ICHEP 2022 BOLOGNA

Measurement of Standard and Non-standard Oscillations at NOvA

THE UNIVERSITY of MISSISSIPPI

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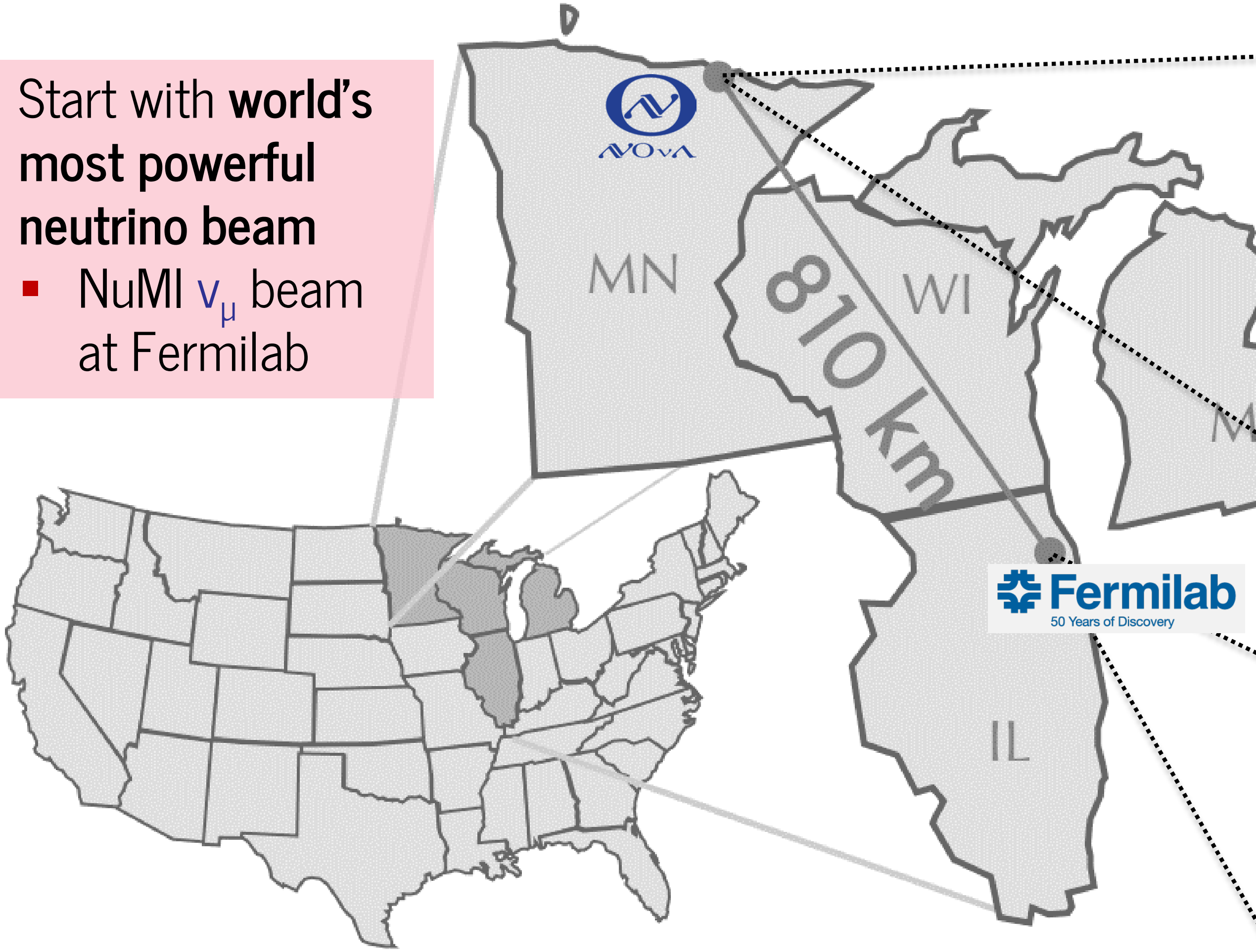
for the NOvA collaboration

Bologna, Italy: July 7th, 2022

The NOvA experiment

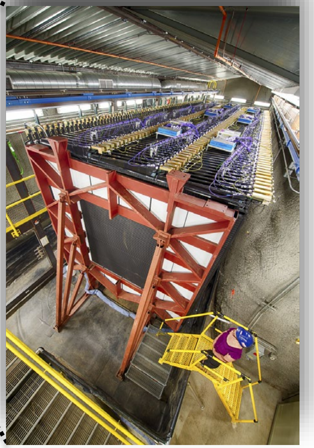
Start with **world's most powerful neutrino beam**

- NuMI ν_μ beam at Fermilab



Far Detector

Near Detector

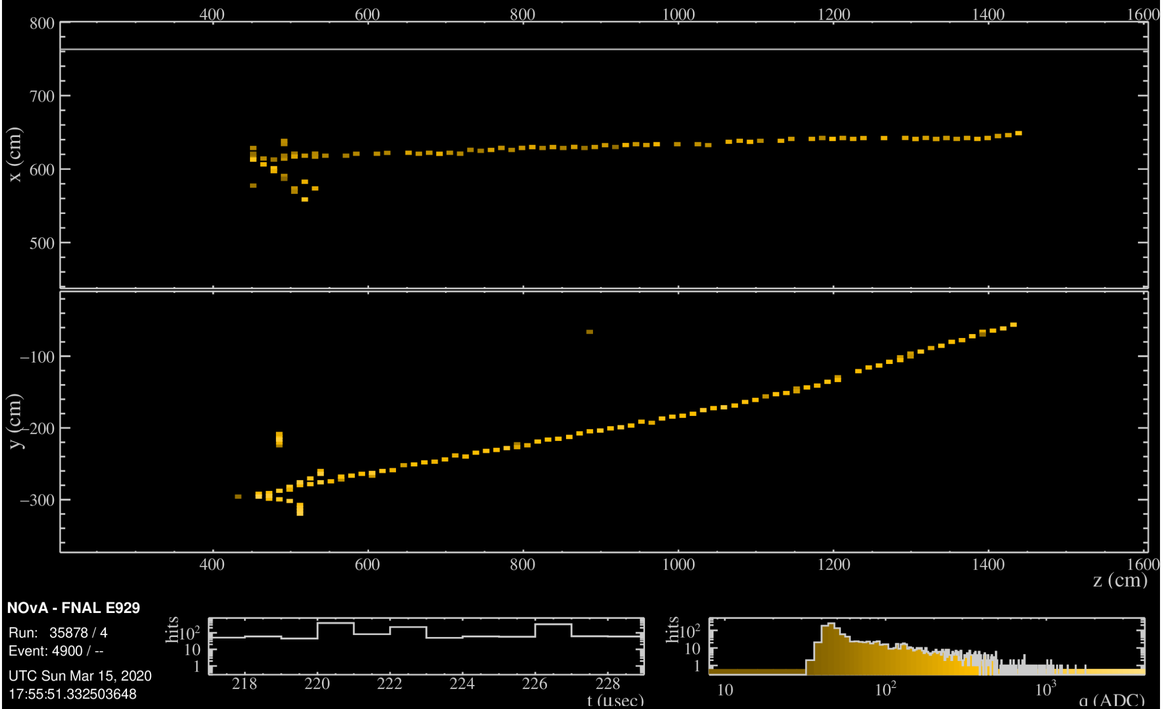


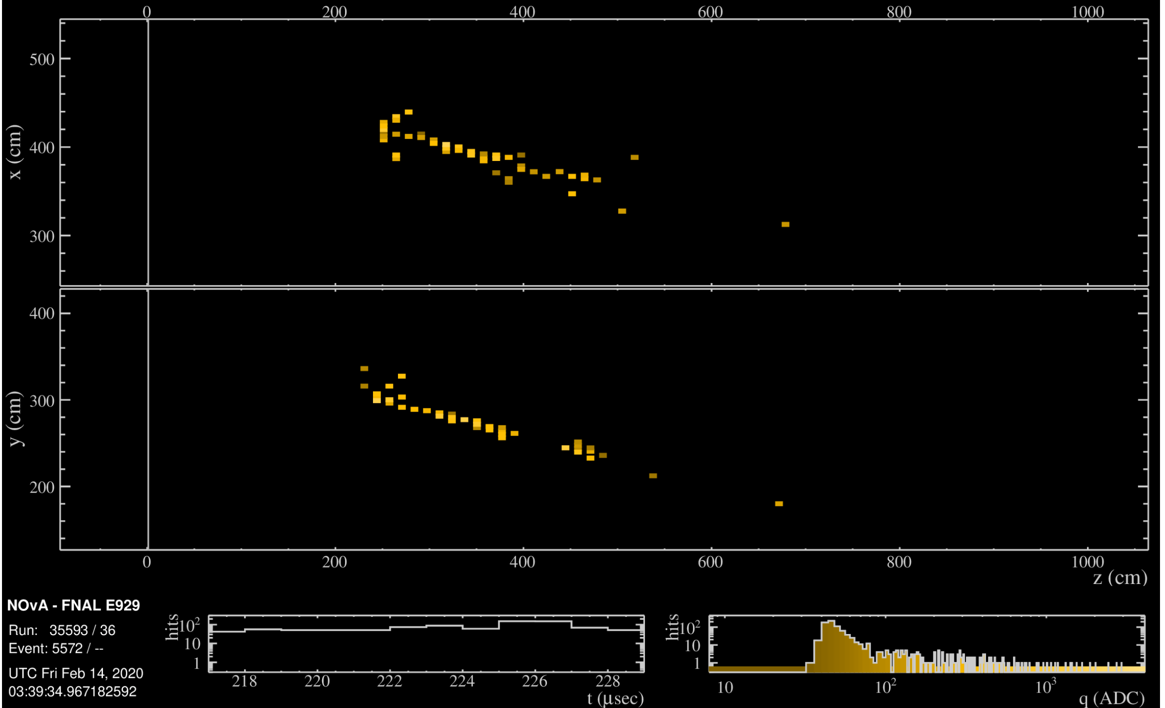
NOvA addresses many compelling questions surrounding the nature of neutrino mass

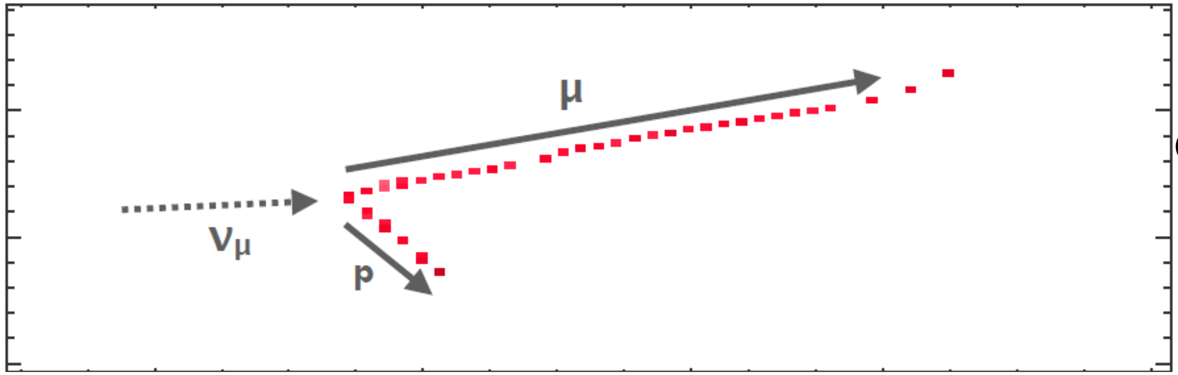
- What is the Neutrino Mass Hierarchy?
- Is there CP symmetry violation in neutrinos?
- Is there more to it than 3x3 PMNS?

New MW-capable target and MW-capable horn installed.
New **NuMI** power record **893 kW**

Candidate Events

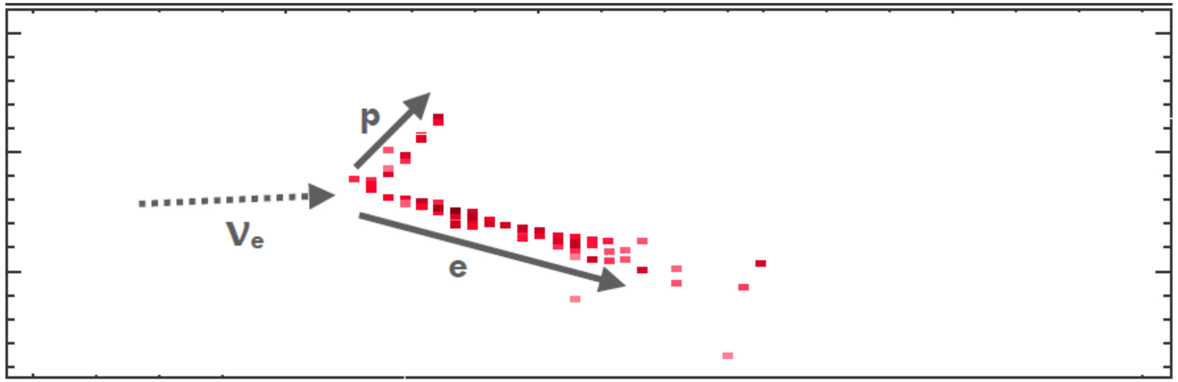




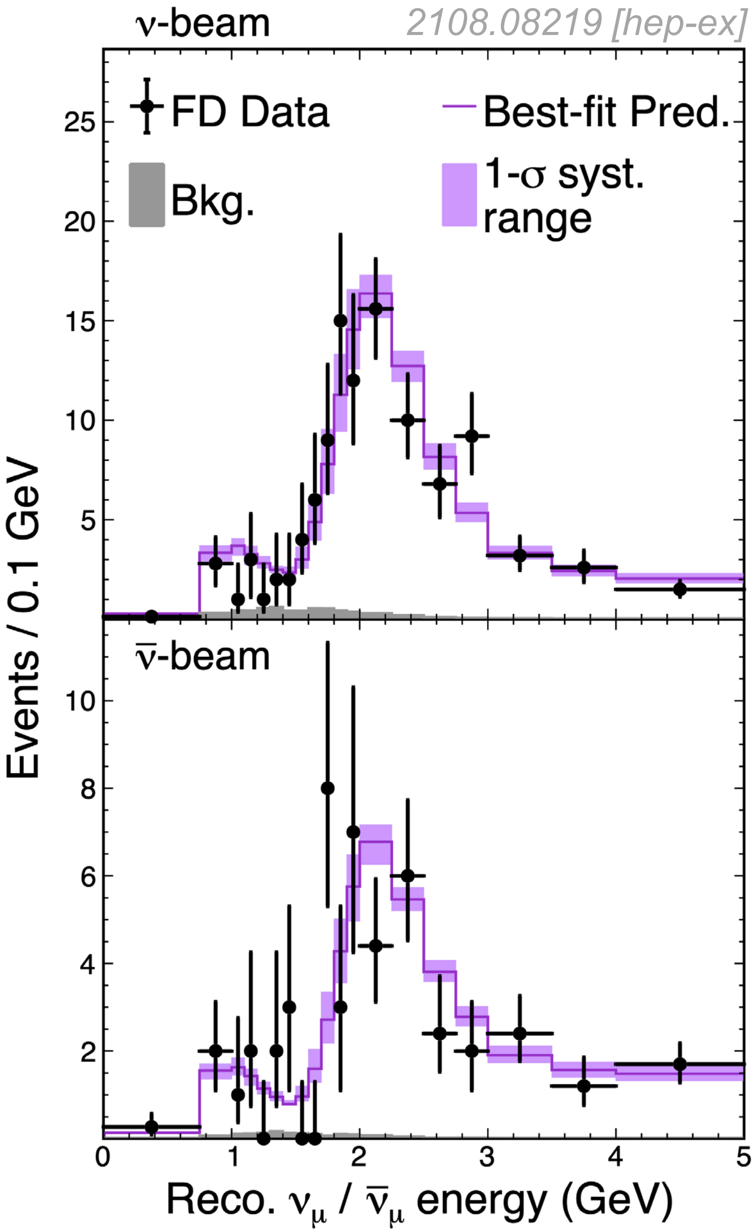


ν_μ CC

ν_e CC



2020 Far Detector Spectra



Fit the four datasets simultaneously:

ν_μ	Obs.	Best Fit	Bg.
ν	211	222.3	8.2
$\bar{\nu}$	105	105.4	2.1

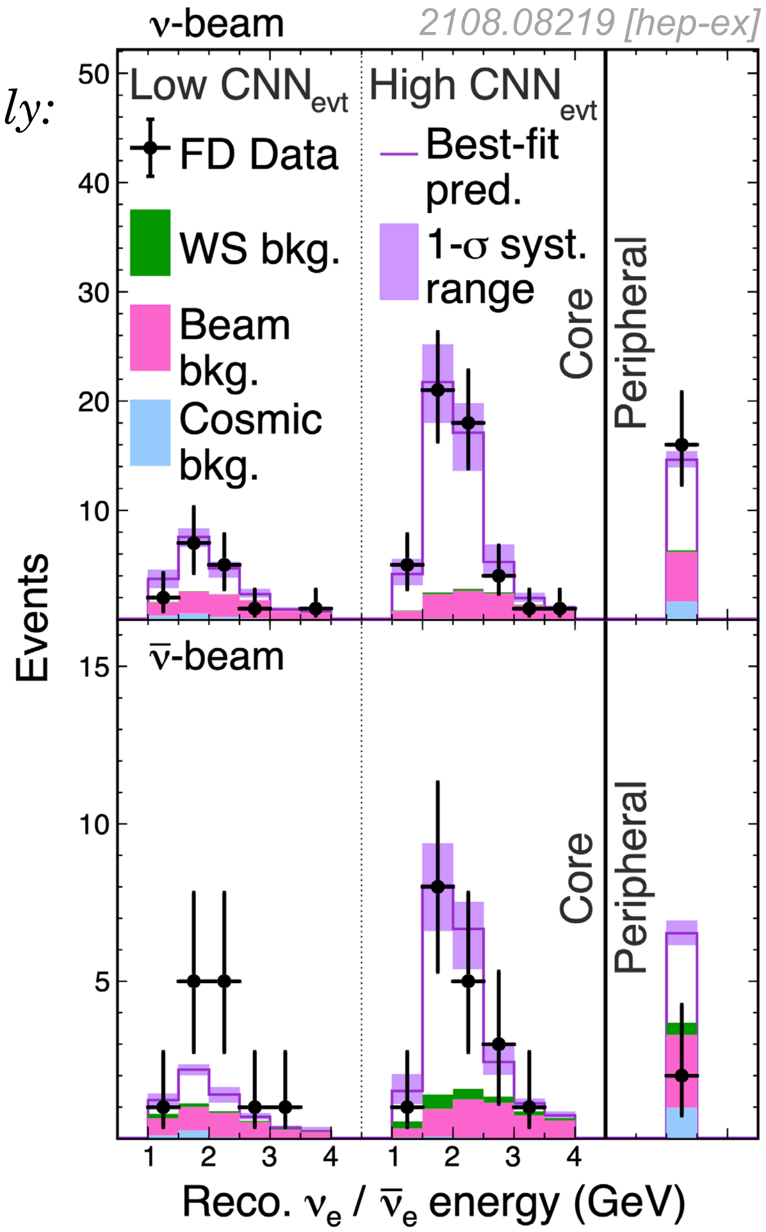
Very high purity selection for both ν and $\bar{\nu}$ modes

ν_e	Obs.	Best Fit	Bg.
ν	82	85.8	26.8
$\bar{\nu}$	33	33.2	14.0

Backgrounds primarily from $\boldsymbol{\nu_e}$ **intrinsic** to the beam (irreducible)

>4σ $\bar{\boldsymbol{\nu}}_{\boldsymbol{e}}$ appearance

Disfavor strong asymmetry in $\boldsymbol{\nu_e}$-$\bar{\boldsymbol{\nu}}_{\boldsymbol{e}}$ appearance



Bayesian Analysis Results

An alternative statistical treatment

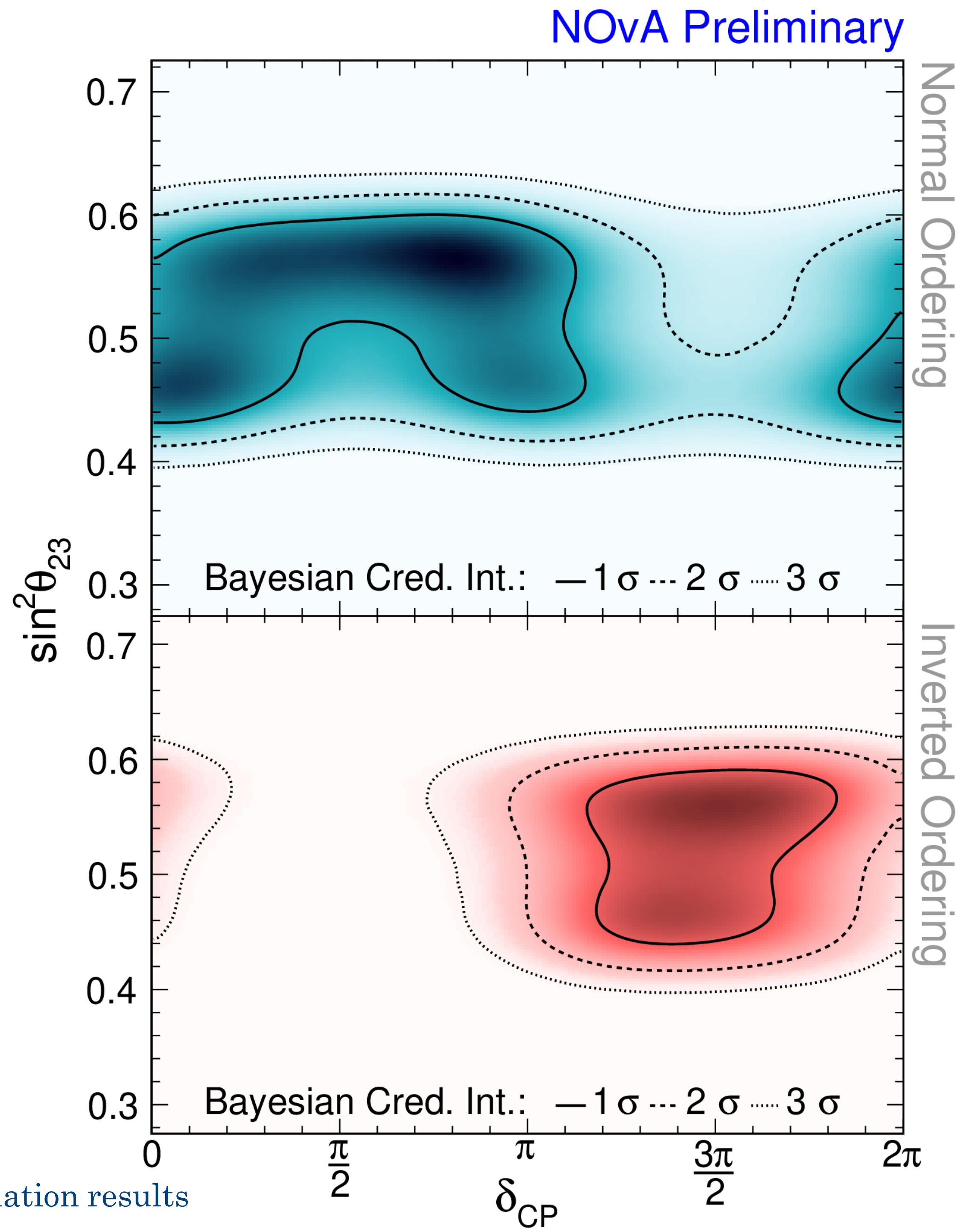
Markov Chain MC Bayesian analysis

Conclusions drawn from the data are the same as in previous frequentist analysis

Exclude δ_{CP}=π/2 at >3σ (IO)

Less strong constraint on δ_{CP} in the NO, but **disfavour** region around δ_{CP}= 3π/2

Weak preference for NO, Upper octant



Beyond standard oscillations: NSI

Non-standard interactions (NSI): anomalous interactions between neutrinos with matter.

