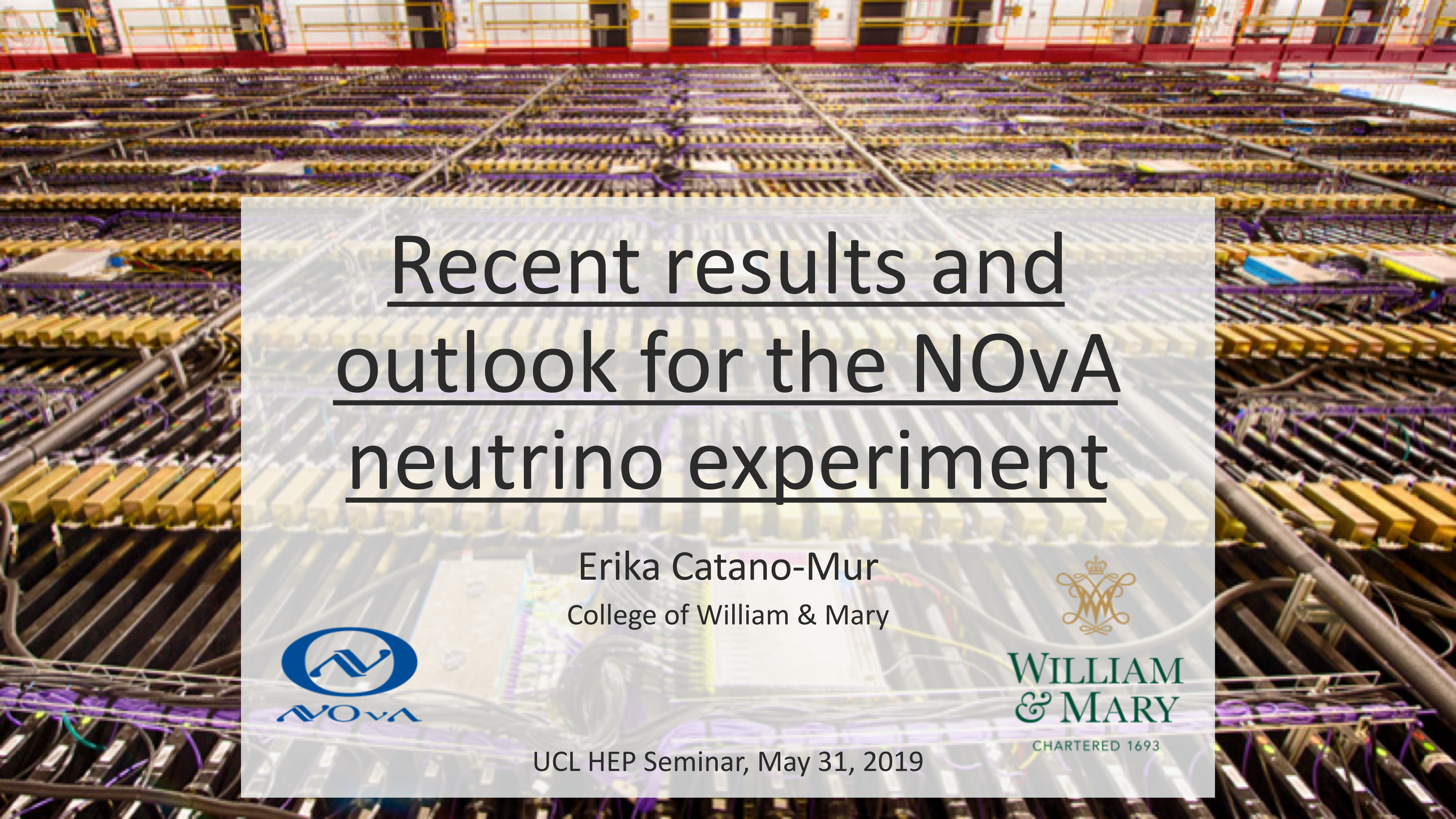


Recent results and outlook for the NOvA neutrino experiment

Erika Catano-Mur

College of William & Mary

UCL HEP Seminar, May 31, 2019

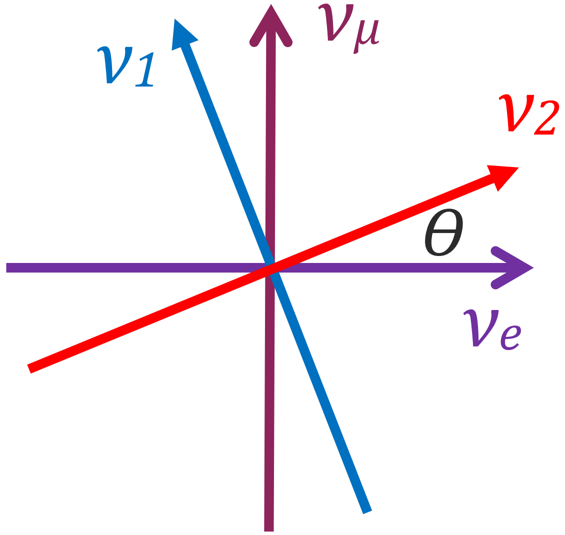
Neutrino oscillations

- In the SM, neutrinos are massless. We now have experimental evidence for oscillations of neutrinos caused by nonzero masses and neutrino mixing → (new) physics beyond the Standard Model.
- Create in one flavor (ν_μ), but detect in another (ν_e)

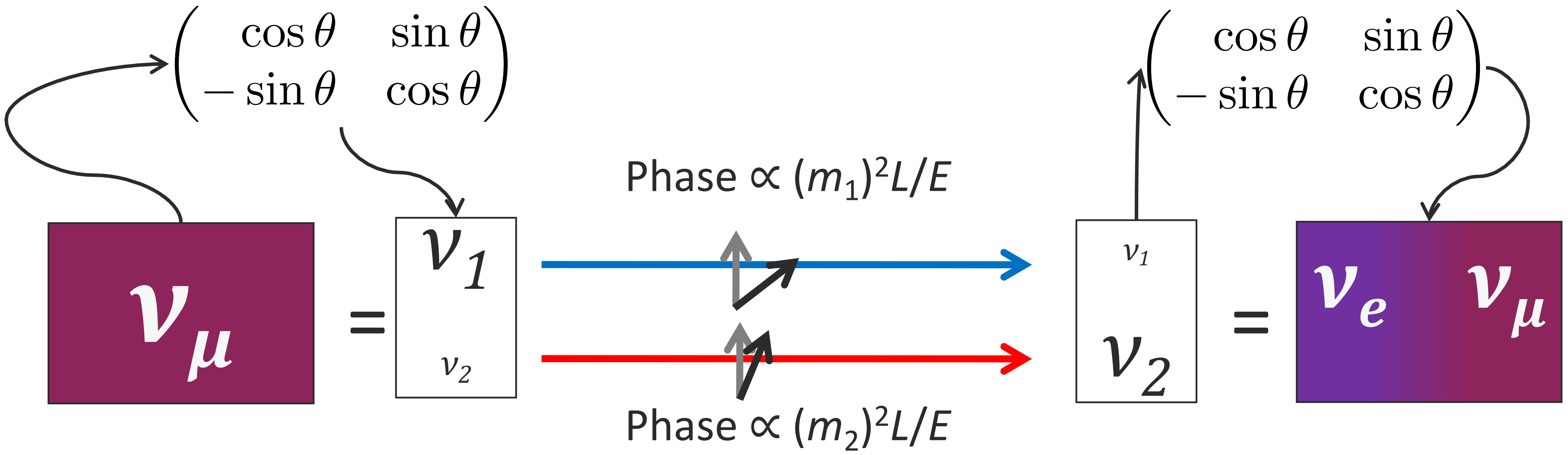
- Each **flavor (e, μ)** is a superposition of different **masses (1, 2)**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

"Mixing Matrix"



Two-flavor oscillations



$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

ν_μ = ν_1 ν_2

Phase ∝ $(m_1)^2 L/E$

Phase ∝ $(m_2)^2 L/E$

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

ν_1 ν_2 = ν_e ν_μ

Neutrino oscillations require that neutrinos have mass!

Appearance probability

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Survival (disappearance) probability

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e)$$

Experimentally, we care about:

1. The elements of the mixing matrix
2. Squared differences of neutrino masses

(Measurement)

3. Distance/energy (L/E) ratio (Set by expt.)

Three-Flavor Oscillations

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

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

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

- The (12) sector: Solar and Reactor, L/E 15,000 km/GeV
- The (23) sector: Atmospheric and Accelerator, L/E 500 km/GeV
- The (13) sector: Reactor and Accelerator, L/E 500 km/GeV

$$\sin^2\theta_{12} = 0.304 \pm 0.014 \qquad \sin^2\theta_{23} = 0.51 \pm 0.05$$
$$\sin^2\theta_{13} = 0.0219 \pm 0.0012 \qquad \delta_{CP} = ?$$

(from global averages)

$\delta_{CP} \neq 0, \pi$

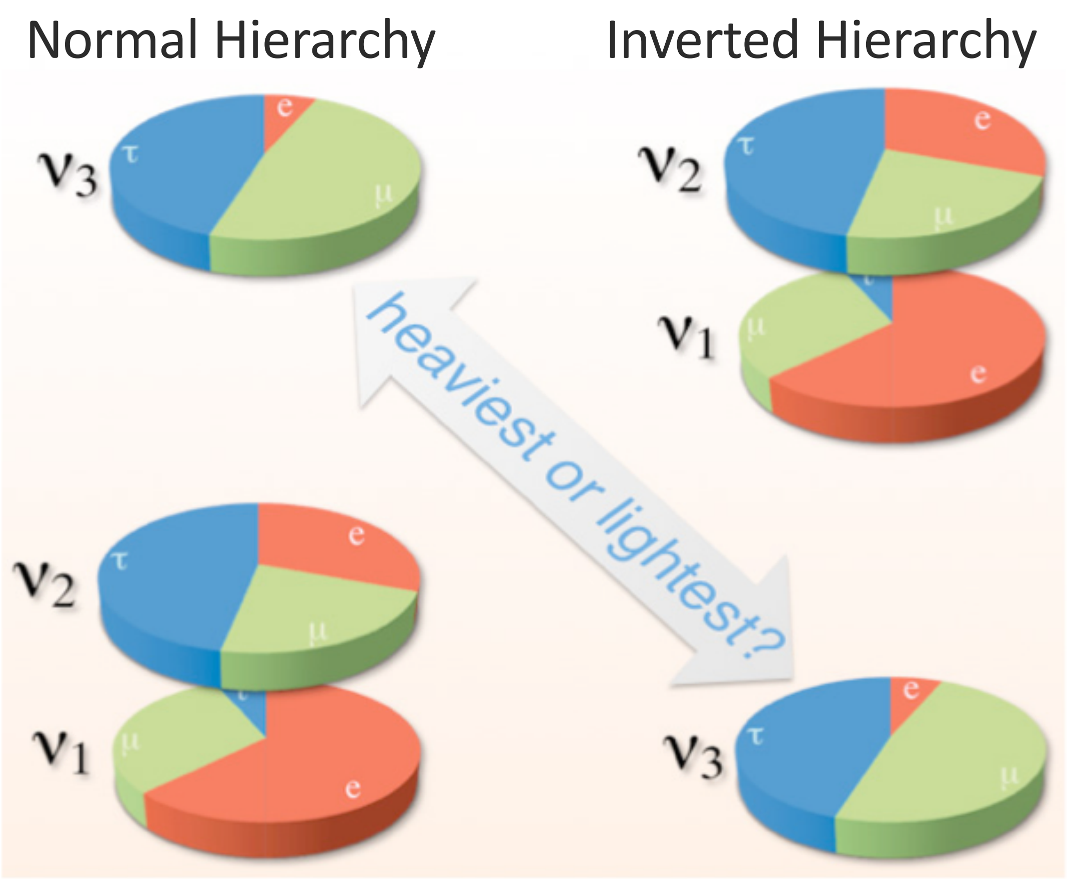
→CP violation

→ diff. (anti)neutrinos

Squared mass differences and hierarchy

- Neutrino oscillation experiments can access the mass differences squared

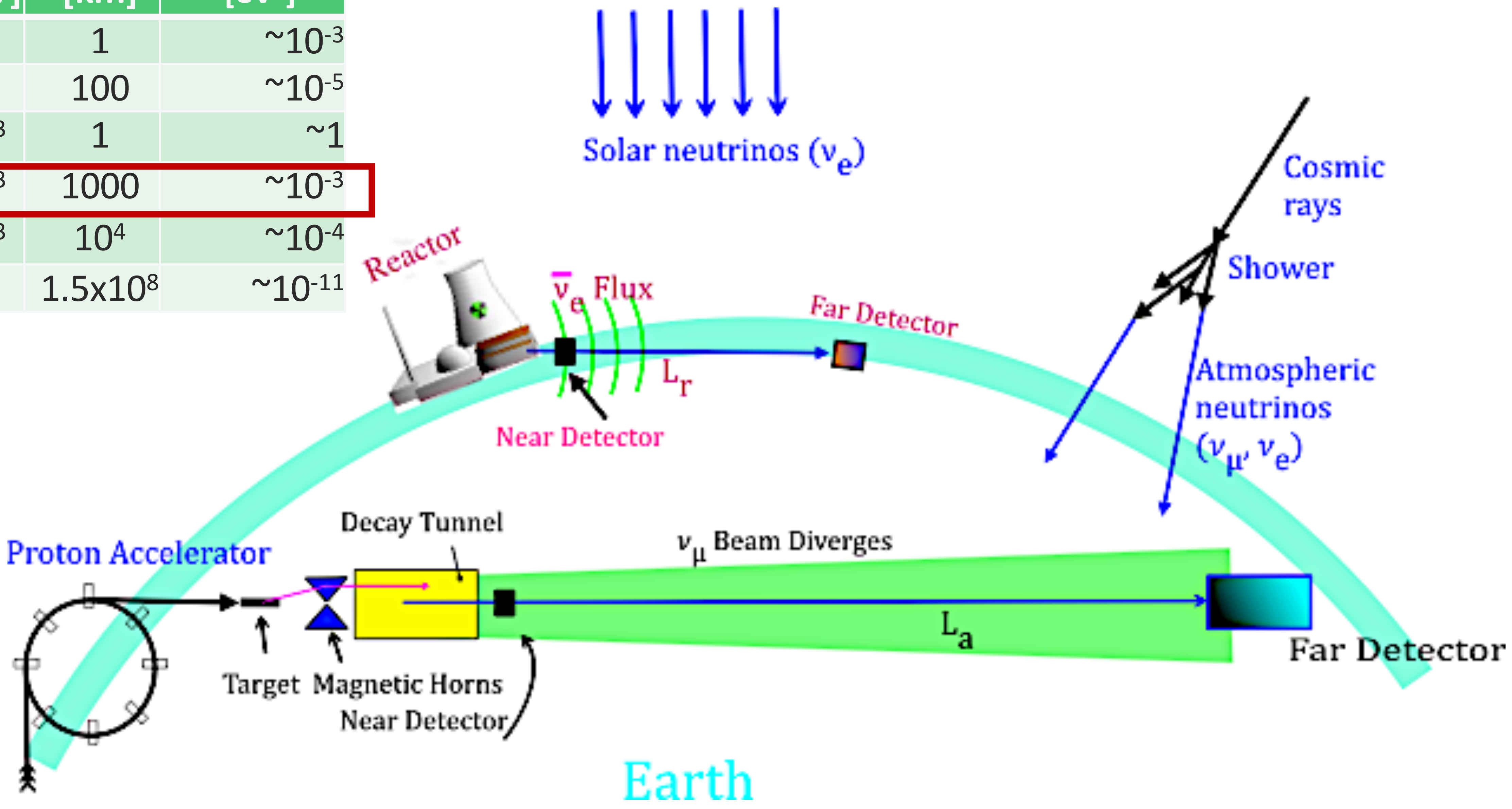
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$$



- By convention, we denote the mass eigenstate with the largest fraction of ν_e as ν_1
- We haven't determined which 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

Sources of ν's for oscillation studies

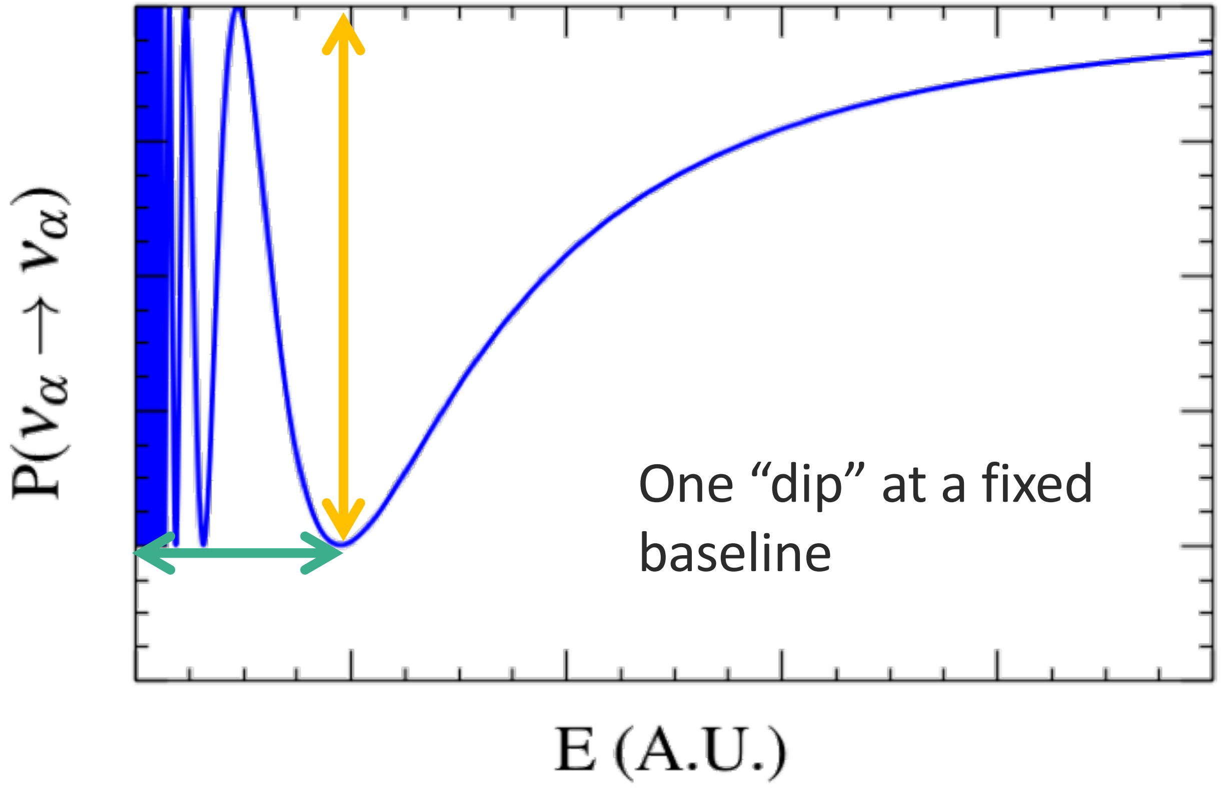
Source	Type of ν	E [MeV]	L [km]	$\min(\Delta m^2)$ [eV²]
Reactor	$\overline{\nu}_e$	~1	1	~10^{-3}
Reactor	$\overline{\nu}_e$	~1	100	~10^{-5}
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	~10^3	1	~1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	~10^3	1000	~10^{-3}
Atmospheric	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	~10^3	10^4	~10^{-4}
Solar	ν_e	~1	1.5×10^8	~10^{-11}



$\nu_\mu \to \nu_\mu$ oscillations

- Probability of ν_μ survival in a ν_μ beam

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



One “dip” at a fixed baseline

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

- Probability of ν_e appearance in a ν_μ beam

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

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

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

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

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

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

Open Questions

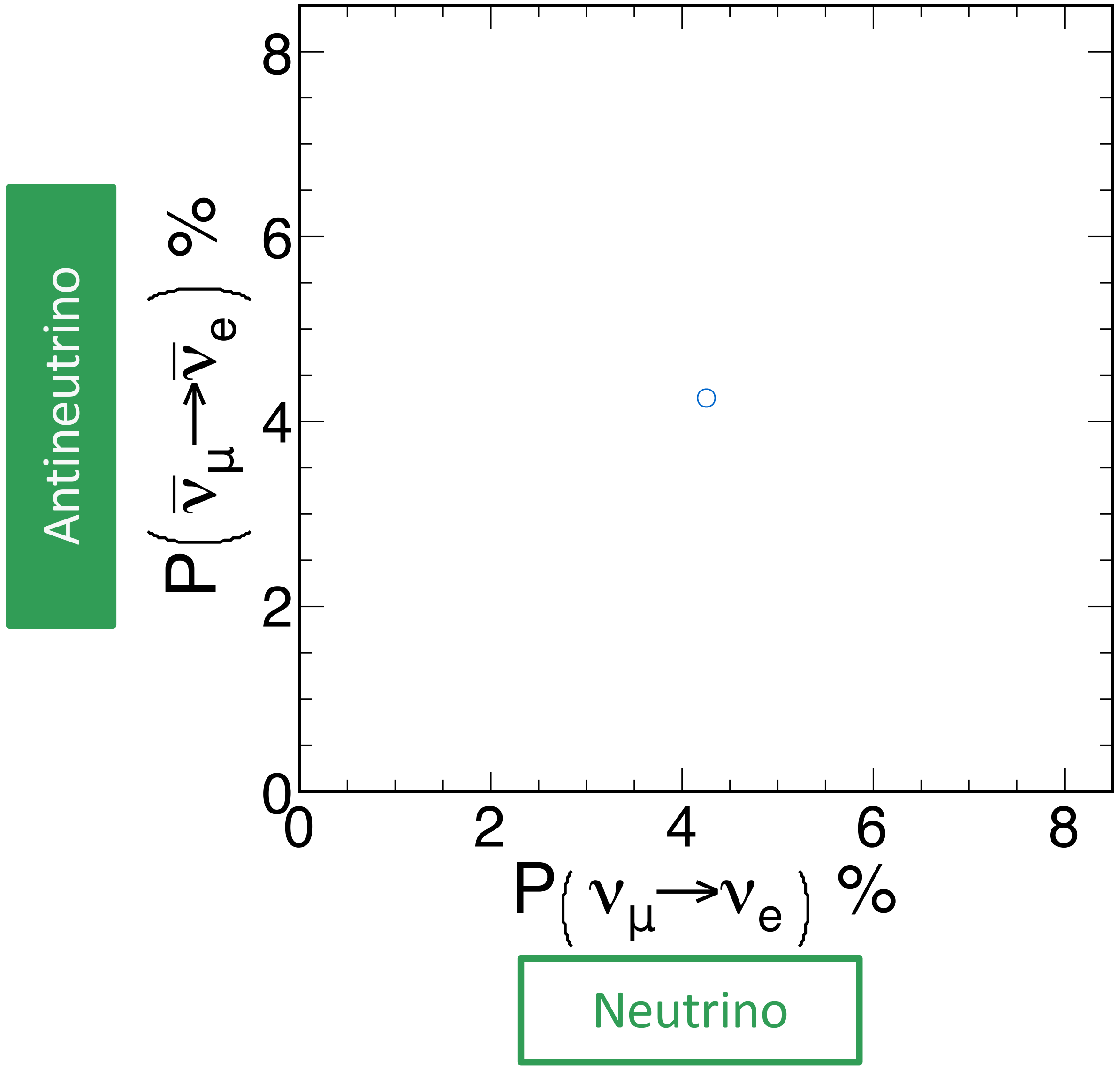
Disappearance Constraints

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

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

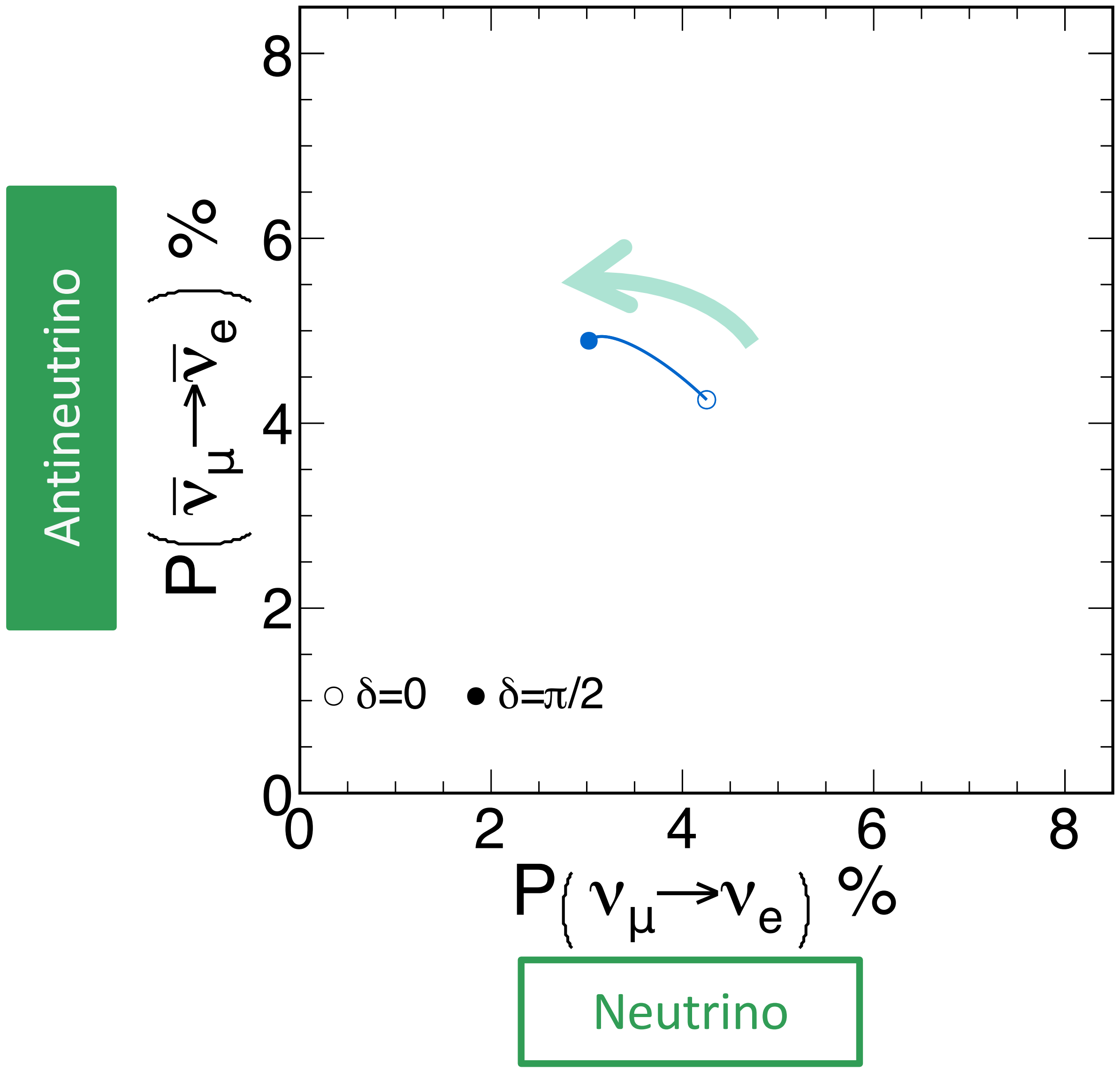
Solar: $\nu_e \to \nu_e$

Electron neutrino vs antineutrino appearance



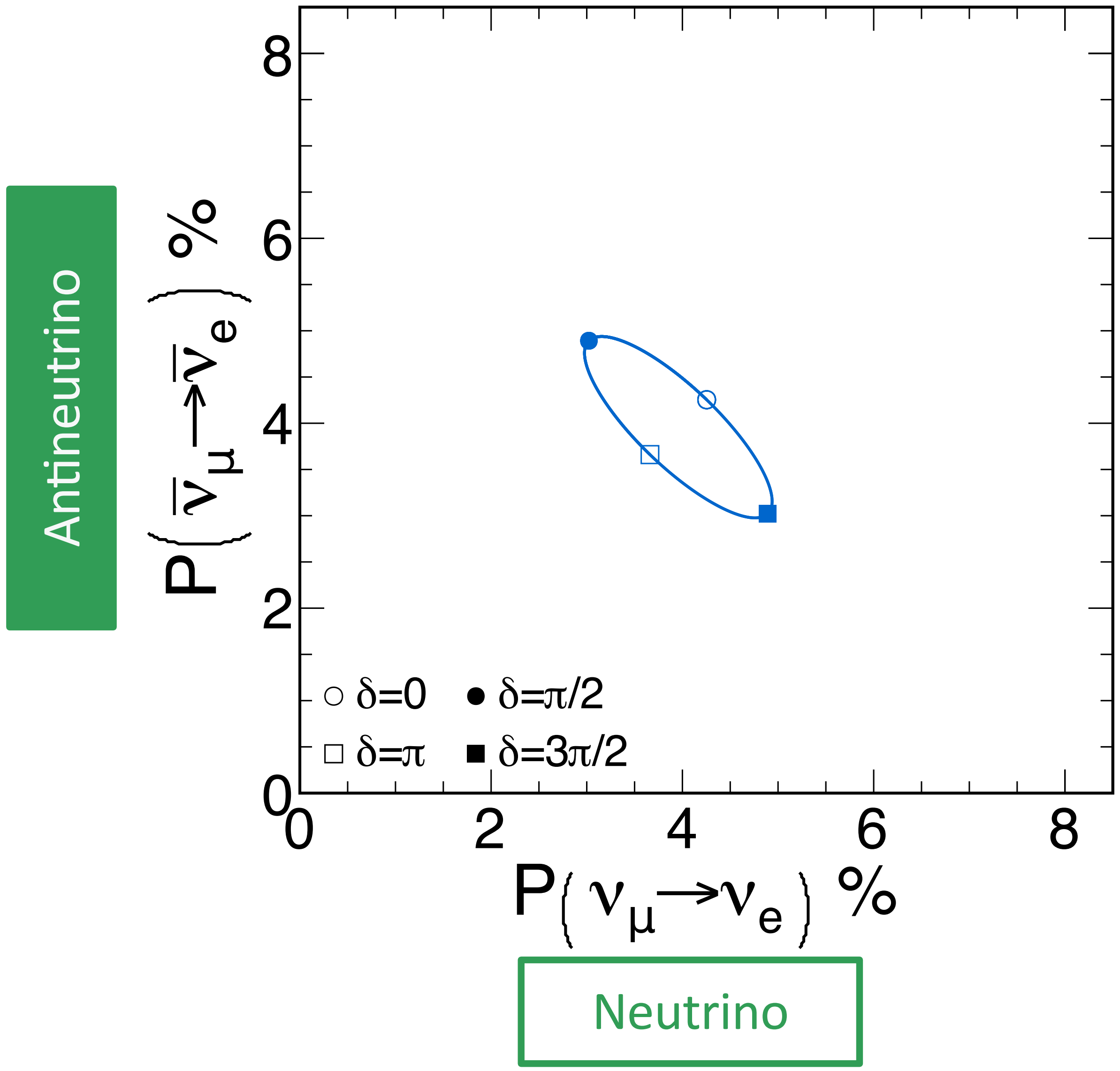
Vacuum and no CP violation: neutrinos and antineutrinos are the same

Electron neutrino vs antineutrino appearance



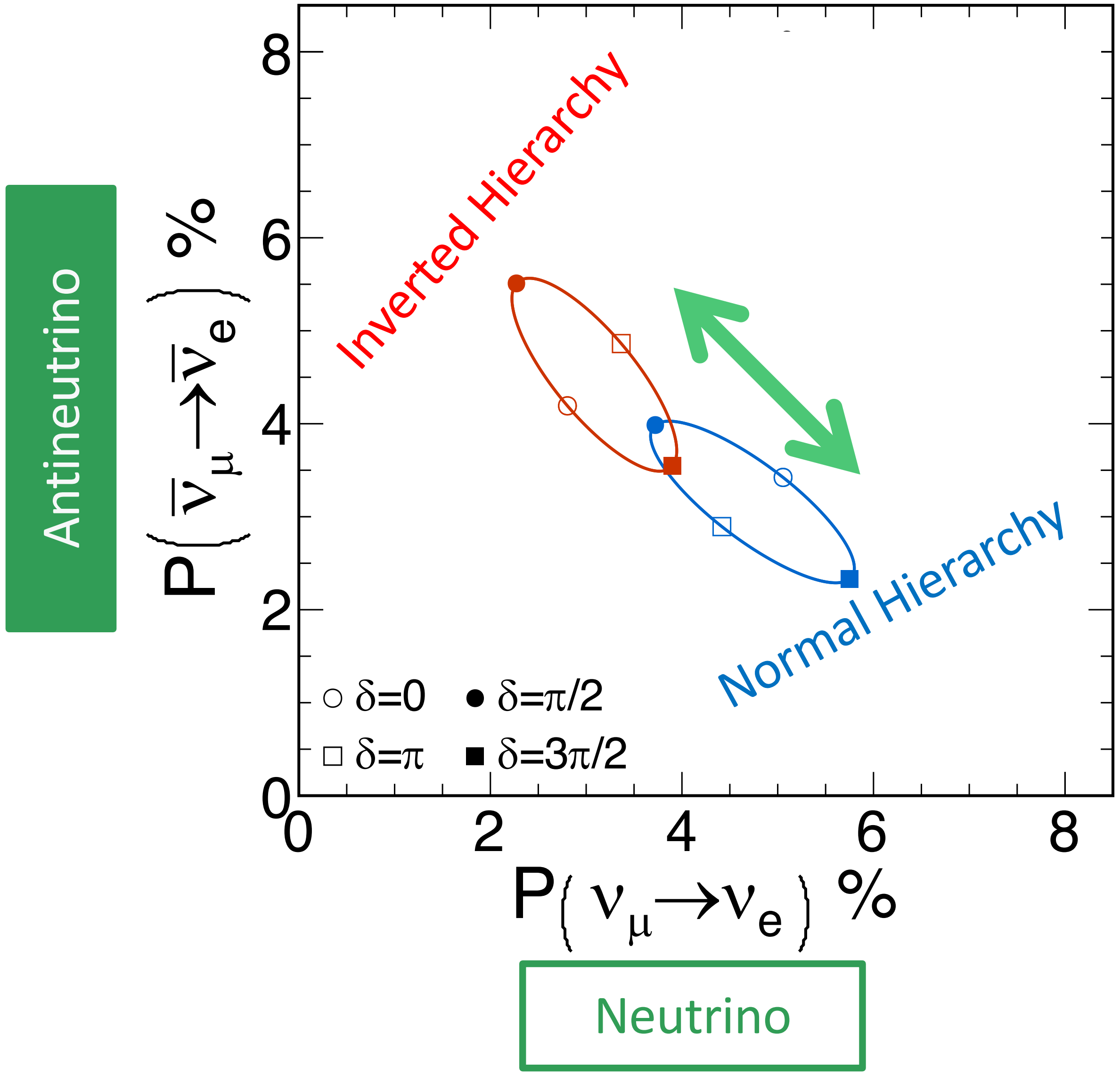
CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Electron neutrino vs antineutrino appearance



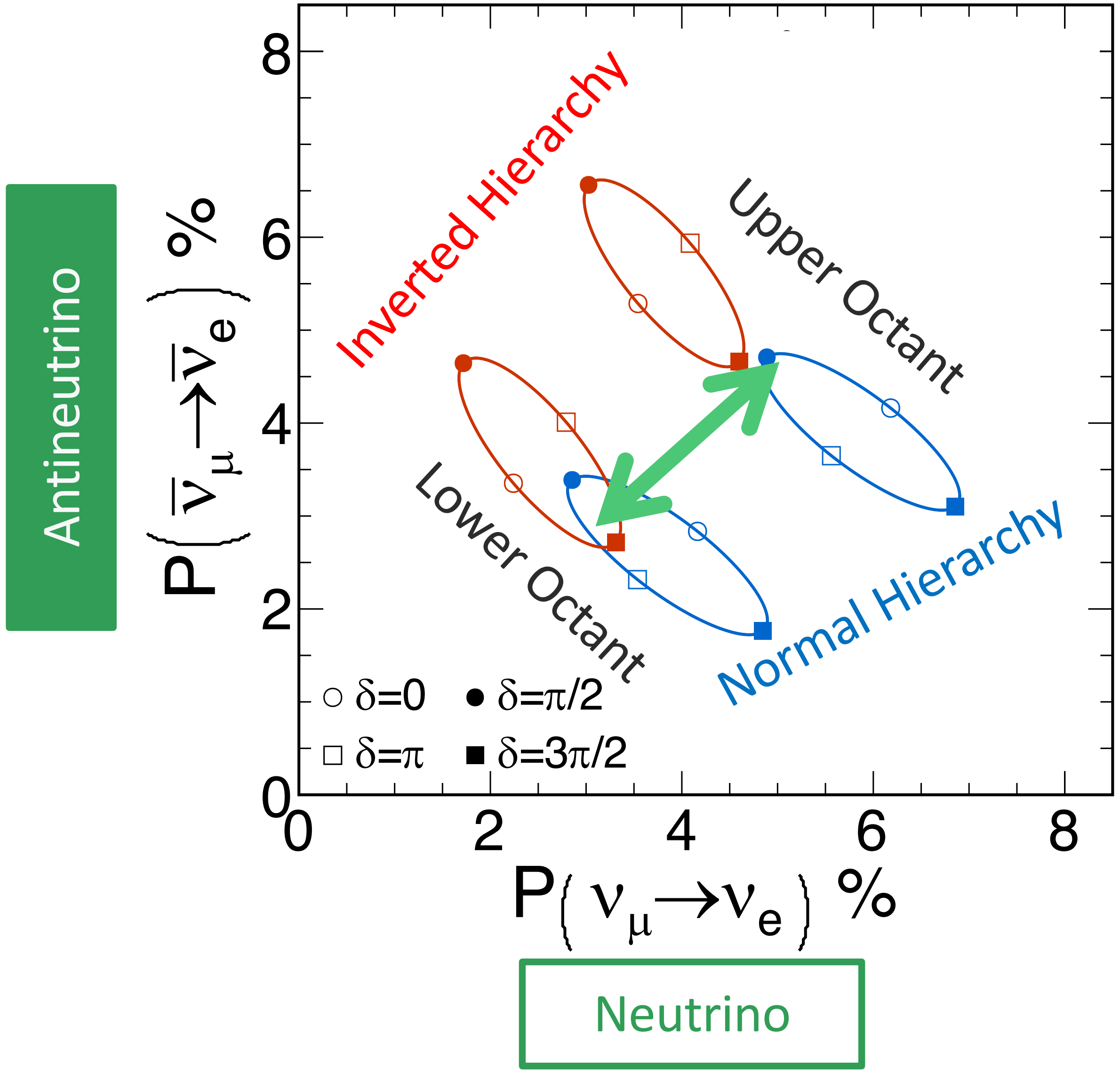
CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Electron neutrino vs antineutrino appearance



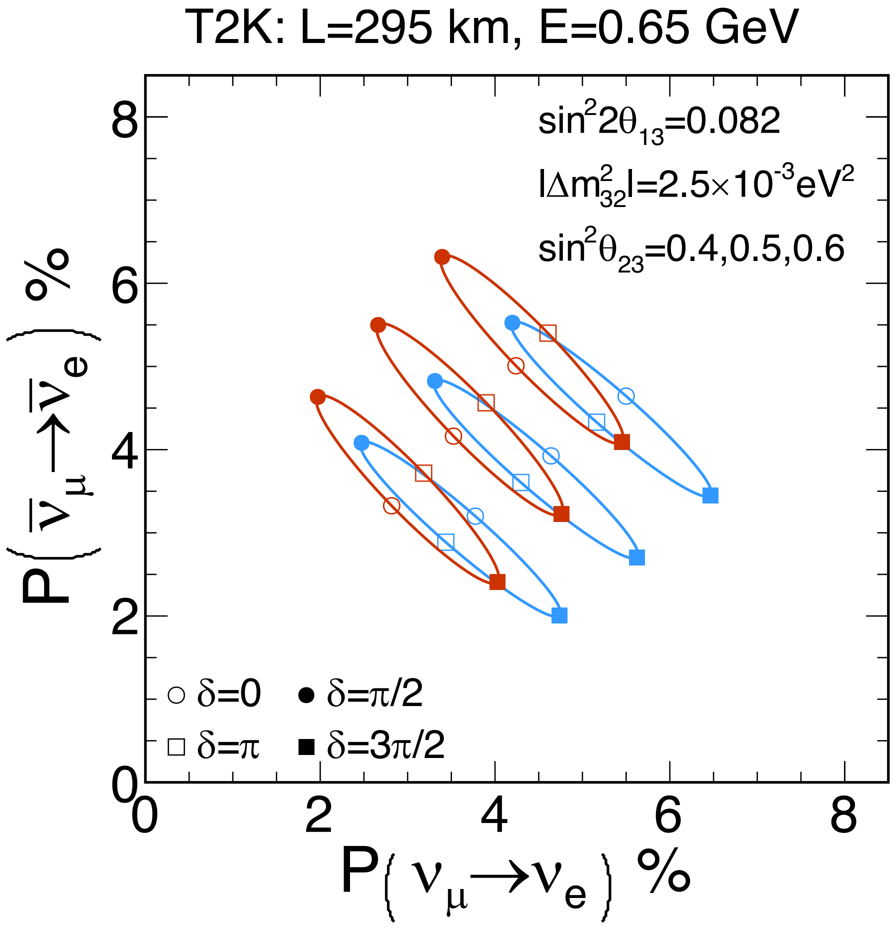
Matter effects also introduce opposite neutrino-antineutrino effects.

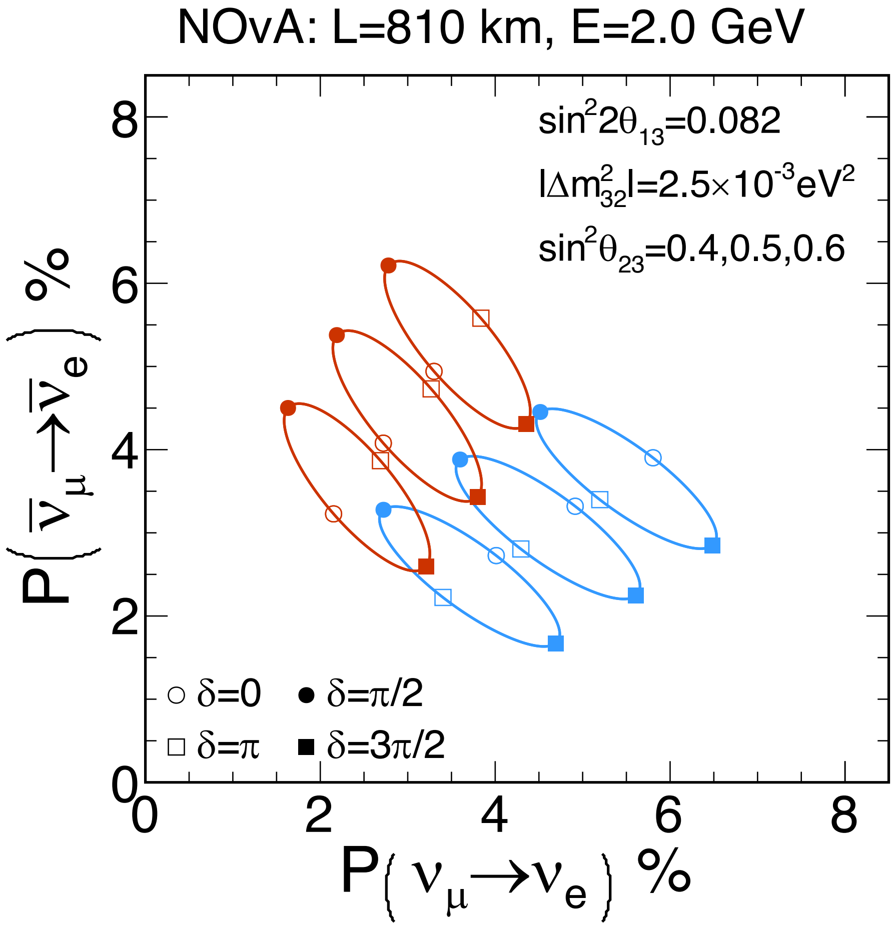
Electron neutrino vs antineutrino appearance

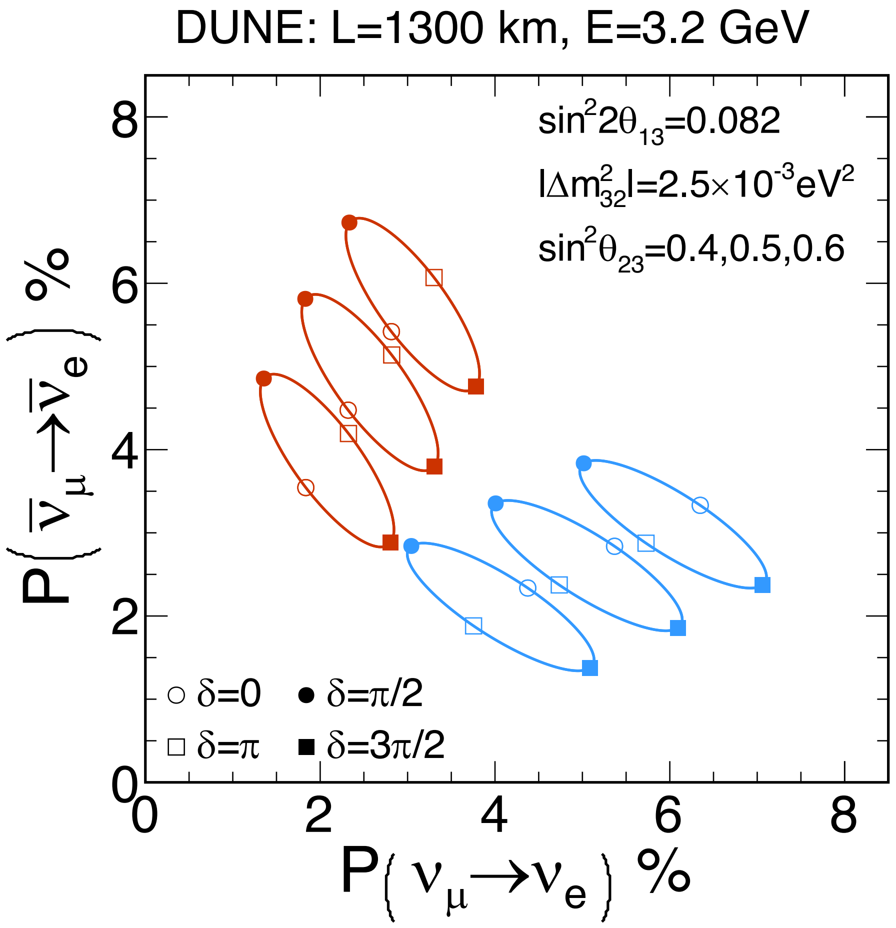


The octant creates the same effect in neutrinos and antineutrinos.

Comparing long baseline experiments

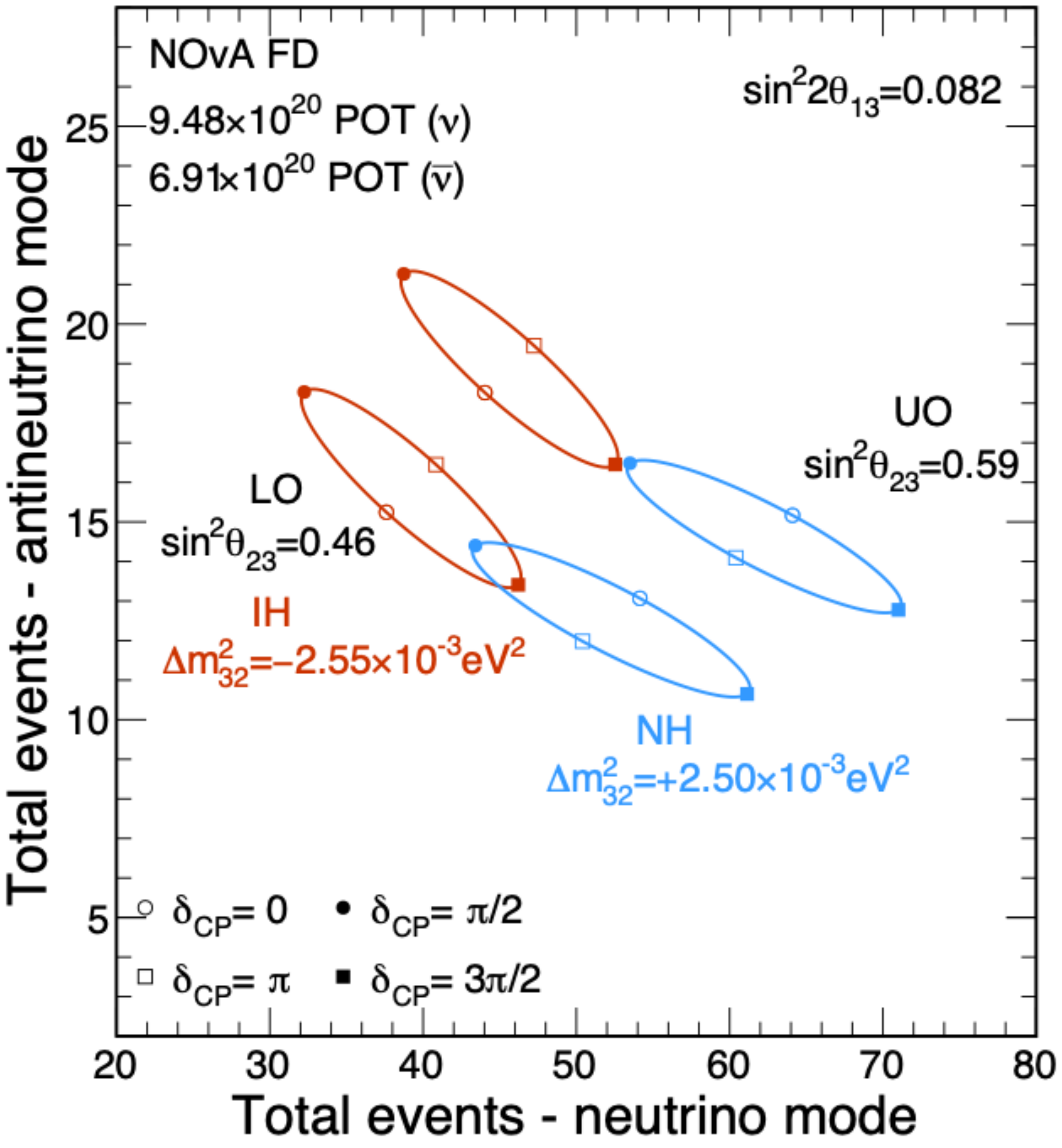

T2K: L=295 km, E=0.65 GeV


NOvA: L=810 km, E=2.0 GeV


DUNE: L=1300 km, E=3.2 GeV

NOvA's physics goals

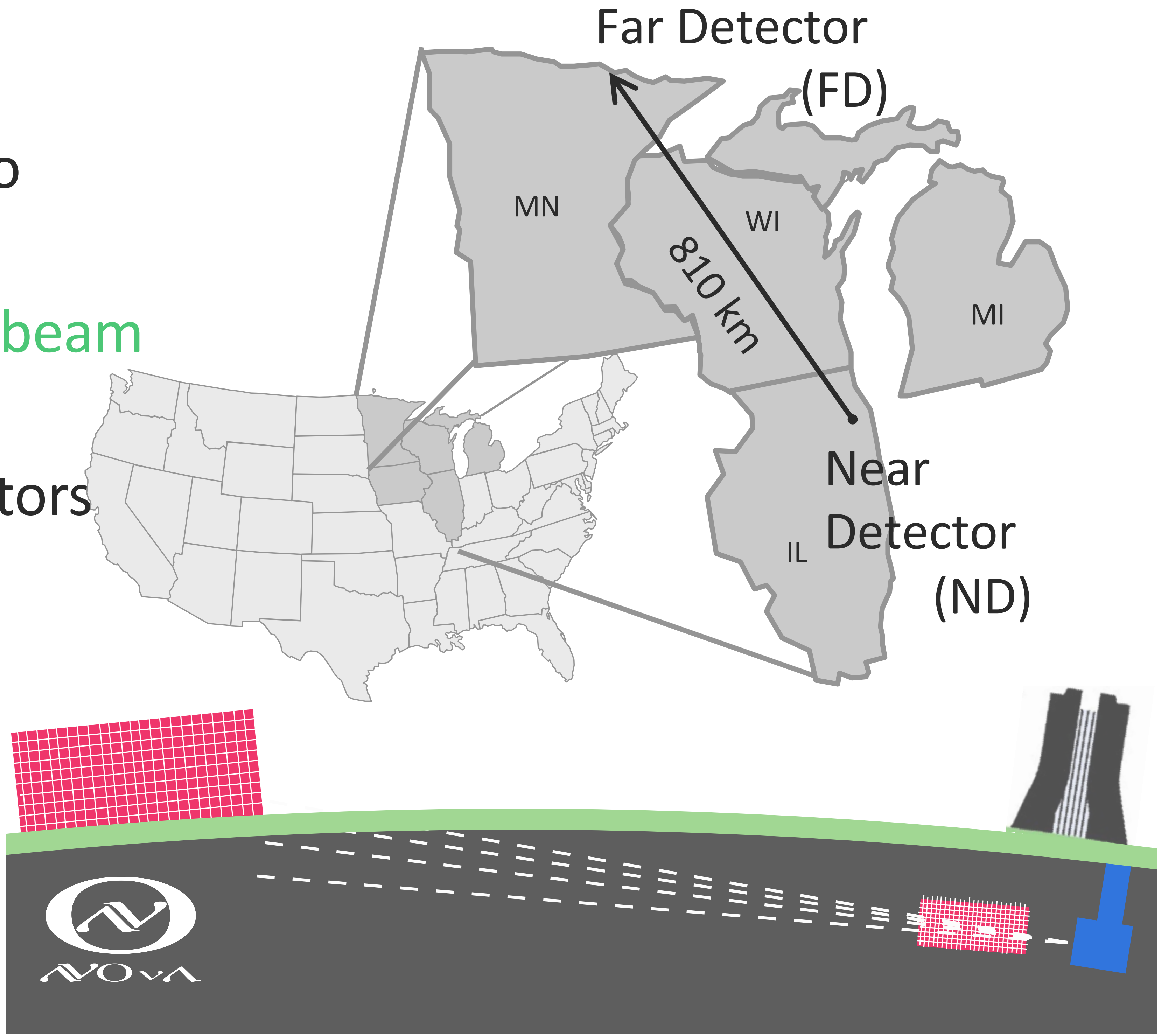
- Is the mass hierarchy "normal" or "inverted"?
- Is there a ν_μ - ν_τ symmetry? I.e., is the large mixing angle maximal? If not, what is the octant?
- Is CP violated in the lepton sector?



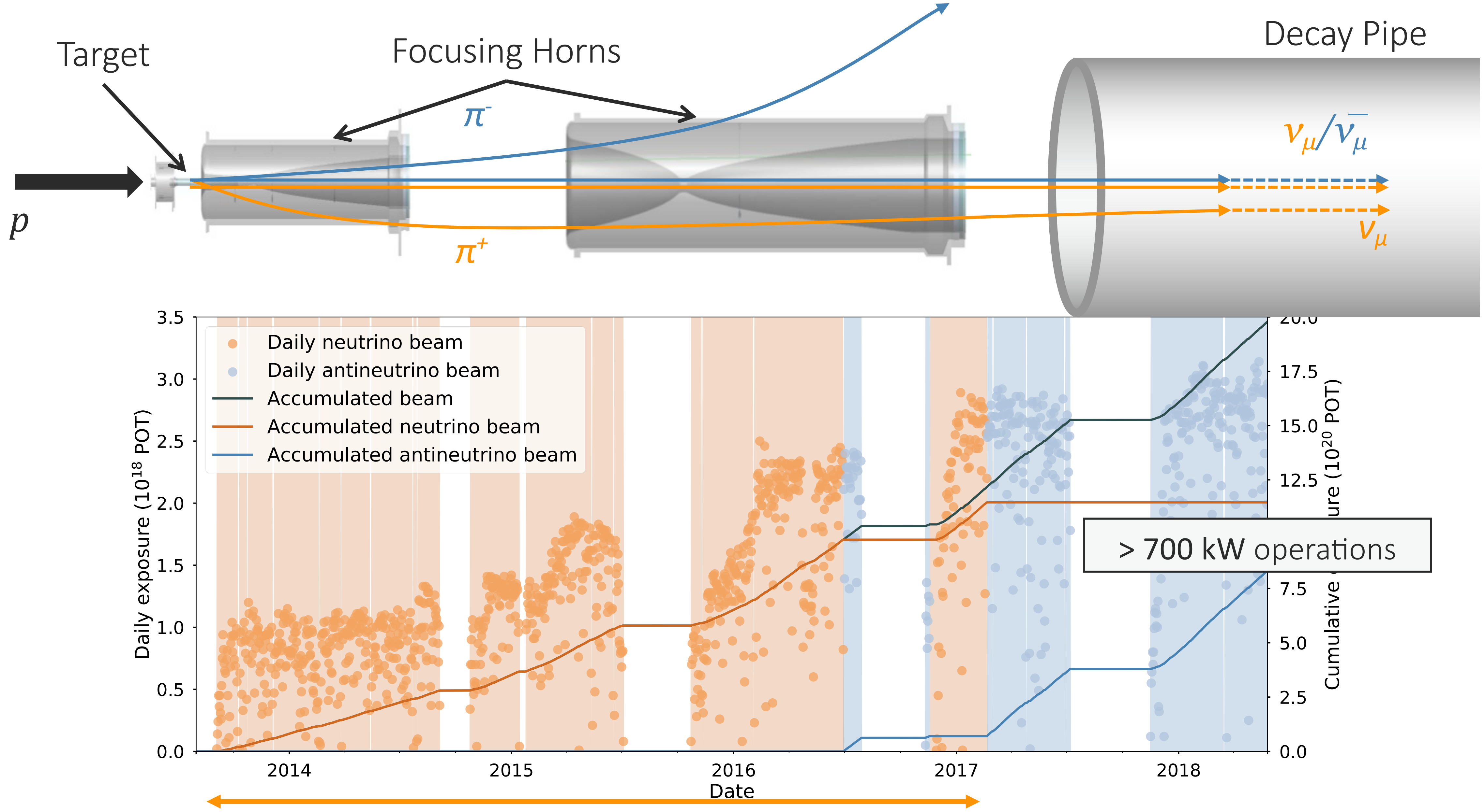
In addition: Are there other neutrinos beyond the three known active flavors?
Plus: cross section analyses, searches for exotic phenomena and non-beam physics

NOvA

- NOvA is a long-baseline neutrino oscillation experiment
- Study neutrinos from the NuMI beam at Fermilab
- Two functionally identical detectors
  - Far Detector (FD)
    14 kton; on the surface
  - Near Detector (ND)
    0.3 kton; underground



The NuMI neutrino beam

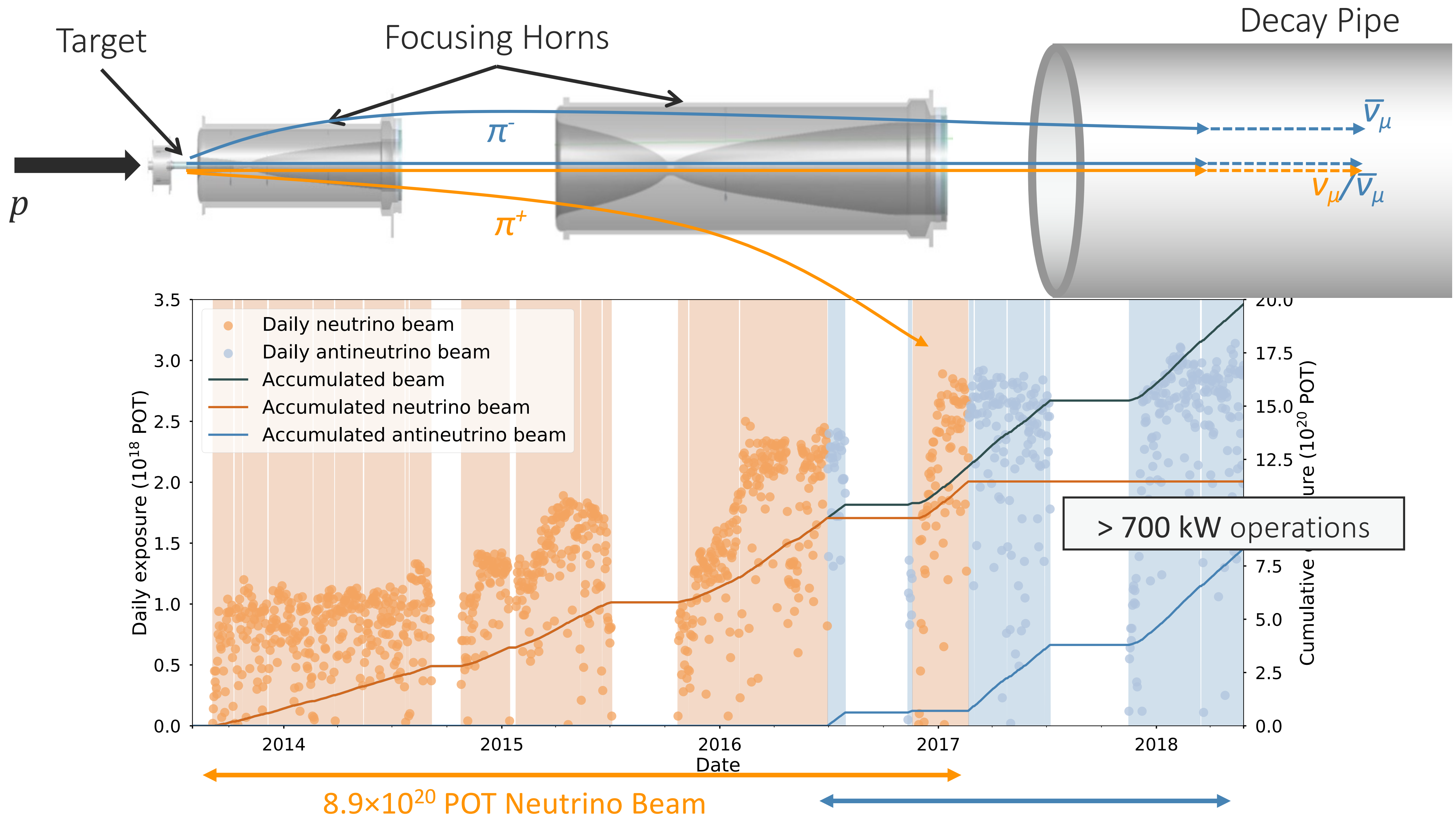


> 700 kW operations

8.9×10^{20} POT Neutrino Beam

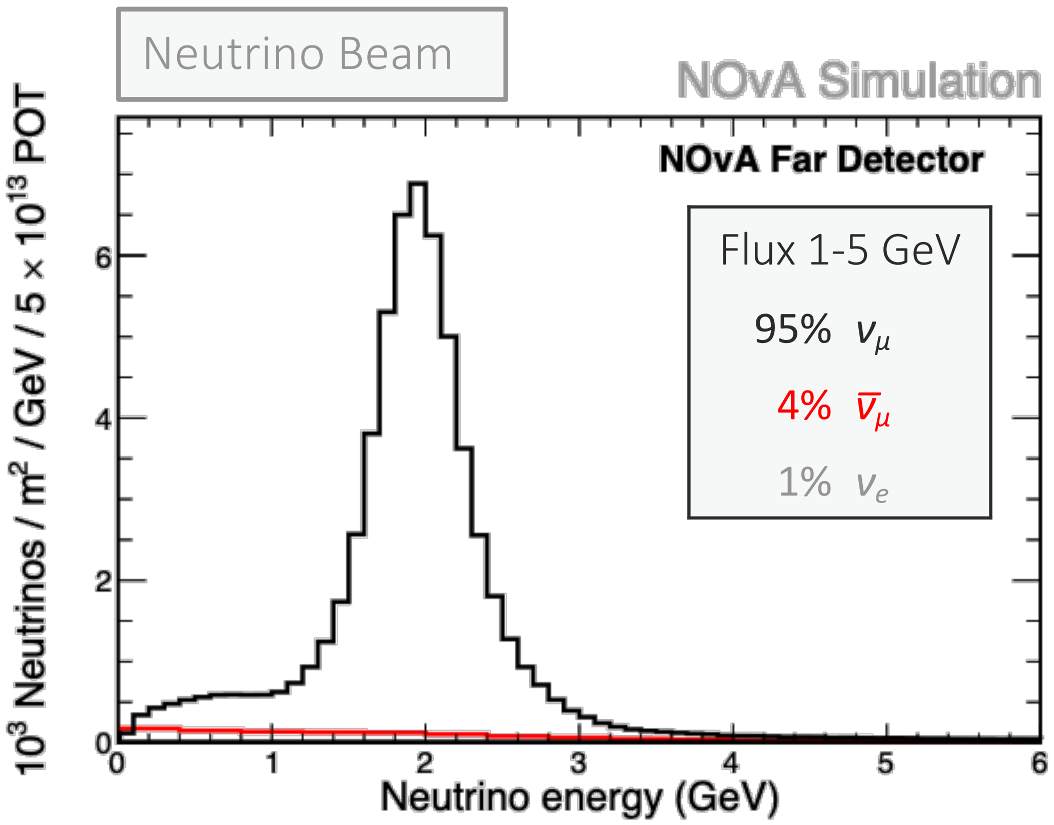
Erika Catano-Mur (William & Mary, NOvA)

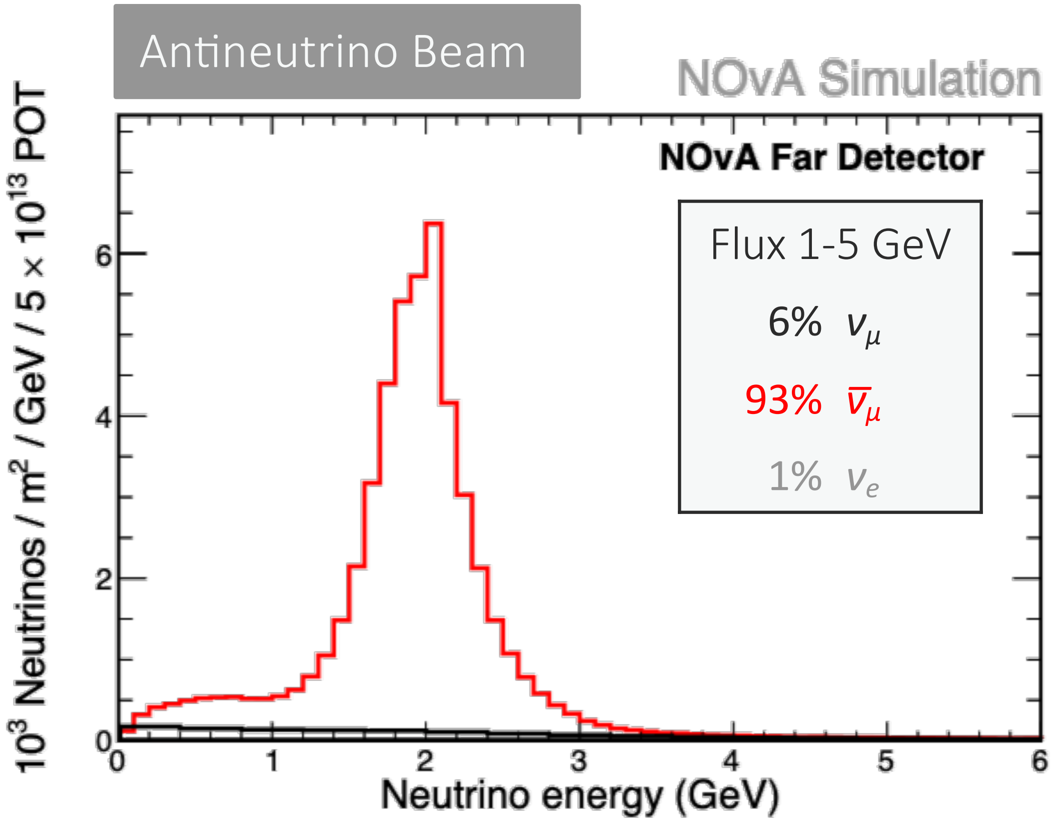
The NuMI antineutrino beam



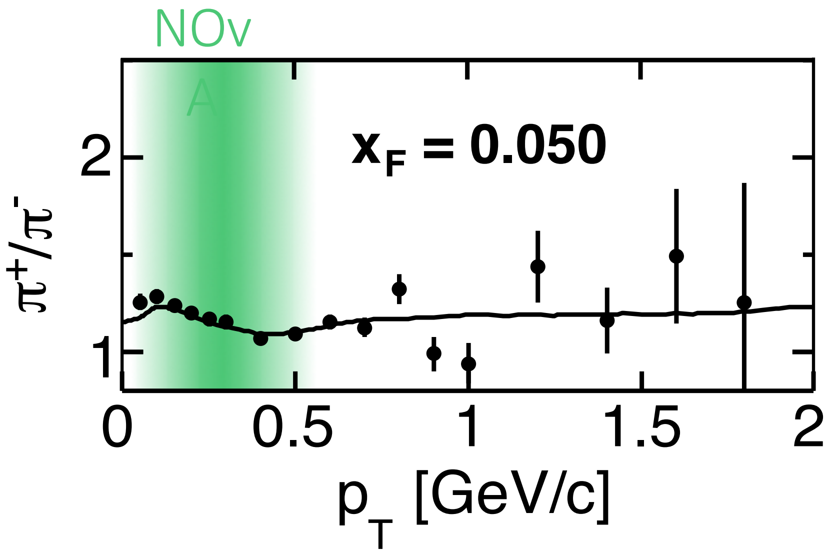
8.9×10^{20} POT Neutrino Beam

6.9×10^{20} POT Antineutrino Beam

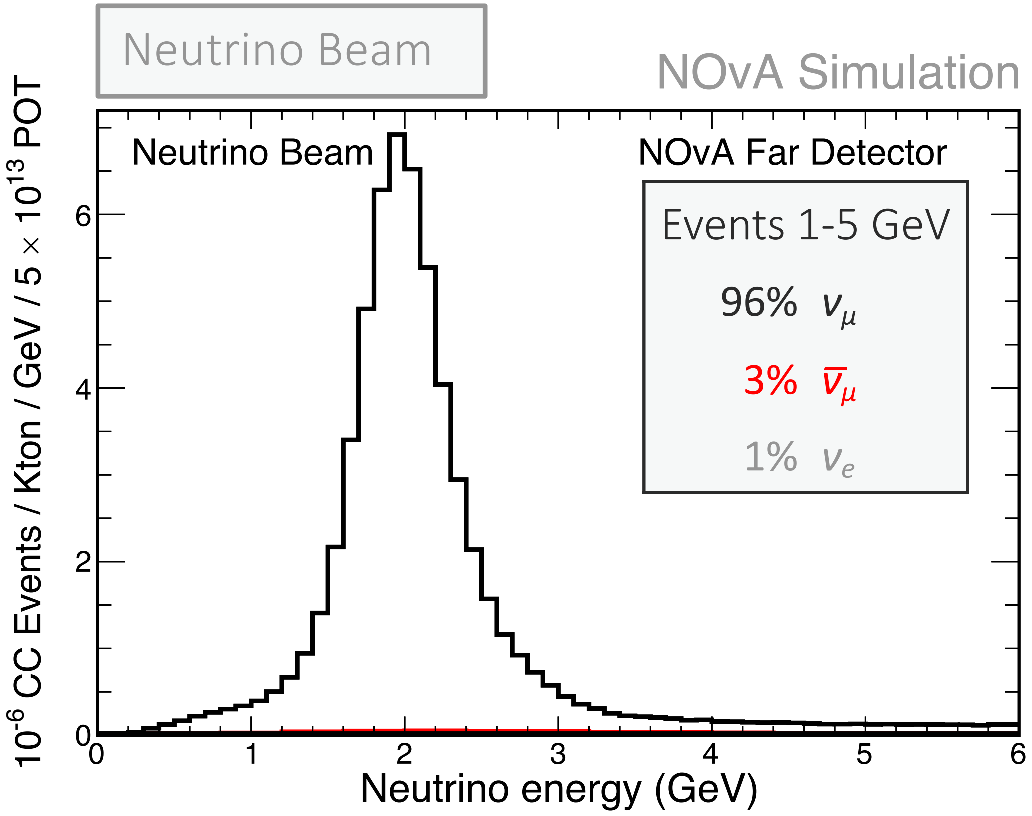


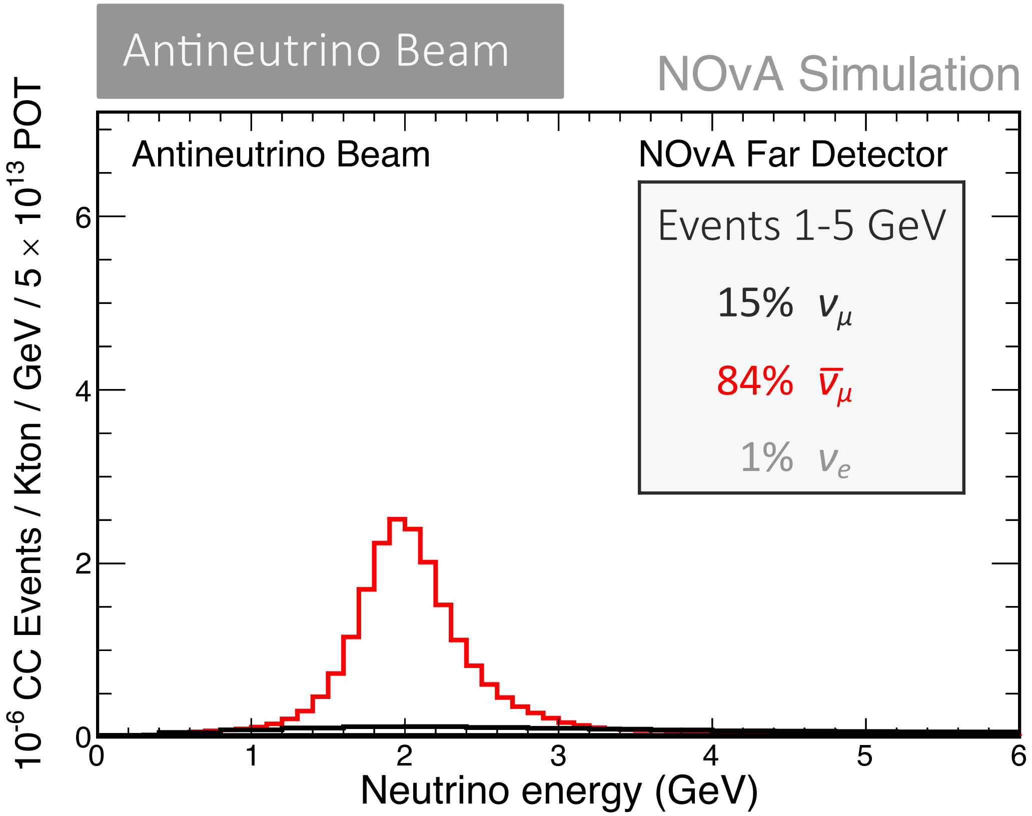


- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
  - p^+ colliding with p^+ and n^0 in the target
- *Wrong-sign*: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign.
  - WS primarily would primarily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

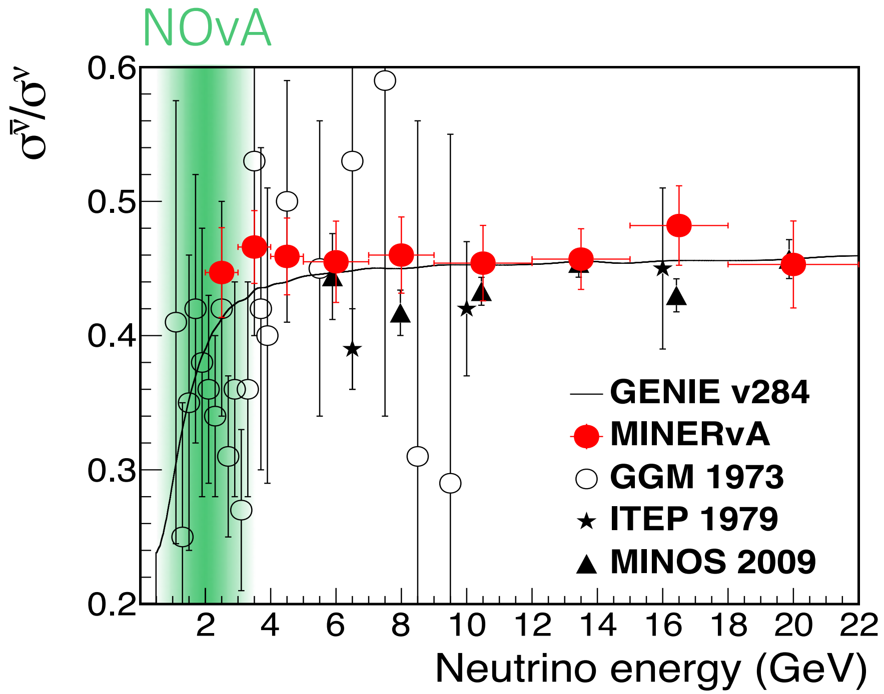


NA49, Eur. Phys. J. C 49 897 (2007)



