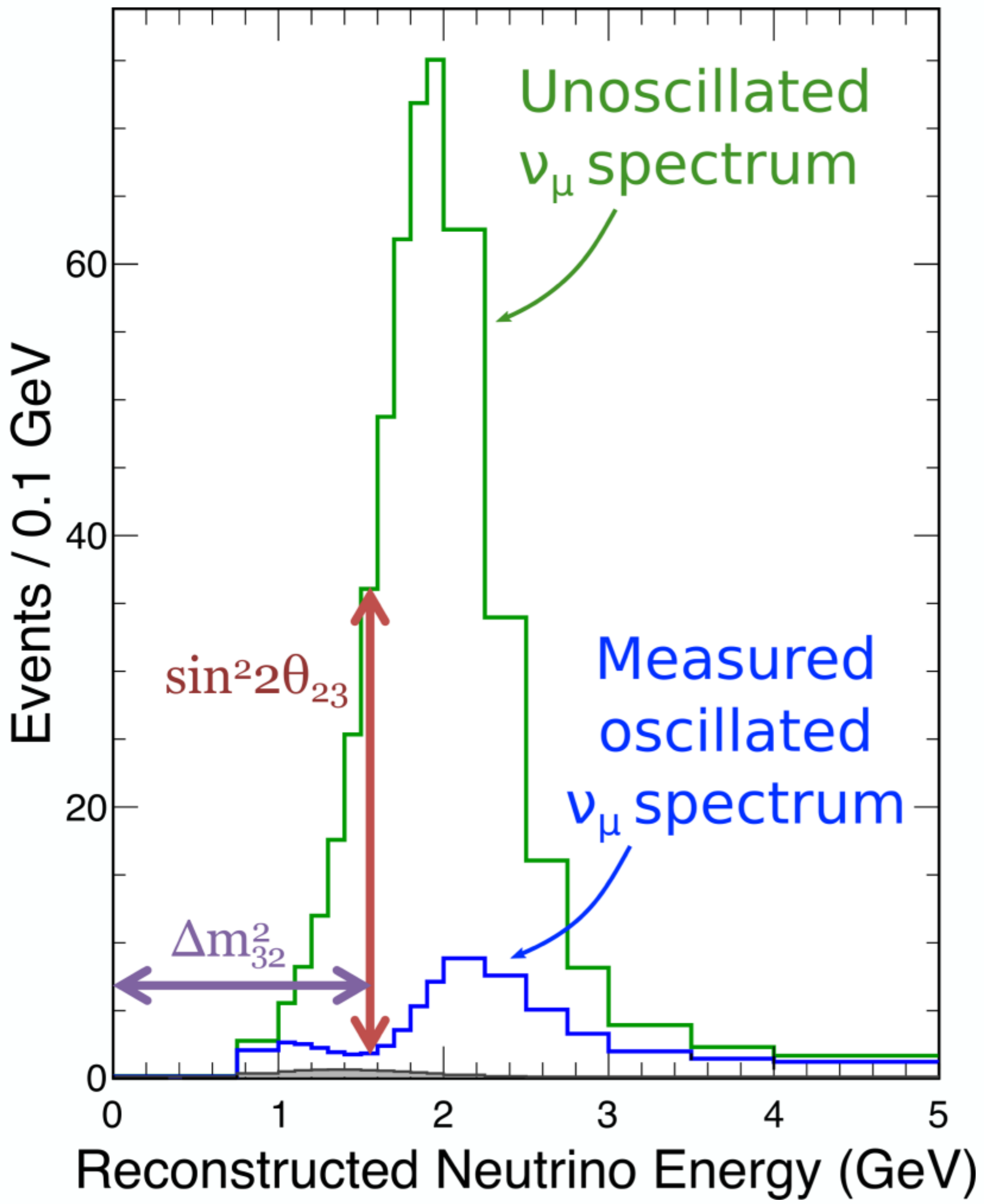


NOvA measures:

- disappearance $P(\nu_\mu \rightarrow \nu_\mu)$ and appearance $P(\nu_\mu \rightarrow \nu_e)$
- in a muon neutrino and antineutrino beam
- over a 810 km baseline
- with 2 functionally-identical detectors

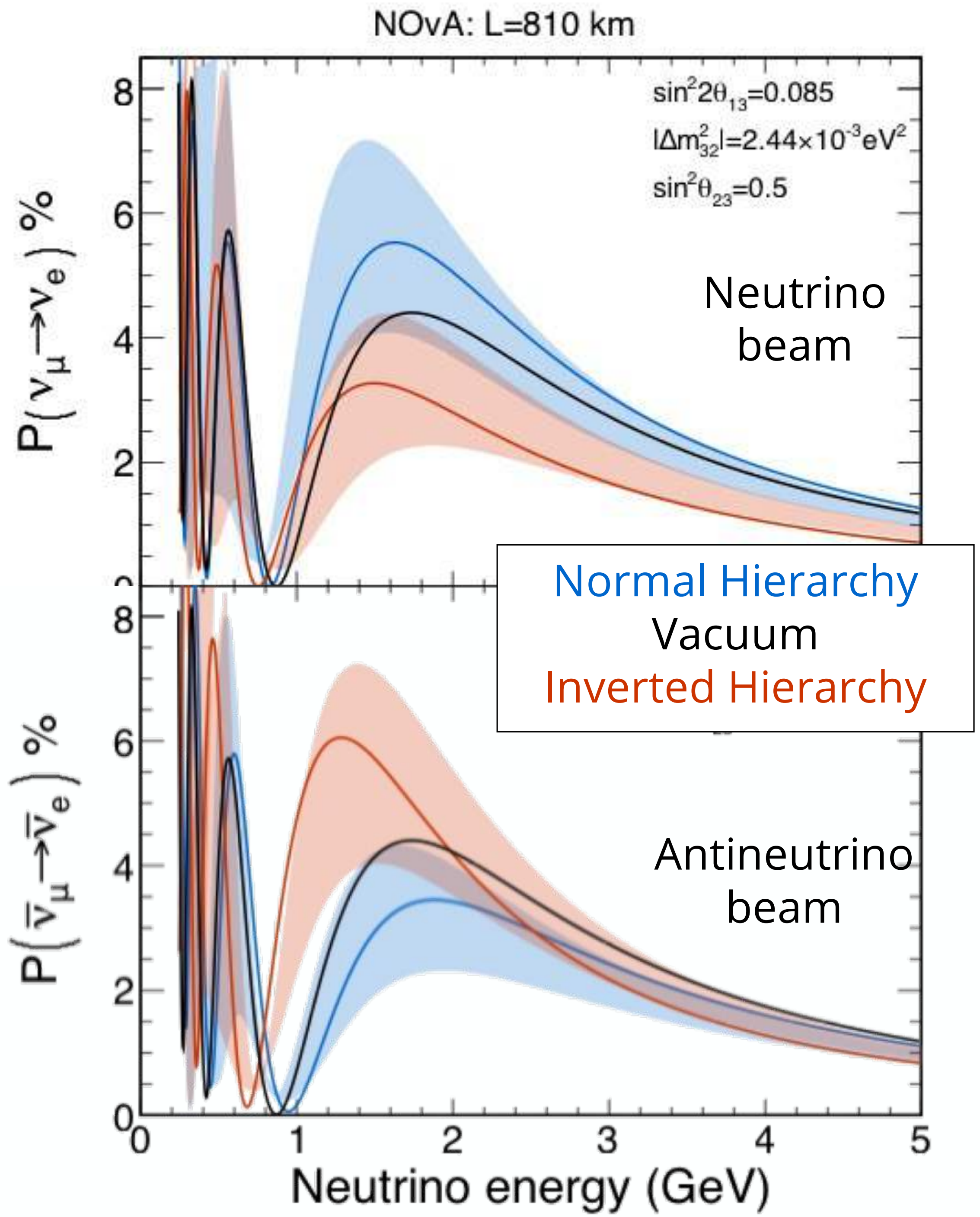
$\nu_\mu \rightarrow \nu_\mu$ oscillations

- $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance can constrain **$\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$**
- Strategy:
  - Identify muon neutrinos
  - Reconstruct their energy
  - Compare the data with the unoscillated prediction
    - "Dip" location → $|\Delta m^2_{32}|$
    - Amplitude → $\sin^2 2\theta_{23}$



$\nu_\mu \rightarrow \nu_e$ oscillations

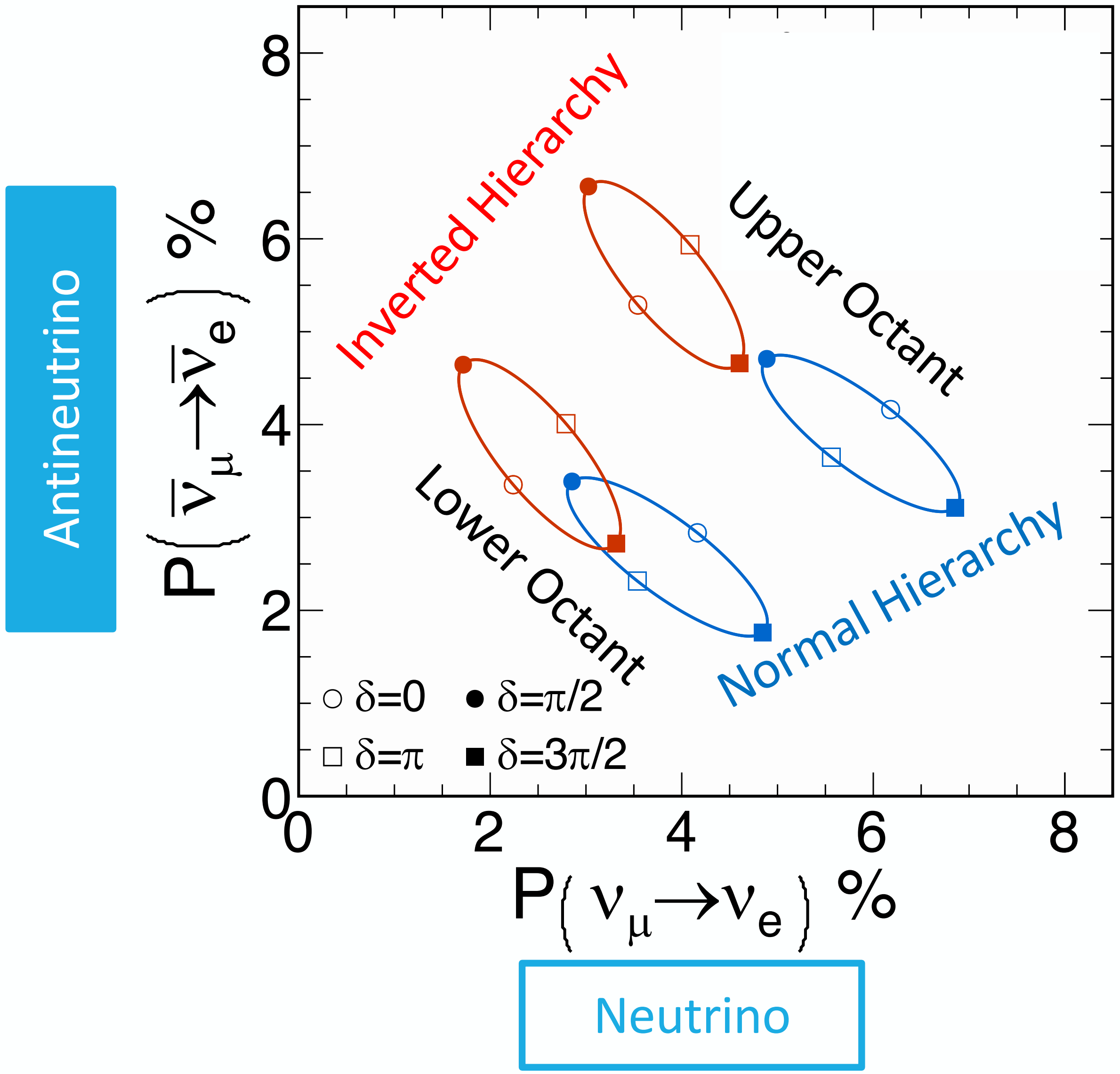
- $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ appearance depend on **$\sin^2\theta_{23}$, Δm^2_{32} and δ_{CP}**



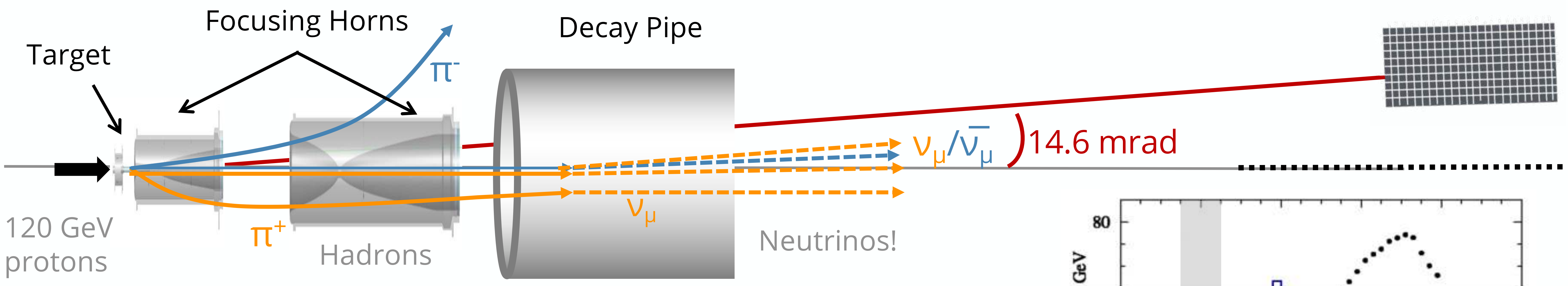
$\nu_\mu \rightarrow \nu_e$ oscillations

- $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance depend on **$\sin^2\theta_{23}$, Δm^2_{32} and δ_{CP}**

- Strategy:
  - Identify electron neutrinos
  - Analyze neutrino and antineutrino beam data simultaneously
  - Use the relative (a)symmetries between ν_e and $\bar{\nu}_e$ appearance rates to set constraints



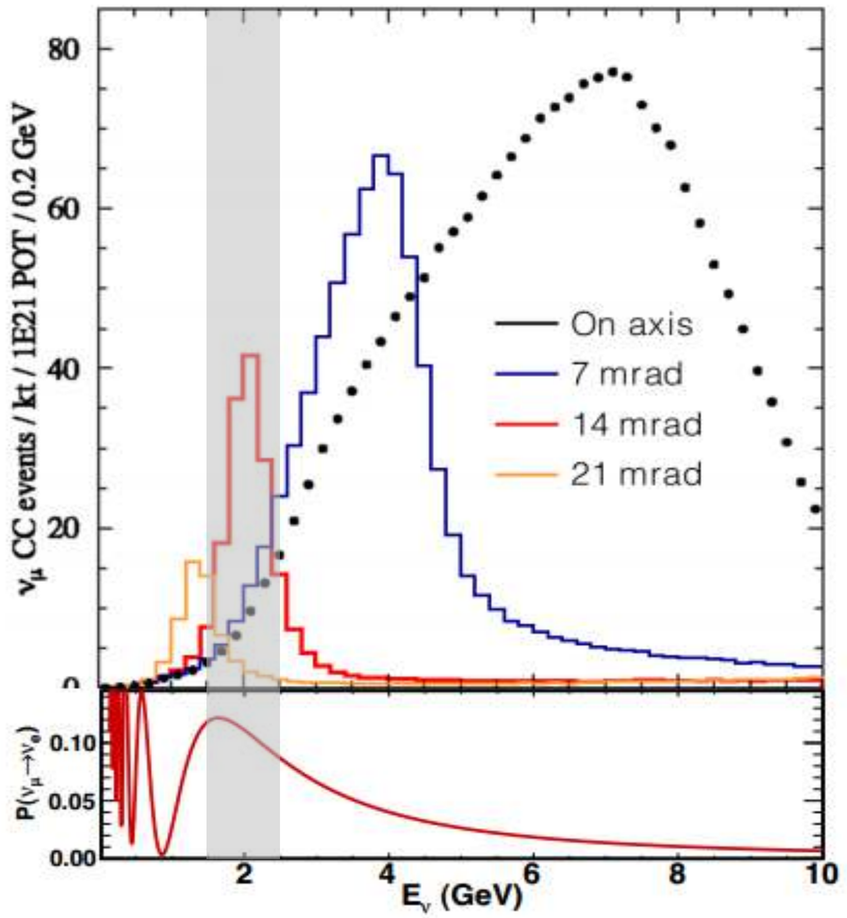
NuMI muon neutrino beam



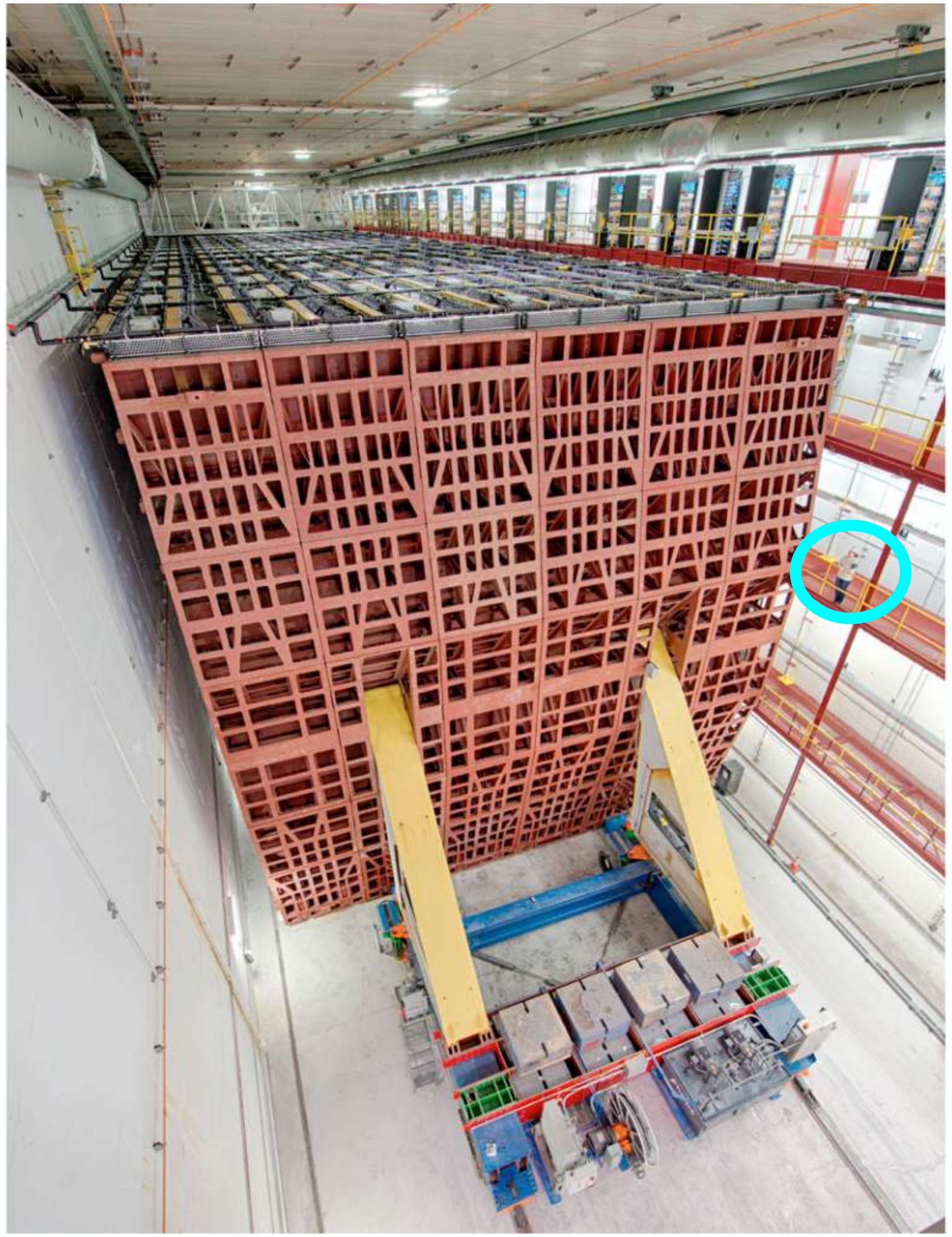
- NuMI: Neutrinos from the Main Injector.

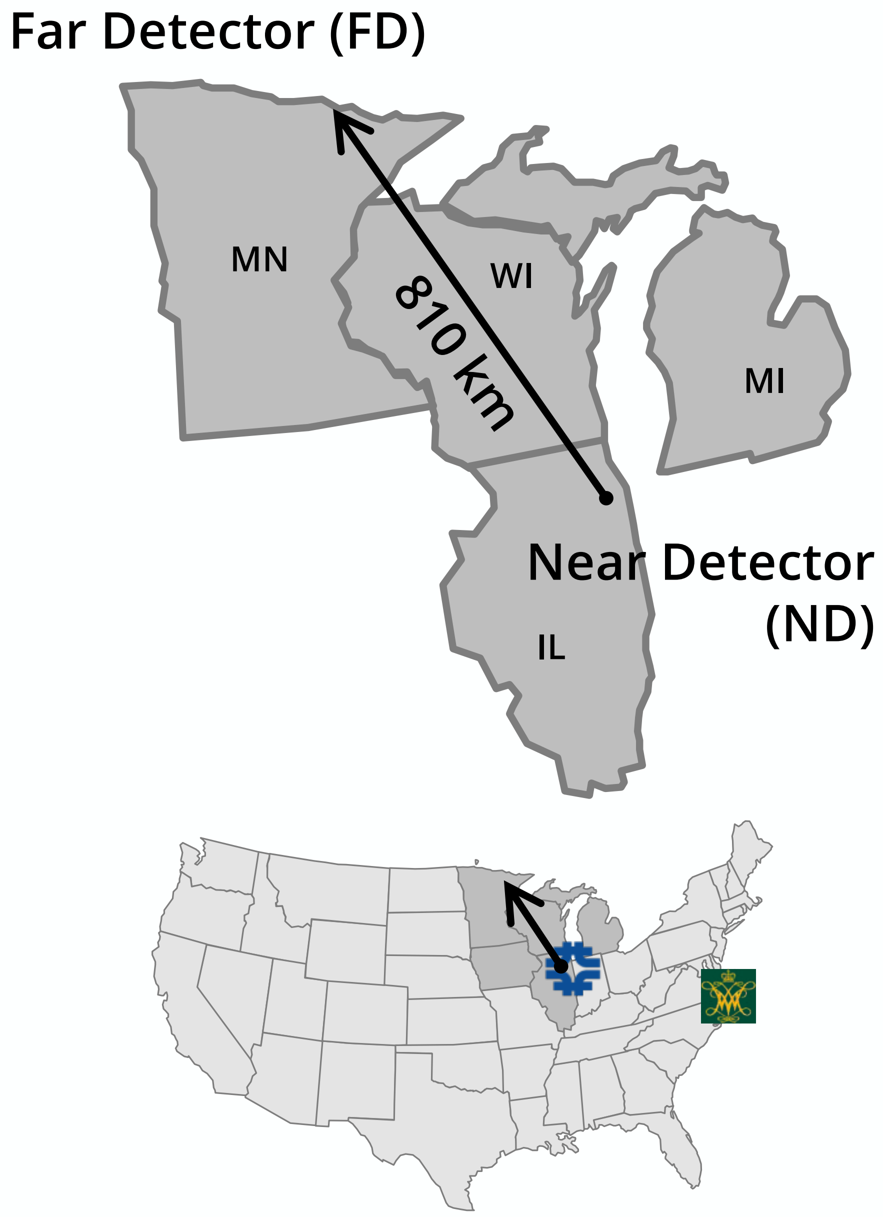
  Part of the Fermilab Accelerator Complex
- Two running configurations:
  - Neutrino beam (ν_μ)
  - Antineutrino beam ($\bar{\nu}_\mu$)

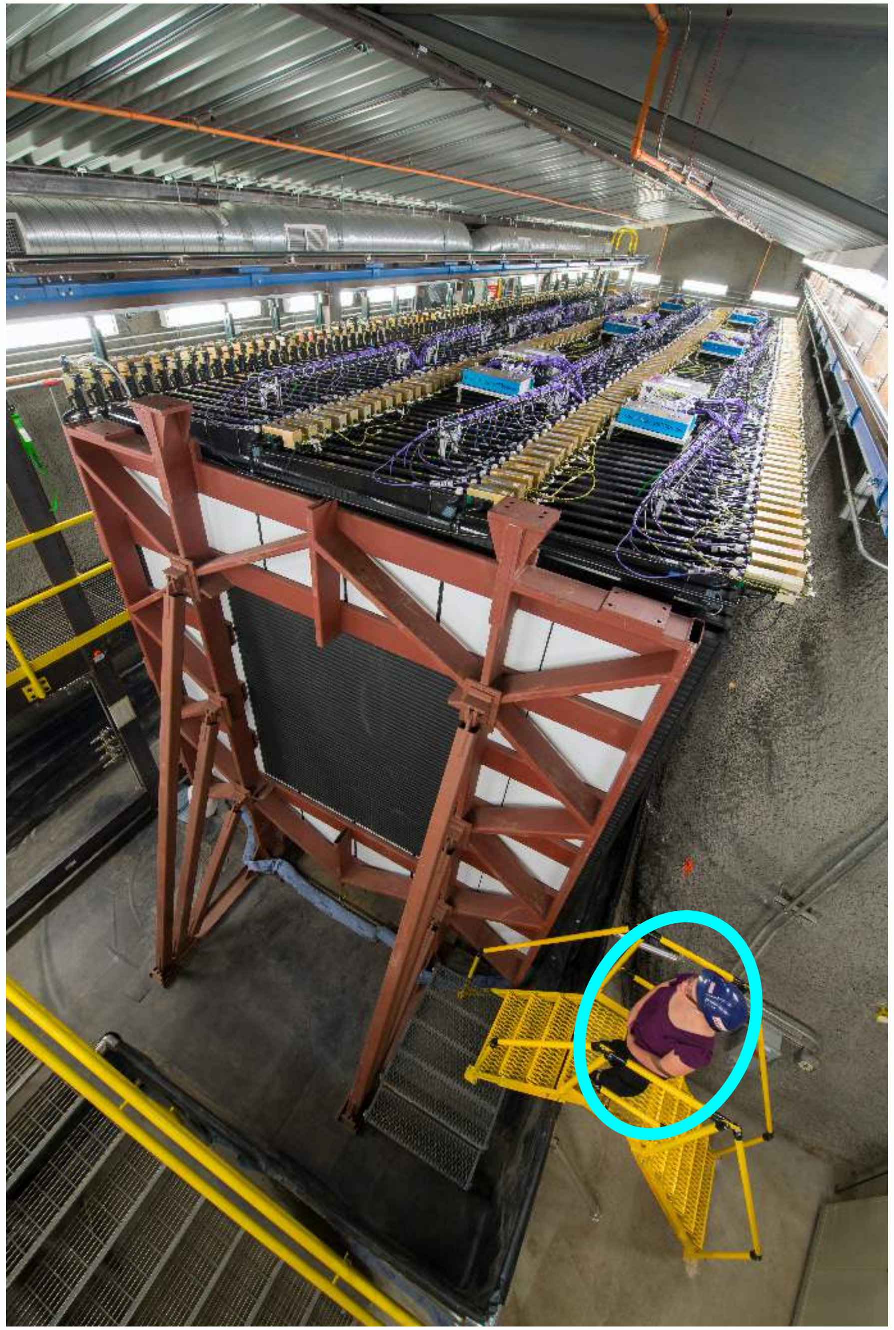
- The NOvA detectors are located off-axis.
- Flux peaks around 2GeV



The NOvA detectors







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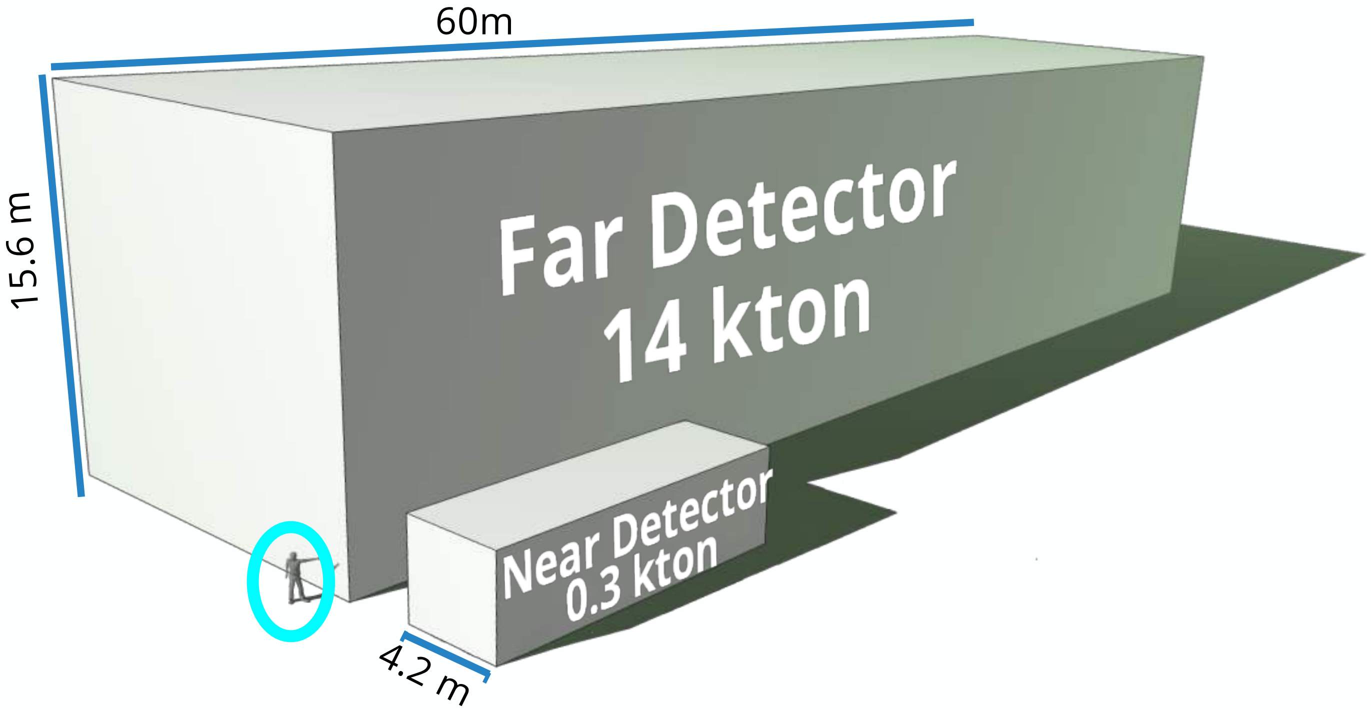
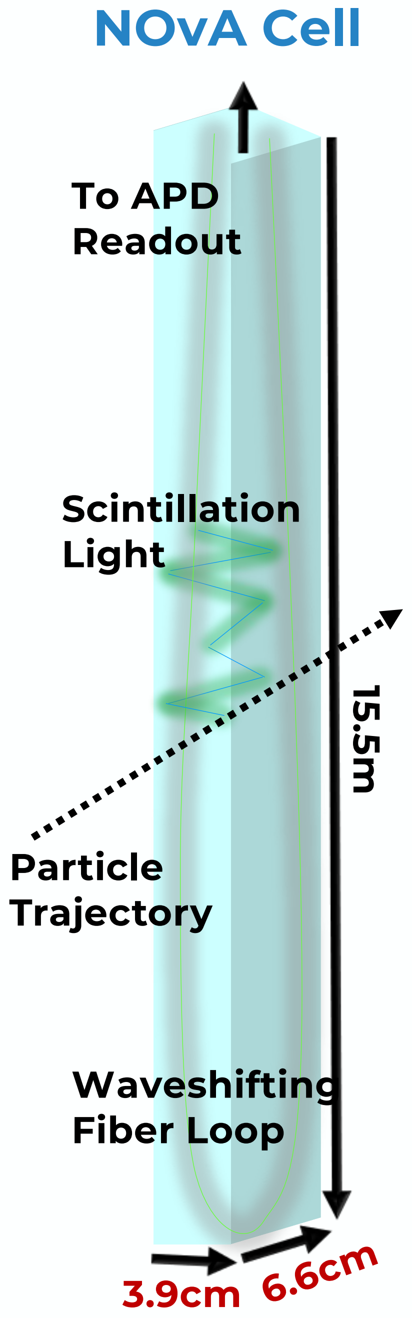
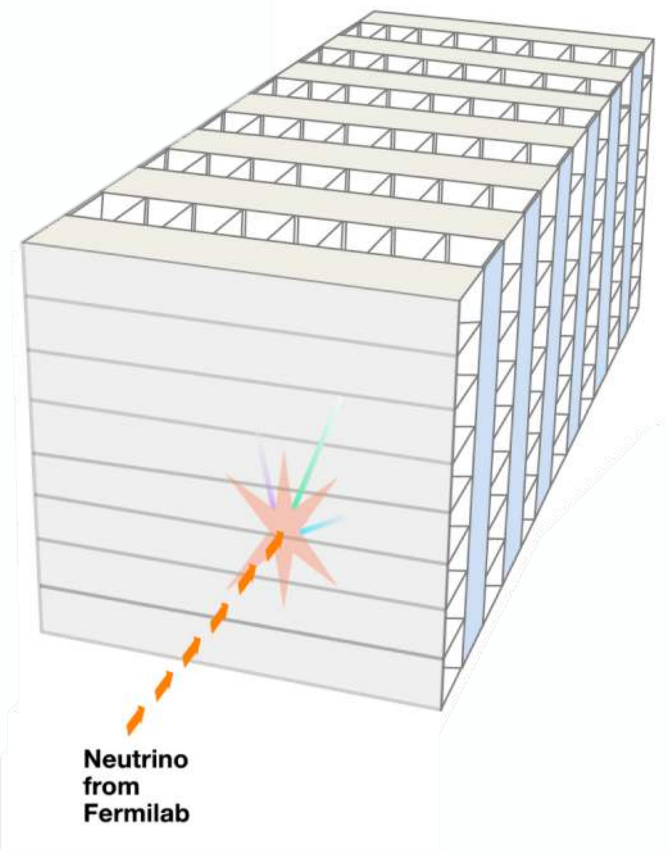
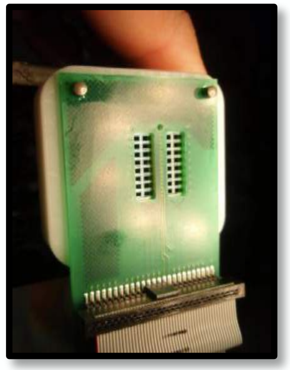


- Detectors are fine-grained, low-*Z*, highly-active tracking calorimeters
- **Cells are PVC, filled with liquid scintillator**
- Read out via wavelength shifting fiber to APD
- **Orthogonal layers of cells → top and side view for each event**

