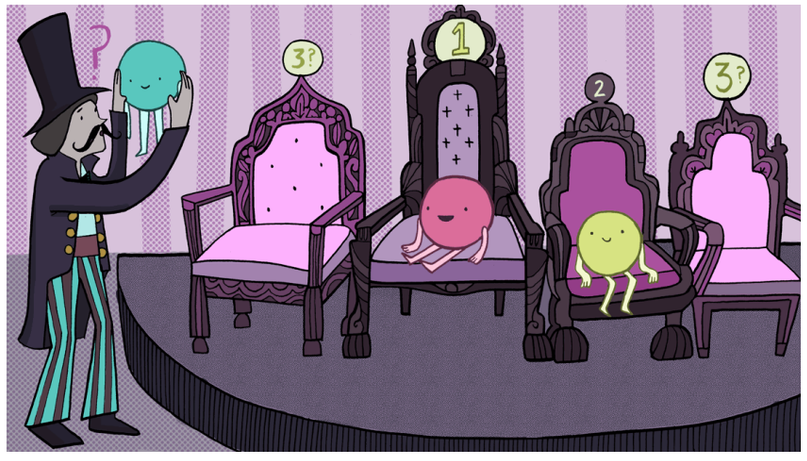
THE NOvA EXPERIMENT: LATEST RESULTS

Alexander Booth, for the NOvA Collaboration

Lake Louise Winter Institute

February 22, 2023

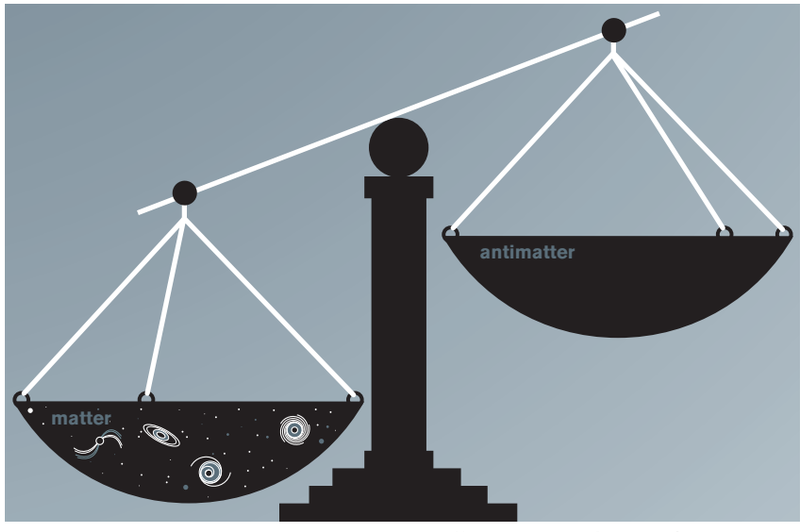
Open Questions



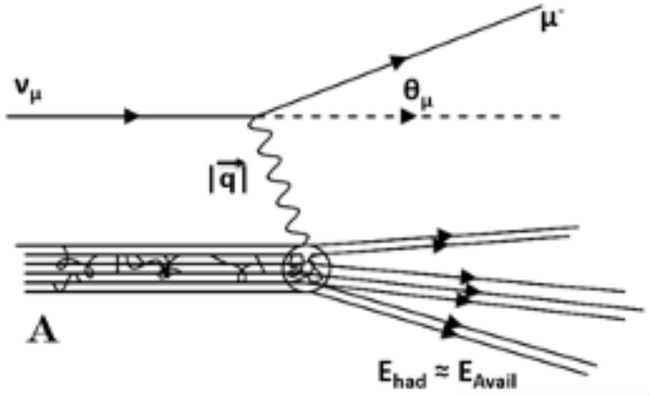
Sandbox Studio, Chicago

What is the neutrino mass ordering?

Do neutrinos violate CP symmetry?



Sandbox Studio, Chicago

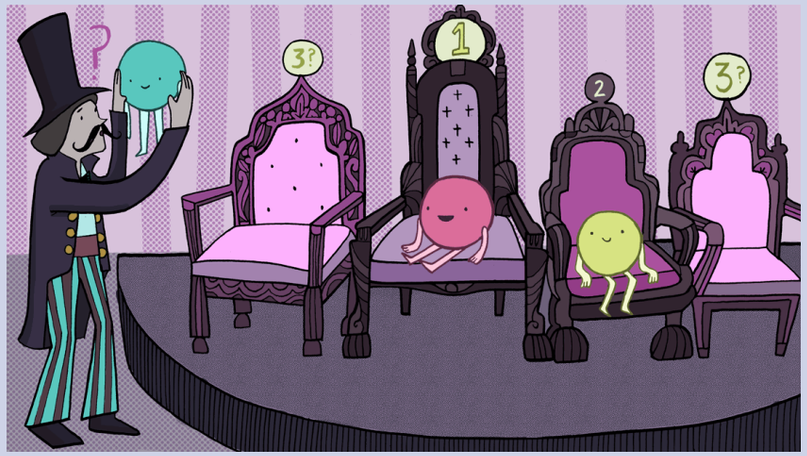


How are nuclear effects changing the interaction probability of neutrinos?

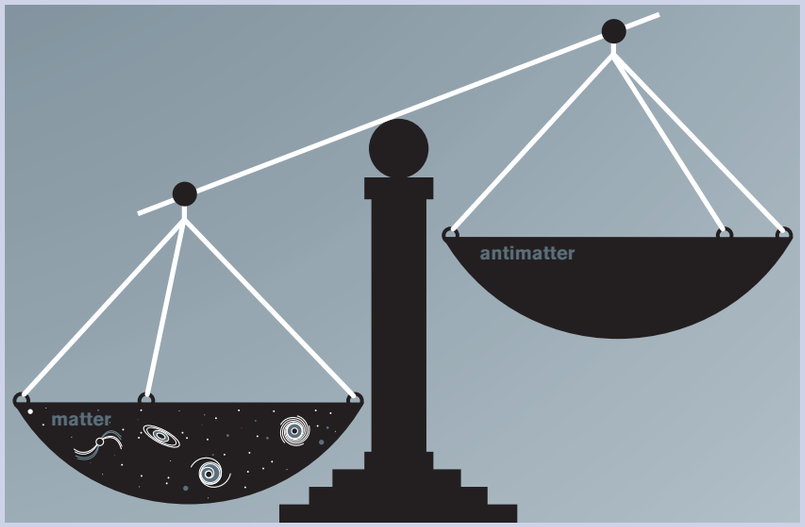
Are 3-flavour oscillations the full picture?

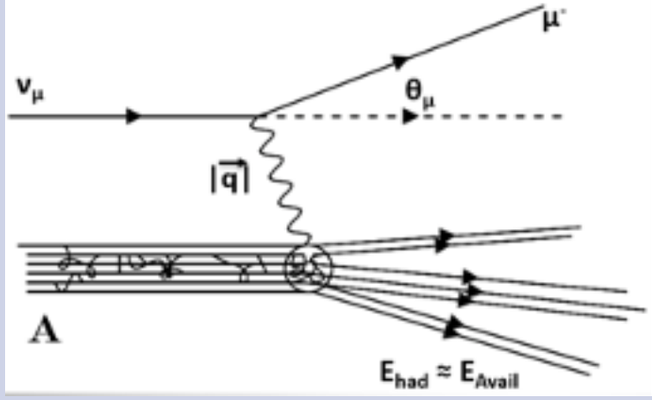
Sandbox Studio, Chicago

In This Talk...



3 flavour oscillations via a new, alternative statistical treatment.





New ν_μ CC cross section measurement with a focus on nuclear effects - e.g. 2p2h/ MEC interactions.

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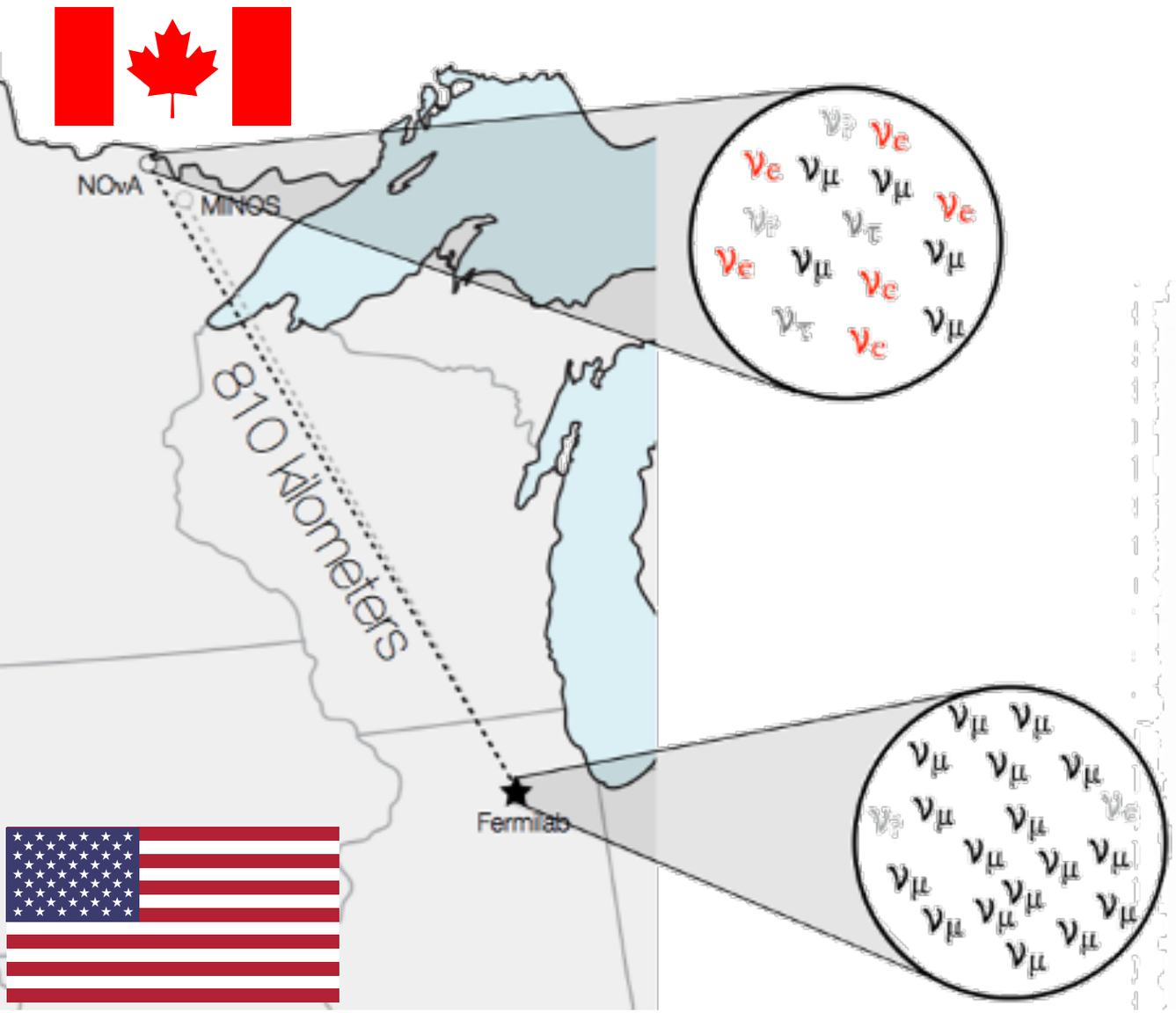
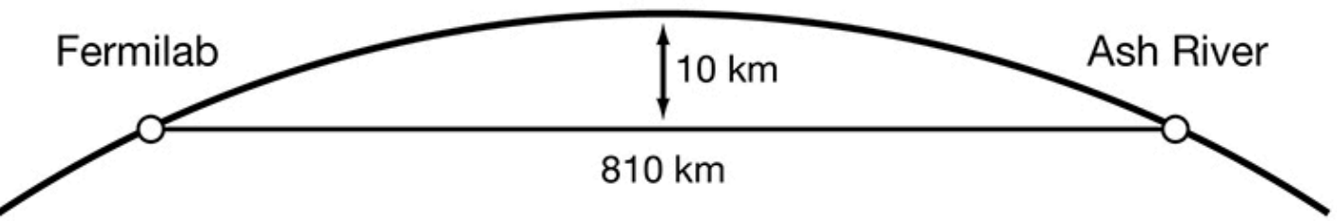
NOvA Overview

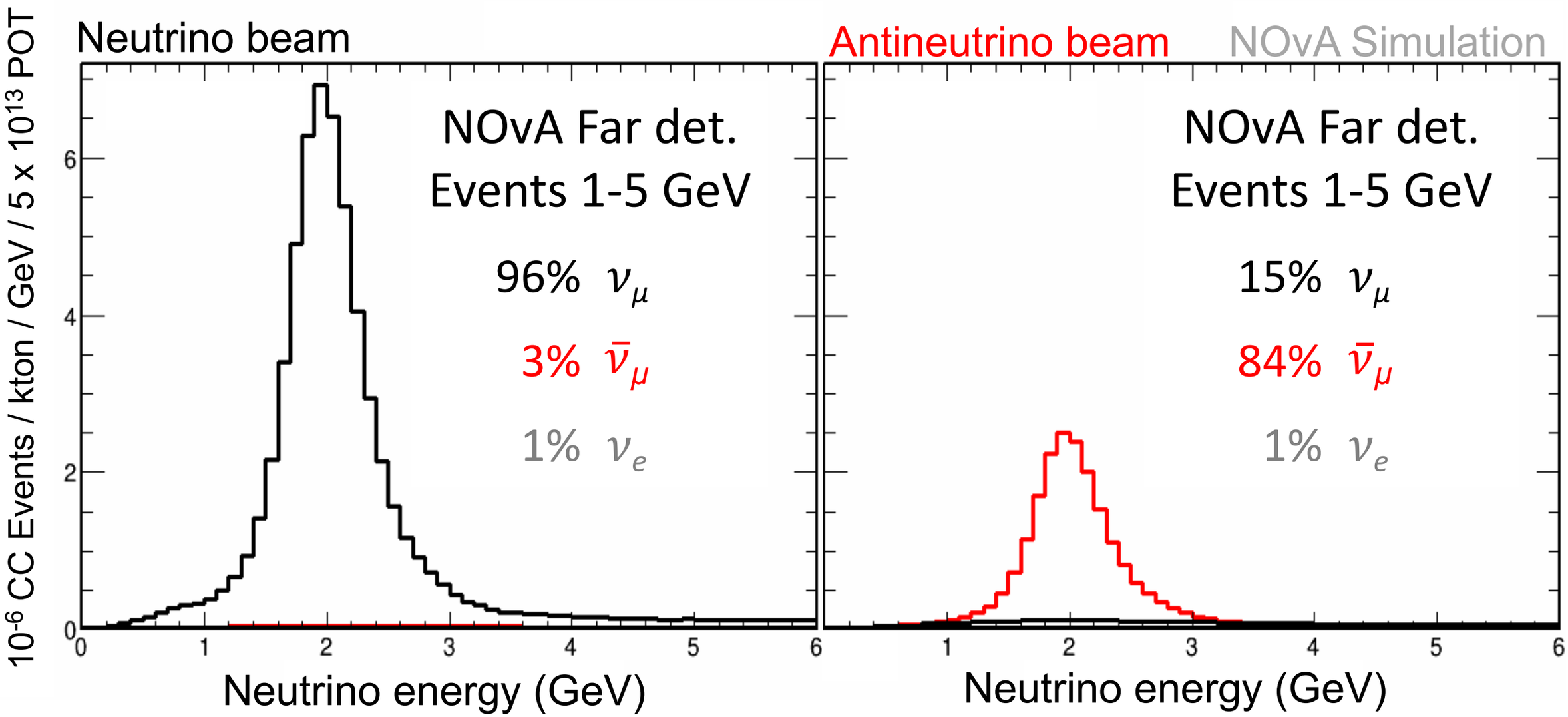




- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab.
  - **Near detector** to measure beam before oscillations.
  - **Far detector** measures the oscillated spectrum.
- **Primary goals are to** study 3-flavour oscillations via:
  - $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

