Neutrino Oscillation Physics with the NOvA Experiment

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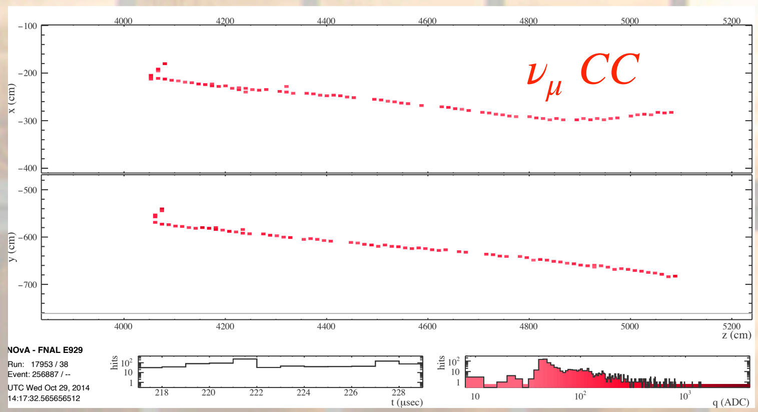

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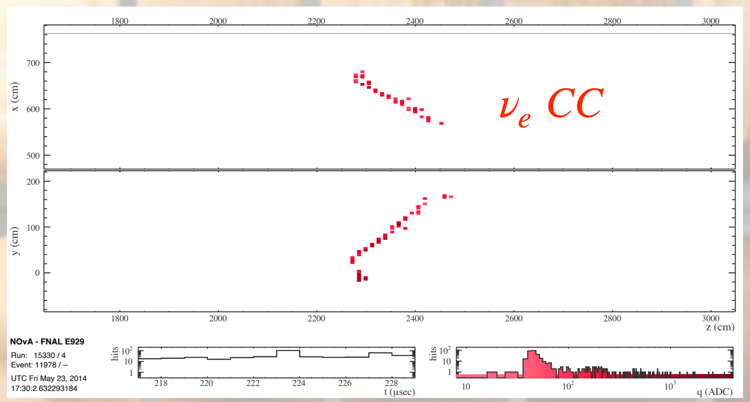

Thursday, April 8, 2021

Fermilab

UNIVERSITY OF DELHI

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Department of Science & Technology
Govt. of India

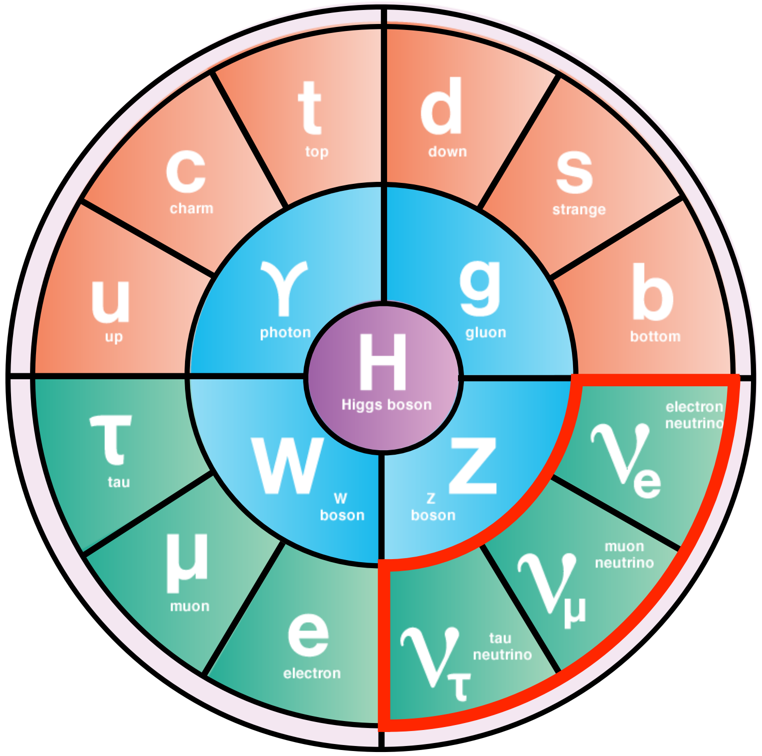
NOvA

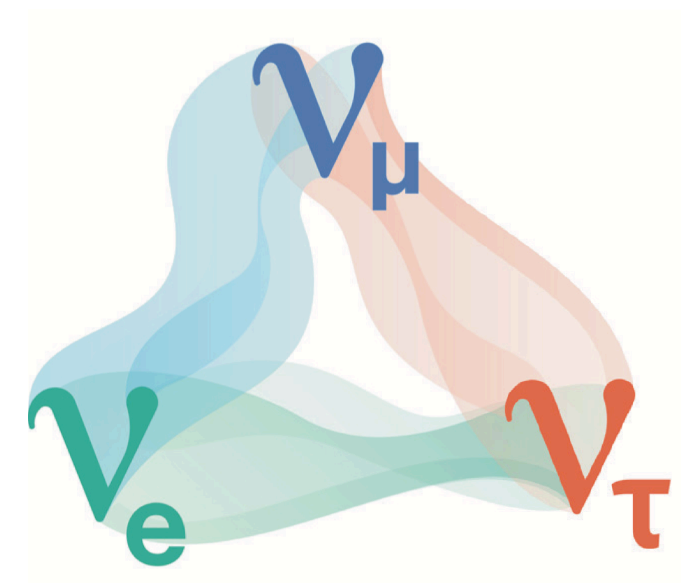
Outline

- Introduction to Neutrino Physics and Oscillations
- NOvA Experiment
- Cosmic Ray Muons in the Detector
- Detector Calibration
- Oscillation Analysis and Results

Brief Introduction to Neutrinos

- The most abundant particle in the Universe after photon
- Postulated in 1930 by W. Pauli to explain the continuous spectrum of the beta decay
- Sources: Big Bang, the core of the Sun, Supernovae, radioactive processes, cosmic ray showers, nuclear reactions, and particle accelerators
- Three generations: ν_e , ν_μ and ν_τ (and anti-neutrinos)
- Charge-less, spin 1/2, weakly interacting and massless in the Standard Model (SM)
- Neutrinos oscillate between different flavors
- Transformation of one flavor of neutrinos to another flavor without involving any intermediating particle is termed neutrino oscillations
- Oscillation implies non-zero masses of neutrinos





Neutrino Oscillations - Phenomenology

- **The flavor neutrino eigen states ($|\nu_\alpha\rangle$) are quantum superposition of mass eigen states ($|\nu_i\rangle$)**

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

- **U is an unitary mixing matrix and defines the mixing of mass states in flavor eigen states**

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta_{cp}} \\ -c_{12}s_{13}s_{23}e^{i\delta_{cp}} - c_{23}s_{12} & -s_{12}s_{13}s_{23}e^{i\delta_{cp}} + c_{12}c_{23} & c_{13}s_{23} \\ -c_{12}s_{13}c_{23}e^{i\delta_{cp}} + s_{23}s_{12} & -s_{12}s_{13}c_{23}e^{i\delta_{cp}} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- **Here $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ and δ_{cp} is the charge-parity (CP) violation factor**

- **Oscillation probability from flavor α to α'**

$$P_{\nu_\alpha \longrightarrow \nu_{\alpha'}} = \delta_{\alpha,\alpha'} - 4\sum_{i>k} \mathbf{Re} U_{\alpha' i}U^*_{\alpha i}U^*_{\alpha' k}U_{\alpha k} \sin^2 \frac{\Delta m^2_{ki} L}{4E} + 2\sum_{i>k} \mathbf{Im} U_{\alpha' i}U^*_{\alpha i}U^*_{\alpha' k}U_{\alpha k} \sin^2 \frac{\Delta m^2_{ki} L}{2E}$$

- **Here $\Delta m^2_{ki} = m^2_k - m^2_i$ is the differences in the masses of mass eigen states**

Current Status of the Neutrino Oscillation Parameters

Oscillation Parameters

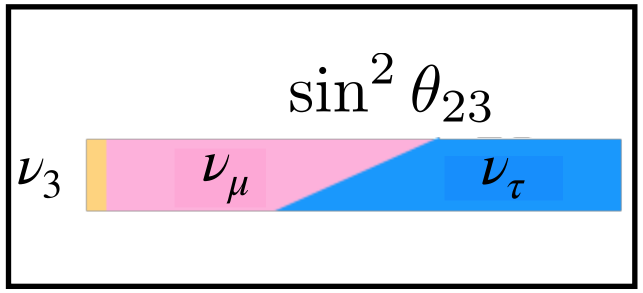
- **Mixing angles:** $\theta_{12}, \theta_{13}, \theta_{23}$
- **Mass squared:** $\Delta m^2_{32}, \Delta m^2_{21}$
- **CP violation phase:** δ_{cp}

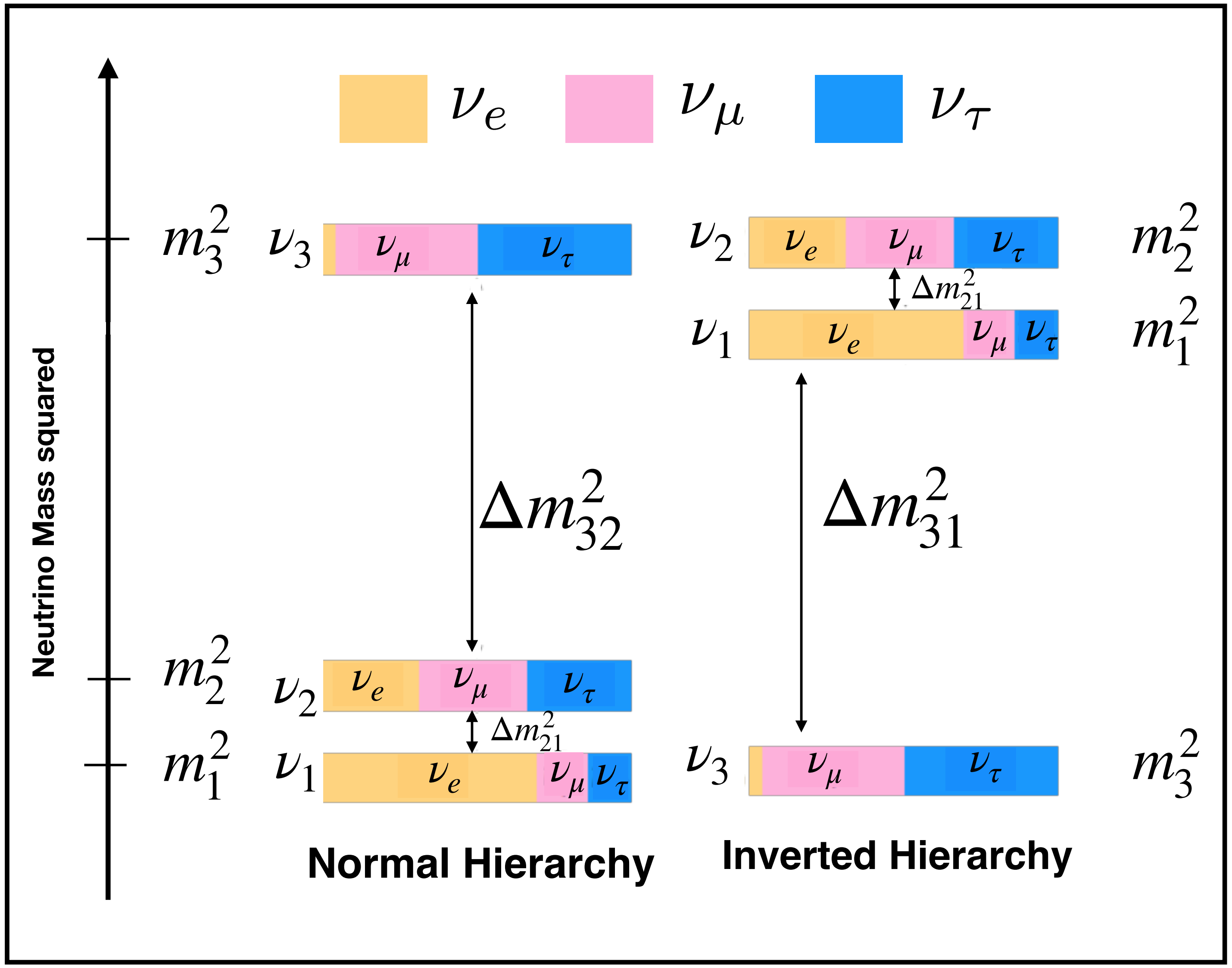
Known Parameters

$\theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, |\Delta m^2_{32}|$

Unknown Parameters

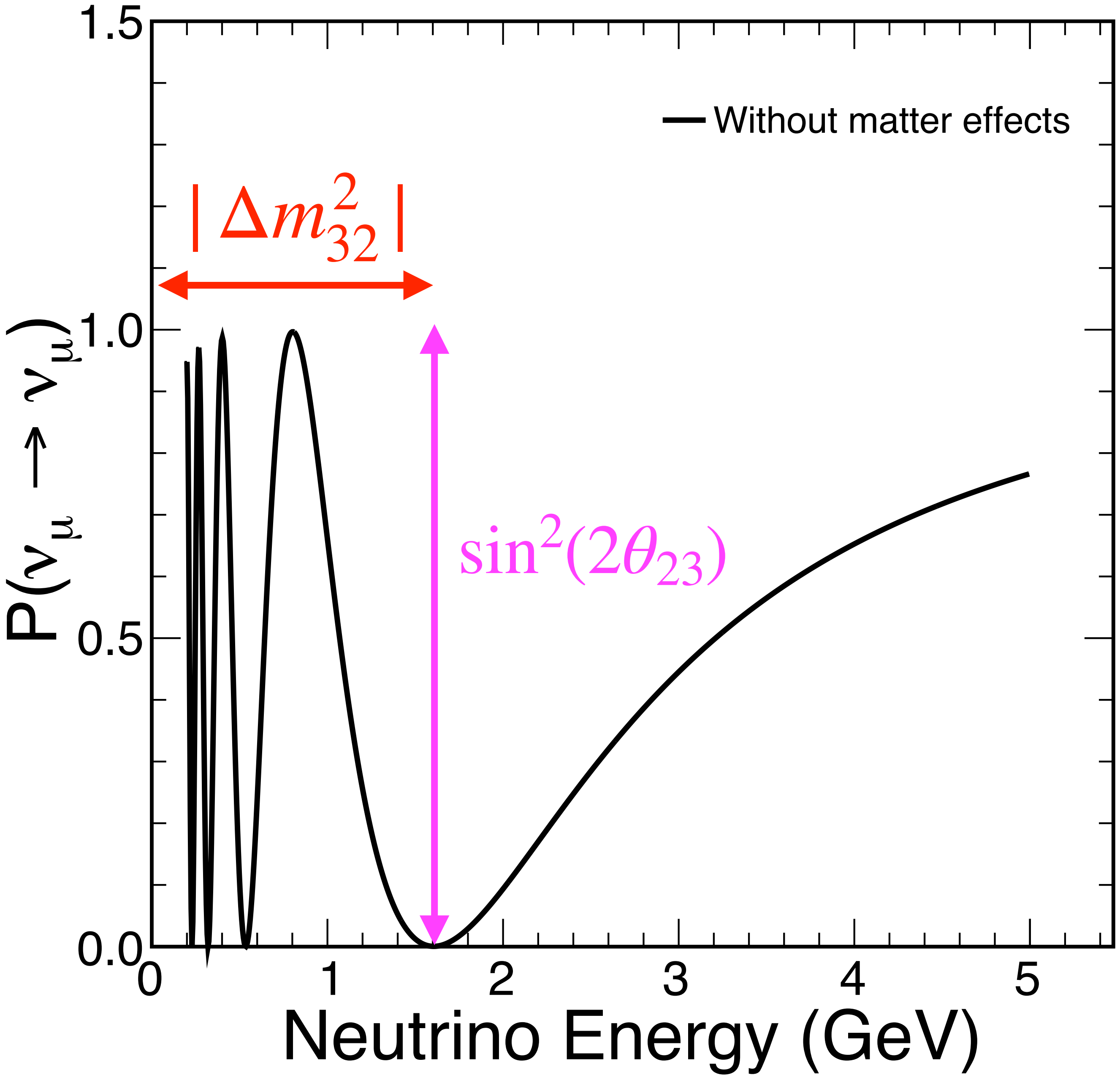
- **Mass hierarchy: sign of** $|\Delta m^2_{32}|$
- **Octant of** θ_{23}
- **CP violation:** δ_{cp}





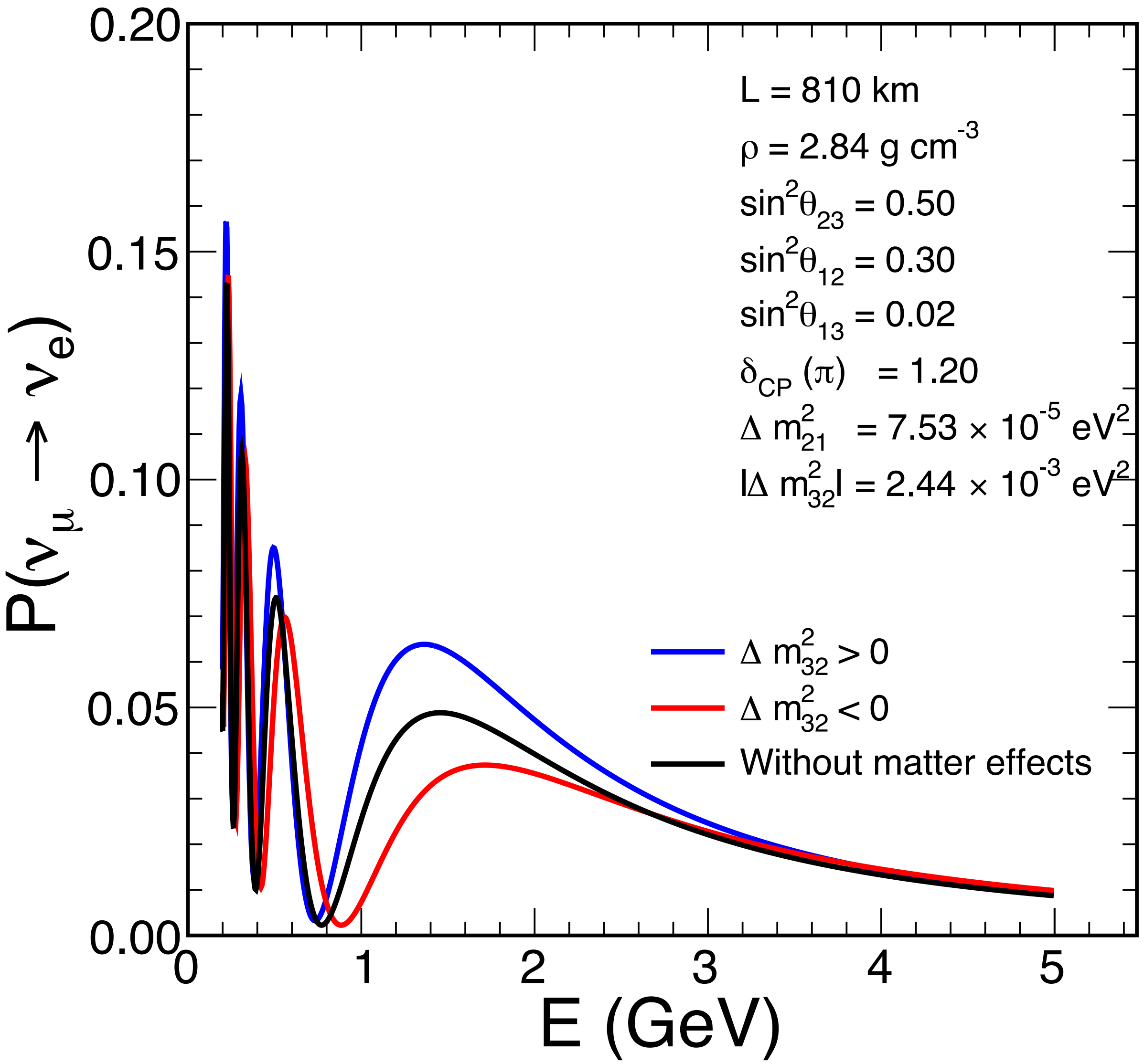
$\nu_\mu \to \nu_\mu$ Disappearance Oscillations

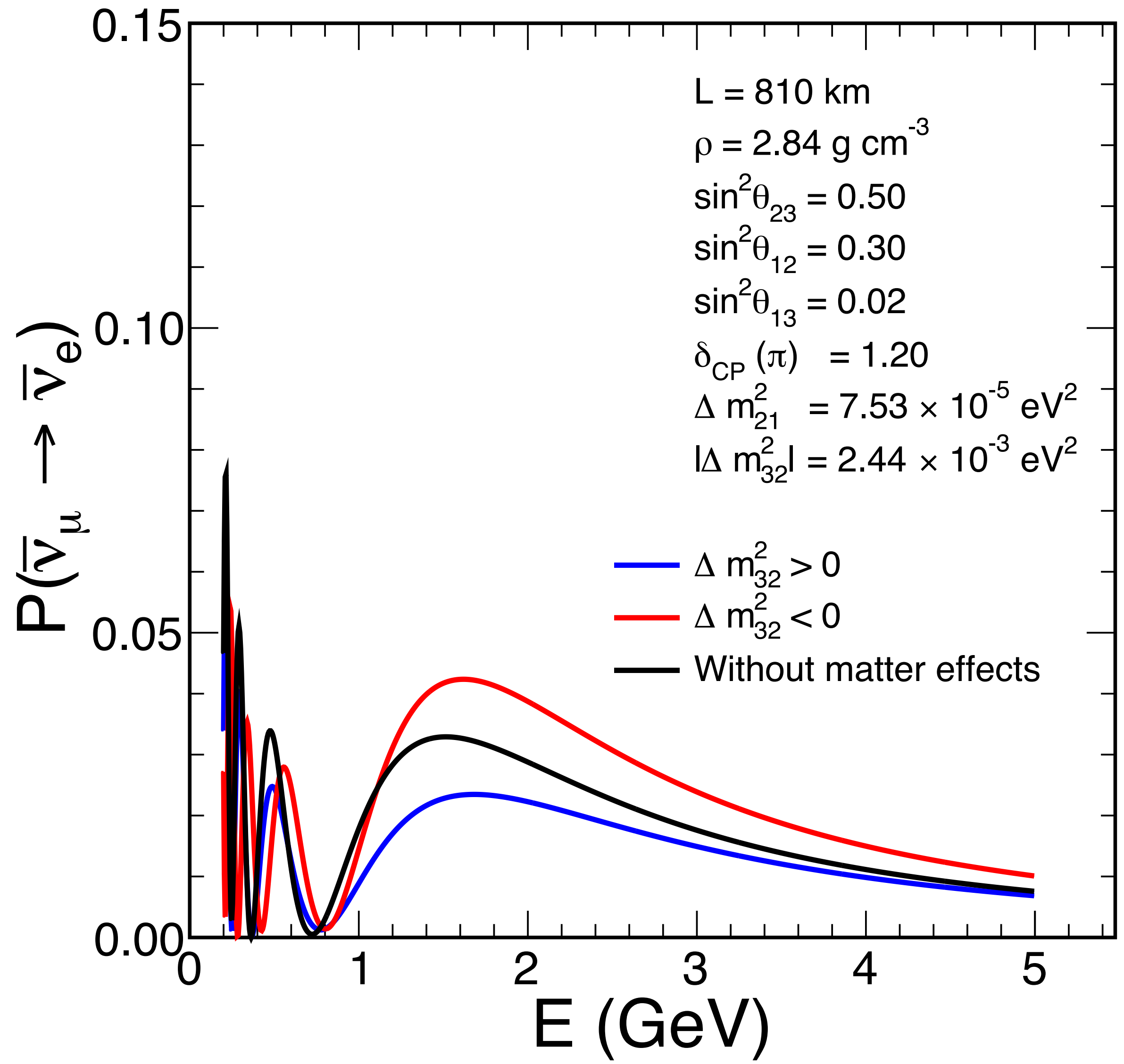
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{23} \; \sin^2\left(\frac{1.27 \; \Delta m^2_{32} \; (eV^2) \; L \; (km)}{E \; (GeV)}\right)$$



Survival probability gives direct measurement of $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$

$\nu_\mu \to \nu_e$ Appearance Oscillations





- **Matter has the opposite effect on neutrino and anti-neutrino oscillation**
- **Matter effect determine the CP-violating phase and the sign of the** $|\Delta m^2_{32}|$