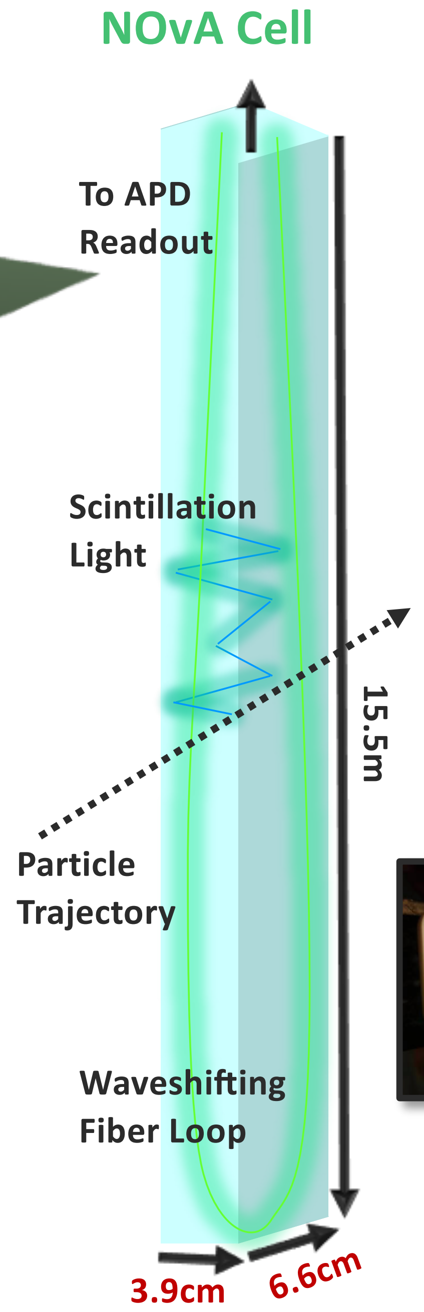


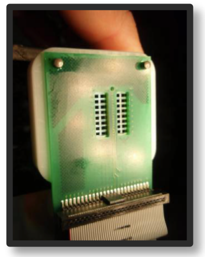
- The big difference is in the interaction: the cross section for antineutrinos is **~2.8 times lower** than for neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.
  - Lower kinematic *y*
  - More forward-going

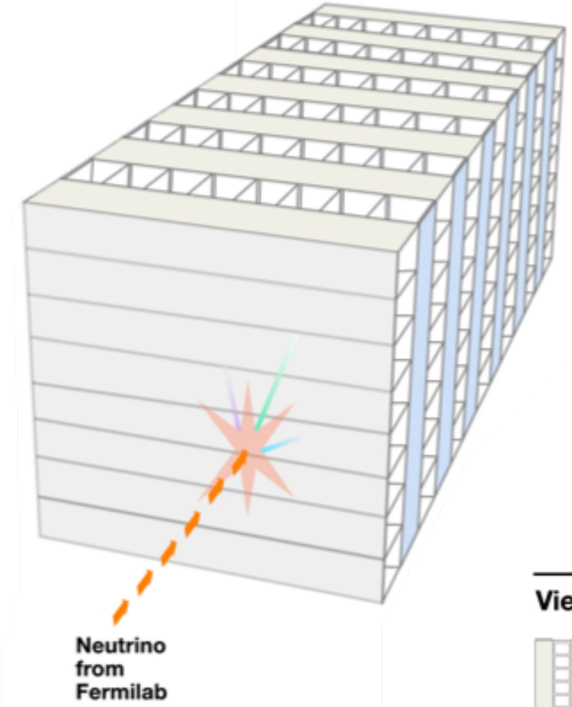


MINERvA, Phys.Rev. D95 (2017) no.7, 072009

NOvA Detectors

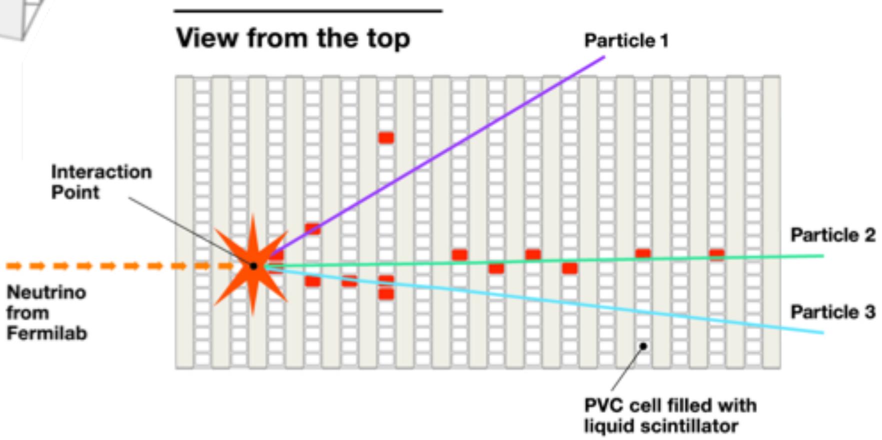


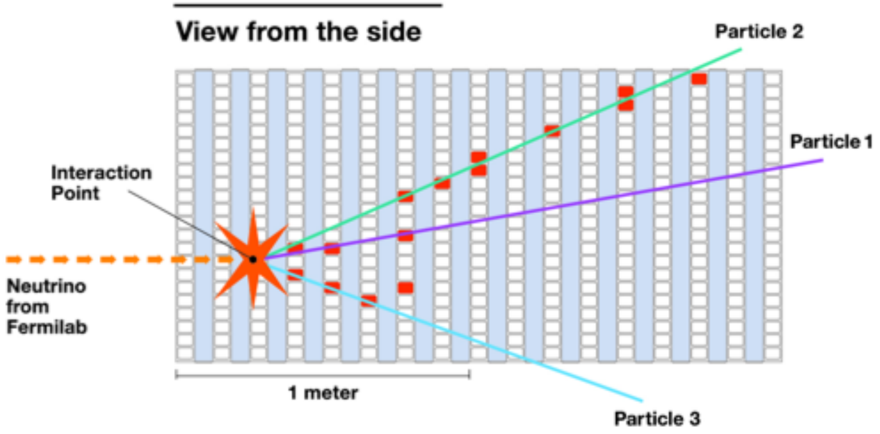




Detectors are fine-grained, low-*Z*, highly-active tracking calorimeters

Orthogonal layers → top and side views for each event



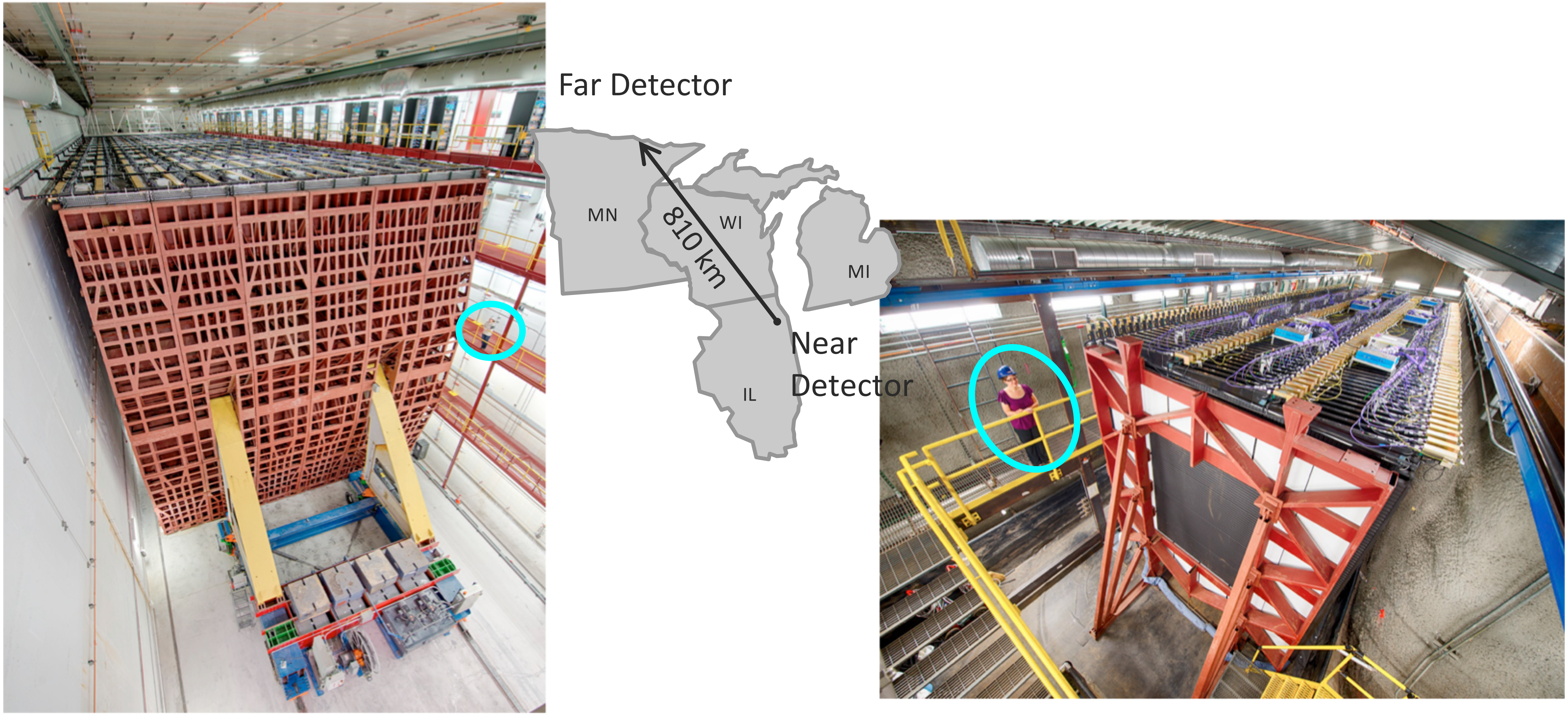


- PVC + Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
- Read out via wavelength shifting fiber to APD
- Layered planes of orthogonal views

ND: 214 layers, 18 000 channels

FD: 896 layers, 344 000 channels

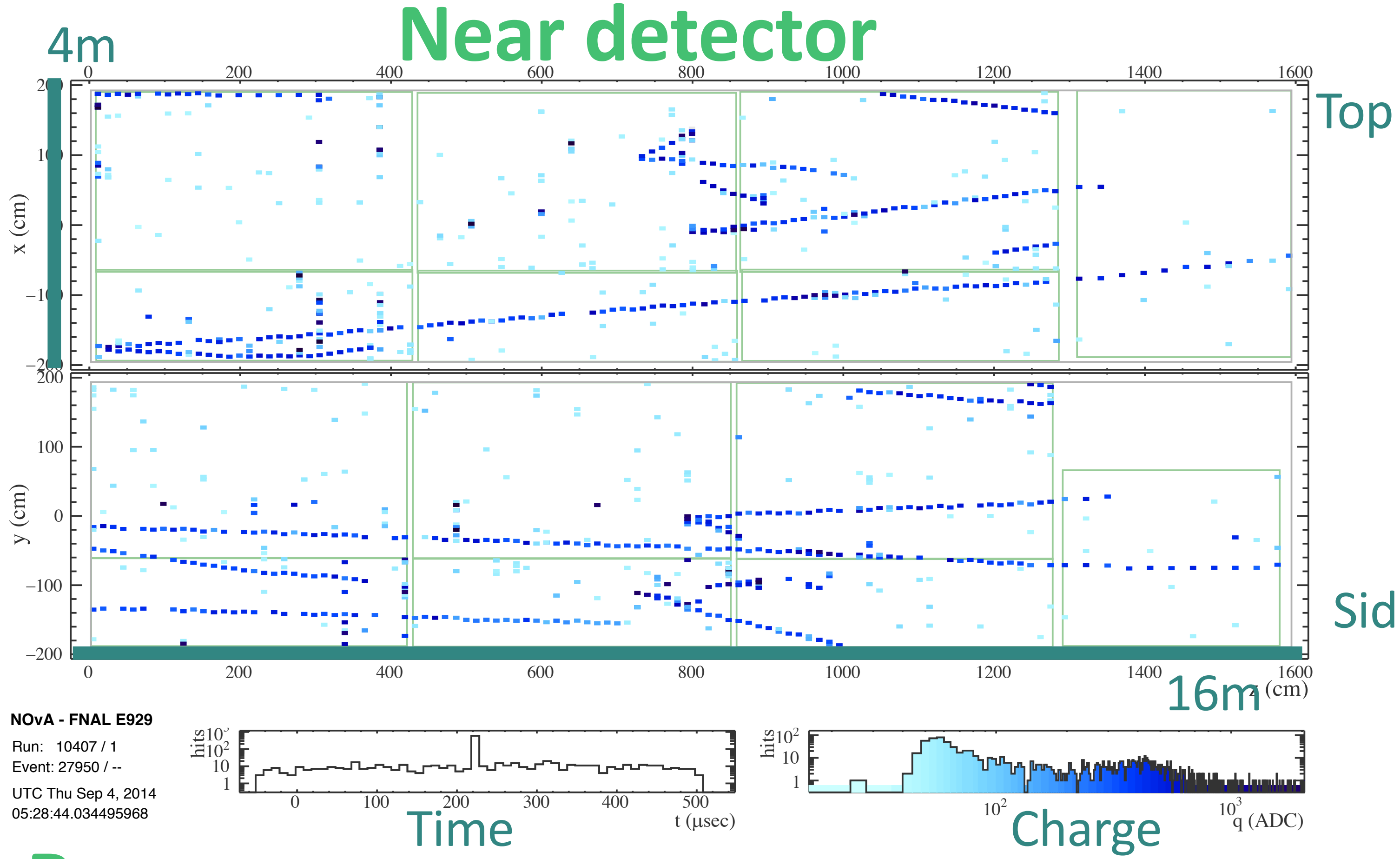
NOvA detectors


Far Detector

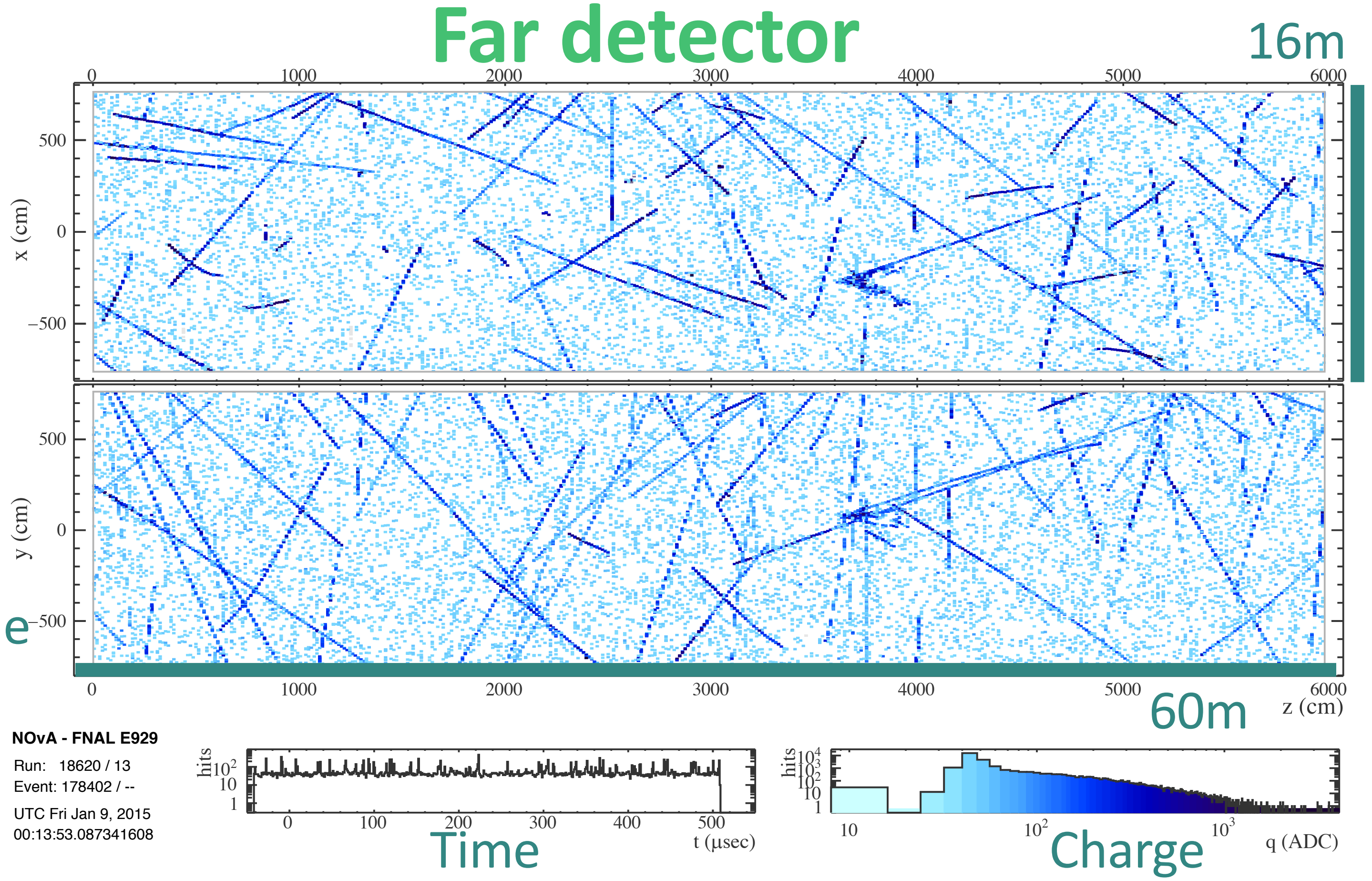
Near Detector

Finding neutrino events

Near detector



Far detector

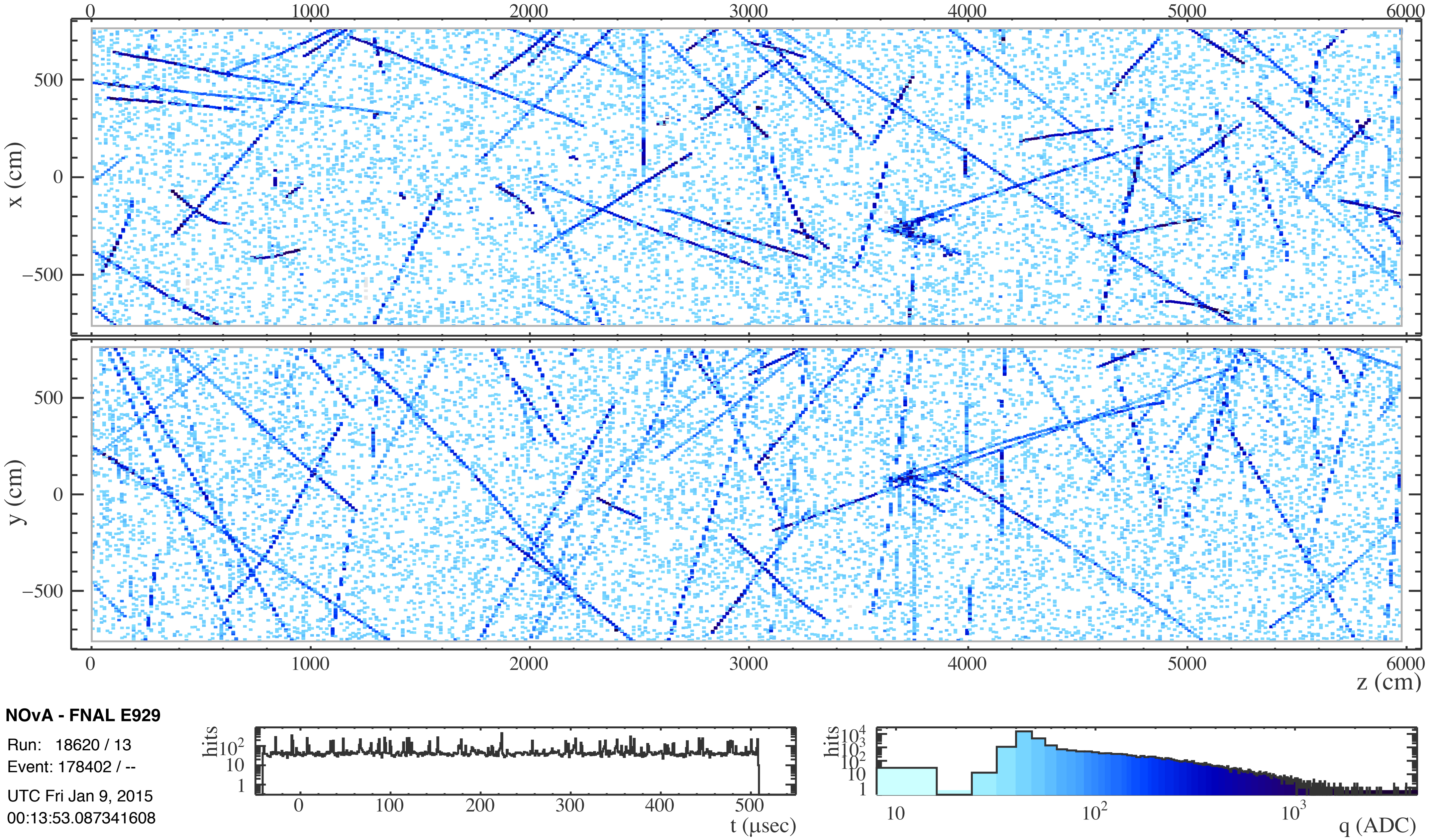


Beam

18000 channels. 1 km from beam source
~5 neutrino events per spill (every 1.33 seconds)
Negligible cosmic background (underground)

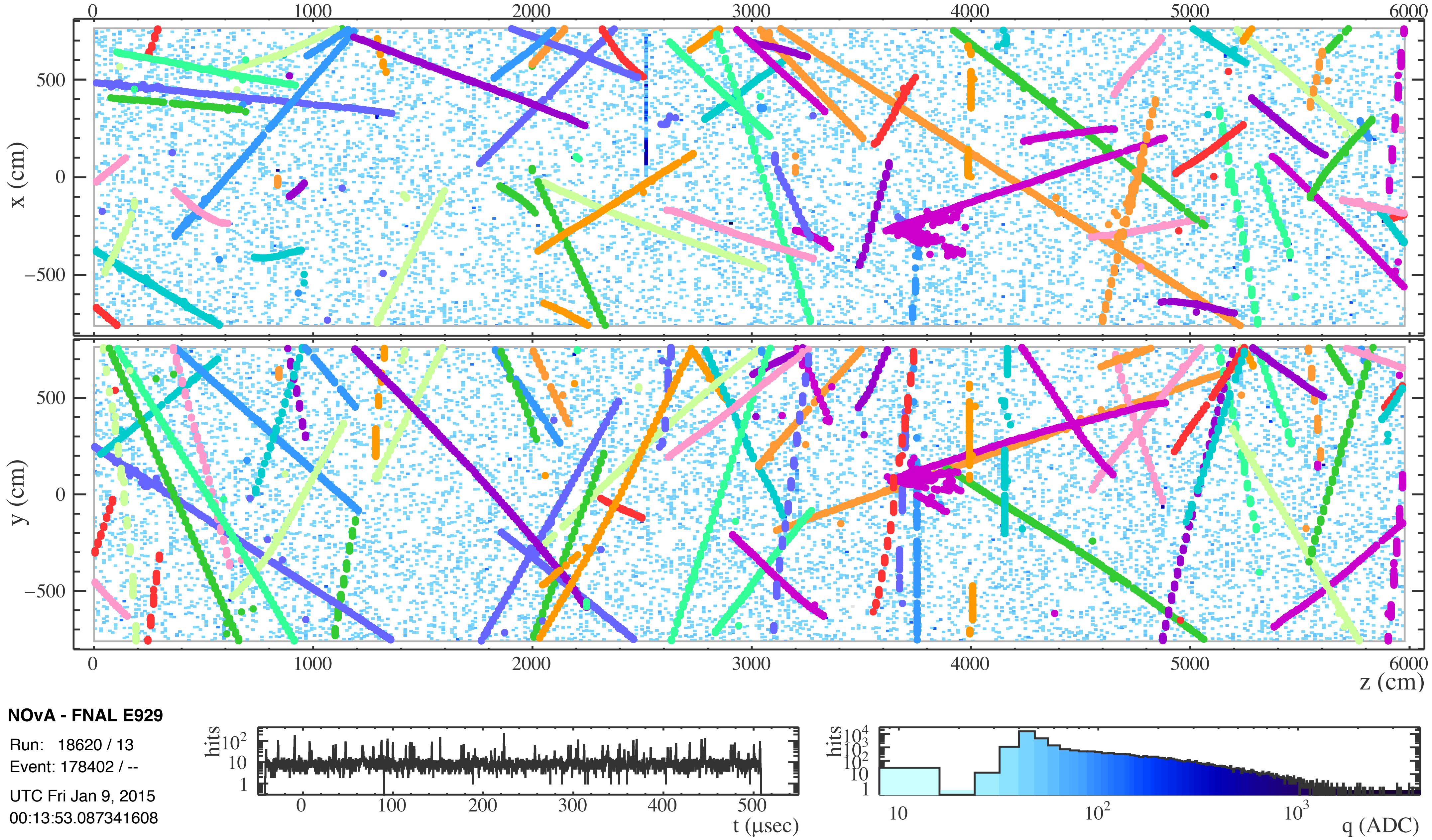
344000 channels. 810 km from source
<1 neutrino event per day
130 kHz cosmic ray background

Finding neutrino events



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

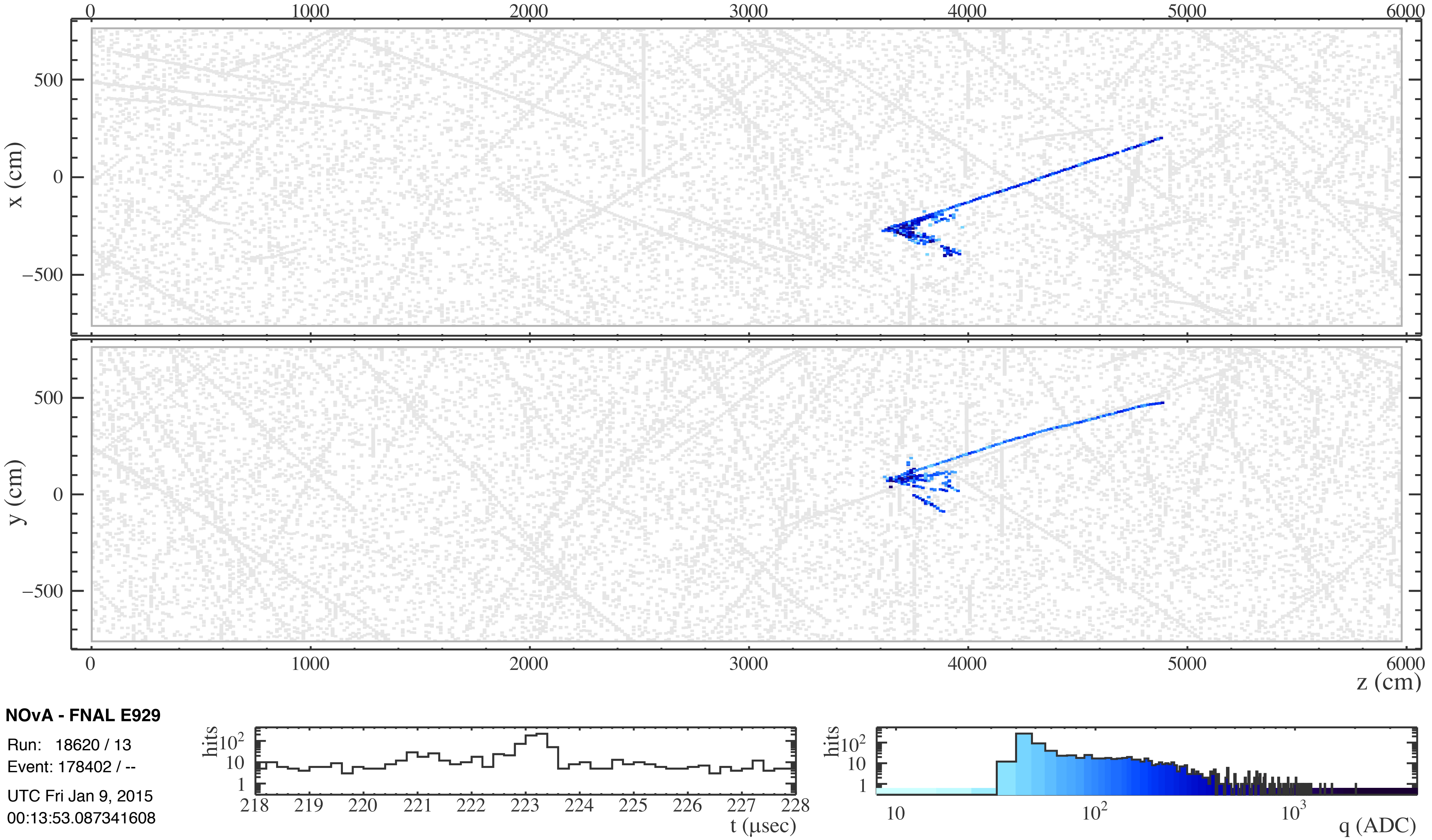
Finding neutrino events



Slicing:

Coarse event-level time-space clustering

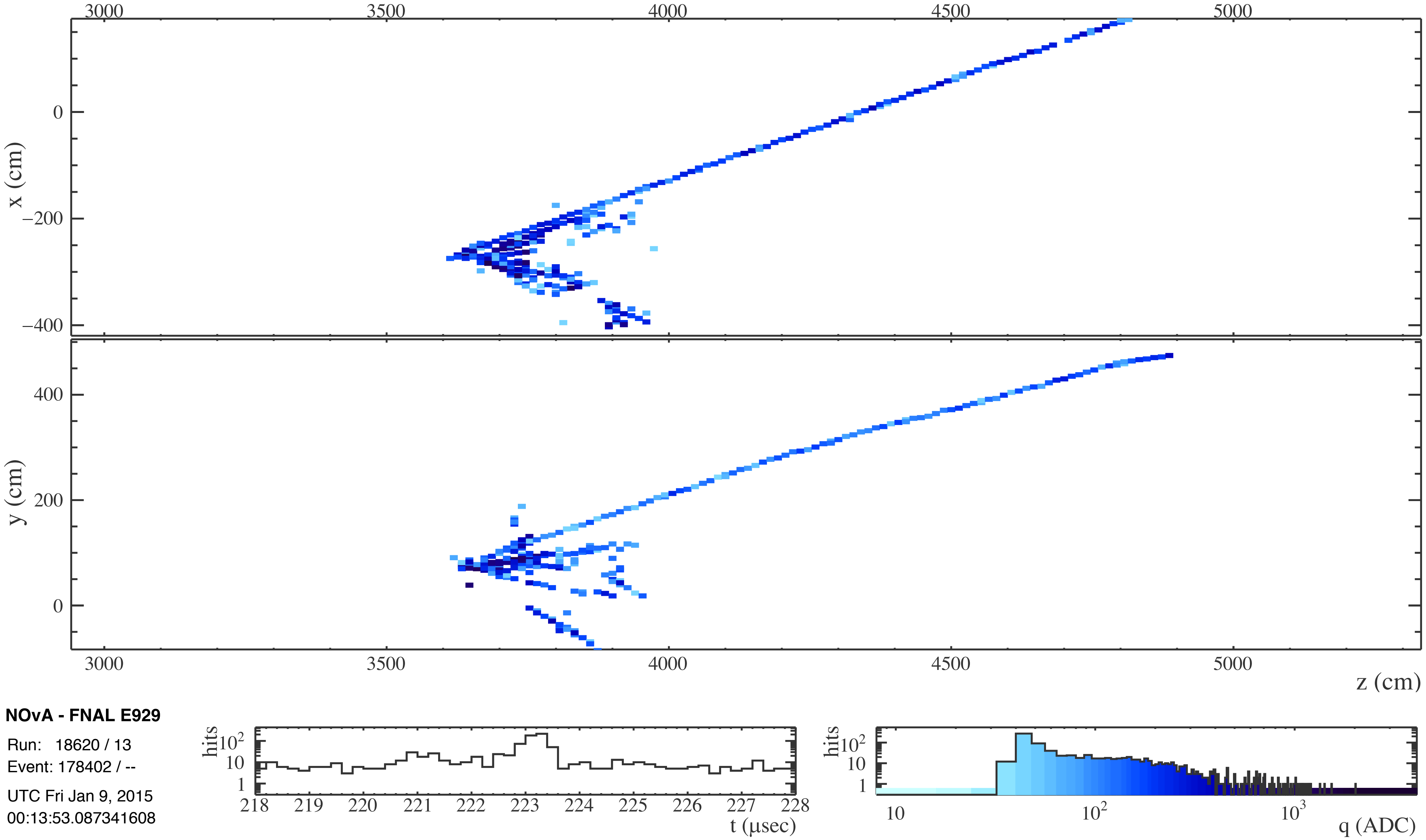
Finding neutrino events



Zoom-in in time

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

Finding neutrino events



NOvA - FNAL E929

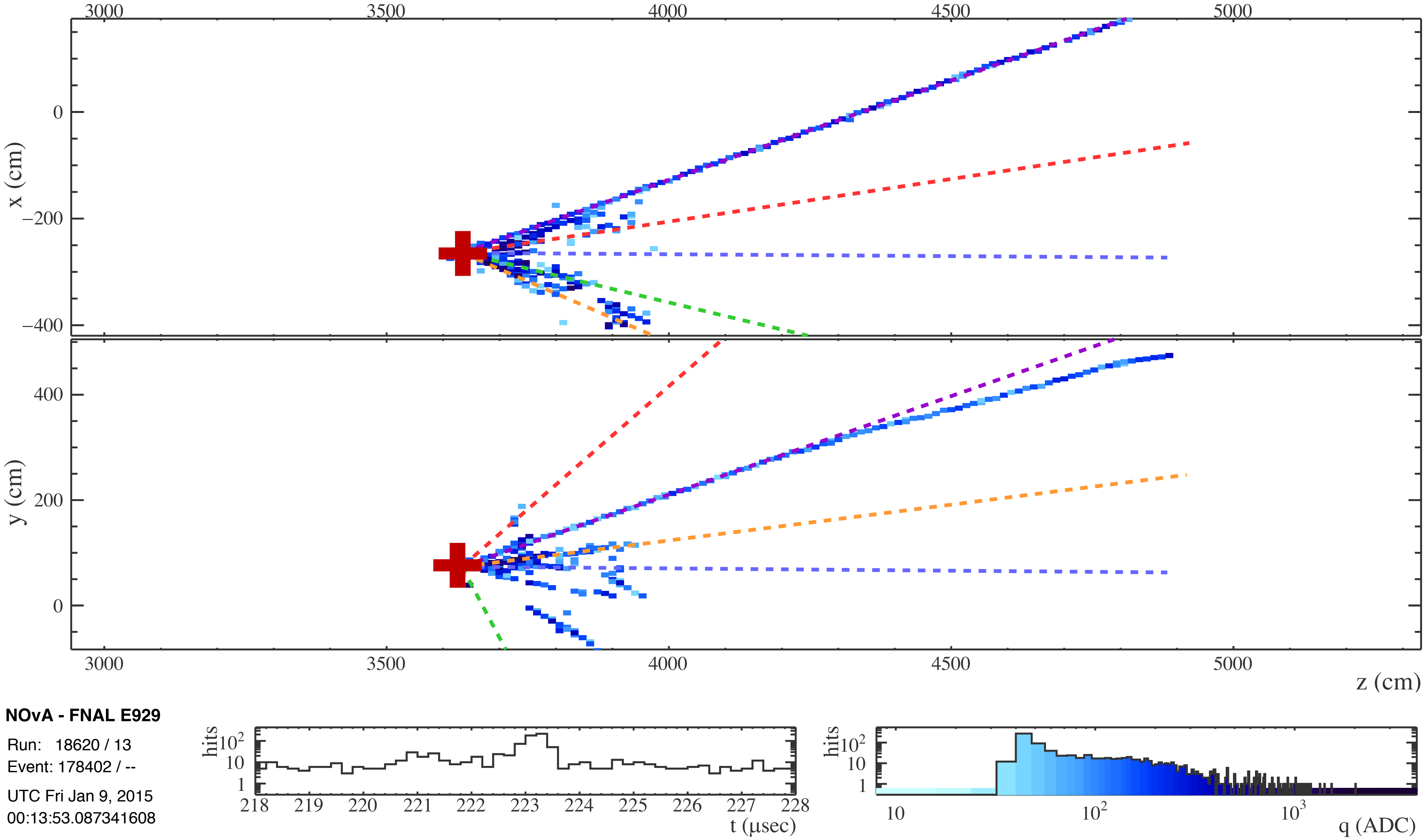
Run: 18620 / 13
Event: 178402 / --

UTC Fri Jan 9, 2015
00:13:53.087341608

Zoom-in in space

Same neutrino beam candidate

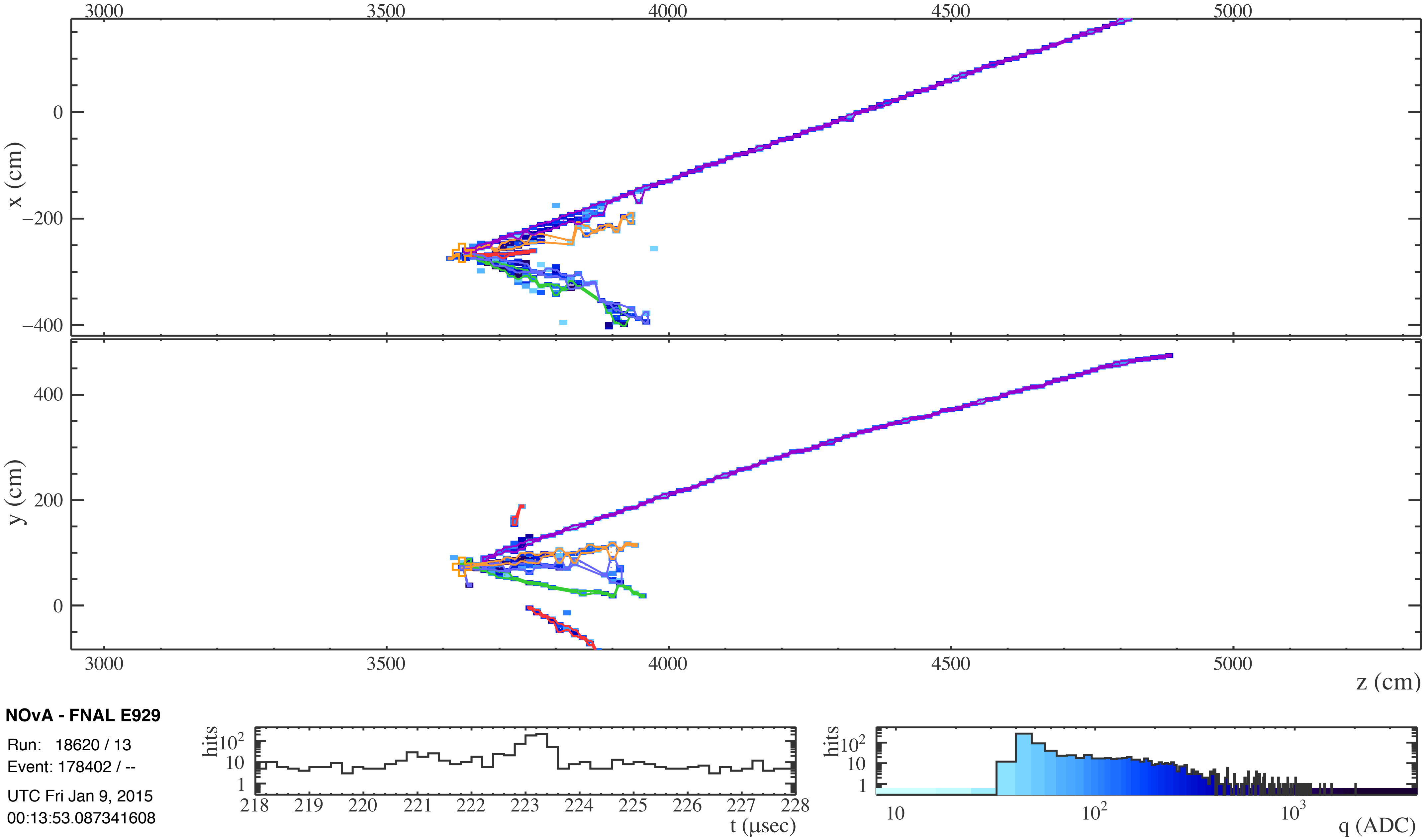
Finding neutrino events



Vertexing:

Find lines of energy depositions + optimize

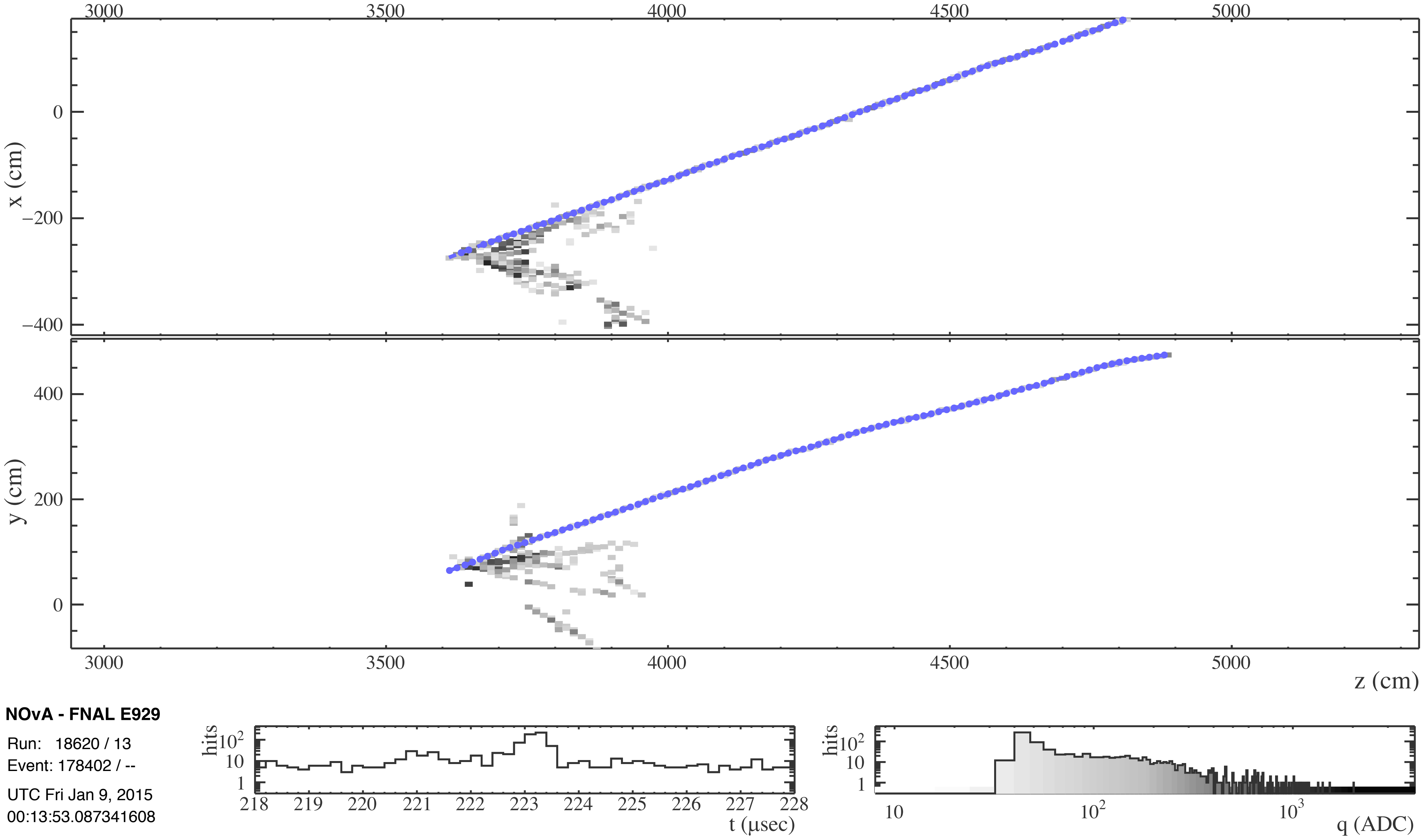
Finding neutrino events



Clustering:

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

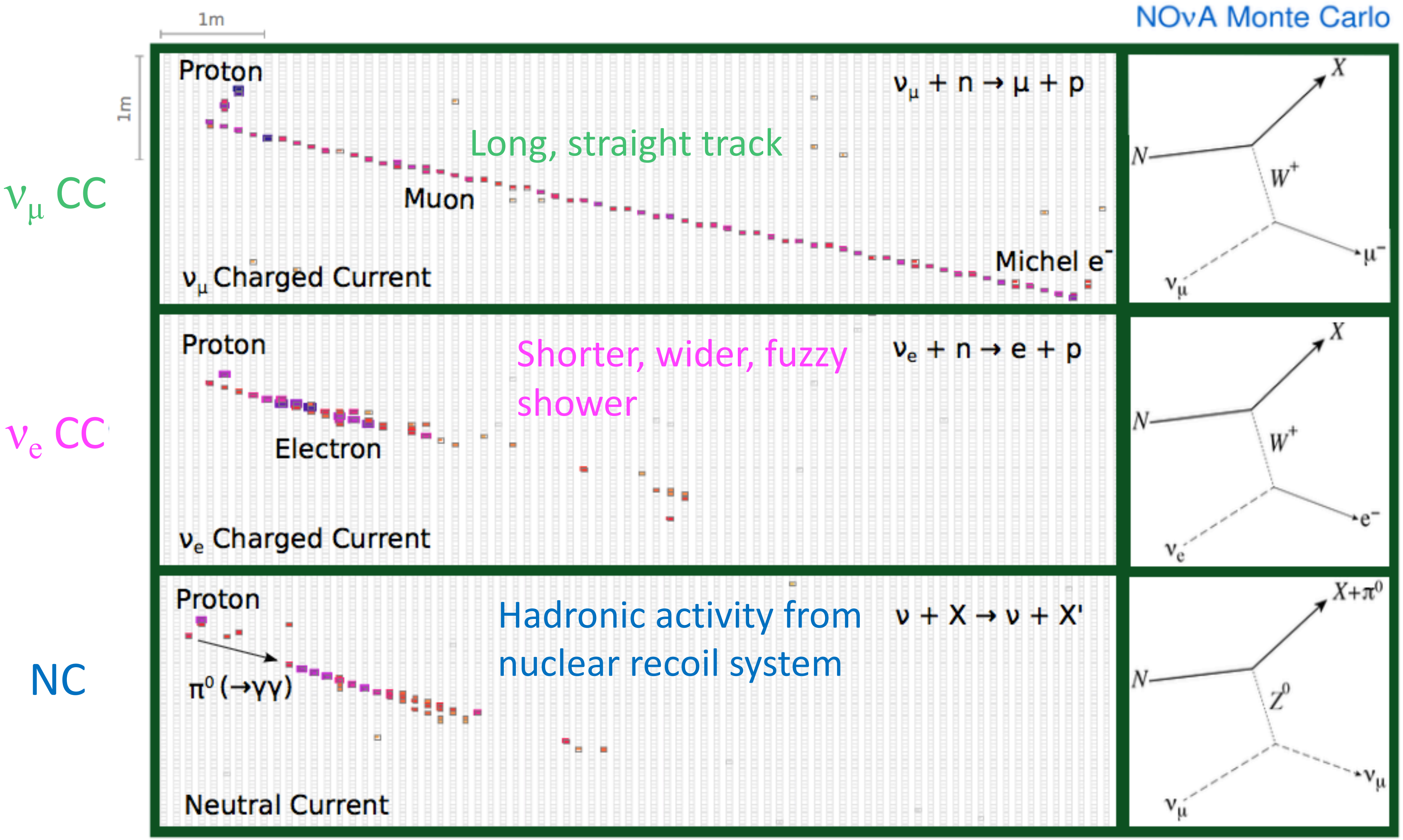
Finding neutrino events



Tracking:

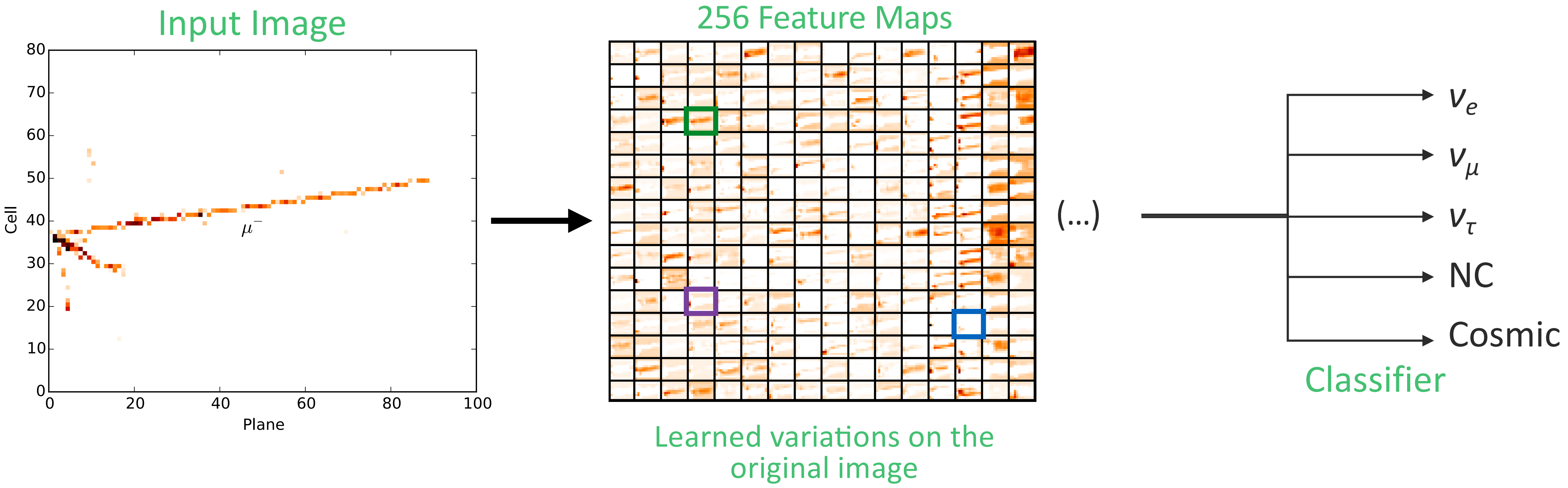
Trace single particle trajectories (muons)

Event topologies

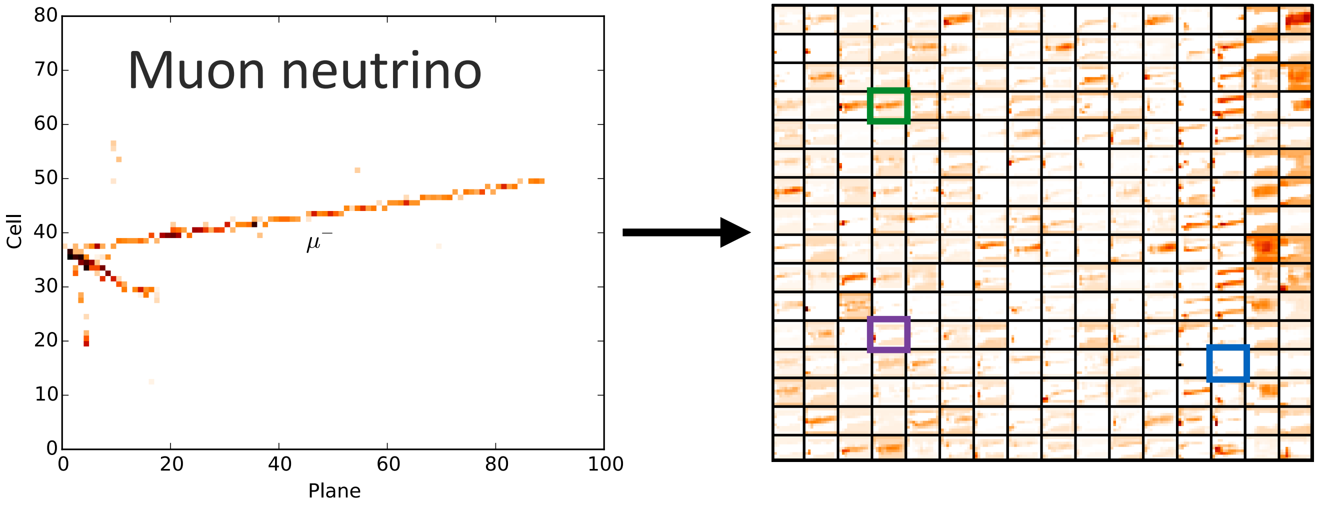


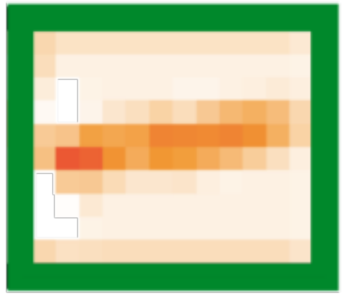
Particle identification

- We use a *convolutional neural network*.
- Successive layers of “feature maps”:
  - Create many variants on the original image which enhance different features.
  - Later layers apply variations to the feature maps from the previous layer.
- Ends with a “feed forward” neural network to create a multi-label classifier.

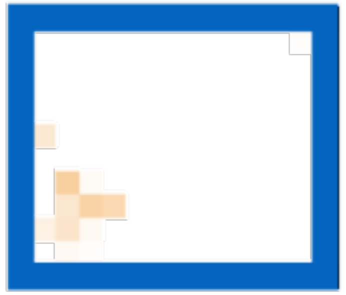


Particle identification

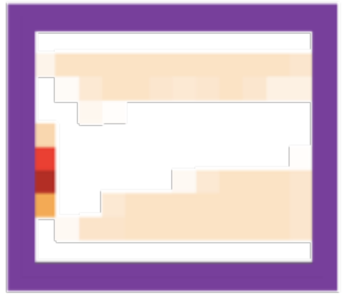




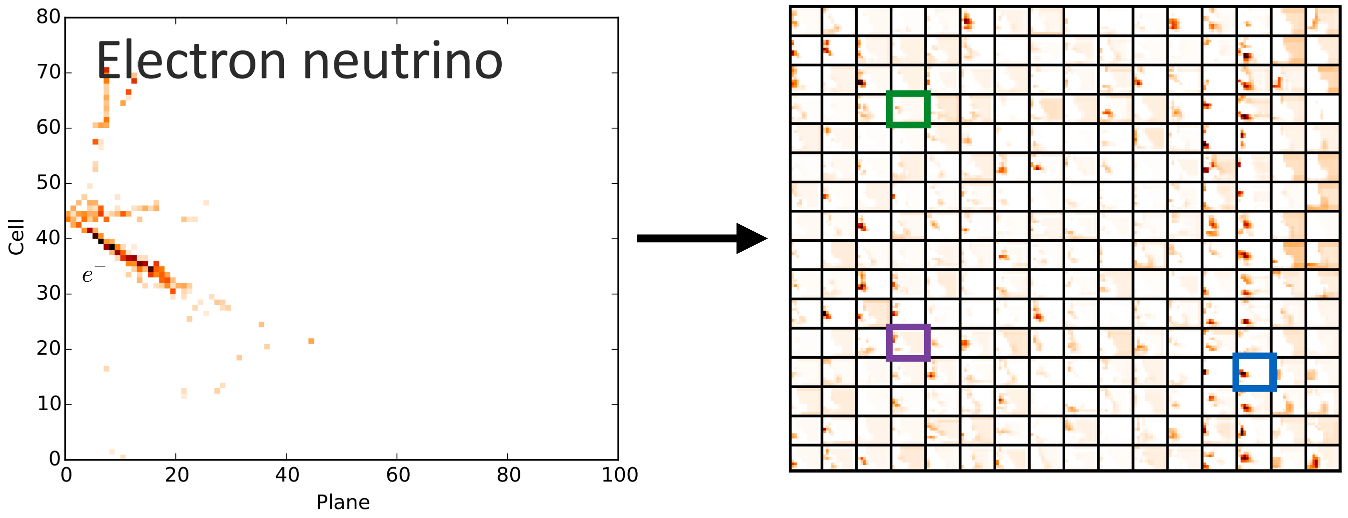
Responding to *μ tracks*

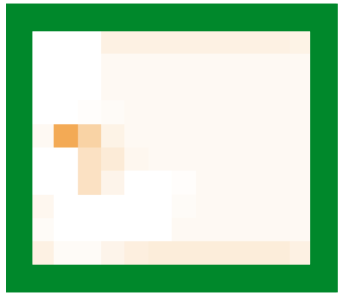


Responding to *e showers.*

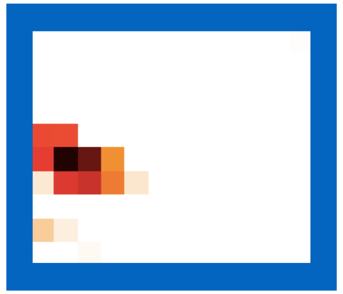


Responding to *hadronic activity.*

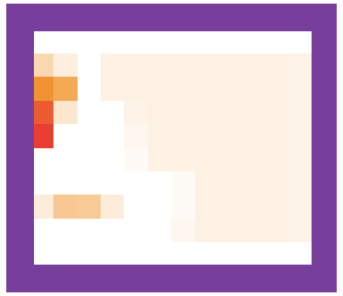




Responding to *μ tracks*



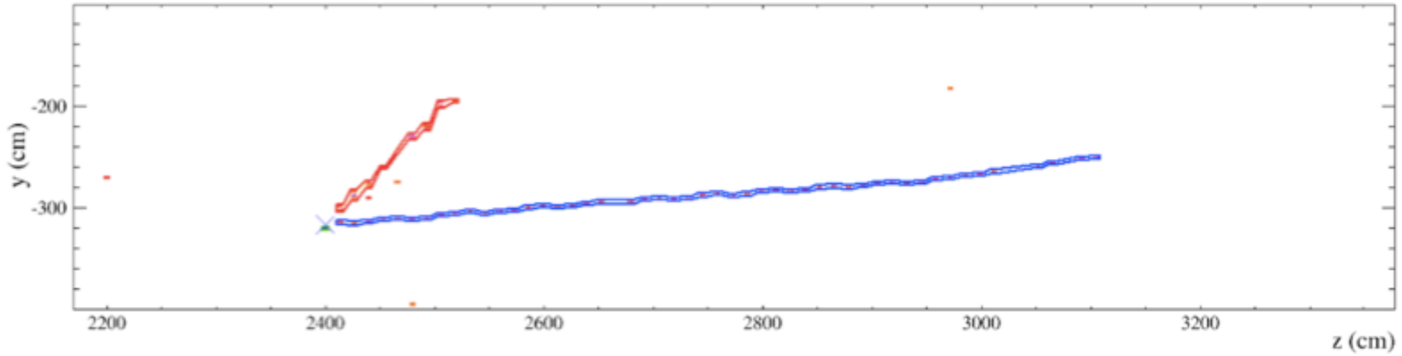
Responding to *e showers.*



Responding to *hadronic activity.*

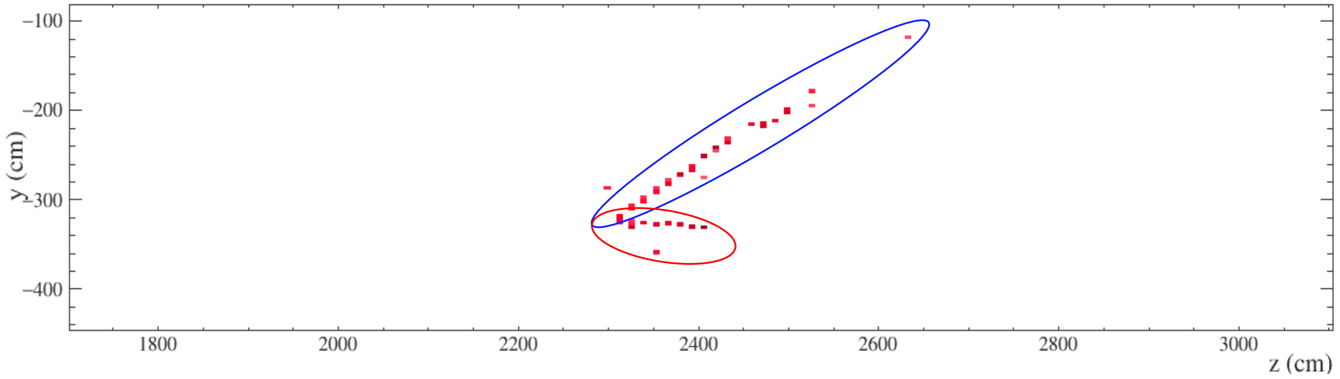
Measuring Neutrino Energy

ν_μ events



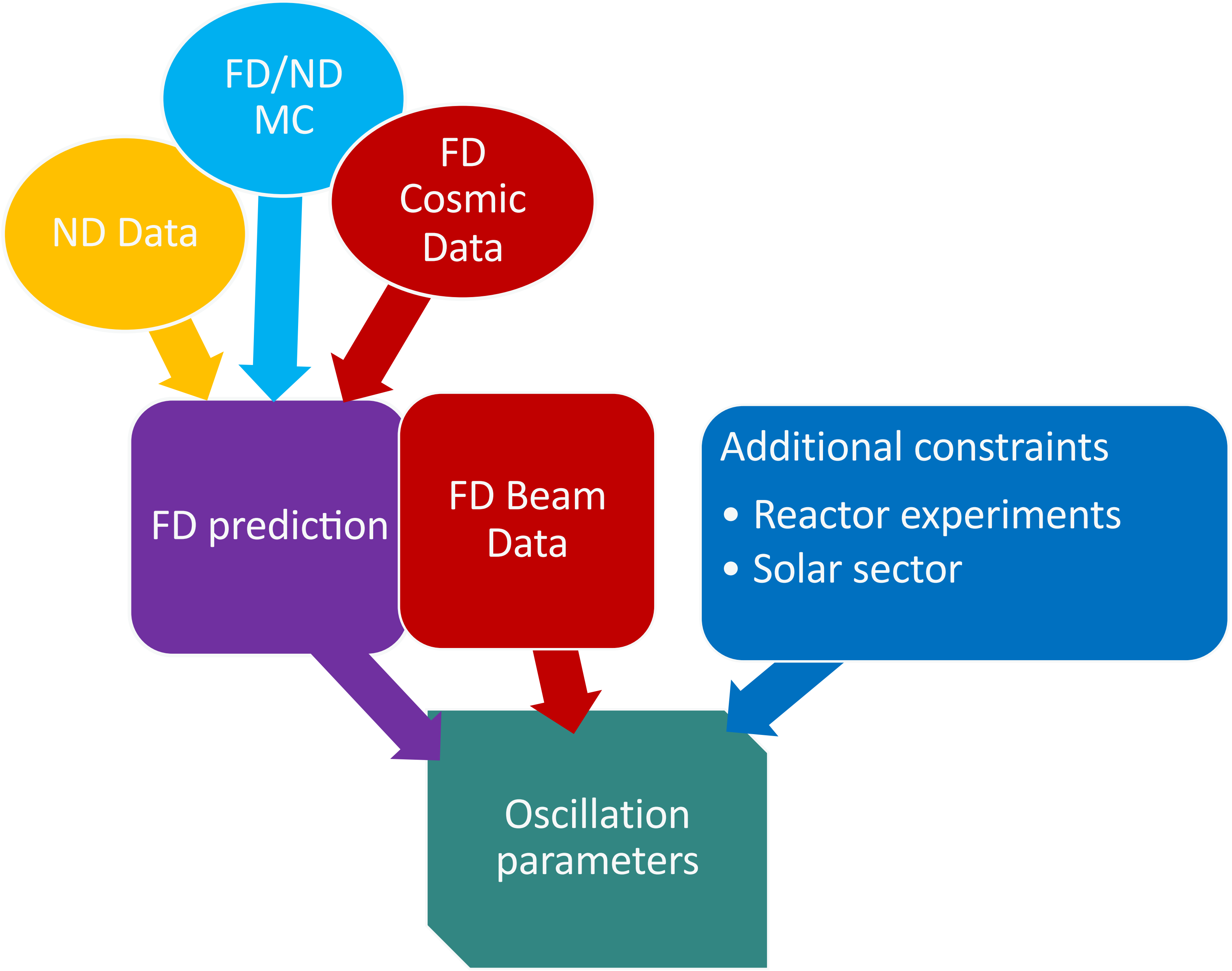
- Neutrino energy is the sum of muon and hadronic energy.
- Muon energy is a function of track length.
- Hadronic energy reconstructed calorimetrically.
  - Includes activity overlapping the muon track.

ν_e events



- Neutrino energy is a function of EM and hadronic energy.
- EM “prongs” are identified with a single-prong CVN variant.
  - All remaining activity is hadronic.
- Both energies reconstructed calorimetrically.

