Recent three-flavor neutrino oscillation results from the NOvA experiment

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for the NOvA collaboration

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The NOvA Experiment

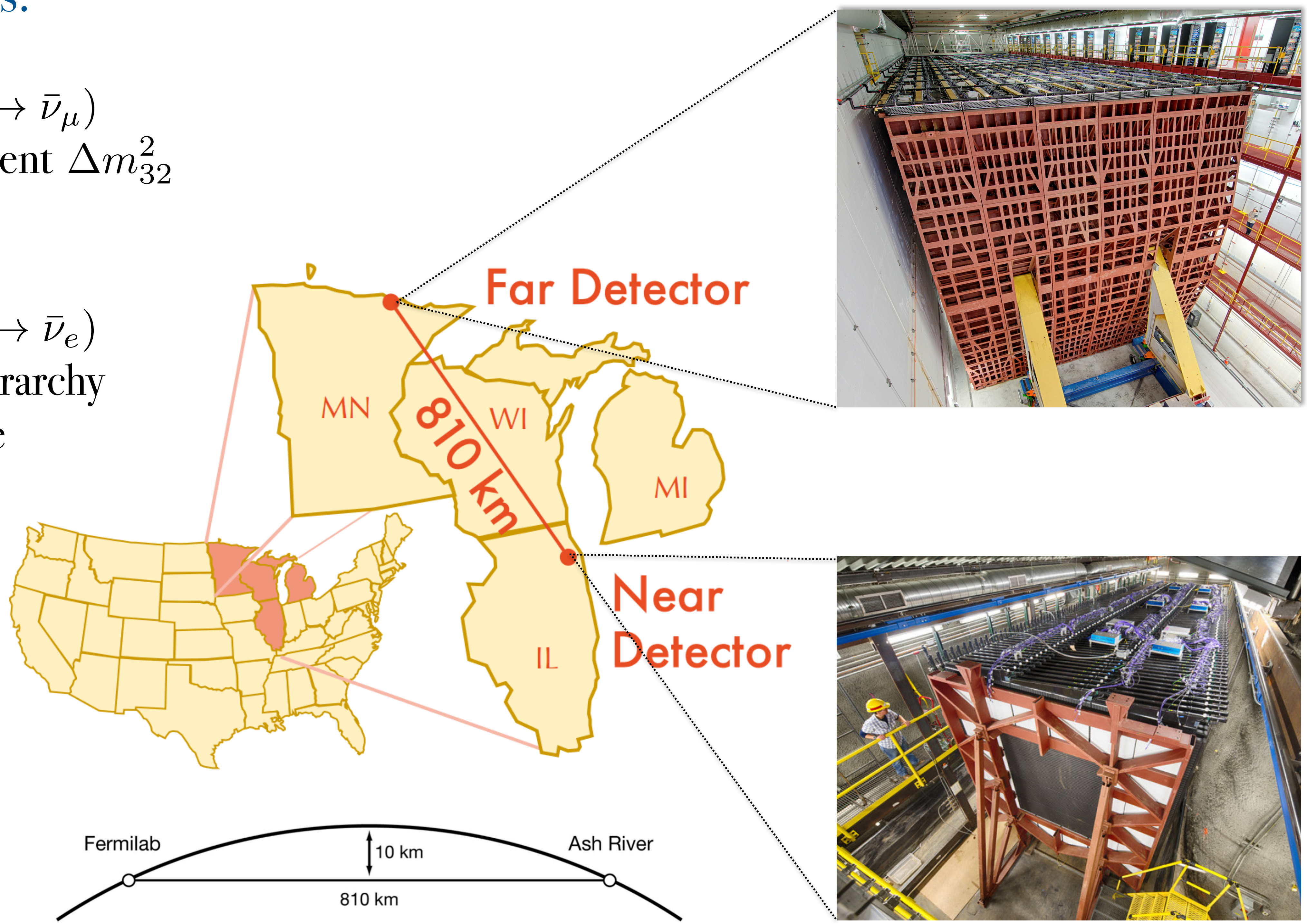
The NuMI Off-Axis ν_e Appearance Experiment

Experiment goals:

Using $\nu_\mu \rightarrow \nu_\mu$ $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$
- ✳ Precise measurement Δm^2_{32}
- ✳ Mixing angle θ_{23}

Using $\nu_\mu \rightarrow \nu_e$ $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- ✳ Neutrino mass hierarchy
- ✳ CP violating phase
- ✳ Mixing angle θ_{23}

Long-baseline, beam from Fermilab, two detectors sit at 14 mrad off-axis



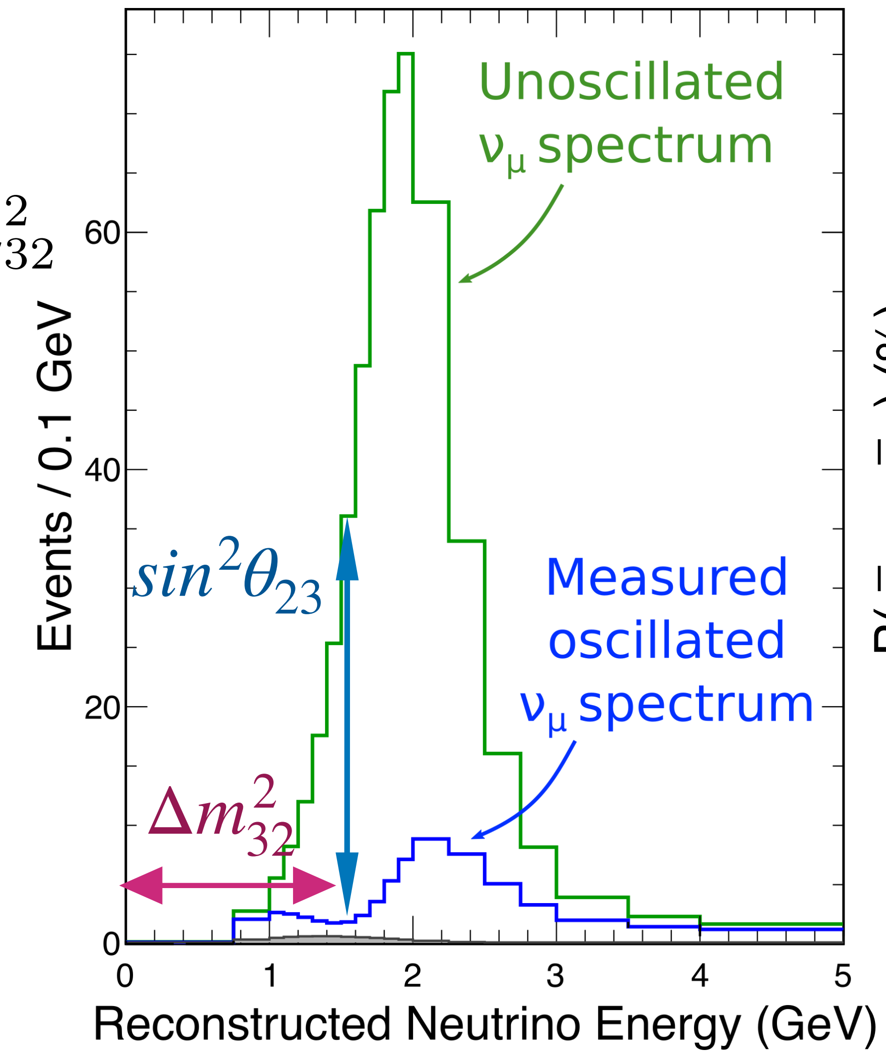
Strategy

Experiment goals:

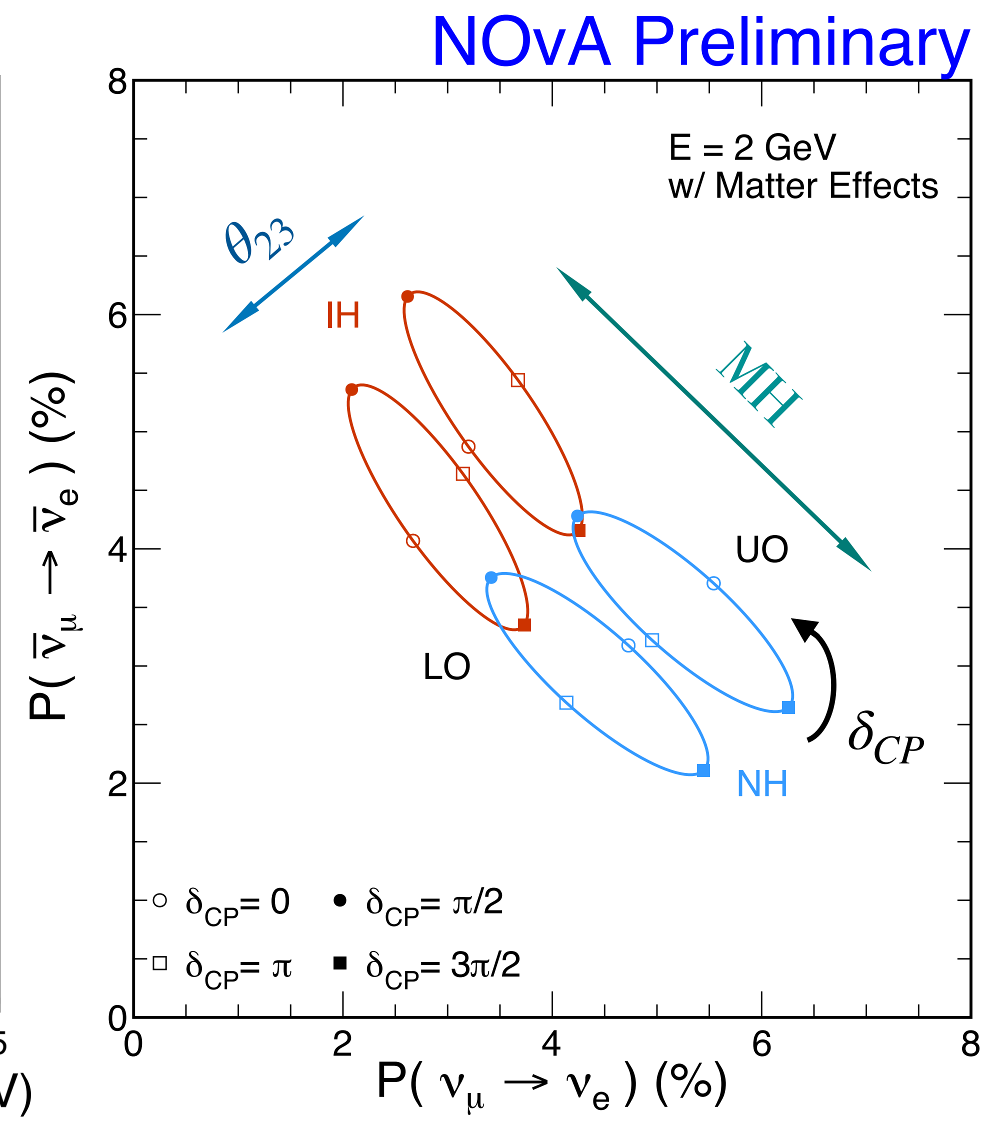
Using $\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
- ✳ Precise measurement Δm^2_{32}
- ✳ Mixing angle θ_{23}

Using $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$
- ✳ Neutrino mass hierarchy
- ✳ CP violating phase
- ✳ Mixing angle θ_{23}

Disappearance



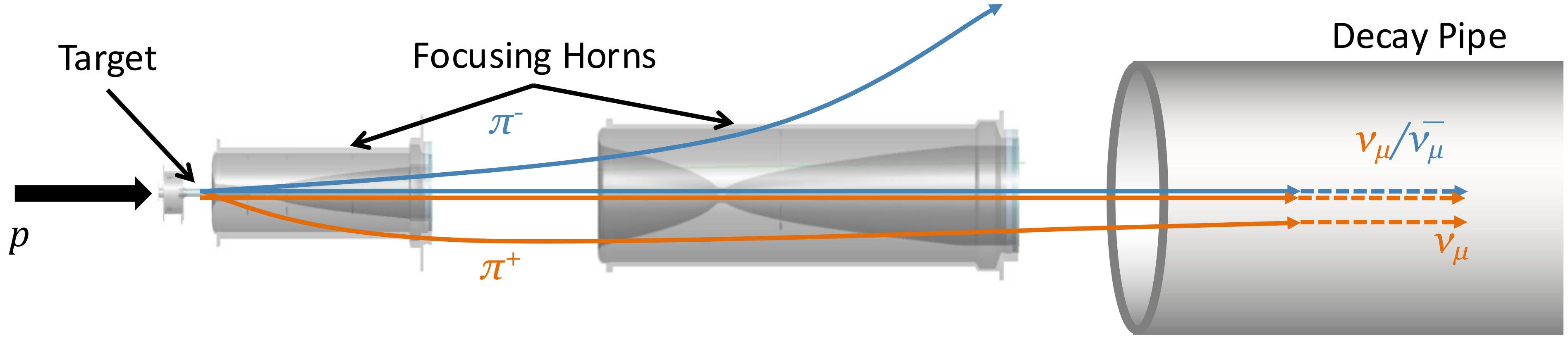
Appearance



Obtain sensitivity to the mass hierarchy due to matter effects.