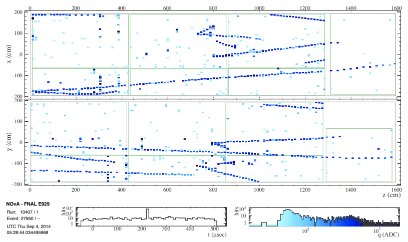




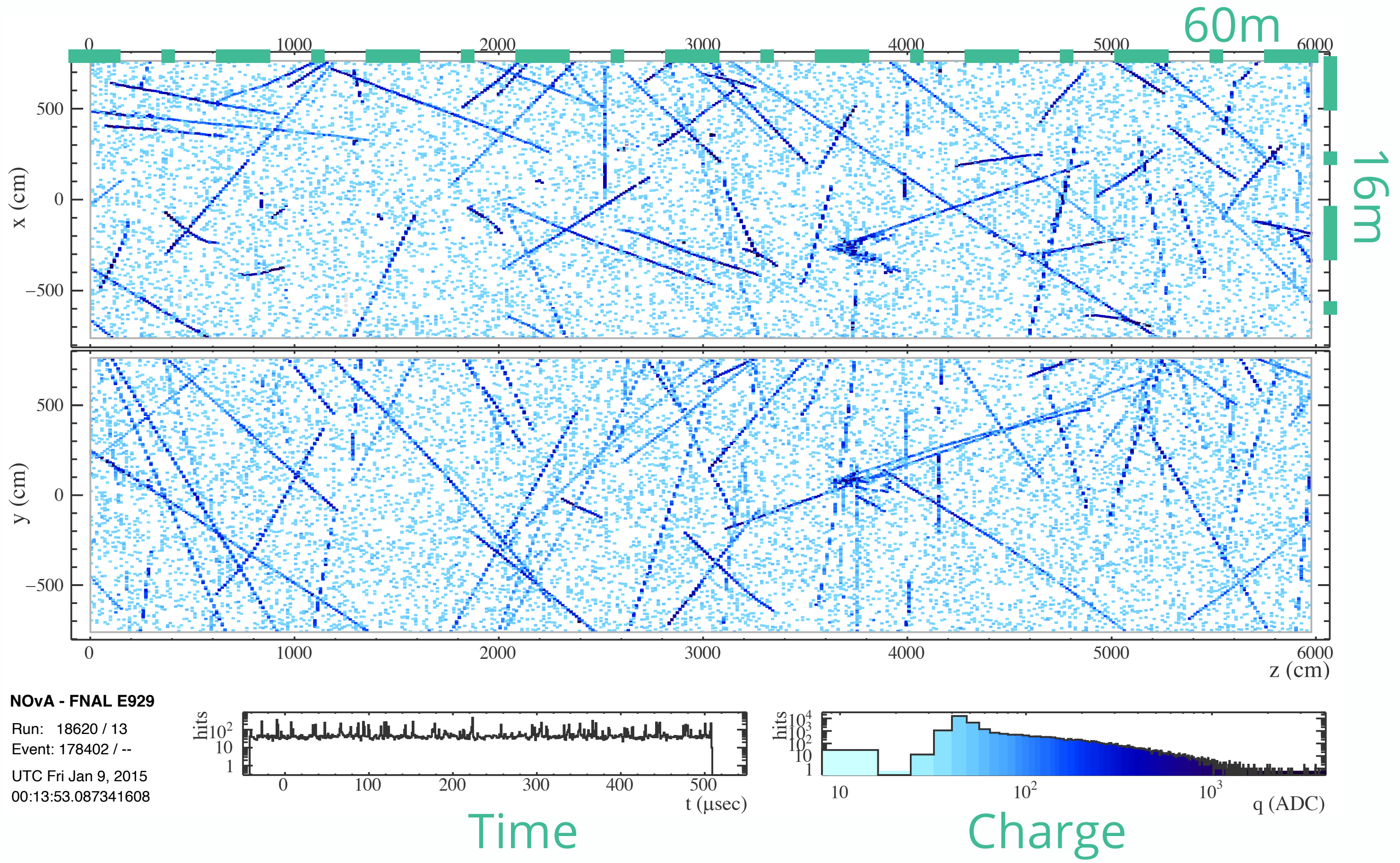


Collecting neutrinos

Near detector



Far detector



Beam direction

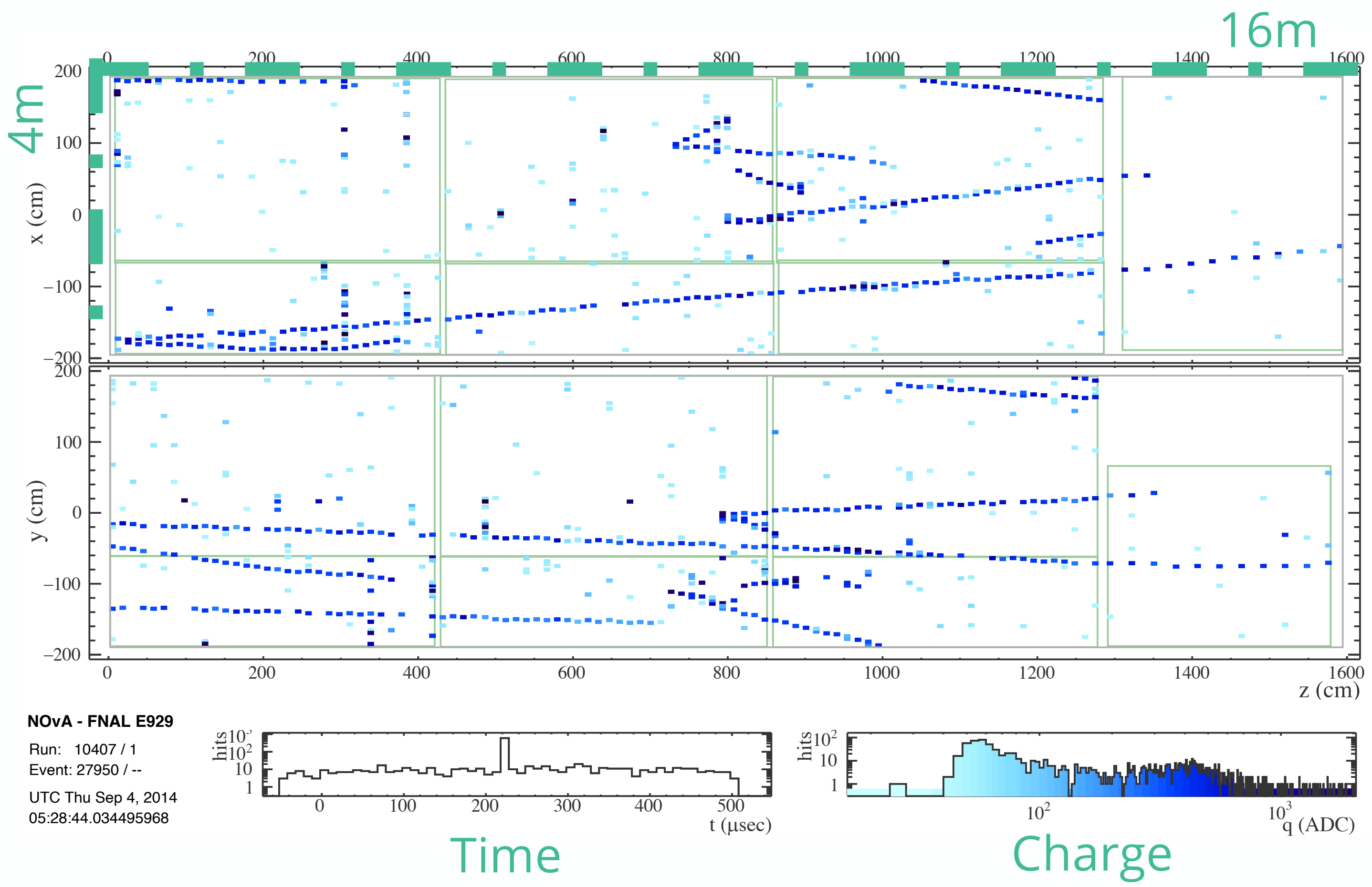
Collecting neutrinos

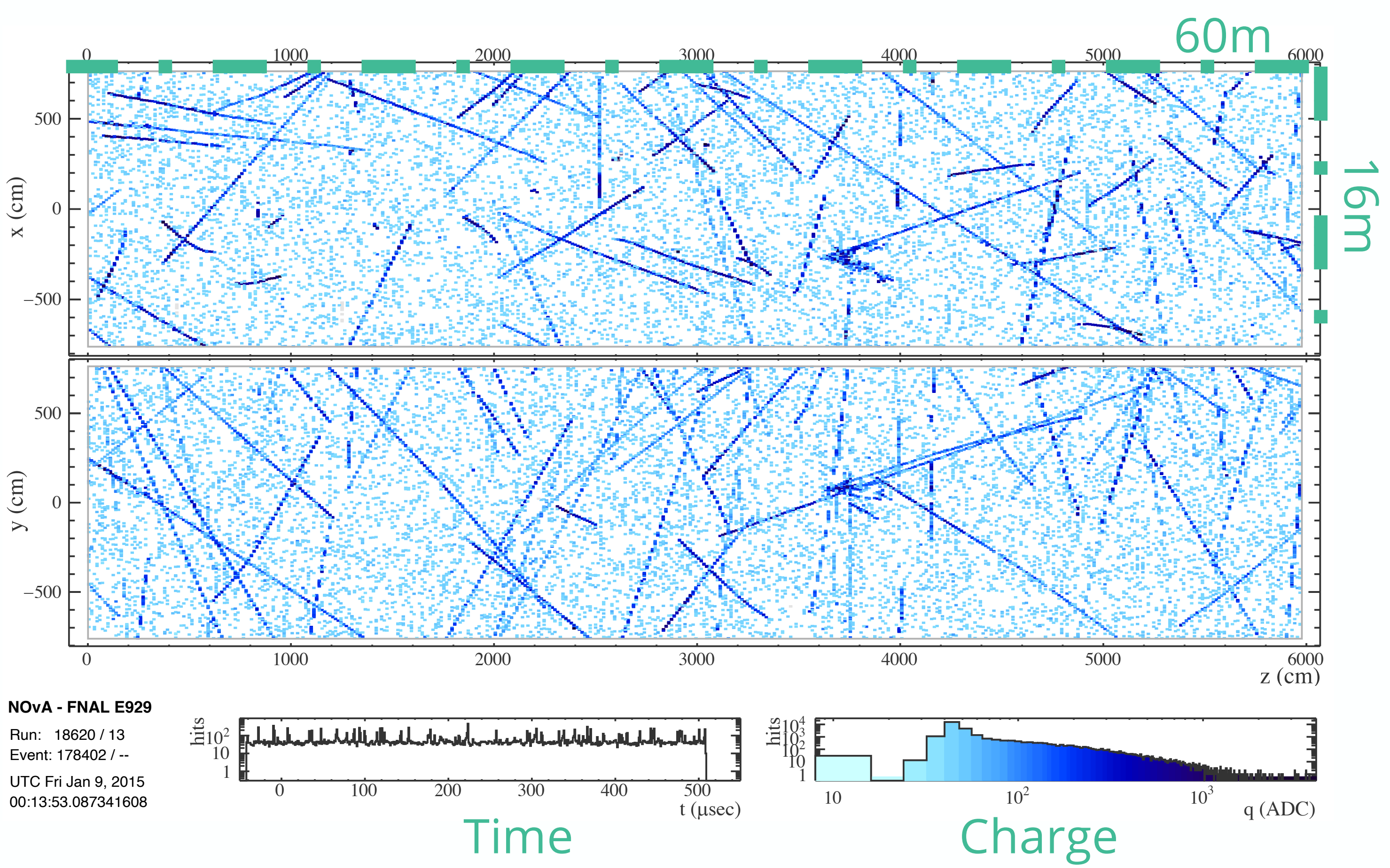
Near detector

20193 channels. 1 km from beam source
~5 contained neutrino events per beam pulse (every 1.33 s)
Negligible cosmic background (underground)

Far detector

344064 channels. 810 km from source
<1 signal neutrino event per day
130 kHz cosmic ray background





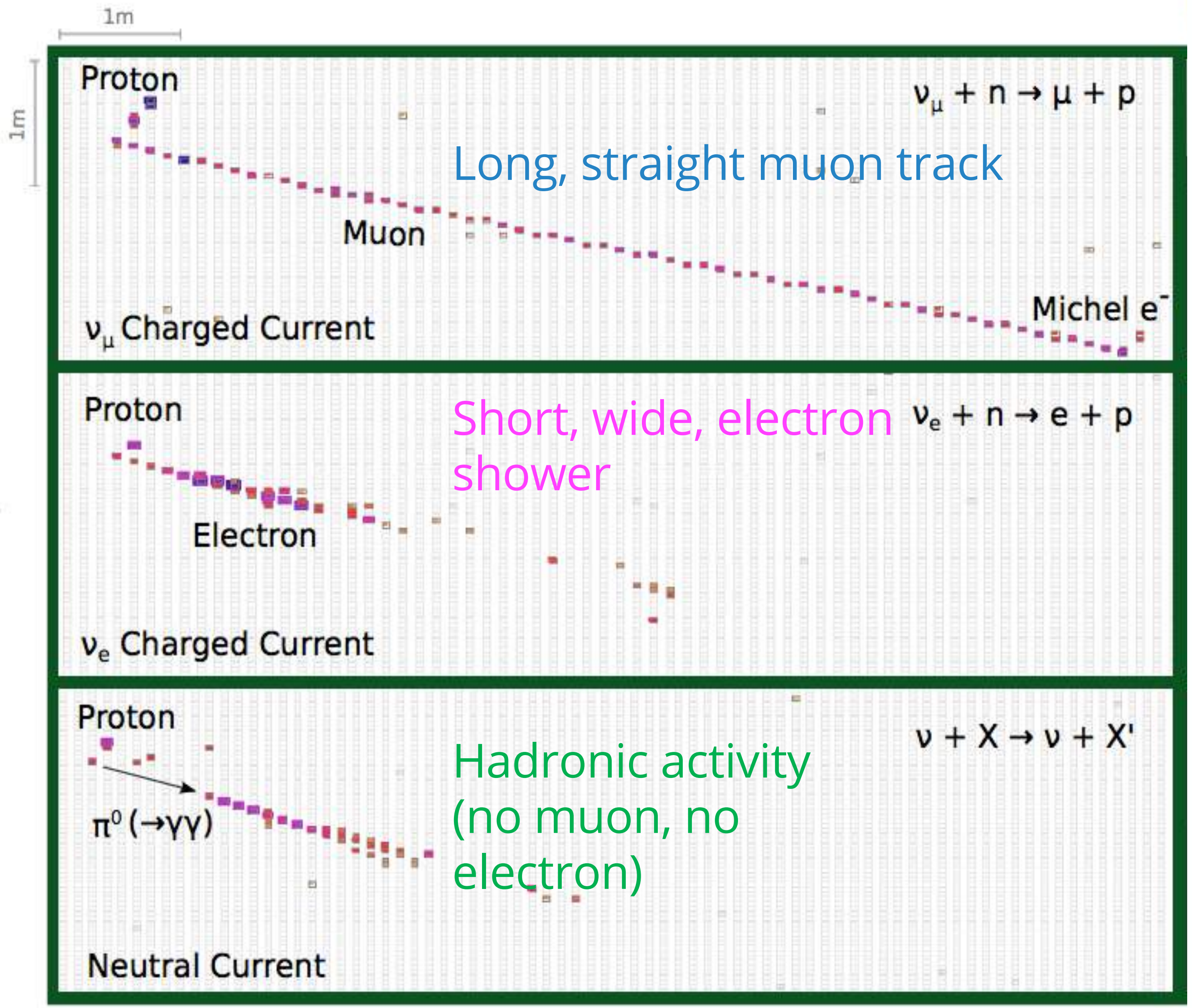
Beam direction

Identifying neutrino events

ν_μ CC

ν_e CC

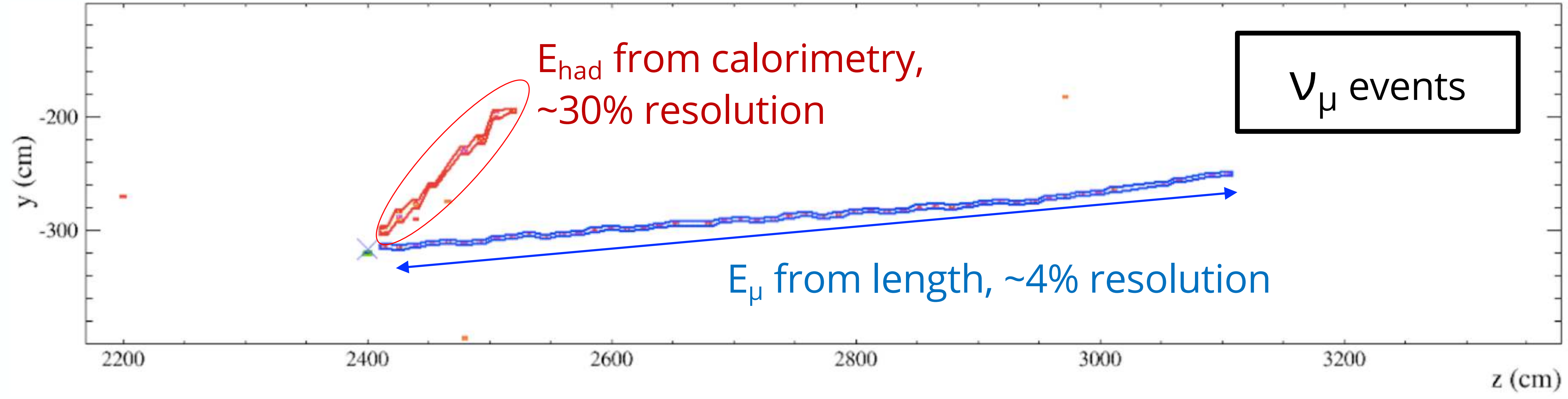
NC

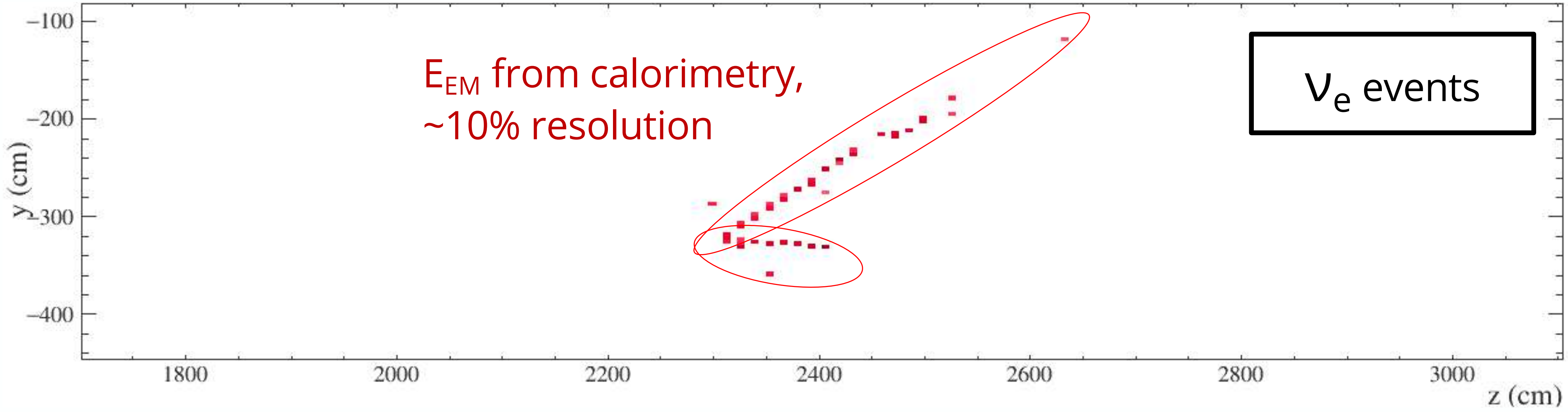


- Neutrino interaction candidates are identified using a **convolutional neural network (CNN)**
  - A deep-learning technique from computer vision
  - New, faster network for 2020.

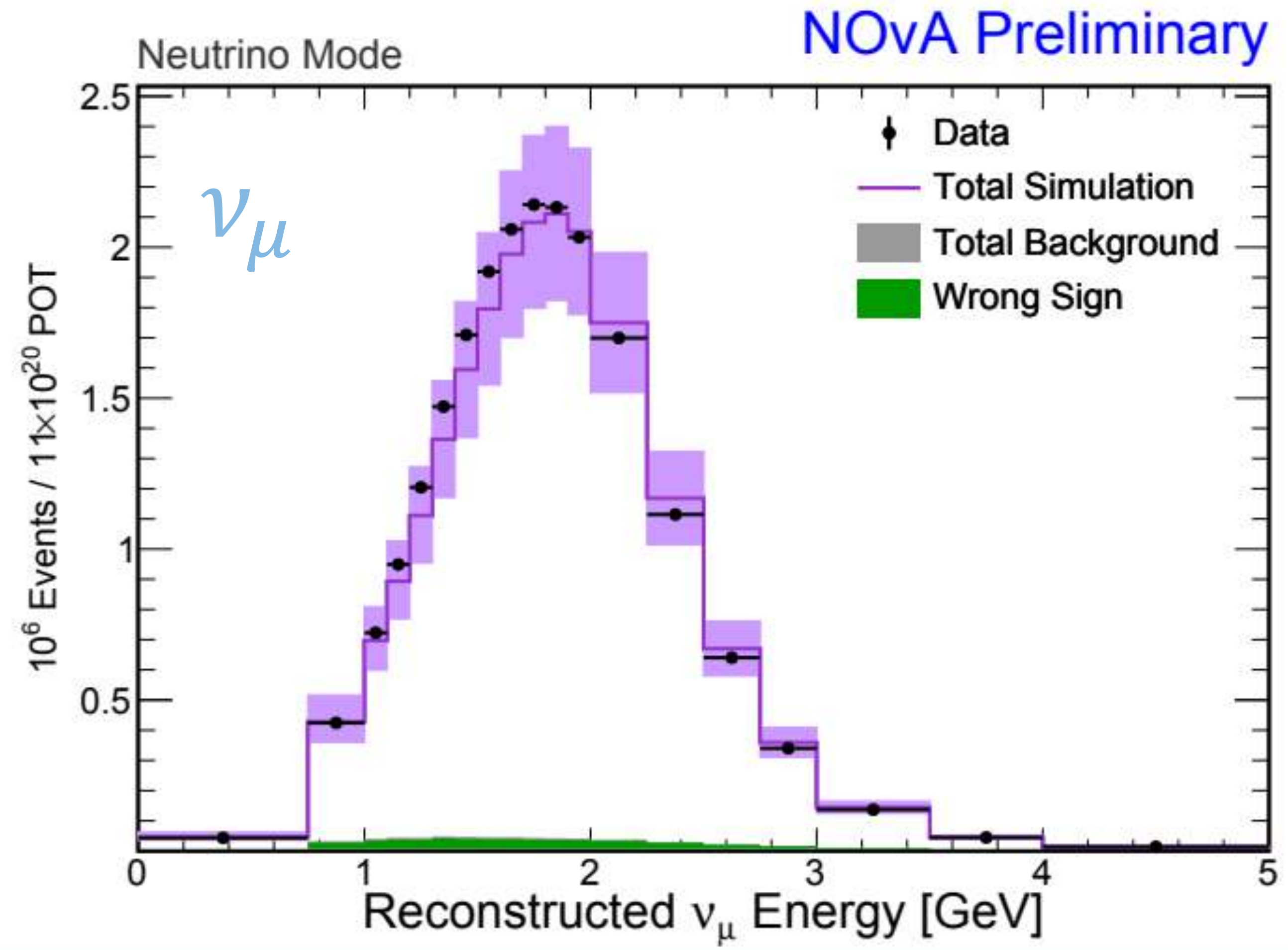
- In addition to the event CNN selection:
  - Events are contained in the detector
  - In-time with the beam
  - CC ν_μ require a well-reconstructed μ track
  - Reject cosmic rays with BDTs

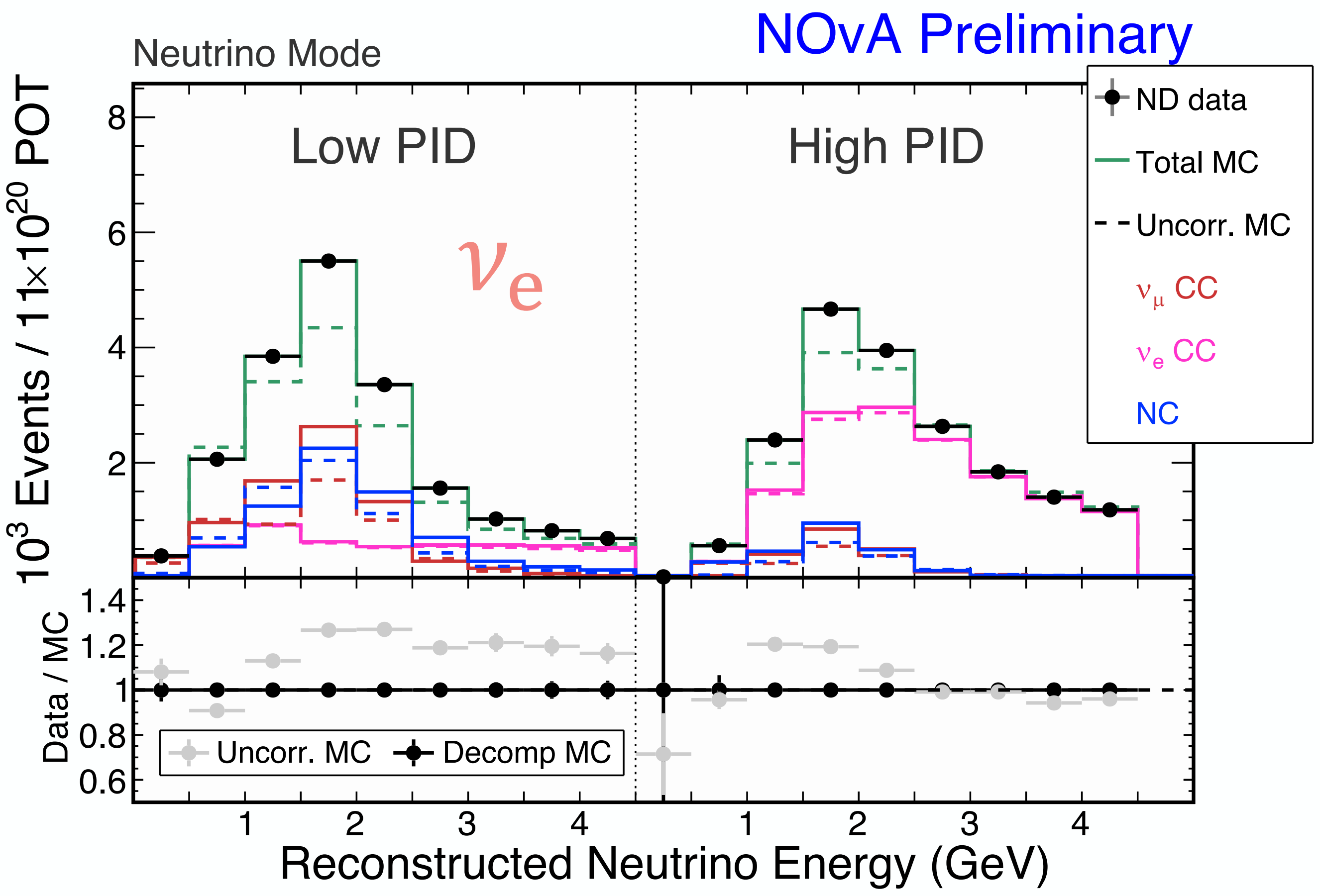
Estimating the neutrino energy





Constraints using ND data



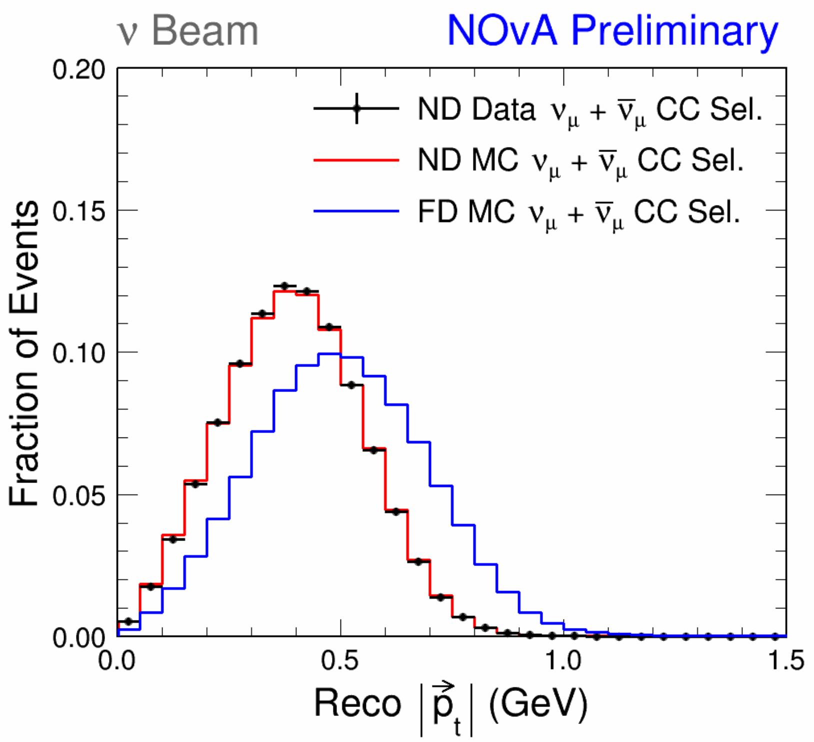


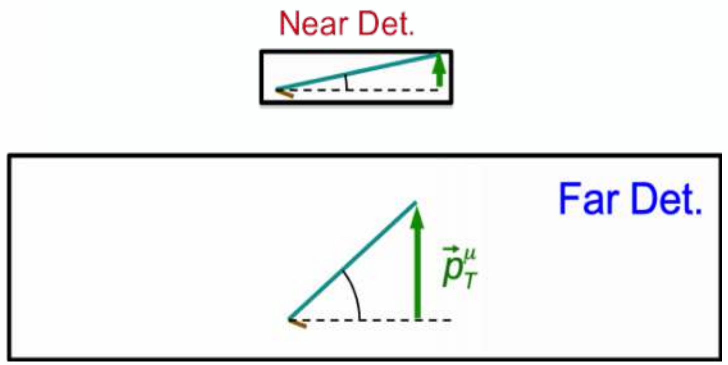
ND ν_μ-like samples are used to correct the FD $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ **signal** predictions

ND ν_e-like samples are used to correct the FD $\boldsymbol{\nu_e}$ **background** predictions

Constraints using ND data

- Choice of binning / subsamples → additional power to control systematic uncertainties
- **p_T binning (lepton transverse momentum)**
  - "Rebalance" ND/FD kinematics





- ν_μ binning optimized to see the "dip" in the energy spectrum
- ν_e binning optimized to separate signal/background

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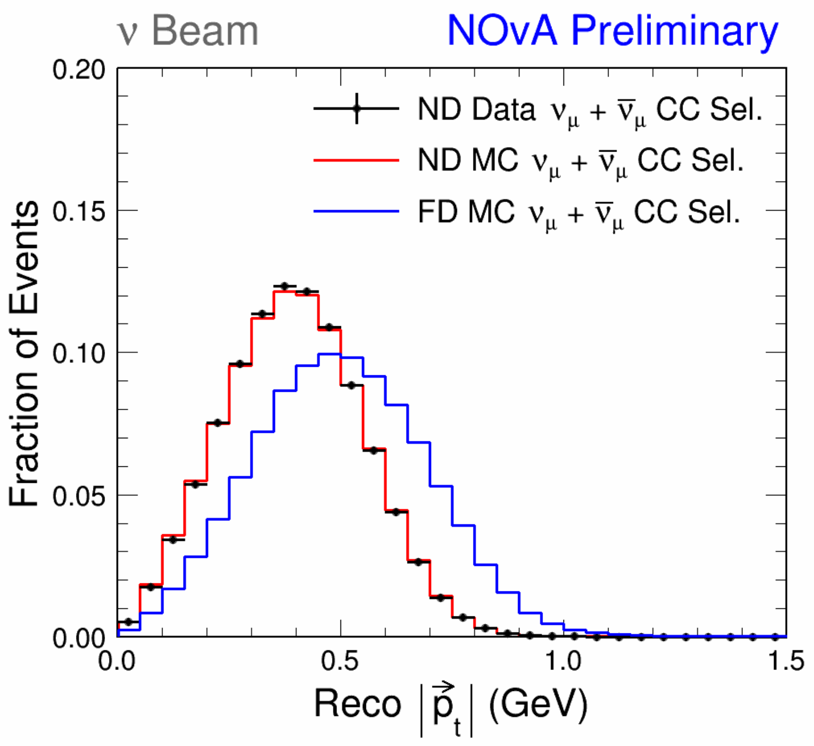

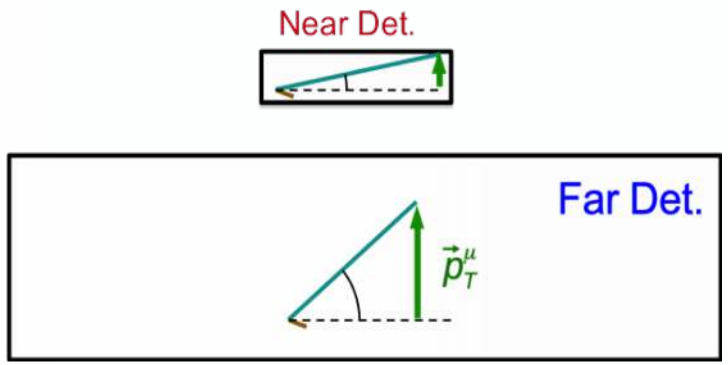

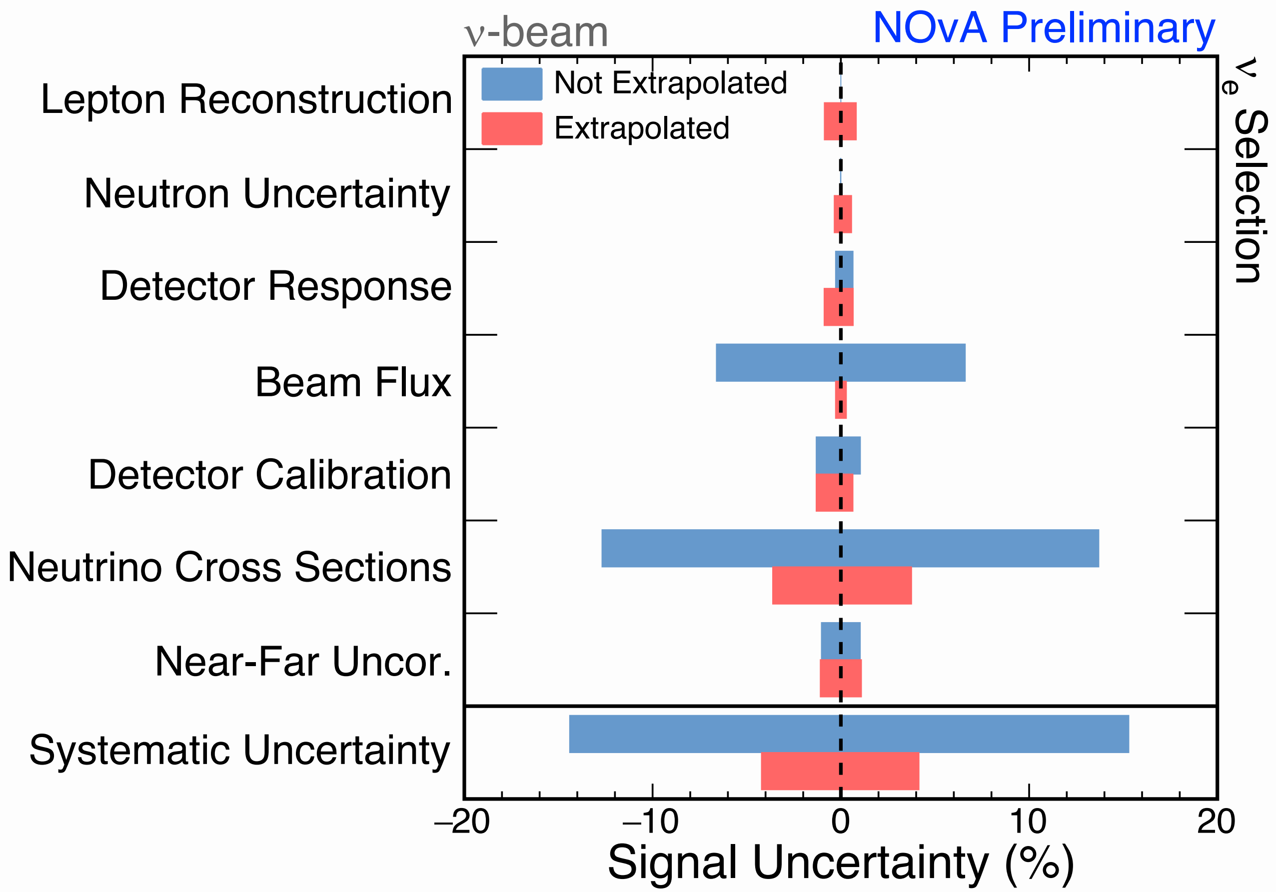

ND constraints reduce systematic uncertainties in the FD prediction from >15% to 4-5%