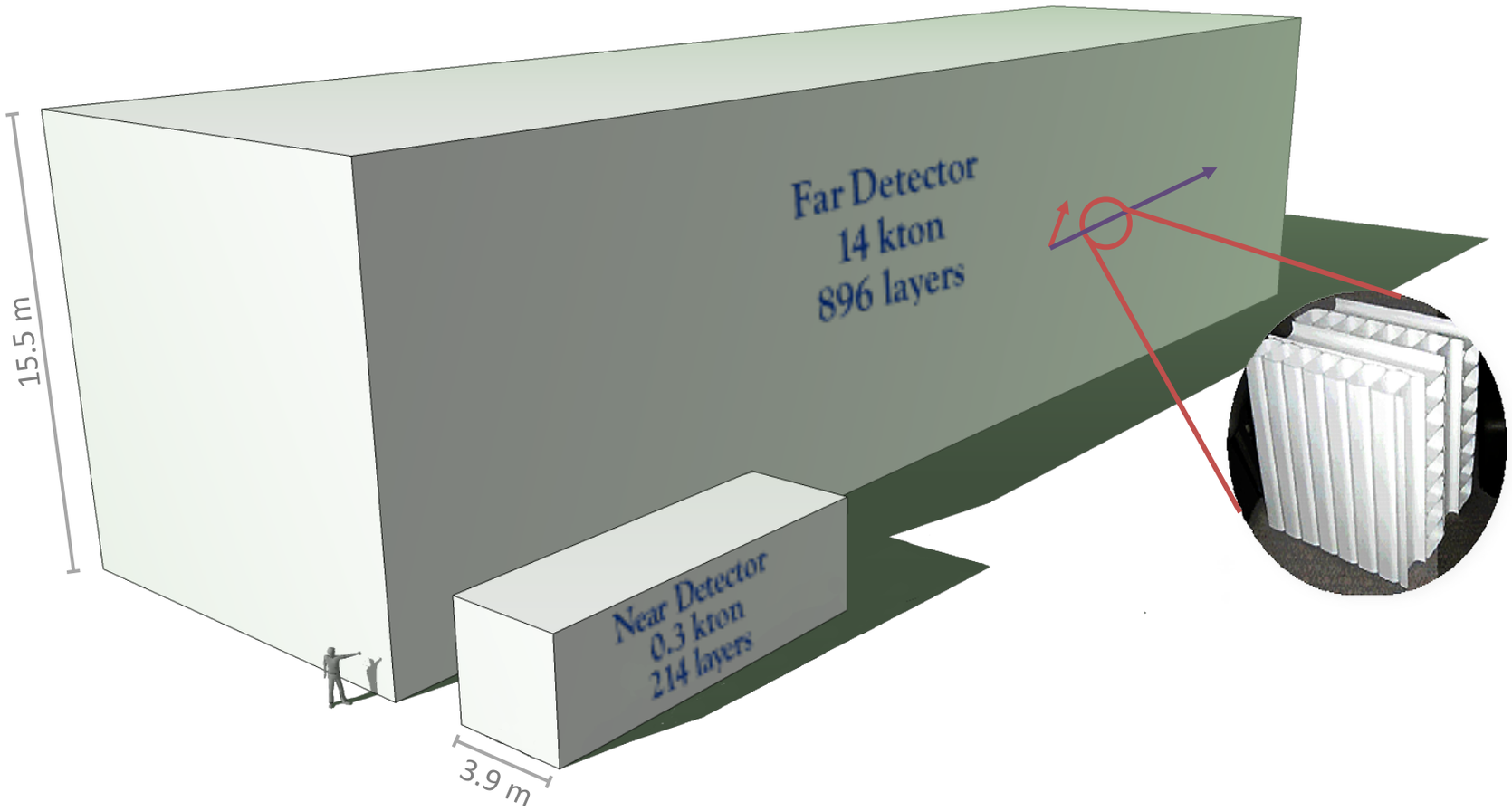
  and measure neutrino cross sections.

NuMI Off-axis Narrow Band Beam



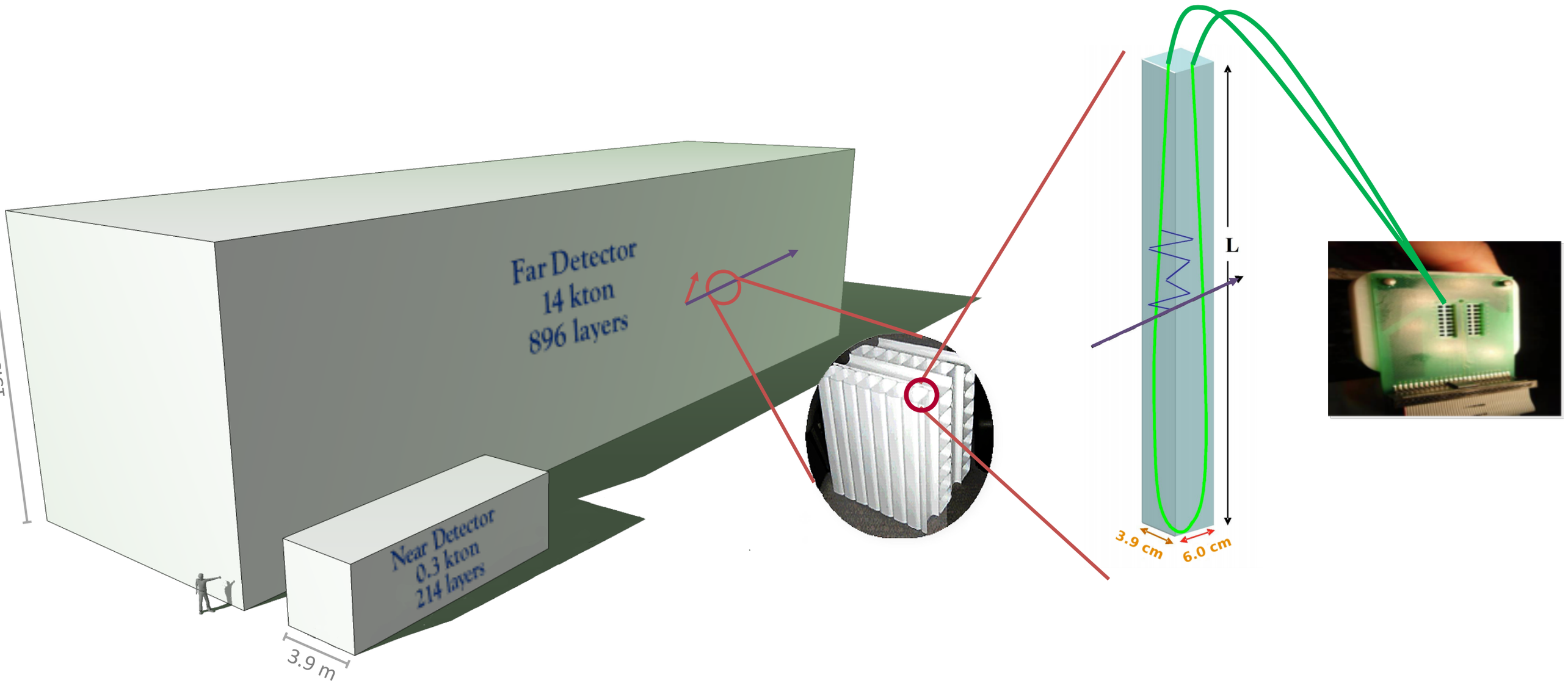
- Peak flux around 2 GeV.
- Neutrino or antineutrino modes.
- High ν_μ ($\bar{\nu}_\mu$) purity.
- Delivered ~ 40 x 10^{20} POT to date.

The NOvA Detectors



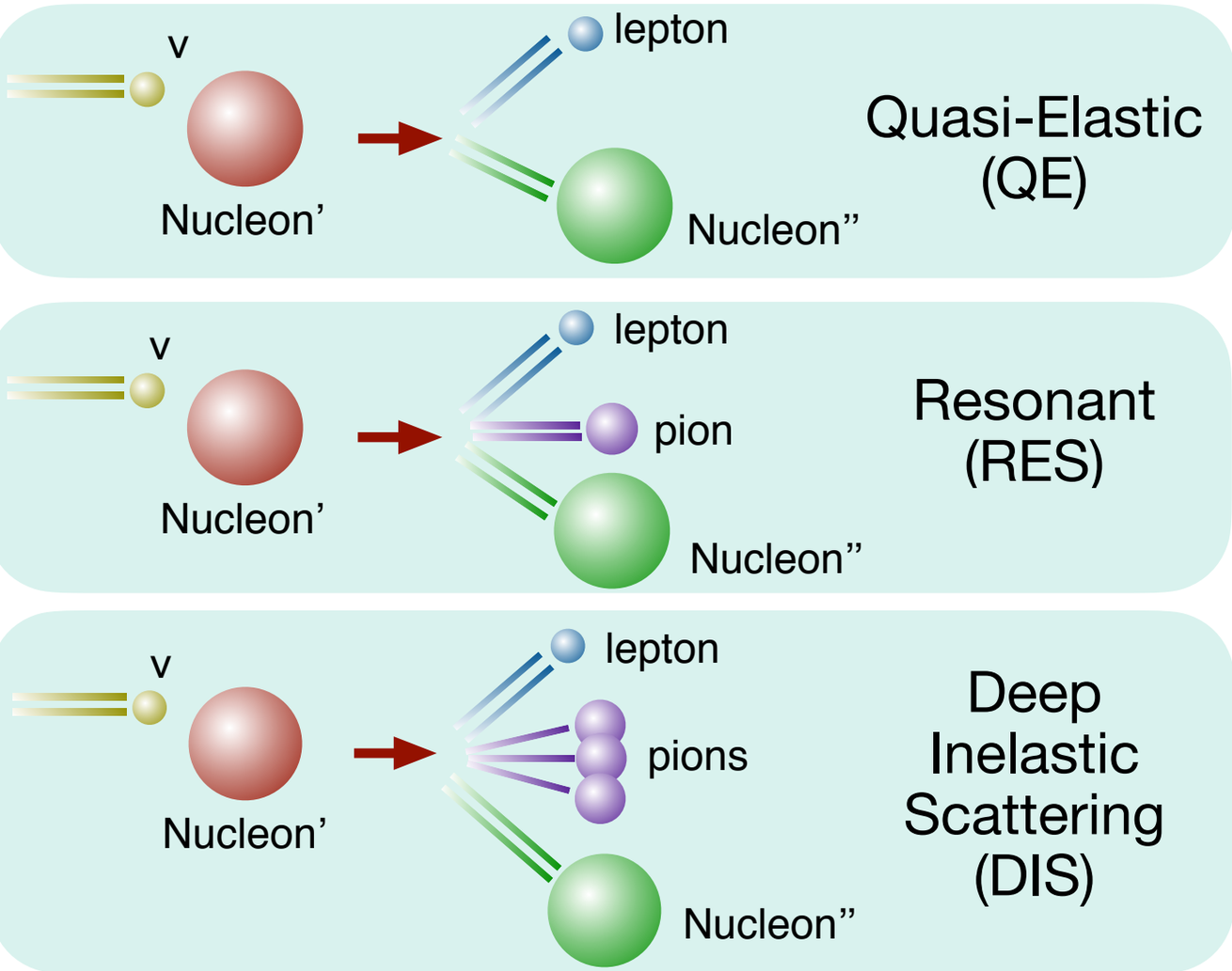
- Both are large, (FD 60 m long).
- Functionally identical: consist of extruded PVC cells filled with 11 million litres of liquid scintillator.
- Arranged in alternating directions for 3D reconstruction.

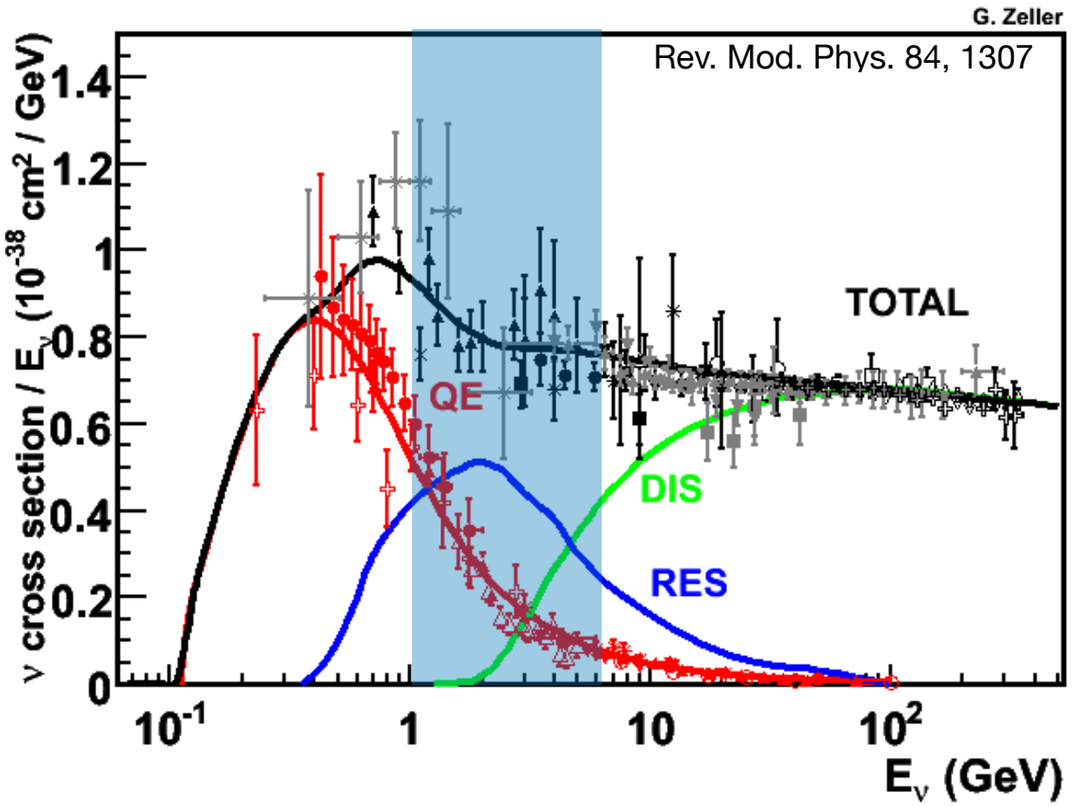
The NOvA Detectors



- Light produced when charged particle passes through cells.
- The light is picked up by wavelength shifting fibre. Transported to an Avalanche PhotoDiode - light collected and amplified.
- Image hadronic recoil system to ~ 5 MeV / cell sensitivity and ~ cm-scale tracking resolution.

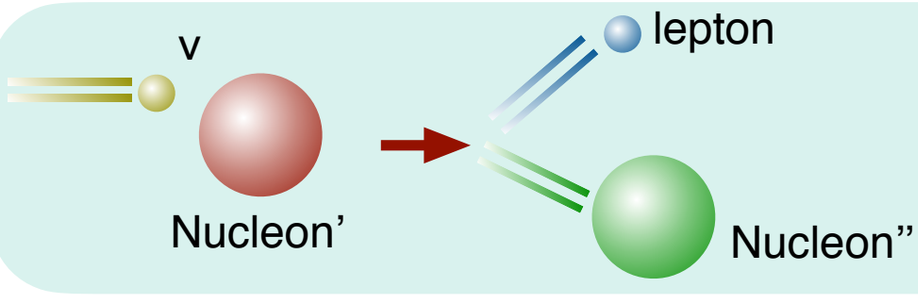
Neutrino Interaction Types



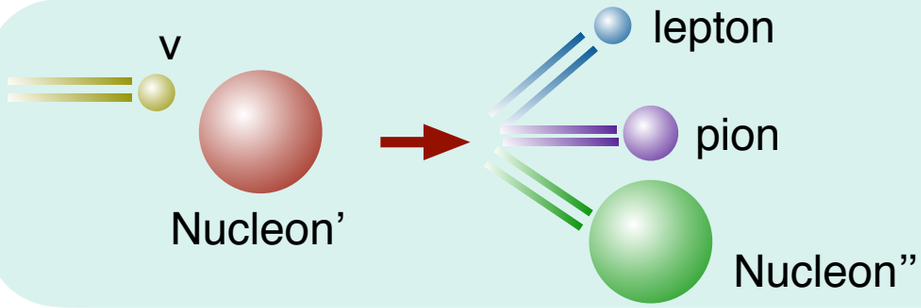


- All interaction types can be studied with huge statistics.