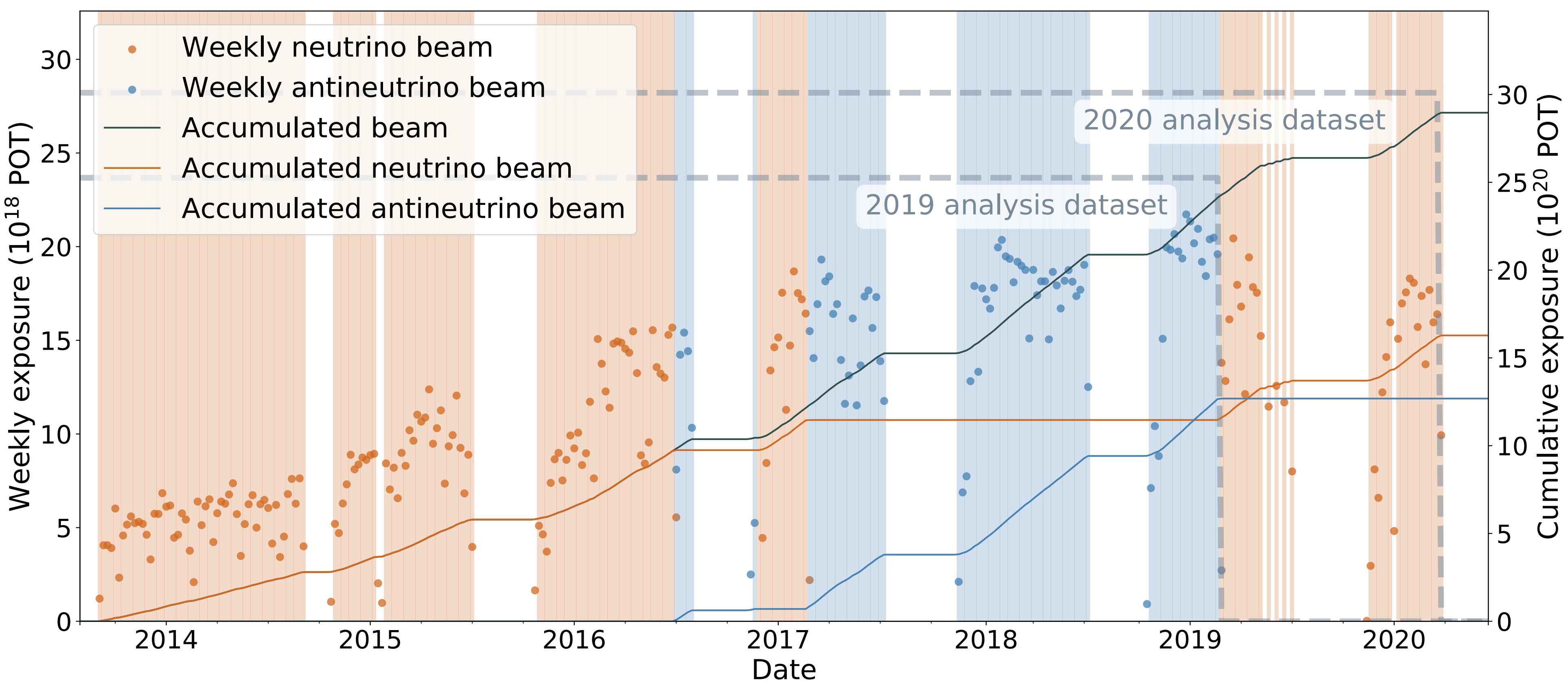
In order to avoid degeneracy "θ_{23} - mass hierarchy - δ_{CP}" need both neutrino and antineutrino beams

Neutrino beam



✳ 120 GeV protons on a carbon target, produce mesons which yield neutrinos. Beam purity with $\nu(\bar{\nu})$: $95\%\ \nu_\mu, 4\%\ \bar{\nu}_\mu, 1\%\ \nu_e/\bar{\nu}_e$ $(93\%\ \bar{\nu}_\mu, 6\%\ \nu_\mu, 1\%\ \nu_e/\bar{\nu}_e)$.

✳ NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT/year (POT = Proton On Target).



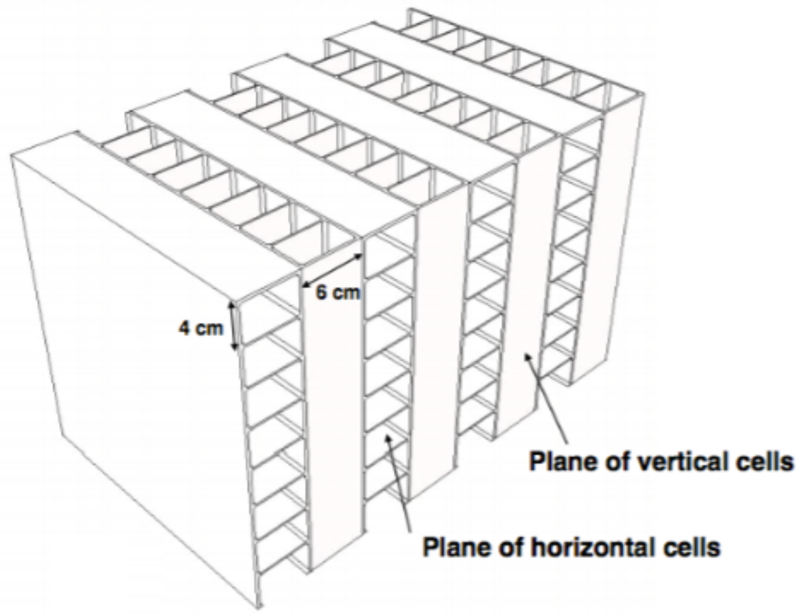
54% increase in ν exposure:
$8.85 \times 10^{20} \rightarrow 13.6 \times 10^{20}$
(2019 $\rightarrow$ 2020)

13.6×10^{20} POT neutrino beam

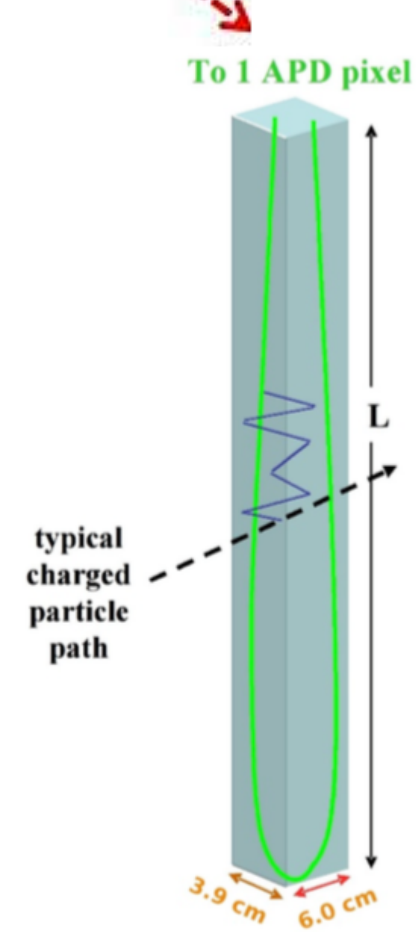
+

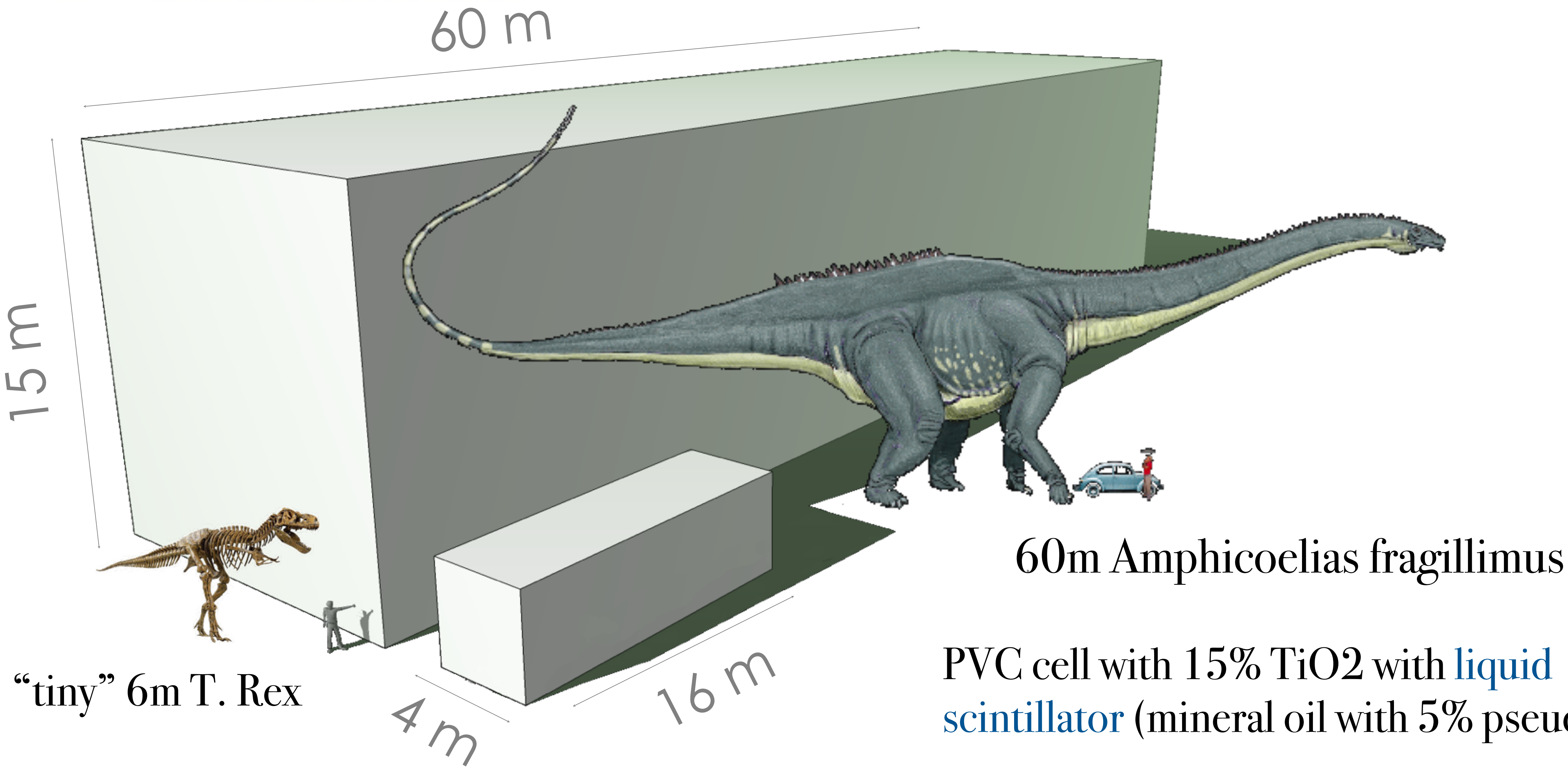
12.5×10^{20} POT antineutrino beam

Detectors



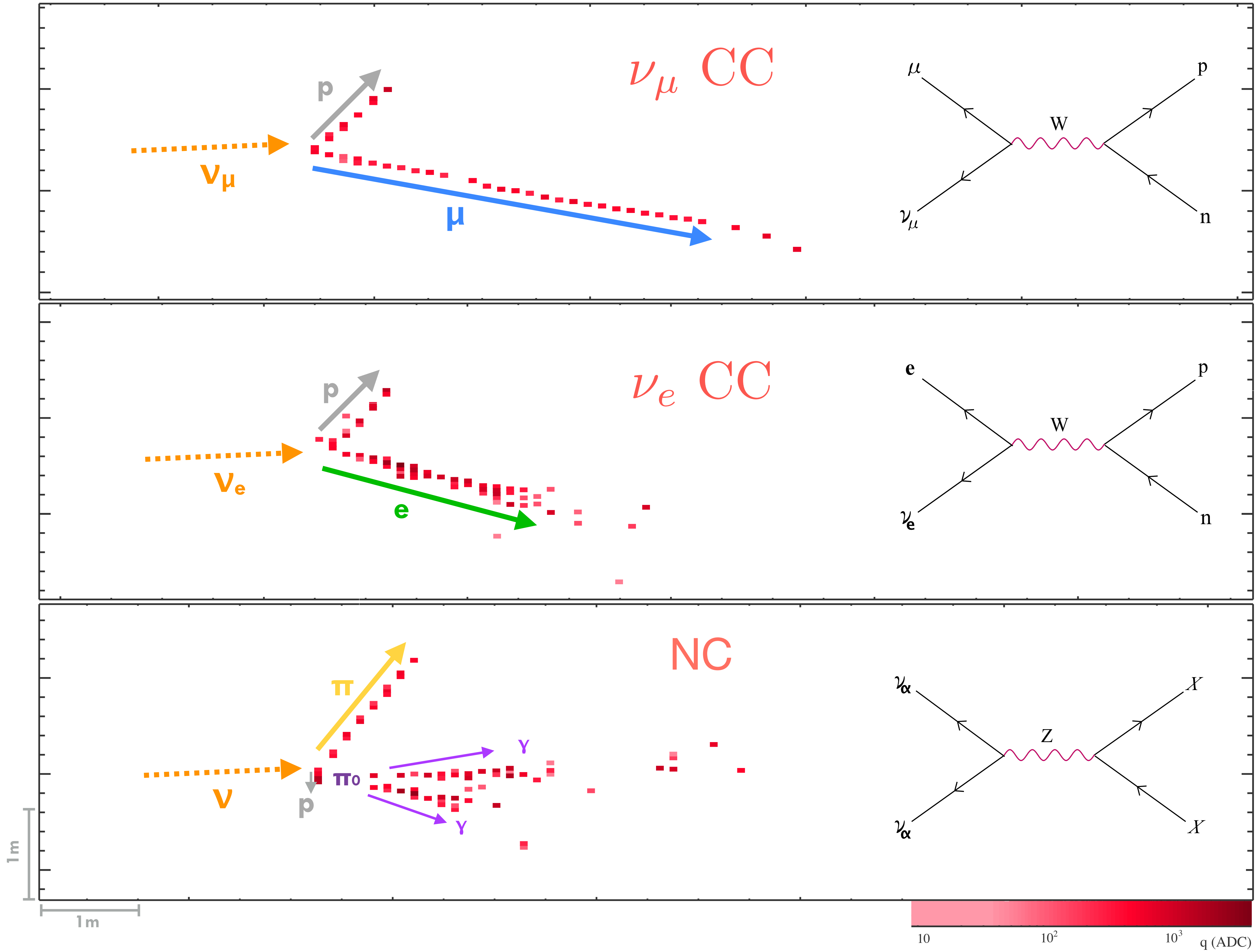
FD: 344 064 cells
ND: 20 193 cells



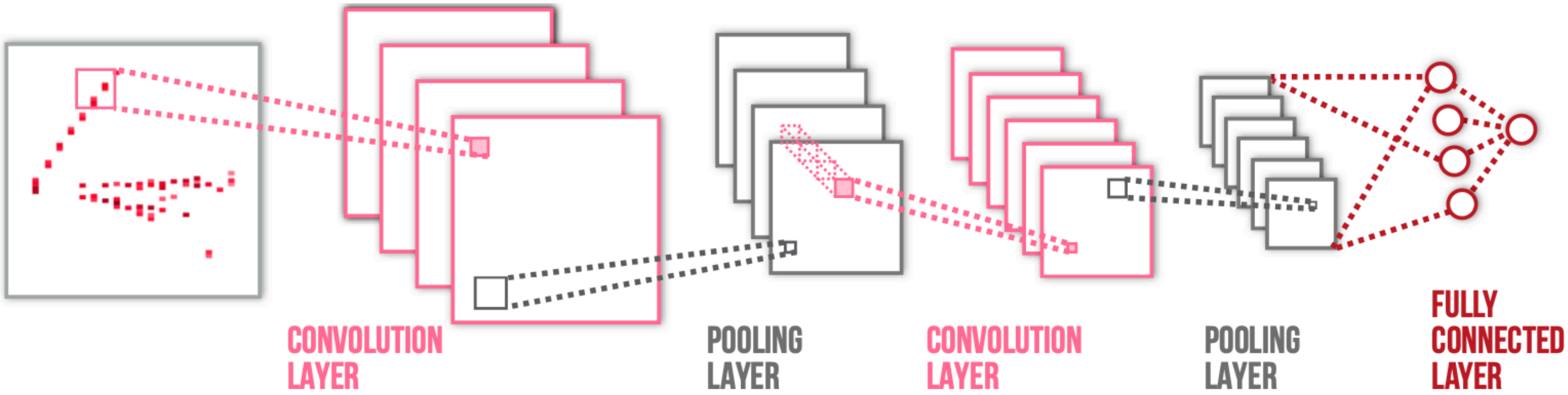


PVC cell with 15% TiO_2 with liquid scintillator (mineral oil with 5% pseudocumene)

Event topologies



ν_e / ν_μ event selection with CVN



- We use convolution neural network called CVN (Convolutional Visual Network).
- Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic.