NOvA Collaboration

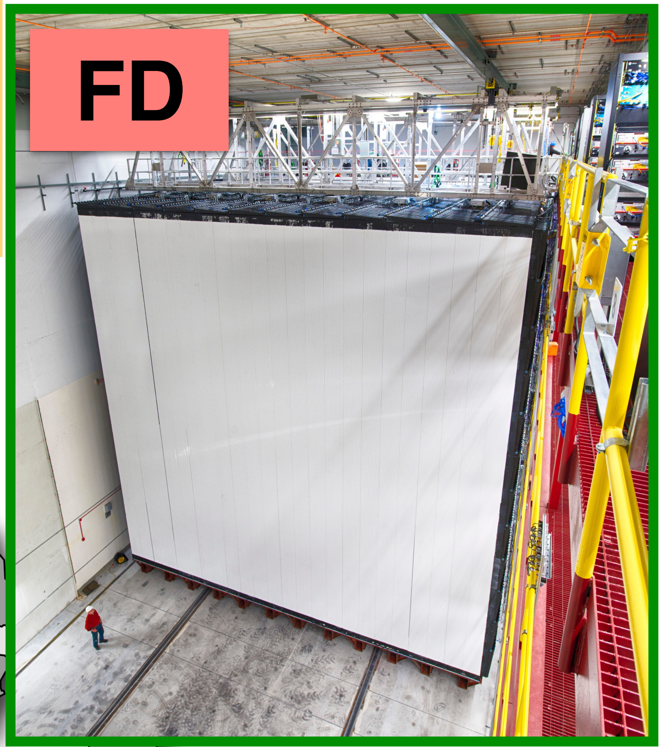
50 Institutions, 6 countries, 240+ collaborators

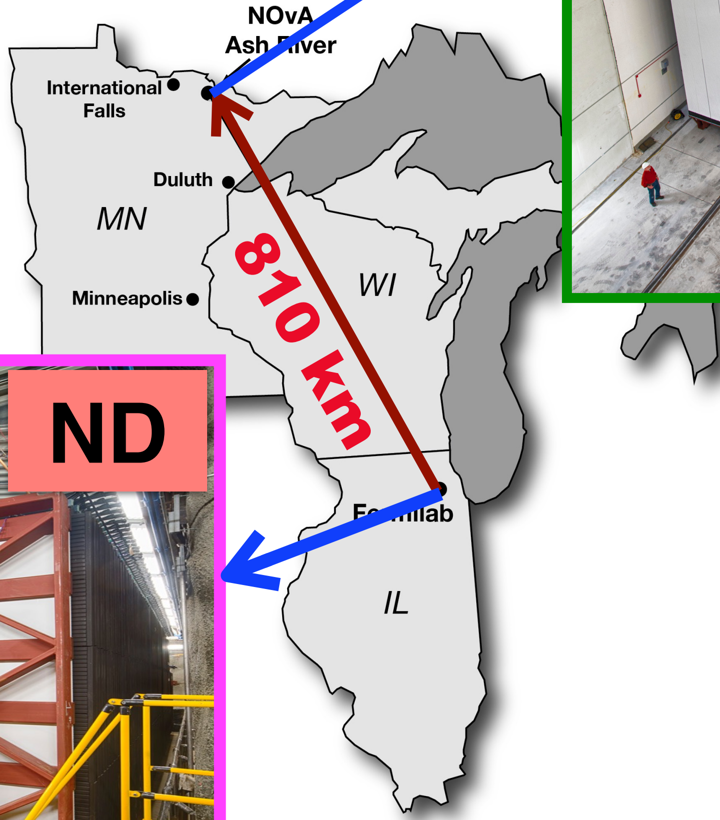
Argonne, Atlantico, BHU, Caltech, CUSAT, Czech Academy of Science, Charles, Cincinnati, Colorado State, Czech Technical University, Dallas, Delhi University, Dubna, Fermilab, Goias, Illinois, IIT-Guwahati, Harvard, Houston, IIT-Hyderabad, Hyderabad University, Indiana, Iowa State, California-Irvine, Jammu University, Lebedev, Michigan State, Minnesota Twin Cities, Minnesota-Duluth, NISER, INR Moscow, Panjab University, Pittsburgh, QMUL, South Alabama, SDMT, South Carolina, SMU, Stanford, Sussex, Syracuse, Tennessee, Texas-Austin, Tufts, UCL, Virginia, Wichita State, William and Mary, Wisconsin

NOvA Experiment

- **N**uMI **O**ff-Axis **ν$_e$** **A**ppearance (NOvA) experiment
- **Neu**trinos at **M**ain **I**njector (NuMI) beam
- Two detectors (Near and Far)
- Long-baseline (810 km)

Ash River, MN, 810 km from the FNAL





1 km from neutrino source

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- **Neutrino Mass Hierarchy**
- **Value of angle θ_{23}**
- **Search for CP violation**

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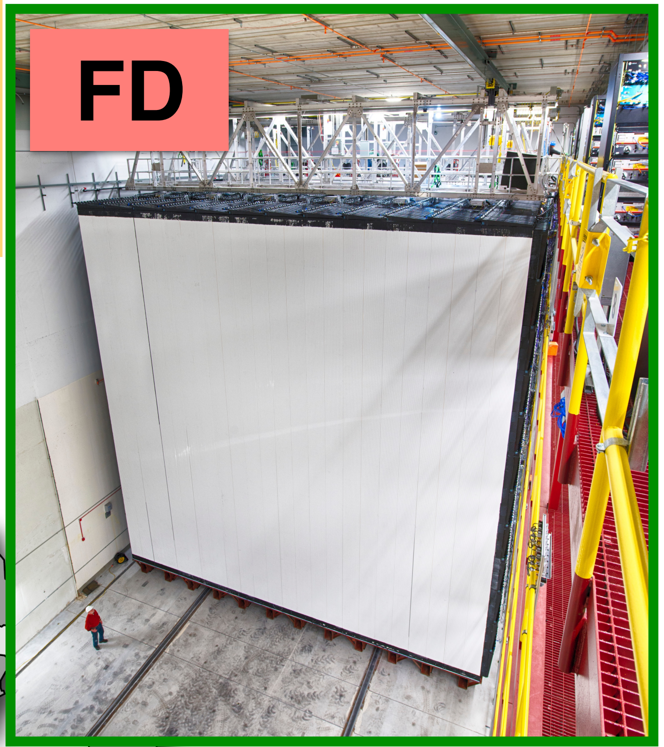

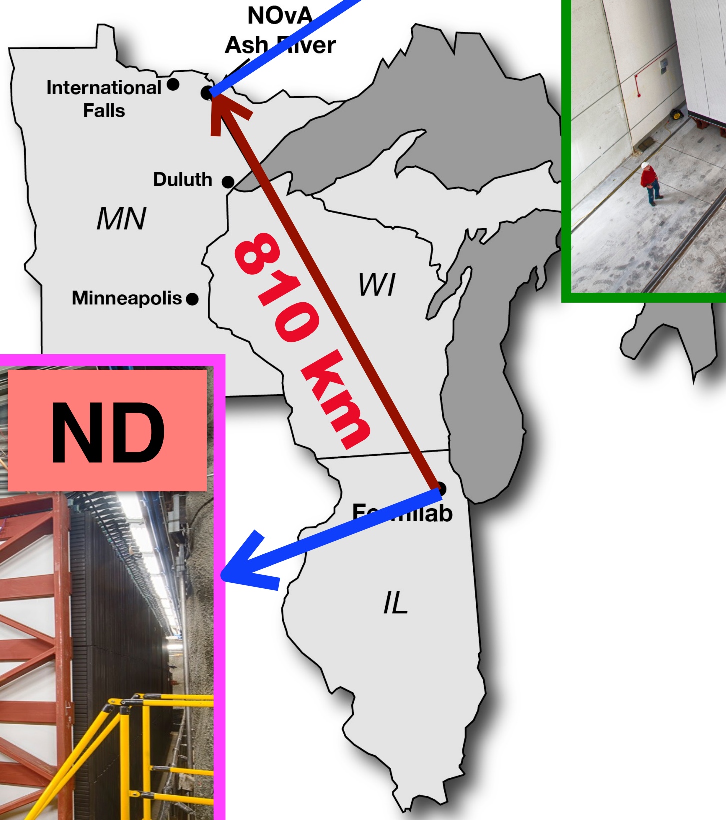

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- Neutrino spectrum peaks at 2 GeV

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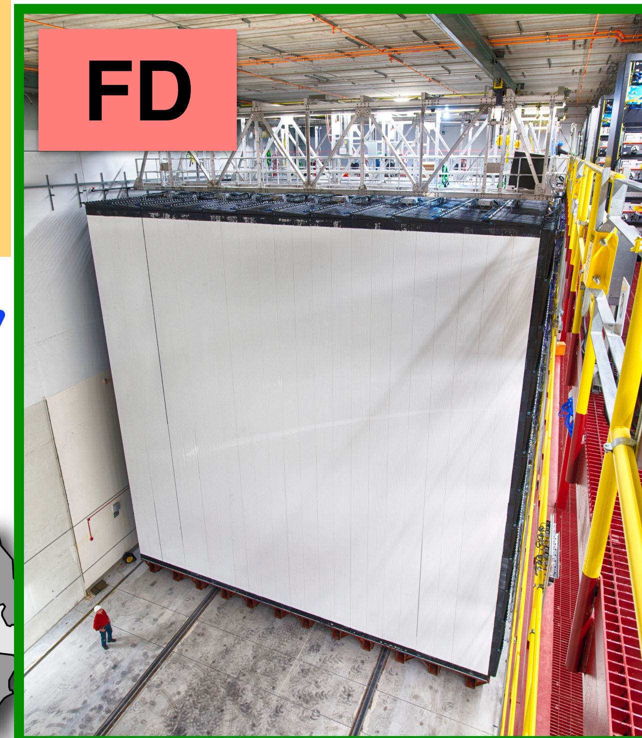

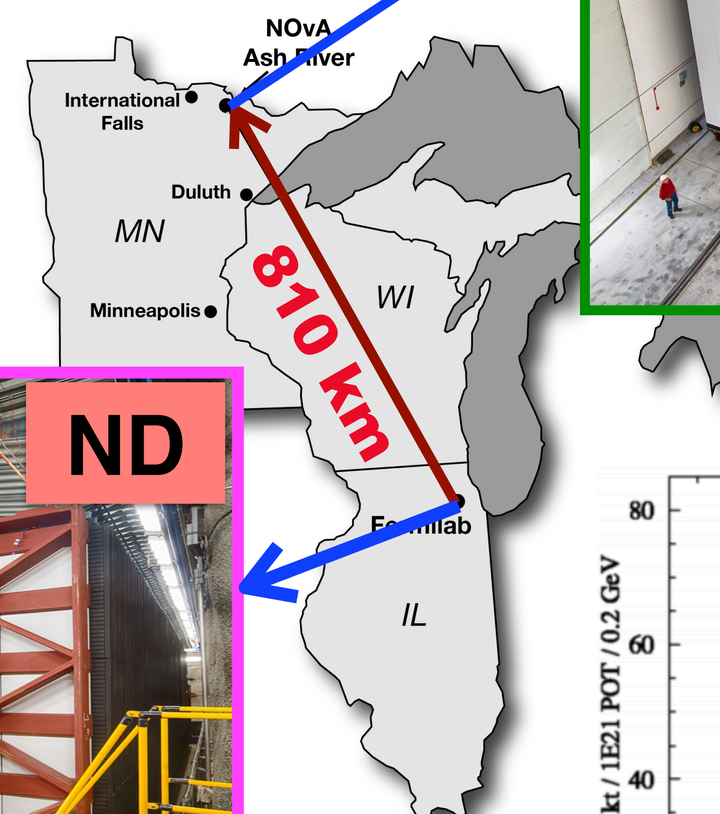

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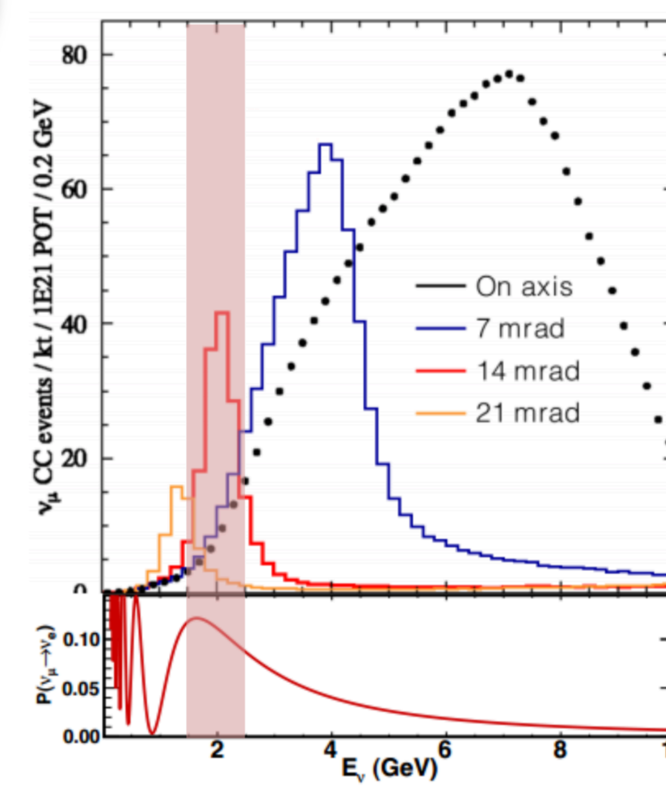

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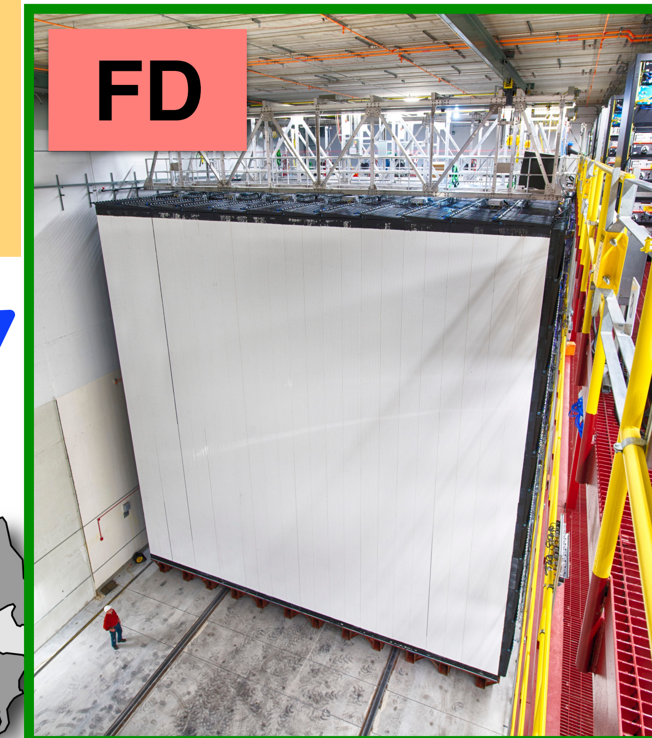

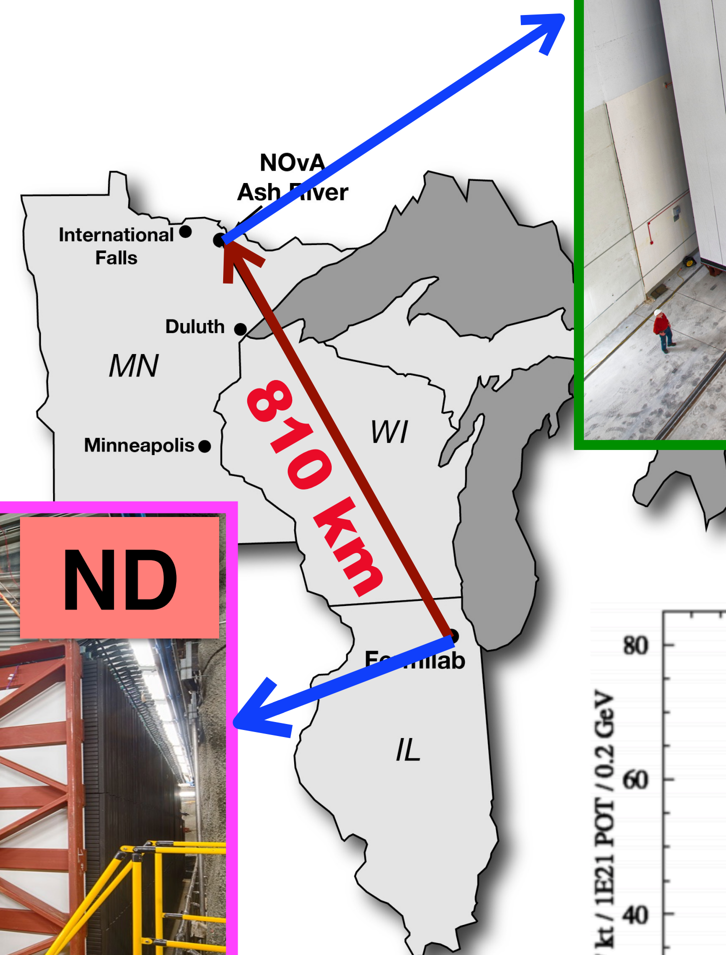

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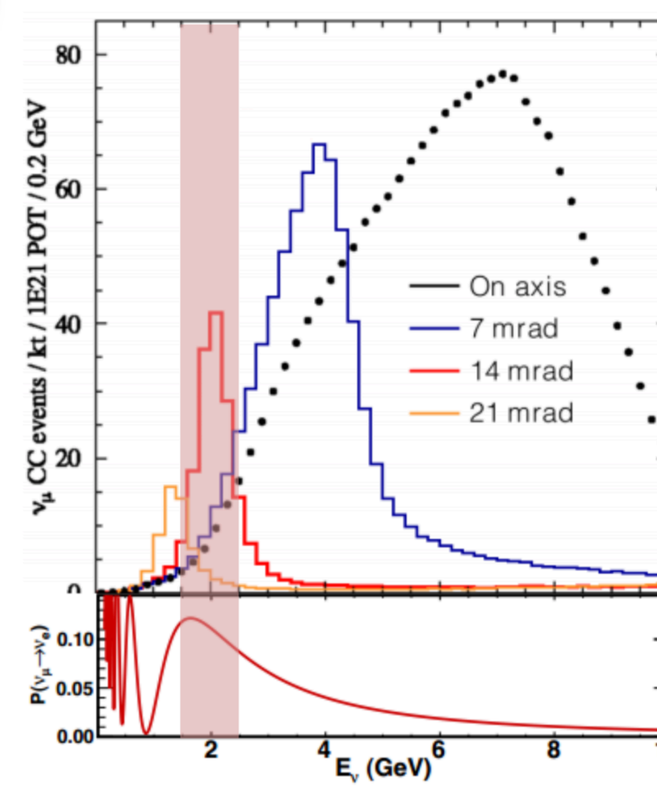


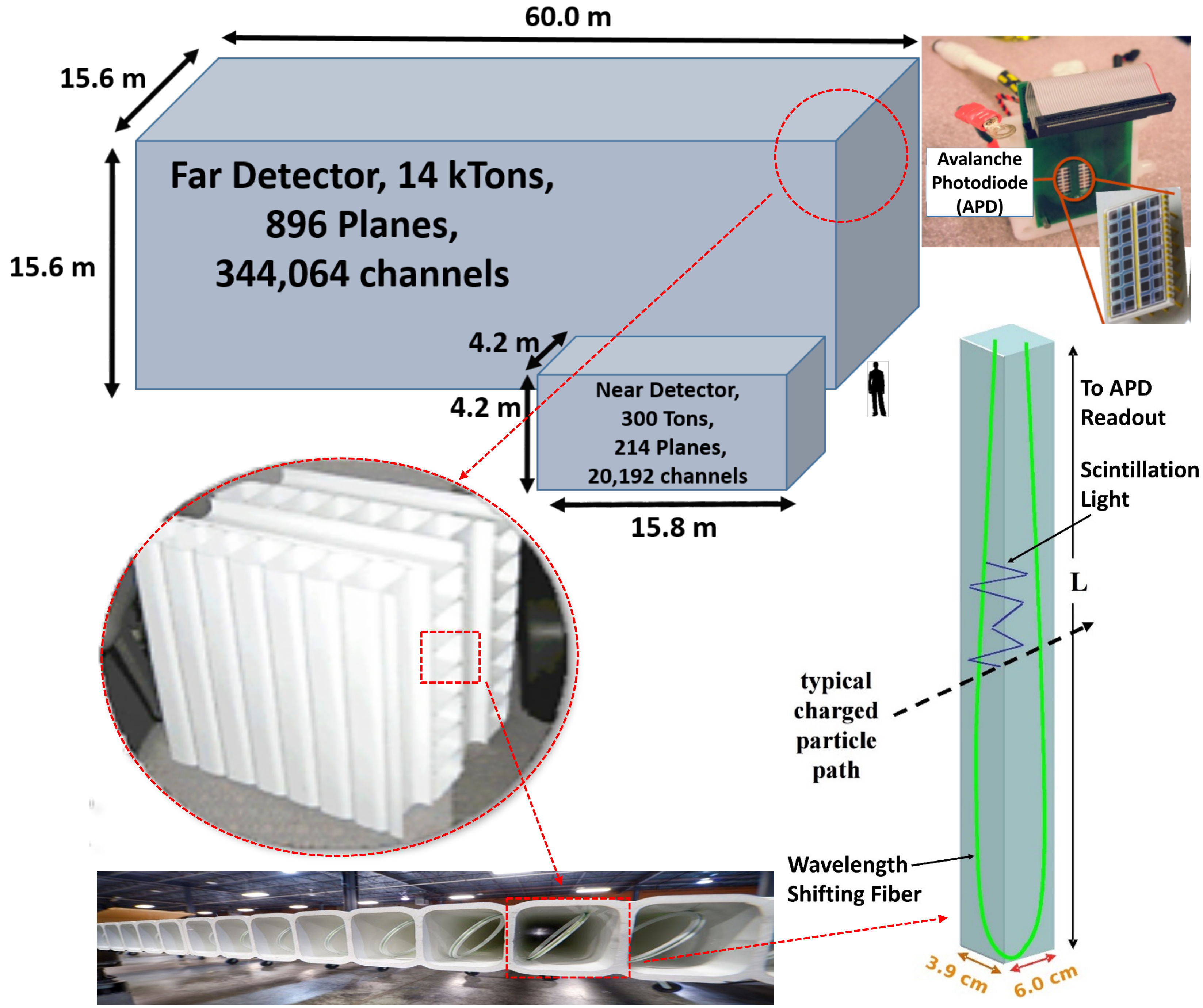
Oscillation channels

- **$\nu_\mu \to \nu_\mu$ disappearance**
- **$\nu_\mu \to \nu_e$ appearance**
- **Anti-neutrino modes**

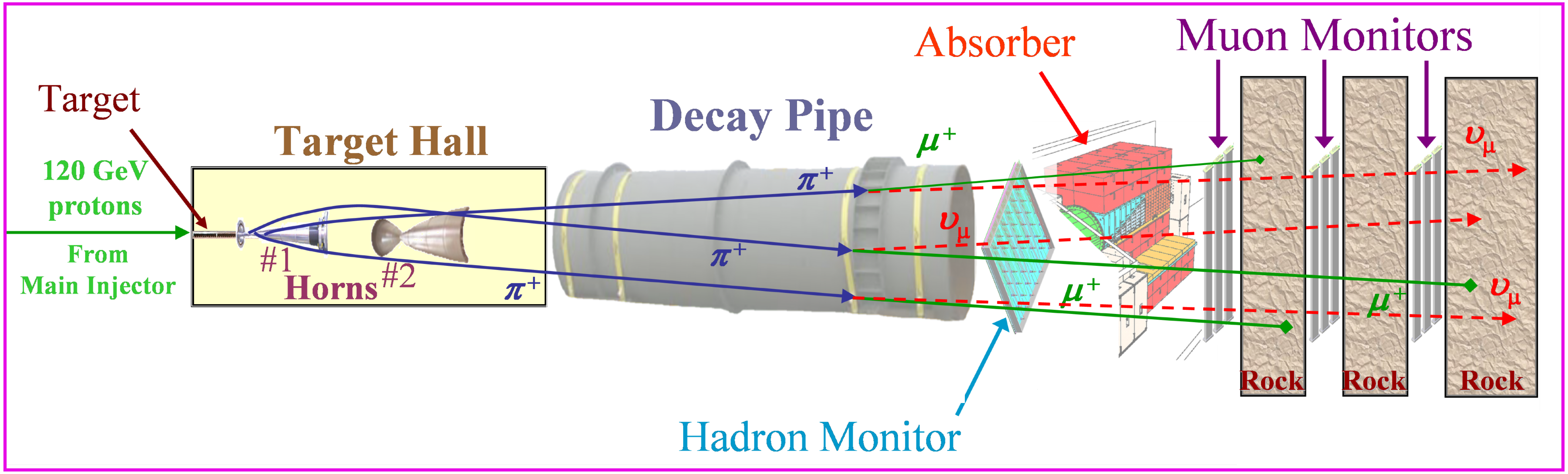
NOvA Detectors

- Identical ND and FD
- Polyvinyl chloride (PVC), liquid scintillator detectors
- 3D reconstruction of tracks using orthogonal planes

