Neutrino oscillation analysis in the NOvA experiment

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Neutrino Oscillations

ATMOSPHERIC ACCELERATOR	SHORT BASELINE REACTOR ACCELERATOR	SOLAR LONG BASELINE REACTOR

$$\left| \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \right\rangle$$

Oscillation parameters and how precisely do we know them:

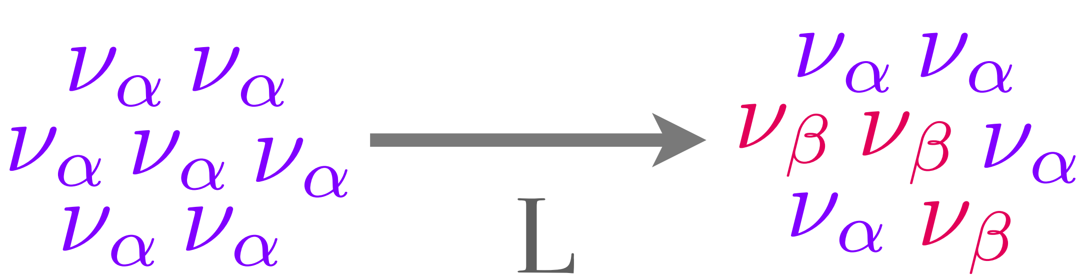
$\theta_{12} \approx 34^\circ$ (4.4%)

$\theta_{23} \approx 49^\circ$ (5.2%)

$\theta_{13} \approx 9^\circ$ (3.8%)

$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ \text{eV}^2$ (2.2%)

$\Delta m^2_{32} \approx +2.5 \times 10^{-3}\ \text{eV}^2$ (1.4%)

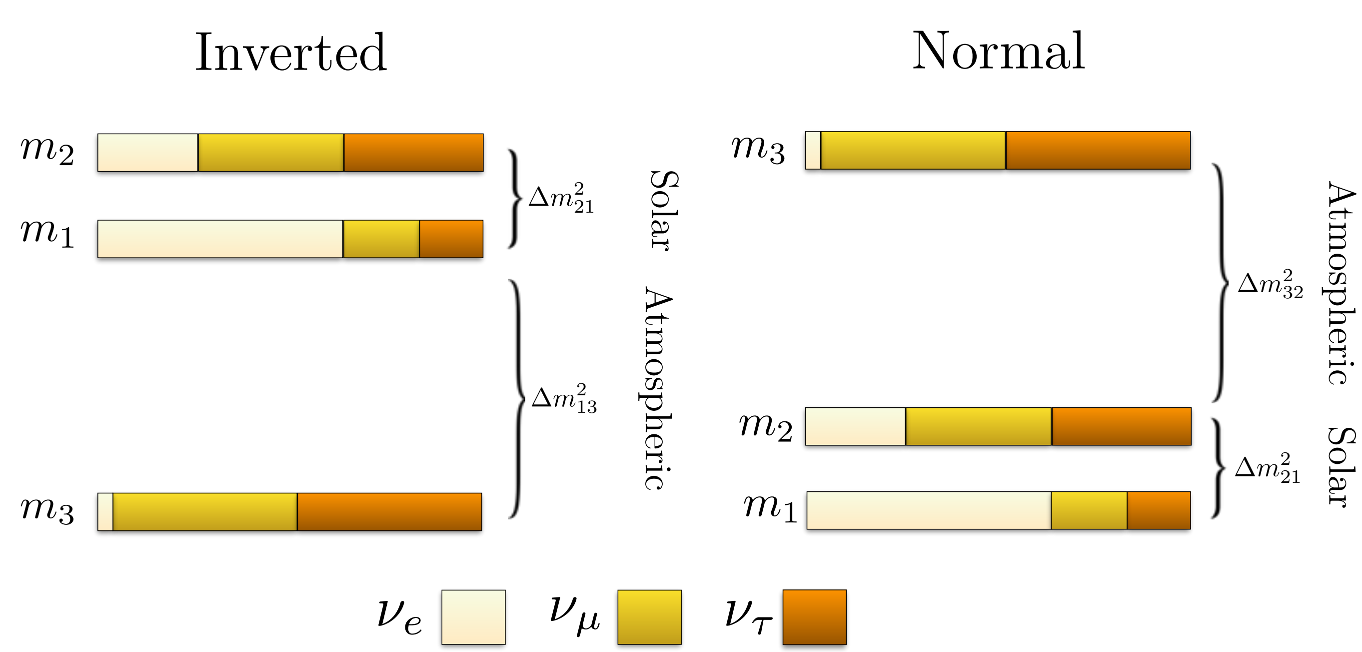


Opened questions:

Is θ_{23} 45°?

Is there CP violation in lepton sector?

Neutrino mass hierarchy is Normal or Inverted?




NOvA Collaboration
7 countries
50 institutions
240 collaborators
VIRGINIA
[June 2019 meeting @ Sussex University, Brighton, UK]

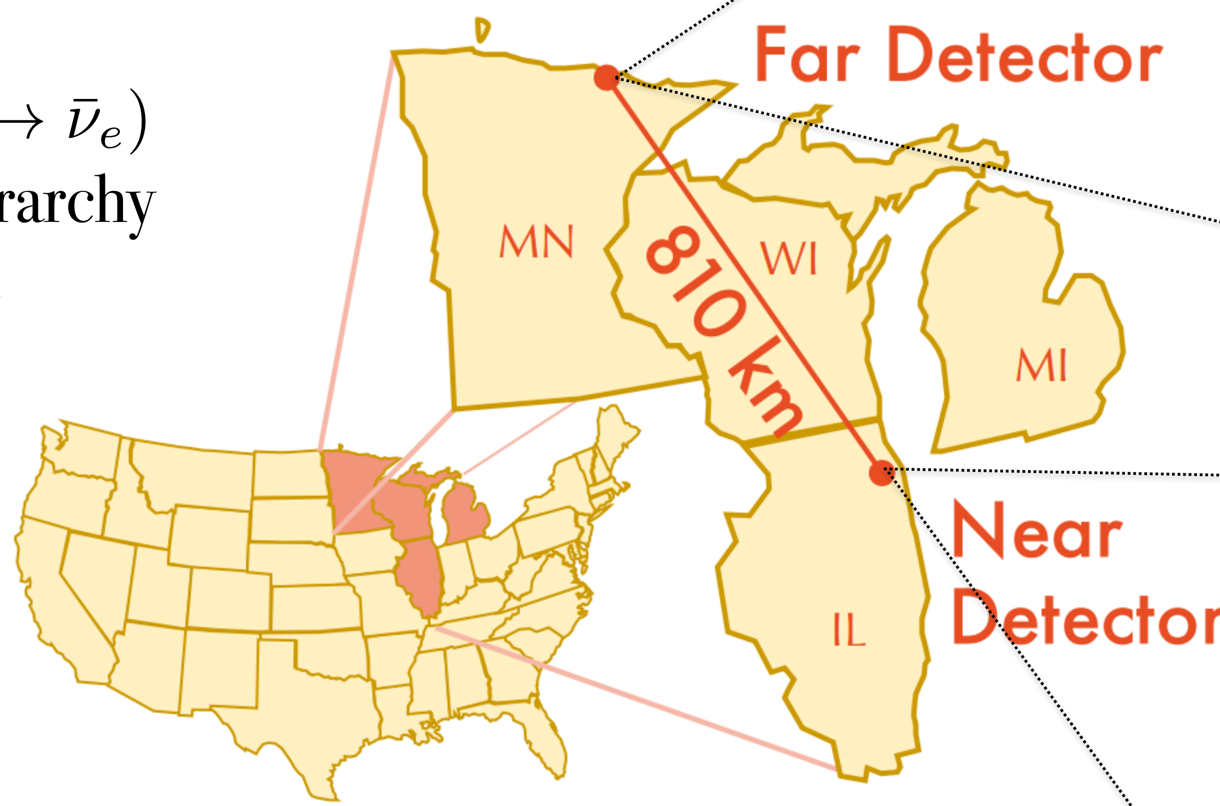
The NOvA Experiment

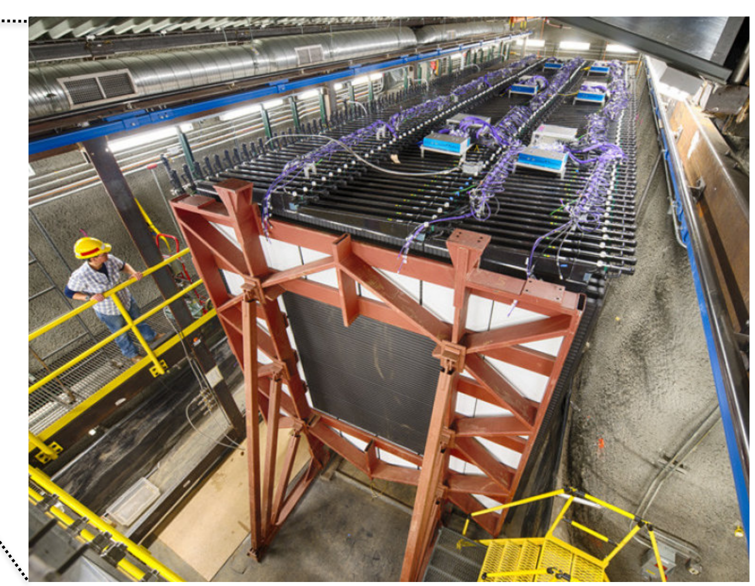
The NuMI Off-Axis ν_e Appearance Experiment

Experiment goals:

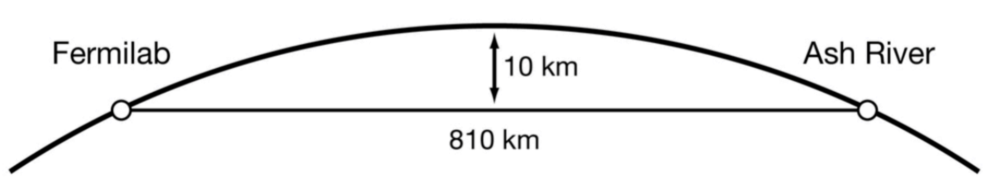
Using $\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
* Precise measurement Δm^2_{32}
* Mixing angle θ_{23}

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



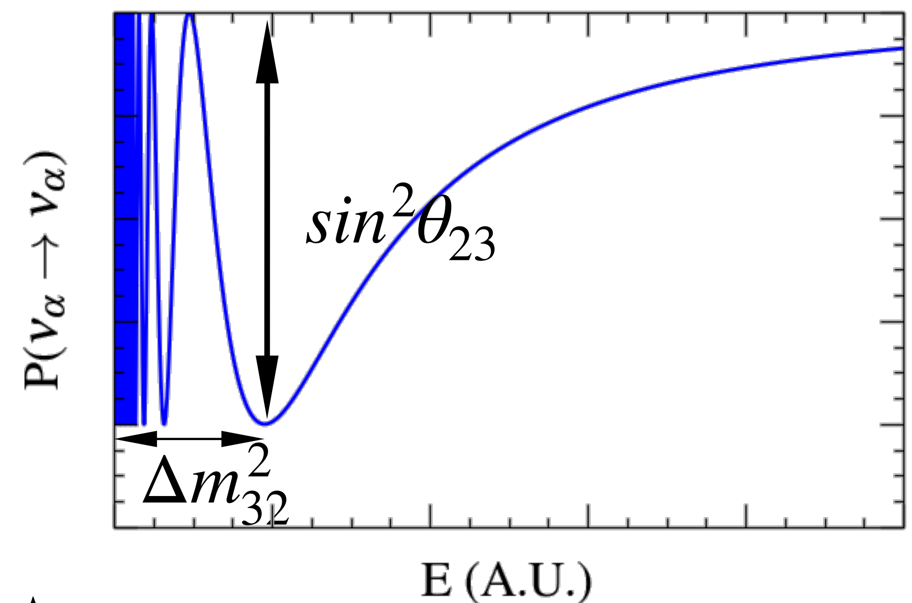


Long-baseline,
beam from Fermilab,
two detectors sit at
14 mrad off-axis



Strategy

Disappearance



Experiment goals:

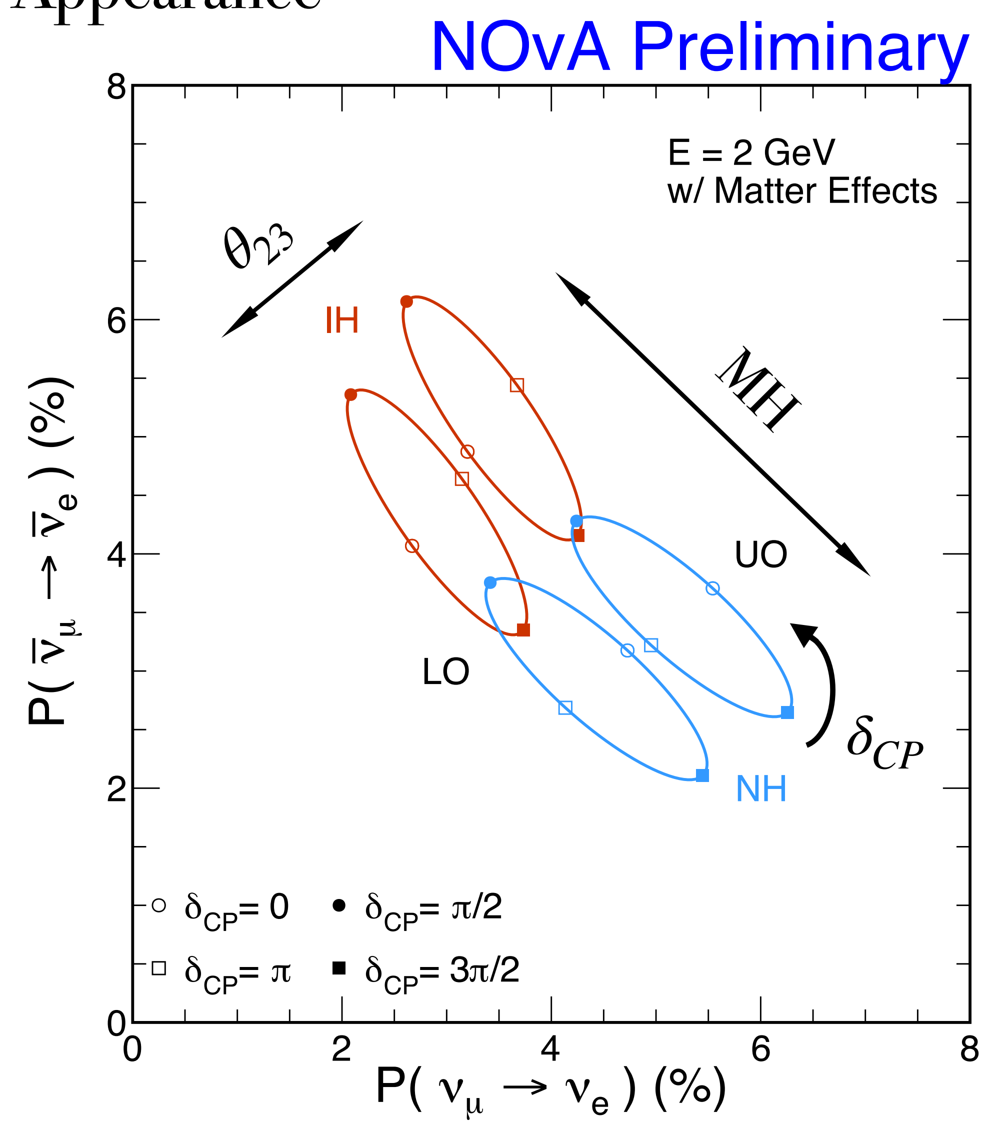
Using $\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