Oscillation analysis strategy



FD/ND MC

ND Data

FD Cosmic Data

FD prediction

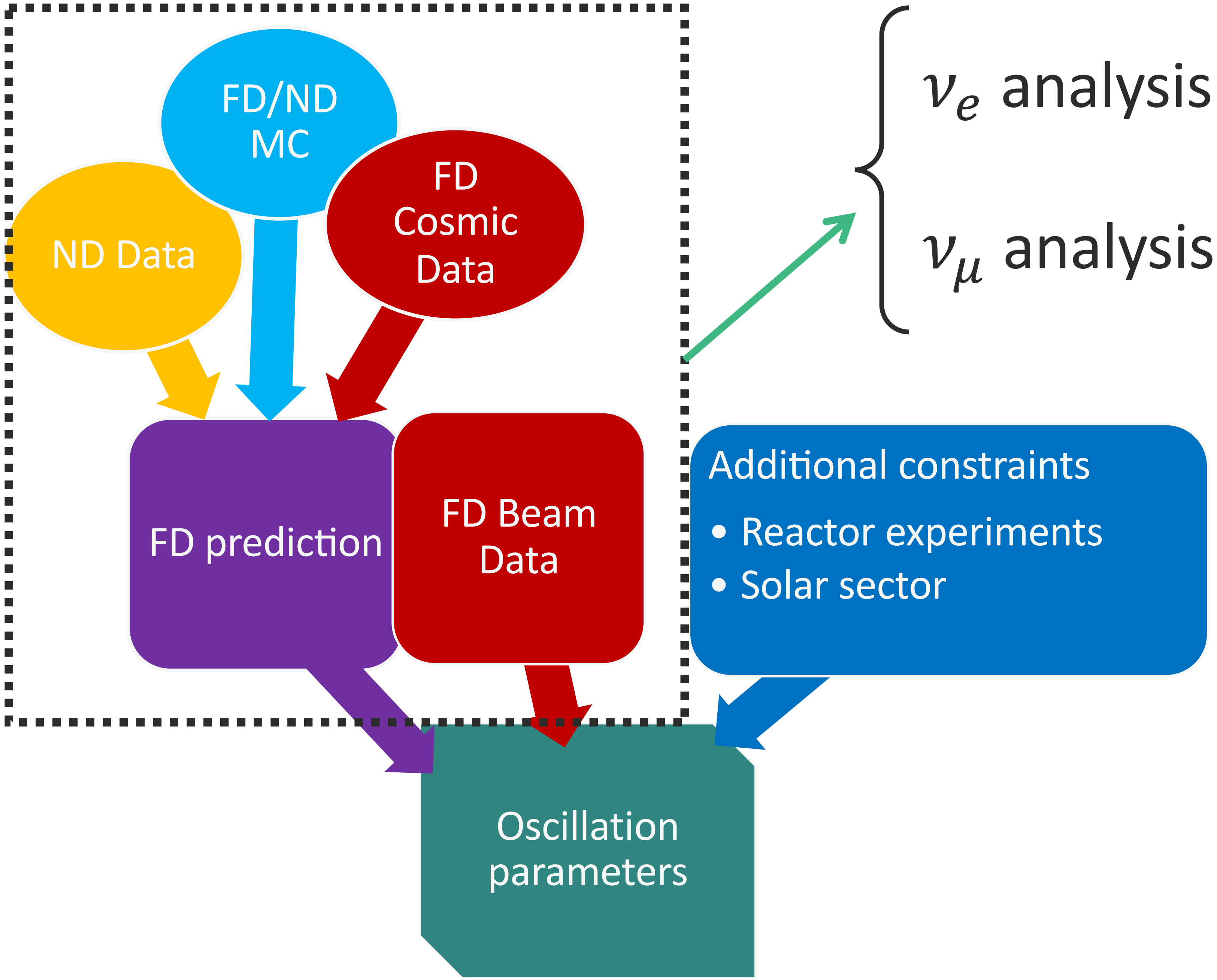
FD Beam Data

Additional constraints

- Reactor experiments
- Solar sector

Oscillation parameters

Oscillation analysis strategy



ND Data

FD/ND MC

FD Cosmic Data

FD prediction

FD Beam Data

Additional constraints

- Reactor experiments
- Solar sector

Oscillation parameters

ν_e analysis

ν_μ analysis

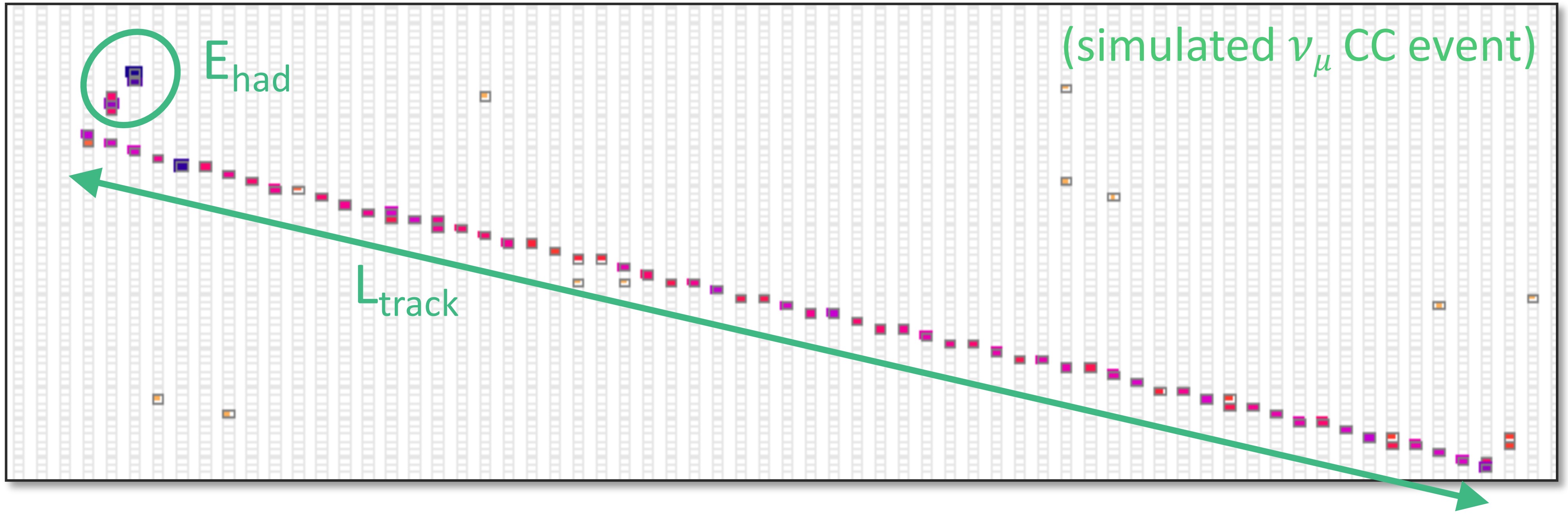
Neutrino beam

Antineutrino beam

“Analysis”→ specific selection of the samples, energy estimation, data-driven-constraints

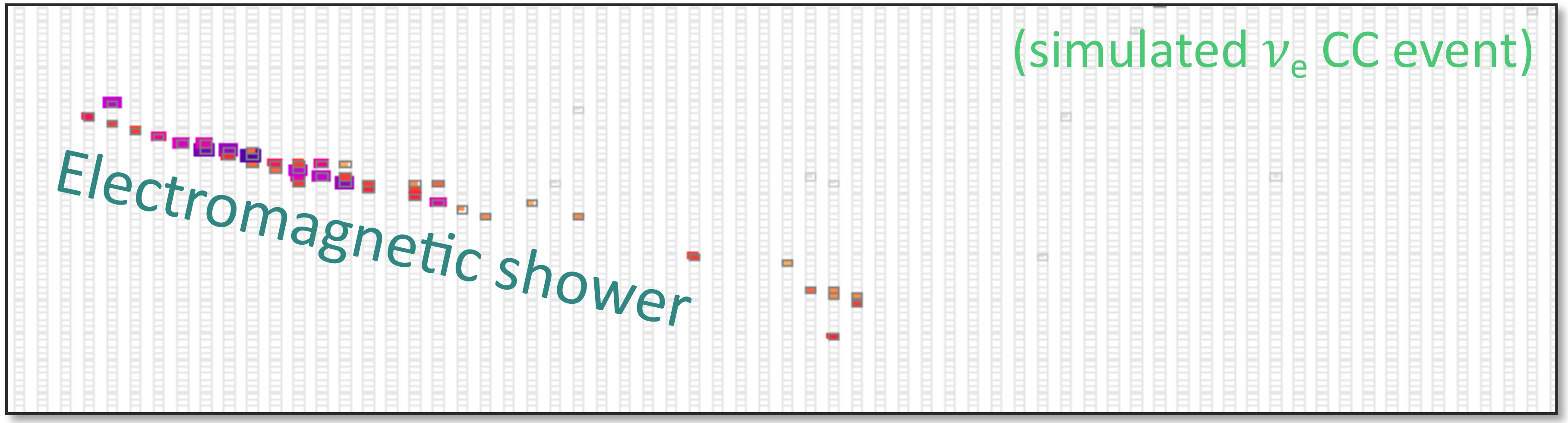
Muon neutrino analysis

1. Identify contained ν_μ CC events in each detector
2. Measure Near and Far energy spectra
3. Extract oscillation information from differences between both energy spectra



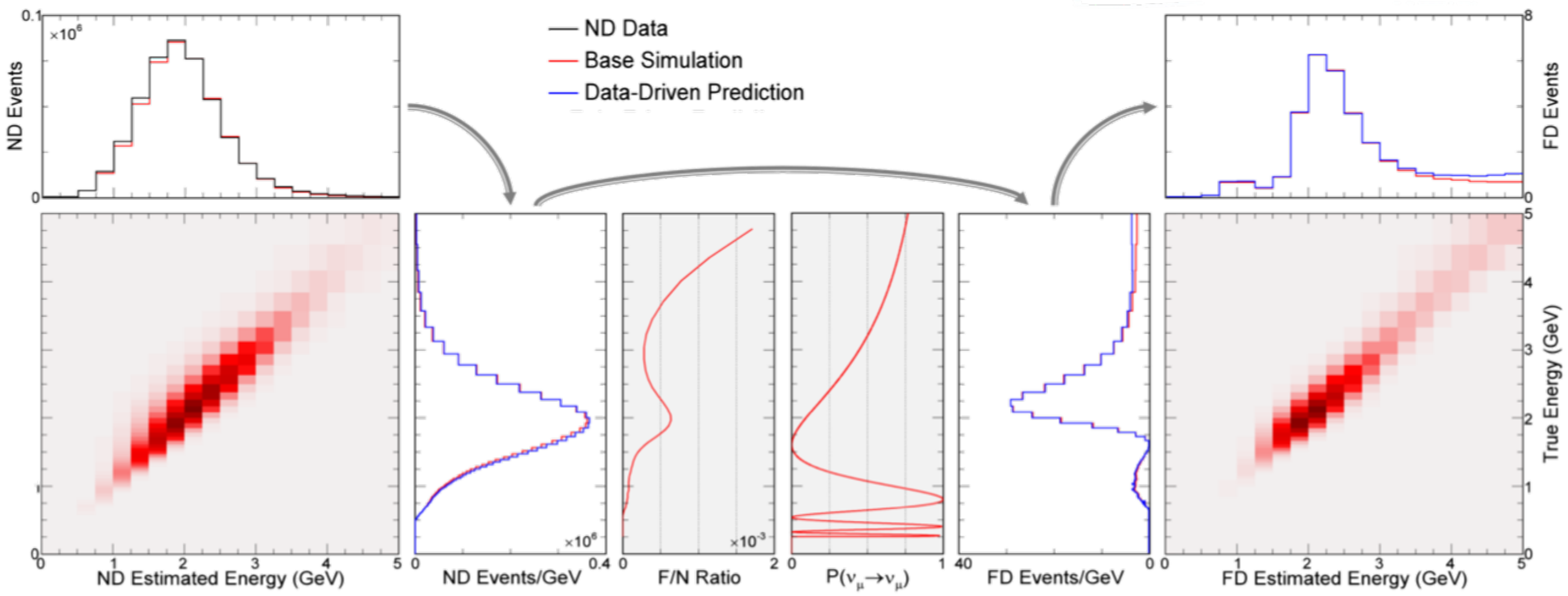
Electron neutrino analysis

1. Identify contained ν_e (ν_μ) CC candidates in each detector.
2. Use data to improve the prediction from the simulation:
   - ND ν_μ candidates → ν_e signal in the FD
   - ND ν_e candidates → FD beam backgrounds
   - FD data outside of the beam time window →FD cosmic ray background
3. Interpret any FD data excess over predicted backgrounds as ν_e appearance



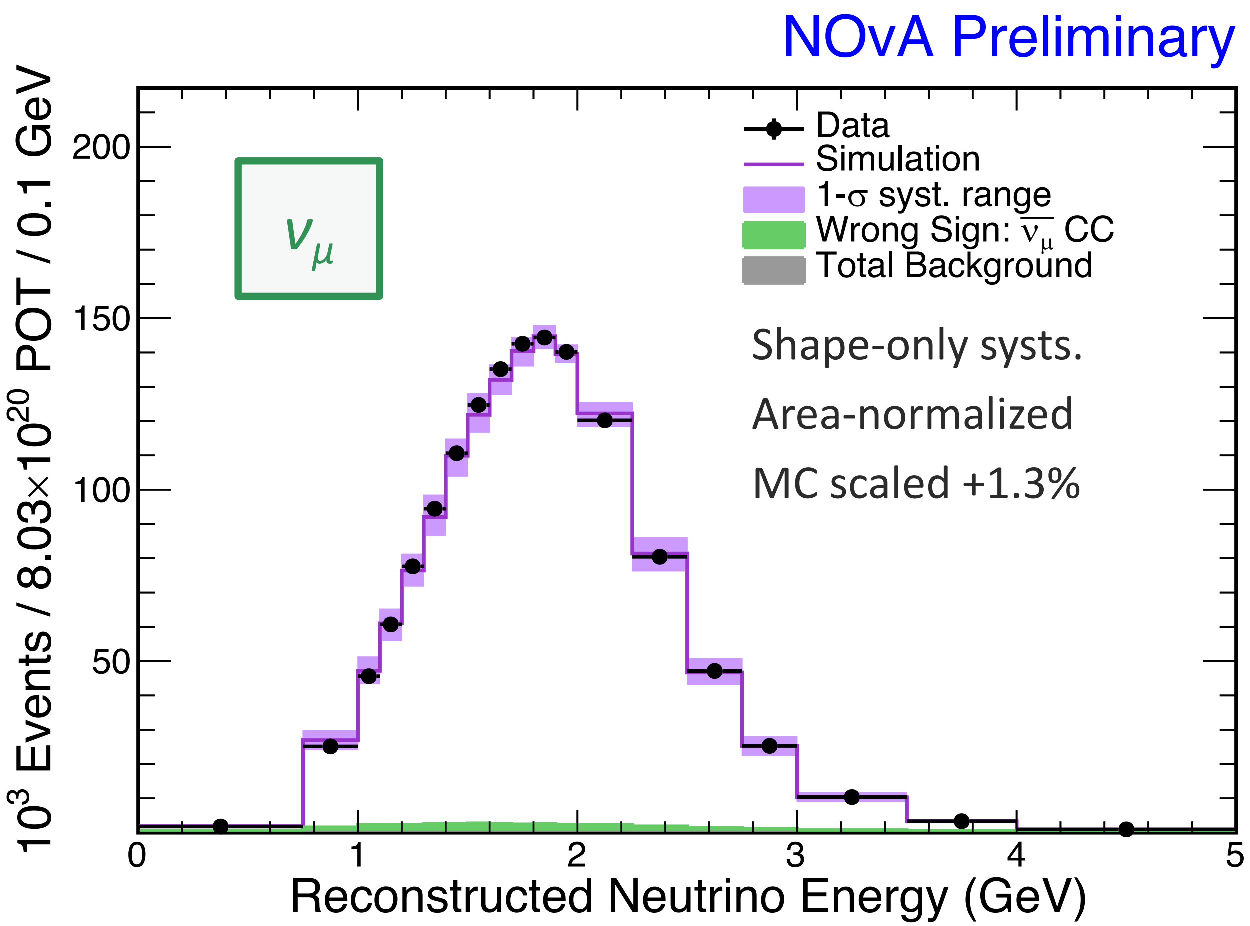
Constraints from ND Data

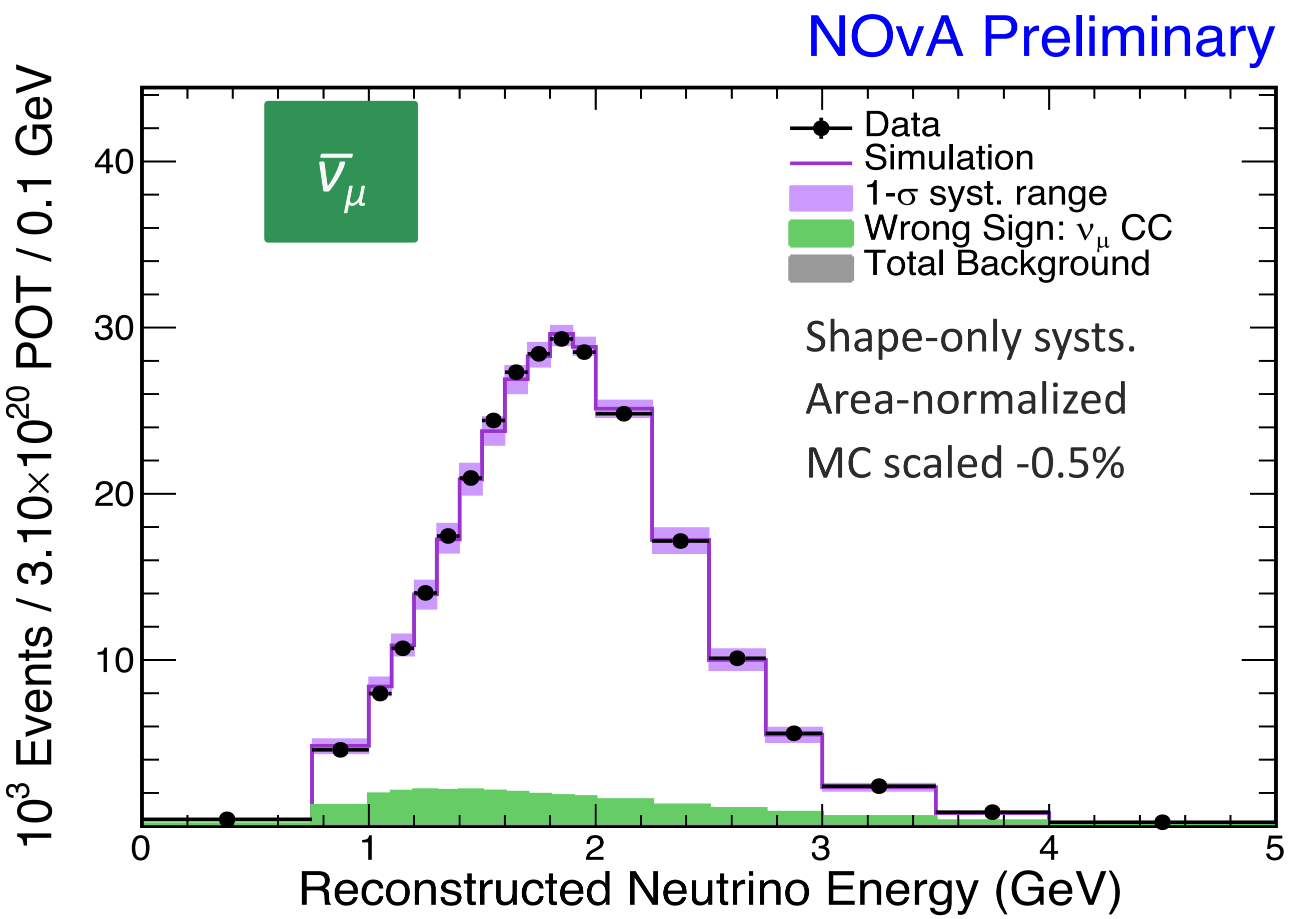
- Use Reco-to-true migration for $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ signal "extrapolation"



- ν_e backgrounds use the F/N in bins of reconstructed energy
- Other (small) beam backgrounds are taken directly from the simulation

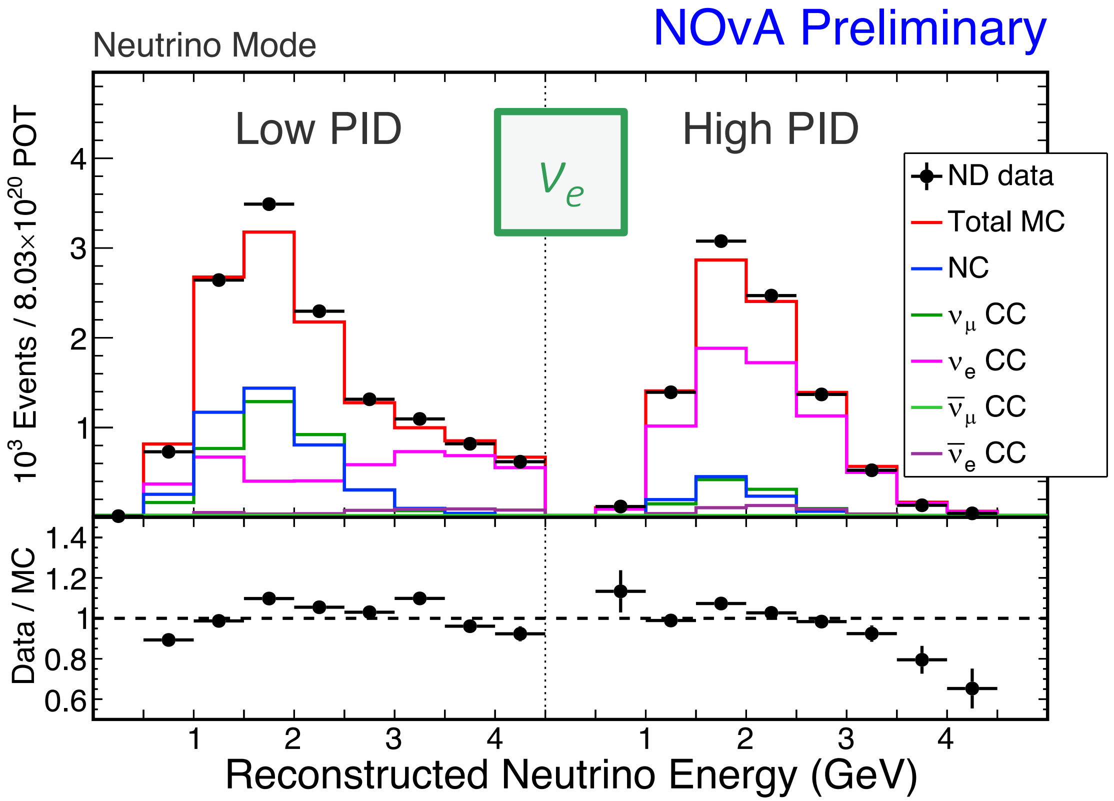
Muon neutrinos in the ND

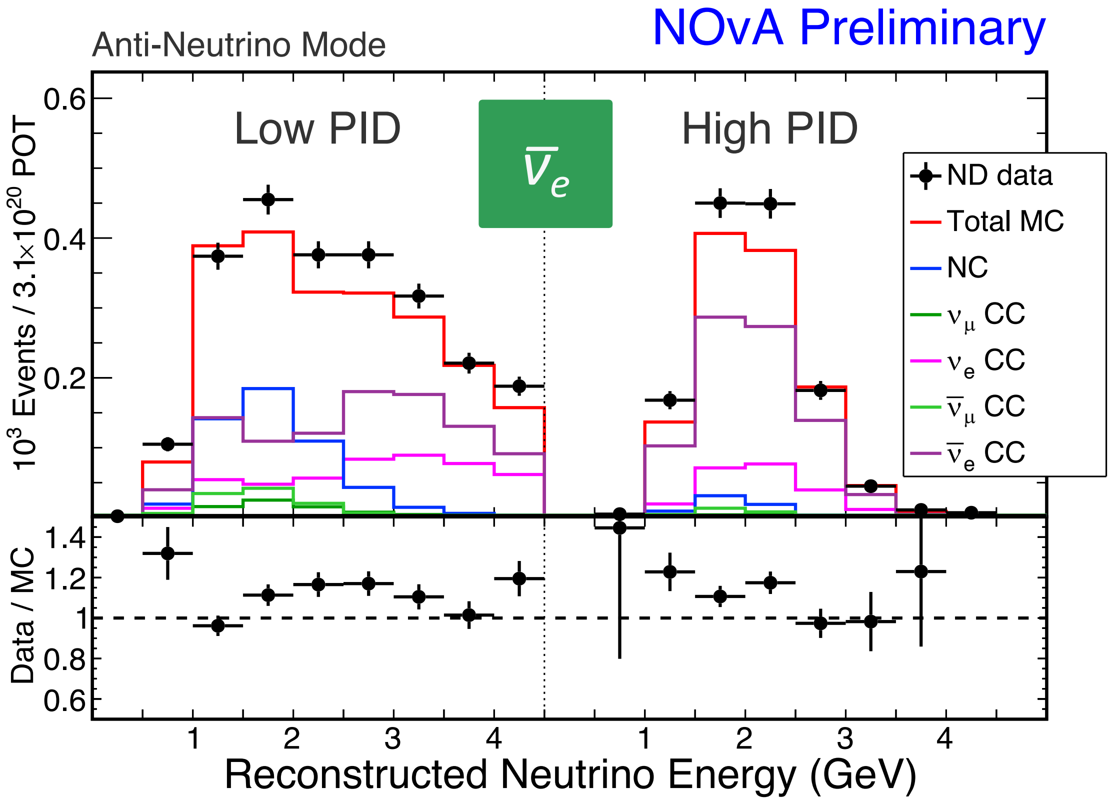




- Selected muon neutrino and antineutrino charged current interactions in ND.
- Used in the signal extrapolation
- Wrong sign contamination in ND is estimated to be 3% for neutrino beam and 11% for antineutrino beam.

Electron neutrinos in the ND

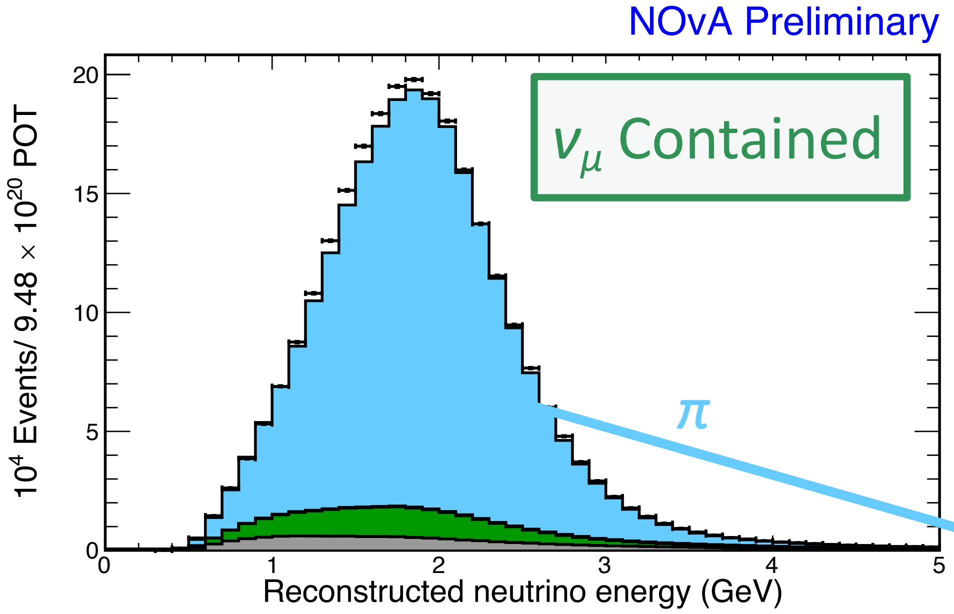


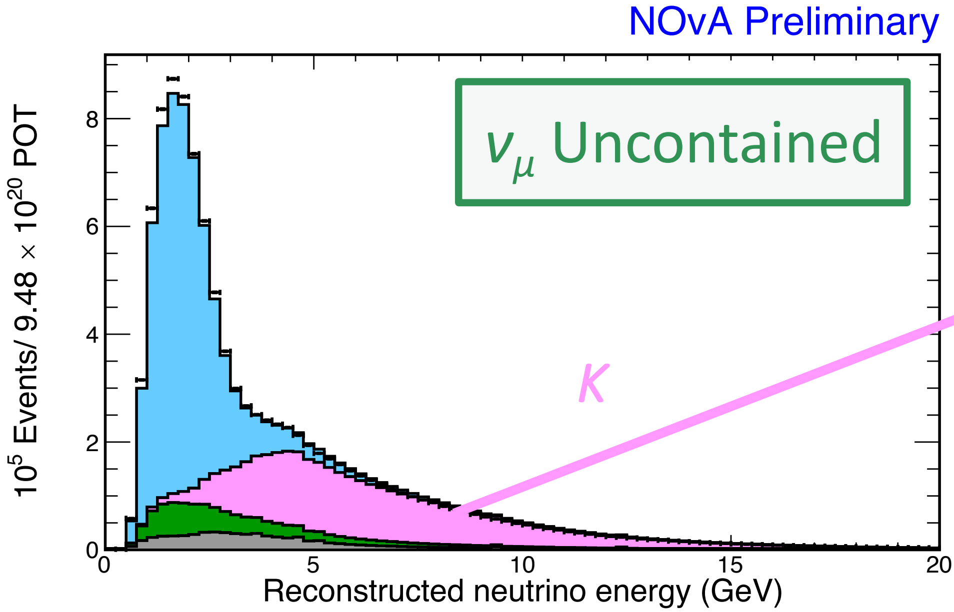


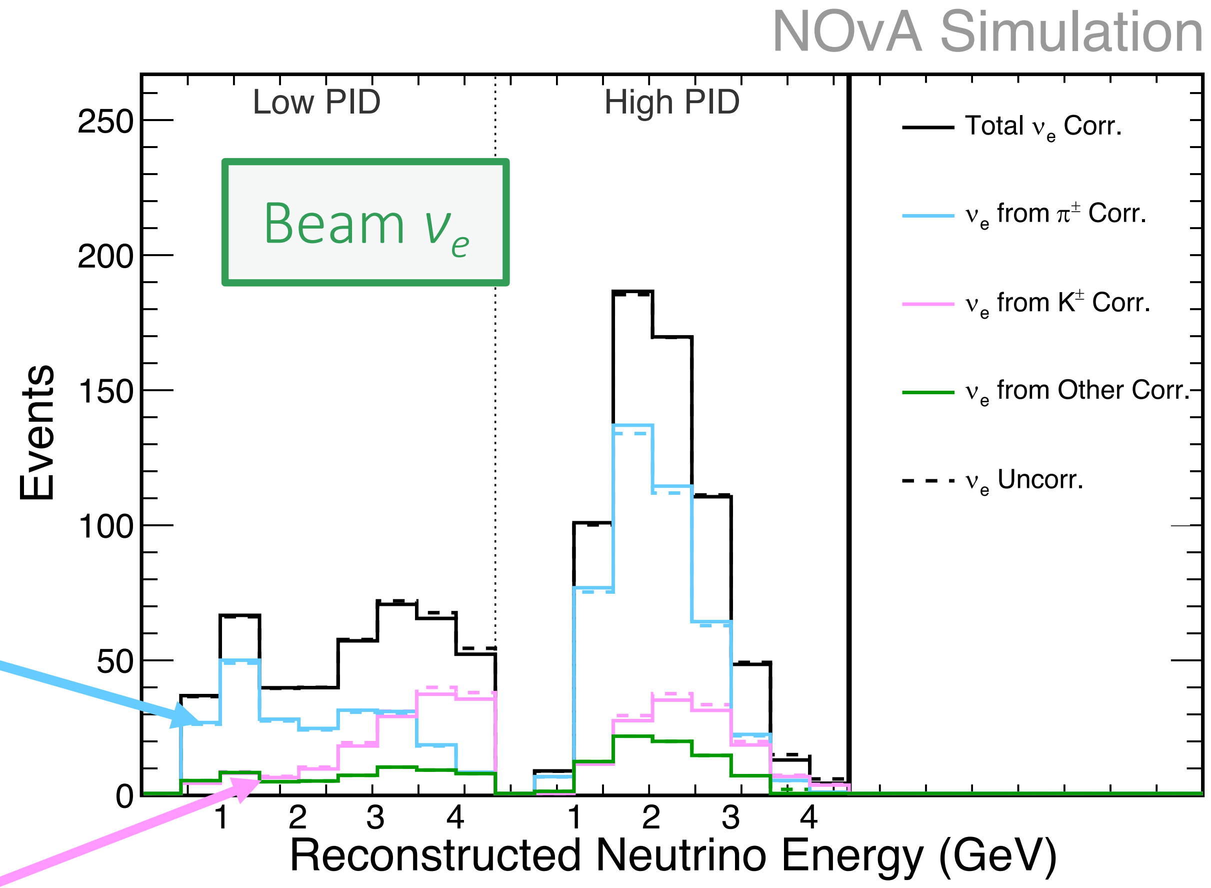
- The ND ν_e-like sample has no $\nu_e/\bar{\nu}_e$ appearance – all background.
- For the neutrino beam we use two data-driven techniques to constraint the background composition.
- For the antineutrino beam scale all components proportionally for now.

	Neutrino	Antineutrino
Beam $\nu_e/\bar{\nu}_e$	55%	76%
NC	24%	17%
CC $\nu_\mu/\bar{\nu}_\mu$	21%	7%

ν_e Decomposition





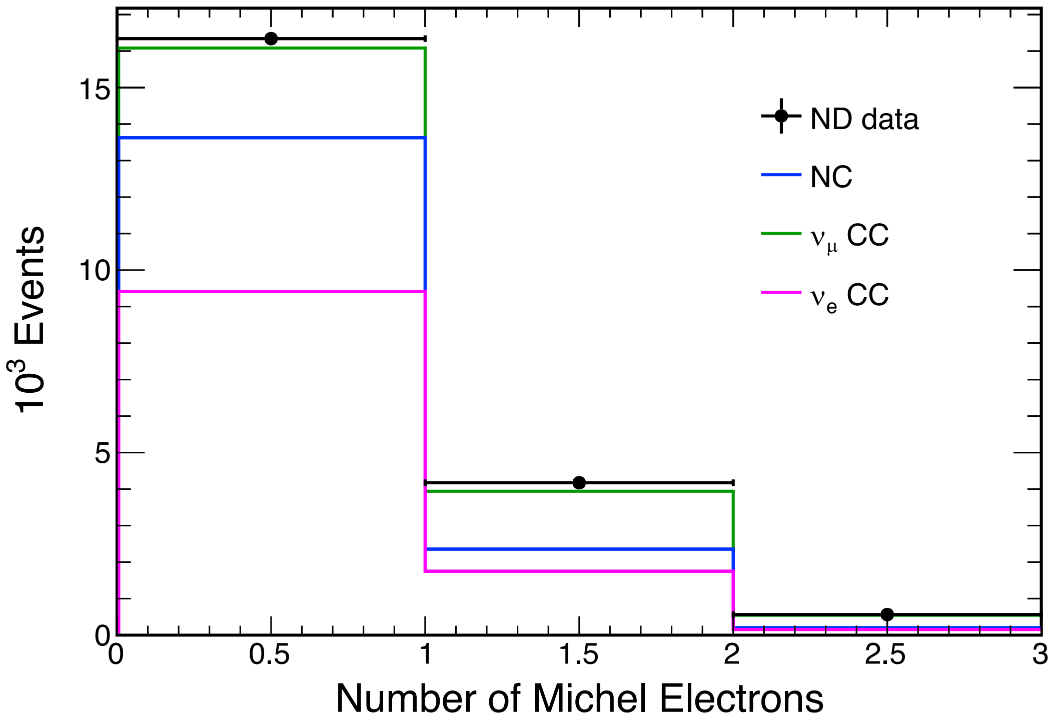


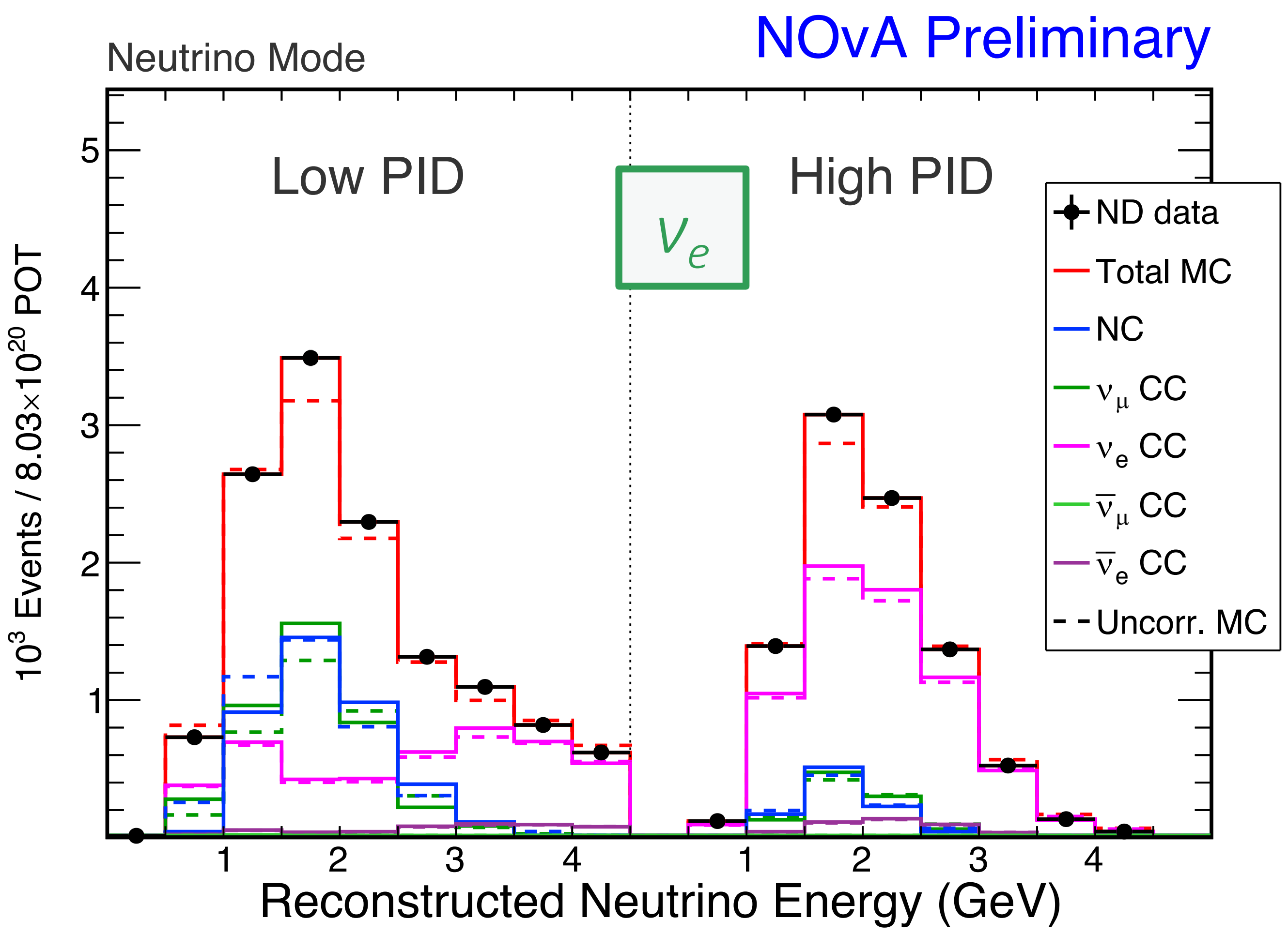
- ν_e and ν_μ events come from the same parents:
  - Lower energy neutrinos come primarily from ***π*** decay.
  - Higher energy neutrinos come primarily from ***K*** decay.
- Use contained ν_μ data to constrain the ***π* flux**
- Use higher energy uncontained events to constraint the ***K* flux**.

ν_e Decomposition

The CC/NC constrained using the number of observed Michel electrons.

- Determine the fraction of the two components in each analysis bin.

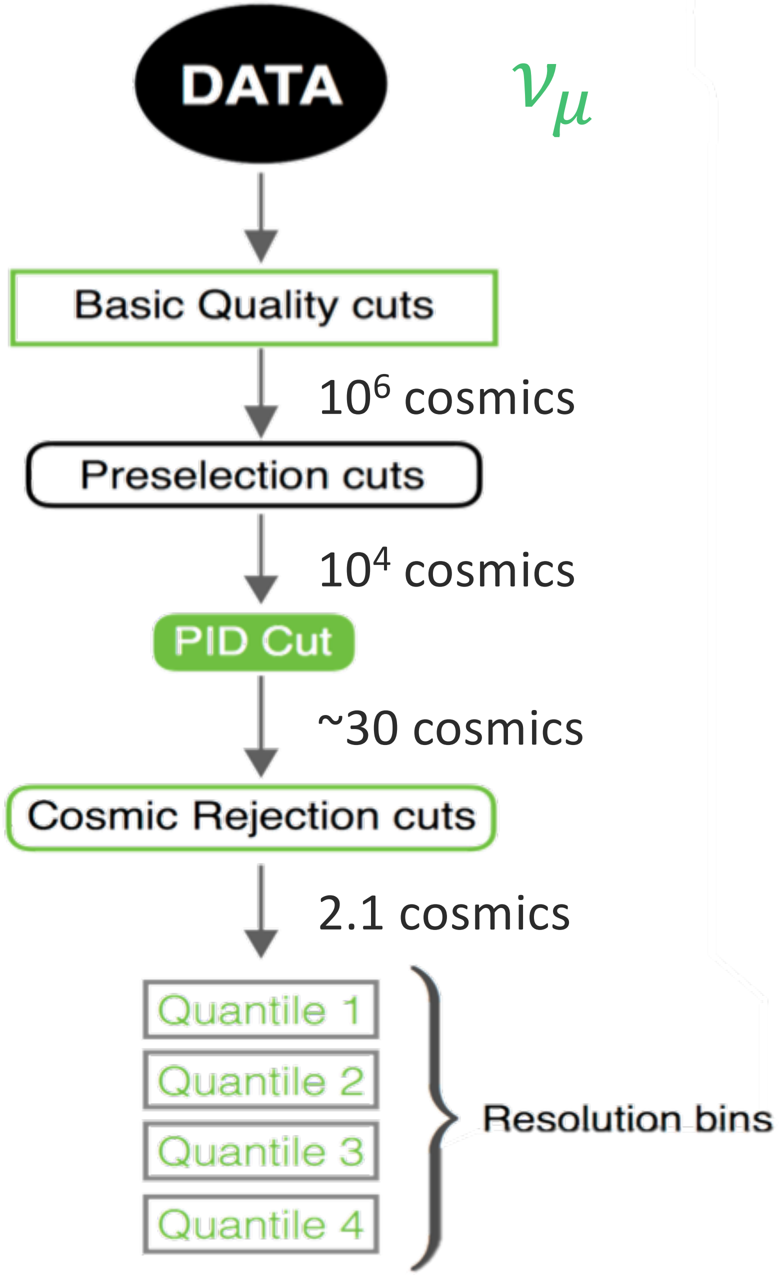


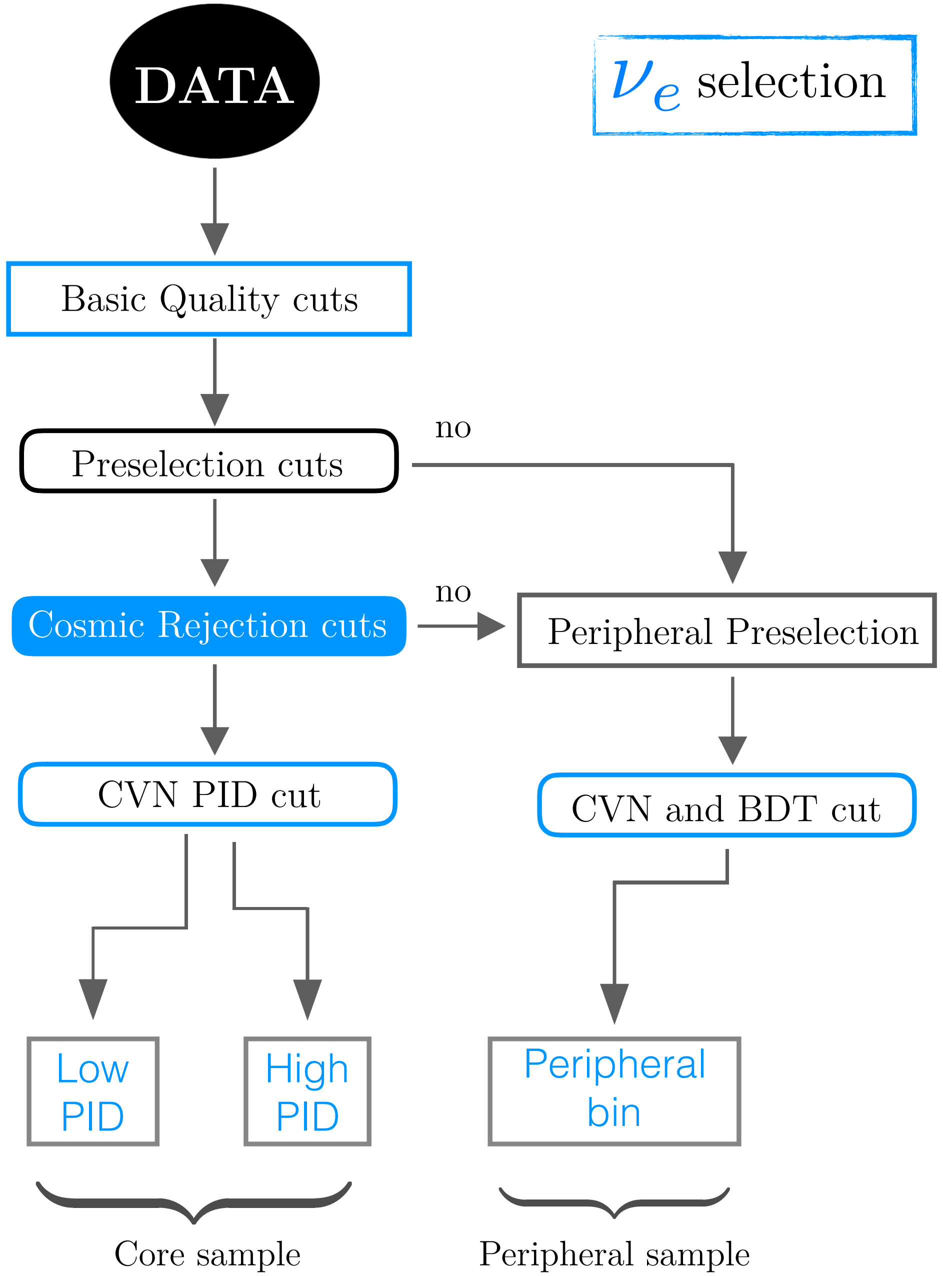


Change in Total	
ν_e CC	+3%
ν_μ CC	+7%
NC	-4%

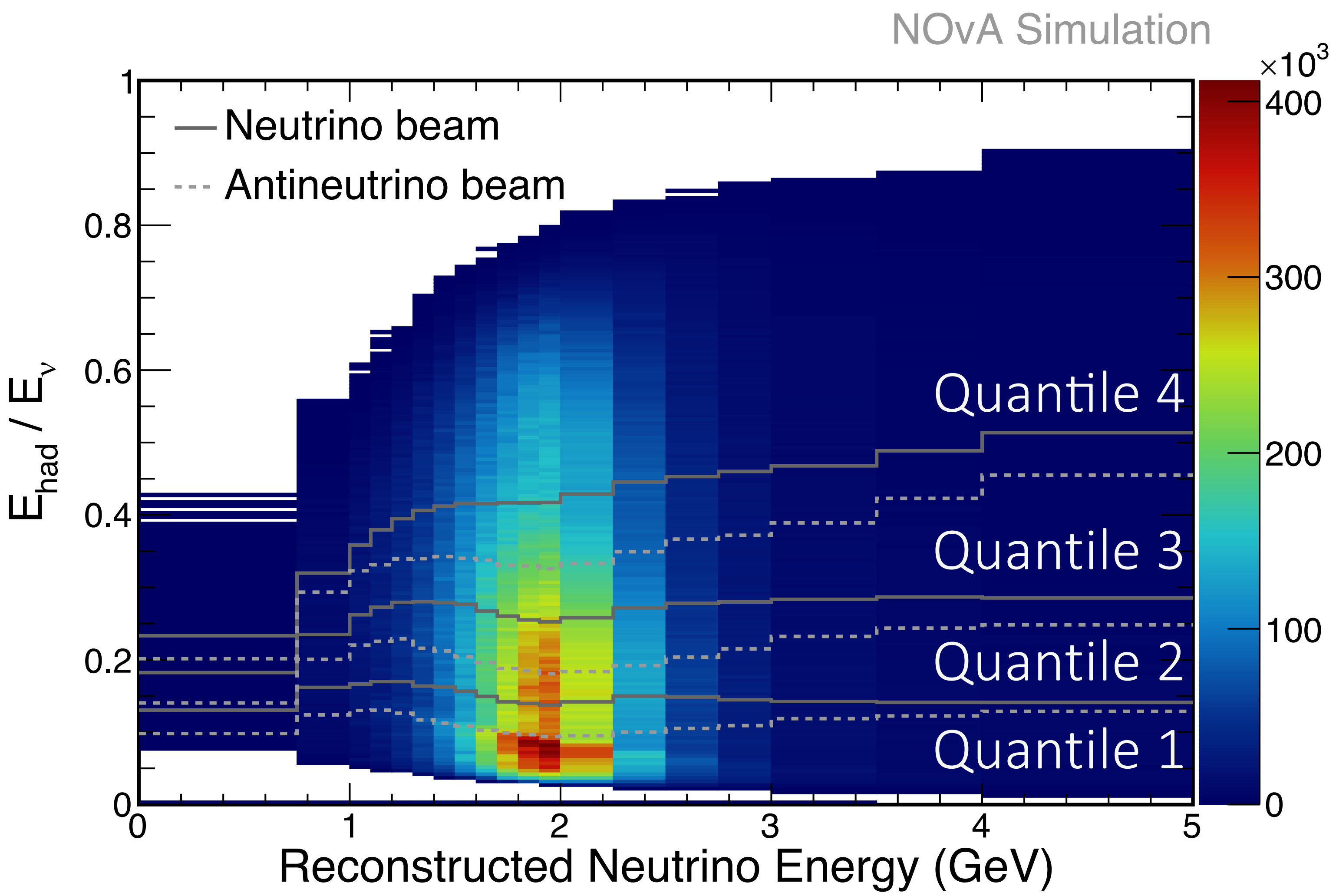
FD selection and cosmic rejection

- Because the far detector sits on the surface, cosmic backgrounds are a significant issue.
- Even with a pulsed beam and excellent timing resolution, there is still a significant cosmic background.
- Selection steps are tuned to reduce cosmic backgrounds while maintaining sensitivity to oscillations



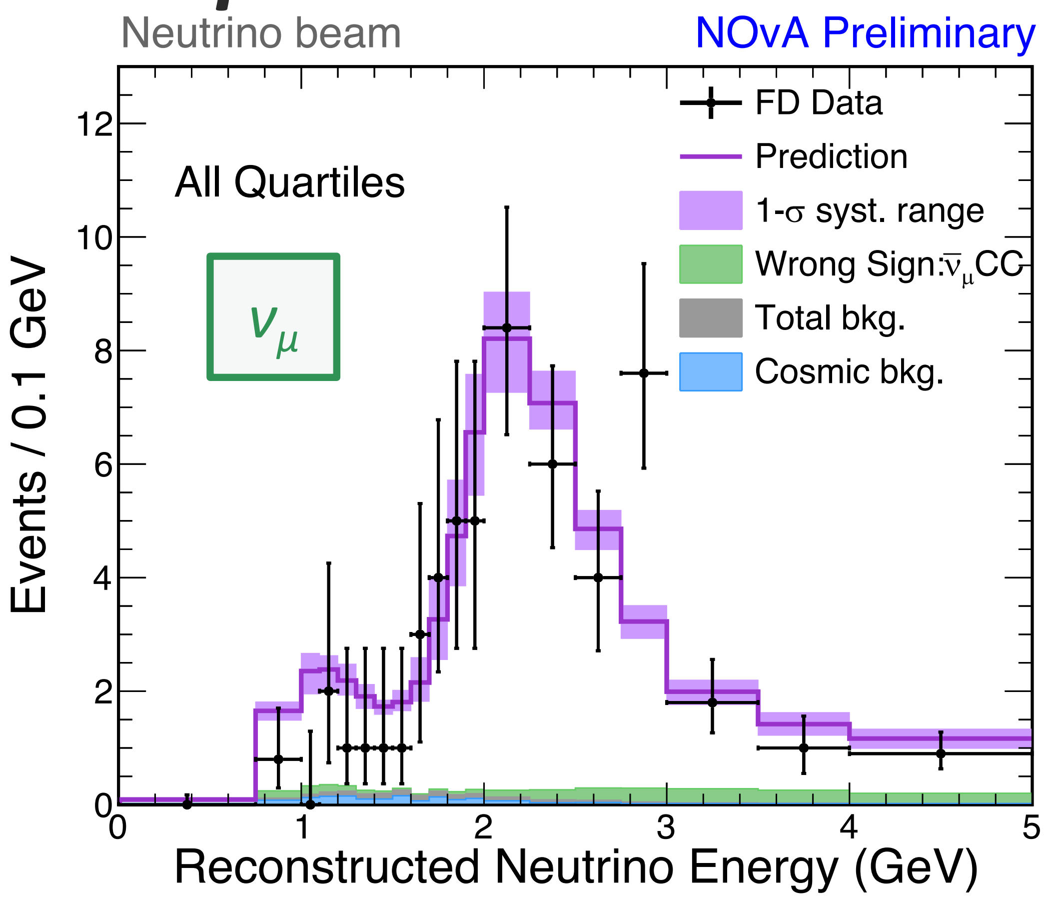


Binning for Sensitivity: ν_μ Events

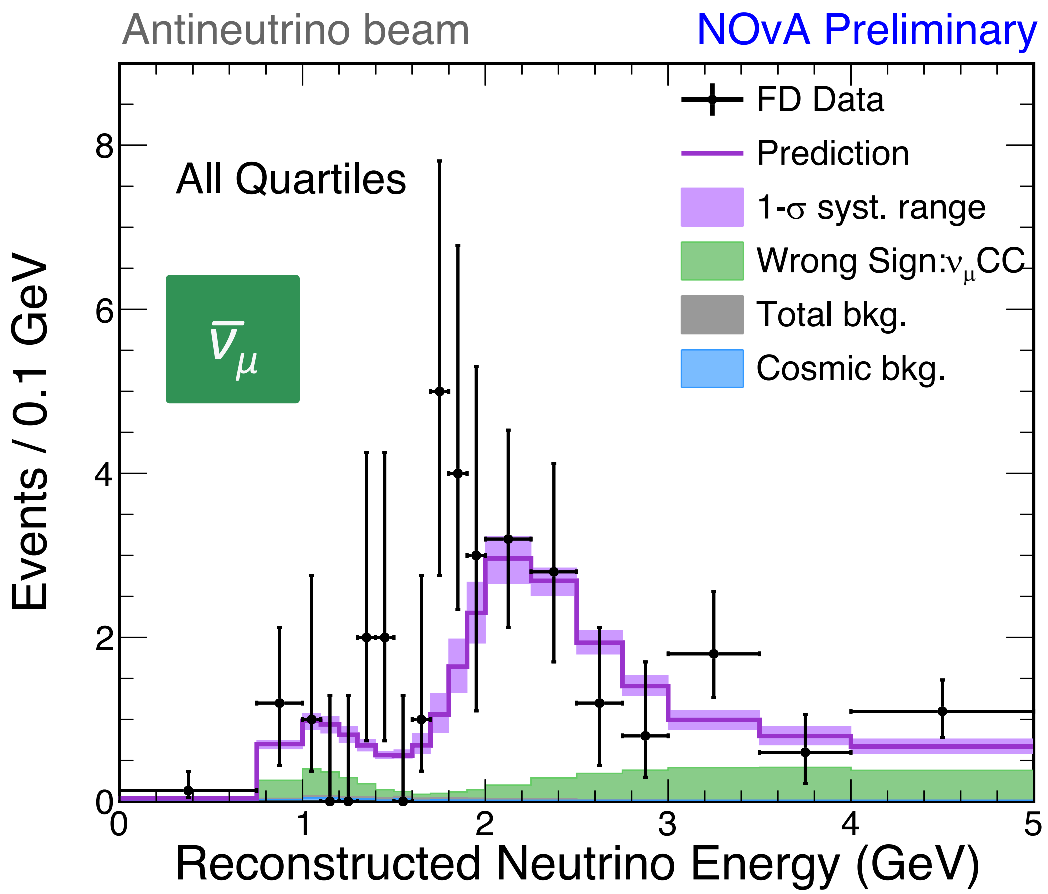


- Oscillation sensitivity depends on spectrum shape
- Improve sensitivity by separating high-resolution and low-resolution events.
- Split into 4 quantiles by hadronic energy fraction.
  - Muon energy resolution (3%) is much better than hadronic energy resolution (30%).

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



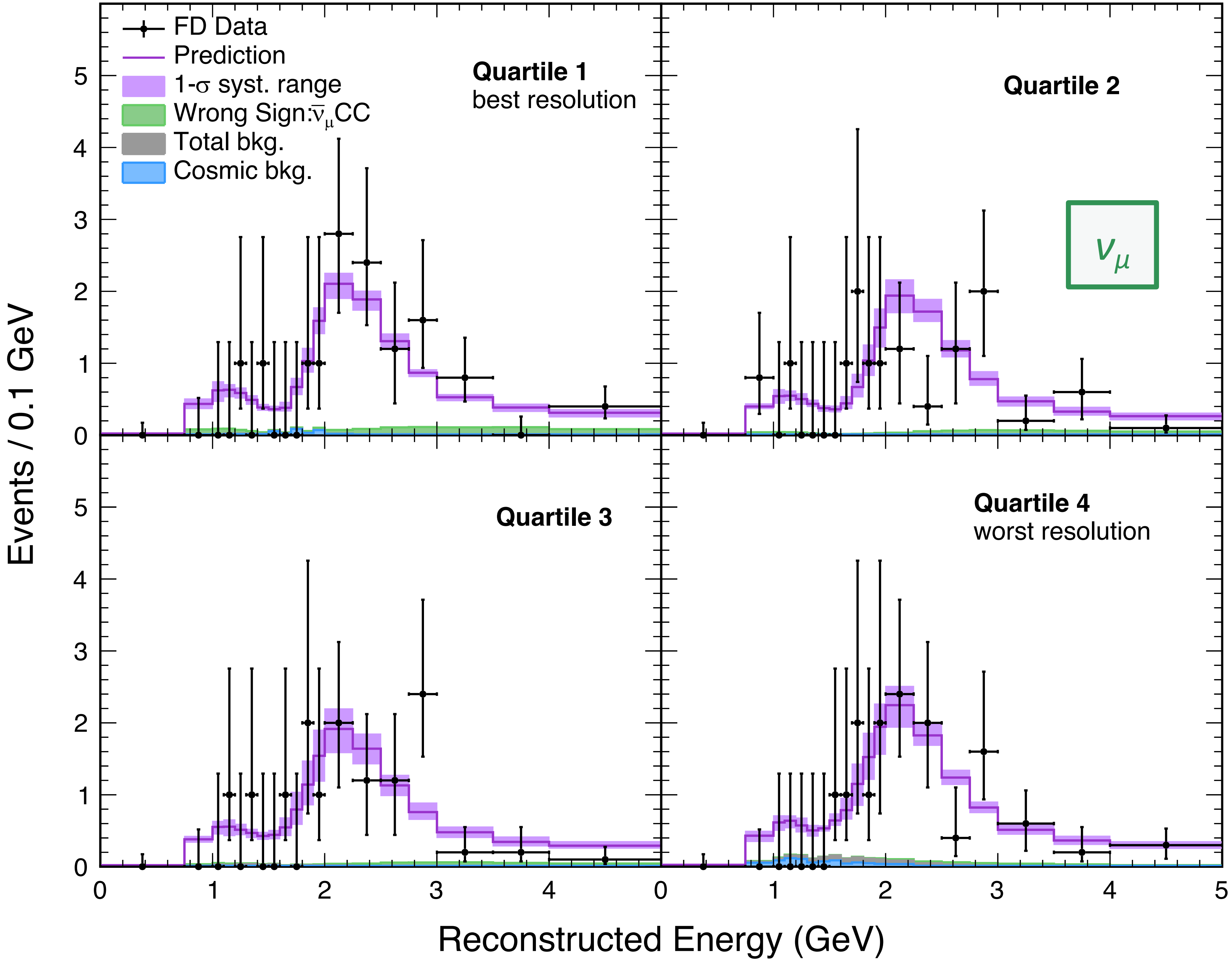
Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730



Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

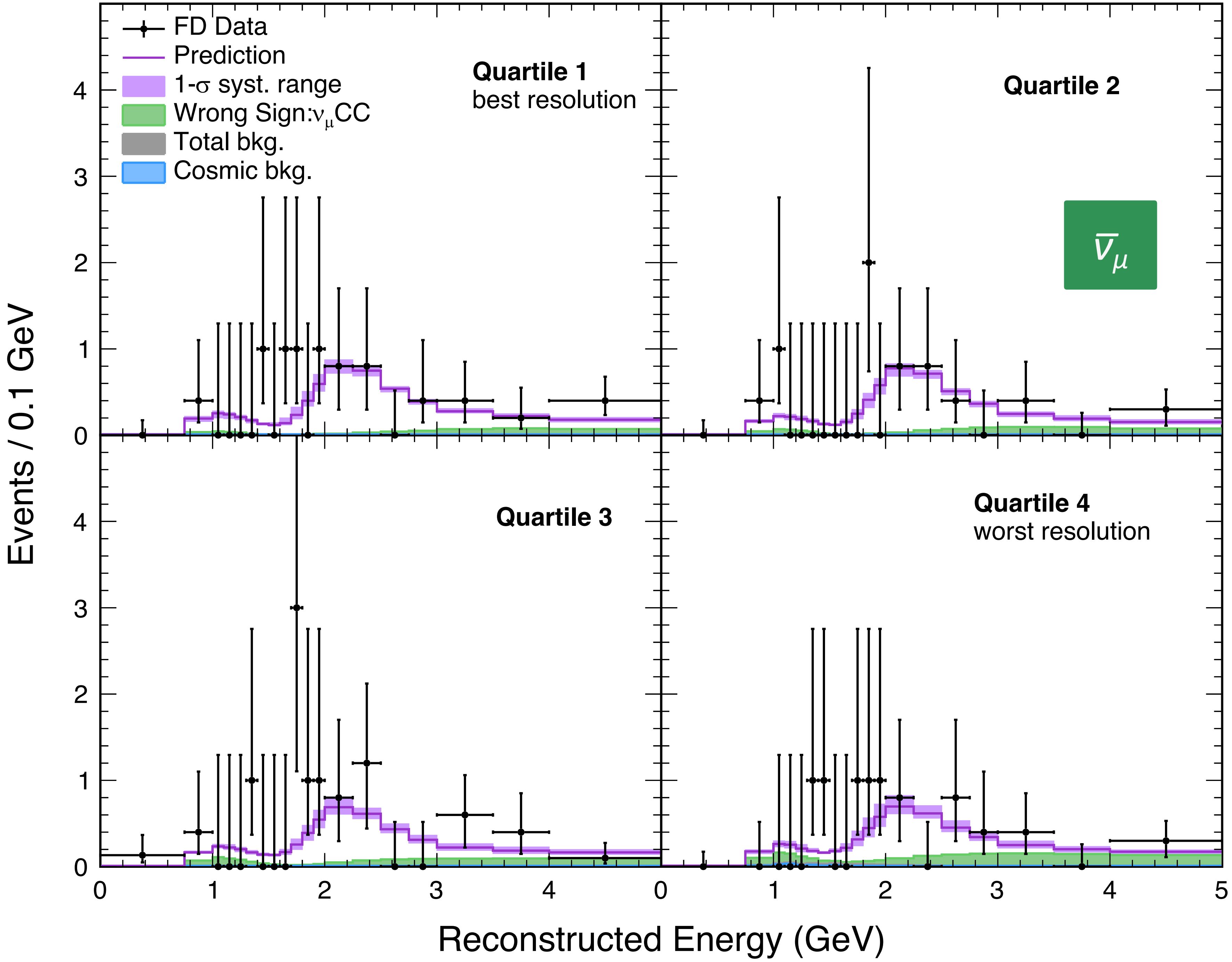
Neutrino beam

NOvA Preliminary

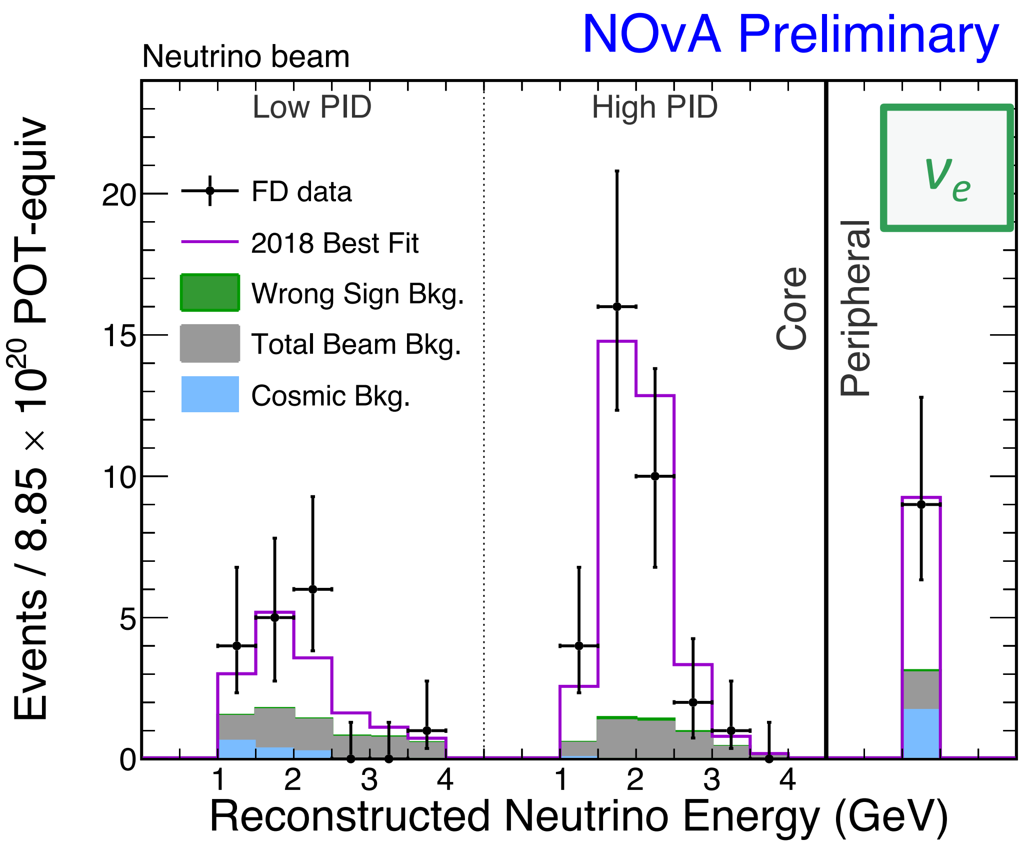


Antineutrino beam

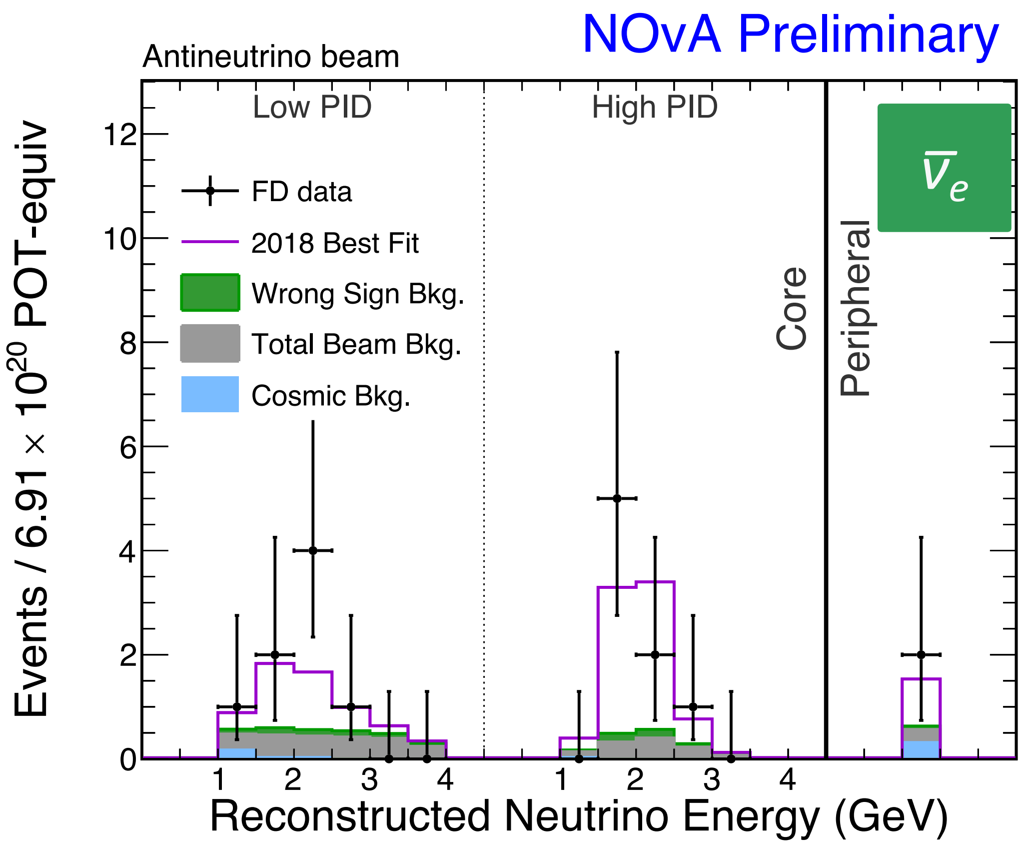
NOvA Preliminary



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



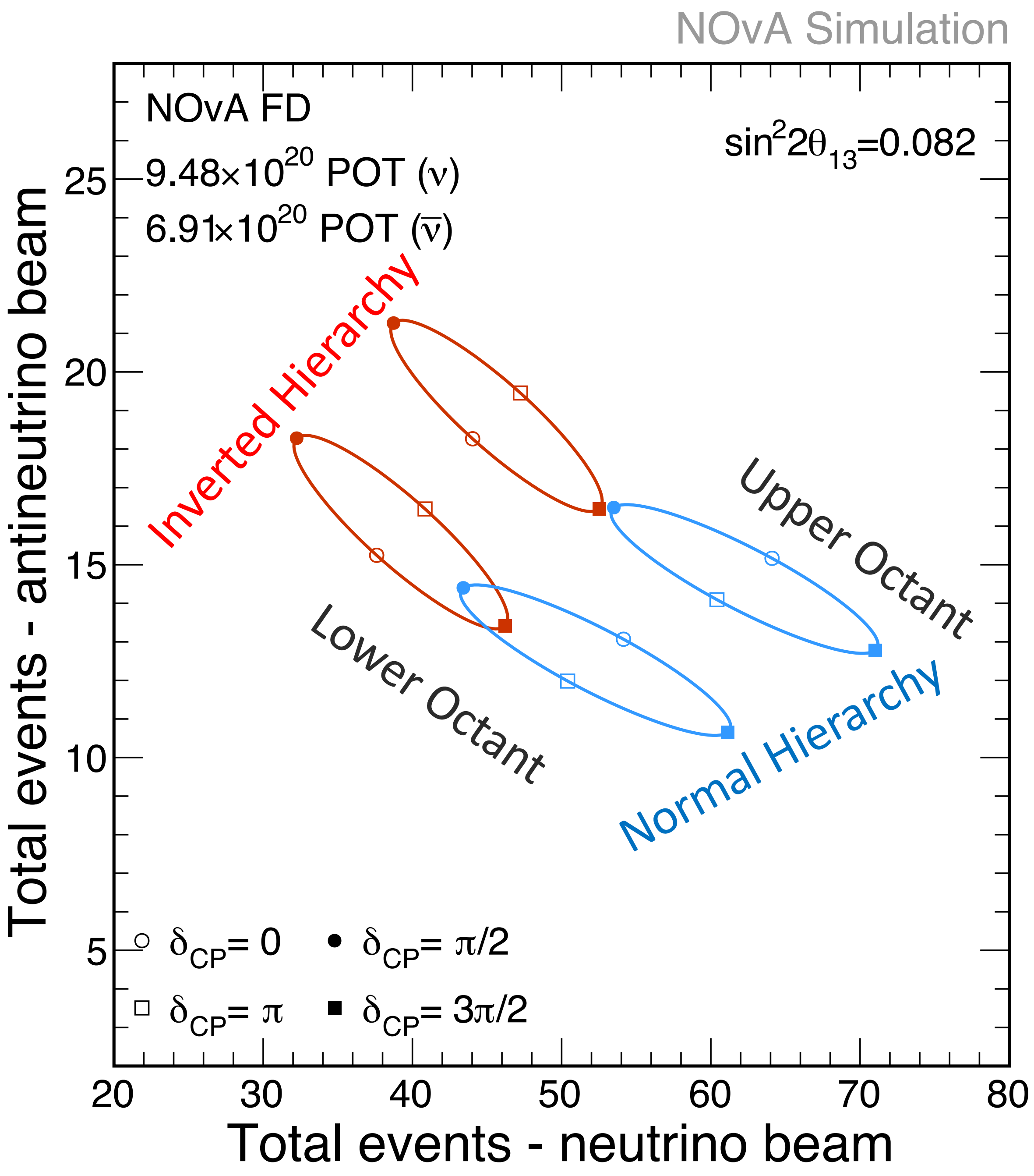
Total Observed	**58**	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4



Total Observed	**18**	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

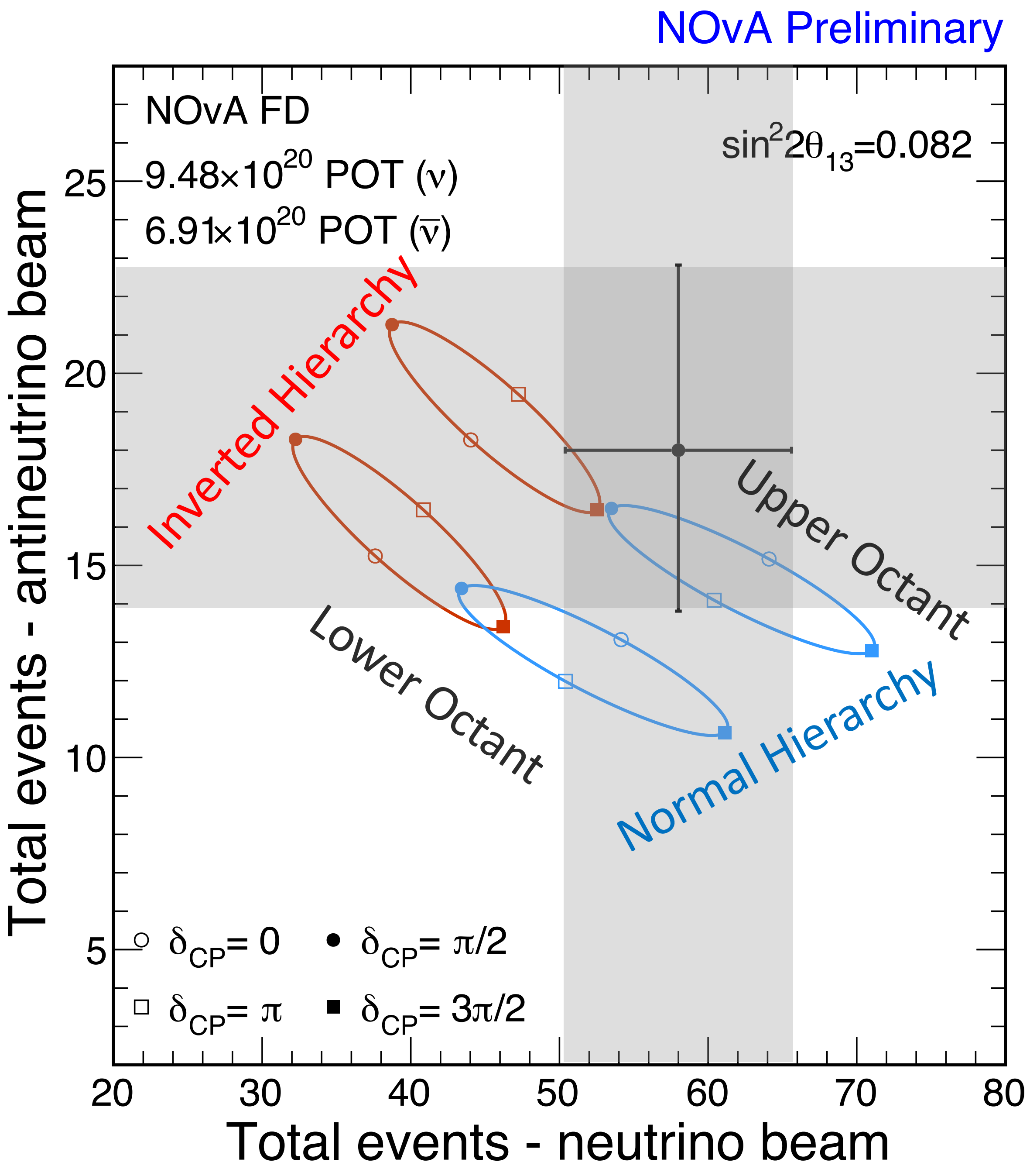
Strong (>4σ) evidence of $\bar{\nu}_e$ appearance

