Long-Baseline Accelerator Neutrino Oscillations

Louise Suter, Fermilab

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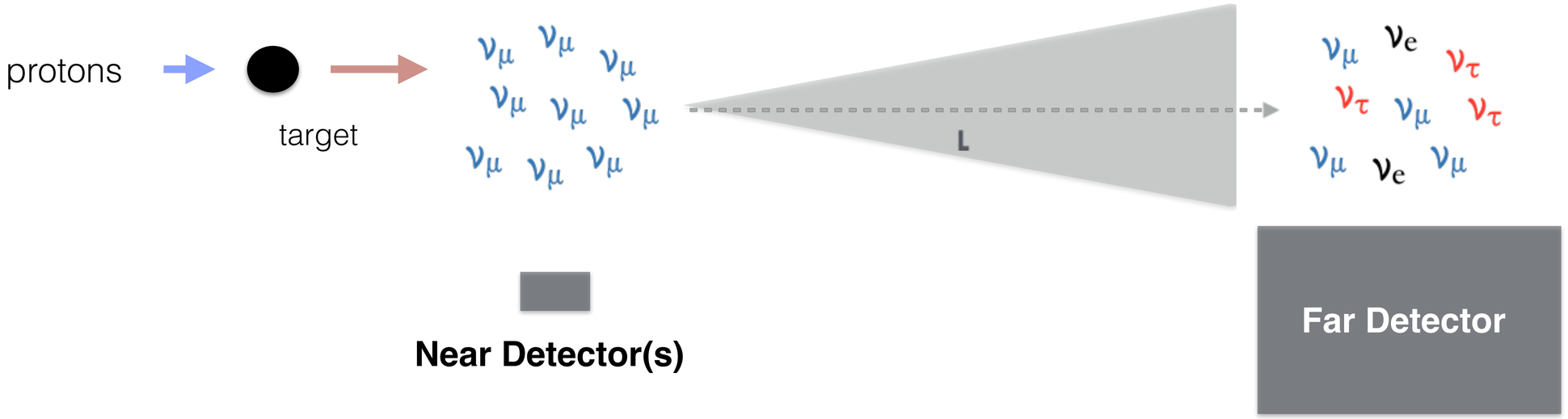
Create ~100% muon-neutrino beam (or anti-neutrino beam)

Characterize beam with ND

Measure beam content after oscillation,
ν_e appearance ($\nu_\mu \longrightarrow \nu_e$)
ν_μ survival (disappearance) ($\nu_\mu \longrightarrow \nu_\mu$)



Make precision measurements of PMNS neutrino mixing parameters
Investigate BSM physics: Non-standard Interactions, additional flavors of neutrinos

Neutrino mass mixing matrix factorizes into three terms

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

$\Delta m^2_{32} \simeq 2 \times 10^{-3}\text{eV}^2$
$L/E = 500$ km/GeV

$\Delta m^2_{31} \approx \Delta m^2_{32}$

$\Delta m^2_{21} \simeq 8 \times 10^{-5}\text{eV}^2$
$L/E = 15,000$ km/GeV

$\nu_\mu \longrightarrow \nu_\mu$
$\nu_\mu \longrightarrow \nu_\tau$

atmospheric and long baseline

$\nu_e \longrightarrow \nu_e$
$\nu_\mu \longrightarrow \nu_e$

reactor and long baseline

$\nu_e \longrightarrow \nu_e$
$\nu_e \longrightarrow \nu_\mu + \nu_\tau$

solar and reactor

$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$

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Long-Baseline experiments can probe

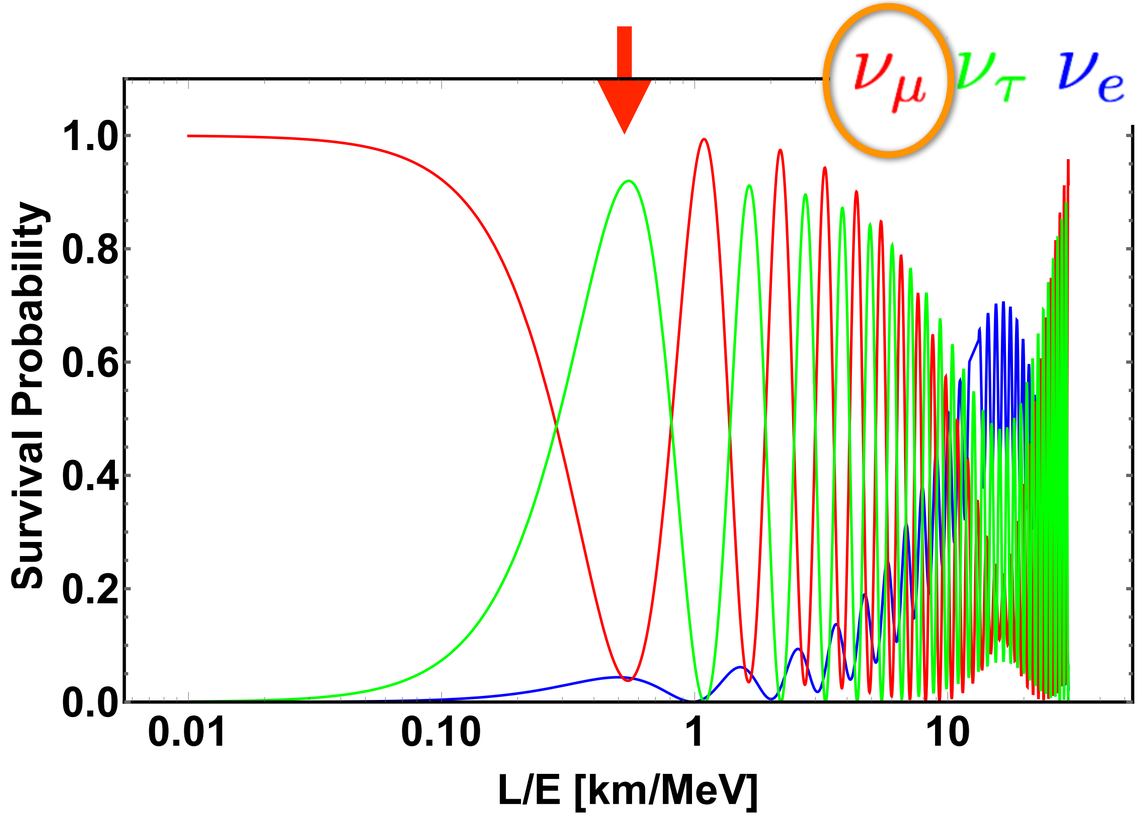
$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$

$\nu_\mu \longrightarrow \nu_\mu$, ν_μ disappearance in a ν_μ beam

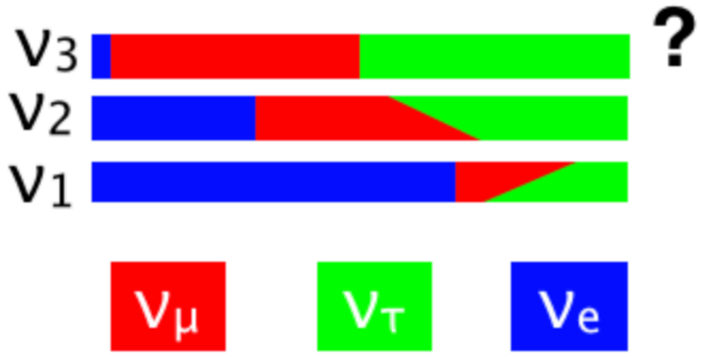
Can make precision measurements of the amplitude, atmospheric mixing angle, **$\sin^2(2\theta_{23})$**, and frequency, mass difference, **Δm^2_{32}**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{32}[\mathrm{eV}^2] L_\nu[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

First maxima, location of most LBL neutrino experiments



θ_{23} has been measured to be near 45 degrees indicating maximal mixing between ν_μ and ν_τ in the ν_3 mass state



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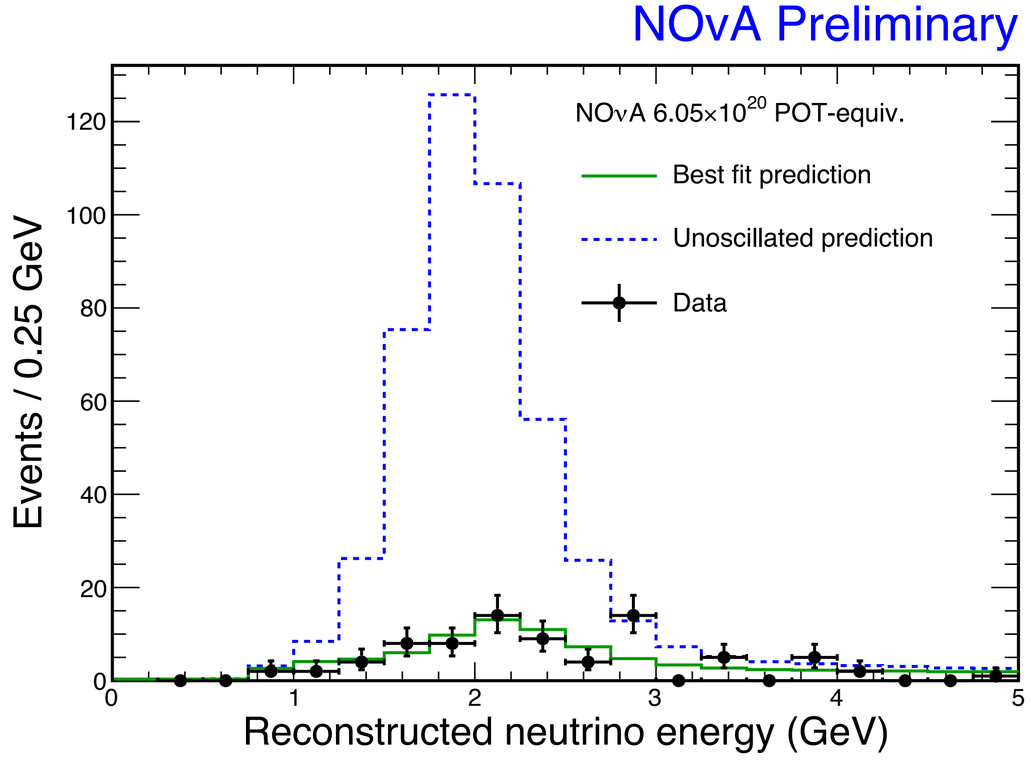