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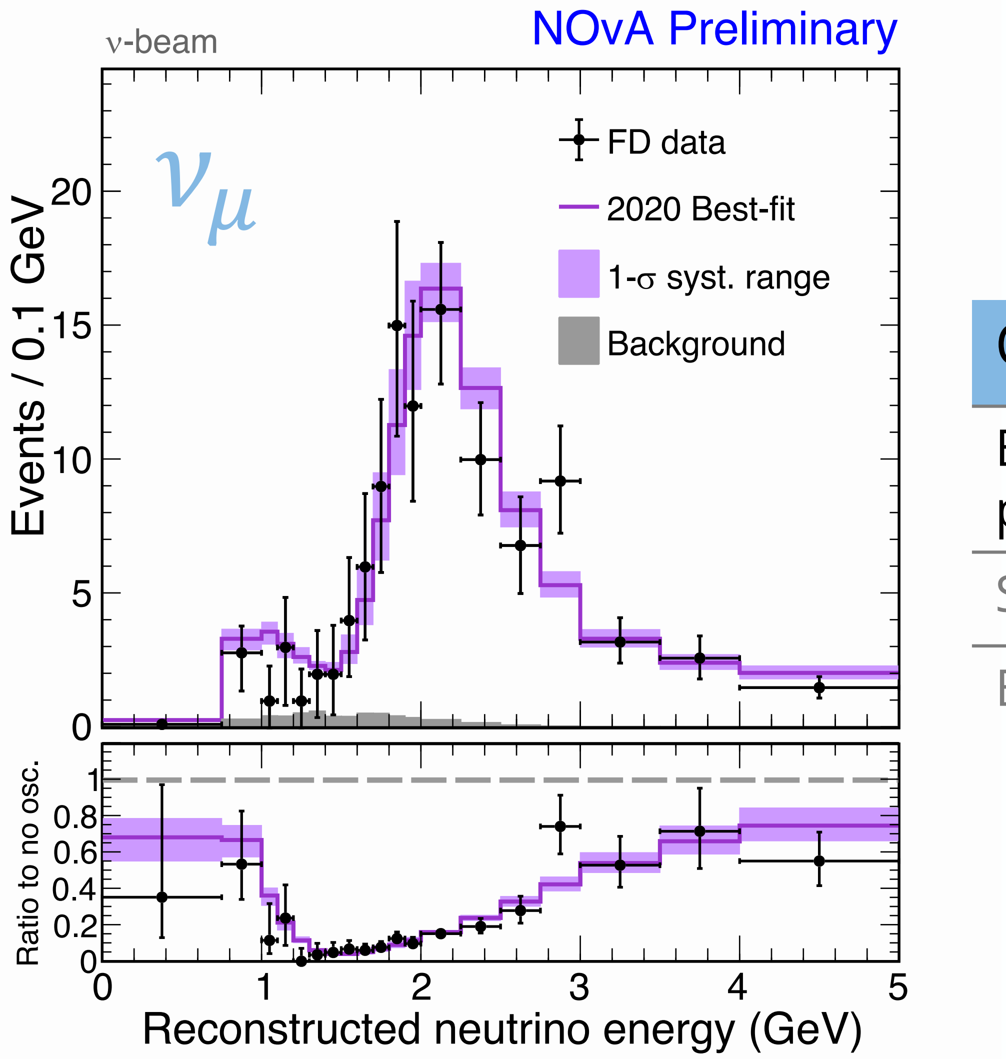
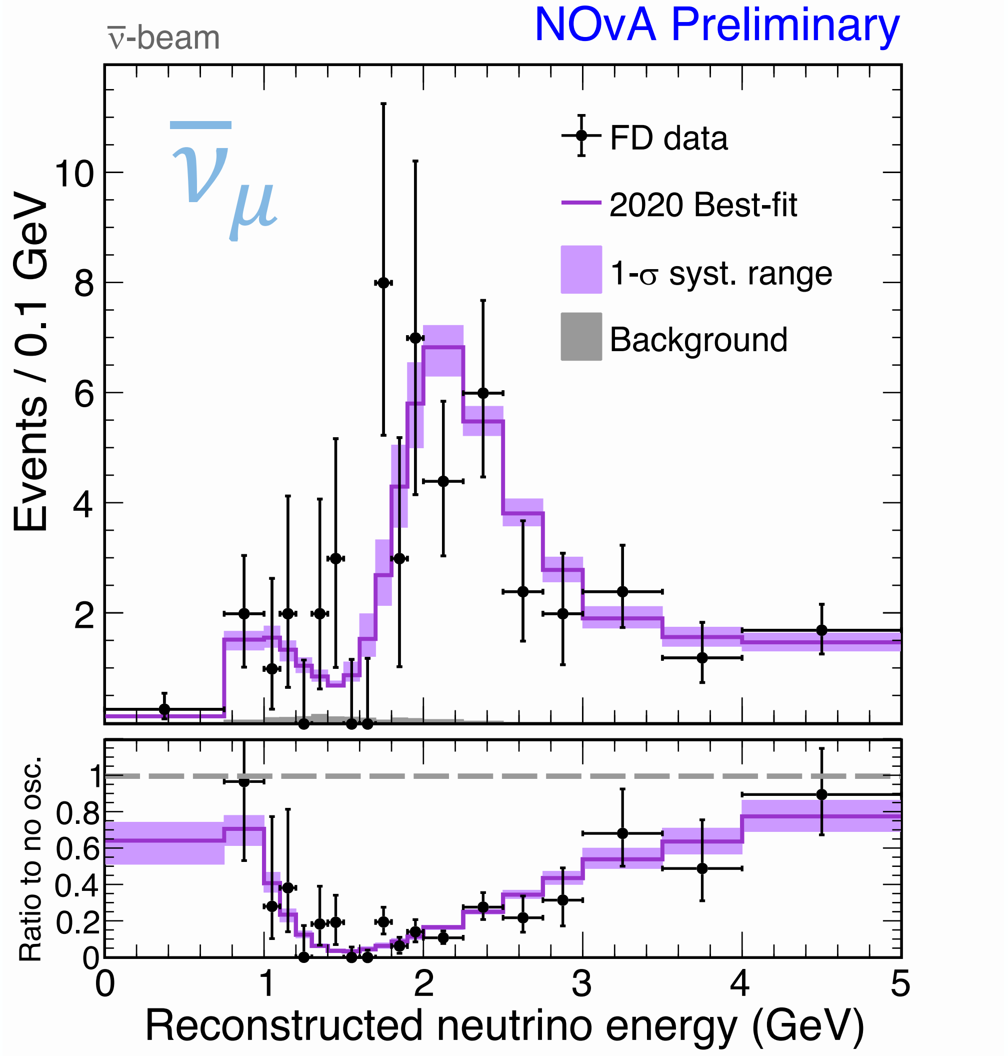
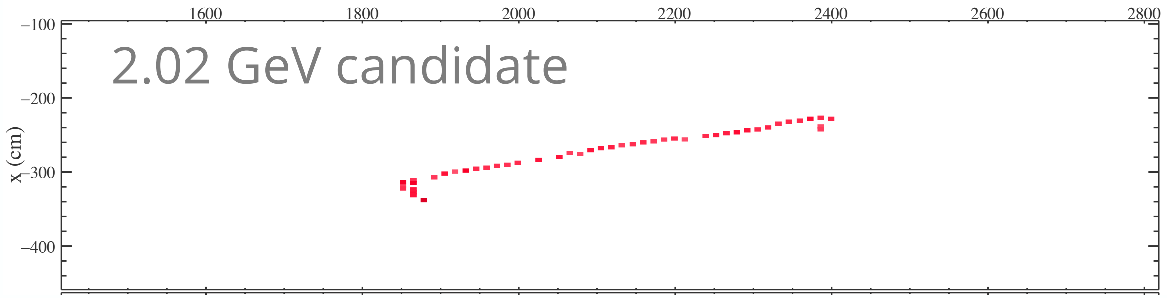
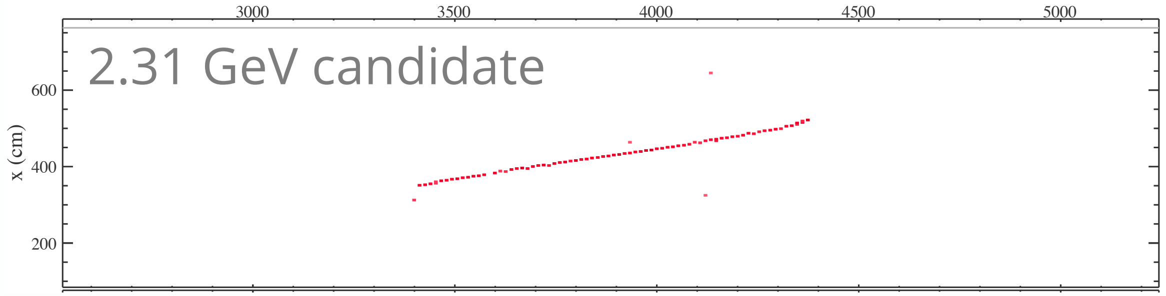
ν_μ and $\bar{\nu}_\mu$ data at the Far Detector



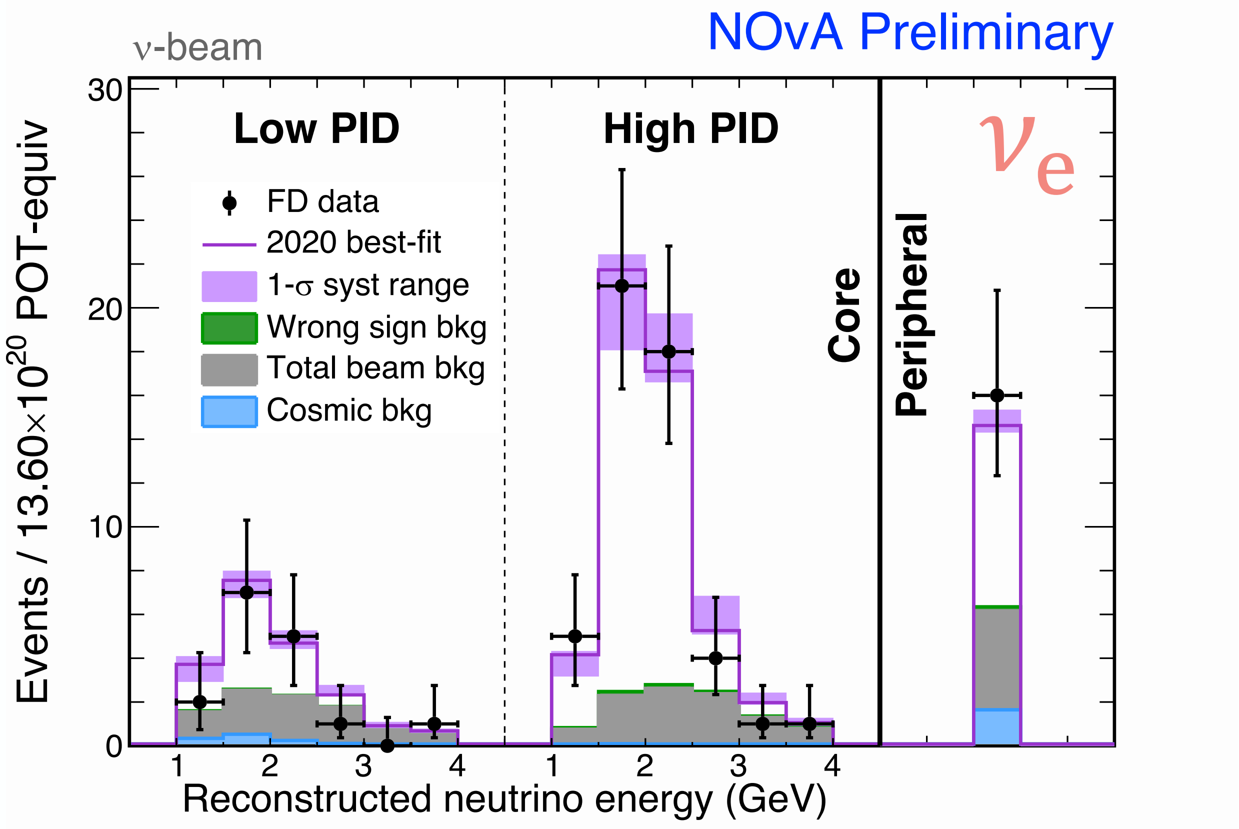
Observed	211 ν_μ	105 $\bar{\nu}_\mu$
Best fit pred.	222.3	105.4
Signal	$214.1^{+14.4}_{-14.0}$	$103.4^{+7.1}_{-7.0}$
Background	$8.2^{+1.9}_{-1.7}$	$2.1^{+0.7}_{-0.7}$

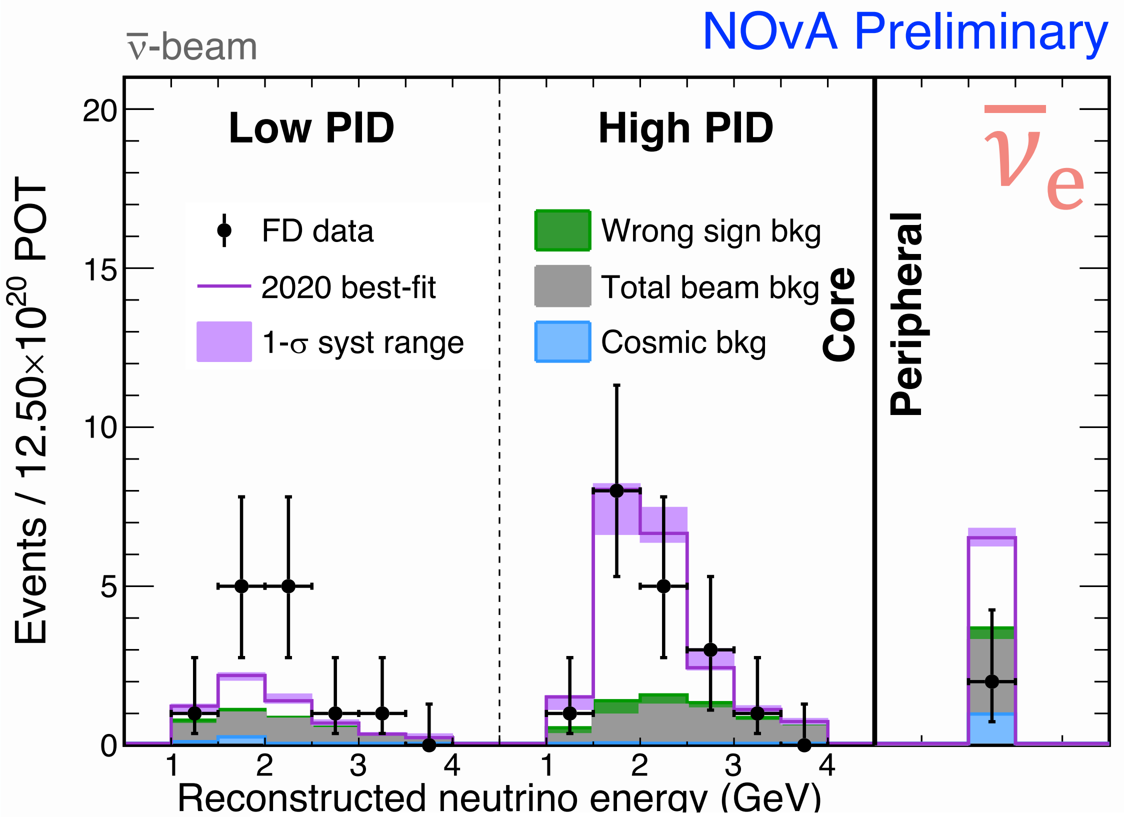


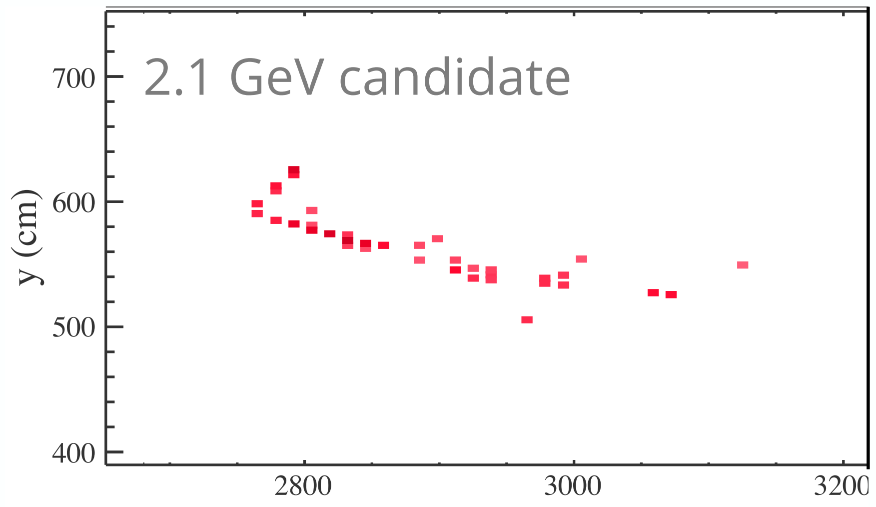




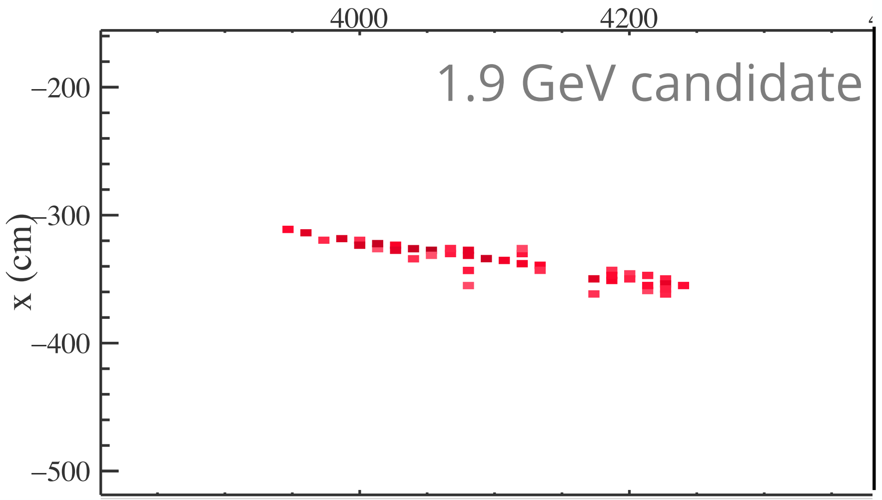
ν_e and $\bar{\nu}_e$ data at the Far Detector







Observed	82 ν_e	33 $\bar{\nu}_e$
Best fit prediction	85.8	33.2
Signal	$59.0^{+2.5}_{-2.5}$	$19.2^{+0.6}_{-0.7}$
Background	$26.8^{+1.6}_{-1.7}$	$14.0^{+0.9}_{-1.0}$

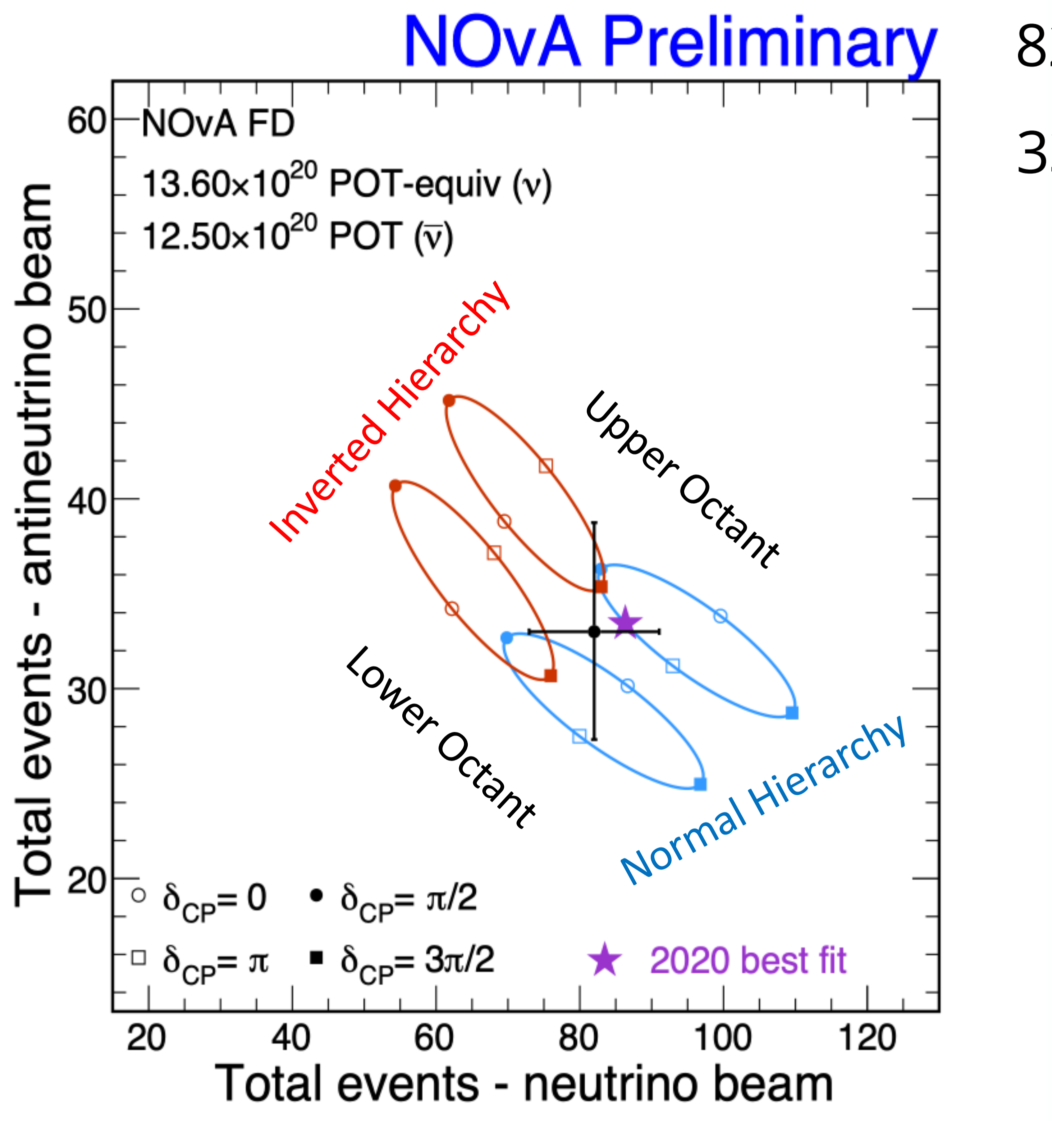


Results: ν_e/ $\overline{\nu}_e$ appearance + δ_{CP}

82 candidates (27 bkgd.) → $\boldsymbol{\nu_e}$ appearance ✓

33 candidates (14 bkgd.) → $\boldsymbol{\overline{\nu}_e}$ appearance ✓

Results: $\nu_e / \bar{\nu}_e$ appearance + δ_{CP}



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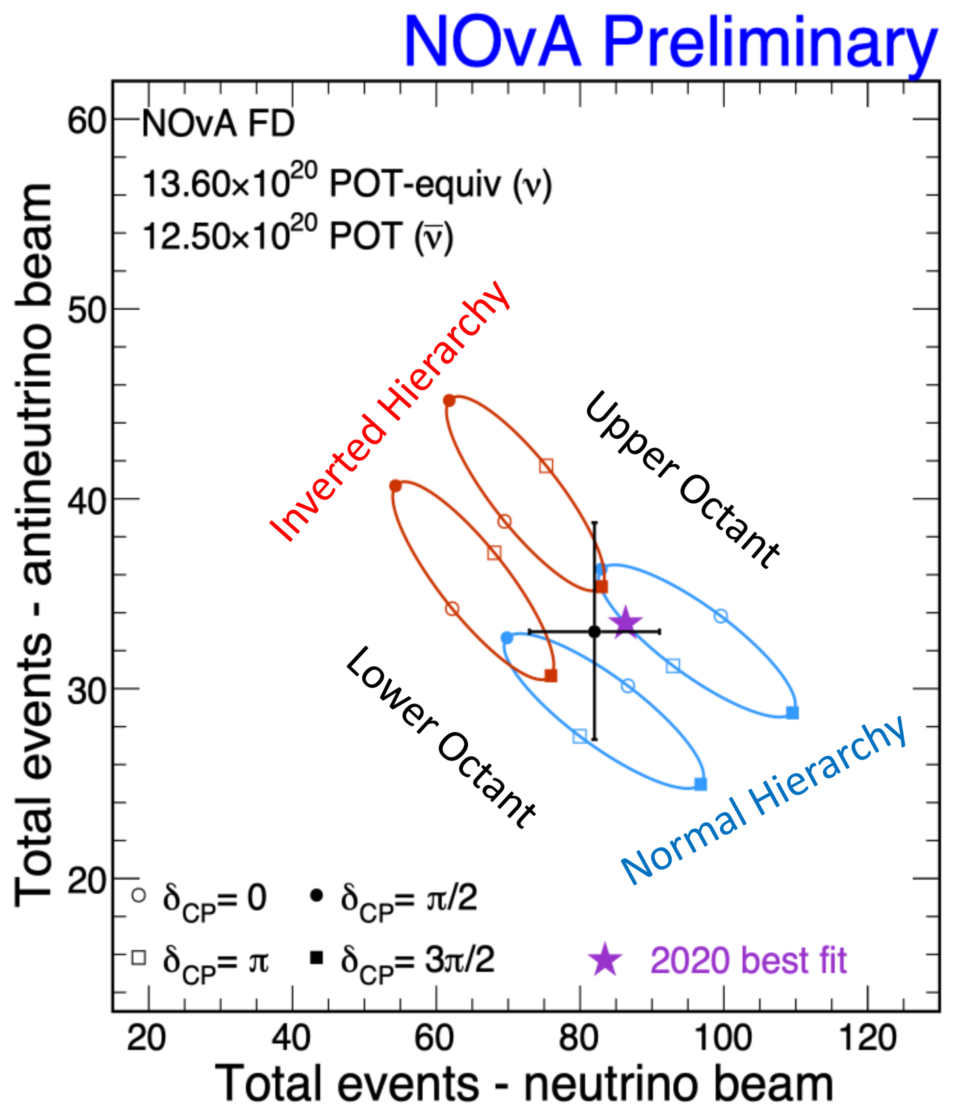


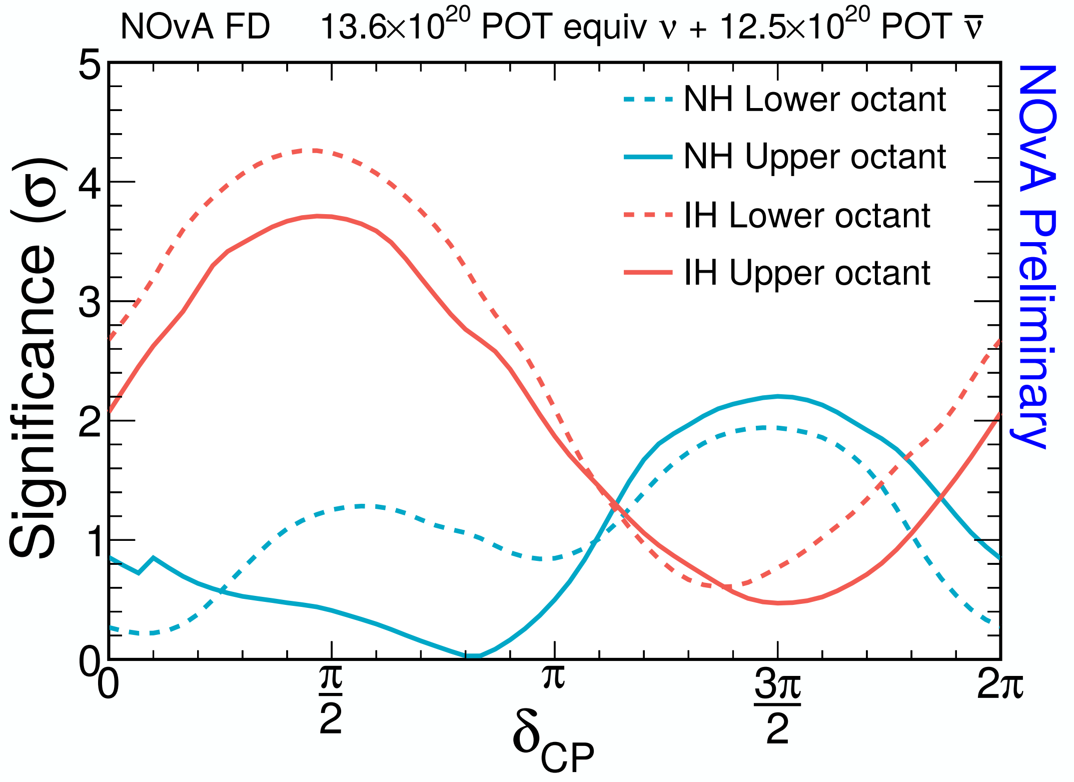
82 candidates (27 bkgd.) → $\boldsymbol{\nu_e}$ appearance ✓

33 candidates (14 bkgd.) → $\boldsymbol{\bar{\nu}_e}$ appearance ✓

We don't see a strong asymmetry between $\boldsymbol{\nu_e}$ and $\boldsymbol{\bar{\nu}_e}$ appearance rates

→Exclude IH $\delta = \pi/2$ at $>3\sigma$

→Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$



Results: Δm^2_{32} and $\sin^2\theta_{23}$

- Best fit:

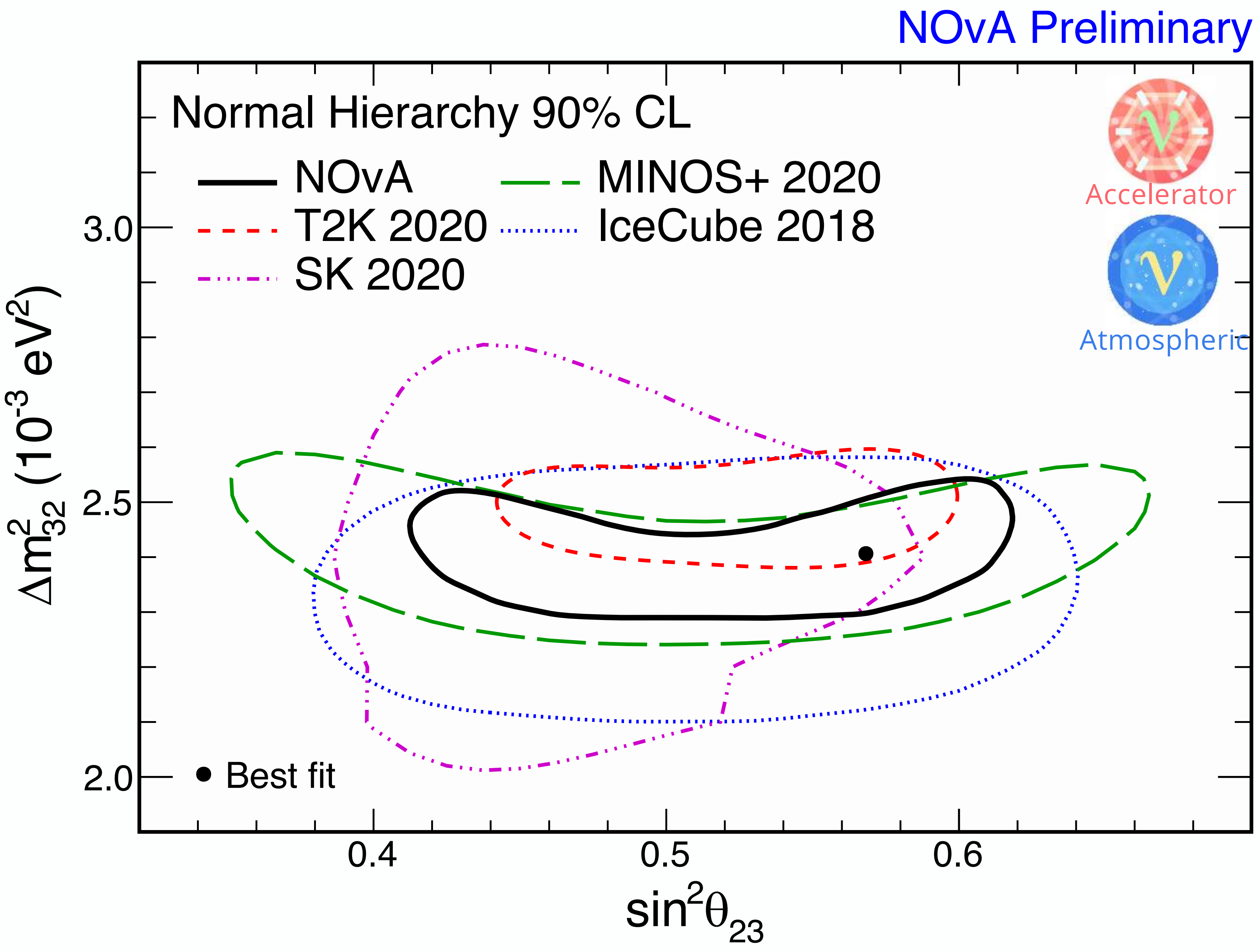
  Normal hierarchy

  Δm^2_{32} = (2.41±0.07)×10^{-3} eV^2

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

  δ_{CP} =0.82π

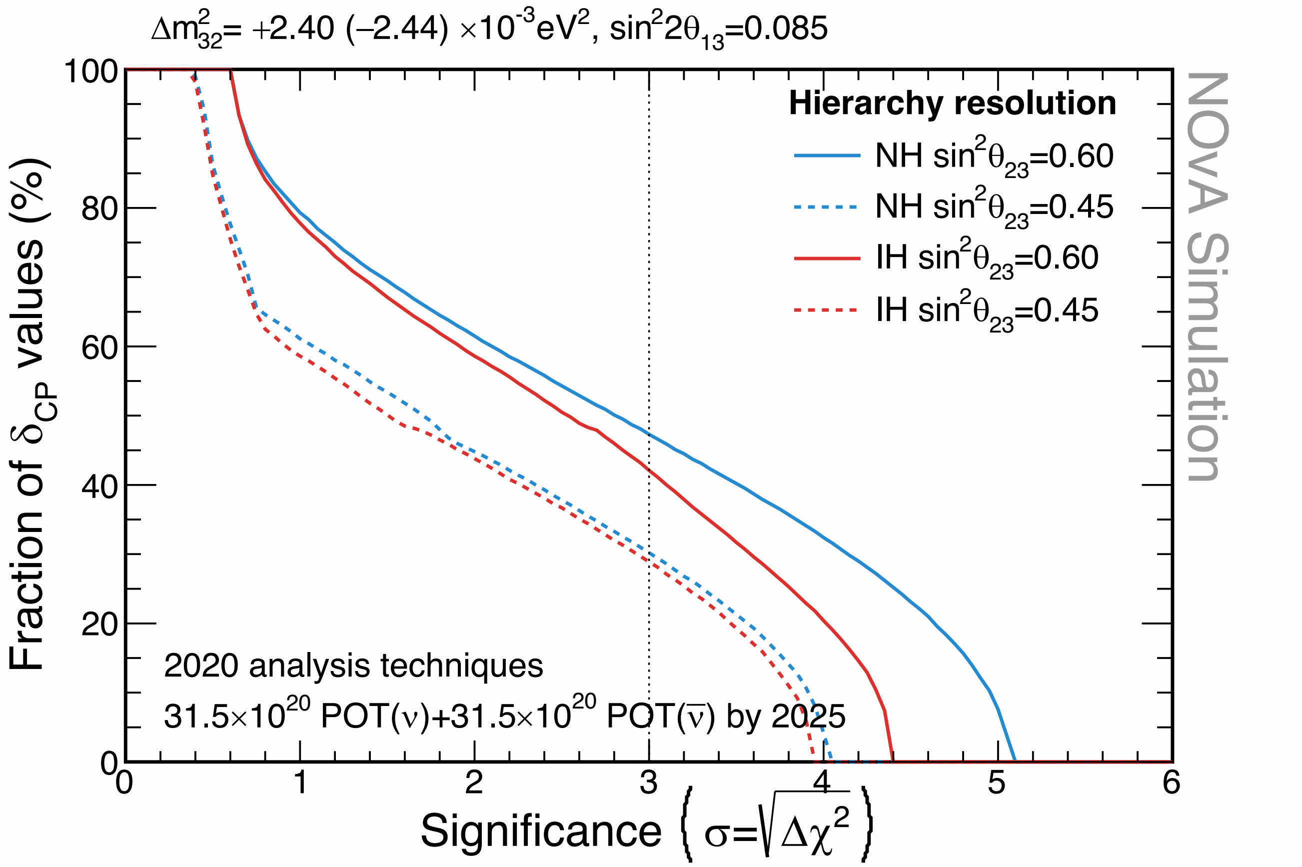
- Precision measurements of Δm^2_{32}(3%) and $\sin^2\theta_{23}$(6%)



NOvA: Future 3-flavor measurements

NOvA is expected to take data through 2026, for a projected total of 60-70 ×10^{20} POT

- We're half way there!
- Expect increasingly precise measurements of Δm^2_{32} and $\sin^2\theta_{23}$.
- We can reach **3σ hierarchy sensitivity** for 30-50% of δ values, and **~5σ** in the most favorable case.
- We can also reach a **~2σ** determination of CP violation.