For NSI, add matter potential terms analogous to MSW allowing for flavor-changing and flavor-conserving NSI scattering

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

$$\mathcal{H} = \frac{1}{2E}\left[U_{PMNS} \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U_{PMNS}^\dagger + a \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \right]$$

$a \equiv 2\sqrt{2} G_F N_e E$ *[Wolfenstein matter potential]*

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| e^{i\delta_{\alpha\beta}}$$

- **On-diagonal terms**, could be interpreted as the NSI *effective mass squared differences:* real-valued
- **Off-diagonal terms**, could play a role similar to the mixing angles: complex; $\boldsymbol{\varepsilon_{\mu\tau}}$, $\boldsymbol{\varepsilon_{e\tau}}$, $\boldsymbol{\varepsilon_{e\mu}}$
    - may carry CP-violating phases; $\boldsymbol{\delta_{\mu\tau}}$, $\boldsymbol{\delta_{e\tau}}$, $\boldsymbol{\delta_{e\mu}}$

NOvA and NSI

NOvA is sensitive to the off-diagonal, flavor-changing NSI parameters (treated as complex)

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| e^{i\delta_{\alpha\beta}} \longrightarrow \begin{array}{l} \boldsymbol{\varepsilon_{\mu\tau}, \varepsilon_{e\tau}, \varepsilon_{e\mu}} \\ \boldsymbol{\delta_{\mu\tau}, \delta_{e\tau}, \delta_{e\mu}} \end{array}$$

Full Hamiltonian has many free parameters.

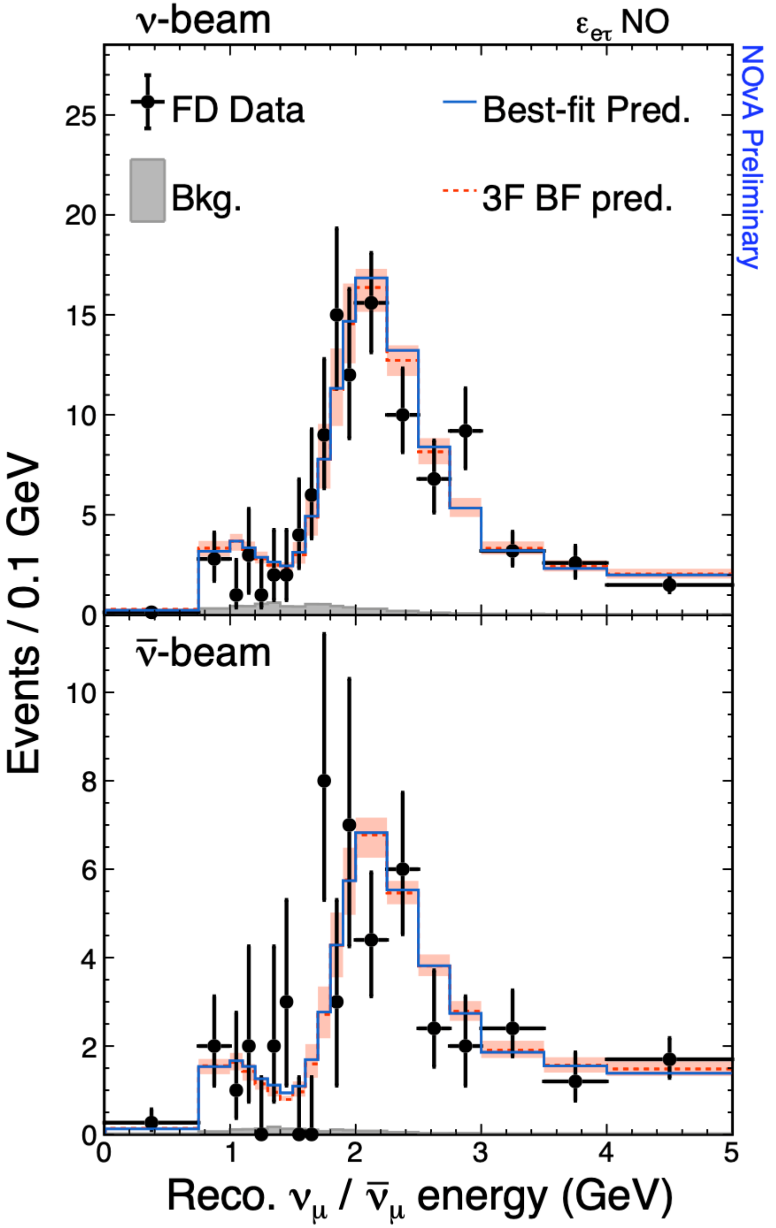
Perform a simultaneous fit to all 6 standard oscillation parameters and 1 NSI along with its associated complex phase: **a joint ν_μ-disappearance and ν_e-appearance fit**

Take the standard 2020 analysis/dataset/selection/extrapolation and refit in an NSI scenario.

Using reactor-only measurements of θ_{12}, θ_{13}, & Δm^2_{21} to avoid possible NSI contamination

Updated matter density, ρ, uncertainty : NSI strength is related to ρ

NSI Far Detector spectra: $\varepsilon_{e\tau}$



Fit the four datasets simultaneously

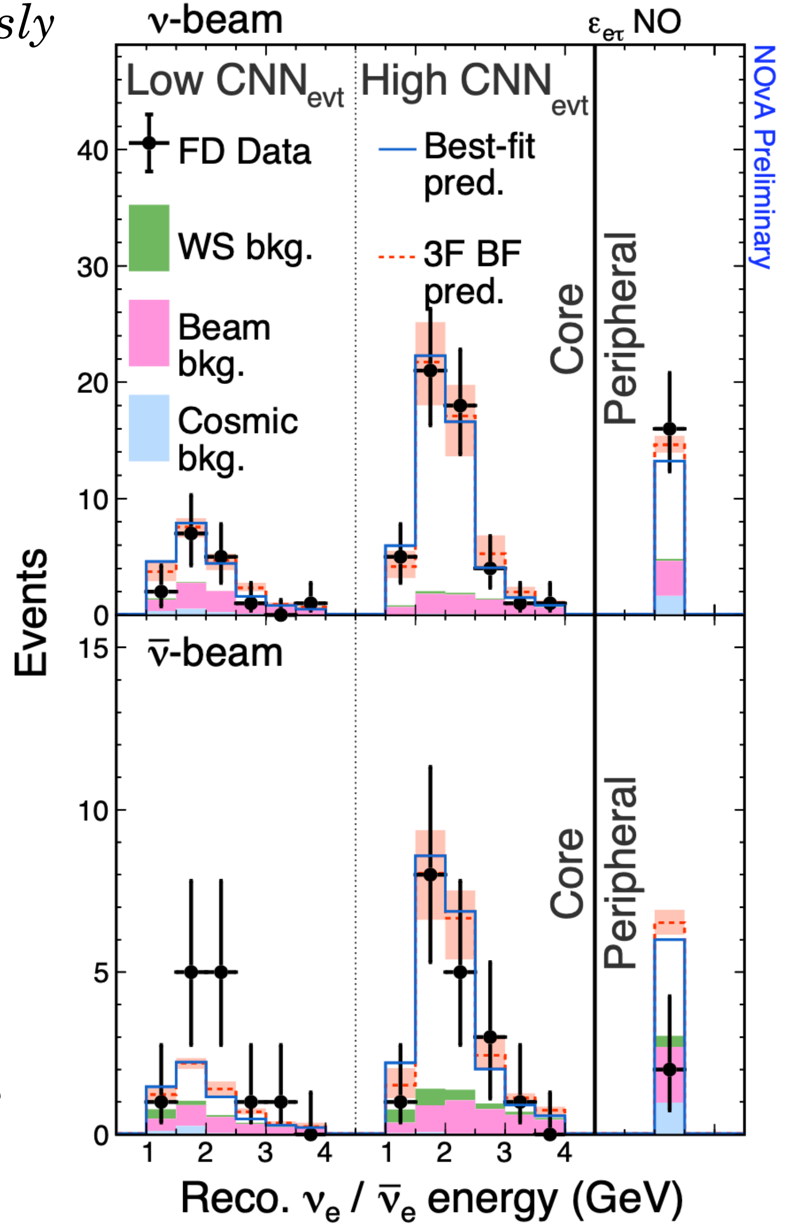
Off-diagonal components lead to a visible change in oscillation probability.
Appearance channel is affected by $\varepsilon_{e\tau}$, $\varepsilon_{e\mu}$

NSI best-fit comparable to the 2020 standard osc. (3-flavor) best fit

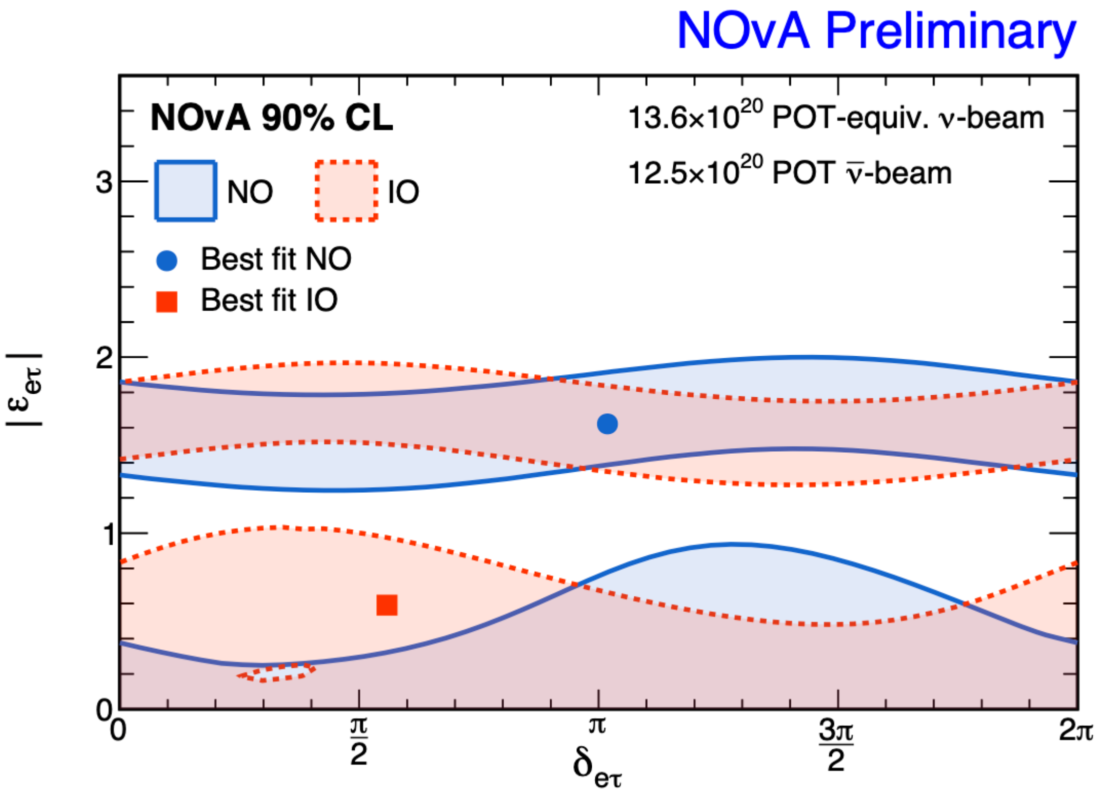
$\Delta\chi^2 \approx 0.65$

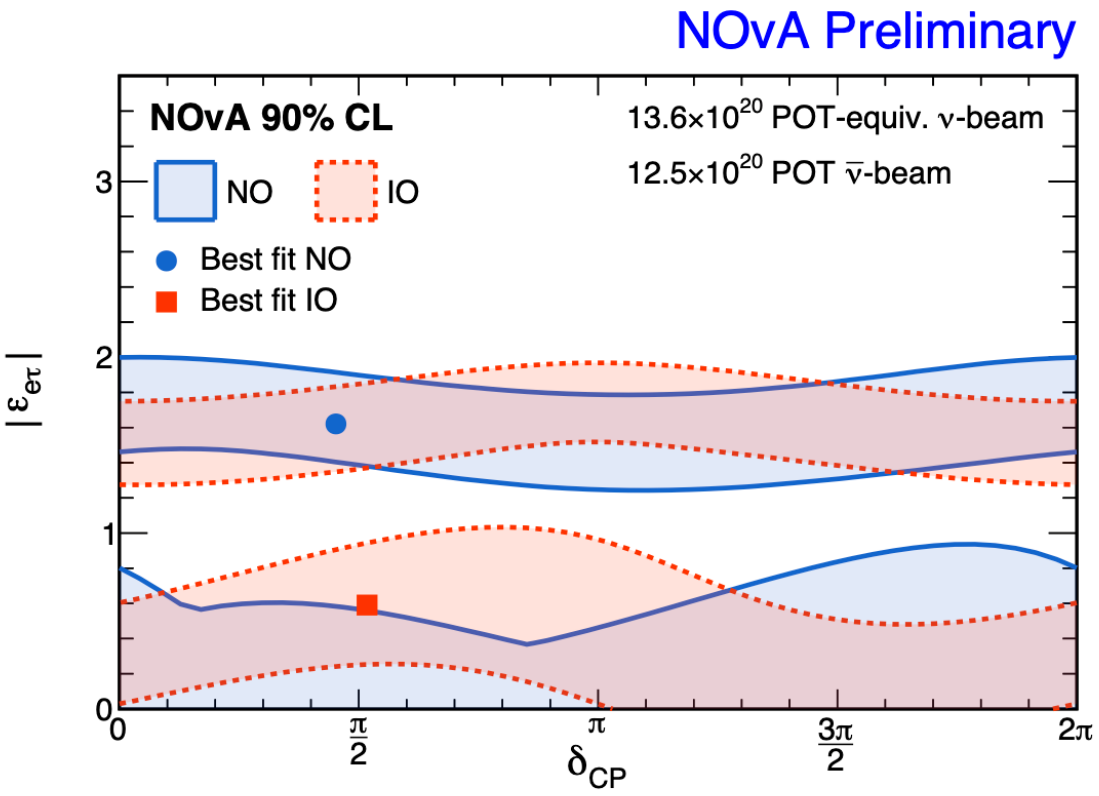
Well within the 3-flavor 1σ systematic range

Consistent with standard oscillations



NSI Analysis Results: $\varepsilon_{e\tau}$





Upper band arises from a degeneracy for which particular values mimic the std. osc. prediction

In the oscillation probability there are terms proportional to:

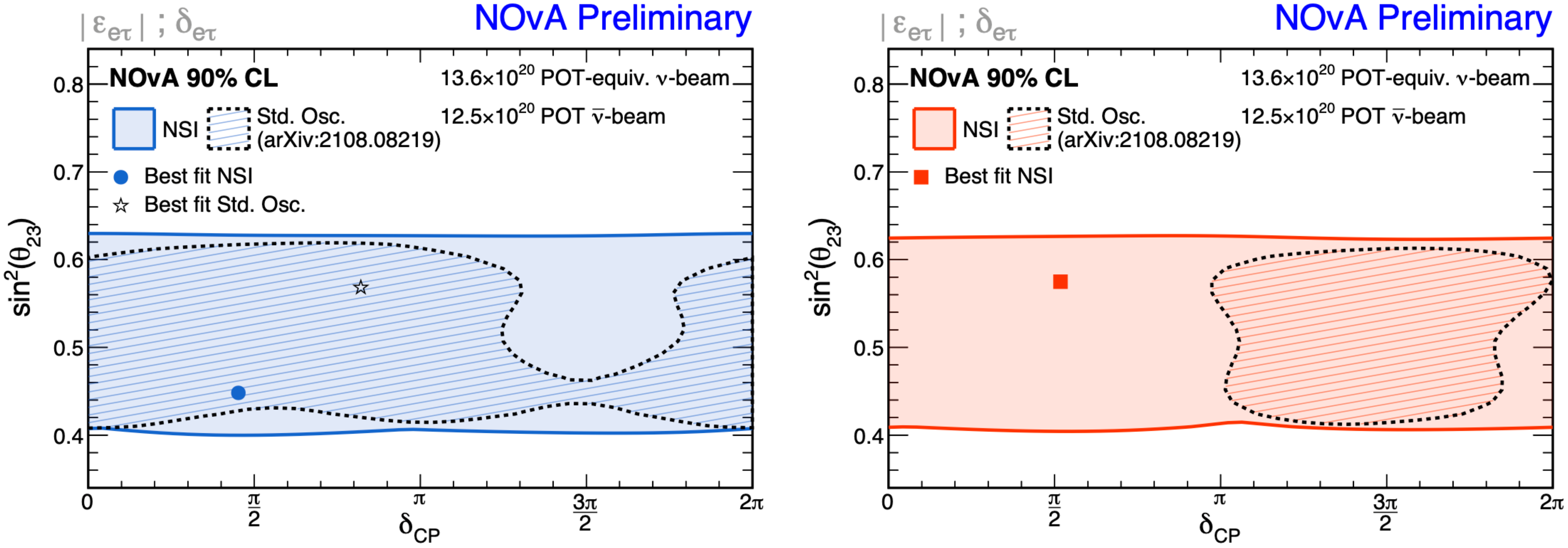
$$|\varepsilon_{e\tau}|\cos(\delta_{CP} + \delta_{e\tau})$$

When measuring one phase and profiling over unseen phase, smears over entire band.

A cyclic cosine dependence on sum of phases.

As $|\varepsilon_{e\tau}|$ increases, becomes dominant term.

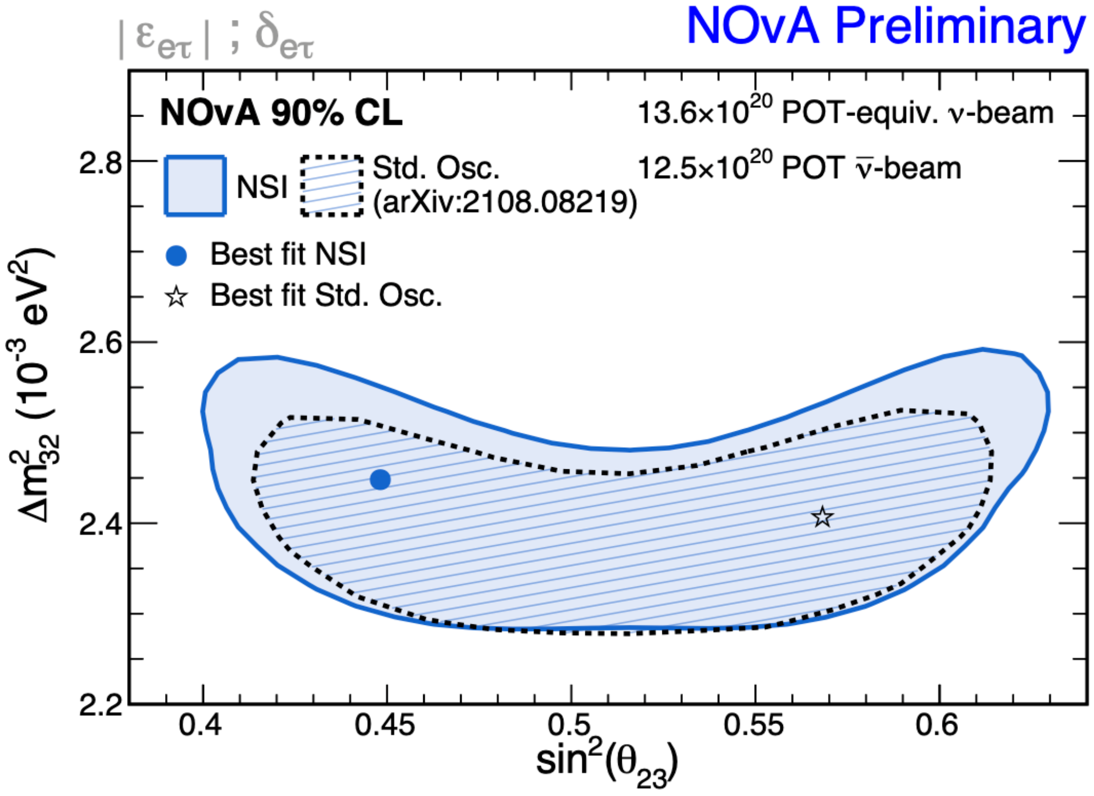
NOvA NSI and standard osc.: $\varepsilon_{e\tau}$

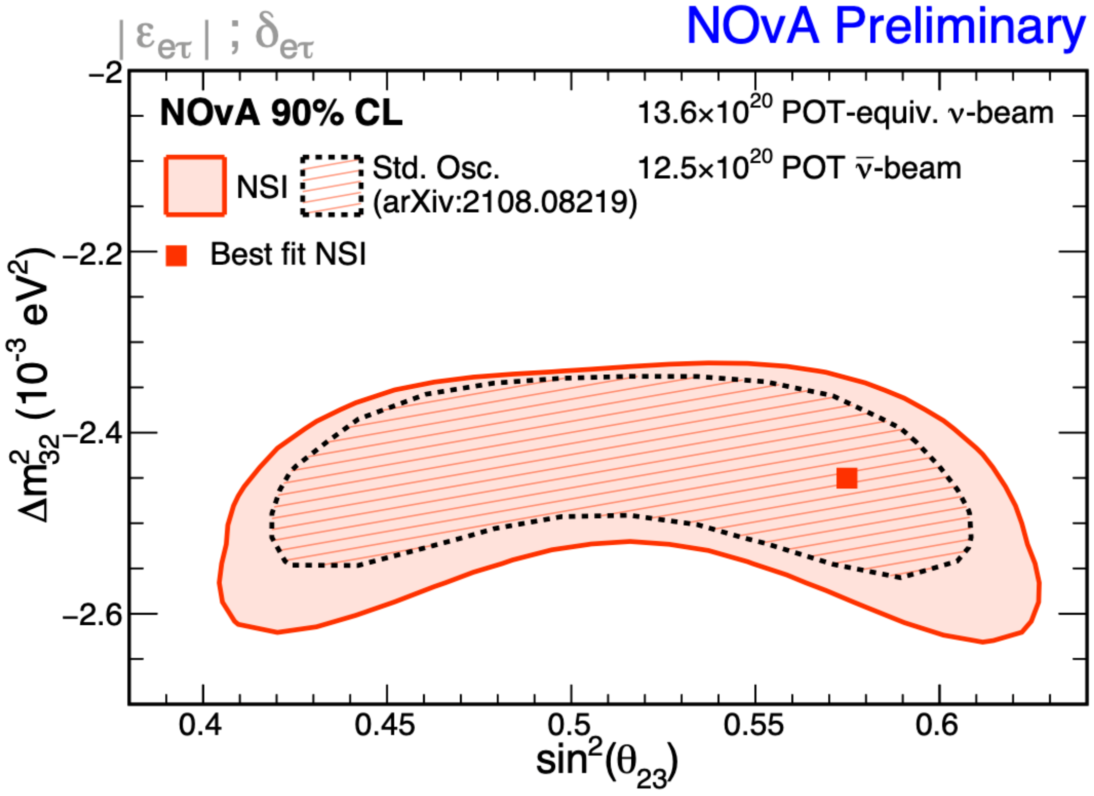


If we live in an NSI world, it can dramatically change our standard oscillation interpretation.