- ND measures un-oscillated neutrino beam
- FD measures oscillated beam
- ND predicts signal and background events in FD
- Reduction in systematic uncertainties due to identical detectors



NuMI (Neutrinos at the Main Injector) Neutrino Beam



NuMI beam in the neutrino mode is mostly made up of ν_μ from the muon and kaon decay

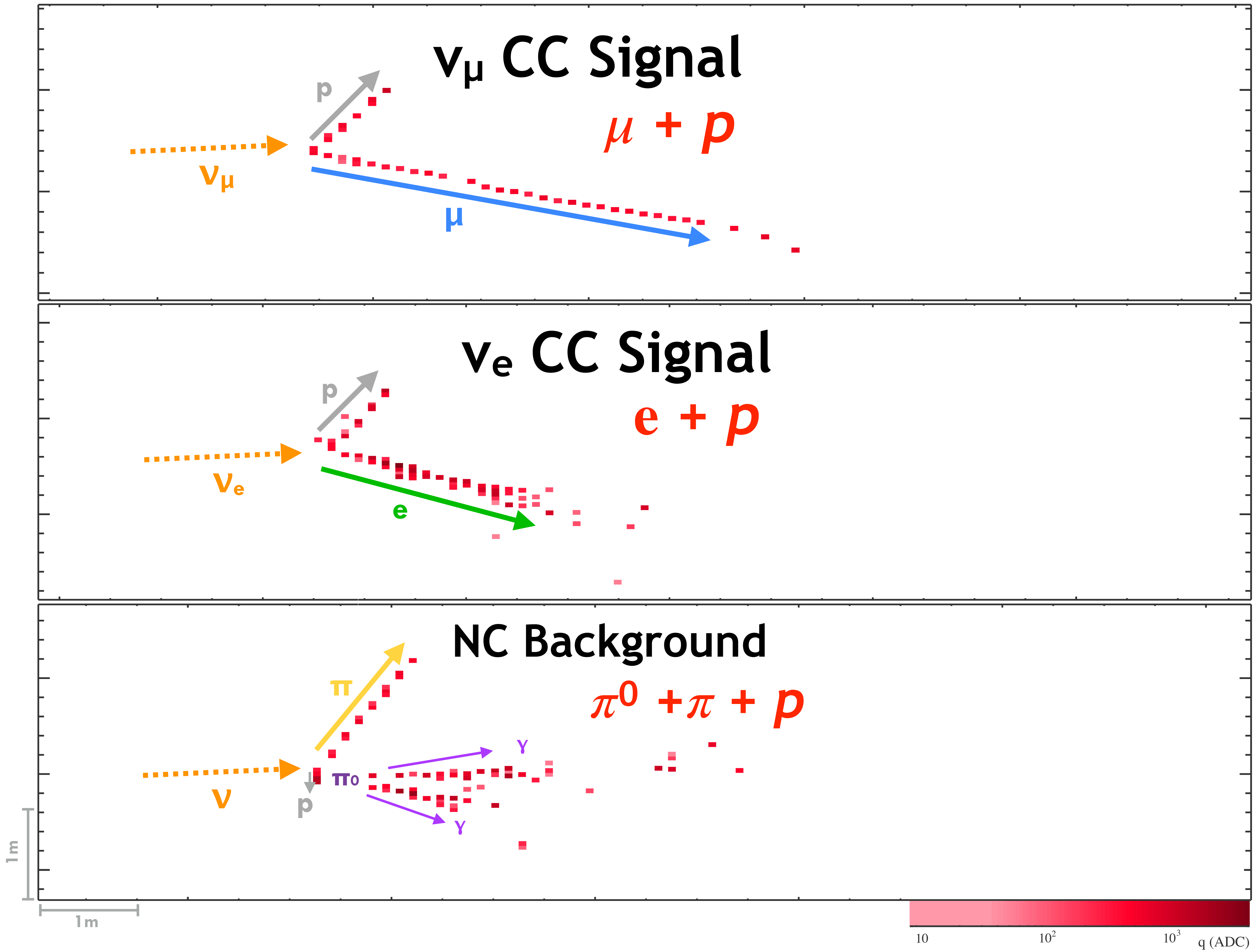
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$K^+ \rightarrow \mu^+ + \nu_\mu \qquad K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

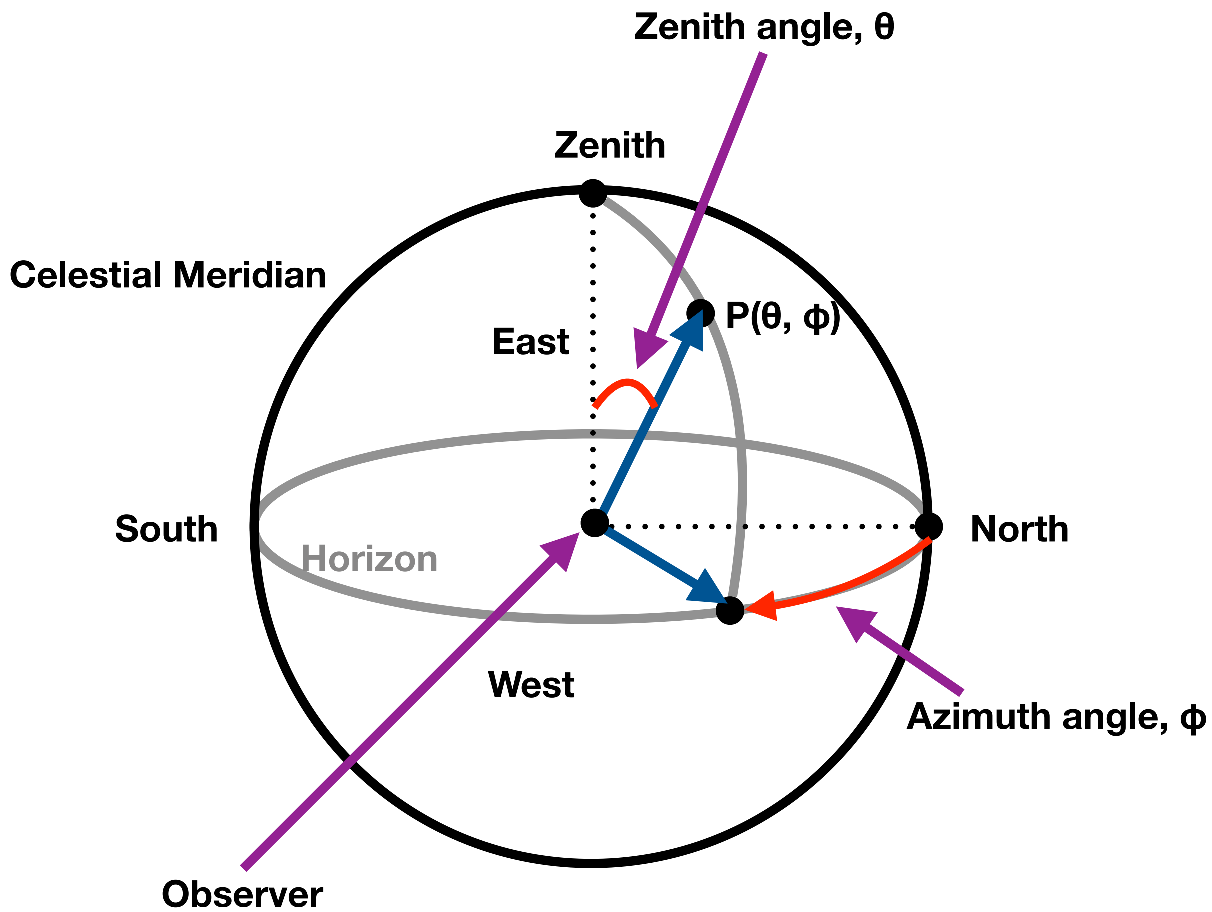
NuMI beam configuration

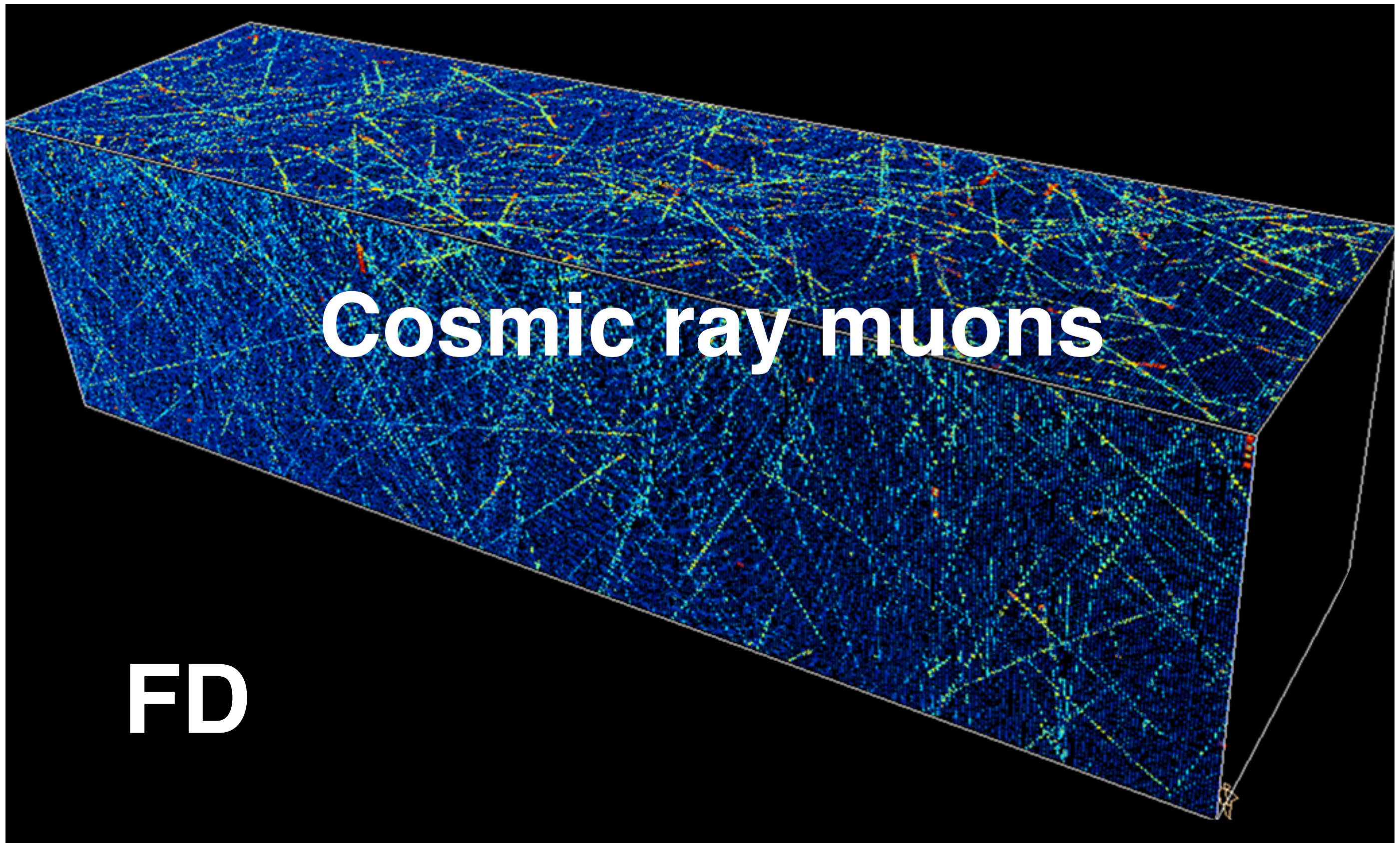
Components	ν_μ	$\bar{\nu}_\mu$	$\nu_e + \bar{\nu}_e$
Neutrino beam	95%	4%	1%
Antineutrino beam	6%	93%	1%

Event Topologies in NOvA



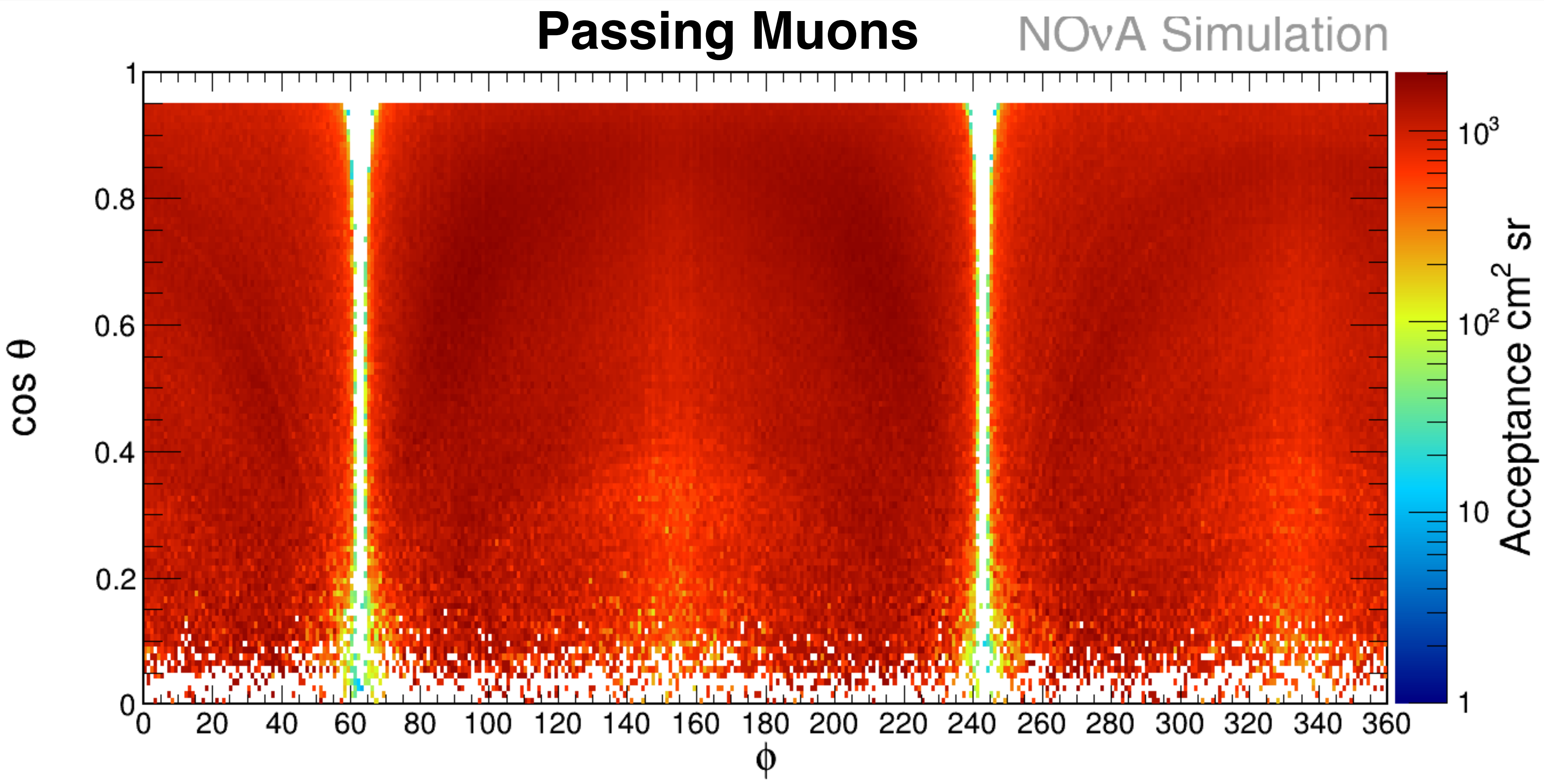
Cosmic Ray Muons

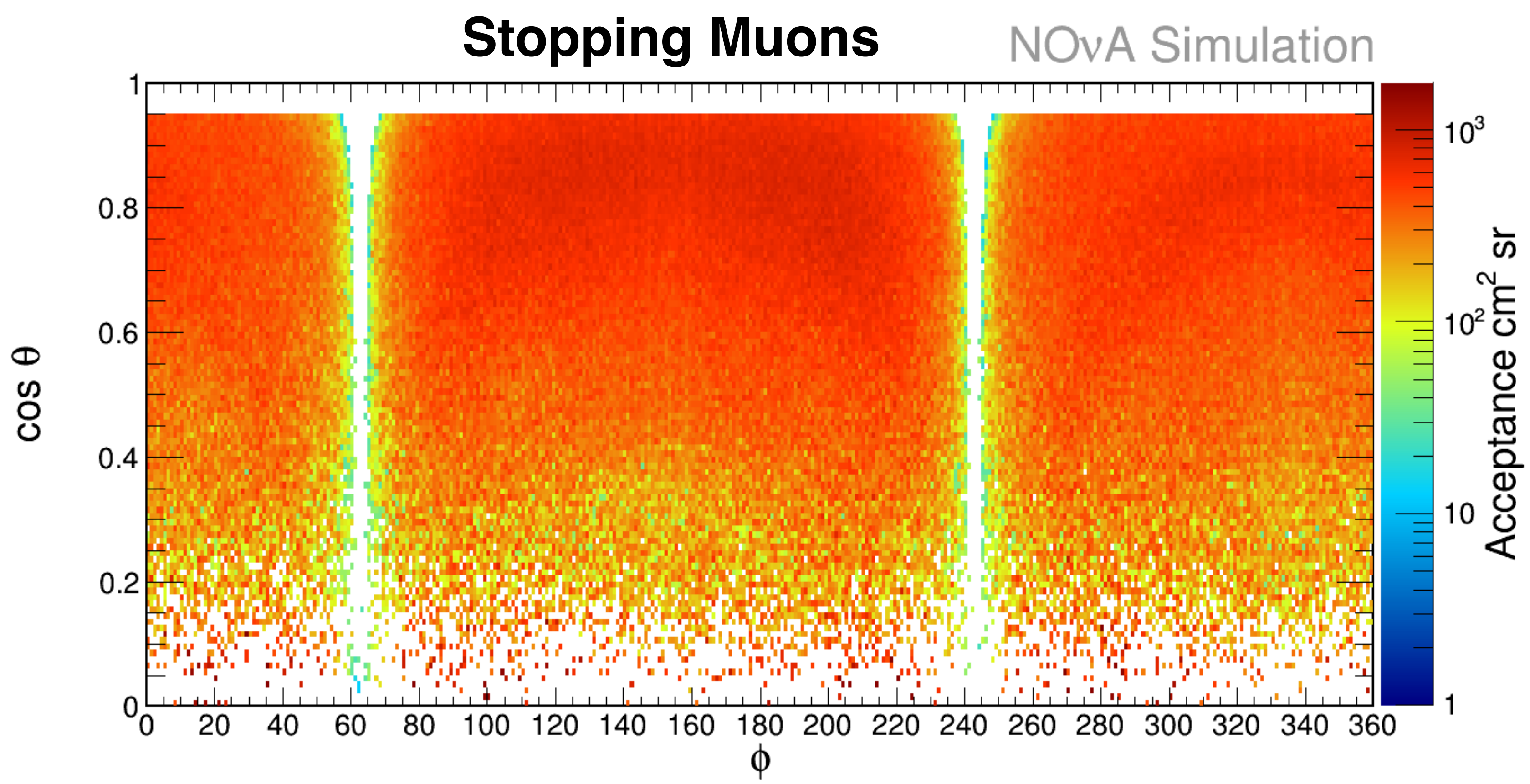




- FD exposed to cosmic ray muons
- Detectors calibrated using cosmic-ray muons
- Acceptance studies optimize cosmic ray selections