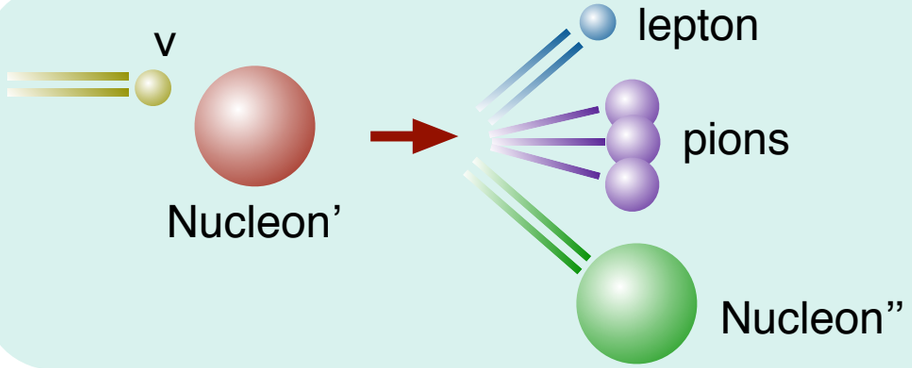
Neutrino Interaction Types



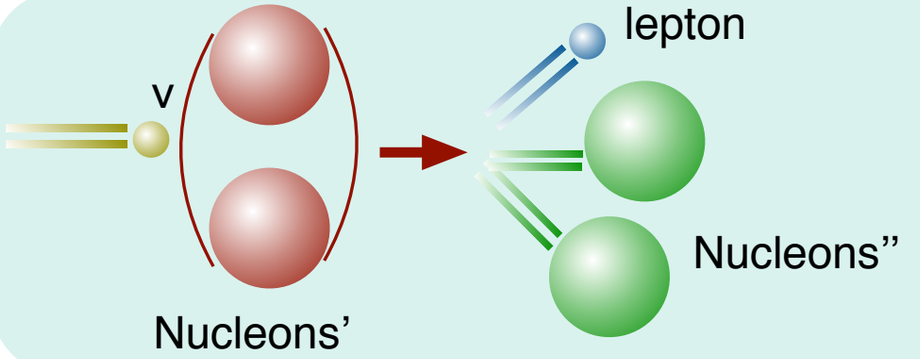
Quasi-Elastic (QE)



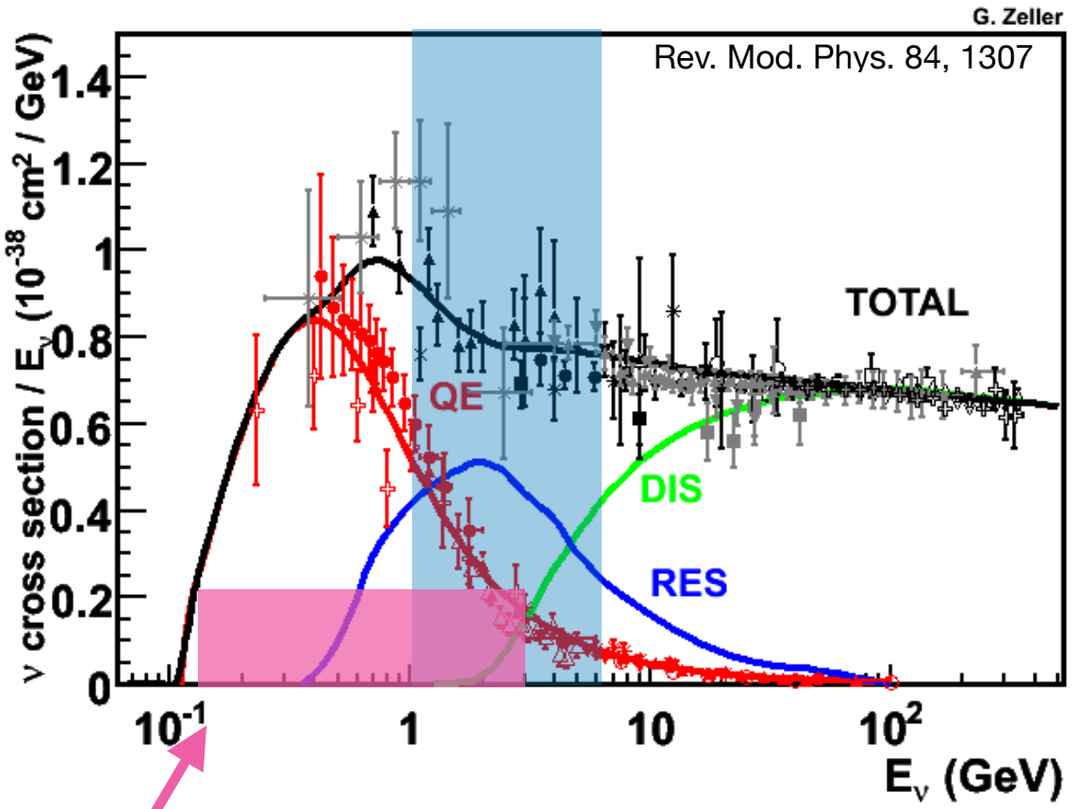
Resonant (RES)



Deep Inelastic Scattering (DIS)



Meson Exchange Currents (MEC)



- All interaction types can be studied with huge statistics.
- Nuclear effects are significant.
- A better understanding is important for reducing systematics on oscillation measurements.

Cross Section Result

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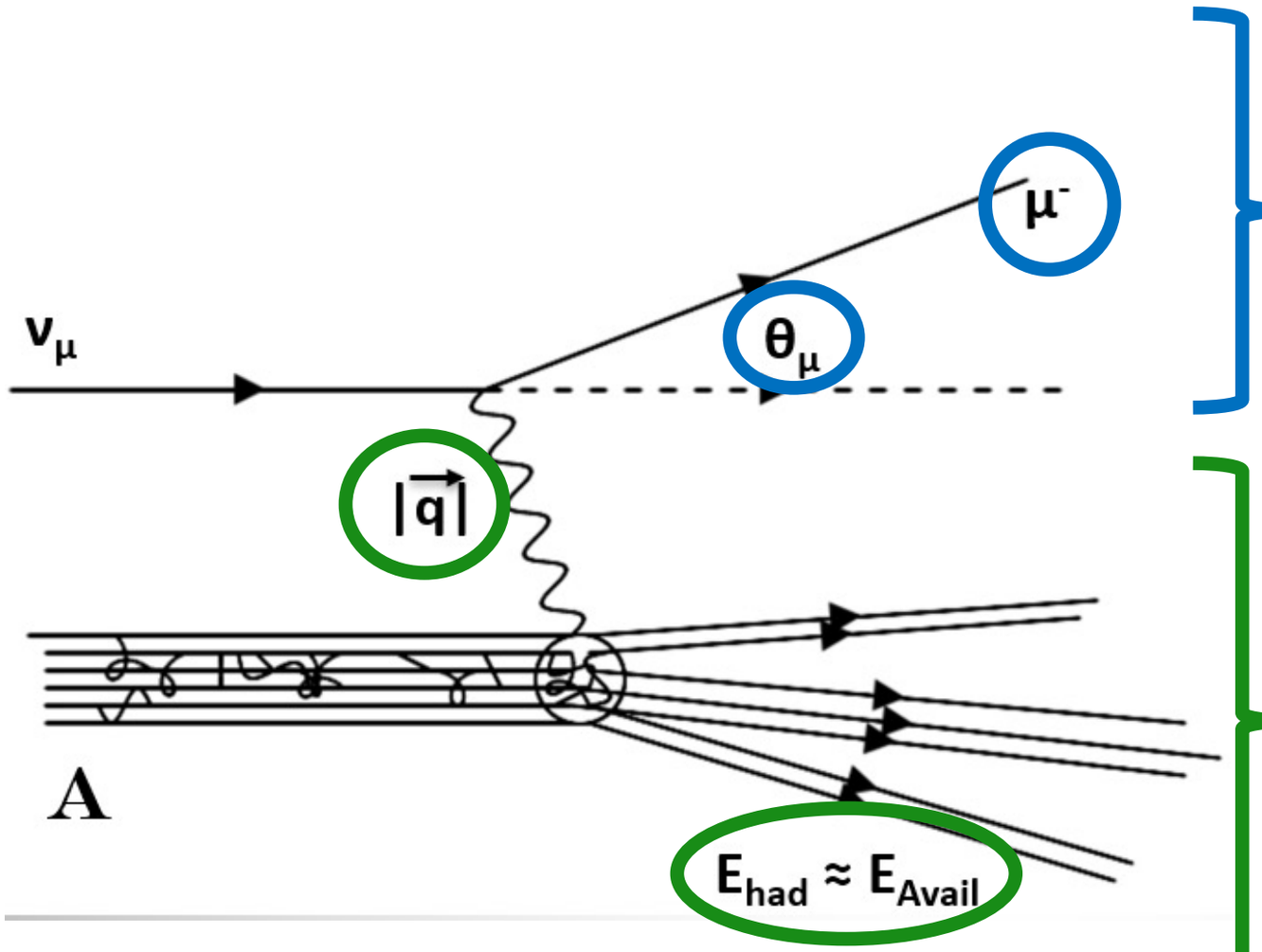
ν_μ CC Cross Section Result(s)

(Both) double differential.

(Both) focus on sensitivity to 2p2h / MEC events.



Muon System ⇨ Energy **vs** angle

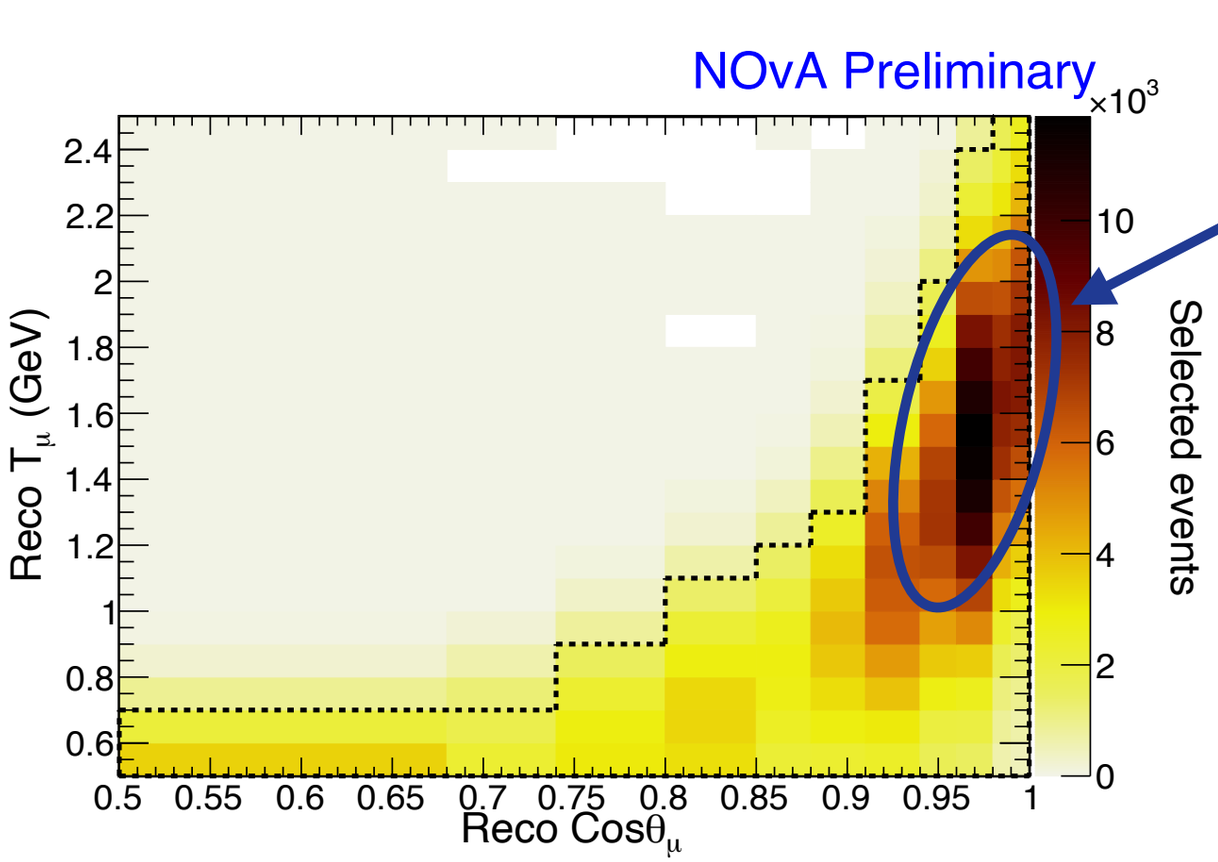
Hadronic System ⇨ 3-momentum transfer $|\vec{q}|$ **vs** energy

Muon System

- **Exclusive**: events must have exactly one reconstructed track:
  - Low hadronic energy.
  - Boost MEC, reduces DIS and RES.

- Cross section reported at 115 kinematic points:
  - Typically 12 - 15% uncertainty.
  - Dominated by flux systematic.

MEC events concentrated here



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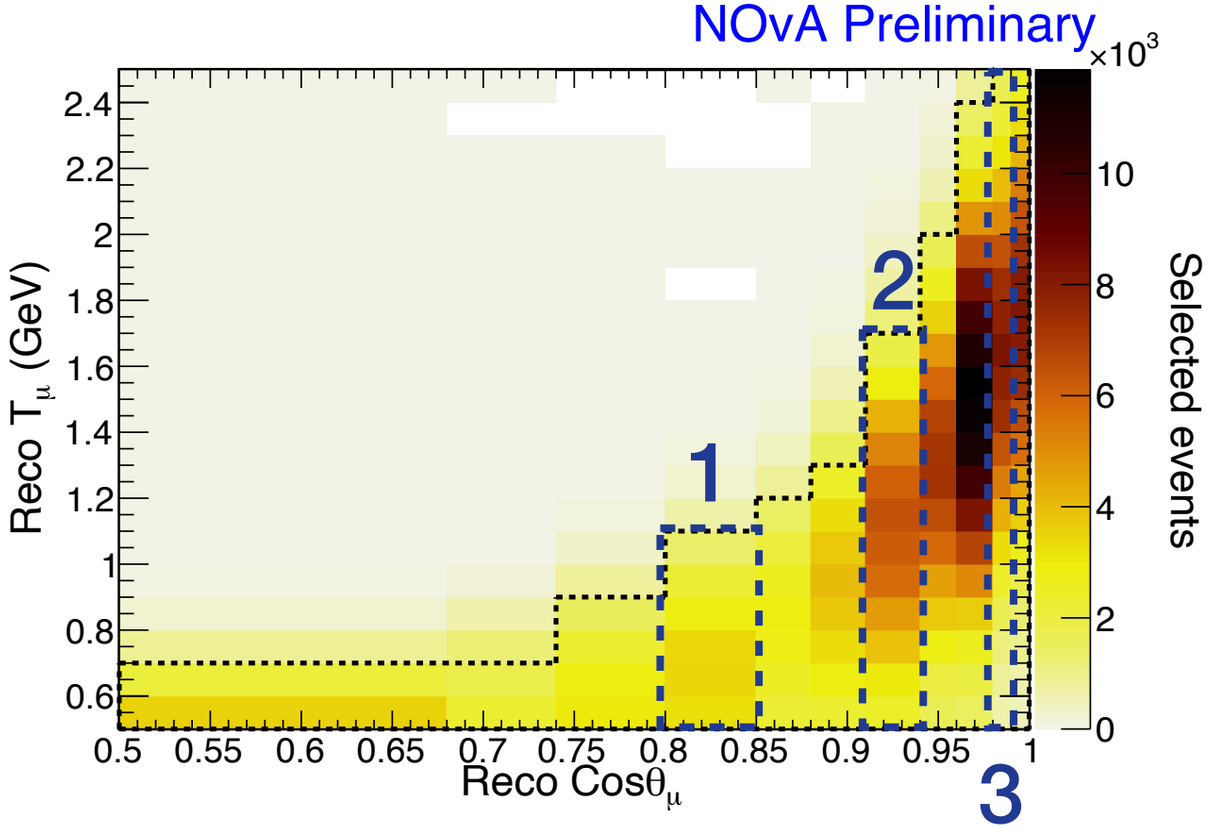