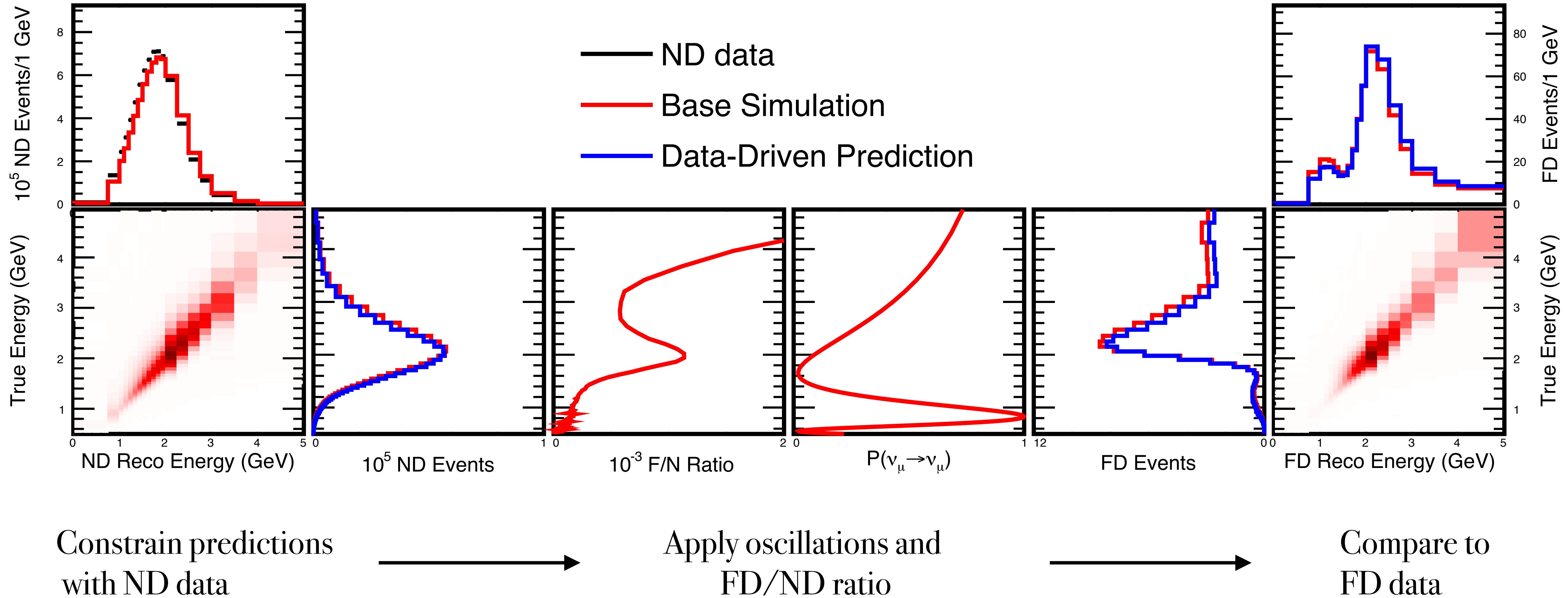
A. Aurisano et. al, JINST 11, P09001 (2016)

Simulation and Predictions

Basic Monte-Carlo simulation chain:

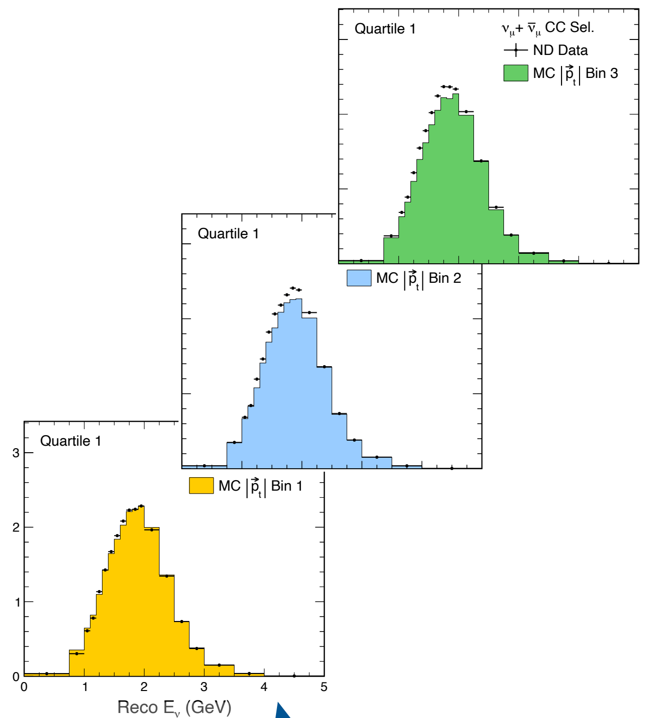
- ✳ Beam hadron production, propagation; neutrino flux: GEANT4/External Data;
- ✳ Neutrino interactions and FSI modeling: GENIE v3.0.6;
- ✳ Detector simulation: GEANT4;
- ✳ Readout electronics and DAQ: Custom simulation routines;
- ✳ Cosmic ray flux: Cosmic Triggers.

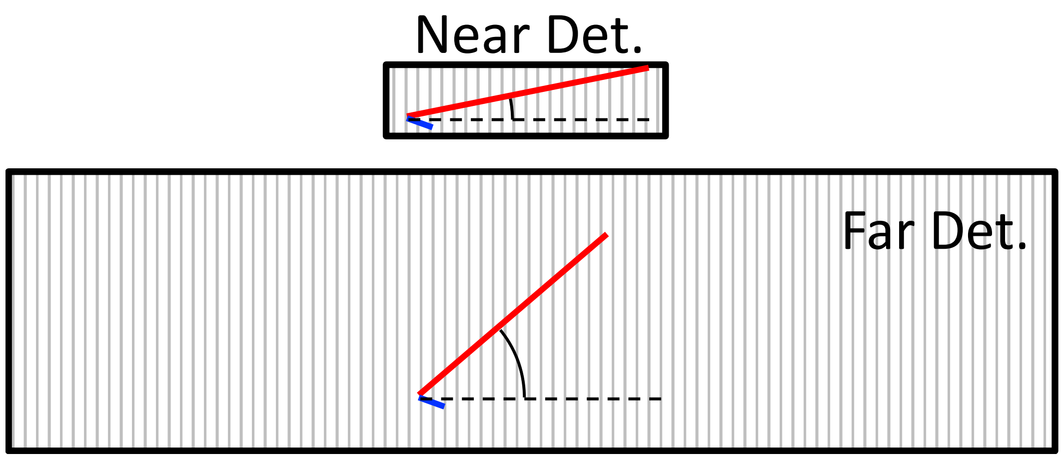
Far Detector predictions are constrained by high-stat unoscillated Near Detector data:

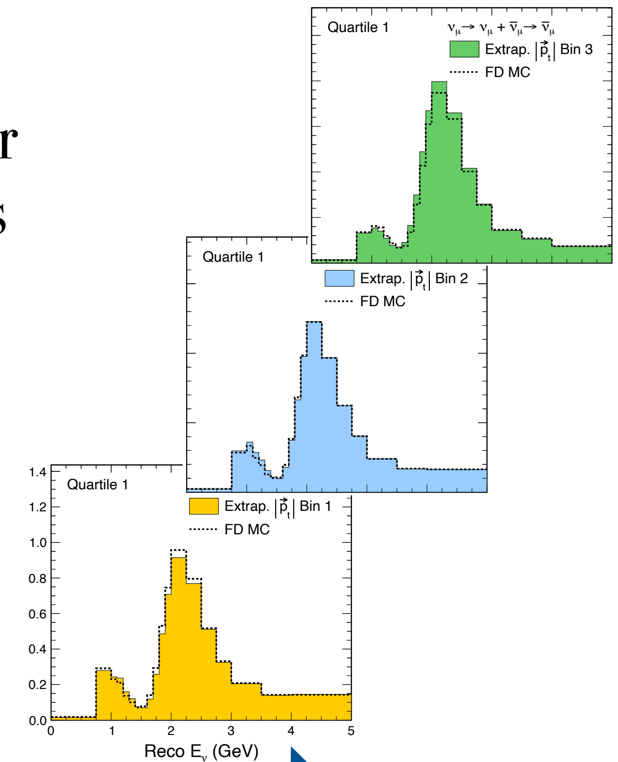


2020 Extrapolation

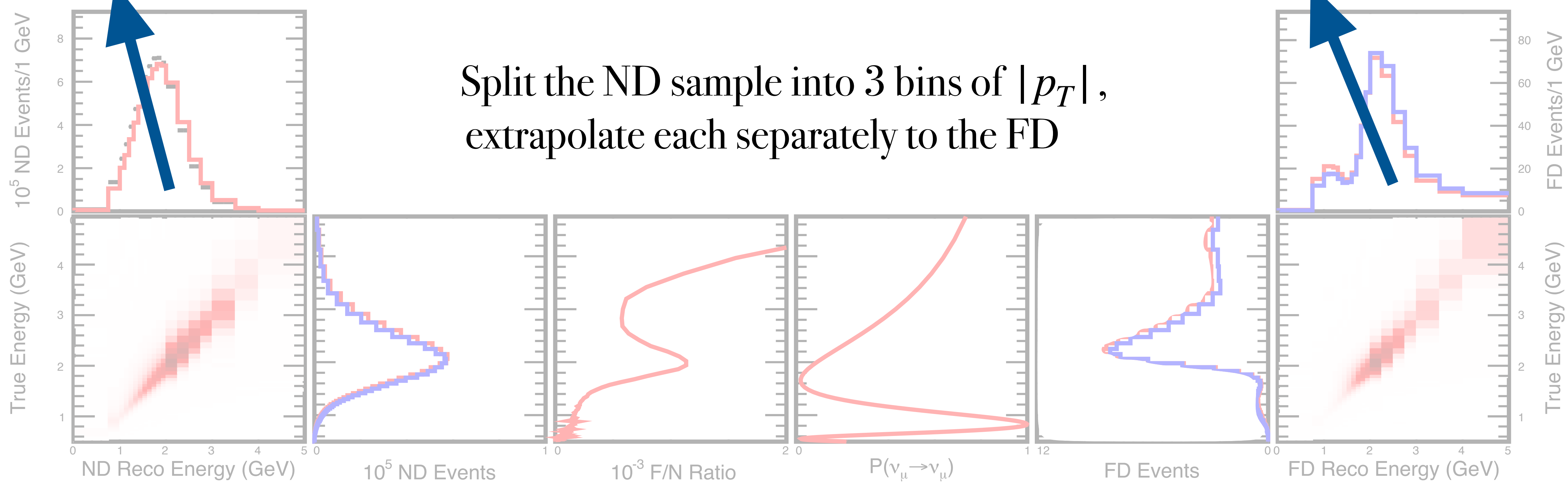
- ND is 1/64 of FD volume
- Extrapolate in sub-ranges of lepton $|p_T|$ for matching the acceptance between detectors







Split the ND sample into 3 bins of $|p_T|$, extrapolate each separately to the FD

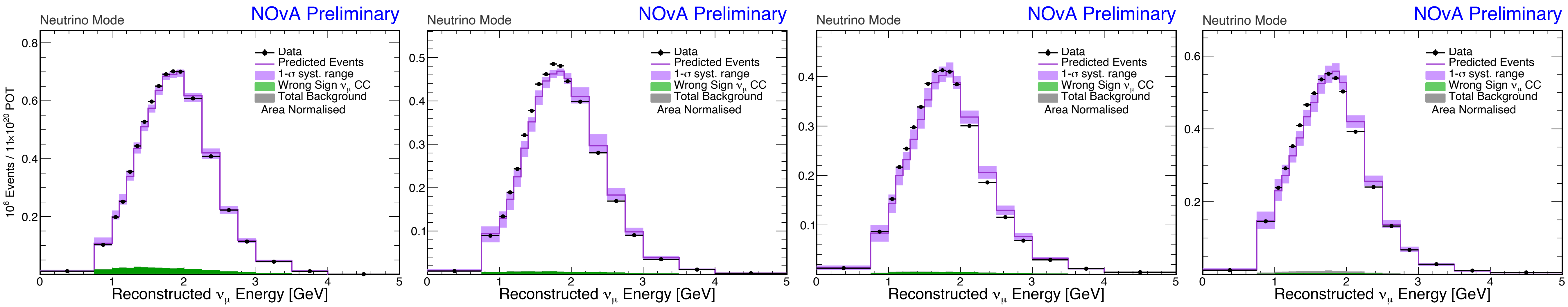


Constrain predictions with ND data → Apply oscillations and FD/ND ratio → Compare to FD data

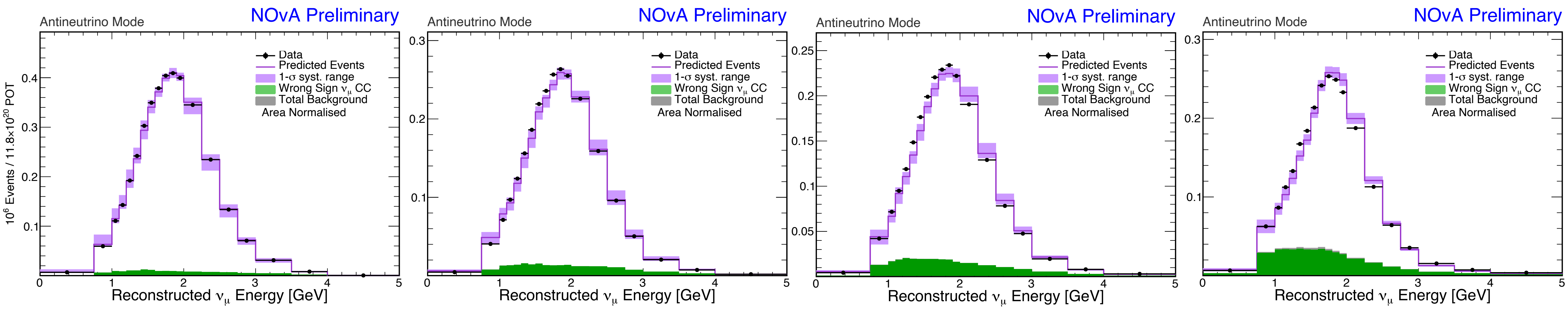
ND data for ν_μ

Quartile 1
(the best resolution ~8%) → Quartile 4
(the worst resolution ~12%)