In the $\varepsilon_{e\tau}$ channel, NSI presence further reduces interpretation

NOvA NSI and standard osc.: $\varepsilon_{e\tau}$





If we live in an NSI world, it can dramatically change our standard oscillation interpretation.

NSI effect is largest and significant on δ_{CP}.
The large mixing angle, θ_{23}, and Δm^2_{32} are comparatively unaffected.

Neutrino 2022 results: [DOI:10.5281/zenodo.6683827](https://doi.org/10.5281/zenodo.6683827)

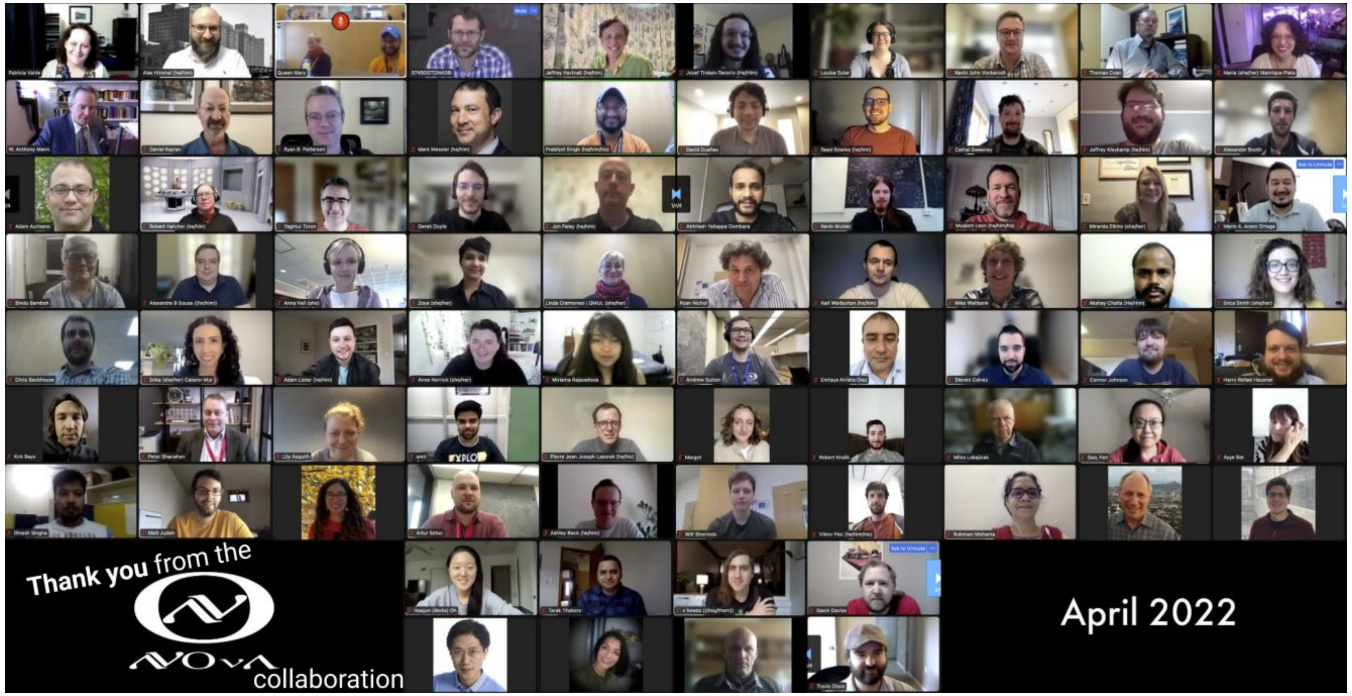
Coming up in this session: **Deep Learning Event Reconstruction at NOvA [Jianming Bian]**
Neutrino Scattering Measurements at NOvA [Linda Cremonesi]

NOvA is well suited to investigating key questions in Neutrino Physics.

Standard Oscillations:
New Bayesian techniques: consistent with Frequentist analysis; measure θ_{13}

NOvA and T2K have joined forces on a joint fit
- Different baselines and energies provide complementary information
- Results expected this year

Non-standard Oscillations:
- Performed the first simultaneous measurement of δ_{CP} and NSI.
- Consistent with standard oscillations



http://novaexperiment.fnal.gov

https://novaexperiment.fnal.gov/publications/

BACKUP

Neutrinos vs. Antineutrinos

The power of two beam modes:

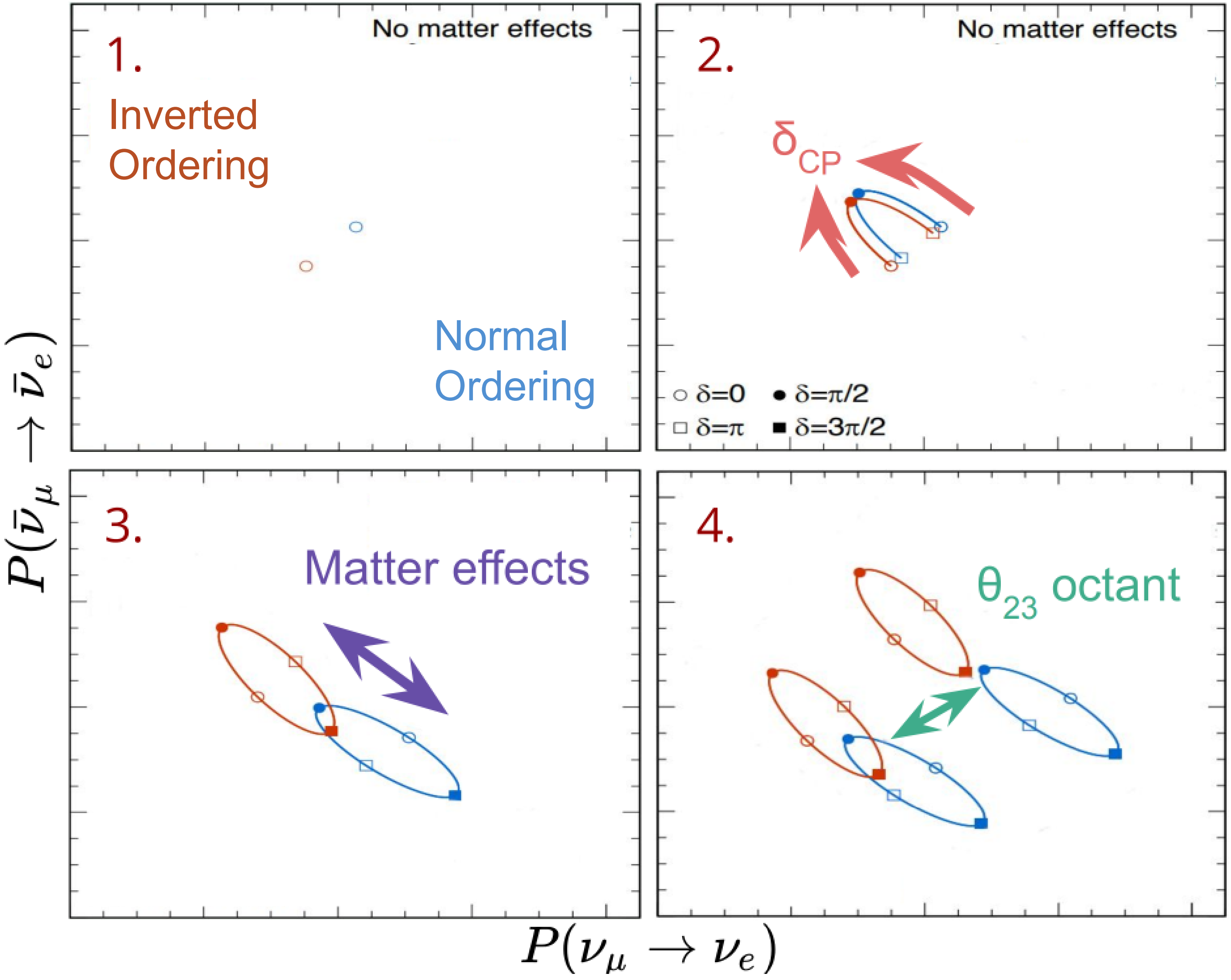
1. Inverted ordering gives a **slight suppression** in both

2. **CP violation** causes **opposite effects** in each ordering

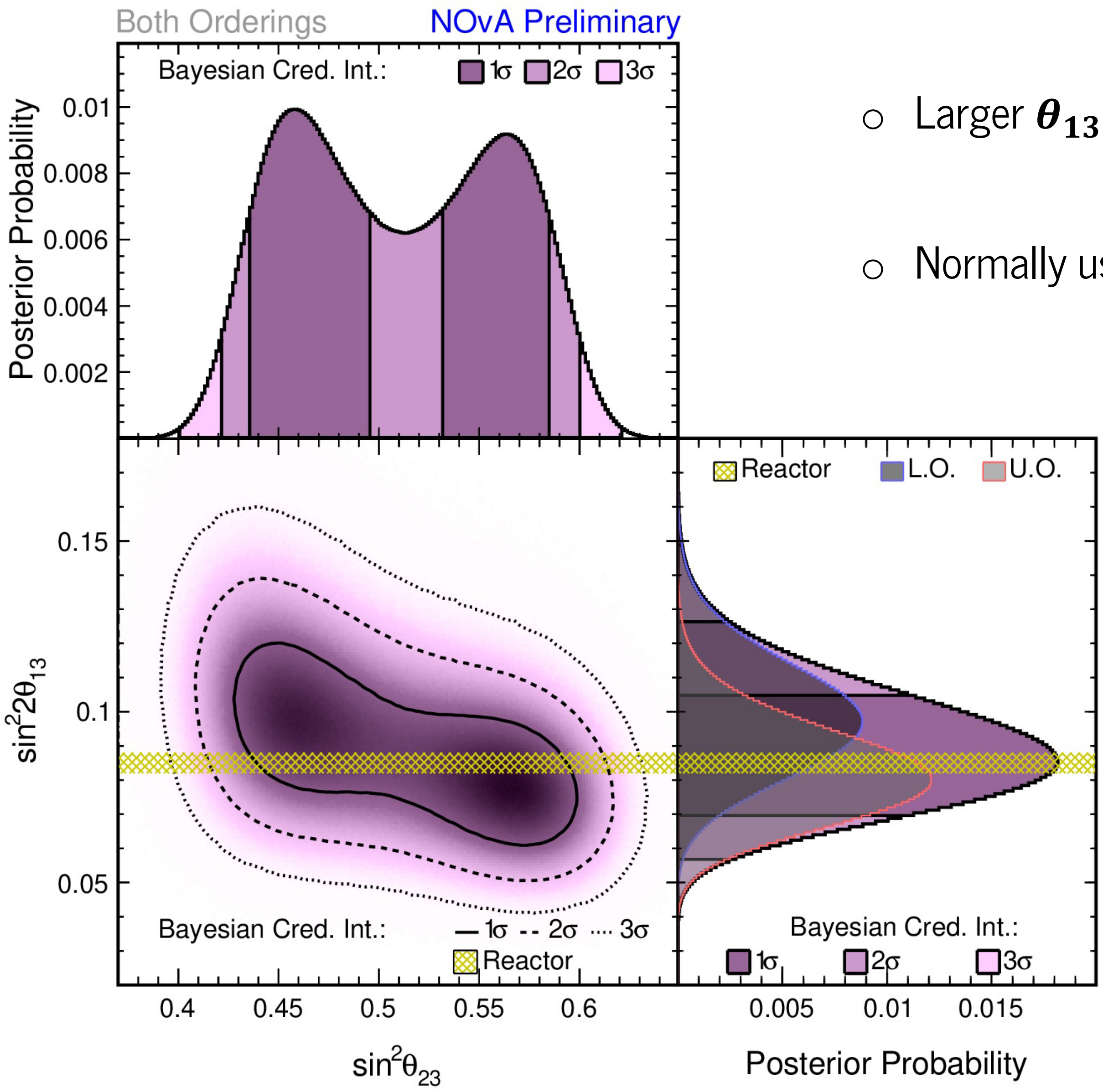
3. **Matter effects** also produce **opposite effects** in neutrinos and antineutrinos

4. The octant of θ_{23} causes either a **suppression** or **enhancement**

   i.e. $\theta_{23} < 0.5$ or > 0.5, where 0.5 is maximal mixing



NOvA-only θ_{13} & θ_{23} Results



- Larger $\boldsymbol{\theta_{13}}$ would favor lower octant for $\boldsymbol{\theta_{23}}$ and vice-versa
- Normally use reactor $\boldsymbol{\theta_{13}}$ constraint in fit
- Here $\boldsymbol{\theta_{13}}$ is measured by NOvA:

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

- Consistent with reactor experiments

NOvA 2020 Standard Osc. Frequentist Result

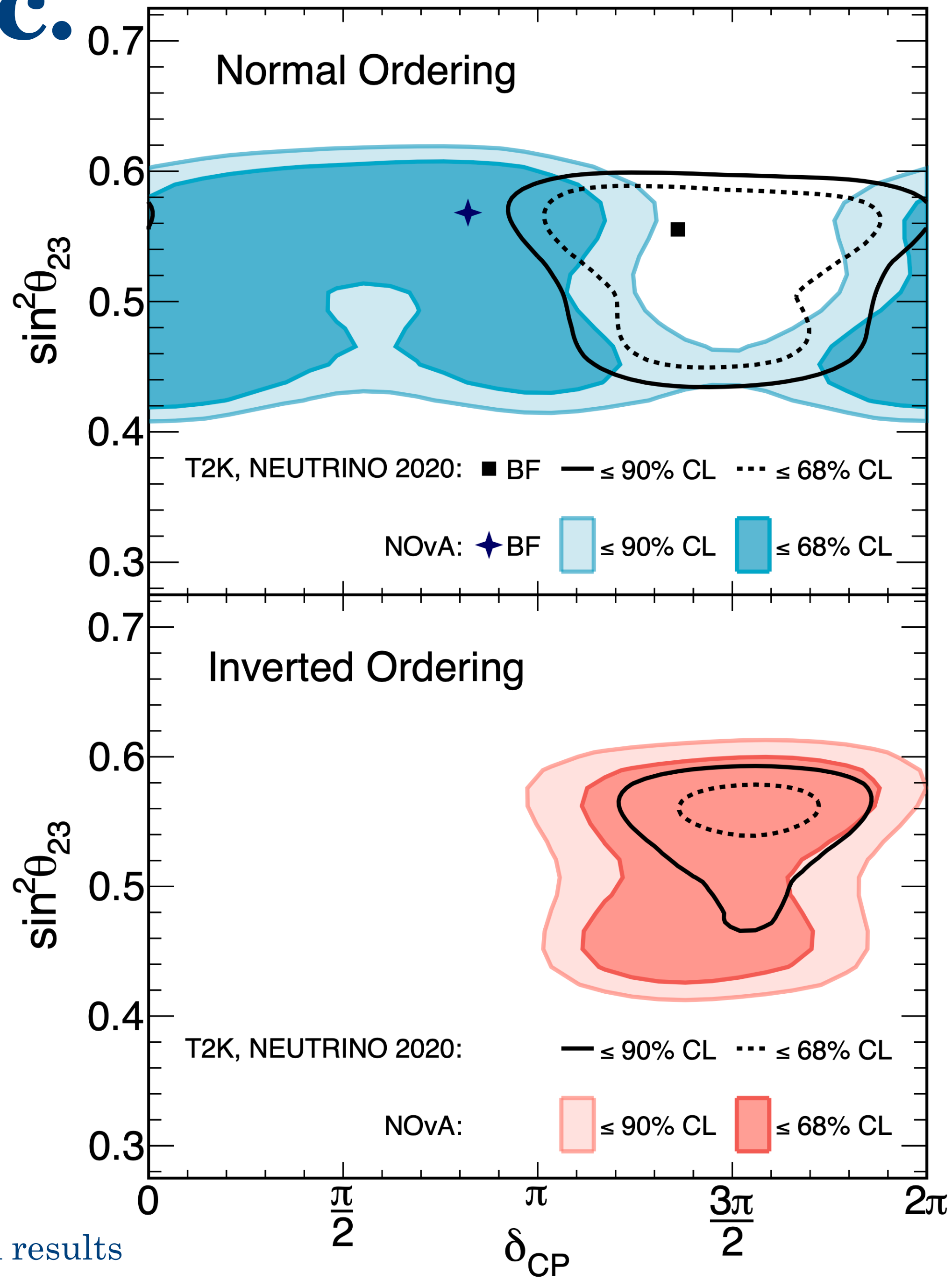
Best Fit

Normal hierarchy

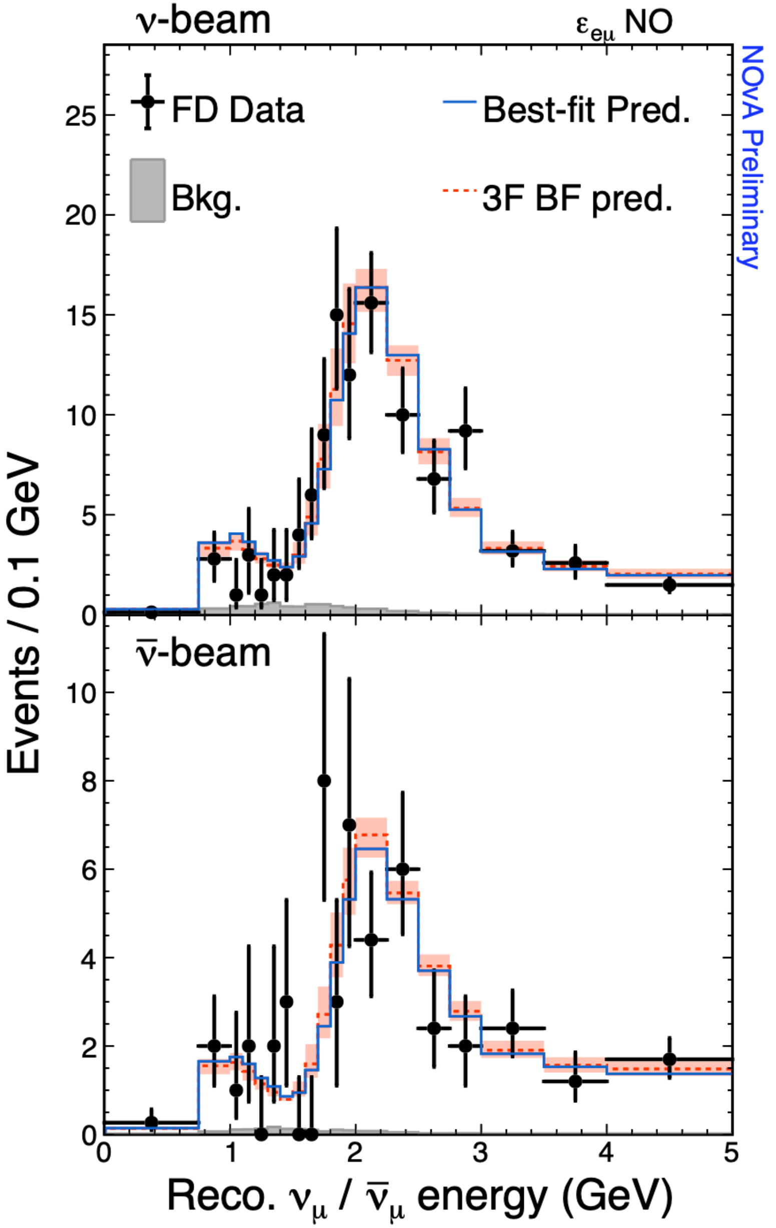
$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$