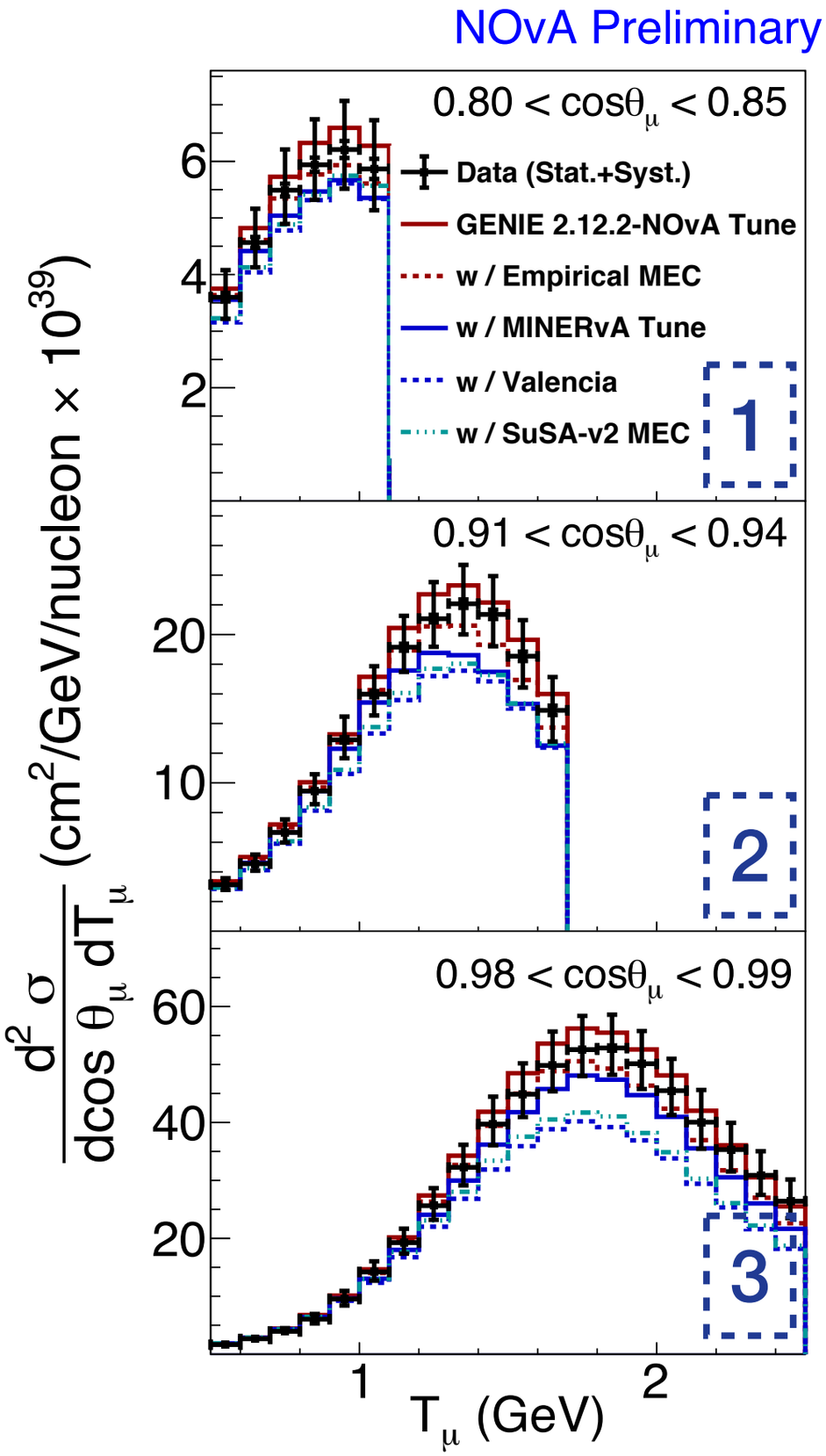

3 Flavour Oscillation Results

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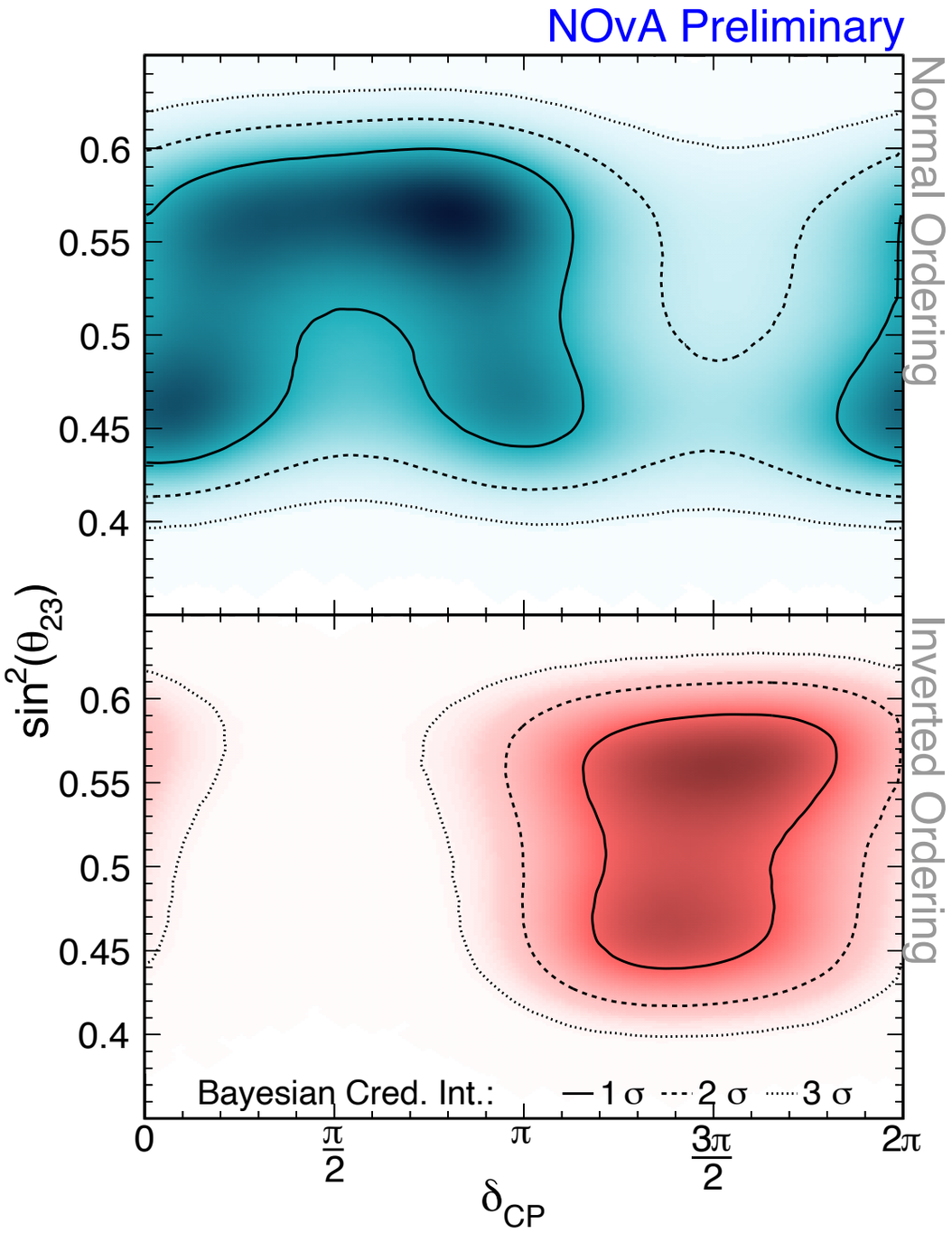
Alternative Statistical Treatment

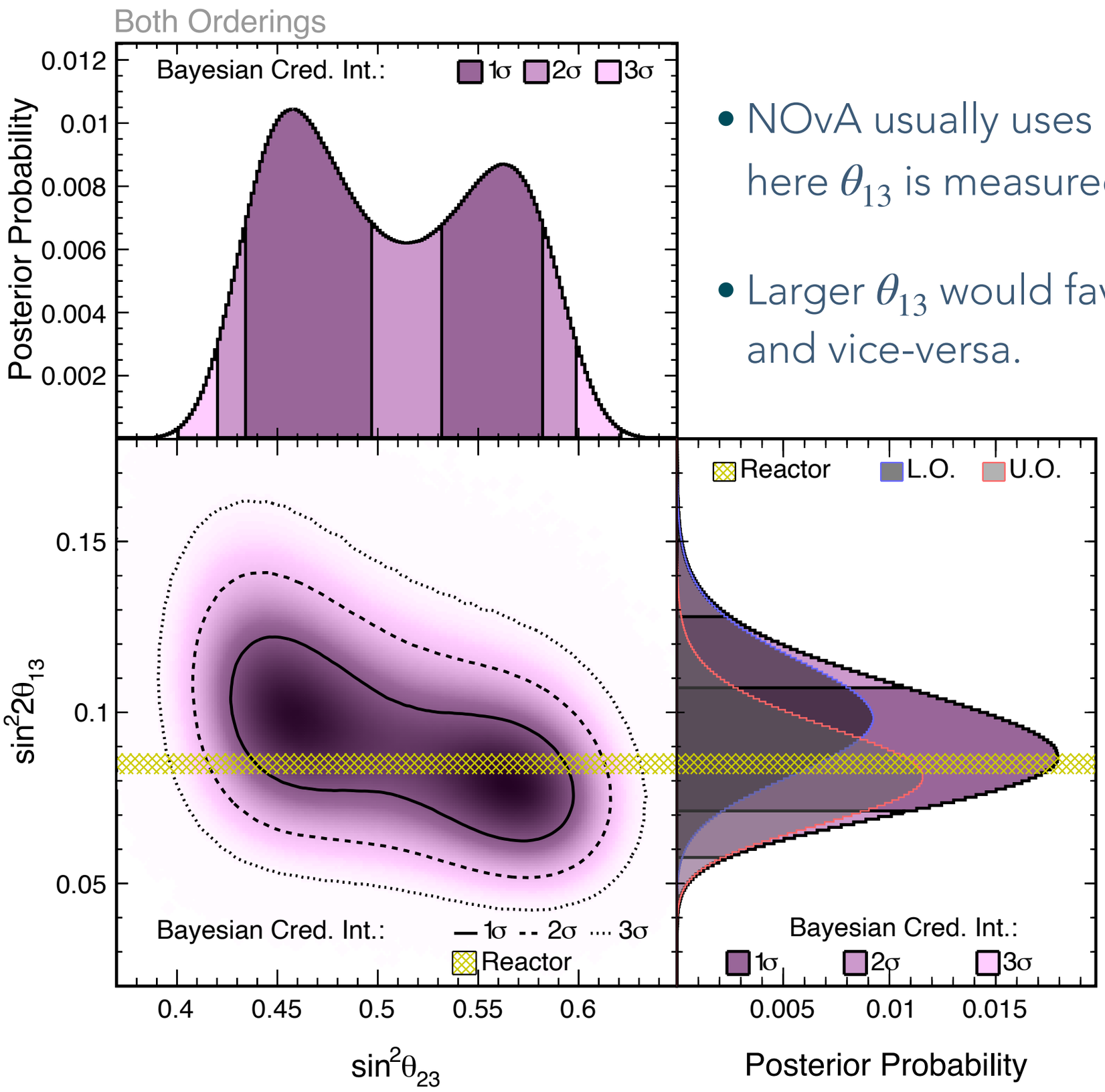
- Markov Chain Monte Carlo Bayesian analysis.
- Allows the result to be examined in new ways.
- Conclusions are the same as frequentist results, preference for the normal ordering and upper octant of $\sin^2\theta_{23}$.

Exclude IH $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$

Disfavour NH $\delta_{CP} = \frac{3\pi}{2}$ at $\sim 2\sigma$



NOvA-only θ_{13} & θ_{23}



- NOvA usually uses reactor θ_{13} constraint in the fit, here θ_{13} is measured by NOvA.
- Larger θ_{13} would favour the lower octant for θ_{23} and vice-versa.

- $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$
- Consistent with reactor experiments.

Summary

- NOvA has performed two new cross section measurements sensitive to MEC interactions.

- NOvA now has a second statistical treatment to probe 3 flavour oscillations.
  - Slight preference for the normal ordering of neutrino masses and the upper octant of $\sin^2\theta_{23}$.
  - Exclude the inverted ordering at $\delta_{CP} = \frac{3\pi}{2}$ at greater than 3 σ.

- NOvA has performed an independent measurement of θ_{13}, consistent with reactor experiments.

- Many more exciting results to come!

NOvA In Duluth, Summer 2022

Back-up

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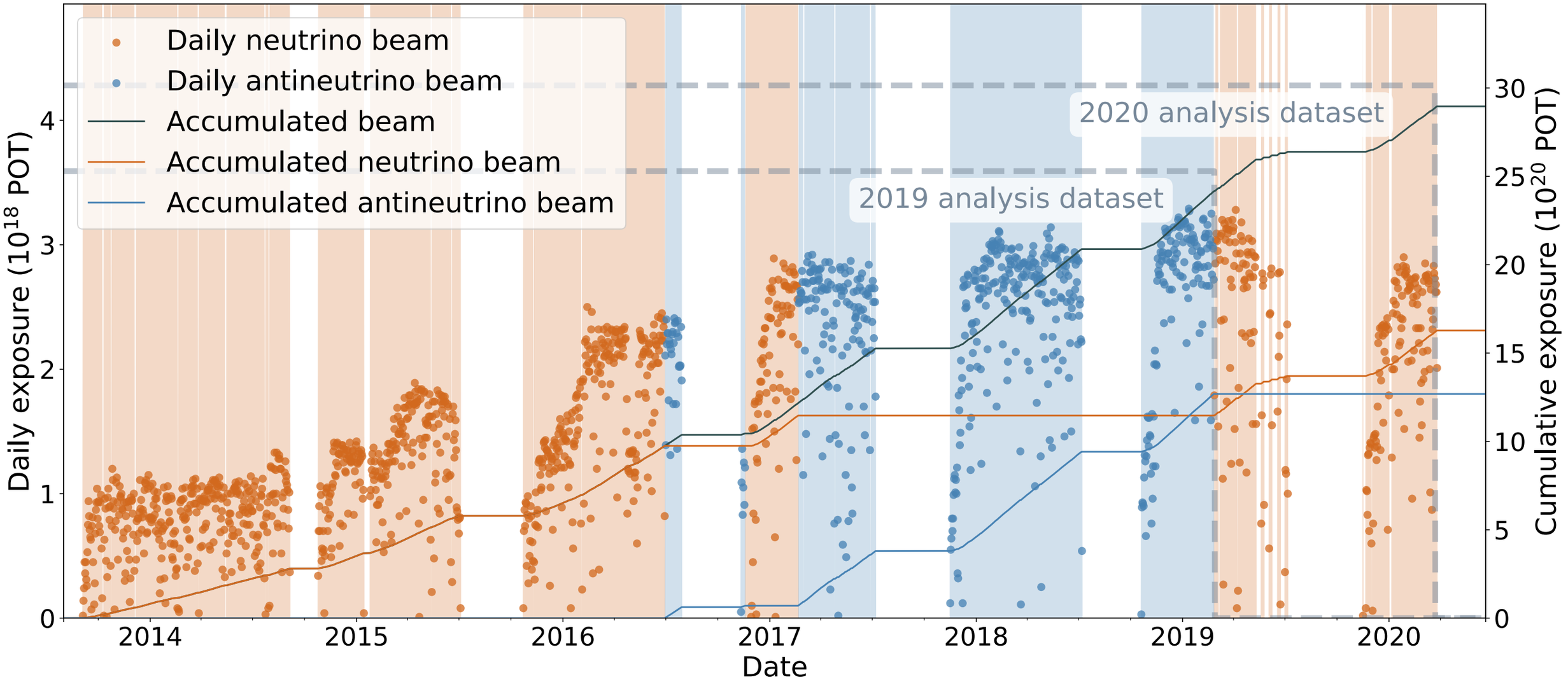
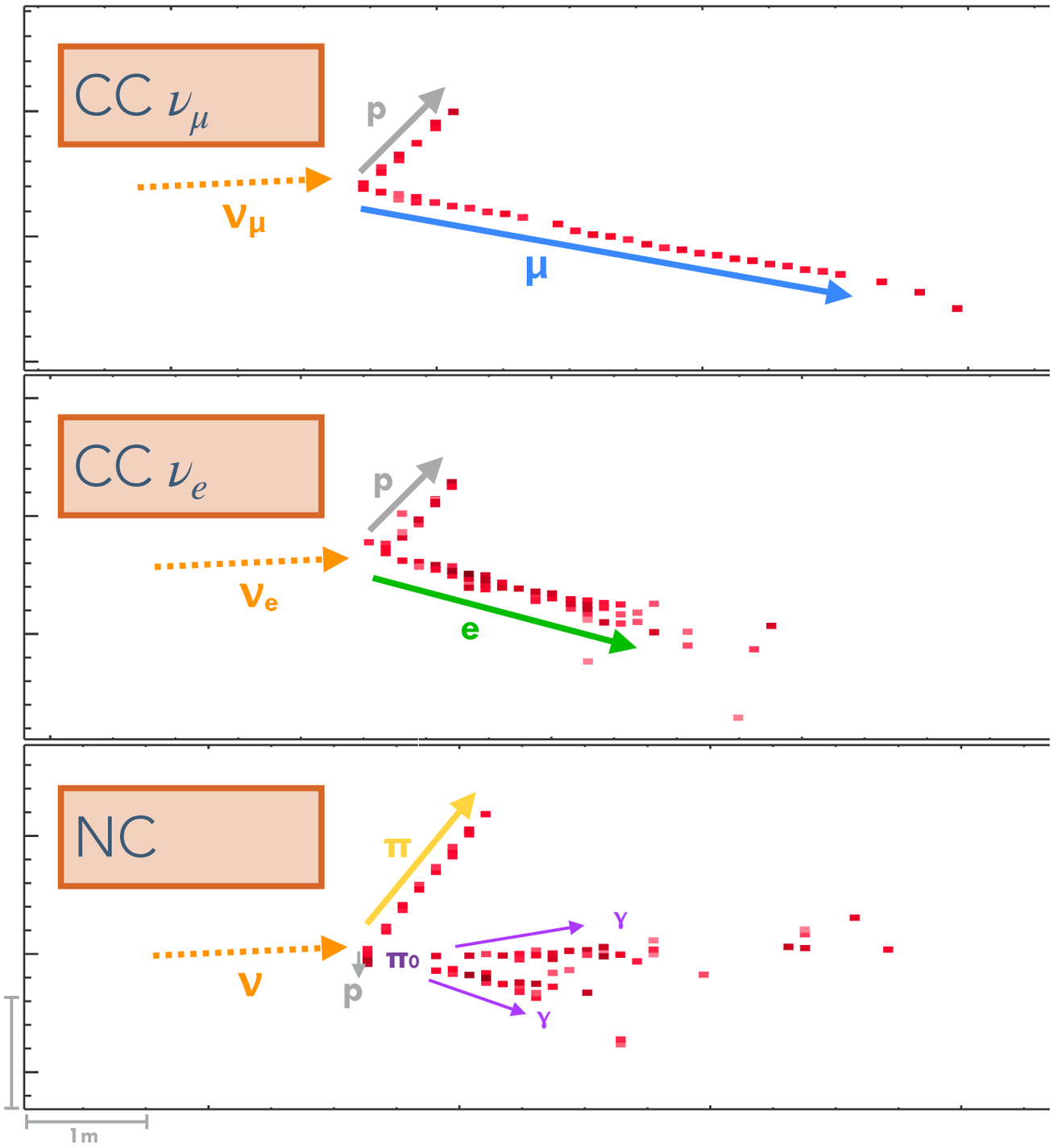
POT Collected Against Time