Neutrino beam

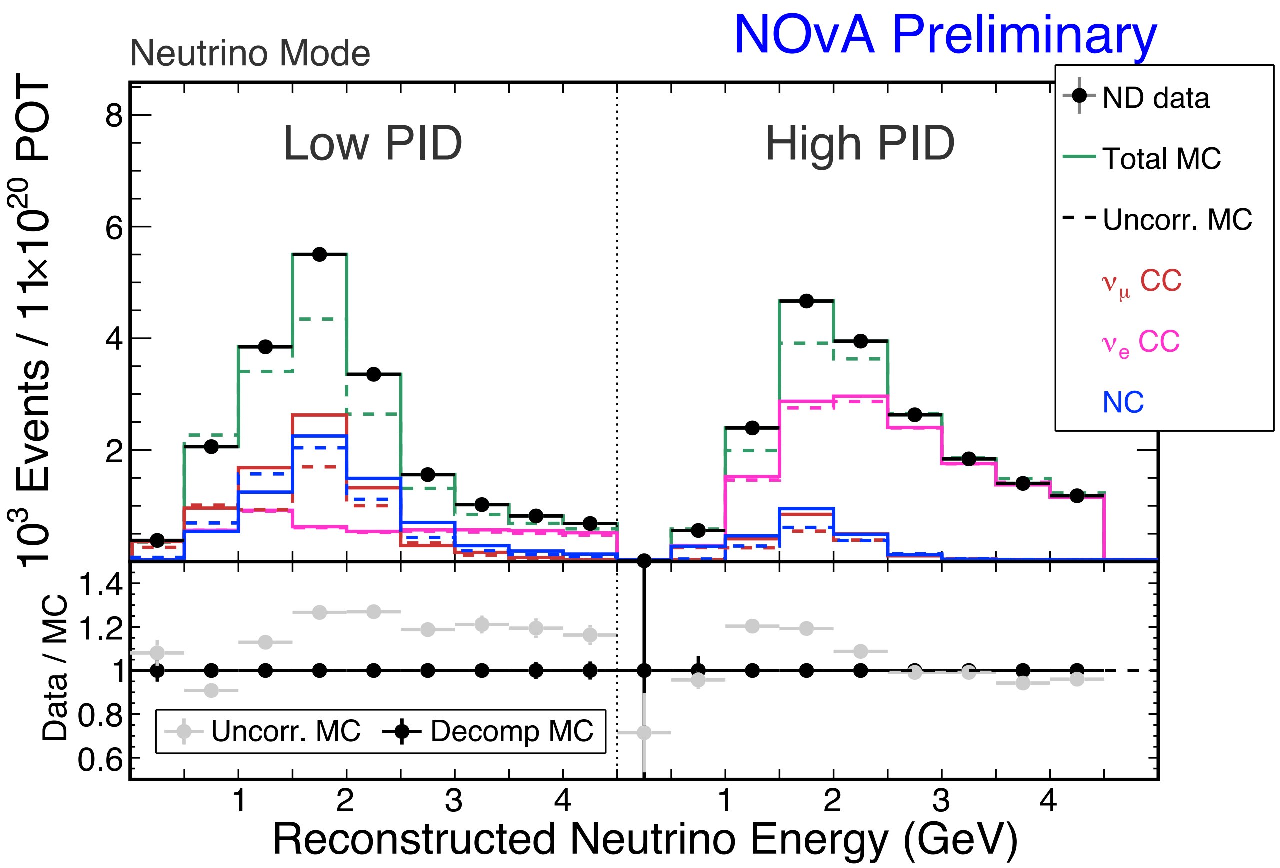


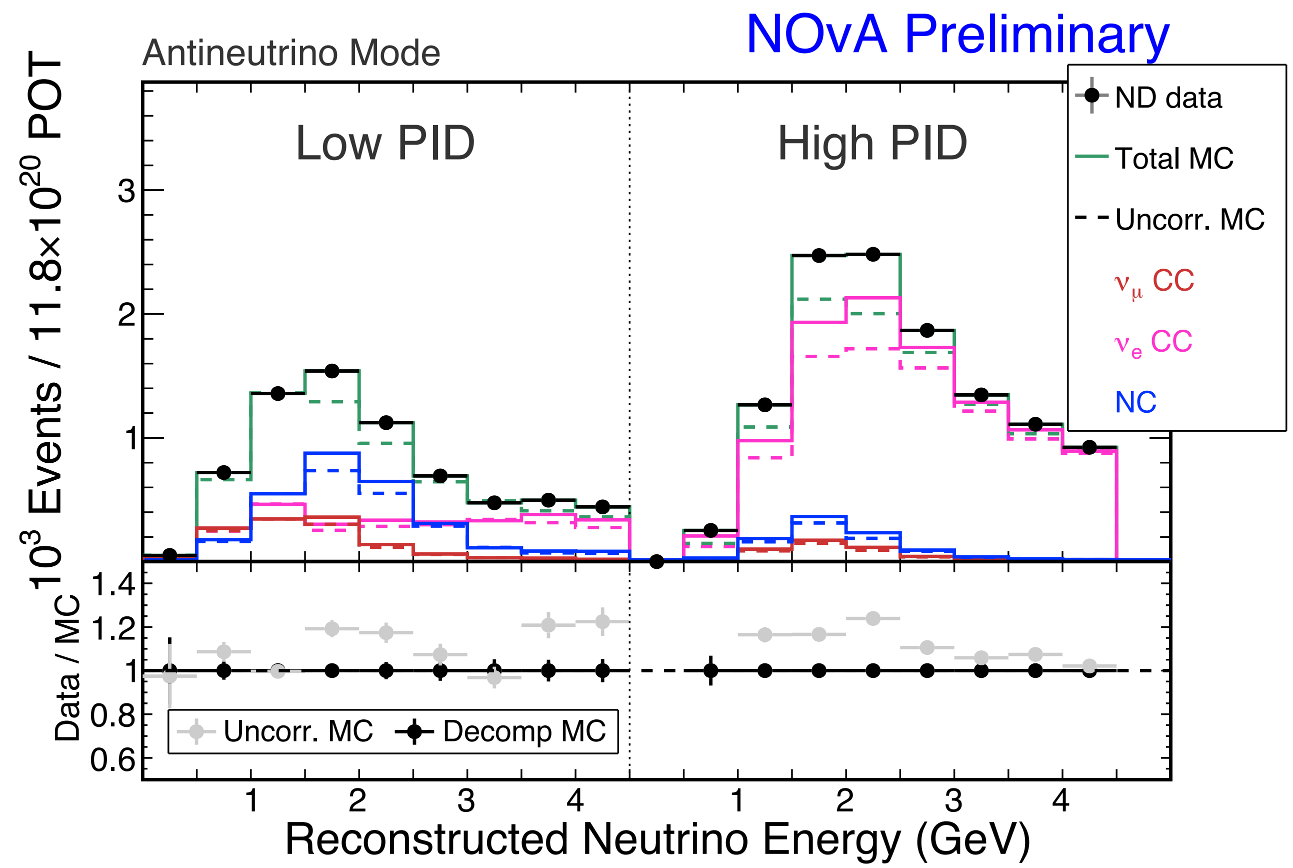
Antineutrino beam

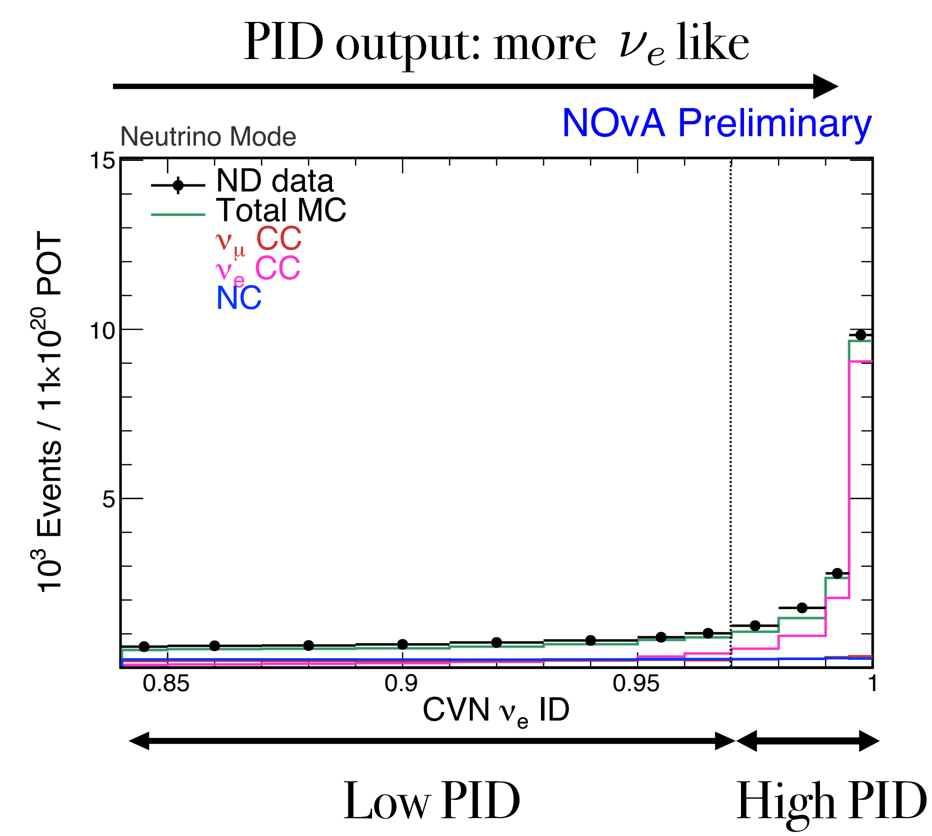


- ✳ ν_μ sample is divided into four quartiles based on E_{had}/E_ν fraction.

ND data for ν_e





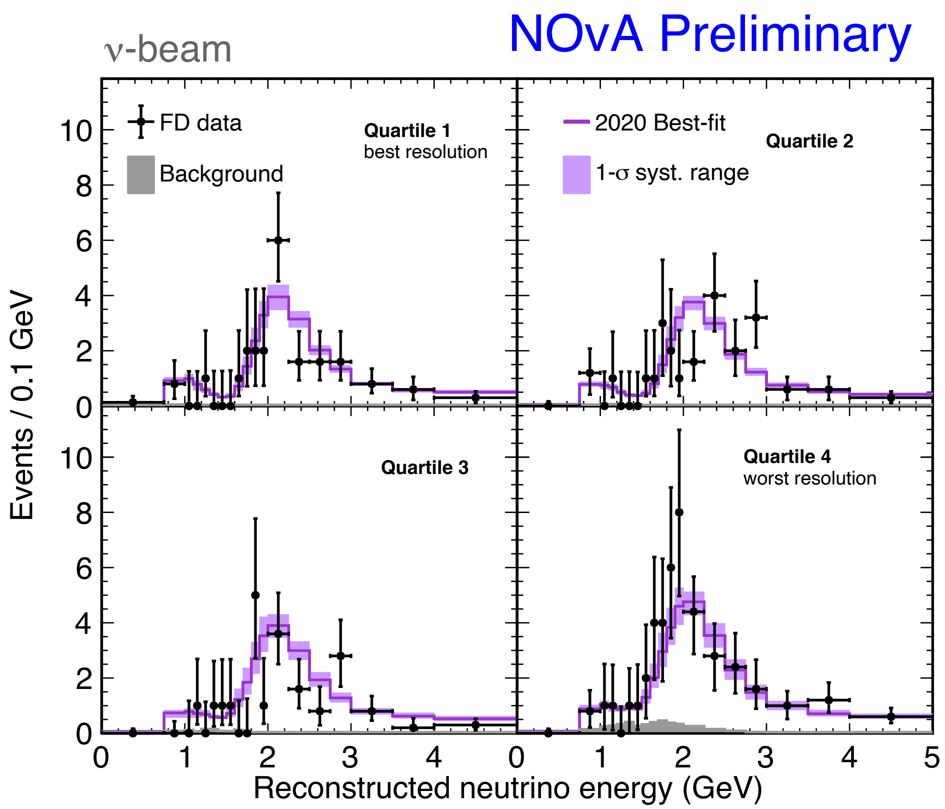


- ✳ Split ν_e sample into Low and High PID spectra.
- ✳ All ν_e ND candidates are background sources in the FD (no oscillations in the ND).
- ✳ Use ND data to correct the predictions.
- ✳ Extrapolate each category separately to the FD.

FD data. Inputs for fit

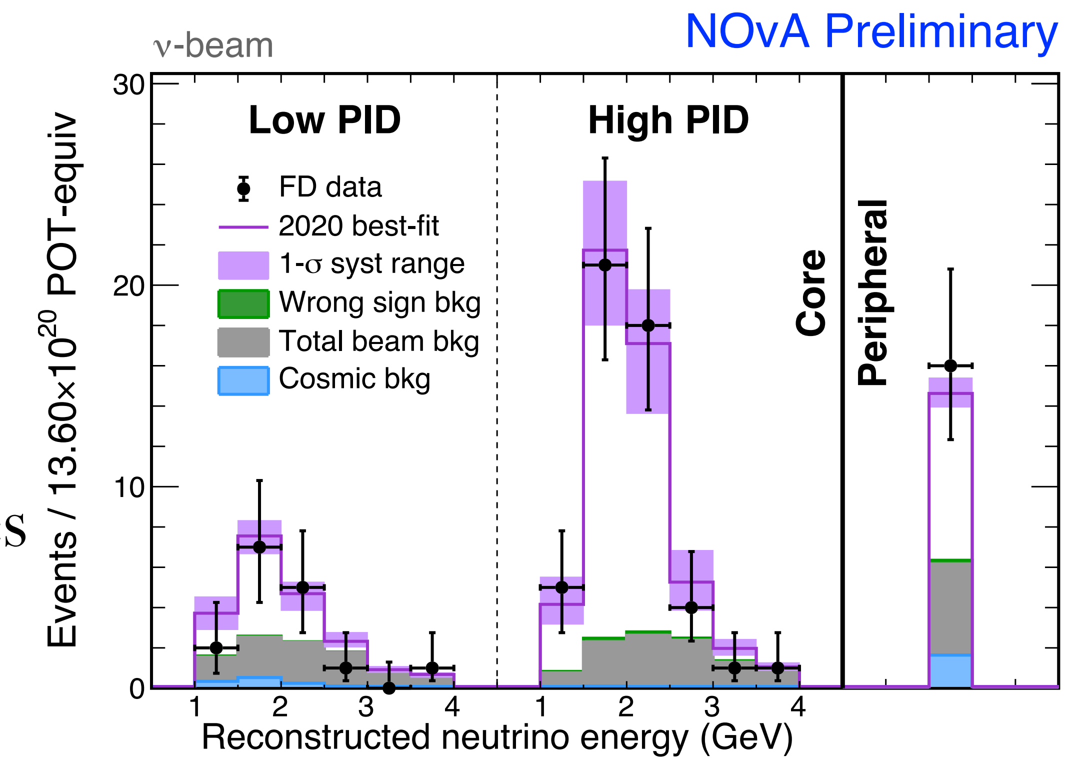
3-flavor oscillations describe data well (goodness-of-fit p =0.705)