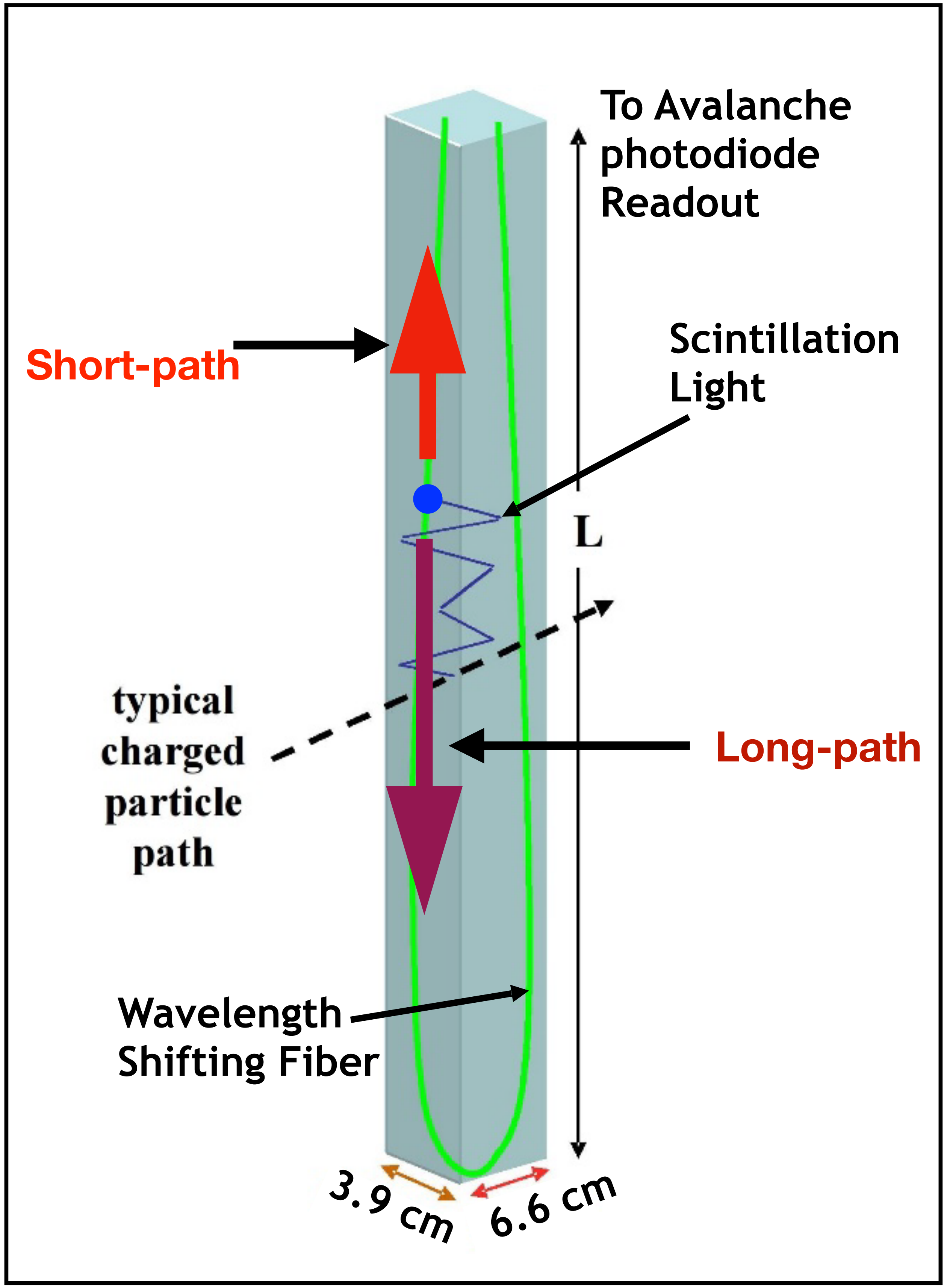
Cosmic Ray Acceptance of the FD





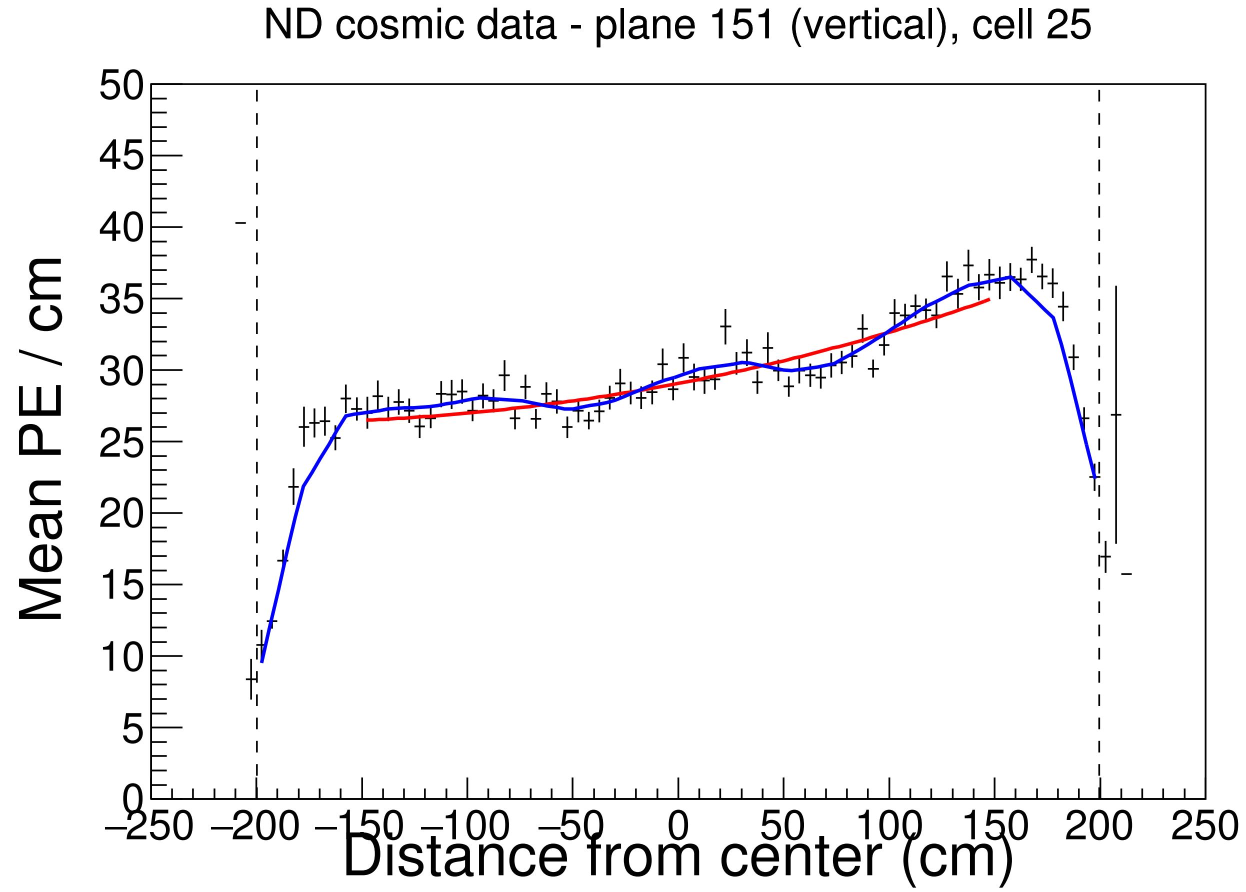
Calibration of the Detectors

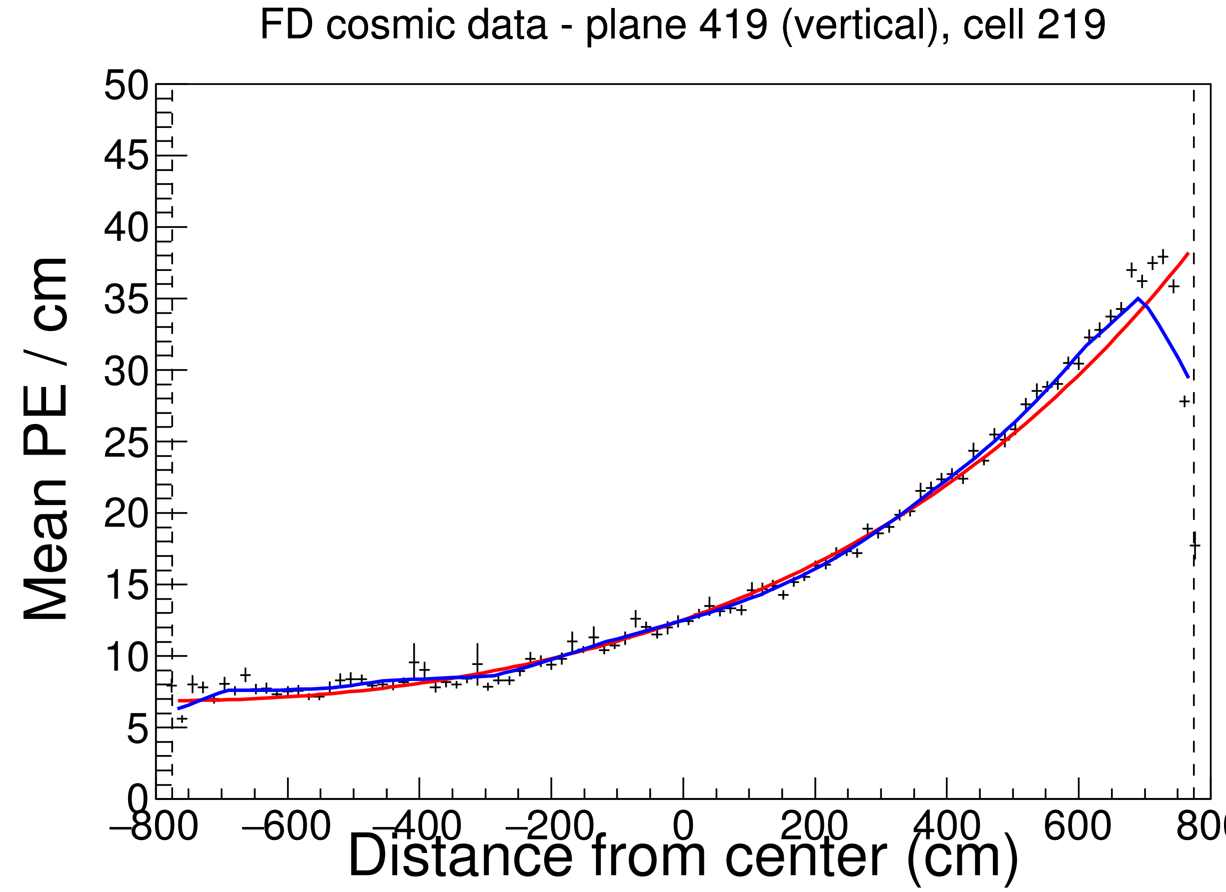
- Charged particle traversing through the scintillator produces scintillation light
- Scintillation light transfer to the APD through fiber
- Attenuation of scintillation light in fiber
- Energy calibration requires attenuation corrections
- Attenuation corrections applied using cosmic-ray muons



Attenuation Fit

Mean photoelectron (PE) per pathlength (cm) in a cell





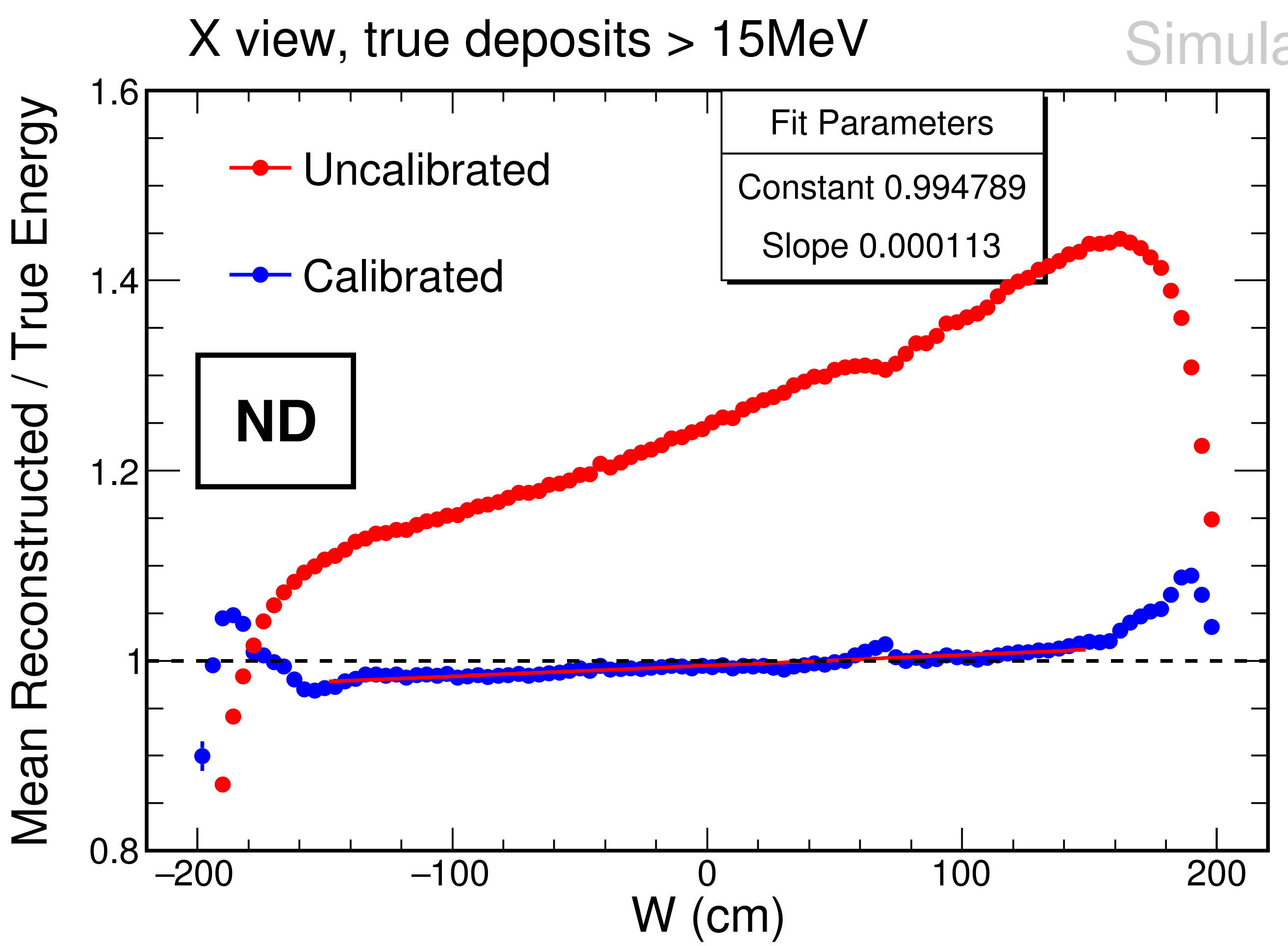
Double exponential fit is performed to the cosmic data for taking into account both short- and long-pathlengths

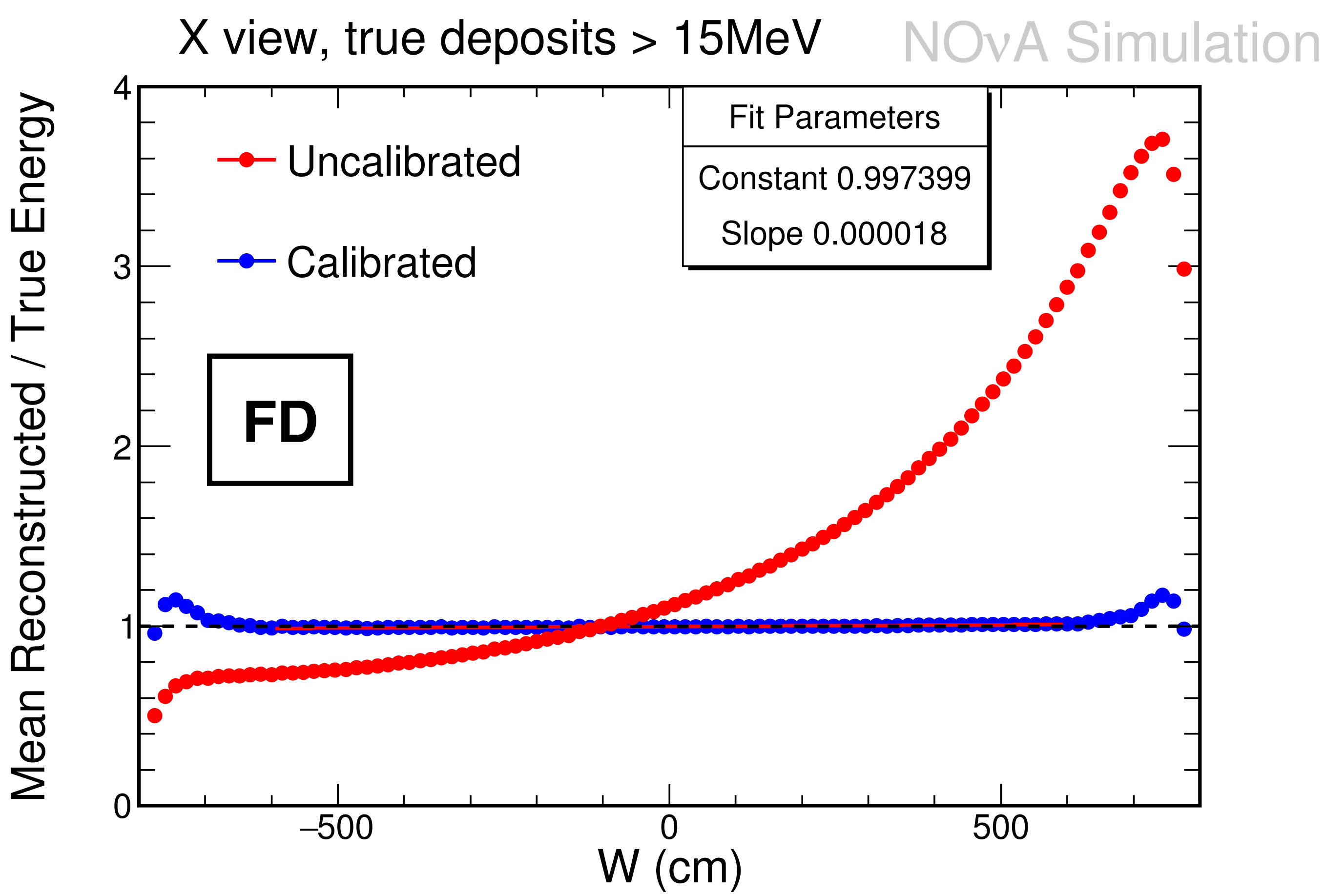
$$y = C + A\left(\exp\frac{W}{X} + \exp\frac{-(W+L)}{X}\right)$$

- **y = cell response**
- **L = length of a cell**
- **W = position in cell**
- **A, C and X are free parameters**

Calibration Performance

Ratios of reconstructed to true energies as a function of position in a cell





- **Detector response is better after calibration**
- **Calibration residuals leads to calibration systematics**
- **Remaining channels uncalibrated due to lack of cosmic data**

Neutrino Oscillation Analysis

- Aim of the oscillation analysis is to measure $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$ and δ_{cp} parameters
- Parameters are extracted by analyzing the $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance data
- Both neutrino and anti-neutrino data is used for the parameter extraction but this seminar only shows the neutrino analysis

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Best fit values of the oscillation parameter are extracted from the χ^2 fit

$$\chi_i^2 = 2 \times \left(F_i^{Pred.} - F_i^{Data} + F_i^{Data} \ln \frac{F_i^{Data}}{F_i^{Pred.}} \right)$$

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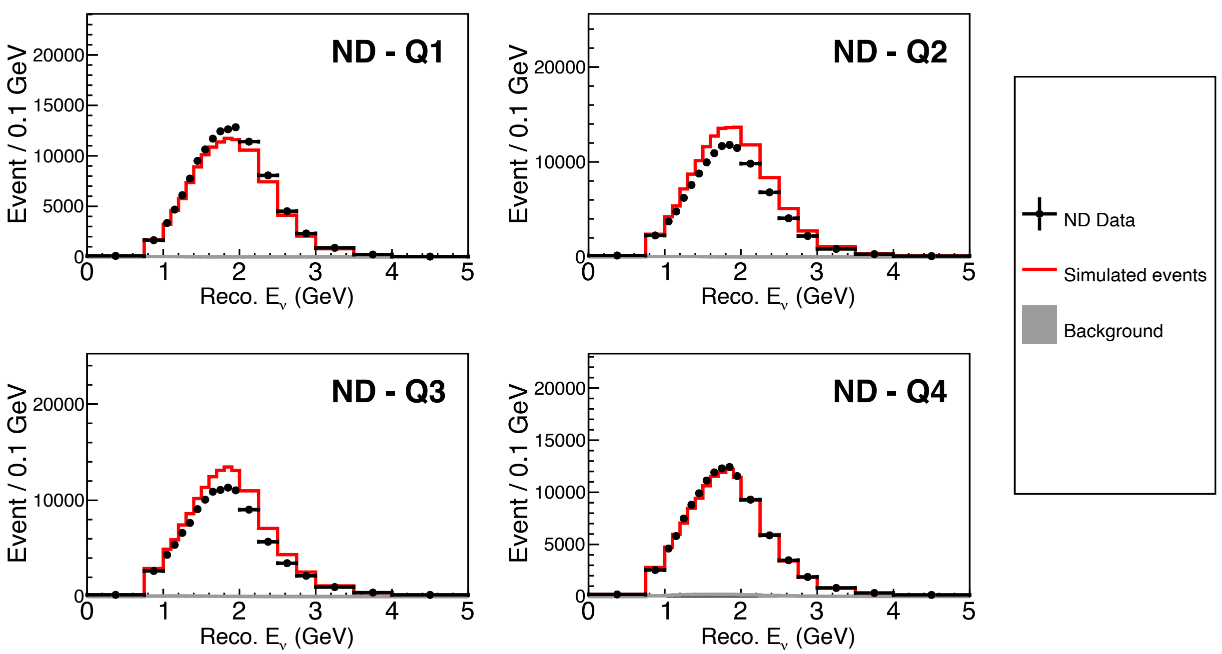
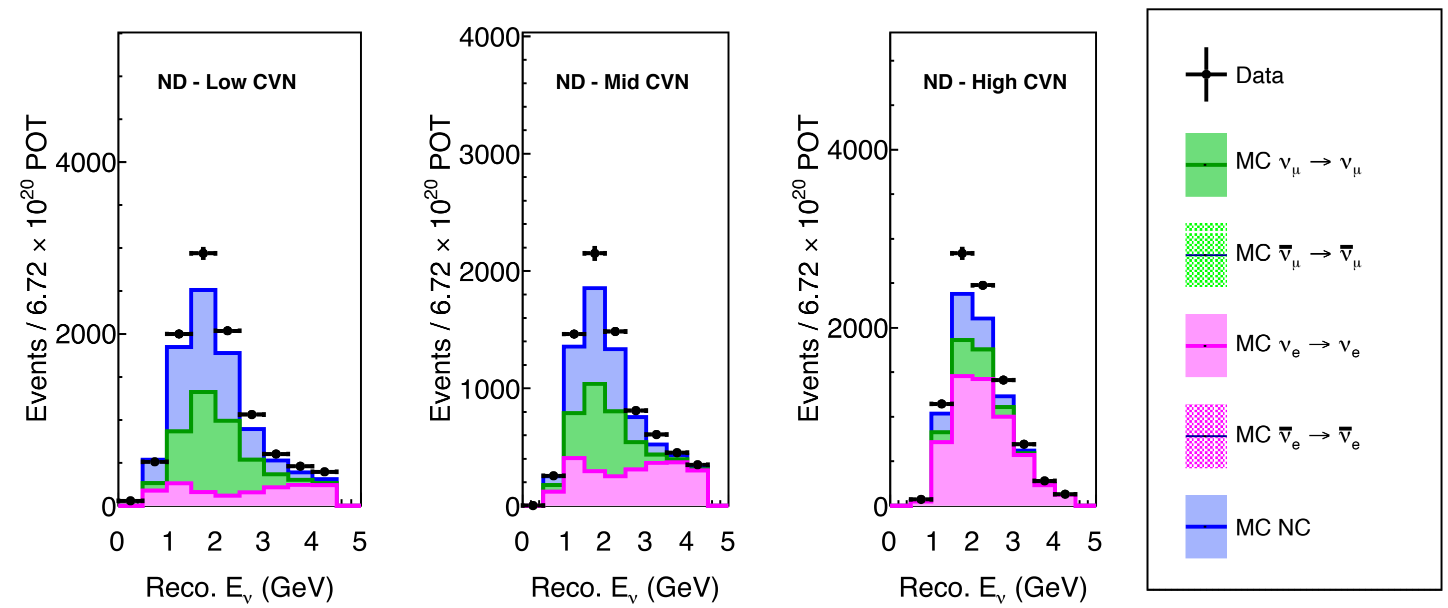
ν_μ Selections



ν_e Selections

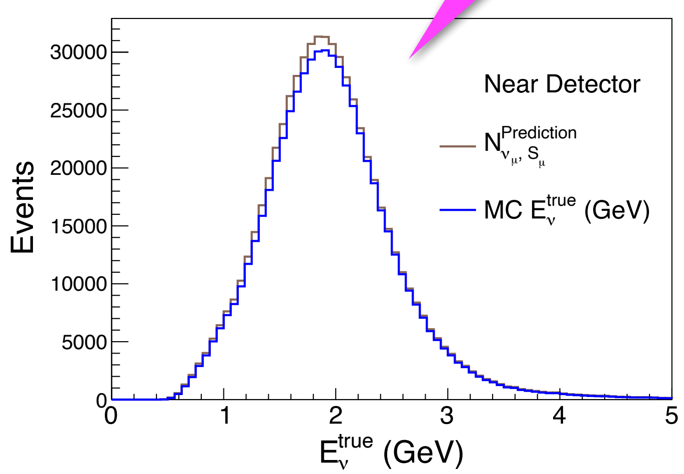


Extrapolation - Constraints from the ND

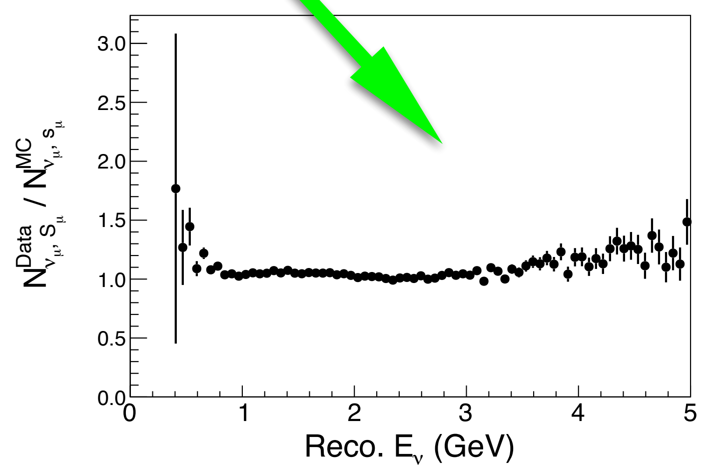
- **Extrapolation: ν_μCC , ν_eCC and NC predictions in FD using ND selected sample**
- **Extrapolation reduces/cancel common systematic uncertainties**