10-22 Expected for $\overline{\nu}_e$



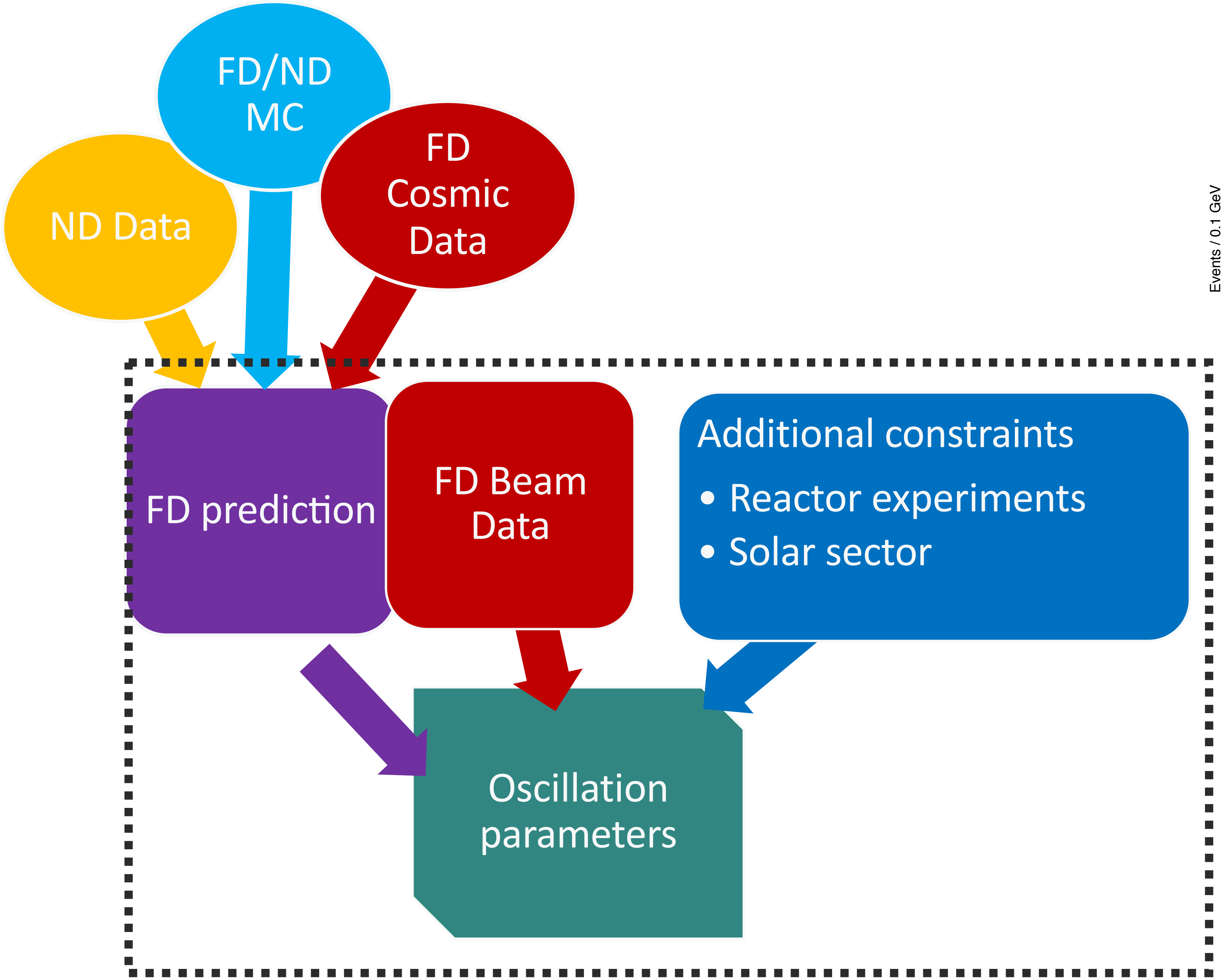
30-75 Expected for ν_e

18 observed $\bar{\nu}_e$



58 observed ν_e

Extracting oscillation parameters



ND Data

FD/ND MC

FD Cosmic Data

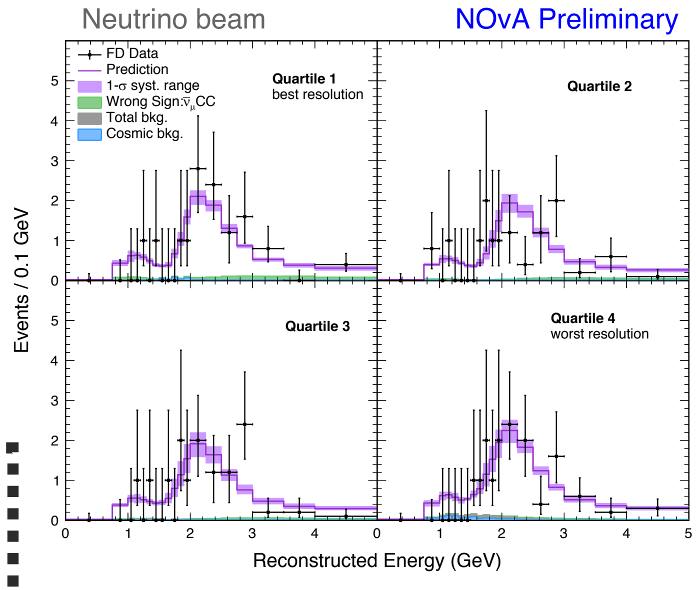
FD prediction

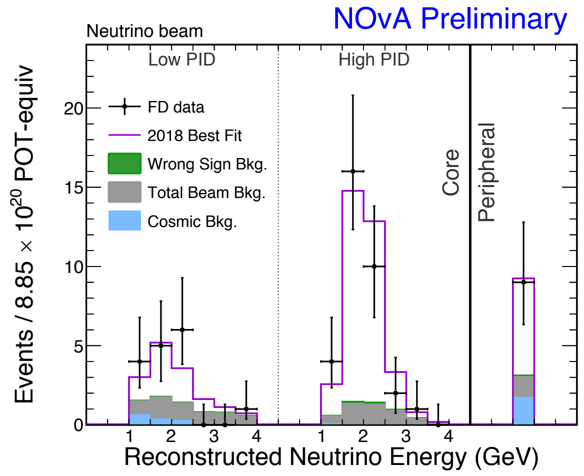
FD Beam Data

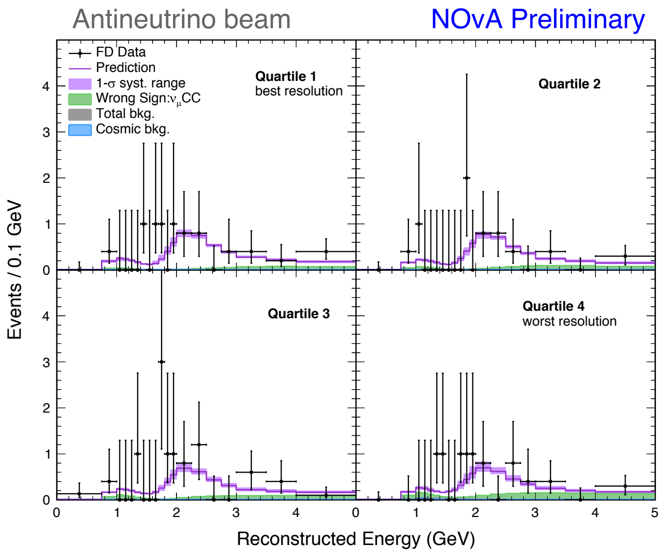
Additional constraints

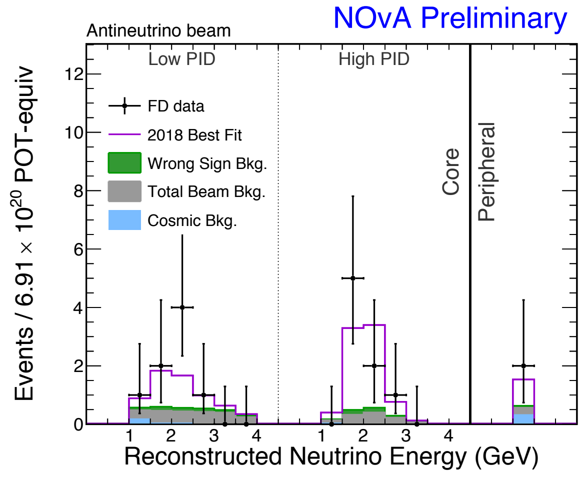
- Reactor experiments
- Solar sector

Oscillation parameters

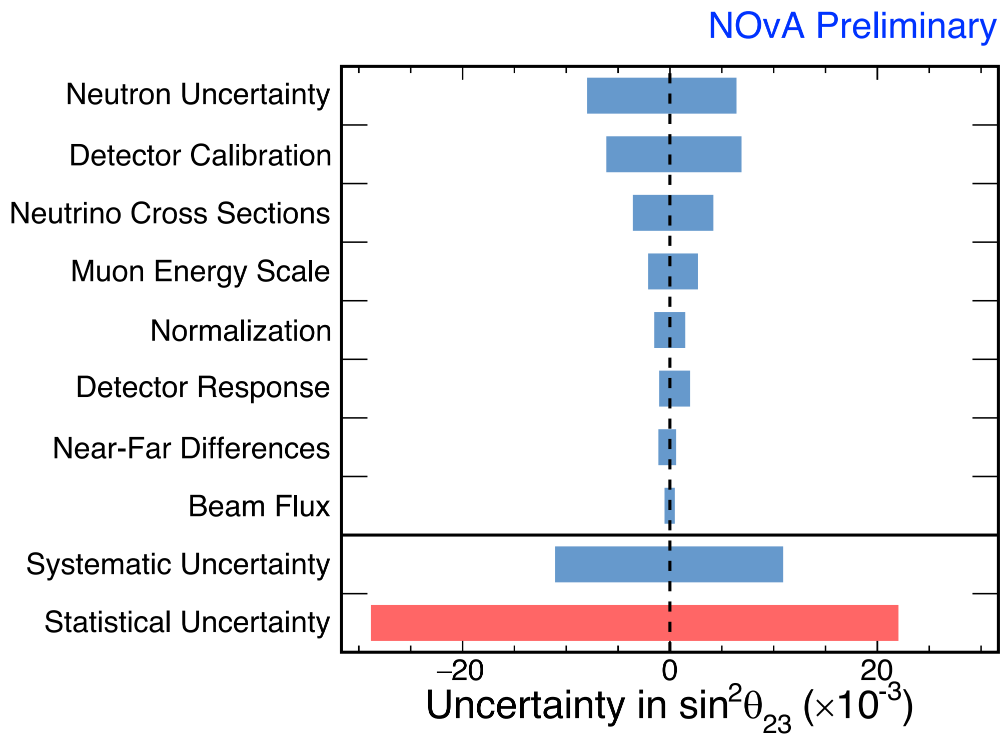


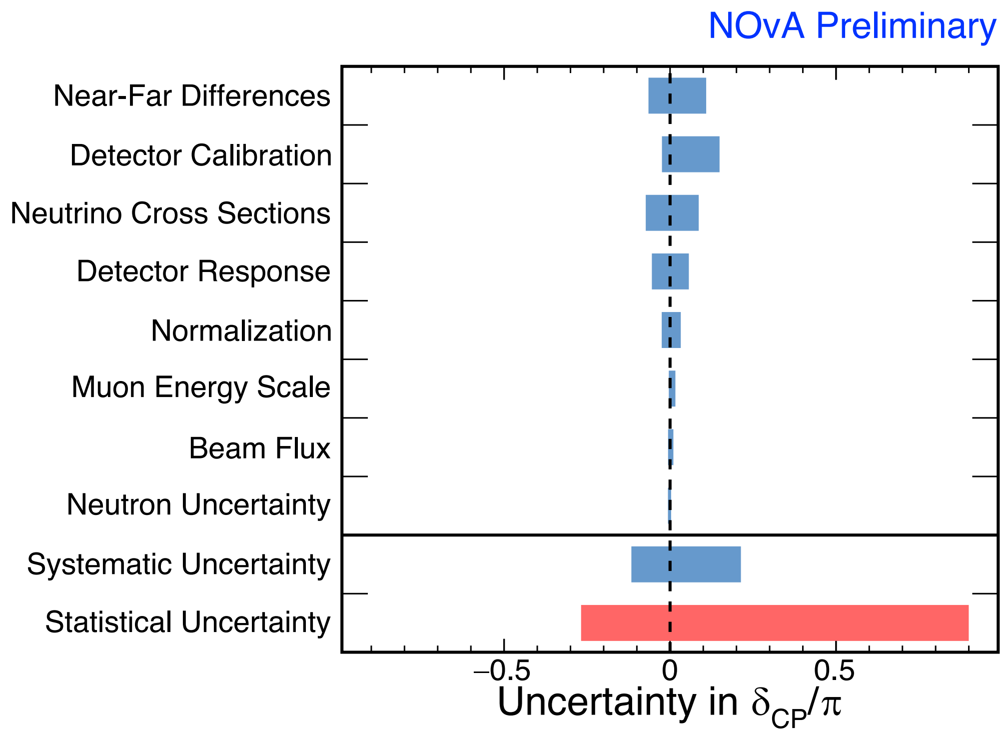


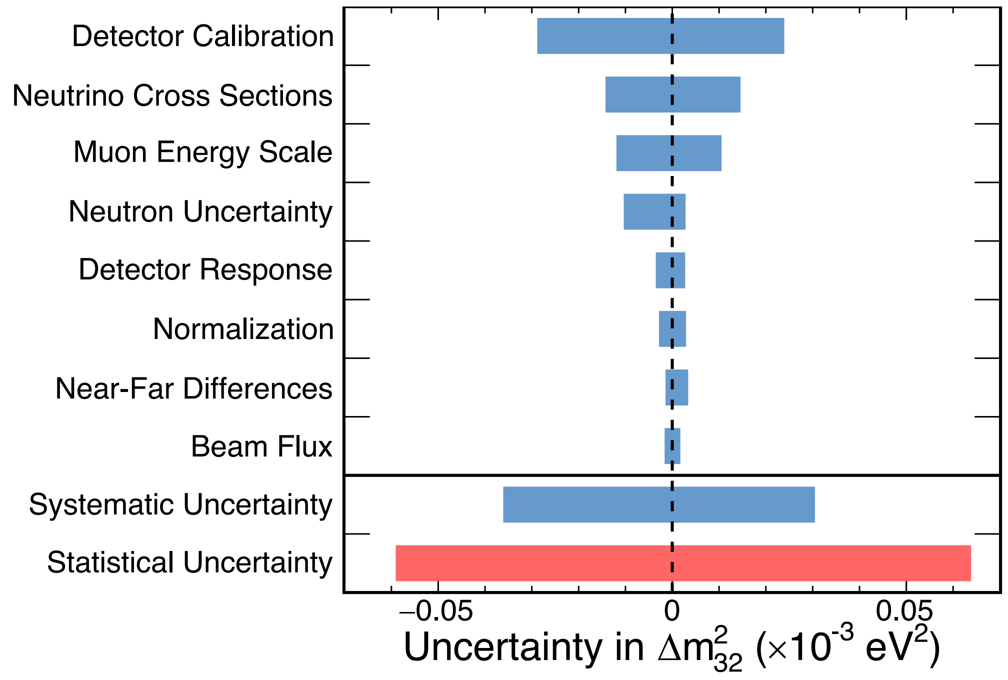




Systematic Uncertainties



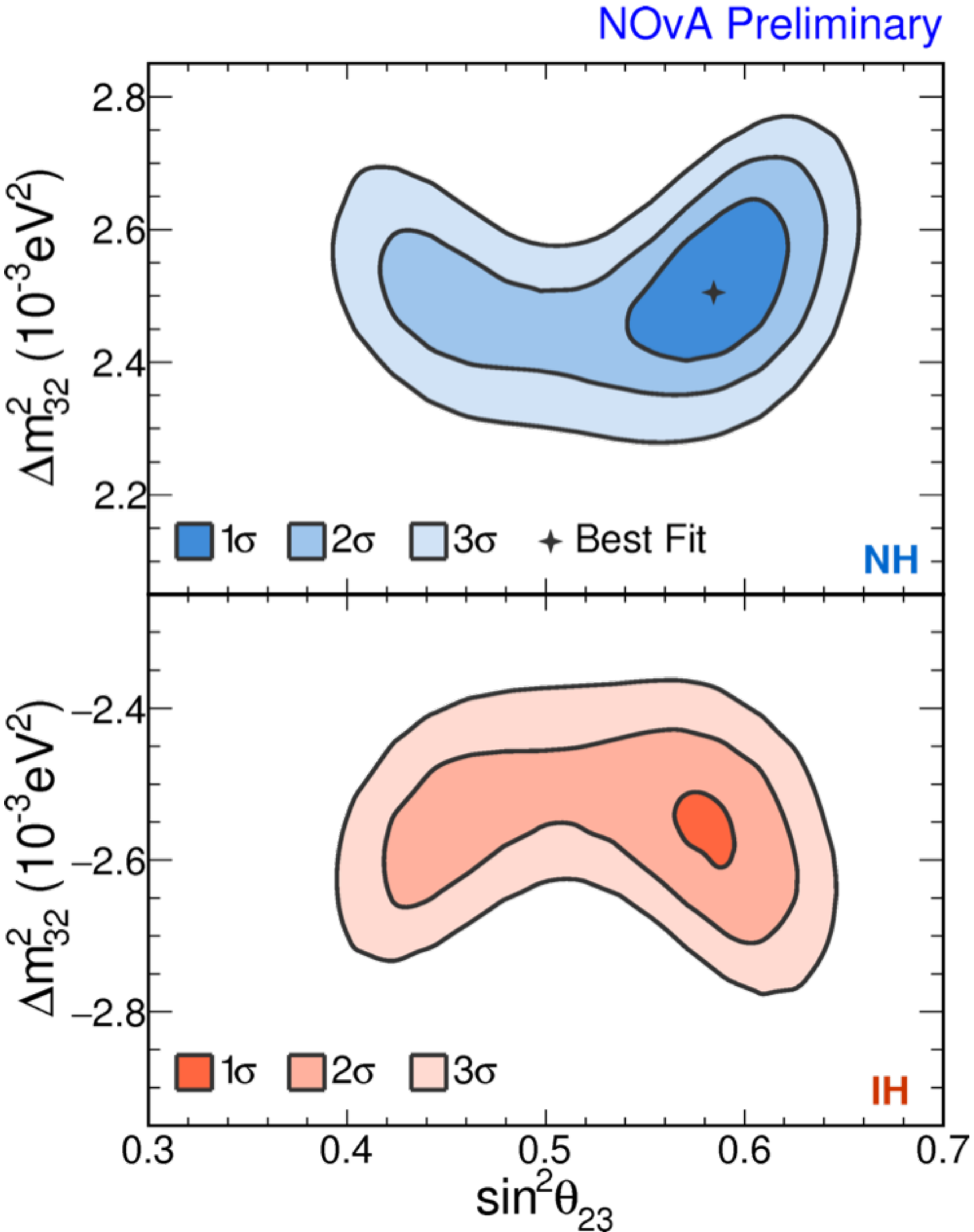




Most important systematics:

- Detector Calibration
  - Will be improved by the test beam program
- Neutrino cross sections
  - Particularly nuclear effects (RPA, MEC)
- Muon energy scale
- Neutron uncertainty – **new** with $\overline{\nu}$'s

Results



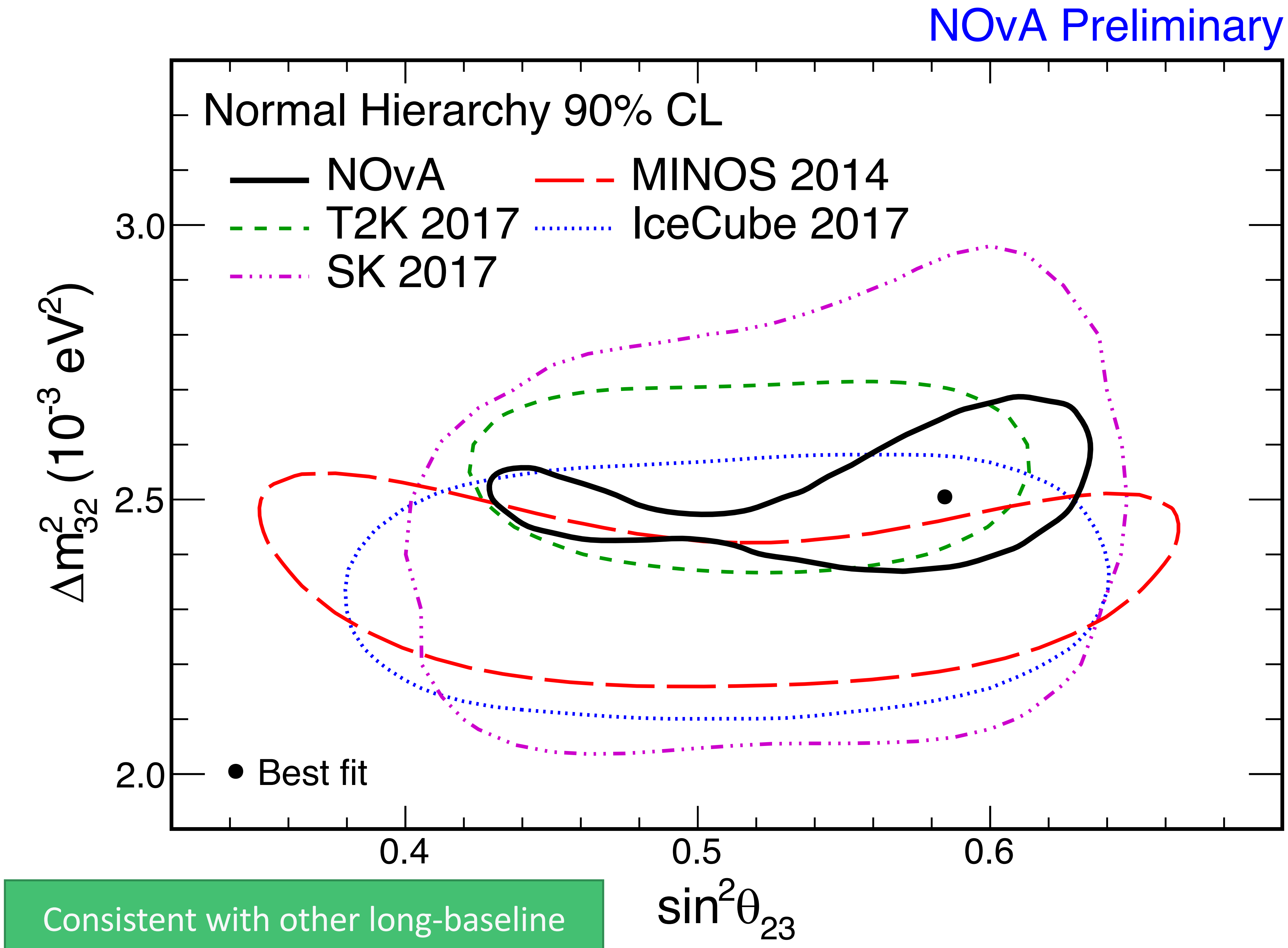
Best Fit

Normal hierarchy

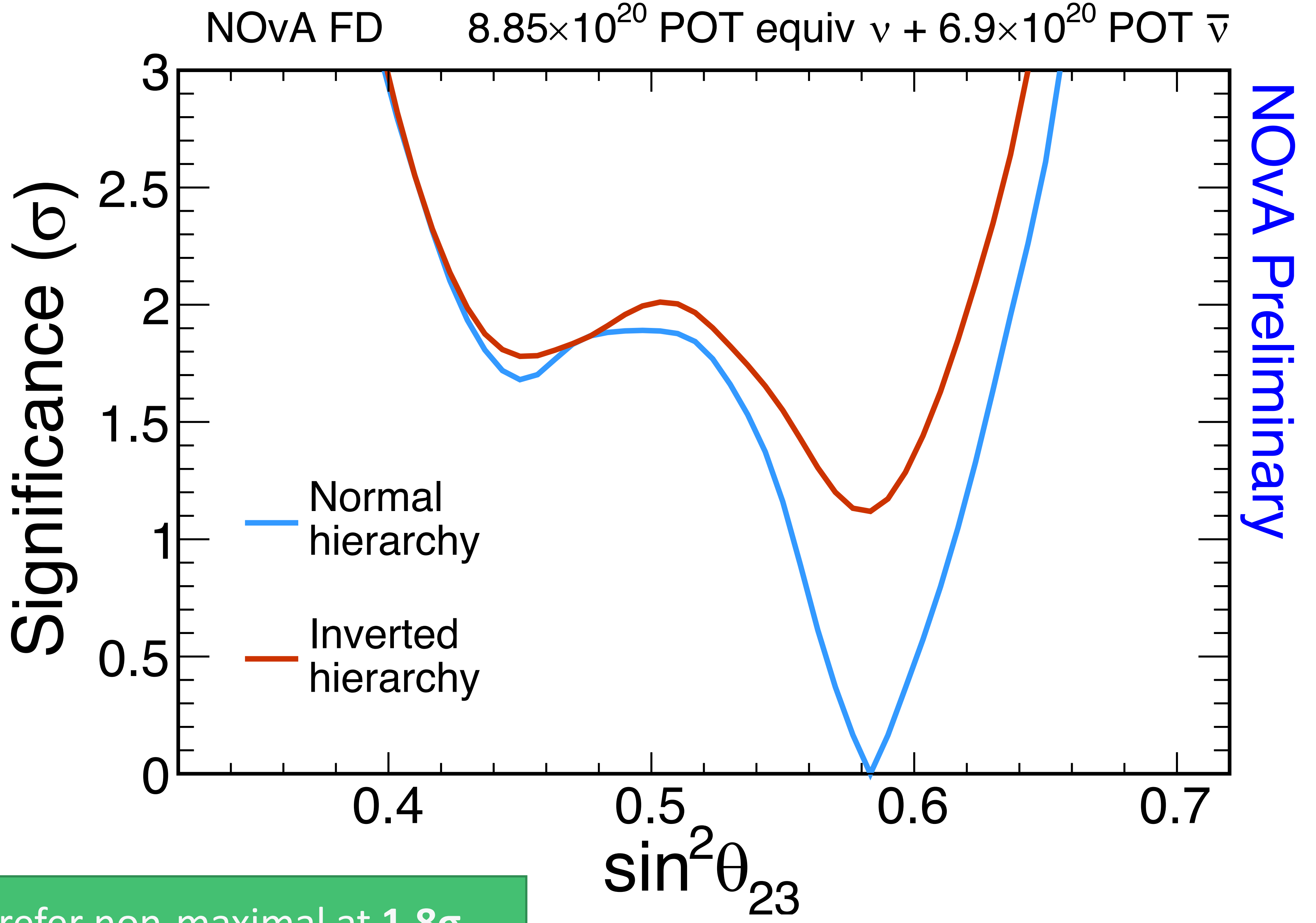
Upper Octant

$\Delta m^2 = (2.51^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2

$\sin^2\vartheta_{23} = 0.58 \pm 0.03$



Consistent with other long-baseline and atmospheric experiments.



Prefer non-maximal at **1.8σ**.

Favor the upper octant
at a similar level.

Best Fit

Normal hierarchy

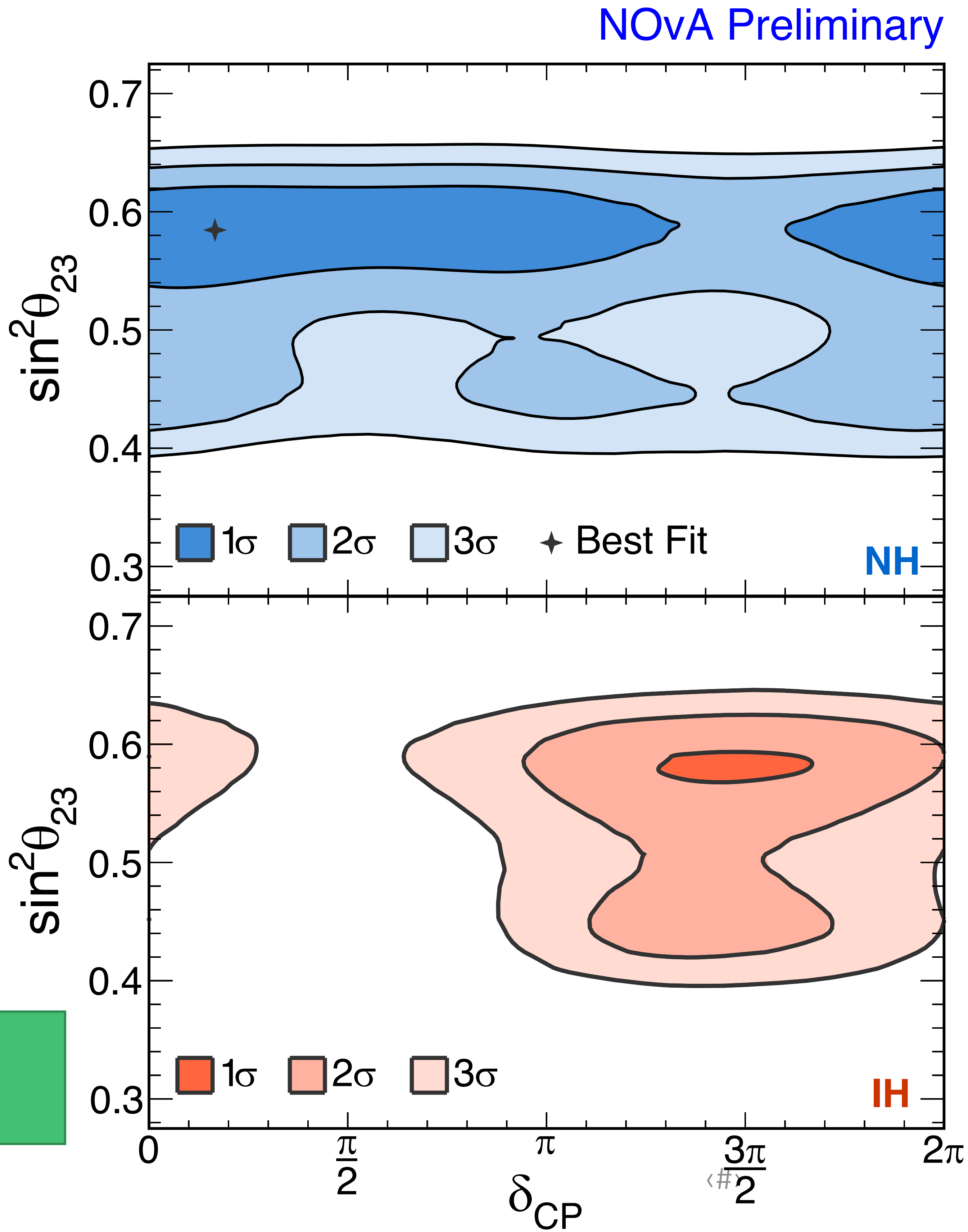
Upper Octant

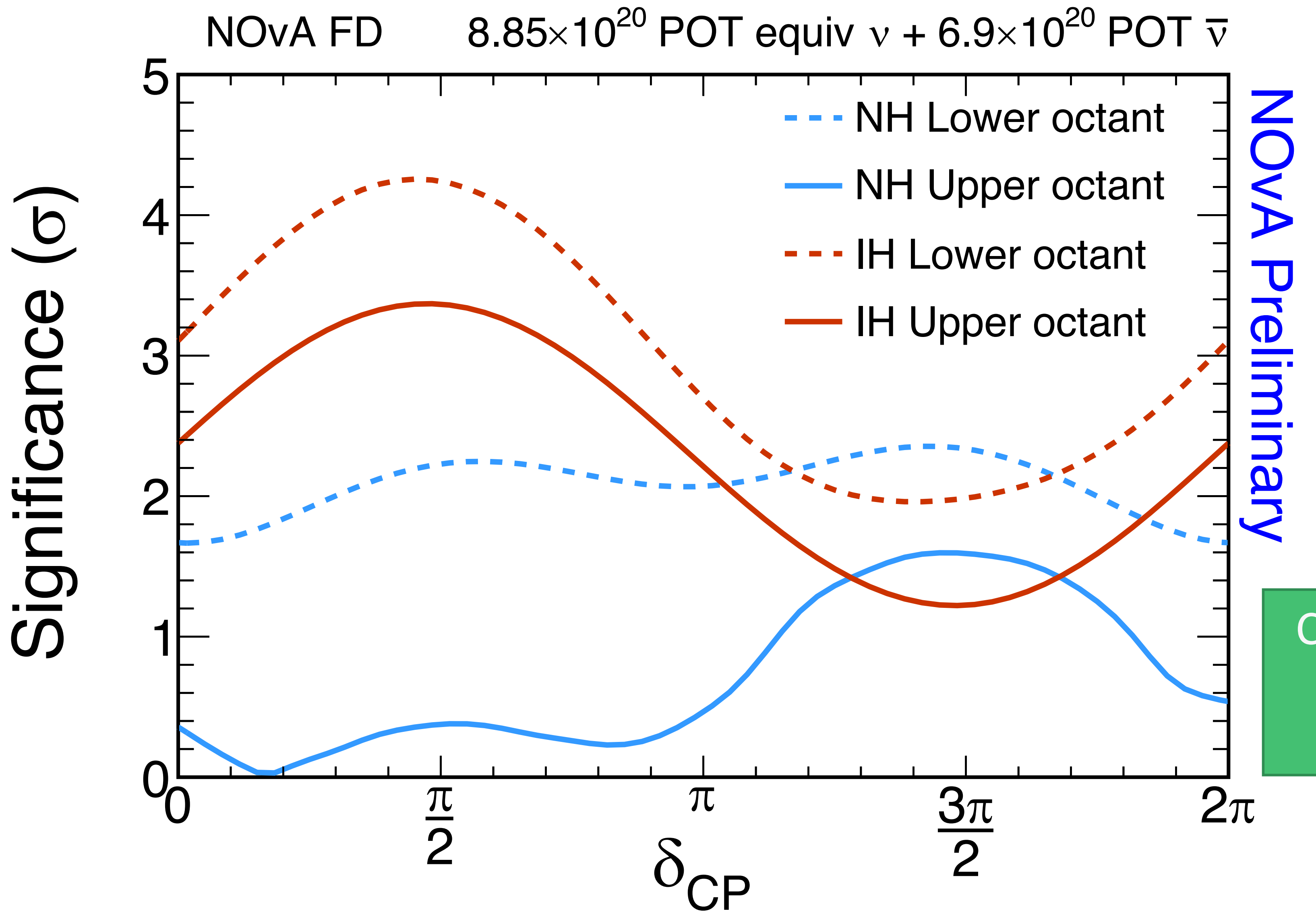
$\Delta m^2 = (2.51^{+0.12}_{-0.08})\times10^{-3}\ \mathrm{eV}^2$

$\sin^2\vartheta_{23} = 0.58 \pm 0.03$

$\delta = 0.17\pi$

Exclude IH, $\delta=\pi/2$ at > 3σ

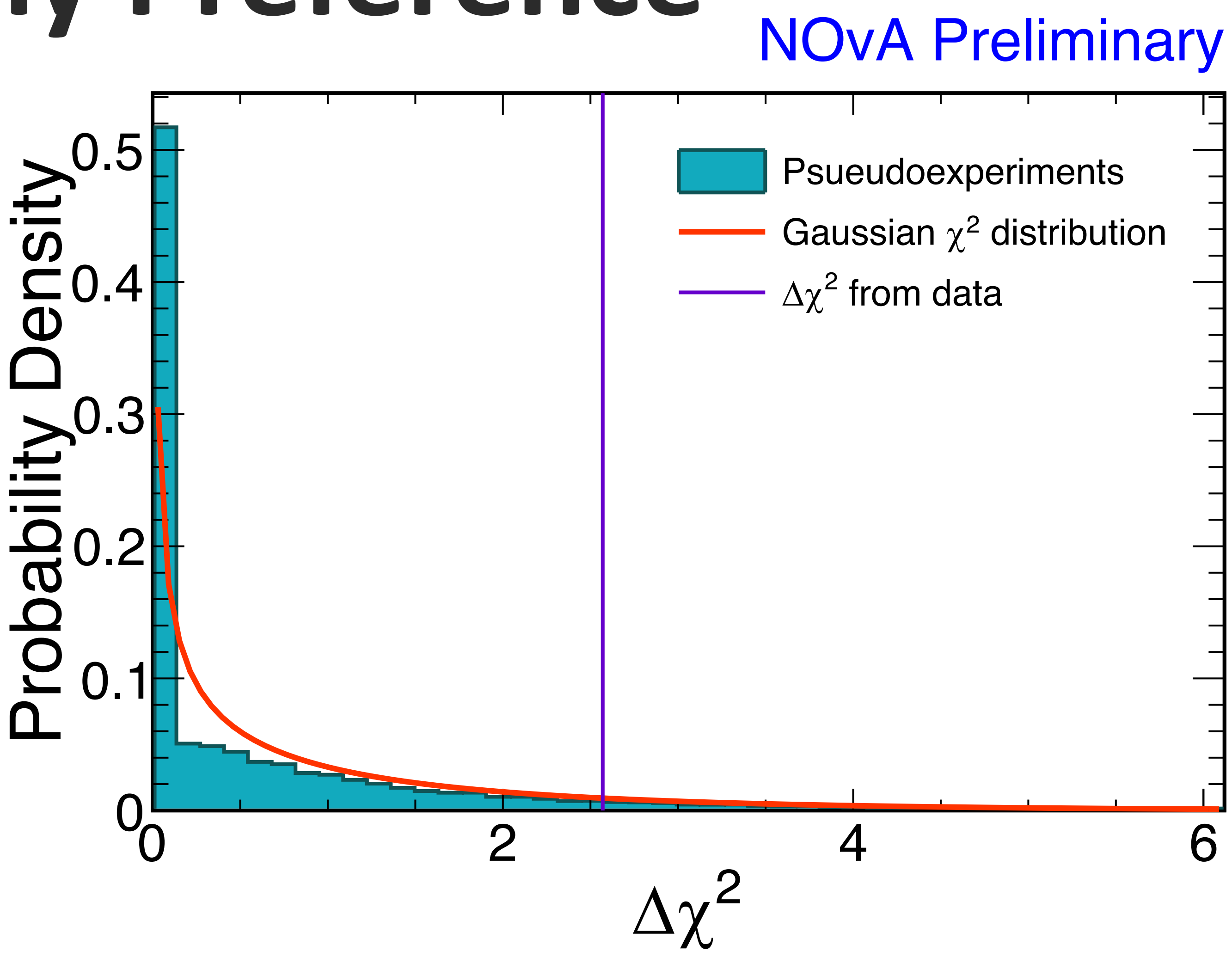




Consistent with all δ_{CP} values in NH at < 1.6σ.

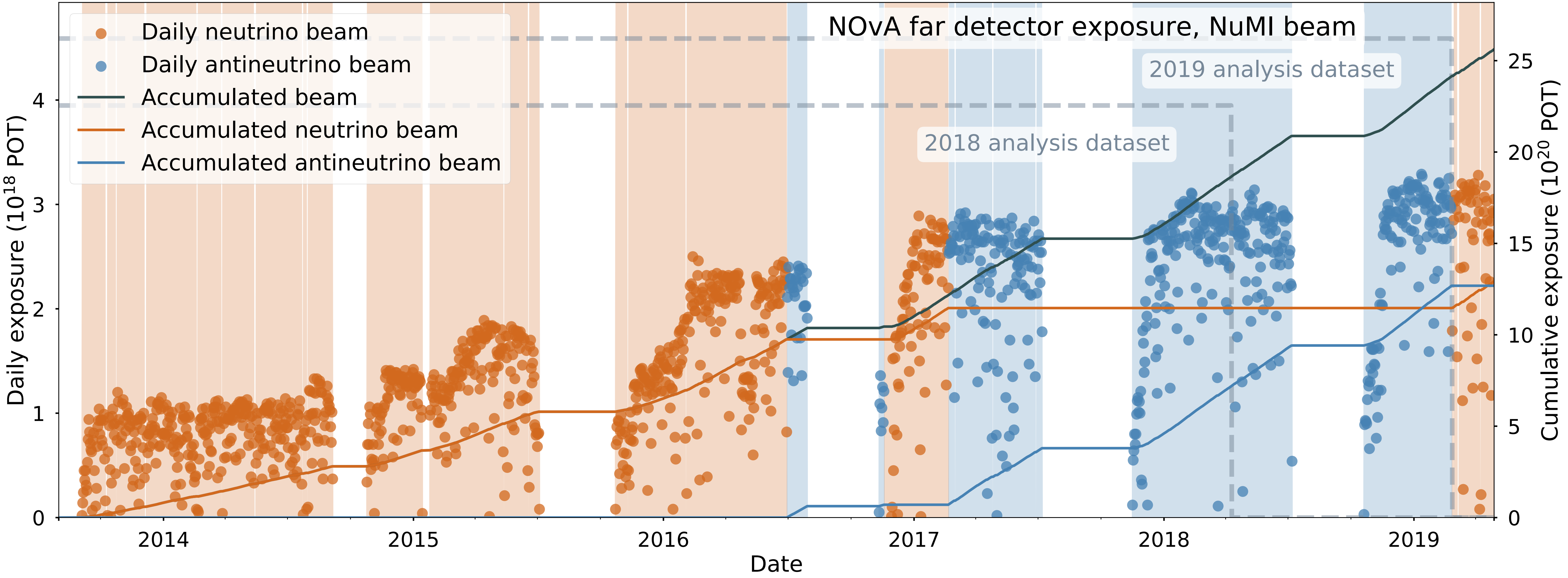
- Note: you cannot read the rejection of the MH from this plot.
  - This is an FC-corrected plot of significance for rejecting particular sets of values (δ, octant, hierarchy).
  - It is *not* a likelihood surface, so it cannot be profiled to remove δ and the octant.
- Additionally, the MH itself is highly non-Gaussian so we need to use FC.
  - A binary choice with degenerate, unknown parameters.

Mass Hierarchy Preference



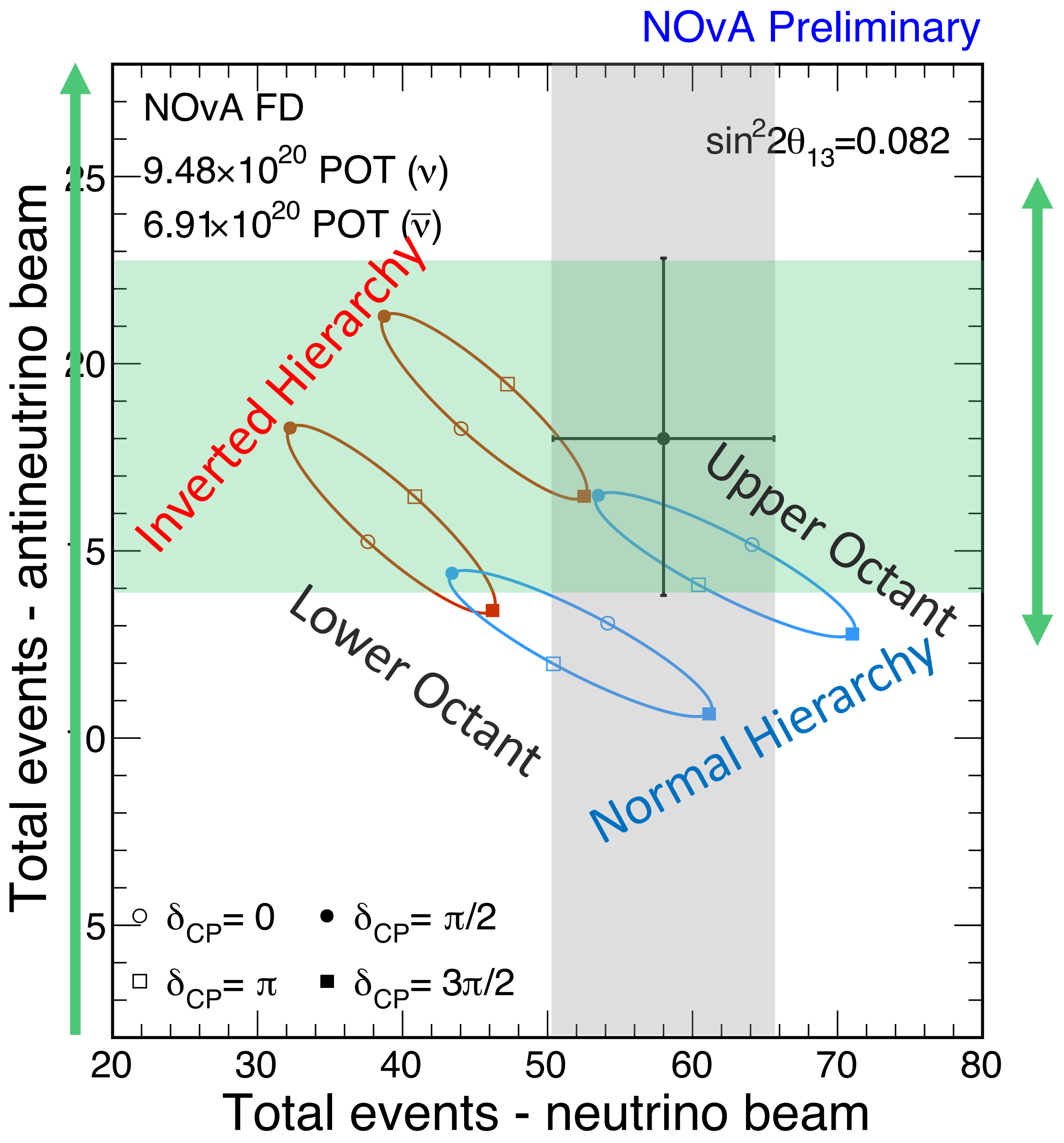
- χ^2(IH) - χ^2(NH)= **2.47**
- giving a *p*-value of **0.076** from the FC empirical χ^2.
- or equivalently **1.8σ**

NOvA prospects - 2019



Update with ~80% more antineutrino data right around the corner!

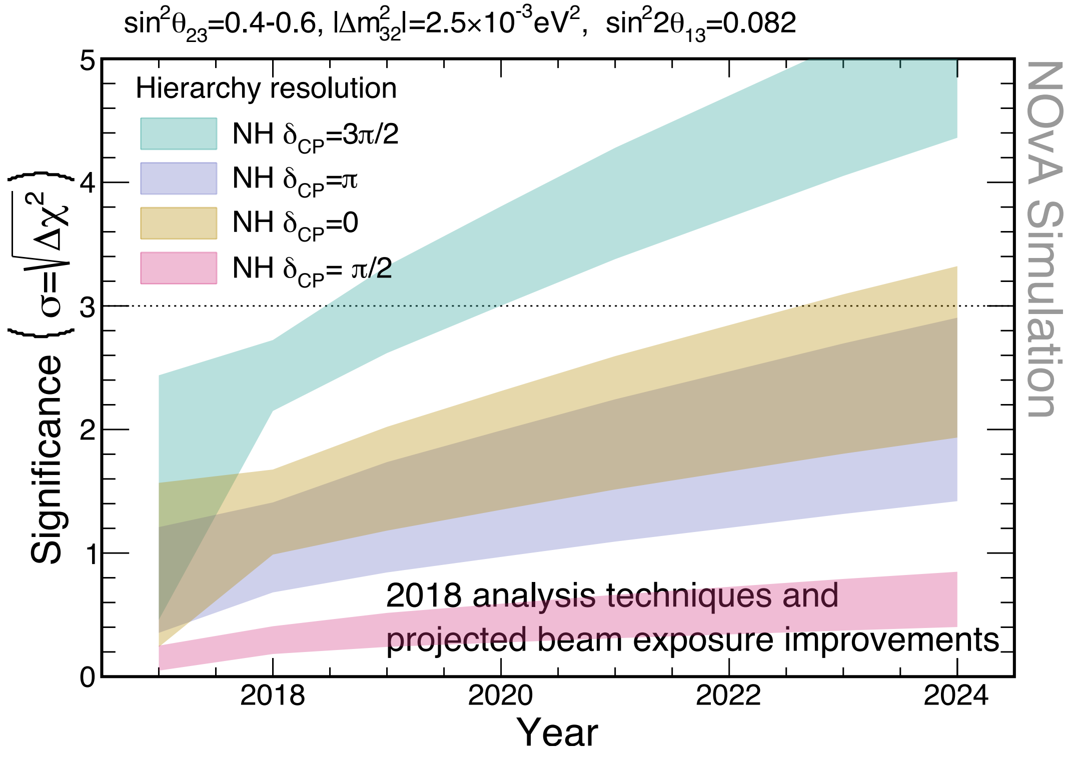
NOvA prospects - 2019

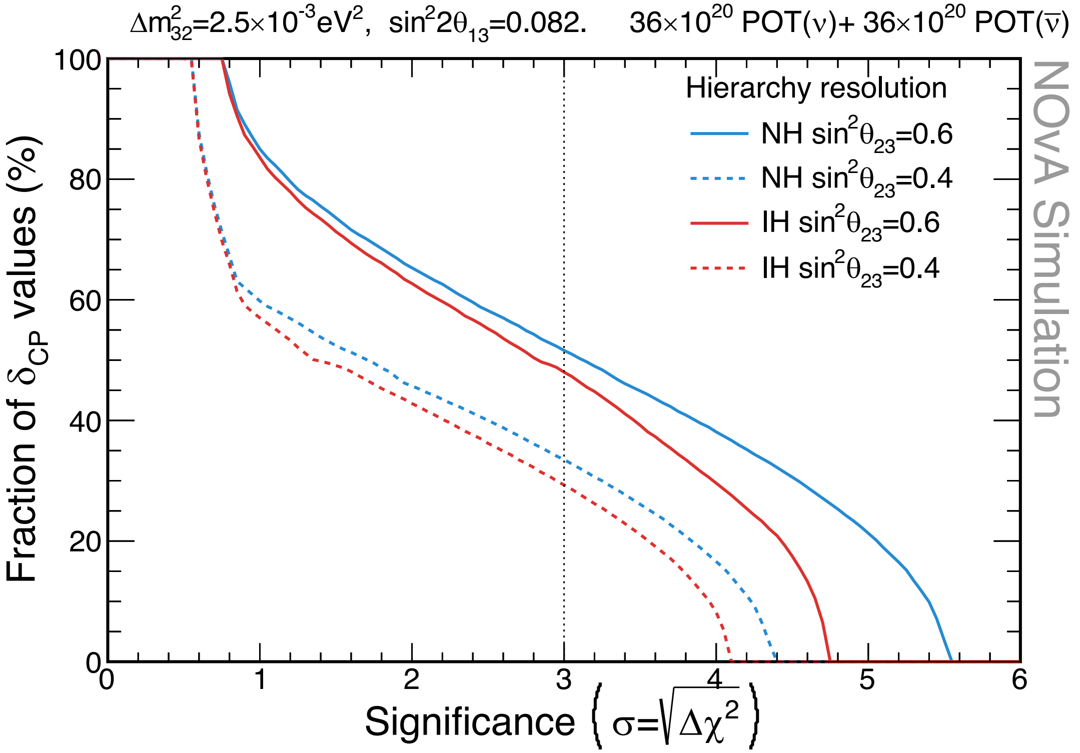


- 2019 analysis to be presented at the Fermilab Users Meeting in June
- Same 9.48E20 POT of neutrino beam data; 12.33 E20 POT antineutrinos
- Using the same analysis techniques as the 2018 analysis
- Potentially observe:
  - Different best fit values for ssth23 and dmsq, driven by the numu data
  - Slightly different significance of rejection of the IH and the lower octant
  - Less likely: extreme fluctuations

NOvA prospects

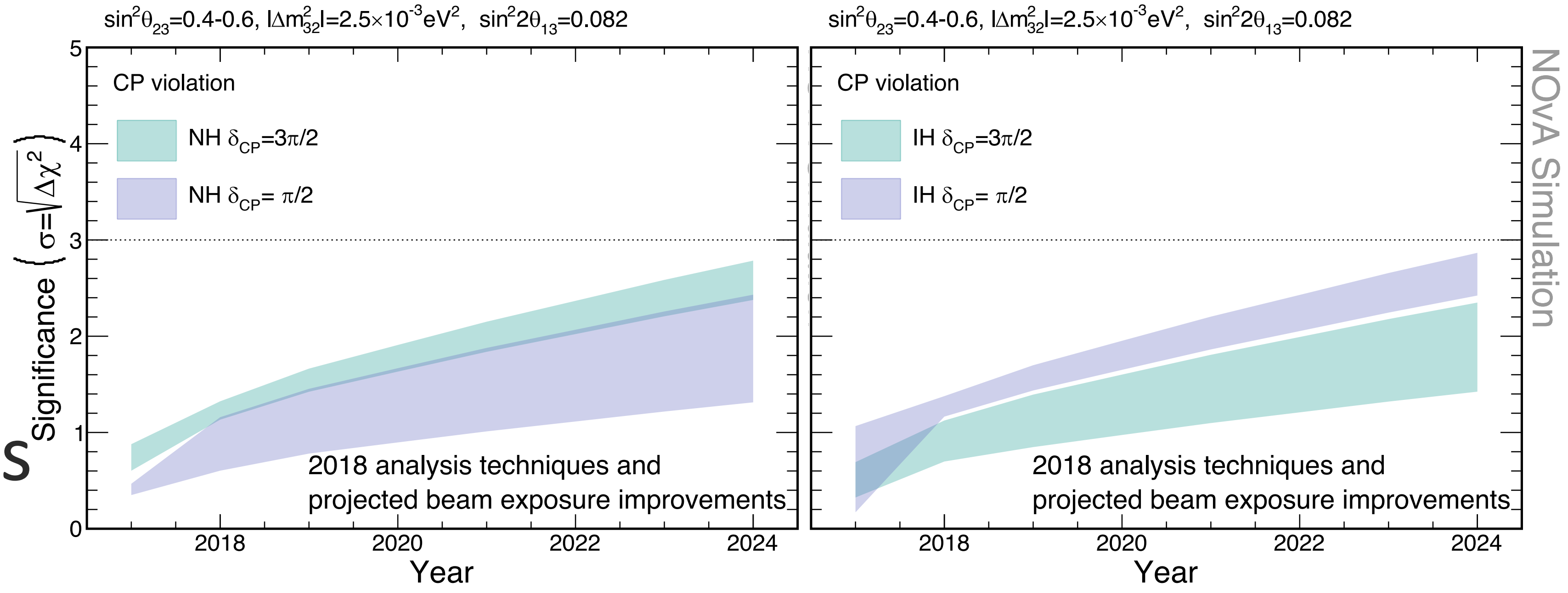
- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach.
- 3 σ sensitivity to hierarchy (if NH and $\delta_{CP}=3\pi/2$) for allowed range of θ_{23} by 2020. 3 σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.

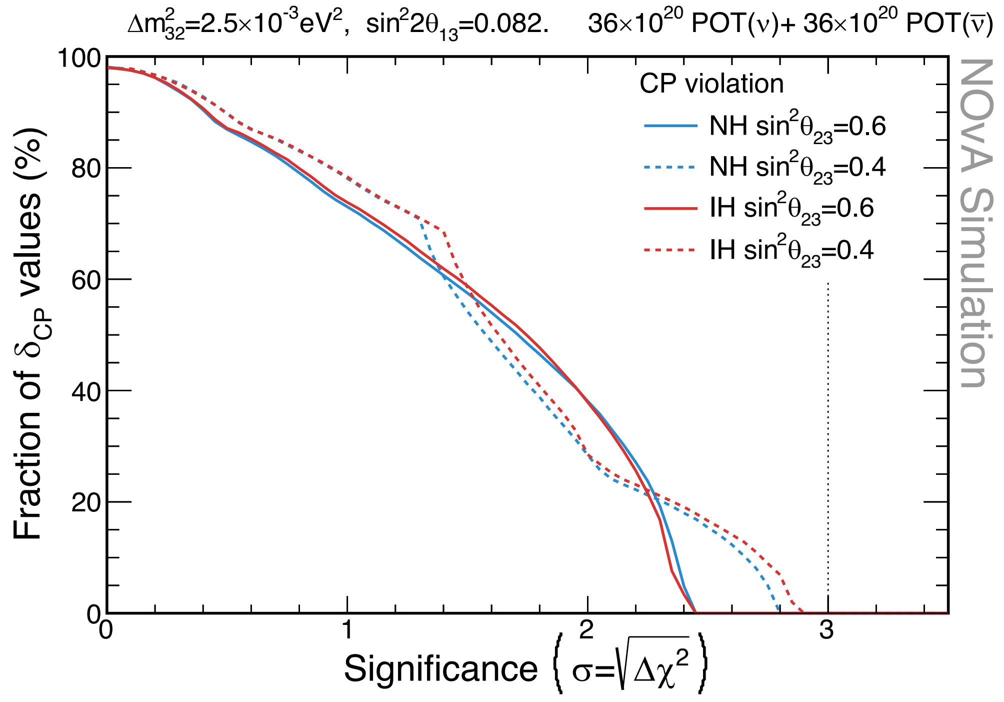




NOvA prospects

- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach.
- 2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024.





Conclusions

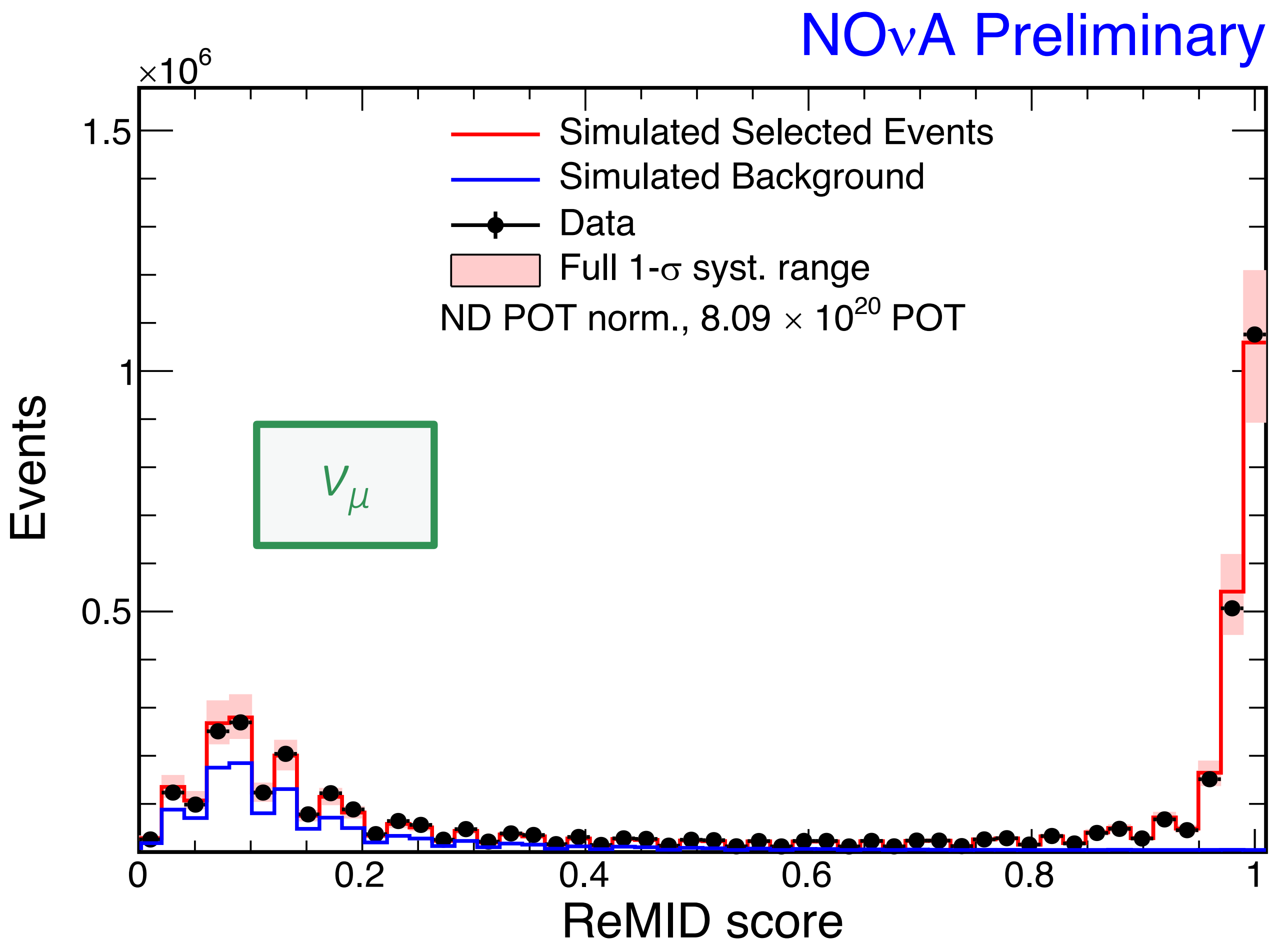
- We have begun the measurement of antineutrino appearance at long baseline.
  - Analyzed the first NOvA antineutrino beam dataset 6.9×10^{20} POT plus 8.9×10^{20} POT of neutrino beam data
  - Update with ~80% more antineutrino data coming very soon!
- We have strong evidence for $\bar{\nu}_e$ appearance at long baseline.
  - >4σ above background, including wrong-sign.
  - Achieved in our **first** antineutrino result thanks to outstanding beam performance and support from Fermilab!
- A joint analysis of $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance prefers:
  - The Normal Hierarchy at 1.8σ and excludes IH, $\delta_{\mathrm{CP}} = \pi/2$ at > 3σ.
  - Non-maximal mixing at 1.8σ and similarly prefers the upper-octant.
- NOvA can reach 3σ sensitivity to the hierarchy by 2020 for the most favorable δ, and >30% of the δ range by 2024.
  - Thanks to extended running, accelerator improvements, and analysis improvements thanks to the test beam.

Thanks!

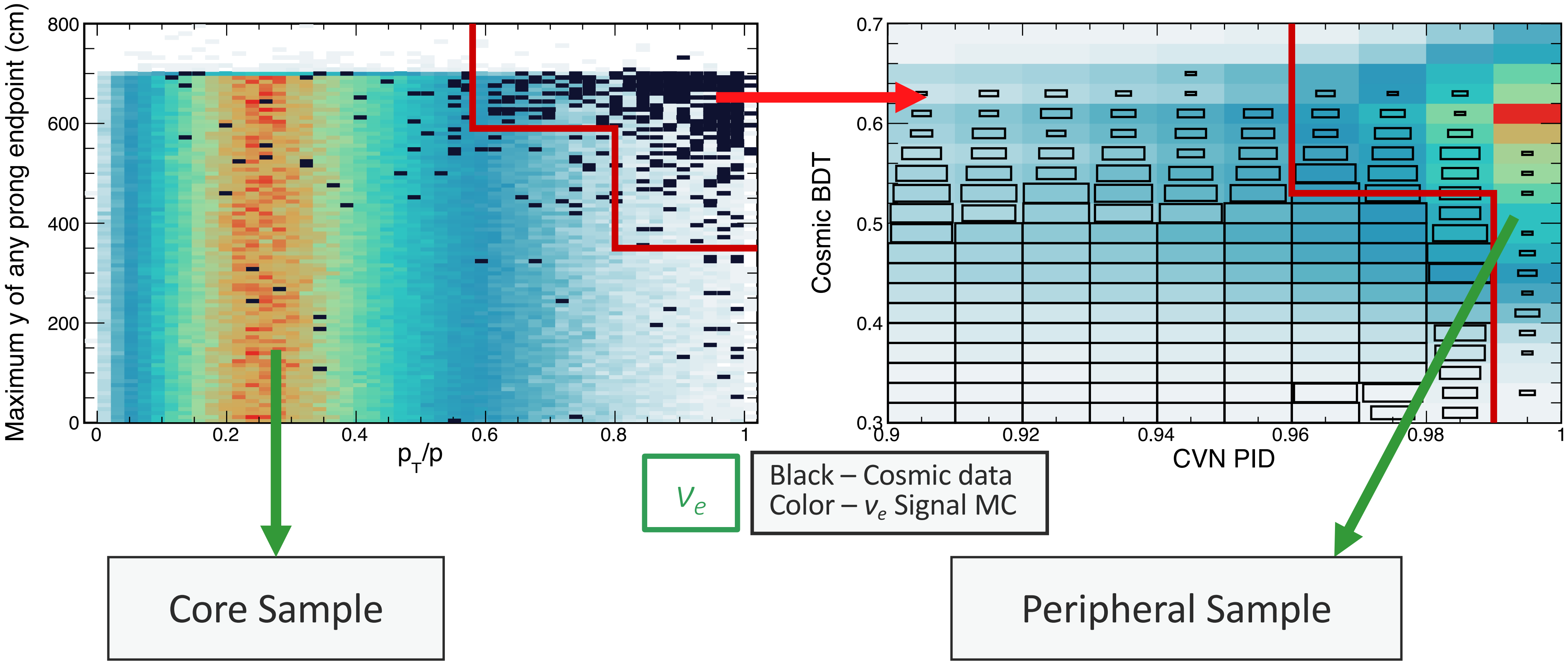
Backup

Other Selections

- Some basic additional cuts:
  - Contained, fiducial events, well-reconstructed, reasonable energy range
- An additional ***ν_μ* requirement**: **a track identified as a muon**.
  - CVN identifies events with a muon, but it does not identify the muon track.
  - Identify muons in reconstructed tracks using a kNN
    - Track length, dE/dx, scattering, fraction of track-only planes



- Additional cosmic rejection needed at the Far Detector.
  - 11 billion cosmic rays/day in the Far Detector on the surface.
  - 10^7 rejection power required *after* timing cuts are applied.
- The **ν_μ sample** uses a BDT based on:
  - Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.
- Cosmic rejection for the **ν_e sample** is in 2 stages:
  - **Core sample**: require contained events, beam-directed events, away from the detector top
  - **Peripheral sample**: events failing the core selection can pass a BDT cut plus a tight CVN cut.
    - Different BDT from ν_μ based on the same containment variables used for cuts in the core sample.



ν_e

Black – Cosmic data
Color – ν_e Signal MC

Core Sample

Peripheral Sample

- Additional cosmic rejection needed at the Far Detector.
  - 11 billion cosmic rays/day in the Far Detector on the surface.
  - 10^7 rejection power required *after* timing cuts are applied.
- The **ν_μ sample** uses a BDT based on:
  - Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.
- Cosmic rejection for the **ν_e sample** is in 2 stages:
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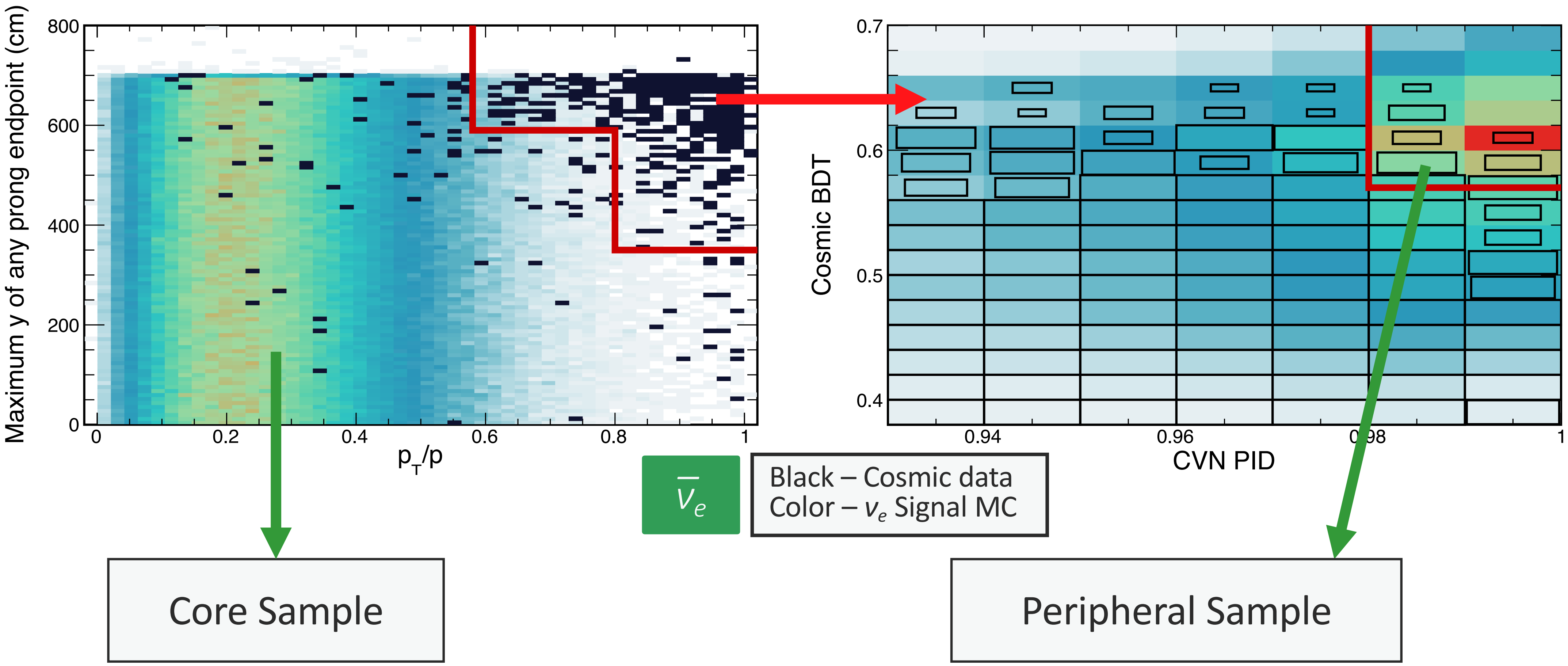


Black – Cosmic data
Color – ν_e Signal MC

Core Sample

Peripheral Sample

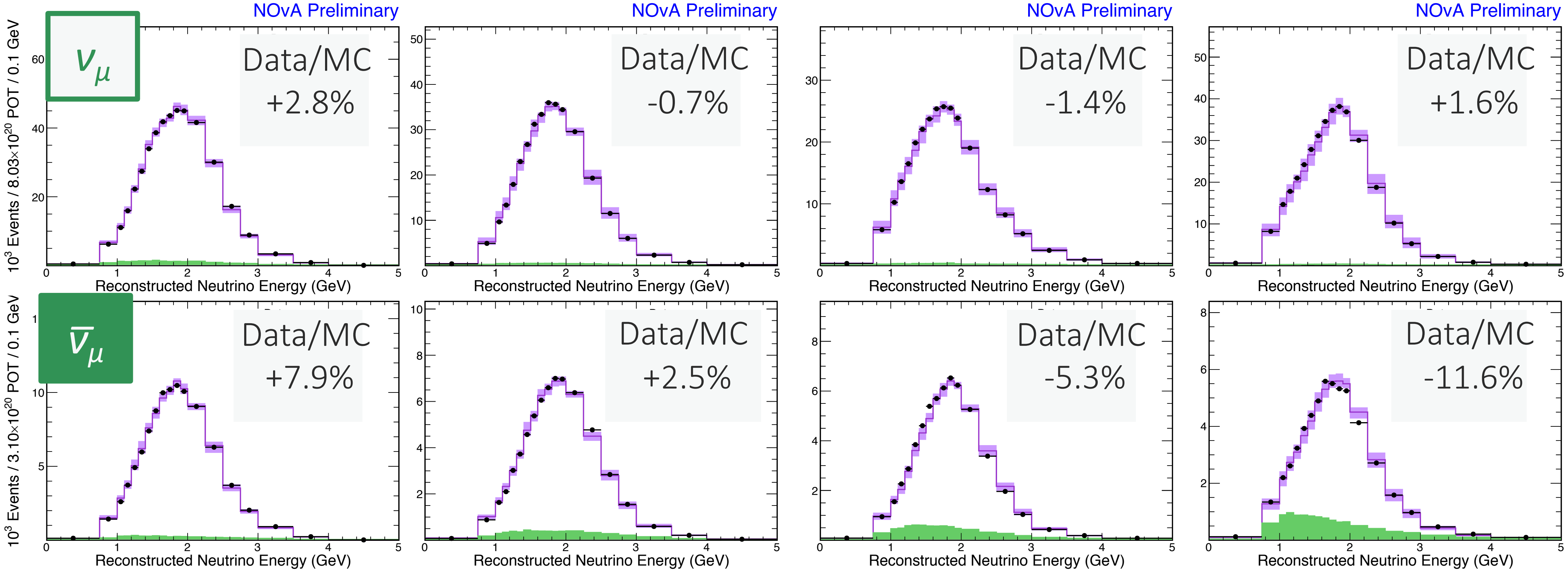
Binning for Sensitivity: ν_μ Events

Quantile 1

Best Resolution ~6%

Quantile 4

Worst Resolution ~12%



Data

Area-normalized MC

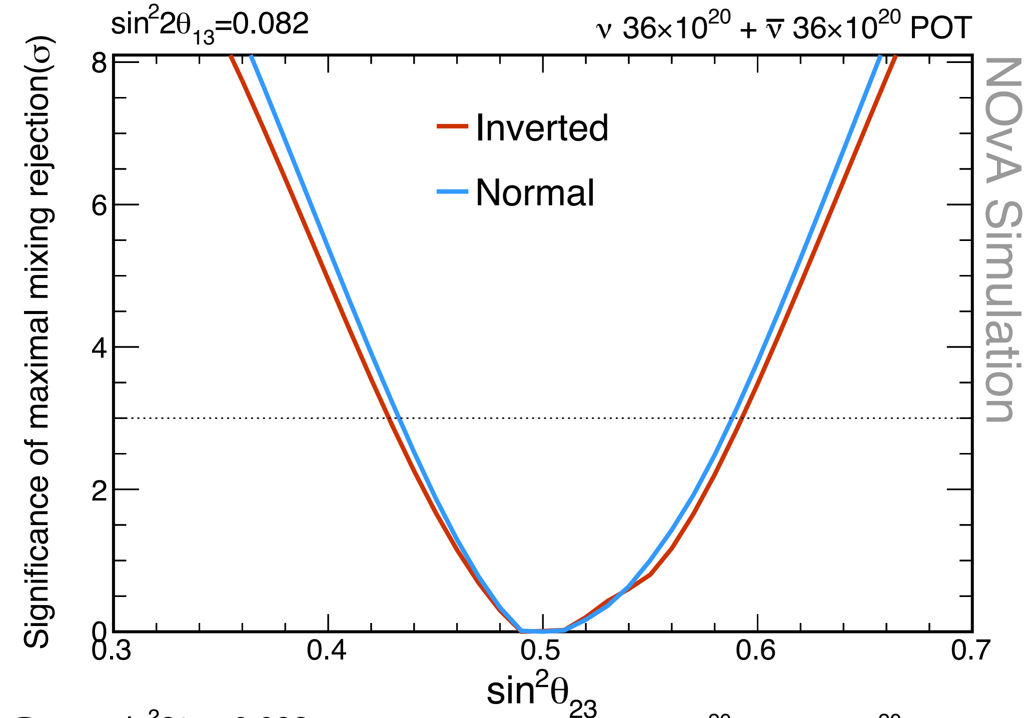
Shape-only systematics

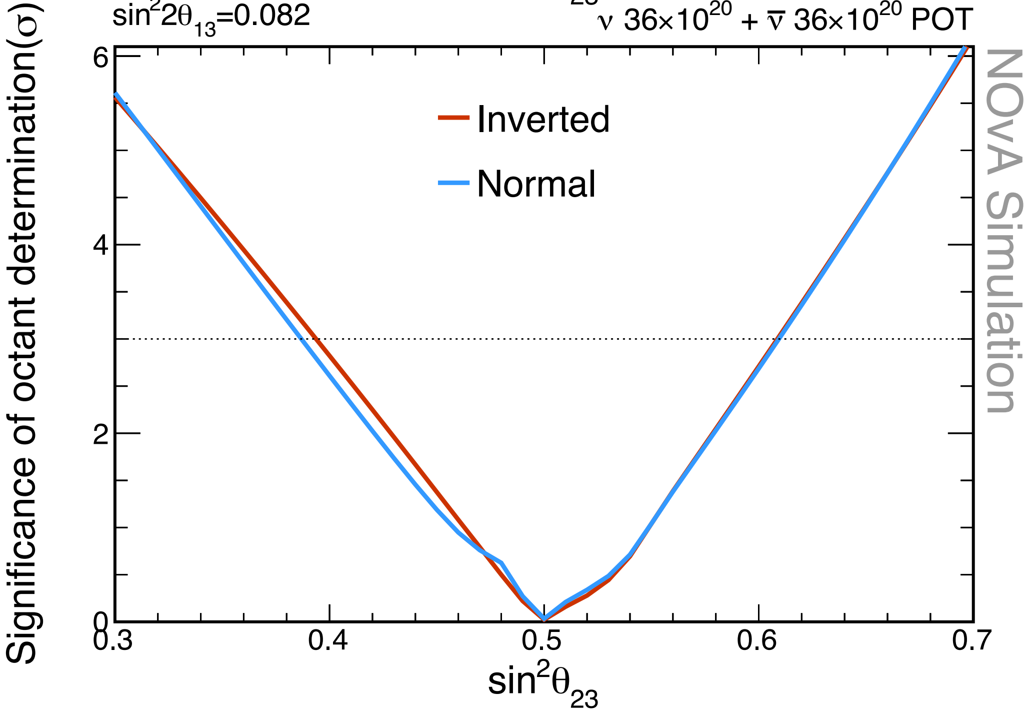
Wrong-sign

- Data-MC shape agreement good within each quantile.
- By extrapolating each separately, we transport kinematic differences between data and simulation to the FD.
    - Can see this in the different normalizations applied to each quantile.

Future Sensitivity: Octant and Maximal Mixing

- Above 3 σ sensitivity to θ_{23} maximal mixing outside of the 0.42-0.58 range by 2024.
- Above 3 σ sensitivity for octant determination outside of 0.4-0.6 range by 2024.

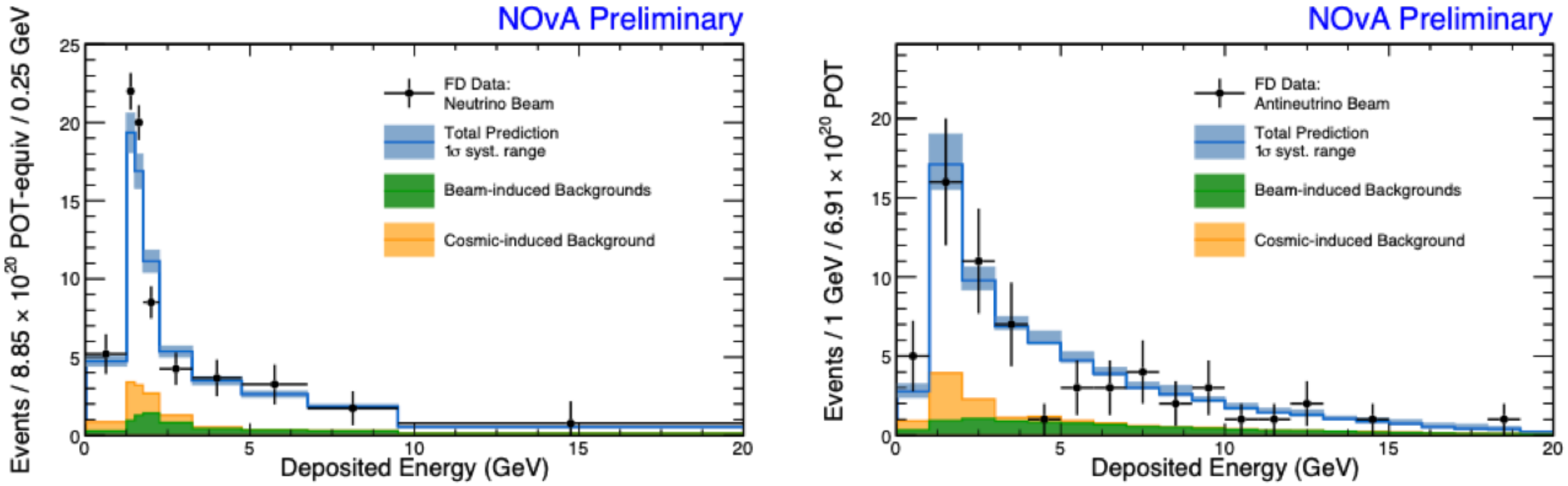




Test Beam Program

- The test beam program is how we will realize those analysis improvements.
  - Reduced systematics
  - Additional validation of ML techniques
  - Simulation improvements
- Installation and commissioning efforts are ongoing
- Full data taking this fall

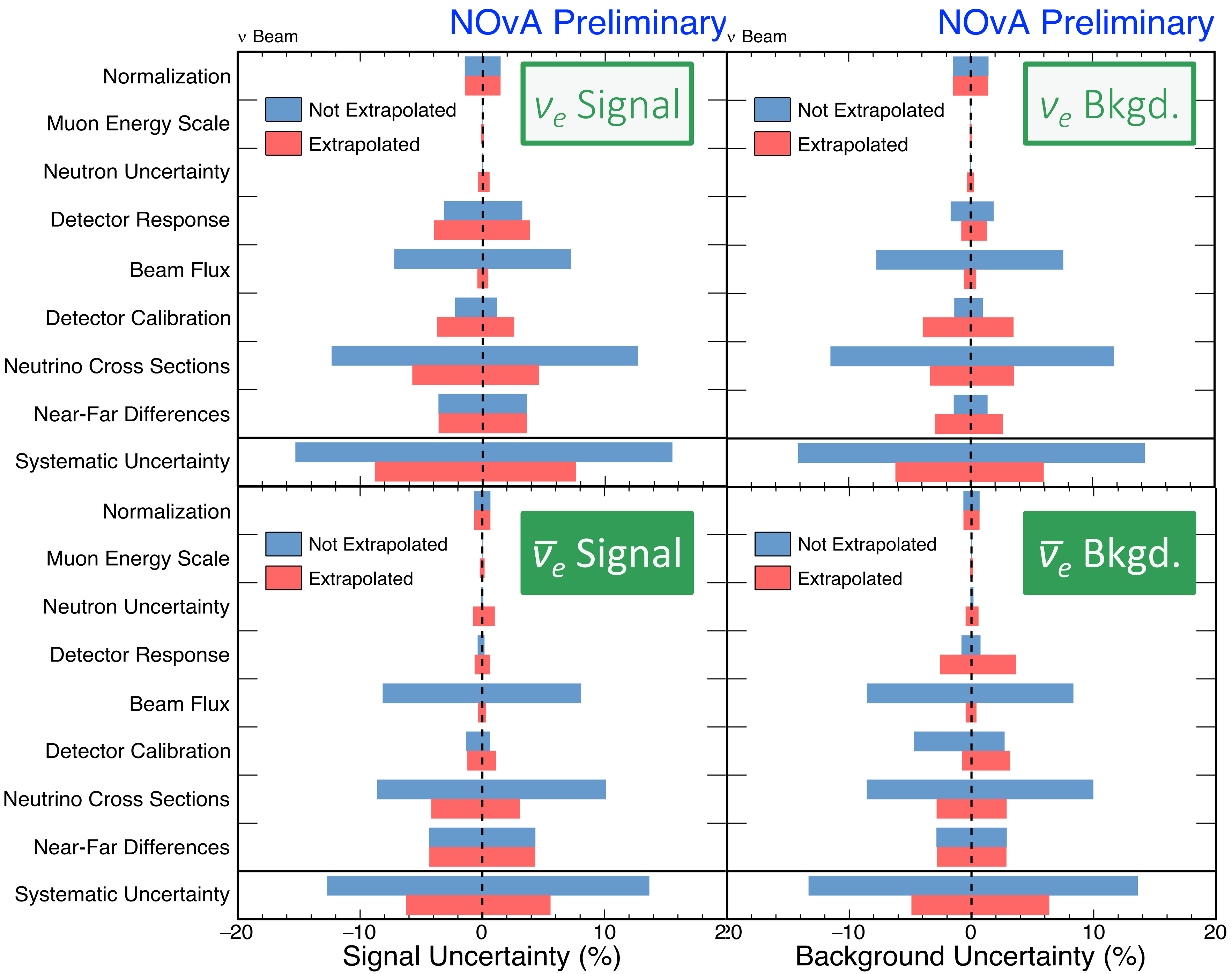
Neutral current disappearance



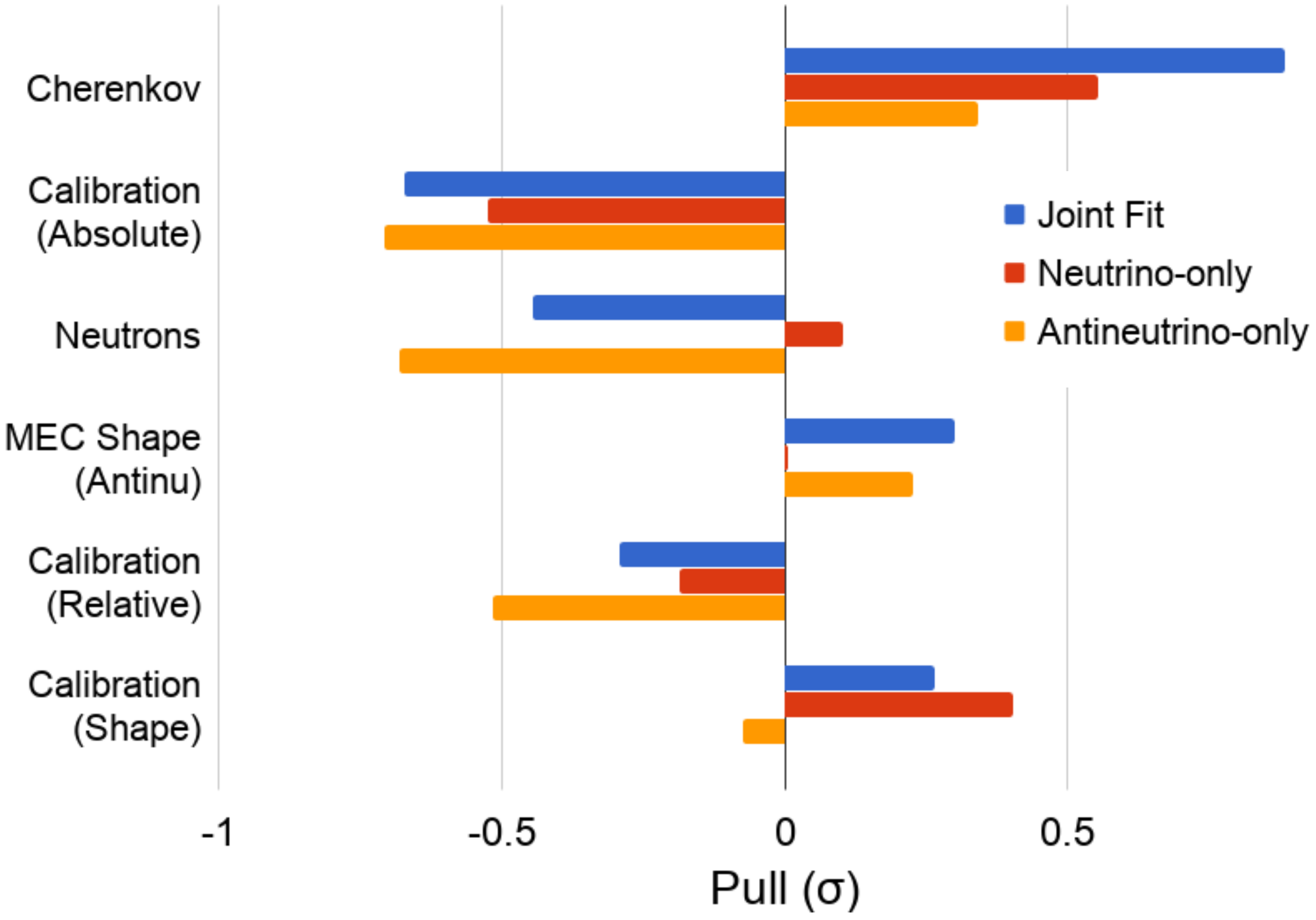
- For the neutrino beam sample we predict 188 ± 13 (syst.) interactions (38 bkg.) and observe 201.
- For the antineutrino beam sample we predict 69 ± 8 (syst.) interactions (16 bkg.) and observe 61.