- ✳ 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}

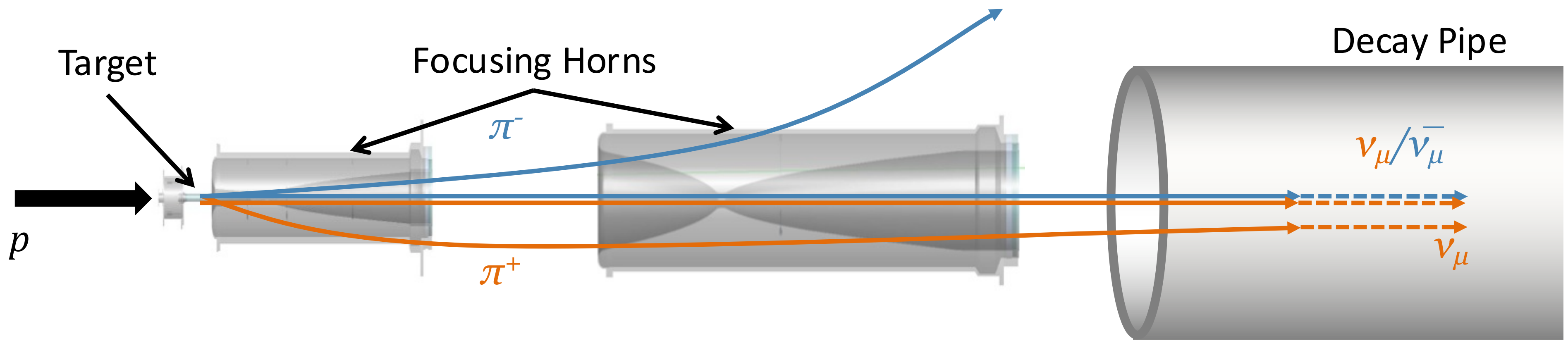
Appearance



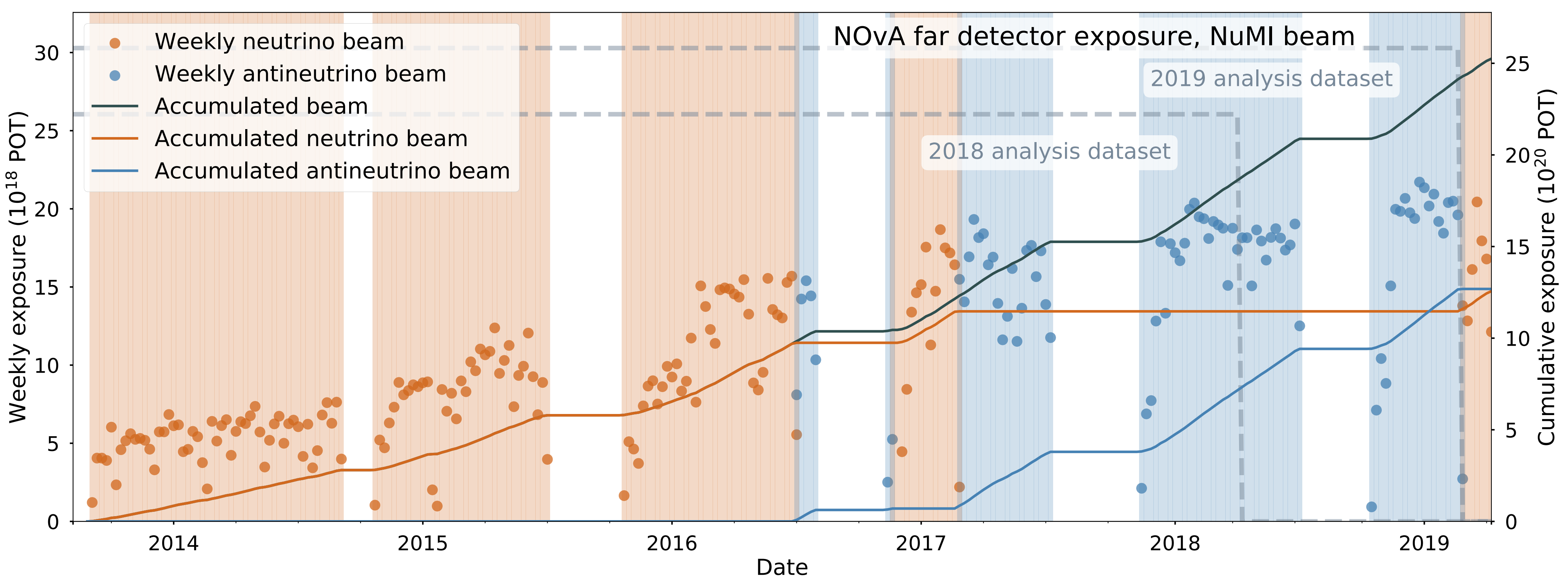
Obtain sensitivity to the mass hierarchy due to matter effects.

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

Neutrino beam



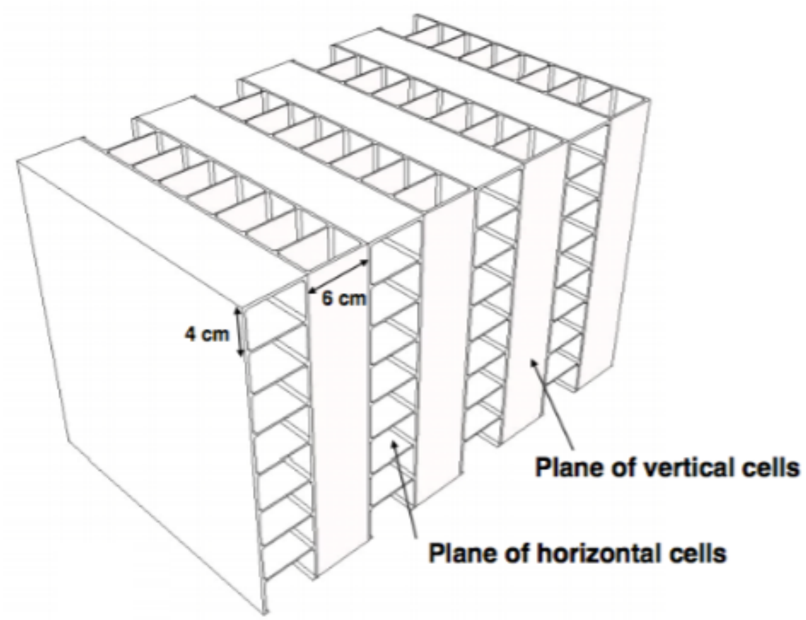
- ✳ 120 GeV protons on a carbon target, produce mesons which yield neutrinos. Beam purity with $\nu(\bar{\nu})$: $95\%\ \nu_\mu,\ 4\%\ \bar{\nu}_\mu,\ 1\%\ \nu_e\ (93\%\ \bar{\nu}_\mu,\ 6\%\ \nu_\mu,\ 1\%\ \nu_e)$.
- ✳ NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT/year (POT = Proton On Target).



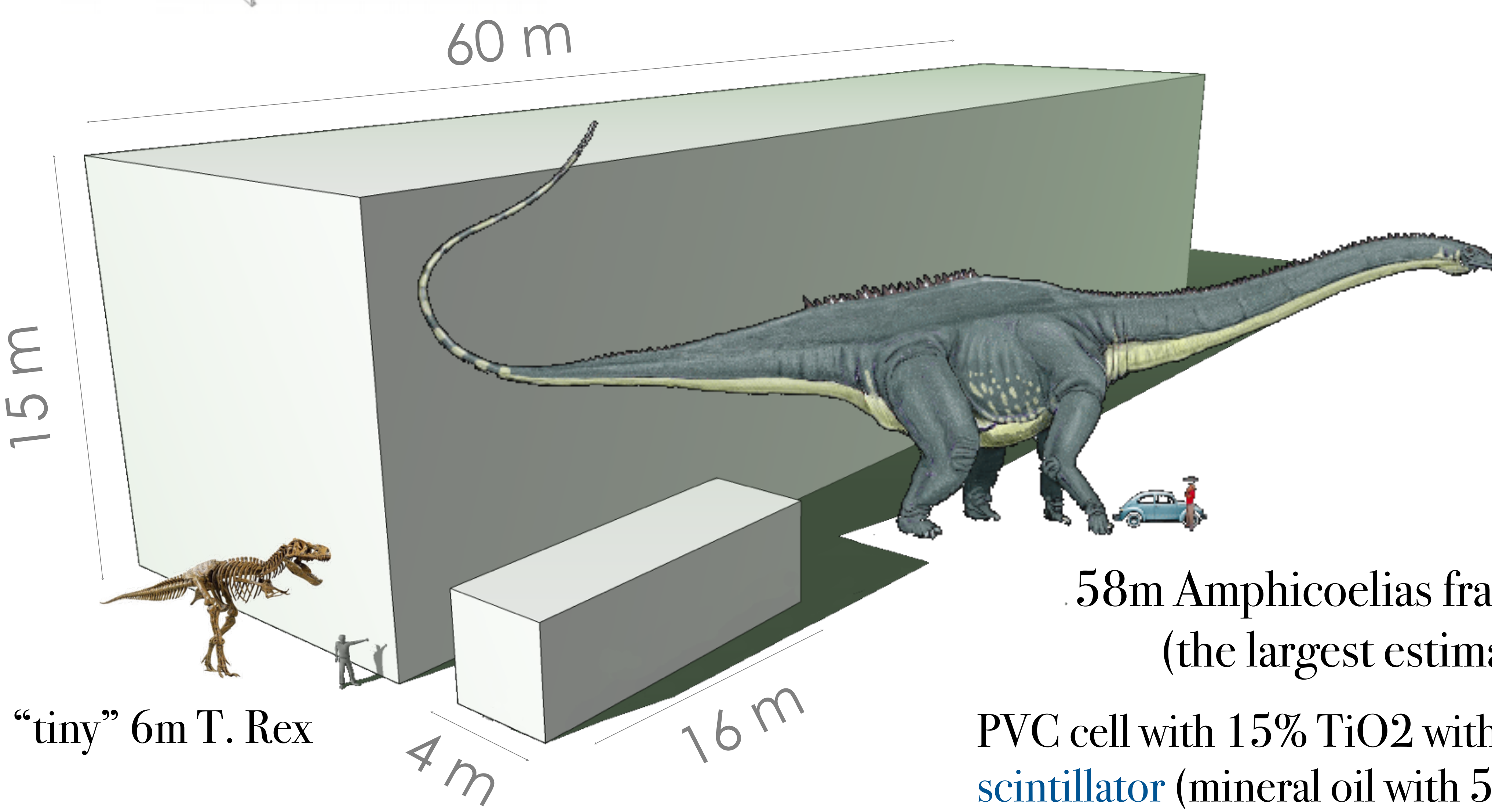
8.85×10^{20} POT neutrino beam

12.33×10^{20} POT antineutrino beam

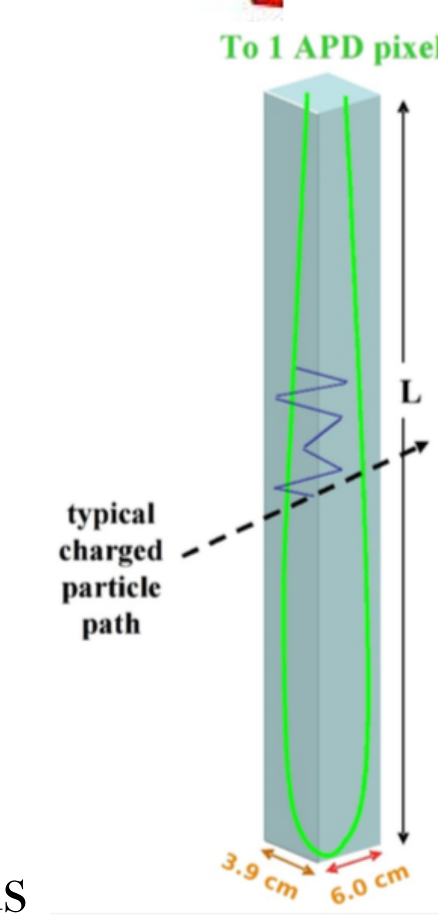
Detectors



FD: 344 064 cells
ND: 20 192 cells

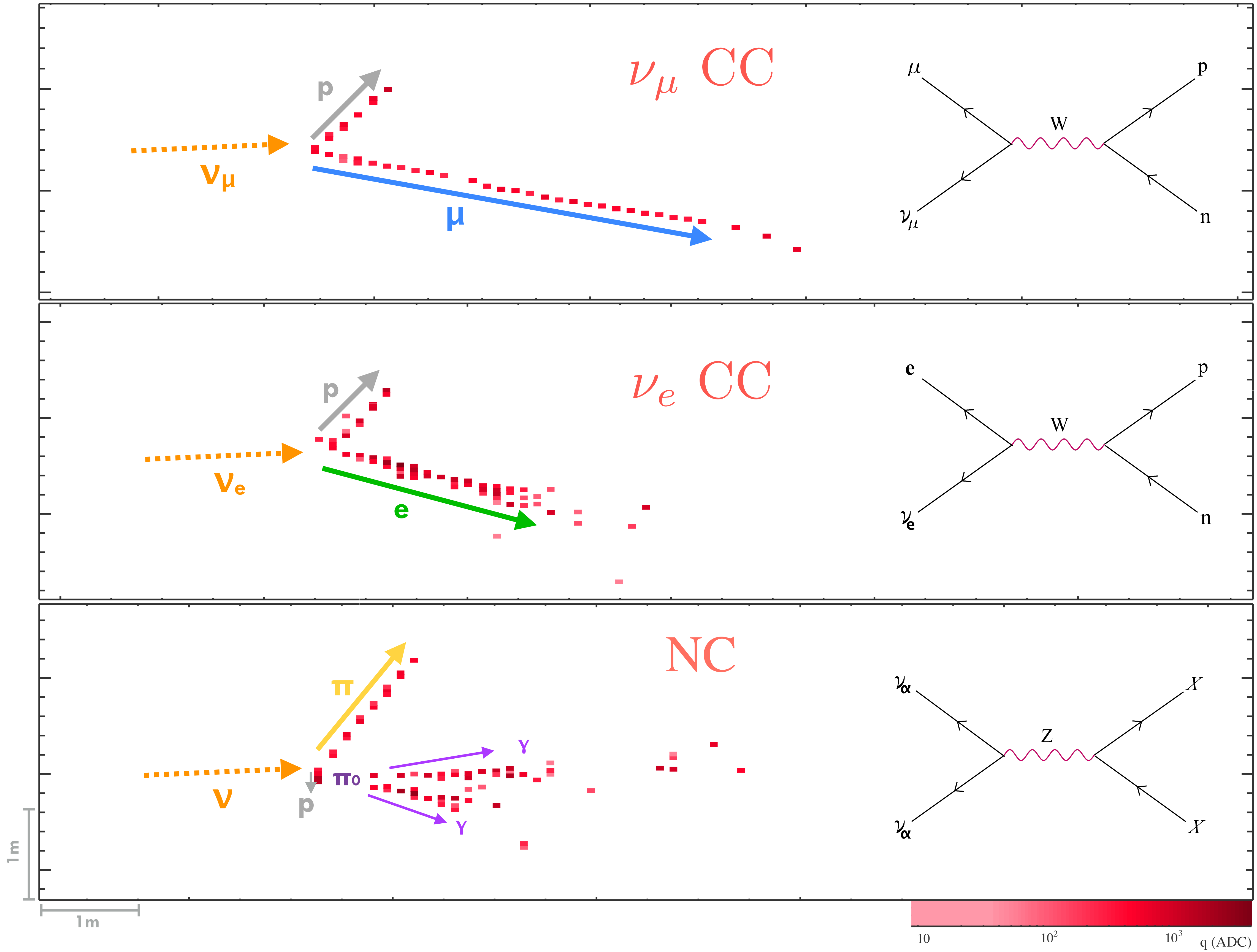


58m Amphicoelias fragillimus
(the largest estimate)