Extrapolation Technique

$$N^{\text{Prediction}}_{\nu_\mu,S_\mu}\left(E_i^{\text{true}}\right) = \sum_{\text{Events with Reco.}}^{\text{Energy in bin k}} \frac{N^{\text{data}}_{\nu_\mu,s_\mu}}{N^{\text{MC}}_{\nu_\mu,s_\mu}}\left(E_k^{\text{reco}}\right)_{\nu_\mu,S_e} \times N^{\text{MC}}_{\nu_\mu,s_\mu}\left(E_i^{\text{true}},E_k^{\text{reco}}\right)$$



$$= \sum_{\text{Events with Reco.}}^{\text{Energy in bin k}}$$



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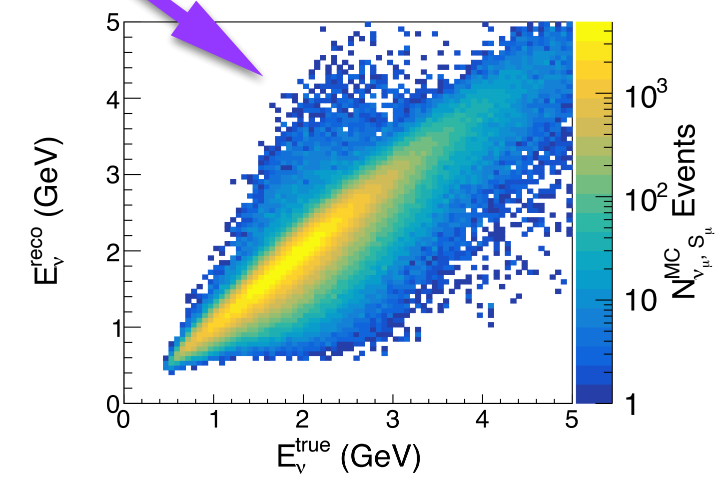
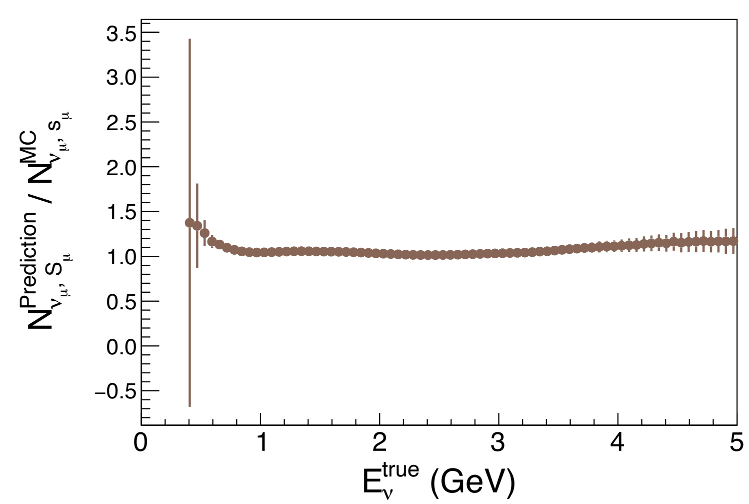


Signal extrapolation weights are

$$R^{\nu_\mu,ND}\left(E_i^{\text{true}}\right) = \frac{N^{\text{pred}}}{N^{\text{MC}}}\left(E_i^{\text{true}}\right)_{\nu_\mu,S_\mu}$$



Total Prediction Extrapolation

Total ν_μ CC signal prediction

$$F^{\text{Prediction}}_{\nu_\mu\to\nu_\mu,S_\mu}\left(E_i^{\text{reco}}\right) = \sum_{\text{Events with Reco.}}^{\text{energy in bin i}} F^{\text{MC}}_{\nu_\mu\to\nu_\mu,S_\mu}(\text{event})\cdot R^{\nu_\mu,ND}\left(E_i^{\text{true}}\right)\cdot P_{\nu_\mu\to\nu_\mu}\left(E^{\text{true}}_{\text{event}}\right)$$

- For ν_e appearance CC signal prediction, $\mathbf{P}_{\nu_\mu\to\nu_\mu}$ oscillation probability is replaced by $\mathbf{P}_{\nu_\mu\to\nu_e}$
- The ND measures beam ν_μ CC, ν_e CC and NC events which constitute beam backgrounds in the FD
- For FD background events prediction only ND Data to MC ratios are used

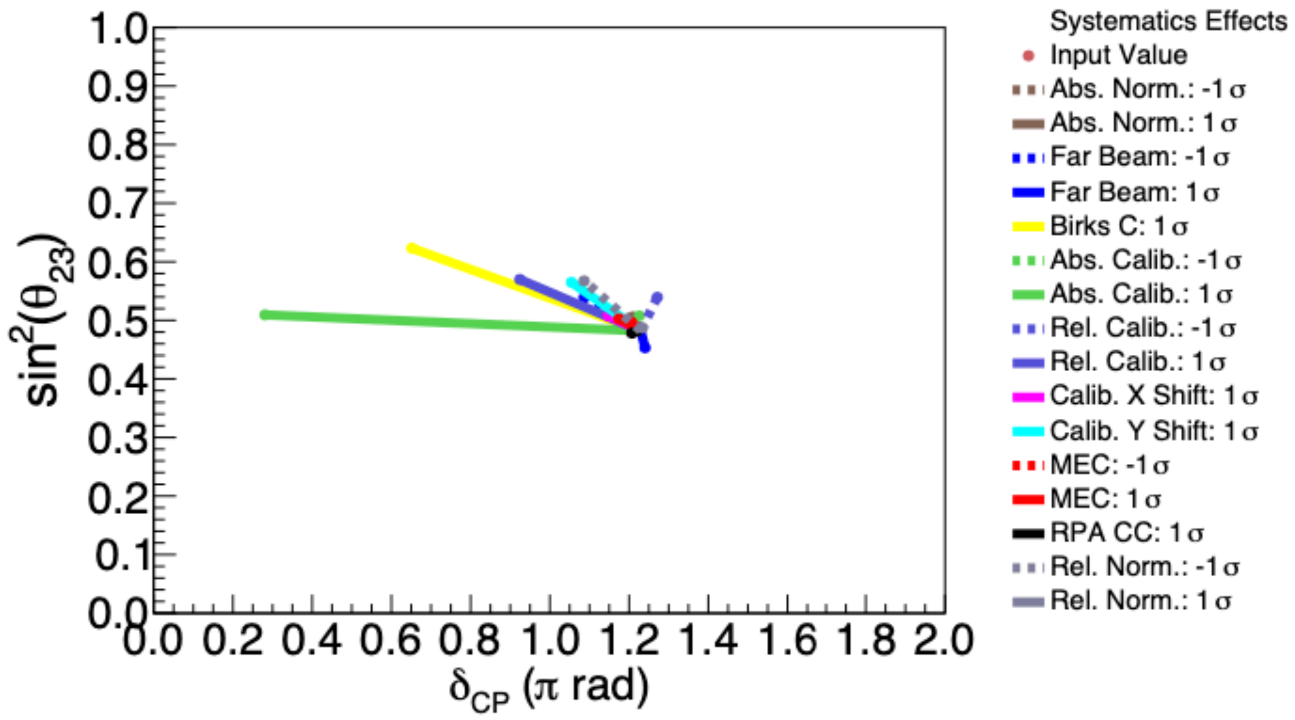
Treatment of Systematic Uncertainties

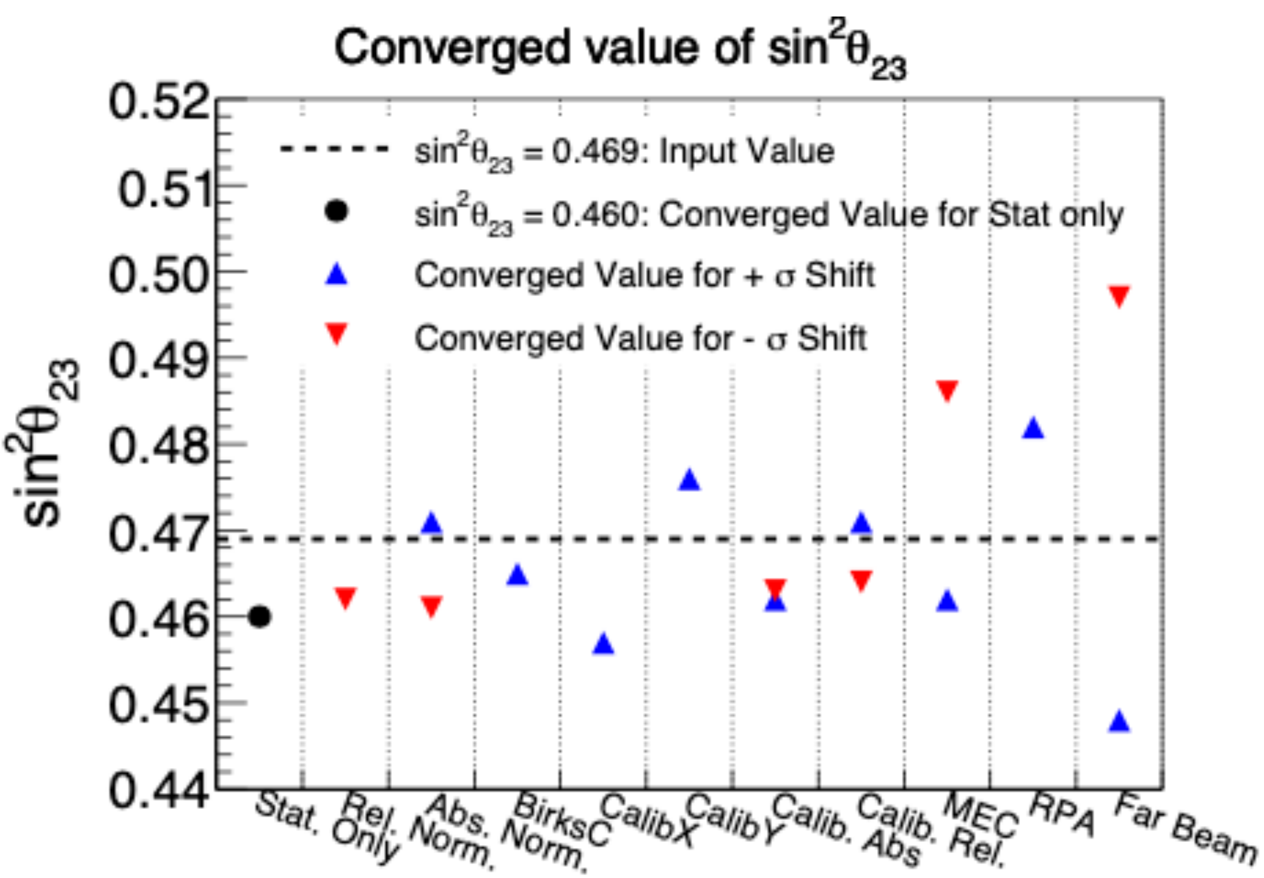
Systematic uncertainties treated as nuisance parameters

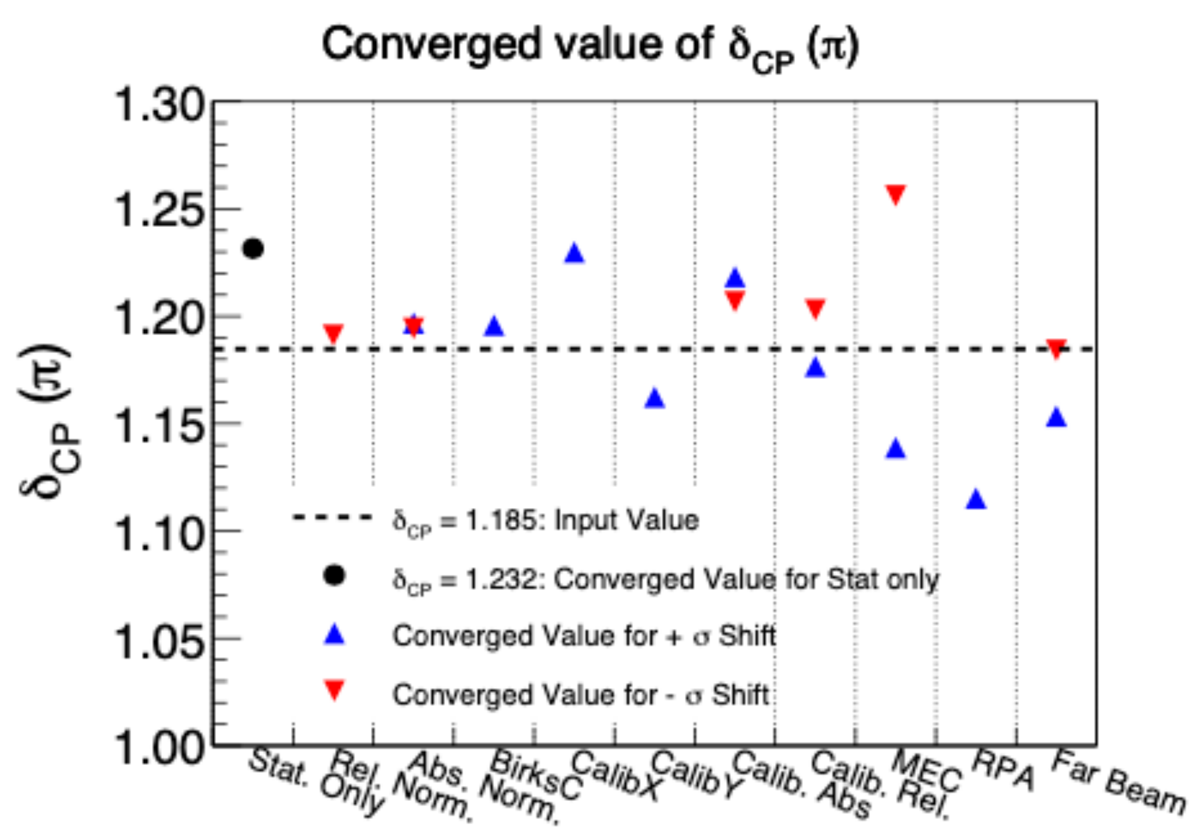
$$\chi^2_{syst} = \sum_j^{syst.} \chi^2_j = \sum_j^{syst.} \frac{(\epsilon_j - <\epsilon_j>)^2}{\sigma^2_{\epsilon_j}}$$

- χ^2_{syst} = sum of contribution from all systematics
- ϵ_j = converged value of j^th systematic uncertainty
- $<\epsilon_j>$ = expected central value for the systematic uncertainty
- $\sigma^2_{\epsilon_j}$ = 1σ uncertainty on central value

Experiment is statistically dominated

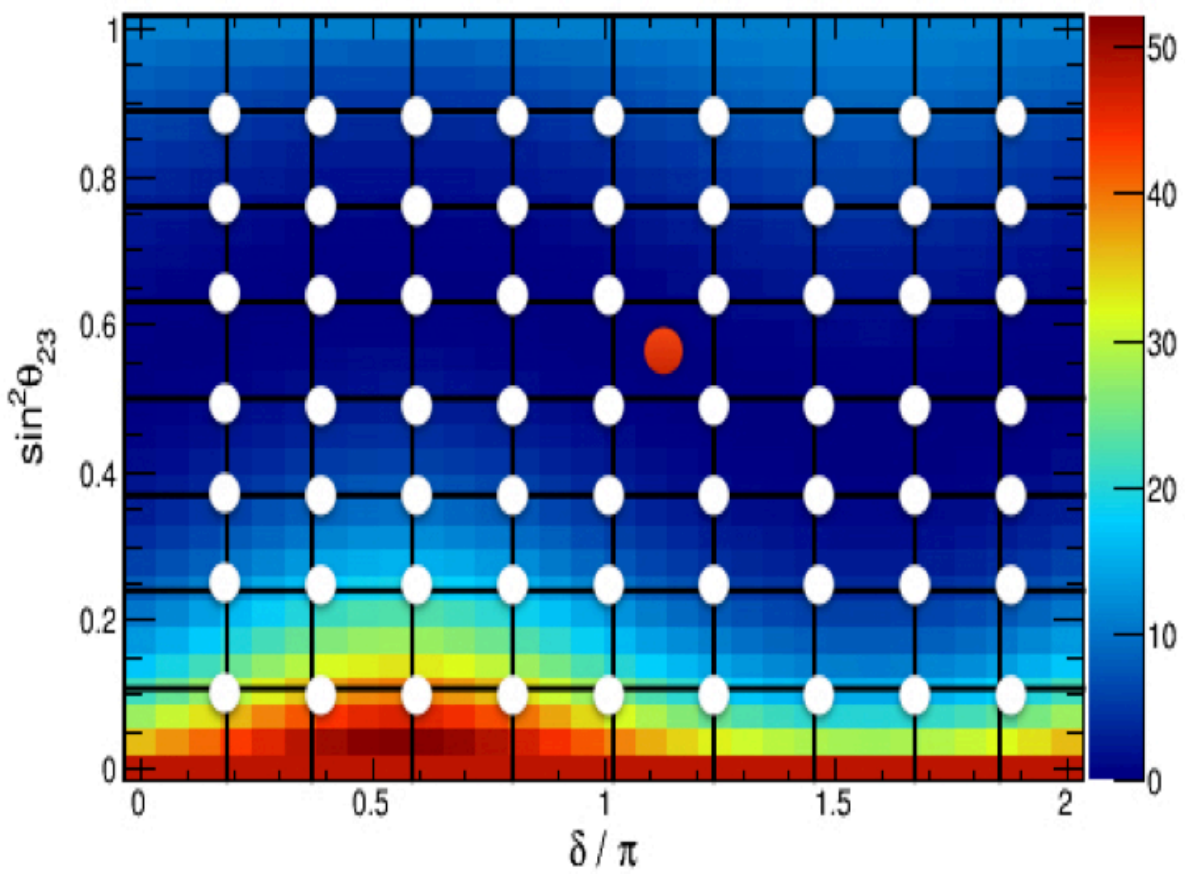






Procedure for Sensitivity Generation

- Sensitivity and contour lines are generated using $\Delta\chi^2$ values
- A grid of points in oscillation space is created
- At each grid point, a fit is run to find χ^2 values
- An overall best-fit point is added to get the minimum χ^2
- At each grid point, $\Delta\chi^2$ is obtained by taking the difference $\chi^2_{Point} - \chi^2_{BF}$
- $\Delta\chi^2 < 2.30$ gives 1σ, $\Delta\chi^2 <$ 6.18 gives 2σ and $\Delta\chi^2 <$ 11.83 makes 3σ lines

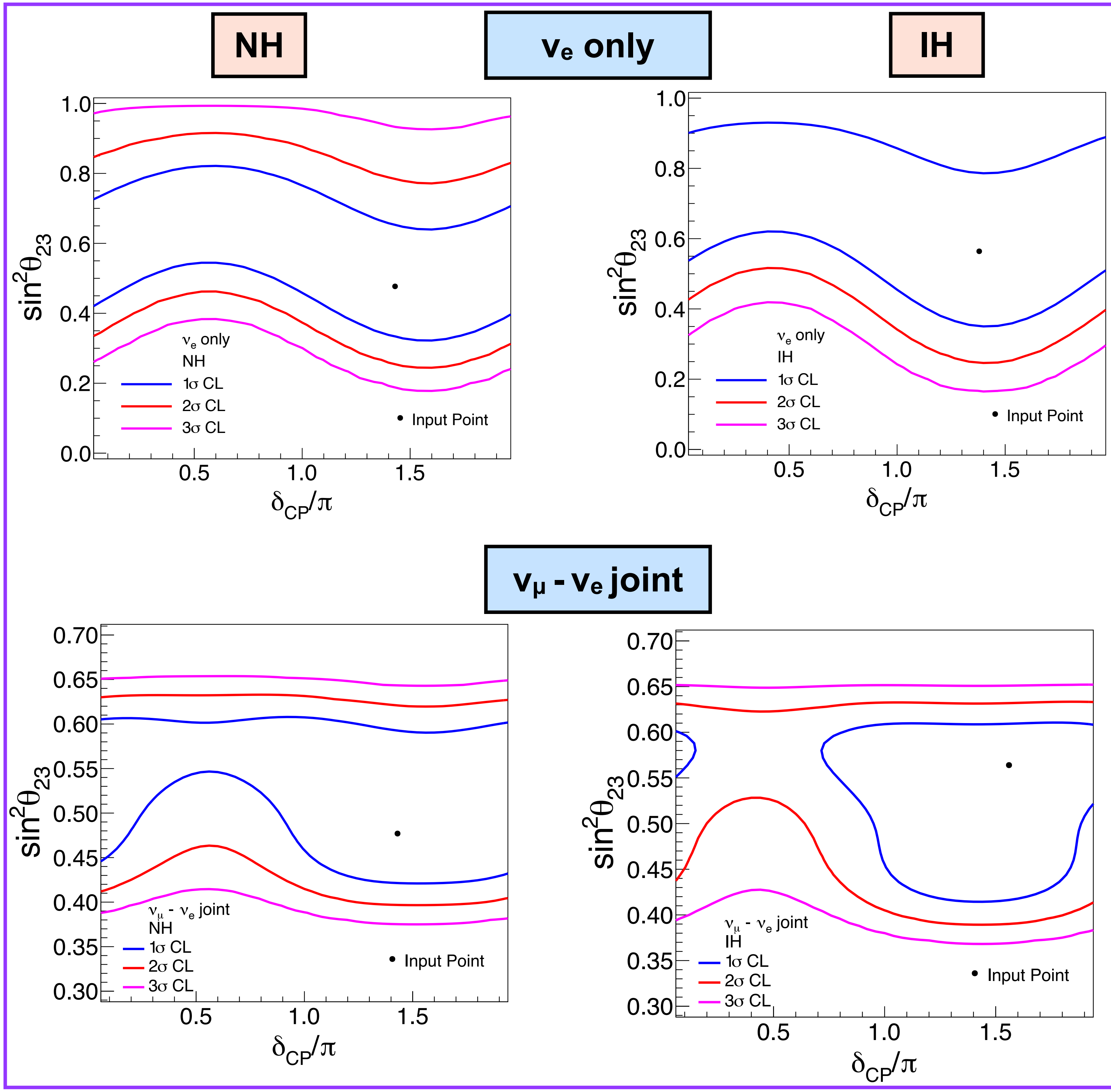


Simulated Physics Sensitivity ($\sin^2\theta_{23}$ - δ_{cp})

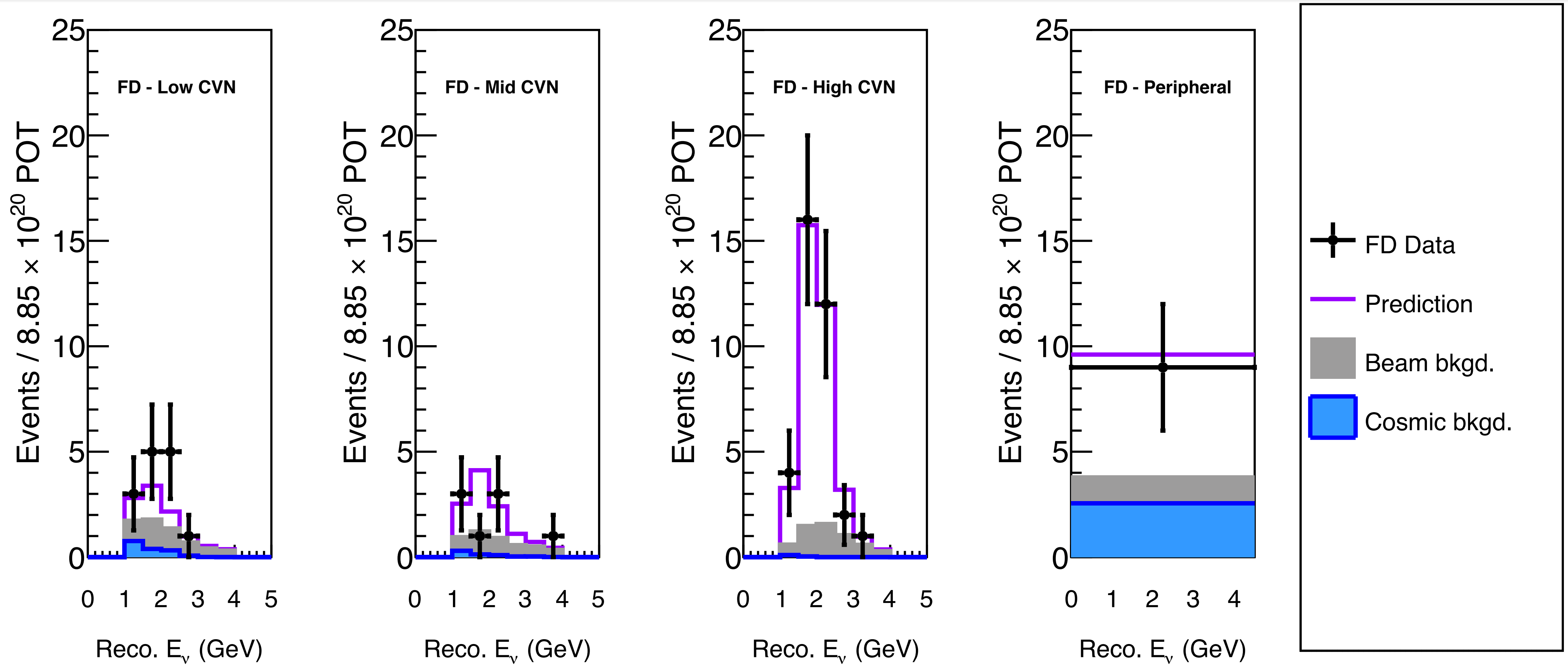
INPUT Points

Oscillation Parameters	ν_e only		ν_μ - ν_e joint	
	NH	IH	NH	IH
Δm^2_{32} (10^{-3}) eV^2/c^4	2.43	-2.50	2.43	-2.50
$\sin^2\theta_{23}$	0.48	0.55	0.48	0.56
δ_{cp} (π)	1.44	1.38	1.44	1.56