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

$\delta = 0.82\pi$



NSI Far Detector spectra: $\varepsilon_{e\mu}$



Fit the four datasets simultaneously

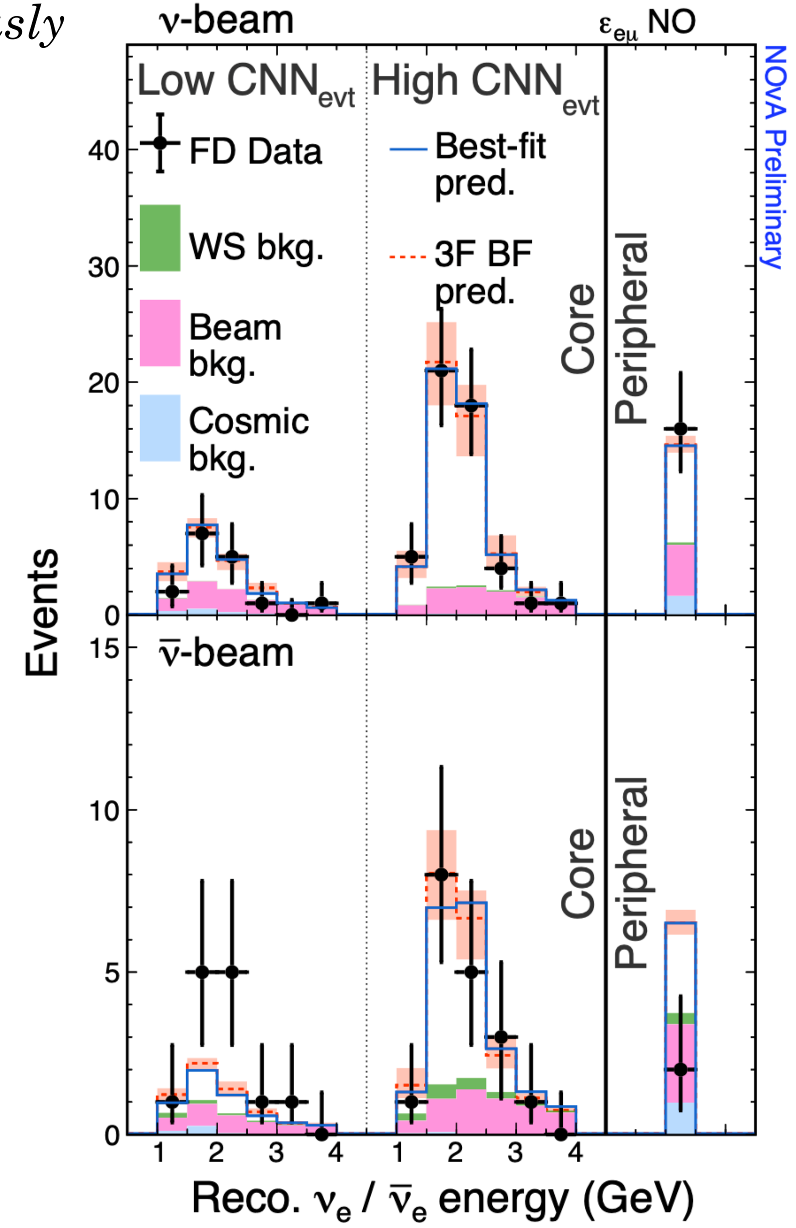
Off-diagonal components lead to a visible change in oscillation probability.
Appearance channel is affected by $\varepsilon_{e\tau}$, $\varepsilon_{e\mu}$

NSI best-fit comparable to the 2020 3-flavor best fit

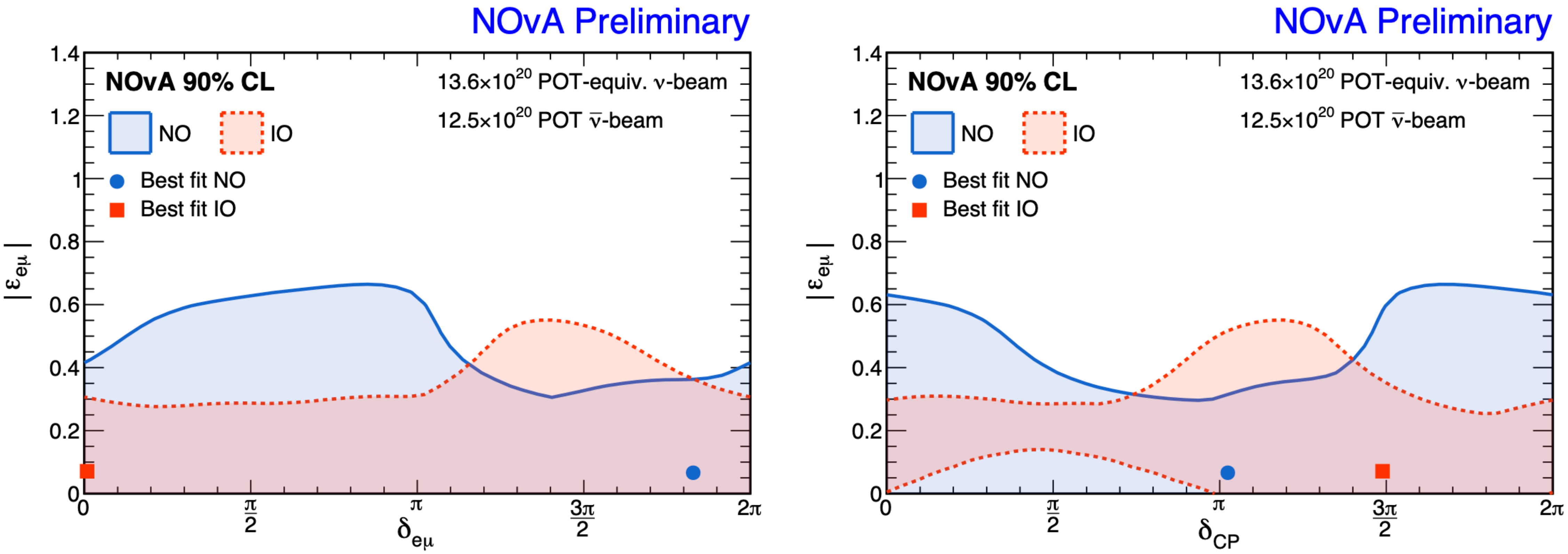
$$\Delta\chi^2 \approx 0.3$$

Well within the 3-flavor 1σ systematic range

Consistent with standard oscillations



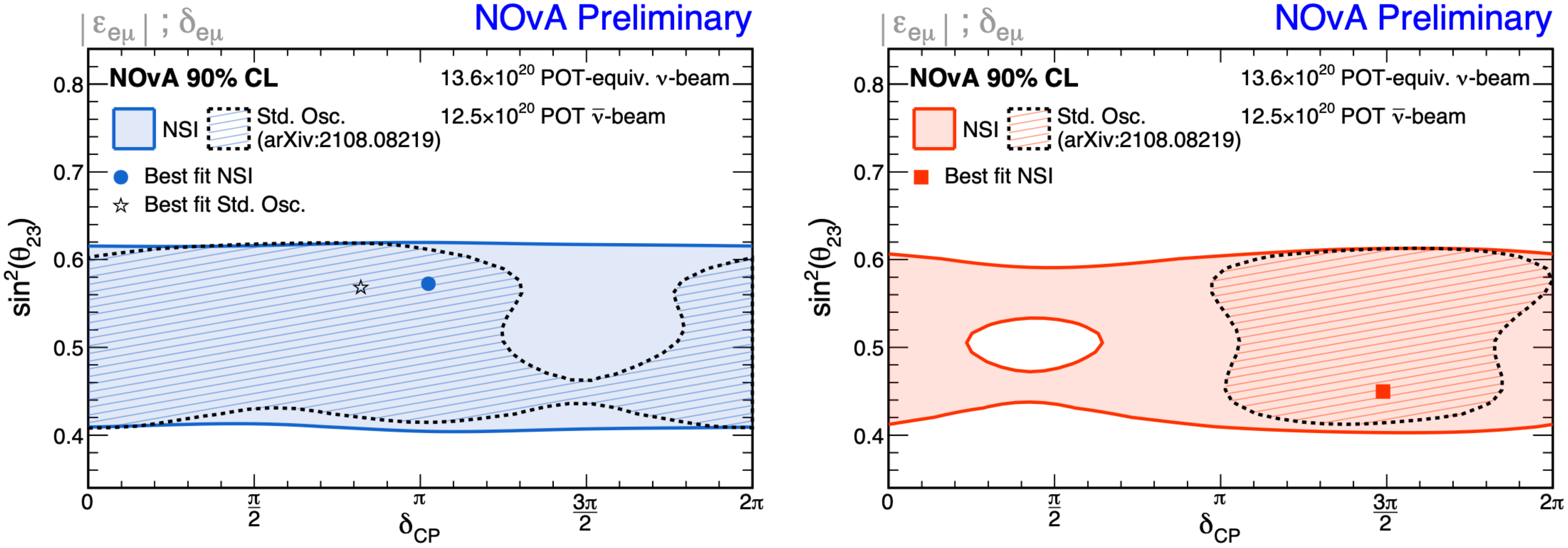
NSI Analysis Results: $\varepsilon_{e\mu}$



Sensitivity to δ_{CP} due to jointly fitting neutrino and anti-neutrino beam data.

All values of CP-violating phases allowed at 90% C.L. for NO
Non-zero NSI for $0 \rightarrow \pi$ δ_{CP} hinting at consistency with IO disfavored by 3-flavor

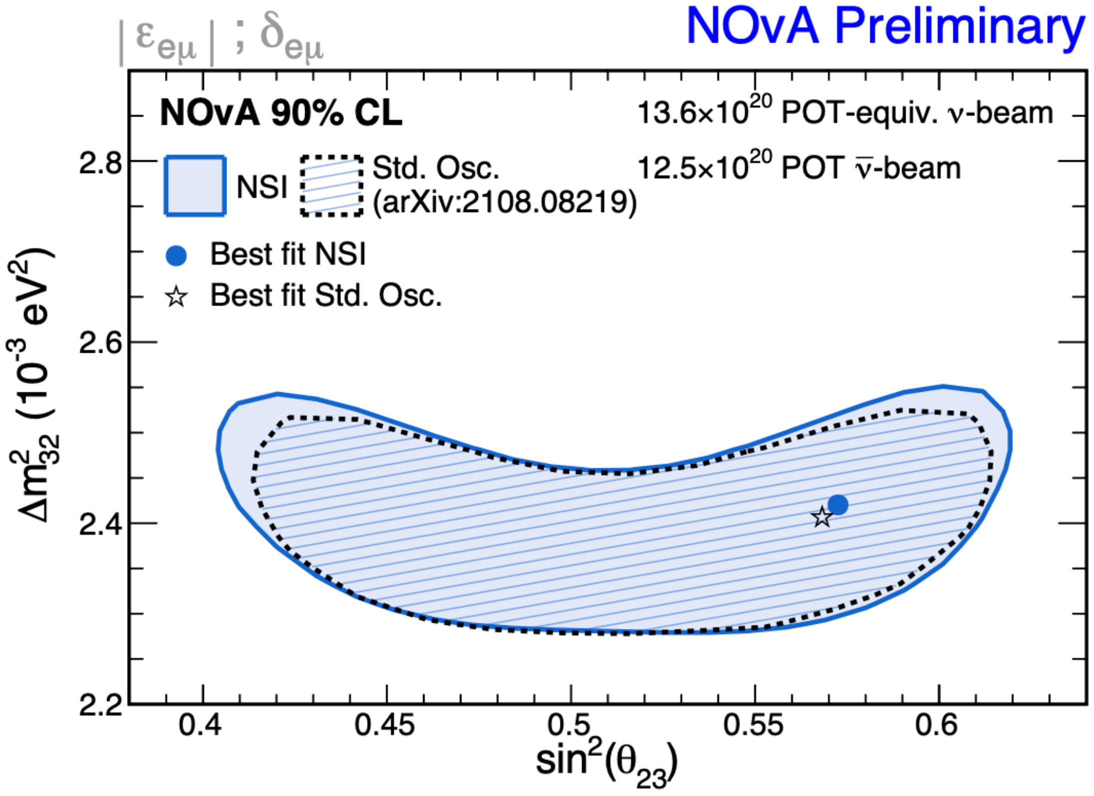
NOvA NSI and standard osc.: $\varepsilon_{e\mu}$

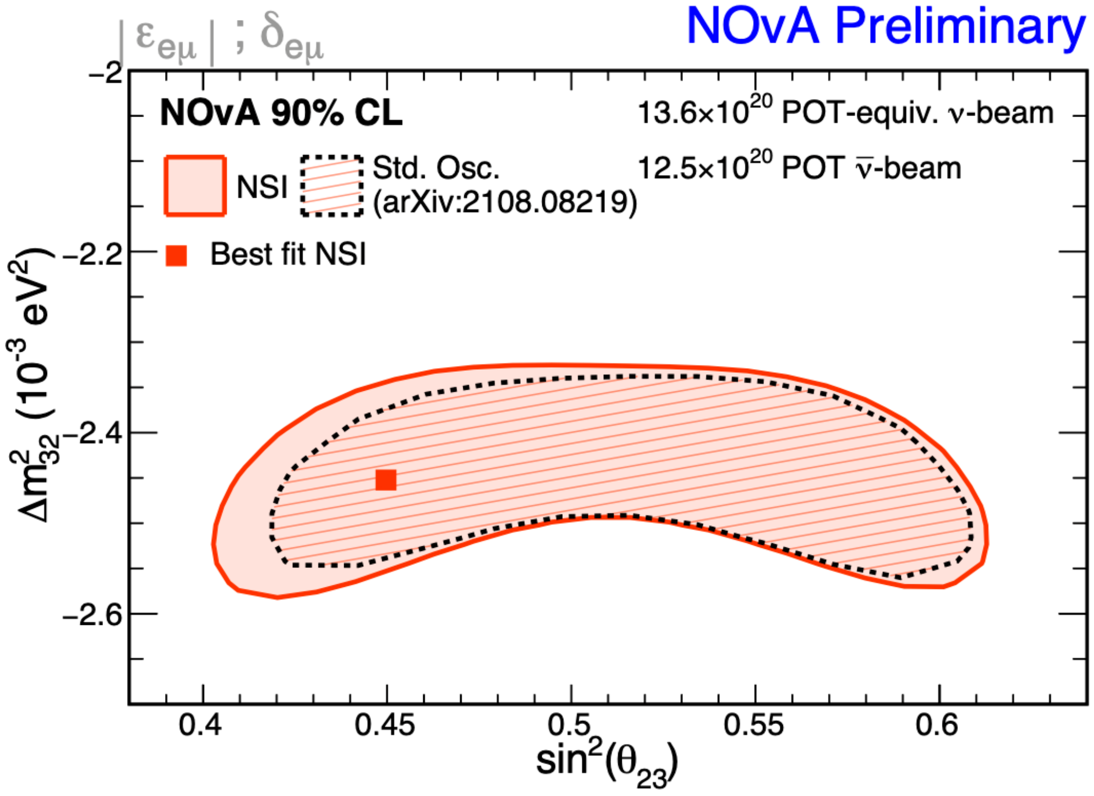


If we live in an NSI world, it can dramatically change our standard oscillation interpretation.

Fractional exclusion of IO for δ_{CP} around $\frac{\pi}{2}$ remains

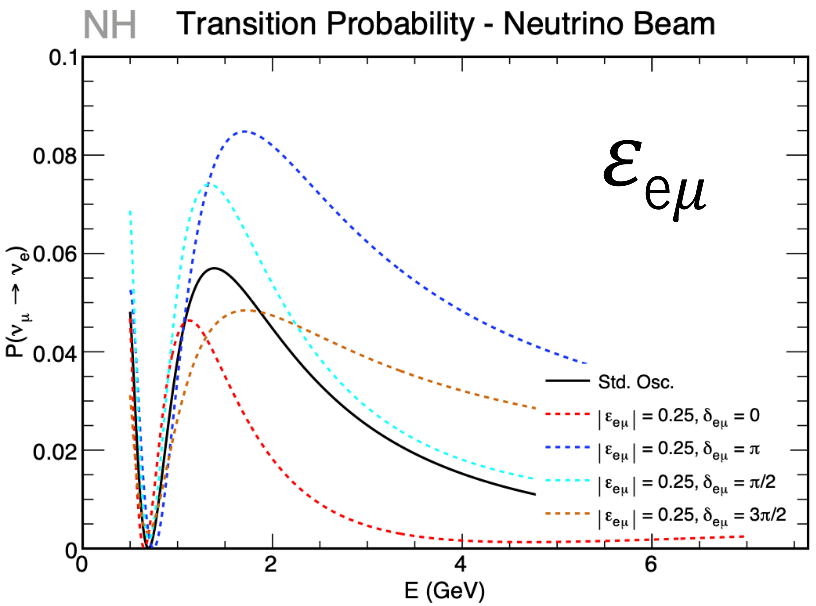
NOvA NSI and standard osc.: $\varepsilon_{e\mu}$

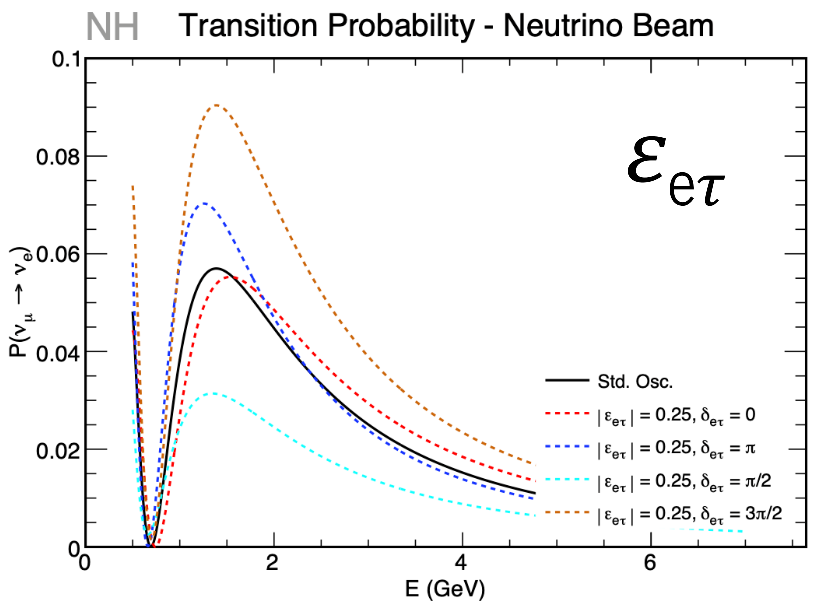




NSI has a marginal effect on the standard oscillation interpretation of the large mixing angle θ_{23} and Δm^2_{32}

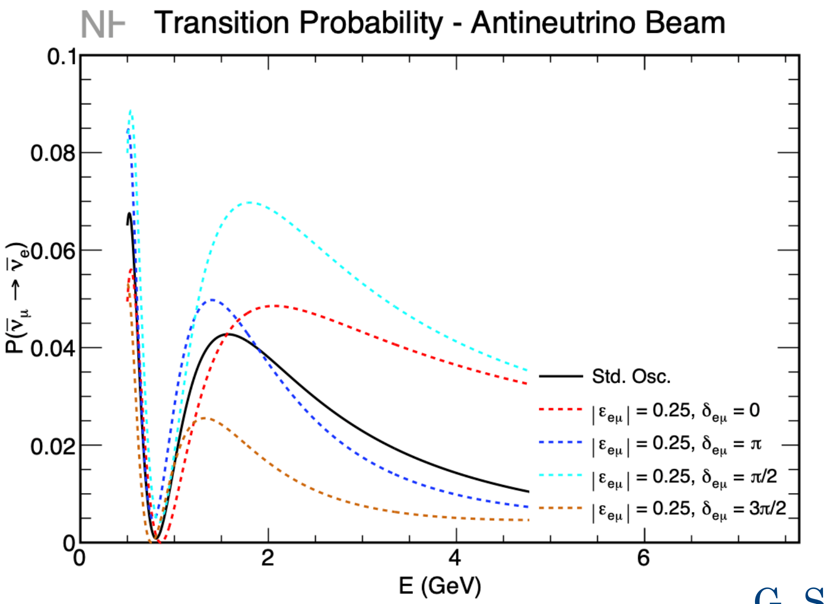
NSI Oscillation Probabilities

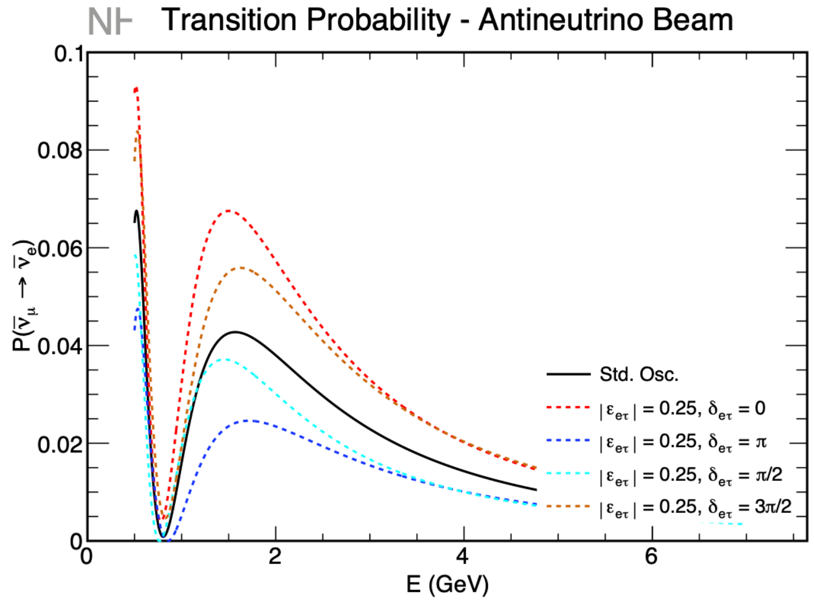




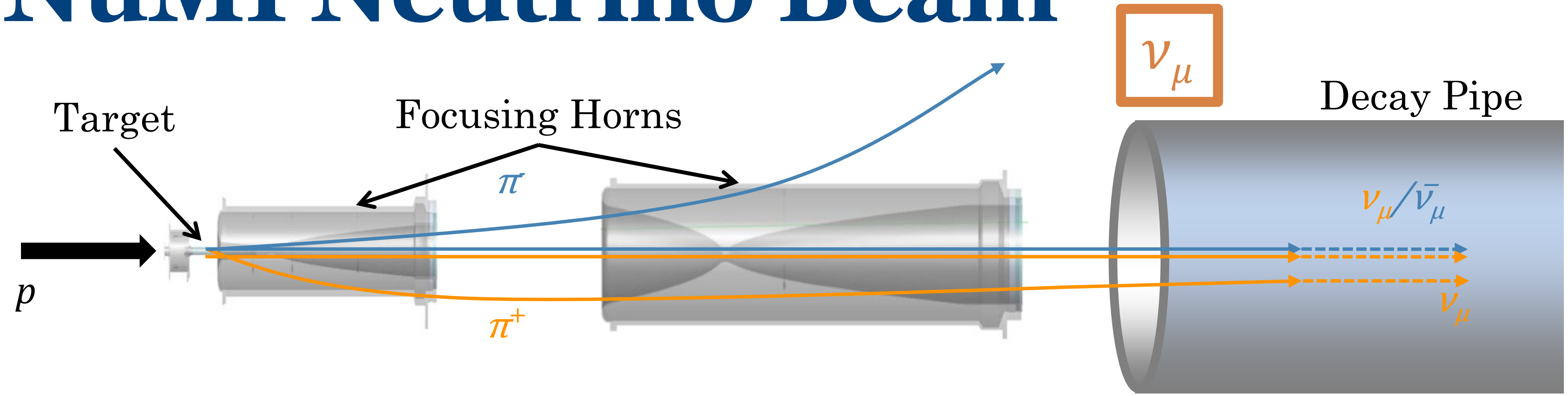
Off-diagonal components lead to a visible change in oscillation probability.