NEUTRINO BEAM

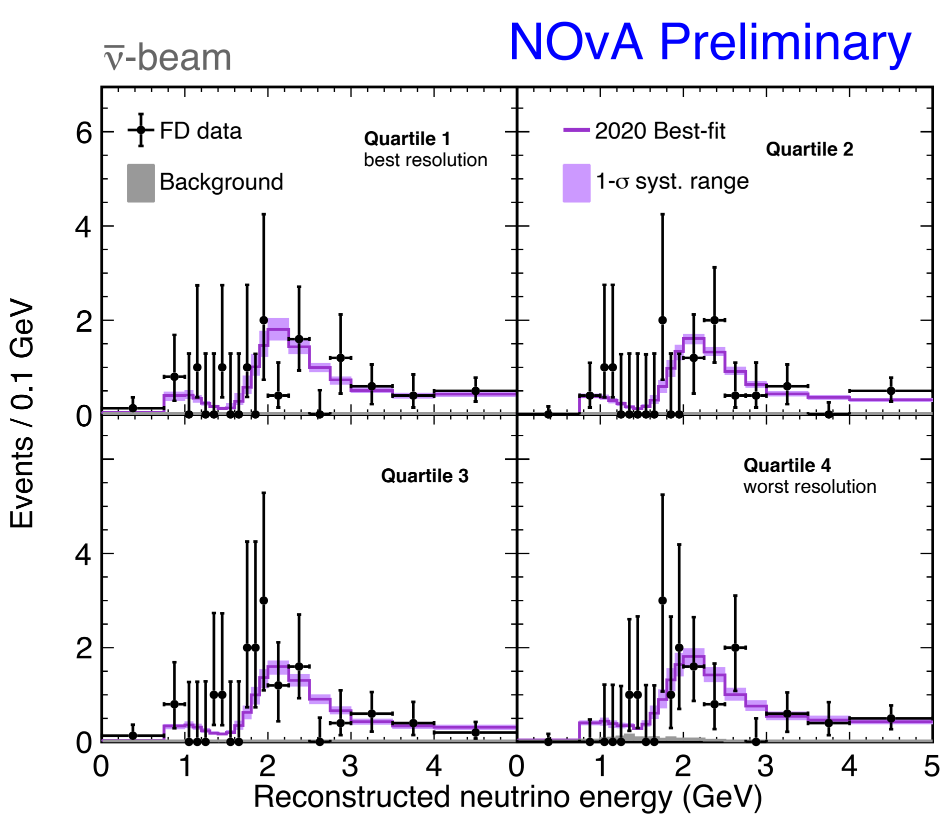


211 ν_μ candidates (bkg: 8.2)

82 ν_e candidates (bkg: 26.8)



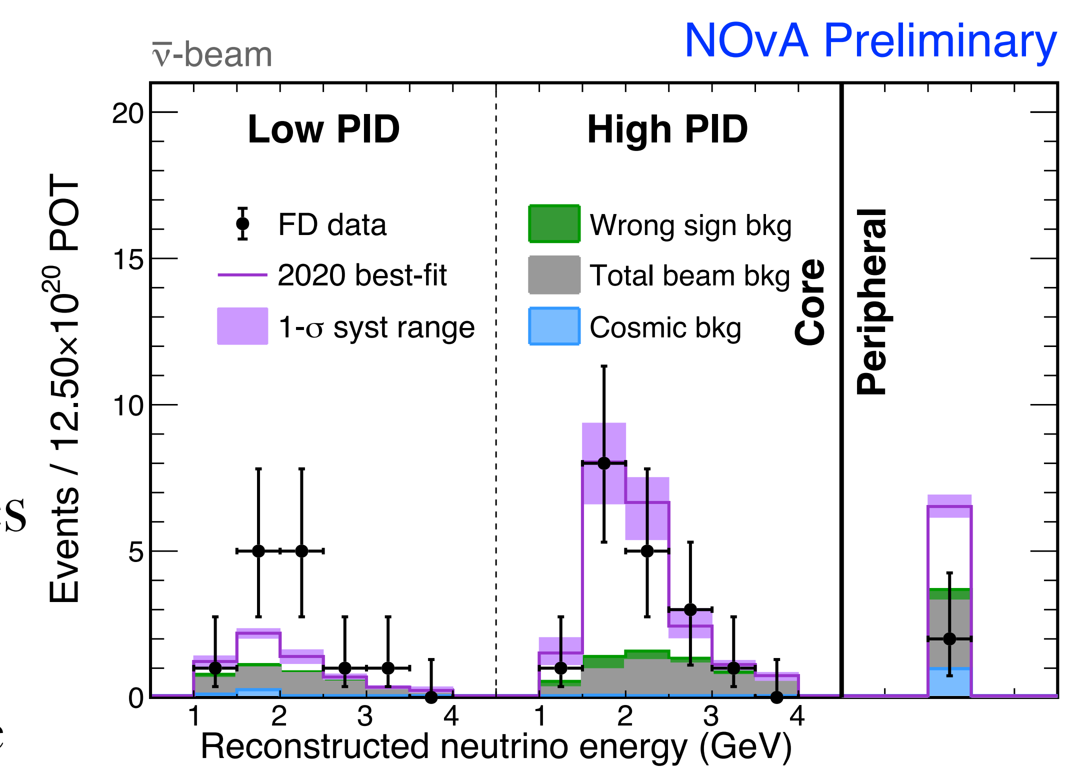
ANTINEUTRINO BEAM



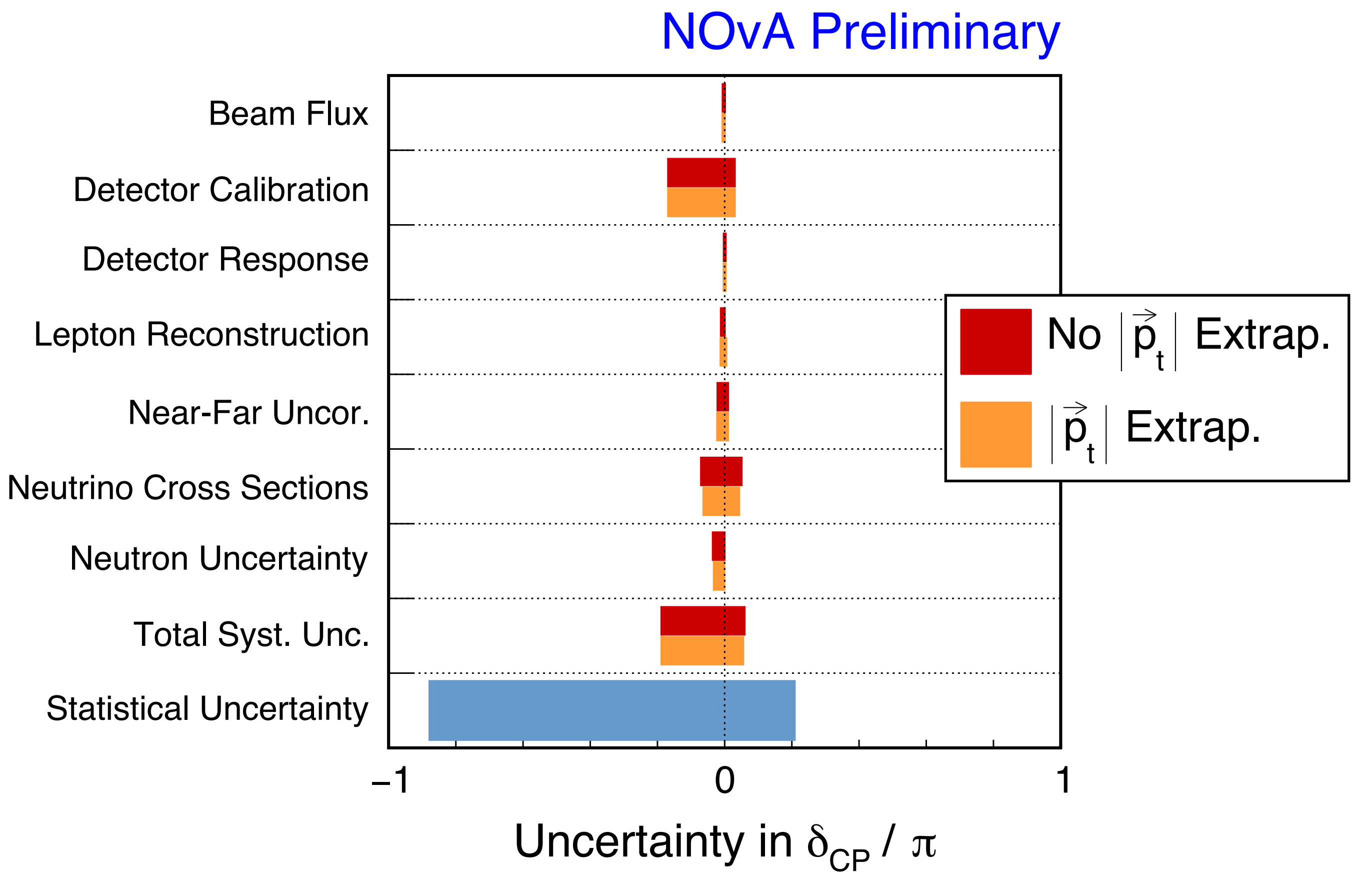
105 $\bar{\nu}_\mu$ candidates (bkg: 2.1)

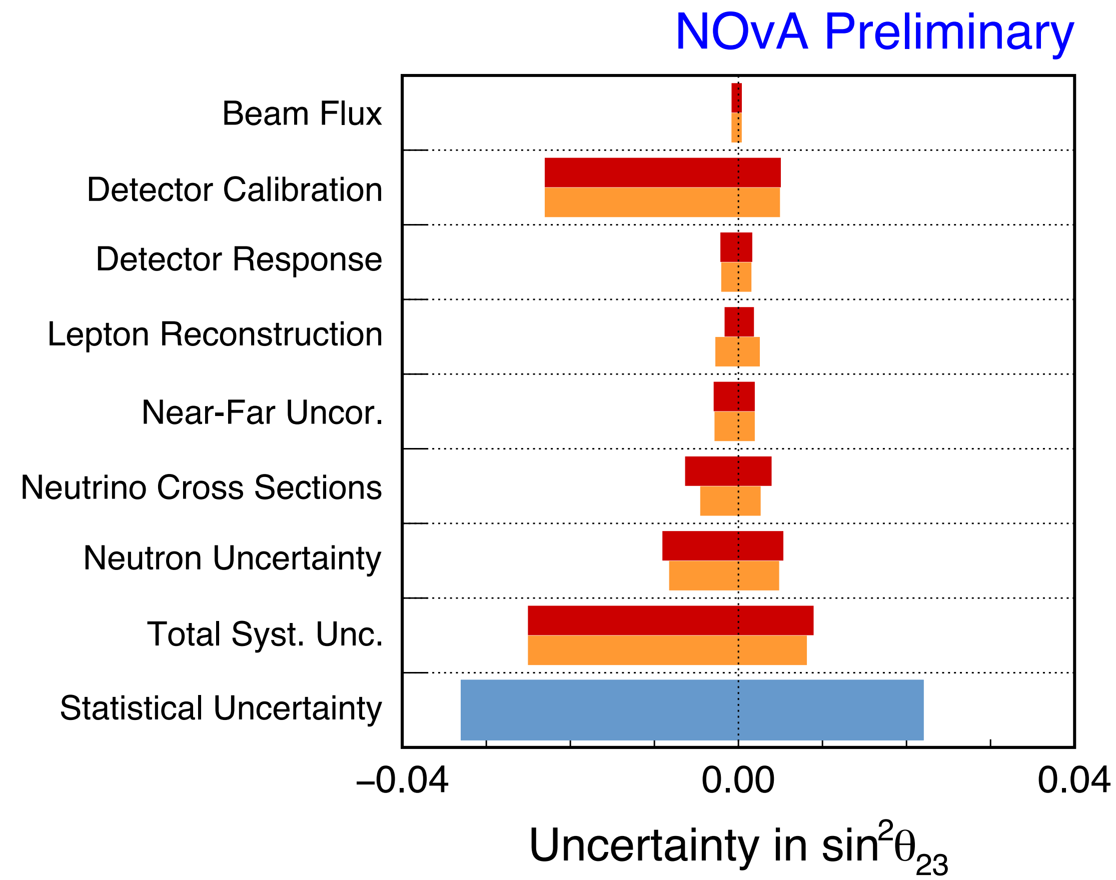
33 $\bar{\nu}_e$ candidates (bkg: 14.0)