No significant suppression of Neutral current interactions observed for neutrinos or antineutrinos

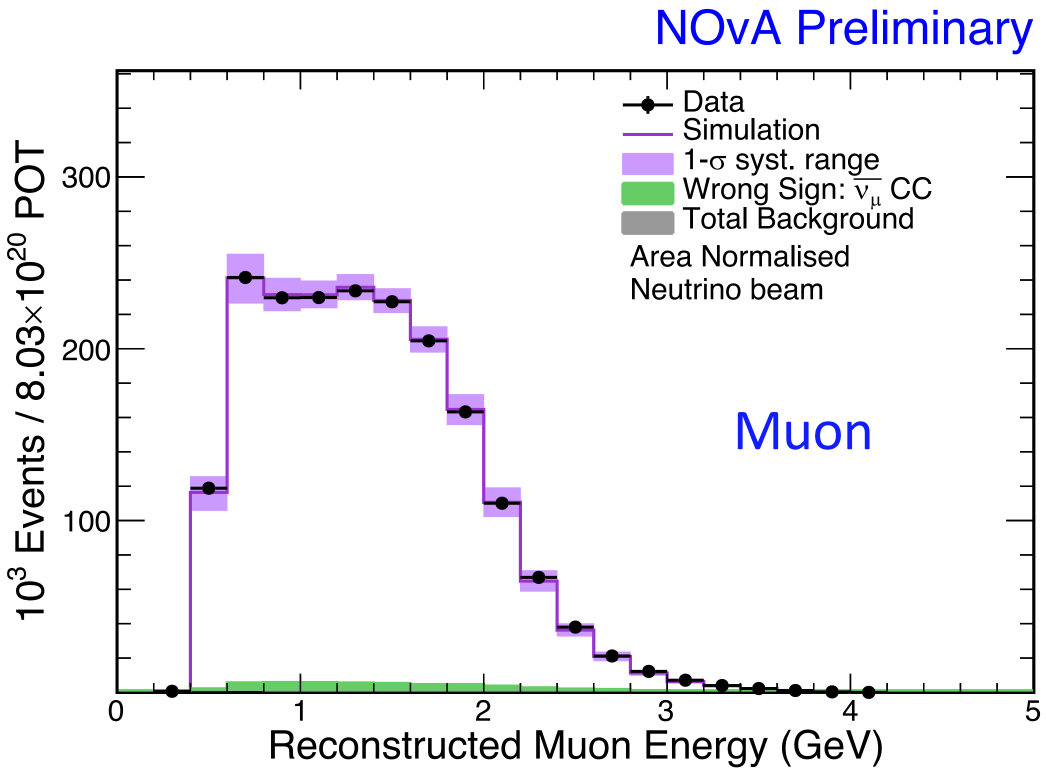
Systematics Reduced with Extrapolation

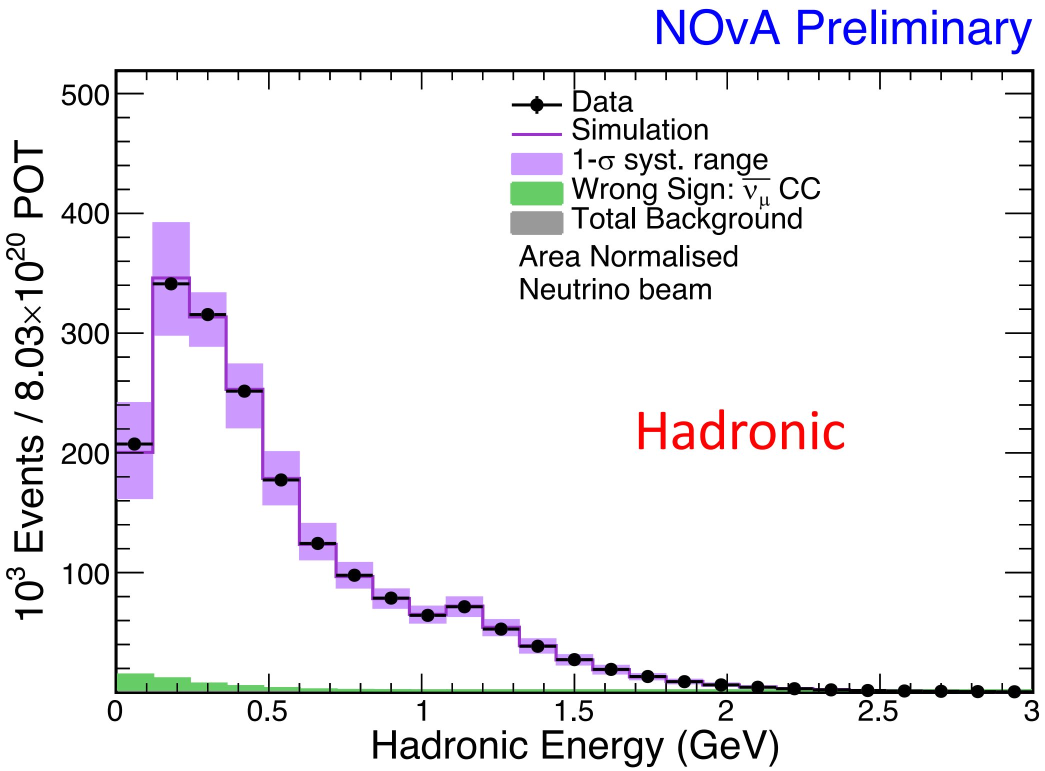


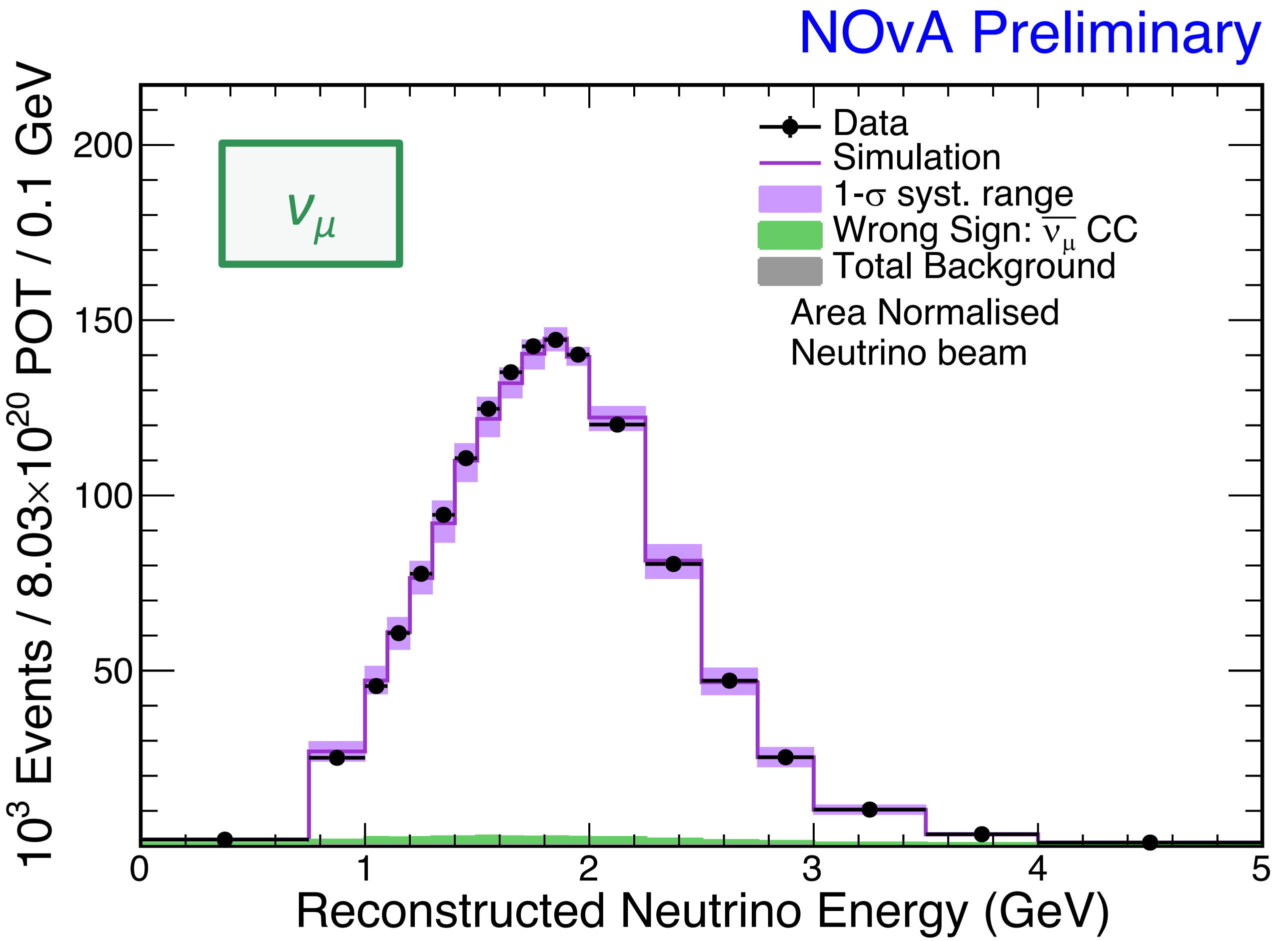
Pulls in the Fit



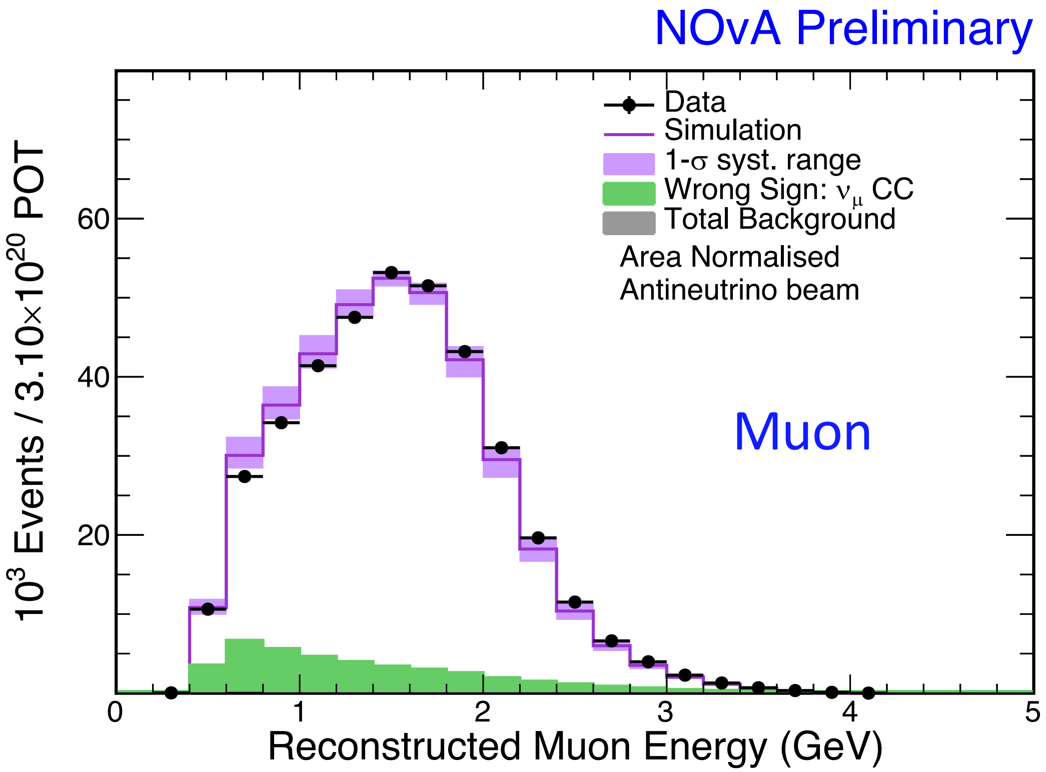
- A total of 49 systematic parameters were included in the fit.
- Largest pulls mostly correspond to the systematics already called out as most important.
    - Exception: Cherenkov is a part of “Detector Response”
- For systematics affecting both neutrinos and antineutrinos, we see consistent pulls from from both parts of the data.

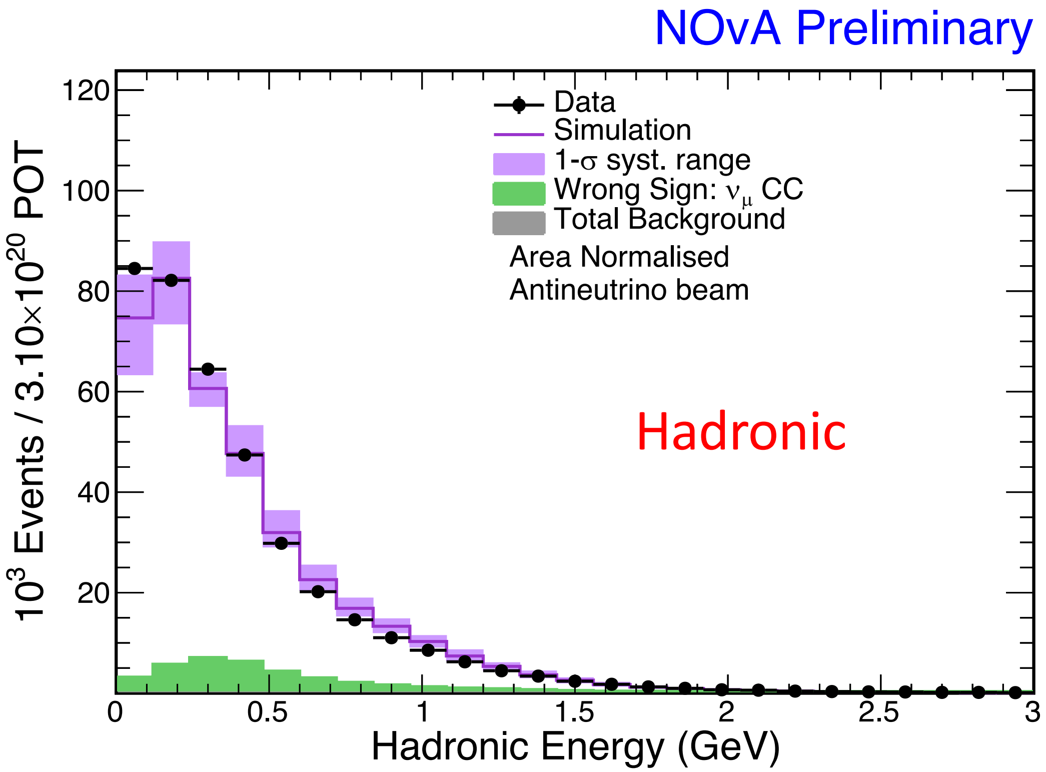


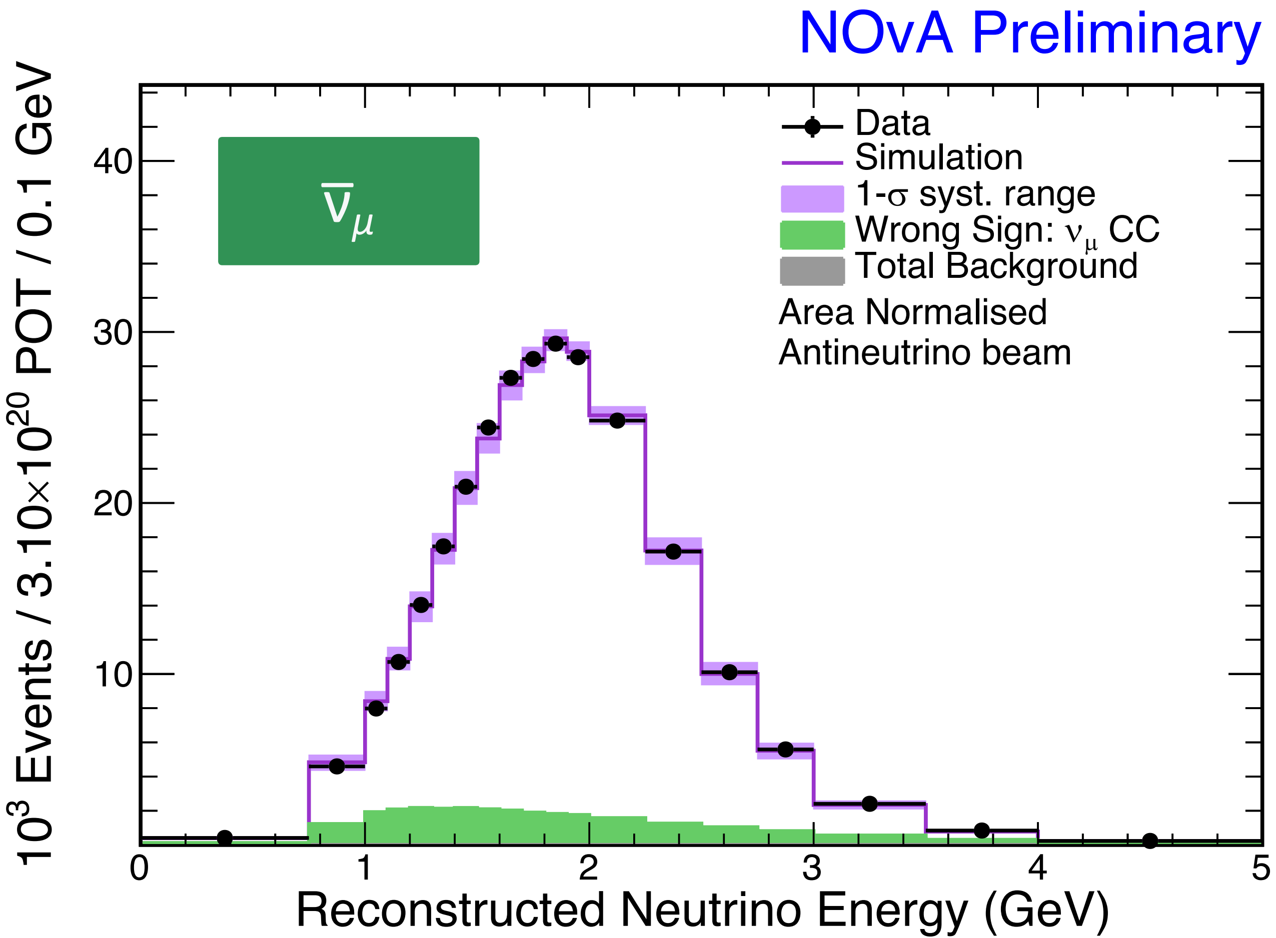




- Good data-MC agreement in both neutrino and antineutrino.
- Area-normalized and shape-only systematics.
  - However, normalization only differs by 1.3% for neutrino and 0.5% for antineutrino.
- 3% resolution in E_μ and 30% in E_{had}.







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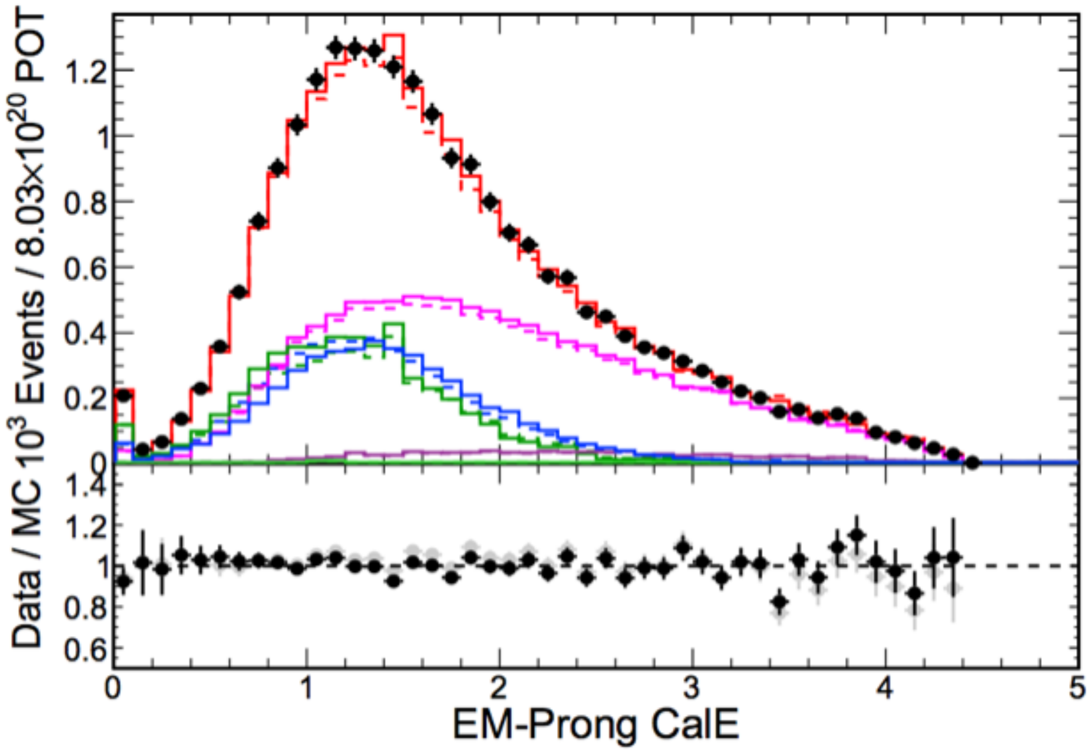
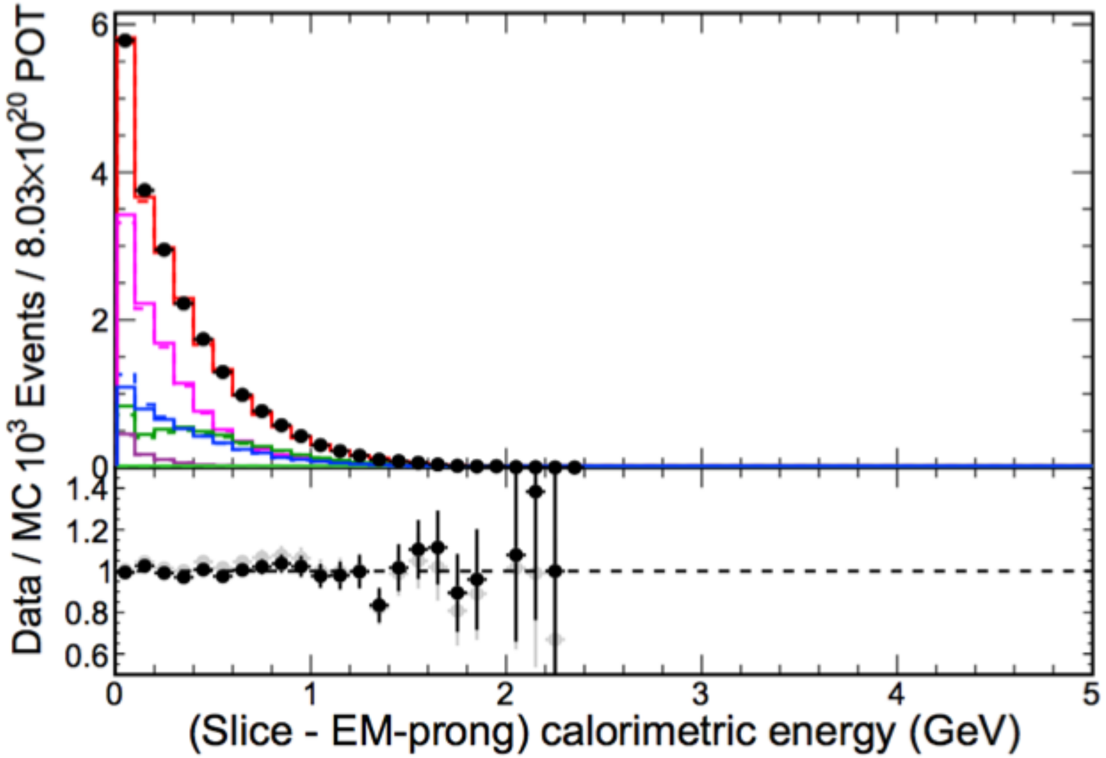
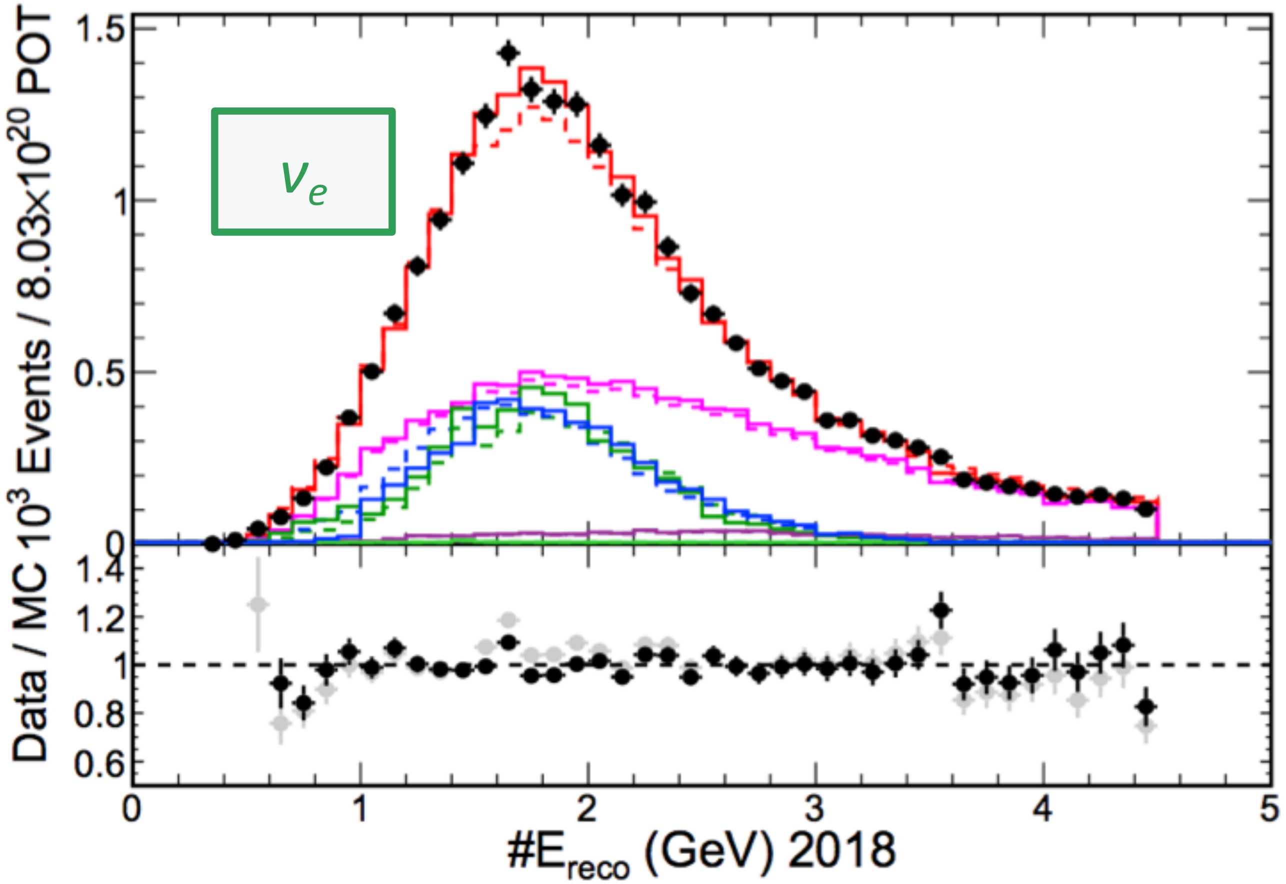
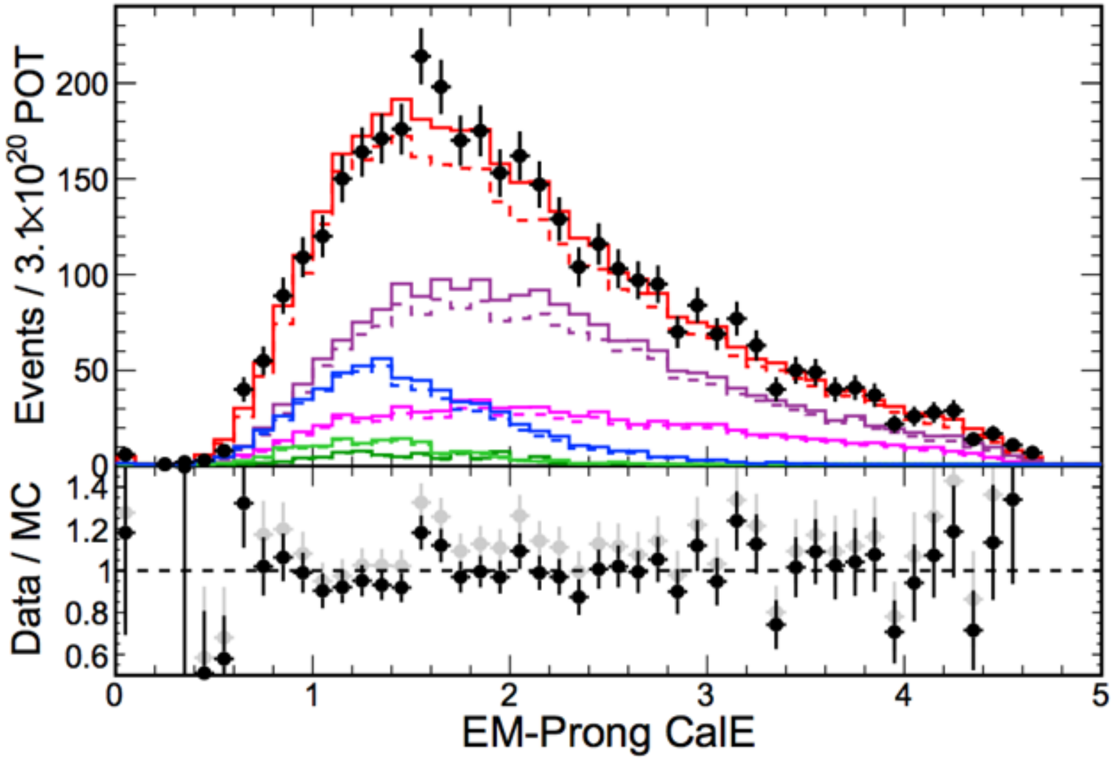
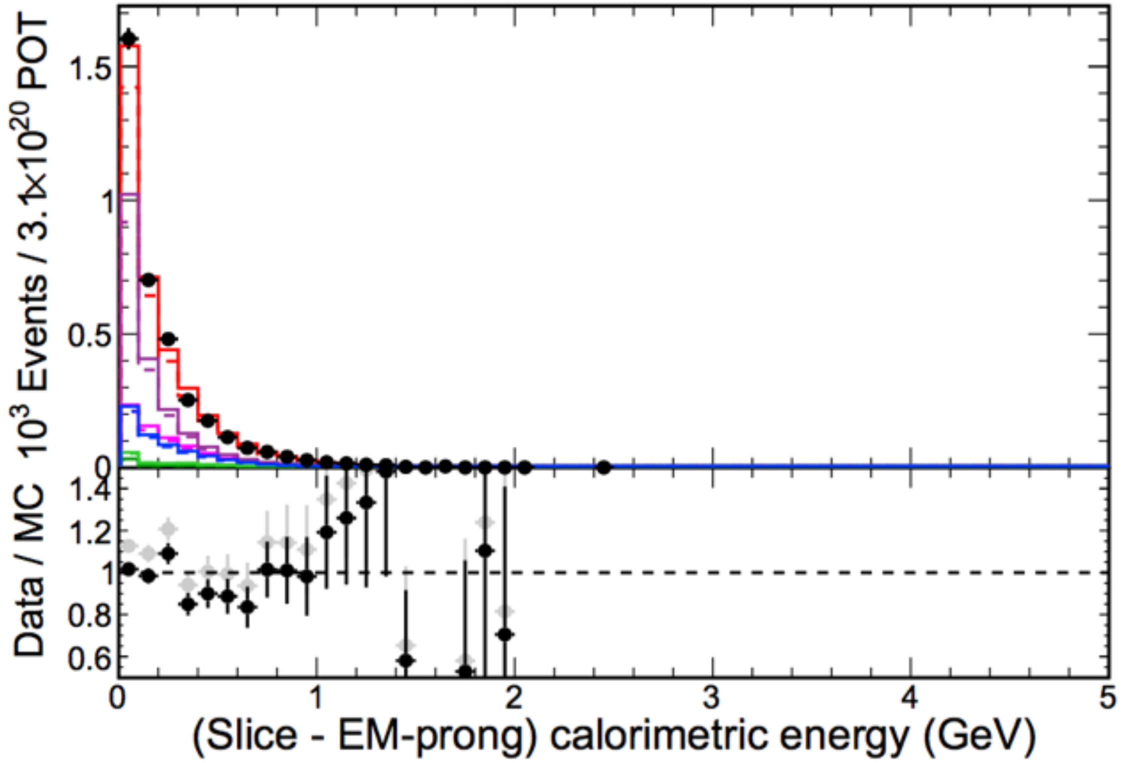


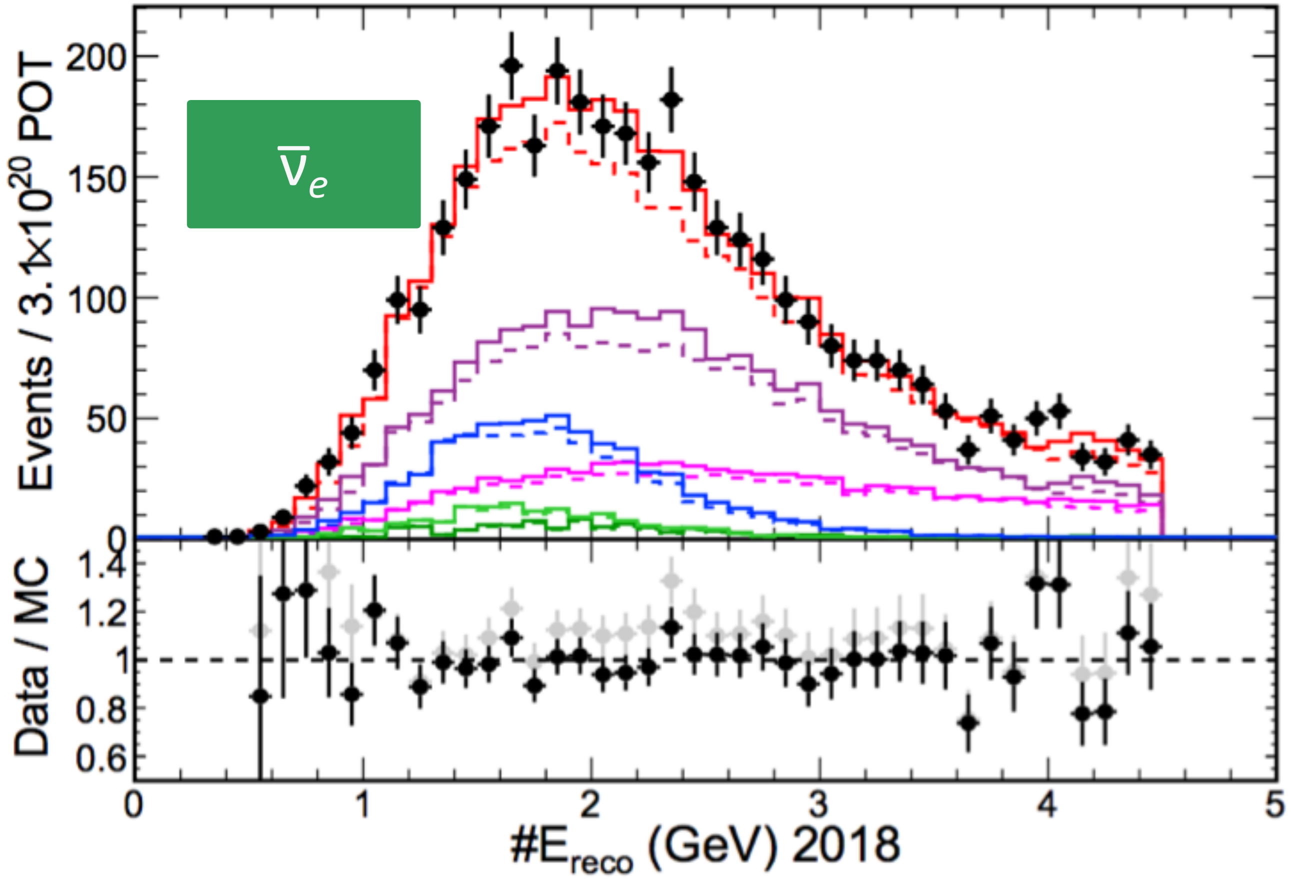




- Good data-MC agreement in both neutrino and antineutrino beams.
- As expected, RHC has significantly less hadronic energy and significantly more wrong-sign background.







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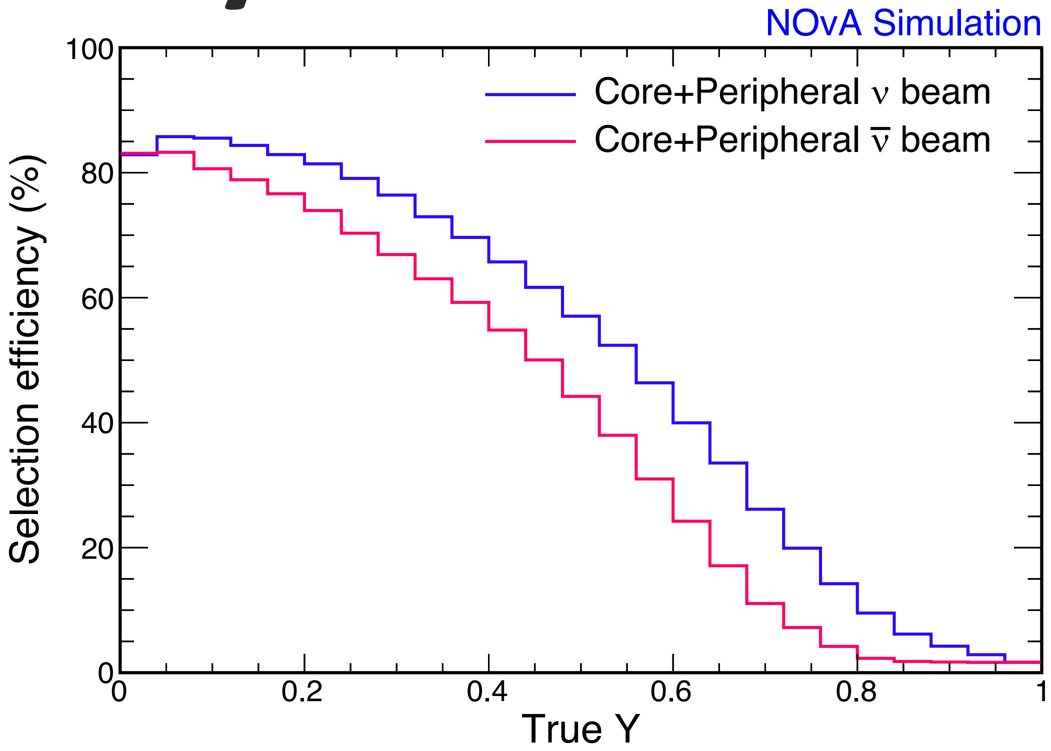
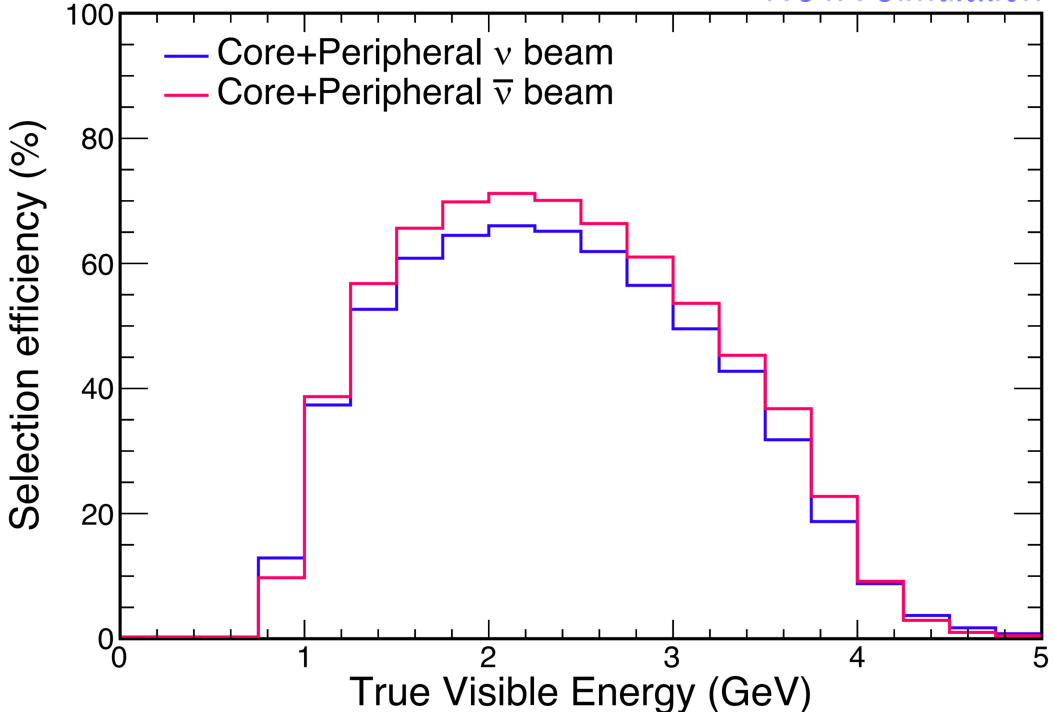
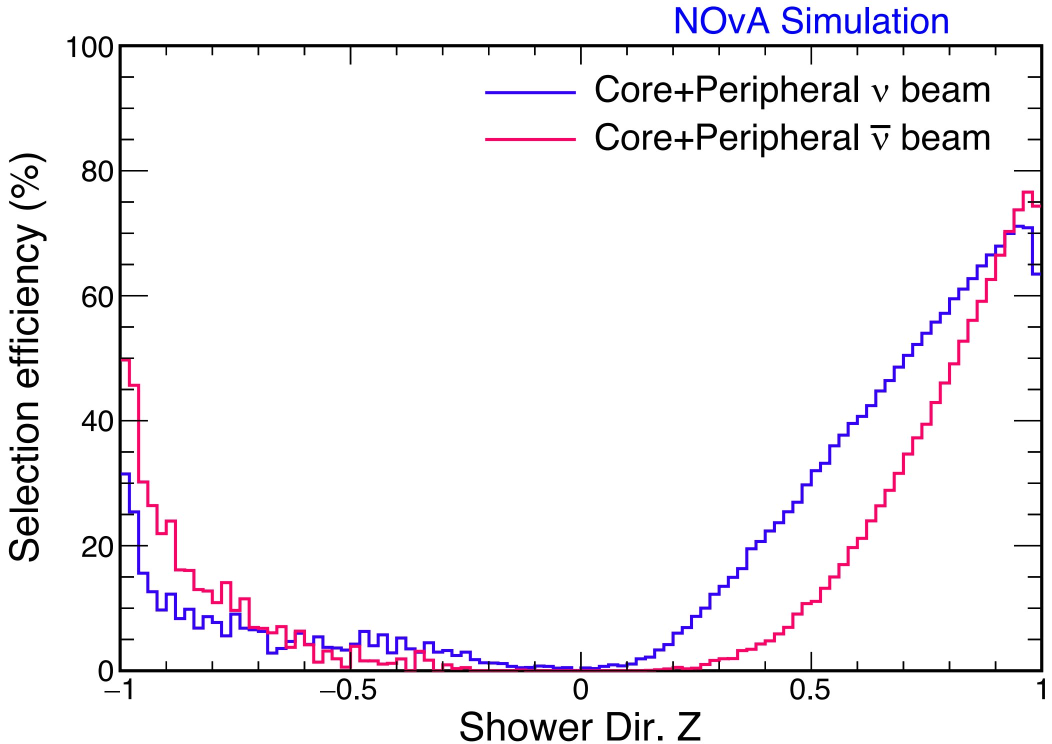
Efficiency for Neutrinos vs. Antineutrinos

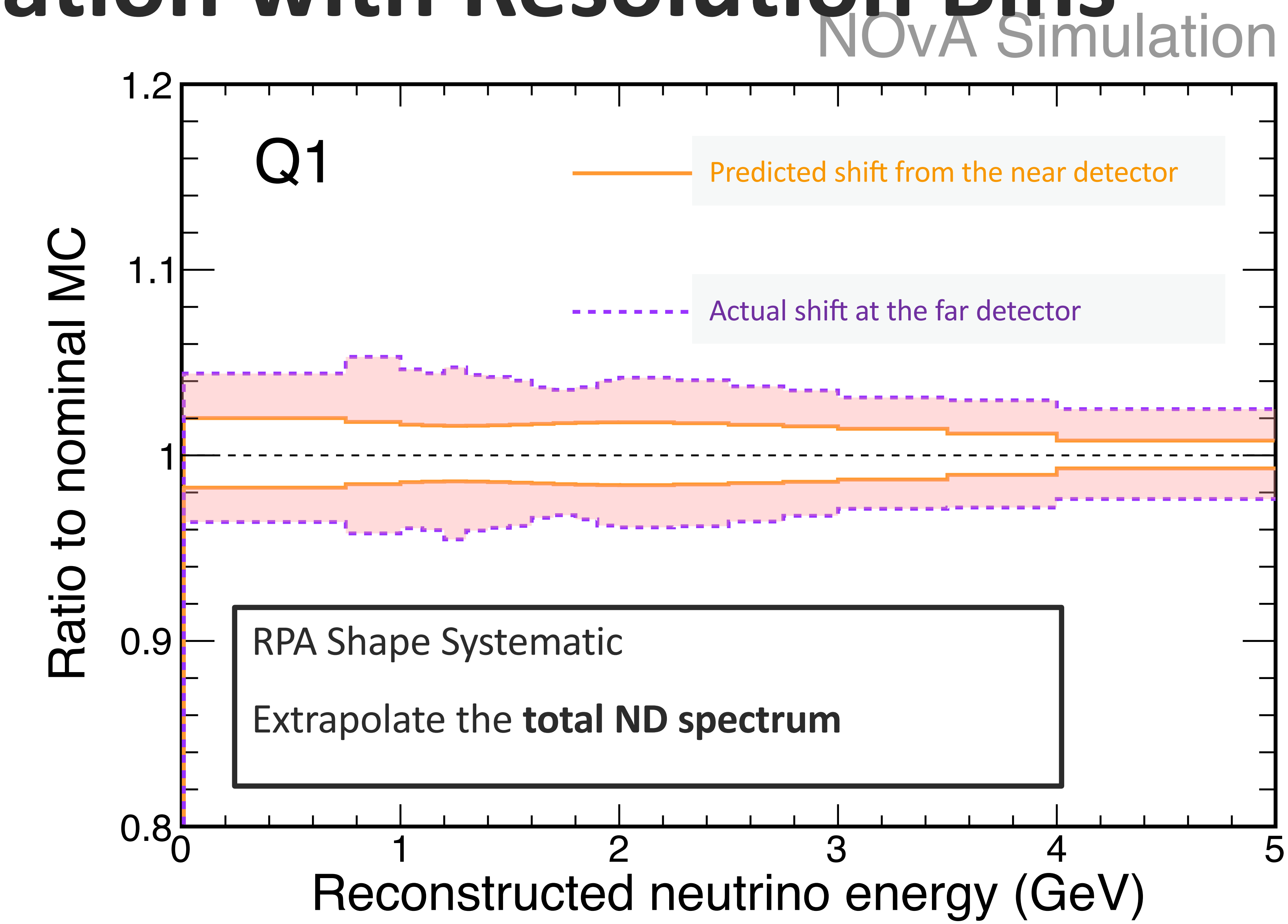


$\bar{\nu}$ Efficiency improvement with $\bar{\nu}$-trained network		
$\bar{\nu}_e$ CC	$\bar{\nu}_\mu$ CC	NC
+14%	+6%	+10%





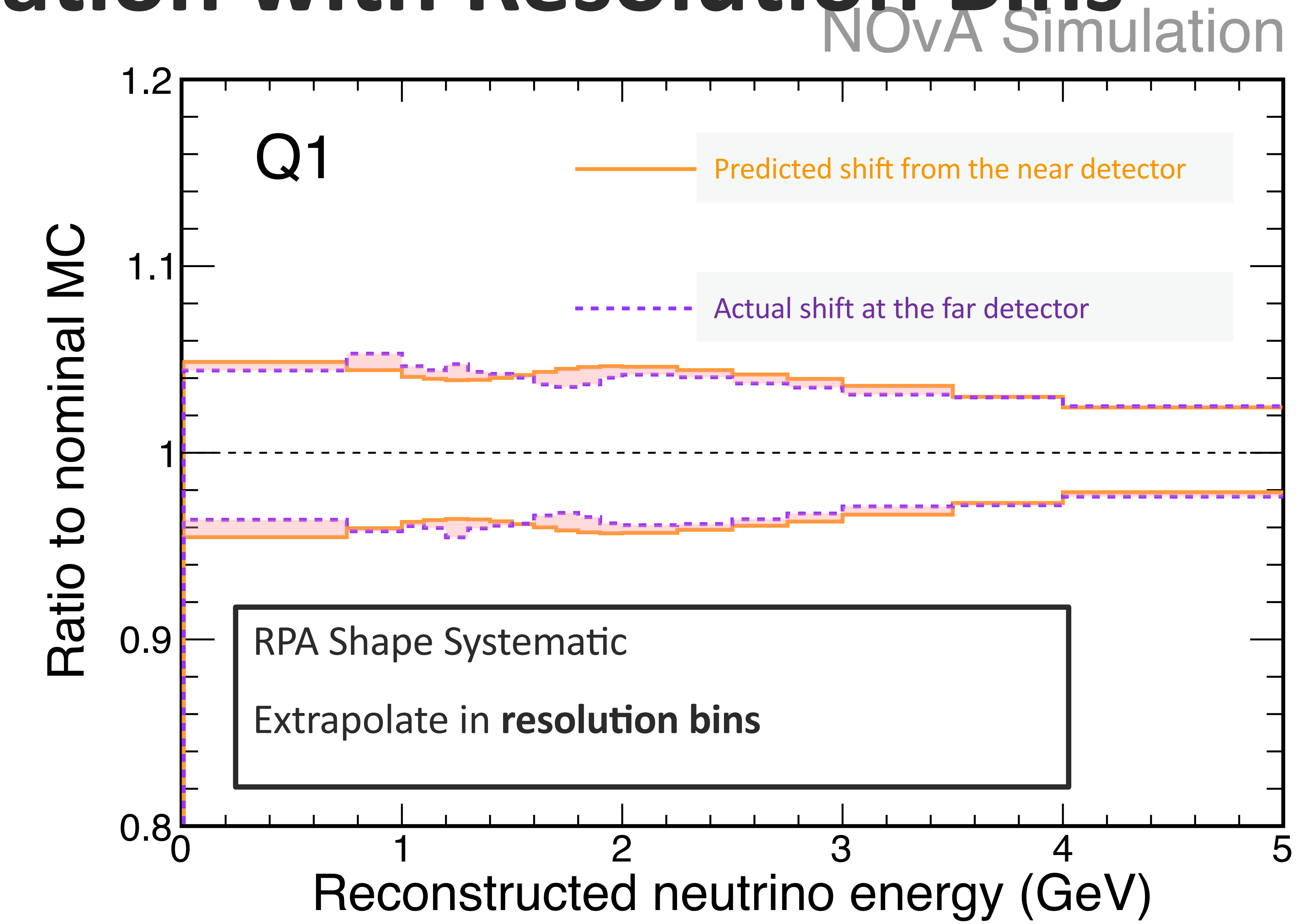
Extrapolation with Resolution Bins



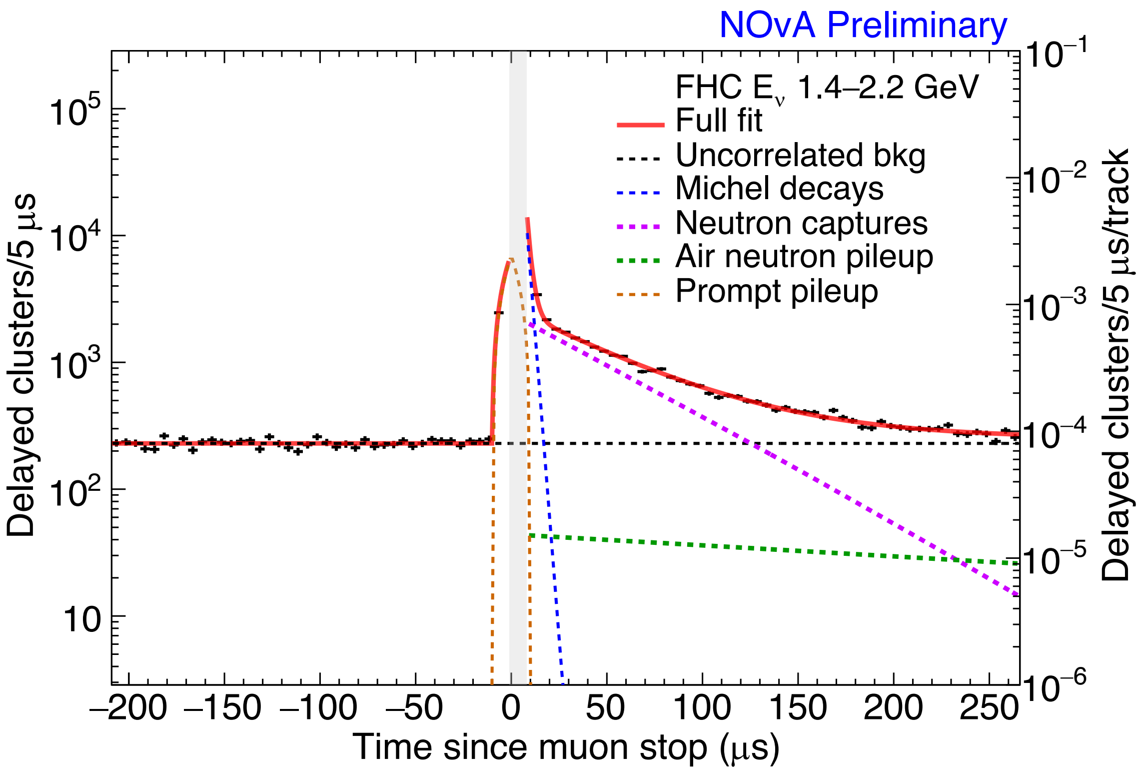
RPA Shape Systematic

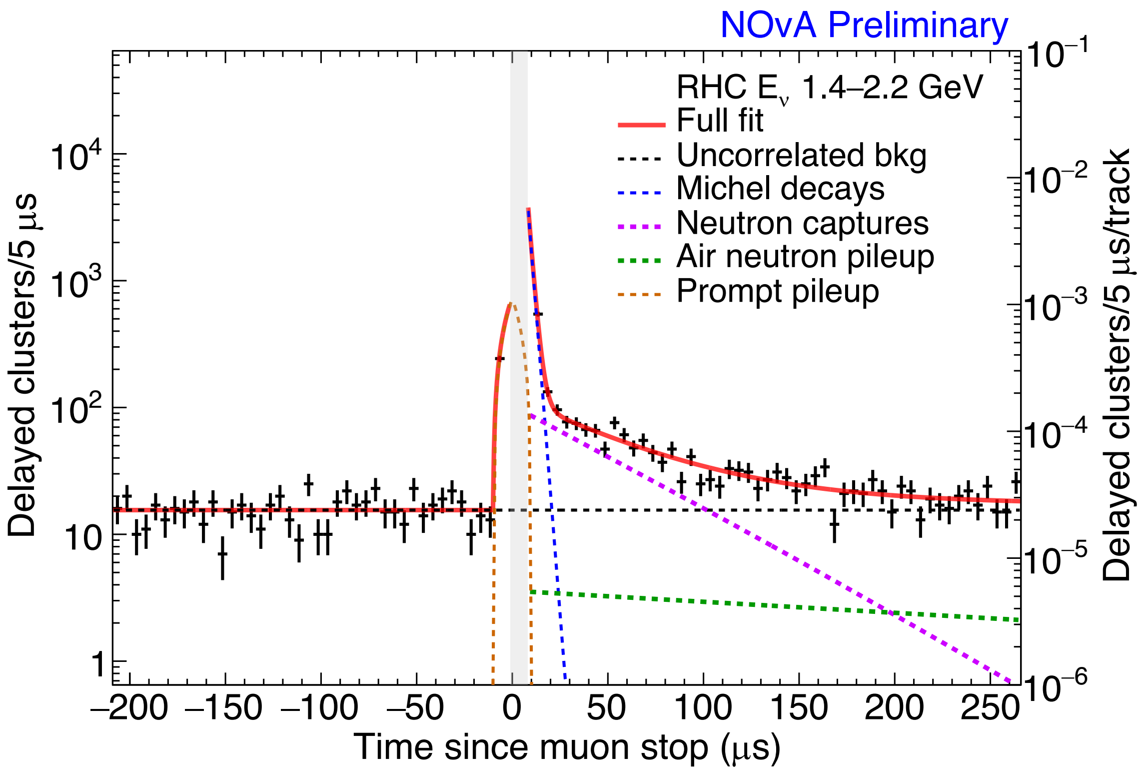
Extrapolate the **total ND spectrum**

Extrapolation with Resolution Bins



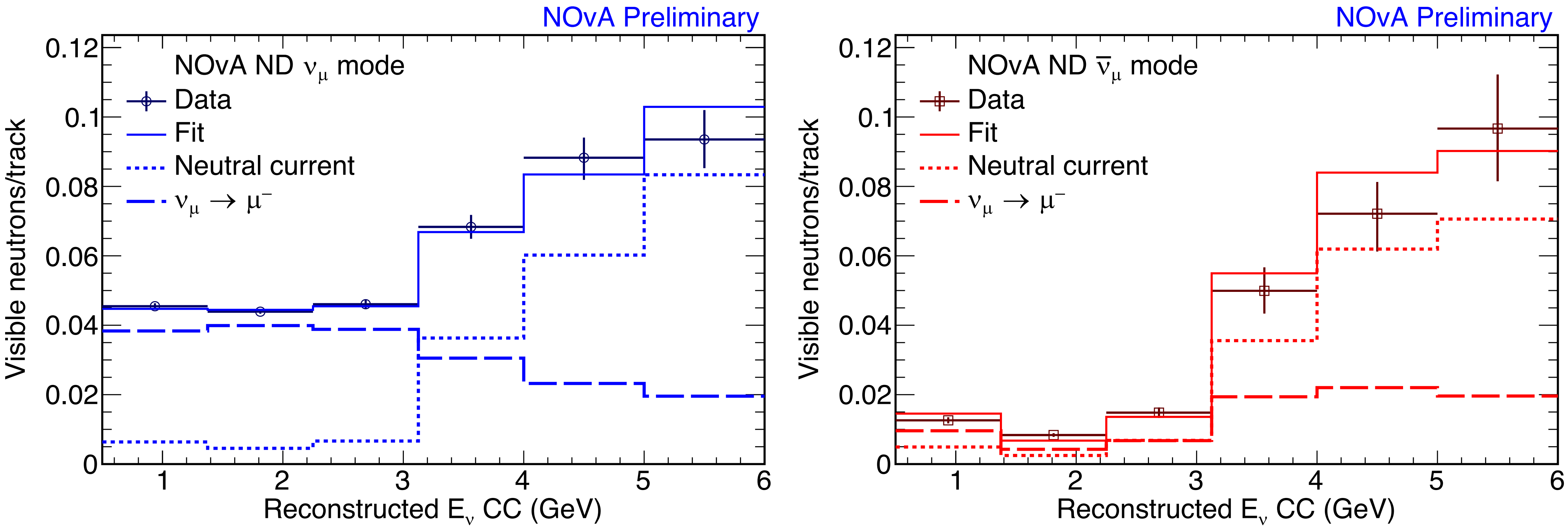
Wrong-sign Constraint with Neutron Capture





- Look for delayed clusters of hits following stopping muons.
- Fit the various time components to measure the rate of neutron captures in bins of neutrino energy.
- Then fit the neutron captures vs. reconstructed energy to extract the number of ν_μ CC and NC events in the neutrino and antineutrino beams.

Wrong-sign Constraint with Neutron Capture



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- Fit the various time components to measure the rate of neutron captures in bins of neutrino energy.
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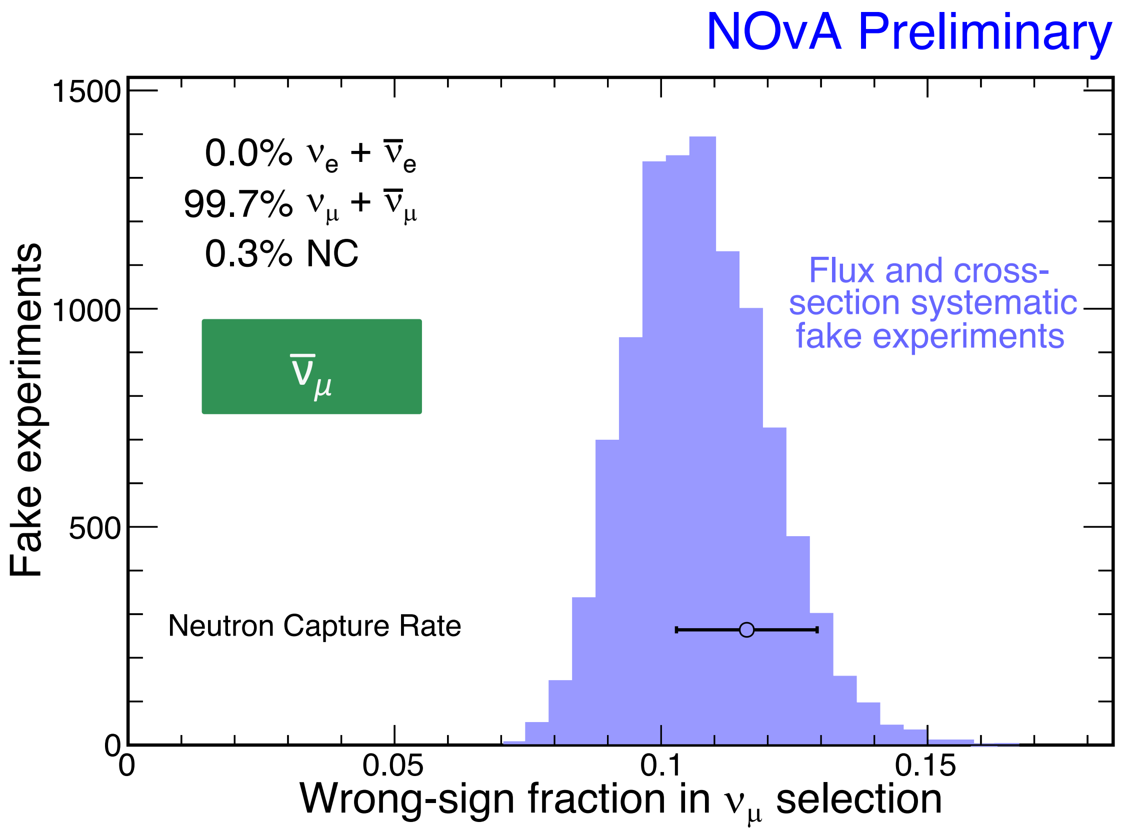
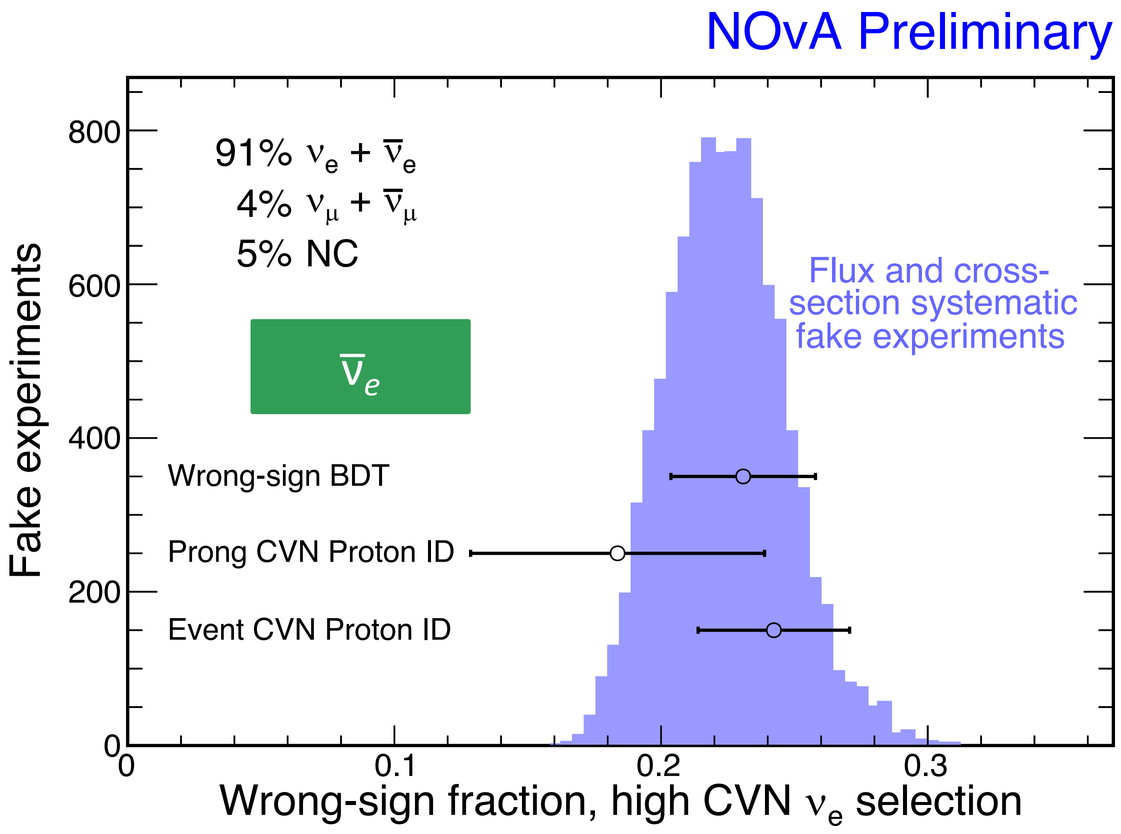
What's new with $\bar{\nu}$'s? Wrong-sign contamination

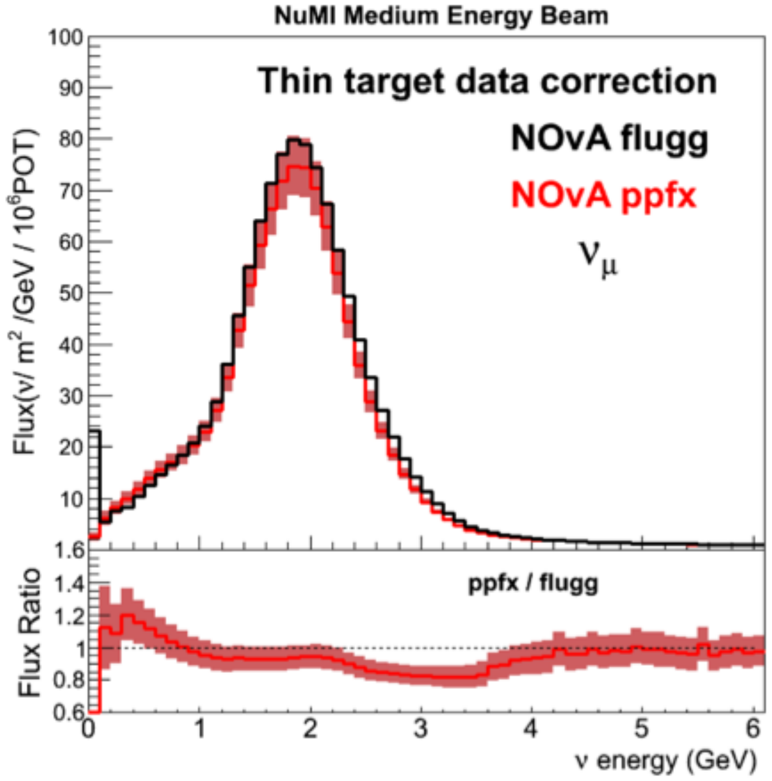




- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Both in ν_μ-like and ν_e-like events.
  - Does not include uncertainties from detector effects.
- Confirm using data-driven cross-checks of the wrong-sign contamination
  - 11% wrong-sign in the ν_μ sample checked using neutron captures.
  - 22% wrong-sign in beam ν_e checked using identified protons and event kinematics.

Simulation Tuning

- We tune our simulation to get a better central value *and* to set systematic uncertainties.
- Beam flux is tuned using the **Package to Predict the FluX** using external data.
  - **Minerva**, Phys. Rev. D 94, 092005 (2016)
- We tune our cross-section model primarily to account for **nuclear effects**.
  - Backstory: disagreements are seen in cross sections as measured on a single nucleons vs. in more complex nuclei.
  - Nuclear effects are a likely solution, but the theory for them remains incomplete.
  - So, we tune using a combination of **external theory** inputs and our own **ND data**.