Physics sensitivities are generated before analyzing FD data events

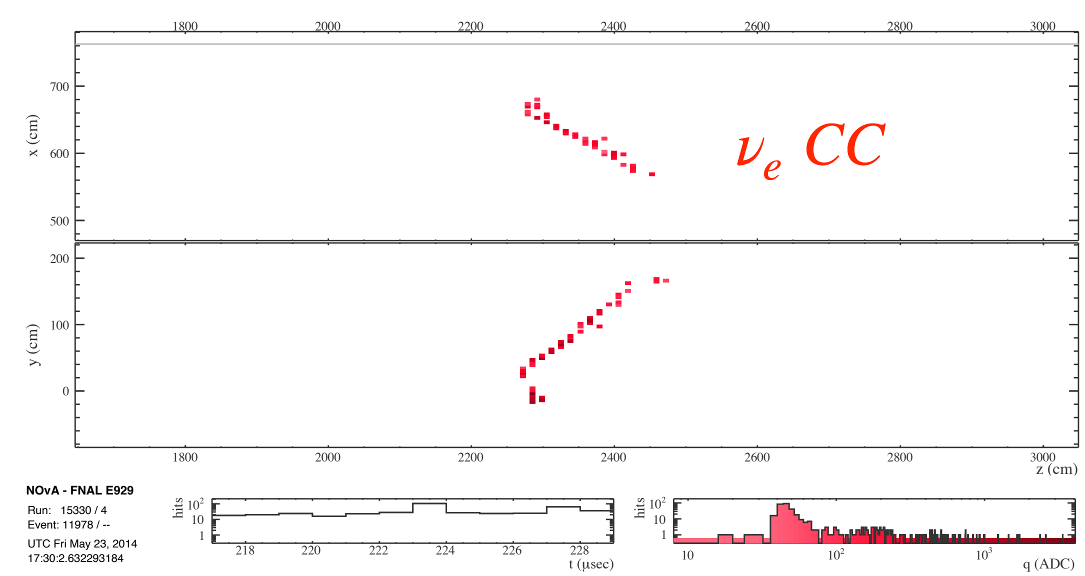


Oscillation Fit to the ν_e Appearance FD Data

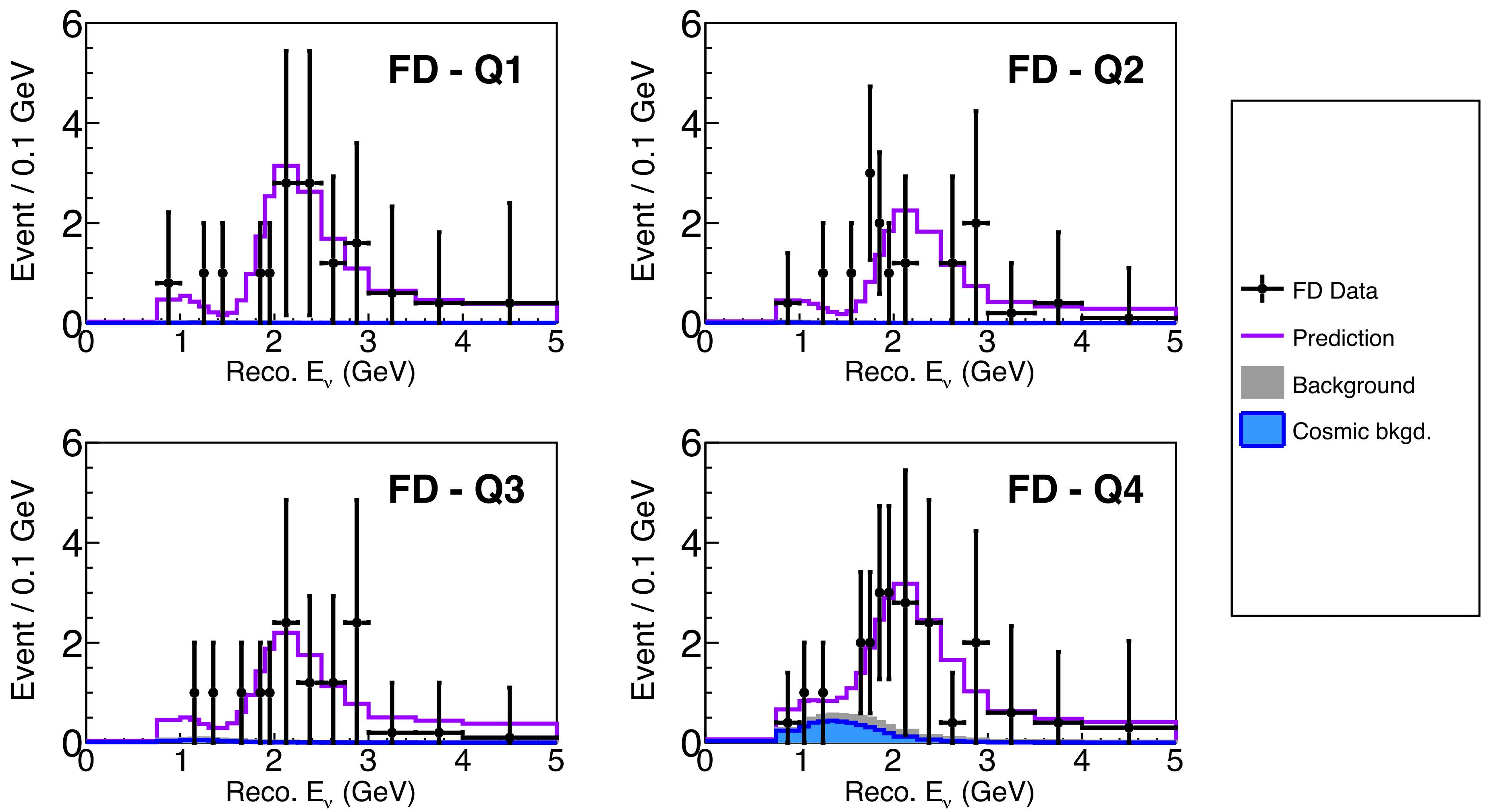


Components	Events
Data	**66**
Signal	46.65
Beam bkgd. (CC)	9.13
Beam bkgd. (NC)	6.10
Cosmic ray bkgd.	4.81
Total signal + background Prediction	**66.70**

Total prediction and data are consistent

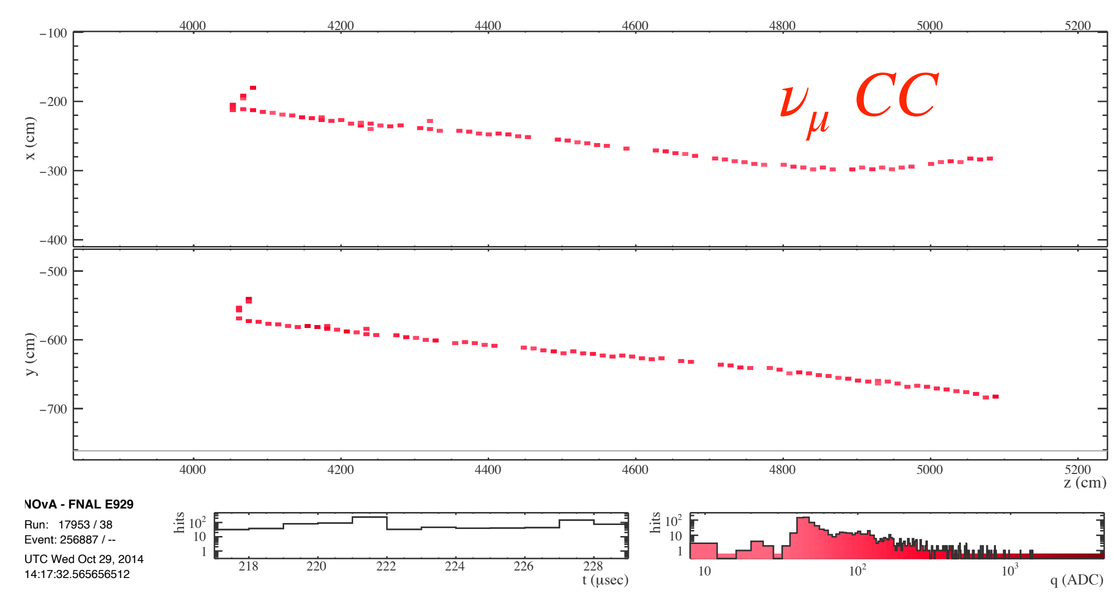


Oscillation Fit to the ν_μ Appearance FD Data



Components	Events
Data	**126**
Signal	138.05
Beam bkgd. (CC)	0.84
Beam bkgd. (NC)	2.59
Cosmic ray bkgd.	5.82
Total signal + background Prediction	**147.3**

Total prediction and data are consistent

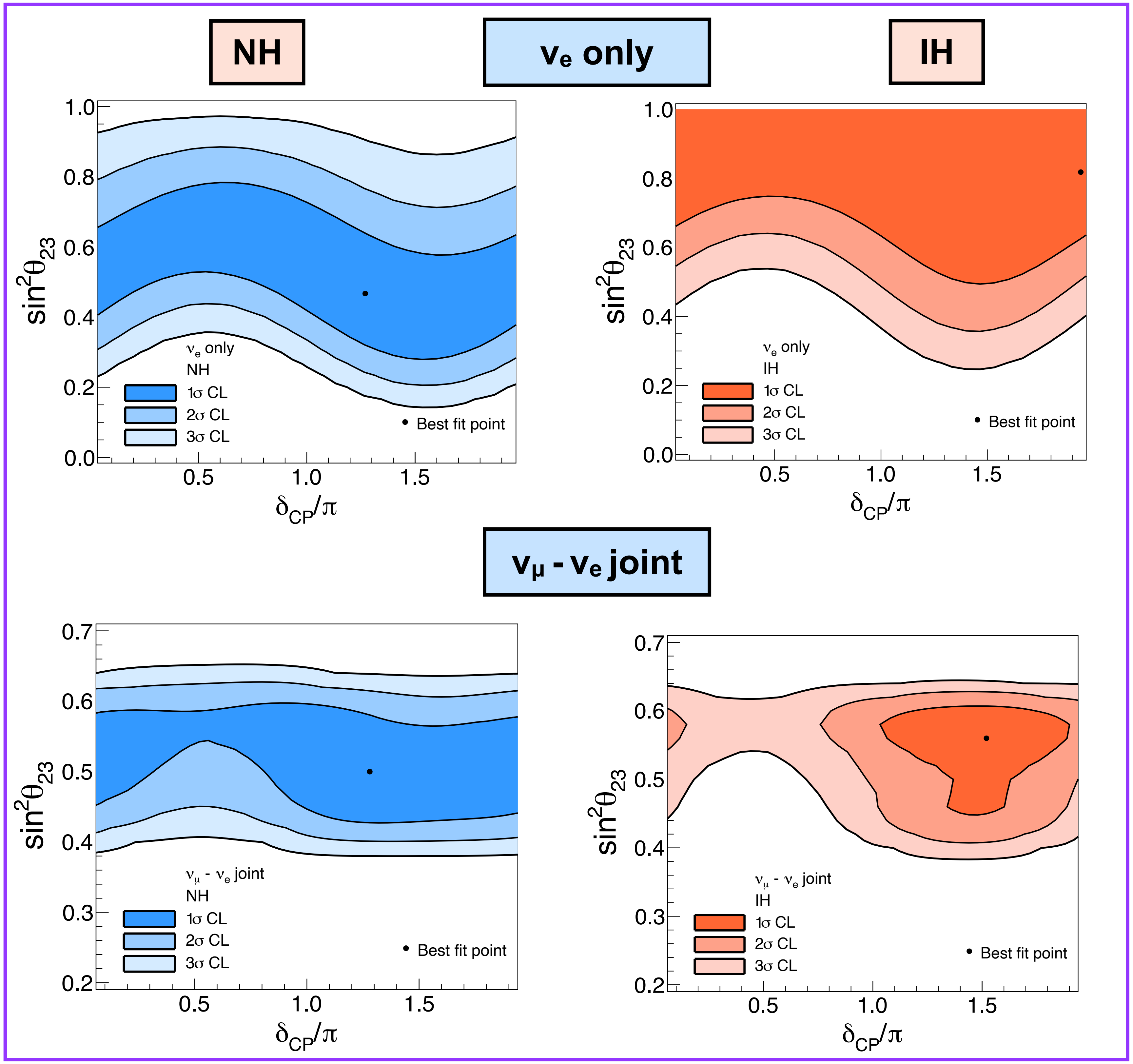


Contour Results ($\sin^2\theta_{23}$ - δ_{cp})

Best Fit Point (BFP)

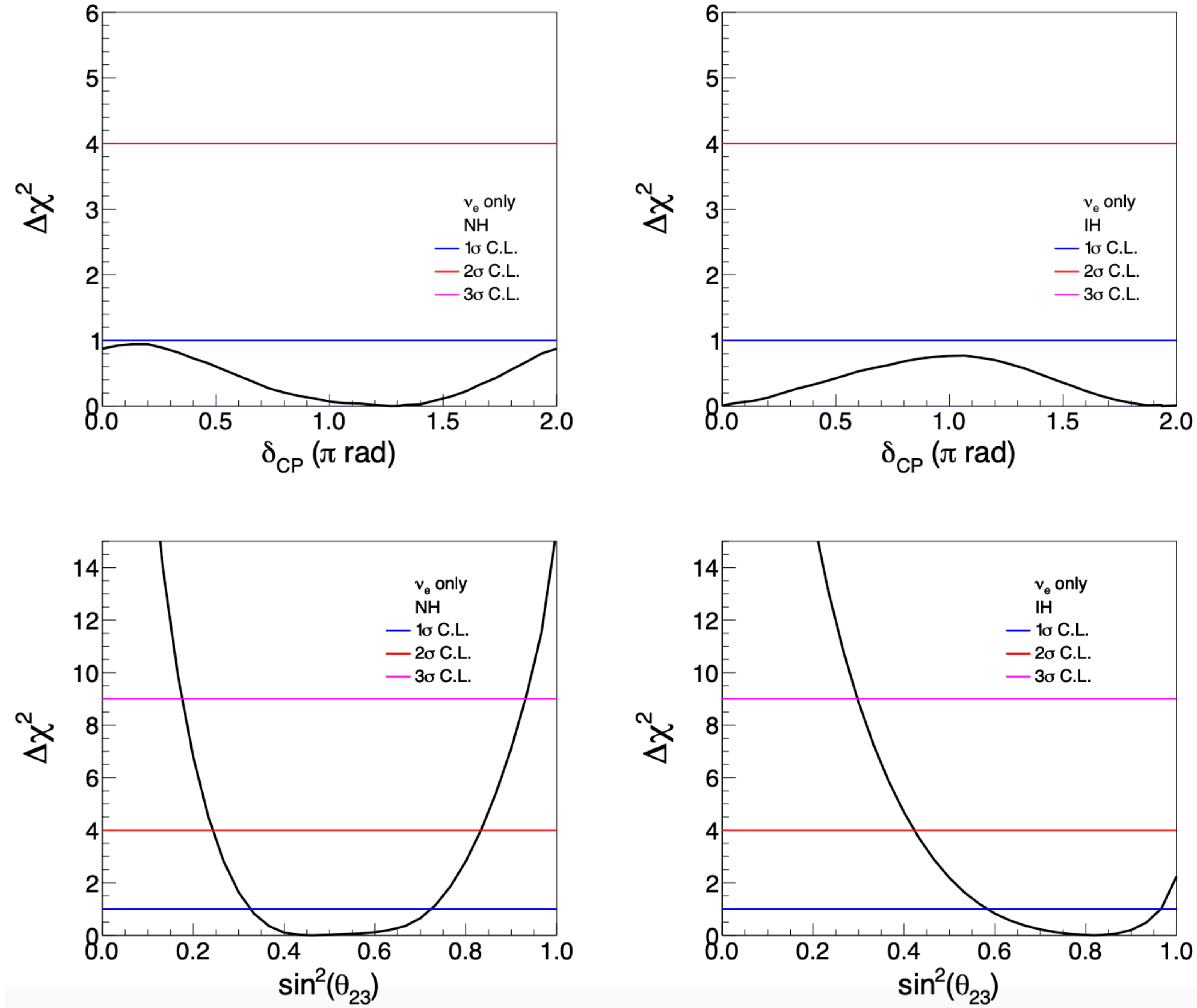
Oscillation Parameters	ν_e only		ν_μ - ν_e joint	
	NH	IH	NH	IH
Δm^2_{32} (10^{-3}) eV^2/c^4	2.43	-2.48	2.35	-2.50
$\sin^2\theta_{23}$	0.47	0.82	0.50	0.56
δ_{cp} (π)	1.27	1.94	1.28	1.52

- Non-zero δ_{cp} value
- θ_{23} consistent with maximal mixing for NH for ν_e only and NH, IH for the ν_μ - ν_e joint
- Preference to normal mass hierarchy



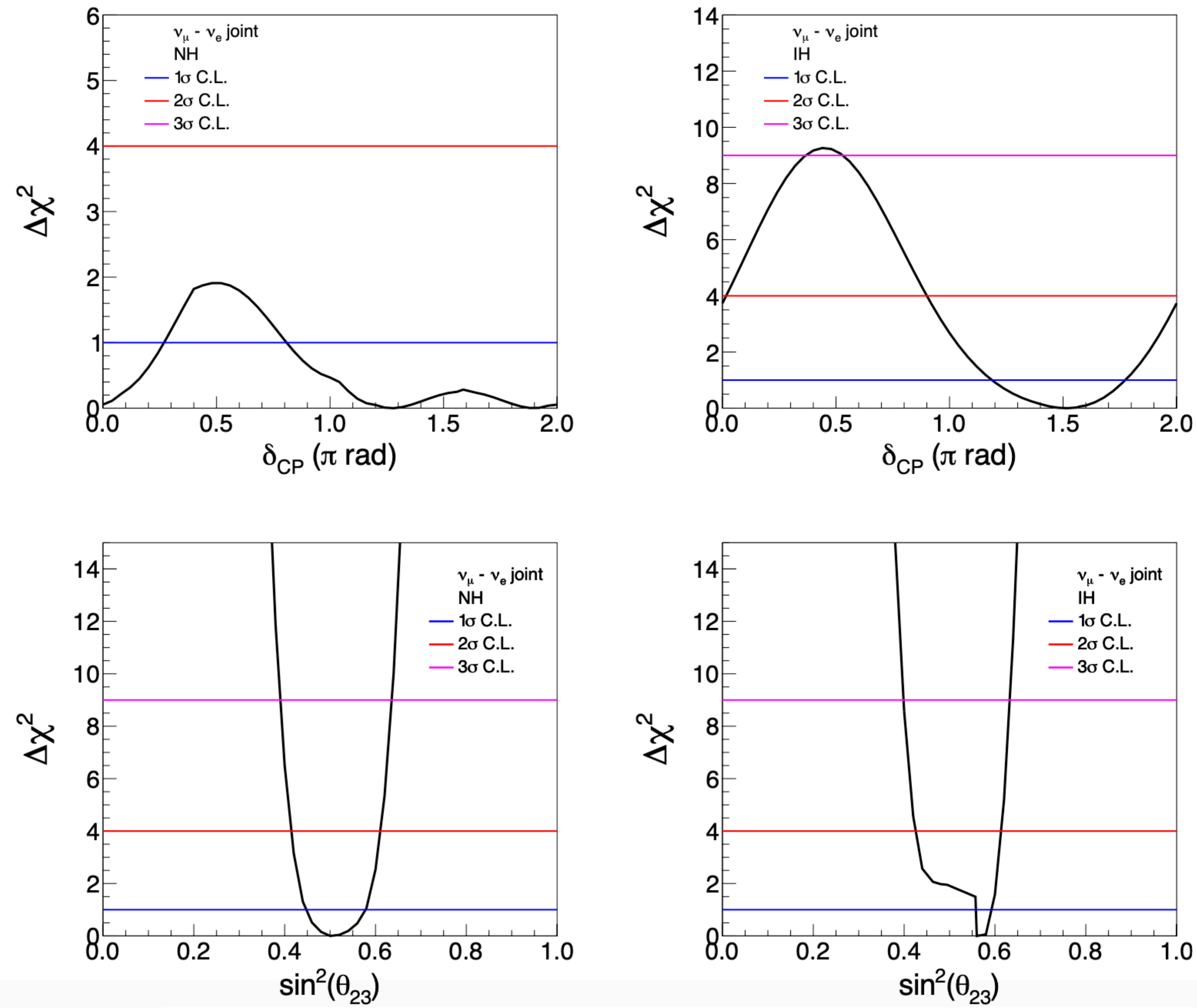
1D Contours for ν_e-Only

- **Marginalize parameters for 1D contours**



Parameters	1σ confidence intervals	
	Normal hierarchy	Inverted hierarchy
$\sin^2\theta_{23}$	[0.33, 0.72]	[0.58, 0.97]
δ_{cp} (π)	[0, 2]	[0, 2]

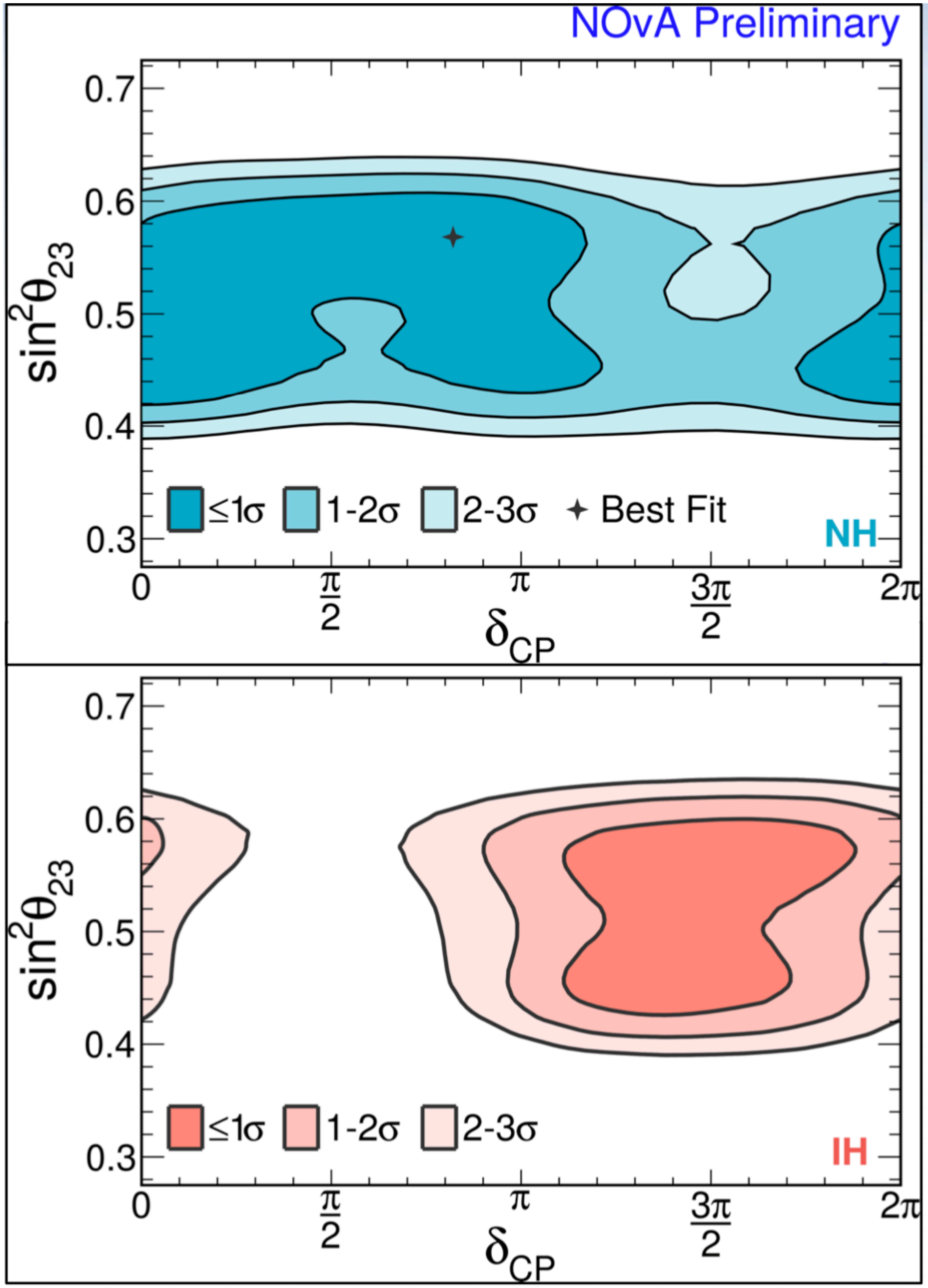
1D Contours for $\nu_\mu - \nu_e$ Joint Fit