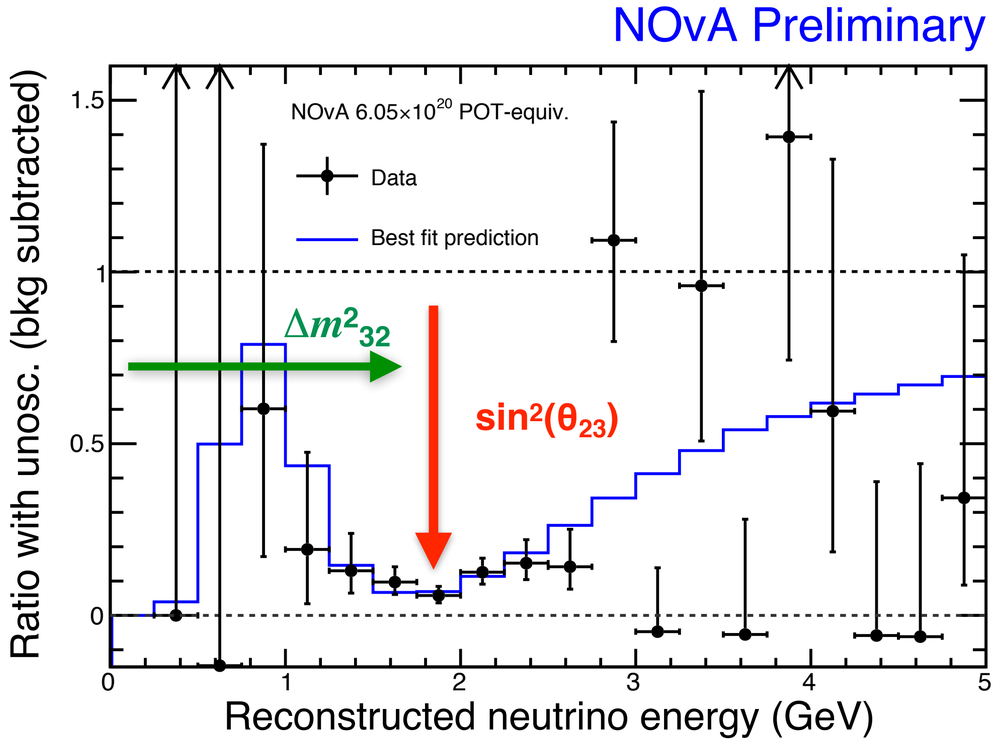

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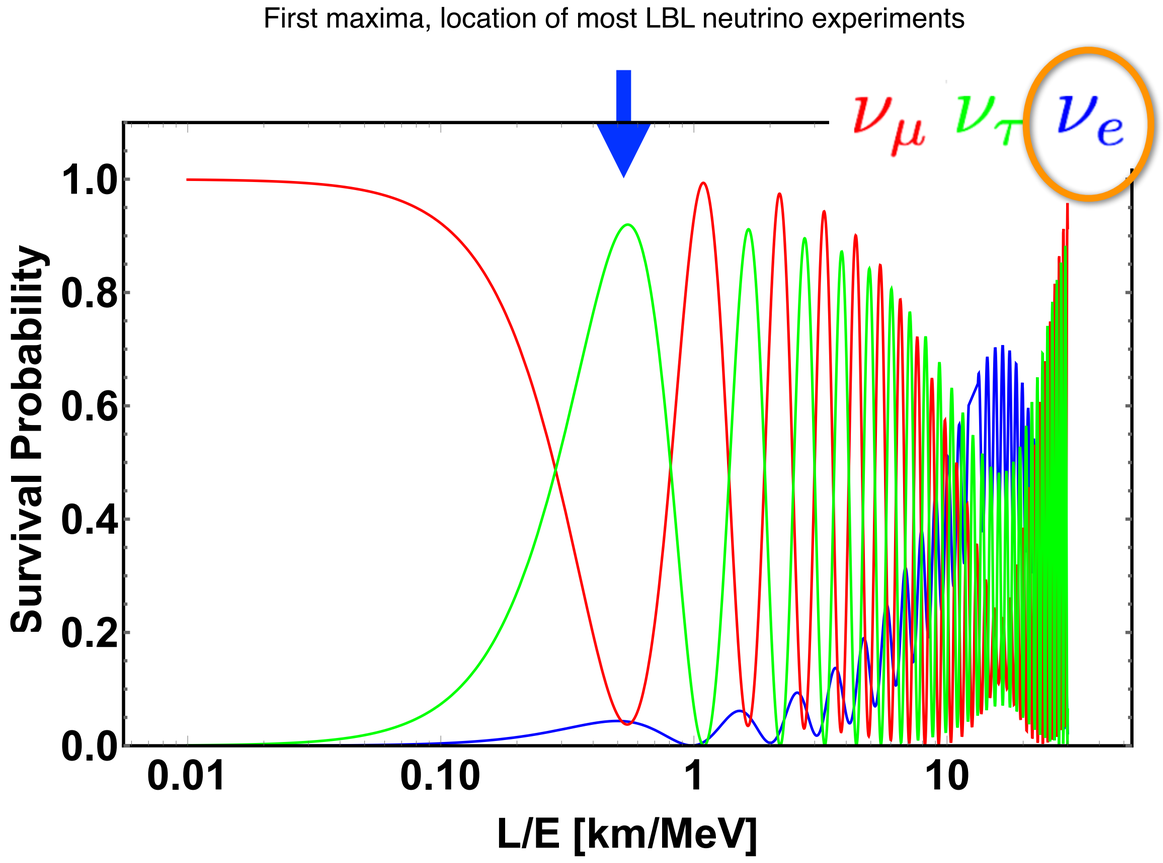
$\nu_\mu \rightarrow \nu_e, \nu_e$ appearance in a ν_μ beam

To describe ν_e appearance must use full 3-flavor description and include effects of interaction of neutrinos with matter



$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{13}, \theta_{13}, \delta_{cp}$

$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

θ_{13} well constrained from reactor experiments

Probe θ_{23}, Δm^2_{13}, and δ_{cp}

Has sensitivity to some of the biggest questions in the field

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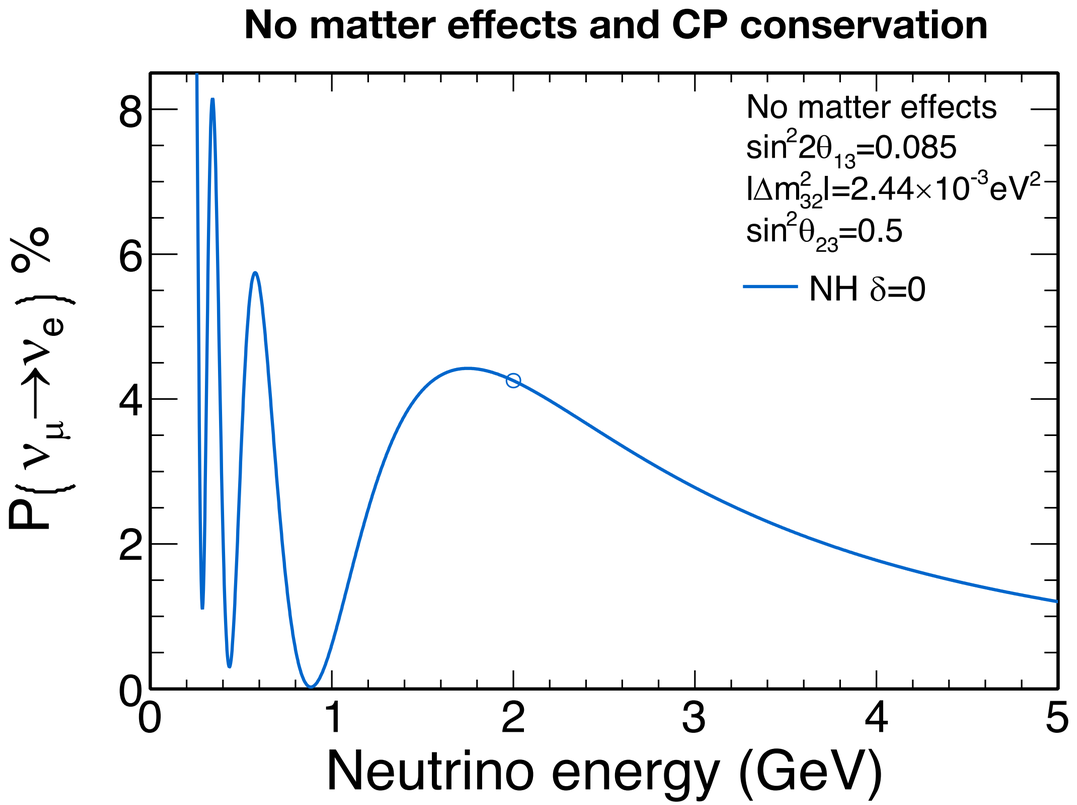

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Neutrino Mass Hierarchy

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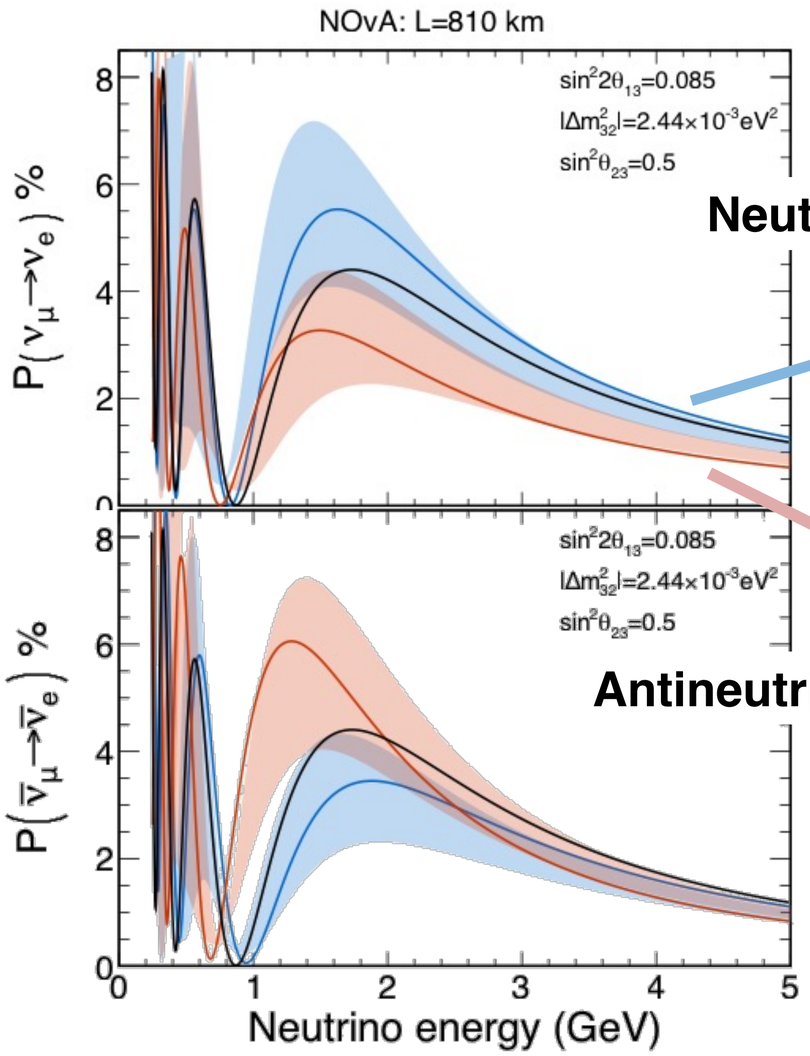
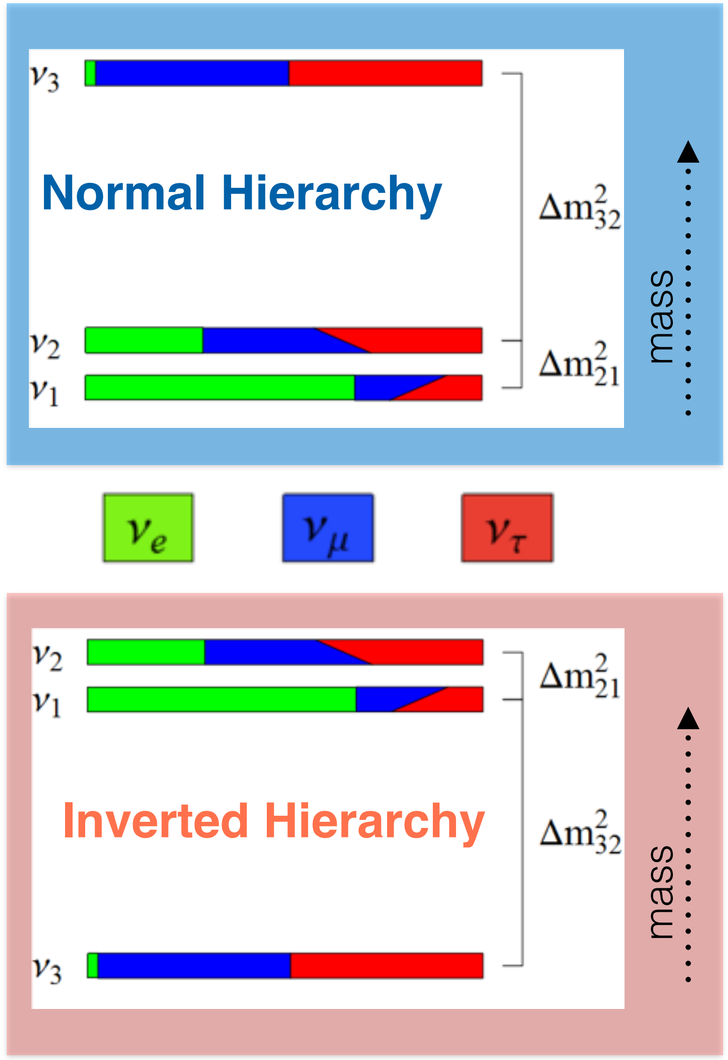
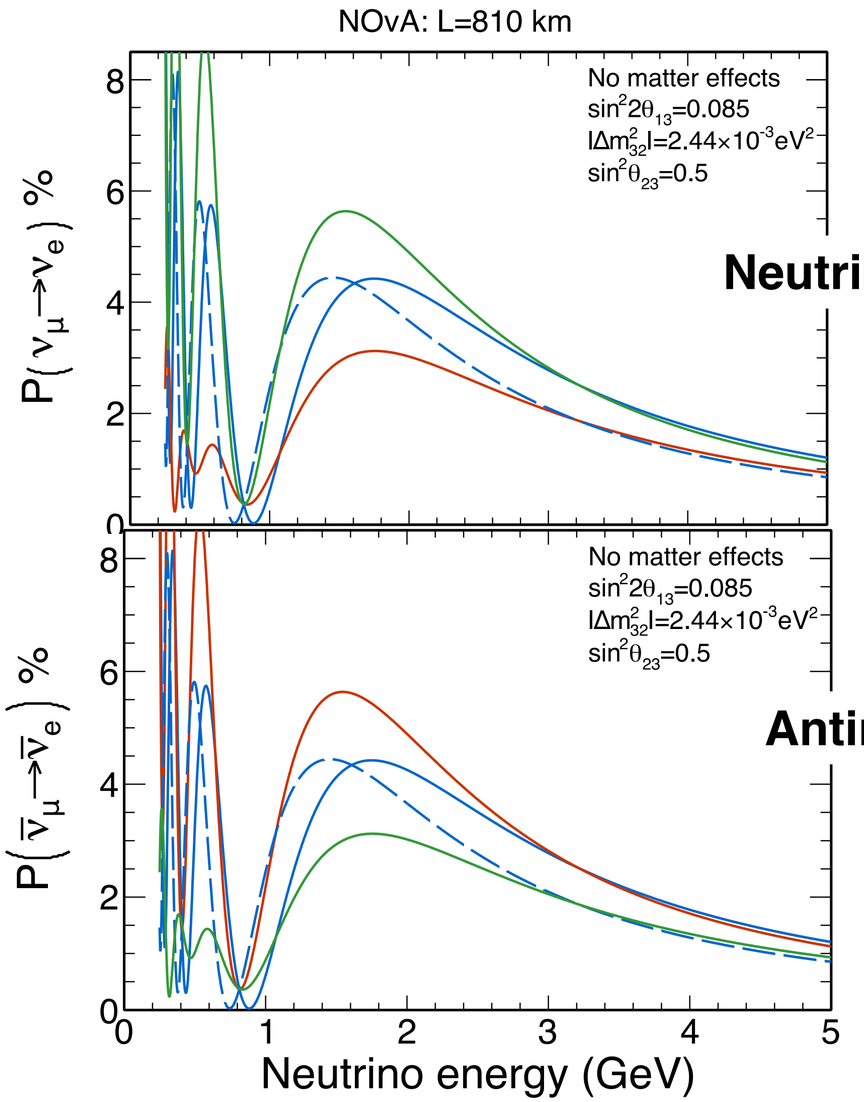