NOvA: Future 3-flavor measurements

NOvA is expected to take data through 2026, for a projected total of 60-70 ×10²⁰ POT

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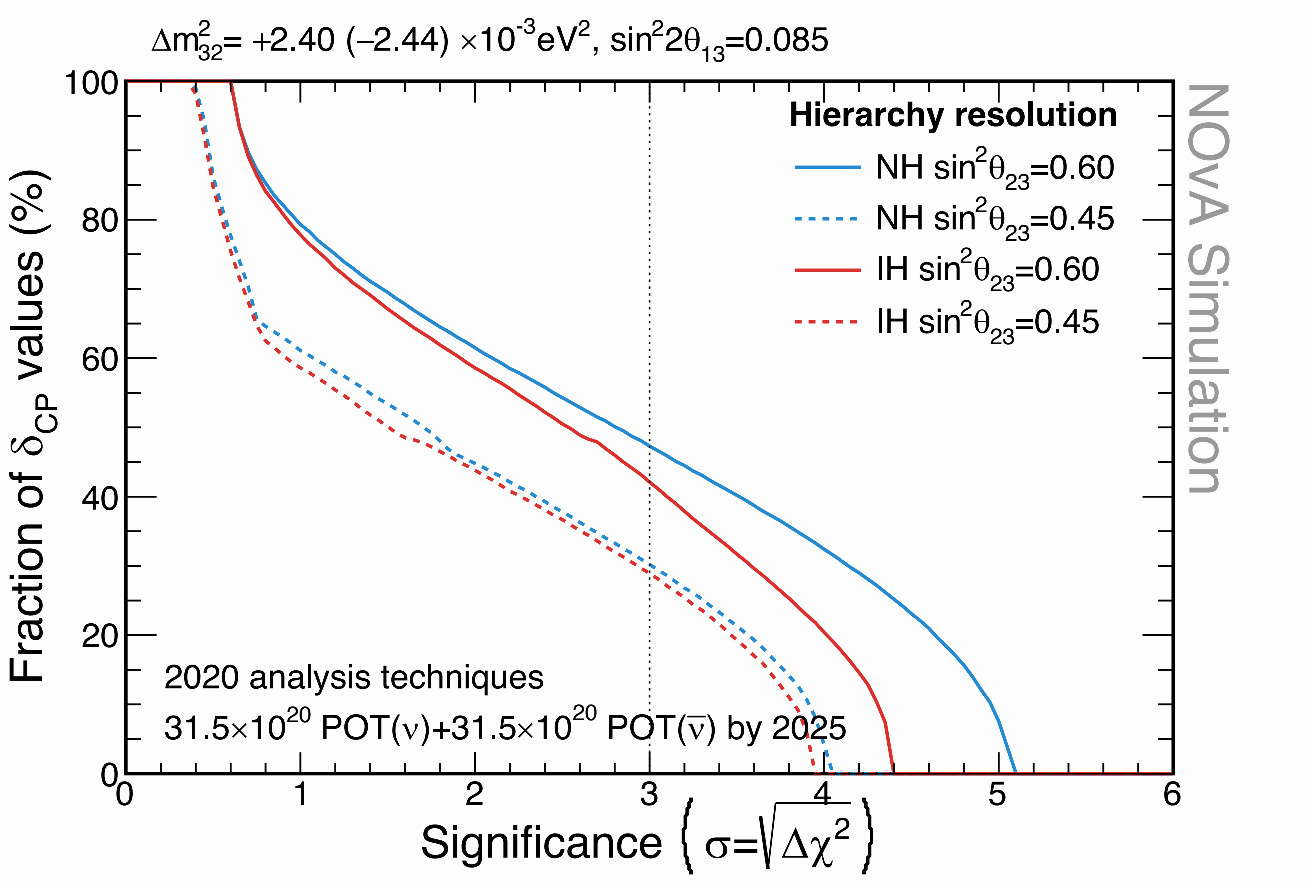
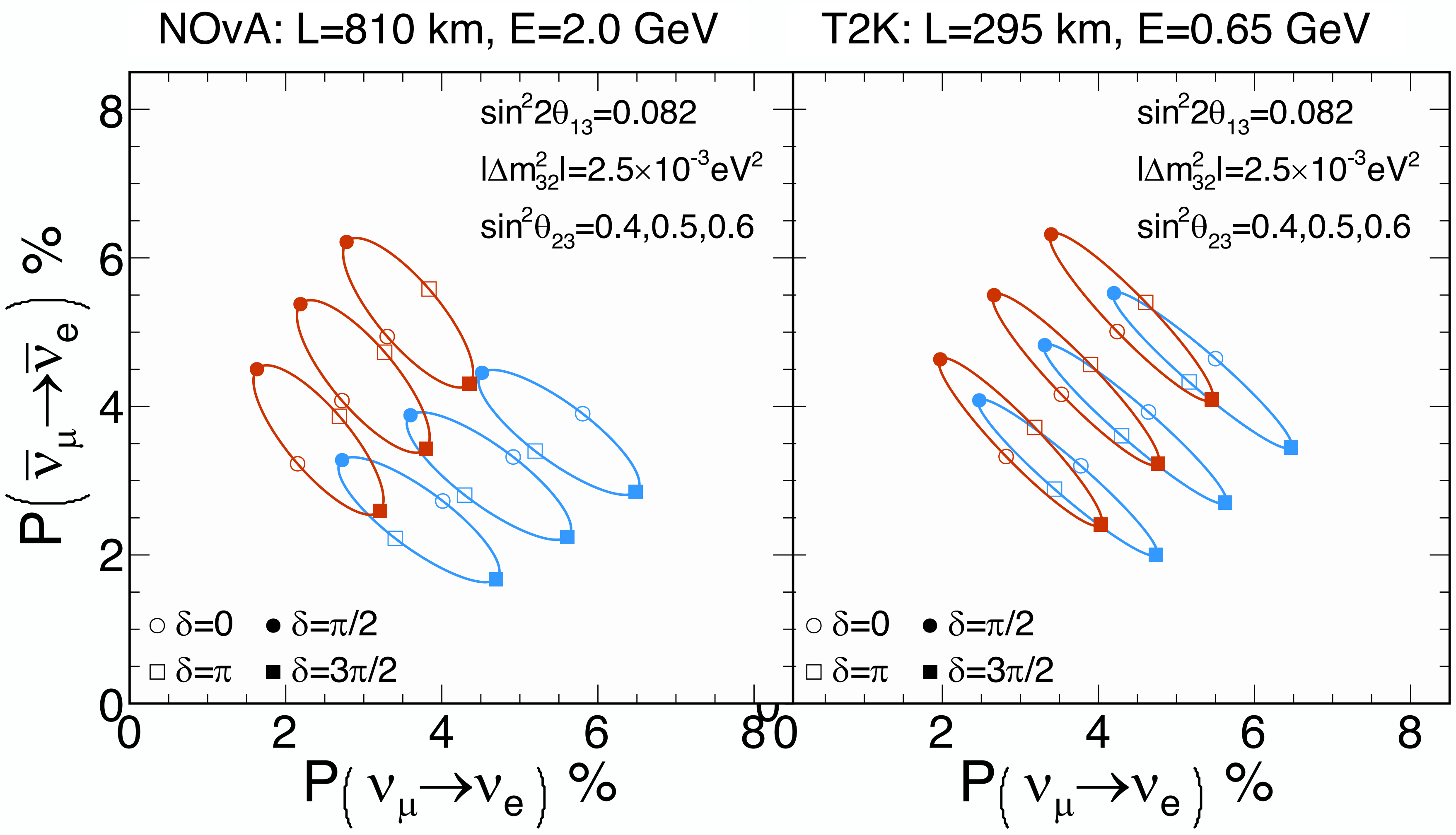


NOvA Test-Beam

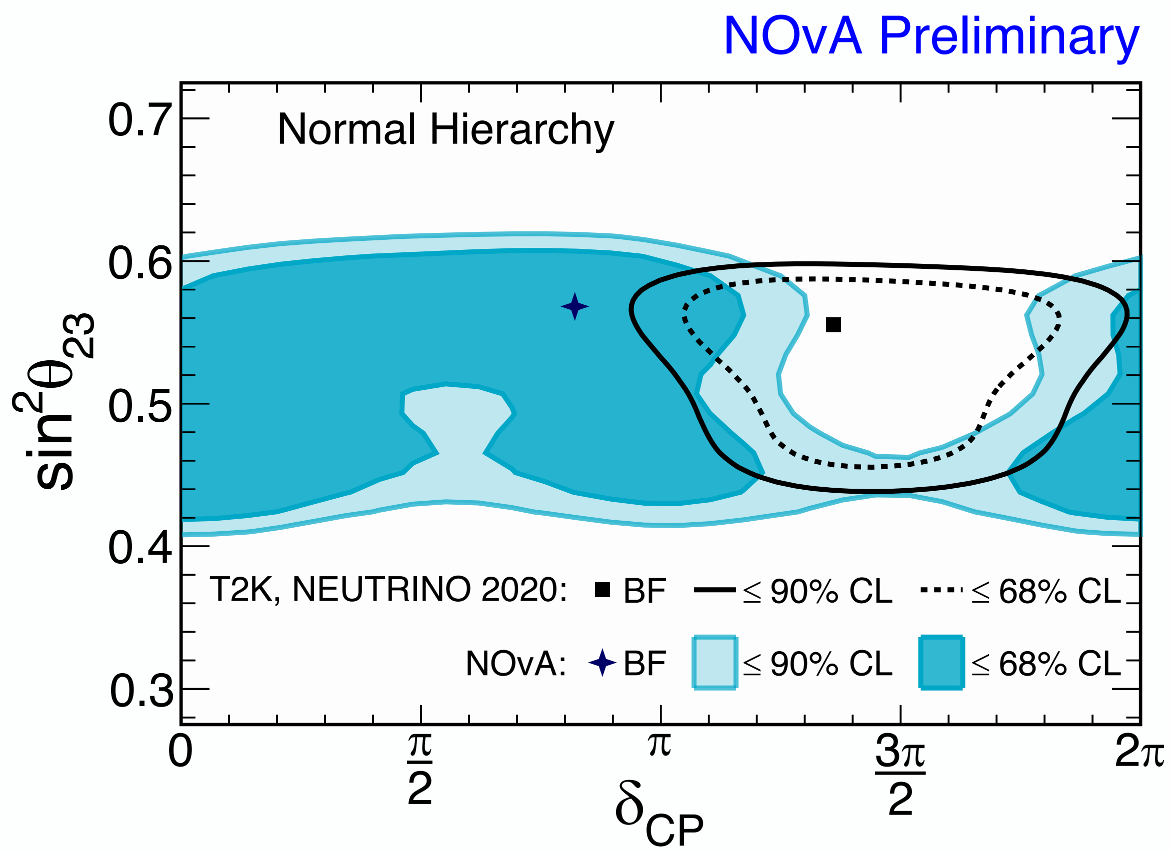
- A scaled- down 30-ton NOvA detector
- Deployed at the Fermilab Test Beam Facility
- Results could address some of the largest systematic uncertainties in NOvA

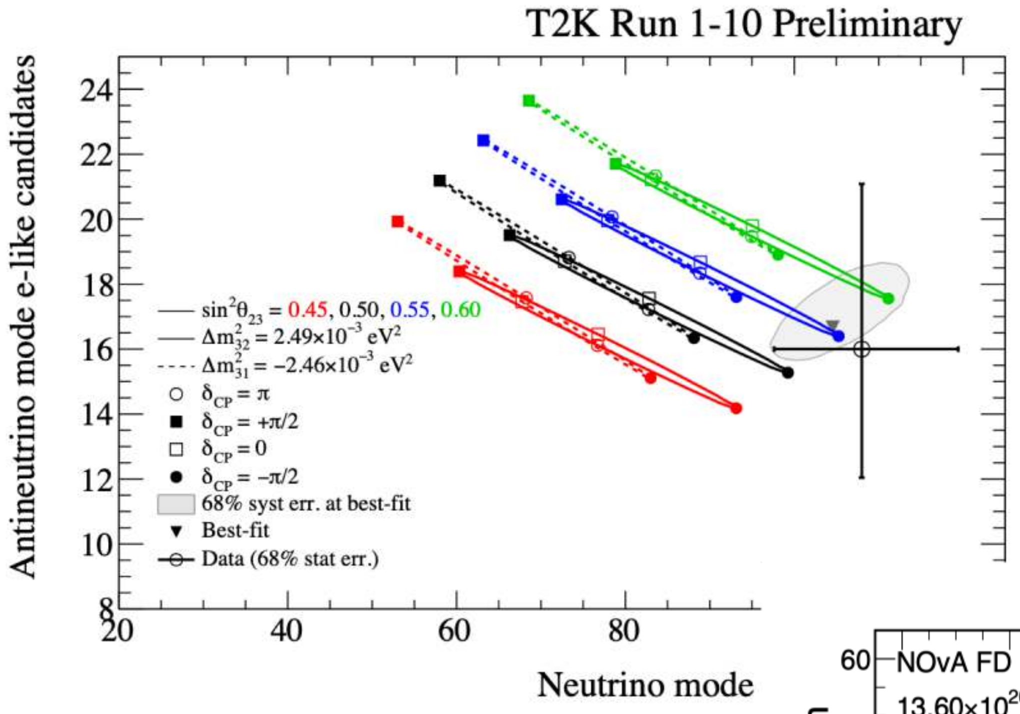
NOvA + T2K

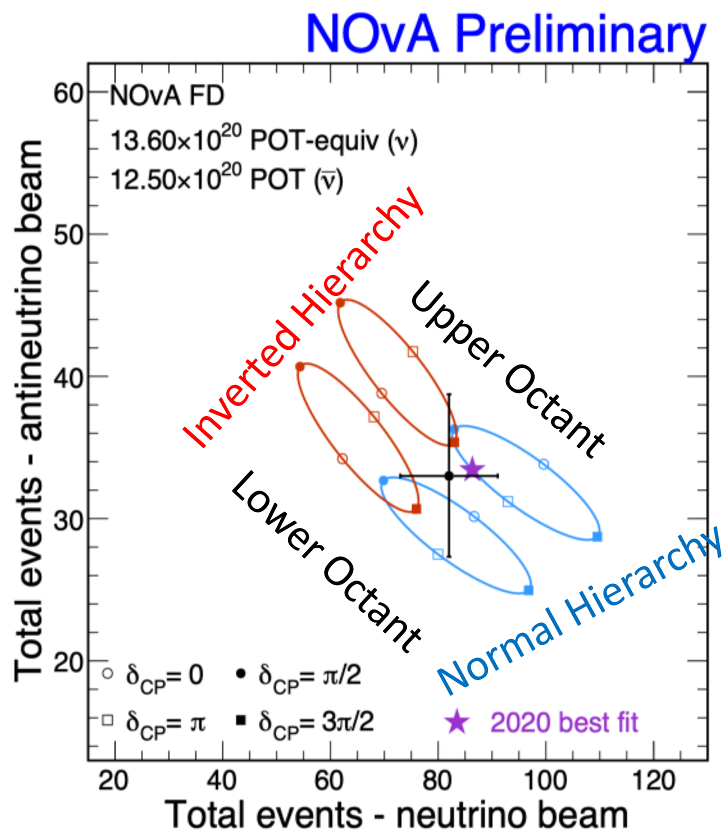


- A joint analysis of NOvA and T2K data is underway!
- Different neutrino energies, different baselines, different systematic uncertainties
- Combined analysis allows degeneracies to be broken and maximizes impact of data taken

NOvA + T2K







- Current results show some tension:
  - NOvA does not see strong neutrino/antineutrino asymmetry in electron neutrino appearance
  - T2K observes more electron neutrino appearance than electron antineutrino appearance
- Quantifying consistency requires a joint fit of the data from the two experiments

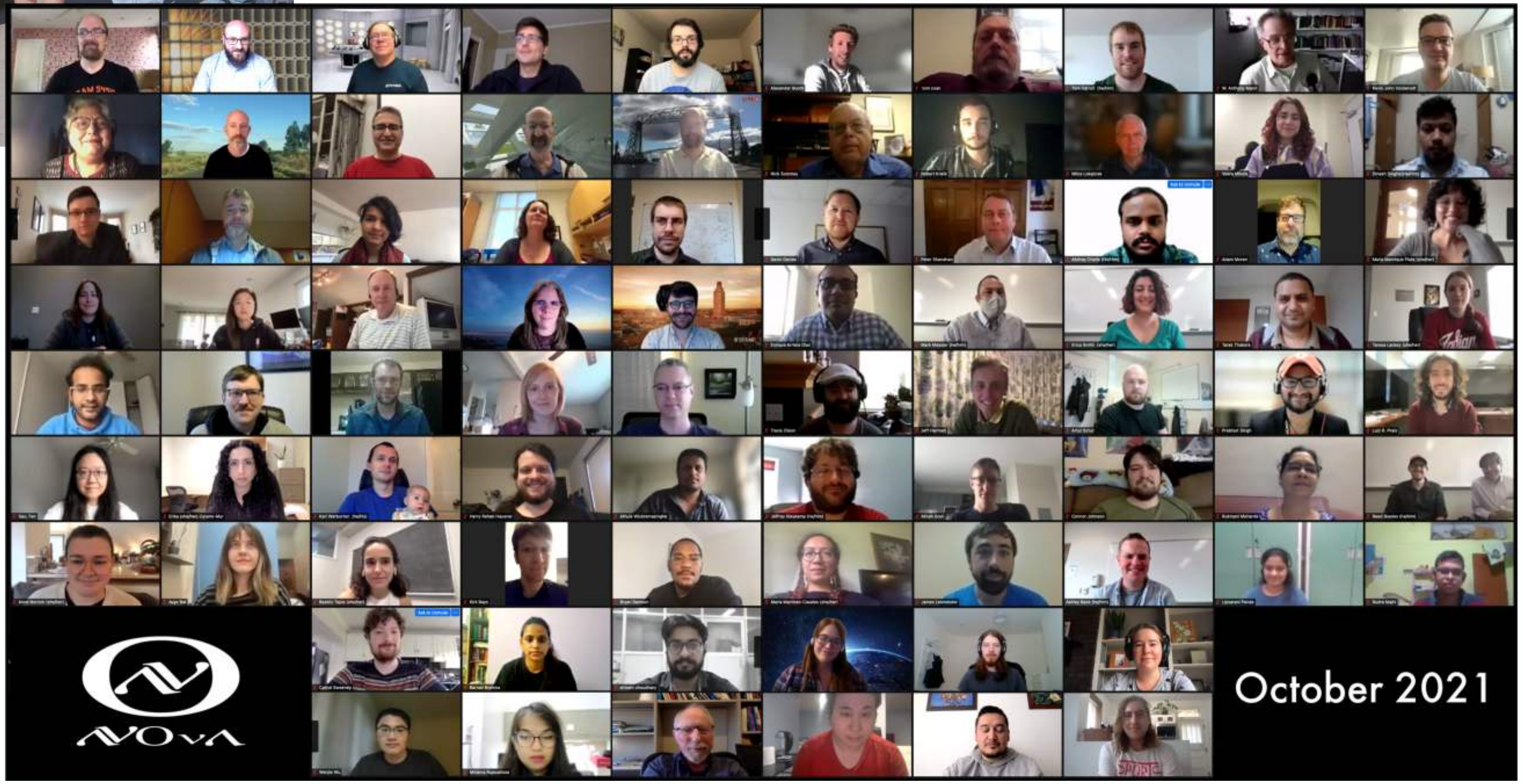
Summary

- NOvA's primary goal is the study of **3-flavor neutrino oscillations**, via measurements of muon (anti)neutrino disappearance and electron (anti)neutrino appearance
- NOvA's most recent oscillation analysis results:
  - **Precision measurements of Δm^2_{32} (3%) and $\sin^2 \theta_{23}$ (6%)**
  - **No strong asymmetry between ν_e and $\overline{\nu}_e$ appearance rates**
  - The data analyzed so far corresponds to ~half of the total expected.
- Coming soon:
  - NOvA Bayesian analysis
  - NOvA+T2K combined analysis
  - Analysis upgrades + new results (2023-24)
  - Cross sections, sterile searches, cosmic ray physics, exotics...

Thank you!

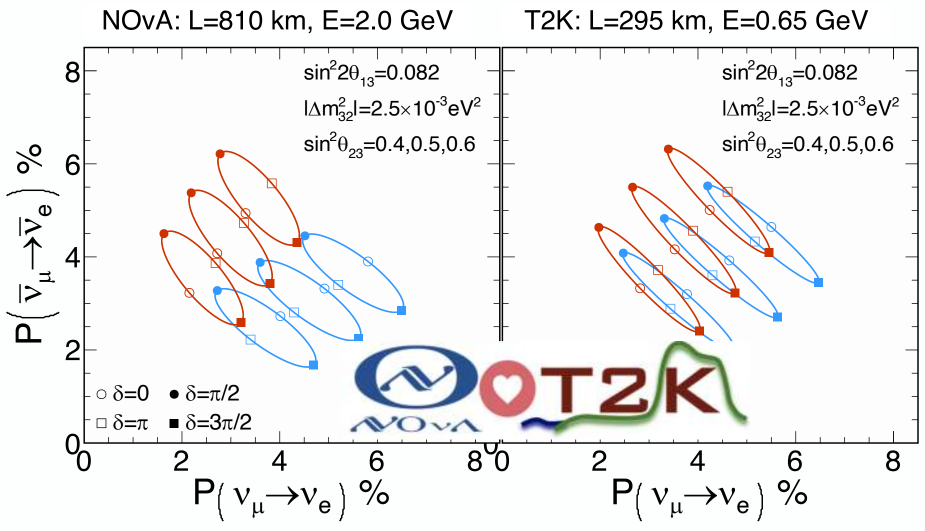
The NOvA Collaboration

https://novaexperiment.fnal.gov/

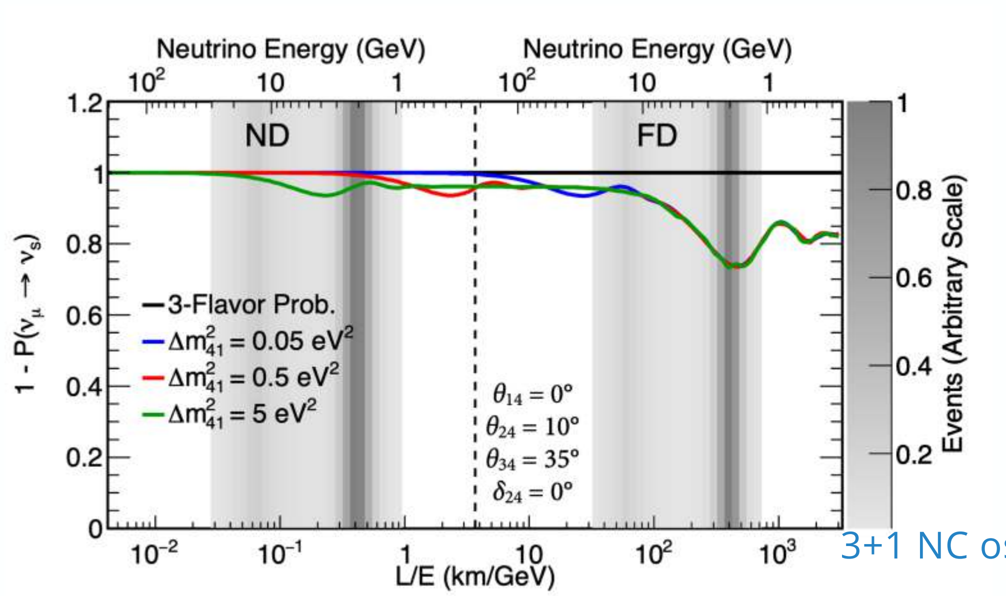


NOvA: a rich physics program!

NOvA + T2K joint analysis

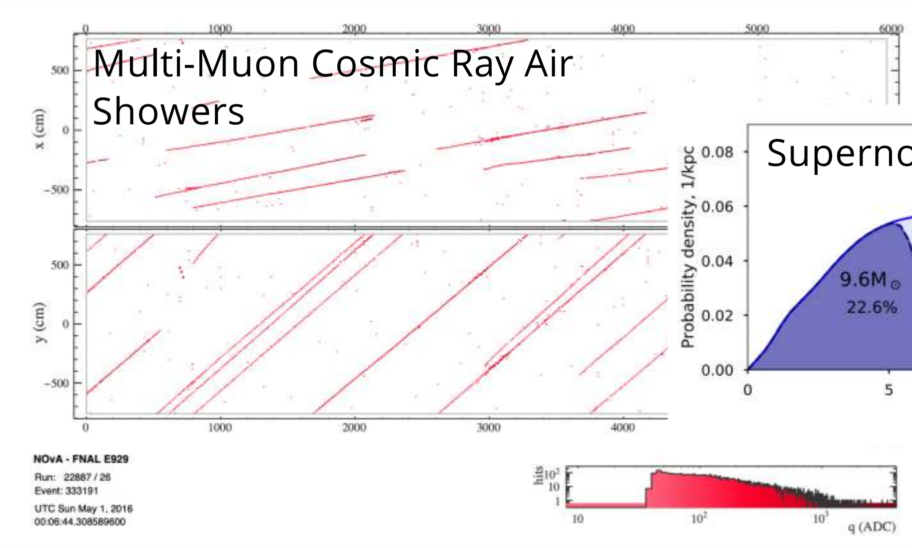


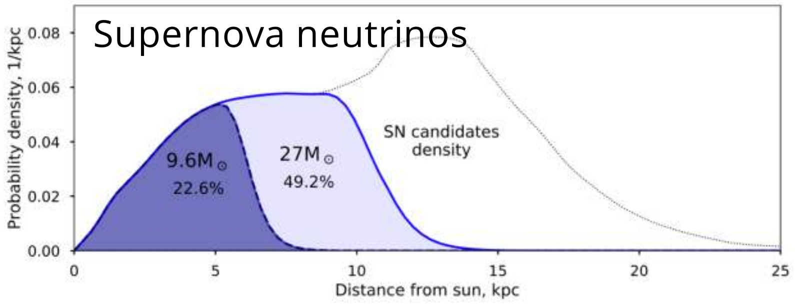
Sterile neutrino searches



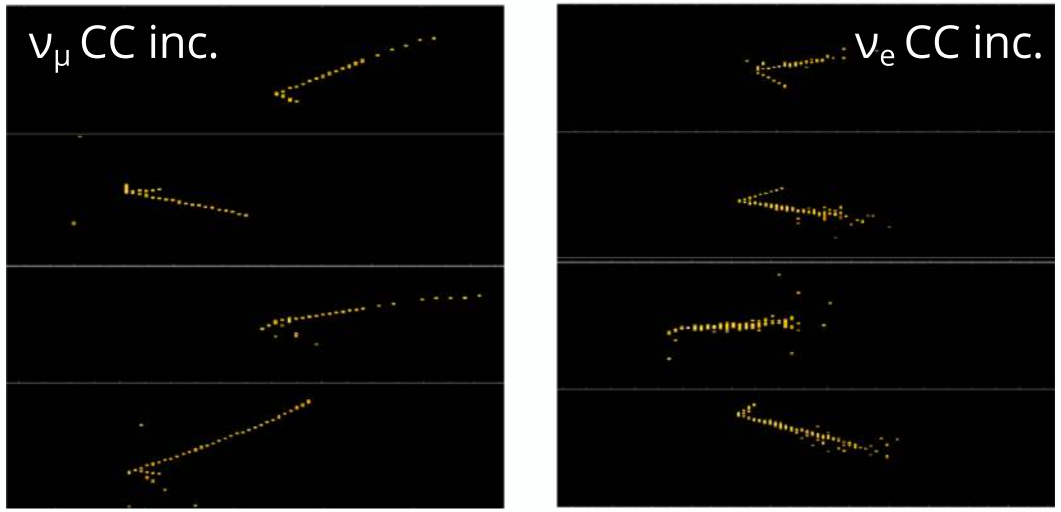
3+1 NC oscillations

Cosmic ray physics and exotics



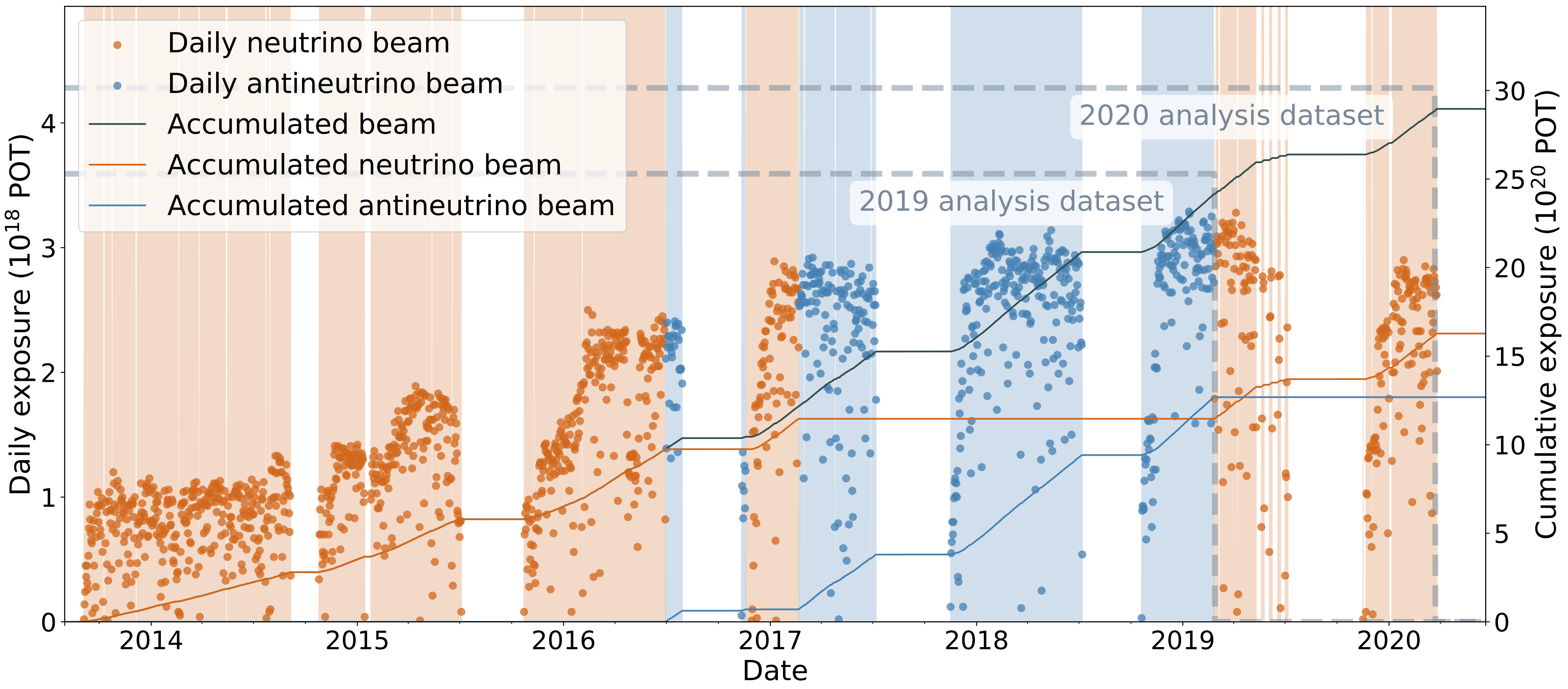


Cross-section measurements



Learn more: NOvA publications. Snowmass LOI: NOvA+T2K, Steriles , Exotics, Cross-sections

The NuMI beam dataset



The following analysis uses:

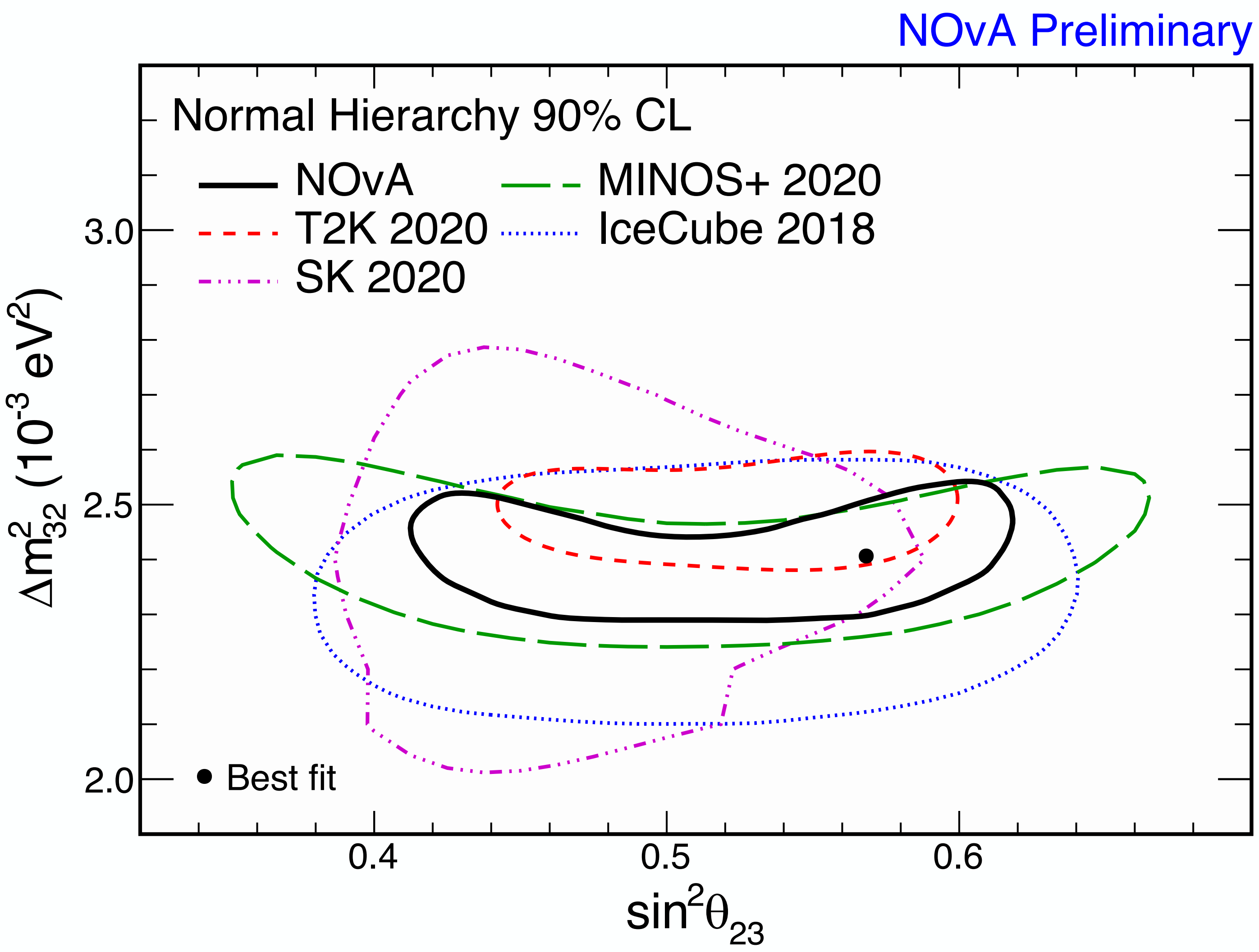
13.6×10^{20} POT neutrino + 12.5×10^{20} POT antineutrino beam mode

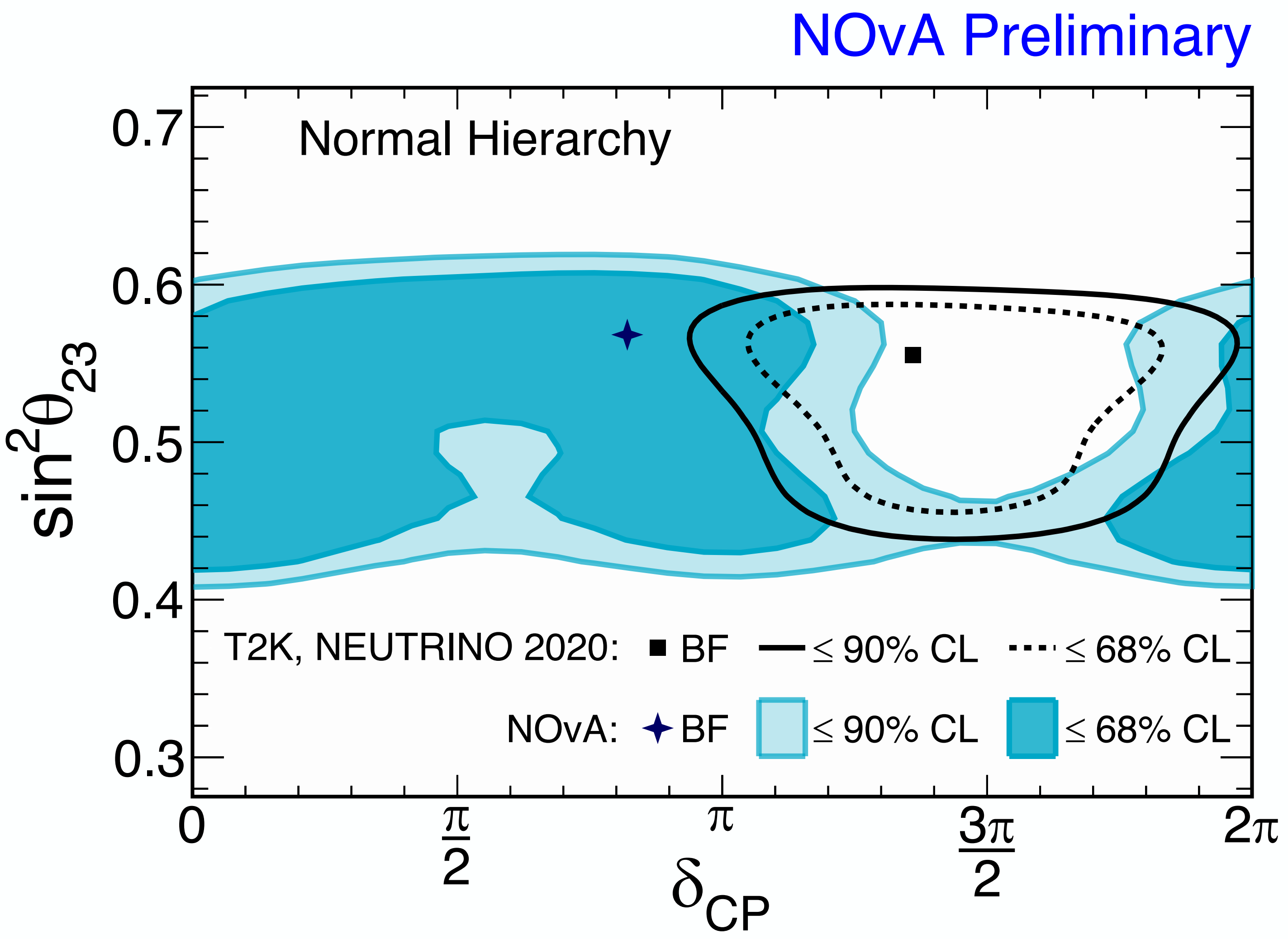
(2014-2020)

Most intense accelerator neutrino beam in the world

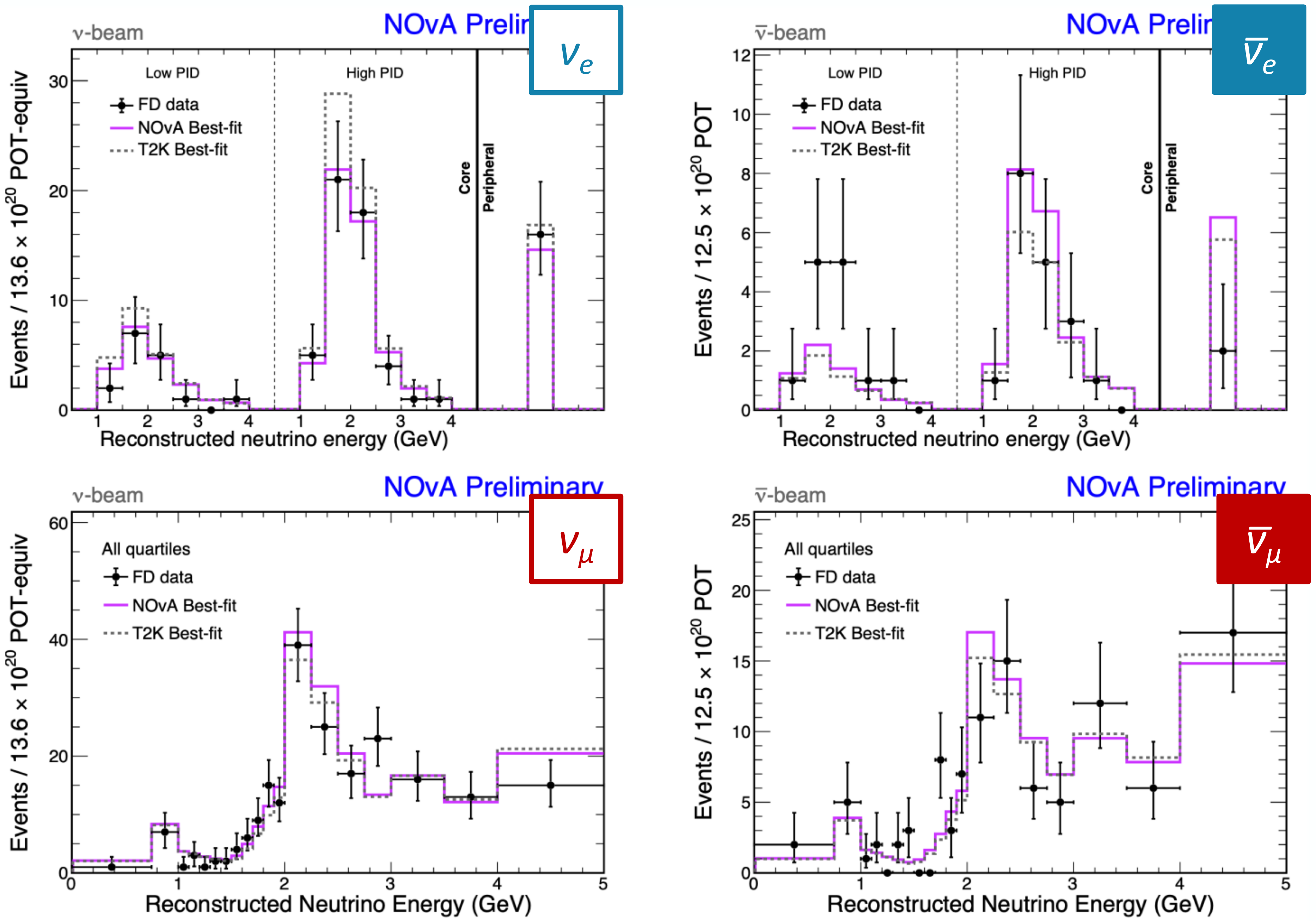
- Achieved MI Beam Power Hour Average record: 843 kW on June 2021
- NuMI Target System upgraded for Megawatt Beam Operation