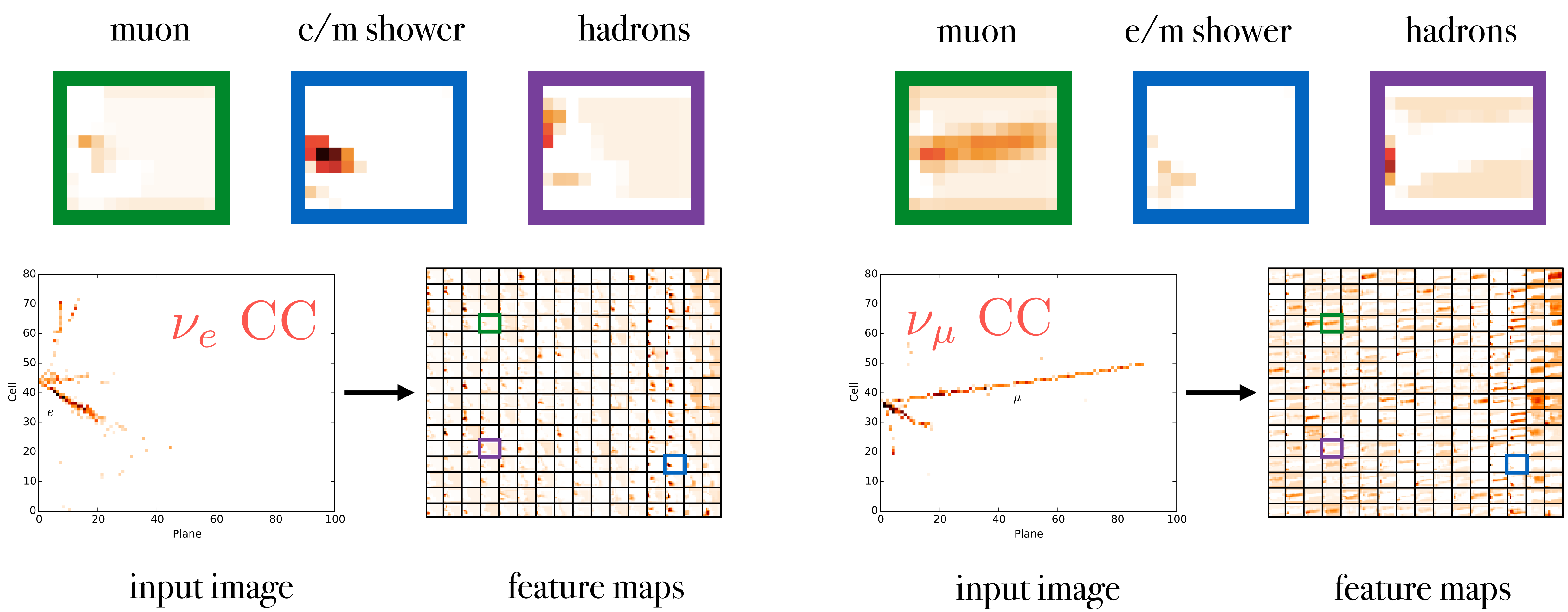
PVC cell with 15% TiO2 with liquid scintillator (mineral oil with 5% pseudocumene)

Event topologies



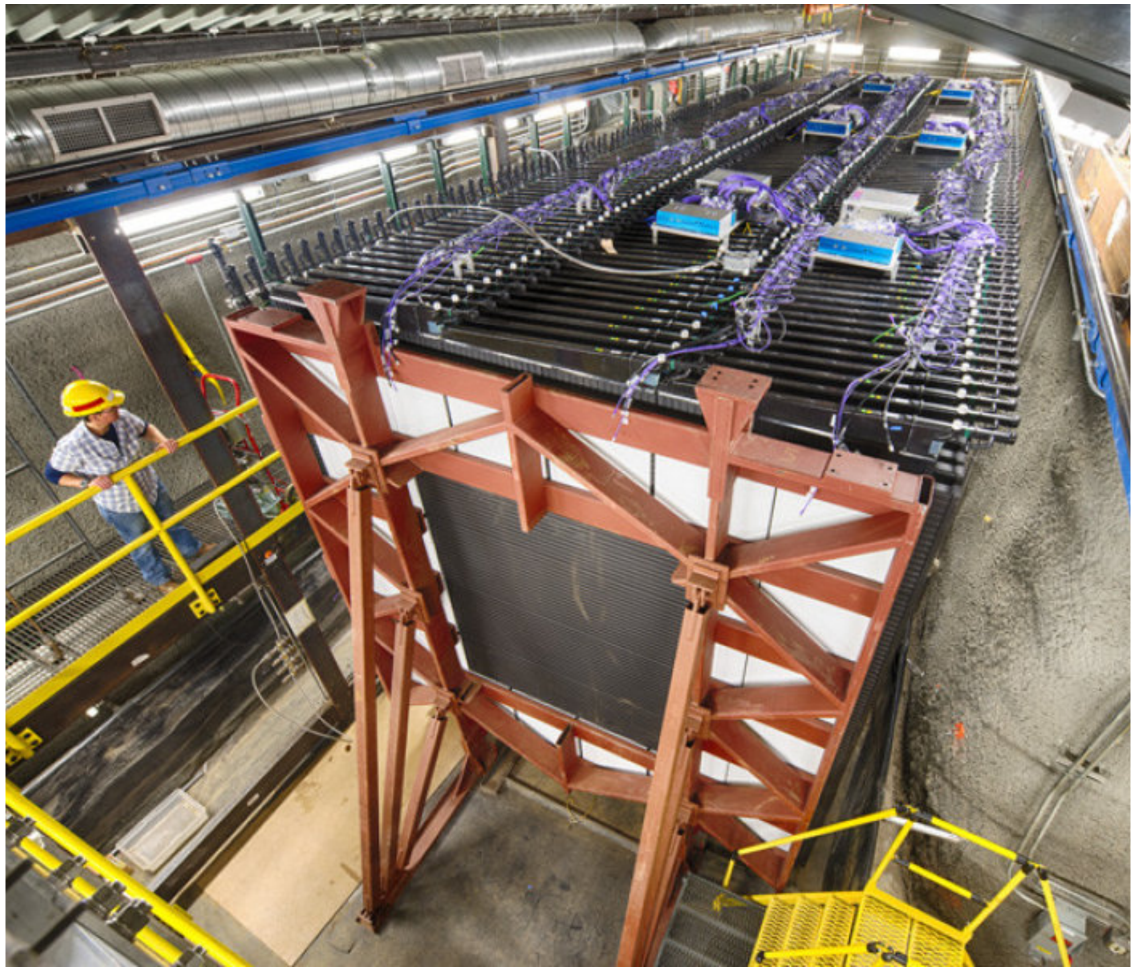
ν_e/ν_μ event selection

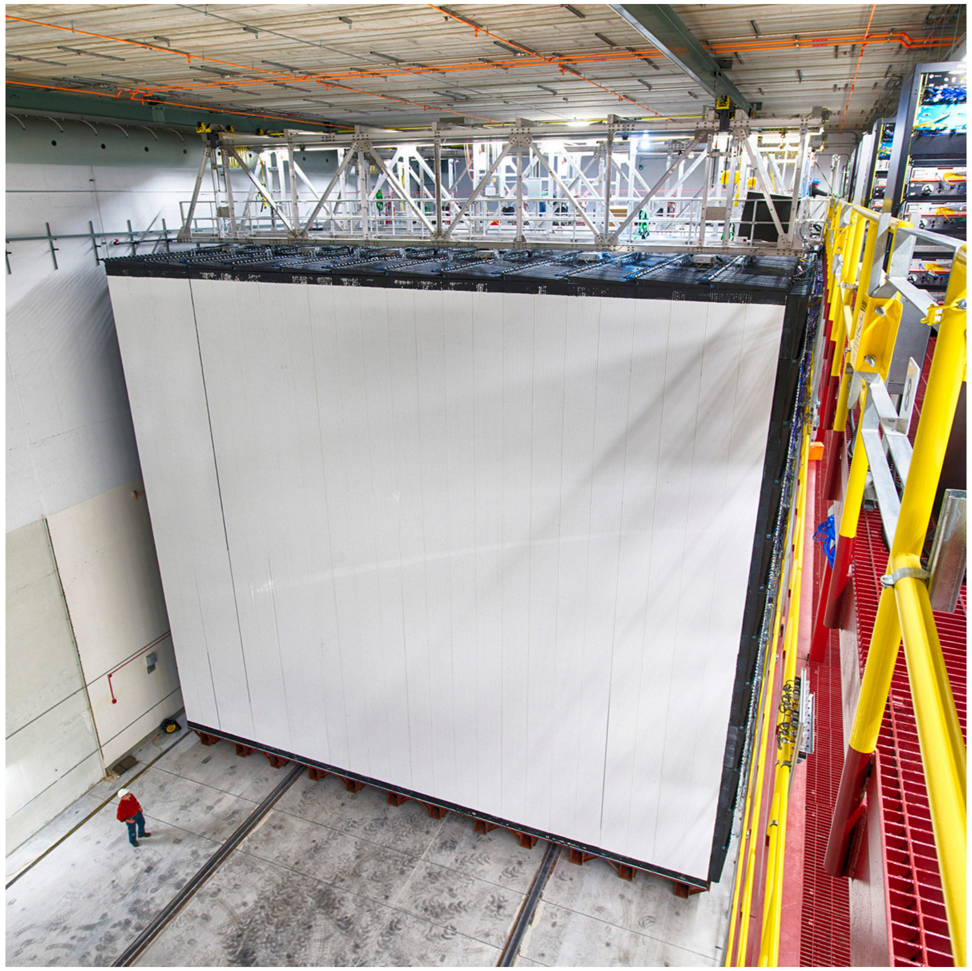
- ✳ Events for analysis pass various cuts: data quality, fiducial volume, BDT cosmic rejection etc. and neutrino flavor identification PID.



- ✳ 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.

Two detector scheme





Near Detector (ND):

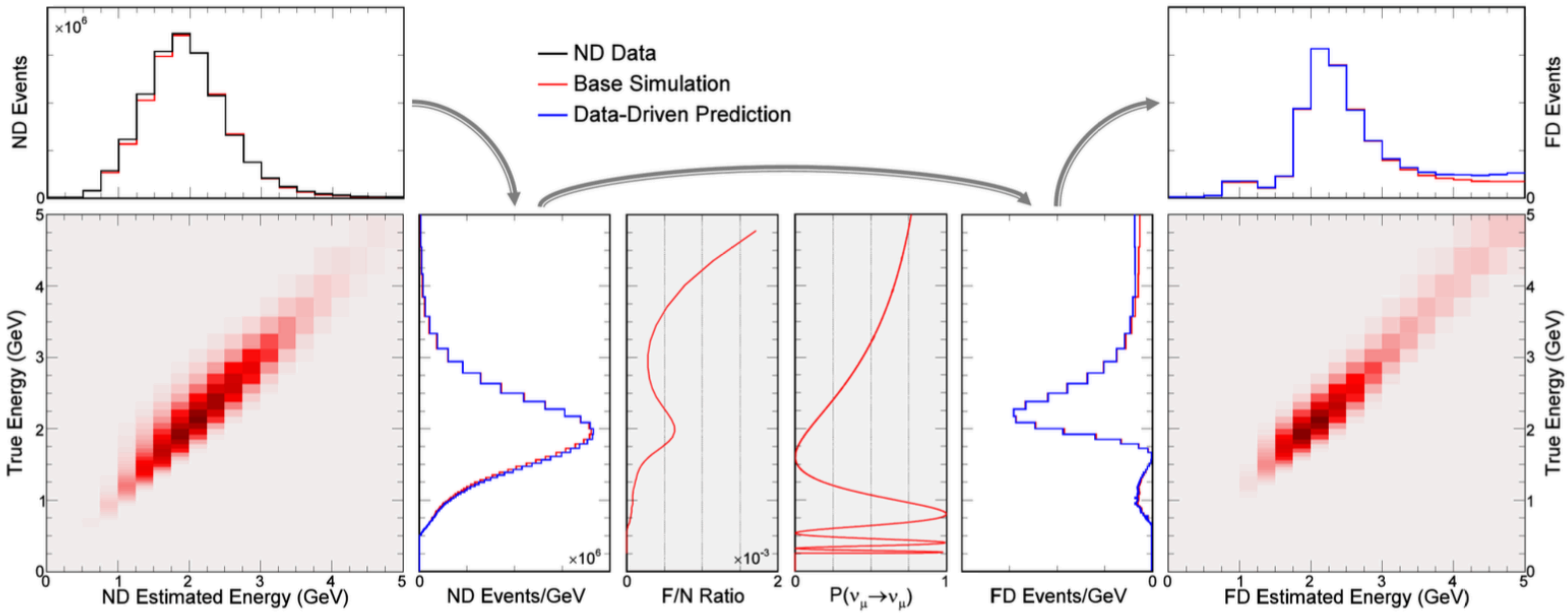
- ✴ 1 km after target
- ✴ measure flux composition before oscillations
- ✴ ND data used for prediction data in FD (extrapolation procedure)

Far Detector (FD):

- ✴ 810 km after target
- ✴ measure neutrino flux after oscillations
- ✴ extrapolation cancels most systematics
- ✴ FD identical to ND