Matter effect: Electron neutrinos experience additional interactions with electrons in the earth

Charge Parity Violation

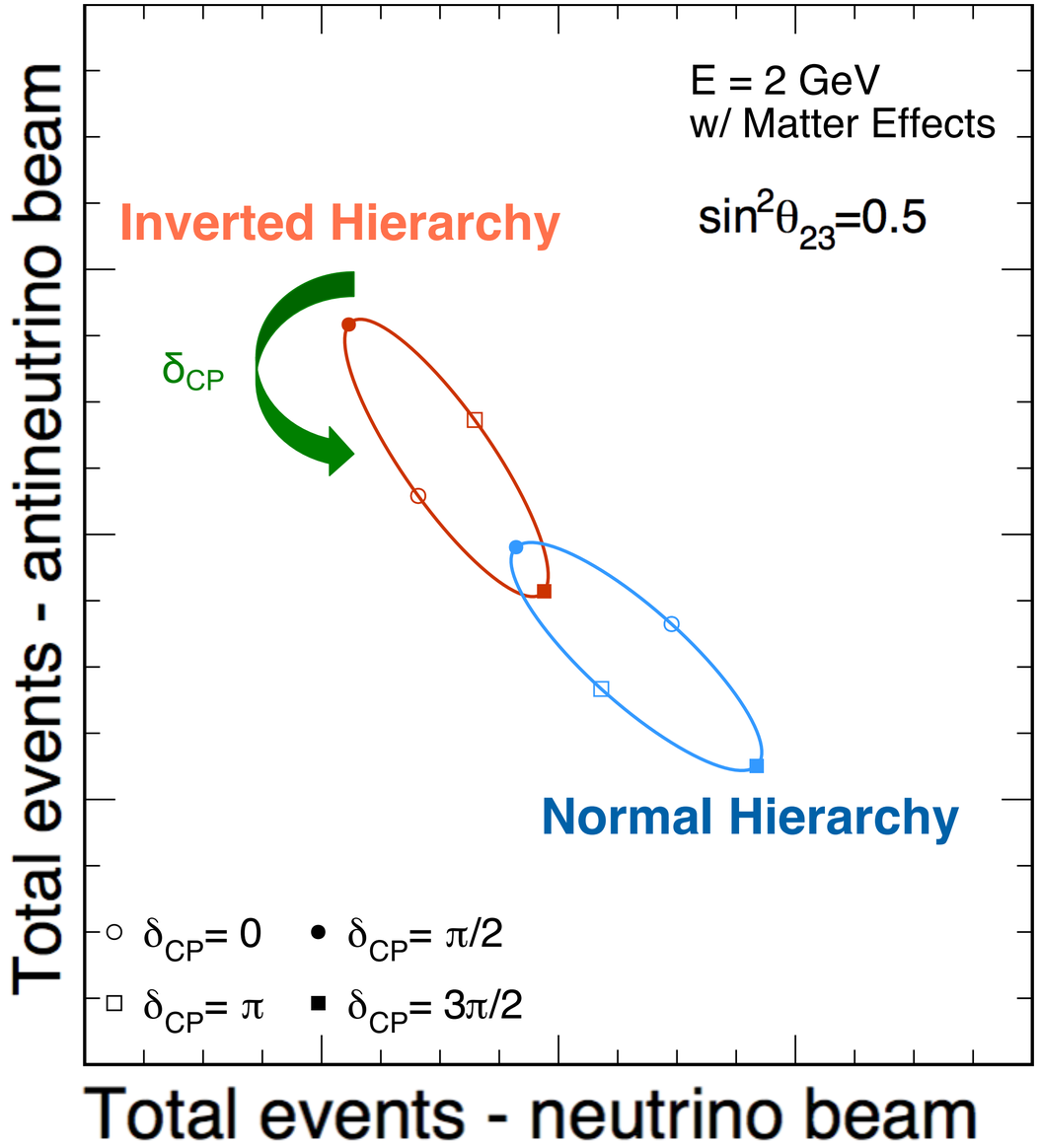
$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{13}, \theta_{13}, \delta_{cp}$



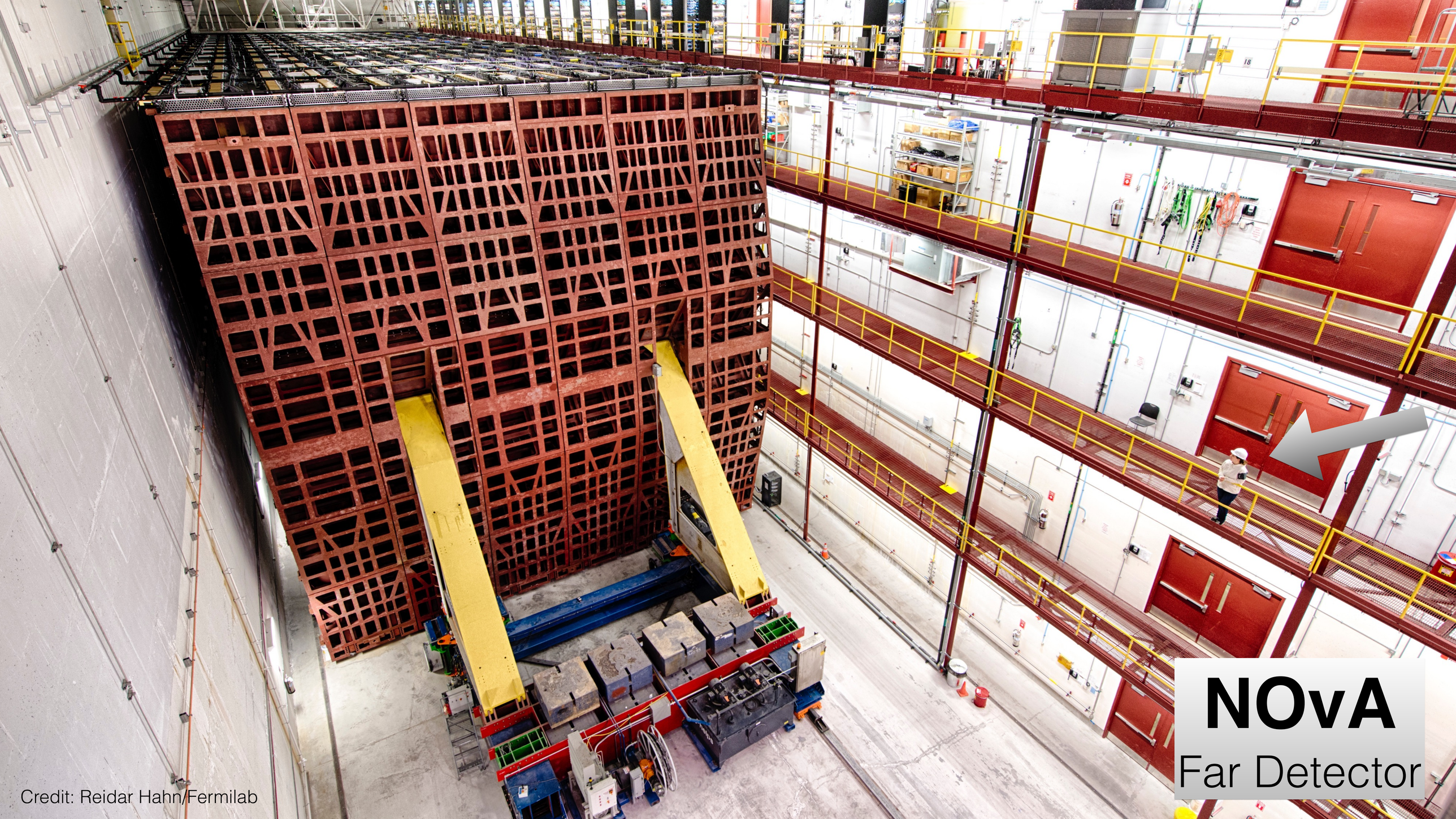
CP conserved
$\delta = \pi/2$
$\delta = 3\pi/2$