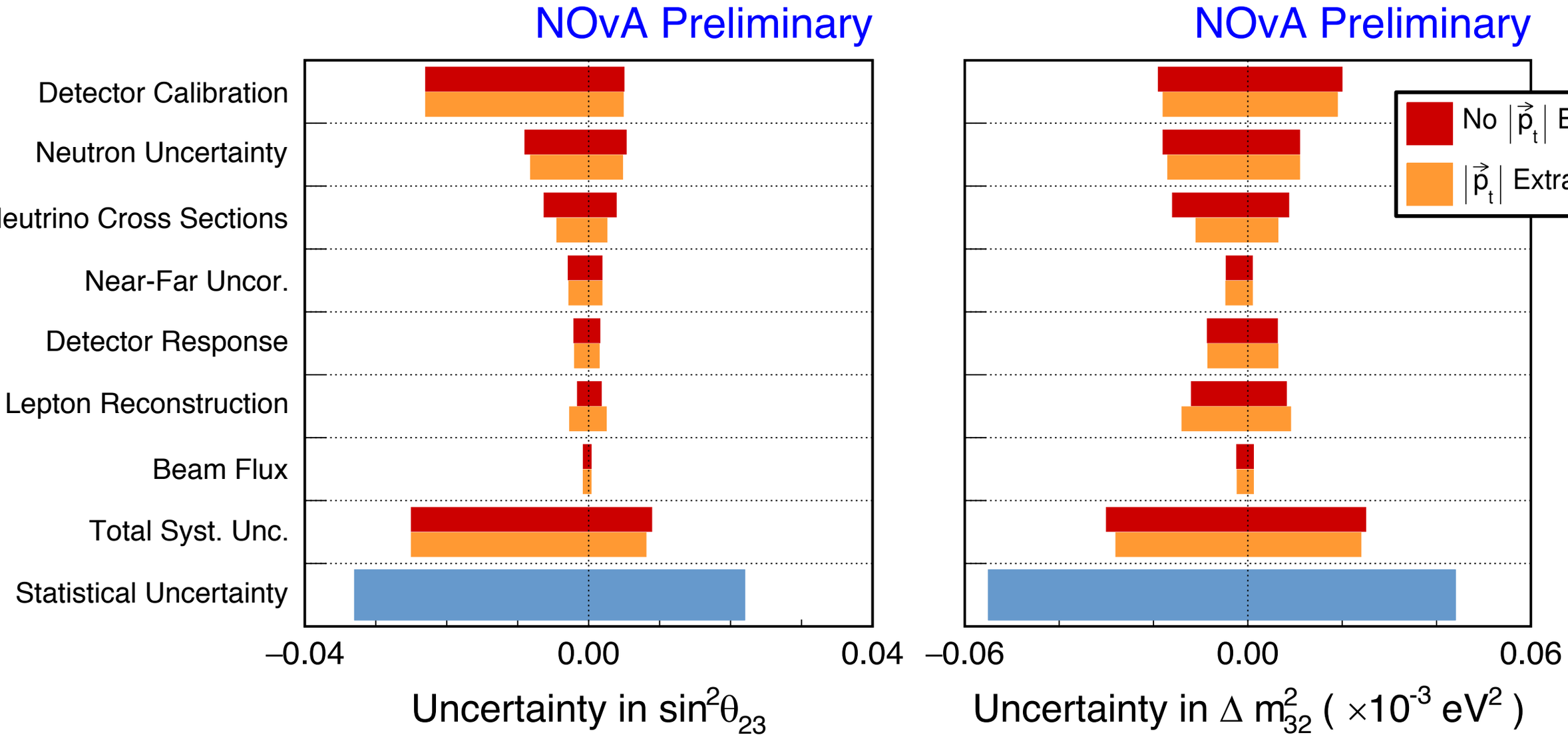


Selecting & Identifying Neutrinos



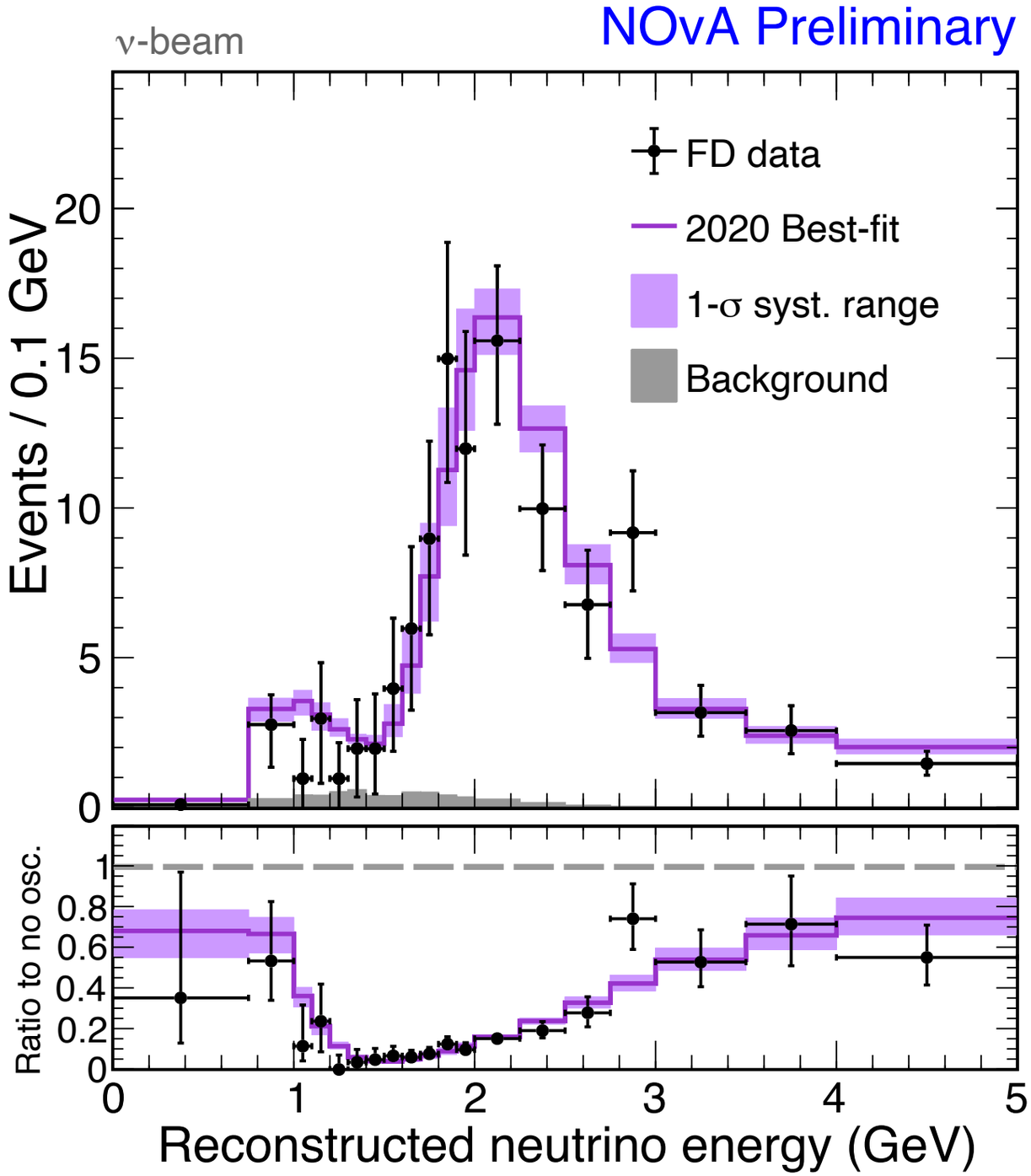
- Each type of neutrino event leaves a unique signature.
- Deep learning is used to aid with classification:
  - Cross section analyses use it to identify **single particles**.
  - Oscillation analyses use a convolution visual network to identify **whole events**.

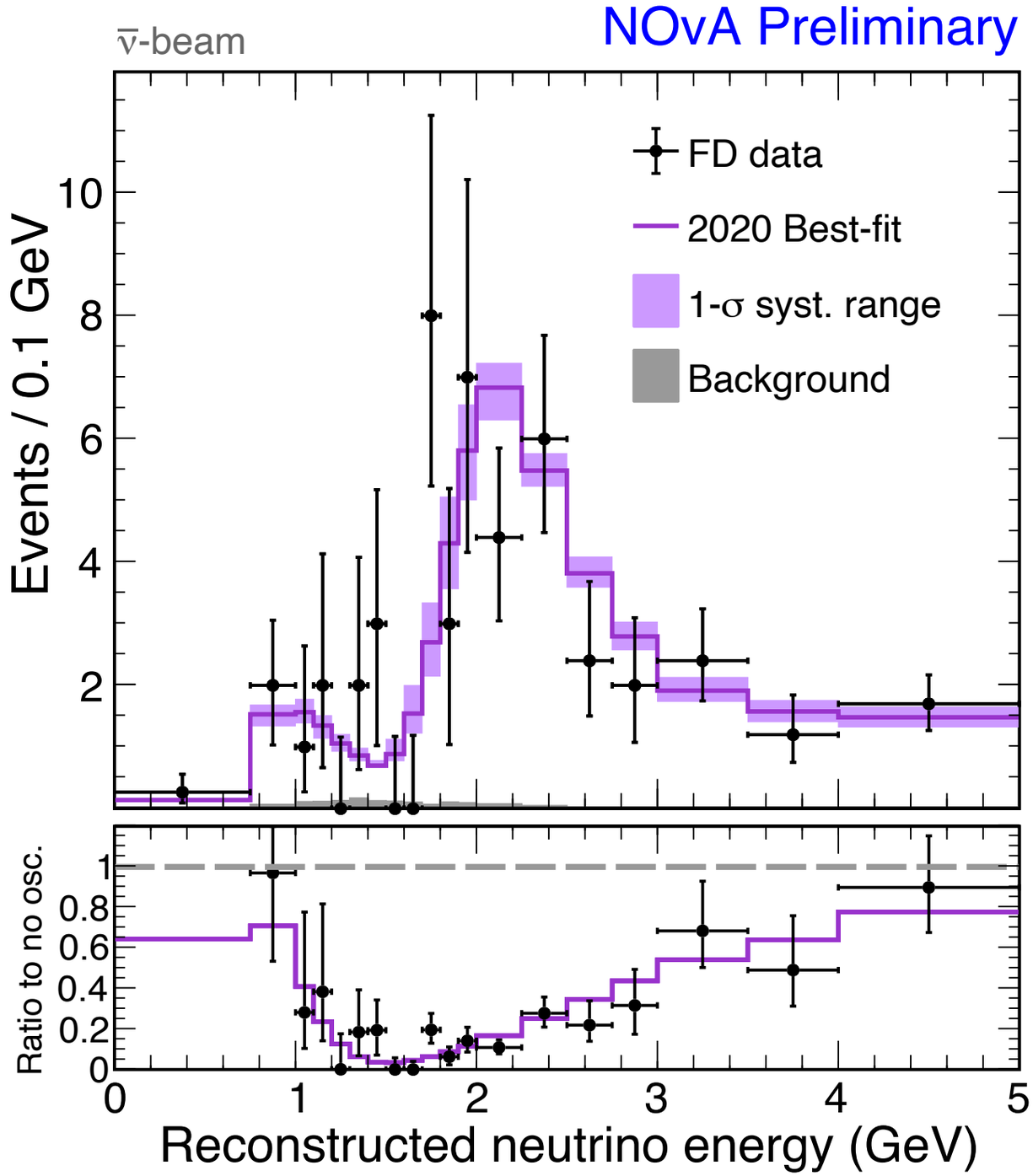
Systematic Uncertainties with p_t Extrapolation



- Overall systematic reduction is 5-10%.
- 30% reduction in cross-section uncertainties.
  - Reduces the size of systematics most likely to contain "unknown unknowns."
  - Slight increase in systematics on lepton reconstruction.