NOvA – T2K

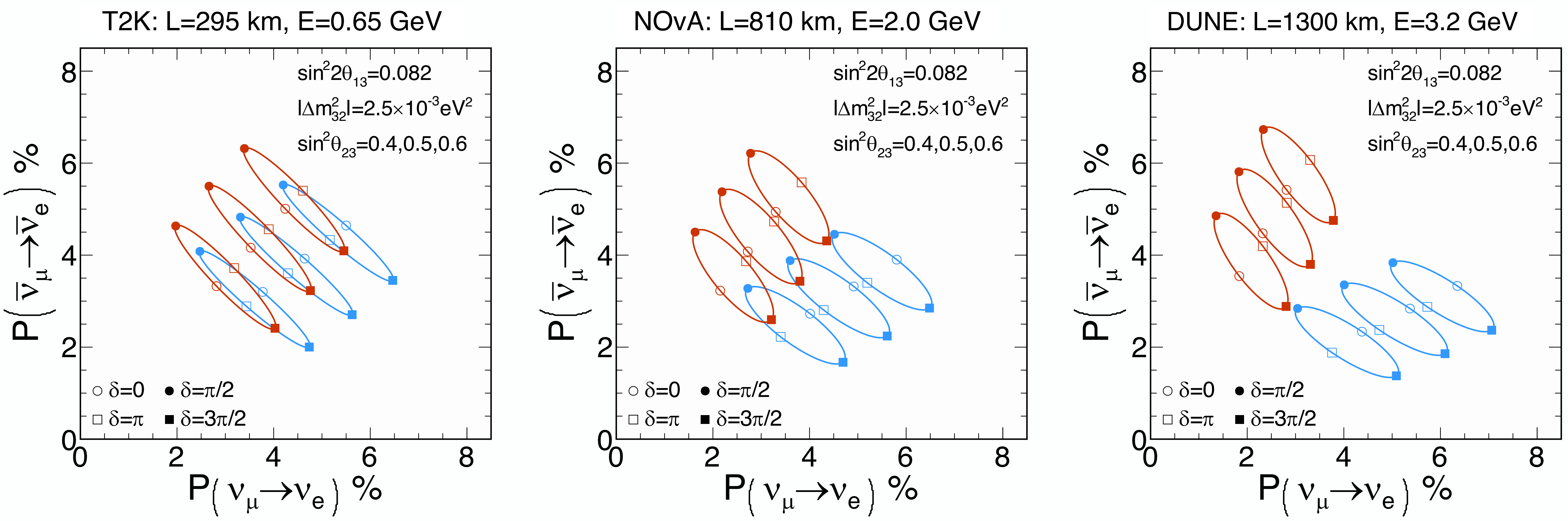

NOvA Preliminary
Normal Hierarchy 90% CL
NOvA
MINOS+ 2020
T2K 2020
IceCube 2018
SK 2020
Best fit
3.0
2.5
2.0
0.4
0.5
0.6
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$


NOvA Preliminary
Normal Hierarchy
0.7
0.6
0.5
0.4
0.3
$\sin^2\theta_{23}$
T2K, NEUTRINO 2020: BF ≤ 90% CL ≤ 68% CL
NOvA: BF ≤ 90% CL ≤ 68% CL
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
δ_{CP}

Spectra with NOvA and T2K Best Fits

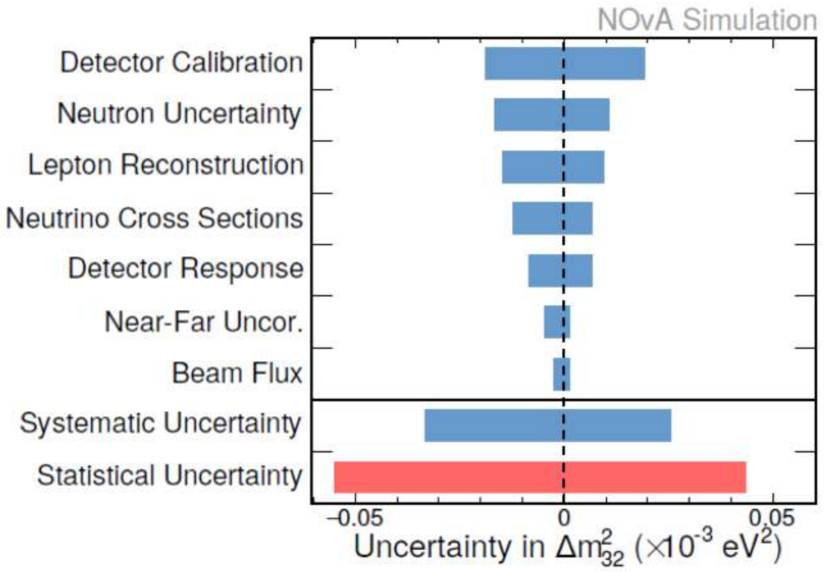


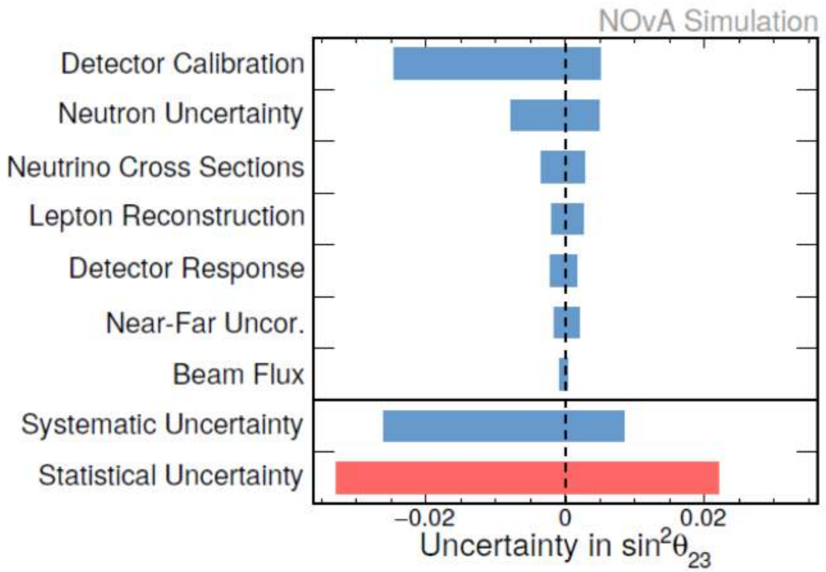
Comparing long baseline experiments

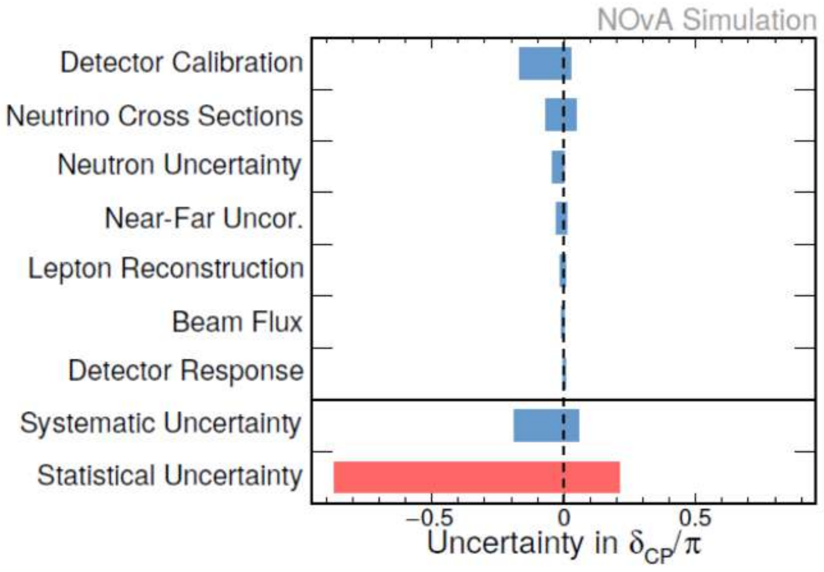


Systematics

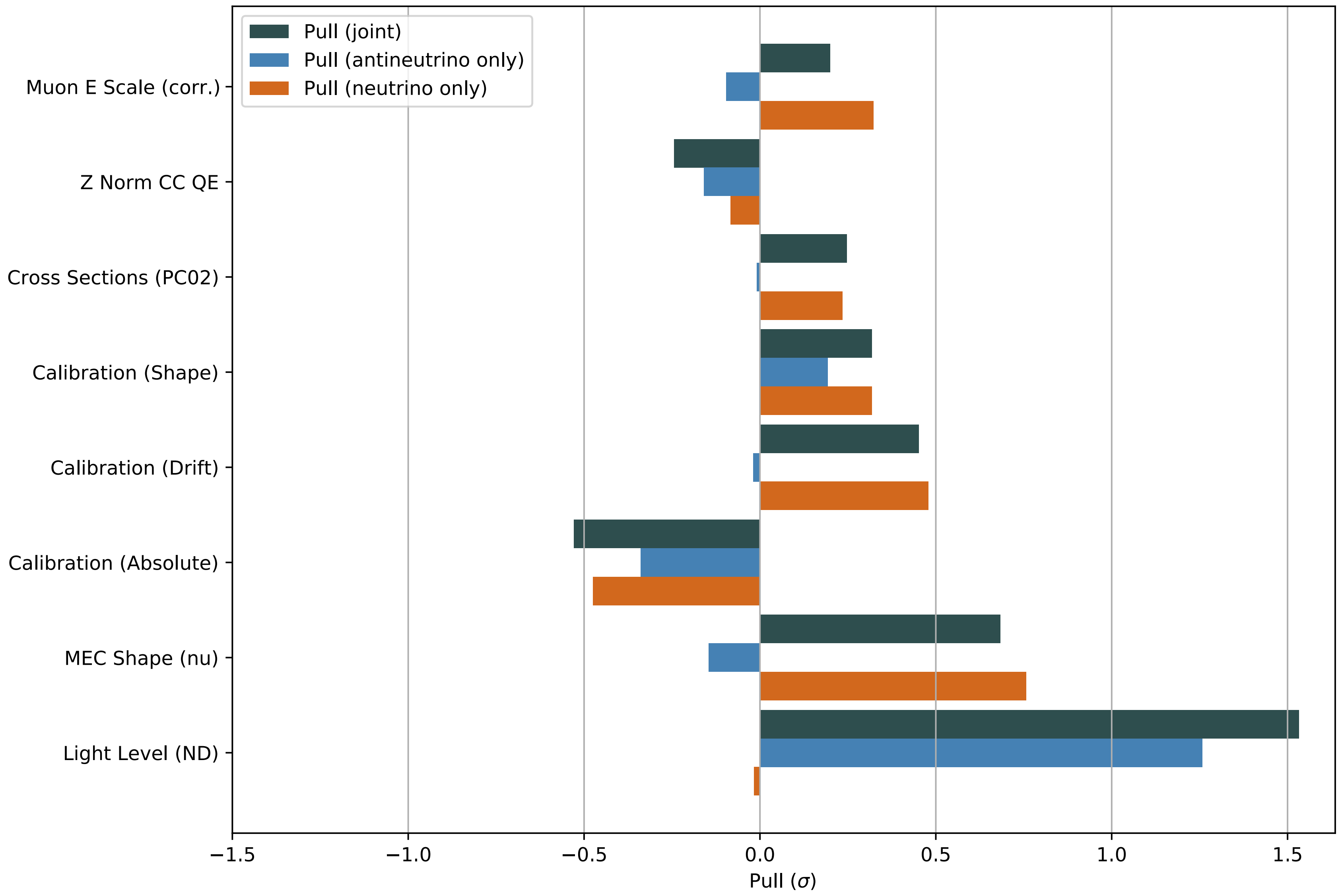
- **Detector calibration**: will be improved by the ongoing test beam program at FNAL.
- **Neutron uncertainty**: cover discrepancies observed in low-energy $\overline{\nu}$ data. Ongoing work to improve our simulation and understanding of neutrons in the detectors.
- **Neutrino cross-sections**: use own tuning but still noticeable nuclear effects (RPA, MEC).





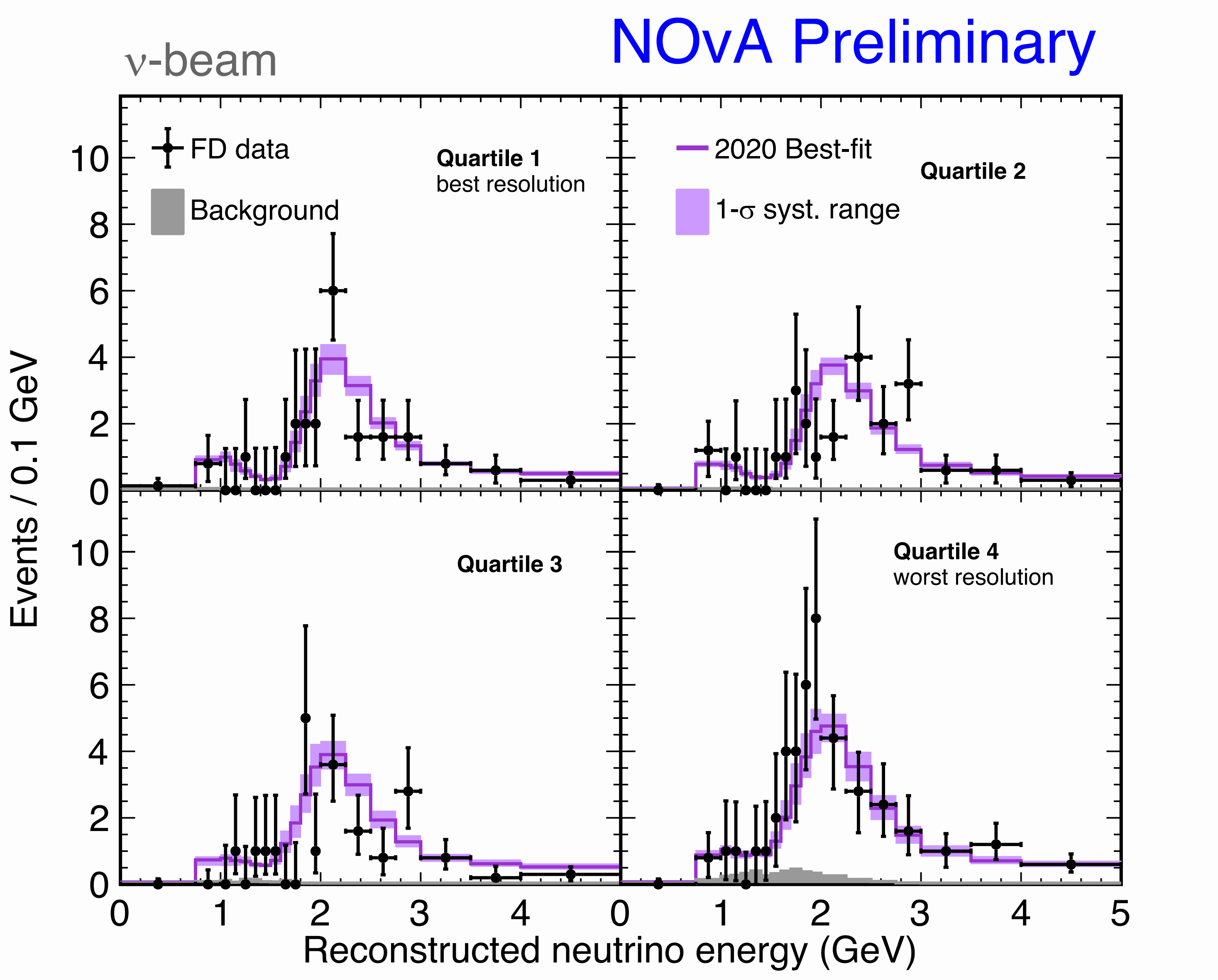


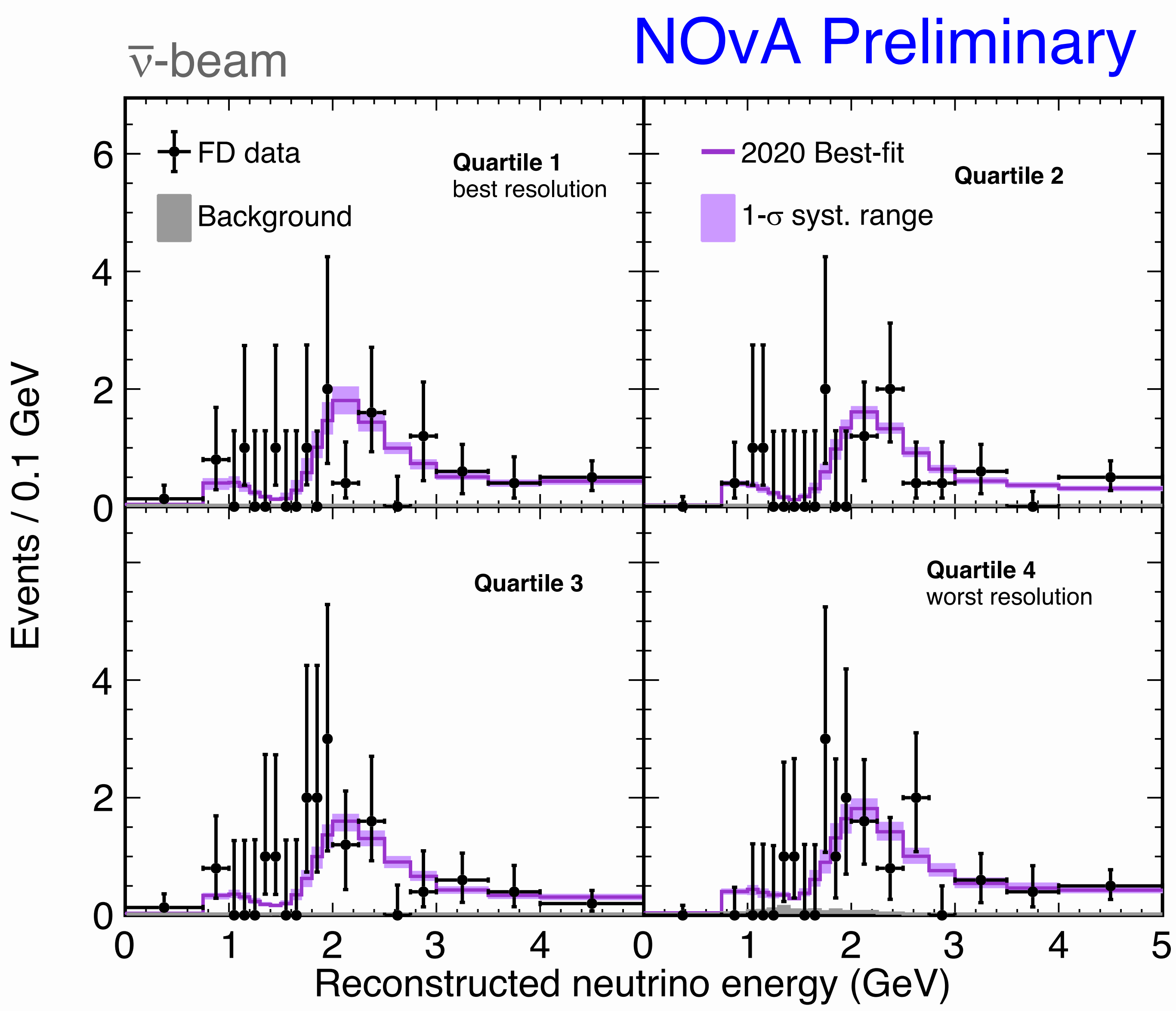
Pulls in the Fit



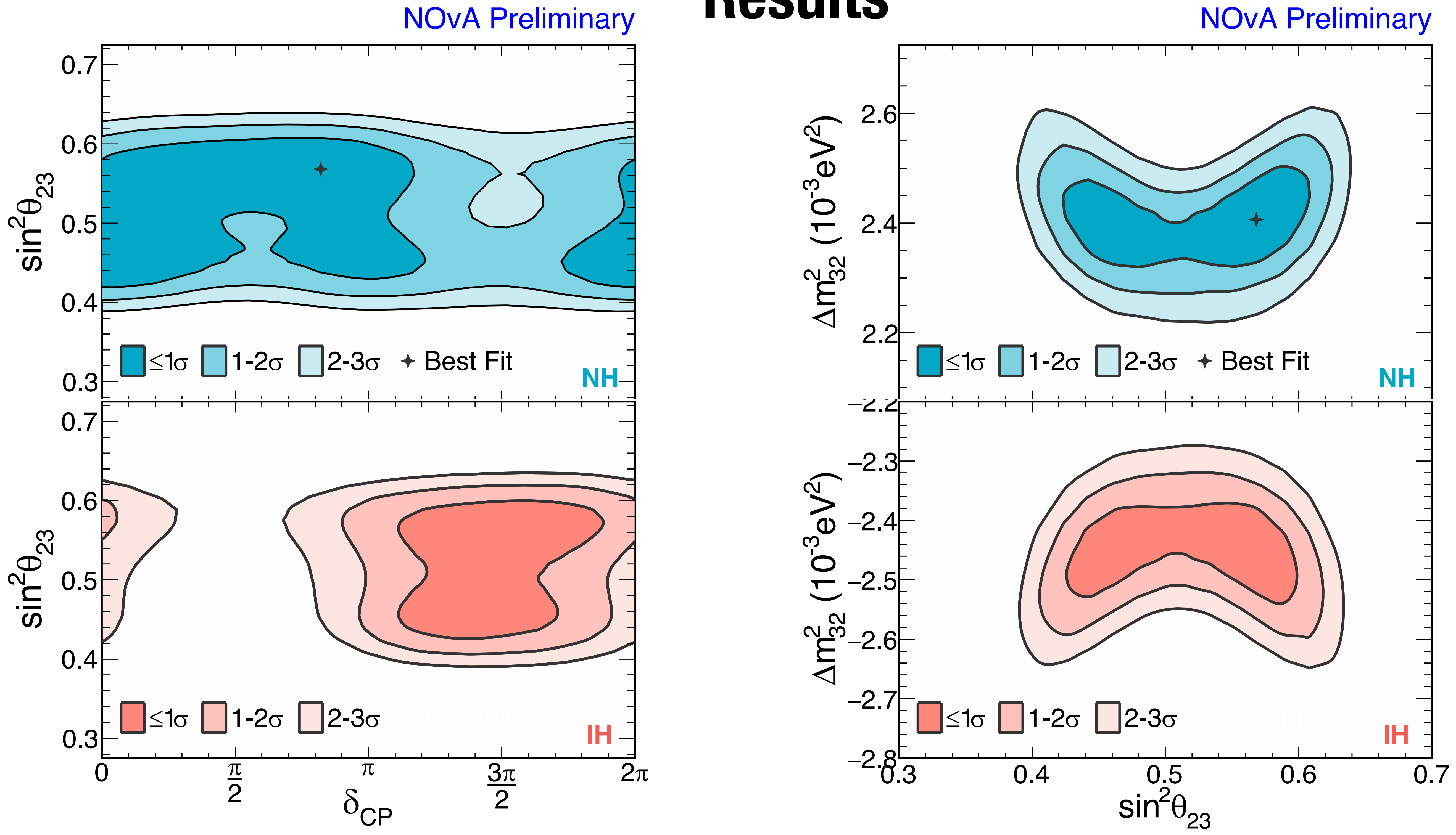
- Largest pulls also correspond to some of our known most important systematics:
  - Detector light model and energy scale (calibration)
  - Multi-nucleon cross section
- We see examples where a pull comes primarily from the neutrino or antineutrino beam, but generally do not see *contradictory* pulls.

Numu FD samples

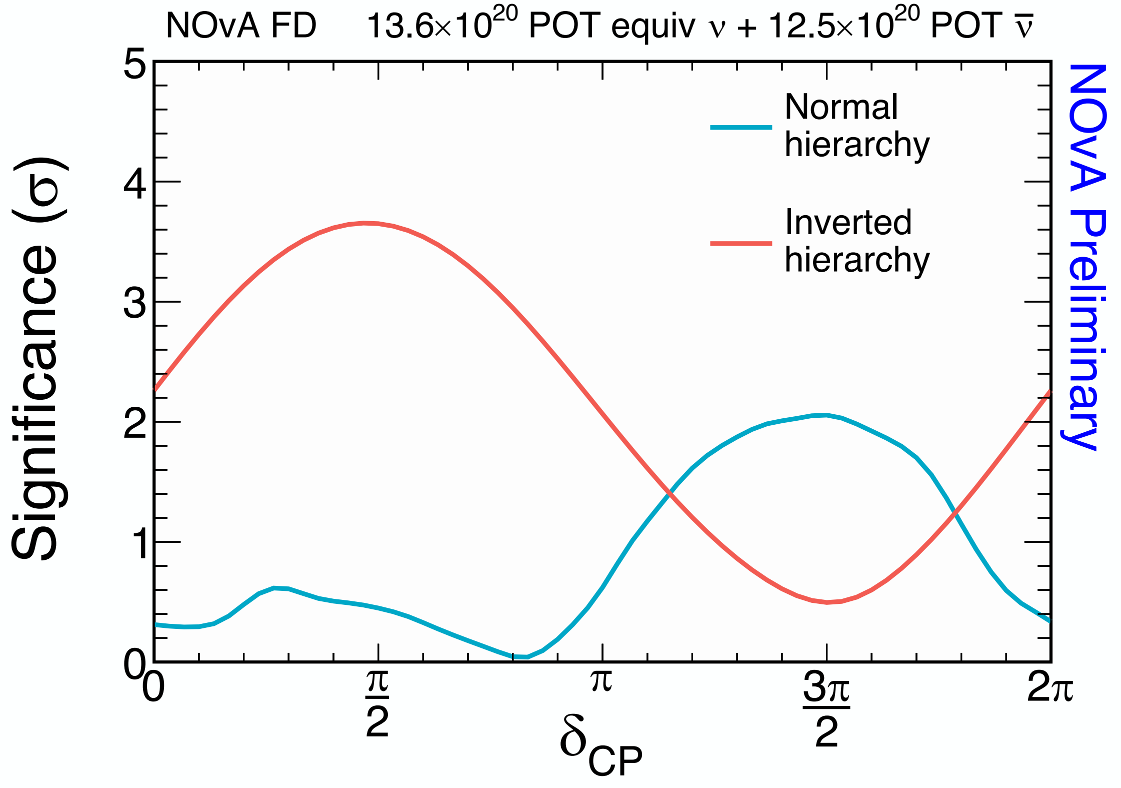


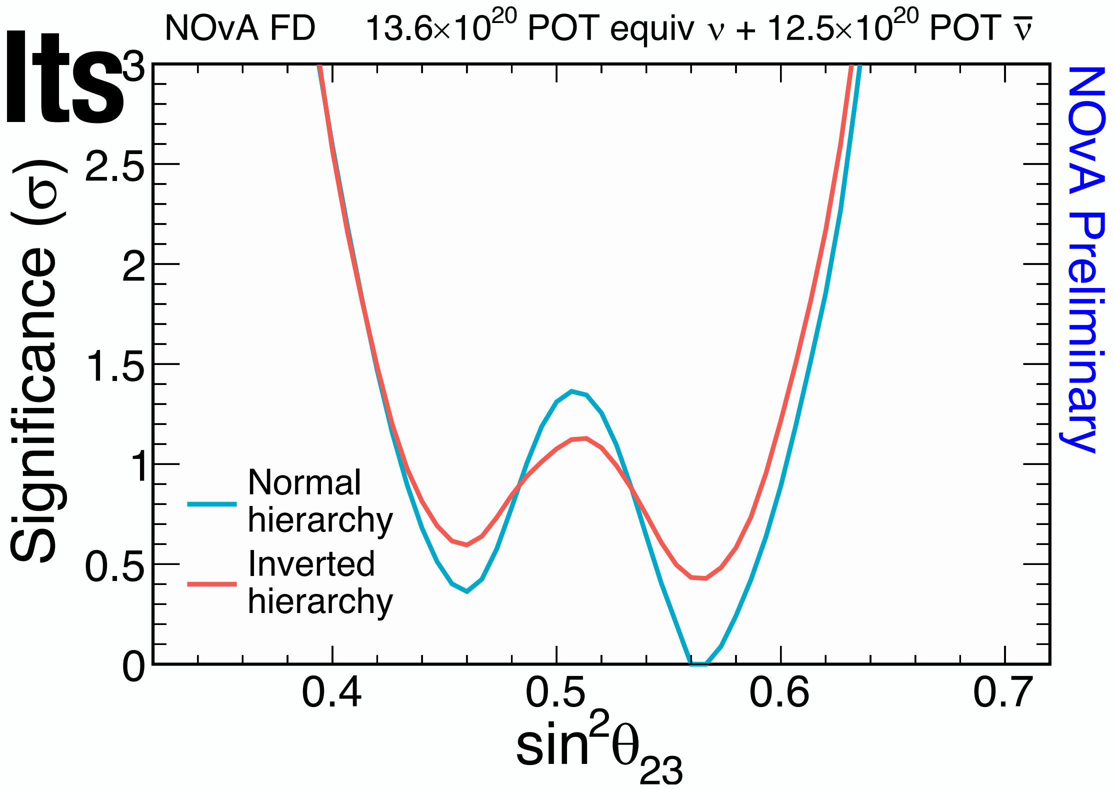


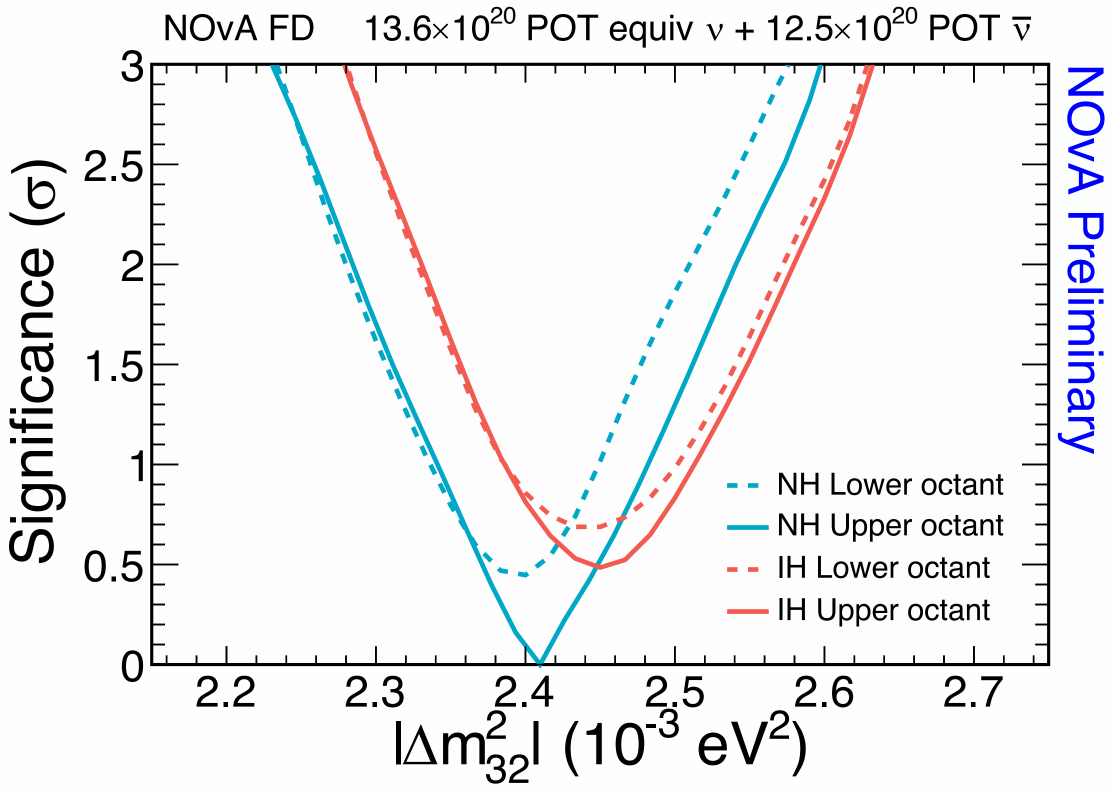
Results


NOvA Preliminary
NOvA Preliminary
0.7
0.6
0.5
0.4
0.3
$\sin^2\theta_{23}$
≤1σ
1-2σ
2-3σ
Best Fit
NH
IH
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
δ_{CP}
Δm^2_{32} $(10^{-3}eV^2)$
2.6
2.4
2.2
−2.2
−2.3
−2.4
−2.5
−2.6
−2.7
−2.8
0.3
0.4
0.5
0.6
0.7

Results







- Best fit:

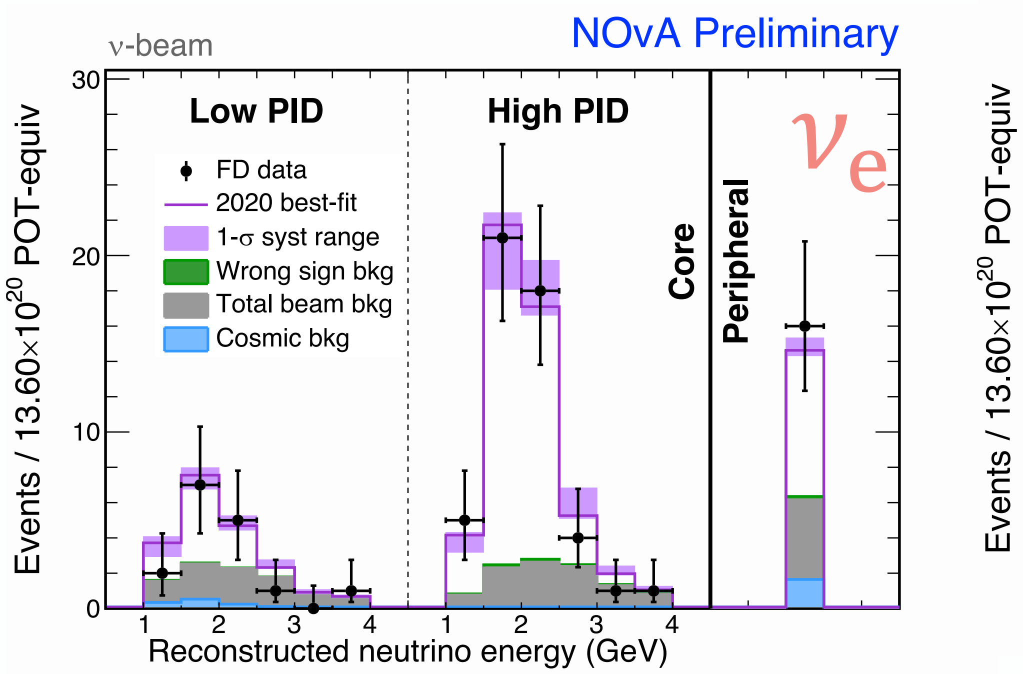
  Normal hierarchy

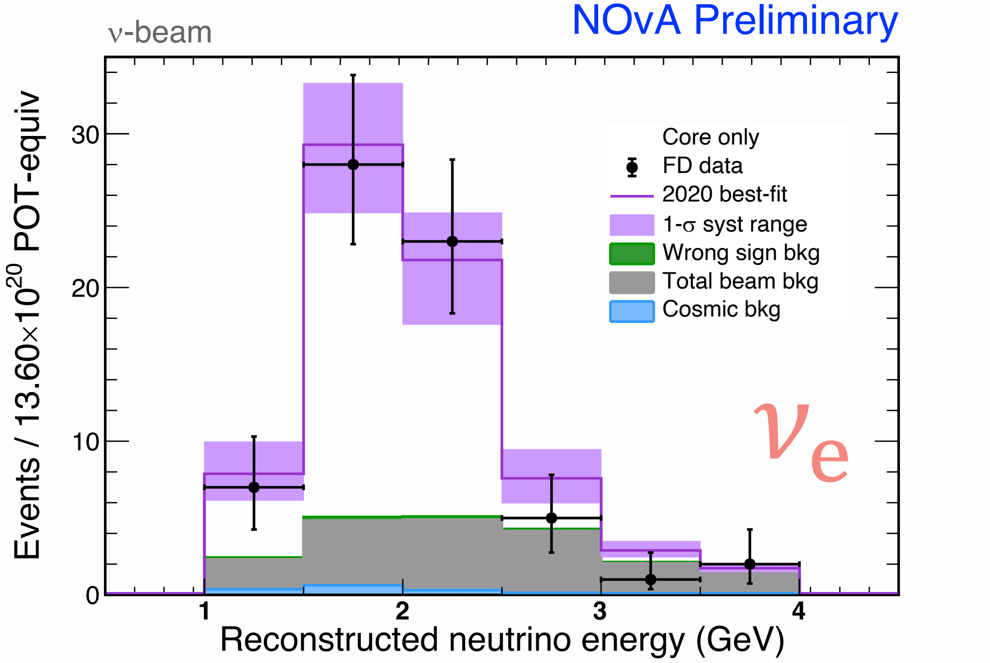
  $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$

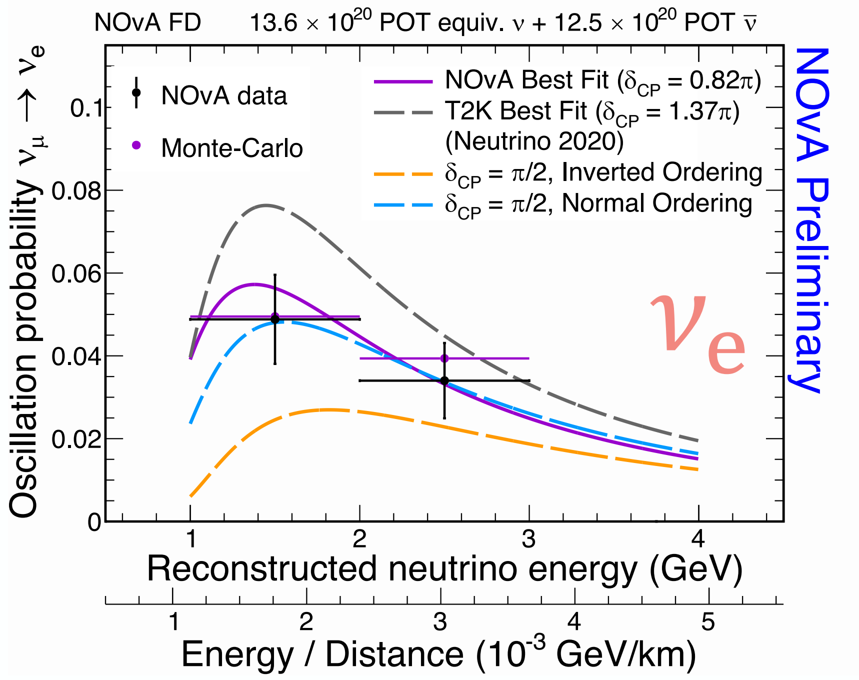
  $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