Do neutrinos conserve CP?
Observing CPV in neutrinos important step towards leptogenisis

$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{13}, \delta_{cp}$

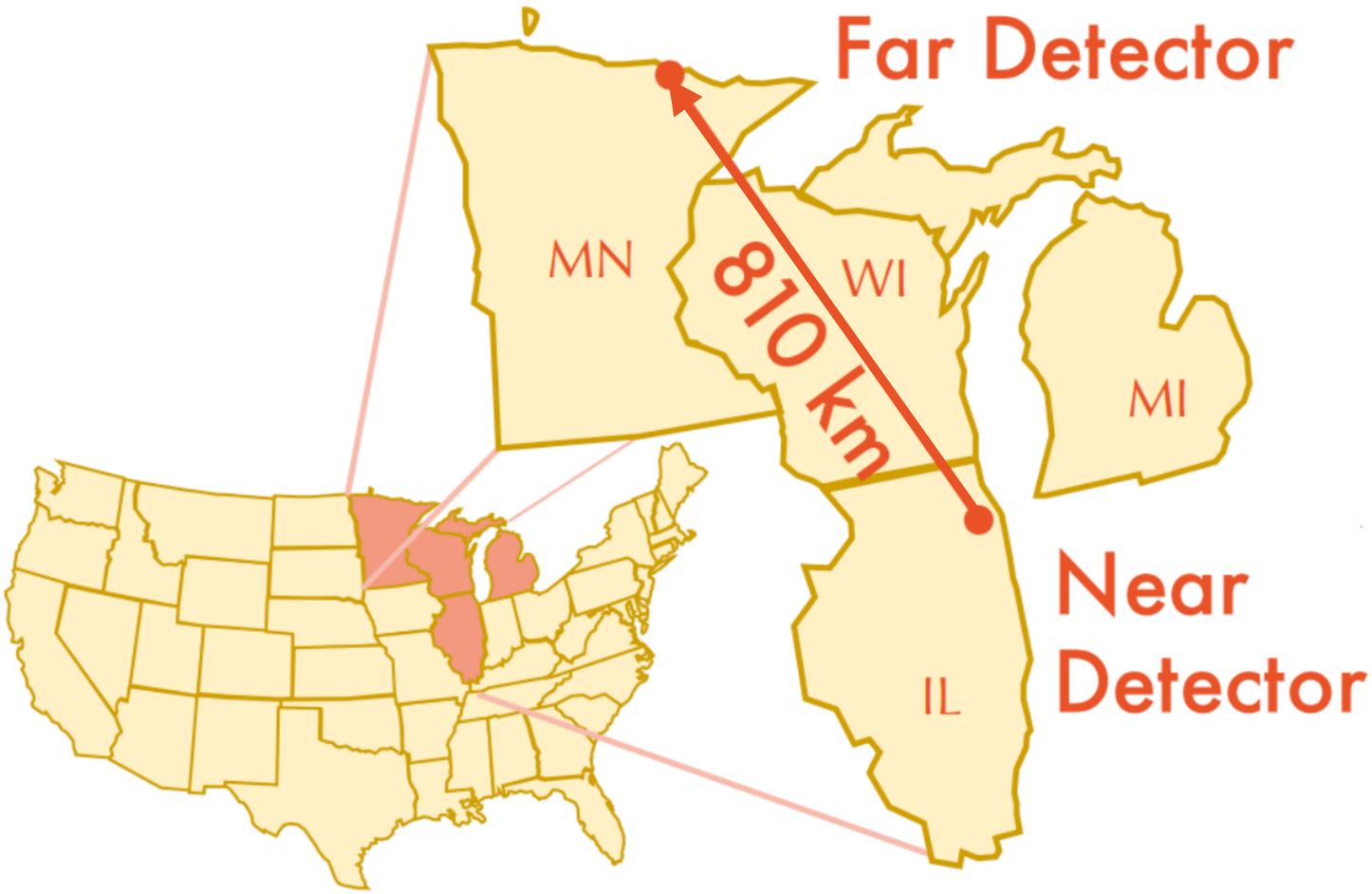


$\sin^2\theta_{23}$ provides amplitude of oscillation



Credit: Reidar Hahn/Fermilab

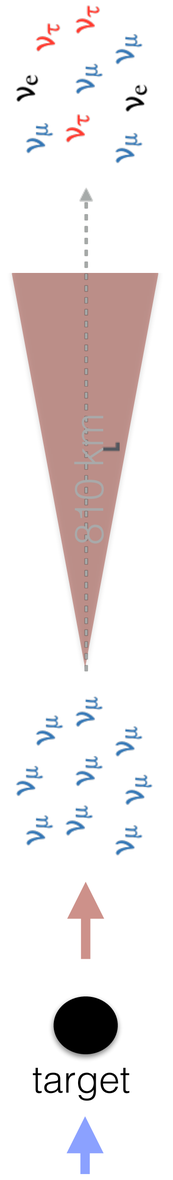
NOvA: Off-axis long-baseline neutrino oscillation experiment



Measure beam content after oscillation

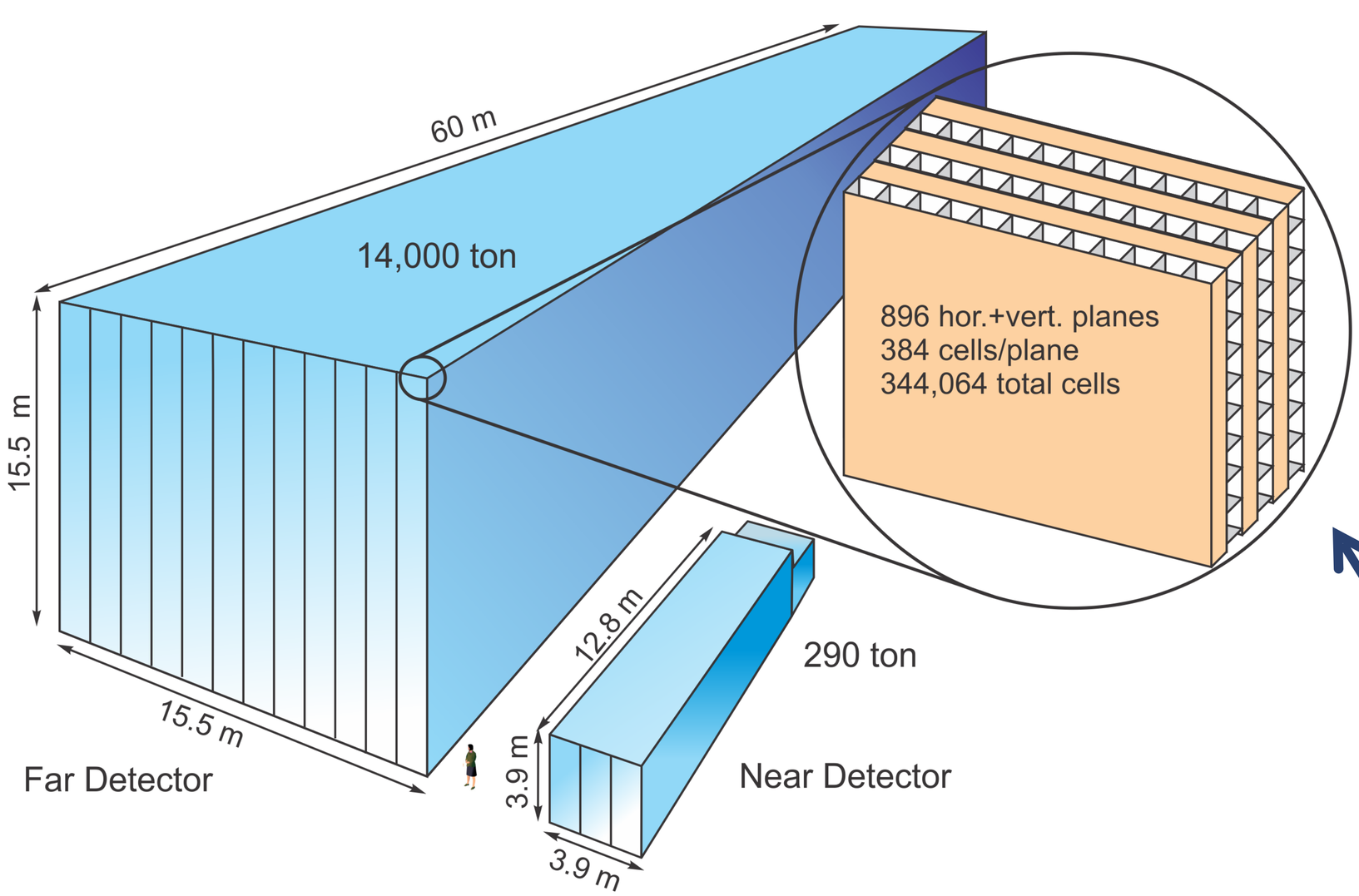
Characterize muon-neutrino beam with ND

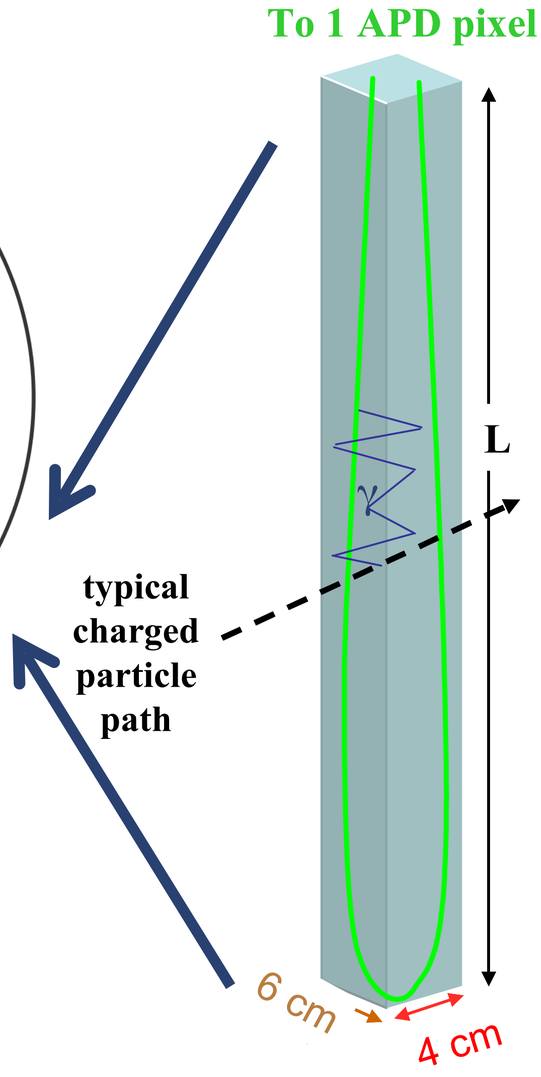
Create ~100% muon-neutrino beam (or anti-neutrino beam)