$>4\sigma$ $\bar{\nu}_e$ appearance

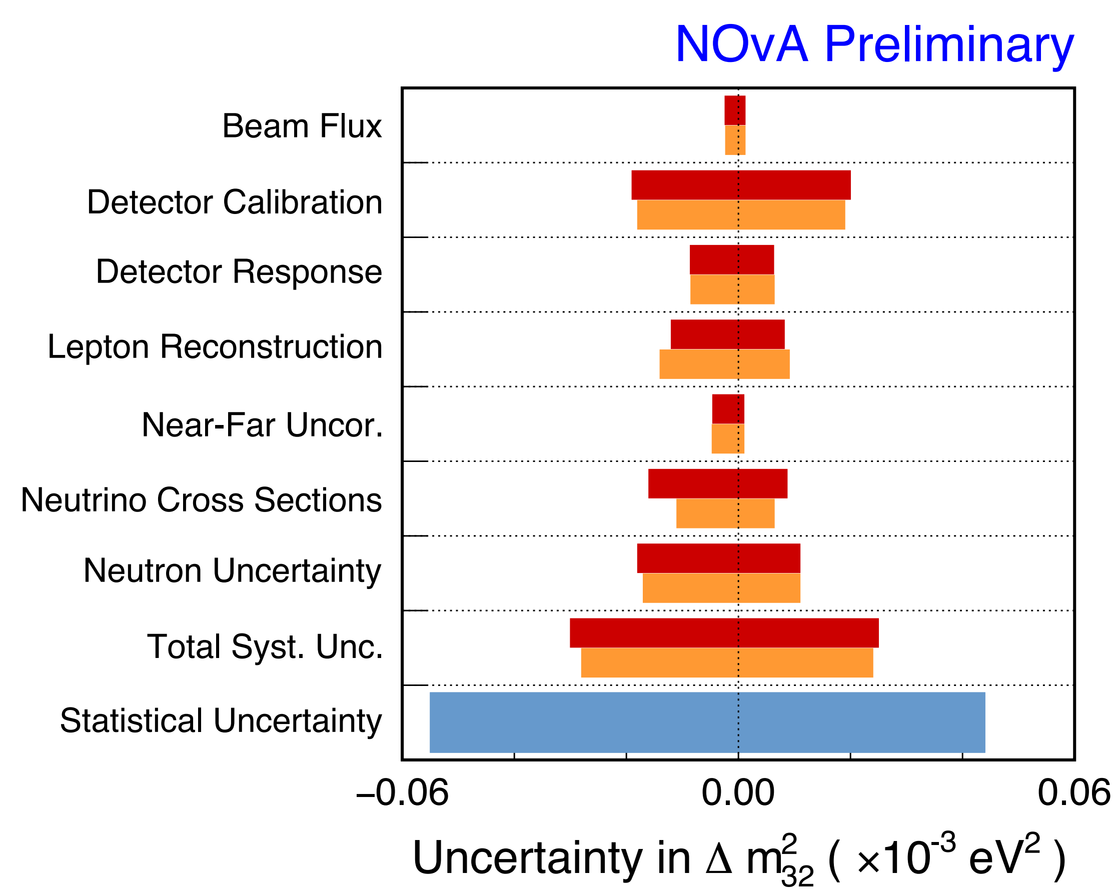


Systematics

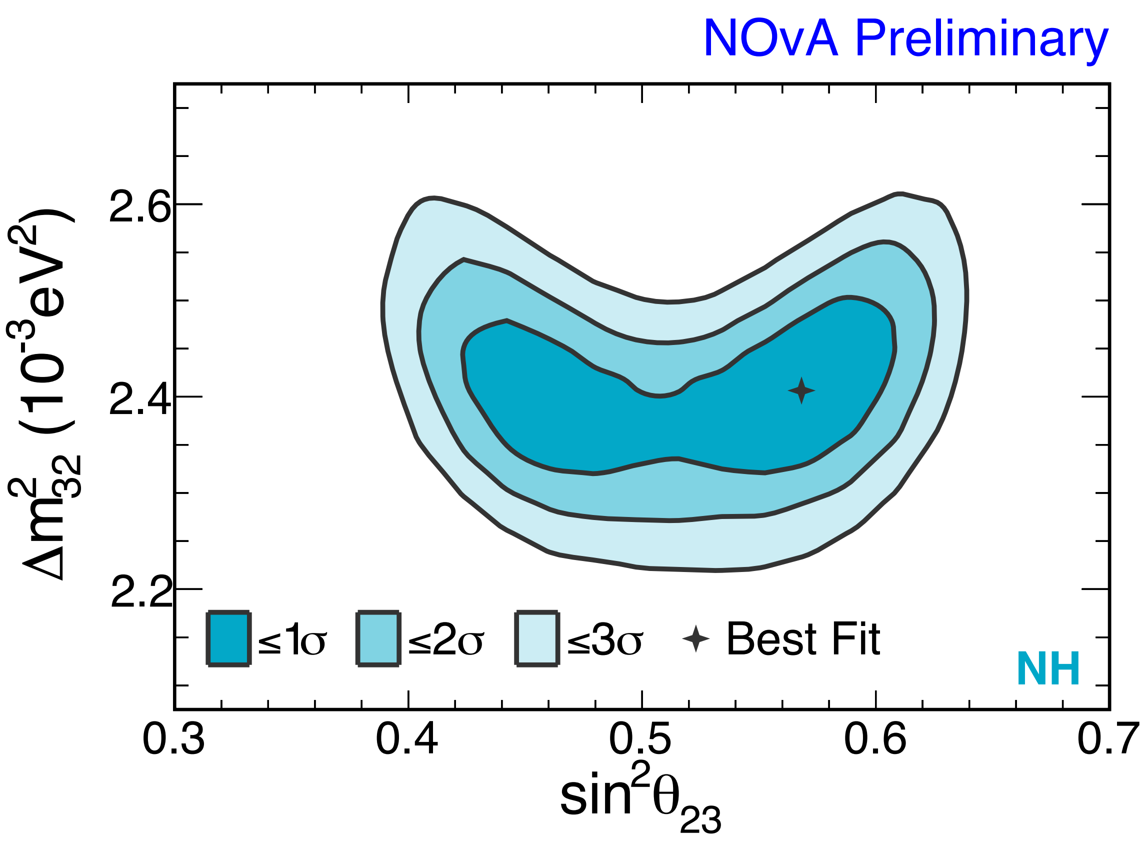


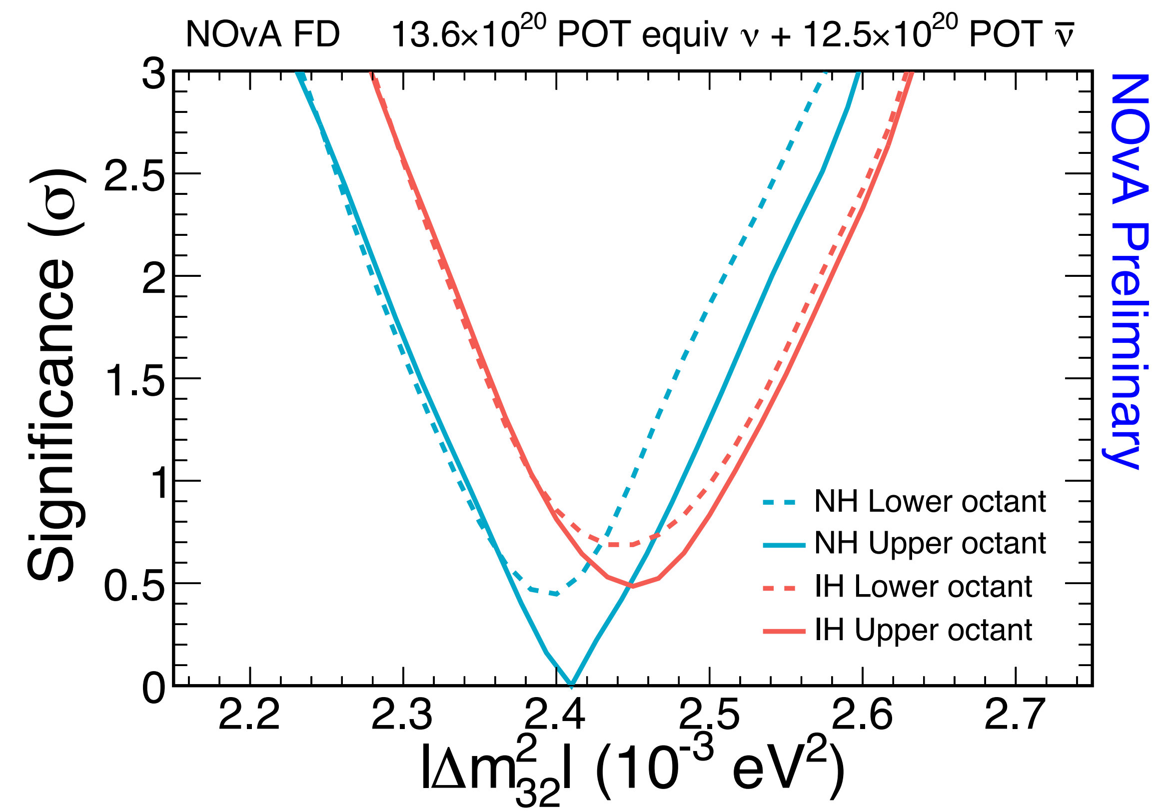


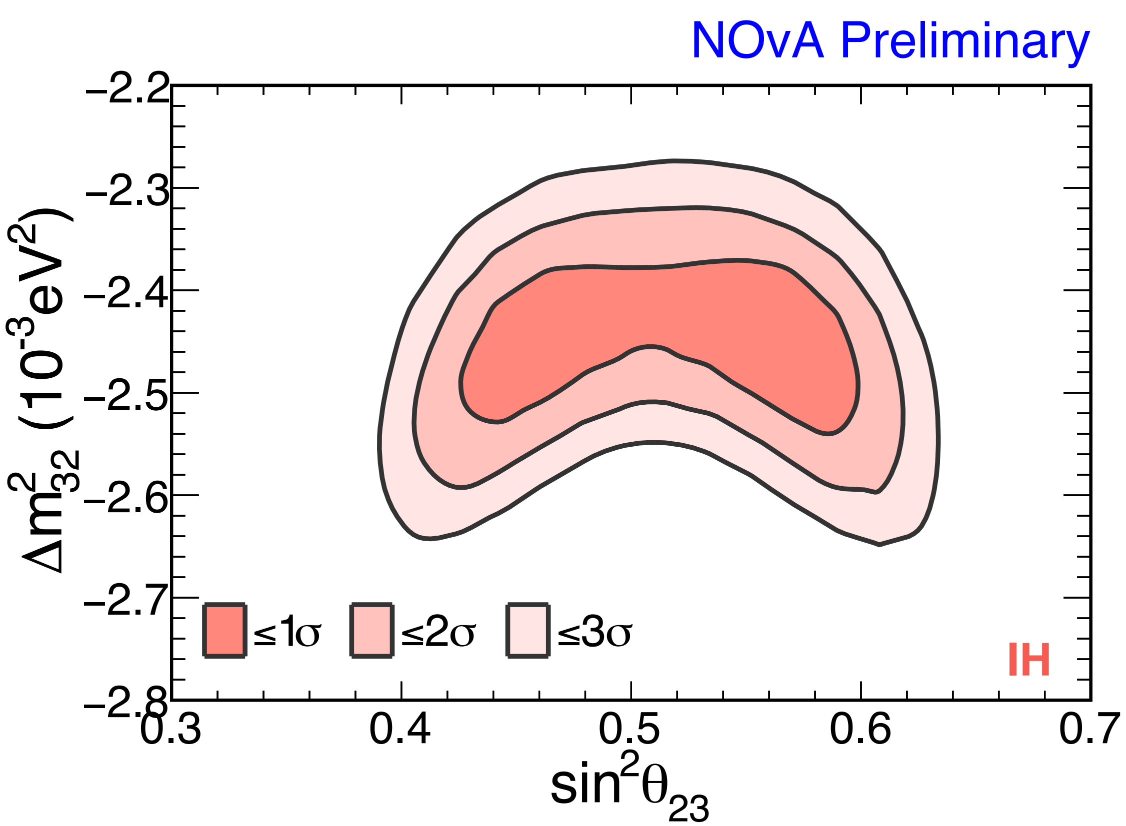
- Still statistically limited.
- New $|p_T|$ extrapolation improves analysis robustness
  - 30% reduction in cross section uncertainties;
- The most important systematics:
  - neutrino cross sections;
  - detector calibration (will be improved by test beam program);
  - neutron uncertainty - with $\bar{\nu}$.



Oscillation results: joint $\nu_e + \nu_\mu$ fit







- ✳ All systematic uncertainties, Feldman - Cousins corrections are applied.
- ✳ Best fit:

6%

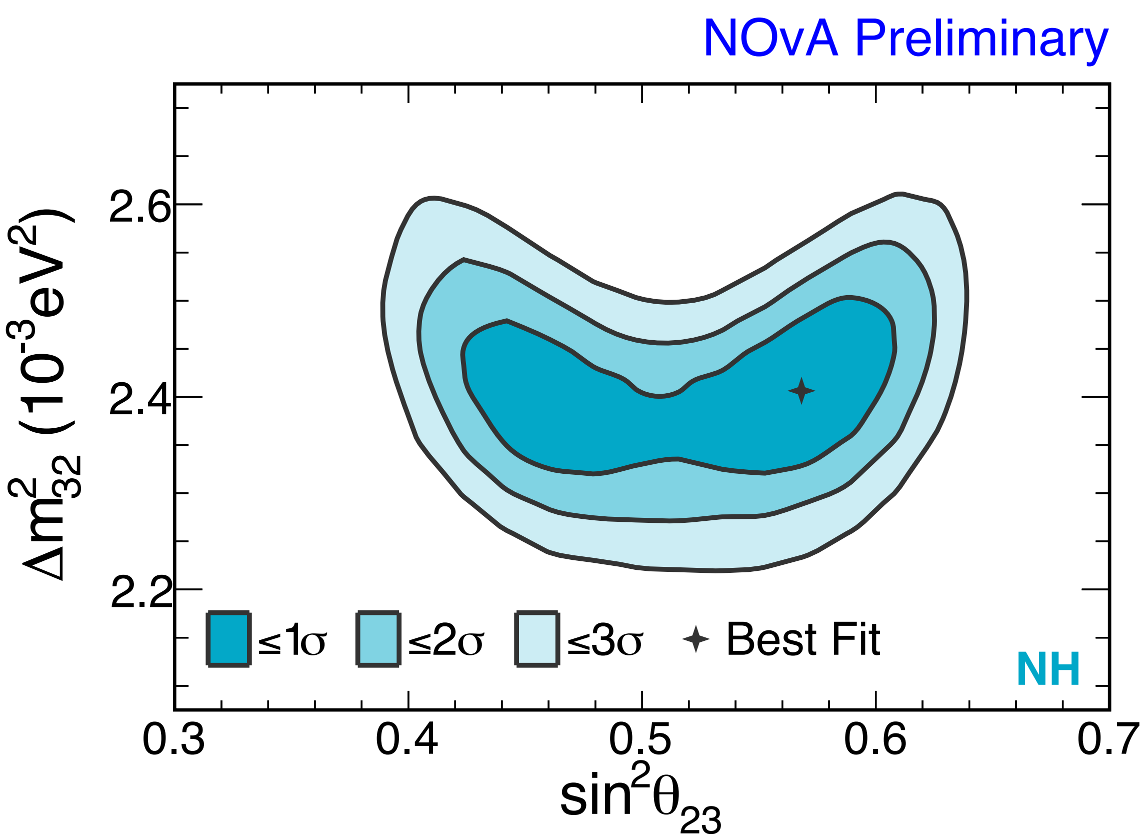
$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

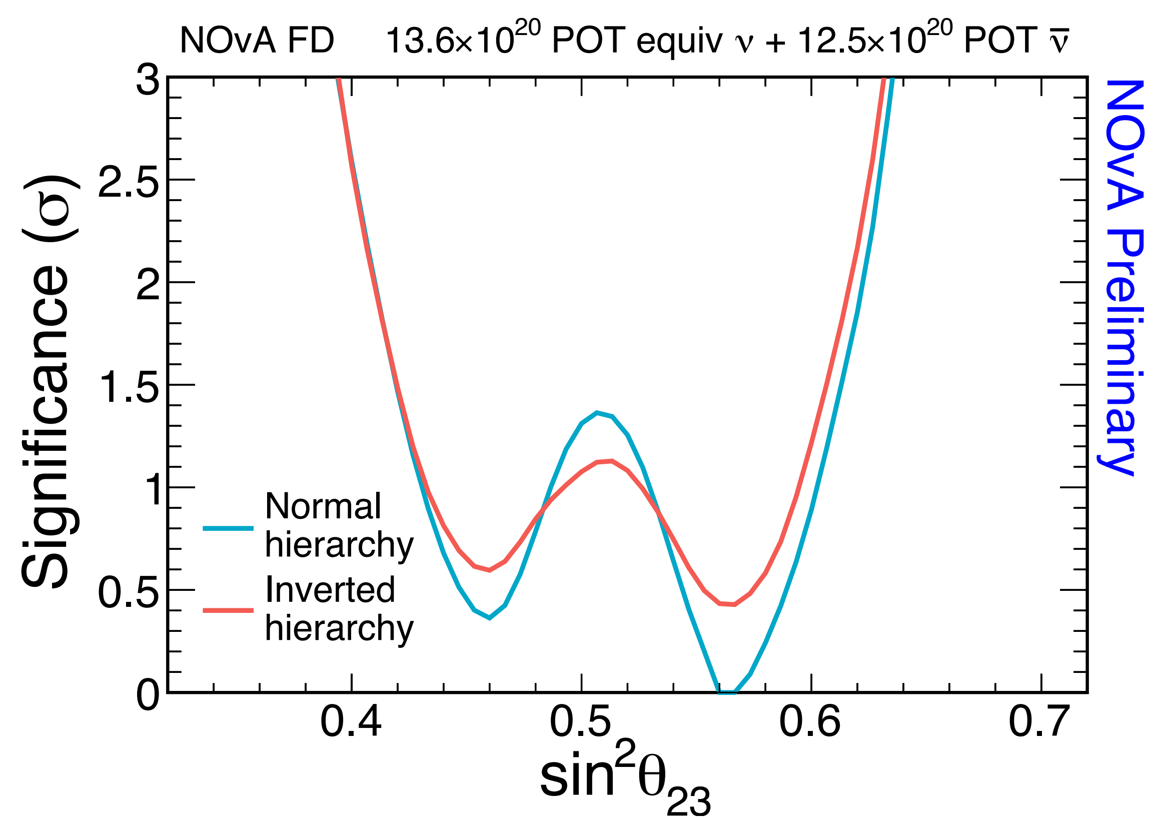
$$\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\,\text{eV}^2\ \text{(NH)}$$