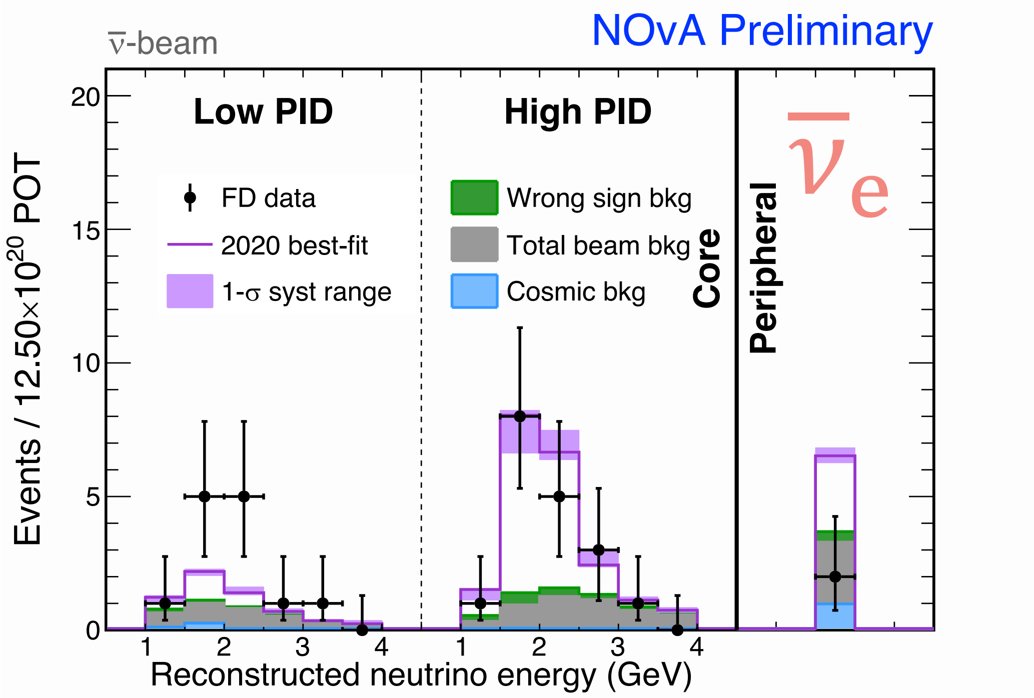
  $\delta_{CP} = 0.82\pi$

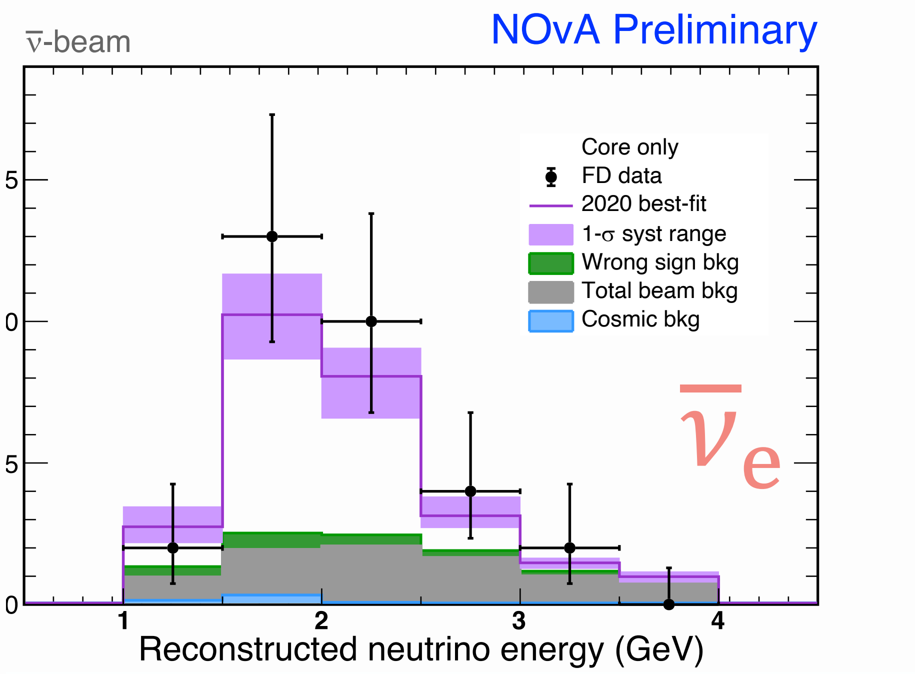
Appearance prob. estimator vs reco E

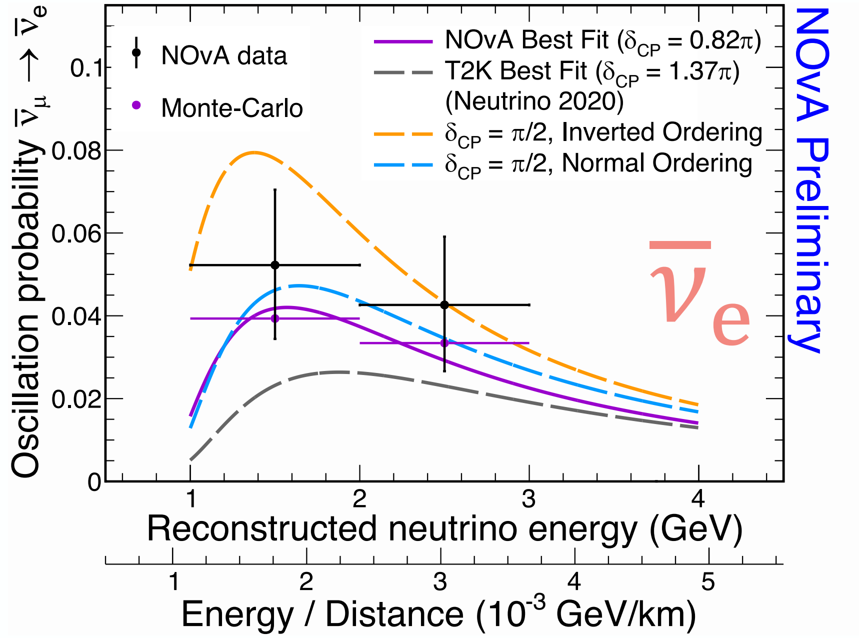




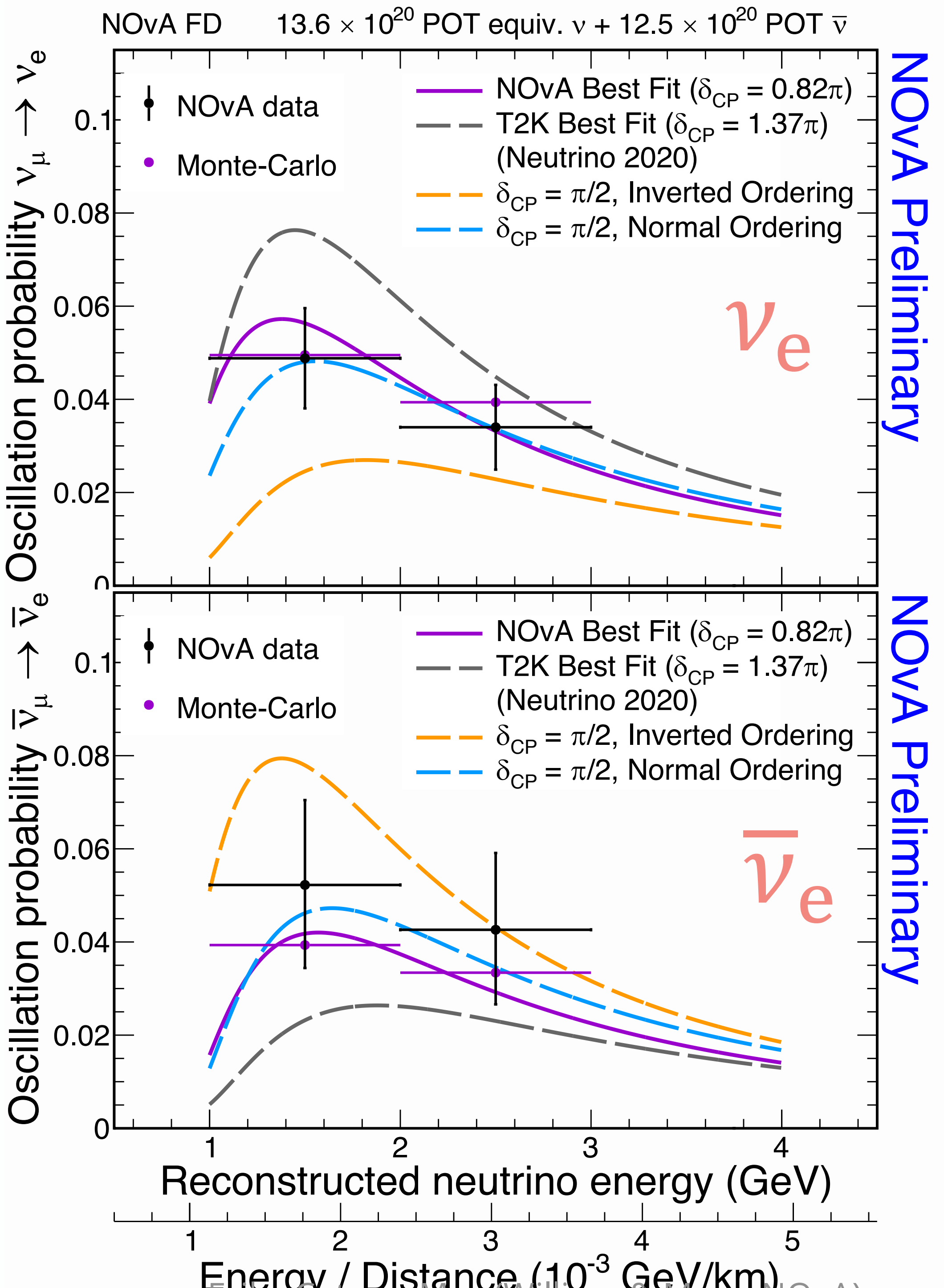




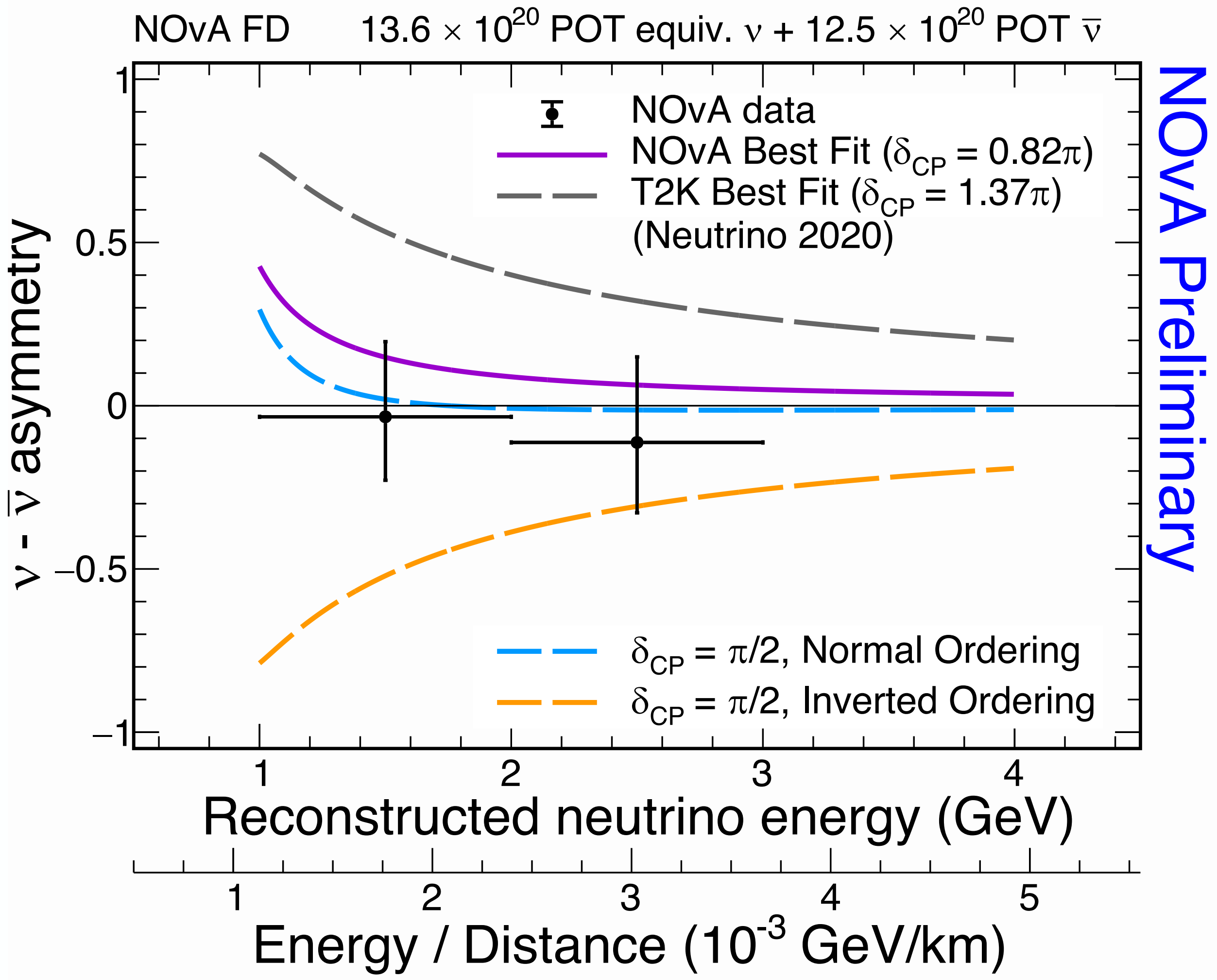




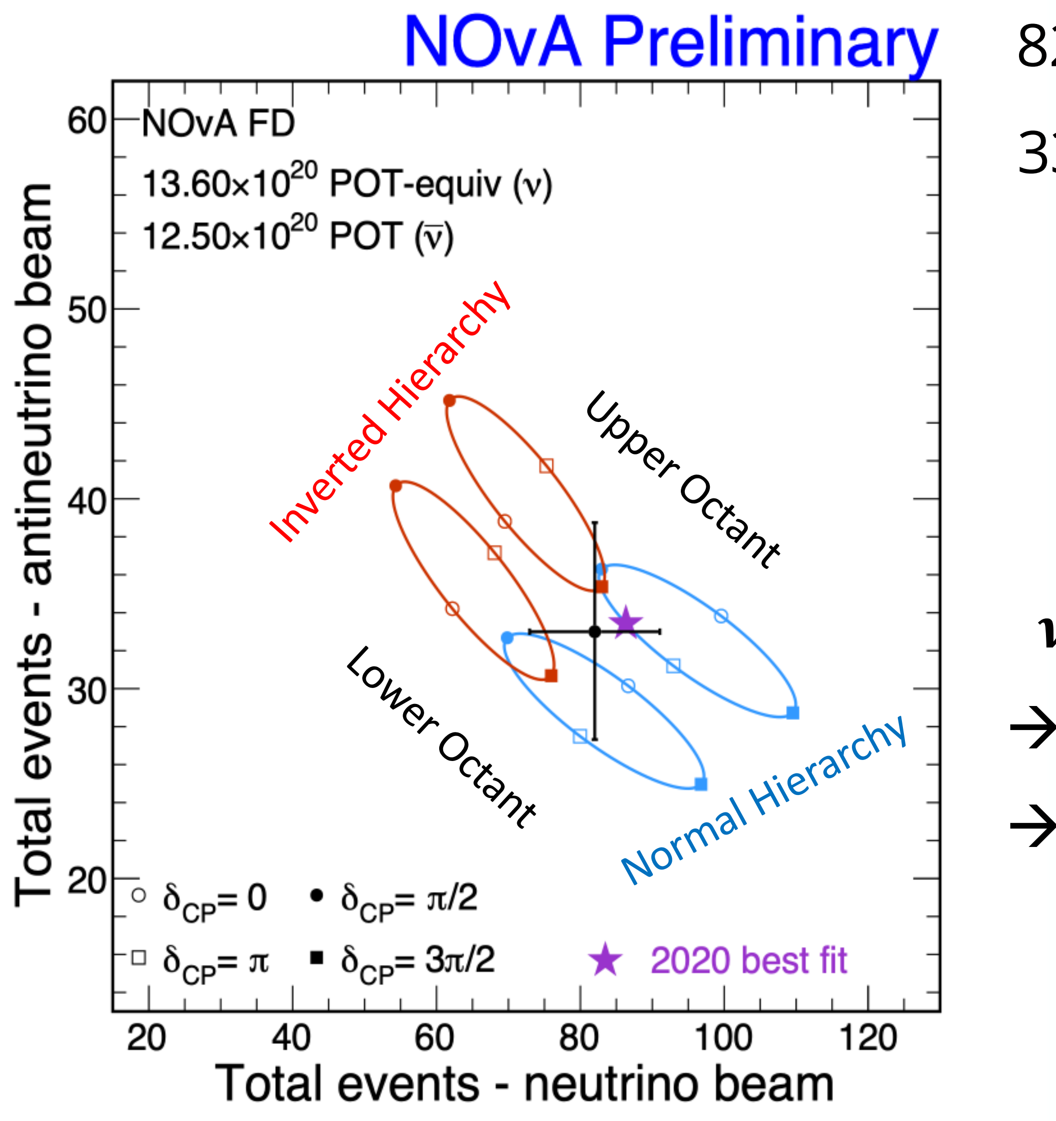
Appearance prob. asymmetry vs Reco E



$$\text{asymmetry} = \frac{\hat{P}_{\nu} - \hat{P}_{\bar{\nu}}}{\hat{P}_{\nu} + \hat{P}_{\bar{\nu}}}$$



Results: $\nu_e / \bar{\nu}_e$ appearance + asymmetry



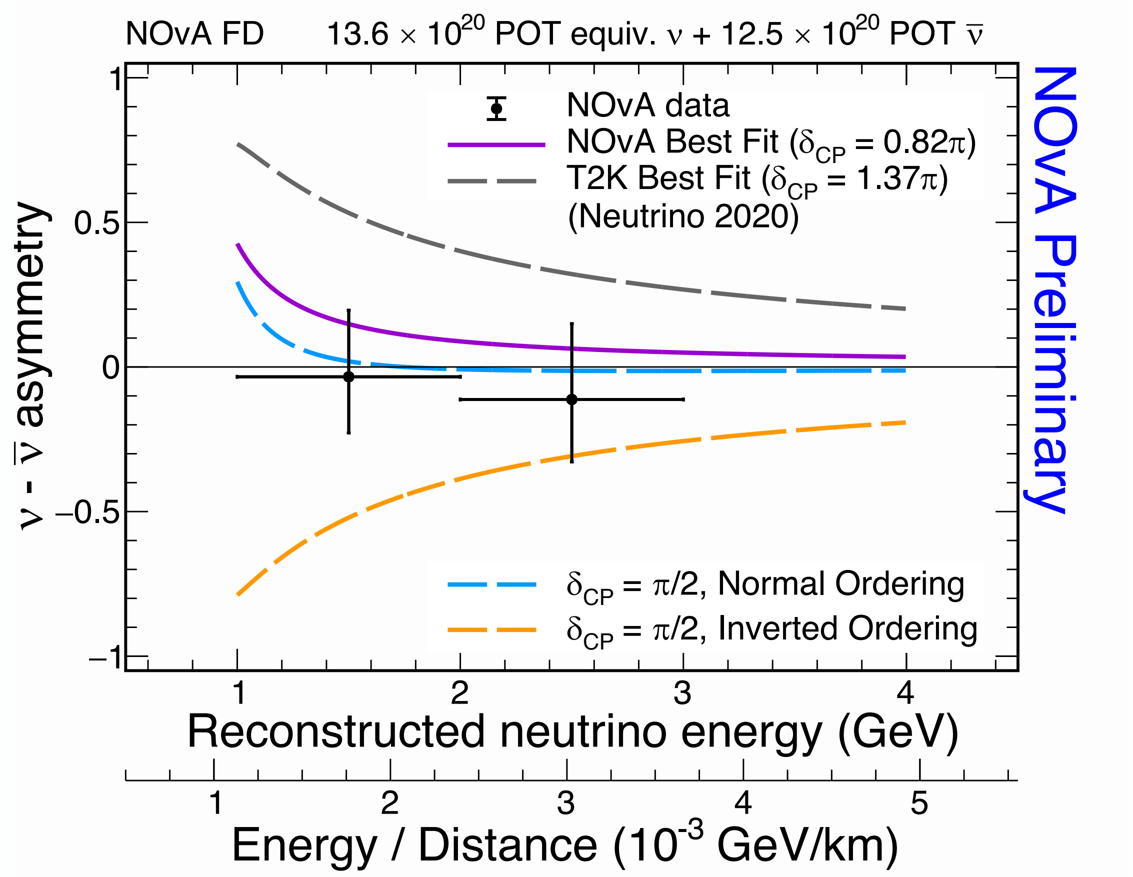
82 candidates (27 bkgd.) → $\boldsymbol{\nu_e}$ appearance ✓

33 candidates (14 bkgd.) → $\boldsymbol{\bar{\nu}_e}$ appearance ✓

We don't see a strong asymmetry between $\boldsymbol{\nu_e}$ and $\boldsymbol{\bar{\nu}_e}$ appearance rates

→Exclude IH δ = π/2 at >3σ

→Disfavor NH δ = 3π/2 at ~2σ

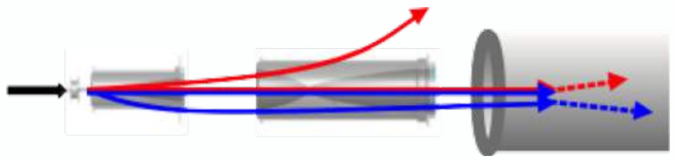


Analysis strategy

1. Simulated predictions → 2. Data-driven improvements → 3. Comparisons with FD data → 4. Constraints on oscillation parameters

1. Simulated predictions

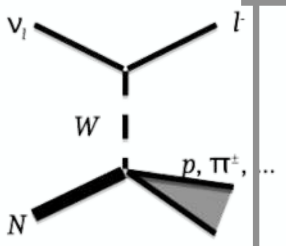
Neutrino flux



GEANT4-based simulations of particle production and transport.

Reweighted to incorporate external measurements (“PPFX”)

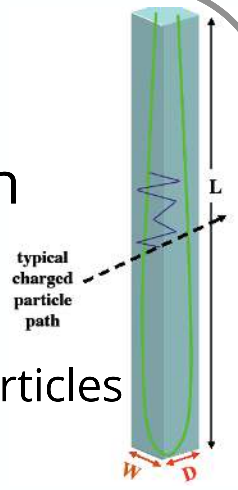
Neutrino interactions on detector materials



Simulated with GENIE 3.0.6*.

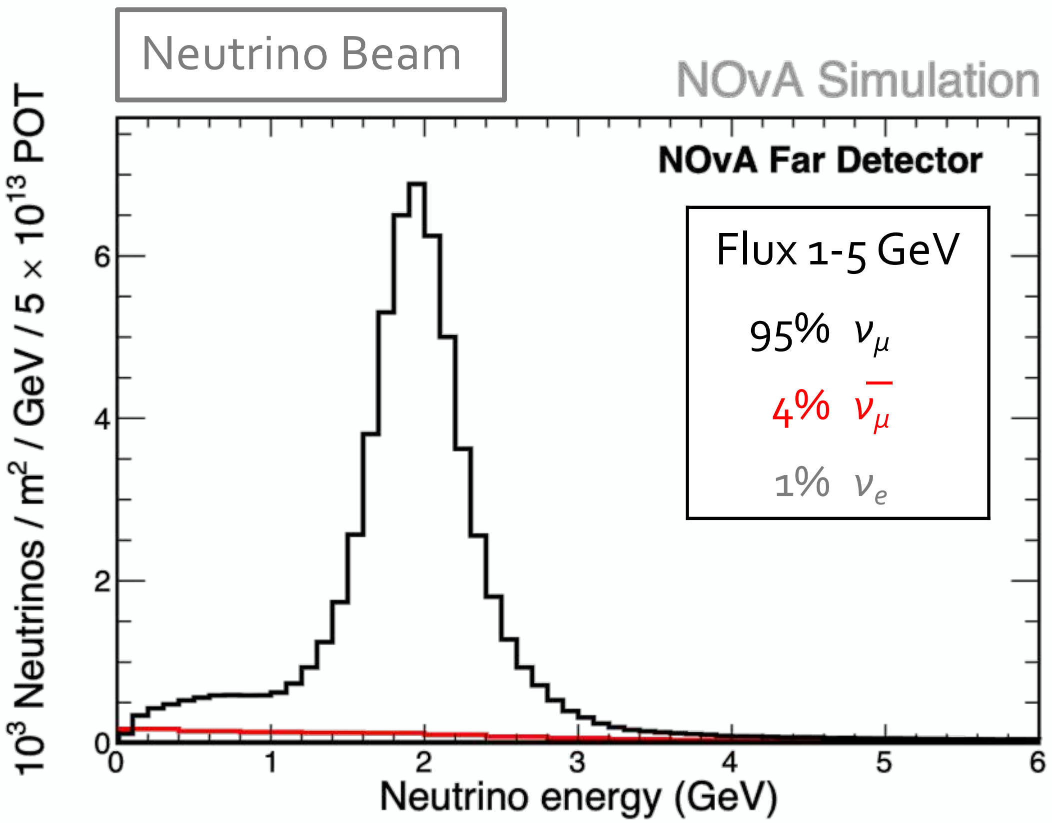
Use a custom configuration, tuned to external data and NOvA ND Data.

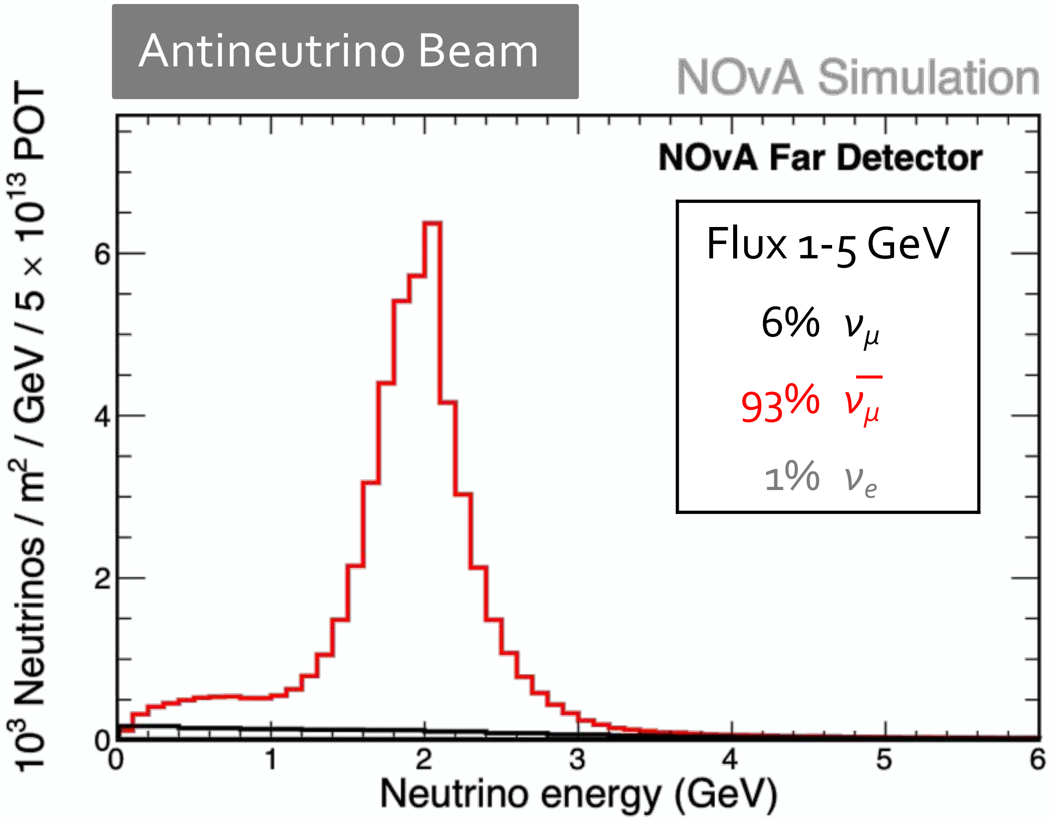
Detector response to charged particles and light propagation



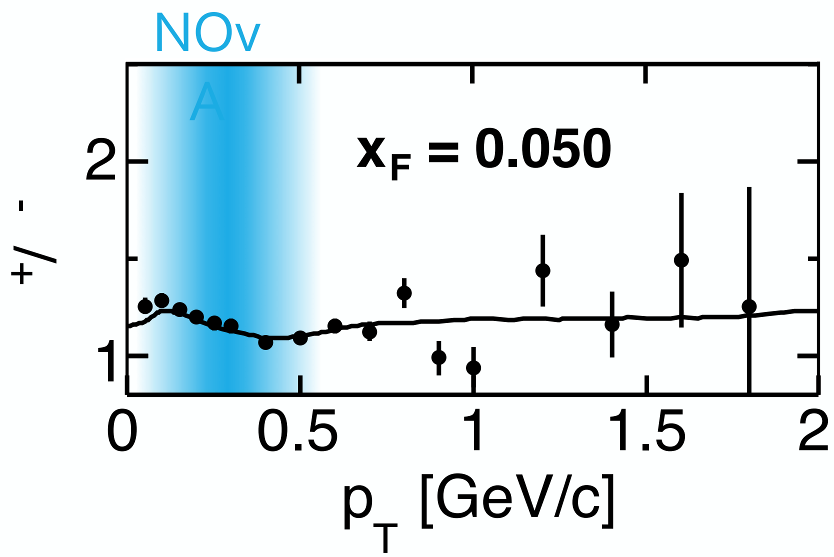
Propagation of final state particles simulated with GEANT4*.
Light readout and front–end electronics use a custom simulation.

* Updated for this analysis

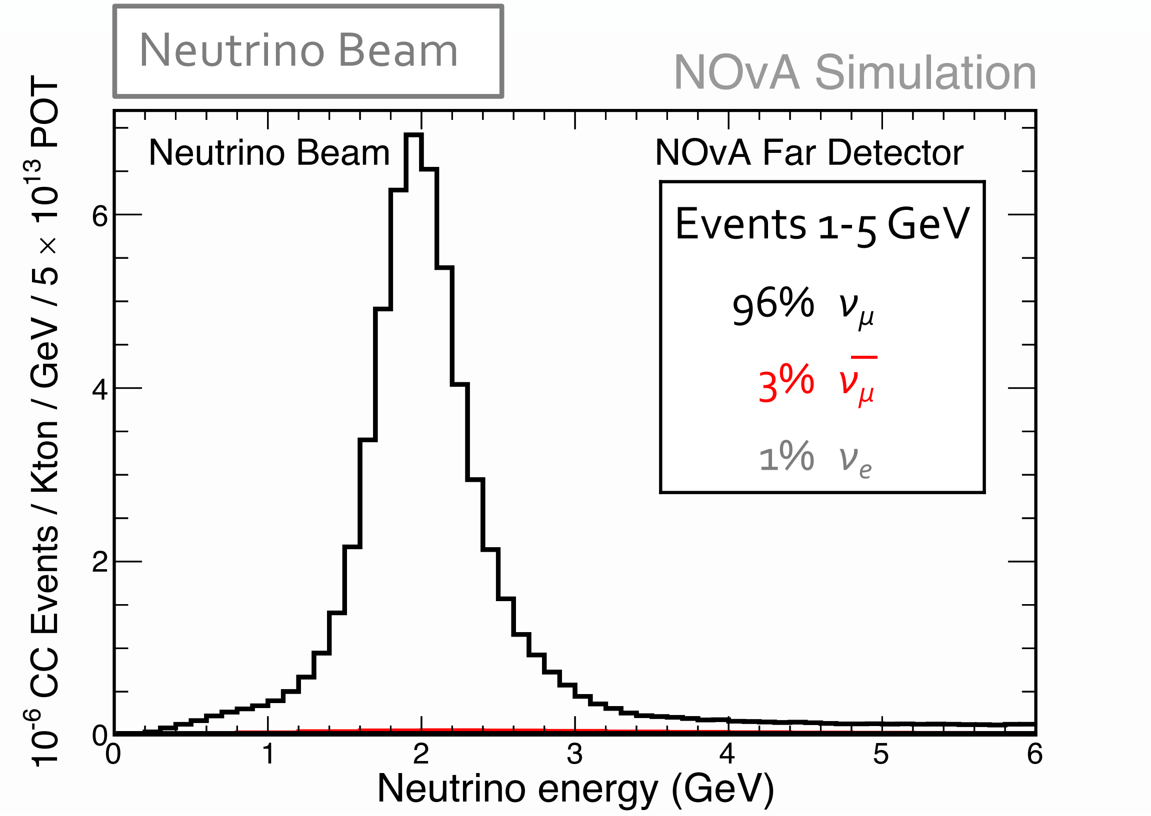


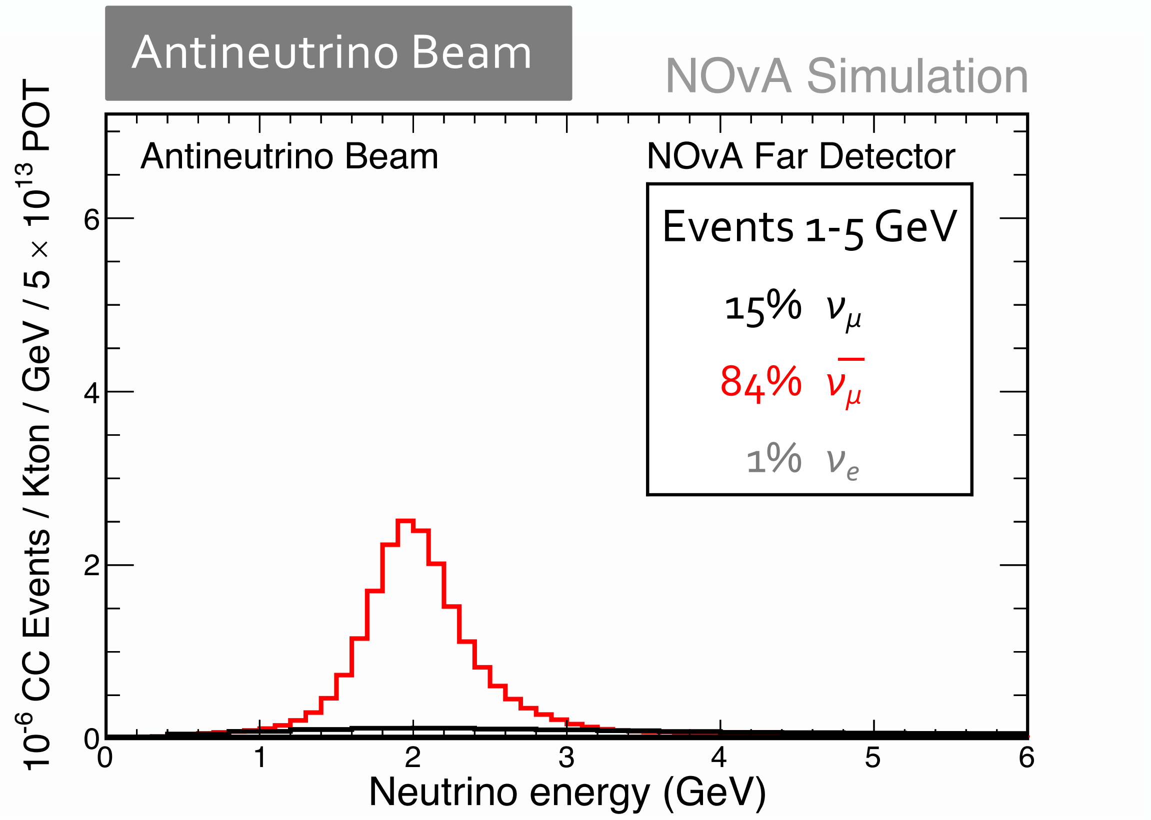


- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
  - p^+ colliding with p^+ and n^0 in the target
- *Wrong-sign*: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign.
  - WS primarily would primarily come from the unfocused high-energy tail.