Data-driven predictions

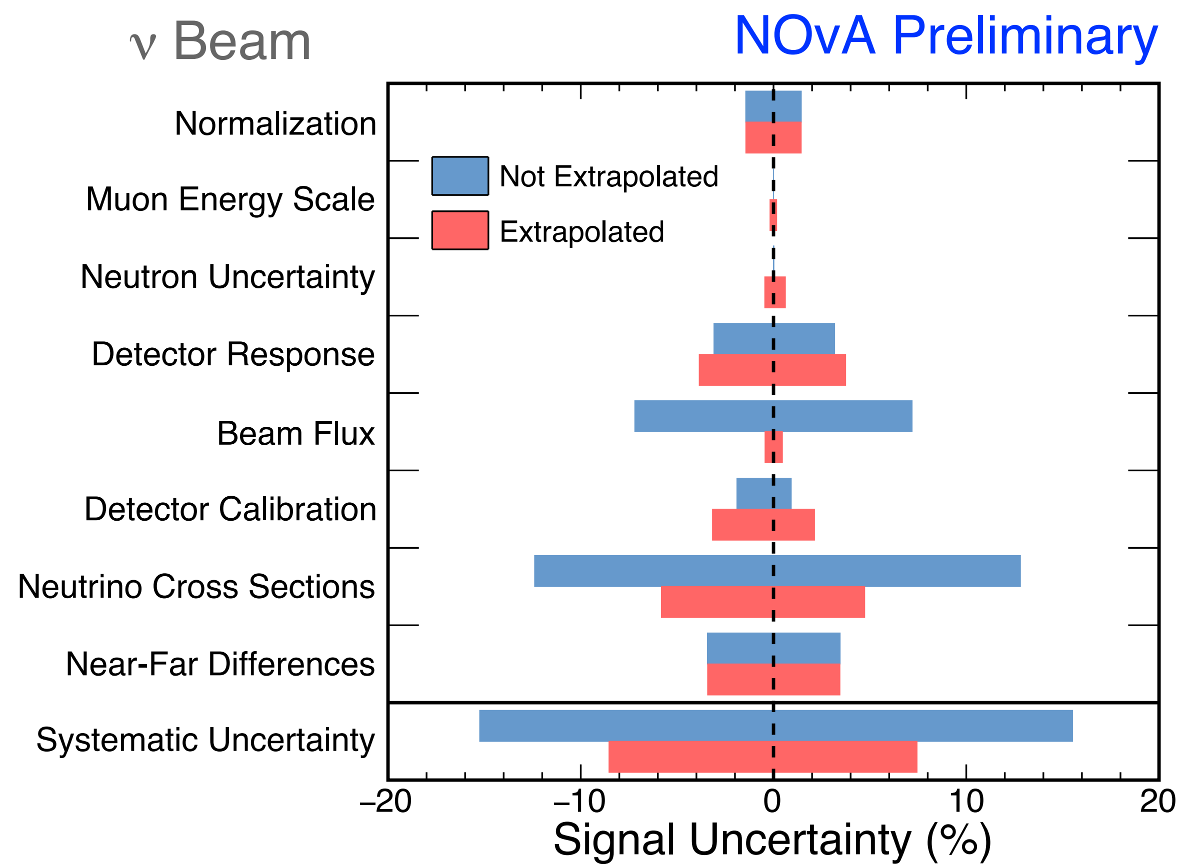
Far Detector predictions are constrained by high-stat unoscillated Near Detector data:

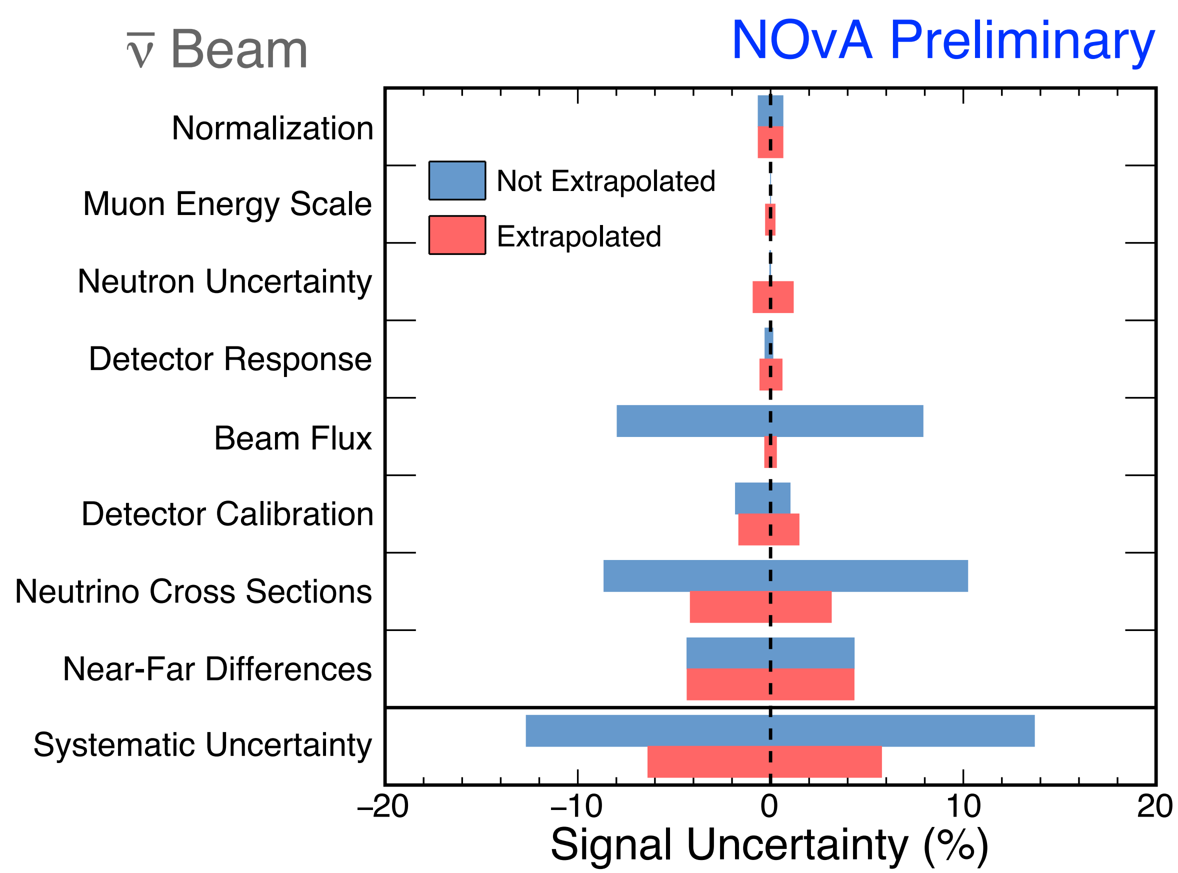


Constrain predictions with ND data → Apply oscillations and FD/ND ratio → Compare to FD data

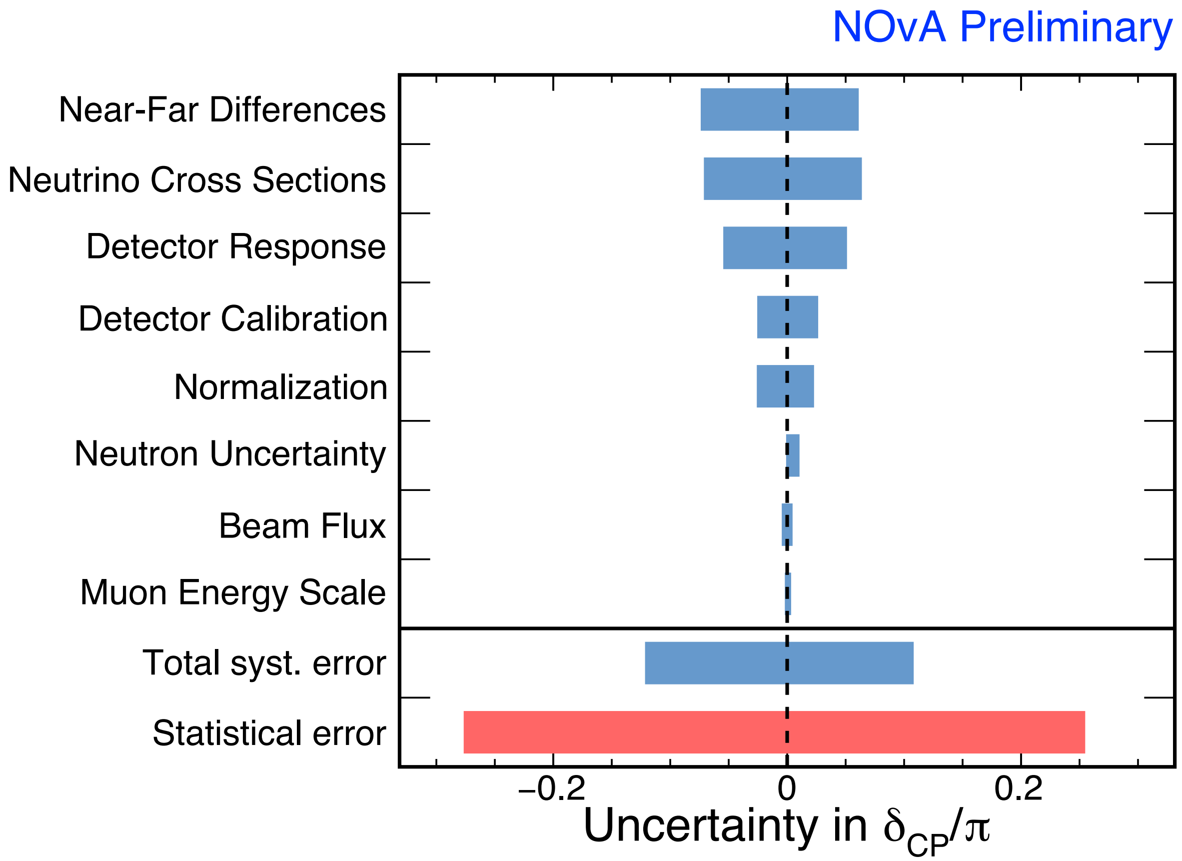
Systematics and extrapolation

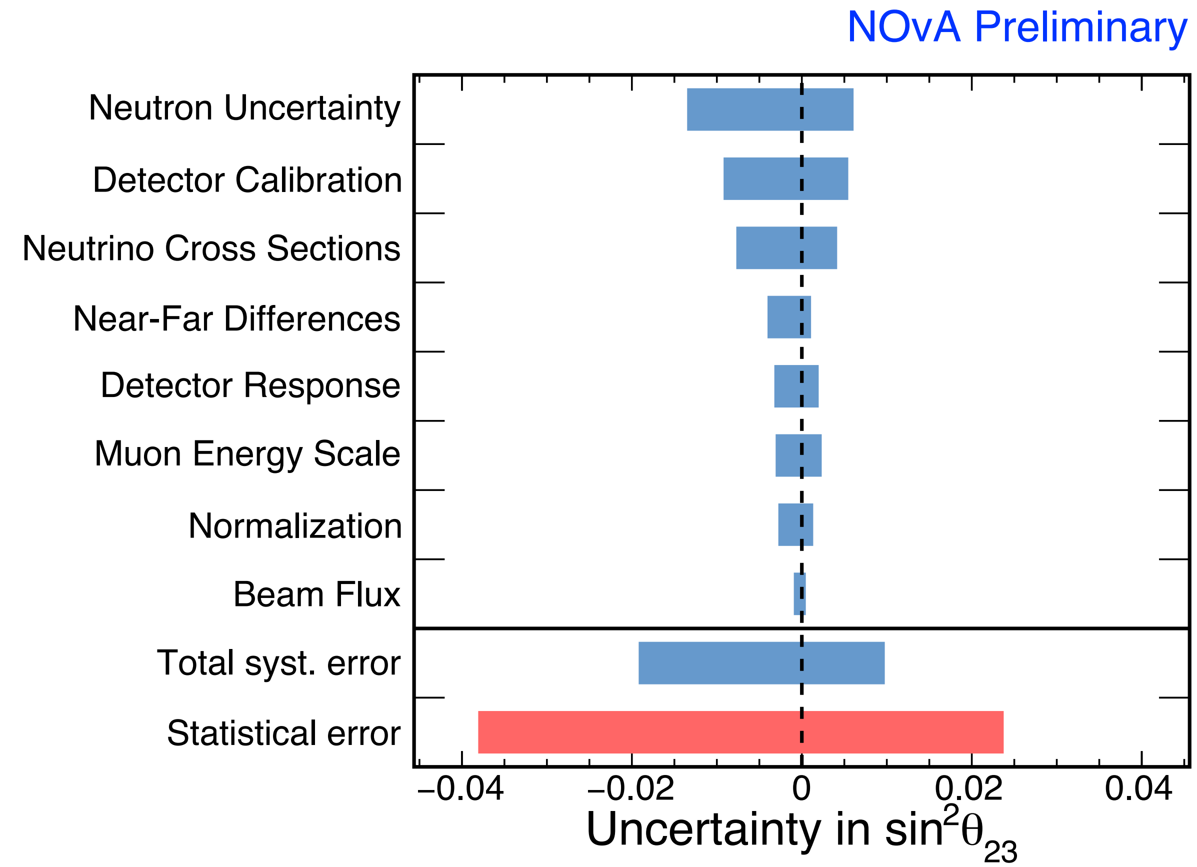
- NOvA uses an extrapolation procedure from Near Detector to Far Detector which helps to reduce systematic uncertainties.
- The impact of systematics is evaluated by carrying each systematic through the entire extrapolation and analysis chain.
- All joint fit systematics (50 items) are marginalized into 8 main categories.
- The total systematic uncertainty is a sum in quadrature of all components.
- Large reduction in beam and cross section uncertainties.
- The overall uncertainty is reduced from 15% to 8.5% for ν and from 12.5% to 5.5% for $\bar{\nu}$.