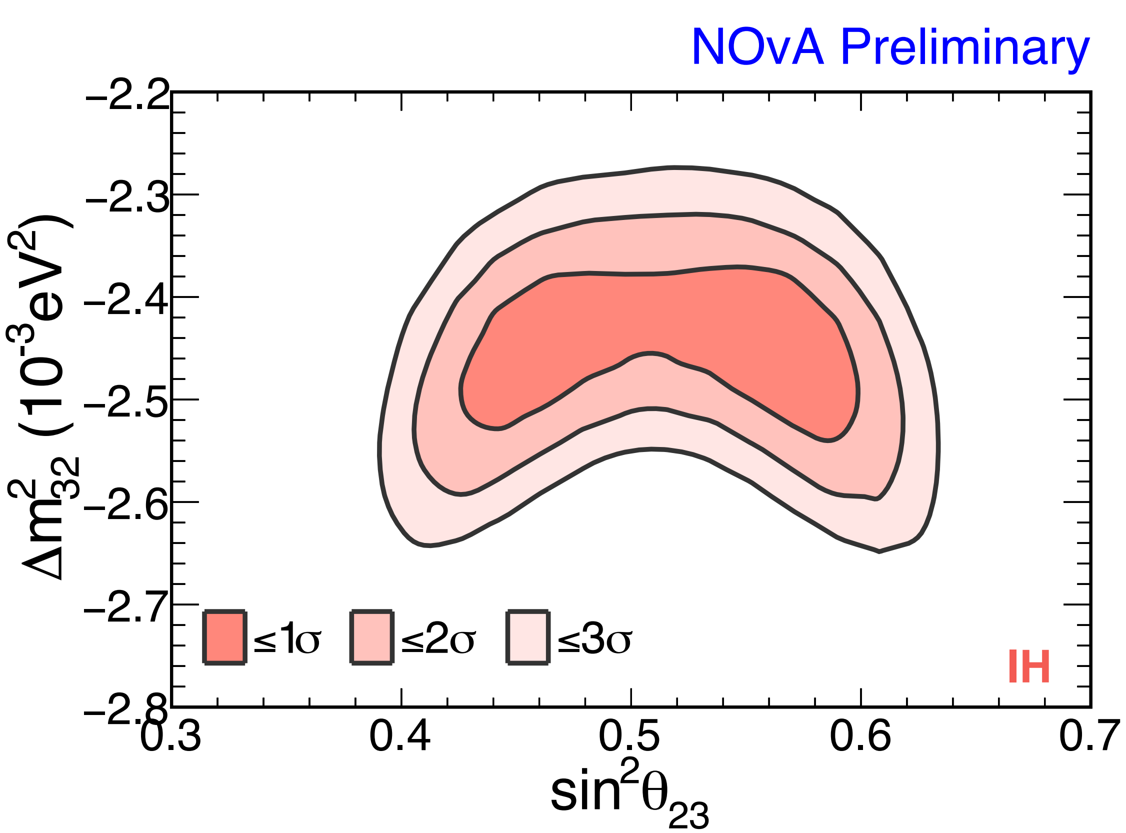
$$\delta_{CP} = 0.82\pi.$$

2.9%

Oscillation results: joint $\nu_e + \nu_\mu$ fit

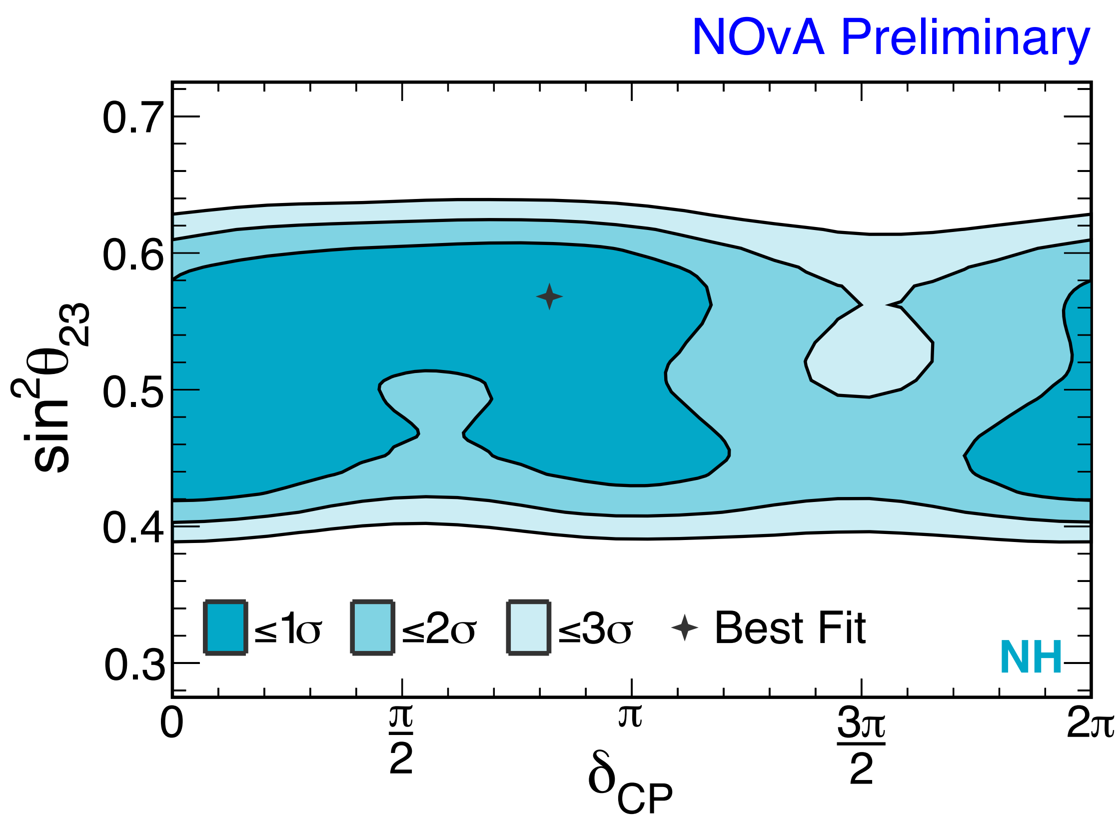


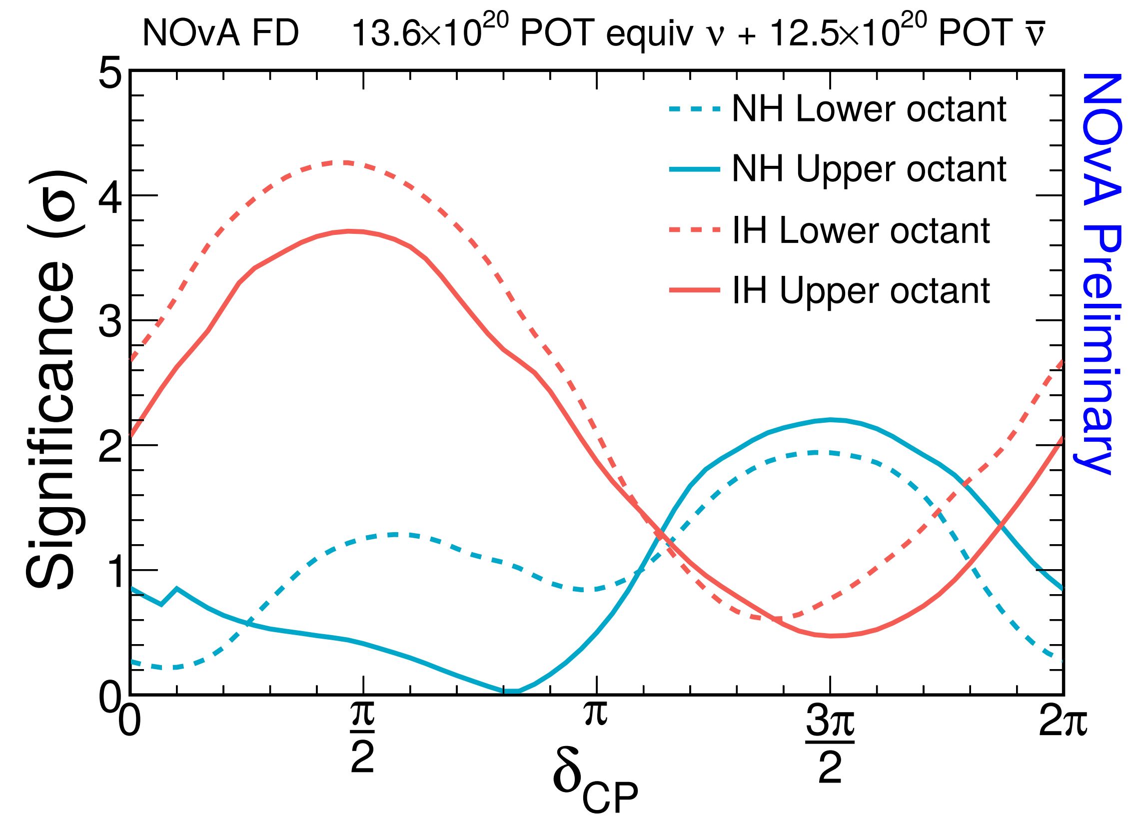


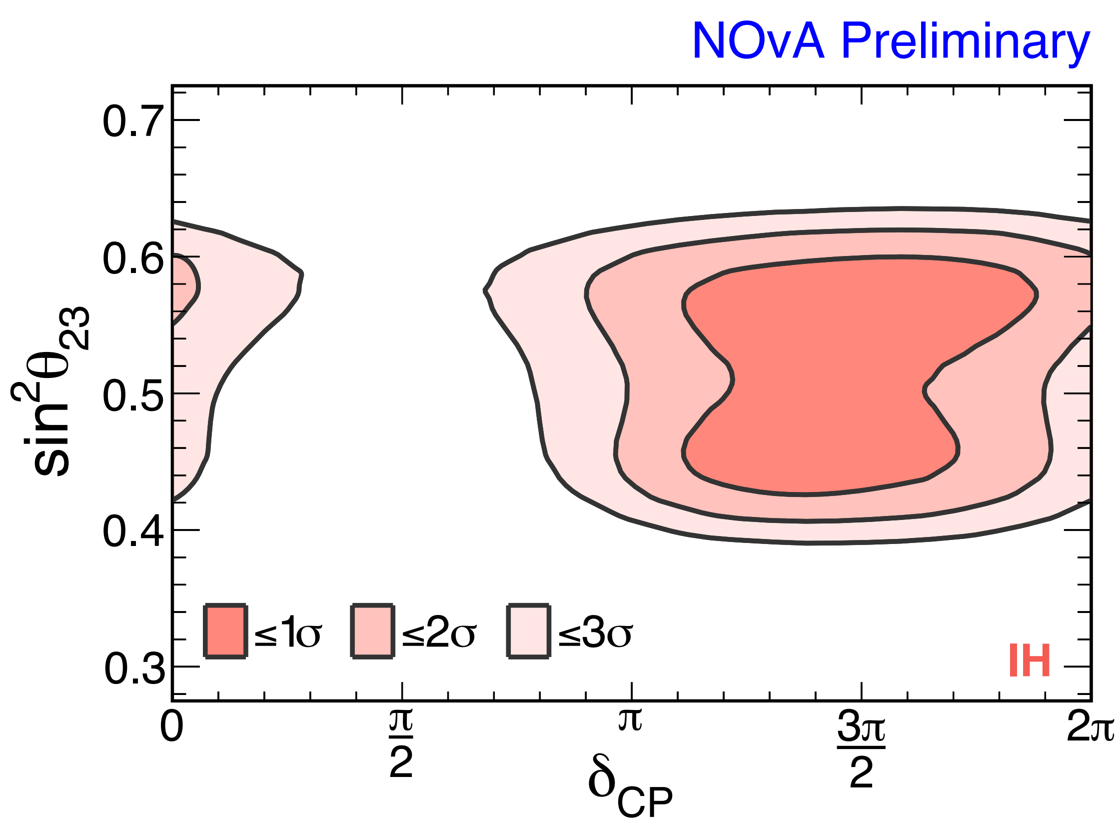


- All systematic uncertainties, Feldman - Cousins corrections are applied.
- Best fit:
  $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
  $\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$ (NH)
  $\delta_{CP} = 0.82\pi$.
- LO disfavored at 1.2σ

Oscillation results: joint $\nu_e + \nu_\mu$ fit







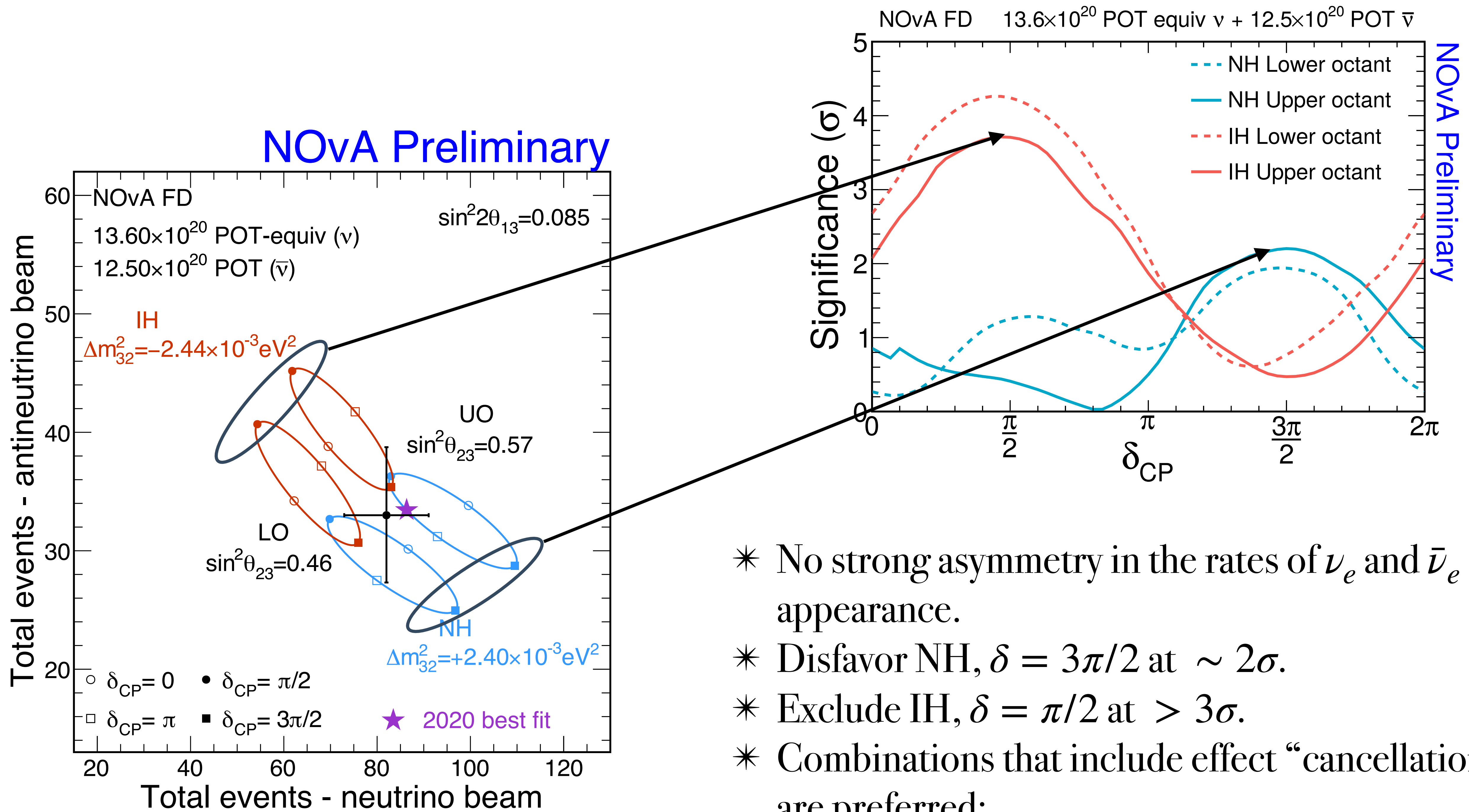
- ✳ All systematic uncertainties, Feldman - Cousins corrections are applied.
- ✳ Best fit:

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

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

  $\delta_{CP} = 0.82\pi.$
- ✳ Disfavor IH at 1σ.