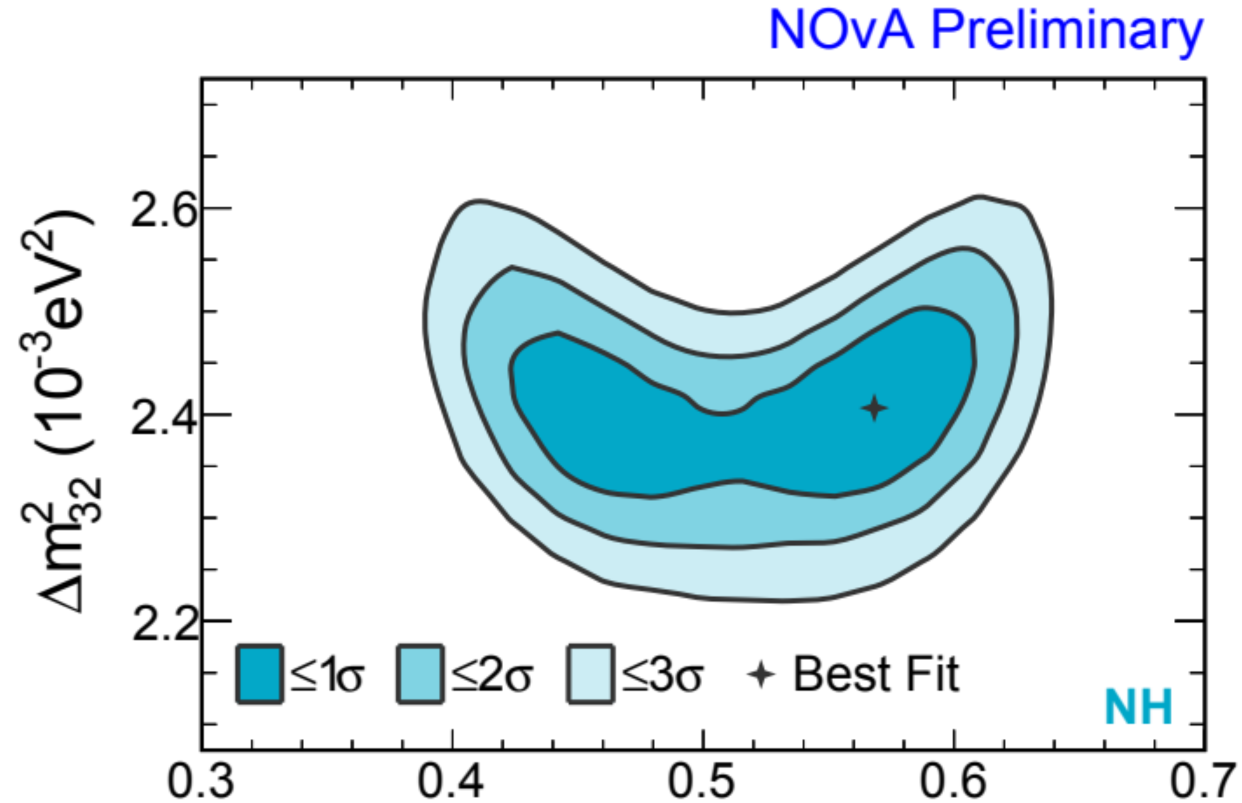


- **Joint fit is more powerful in constraining the oscillation space**
- **Joint fit is also useful in searches of δ_{cp} values**

Parameters	1σ confidence intervals	
	Normal hierarchy	Inverted hierarchy
$\sin^2\theta_{23}$	[0.45, 0.58]	[0.56, 0.59]
δ_{cp} (π)	[0, 0.27], [0.81, 2.0]	[1.19, 1.77]

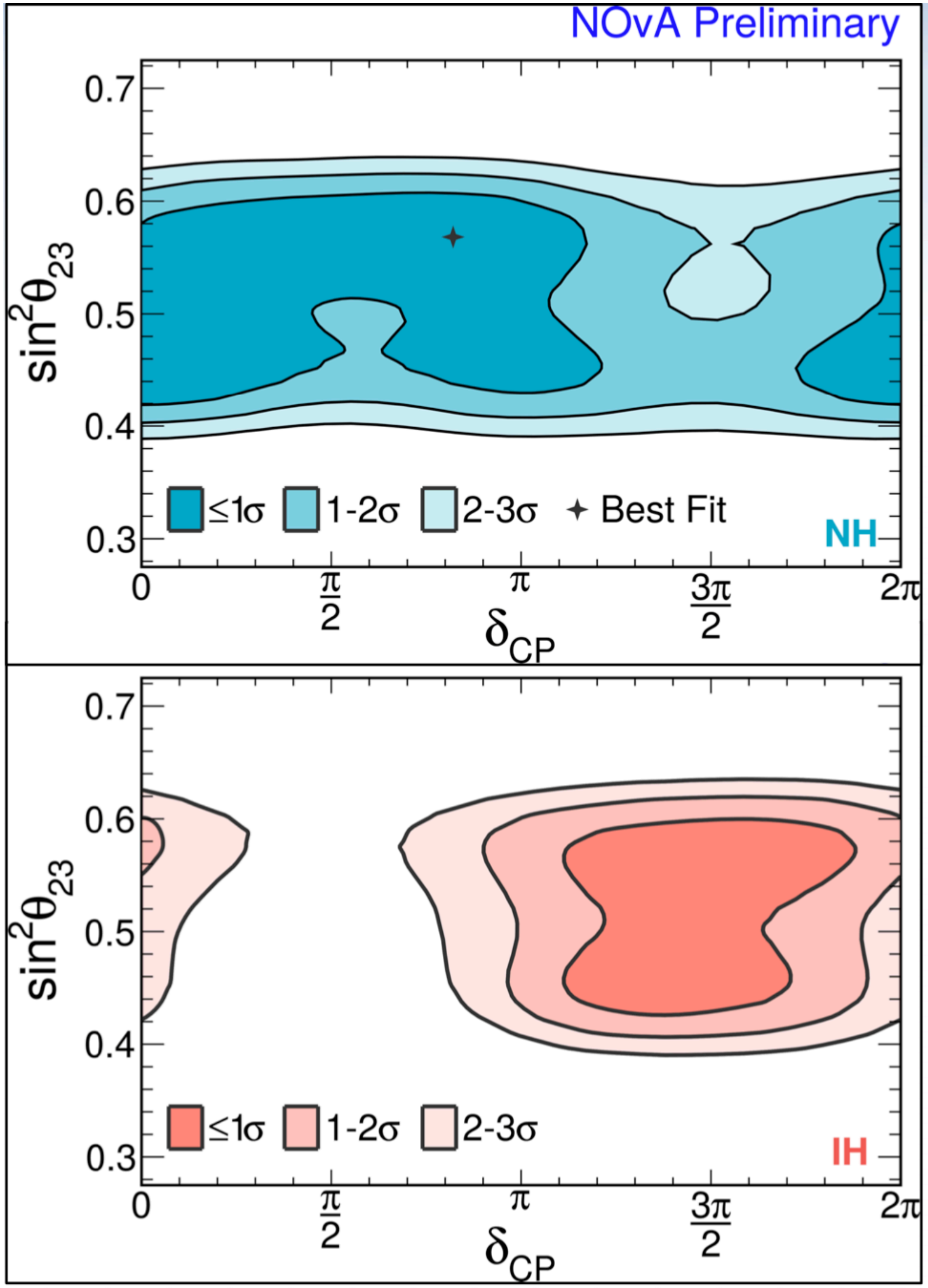
Current Status

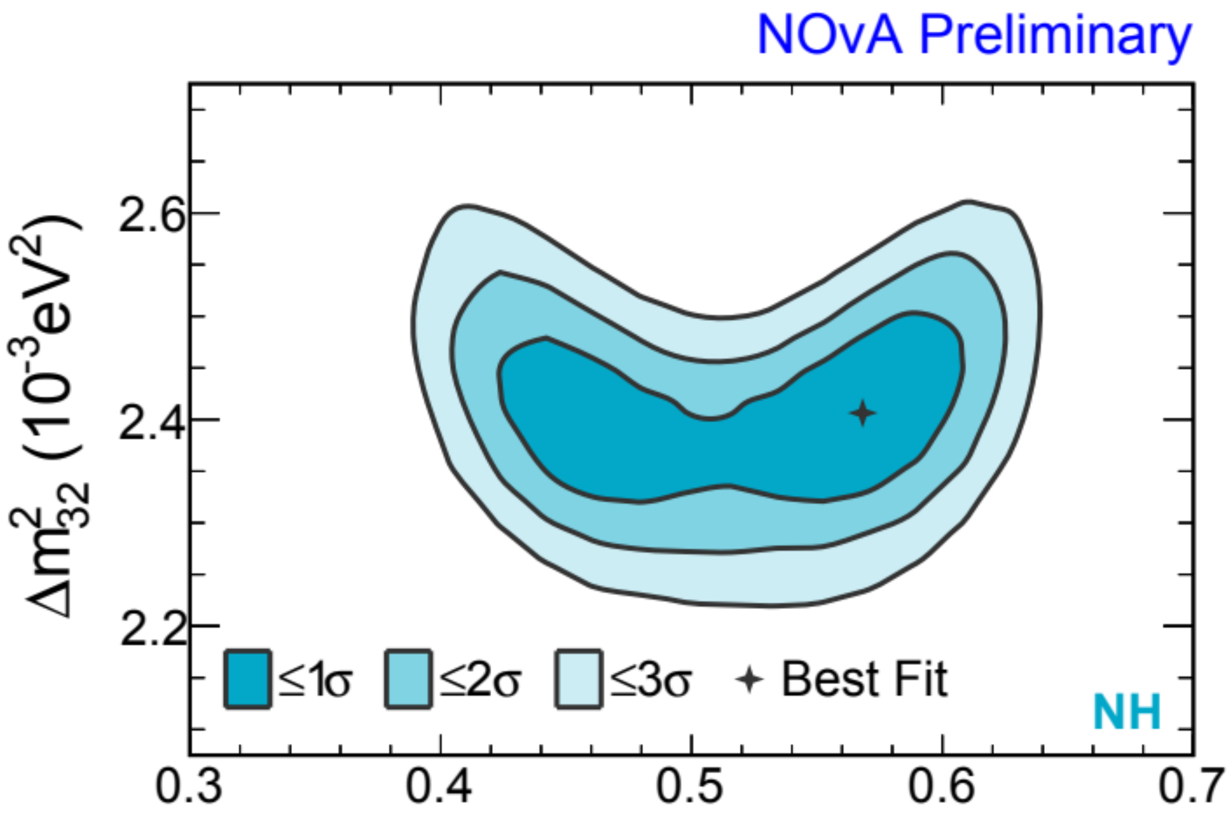




Oscillation Parameters	Values
Δm^2_{32} (10^{-3}) eV^2/c^4	2.41 ± 0.07
$\sin^2\theta_{23}$	$0.57^{+0.04}_{-0.03}$
δ_{cp} (π)	0.82

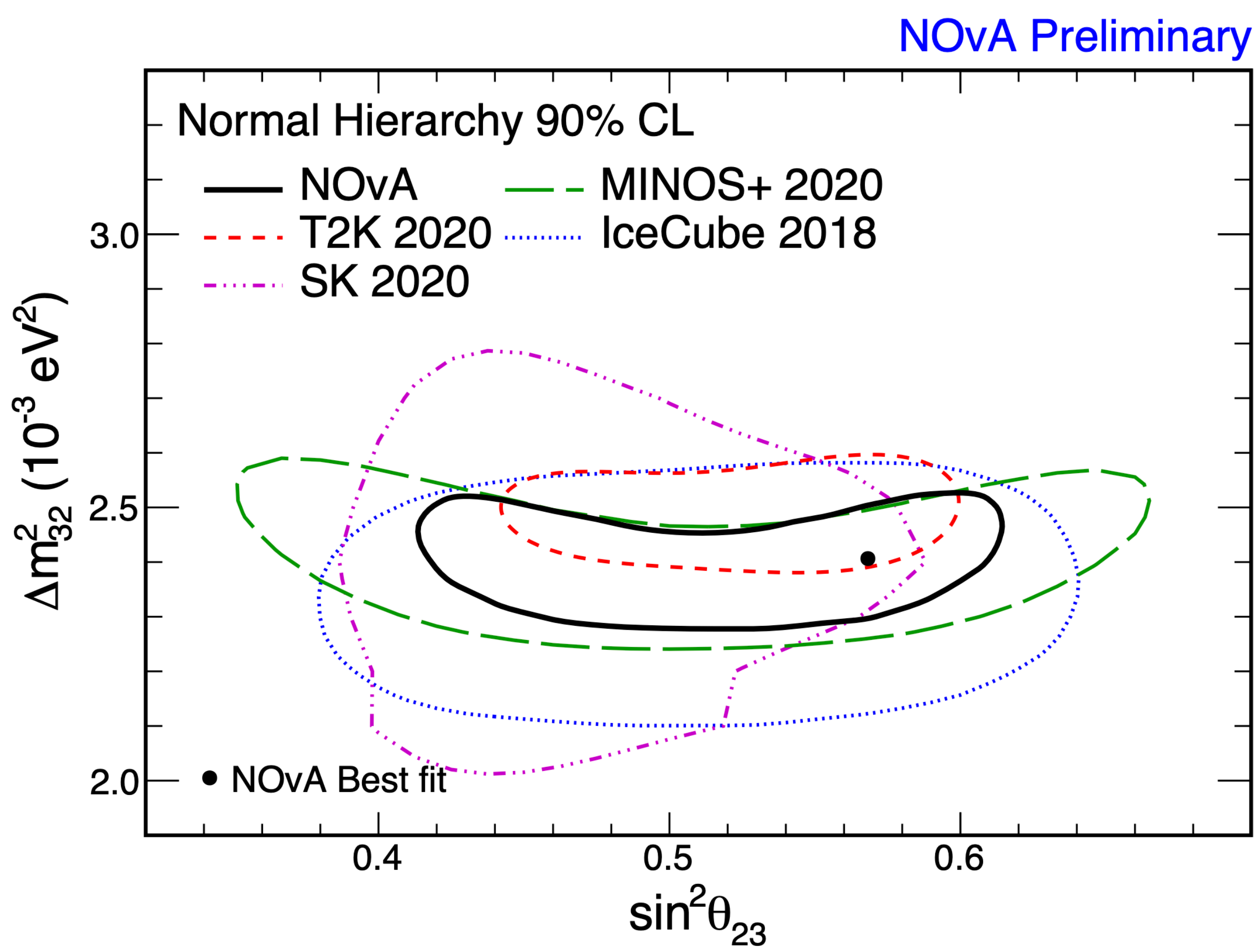
Current Status

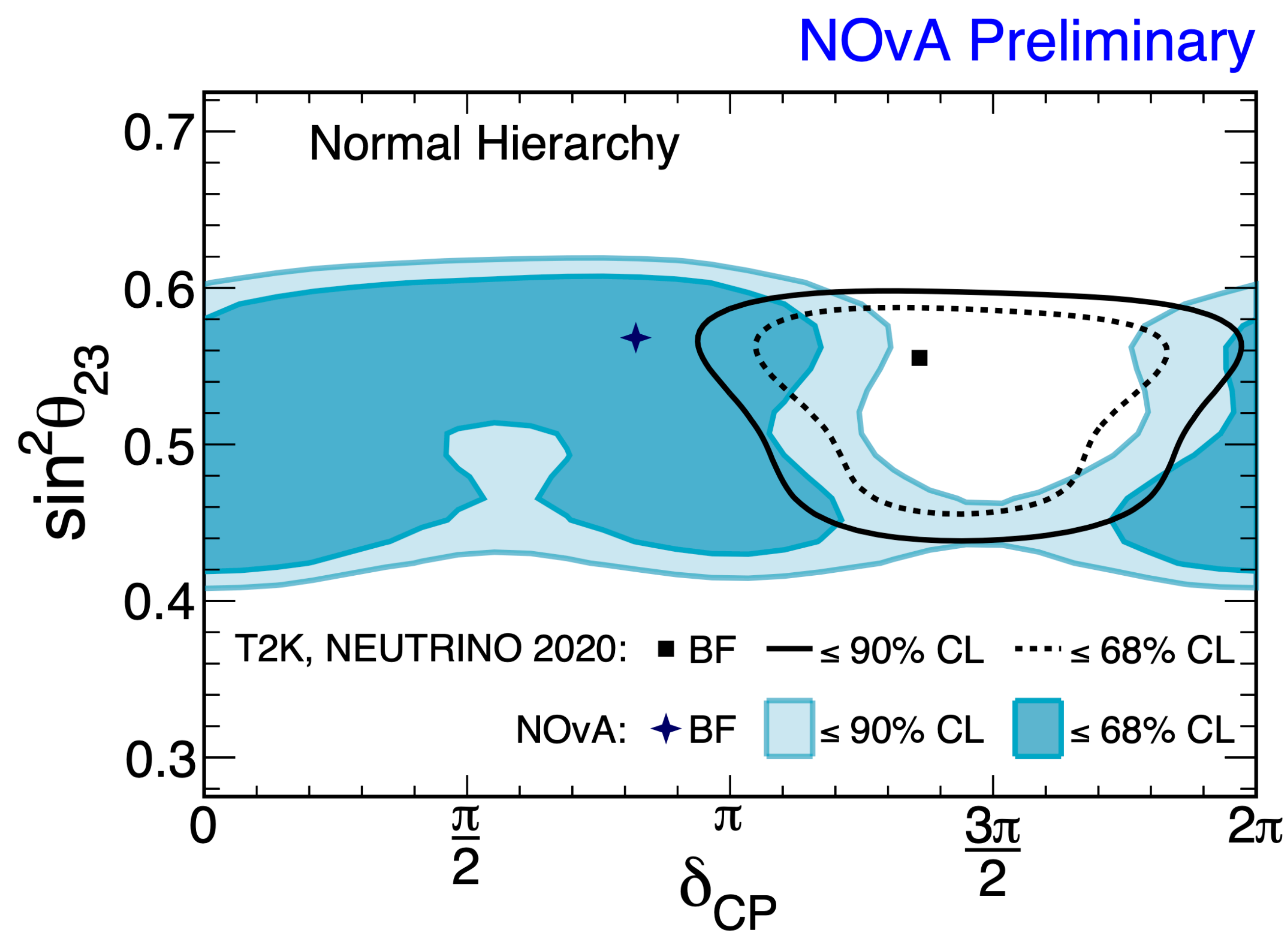




- **Preference for non-maximal mixing at ~1σ**
- **IH δ_{cp} = $\pi/2$ excluded at >3σ**
- **NH δ_{cp} = $3\pi/2$ excluded at ~2σ**