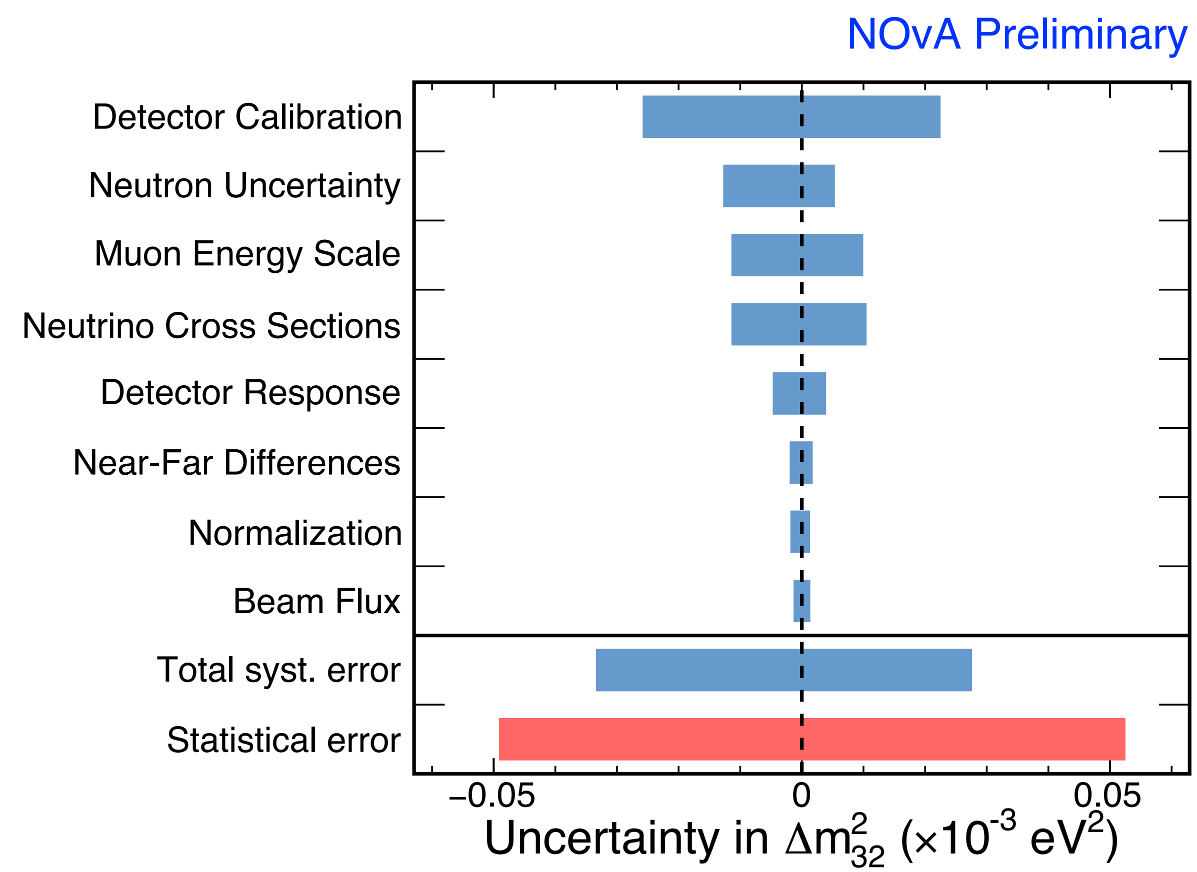




Systematics for the analysis





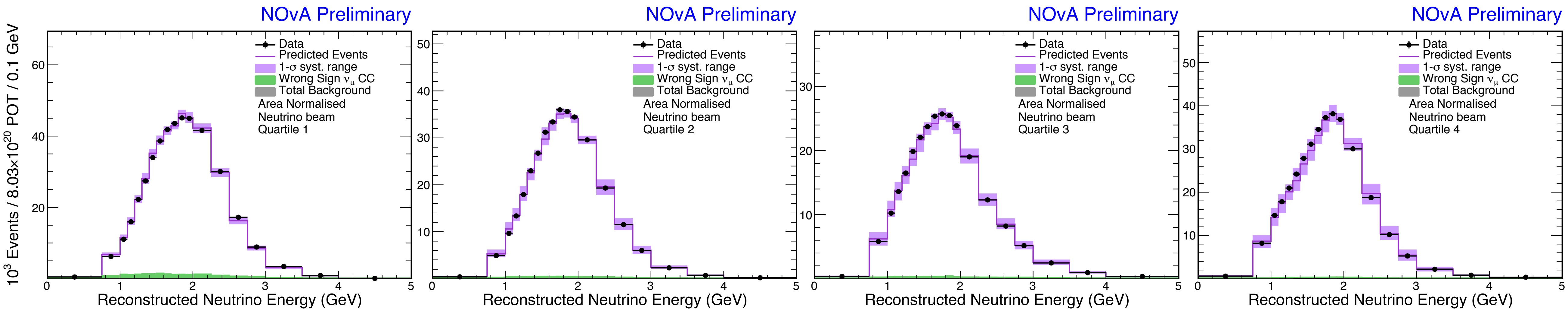


- Still statistically limited.
- The most important systematics:
  - neutrino cross sections;
  - detector calibration
  - neutron uncertainty - with $\bar{\nu}$.

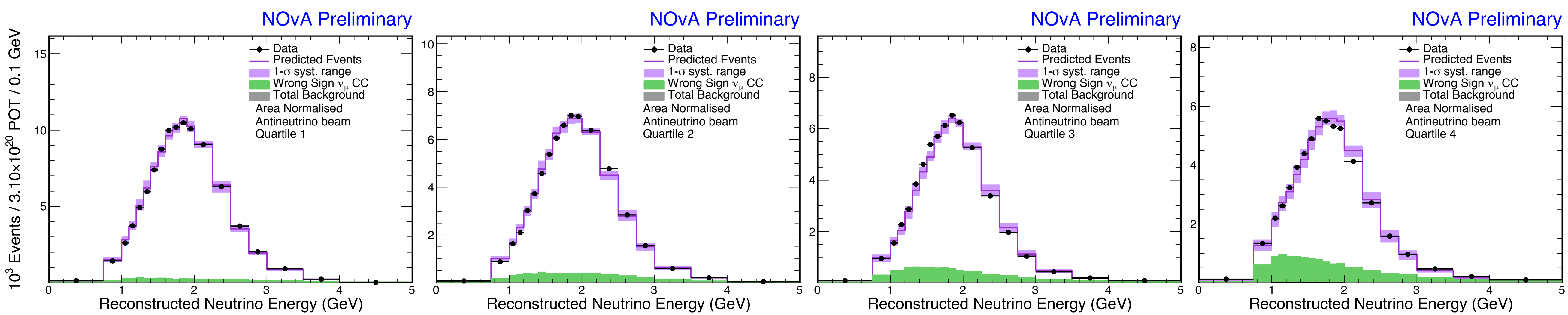
ND data for ν_μ

Quartile 1 (the best resolution ~6%) → Quartile 4 (the worst resolution ~12%)

Neutrino beam

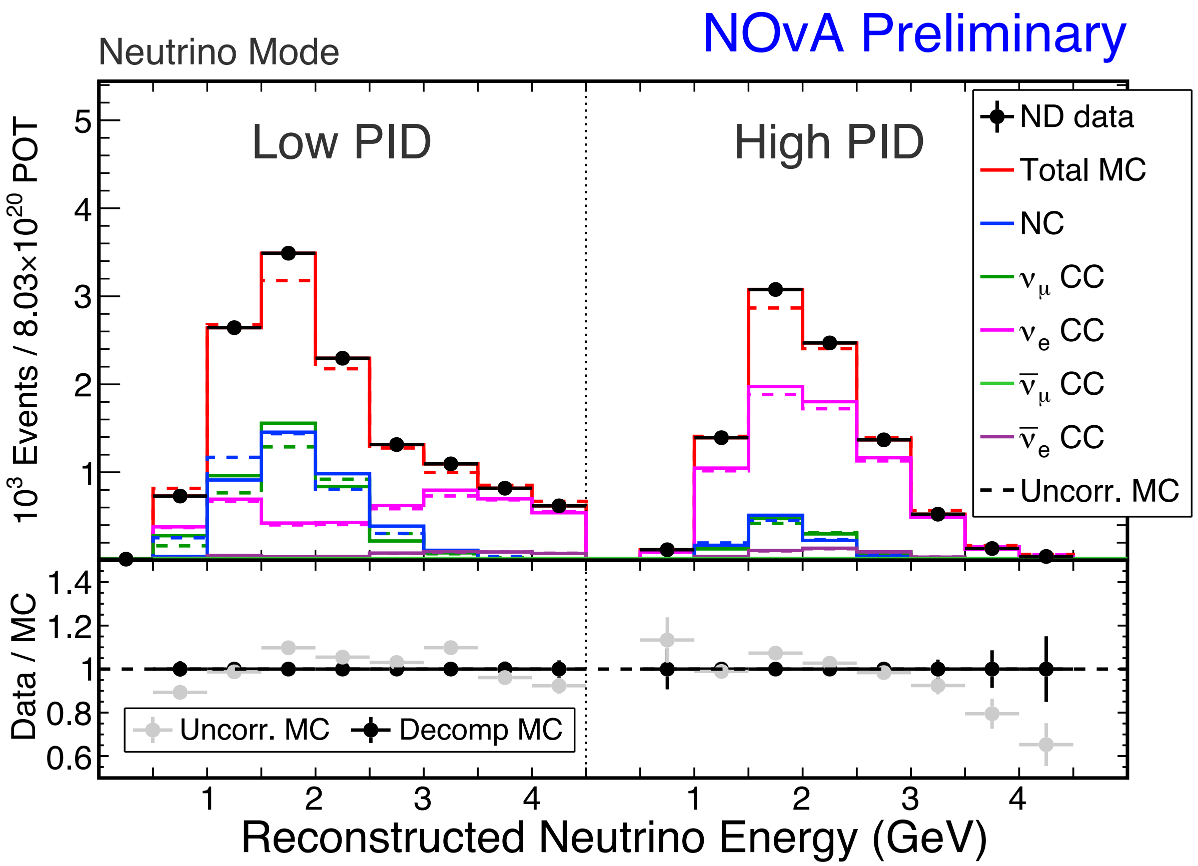


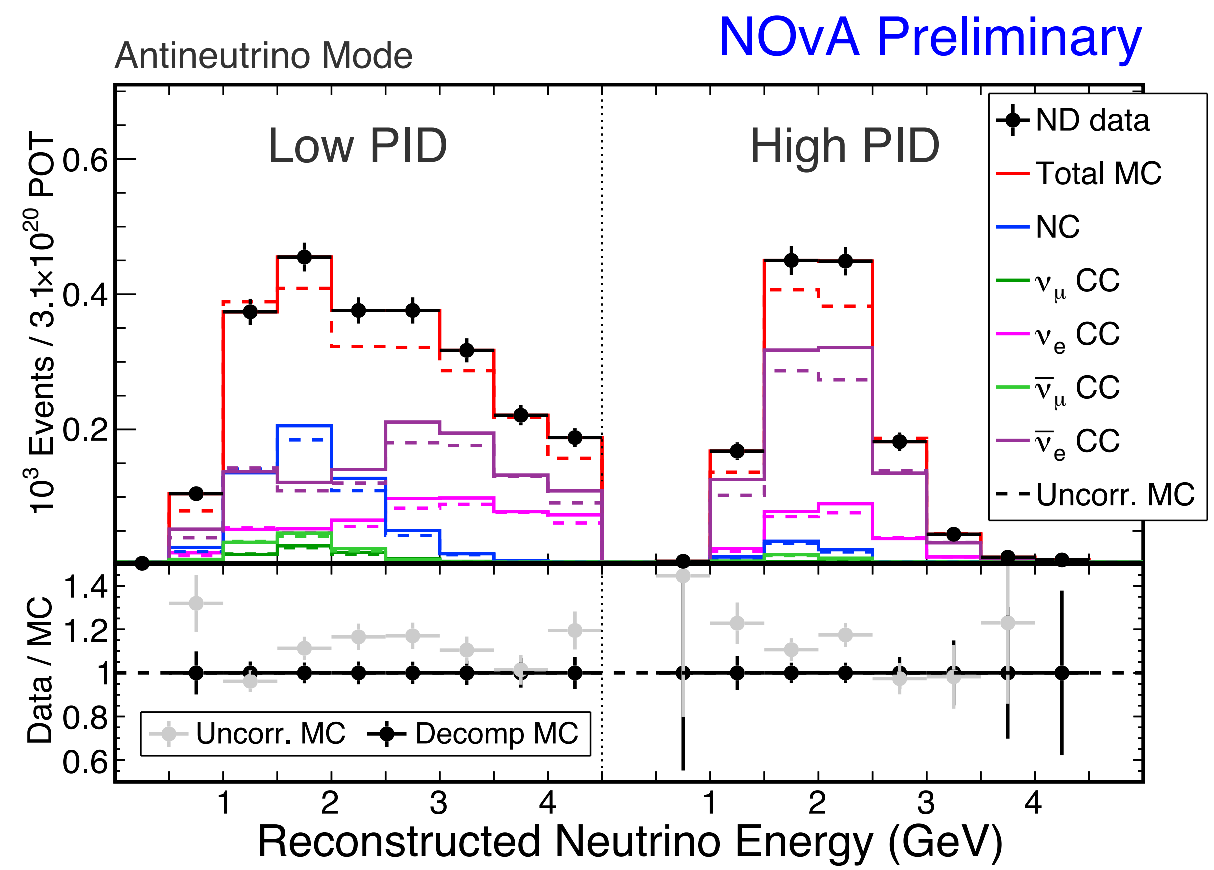
Antineutrino beam

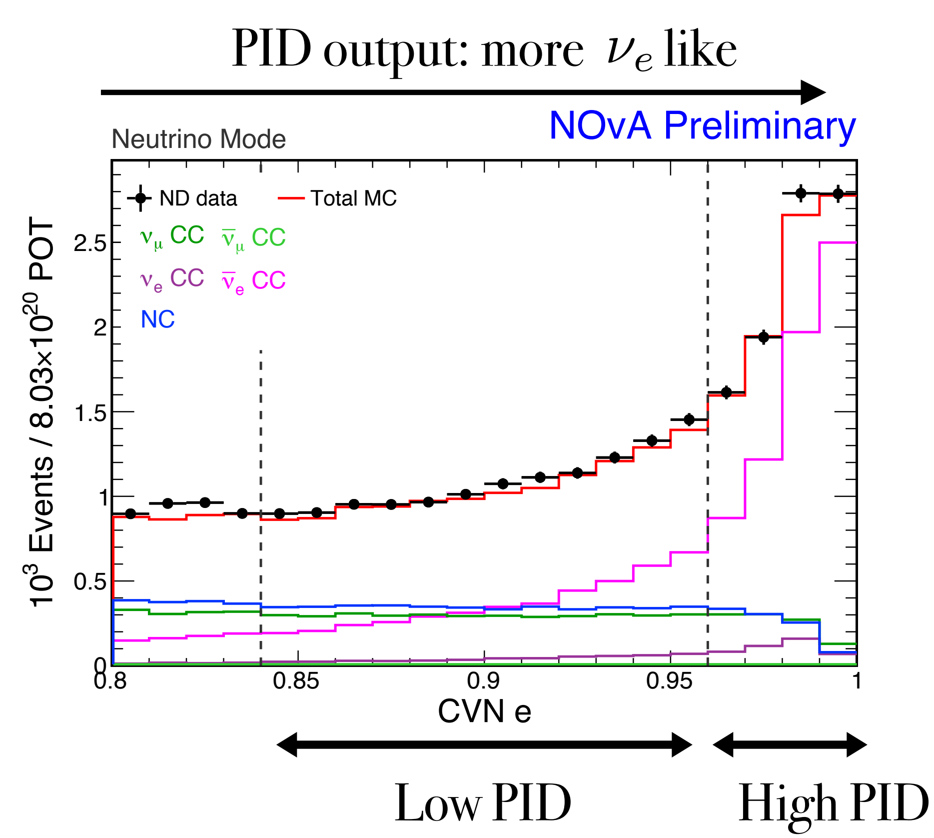


- ✳ ν_μ sample is divided into four quartiles based on E_{had}/E_ν fraction.
- ✳ Wrong-sign background is about 3% in ν beam and 11% in $\bar{\nu}$.