Oscillation results: joint $\nu_e + \nu_\mu$ fit

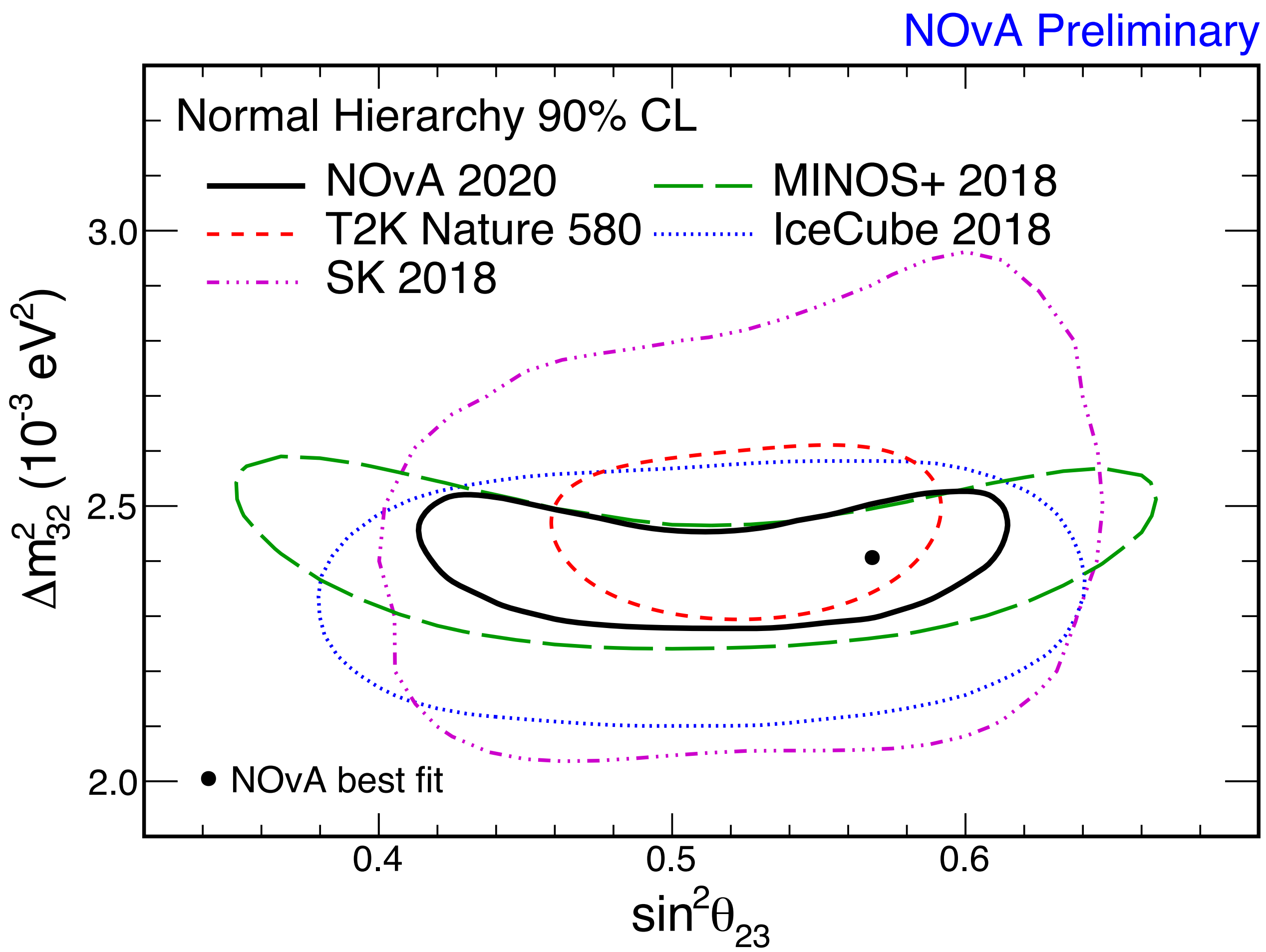


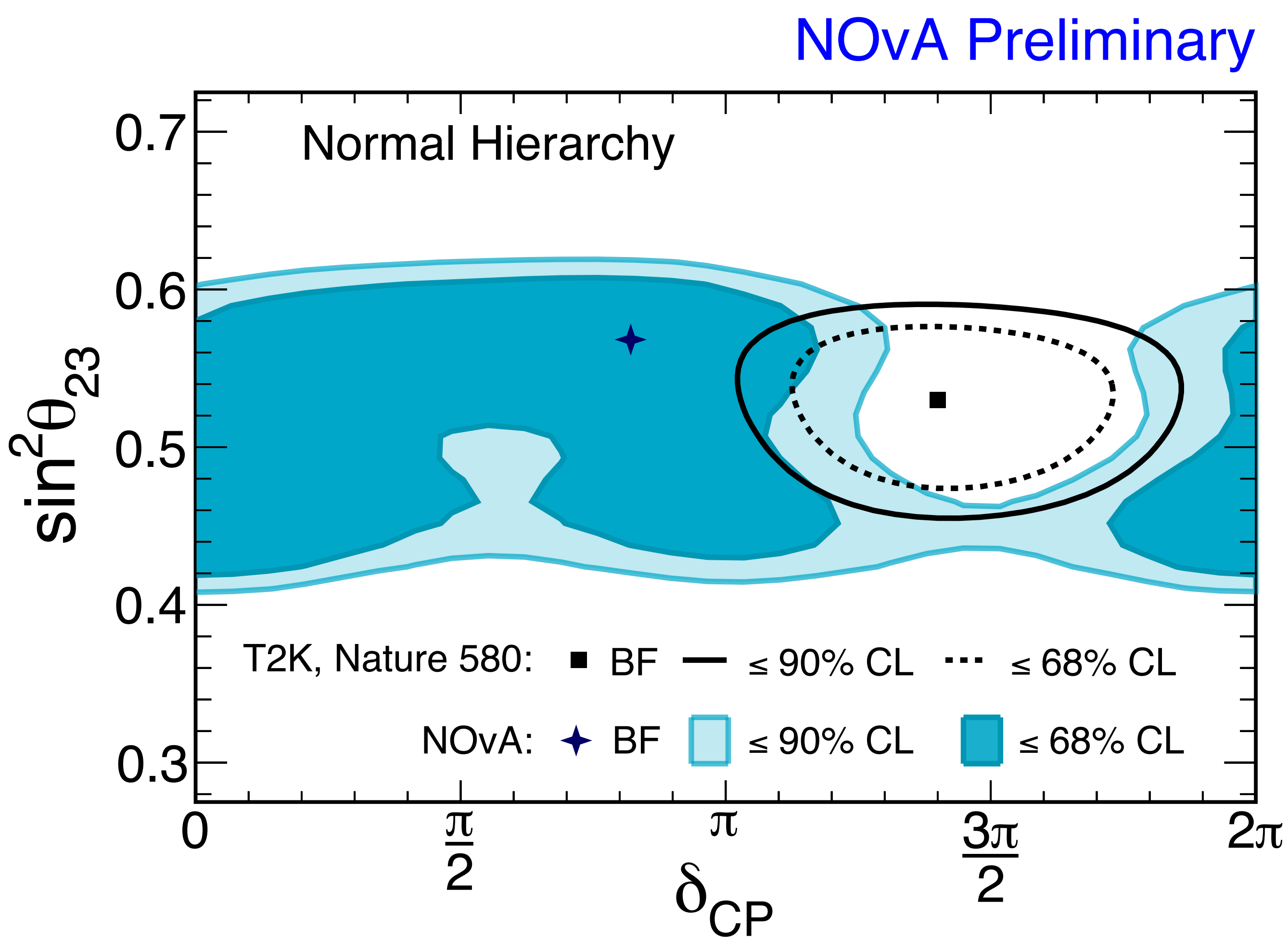
- No strong asymmetry in the rates of ν_e and $\bar{\nu}_e$ appearance.
- Disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$.
- Exclude IH, $\delta = \pi/2$ at $> 3\sigma$.
- Combinations that include effect "cancellation" are preferred:
  - since such options exist for both octants and hierarchies, results show no strong preferences.

Oscillation results: global picture

- ✳ Consistent with other long-baseline and atmospheric experiments for "atmospheric parameters".
- ✳ Apparent tension in allowed values of δ_{CP} for T2K and NOvA.

NB: not all experiments are updated in these plots after NEUTRINO 2020.

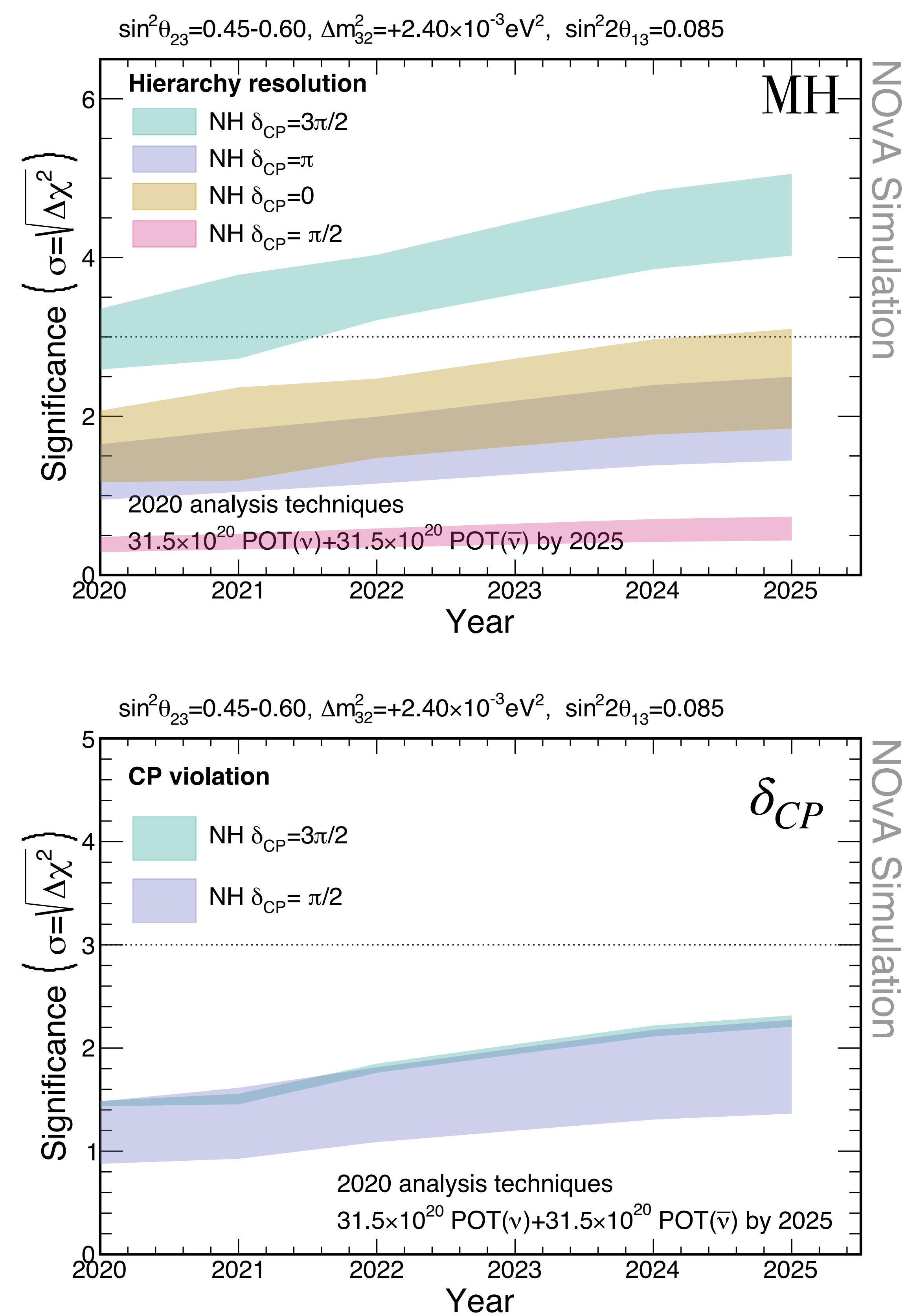




T2K and NOvA are working together on joint fit including systematics

Future

Projected sensitivities



Currently running with neutrino beam.

- ✶ Plan is to run 50:50 $\nu : \bar{\nu}$;
- ✶ NOvA is expected to run until 2025.

With current analysis, expect:

- ✶ potential 3-5σ sensitivity to hierarchy with favorable parameters;
- ✶ possible >2σ sensitivity to CP violation.

Note: sensitivity depends strongly on the true values in nature.

Expected improvements for upcoming analyses:

- ✶ accelerator → $\nu/\bar{\nu}$ beam intensity;
- ✶ Test beam → improved det. response model.

Conclusions

With 13.6×10^{20} $(\nu) + 12.5 \times 10^{20}$ $(\bar{\nu})$ POT exposure NOvA got the following results.

- ✳ Our best fit is in the Normal Hierarchy,
  $\delta_{CP} = 0.82\pi$, $\sin^2\theta_{23} = 0.57$, $\Delta m^2_{32} = +2.41 \times 10^{-3}\,\mathrm{eV}^2$.
- ✳ Constraints on strongly asymmetric $\nu_e - \bar{\nu}_e$ appearance PMNS solutions:
  - ✳ disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$;
  - ✳ exclude IH, $\delta = \pi/2$ at $> 3\sigma$.

With operation through 2025 NOvA expects:

- ✳ possible 3 - 5σ sensitivity to mass hierarchy for some values of δ_{CP};
- ✳ potential sensitivity to CP violation phase > 2σ.

We're waiting for the test beam results, analysis and accelerator improvements.

Stay tuned!