Appearance channel is affected by $\varepsilon_{e\tau}$, $\varepsilon_{e\mu}$





NuMI Neutrino Beam



Flux 1-5 GeV

95% ν_μ

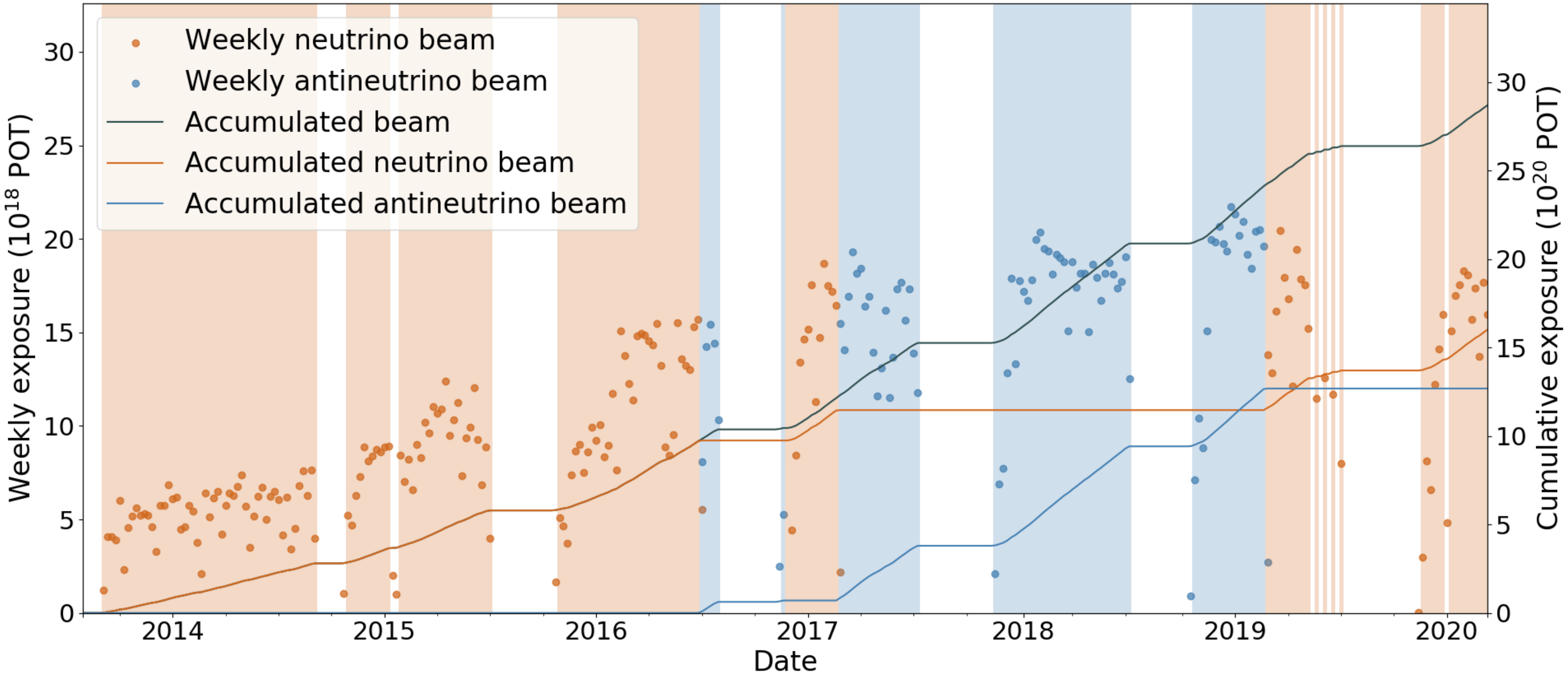
4% $\bar{\nu}_\mu$

1% ν_e

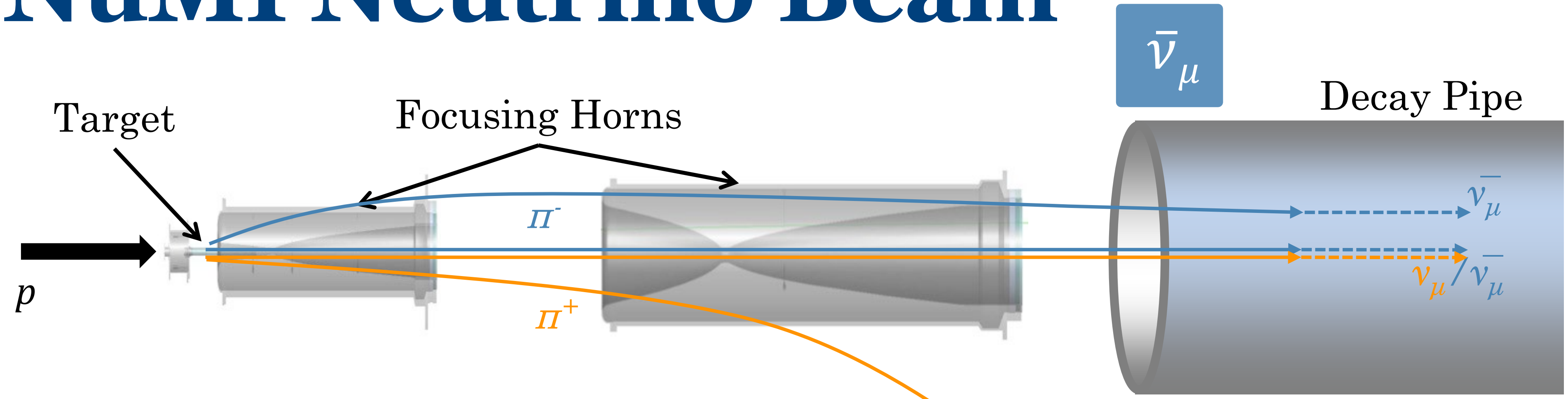
Exposure (POT)

ν: 13.6 x 10^{20}

$\bar{\nu}$: 12.5 x 10^{20}



NuMI Neutrino Beam

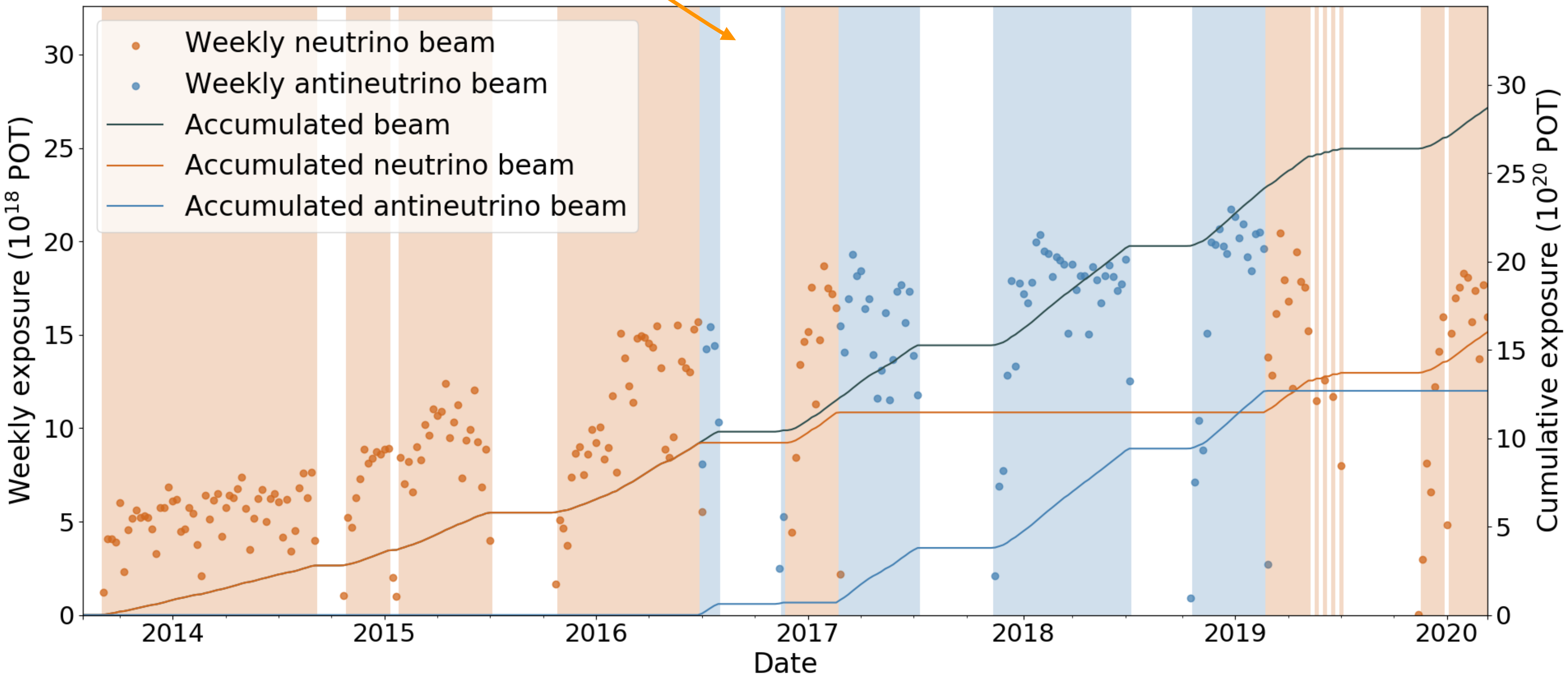


Flux 1-5 GeV

6% ν_μ

93% $\bar{\nu}_\mu$

1% ν_e



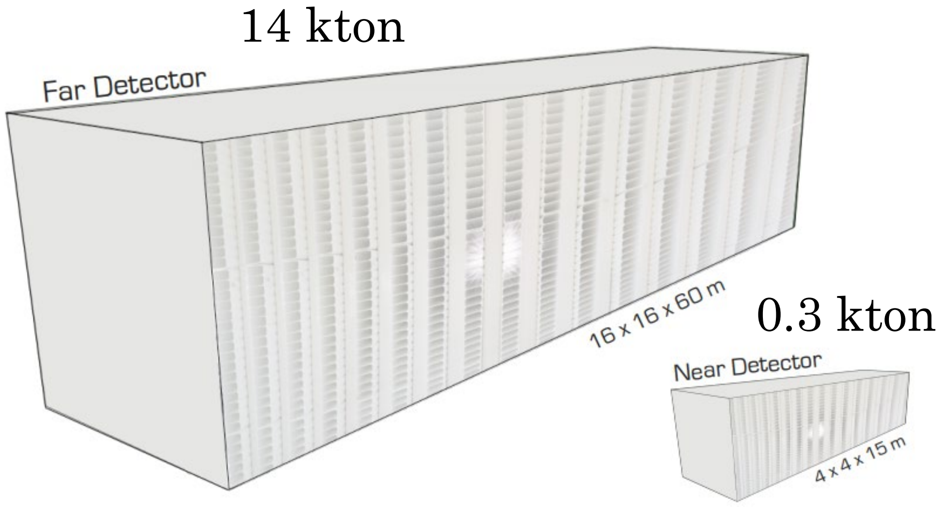
Exposure (POT)

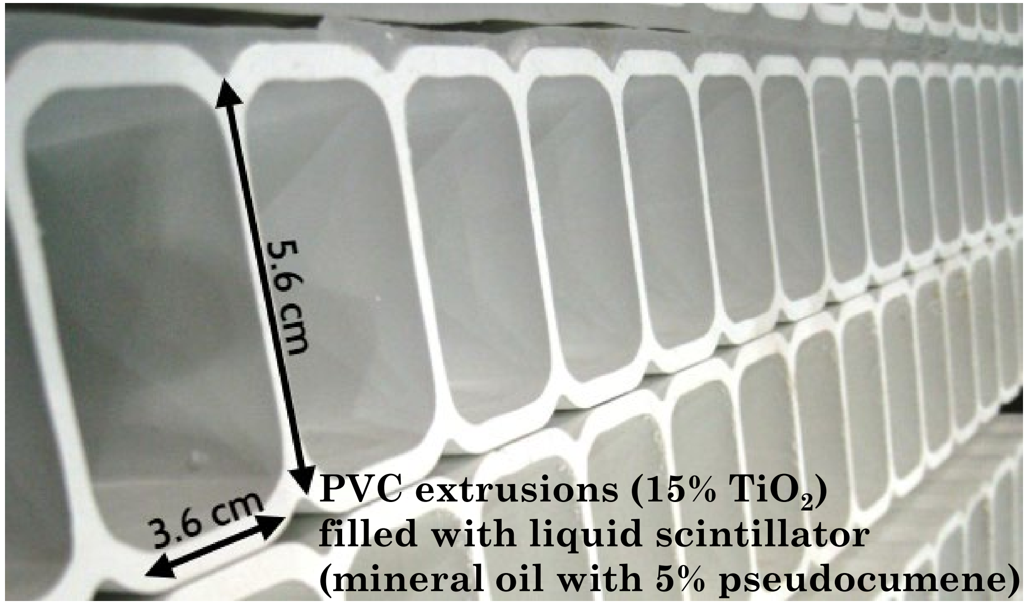
ν: 13.6 x 10^{20}

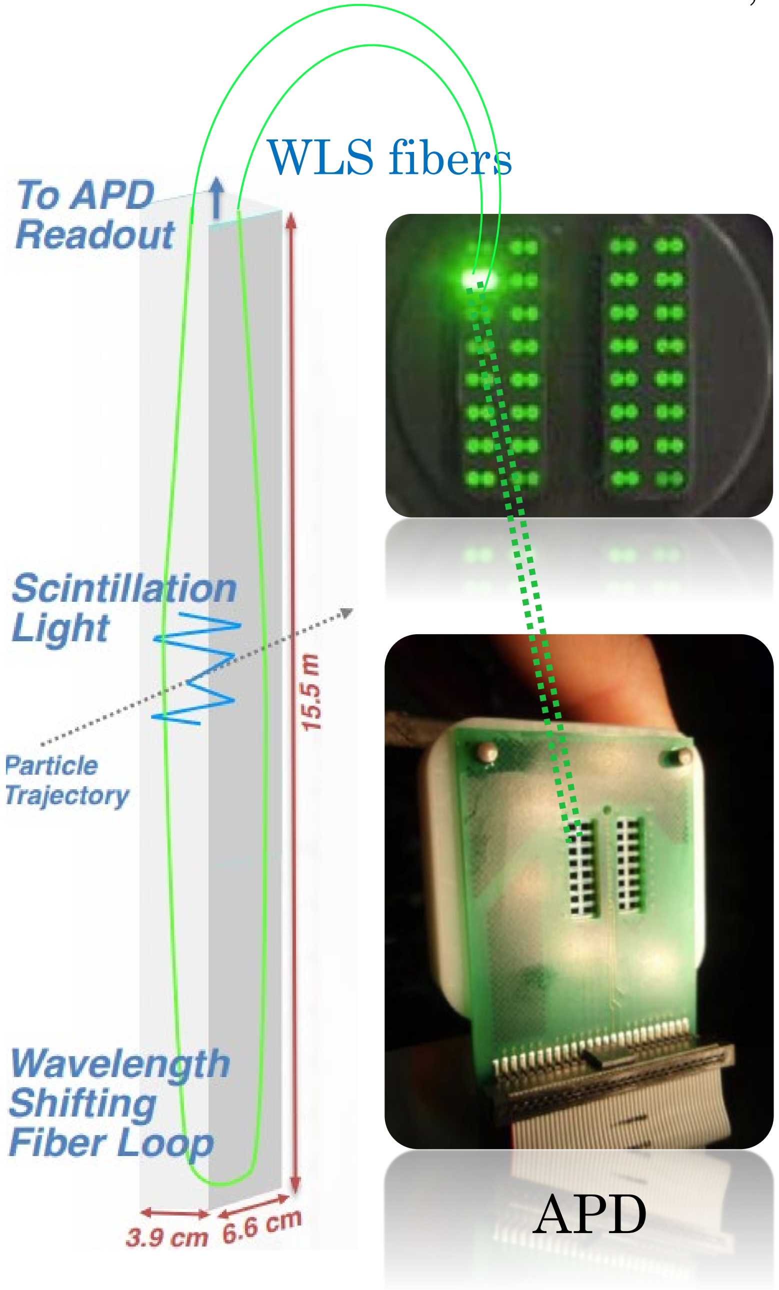
$\bar{\nu}$: 12.5 x 10^{20}

NOvA Detectors

ND: ~20,000 channels
FD: ~344,000 channels

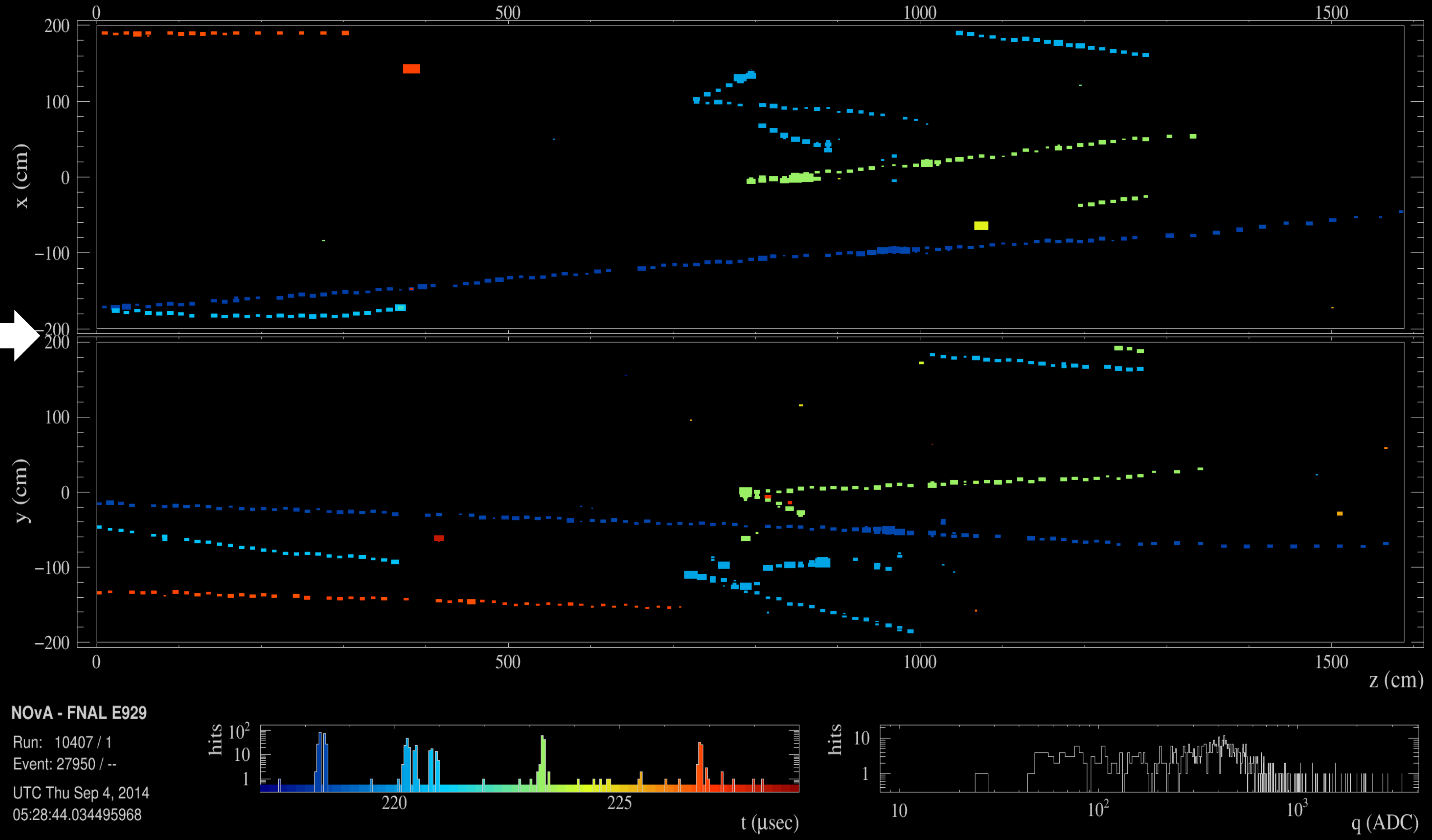






Near Detector Event Display

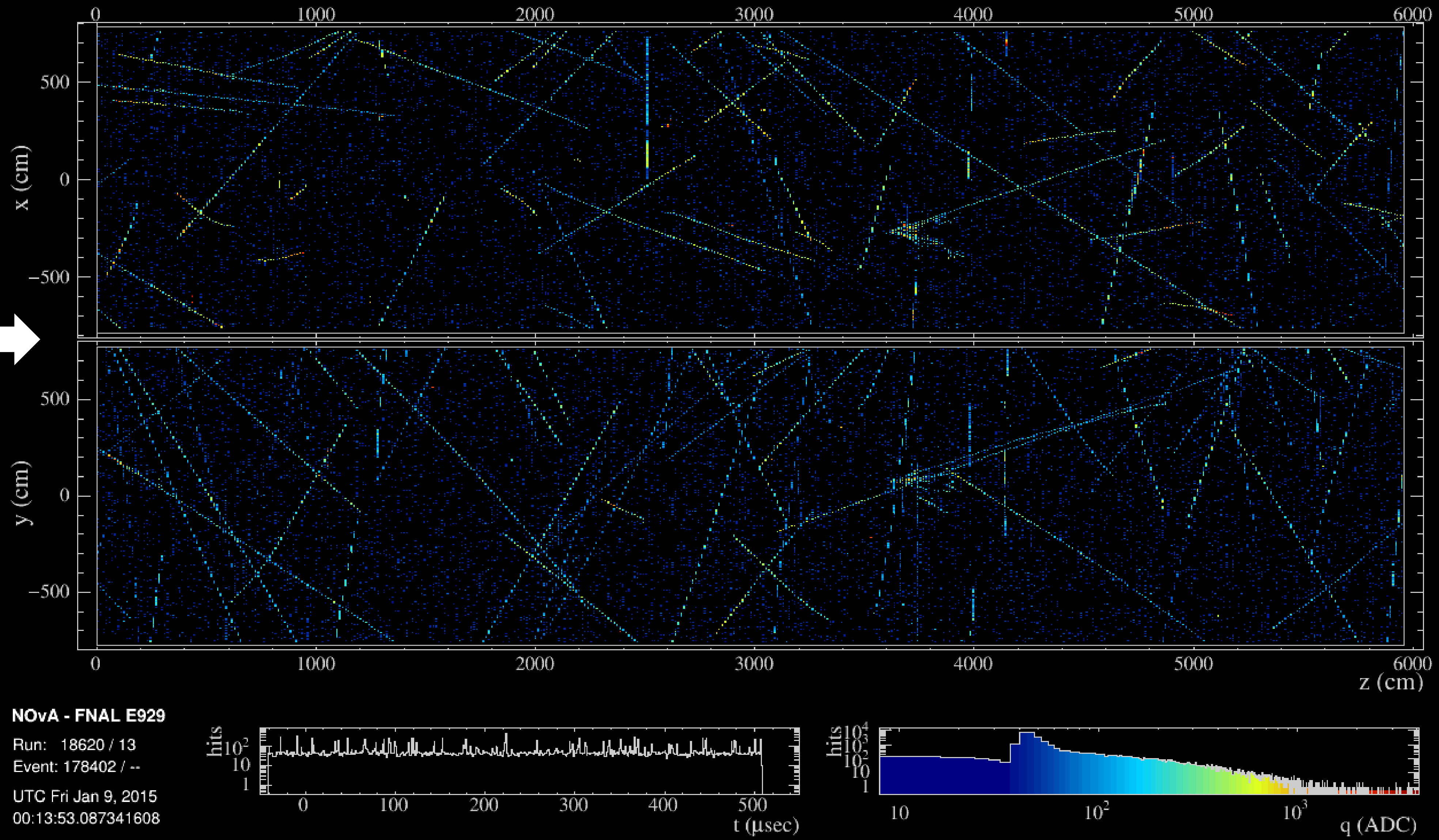
Beam



(colors show hit times)