ND data for ν_e



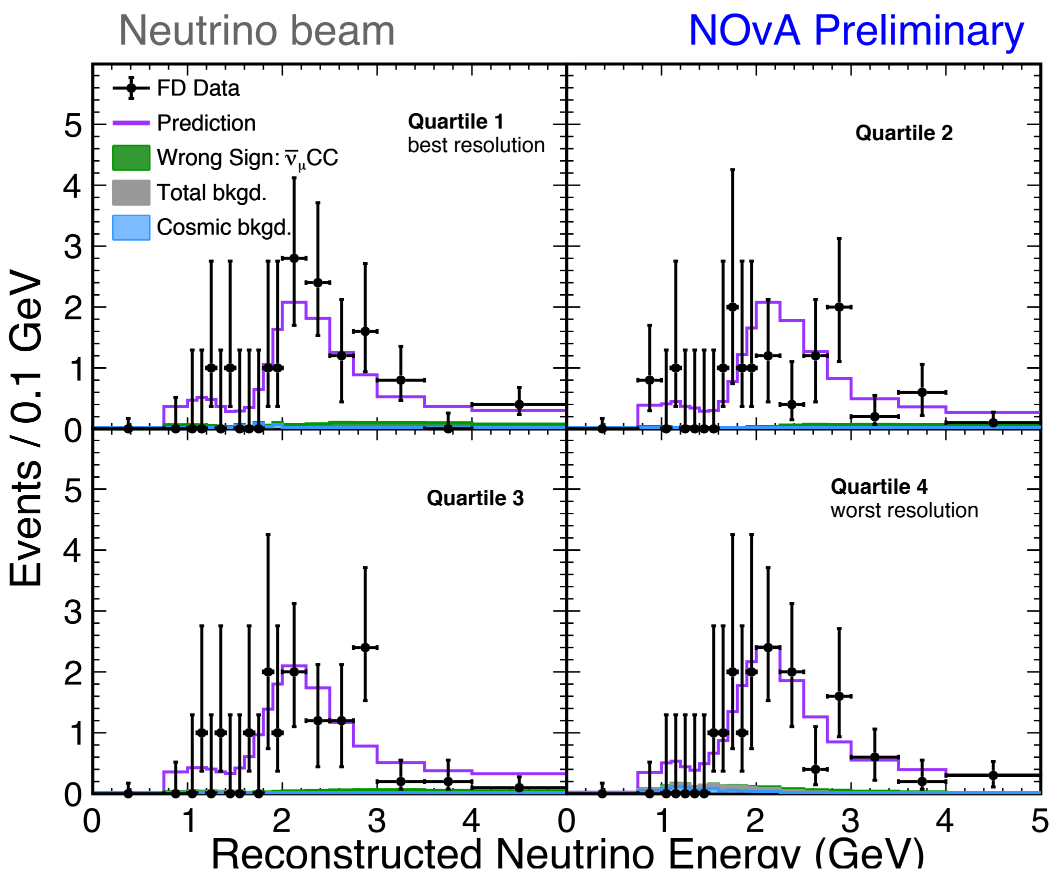


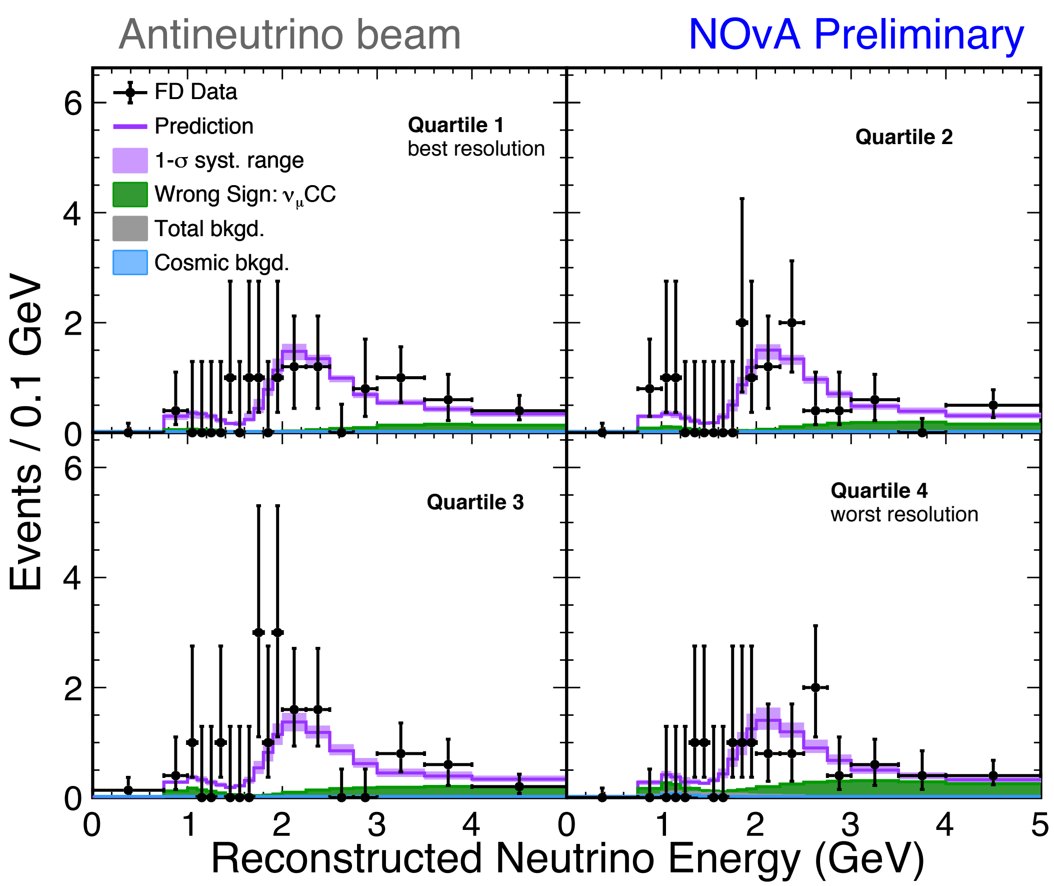


* Split ν_e sample into Low and High PID spectra.
* All ν_e ND candidates are background sources in the FD (no oscillations in the ND).
* Use ND data to correct the predictions.
* Extrapolate each category separately to the FD.

FD data. Inputs for fit - ν_μ sample

3-flavor oscillations describe data well (goodness-of-fit p = 0.91)





Neutrino beam:

Total Observed	**113**
Best Fit prediction	124
Total bkgd	4.2
Cosmic bkg	2.1
Beam bkg	2.1
Unoscillated prediction	730

Antineutrino beam:

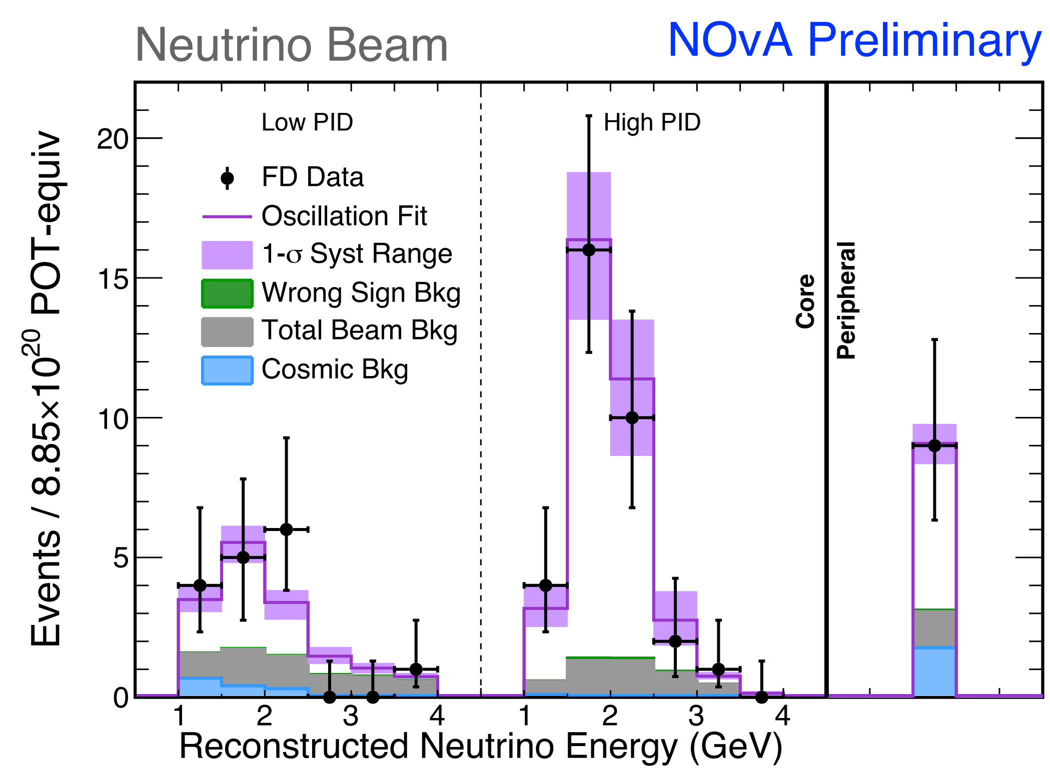
Total Observed	**102**
Best Fit prediction	96
Total bkgd	2.2
Cosmic bkg	0.8
Beam bkg	1.4
Unoscillated prediction	476

FD data. Inputs for fit - ν_e sample

3-flavor oscillations describe data well (goodness-of-fit p = 0.91)

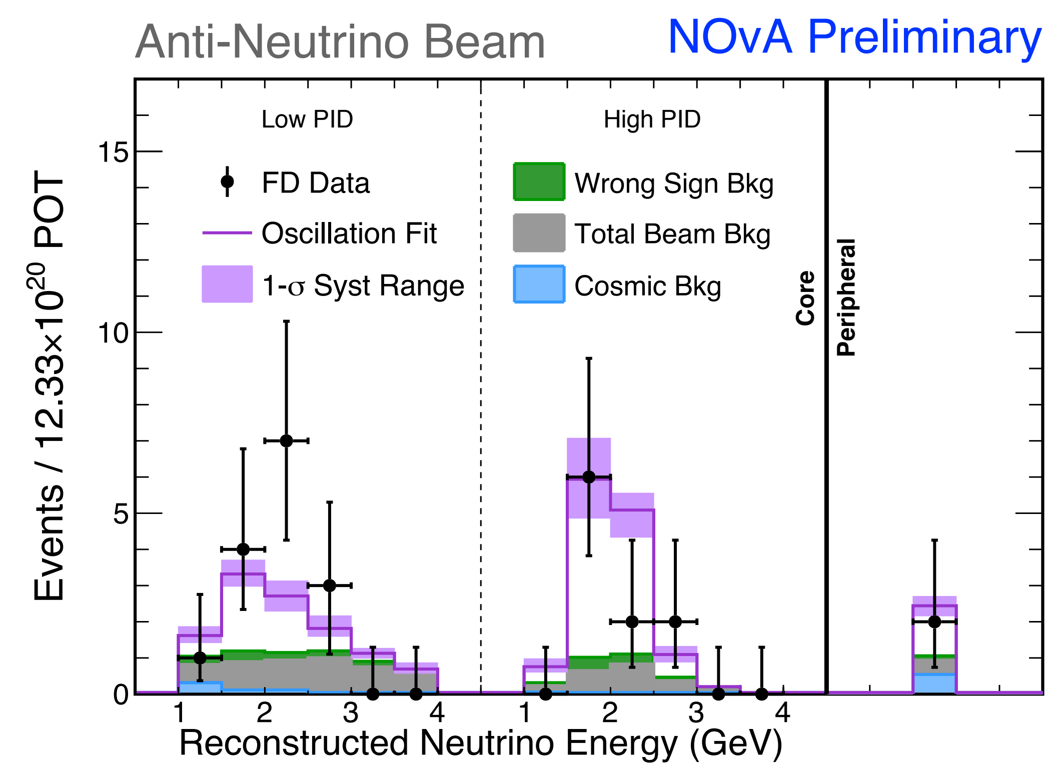
Neutrino beam:

Total Observed	**58**
Best Fit prediction	59
Total bkgd	15.0
Cosmic bkg	3.3
Beam bkg	11.1
Wrong sign ($\bar{\nu}_e$ app.)	0.7



Antineutrino beam:

Total Observed	**27**
Best Fit prediction	27
Total bkgd	10.3
Cosmic bkg	1.1
Beam bkg	7.0
Wrong sign (ν_e app.)	2.2



Evidence for $\bar{\nu}_e$ appearance at 4.4σ

Fitting procedure

- NOvA's analysis is frequentist with profiled systematics and penalty terms.

- We minimise the Poisson log-likelihood function summed over all bins N and all systematic uncertainties S:

$$-2\ \ln\ L(\vec{\theta},\vec{\delta}) = 2\sum_{i}^{\text{bins}}[N_i(\vec{\theta},\vec{\delta}) - O_i + O_i\cdot\ln\frac{O_i}{N_i(\vec{\theta},\vec{\delta})}] + \sum_{j=1}^{S}\frac{\delta_j^2}{\sigma_j^2}$$

where:

- O_i is an observed number of events in the bin i,
- N_i is a predicted number of events in the bin i,
- vector θ stands for all oscillation parameters, vector δ means all systematic nuisance parameters,
- in the second pull term, the δ_j is a fitted value of systematic j and σ_j is its error.

- The resulting gaussian fits were the input for Feldman-Cousins correction procedure. NOvA produced measurements of δ_{CP}, θ_{23}, Δm^2_{32} and mass hierarchy.