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

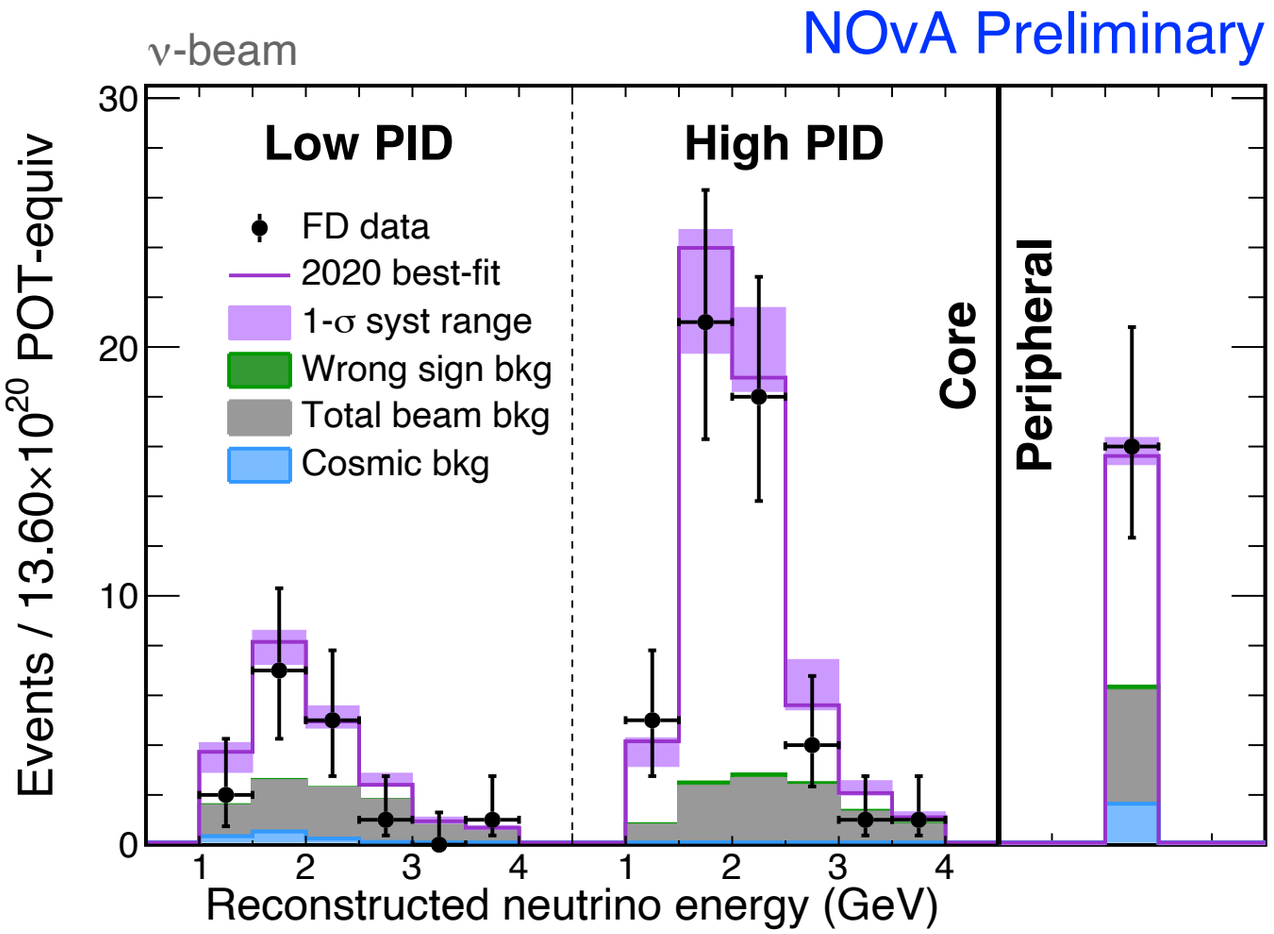


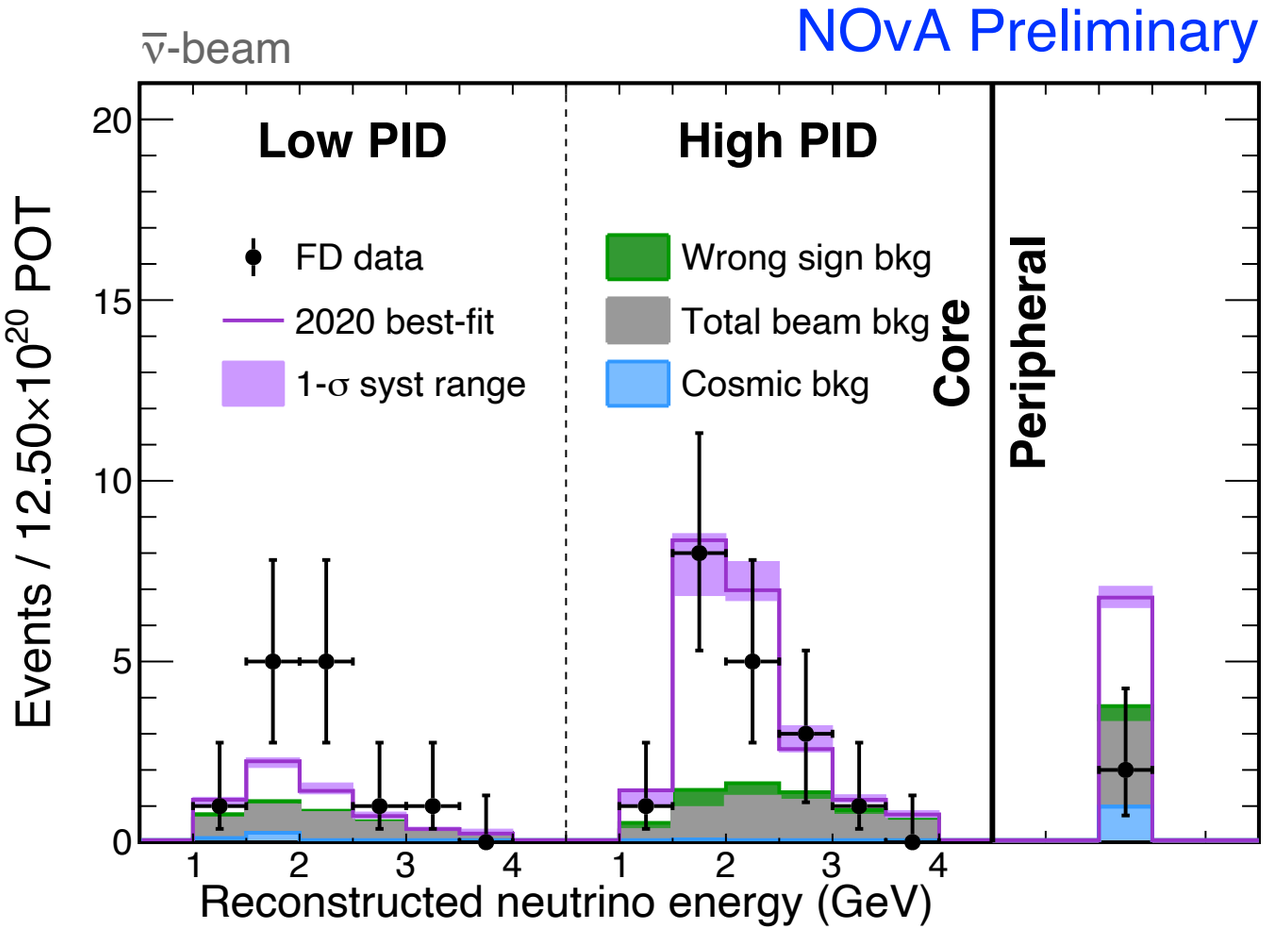


211 events, 8.2 background

105 events, 2.1 background

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





Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

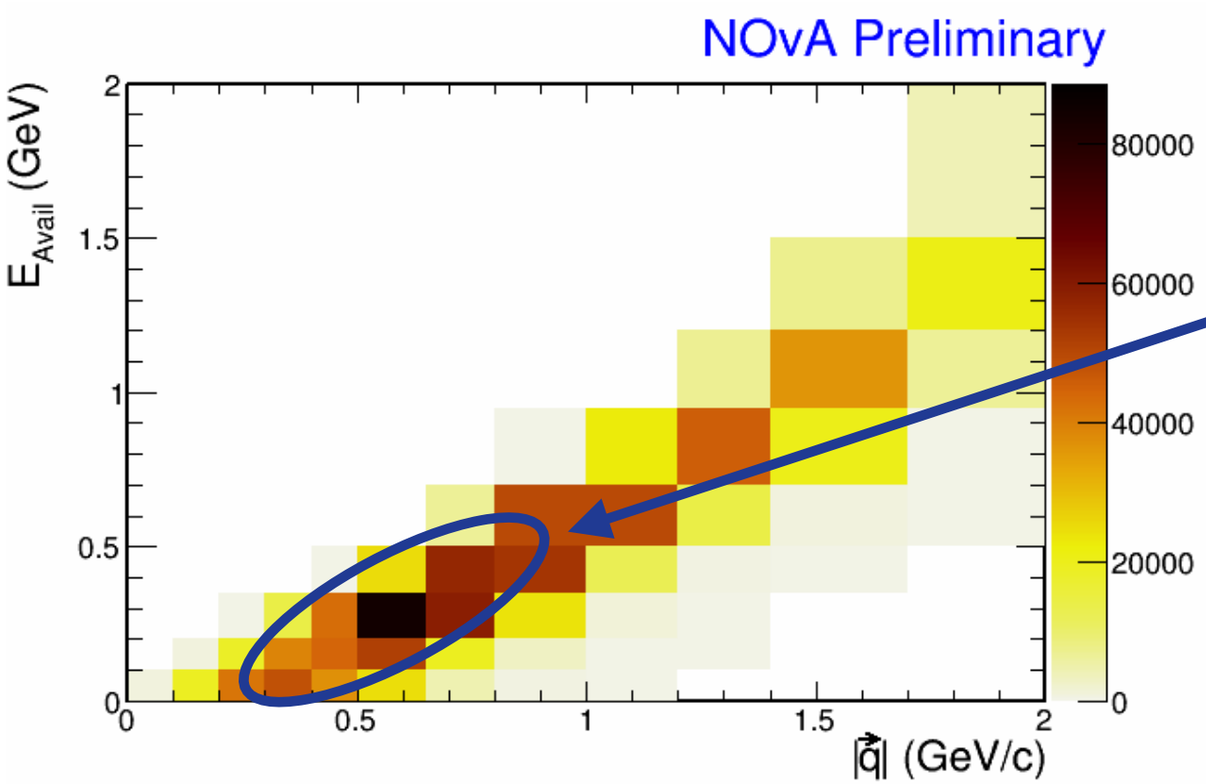
Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ of $\bar{\nu}_e$ appearance

Hadronic System

- NOvA's first measurement in $|\vec{q}|$ and hadronic energy:
  - **Inclusive**.
  - MEC concentrated at low values.

- Cross section reported at 67 kinematic points:
  - Typically ~12% uncertainty.
  - Dominated by flux systematic.



MEC events concentrated here

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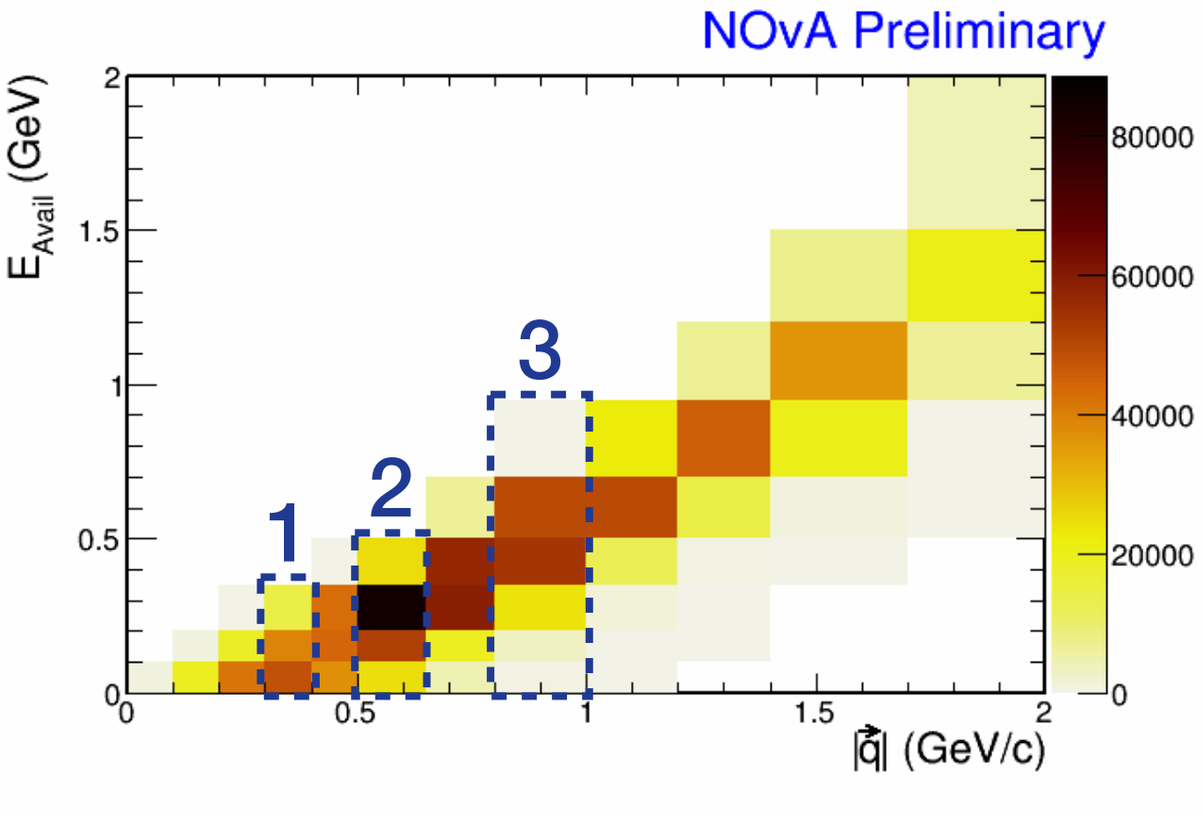
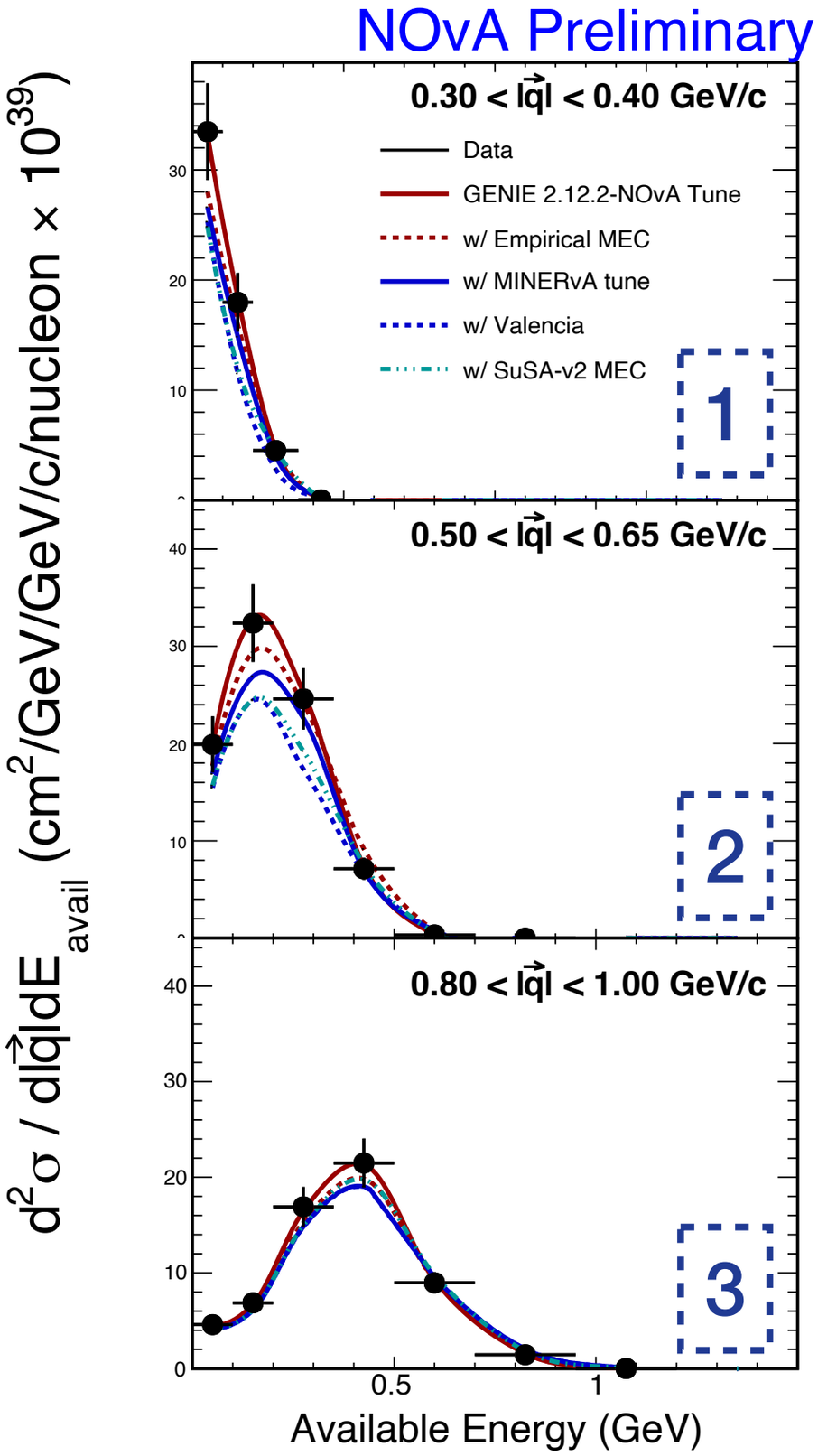
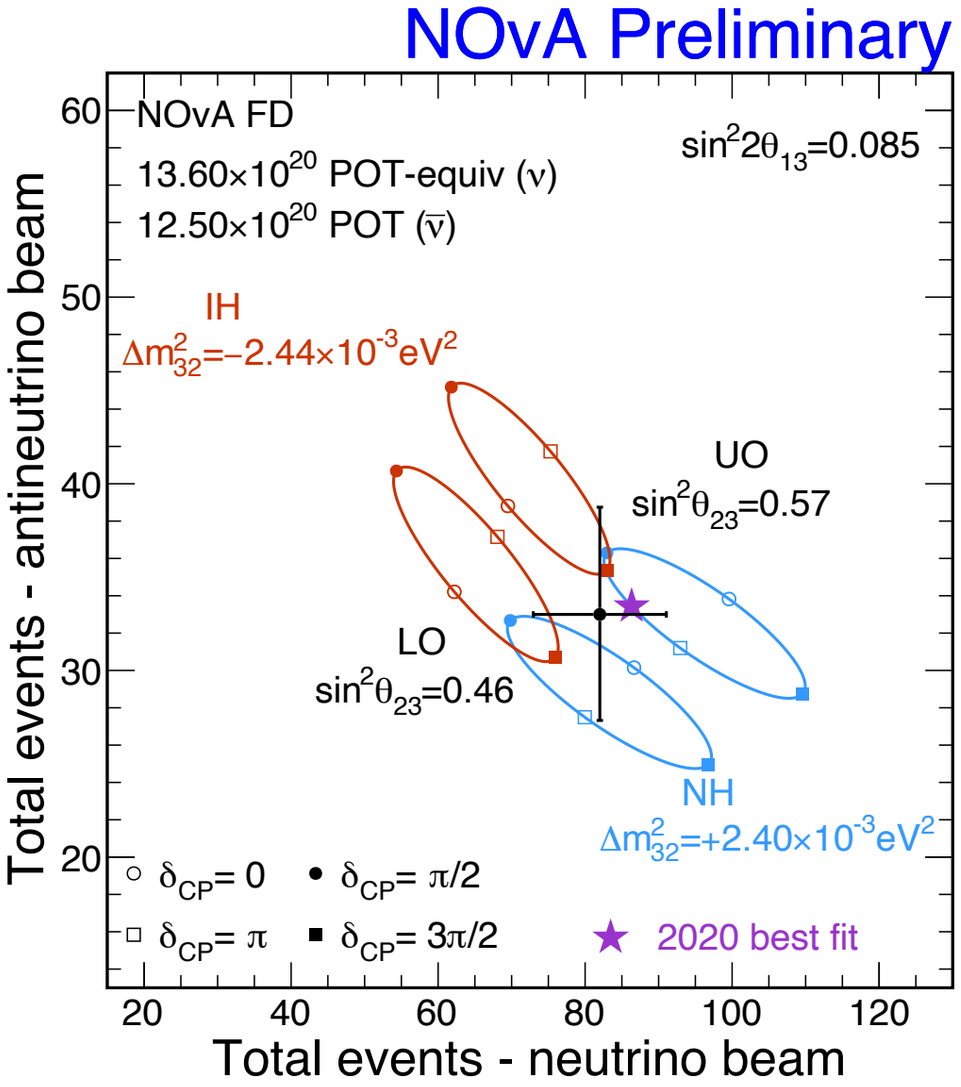
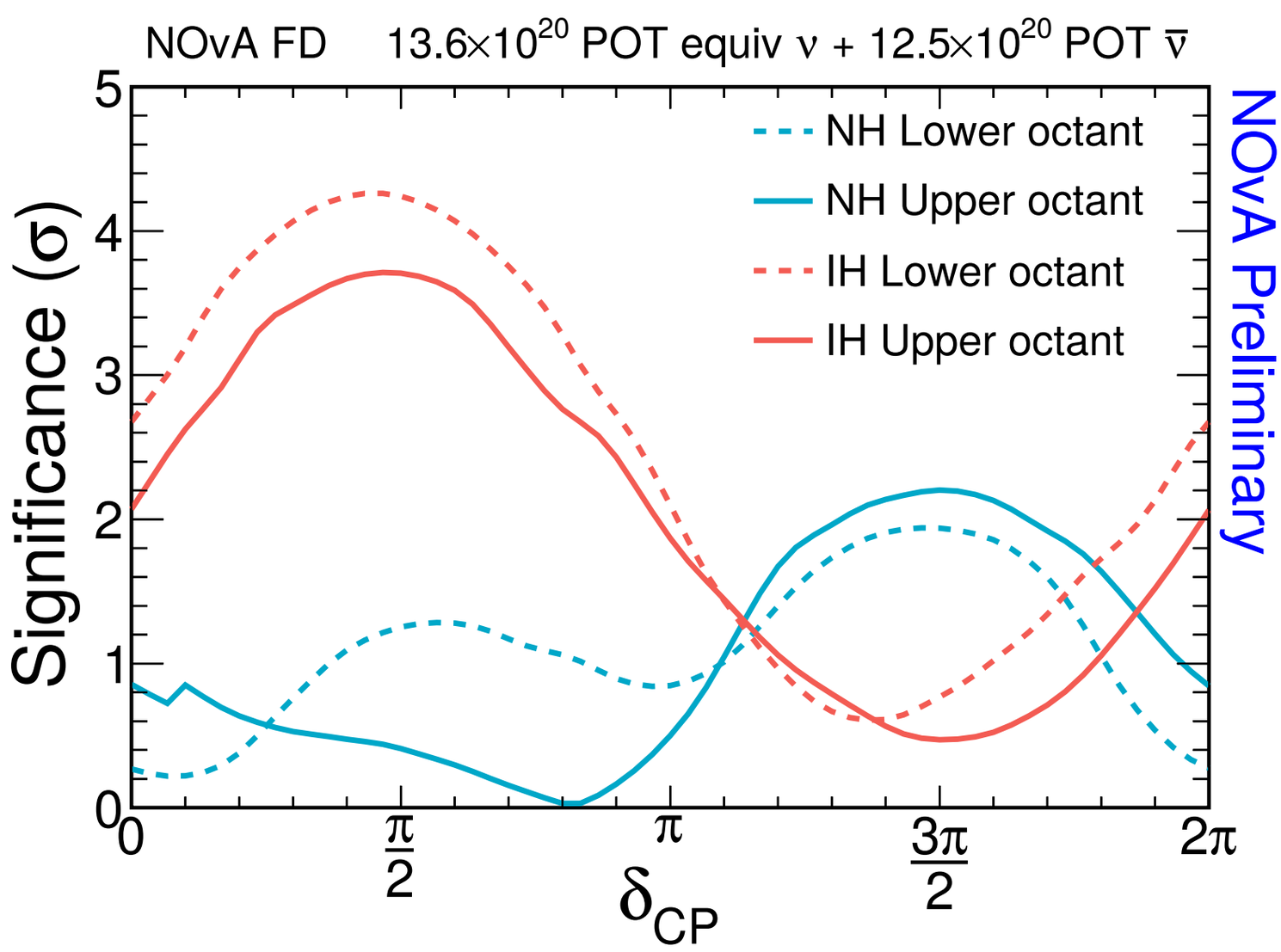