Far Detector Event Display: 550 us

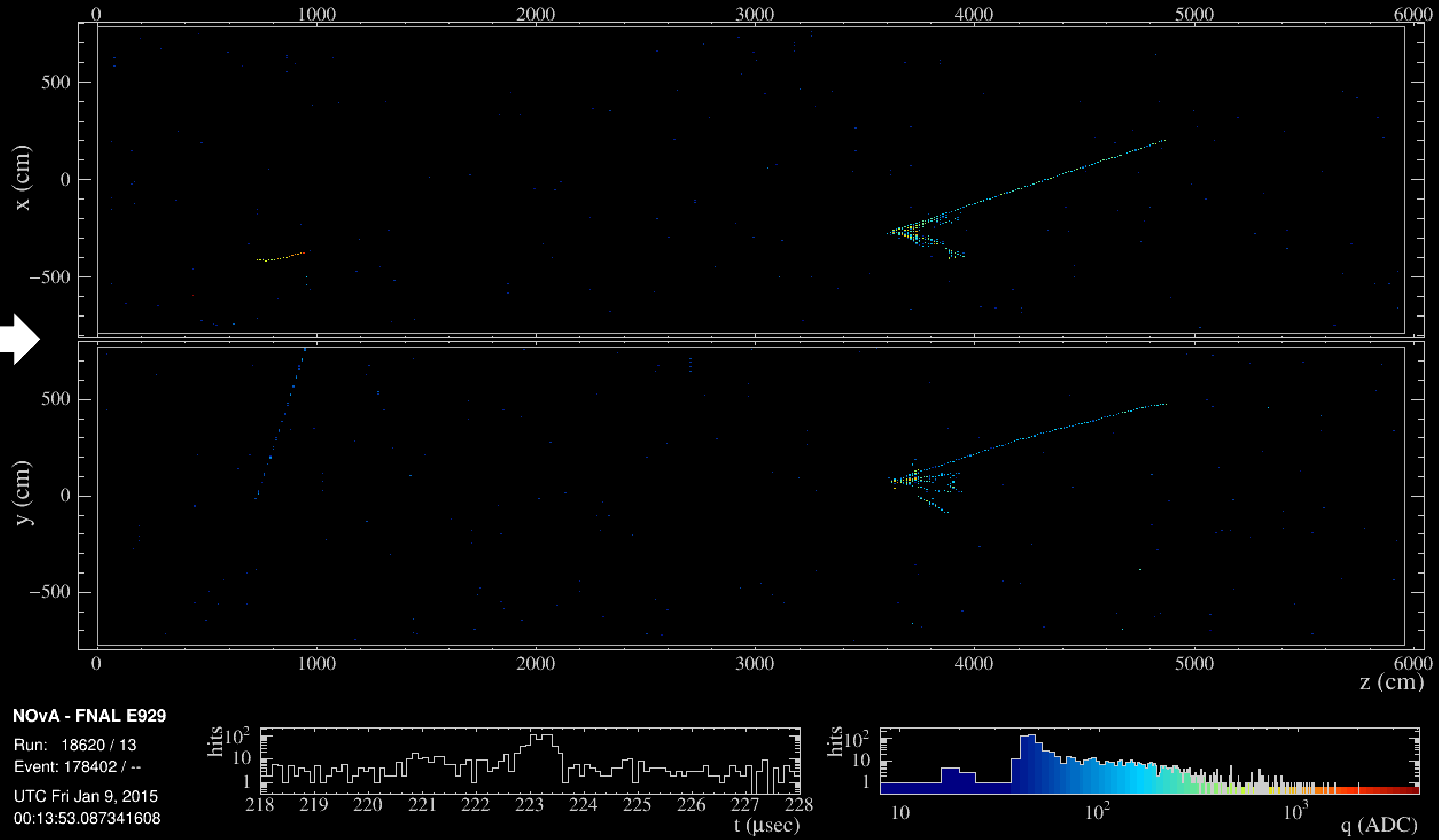
Beam



(colors show charge)

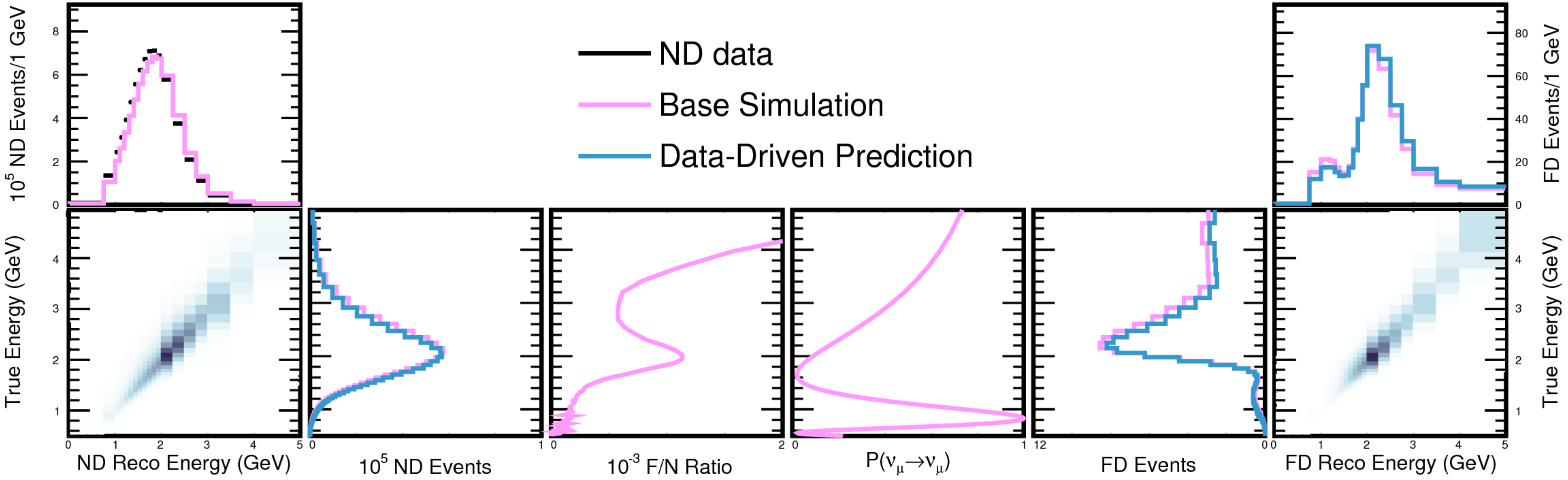
Far Detector Event Display: 10 us

Beam

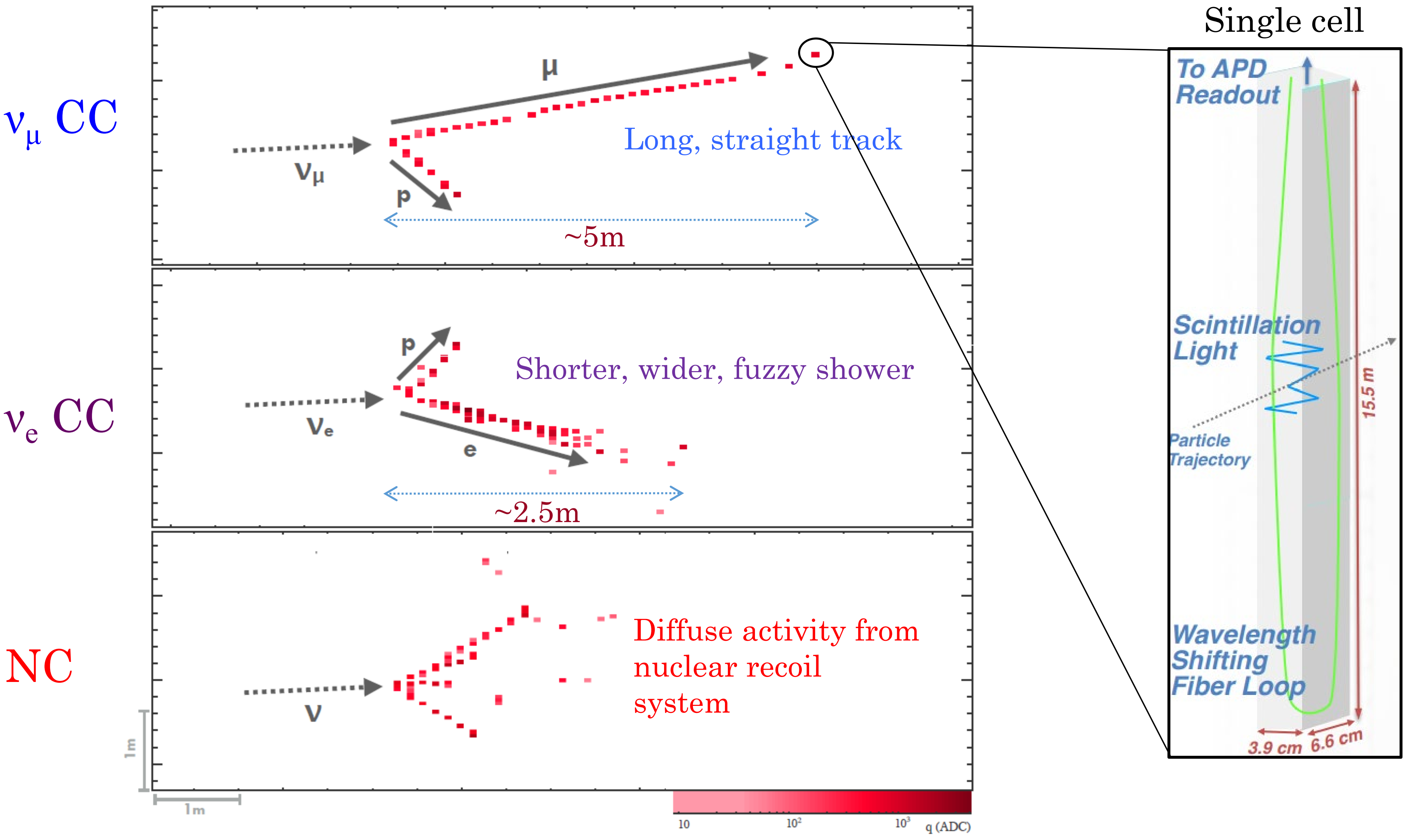


(colors show charge)

ND/FD Extrapolation

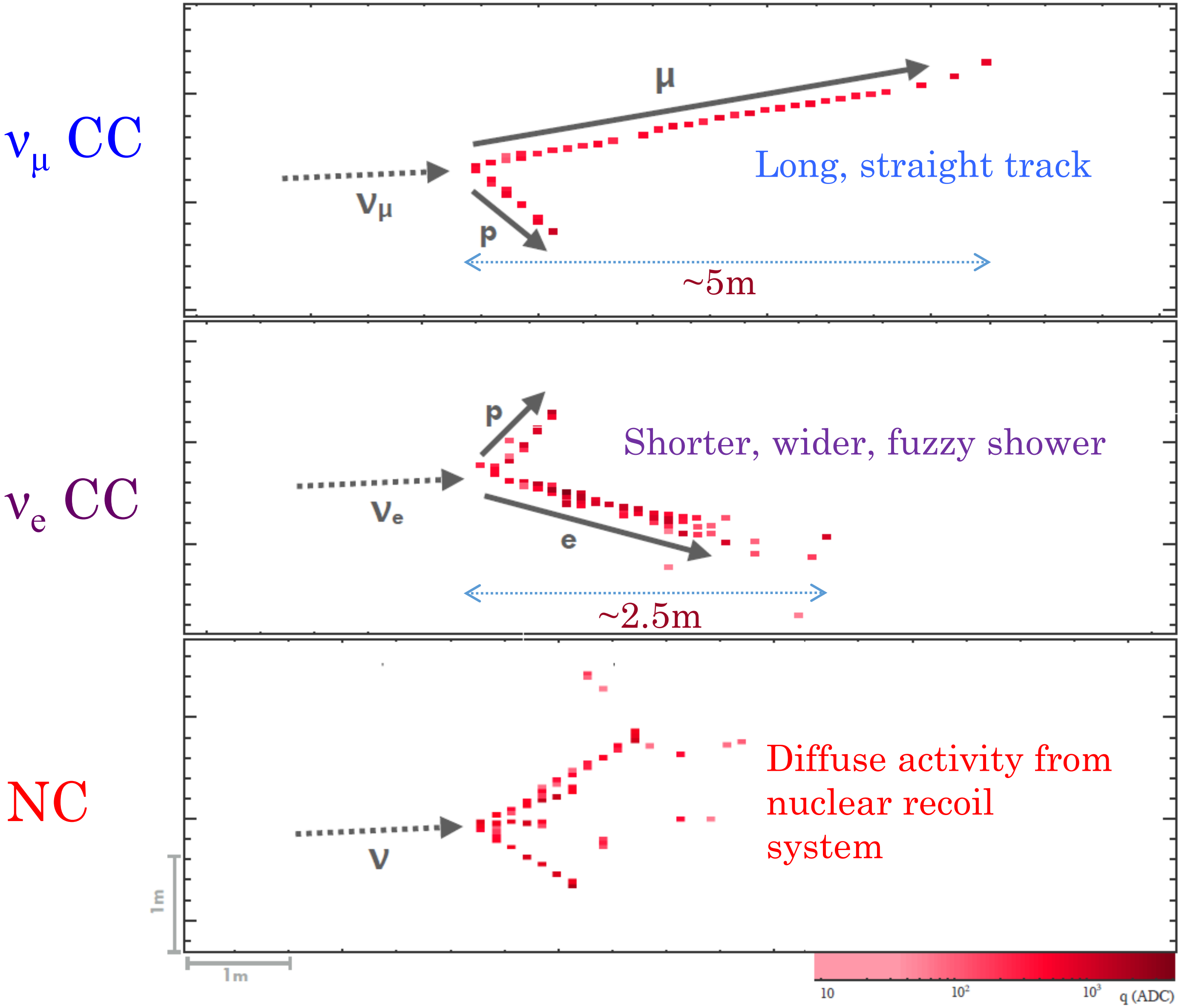


Event Identification



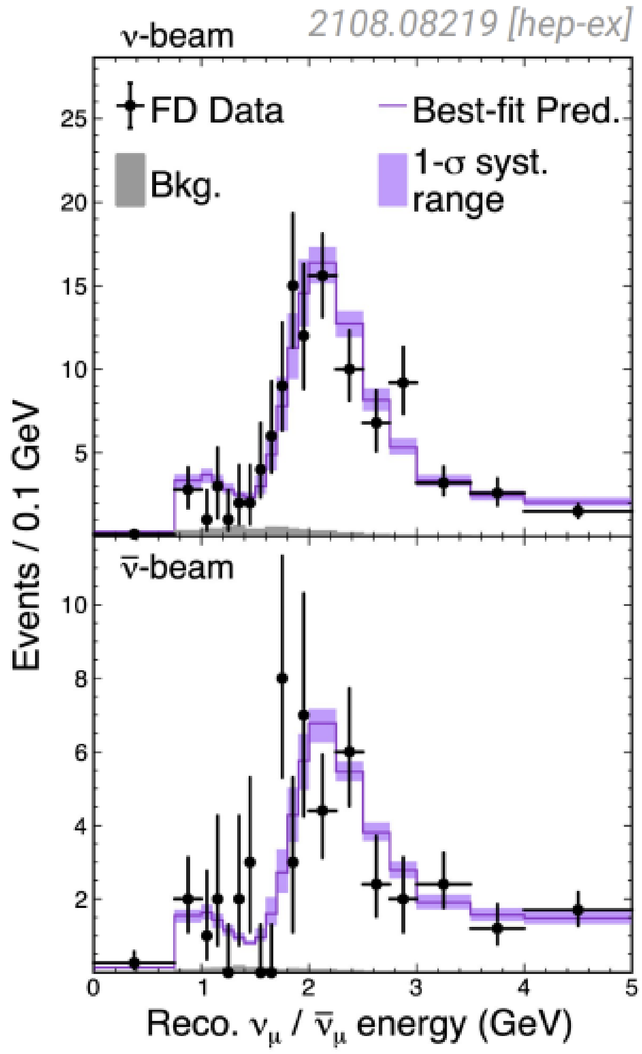
Event Identification

See Jianming Bian's talk



- Identify flavor with convolutional neural network (CNN)
  Aurisano et al., JINST 11 (09), P09001
- Before CNN:
  - Need to be contained
  - ν_μCC needs a well reconstructed muon track
  - First pass of cosmic rejection
- Performance relative to preselection
  - ν_μ : ~90% efficient, 99% bkg rejection
  - ν_e : ~80% efficient, 80% bkg rejection
- New, faster network trained for 2020 analysis
  Psihas et al., Phys. Rev. D 100, 073005 (2019)