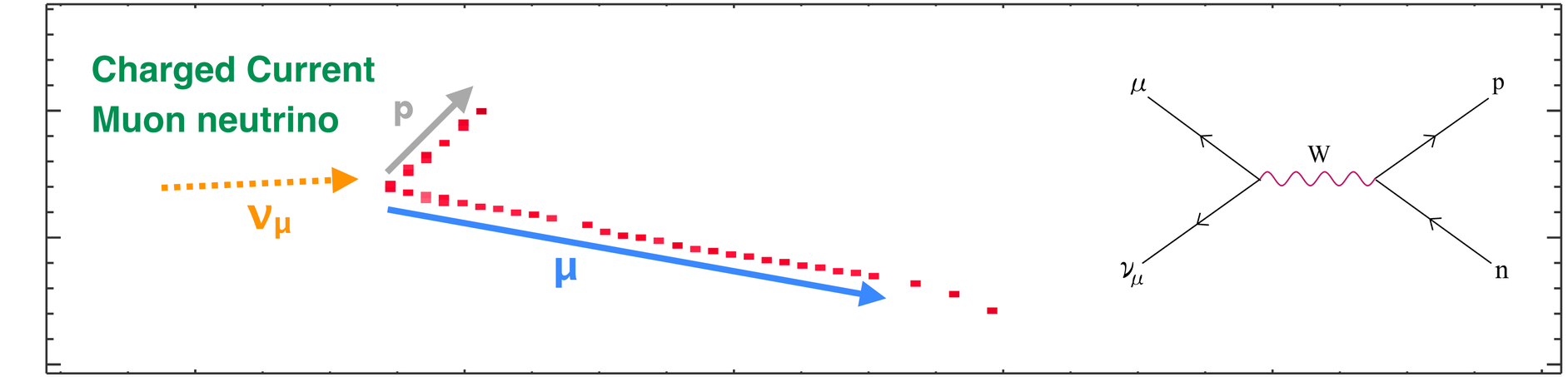
Longest baseline of currently running experiments
Off-axis beam gives narrow band neutrino beam at 2 GeV

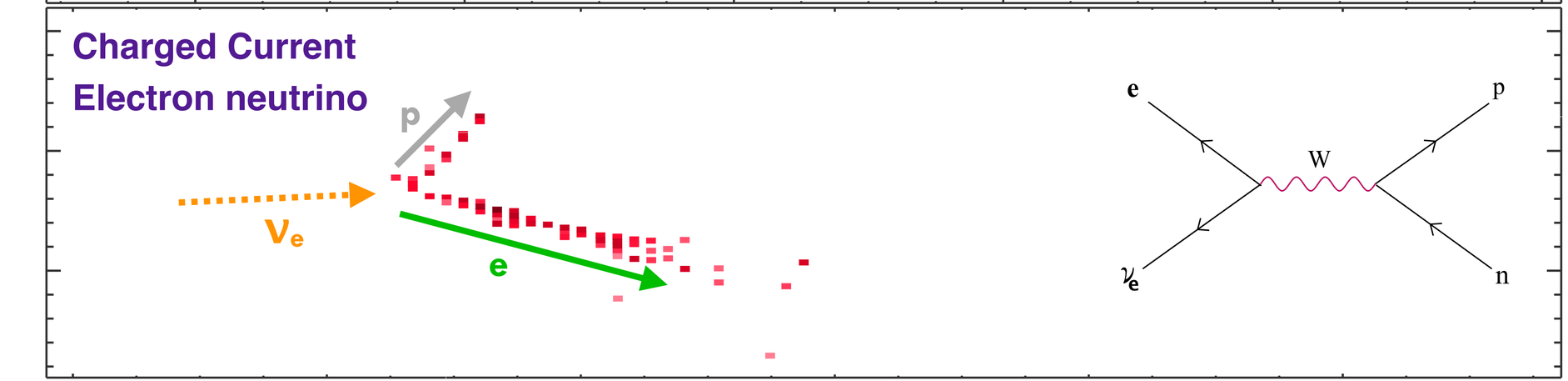
Huge, low-Z, 65% active, liquid scintillator tracking calorimeter

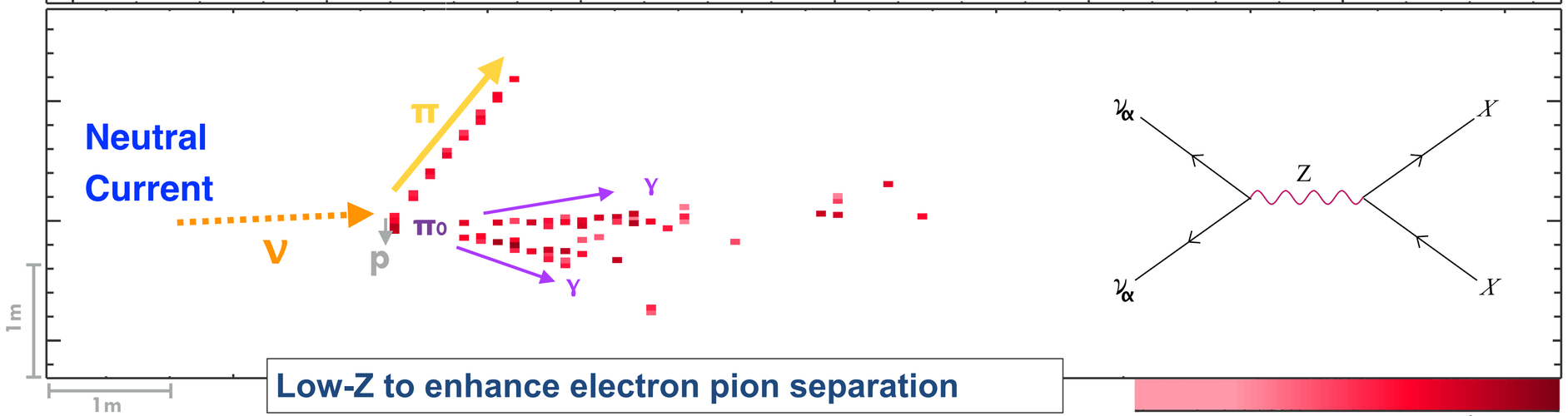




Designed to maximize electron neutrino selection efficiency



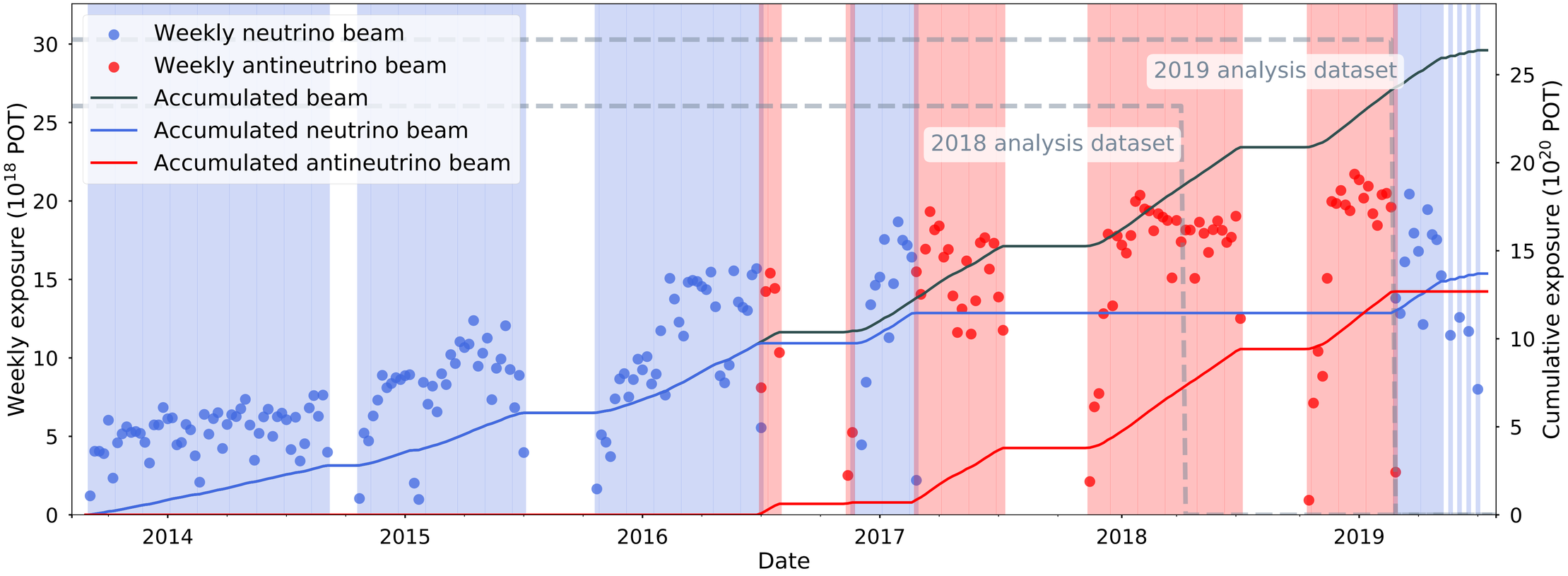




Low-Z to enhance electron pion separation

NuMI beam has been running excellently, regularly exceeding 700 kW designed power.

Recently set a record for average power of 758 kW/hour



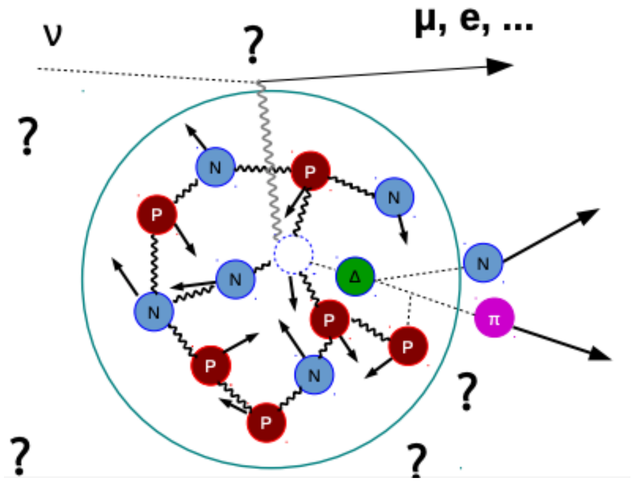
Antineutrino data: ~12.5×10^{20} Protons-on-target

Neutrino data: ~11×10^{20} Protons-on-target collected to date, 8.85×10^{20} POT used in current analysis

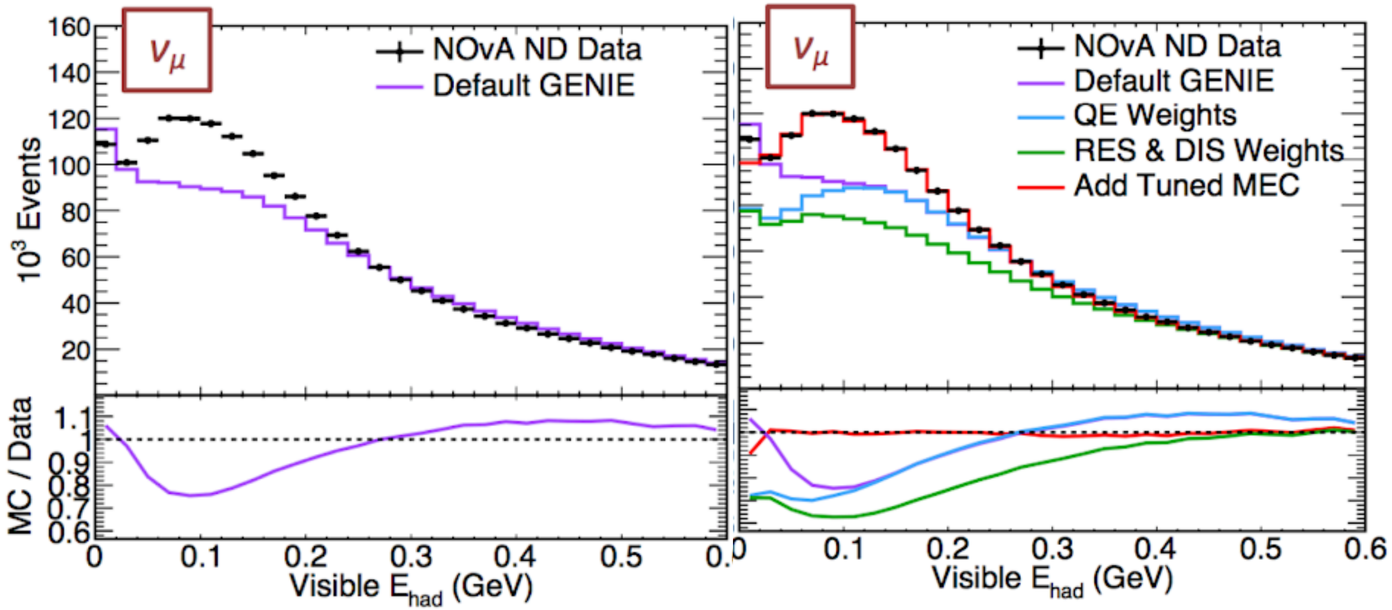
Challenge of Modeling Neutrino Interactions