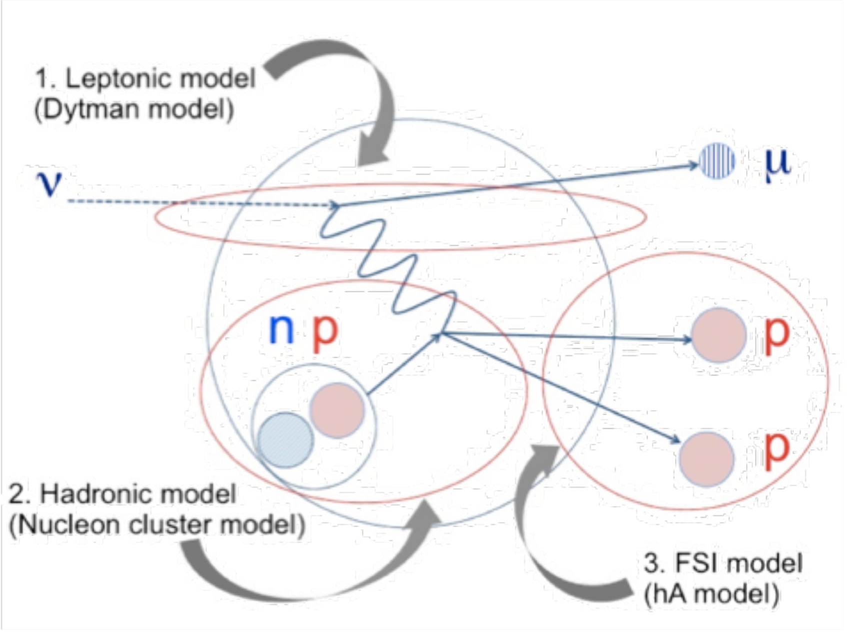
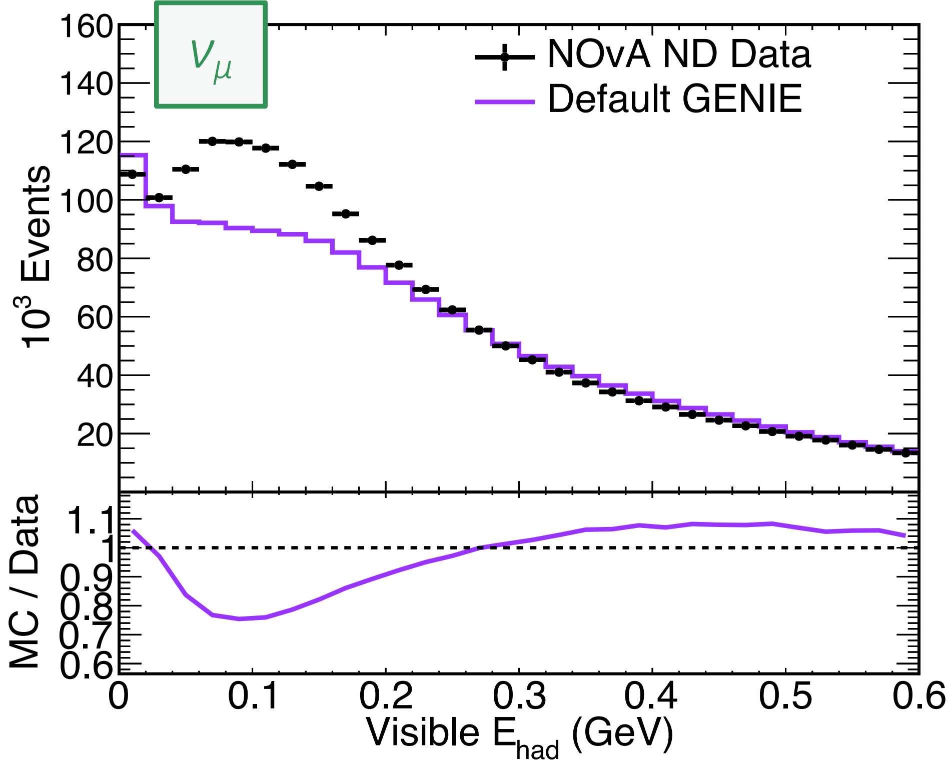
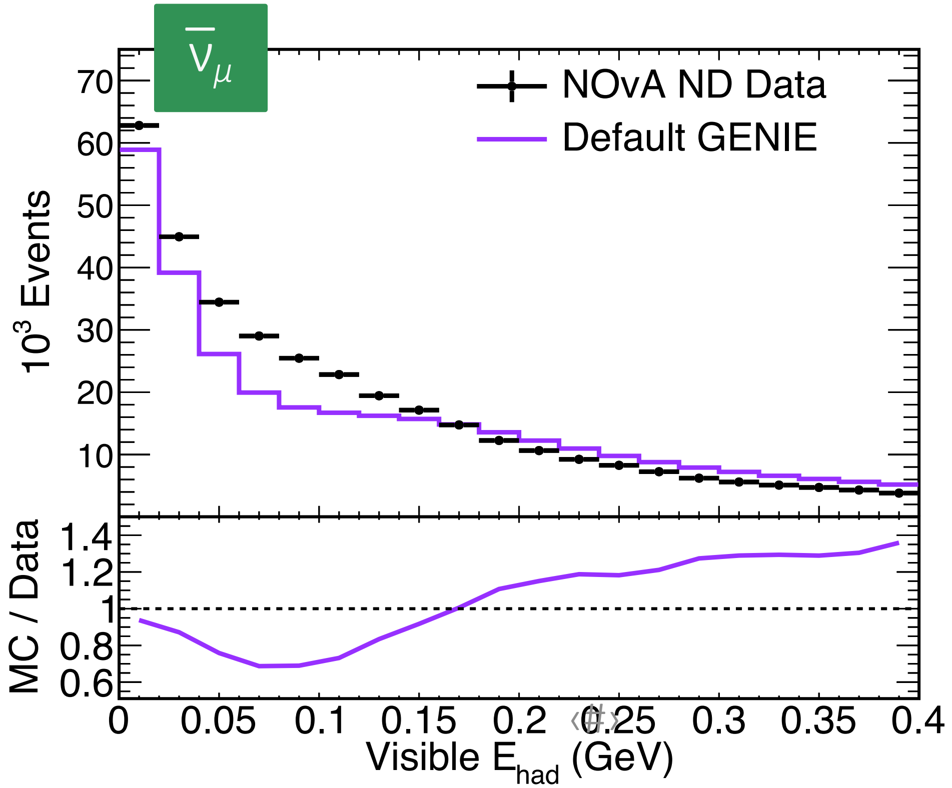


Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

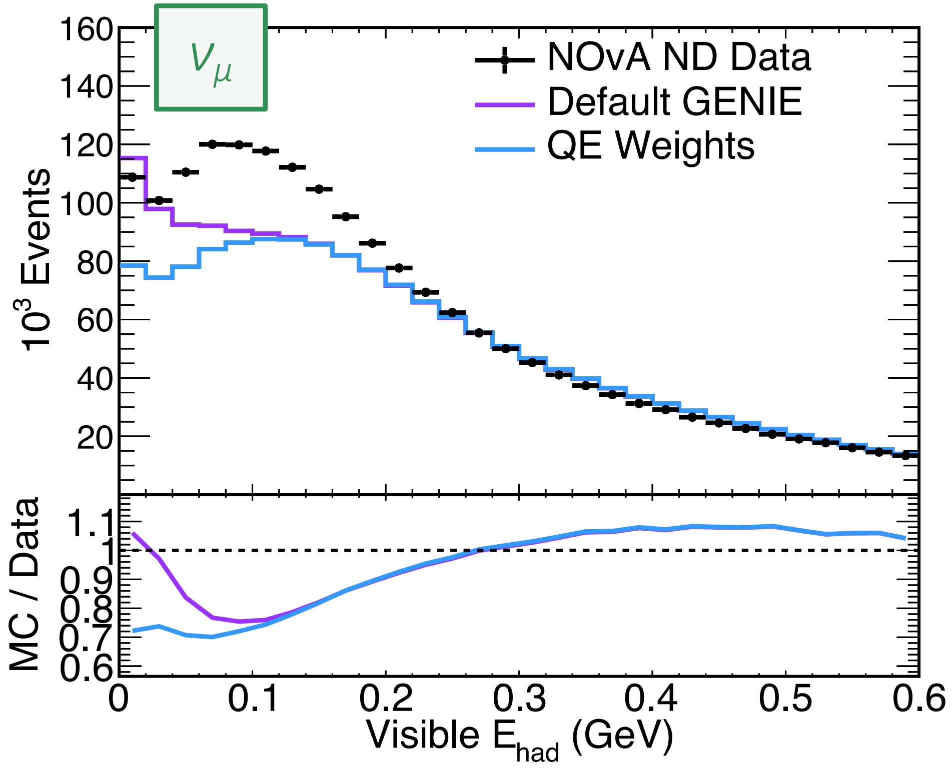
Tuning the Neutrino Interaction Model

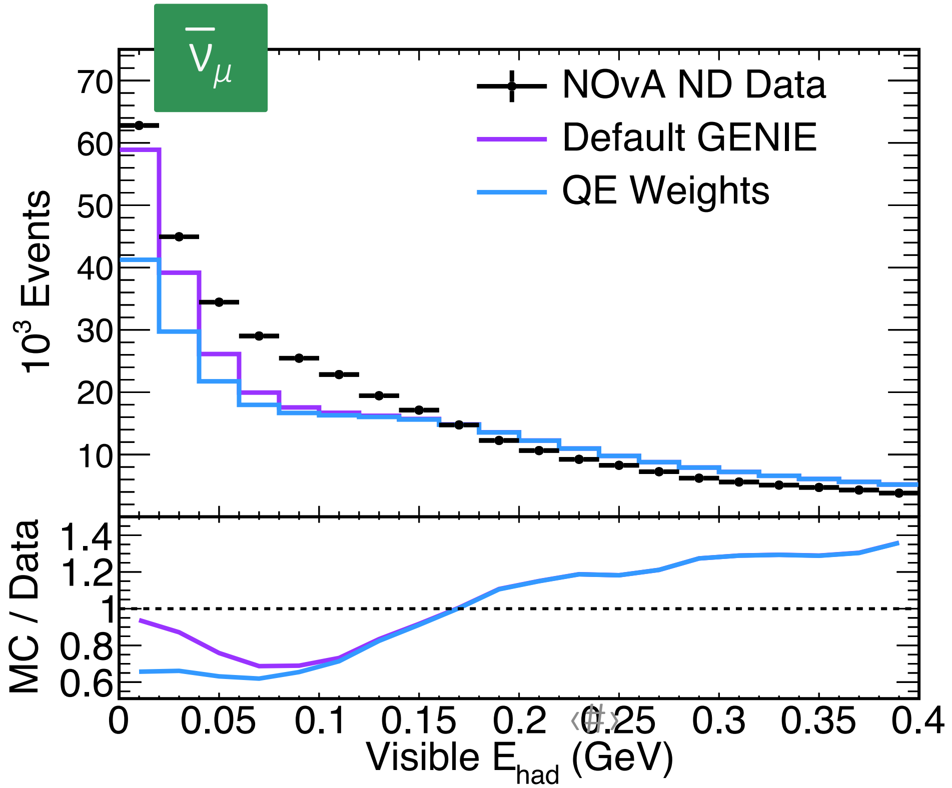




From **external theory**:

- Valencia RPA model† of nuclear charge screening applied to QE.





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† "Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

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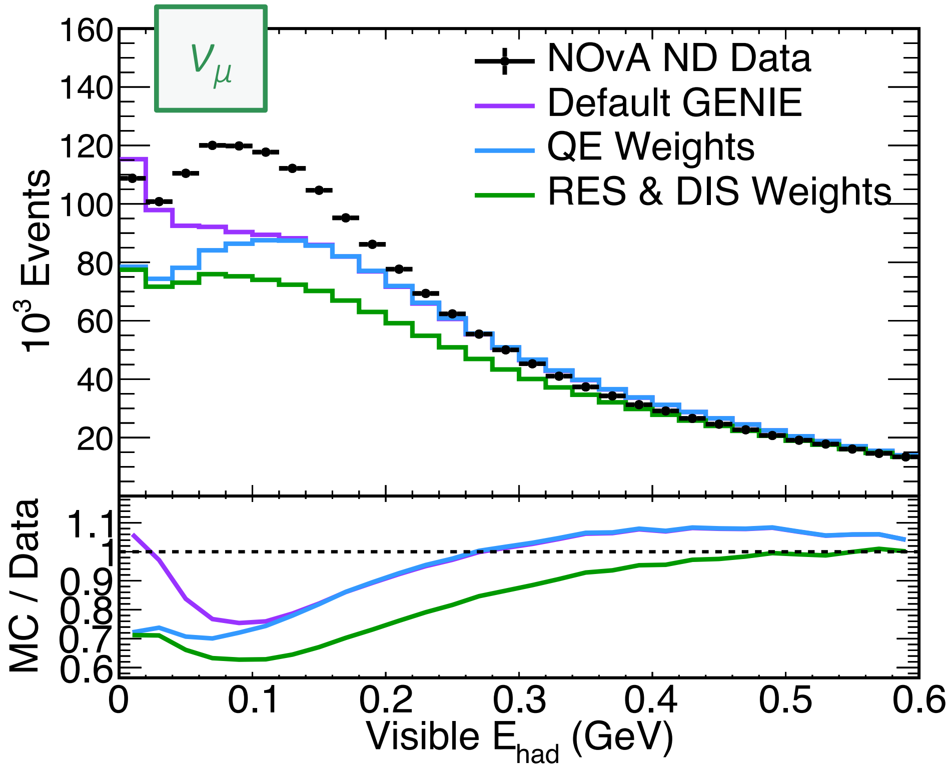
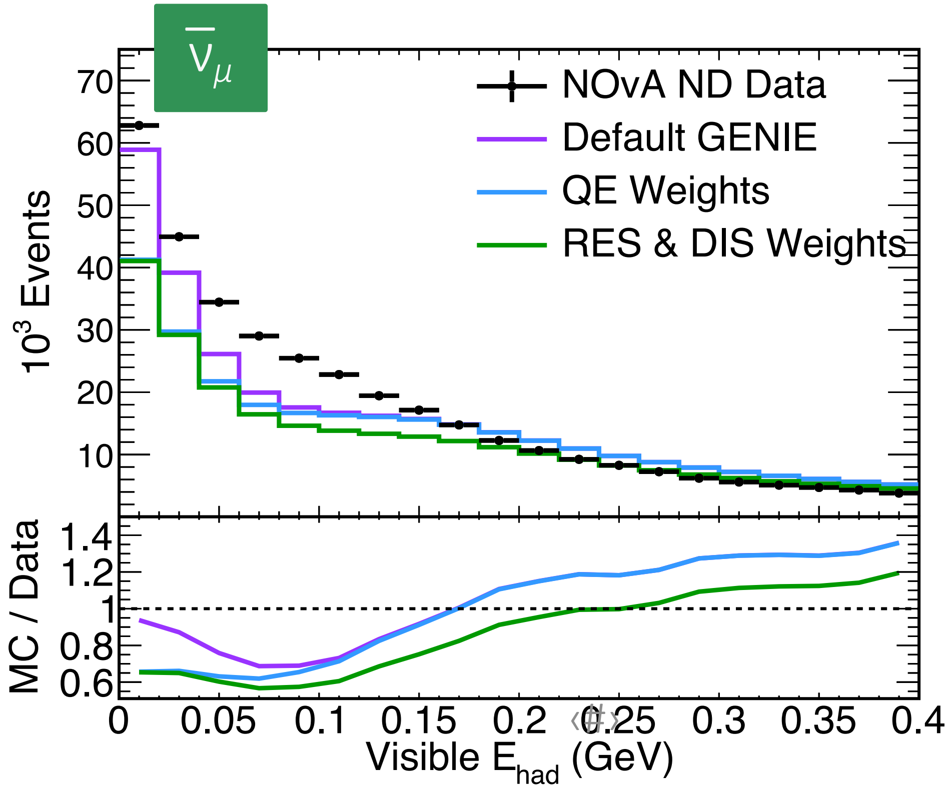
- Same model applied to resonance.

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.





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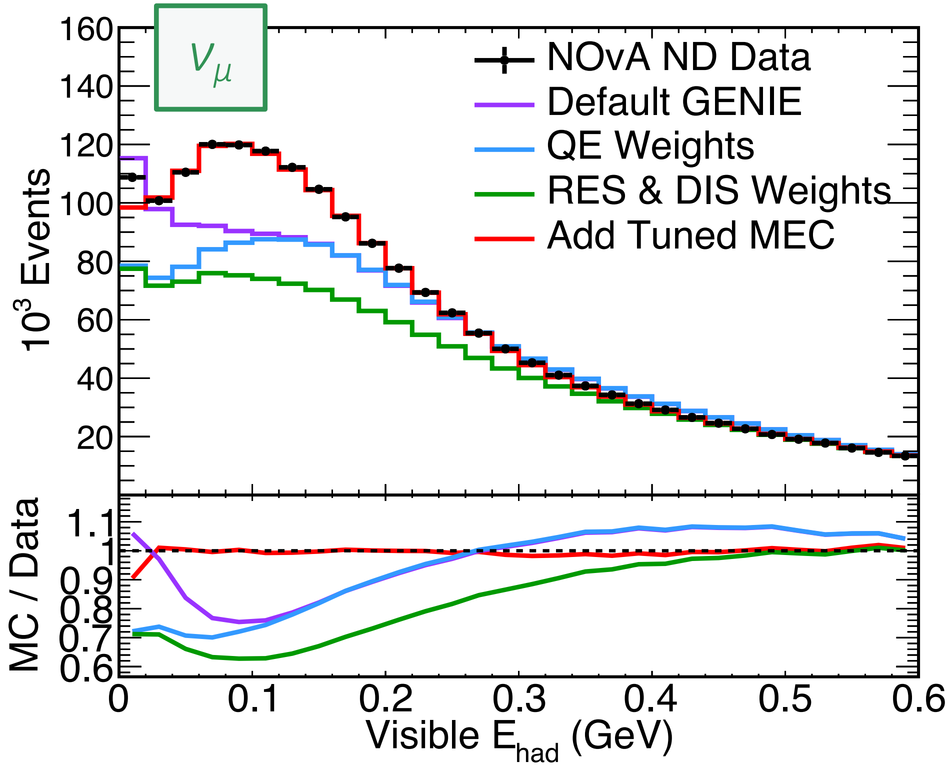
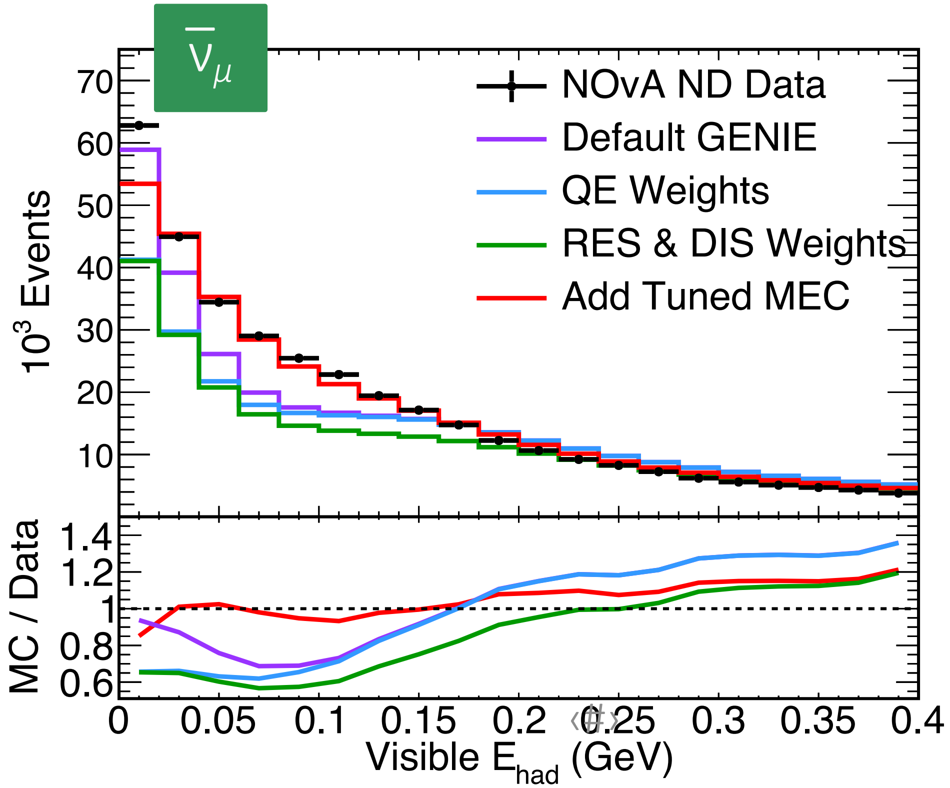
From **external theory**:

- Valencia RPA model† of nuclear charge screening applied to QE.
- Same model applied to resonance.

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.
- Add MEC interactions
  - Start from Empirical MEC*
  - Retune in $(q_0, |\boldsymbol{q}|)$ to match ND data
  - Tune separately for $\nu / \bar{\nu}$





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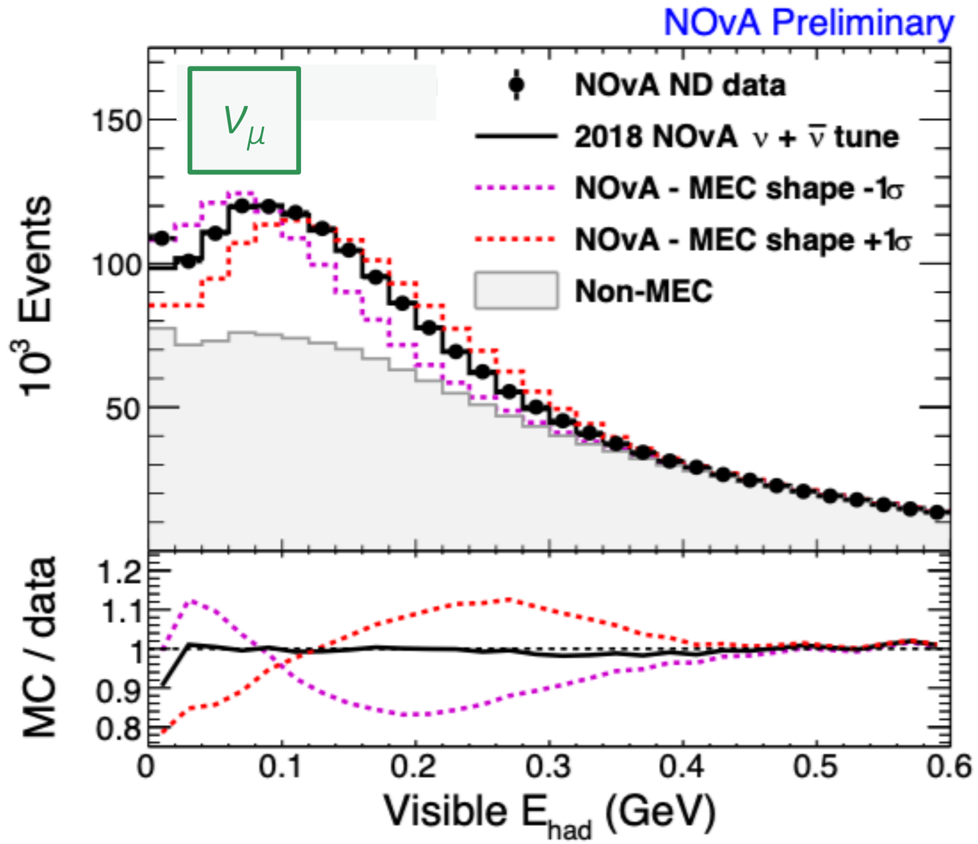
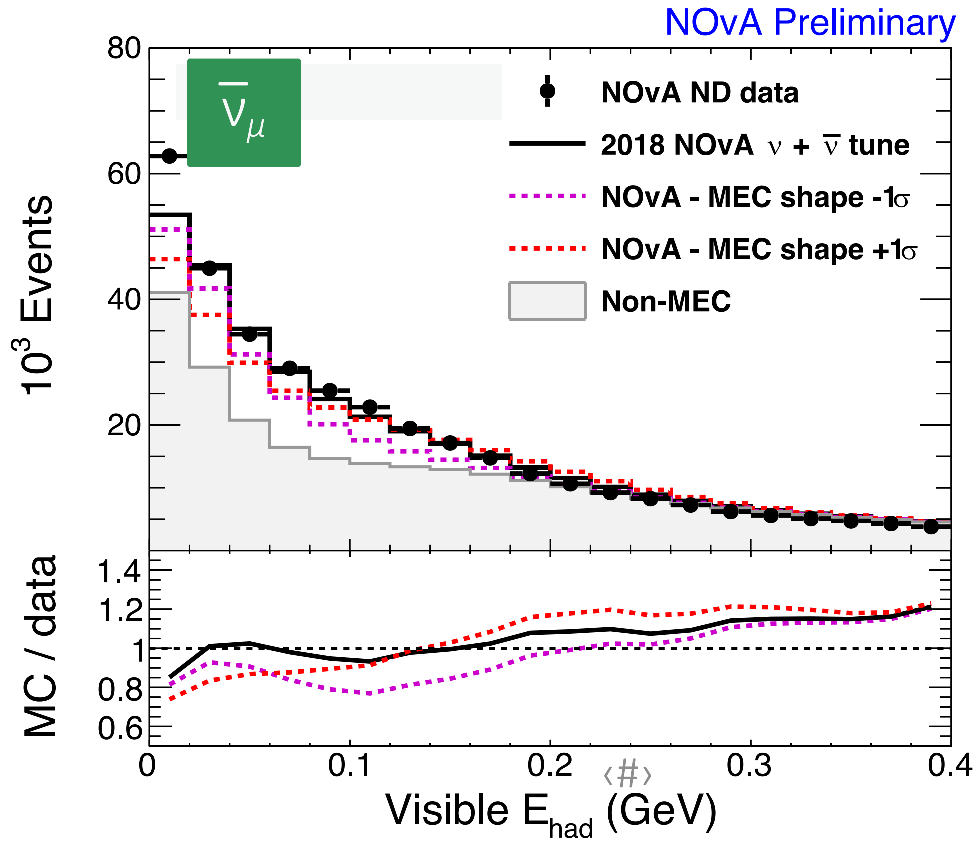
MEC Uncertainties

- We also determine uncertainties on the MEC component we introduce.
  - Both on shape and total rate.
- Repeat the tuning procedure with shifts in the Genie model.
  - Turn Genie systematic knobs coherently to push the non-MEC
    x-sec more QE-like or more RES-like.





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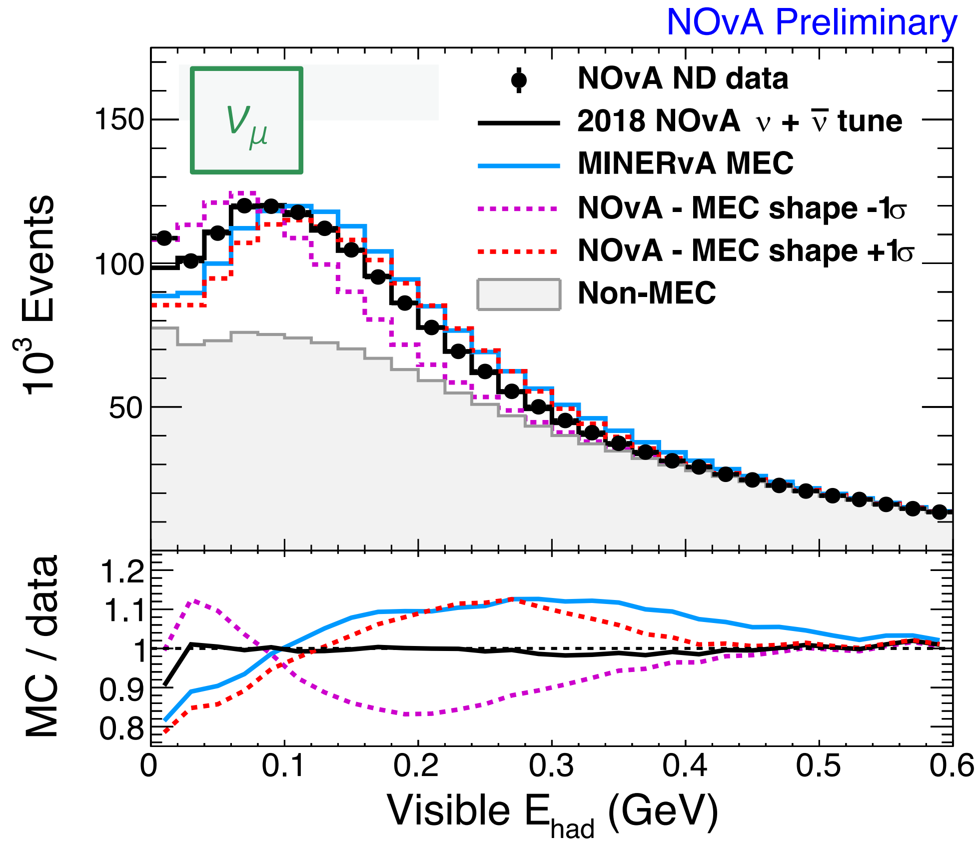
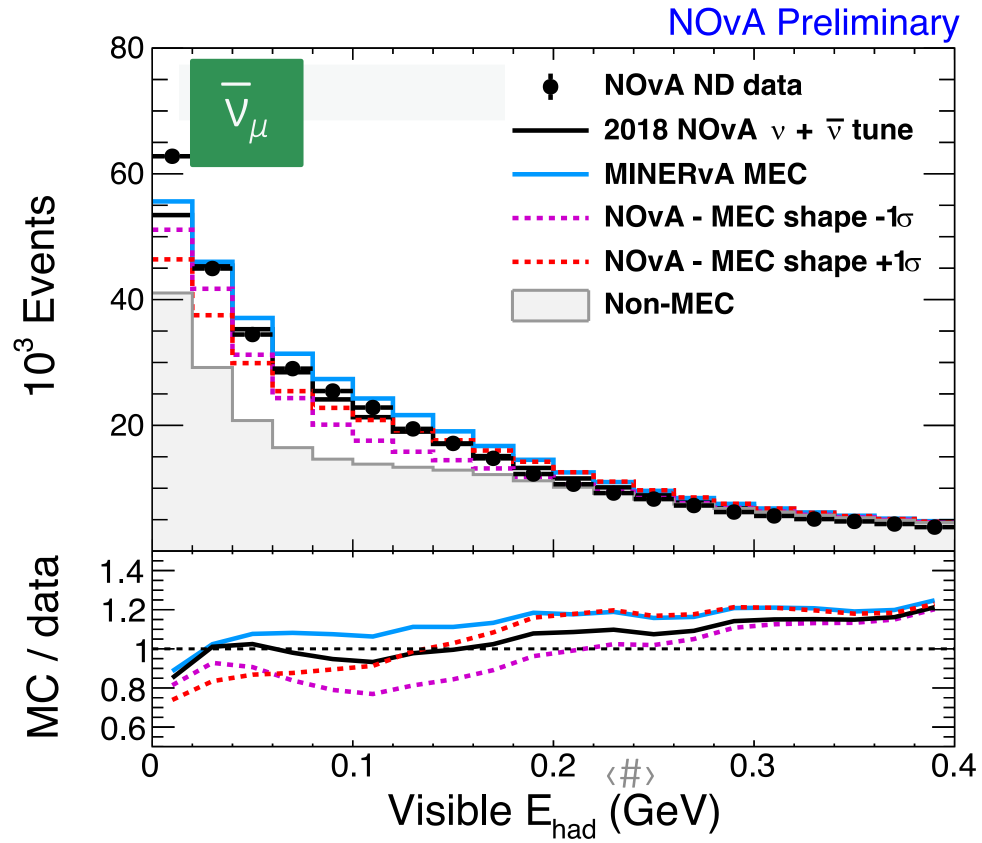
  - Both on shape and total rate.
- Repeat the tuning procedure with shifts in the Genie model.
  - Turn Genie systematic knobs coherently to push the non-MEC
    x-sec more QE-like or more RES-like.
- Independently, **Minerva*** has also tuned a multi-nucleon component to their data.
- The resulting tune is ~1σ away from the NOvA tune.





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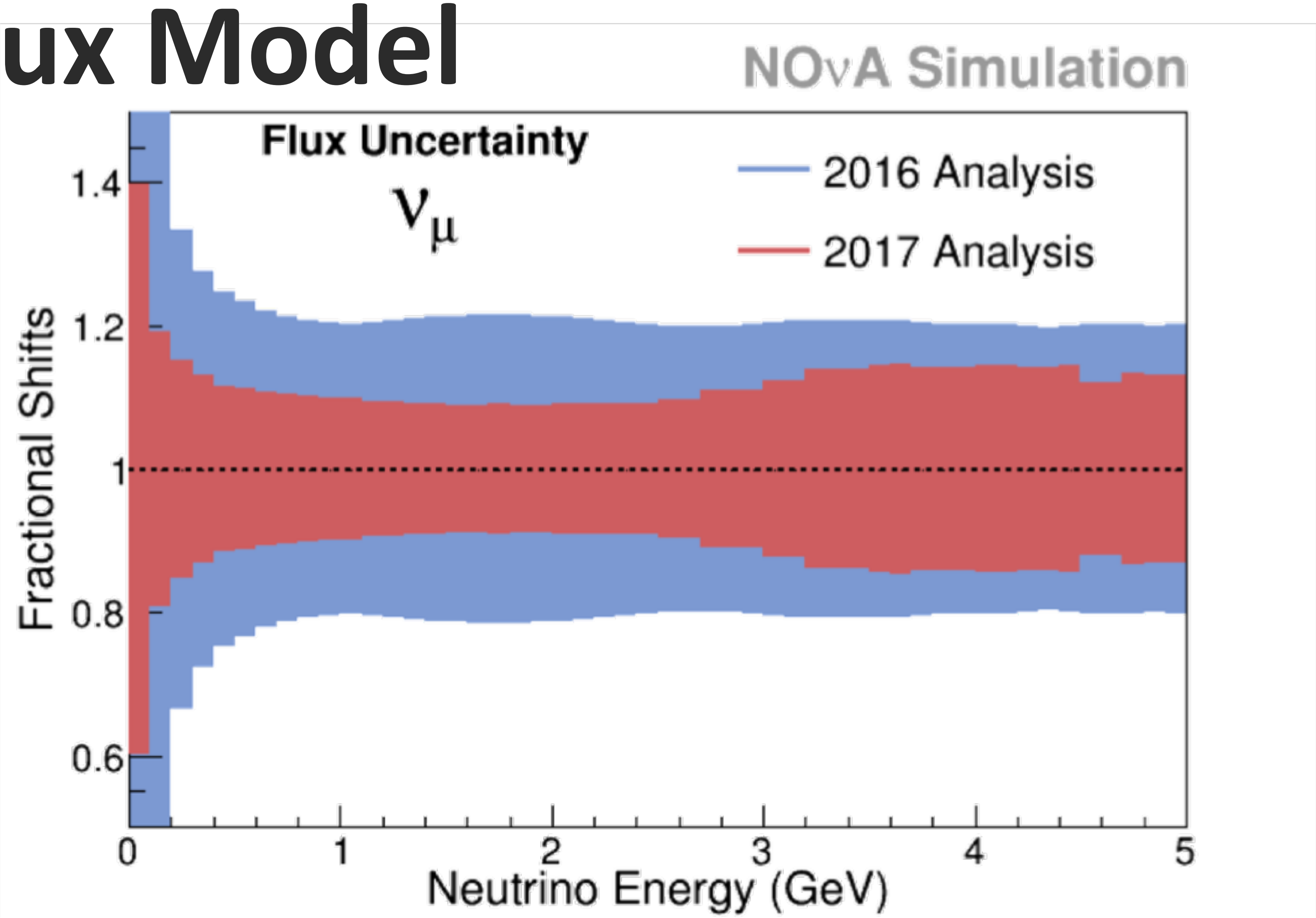
* Minerva, Phys. Rev. Lett. 116, 071802 (2016)

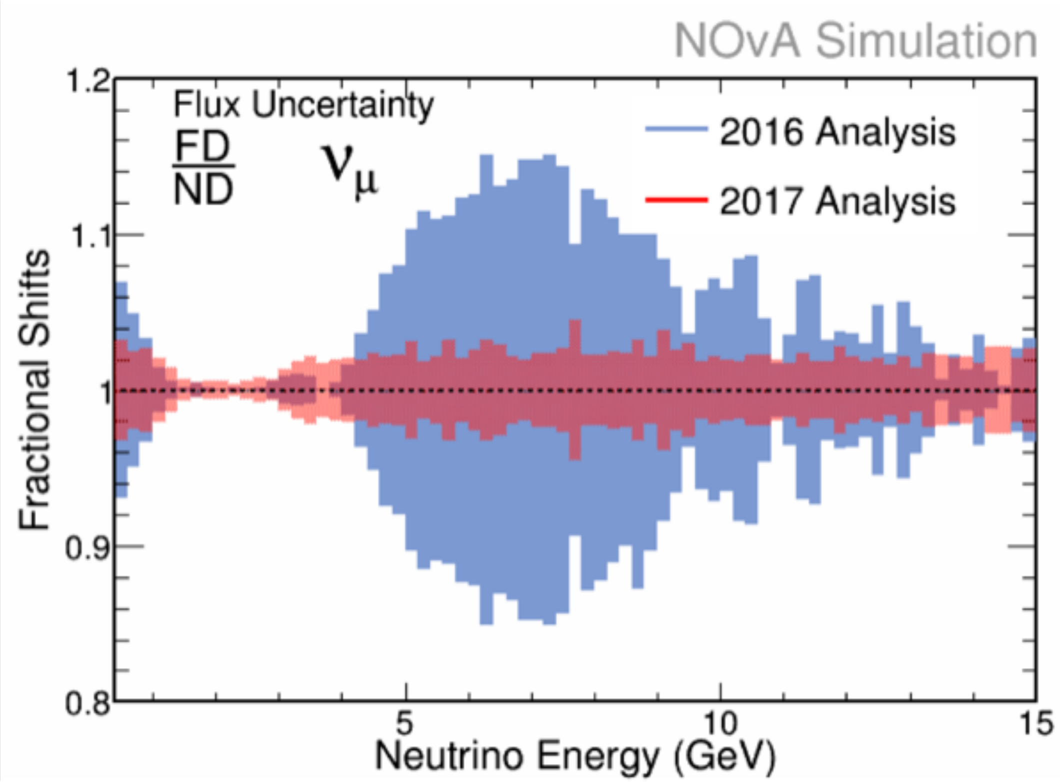
Minerva, Phys. Rev. Lett. 120, 221805 (2018)

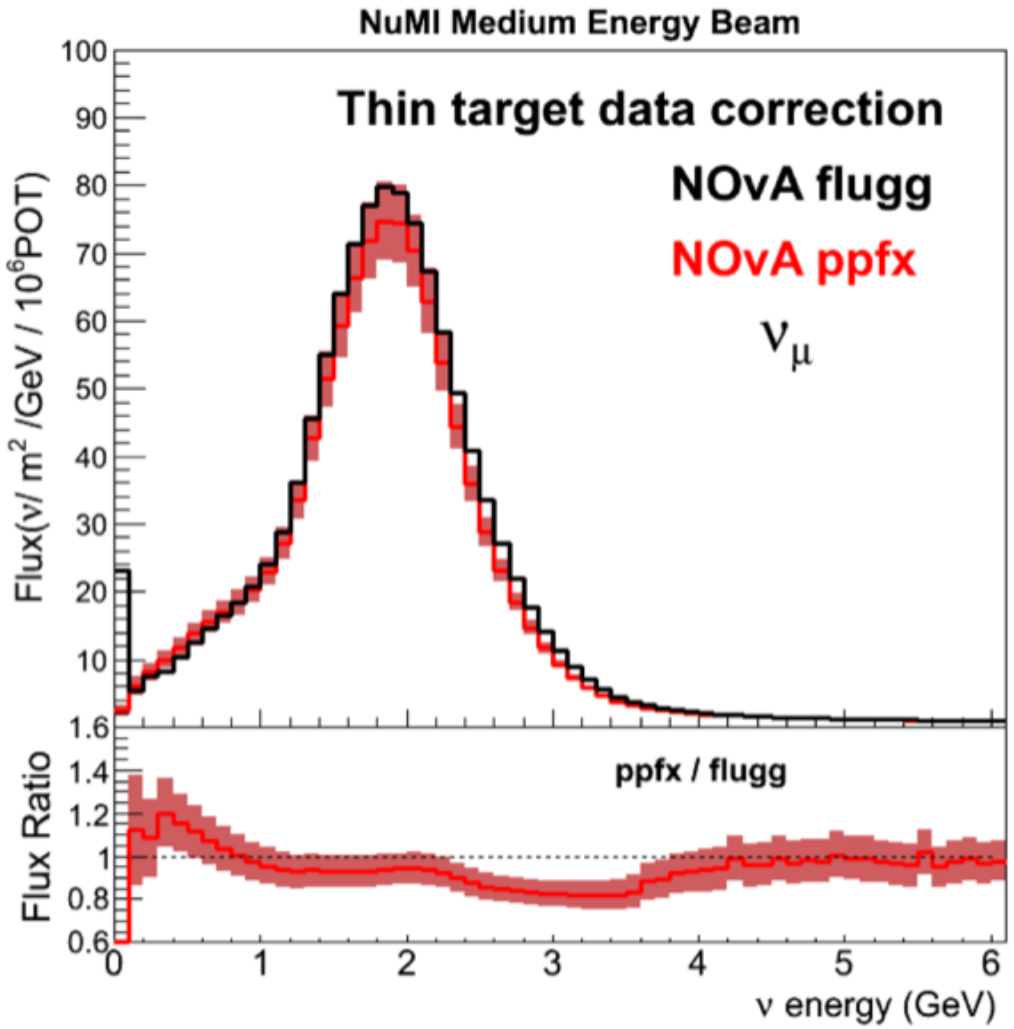
Improved Flux Model



- Package to Predict the FluX (**PPFX**) from MINERvA.
  - Based on thin target hadron production data from NA49 and MIPP.
- Significantly reduced systematic uncertainties.
  - Central values also changed within prior systematics, but not shown here.

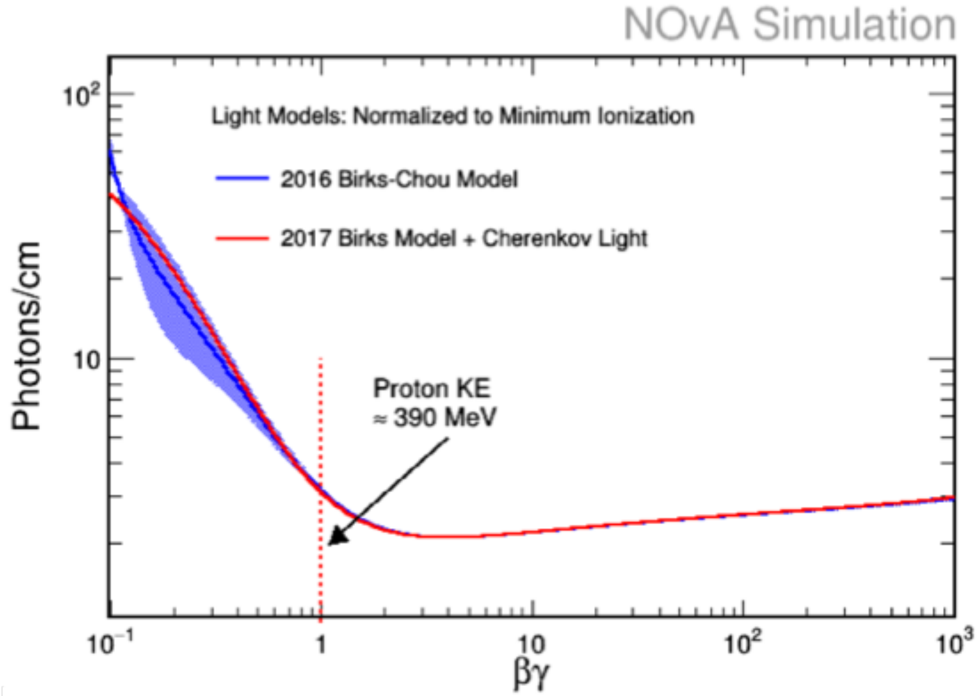
New Flux

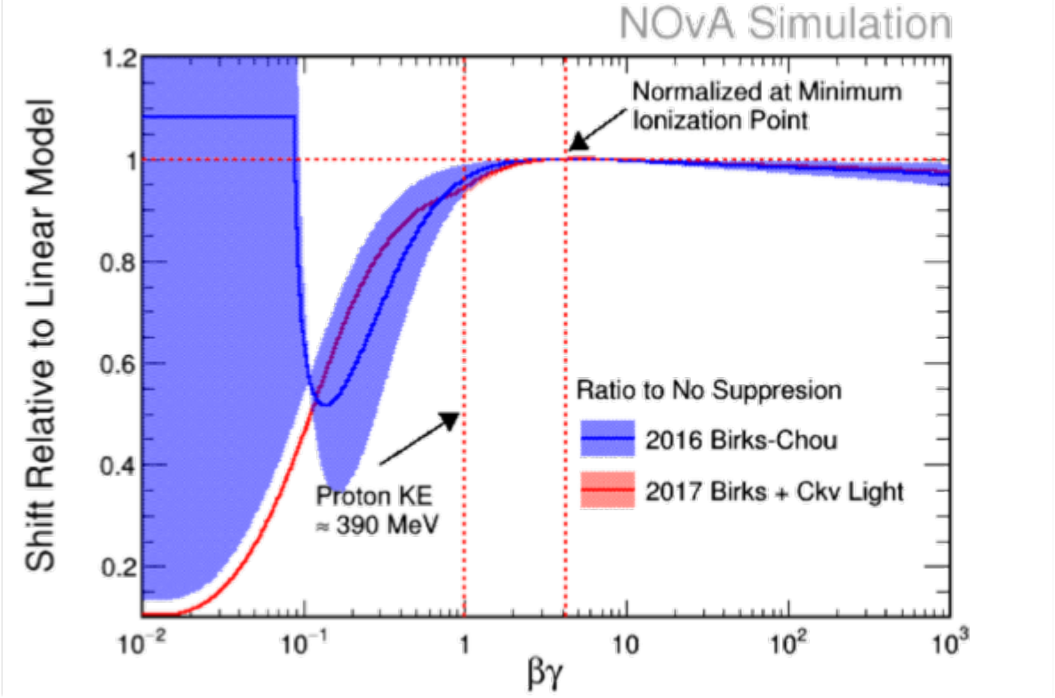

NOvA Simulation
Flux Uncertainty
FD
ND
ν_μ
2016 Analysis
2017 Analysis
Fractional Shifts
1.2
1.1
1
0.9
0.8
5
10
15
Neutrino Energy (GeV)


NuMI Medium Energy Beam
Thin target data correction
NOvA flugg
NOvA ppfx
ν_μ
Flux(ν/ m^2 /GeV / 10^{6}POT)
100
90
80
70
60
50
40
30
20
10
ppfx / flugg
Flux Ratio
1.6
1.4
1.2
1
0.8
0.6
0
1
2
3
4
5
6
ν energy (GeV)

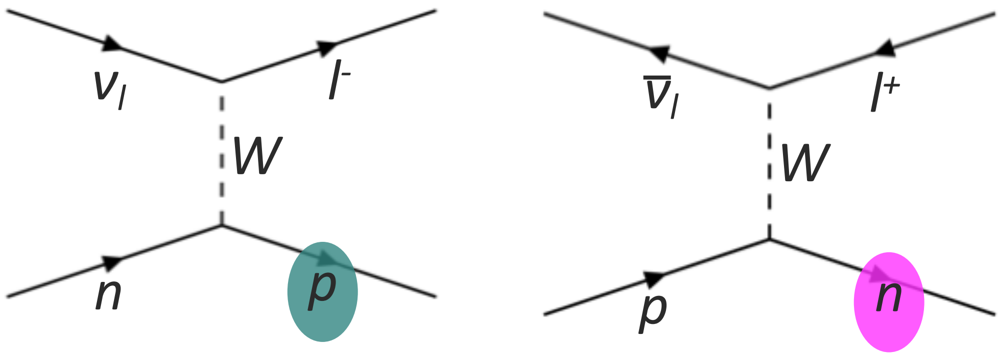
Scintillator Model

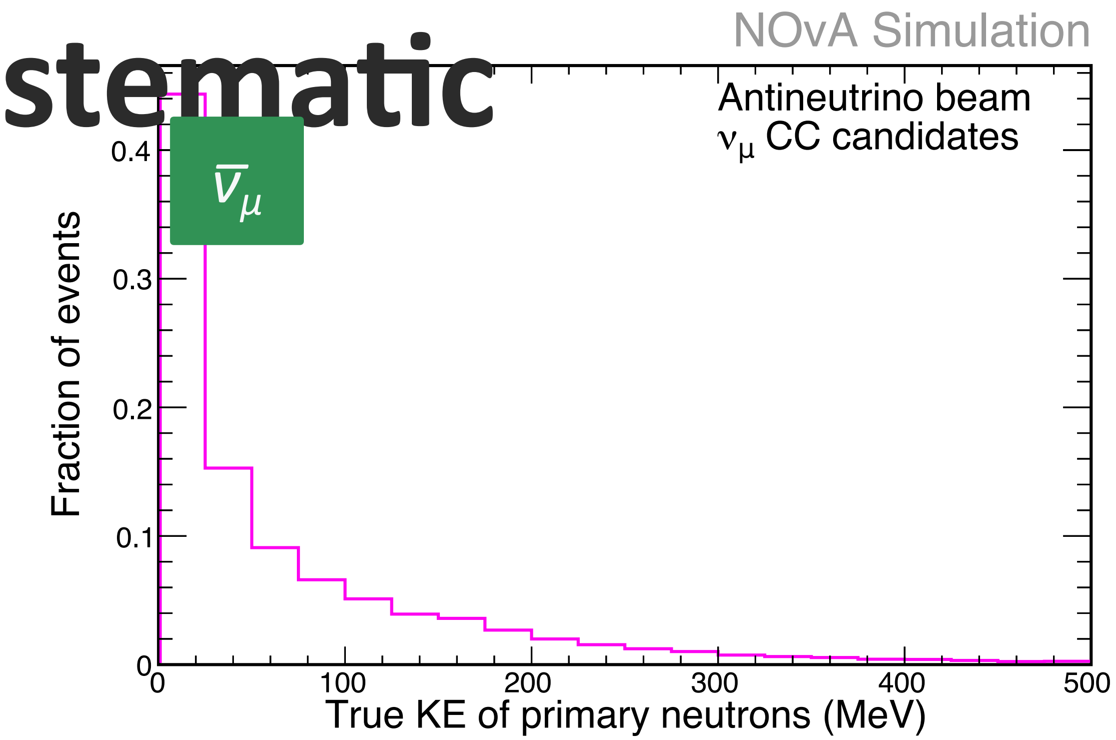
- Absorbed and re-emitted Cherenkov light is a small but important component of our scintillator response.
    - Particularly for low-energy protons in hadronic showers.
- Was one of our largest uncertainties, now reduced by an order of magnitude.
    - Previously accounted for with second order terms in our scintillator model.
    - Those terms were unusual, so we placed large systematics.
- Expected energy resolution for ν_μ CC events increased from 7% to 9%.



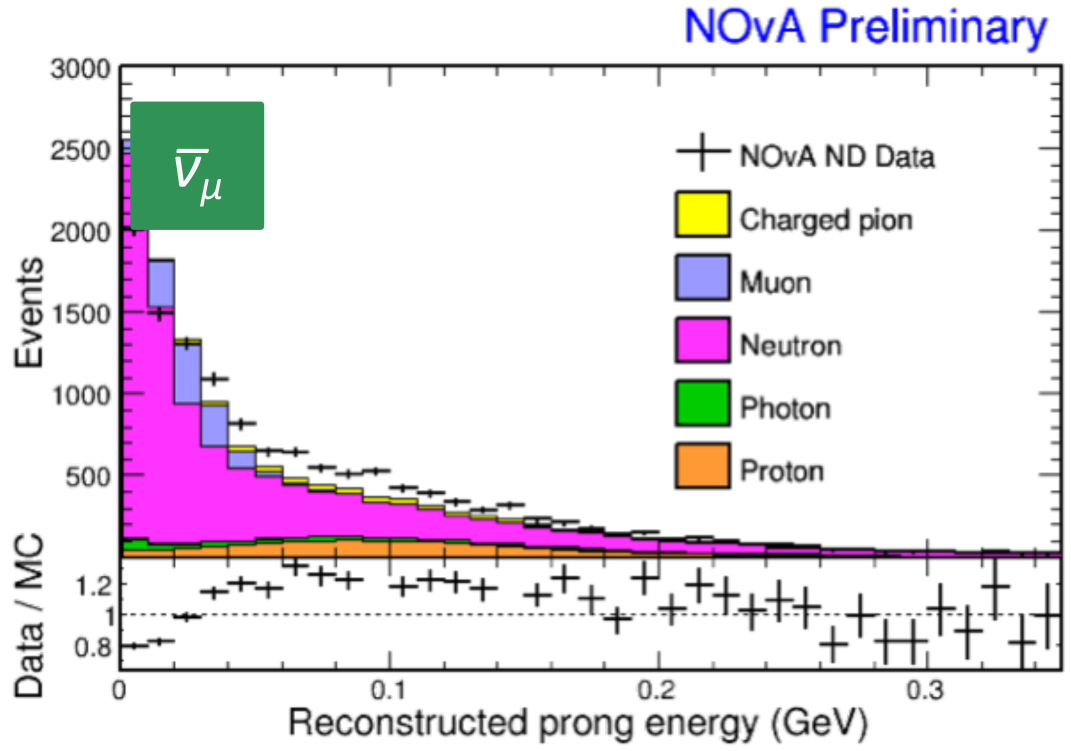


New neutron response systematic





- $\bar{\nu}$'s have neutrons where ν's have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of some neutrons to cover the low-energy discrepancy.
- Shifts the mean ν_μ energy by 1% in the antineutrino beam and 0.5% in the neutrino beam.
  - Negligible impact was seen on selection efficiencies.



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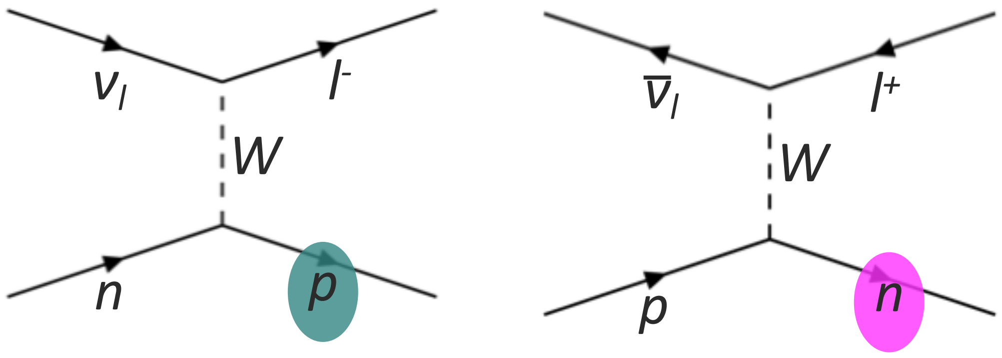

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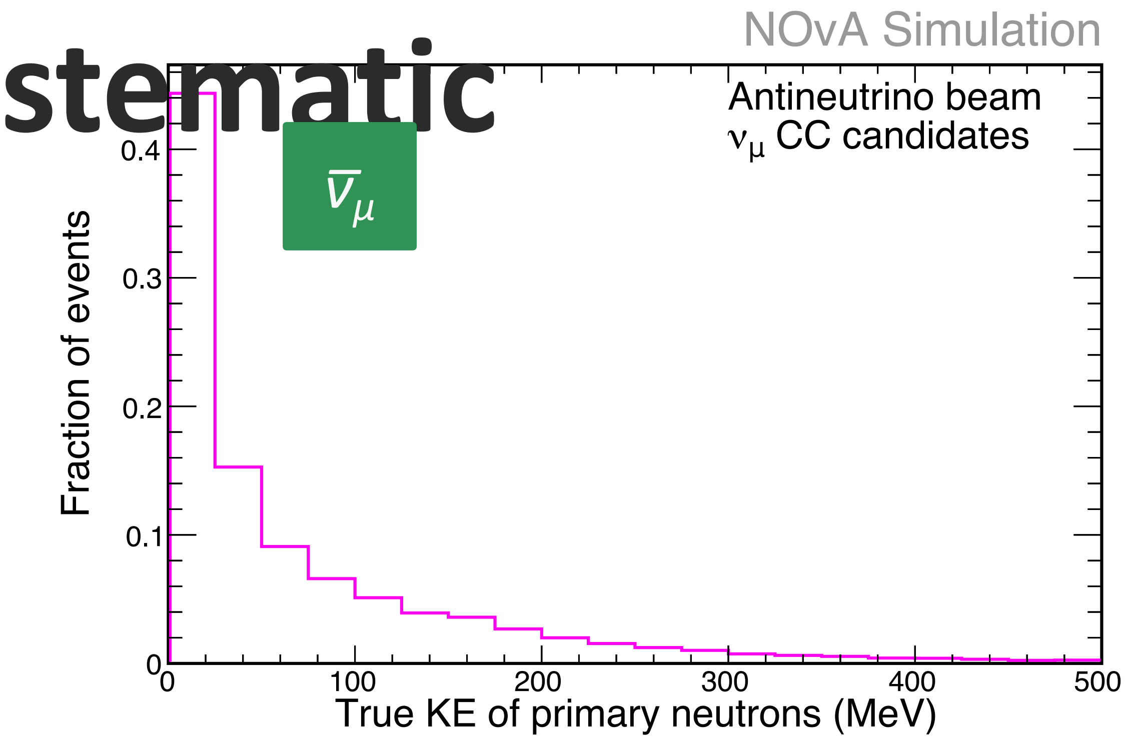
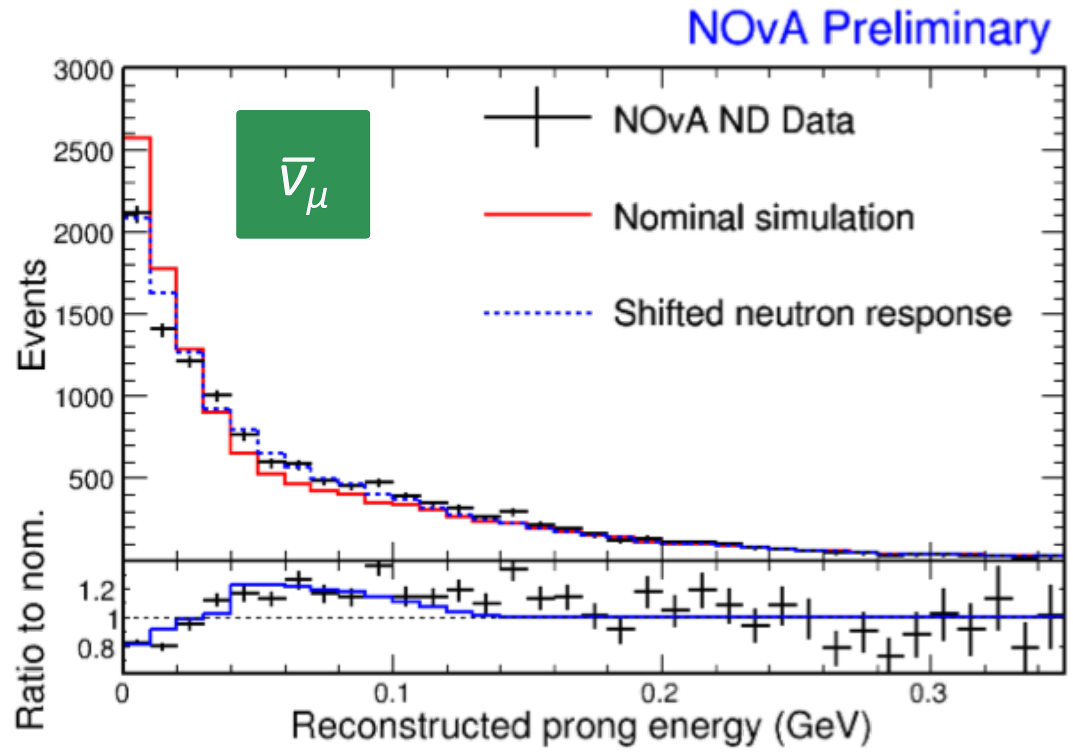
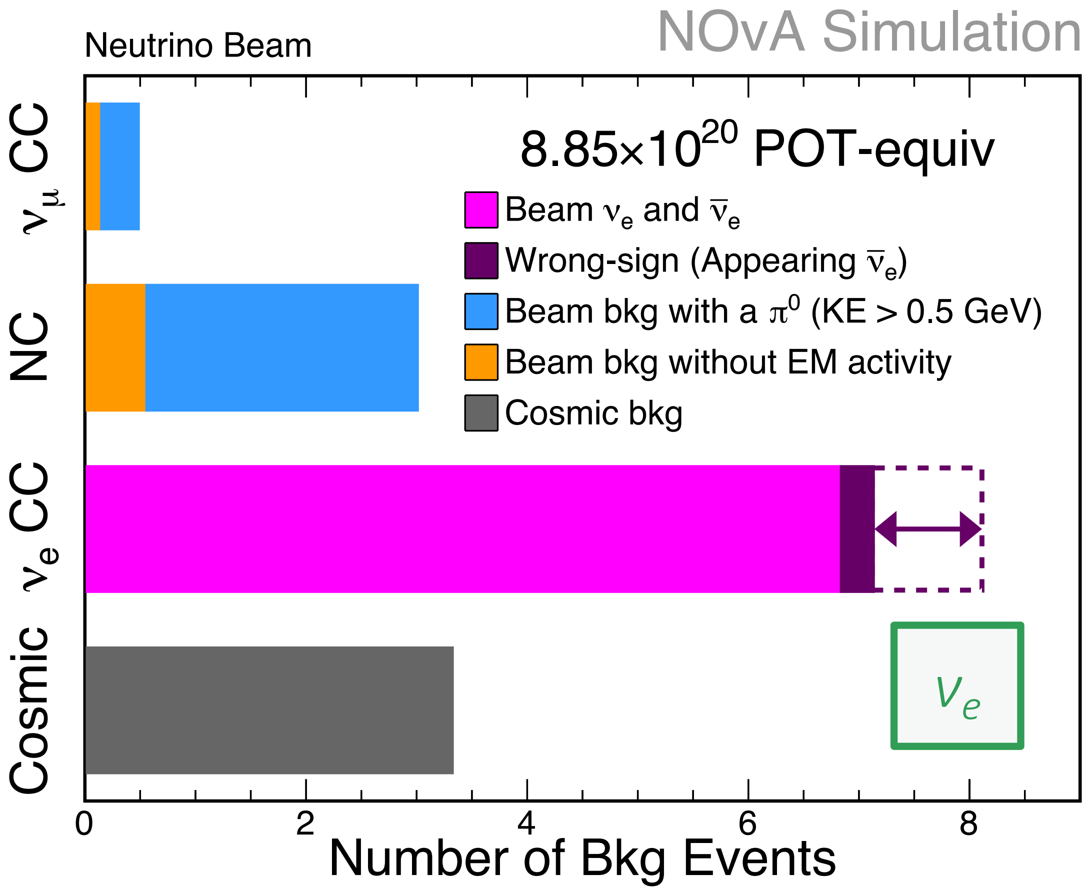
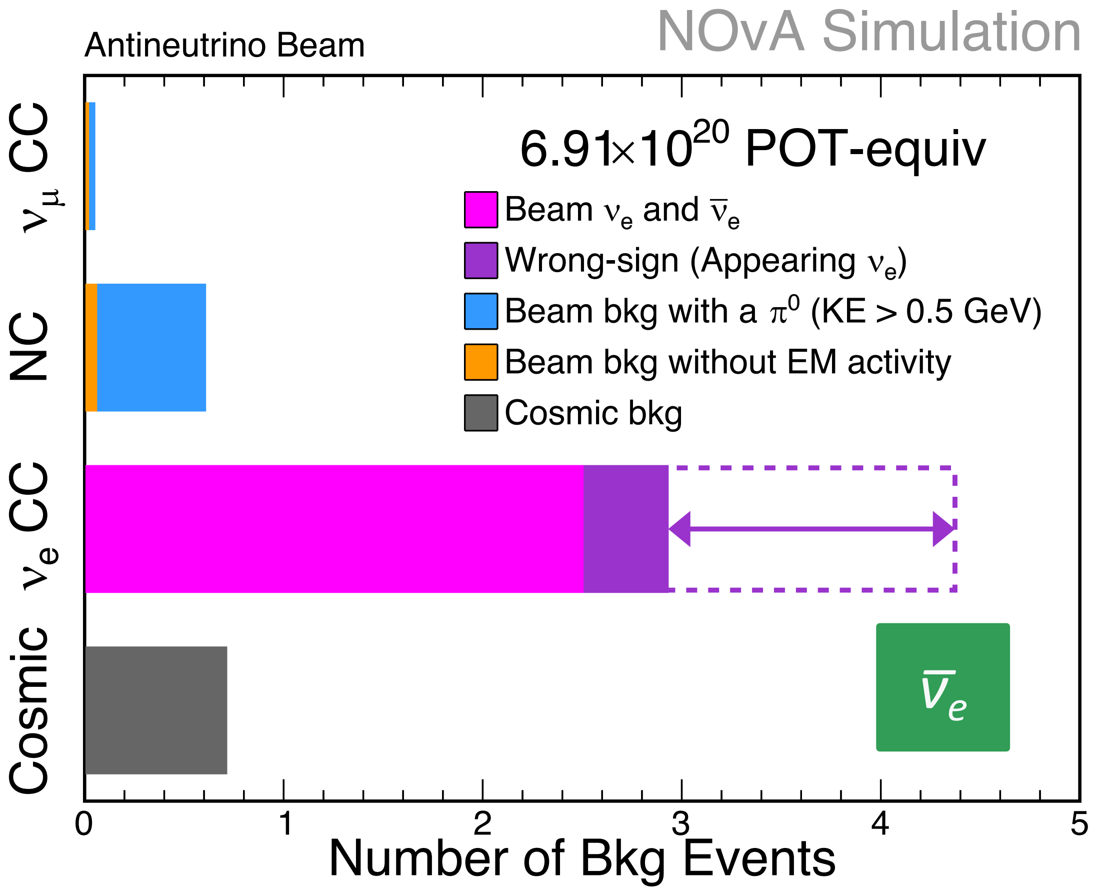




ν_e and $\bar{\nu}_e$ Background at the Far Detector

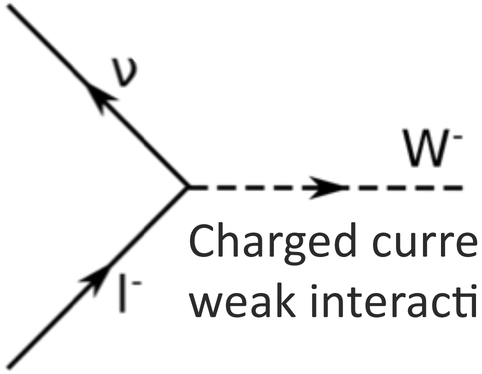




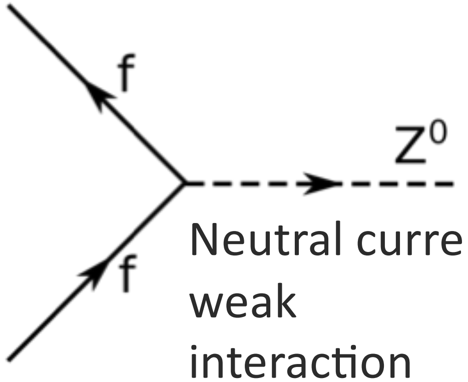
- 14.7 – 15.4 total ν_e background 4.7 – 5.7 total $\bar{\nu}_e$ background
  - Wrong-sign background depends on the oscillation parameters.
- Largest backgrounds are from real electrons: beam $\nu_e/\bar{\nu}_e$ and wrong-sign.
  - The amount of wrong-sign background varies with the oscillation parameters.
- Most other beam backgrounds contain a π^0.

Introduction to neutrino oscillations

- **Neutrinos:** neutral leptons, only interact weakly.
  Names refer to associated charged lepton:
  - Electron neutrino, ν_e
  - Muon neutrino, ν_μ
  - Tau neutrino, ν_τ

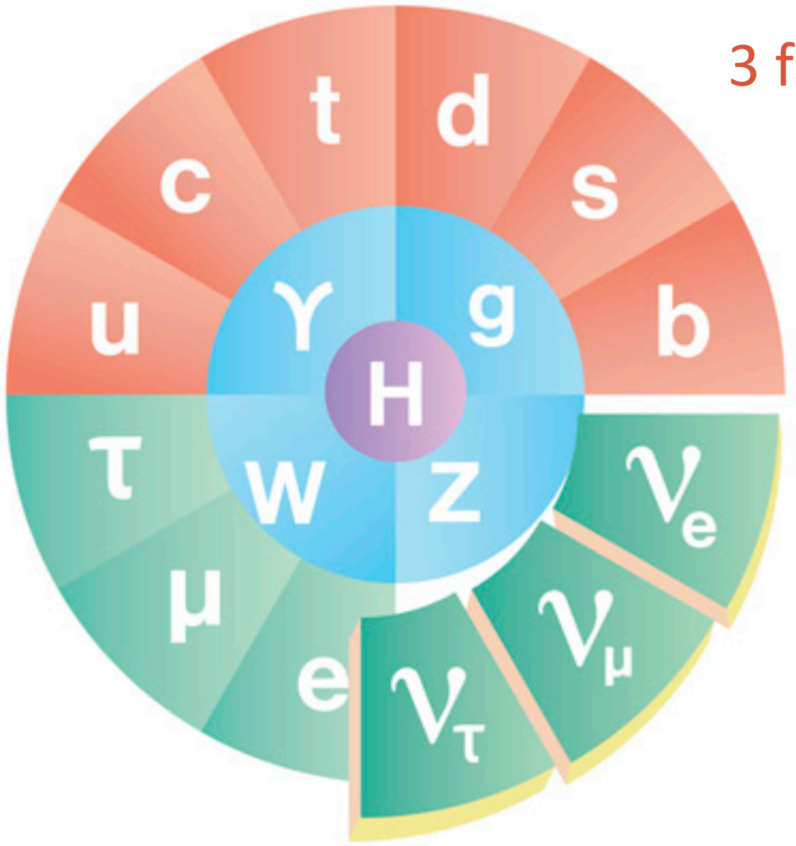


Charged current weak interaction



Neutral current weak interaction

Fundamental particles in the Standard Model



3 families of quarks

4 force carriers

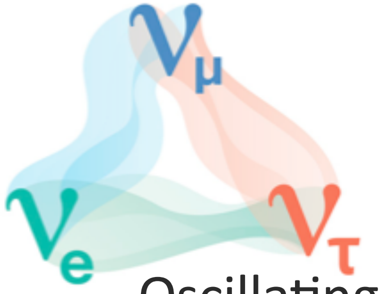
Higgs boson

3 families of leptons

Abundant

Low-interacting

Lightweight



Oscillating

Long baseline experiment design

ν_μ

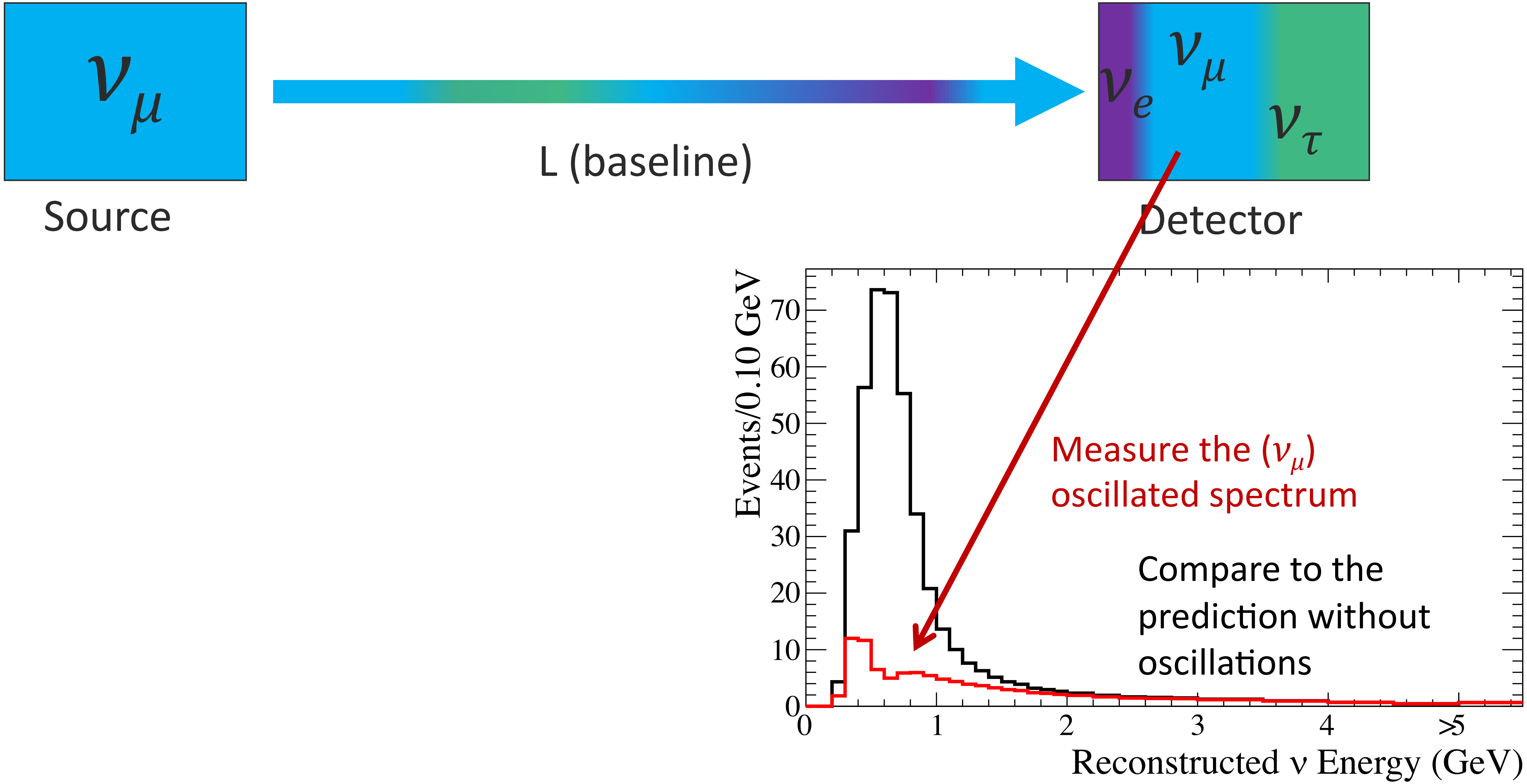
Source

L (baseline

ν_e ν_μ ν_τ

Detector

Long baseline experiment design



Source

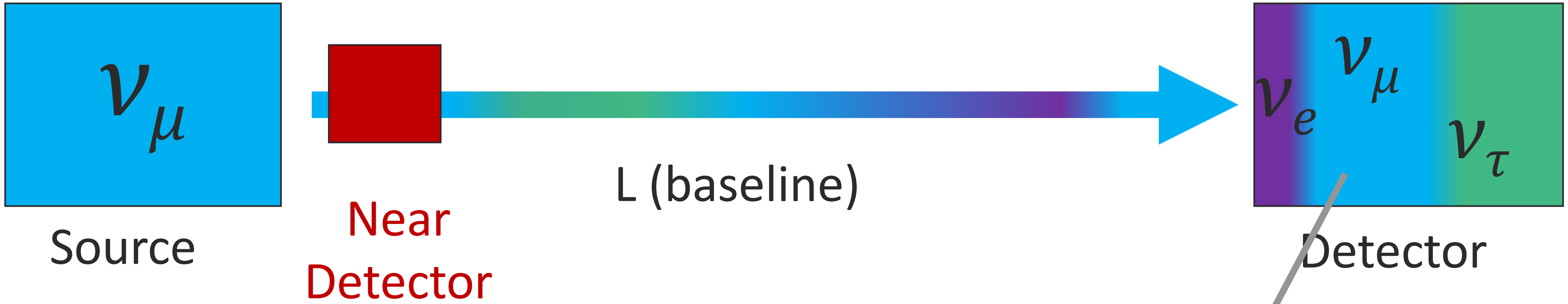
L (baseline)

Detector

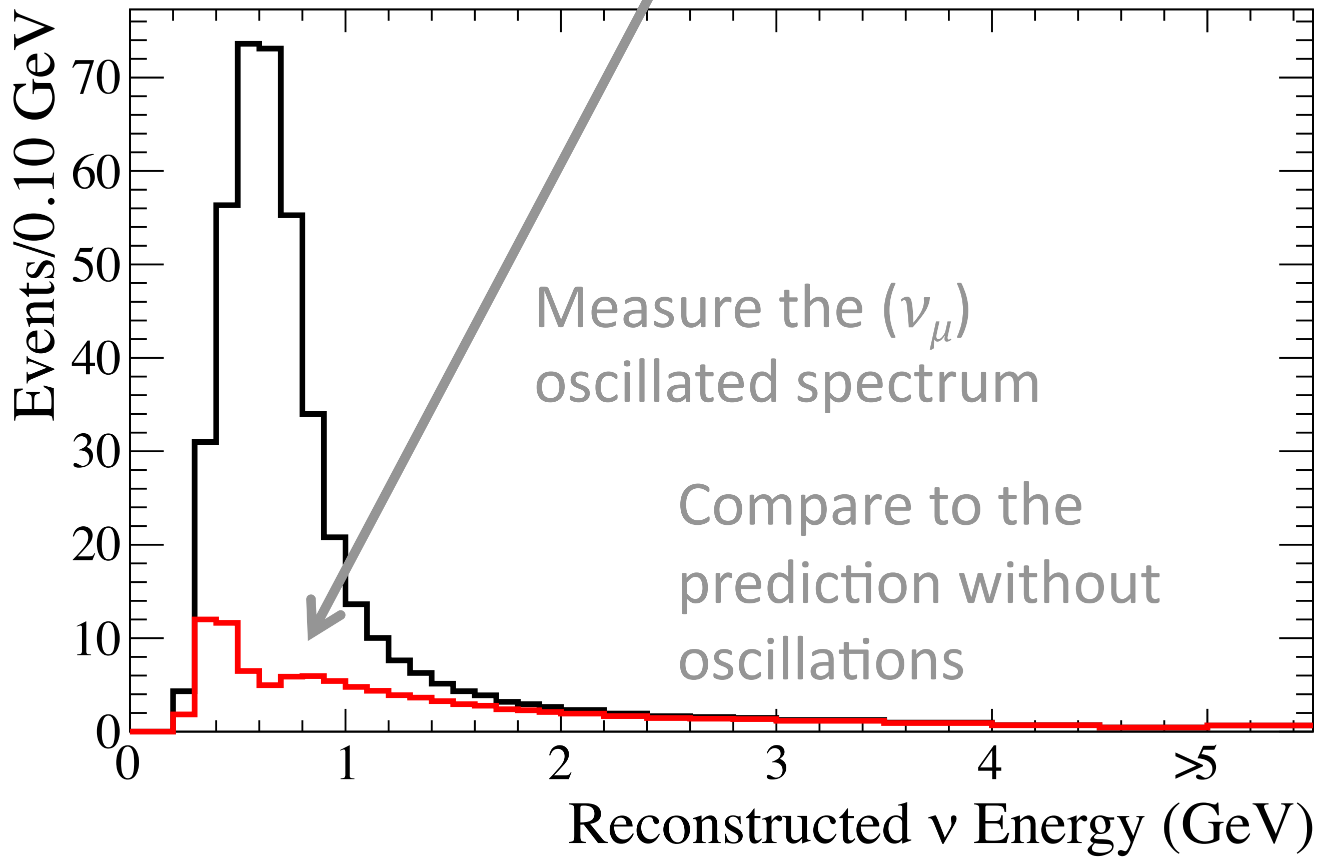
Measure the (ν_μ) oscillated spectrum

Compare to the prediction without oscillations

Long baseline experiment design



- Measurements of the unoscillated beam → improve the predictions
- Sources of uncertainty include
  - **Flux**: number of neutrinos produced
  - **Cross section**: how often they interact



Measure the (ν_μ) oscillated spectrum

Compare to the prediction without oscillations

Long baseline experiment goals

- Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$):
  Sensitive to θ_{23}, δ_{CP}, and the neutrino mass hierarchy

- Muon neutrino disappearance ($\nu_\mu \rightarrow \nu_\mu$):
  Sensitive to θ_{23} and Δm^2_{32}

Joint $\boldsymbol{\nu_e} + \boldsymbol{\nu_\mu}$ analysis

Constrain the parameter space

$\delta_{CP} = ?$

$\sin^2\theta_{12} = 0.304 \pm 0.014$

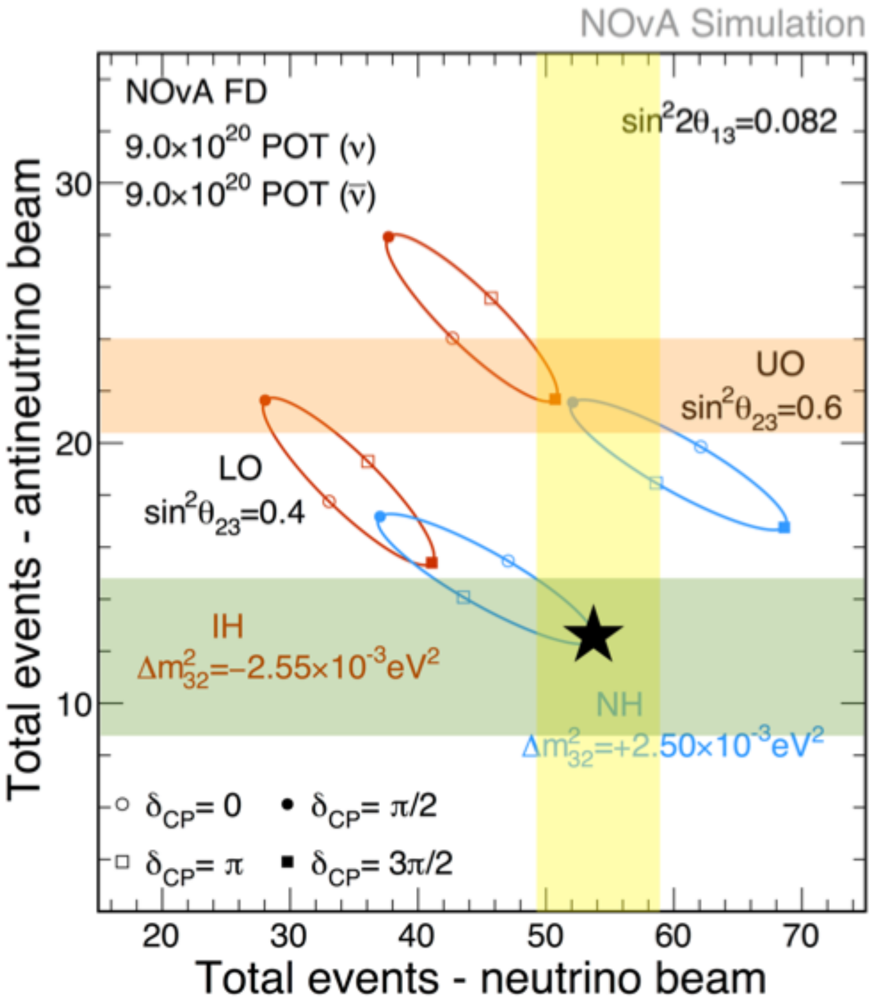
$\sin^2\theta_{13} = 0.0219 \pm 0.0012$

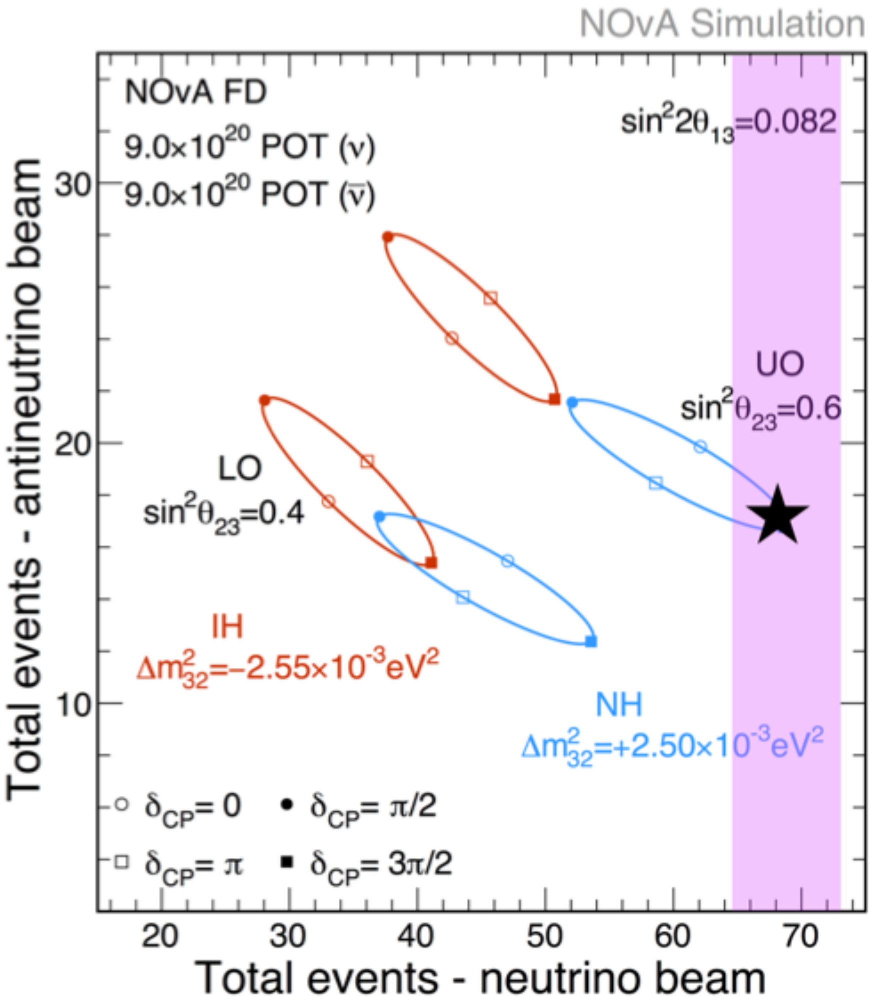
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{32}| = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$

Mass hierarchy: ?