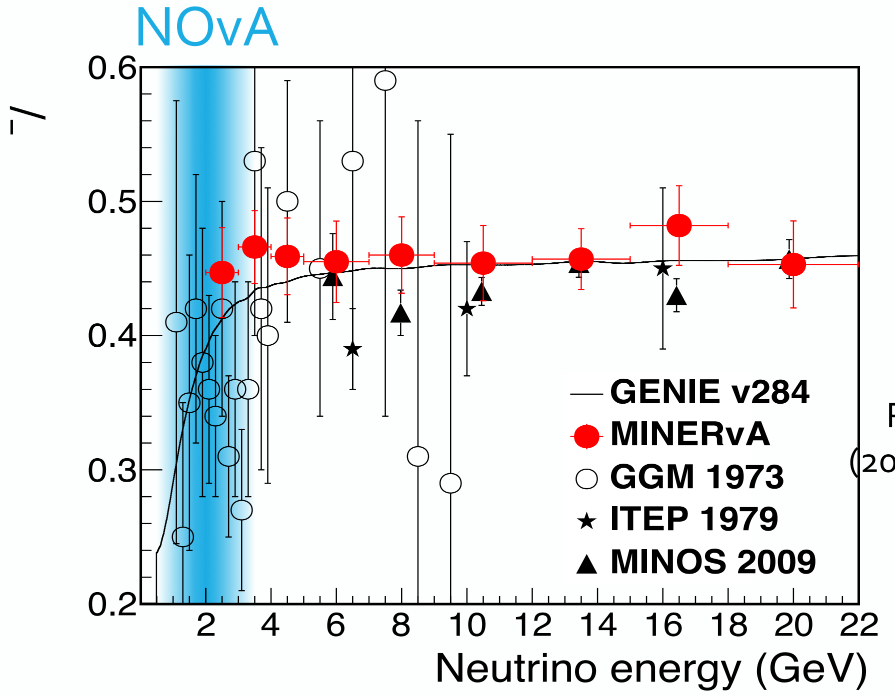


NA49, Eur. Phys. J. C 49 897 (2007)



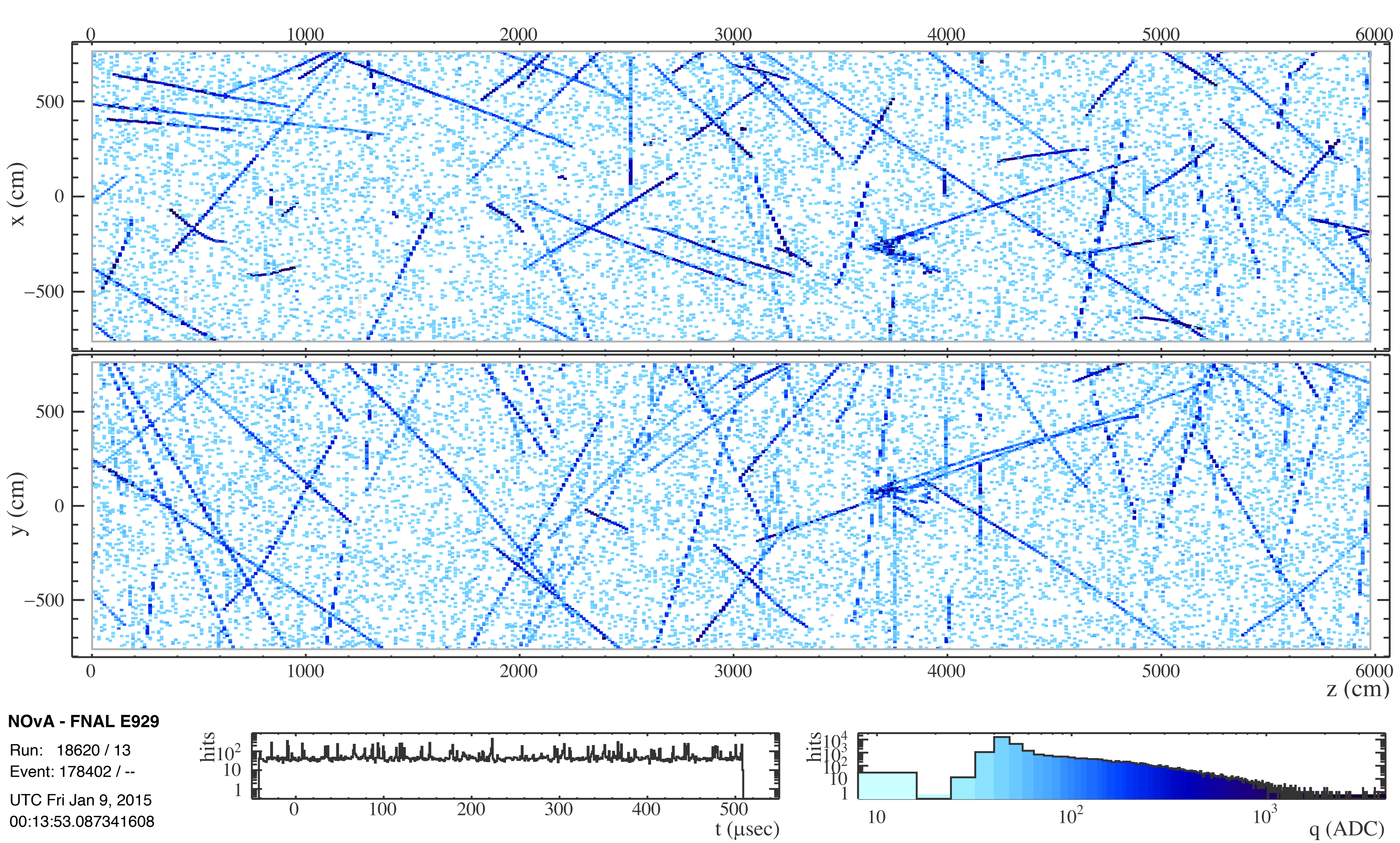


- The big difference is in the interaction: the cross section for antineutrinos is **~2.8 times lower** than for neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.
  - Lower kinematic *y*
  - More forward-going



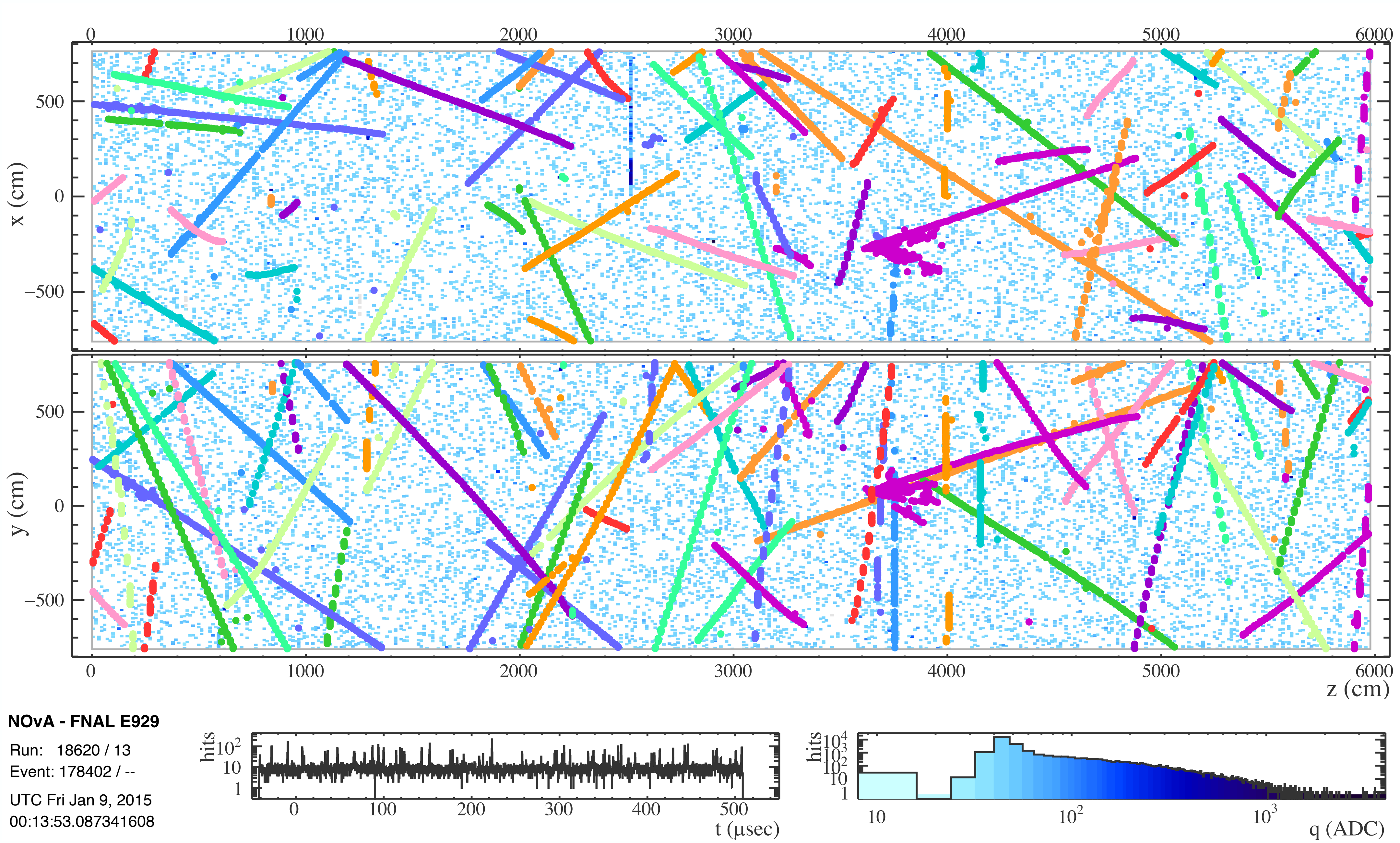
MINERvA, Phys.Rev. D95 (2017) no.7, 072009

Finding neutrino events



All hits recorded in 550 μsec (beam: ~10 μsec)

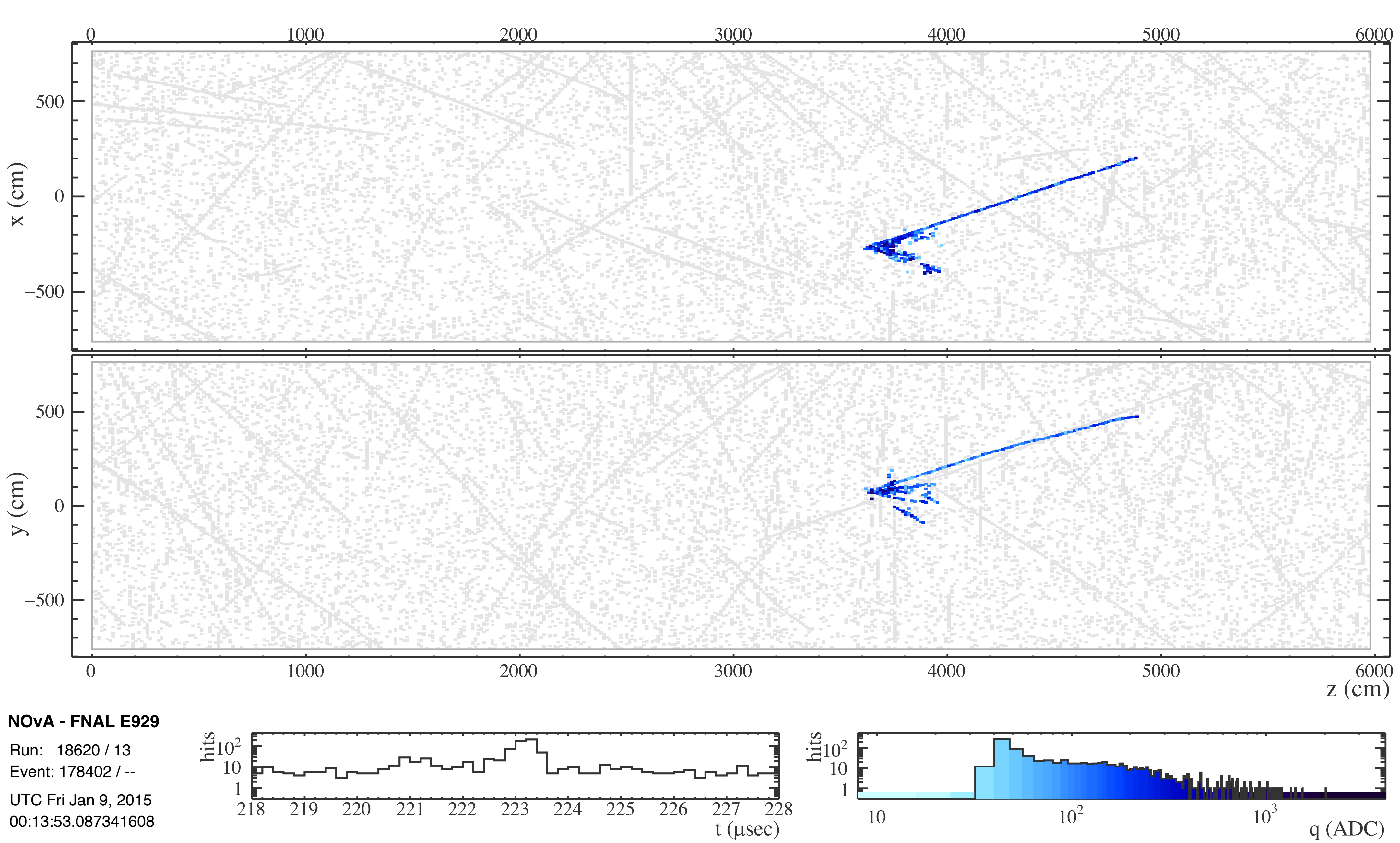
Finding neutrino events



Slicing:

Coarse event-level time-space clustering

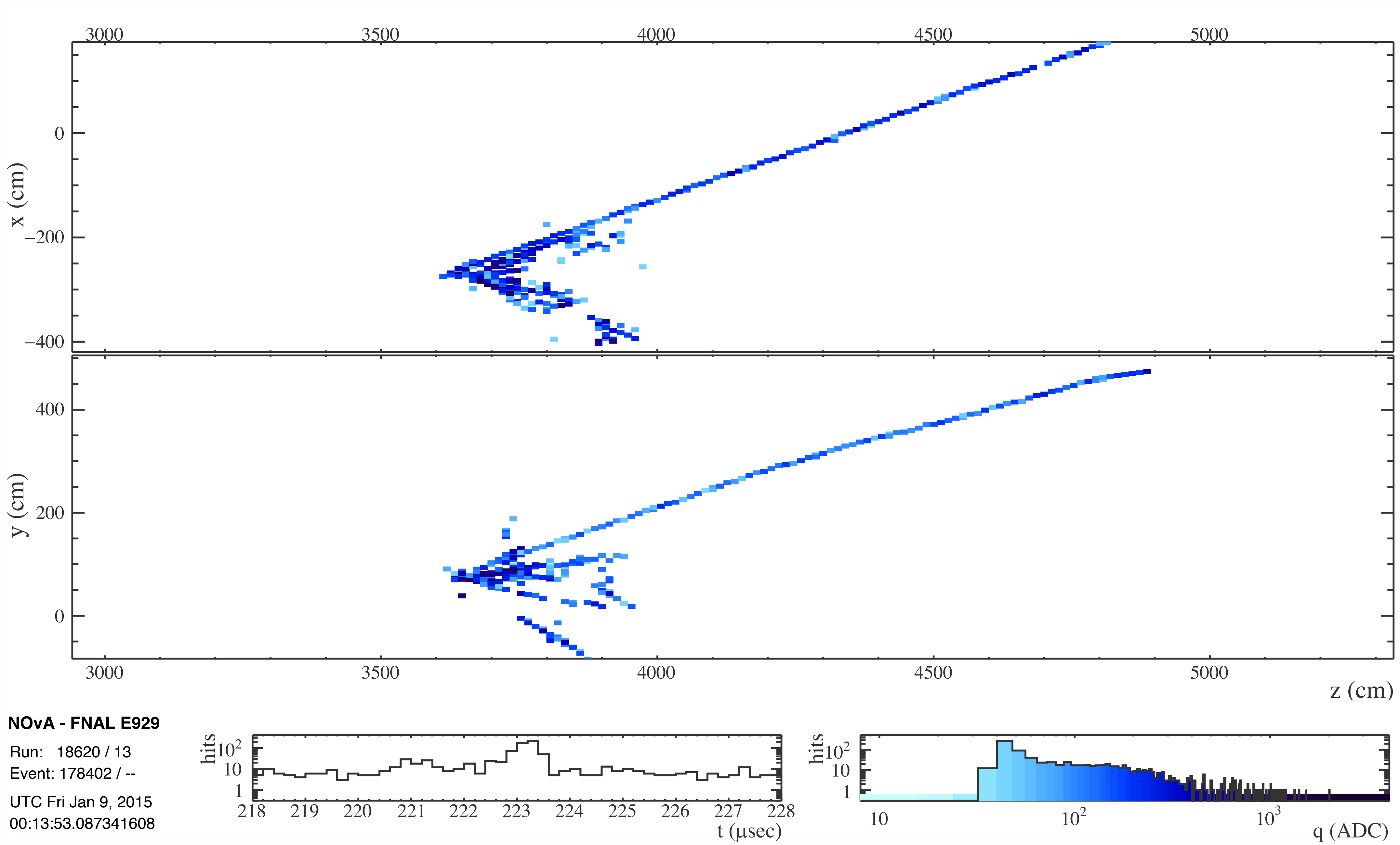
Finding neutrino events



Zoom-in in time

Selected slice in the 10 mus beam window = neutrino beam candidate

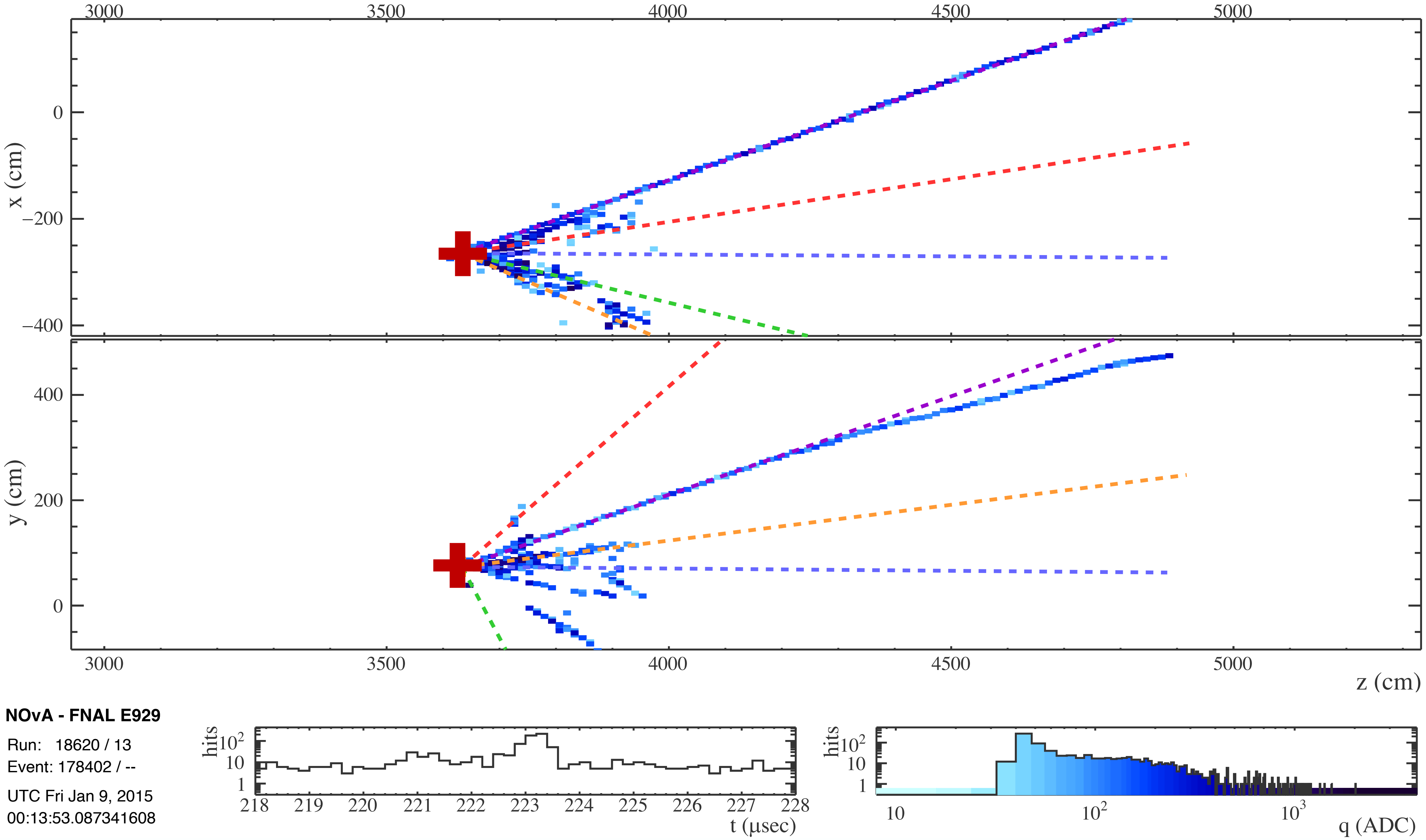
Finding neutrino events



Zoom-in in space

Same neutrino beam candidate

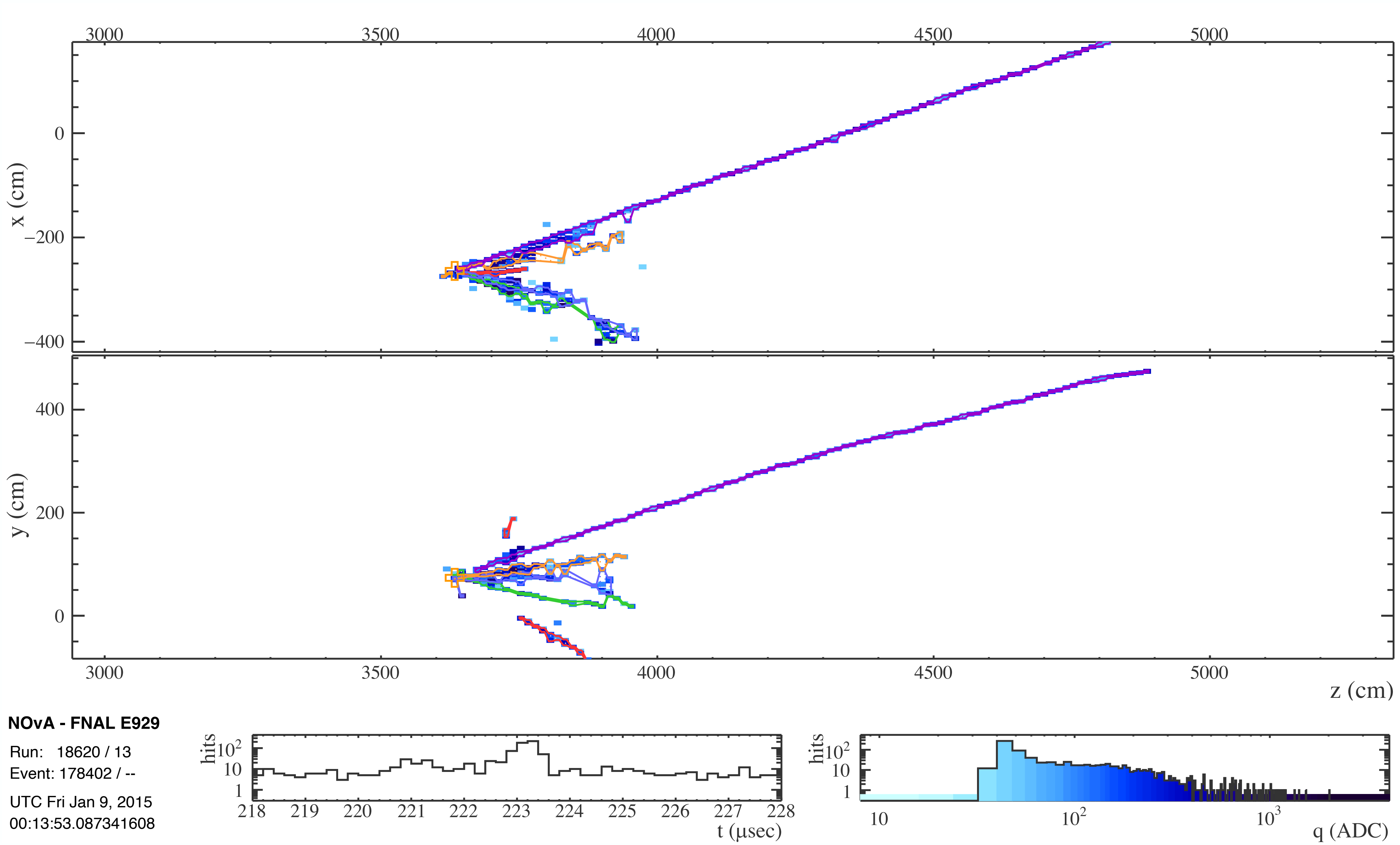
Finding neutrino events



Vertexing:

Find lines of energy depositions + optimize

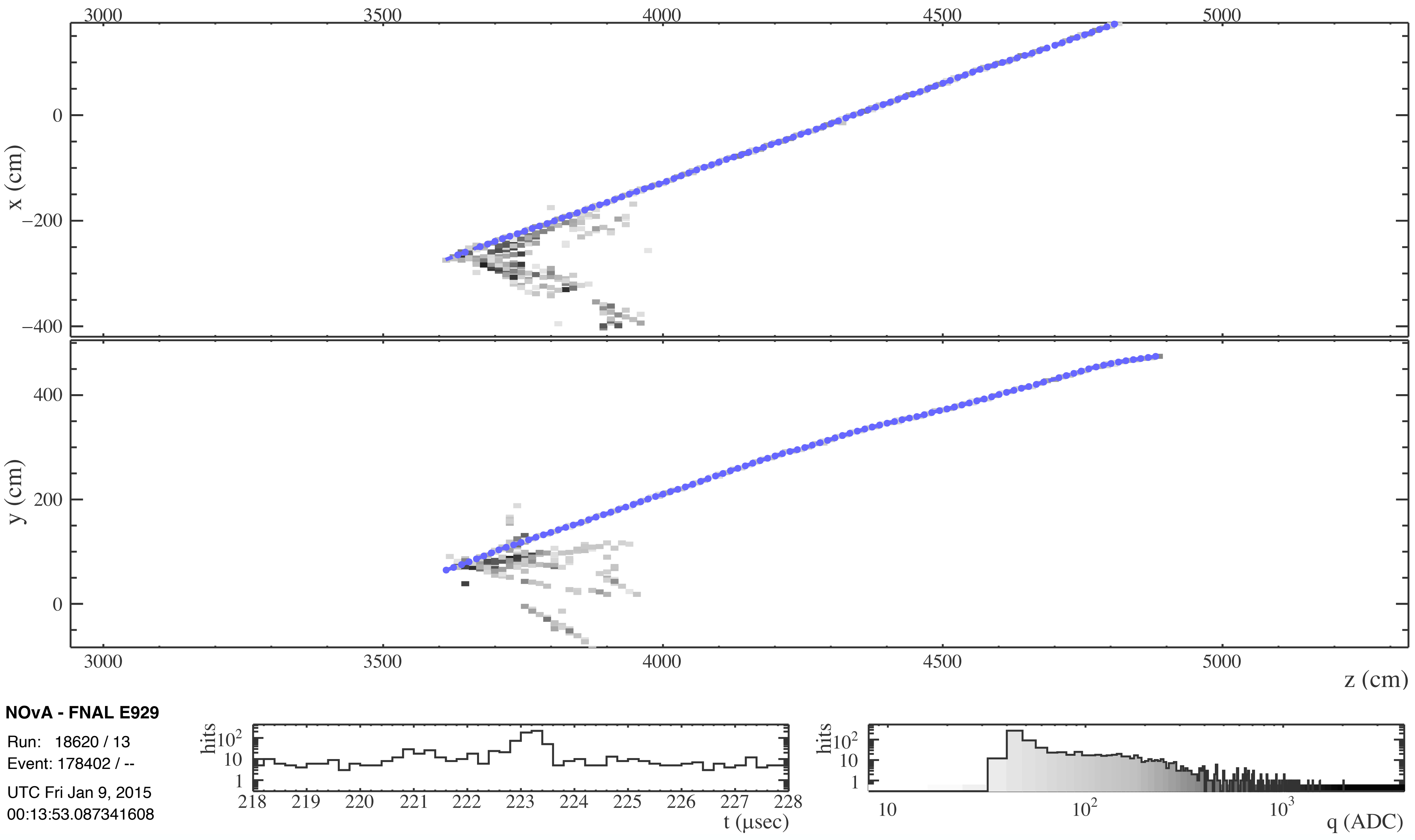
Finding neutrino events



Clustering:

Find clusters in angular space around vertex. Merge views based on topology and prong dE/dx

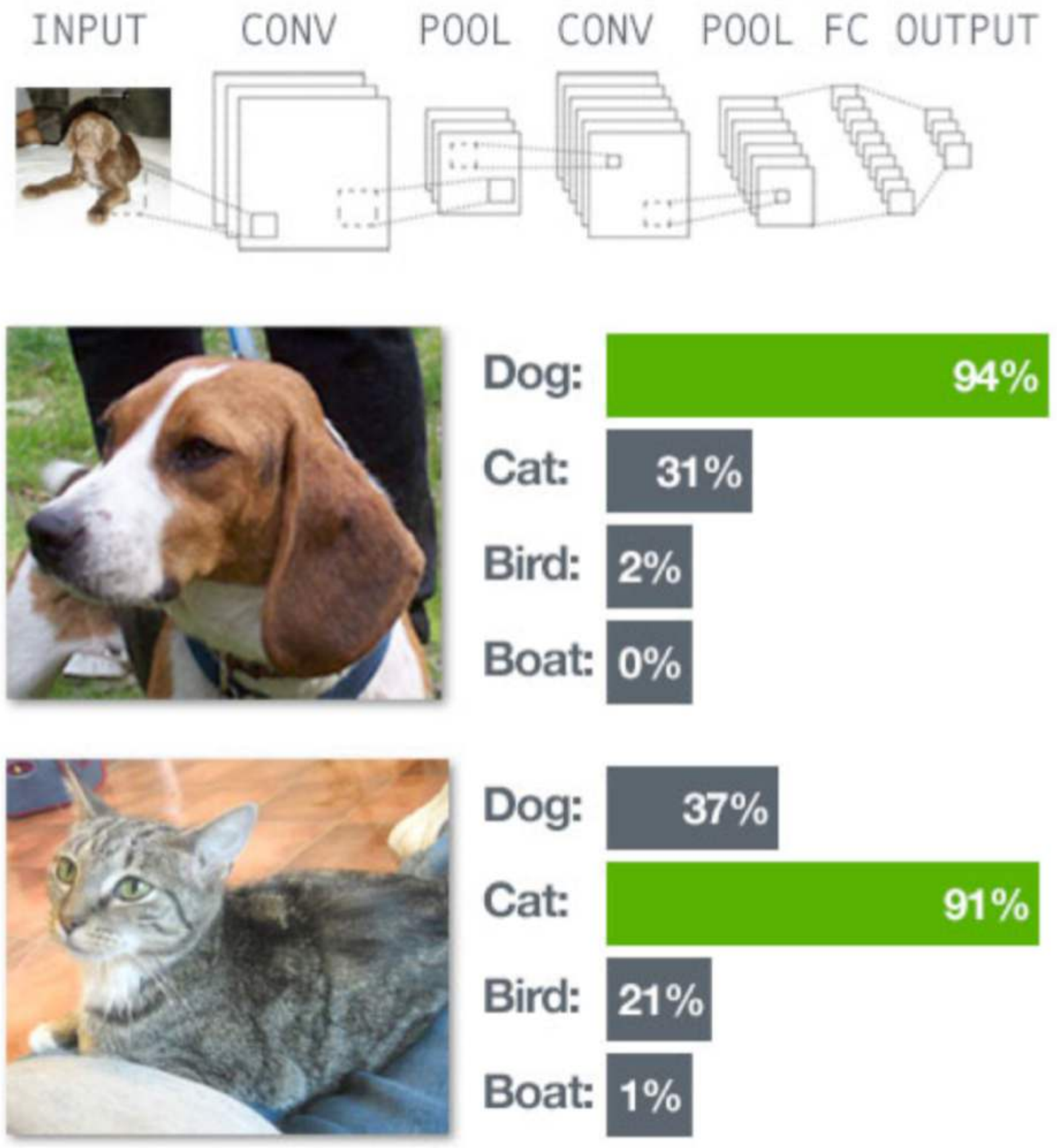
Finding neutrino events



Tracking:

Trace single particle trajectories (muons)

Event selection: Neural Network

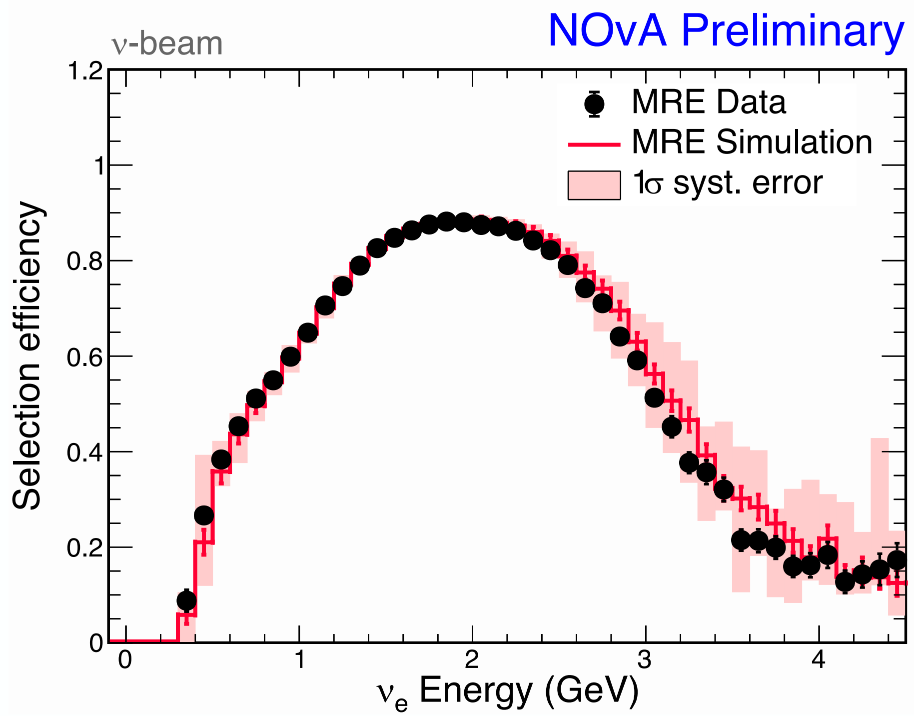


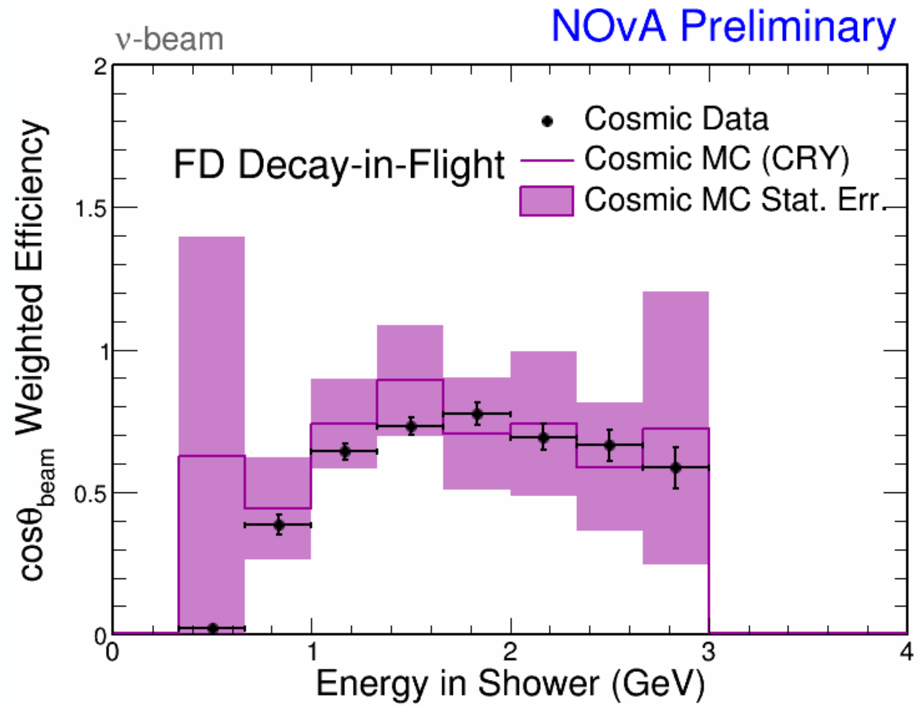
- NOvA Utilizes a Convolutional Neural Network (CNN) to identify particles.
- Networks are trained to use filters which convolve images produced by events in the detector to produce a map of the features.
- This process is repeated, allowing for the emergence of more complex features.
- The end result is a categorization of the events into **muon neutrino**, **electron neutrino**, or **NC events**.

Anne Norrick

Selection: Validating Performance

- Examine PID efficiency relative to pre-selection.
  - Specifically target the behavior of the PID.
- ND: mixed data-MC sample
  - Mix simulated electrons and real hadronic showers
- FD: decay-in-flight electrons
  - Real electron showers from cosmic muons which decay

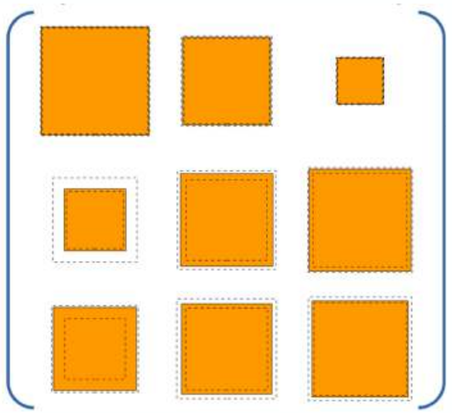




Parametrization of the mixing matrix

- The mixing matrix can be written in terms of 3 angles and 1 phase. Usually factorized into components directly related to the experiments:

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

$U =$ 

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The (23) sector: Atmospheric and accelerator

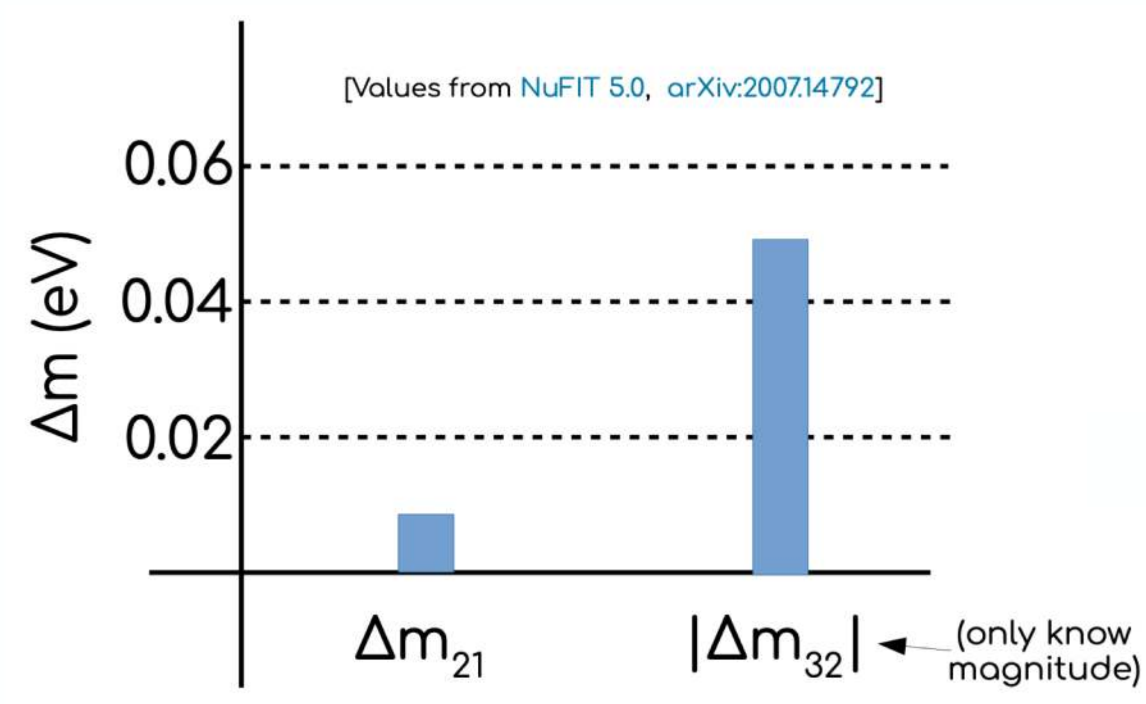
The (13) sector: Reactor and accelerator

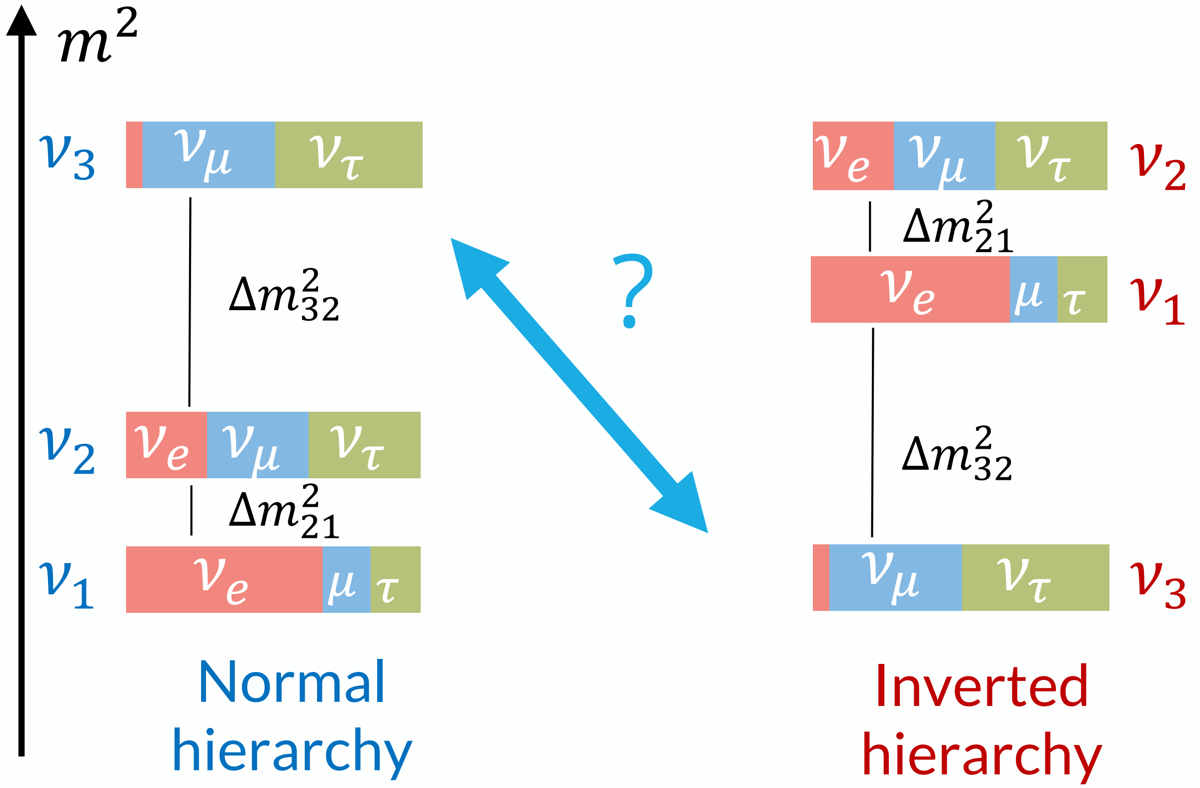
The (12) sector: Solar and reactor

- Current experiments → precision measurements of the angles
- Poorly known: θ_{23} (~5%), δ_{CP} (~unconstrained)
  - Q: is θ_{23} maximal? i.e. is there symmetry in ν_μ, ν_τ mixing to ν_2, ν_3 ? If not, what is the octant?
  - Q: is δ_{CP} ≠0, π? i.e. is CP violated in the neutrino sector?