The modeling of neutrino beams and interactions with complicated nuclei create a challenge for oscillation measurements

Modeling and systematic uncertainties constrained using **near detector**



Near Detector simulation per and post tune



NOvA used theoretical input and observed data-MC differences to improve its cross section model in both detectors

Remaining data-mc differences in Near Detector data, due to flux and detector miss-modeling, used to correct Far Detector prediction

NOvA is planning to run until 2025, results shown here represents about 30% of the total data to be collected

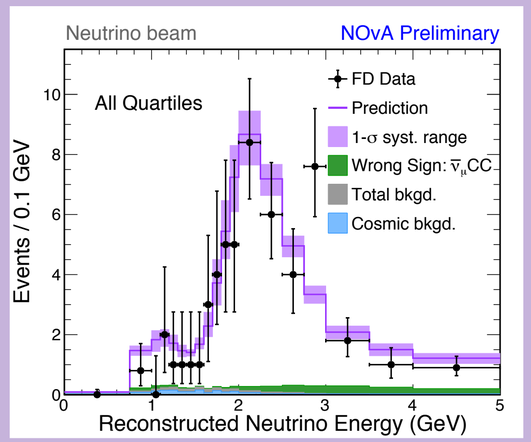
	Data	Prediction (at best fit)	bkgd
$\bar{\nu}_\mu$	113	124	4.2
ν_μ	102	96	2.2
ν_e	58	59	15
$\bar{\nu}_e$	27	27	10.3

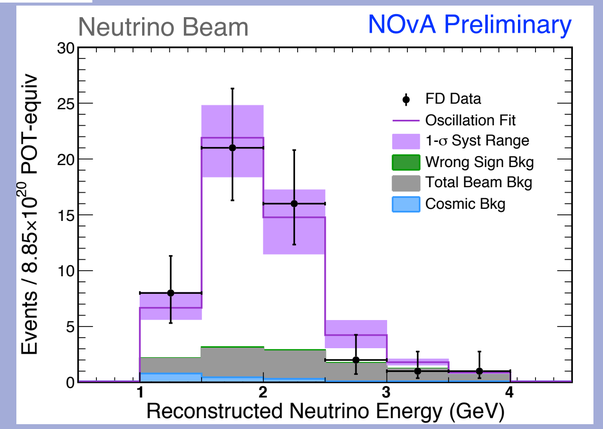
Antineutrinos: 12.33e20 Protons-on-target
Neutrinos: 8.85e20 Protons-on-target

ν_μ sample

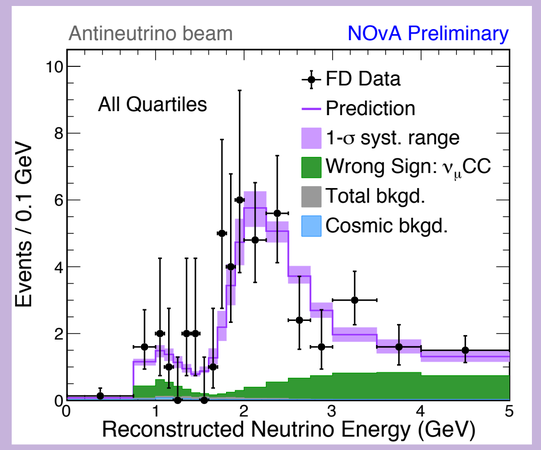
ν_e sample

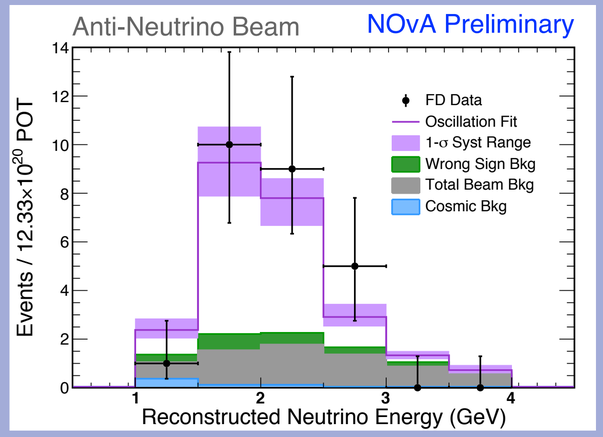
Neutrinos





Antineutrinos





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

Greater than 4.4σ evidence of electron antineutrino appearance in long-baseline beam

CP phase, δ_{CP}, and mass hierarchy

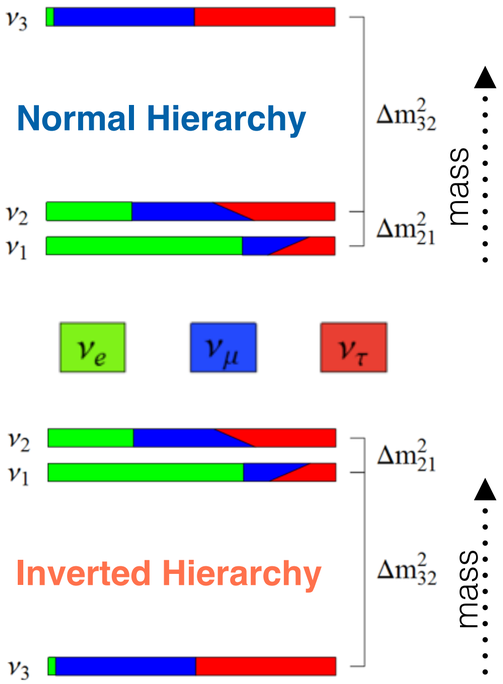
Best fit:

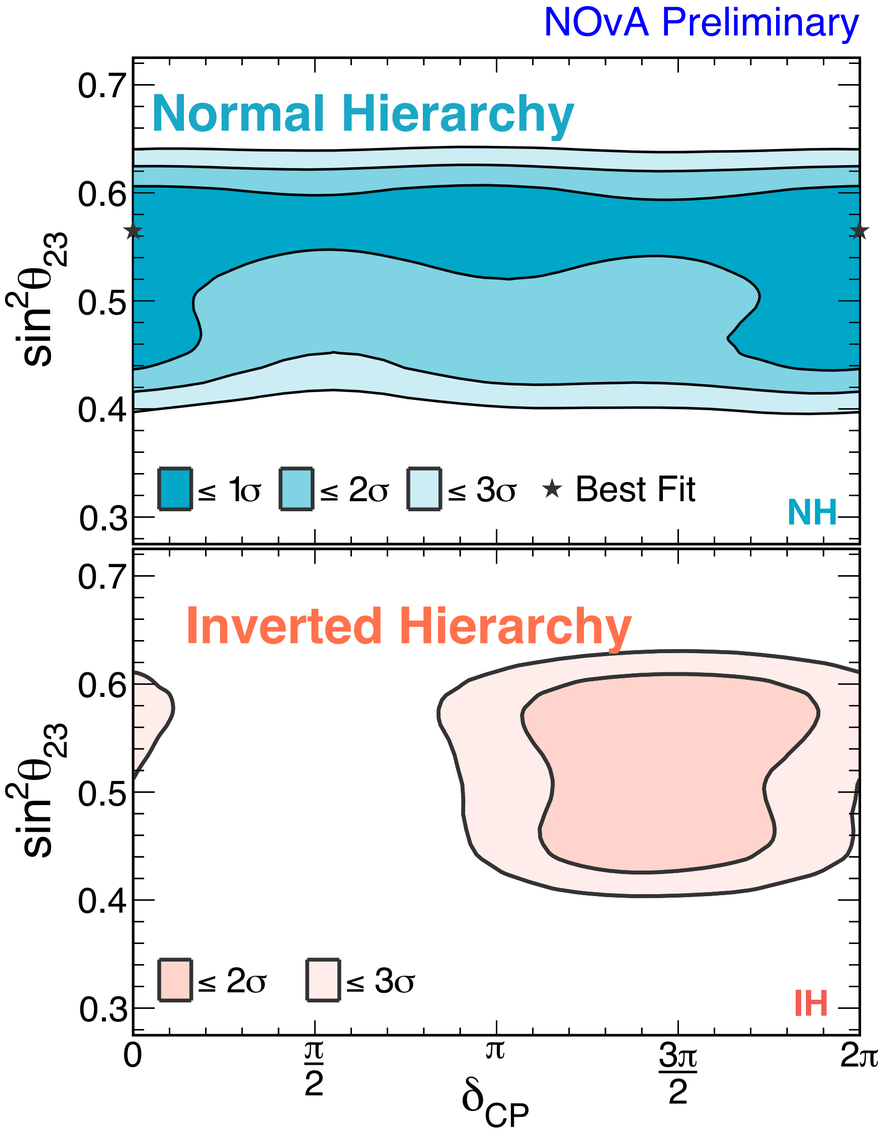
$\sin^2\theta_{23} = 0.56^{+0.11}_{-0.03}$

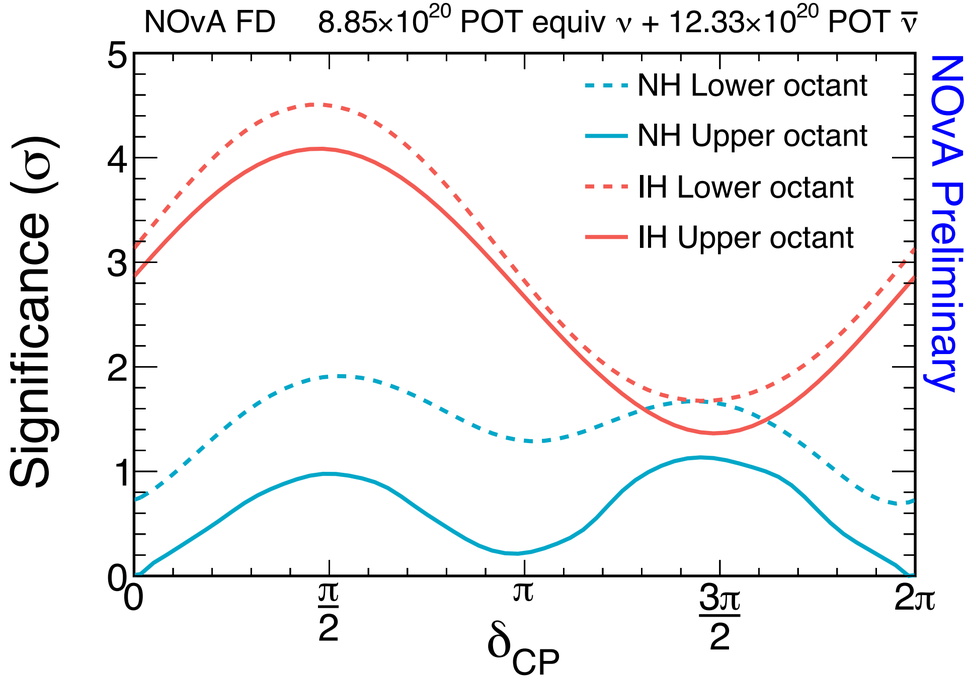
$\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}$ eV^2/c^4

$\delta_{CP} = 0^{+1.3}_{-0.4}$

θ_{13} set to world average from PDG







At 1.1σ all values of δ_{CP} allowed normal hierarchy upper octant

For inverted hierarchy $\delta_{CP} = \pi/2$ ruled out at greater than 4 σ for all values of θ_{23}