$\sin^2\theta_{23} = 0.51 \pm 0.05$


NOvA Simulation
NOvA FD
9.0×10^{20} POT (ν)
9.0×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}$=0.082
UO
$\sin^2\theta_{23}$=0.6
LO
$\sin^2\theta_{23}$=0.4
IH
Δm^2_{32}=−2.55×10^{-3}eV^2
NH
Δm^2_{32}=+2.50×10^{-3}eV^2
○ δ_{CP}= 0
● δ_{CP}= π/2
□ δ_{CP}= π
■ δ_{CP}= 3π/2
Total events - antineutrino beam
10
20
30
Total events - neutrino beam
20
30
40
50
60
70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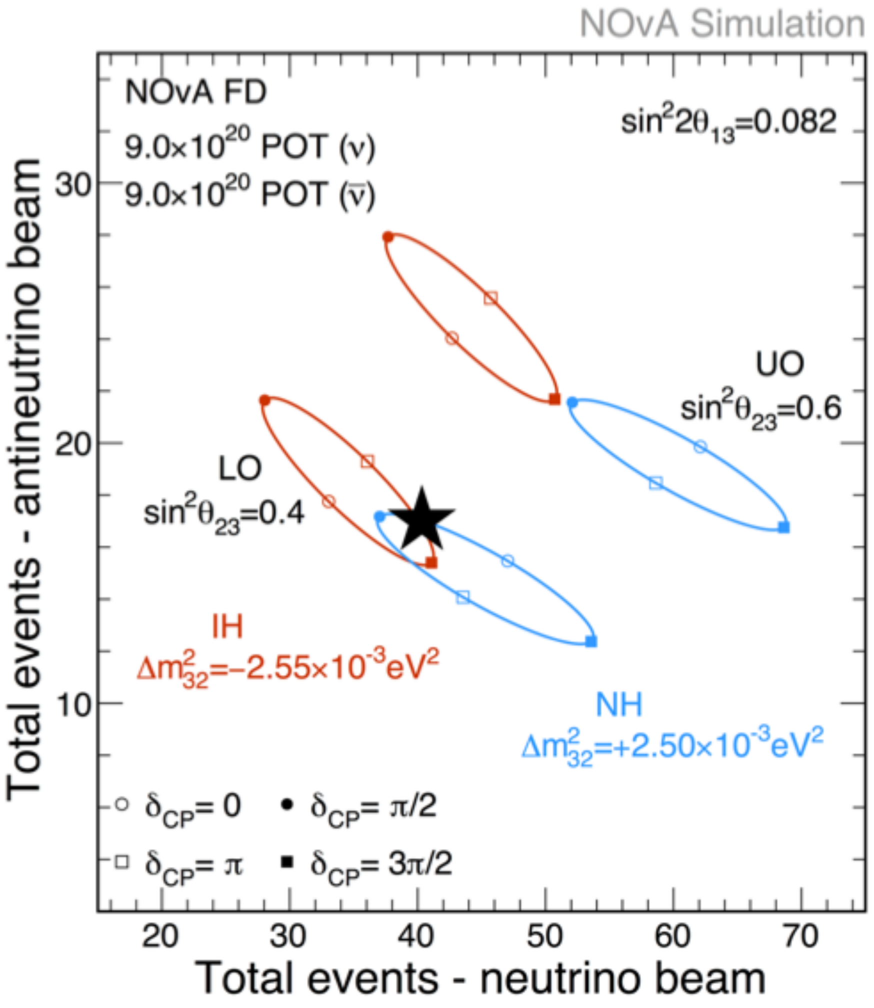
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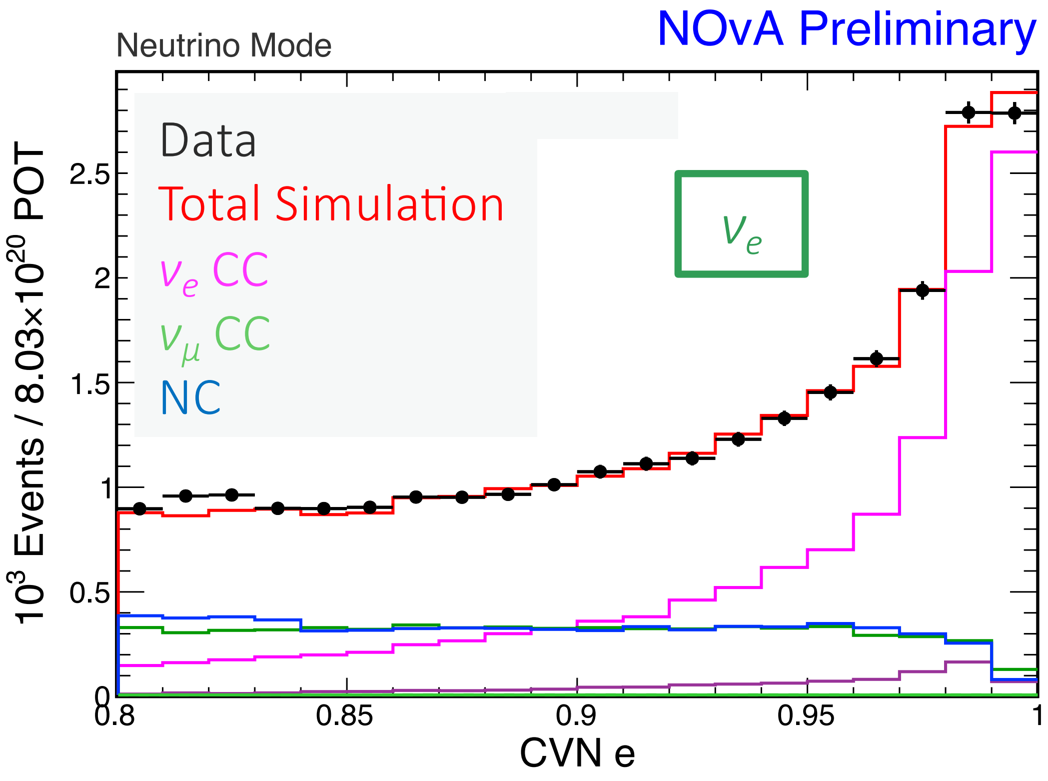
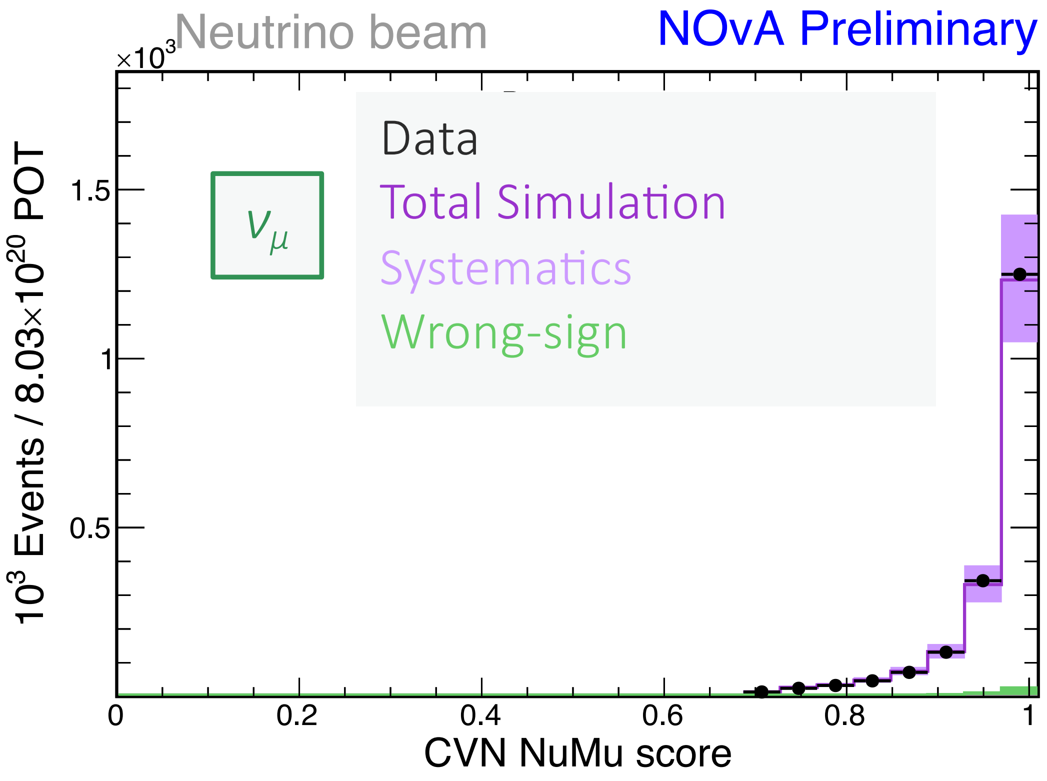
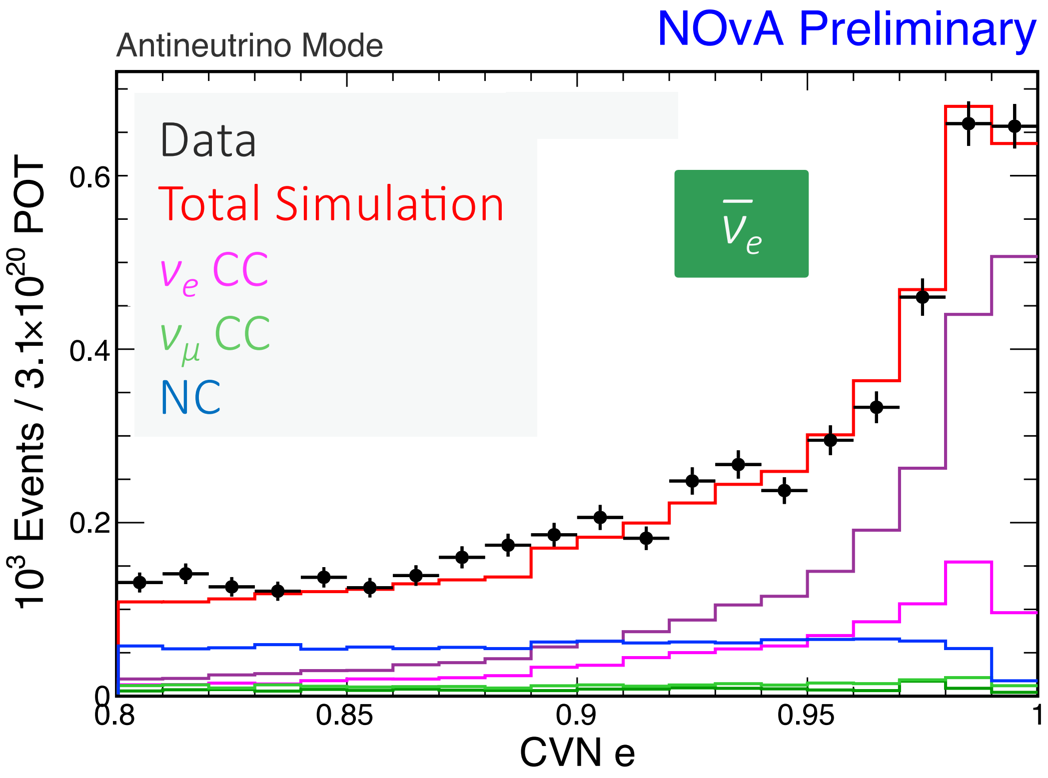
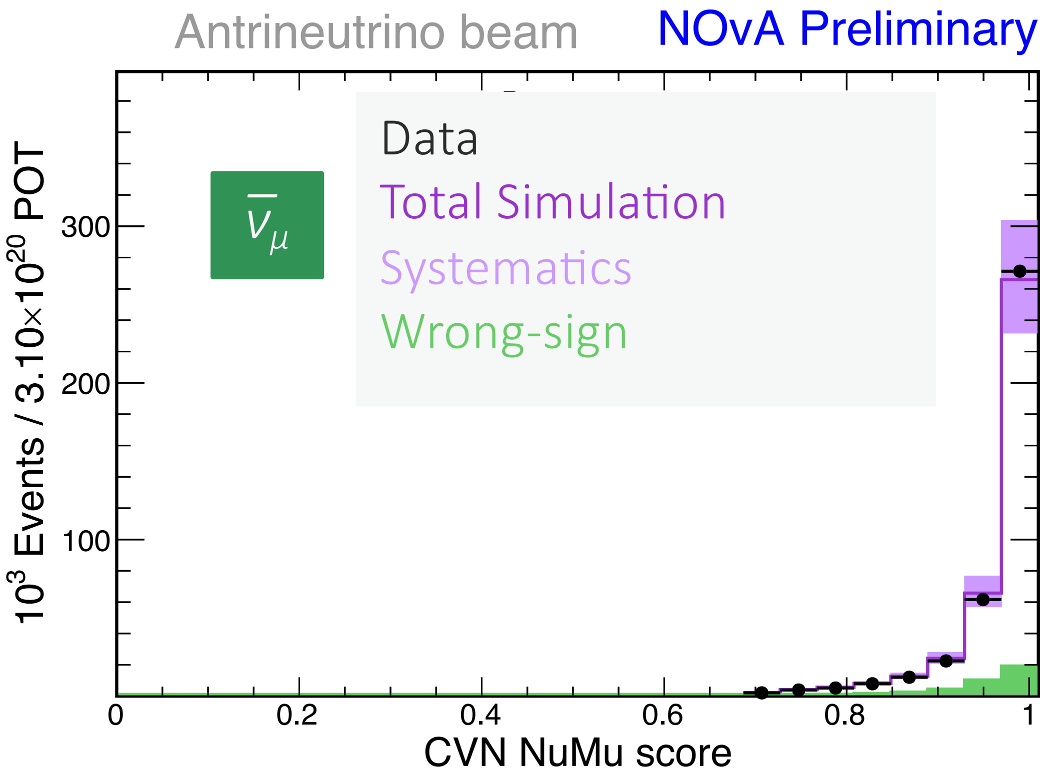




New for this analysis:

- A shorter, simpler architecture trained on updated simulation.
- Replaced Genie truth labels with final state labels.
  - Exploring using final states with protons to constrain WS backgrounds.
- Separate training for the neutrino and antineutrino beams.
  - Wrong-sign treated as signal in training.
  - 14% better efficiency for $\bar{\nu}_e$ with a dedicated network.





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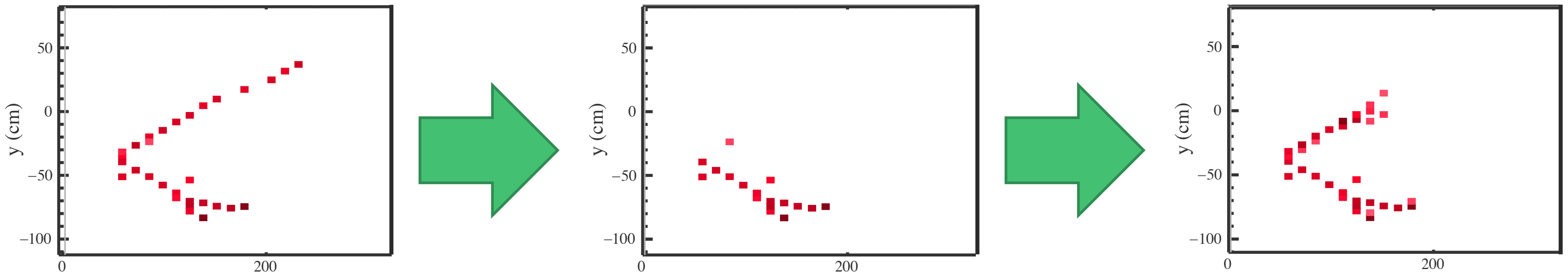
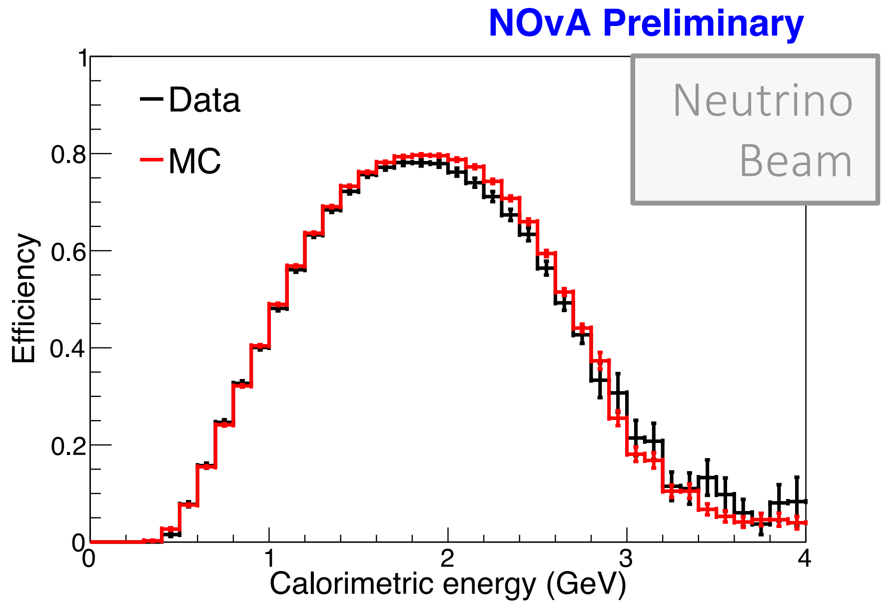
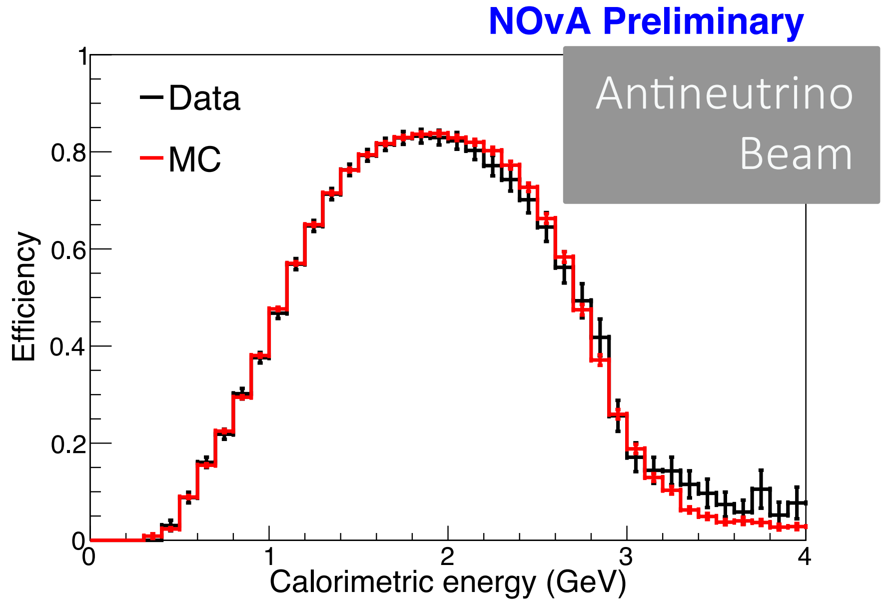
Cross-checks: Muon-removed, Electron-added

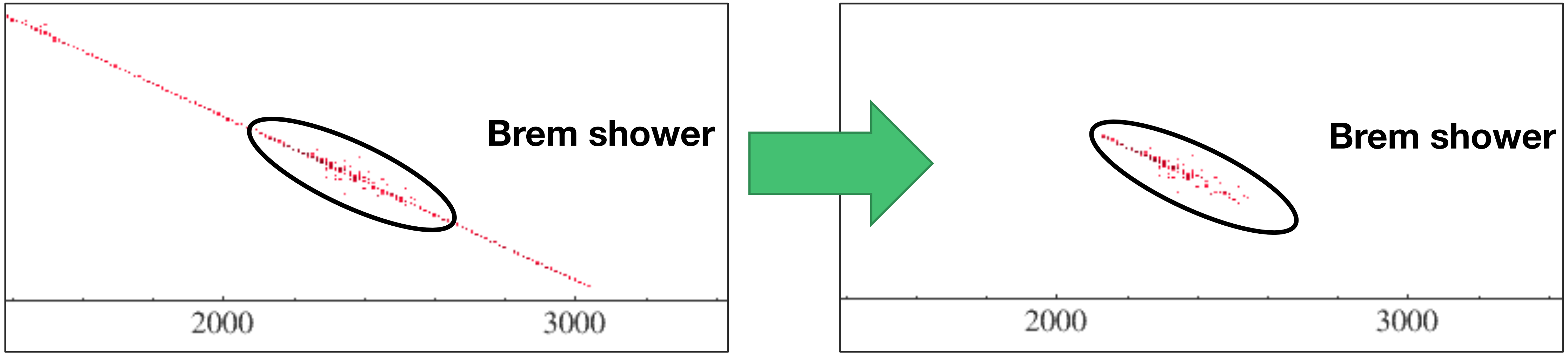


- We can create a control sample of "electron neutrino" events by removing the muon and replacing it with a simulated electron.
- Compare the efficiency between MRE events with real and simulated hadronic showers.
  - Allows us to focus on the effect of the hadronic shower on efficiency.
- Efficiency agrees between data and MC at the 2% level for both neutrino and antineutrino beams.

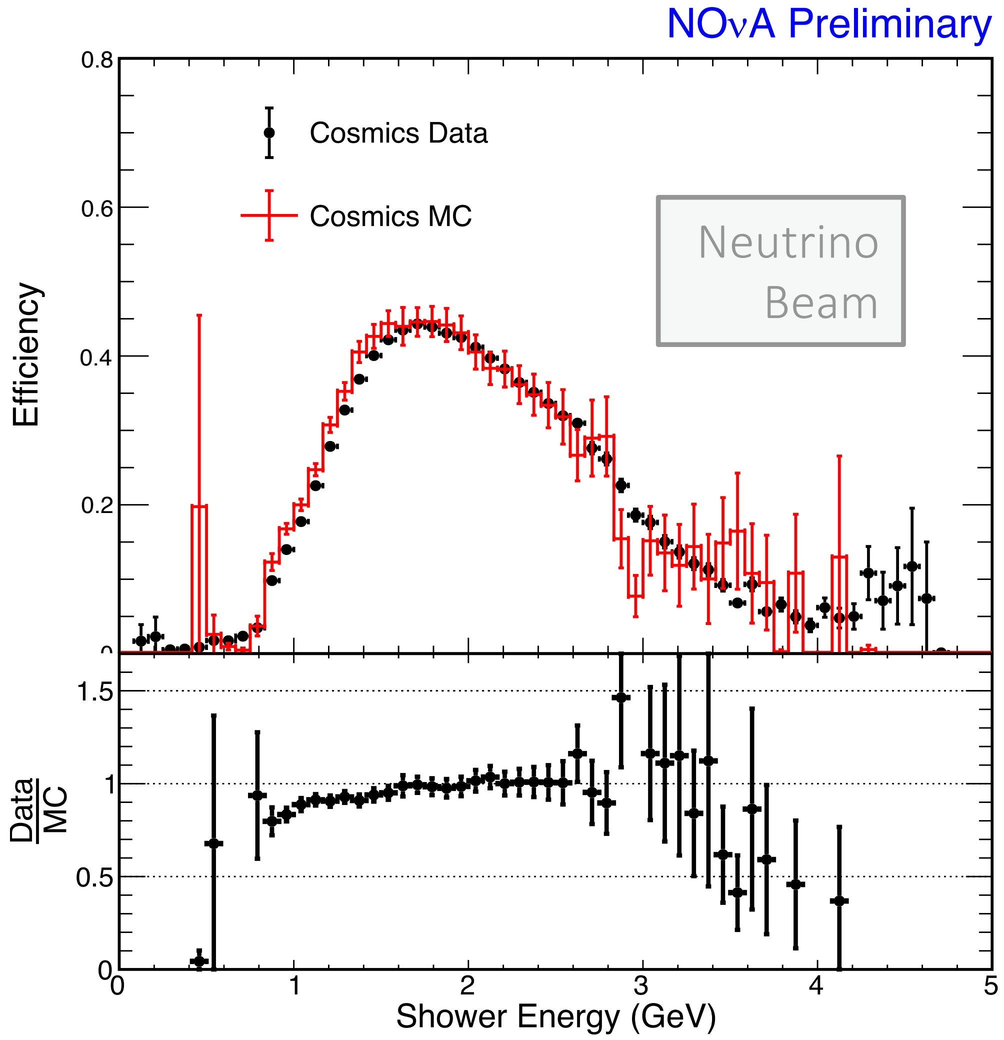




Cross-checks: Muon-removed from bremsstrahlung



- Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector.
- Efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.



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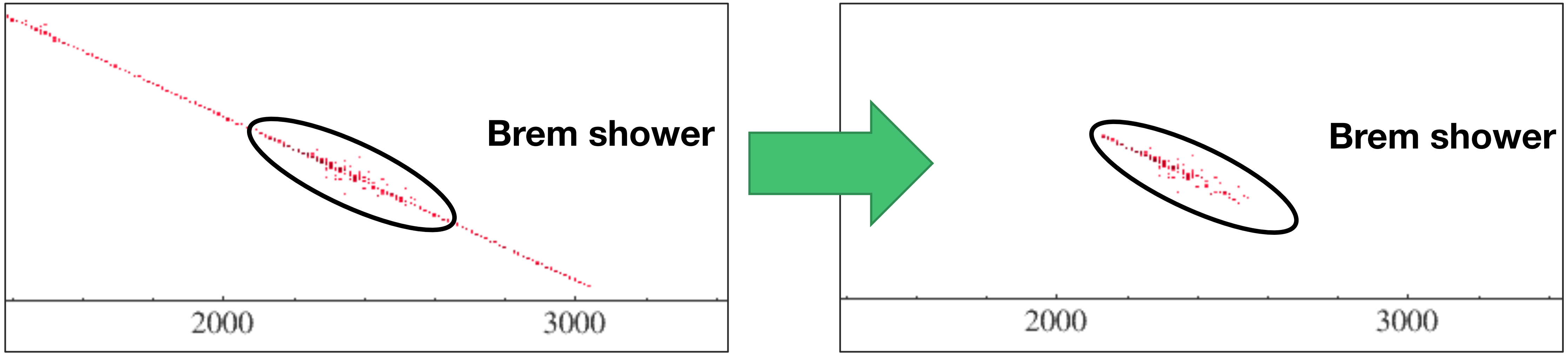

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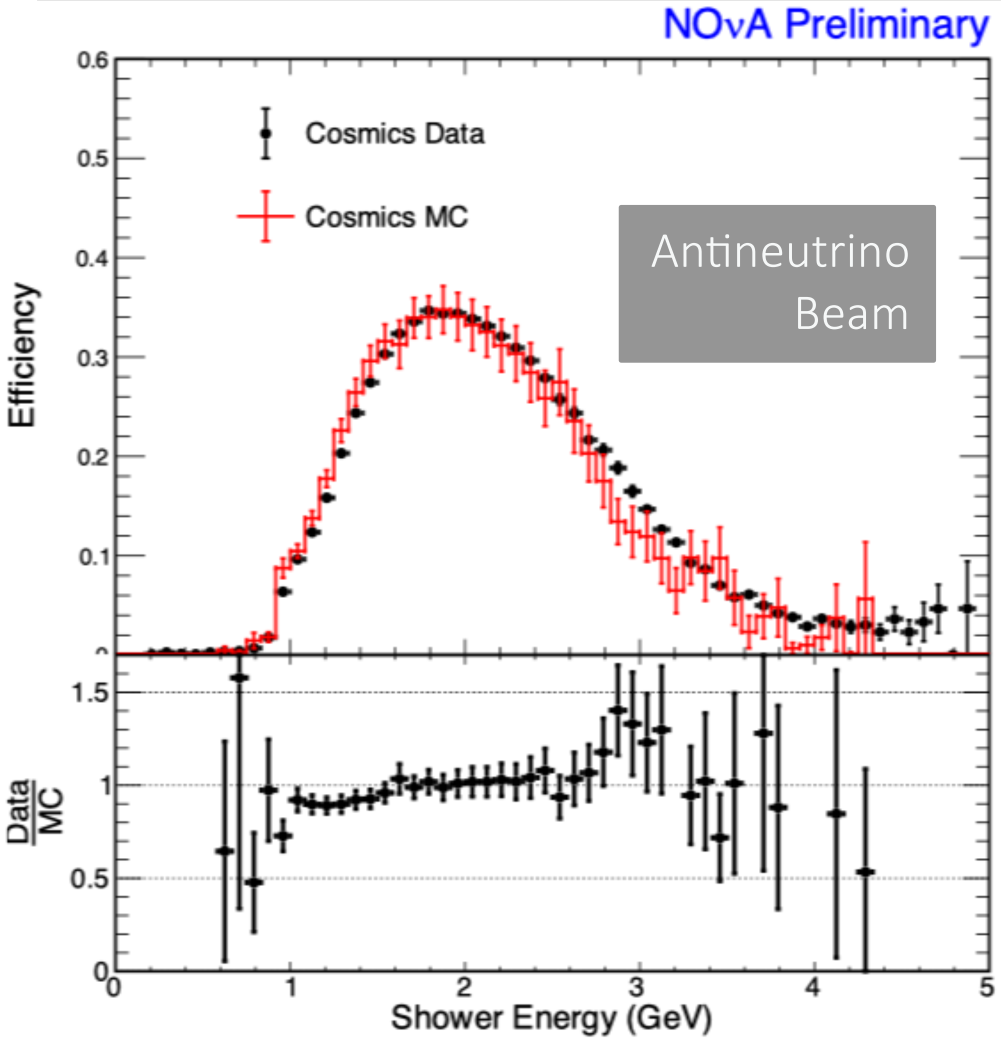
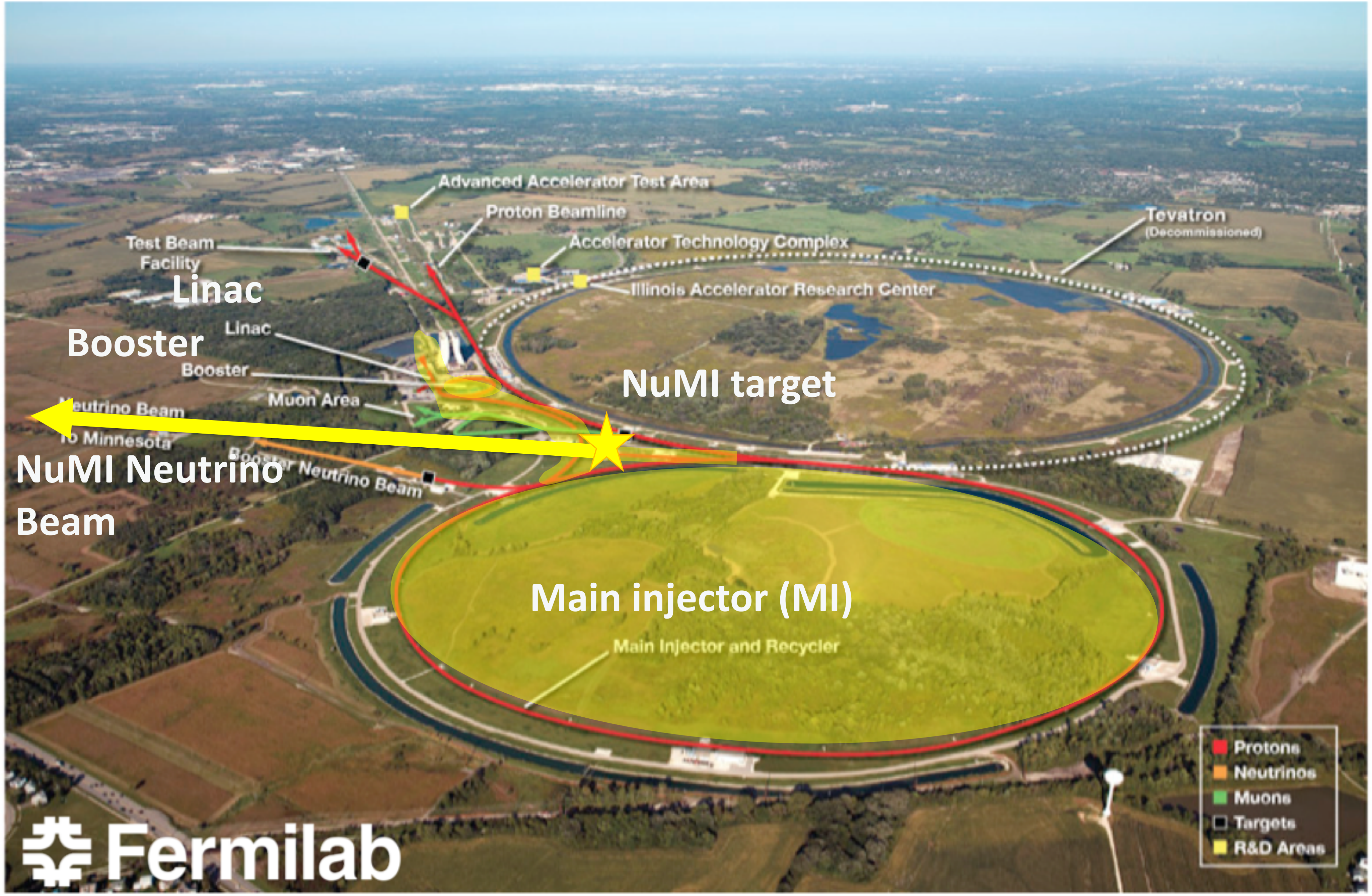


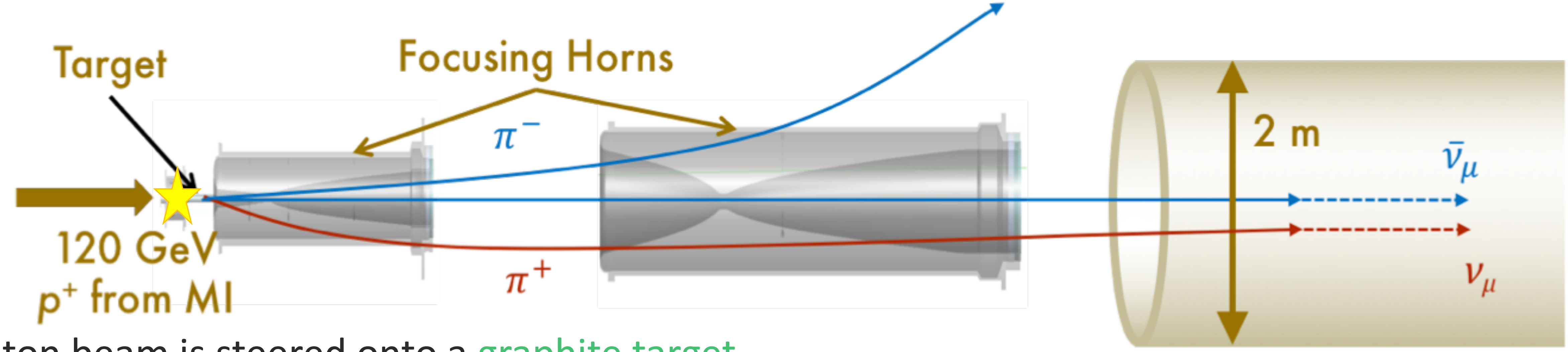
NuMI muon neutrino beam



- NuMI: neutrinos from the Main Injector
- Part of Fermilab's accelerator complex

- Linac: H- ions, 400 MeV
- Booster: protons, 8 GeV
- Main Injector: protons, 120 GeV
- These protons are used to make the NuMI beam

NuMI muon neutrino beam



- MI proton beam is steered onto a graphite target
- Produced hadrons are focused in and charge-sign-selected by two magnetic horns
- 675 m decay pipe
- Predominantly pions and kaons, decay modes:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad K^+ \rightarrow \mu^+ + \nu_\mu \quad \Longrightarrow \boldsymbol{\nu_\mu} \text{ beam}$$

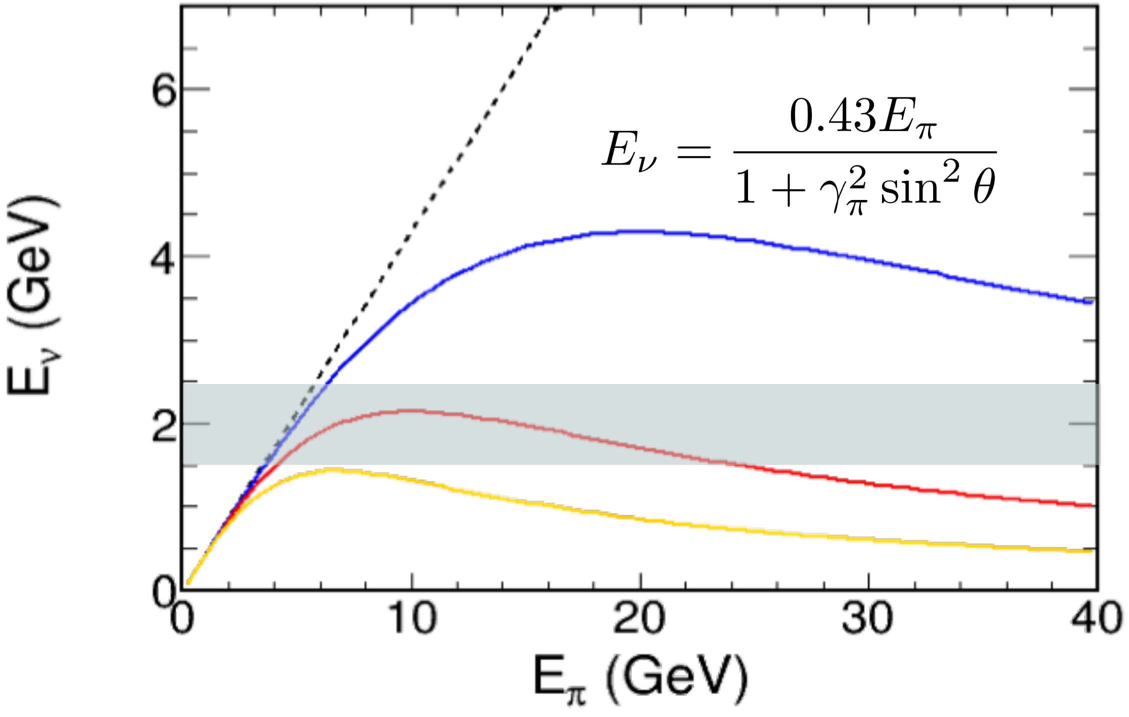
- Small contamination: $\nu_e, \overline{\nu}$
- Reverse the horn current $\Longrightarrow \boldsymbol{\overline{\nu}_\mu}$ beam

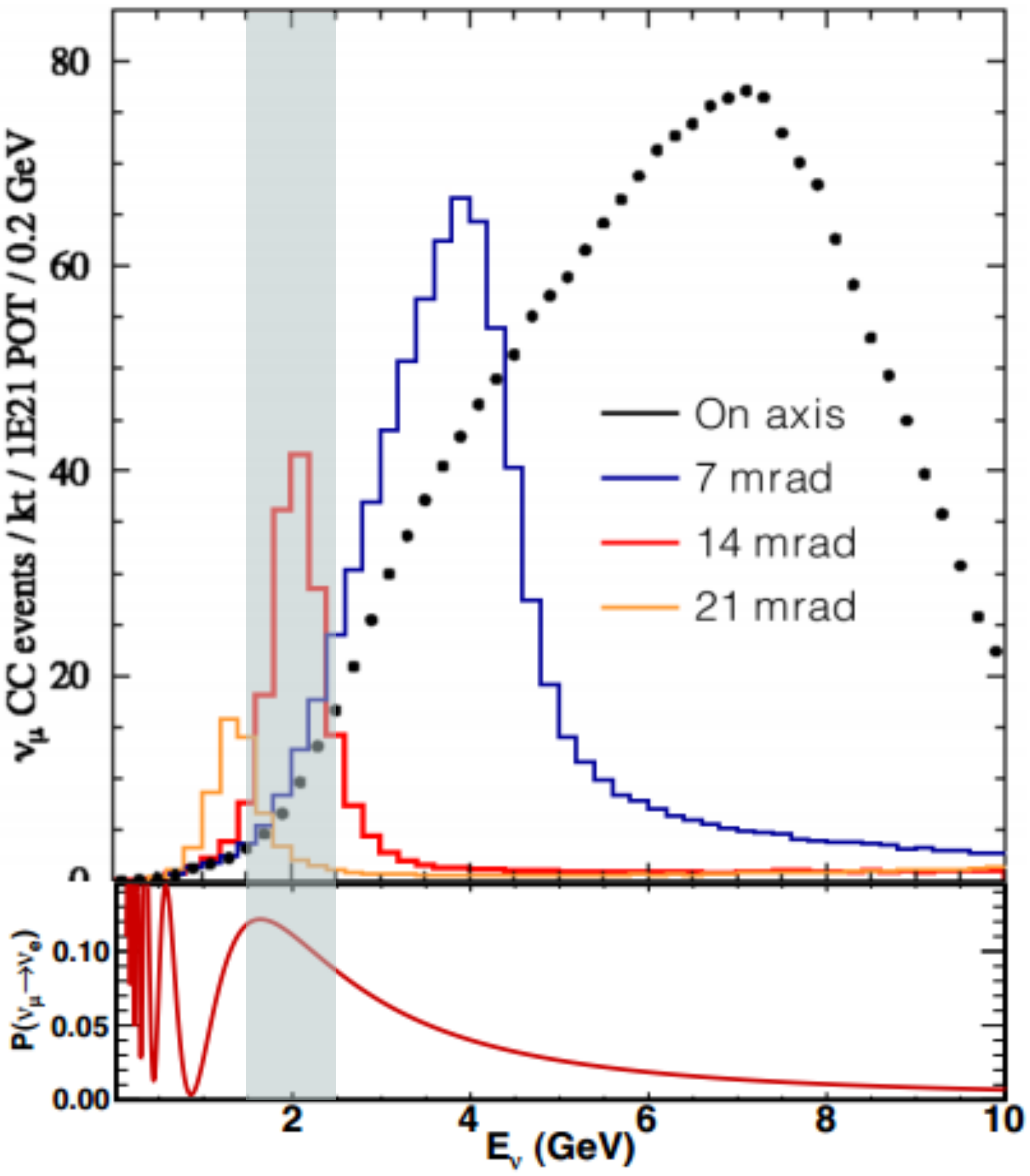
Components	
ν_μ	97.5%
anti-ν_μ	1.8%
ν_e	0.7%

Aside: we use Protons on Target (POT) as the units of neutrino beam intensity

NuMI off-axis

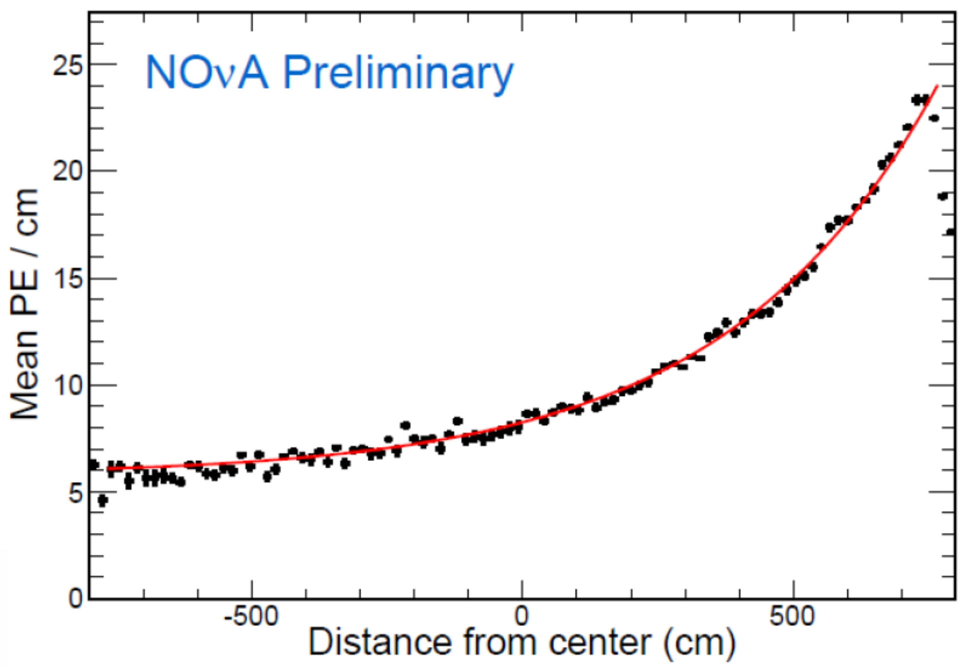
- FD located 14 mrad off-axis angle
  - 2-body π decay gives narrow range of ν energies
- Tune peak energy for oscillations
  - More events at max oscillations
  - Fewer backgrounds.



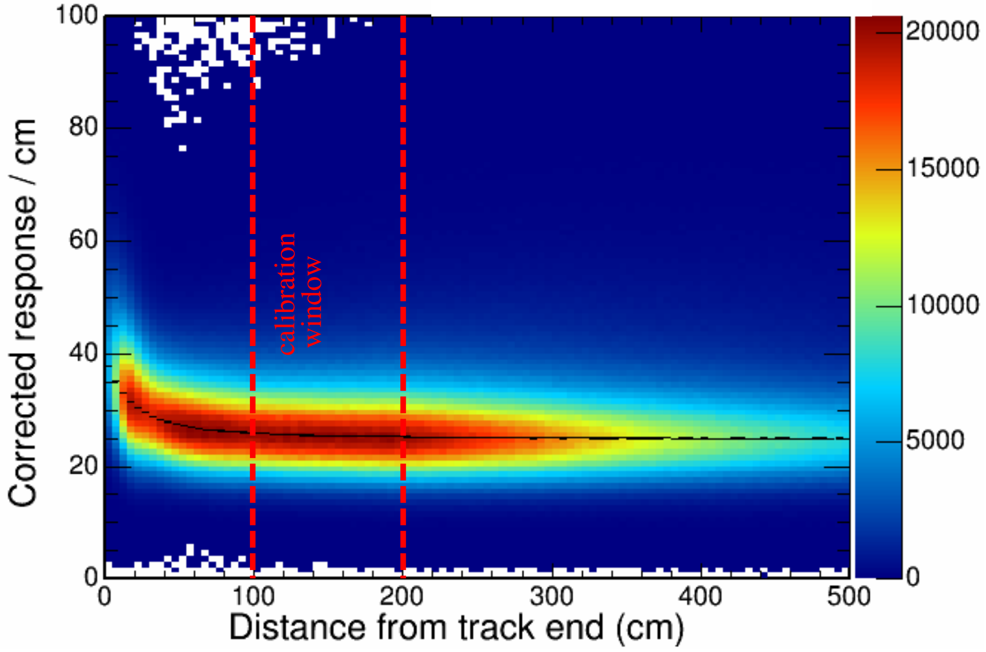


Calibration

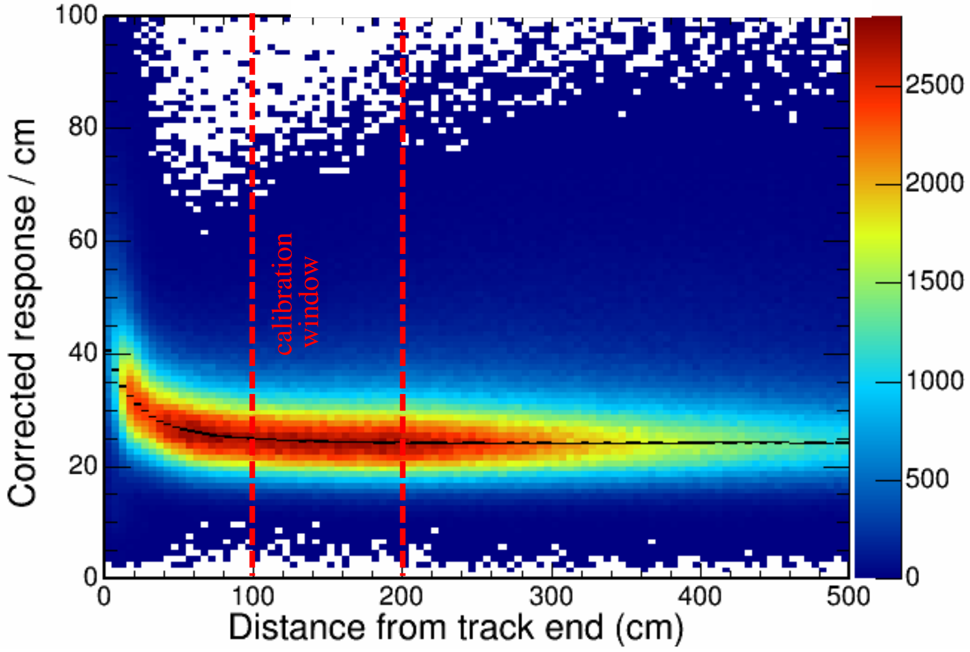
- Largest effect that needs correction is attenuation in the WLS fibre.
- Stopping cosmic muons provide a standard candle for setting absolute energy scale.


FD cosmic data - plane 84 (horizontal), cell 12

Far Detector Data



Far Detector Simulation



$\nu_\mu \to \nu_e$ oscillations

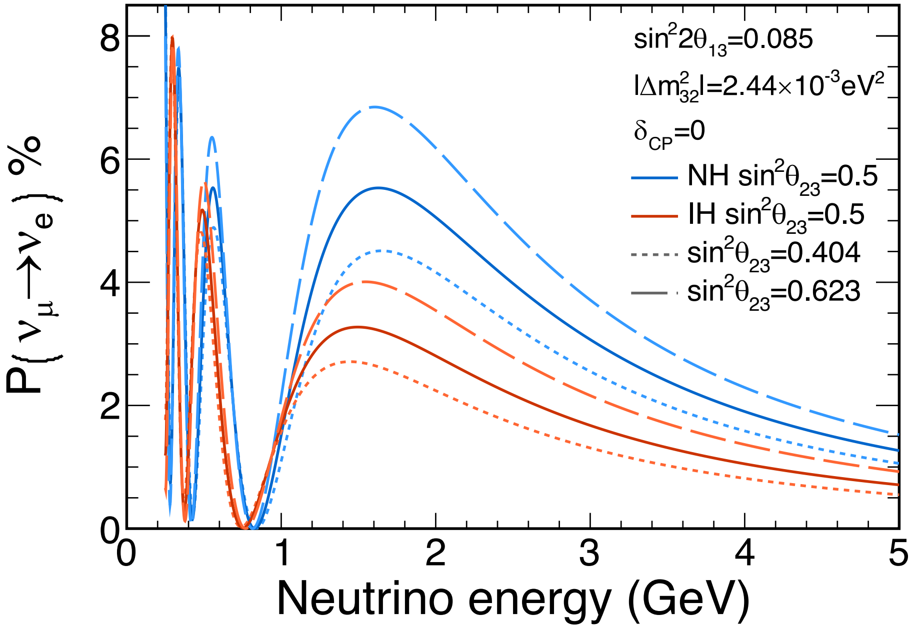
$$A \equiv \frac{G_f n_e L}{\sqrt{2}\Delta} \approx \frac{E}{11\text{GeV}}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

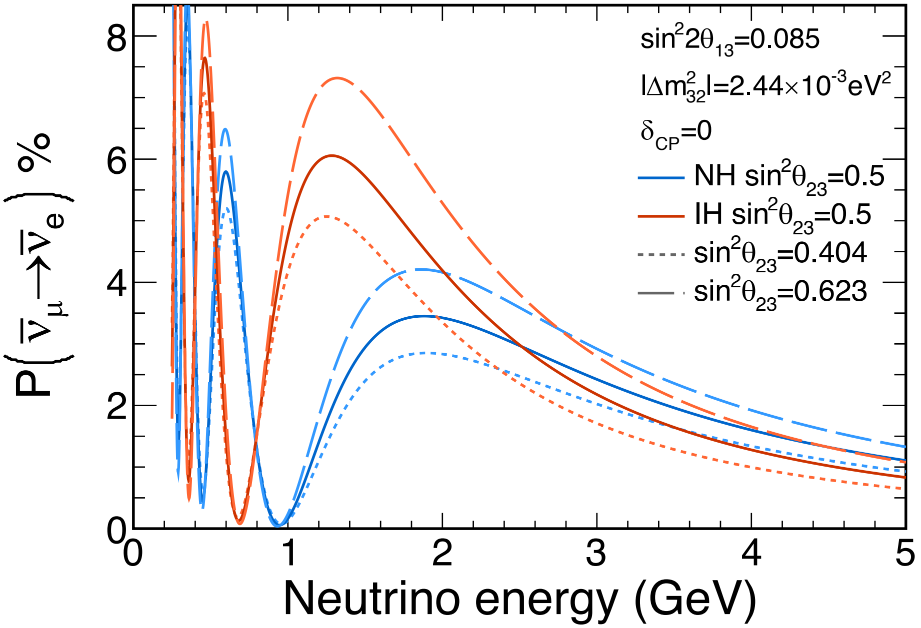
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad + 2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad - 2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

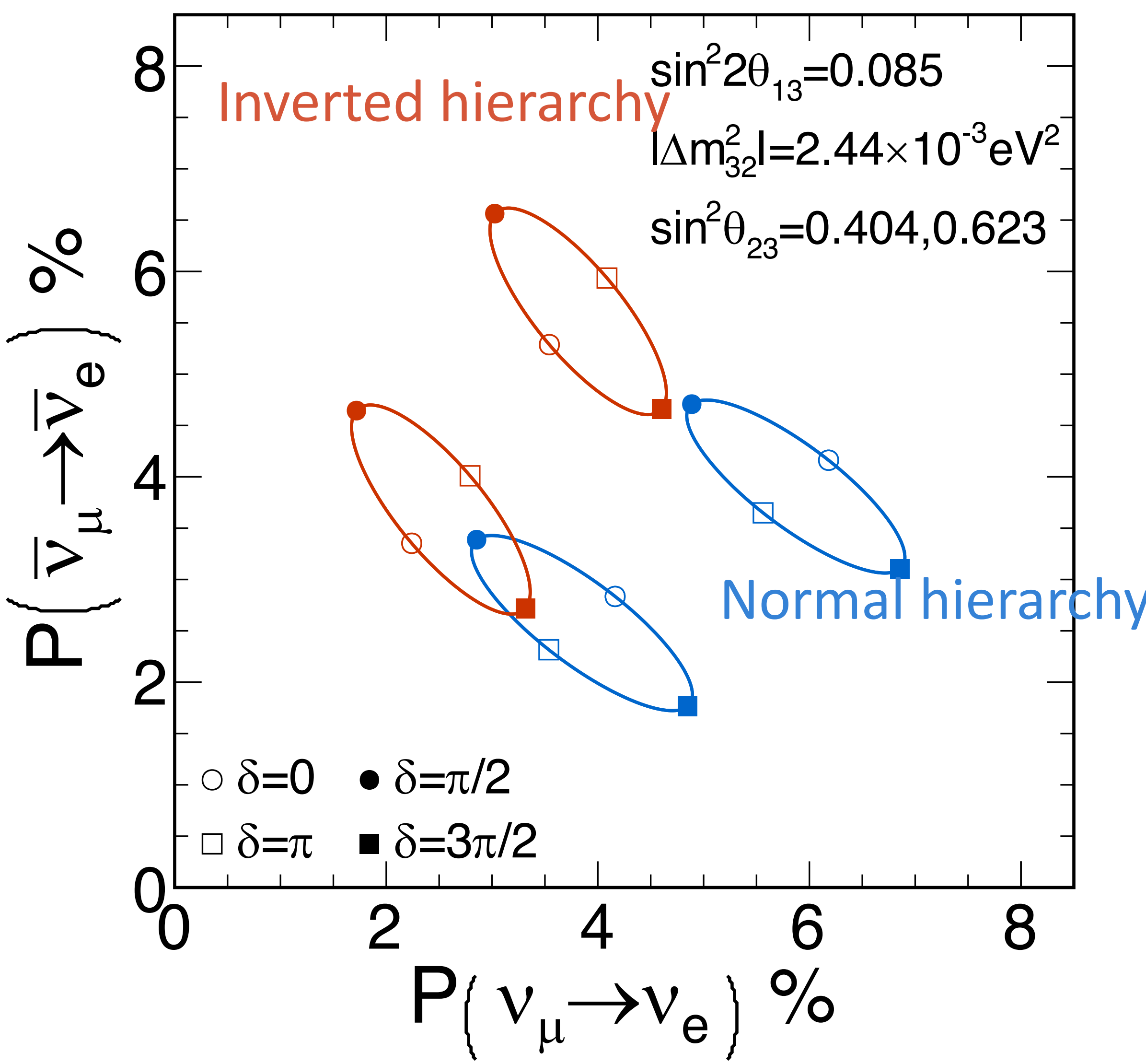
NOvA: L=810 km



NOvA: L=810 km



NOvA: L=810 km, E=2.0 GeV

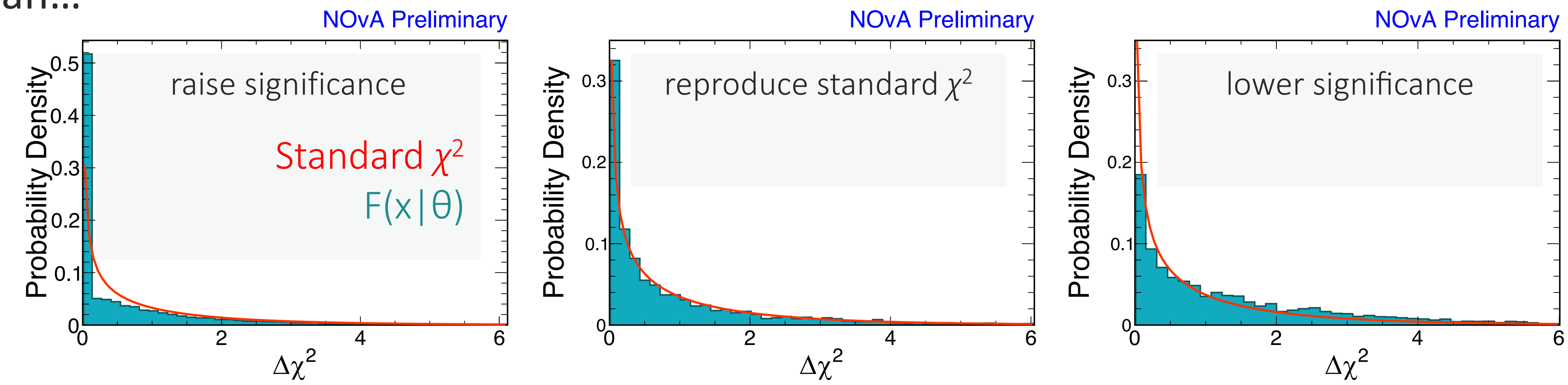


Statistical Approach: Feldman-Cousins

- Replace the standard χ^2 with an empirical distribution, $F(x|\vartheta)$:

$F(x|\vartheta)$ = Fraction of N experiments where [χ^2(fixed ϑ) - χ^2(best fit) = x]

- Pseudo-experiments are generated from the data profile at ϑ.
  - i.e. fit all other parameters to data holding ϑ fixed at a particular value.
  - This procedure gives proper coverage while minimizing over-coverage.*
- A point ϑ is inside the (1-α) confidence interval if less than (1-α) experiments are more extreme than the data.
  - i.e. if the integral of $F(x|\vartheta)$ up to the observed $\Delta\chi^2$ at ϑ is < (1-α).
- $F(x|\vartheta)$ can...



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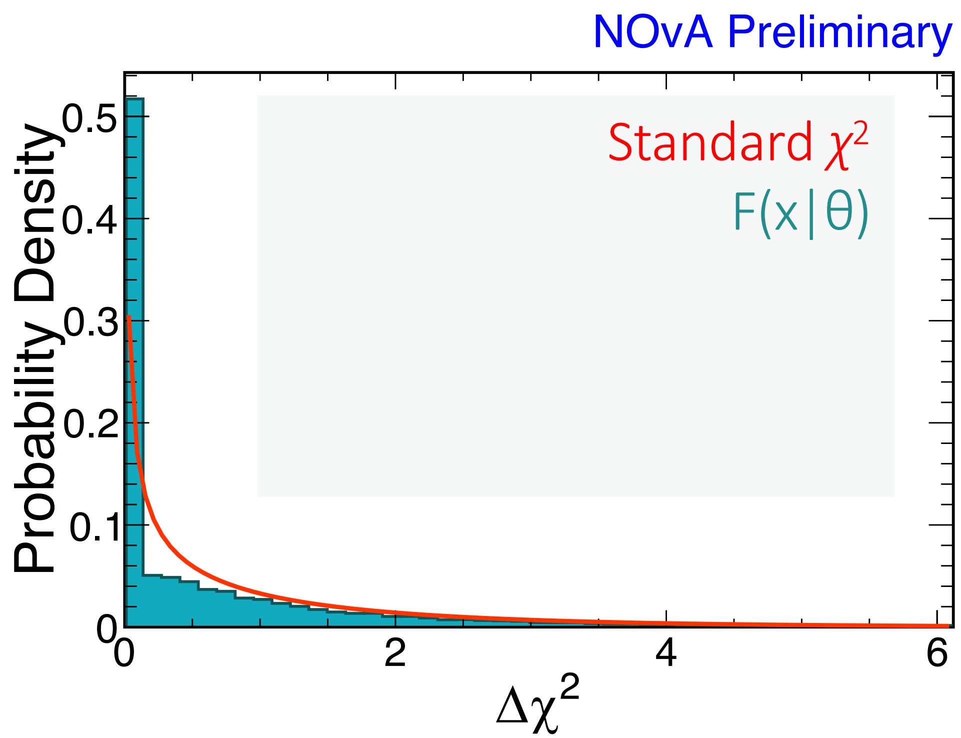
* Test coverage using method from: R. L. Berger and D. D. Boos, J. Amer. Statist. Assoc., 89, 1012 (1994)

FC for Mass Hierarchy

- Note: deciding if any individual point ϑ_0 is outside a CI is equivalent to a hypothesis test where H_0 is $\vartheta = \vartheta_0$.
  - The same technique applies to this mass hierarchy hypothesis test.
- Since our best fit is in the NH, we want to know how strongly we reject the IH.
  - So H_0 is IH and we generate pseudo-experiments at our best fit in the IH.
  - Follow the FC procedure with:

$$\chi^2(\text{fixed } \vartheta) - \chi^2(\text{best fit}) \rightarrow \chi^2(\text{IH}) - \chi^2\,(\text{best fit})$$

  - If an experiment has a best fit in the IH, then the difference is 0.
  - This pile-up at 0 behaves like a physical boundary: it increases significance.