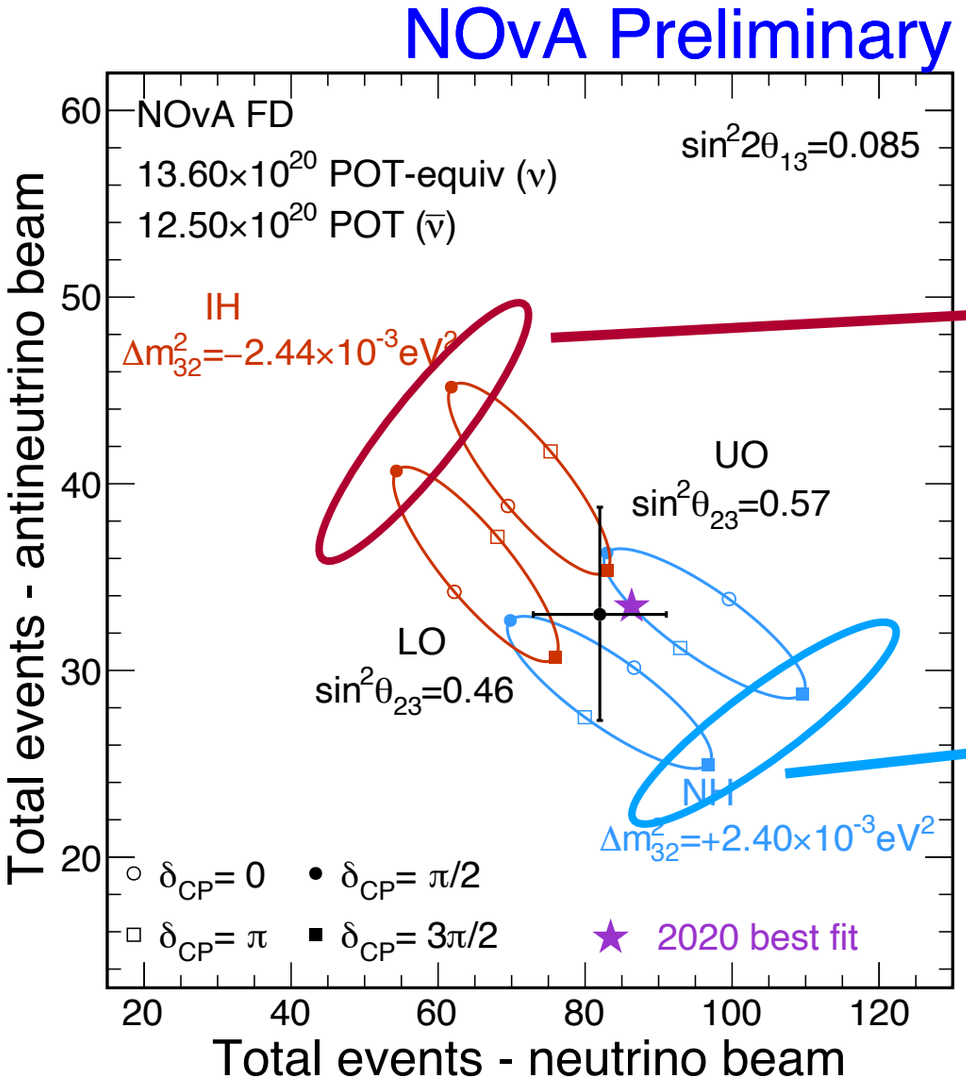
δ_{CP}

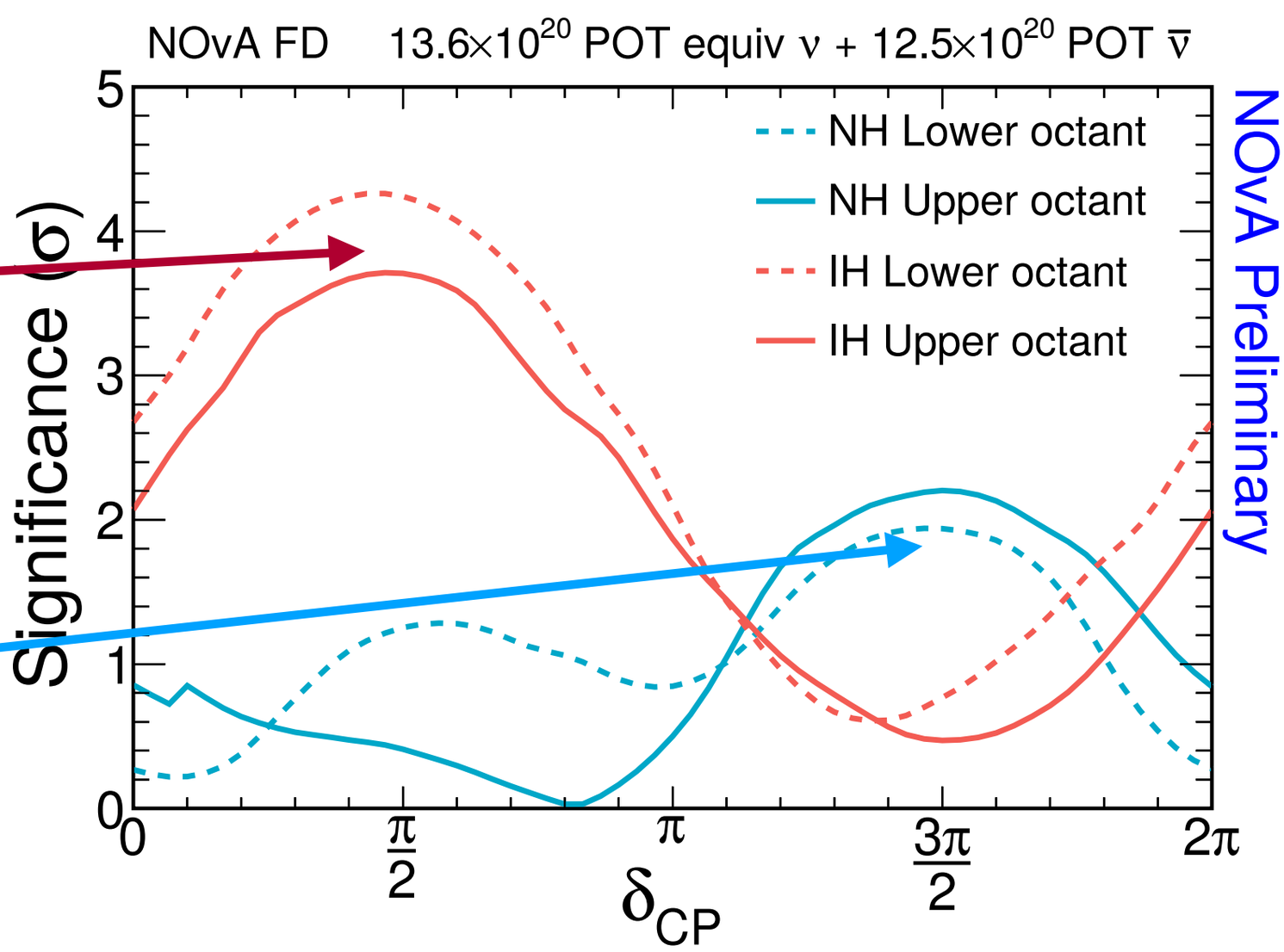




- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.