NOvA atmospheric mixing angle limits, θ_{23}

Best fit in normal hierarchy and θ_{23} upper octant

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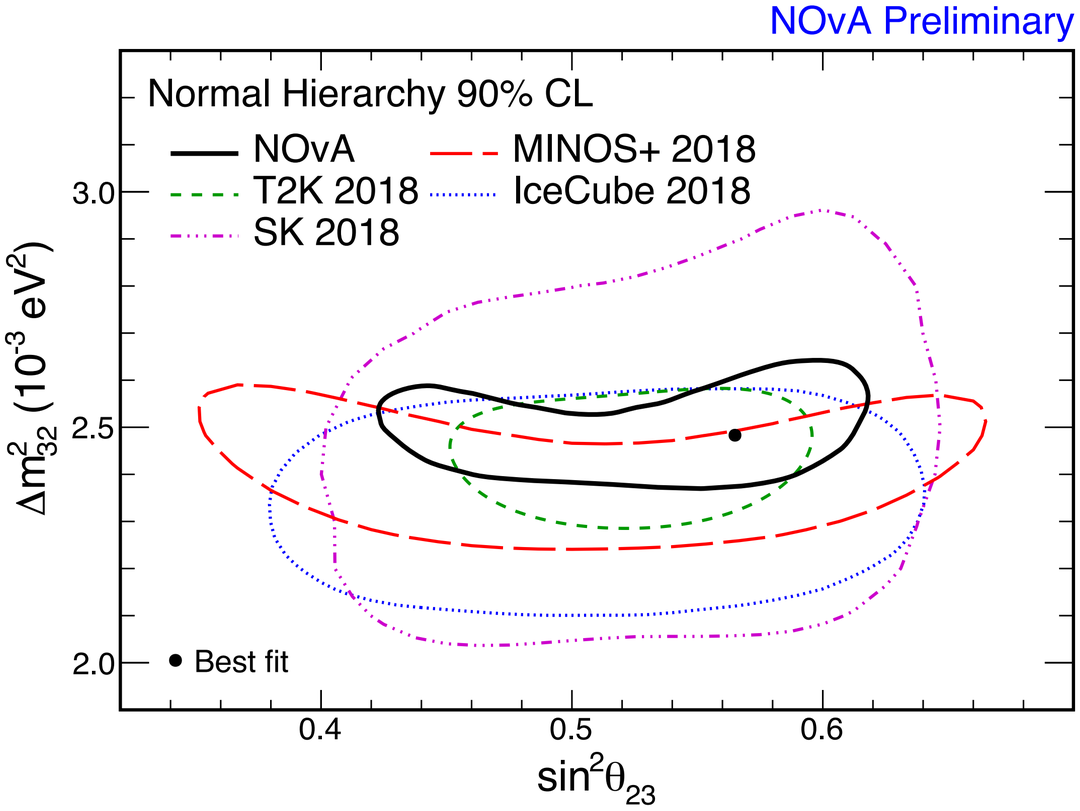
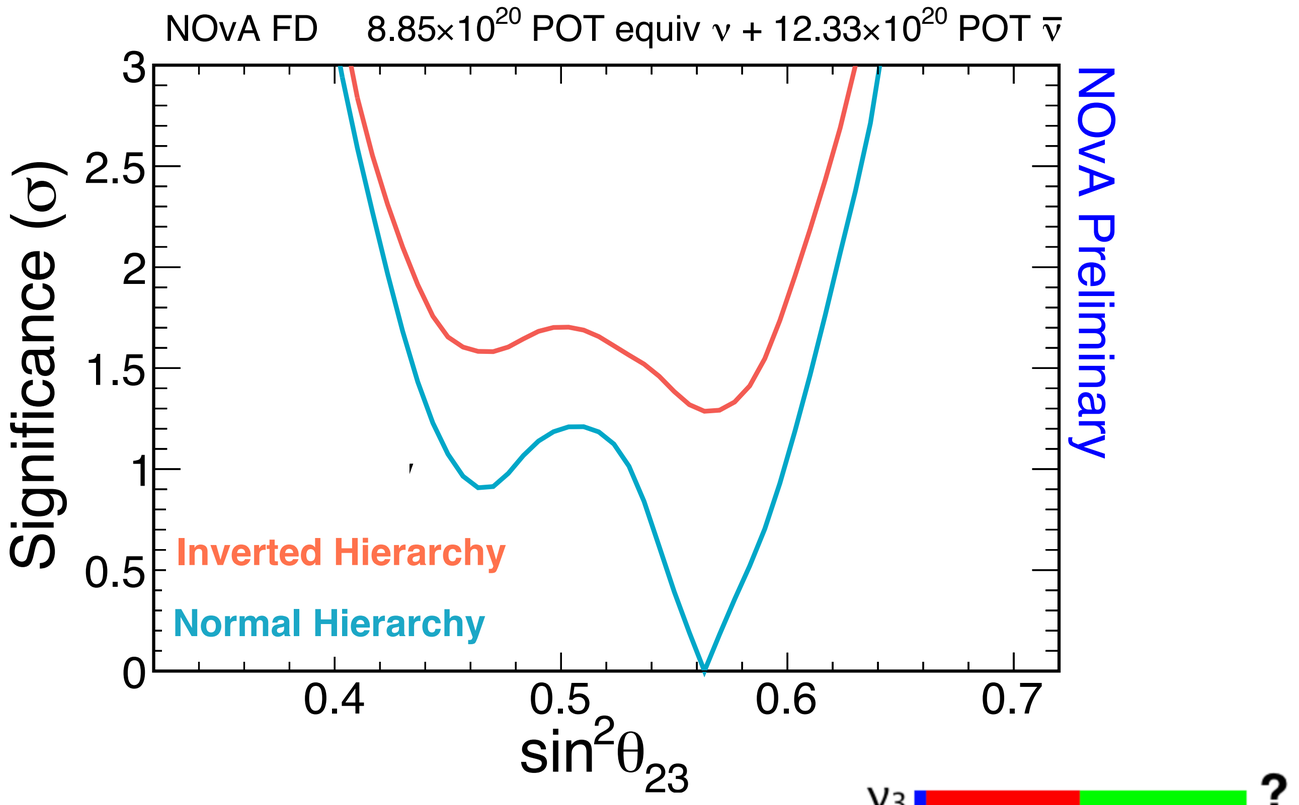
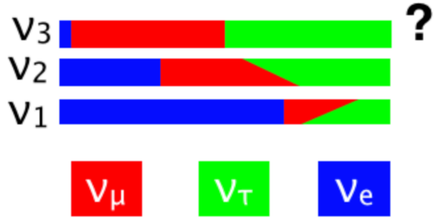
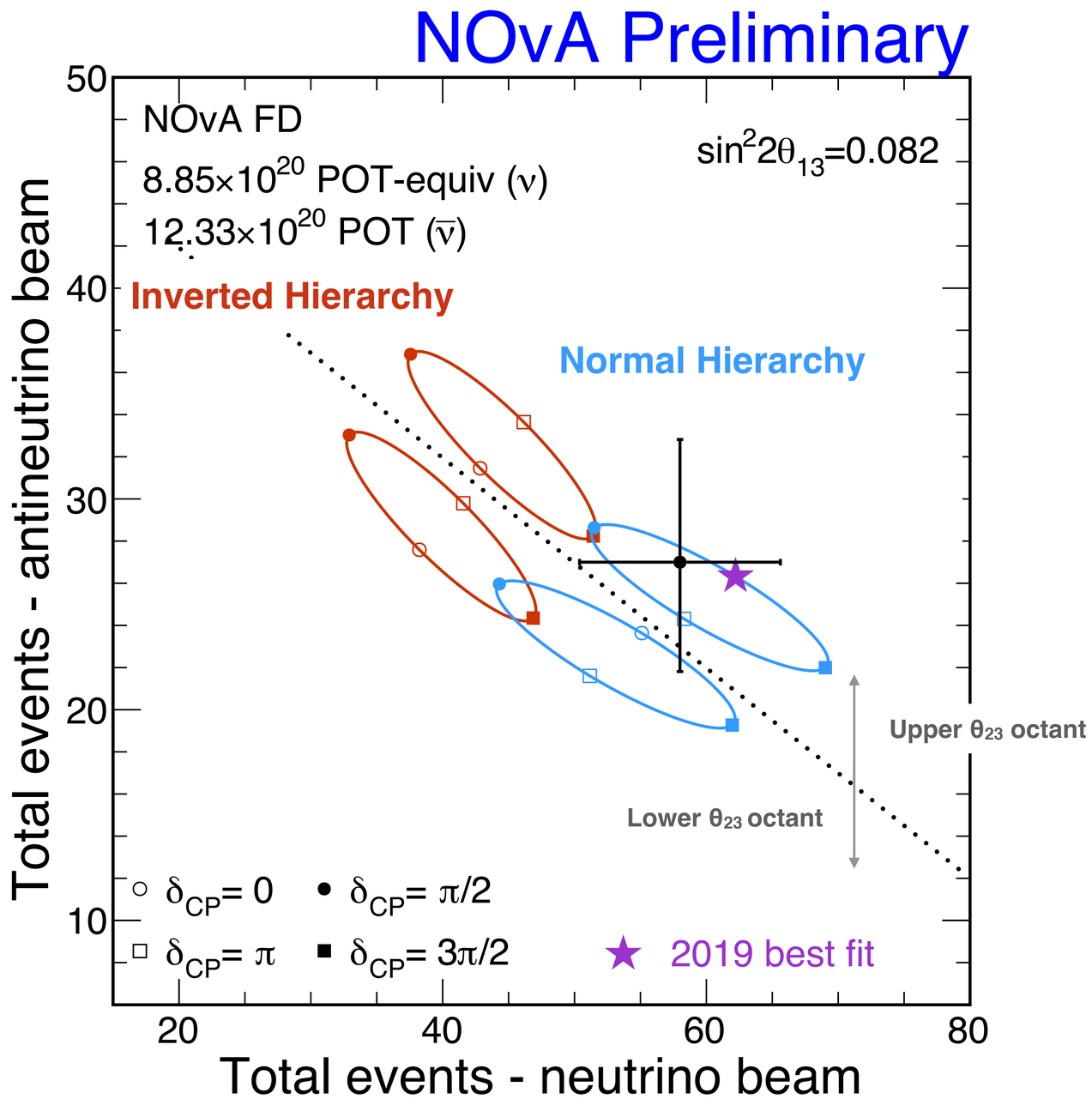