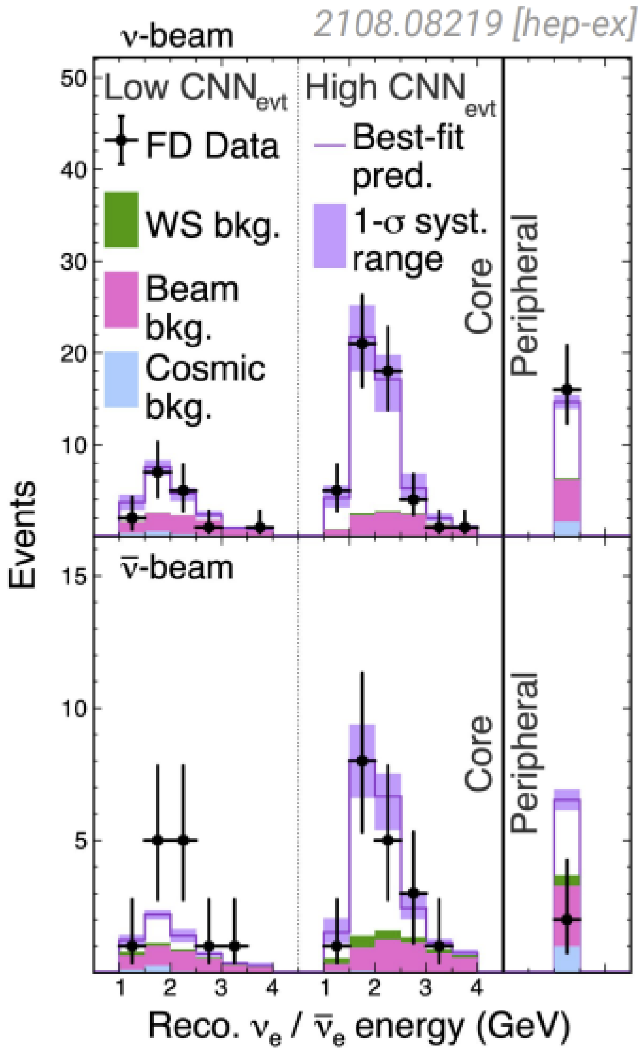
2020 Far Detector Spectra

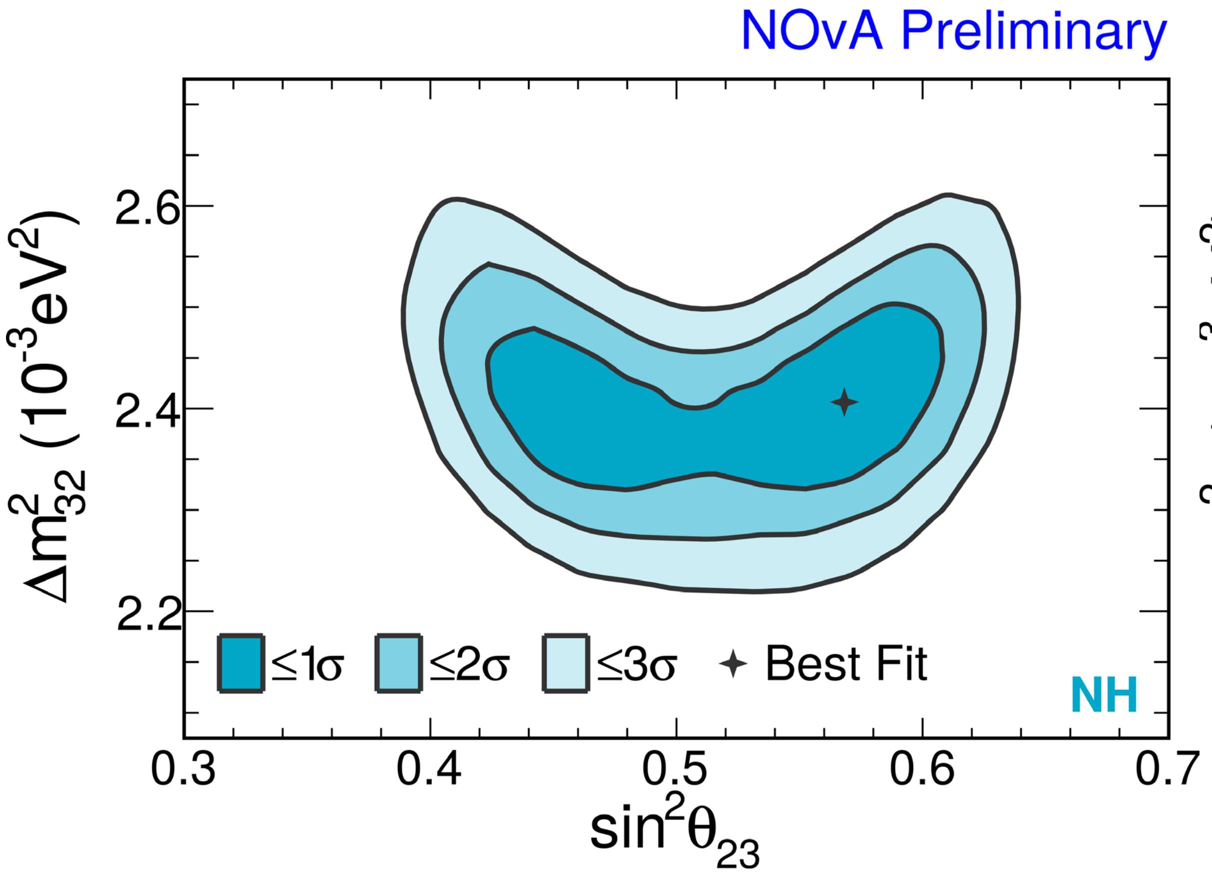


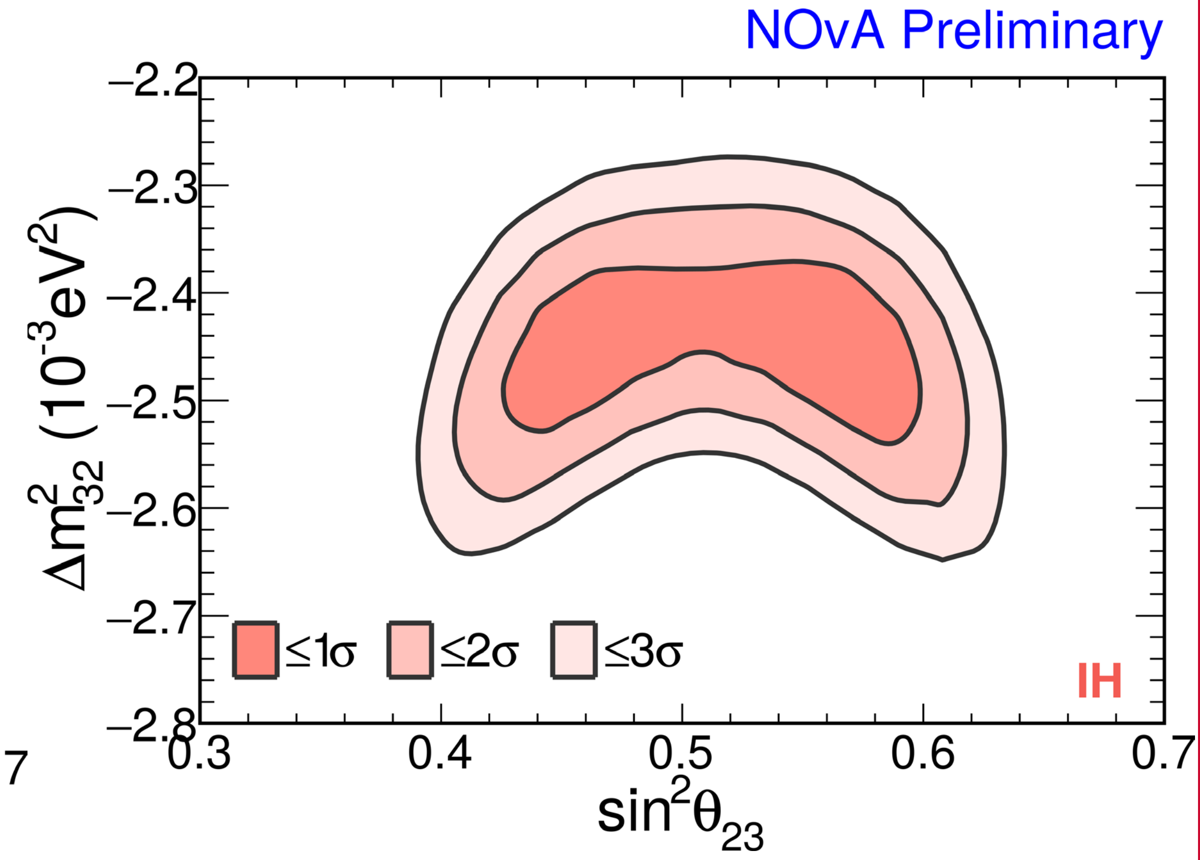
Fit the four datasets simultaneously:

Floating over ~50 systematic uncertainties as individual pulls.

We correct significances with Feldman-Cousins unified approach.





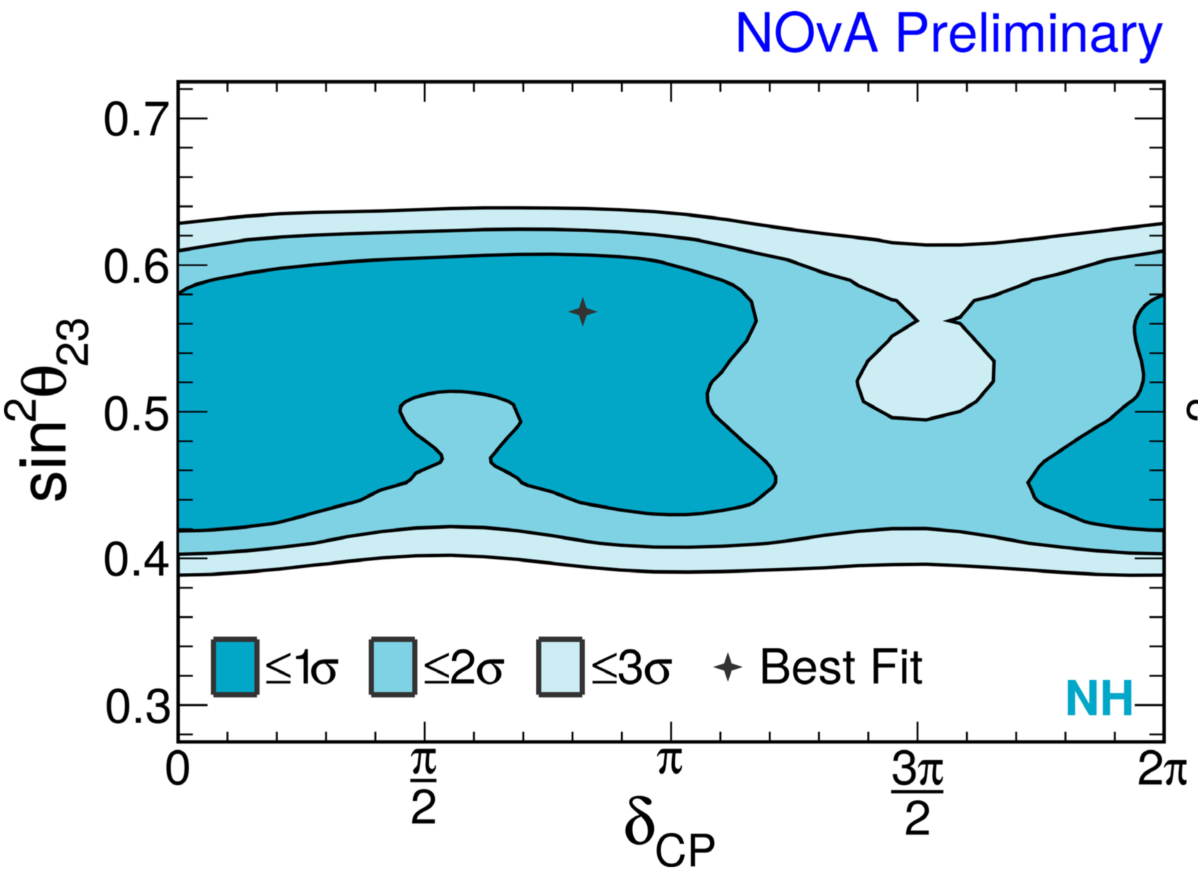


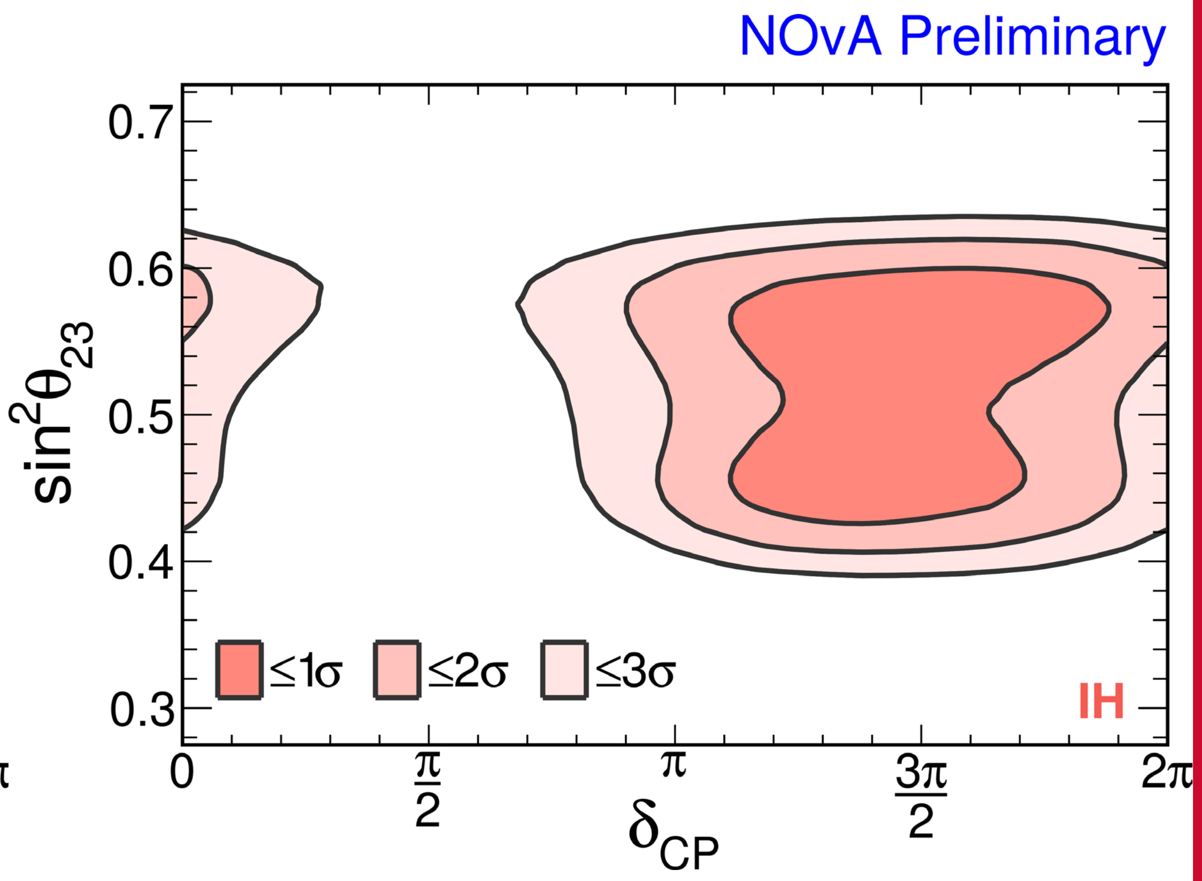
Best Fit

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

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

Oscillation Results





Best Fit

$\Delta m^2 = (2.48^{+0.11}_{-0.06})\times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$

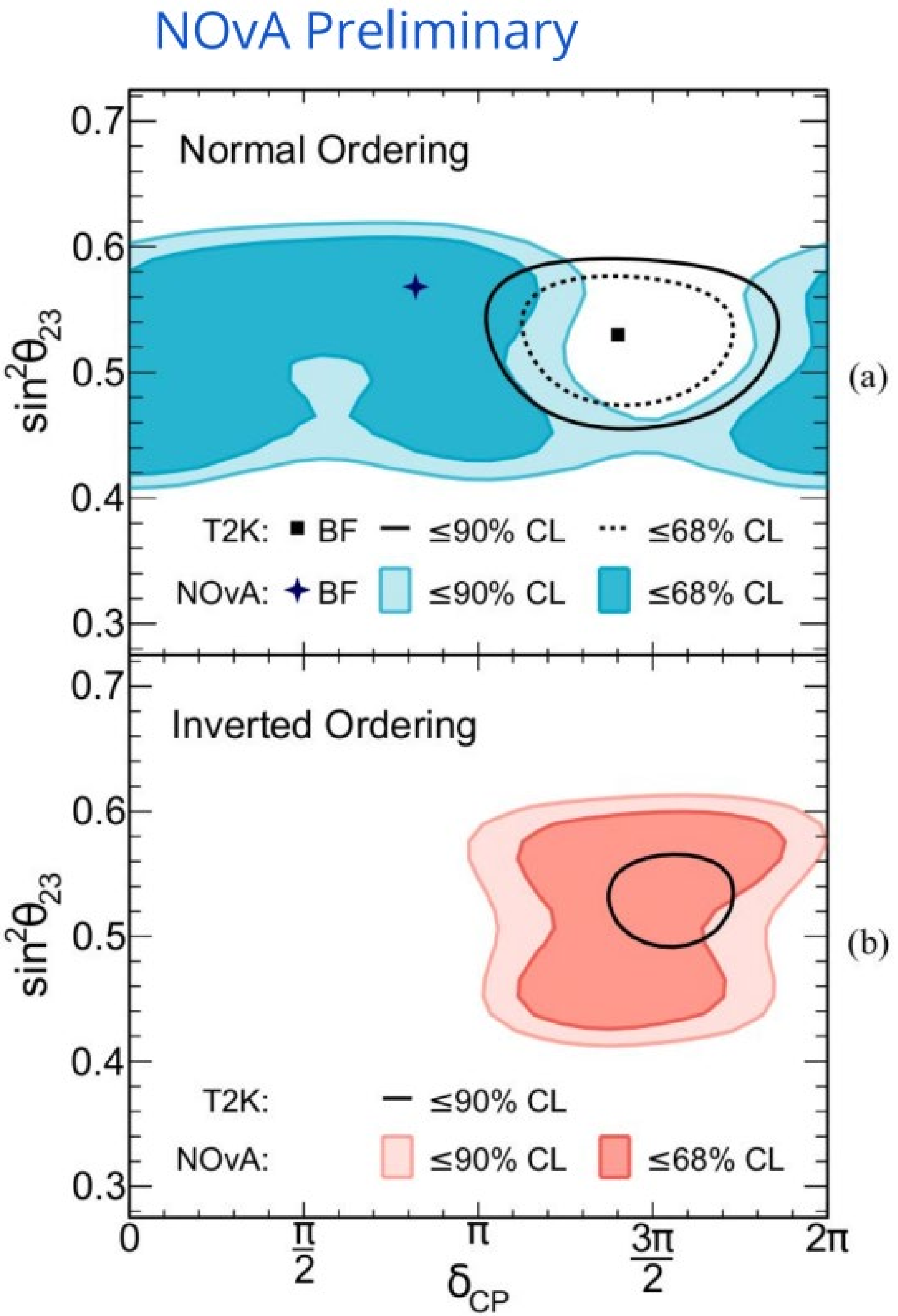
$\delta_{CP} = 0.84\pi$

Comparison to T2K

Clear tension between NOvA and T2K preferred regions in the Normal Hierarchy/Ordering

- Better agreement in the Inverted Hierarchy/Ordering

A joint fit of the data from the two experiments is needed to properly quantify consistency (in progress)

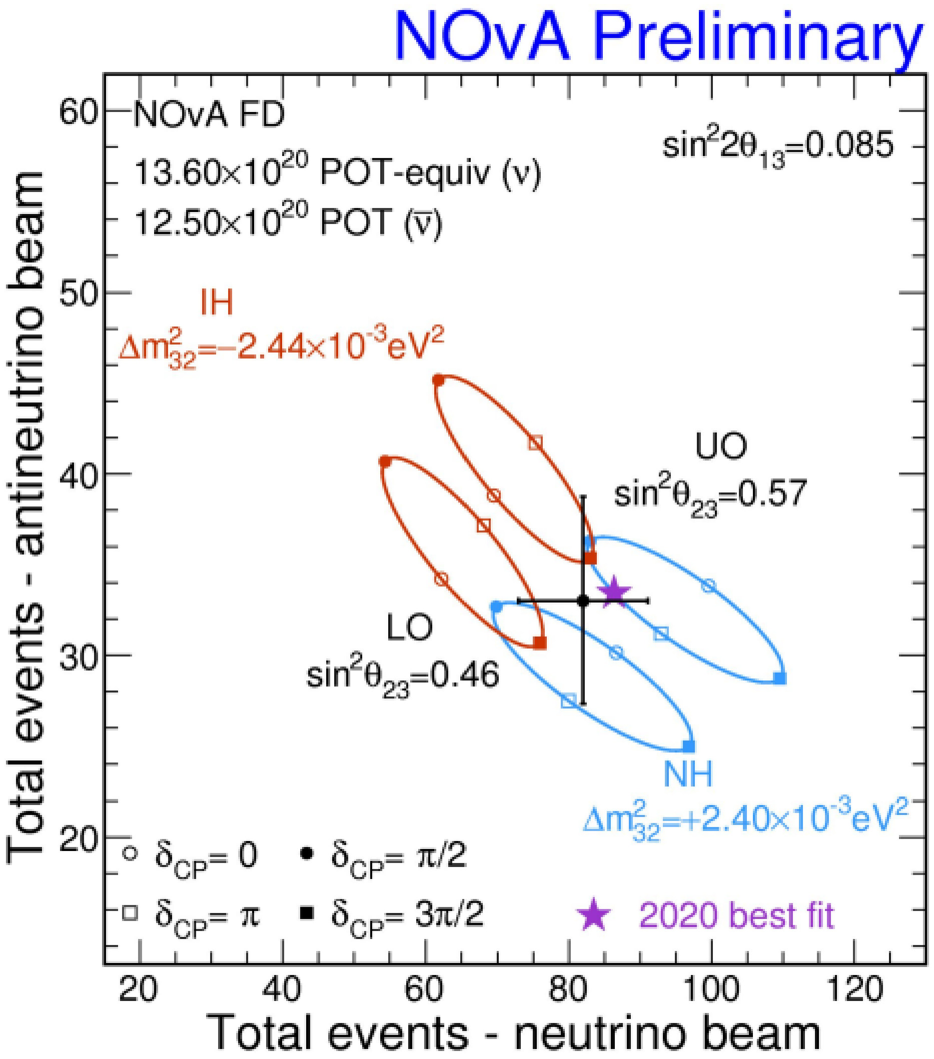


Asymmetry?

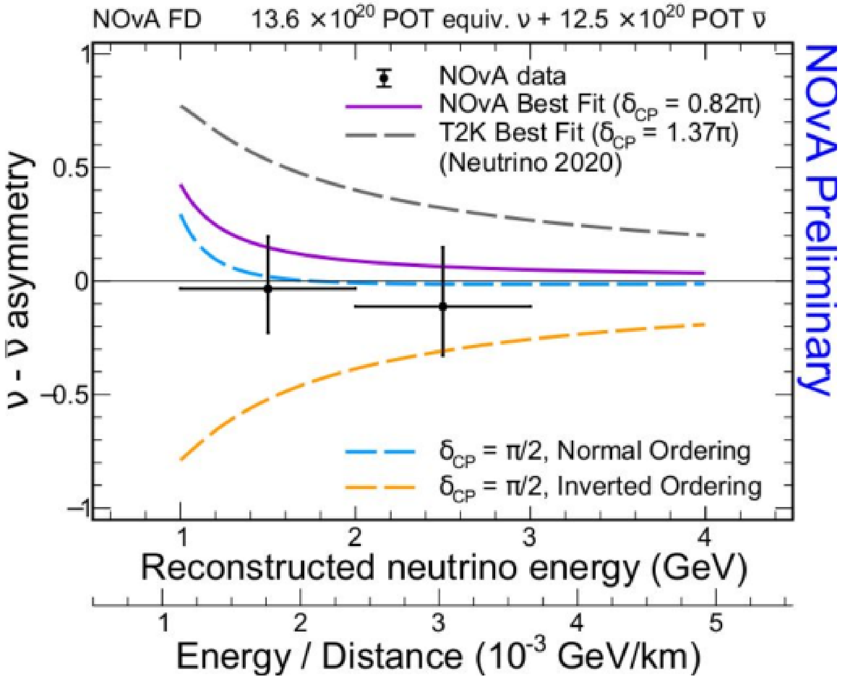
Plotting number of candidates in neutrino vs. antineutrino beam mode, we see **no strong asymmetry** in the appearance rates. Consistent with both slightly negative and slightly positive asymmetries.

Slight preference for NH, Upper Octant

- Exclude IH $\delta = \pi/2$ at $> 3\sigma$
- Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$



$$\frac{P(\nu) - P(\bar{\nu})}{P(\nu) + P(\bar{\nu})}$$



Open questions

Neutrino mixing very different from quark sector mixing
Masses are really small compared to the rest of the Standard Model (SM)

- Do neutrino oscillations violate charge-parity (CP) symmetry?
- Is the mass hierarchy (ordering) "normal" or "inverted"?
- What is the octant of θ_{23}?