Feldman-Cousins procedure

But:

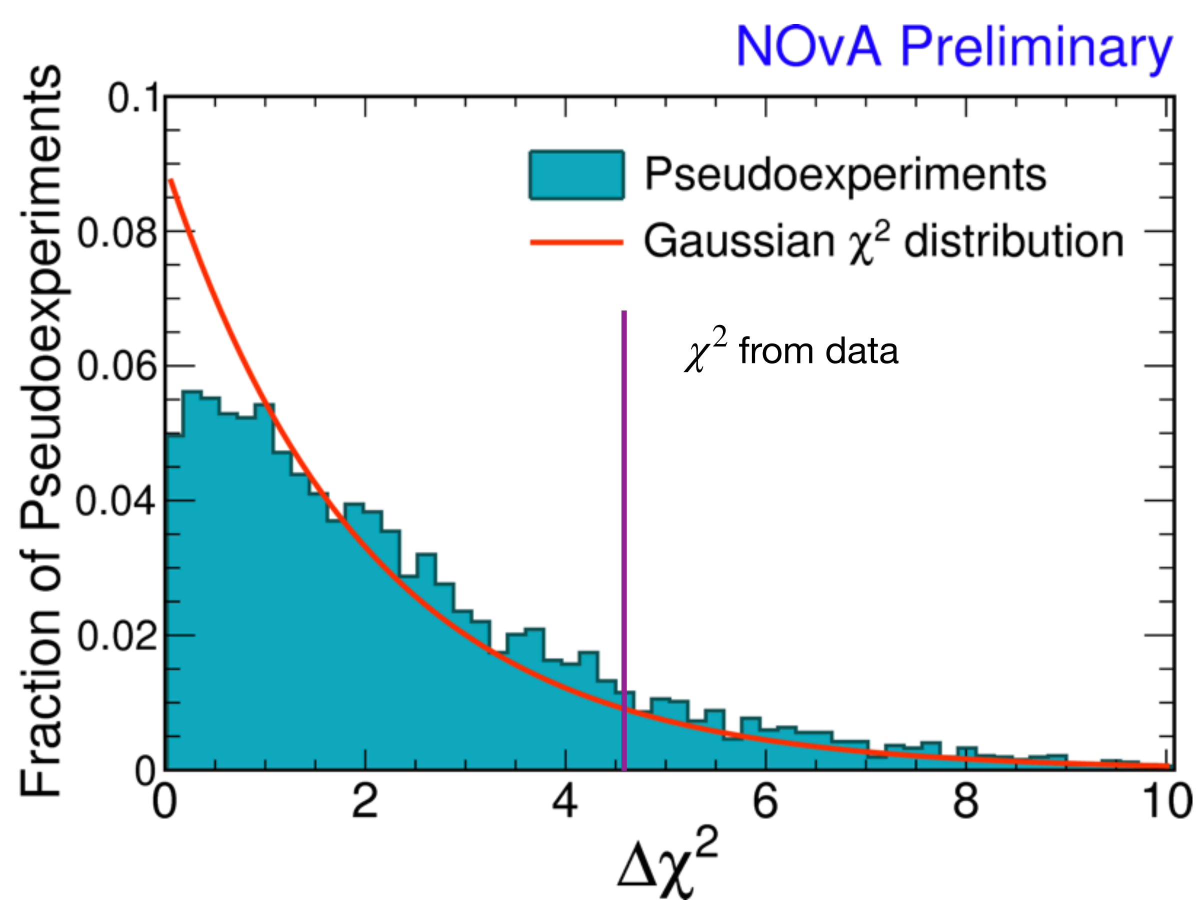
- ✳ low statistics (~100 events) and physics boundaries (δ_{CP} periodical $\in [0, 2\pi]$, MH binary etc) mean Wilks' theorem is not verified $\Rightarrow$ cannot derive significance from standard χ^2.

Solution:

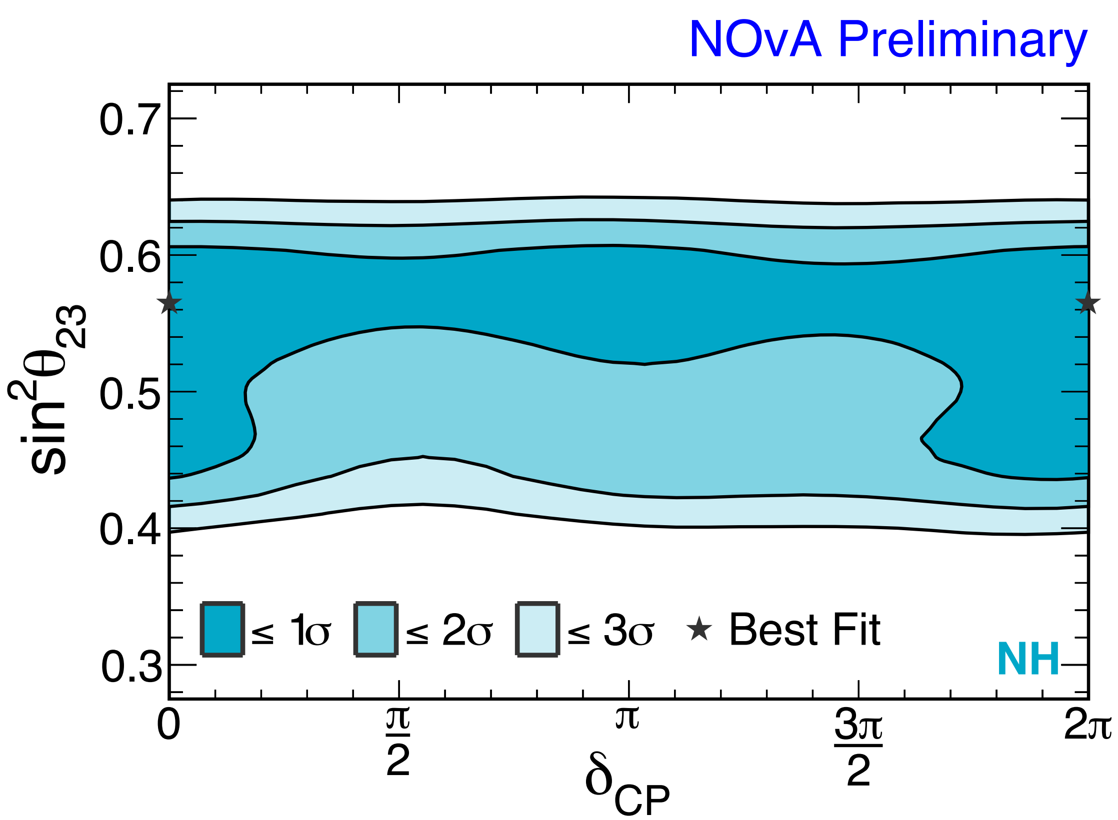
- ✳ follow Feldman-Cousins procedure:
  - ✳ generate Poisson-fluctuated data for a test set of parameters, fit this spectra as regular data and extract

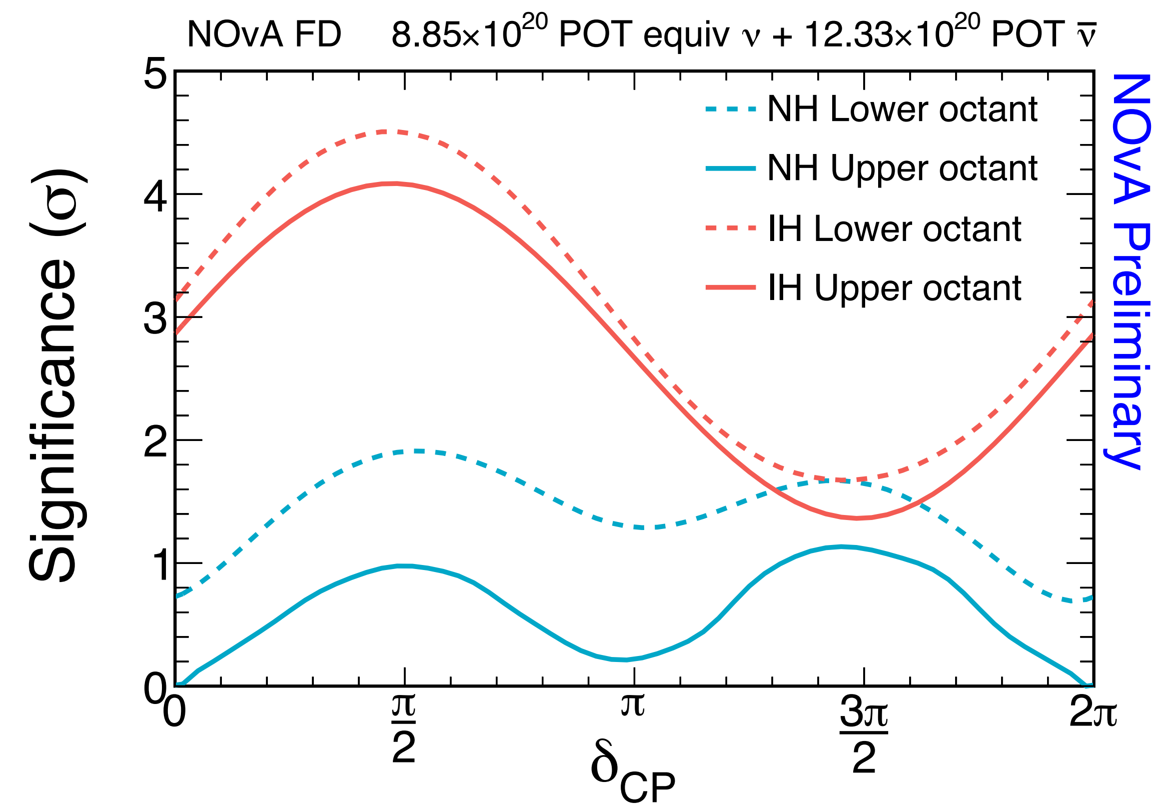
$$\Delta\chi^2 = \chi^2(\text{fixed at test}) - \chi^2(\text{best})$$

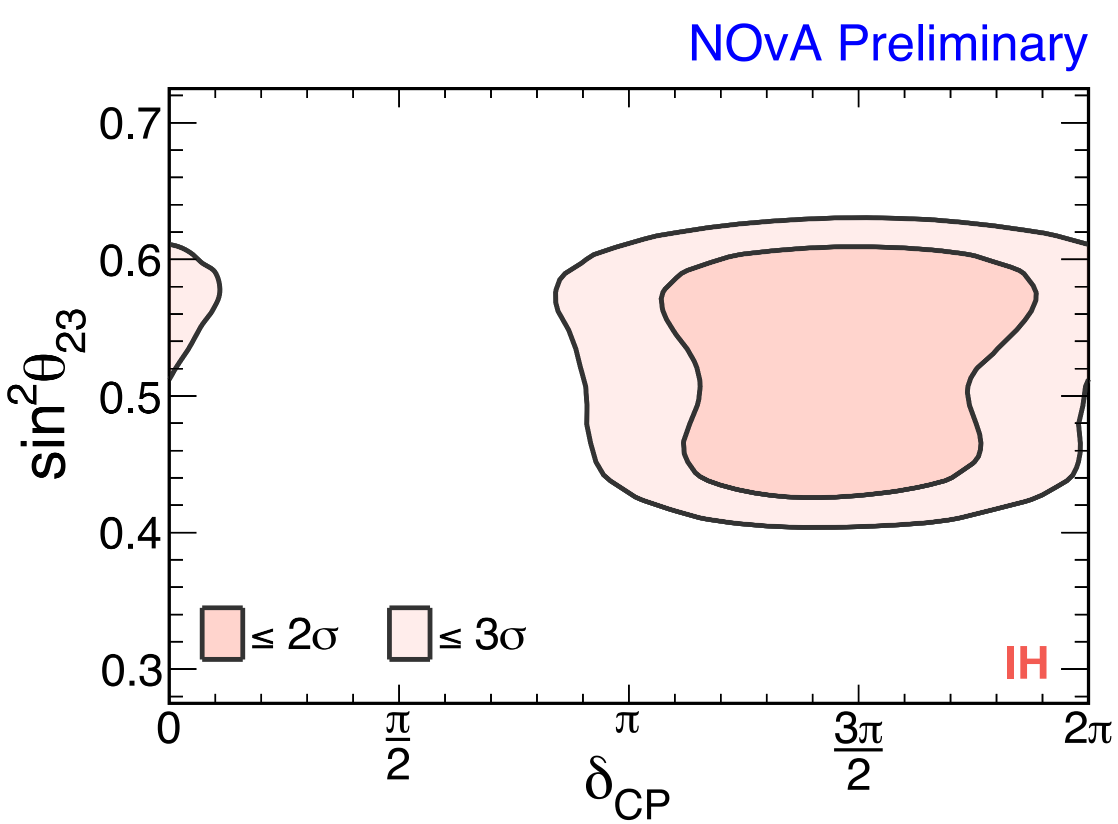
  - ✳ do this many times and get a distribution;
  - ✳ the fraction of pseudo-experiments with a $\Delta\chi^2$ larger than data gives a p-value.
  - ✳ compute a significance from that p - value.
- ✳ Scan parameter space and repeat this procedure.



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







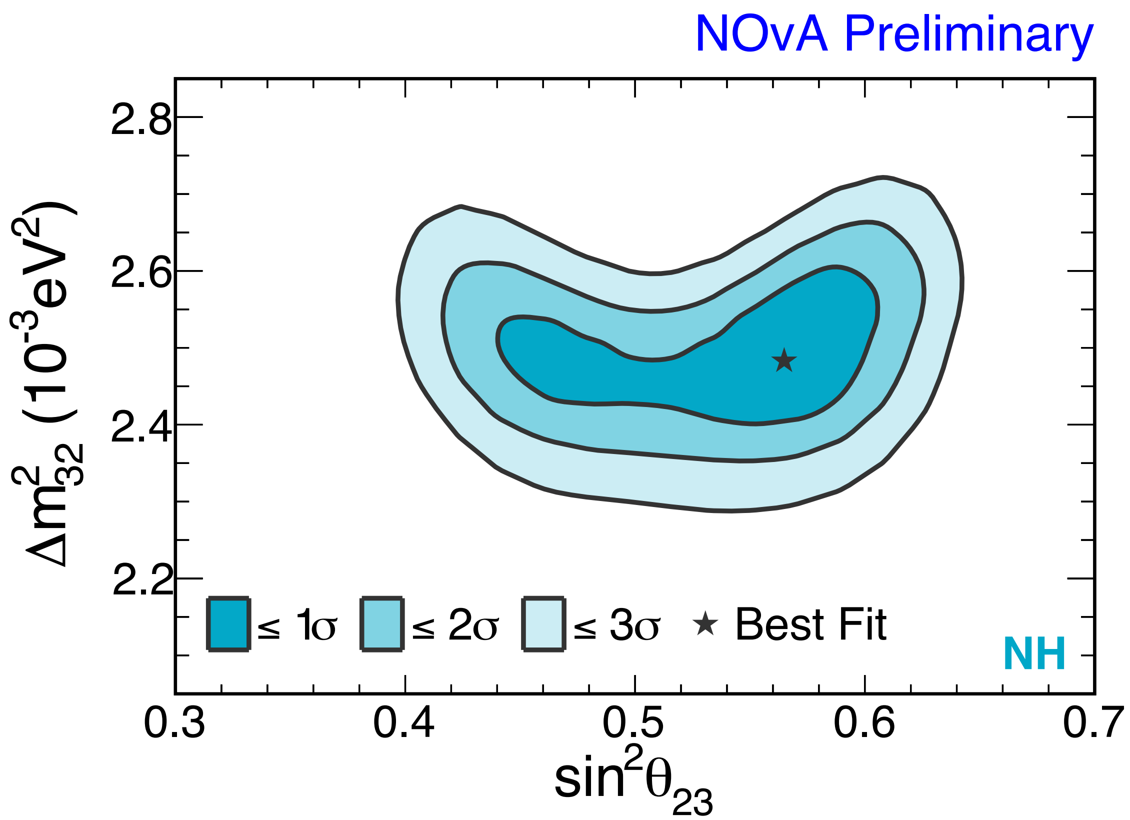
- ✳ All systematic uncertainties, Feldman - Cousins corrections are applied.
- ✳ Best fit:

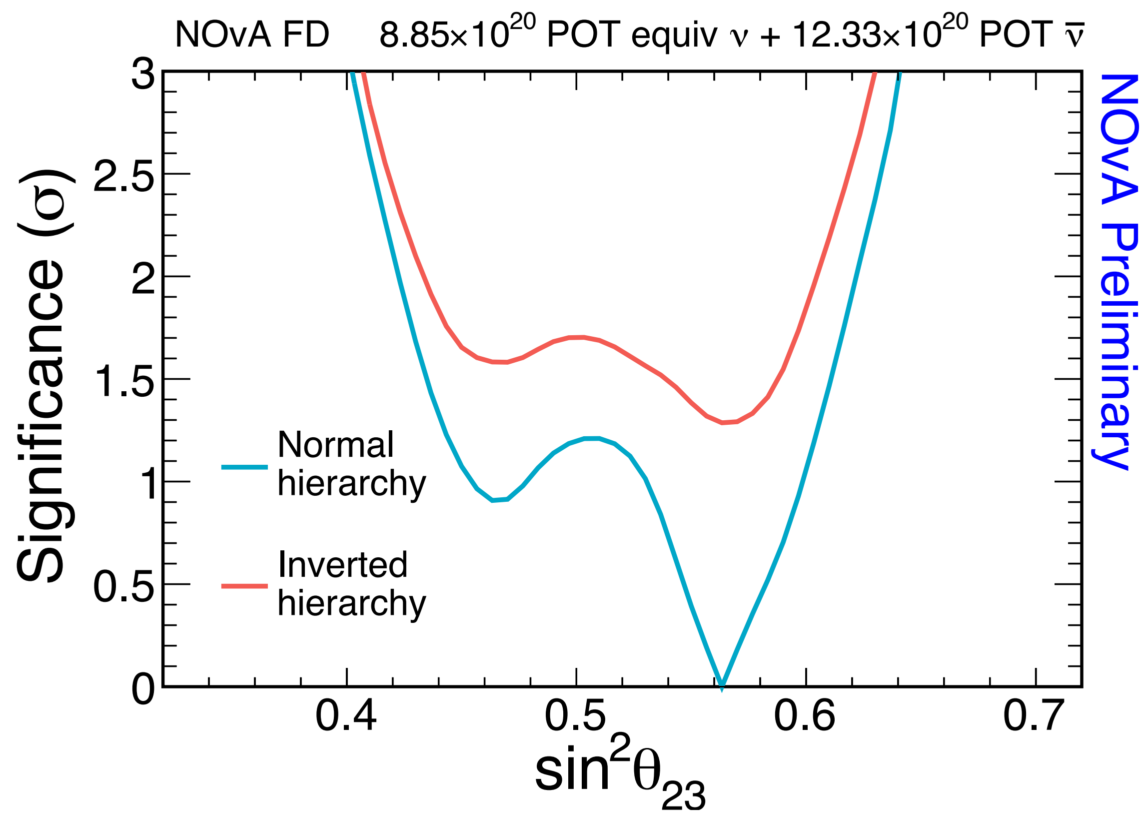
  $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$

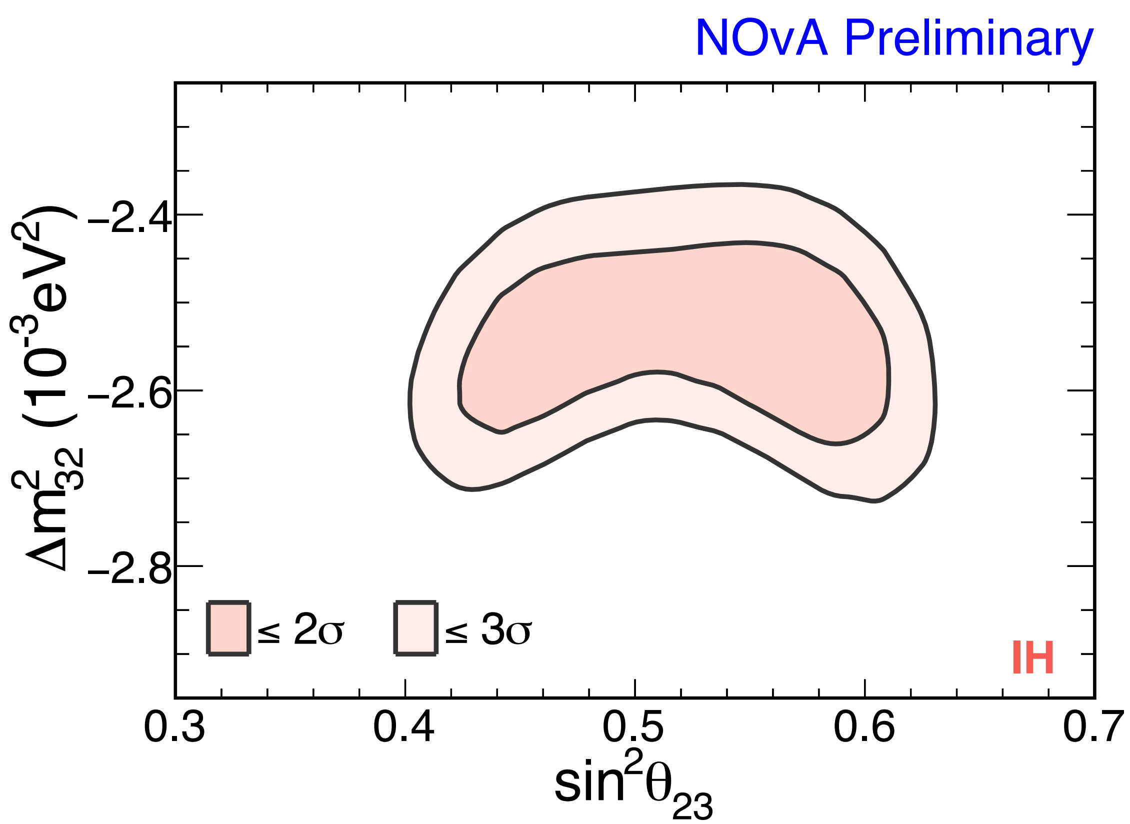
  $\Delta m^2_{32} = +2.48 \times 10^{-3}\ \mathrm{eV}^2$ (NH)

  $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi.$
- ✳ All values of δ_{CP} are allowed at 1.1σ (NH, Upper octant).
- ✳ IH, $\delta_{CP} = \pi/2$ is ruled out > 4σ.
- ✳ Inverted Hierarchy is disfavored at 1.9σ.

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







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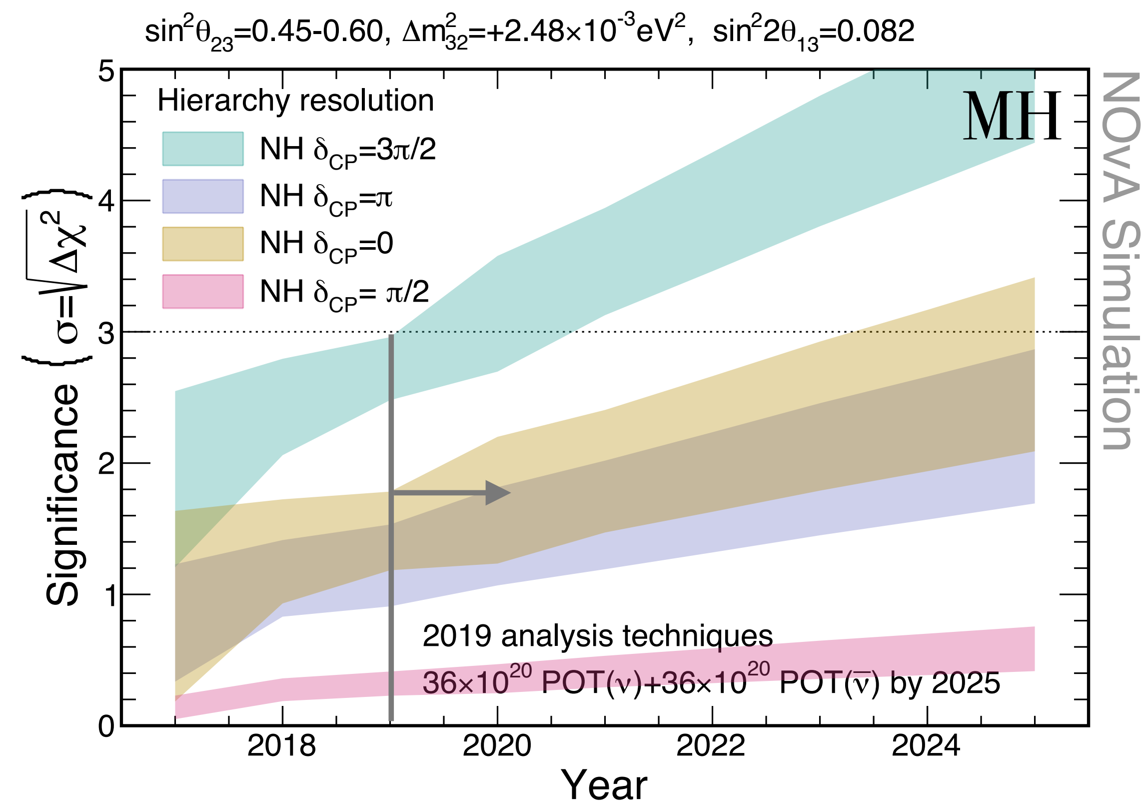
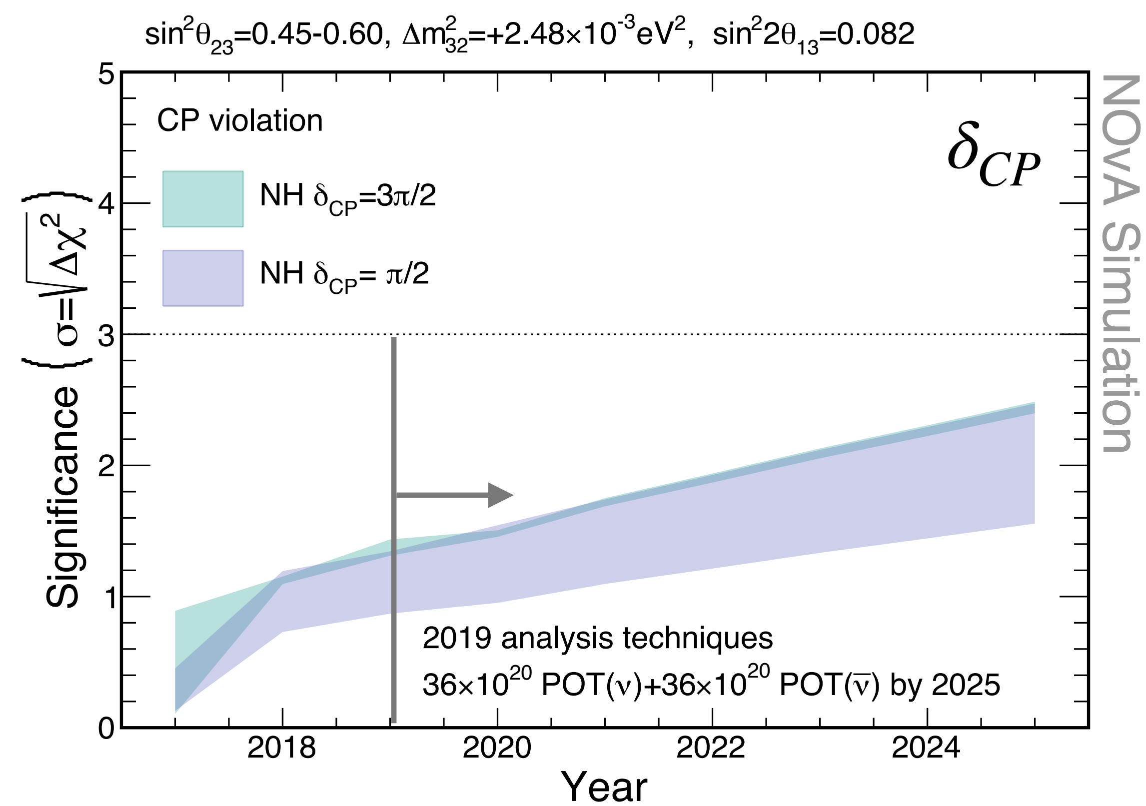
  $\Delta m^2_{32} = +2.48 \times 10^{-3}$ eV^2 (NH)
  $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi.$
- ✳ $\sin^2\theta_{23} < 0.5$ (lower octant) is disfavored at 1.6σ

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;
- ✳ det. response model;
- ✳ cross section models.

JINR participation in NOvA

Group leader: A. Olshevskiy
Deputy at JINR: O. Samoylov

24 JINR collaborators (13 authors) out of 240 in NOvA with the following activities:

- scintillator filling and APD testing (N.Anfimov, O. Samoylov, A. Sotnikov)
- detector construction and response; NOvA test benches at JINR (A. Antoshkin, N.Anfimov, O.Klimov, O. Samoylov, A. Sotnikov)
- Dubna Remote Operation Center for NOvA (A.Antoshkin, N. Anfimov, A.Balandin and A. Dolbilov (emergency contacts), Ch. Kullenberg, O. Samoylov, A. Sheshukov)
- JINR data center for NOvA and IT support (N. Balashov, A. Baranov, A. Dolbilov, N. Kutovskiy, E. Kuznetsov)
- theoretical group (I. Kakorin, K. Kuzmin, V. Naumov)
- detector simulation and calibration (O. Samoylov, O. Petrova)
- cross-section measurements:
  - coherent pion production (Ch. Kullenberg)
  - strange particle production (V. Allakhverdian)
- exotics:
  - atmospheric muons (A. Morozova, O. Petrova)
  - supernova detection (M. Petropavlova, A. Sheshukov)
  - monopole search (A. Antoshkin)
- oscillation analysis:
  - sterile neutrino searches (V. Korsunov)
  - 3 flavour paradigm (A. Kalitkina, L. Kolupaeva)

Conclusions

Strong participation of JINR group in NOvA in all essential parts of experiment.

With 8.85×10^{20} (ν) + 12.33×10^{20} $(\bar{\nu})$ POT exposure the following results were obtained:

* 4.4σ evidence for $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam.
* The best fit is in the Normal Hierarchy,
  $\delta_{CP} = 0\pi$, $\sin^2\theta_{23} = 0.56$, $\Delta m^2_{32} = +2.48 \times 10^{-3}\ \mathrm{eV}^2$
* 1.9σ preference for the Normal neutrino mass hierarchy, exclude $\delta_{CP} = \pi/2$ in Inverted hierarchy at $> 4\sigma$.
* Prefer upper octant of $\sin^2\theta_{23}$ at 1.6σ (consistent with maximal mixing at 1.2σ).

With operation through 2025 NOvA expects:

  * possible 3 - 5σ sensitivity to mass hierarchy ;
  * potential sensitivity to CP violation phase $> 2\sigma$.