δ_{CP}



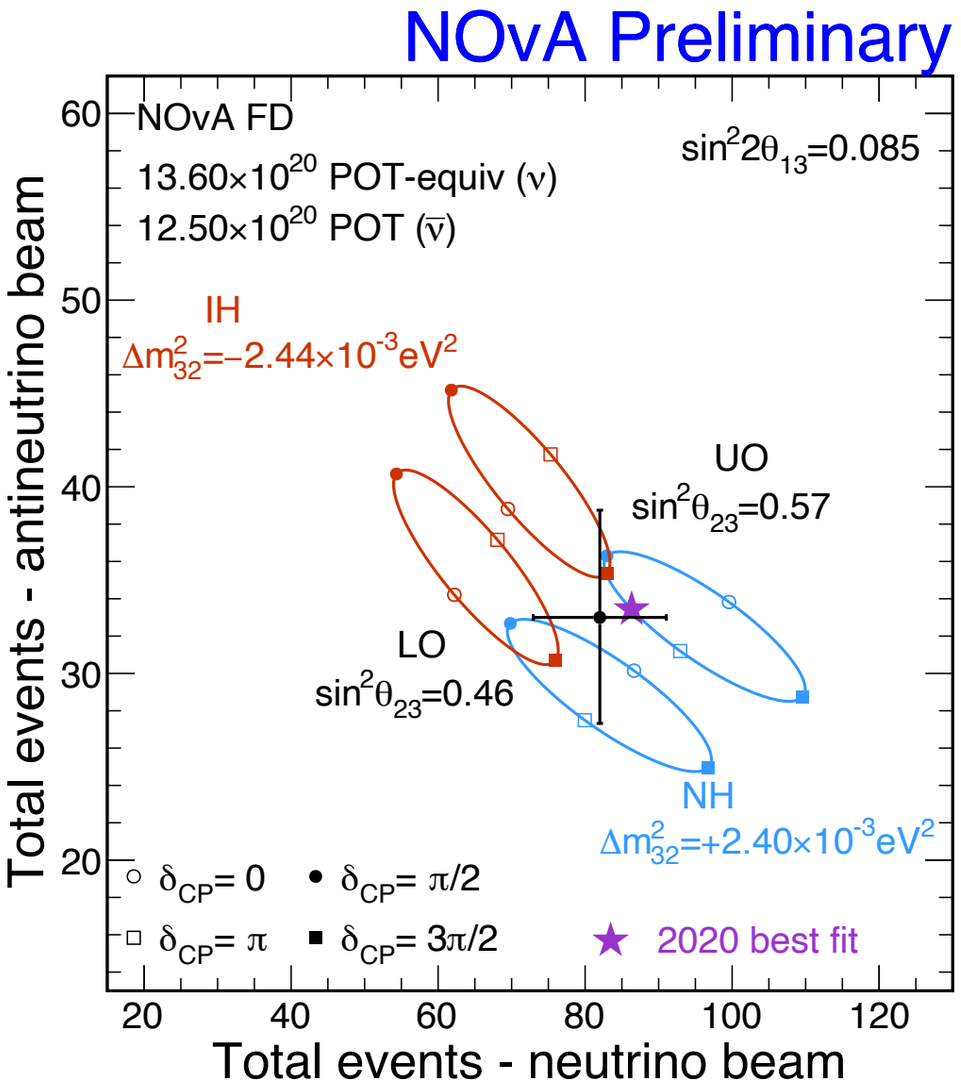


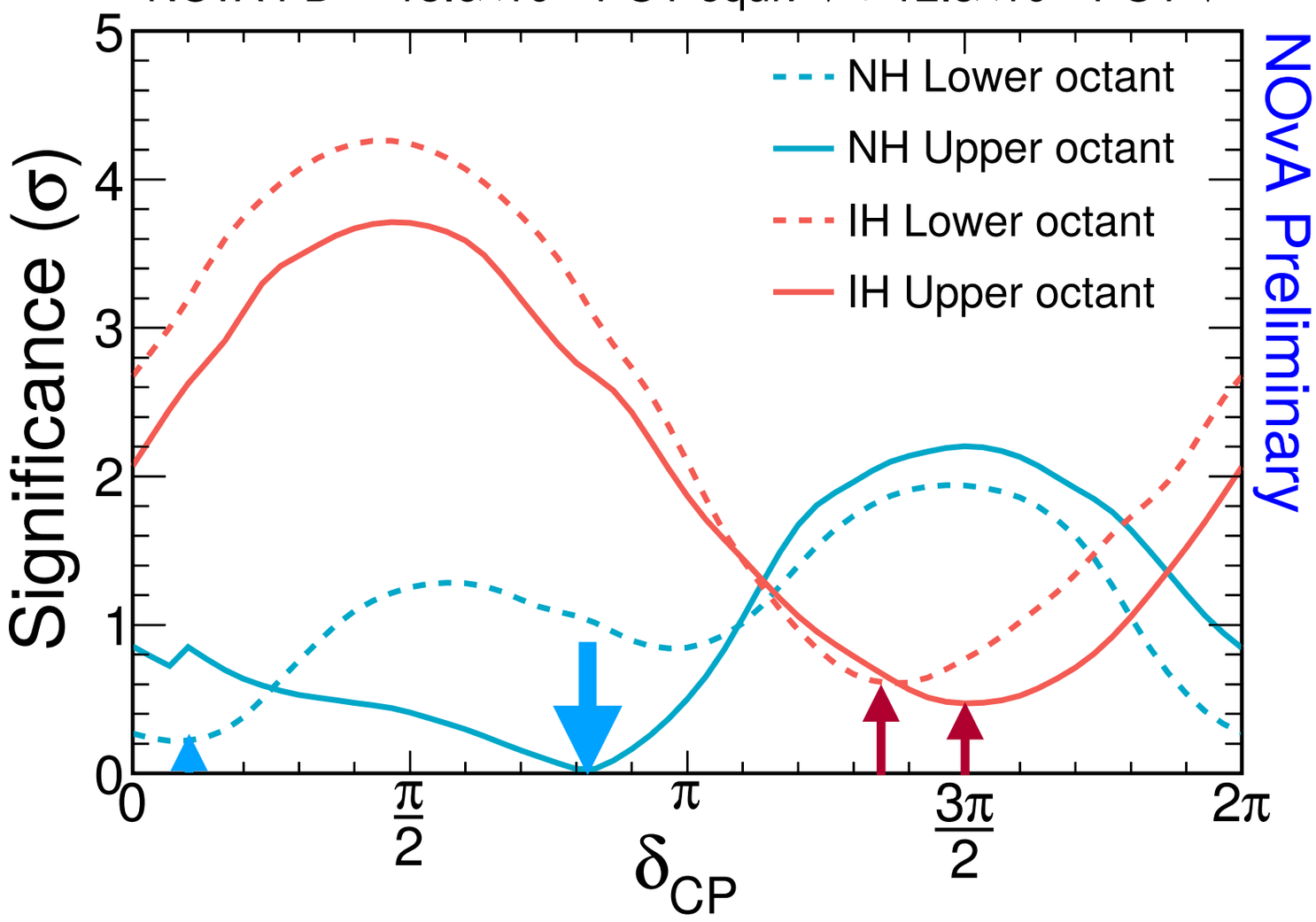
- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour hierarchy-δ_{CP} combinations which would produce asymmetry.

Exclude IH $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$

Disfavour NH $\delta_{CP} = \frac{3\pi}{2}$ at $\sim 2\sigma$

δ_{CP}





- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour hierarchy-δ_{CP} combinations which would produce asymmetry.

Prefer:
Normal Hierarchy at 1σ
Upper Octant at 1.2σ

Frequentist Result: NOvA-T2K

Best Fit

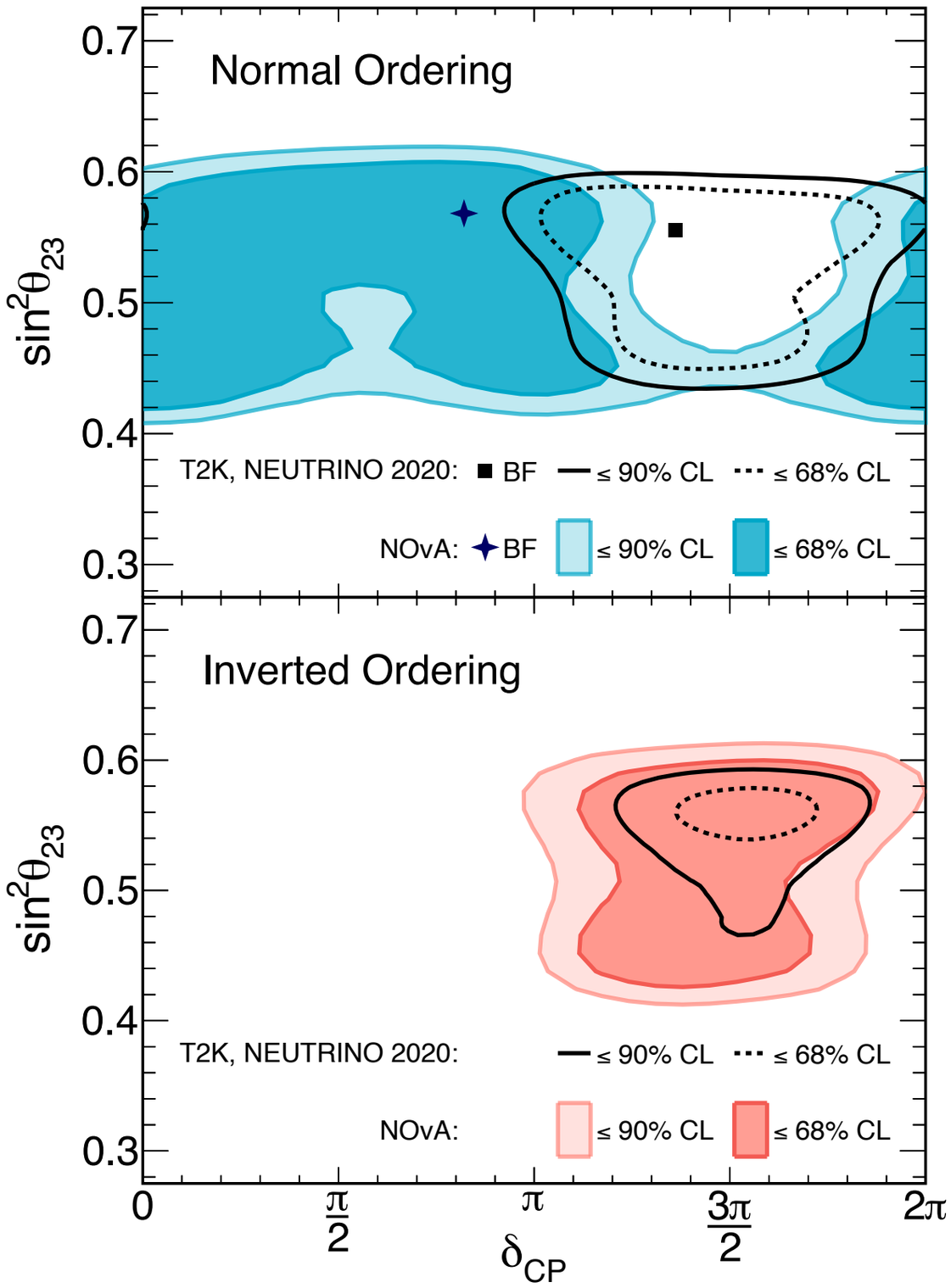
Normal hierarchy

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

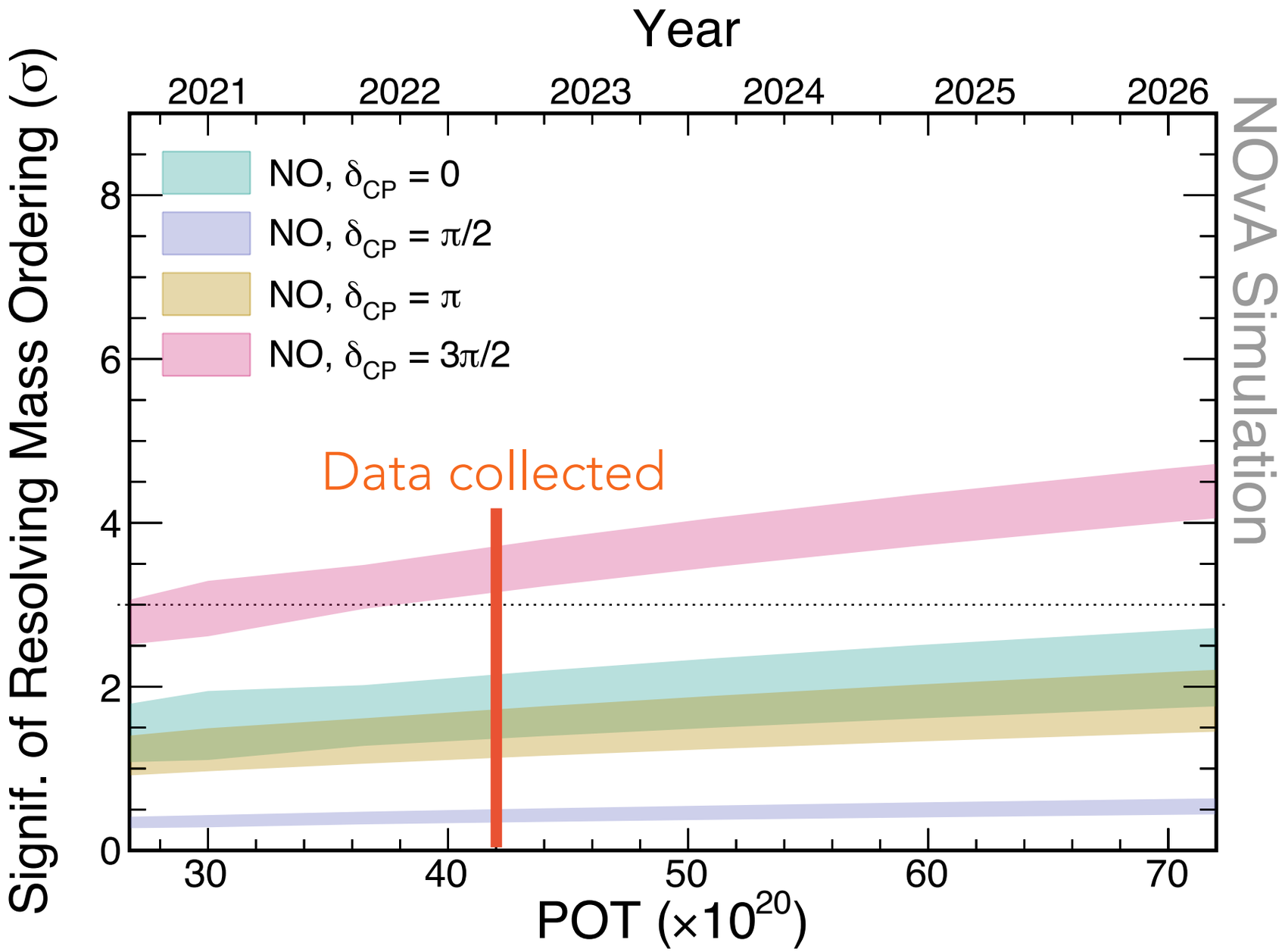
$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$

- Significant progress on a joint fit with T2K.
- Coming later this year!



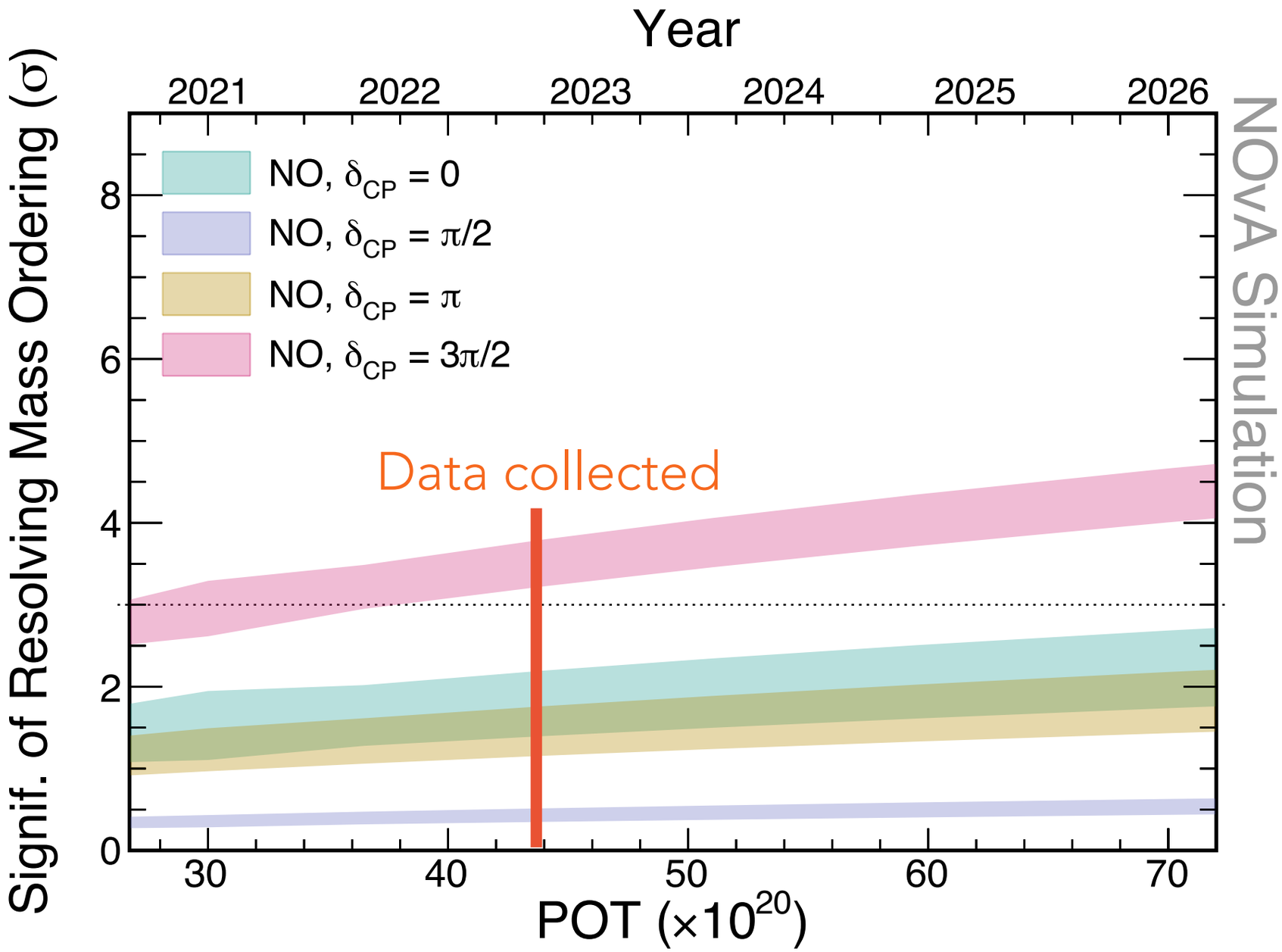
Future Prospects



- Increasing sensitivity to the mass ordering to come, will more than double the dataset in both beam modes.

- Greater than 3 σ mass ordering sensitivity for 30 - 40% of δ_{CP} values.

Future Prospects



- Joint fit with T2K coming this year.
- Antineutrino beam cross section measurements.