CP Violation

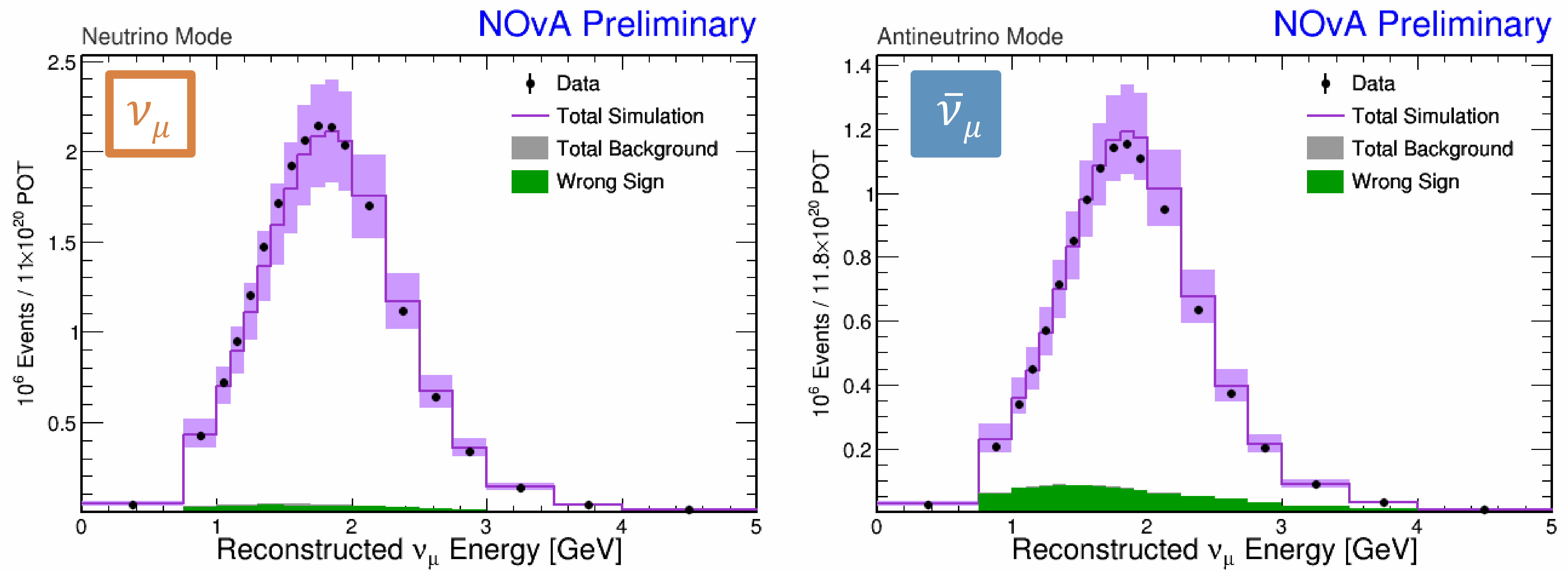
Mass Hierarchy

θ_{23} Octant

"The existence of non-zero neutrino masses, inferred from neutrino oscillation experiments, is the only lab-based evidence of physics beyond the standard model."

P.A.N. Machado

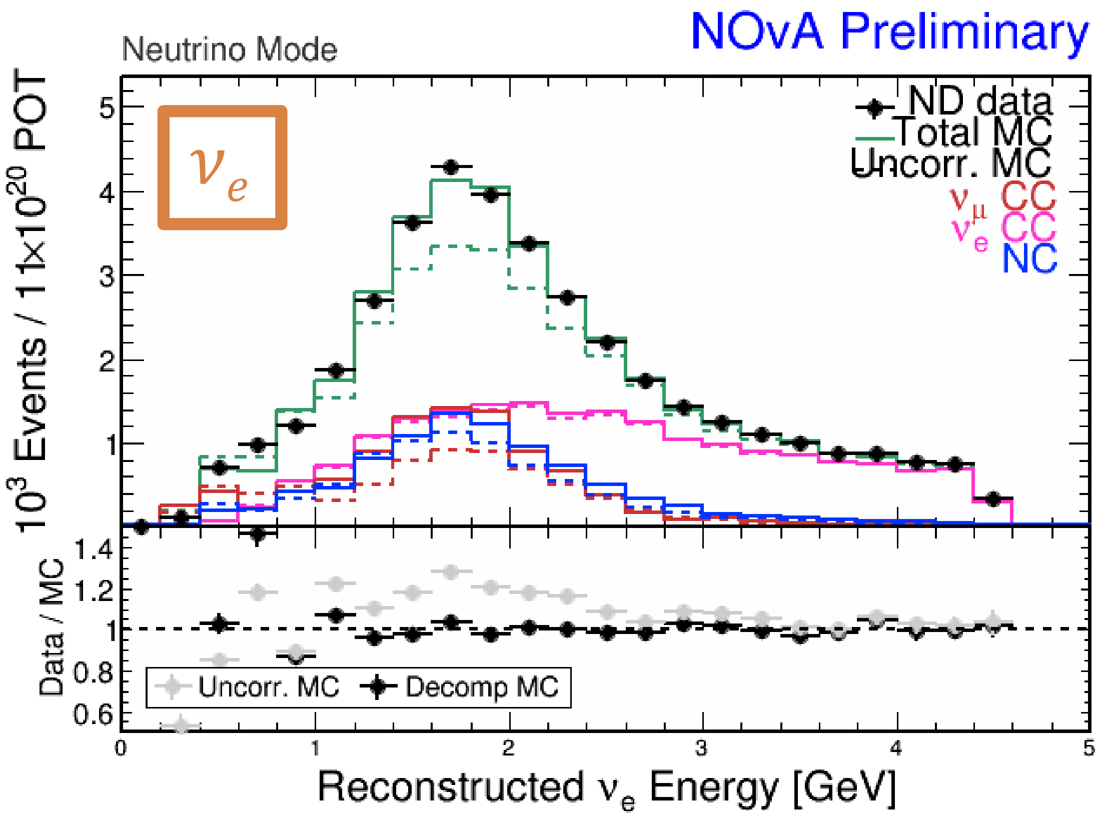
Muon Neutrinos at the ND

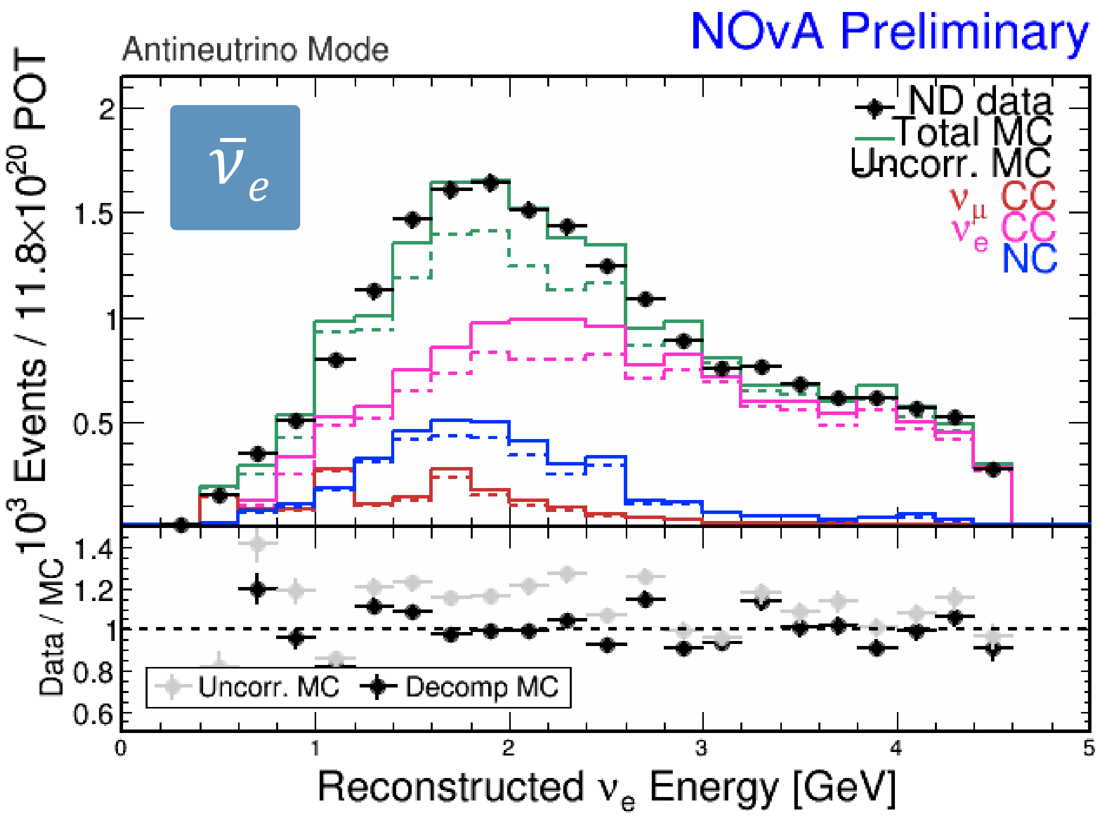


We use the fit to ND data to constrain the FD prediction.
Used to predict both ν_μ and ν_e spectra at the FD

Large error band shows the effect of flux and cross-section uncertainties in one detector

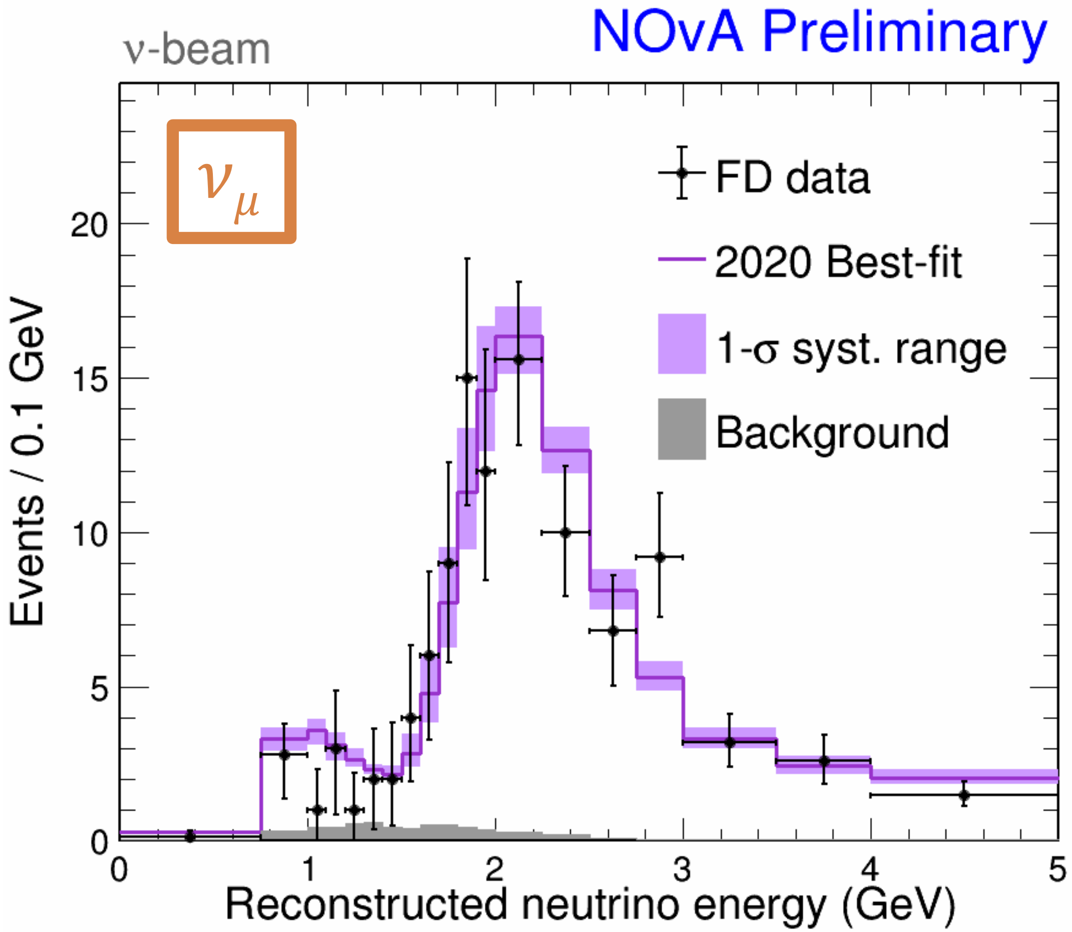
Electron Neutrinos at the ND



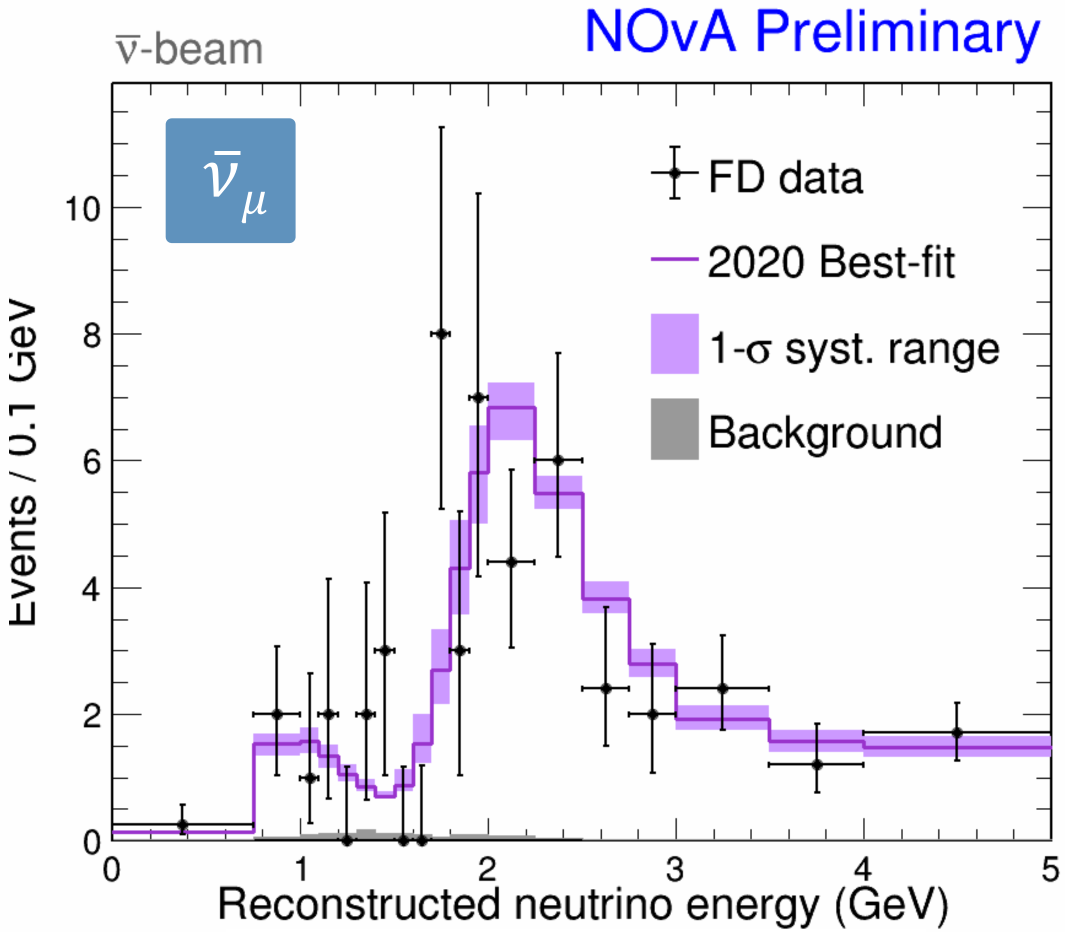


- ND ν_e-like sample has no appearance – all background
- This sample is used to predict the background at the FD
- Largest background is the irreducible beam $\nu_e/\bar{\nu}_e$

Muon Neutrinos at the FD

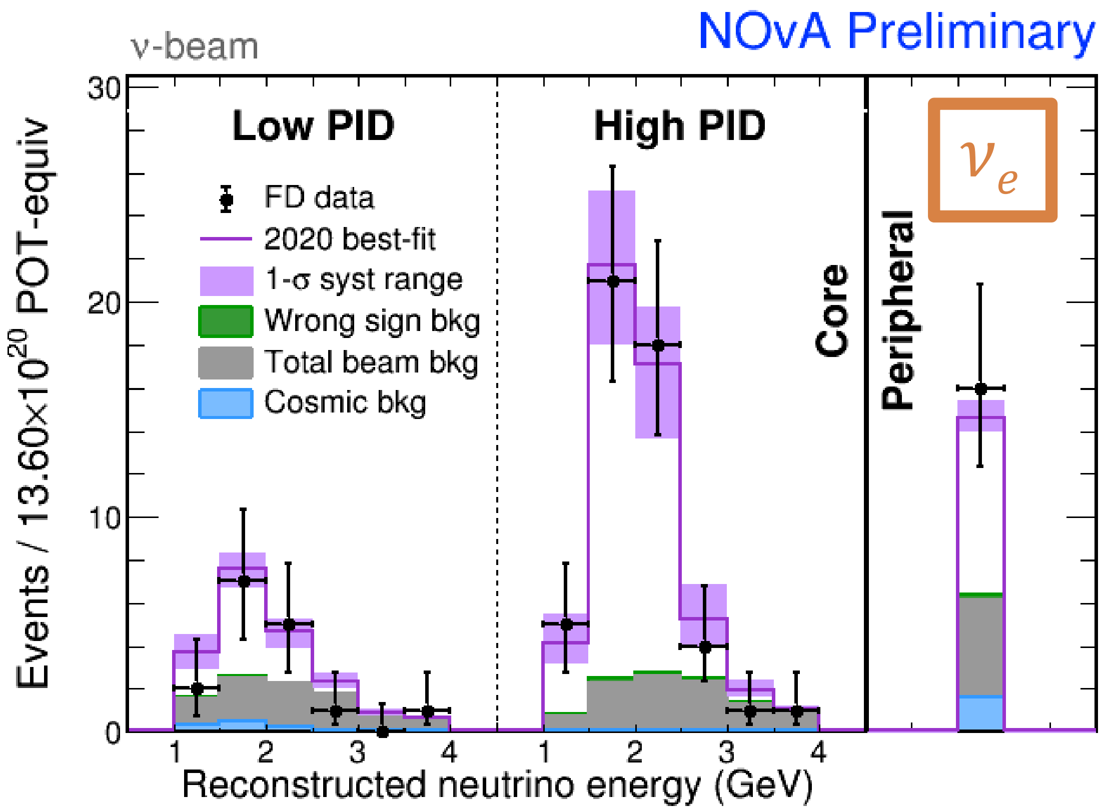


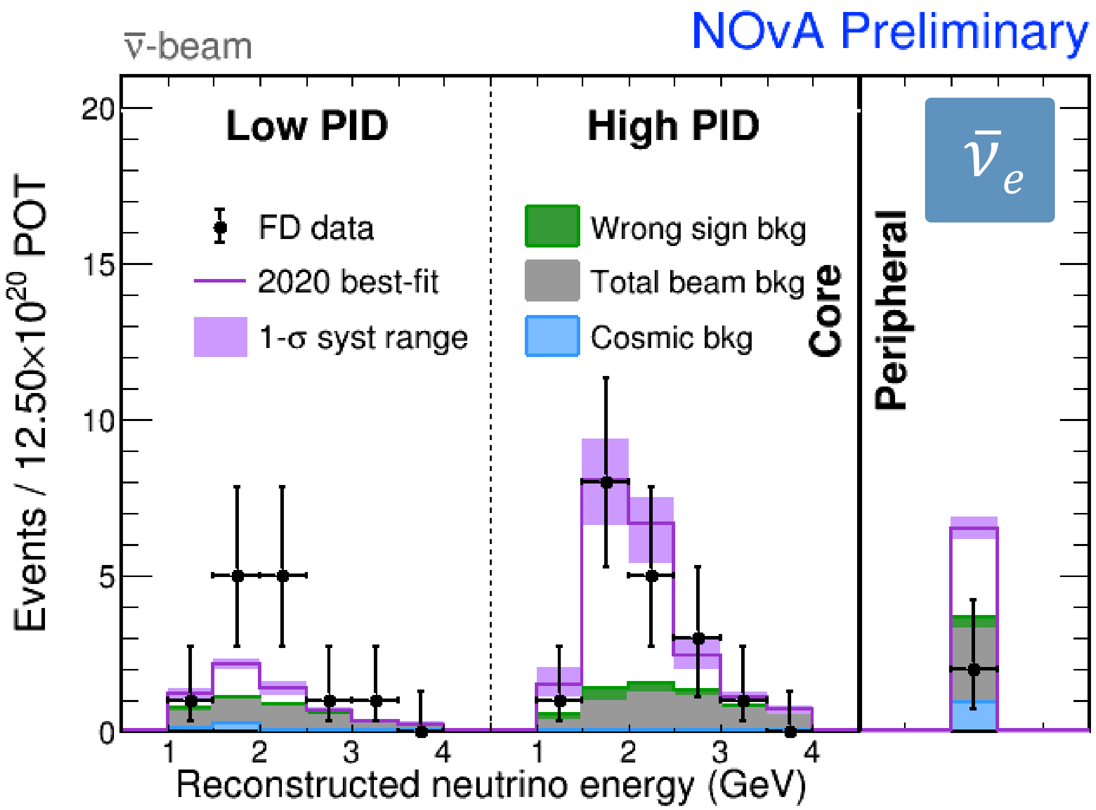
Total observed	211
Integral at best fit	222.3
Signal prediction	214.1
Background prediction	8.2



Total observed	105
Integral at best fit	105.4
Signal prediction	103.4
Background prediction	2.1

Electron Neutrinos at the FD





Total observed	**82**
Integral at best fit	85.8
Electron antineutrino	1.0
Total beam background	22.7
Cosmic background	3.1

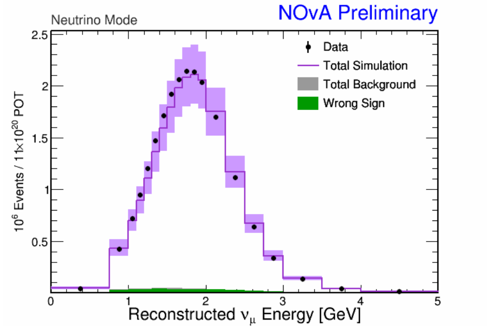
>4σ evidence of $\bar{\nu}_e$ appearance

Total observed	**33**
Integral at best fit	33.2
Electron neutrino	2.3
Total beam background	10.2
Cosmic background	1.6

Two-detector technique

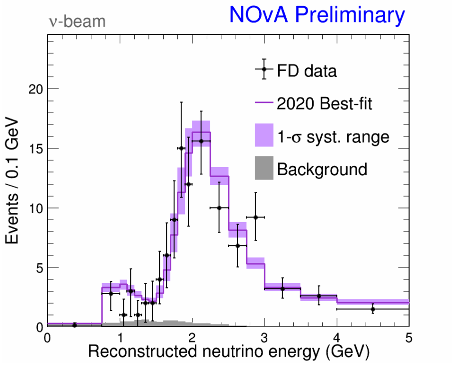
We use ND data to predict the oscillated spectra in the FD

Both disappearance ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$) and appearance ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$) analyses start with ν_μ's in ND

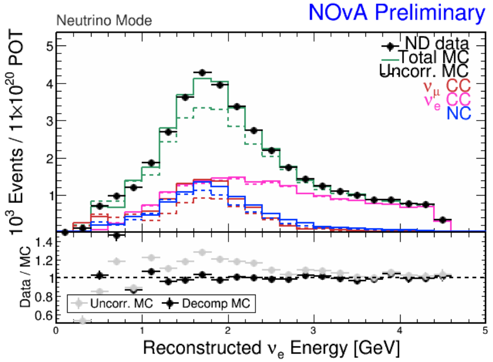


F/N x P ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$)

ν_μ in FD



Constrain predictions with ND data → **Apply oscillations and FD/ND ratio** → **Compare to FD data**



F/N x P ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$)

ν_e in FD