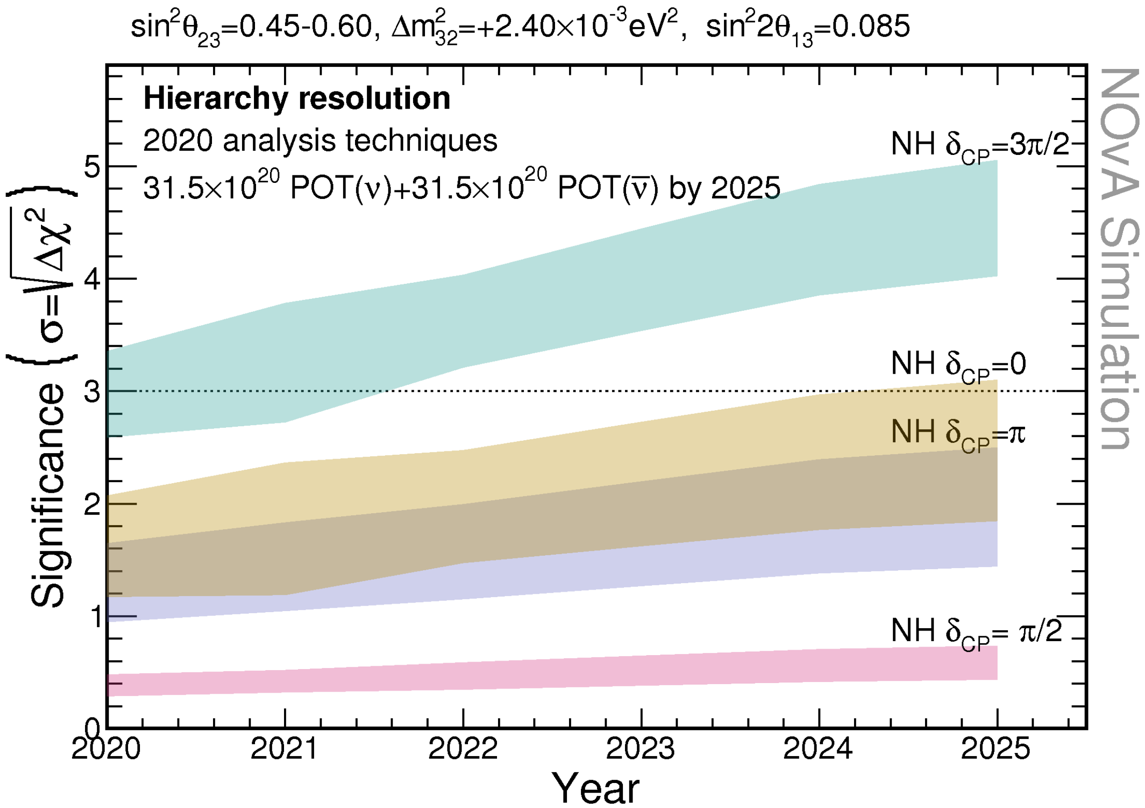
Global Comparison

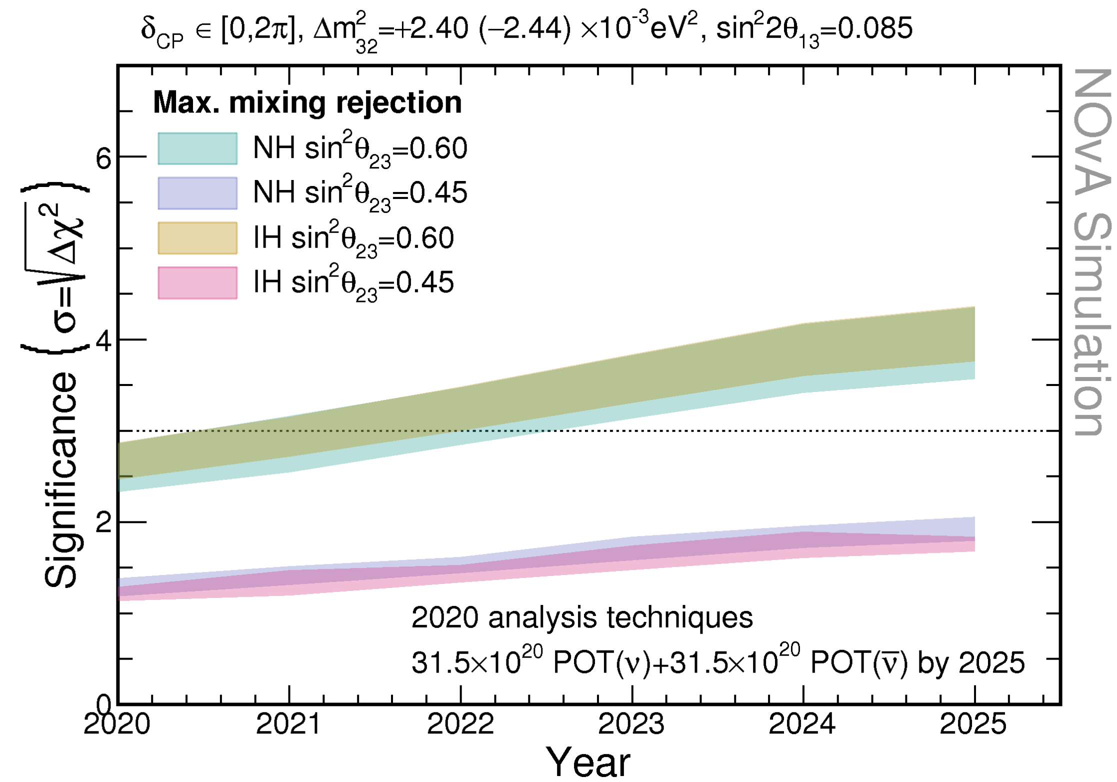


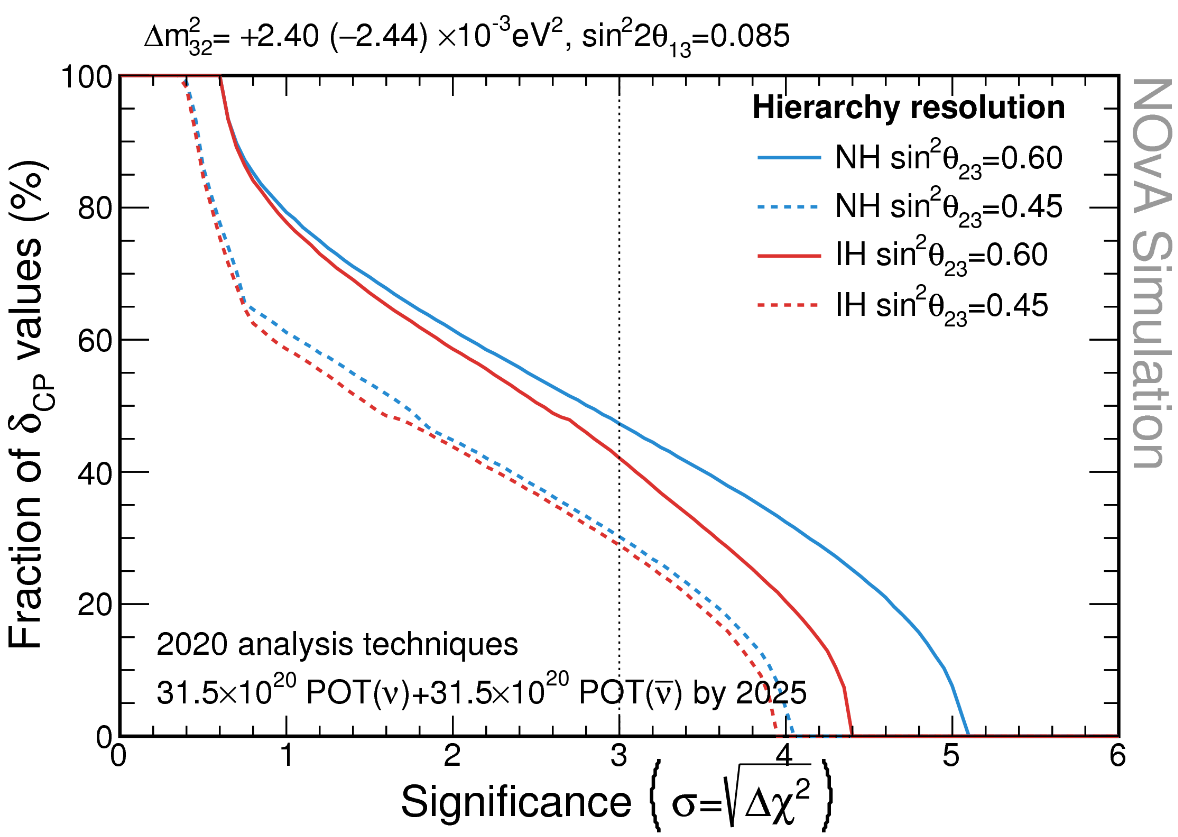


- **NOvA's $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$ results are in good agreement with other neutrino experiments**
- **Slight tension between NOvA and T2K δ_{cp} values at 90% CL**
- **NOvA and T2K collaborations are currently working on a joint fit to understand differences**

Future Outlook







- **NOvA will be collecting data till 2025**
- **We can reach >3σ mass-hierarchy sensitivity for 30-50% of the δ_{cp} values**

Conclusions

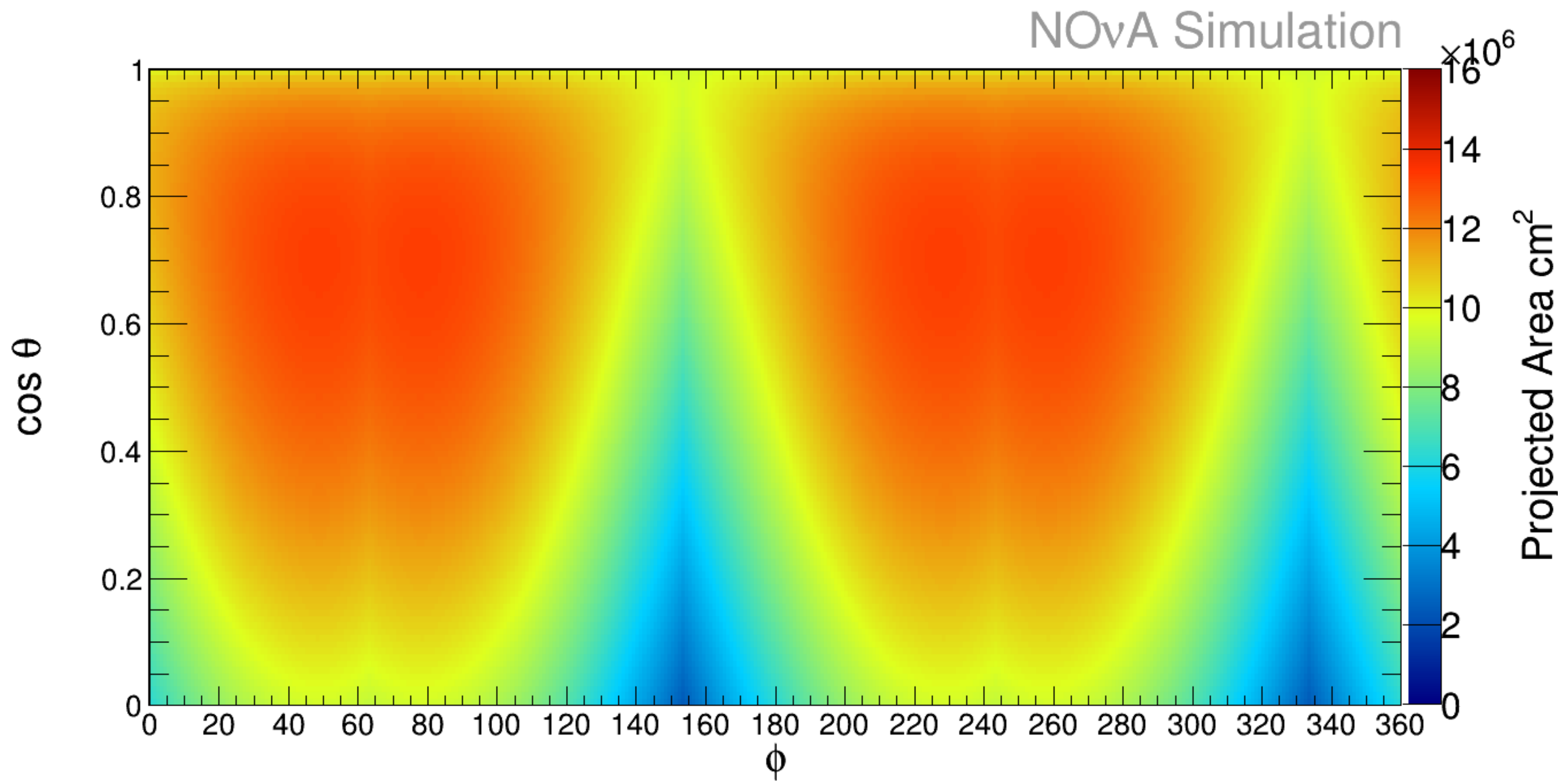
- NOvA is a globally competitive neutrino oscillation experiment with many exciting results
- NOvA and T2K are both working together towards joint fit results
- Other exciting NOvA analyses are
  - ➡ Cross-section analysis (to improve model and potential constrain cross section uncertainties, papers are coming soon)
  - ➡ Sterile Neutrinos (First ever look at NC disappearance in antineutrinos is coming in the next couple of weeks)
  - ➡ Test beam (constrain calibration uncertainties for oscillation analyses)
  - ➡ Non-standard Interactions
  - ➡ Magnetic Monopoles
  - ➡ Supernova neutrinos
  - ➡ Multi-messenger signals

Thanks

http://novaexperiment.fnal.gov

Backup

Projected Area of the Far Detector



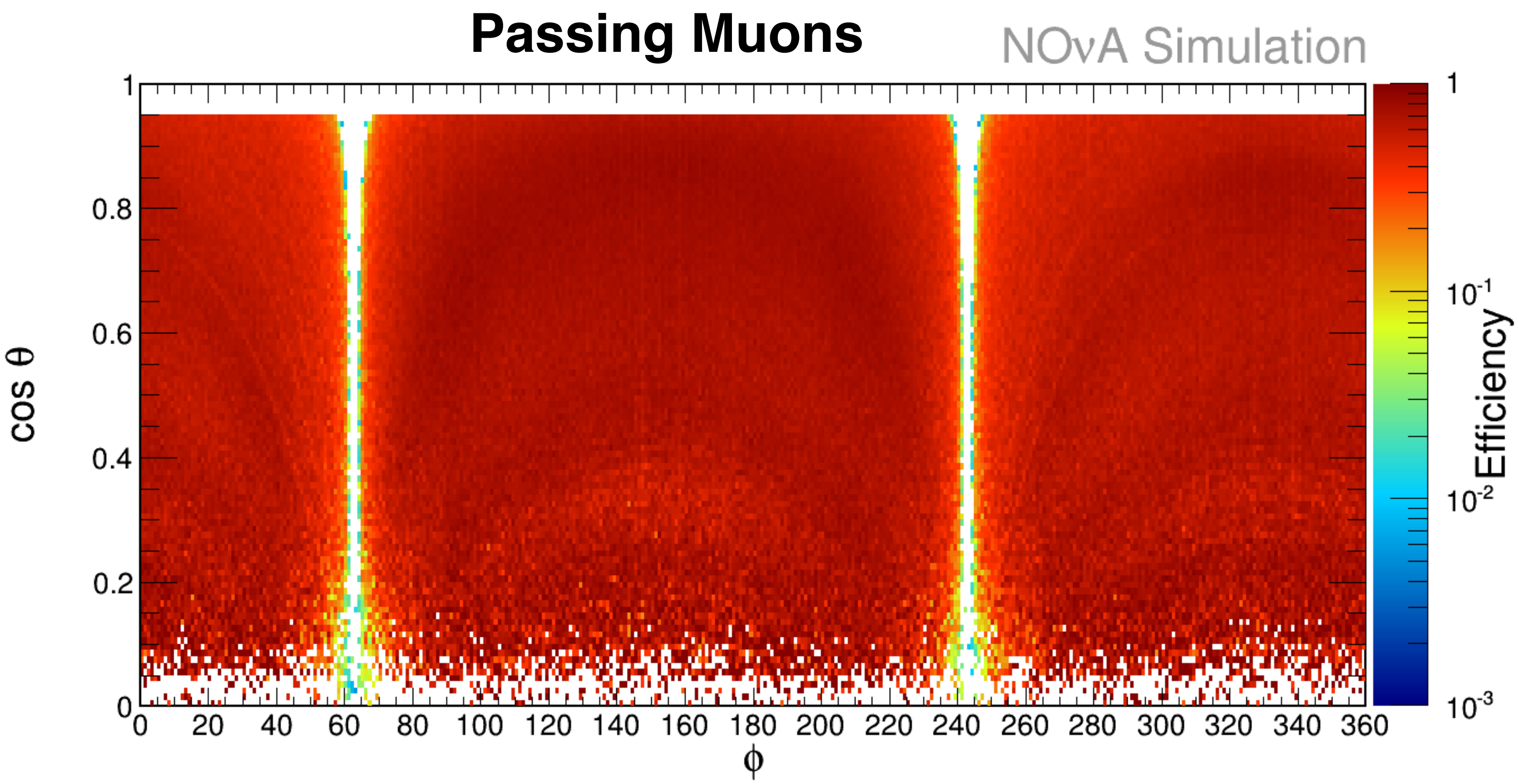
Surface area seen by cosmic ray muons

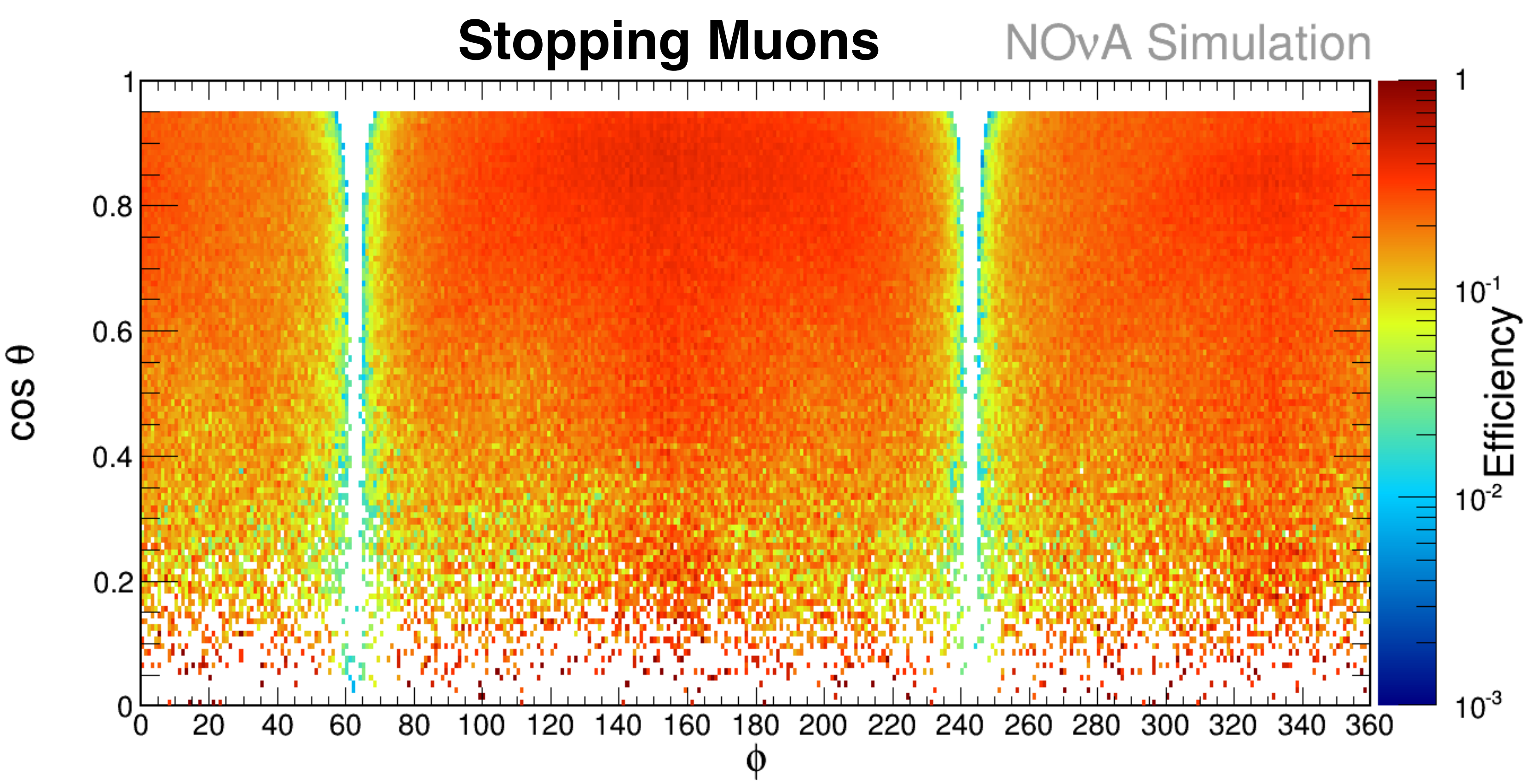
$$A_p = \sum_i A_{p,i}(\theta, \phi) = \sum_{s,i} \mathscr{A}_{s,i} \cdot \vec{U}_s \cdot \vec{V}(\theta, \phi)$$

- $\vec{V}(\theta, \phi)$ = particle's unit momentum vector
- $\vec{U}_s$ = normal vector to the surface of the FD
- $\mathscr{A}_{s,i}$ = area of a detector side
- $A_{p,i}(\theta, \phi)$ = projected area of side s
- A_p = total projected area

Projected area decreases near φ = 153.45^0 (South face) and φ = 333.45^0 (North face)

Efficiency of the FD





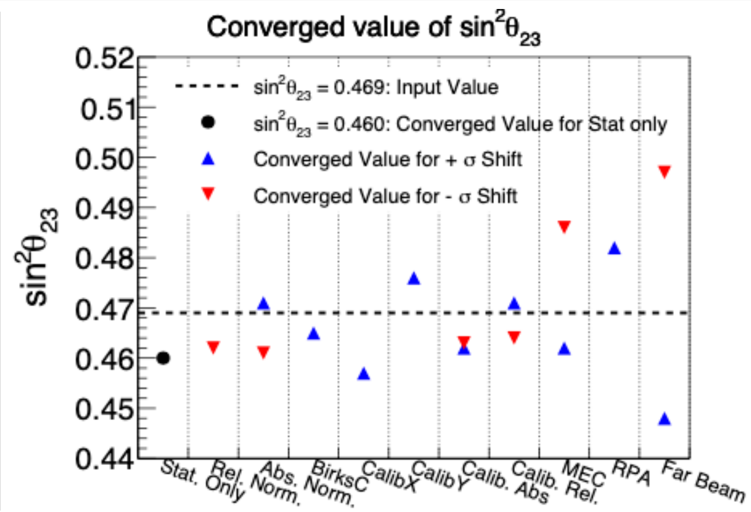
$$\epsilon = \frac{\text{Selected Cosmic Muons}}{\text{Total Cosmic Muons}}$$

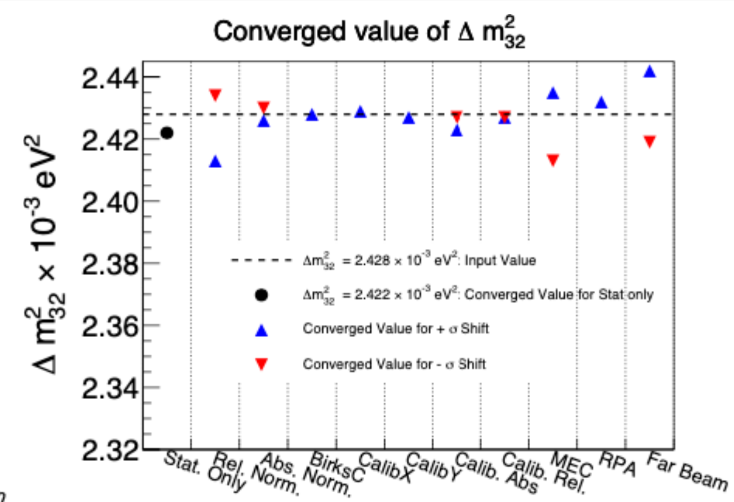
Treatment of Systematic Uncertainties

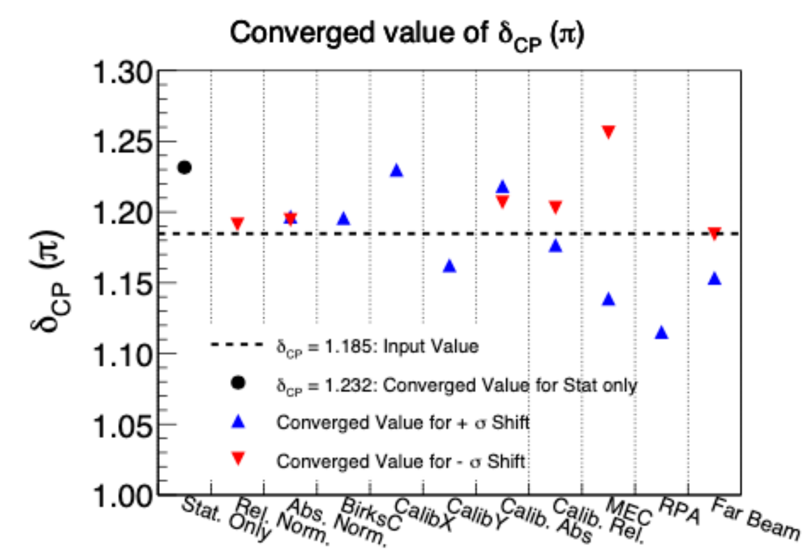
Systematic uncertainties treated as nuisance parameters

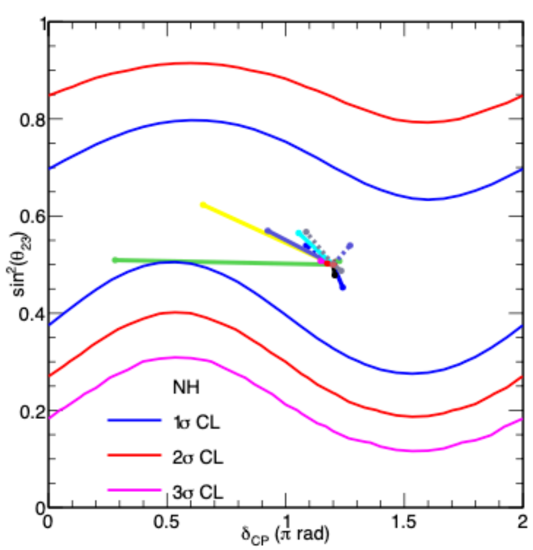
$$\chi^2_{syst} = \sum_{j}^{syst.} \chi^2_j = \sum_{j}^{syst.} \frac{(\epsilon_j - <\epsilon_j>)^2}{\sigma^2_{\epsilon_j}}$$

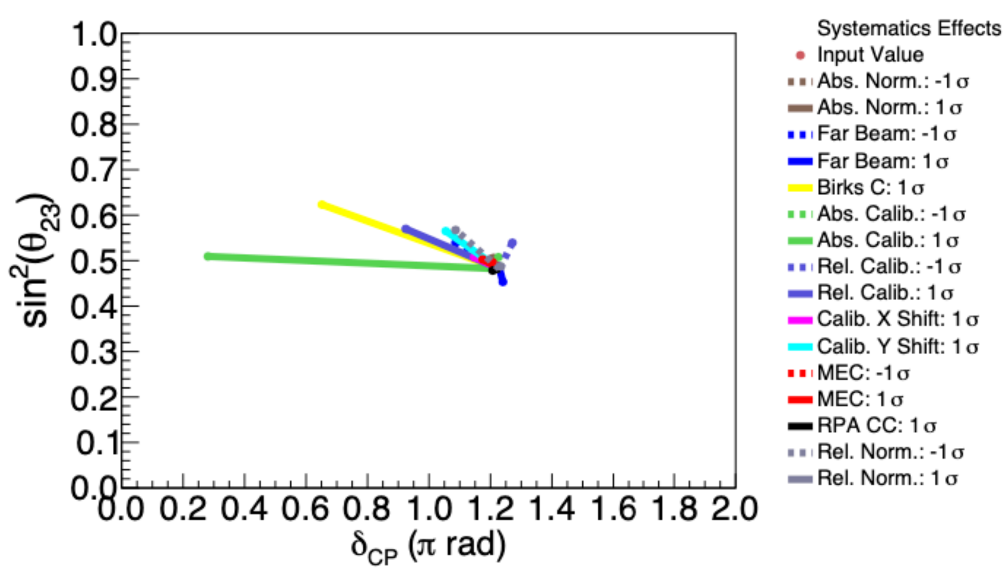
- χ^2_{syst} = sum of contribution from all systematics
- ϵ_j = converged value of jth systematic uncertainty
- $<\epsilon_j>$ = expected central value for the systematic uncertainty
- $\sigma^2_{\epsilon_j}$ = 1σ uncertainty on central value











Systematic Uncertainties	Signal (%)	Background (%)
Cross sections and GENIE	7.7	8.6
Normalization	3.5	3.4
Calibration	3.2	4.3
Detector response	0.67	2.8
Beam	0.63	0.43
Extrapolation	0.36	1.2
Total systematic	9.2	11
Statistical	15	22
Total uncertainty	18	25

Biggest Systematics

- Uncertainty in neutrino cross-sections in GENIE model
- Data/MC normalization
- Energy calibration

Experiment is statistically dominated