Squared mass differences and hierarchy

- Neutrino oscillation experiments can access the mass differences squared
- By convention, we denote the mass eigenstate with the largest fraction of ν_e as ν_1
- Q: mass eigenstate is the lightest? → "hierarchy"
  - Normal: ν_1 is the lightest, just like the electron is the lightest charged lepton
  - Inverted: ν_3 is the lightest

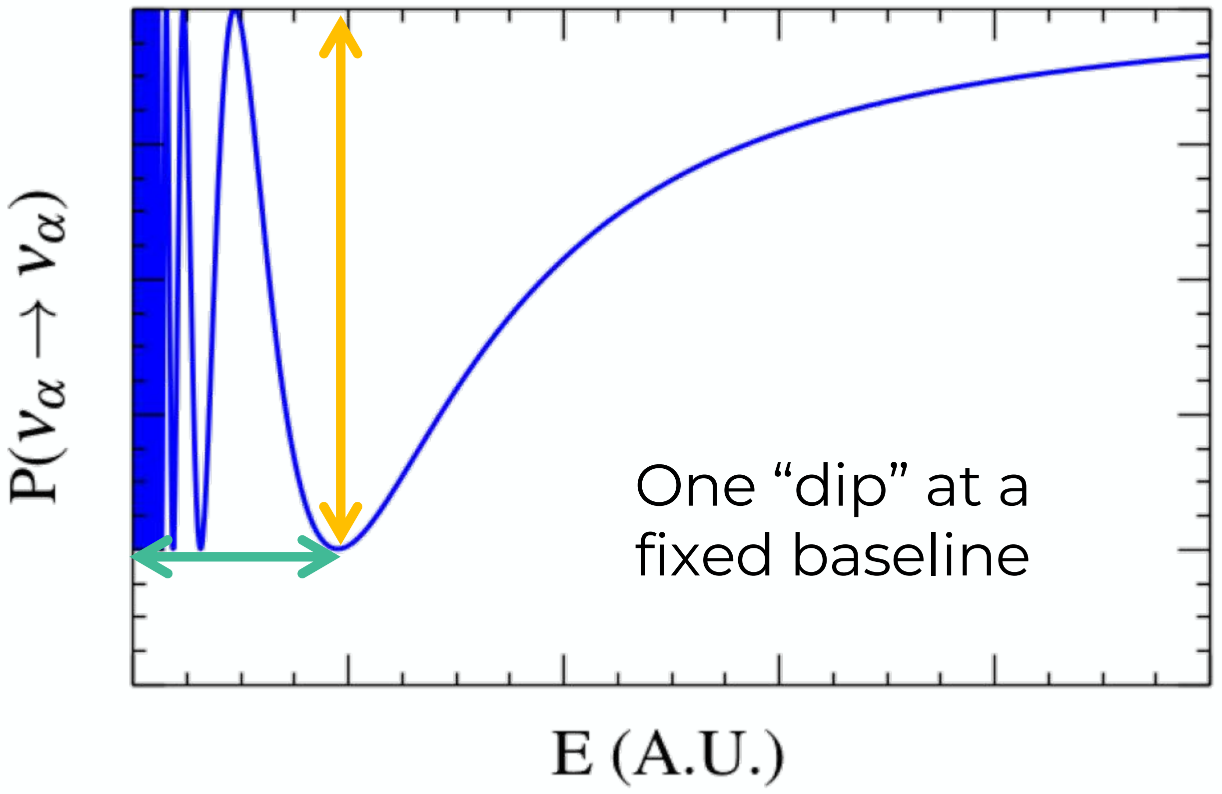




$\nu_\mu \rightarrow \nu_\mu$ oscillations

- Probability of ν_μ survival in a ν_μ beam

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



$\nu_\mu \to \nu_e$ oscillations in matter

- Probability of ν_e appearance in a ν_μ beam

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\rm atm}} e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}} \right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm} P_{\rm sol}} \left(\cos\Delta_{32} \cos\delta_{CP} \mp \sin\Delta_{32} \sin\delta_{CP}\right)$$

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

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31} \qquad \sqrt{P_{\rm sol}} = \cos\theta_{23}\sin(2\theta_{12})\frac{\sin(aL)}{aL}\Delta_{21}$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$

- $\nu_\mu \to \nu_e$ depends on:
  - CP phase: δ_{CP}
  - Mass hierarchy and matter effects
  - Atmospheric parameters: $\sin^2(\theta_{23})$, Δm^2_{32}
  - The smallest mixing angle: θ_{13}
  - Solar parameters: $\sin^2(\theta_{12})$, Δm^2_{12}

Open Questions

Disappearance Constraints

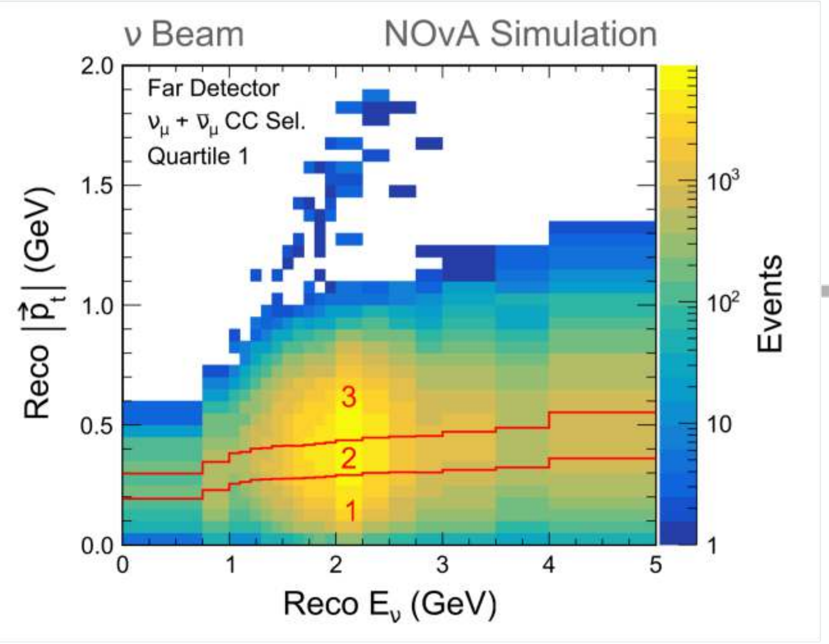
NOvA: $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$

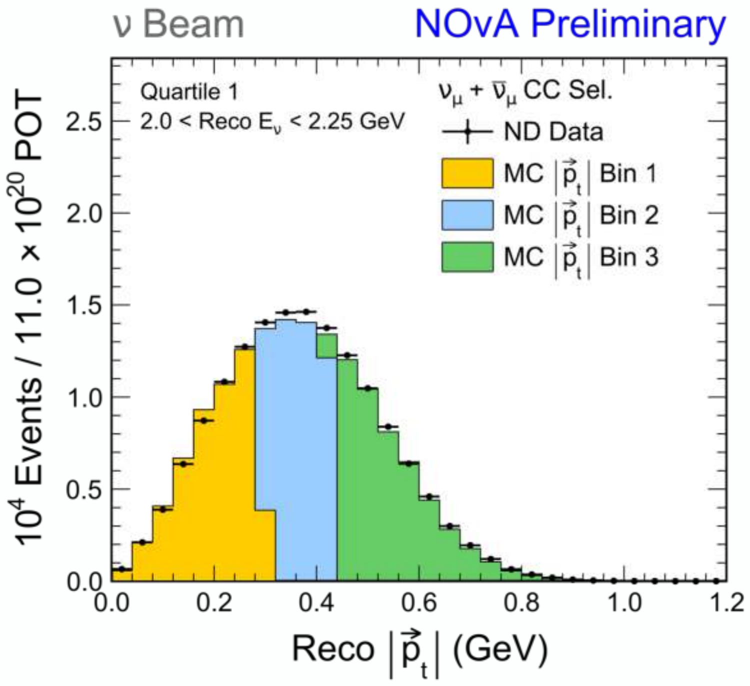
Reactor: $\bar{\nu}_e \to \bar{\nu}_e$

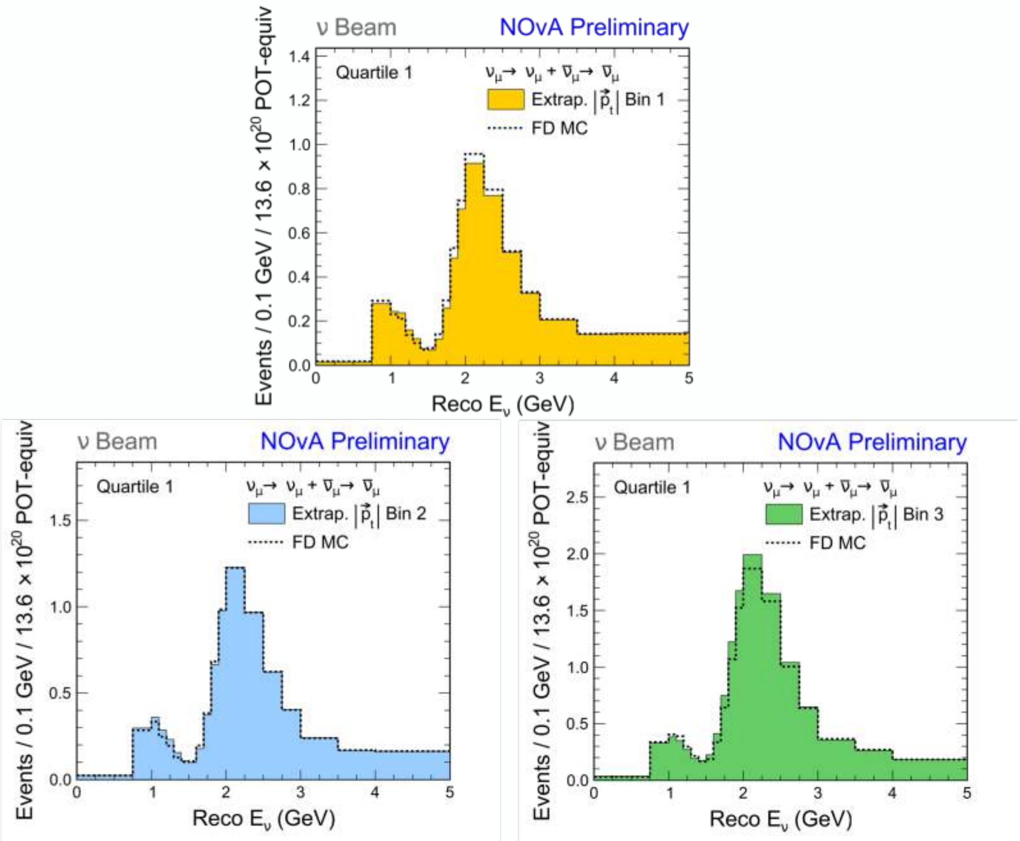
Solar: $\nu_e \to \nu_e$

pT extrapolation

- ND/FD containment difference.
- Split ND samples into 3 bins of transverse momentum and extrapolate separately.
- Reduce cross-section uncertainty by 30%. Overall systematics reduction is 10%.

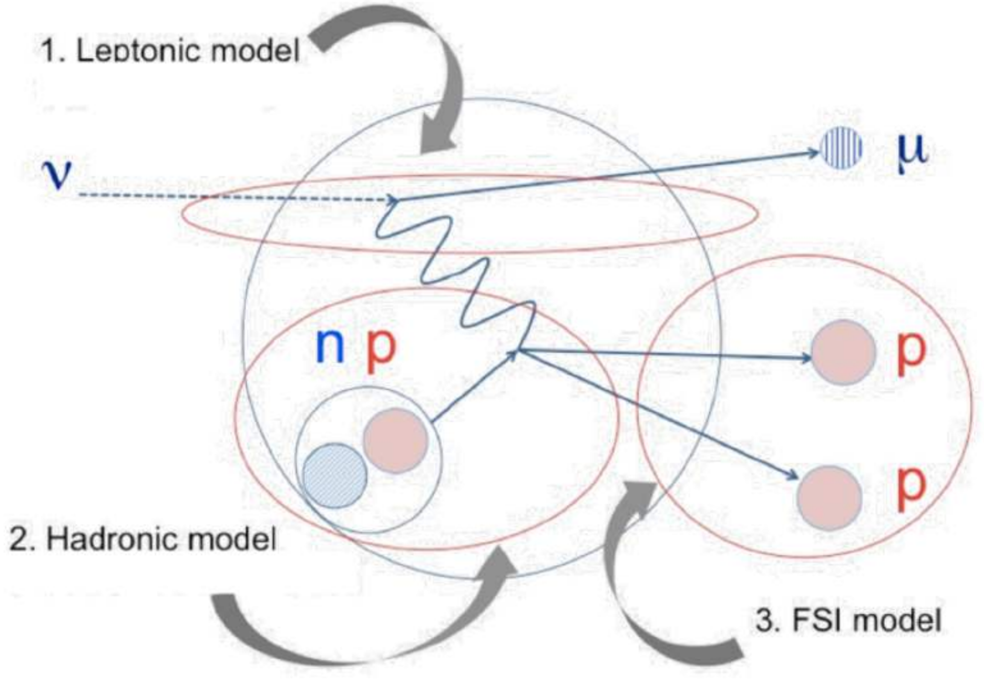






GENIE tune (1)

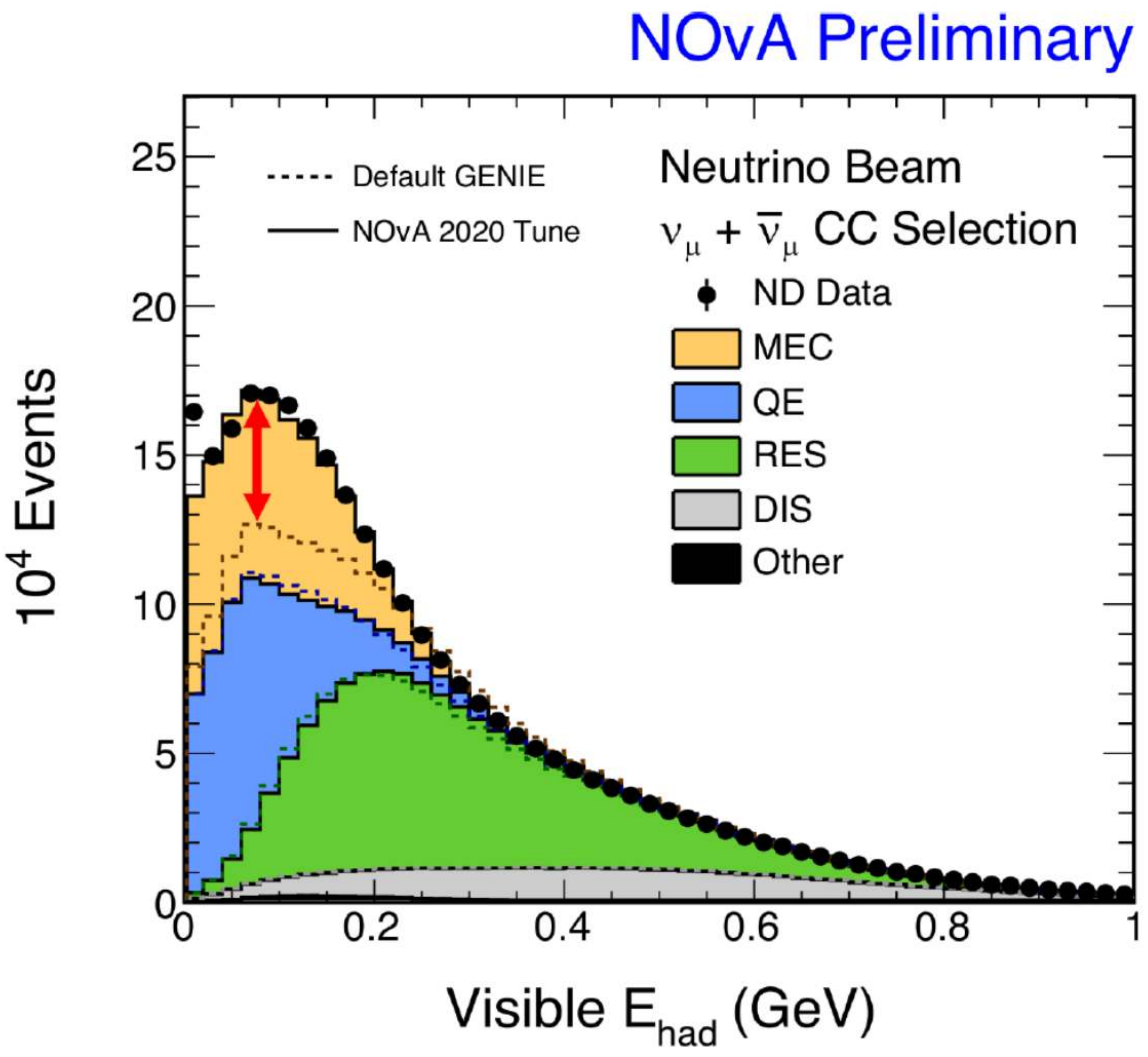
- Used **GENIE 3.0.6** in NOvA 2020 analysis: choose the most theory-driven models and retune some parameters to better match ND data.



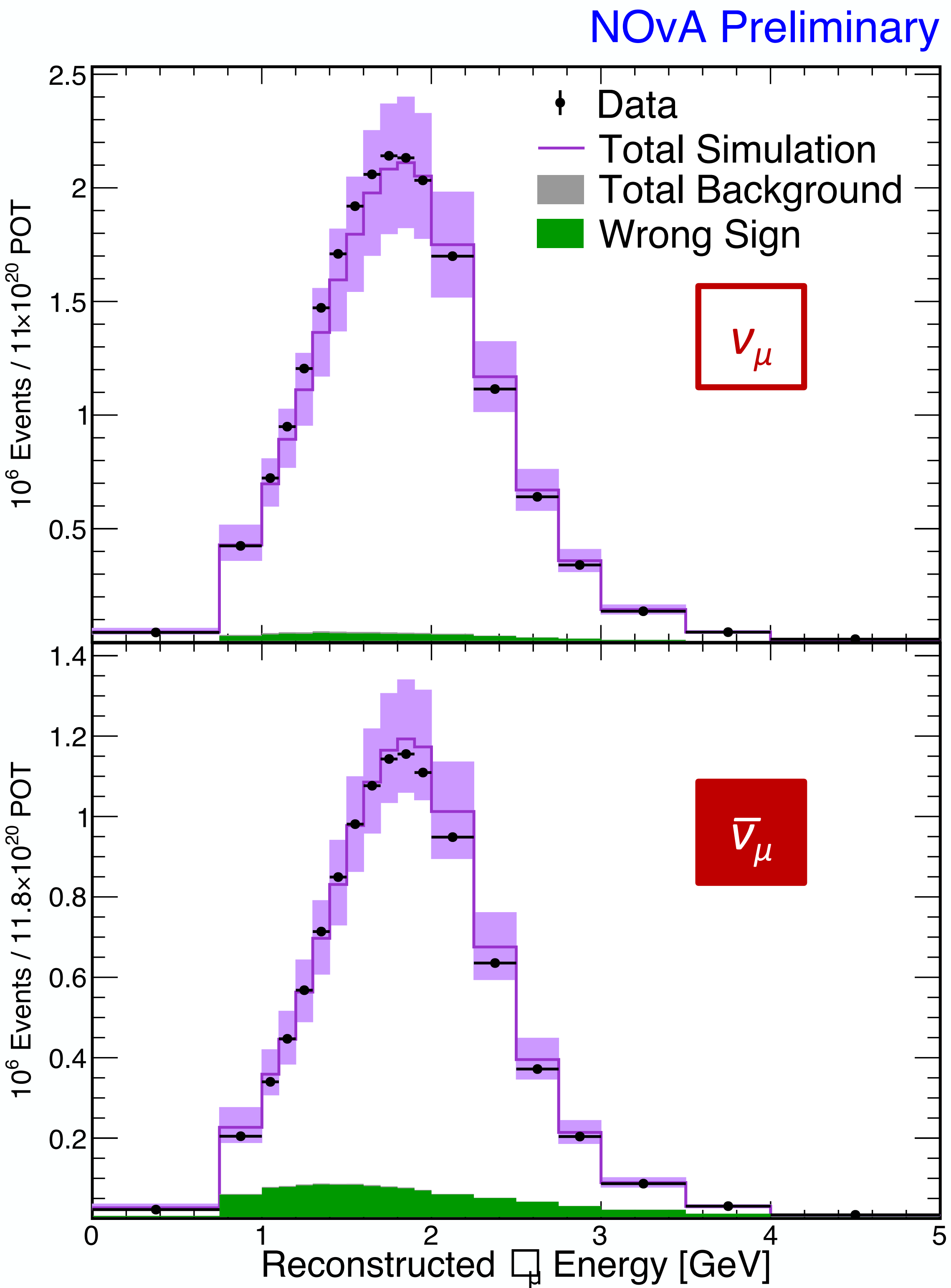
Process	Model
Quasielastic	Valencia 1p1h
Form Factor	Z-expansion
Multi-nucleon	Valencia 2p2h
Resonance	Berger-Sehgal
DIS	Bodek-Yang
Final State Int.	hN semi-classical cascade

GENIE tune (2)

- Largest **tunes**:
  - Meson Exchange Current (MEC or 2p2h): tune to **ND data**
  - Final State Interactions (FSI): use external π-**scattering data**



Near Detector ν_μ Spectra



- Band around the MC shows the large impact of flux and cross-section uncertainties in only a single detector.
- We use this sample to predict both $\boldsymbol{\nu_\mu}$ and $\boldsymbol{\nu_e}$ signal spectra at the Far Detector.
  - Appearing ν_e's are still ν_μ's at the ND

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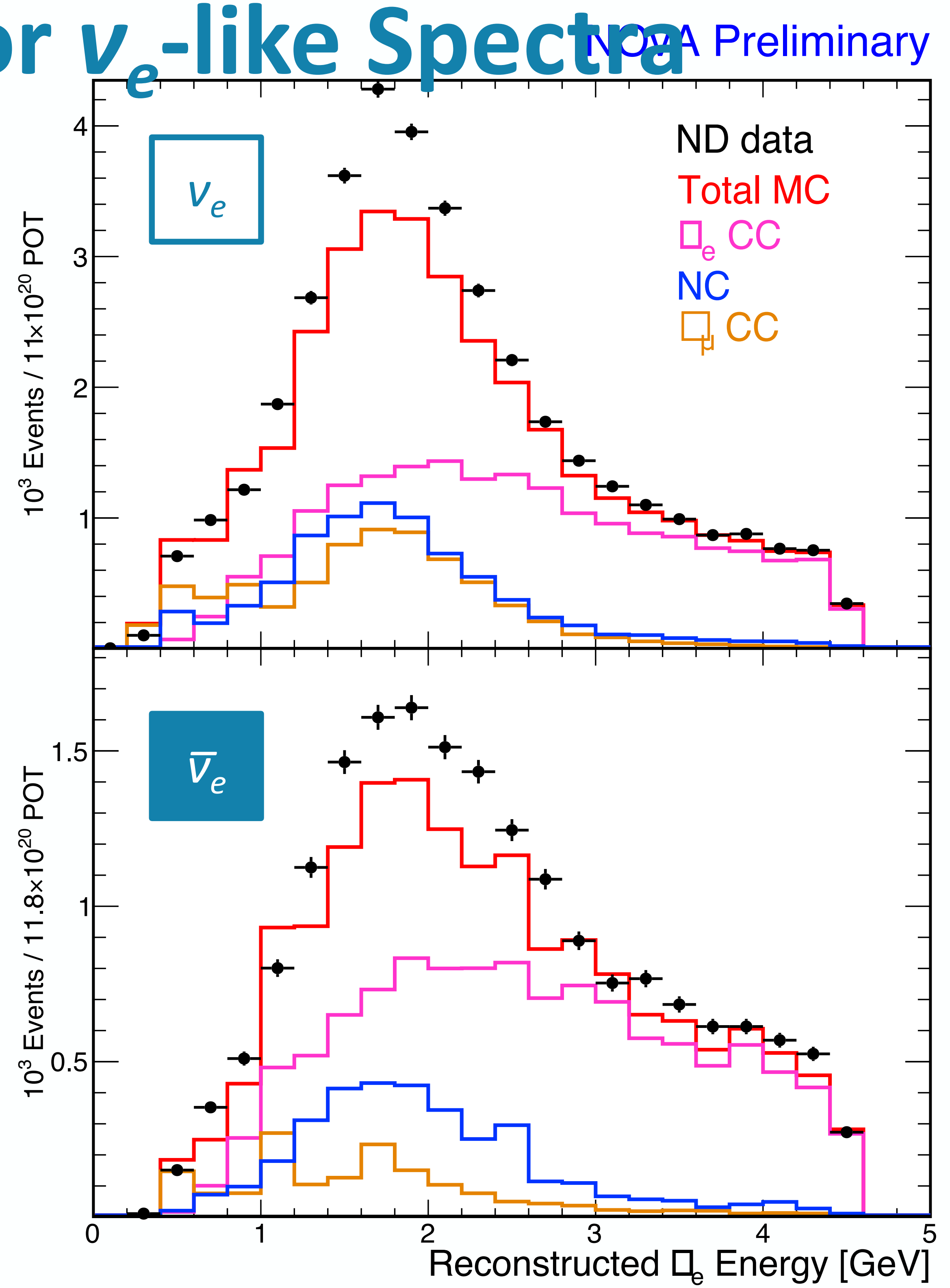
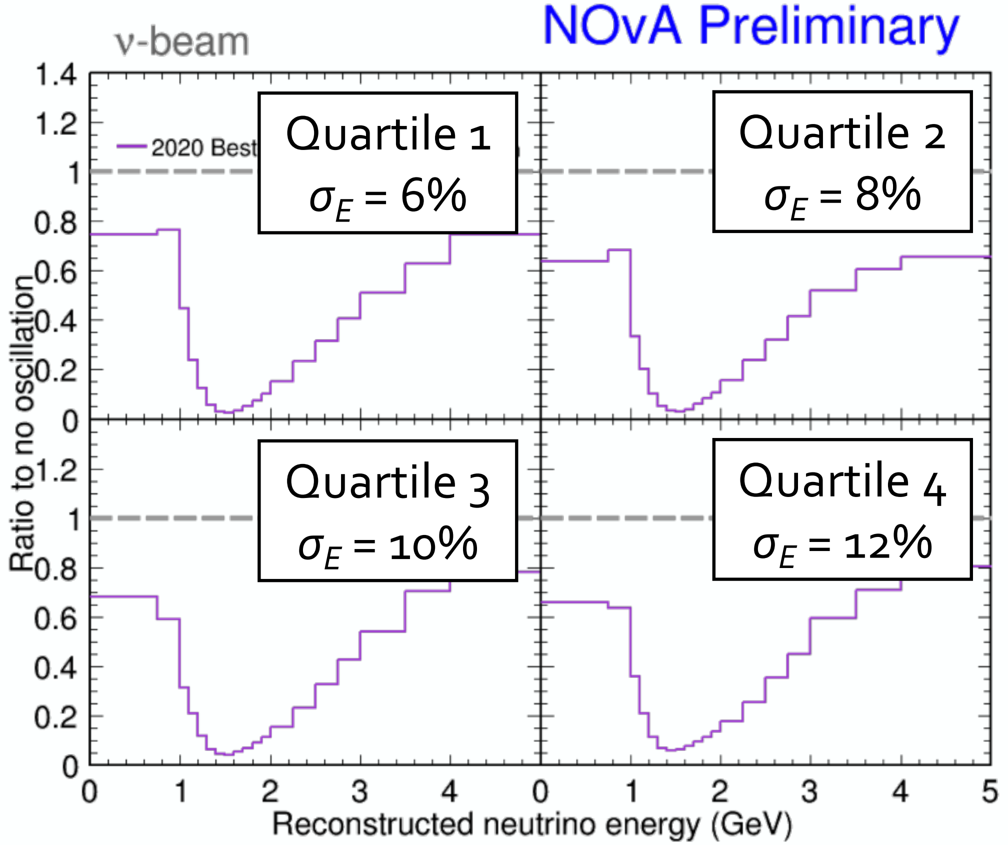
Near Detector ν_e-like Spectra

- The ND ν_e-like spectrum contains the **background** to the appearing ν_e's at the FD.
- Largest background is the irreducible $\nu_e/\bar{\nu}_e$ flux component.
    - 50% in neutrino-mode
    - 71% in antineutrino mode
- We use this sample to predict the background to ν_e appearance.

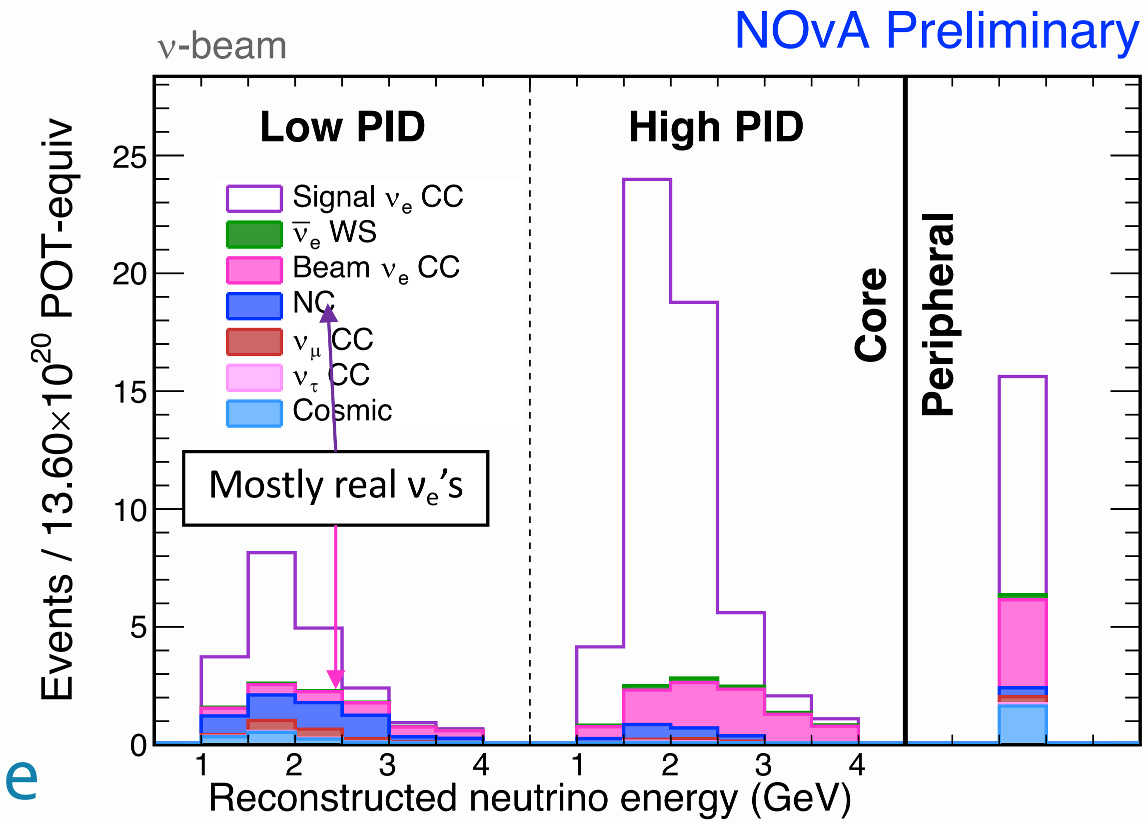


Enhancing Sensitivity to Oscillations



ν_μ sample

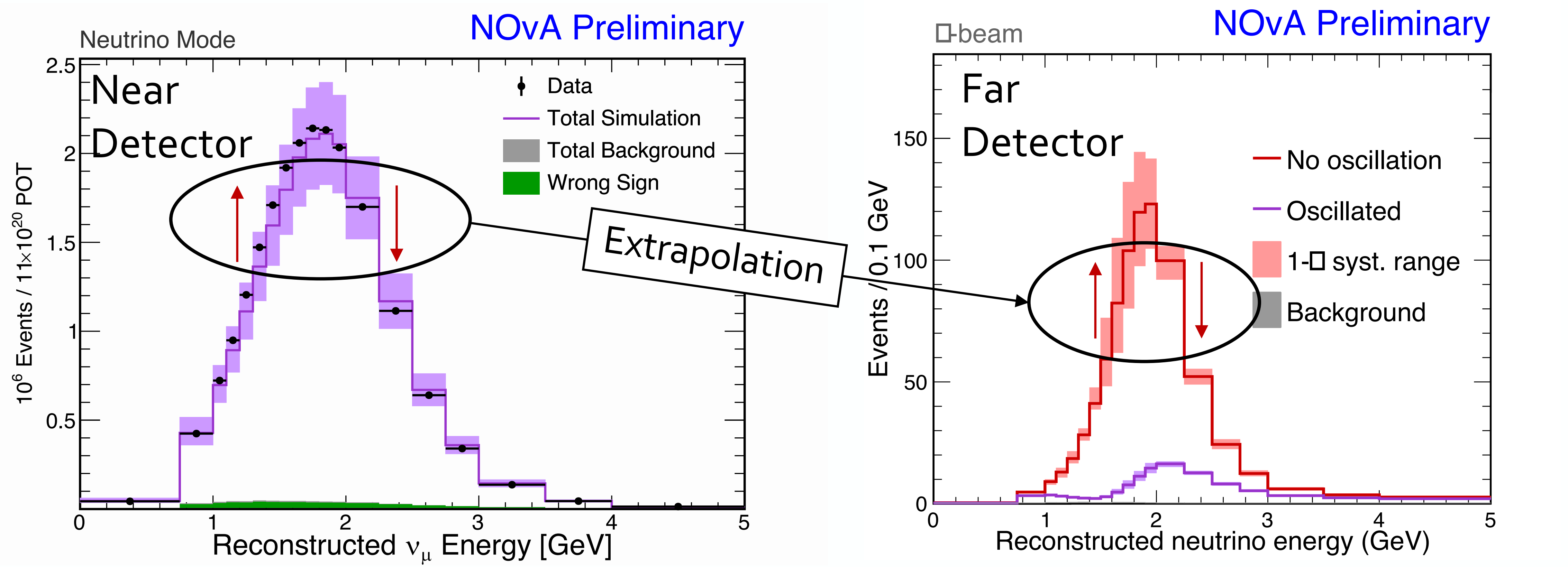
- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by *energy resolution* → bin by hadronic energy fraction



ν_e sample

- Sensitivity depends primarily on separating signal from background.
- Bin by *purity* → bins of low & high PID
- Peripheral sample:
  - Captures high-PID events which might not be contained close to detector edges.
  - No energy binning.

Extrapolating from Near to Far Detector



- Observe data-MC differences at the ND, use them to modify the FD MC.
  - Extrapolation performed in the analysis binning of energy + (resolution or PID).
- Significantly reduces the impact of uncertainties correlated between detectors
  - Especially effective at rate effects like the flux (7% → 0.3%).