Limiting Case: No sensitivity

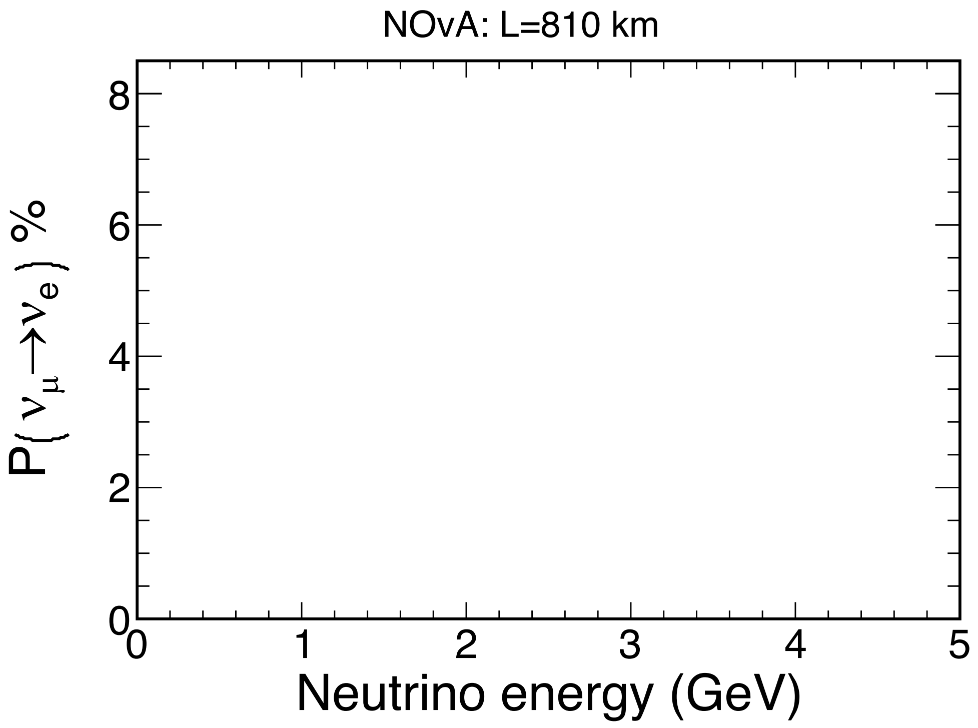
- Half of experiments in each hierarchy and $\Delta\chi^2 = 0$
- $p = 0.5$
- 50% for either NH or IH
- All "prior"

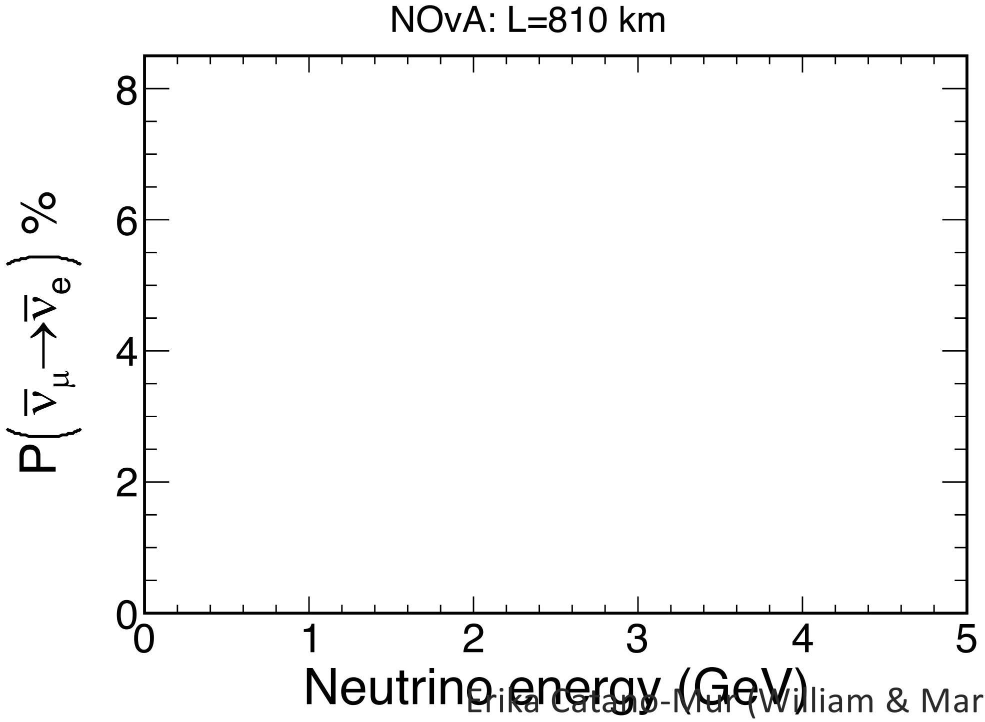
Probability & biprobability

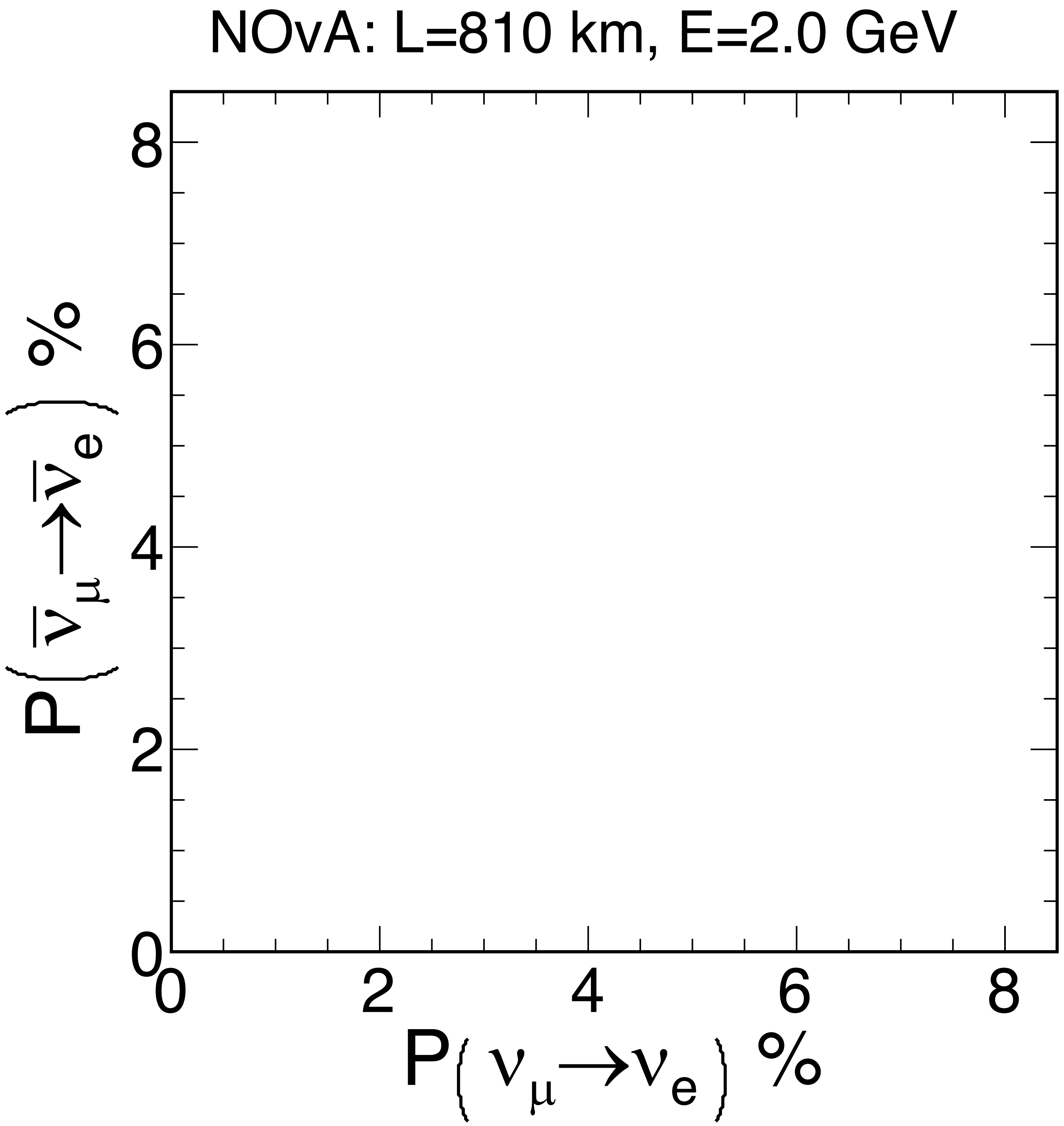
Electron neutrino appearance

"Electron neutrino appearance":
3-flavor oscillations

$\nu_\mu \rightarrow \nu_e$
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



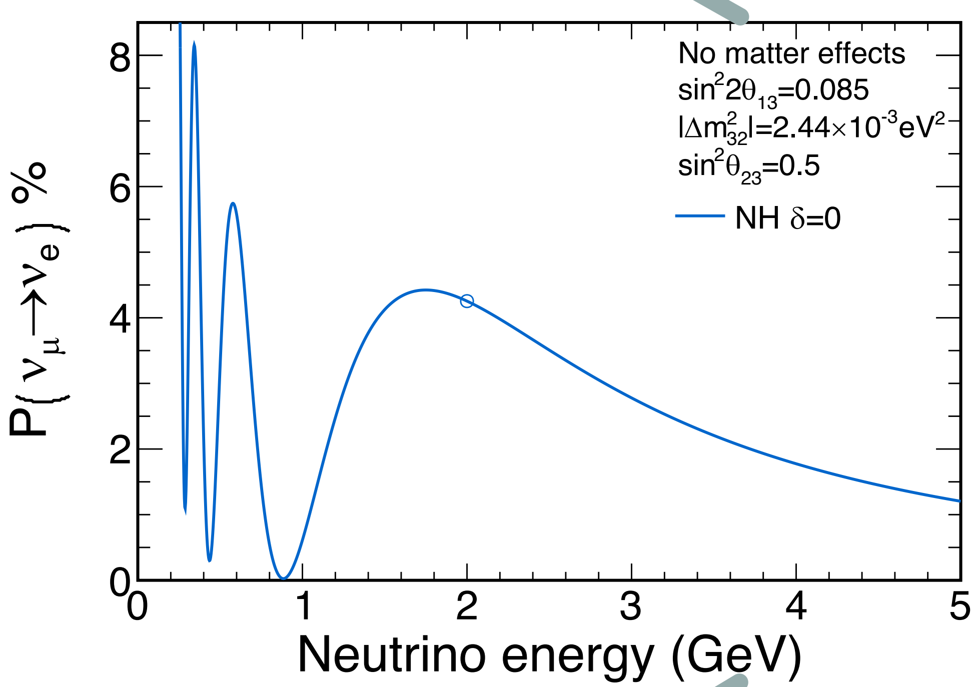


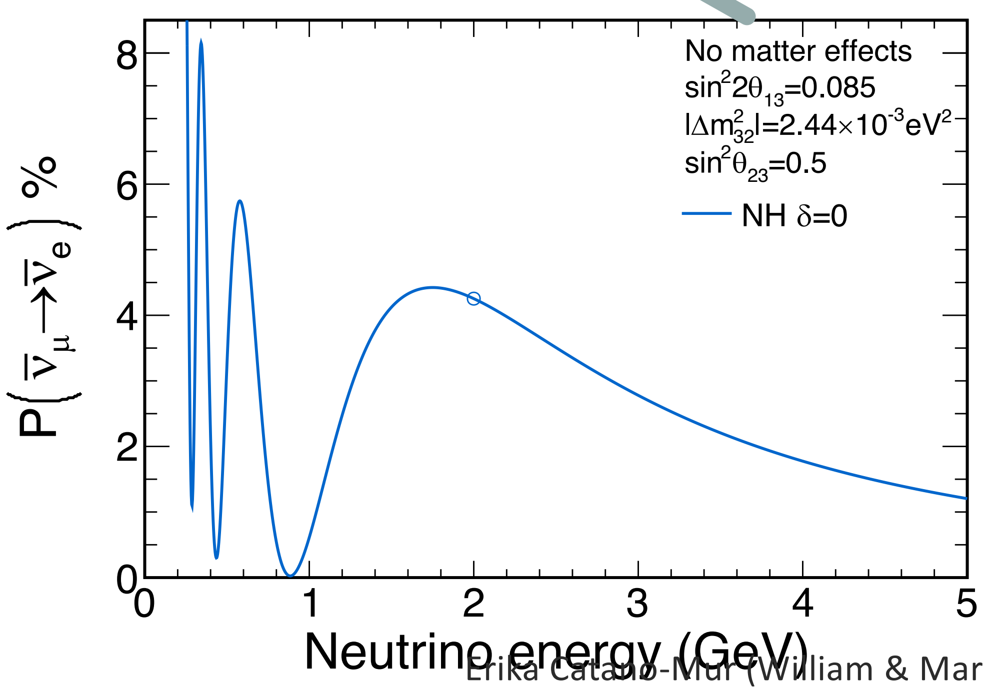


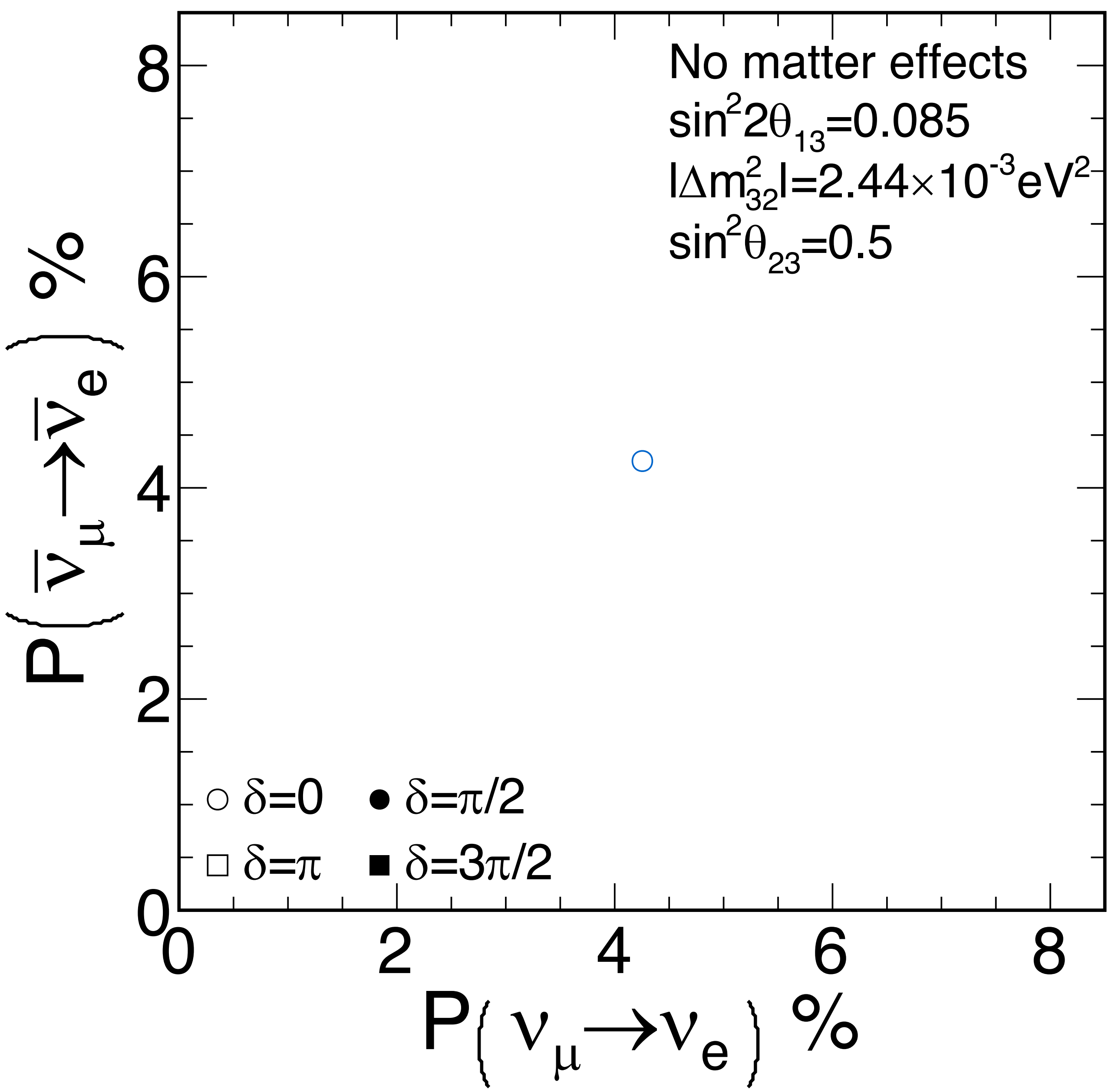
Electron neutrino appearance

Oscillation probabilities depend on:

- Source-detector distance (L)
- Neutrino energy (E_ν)
- parameters ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)
- Mass squared differences (Δm^2_{21}, $|\Delta m^2_{32}|$)
- Neutrino mass hierarchy (sign(Δm^2_{32}))


NOvA: L=810 km

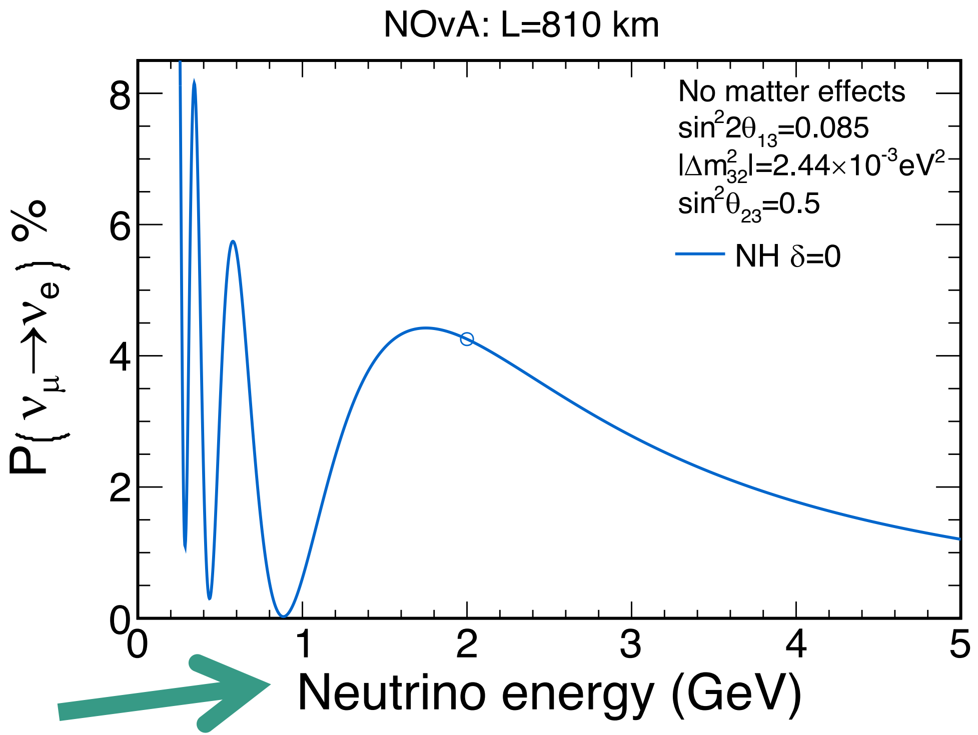

NOvA: L=810 km

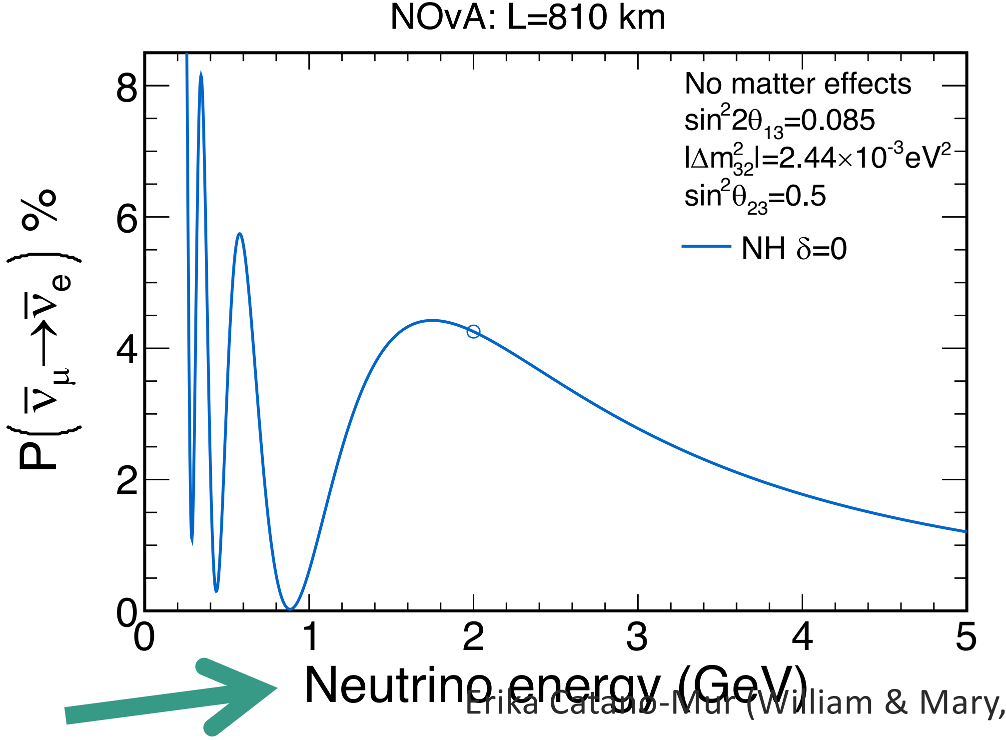

NOvA: L=810 km, E=2.0 GeV

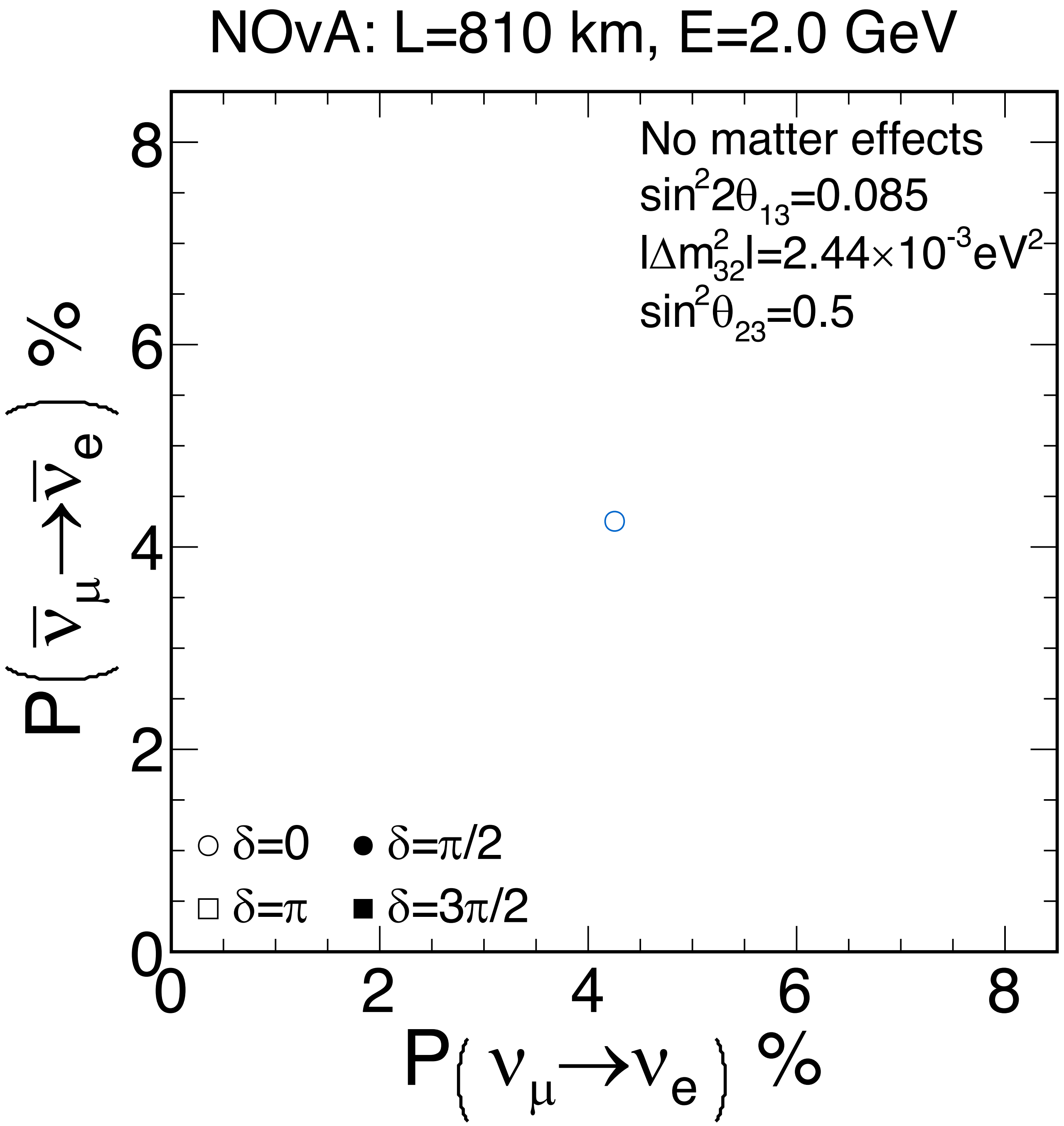
Electron neutrino appearance

Oscillation probabilities depend on:

- Source-detector distance (L)
- Neutrino energy (E_ν)
- parameters ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)
- Mass squared differences (Δm^2_{21}, $|\Delta m^2_{32}|$)
- Neutrino mass hierarchy ($\mathrm{sign}(\Delta m^2_{32})$)







Electron neutrino appearance

Oscillation probabilities depend on:

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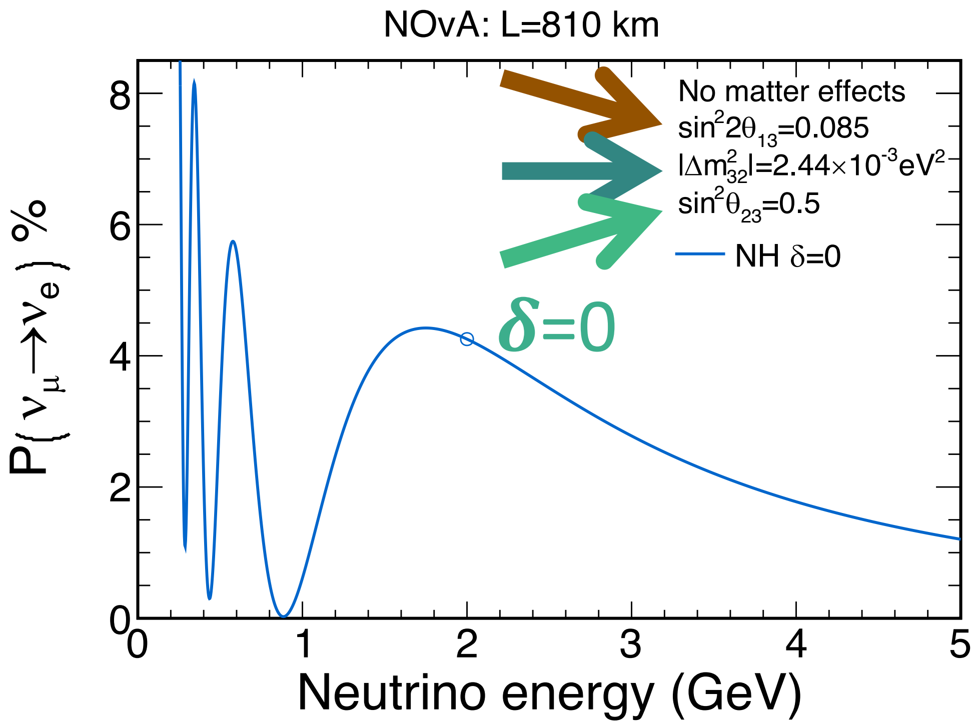
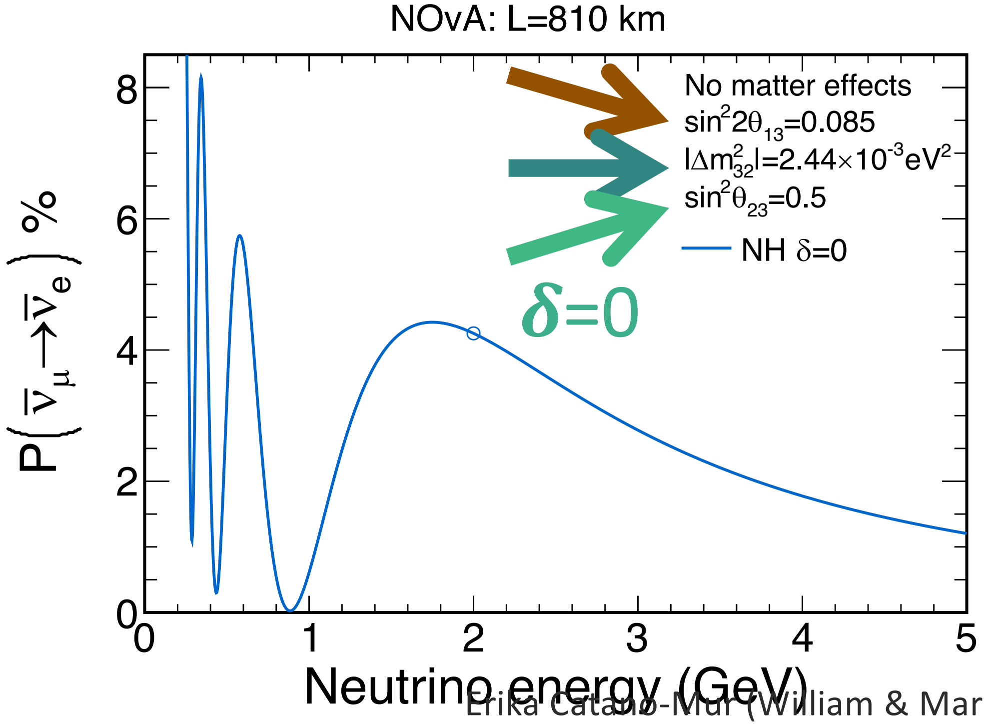
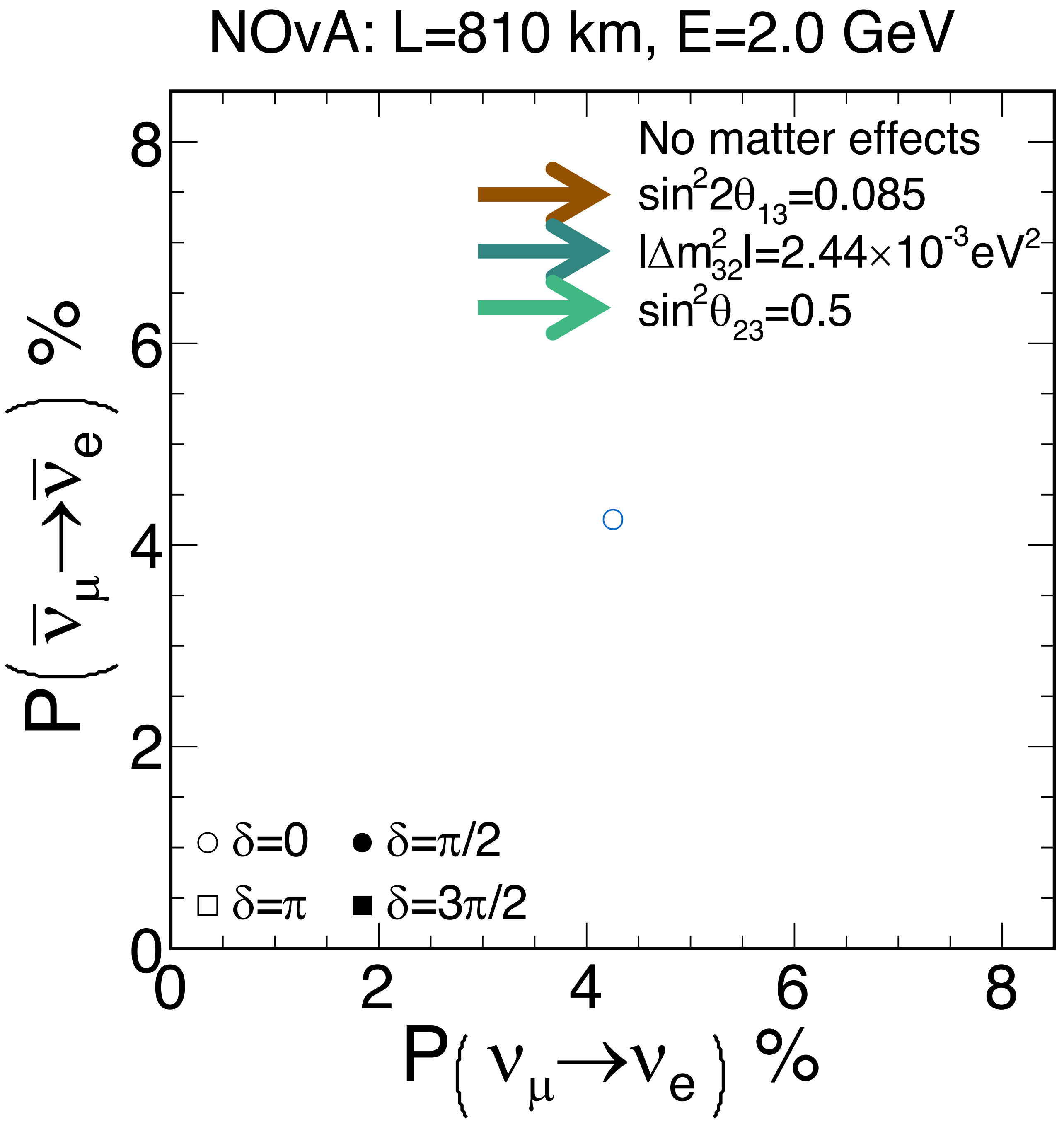
- Neutrino energy (E_ν)
- Osc. parameters ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)
- Mass squared differences ($\Delta m^2_{21}, |\Delta m^2_{32}|$)

Neutrino mass hierarchy ($\mathrm{sign}(\Delta m^2_{32})$)







Electron neutrino appearance

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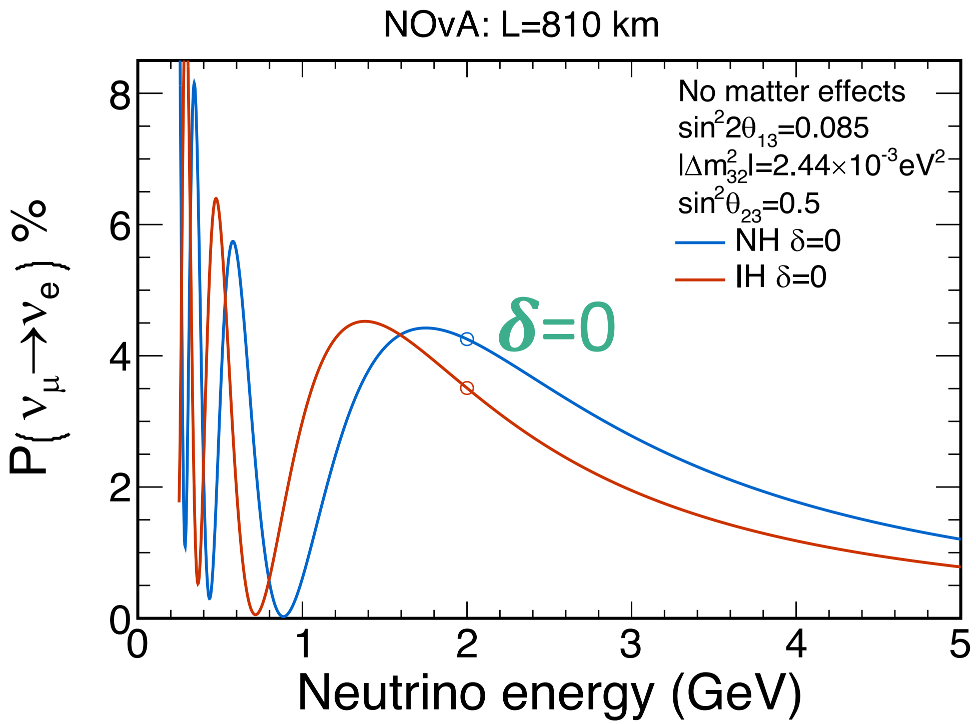
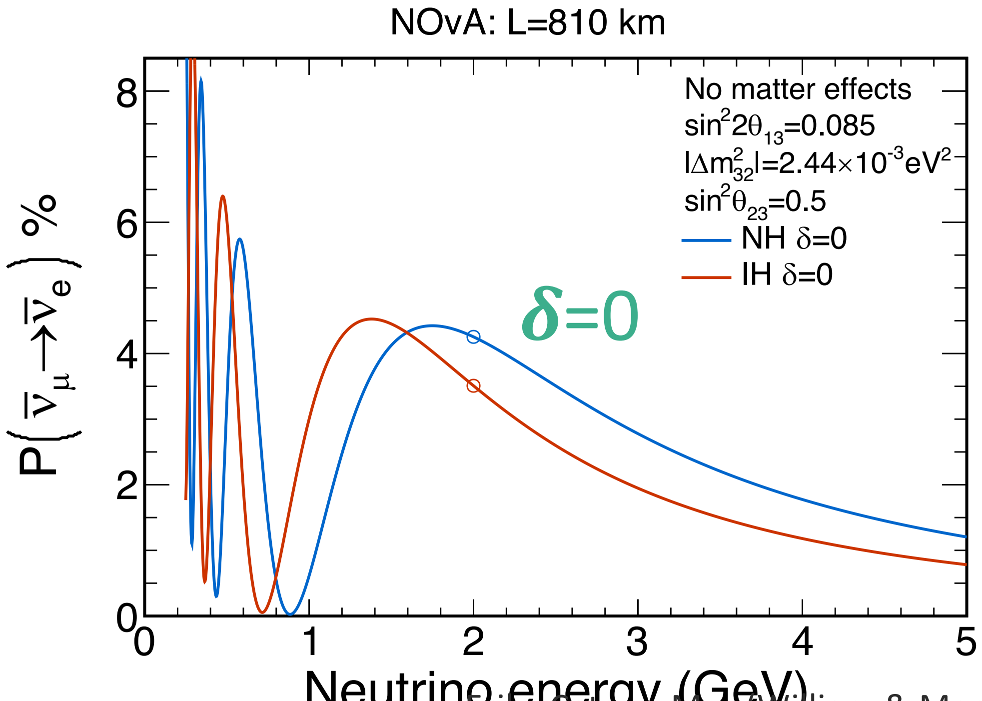
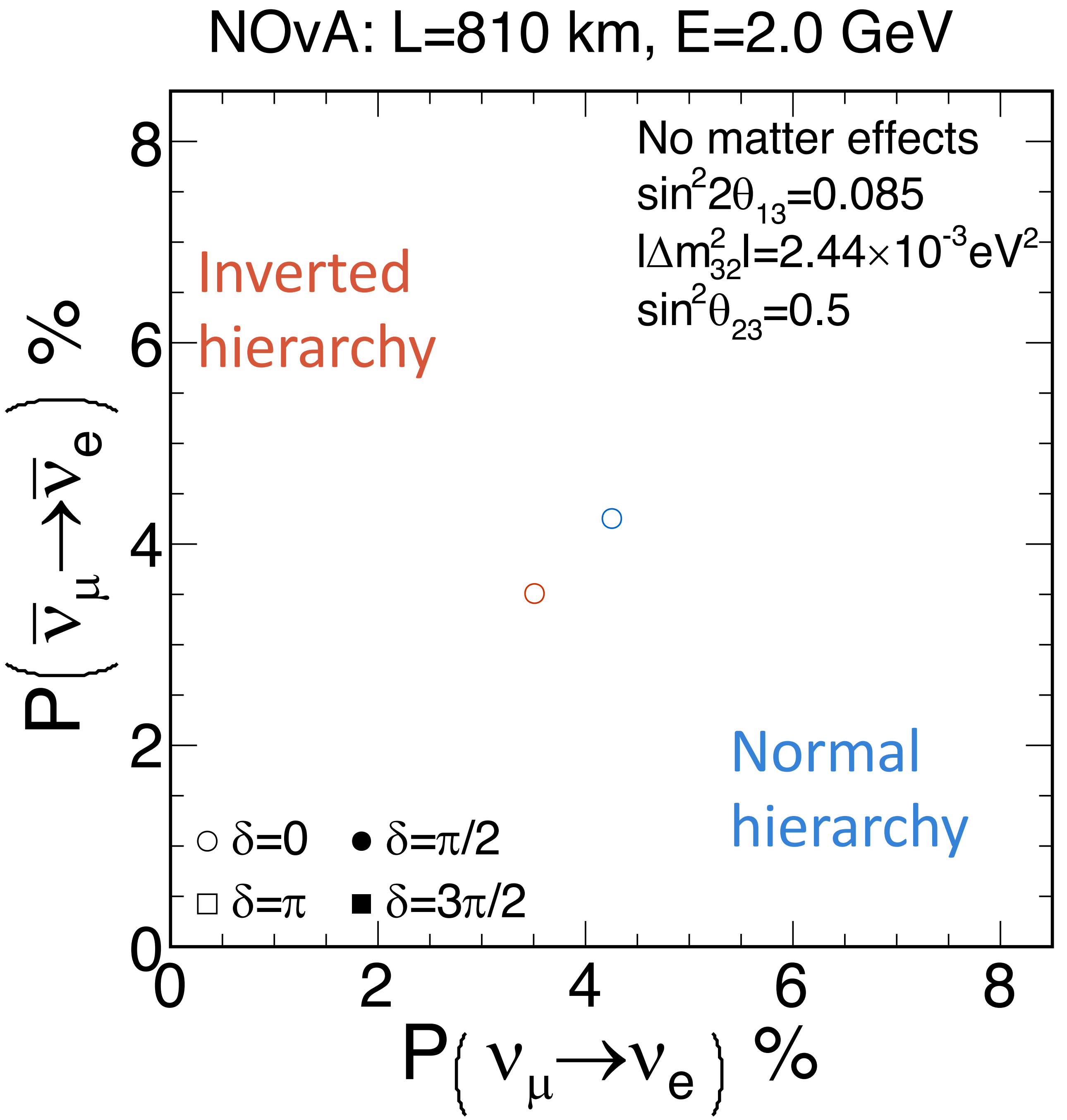
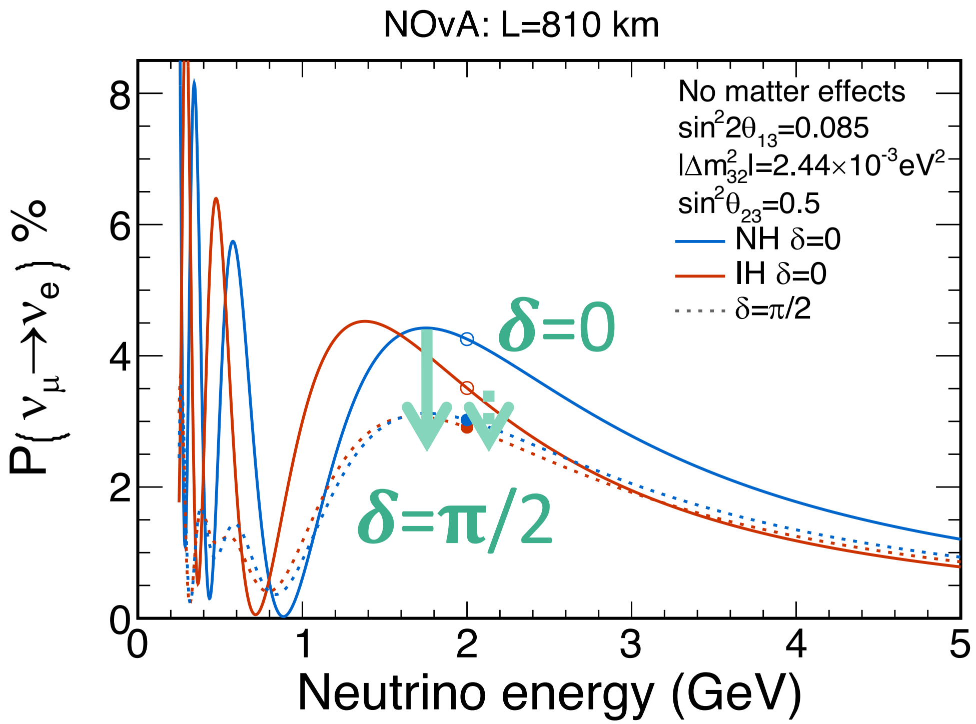

NOvA: L=810 km

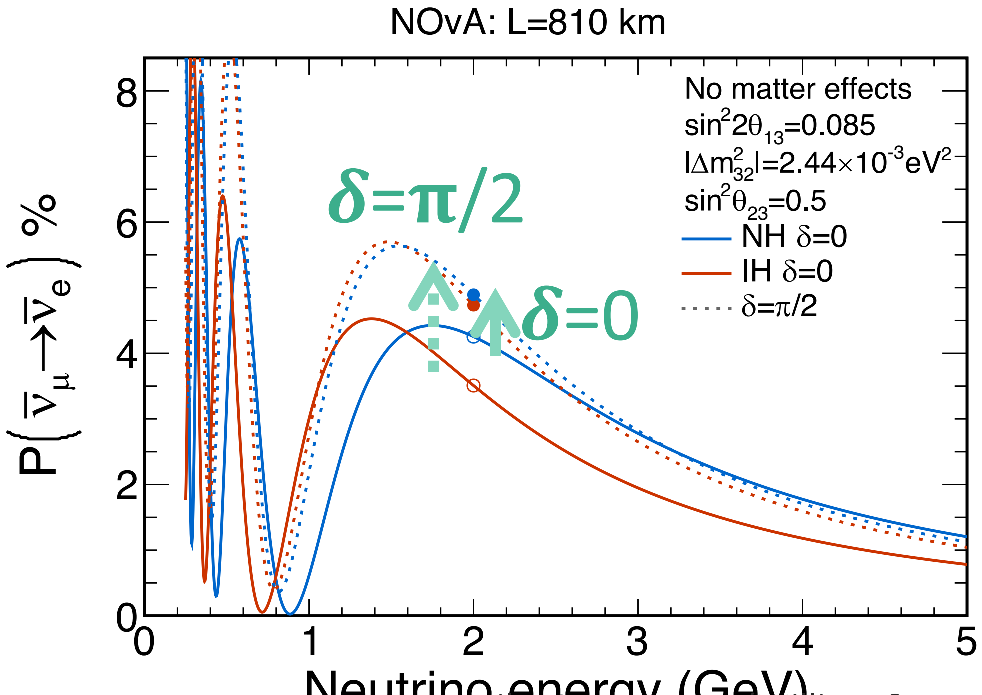

NOvA: L=810 km

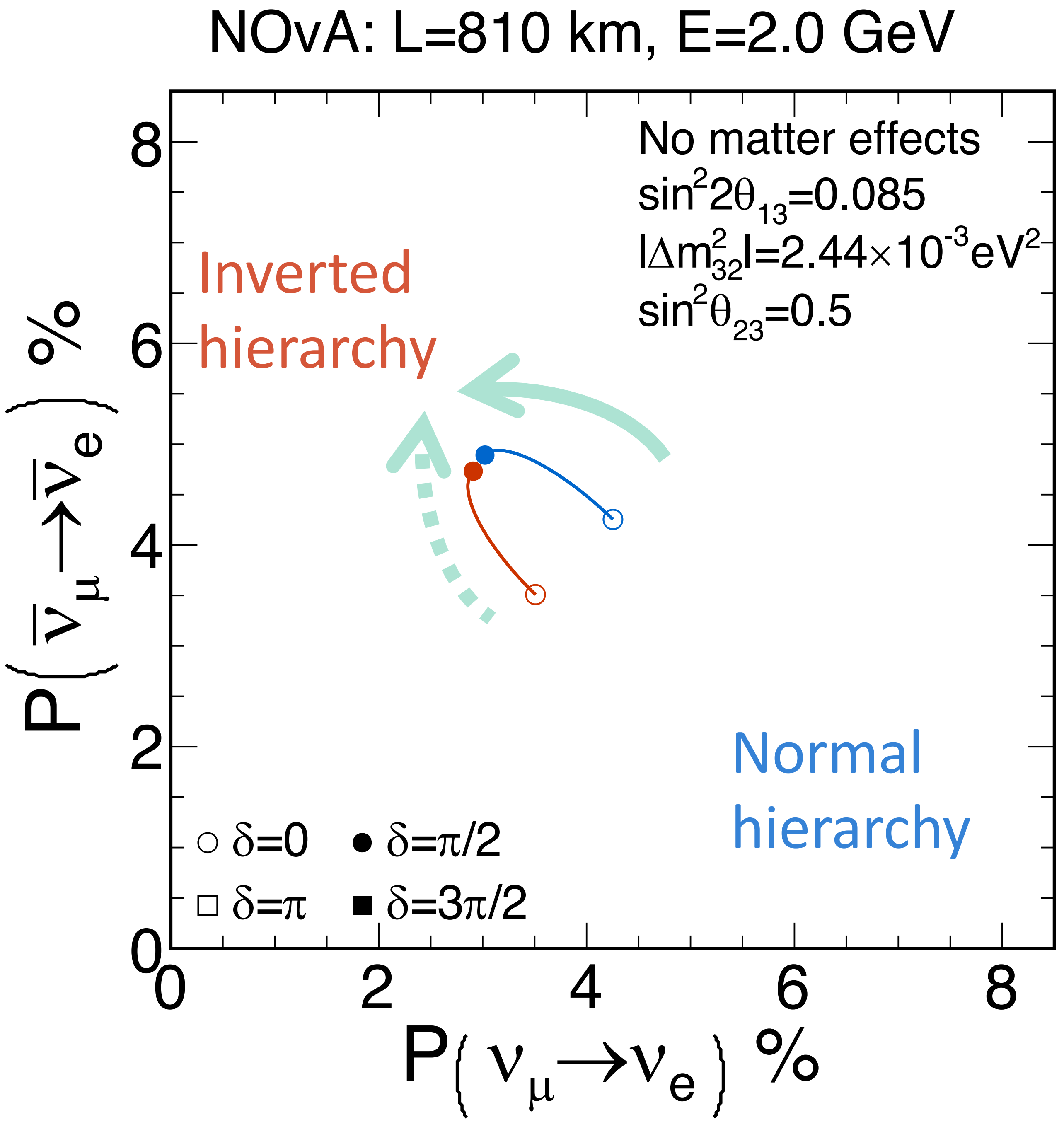

NOvA: L=810 km, E=2.0 GeV

Electron neutrino appearance

- Allowed range for $\delta_{CP} \in [0,2\pi)$
- CP-conservation: $\delta_{CP} = 0, \pi$
- Max. CP violation: $\delta_{CP} = \pi/2, 3\pi/2$







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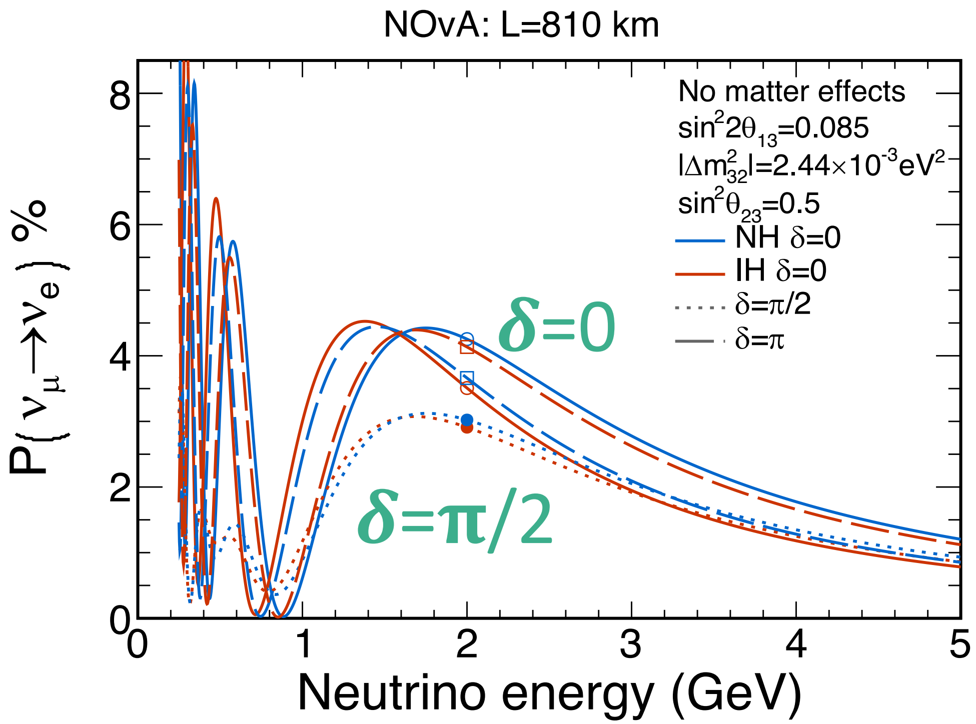

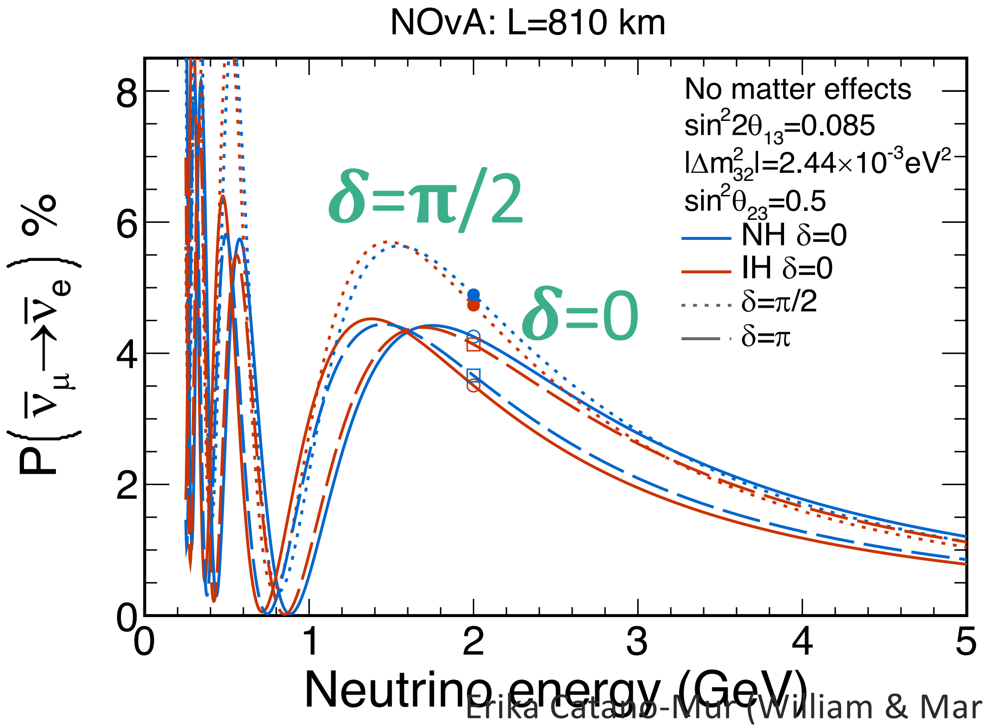

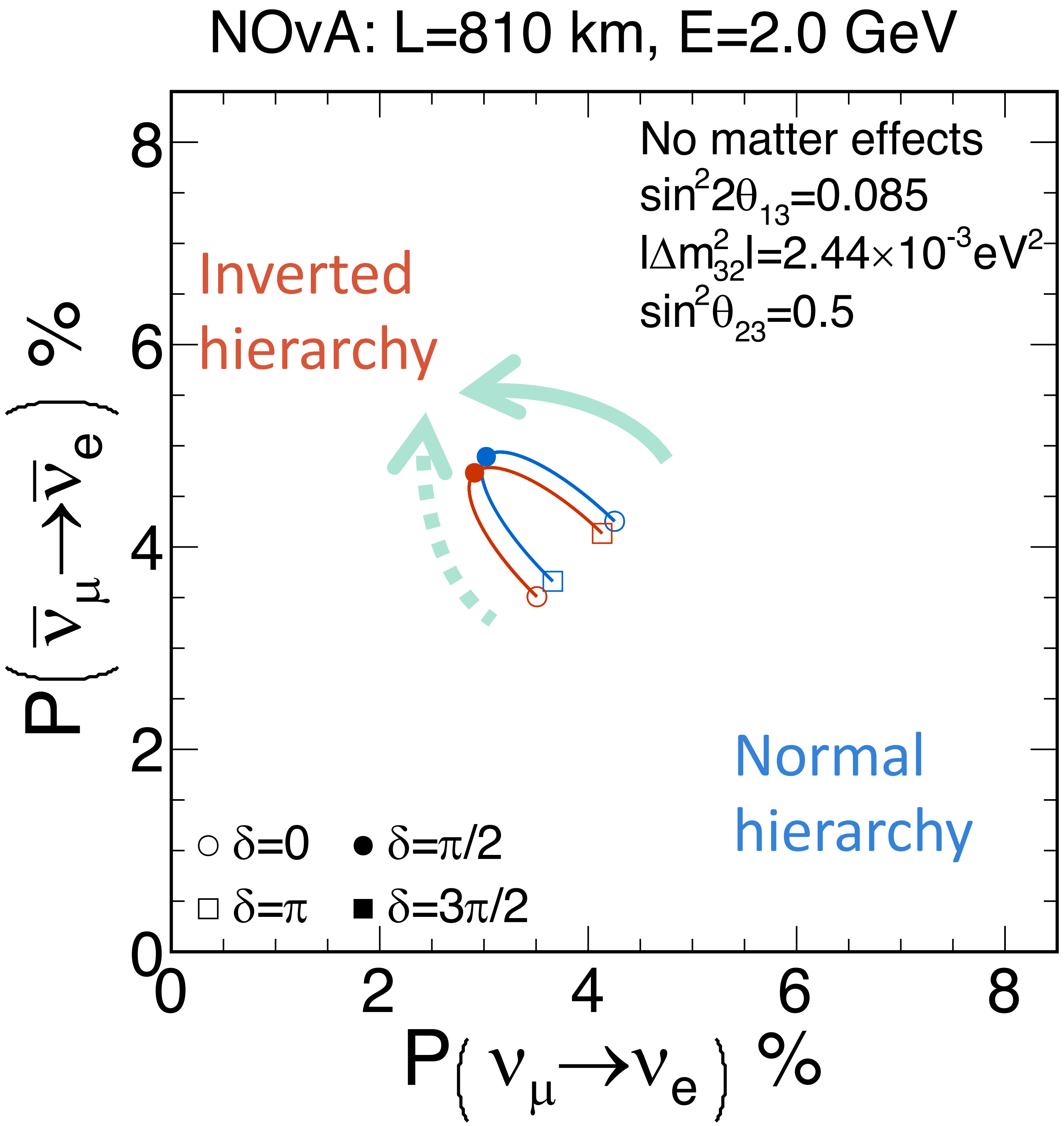

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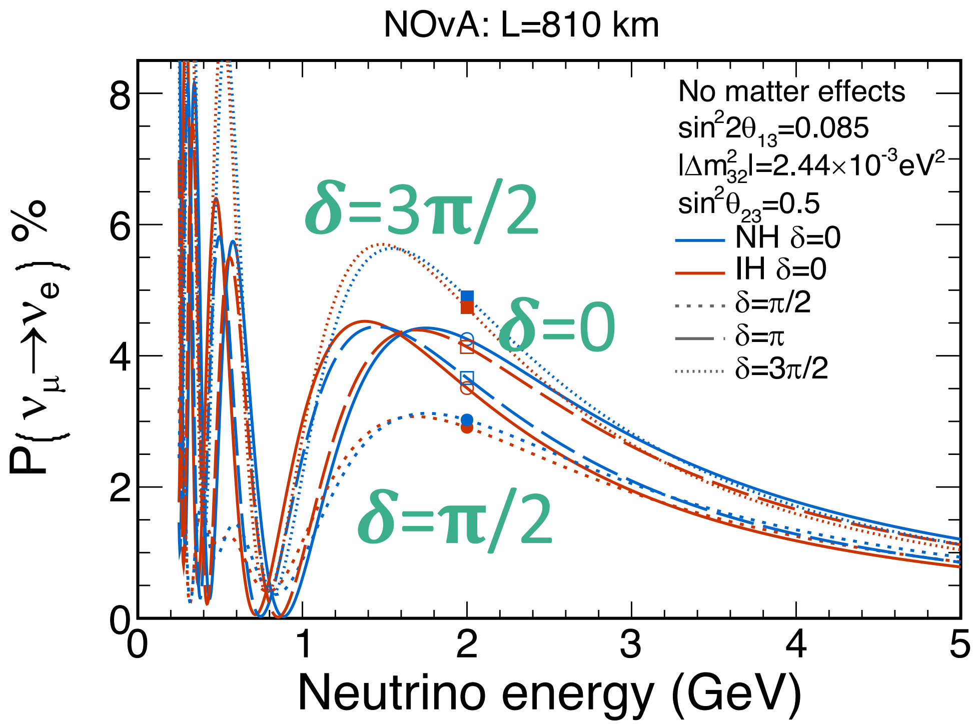
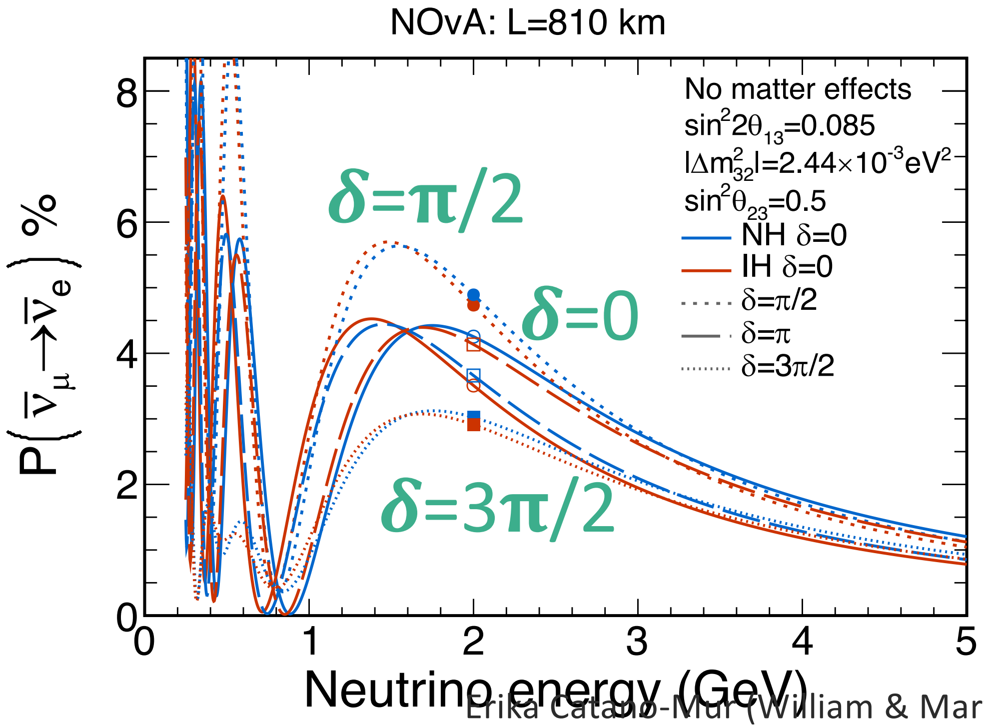
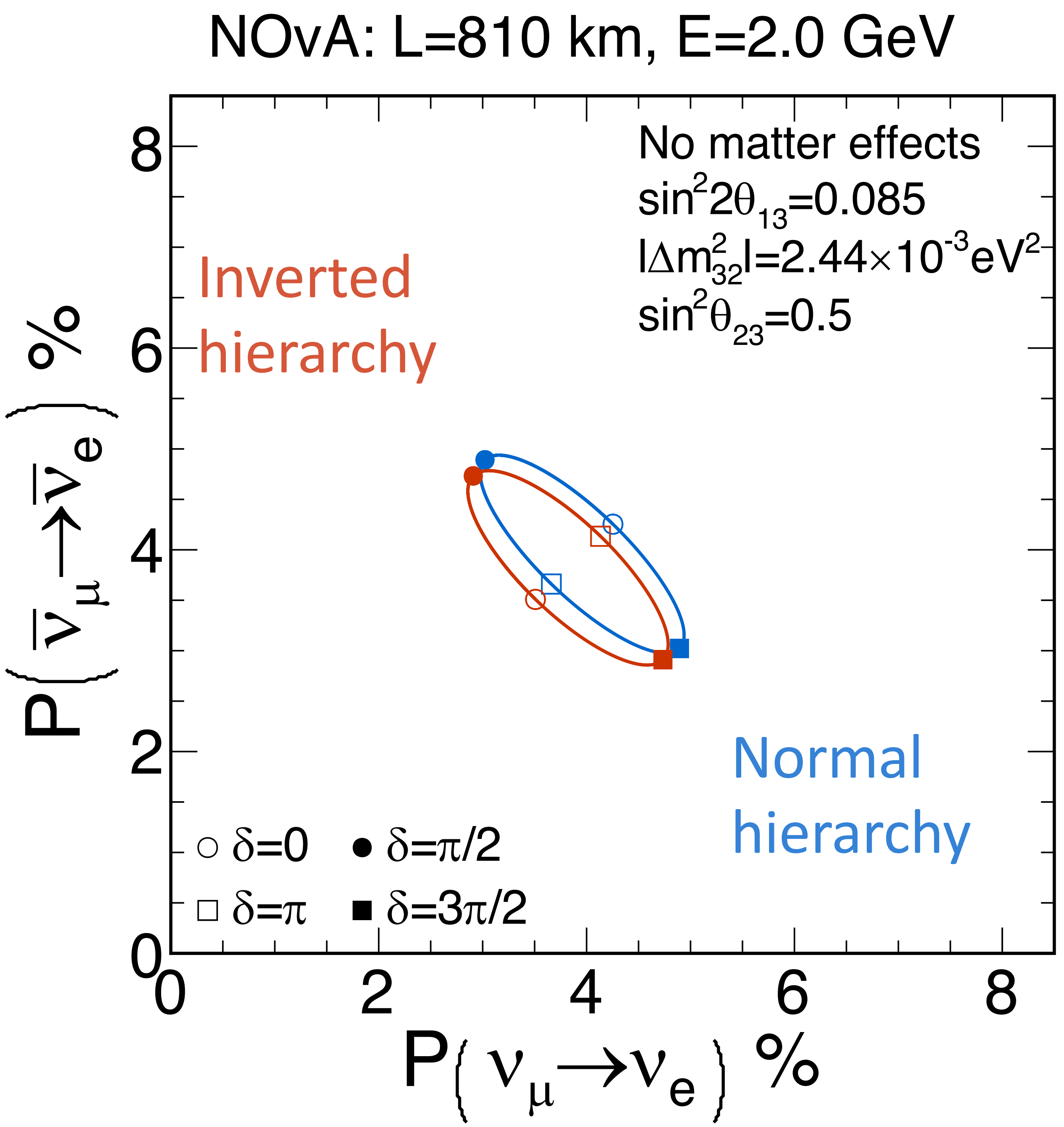
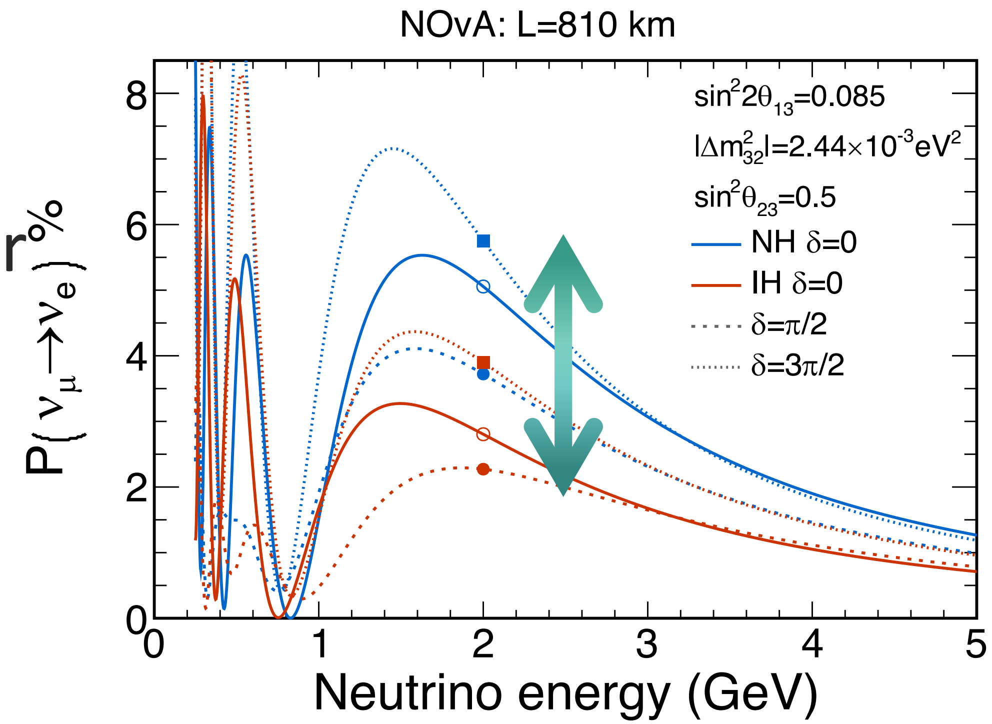


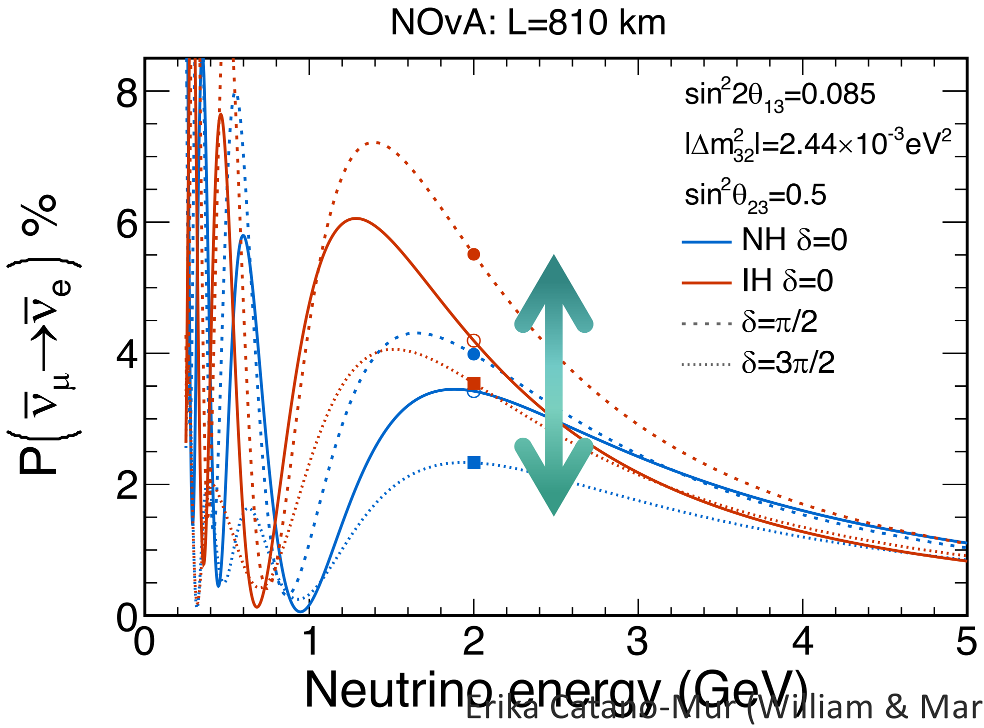


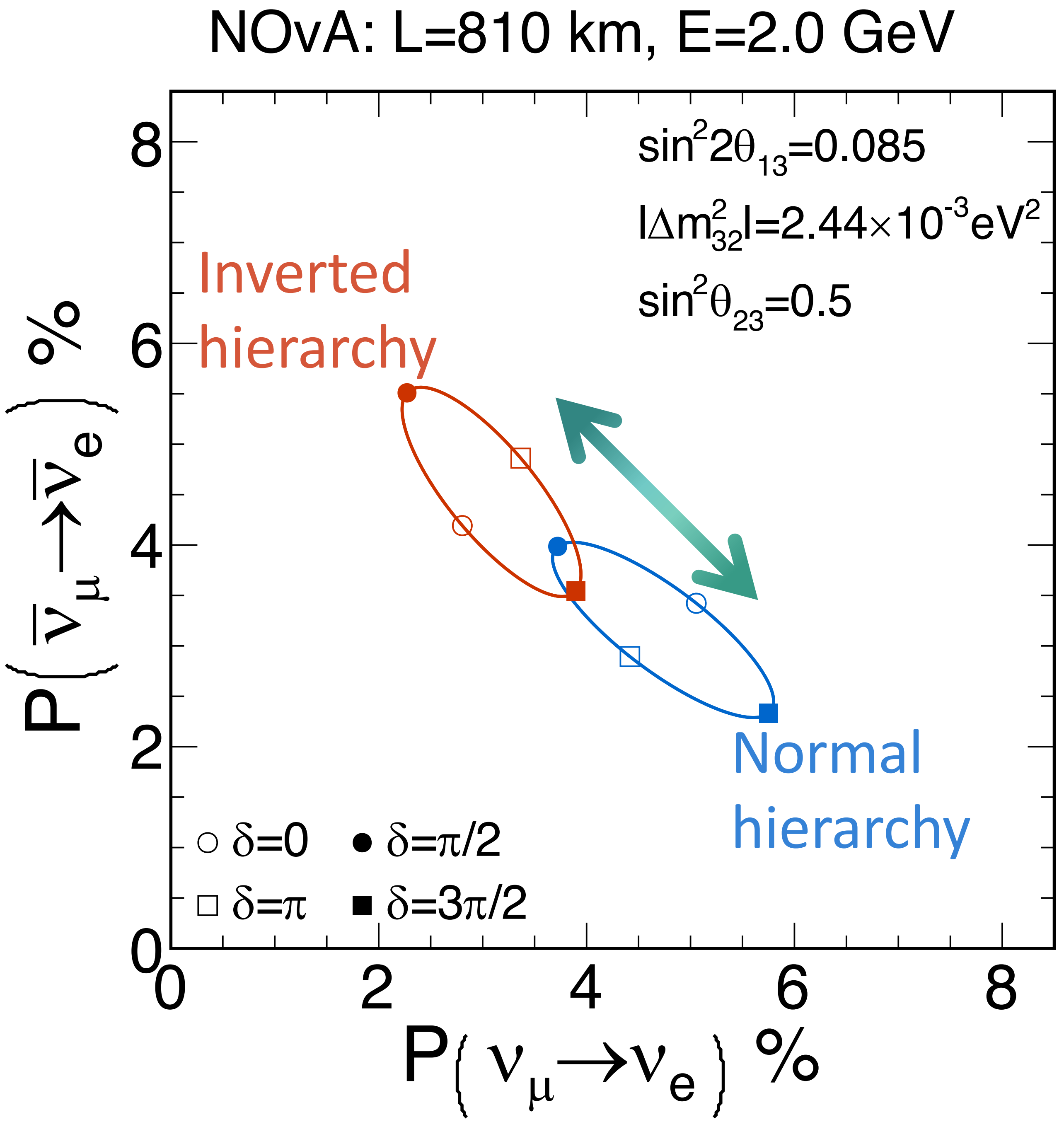


Electron neutrino appearance

Matter effects: in the normal hierarchy, increase for neutrinos and decrease for antineutrinos. Opposite effect for inverted hierarchy.

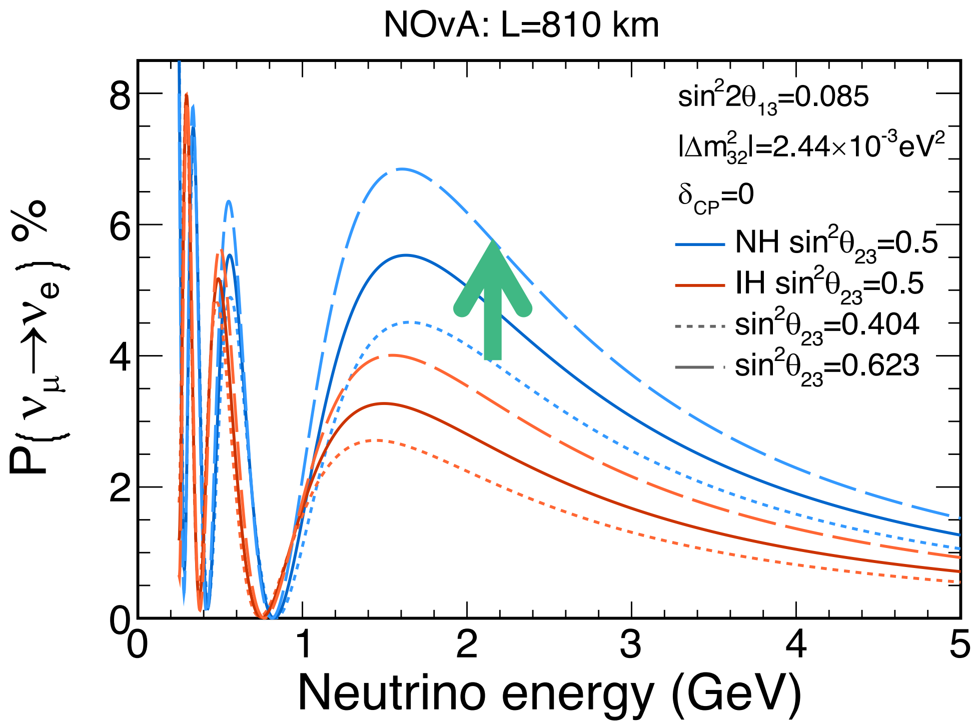


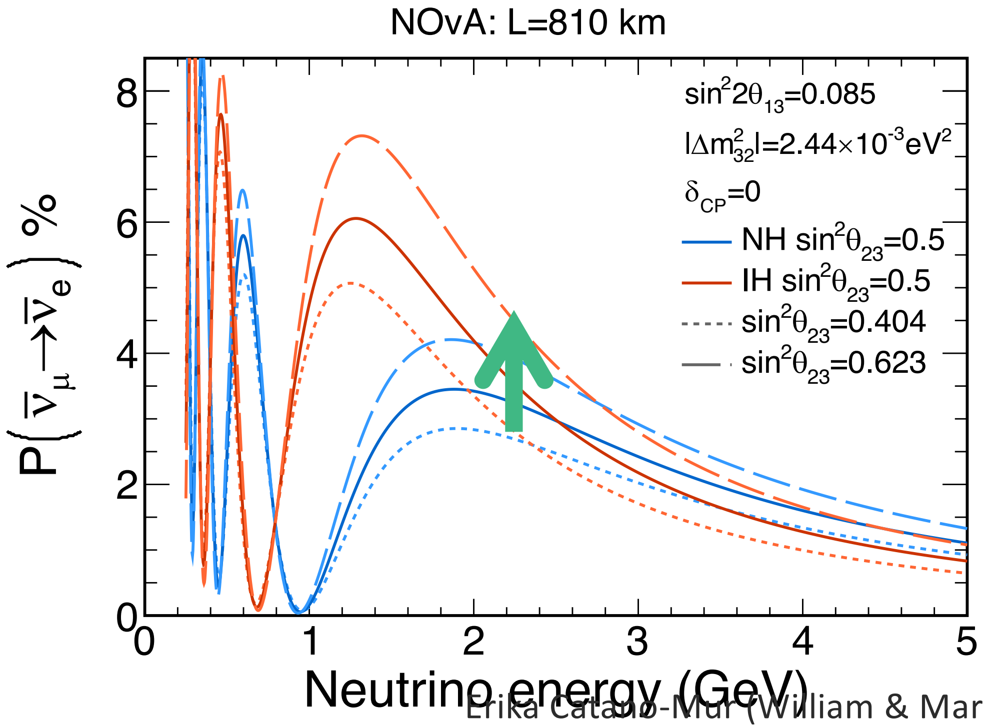


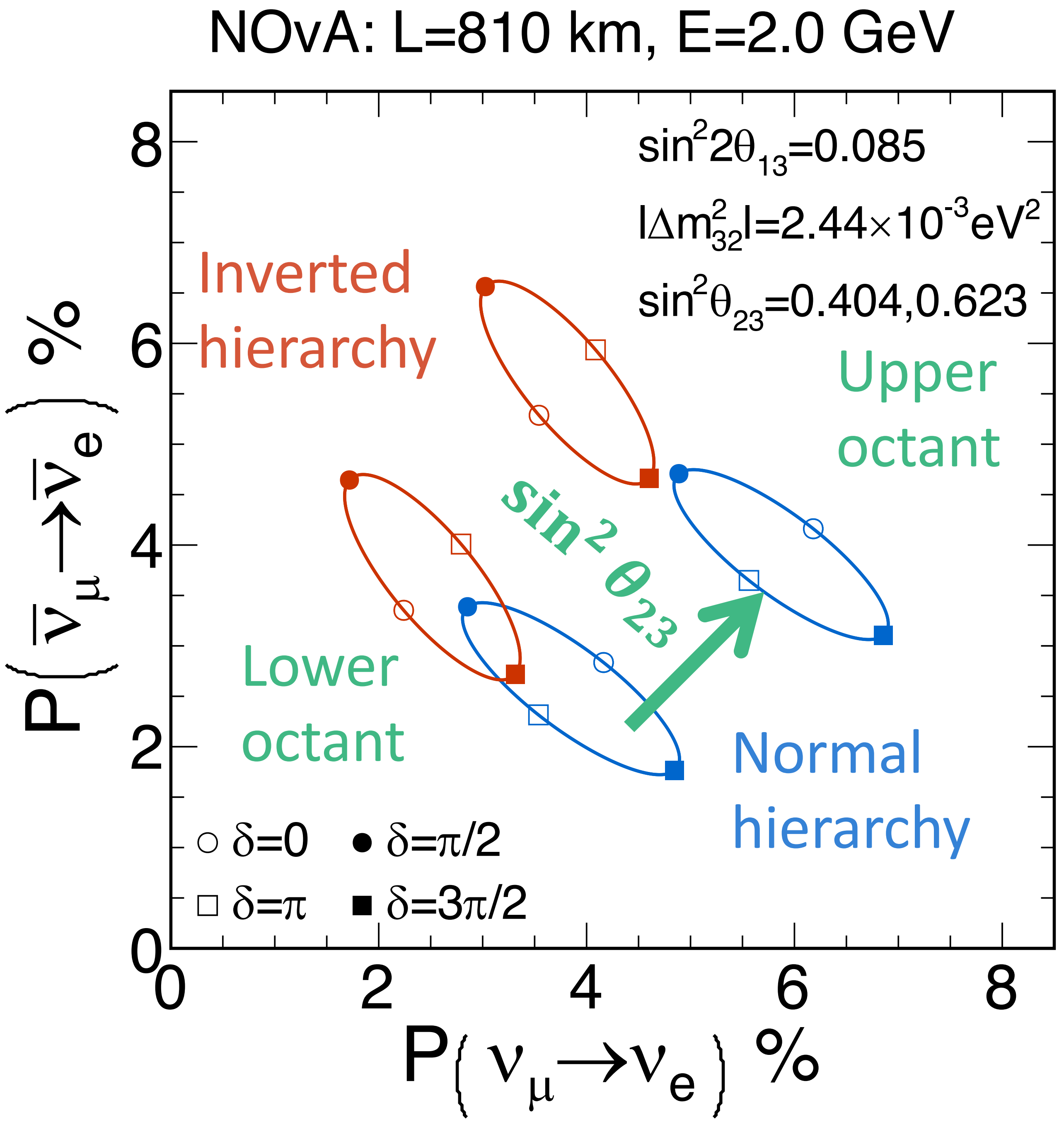


Electron neutrino appearance

Moving from the lower octant ($\sin^2\theta_{23}<0.5$) to the upper octant ($\sin^2\theta_{23}>0.5$): probabilities increase for both neutrinos and antineutrinos, both hierarchies.







Electron neutrino appearance

A different $\left|\Delta m^2_{32}\right|$ results in an overall shift of the probability curves