Lower octant, $\sin^2\theta_{23} < 0.5$, disfavored at 1.6σ

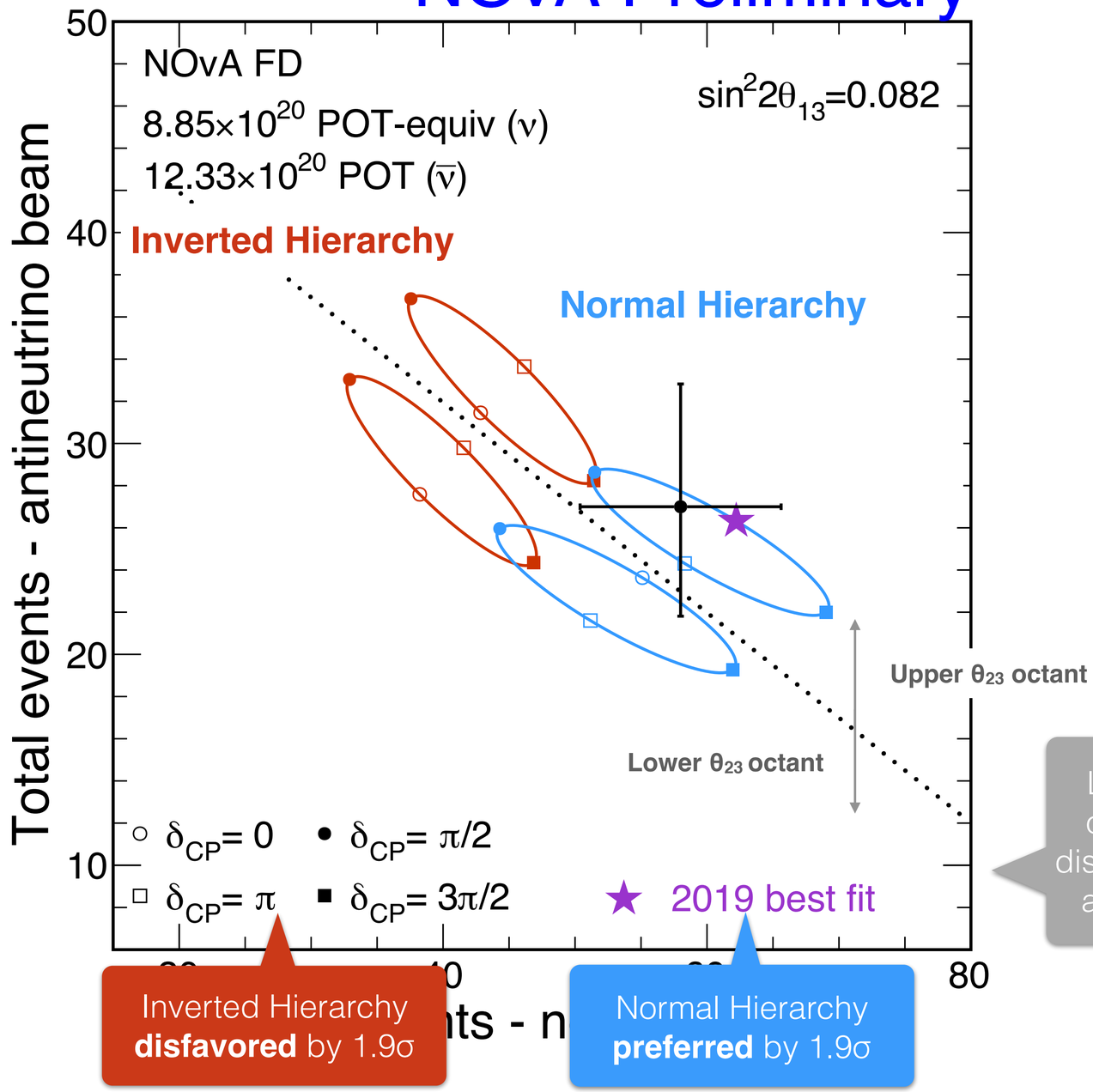
Maximal mixing, $\sin^2\theta_{23} = 0.5$, disfavored at 1.5σ



Values used in bi-probability

Inverted Hierarchy	$\Delta m^2_{32}=-2.54\times10^{-3}\text{eV}^2$
Normal Hierarchy	$\Delta m^2_{32}=+2.48\times10^{-3}\text{eV}^2$
Upper θ_{23} octant	$\sin^2\theta_{23}=0.56$
Lower θ_{23} octant	$\sin^2\theta_{23}=0.48$

NOvA Preliminary



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Upper θ_{23} octant	$\sin^2\theta_{23}=0.56$
Lower θ_{23} octant	$\sin^2\theta_{23}=0.48$

	Inverted Hierarchy	Normal Hierarchy
Upper octant $\sin^2\theta_{23} > 0.5$	Disfavored 1.8σ	Best fit
Lower octant $\sin^2\theta_{23} < 0.5$	Disfavored 2σ	Disfavored 1.6σ

Lower octant disfavored at 1.6σ

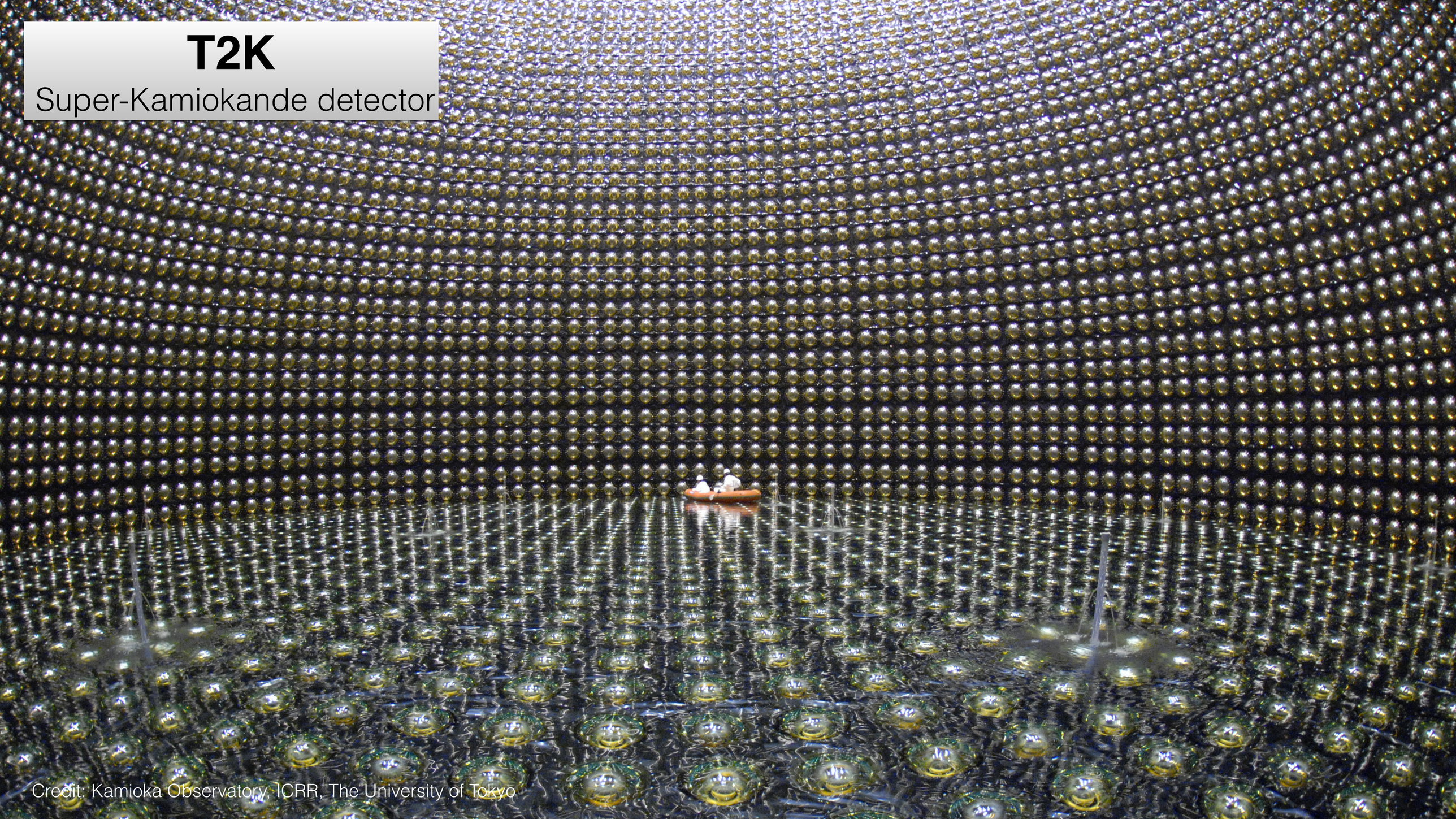
Inverted Hierarchy **disfavored** by 1.9σ

Normal Hierarchy **preferred** by 1.9σ

Within best fit region, Normal Hierarchy upper octant, all values of δ_{CP} allowed at 1.1 σ

T2K

Super-Kamiokande detector

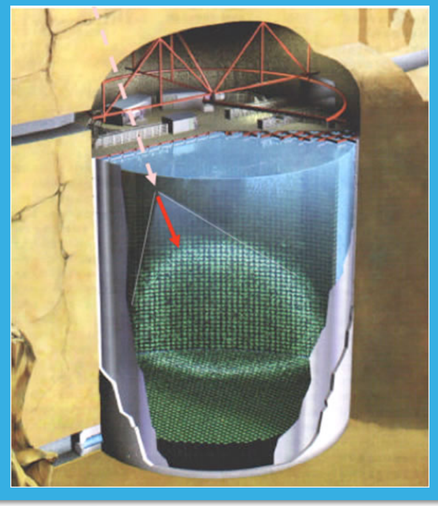


Credit: Kamioka Observatory, ICRR, The University of Tokyo

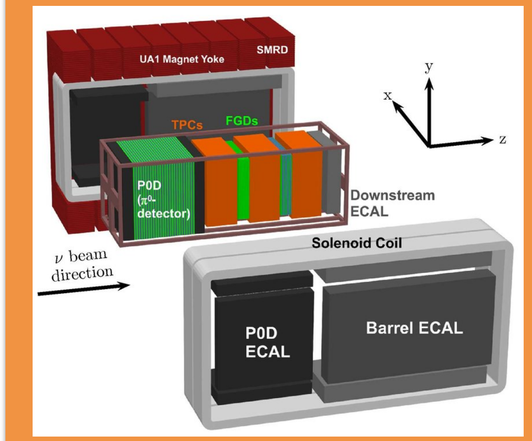
T2K: Off-axis long-baseline neutrino oscillation experiment

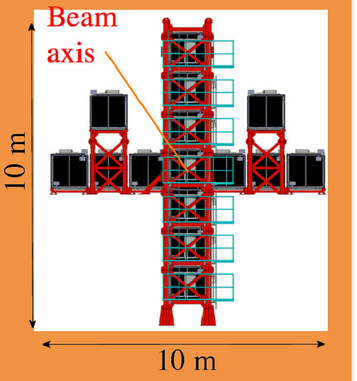
Off-axis beam gives narrow band neutrino beam at 600 MeV

Far Detector, Super-Kamiokande

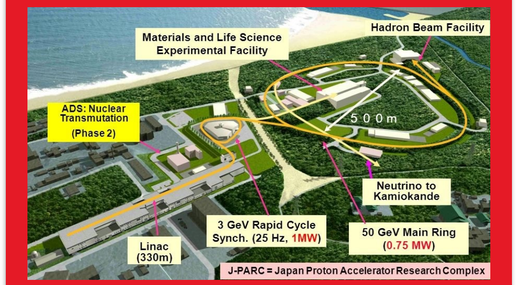


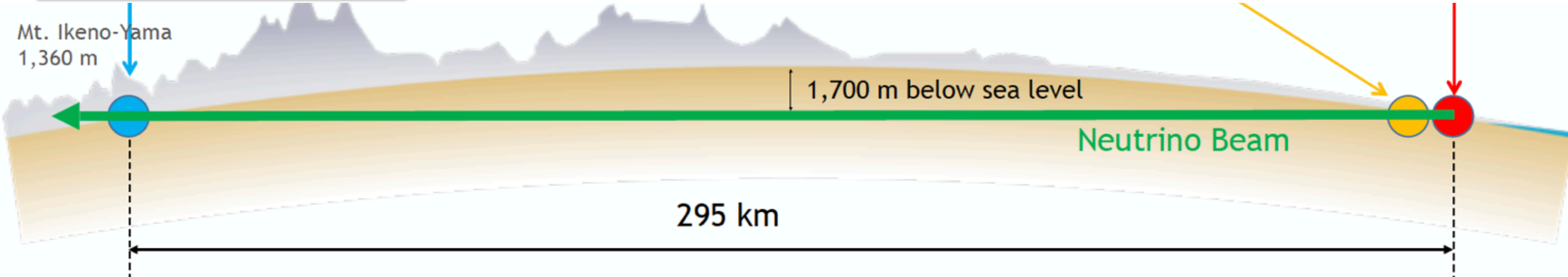
Near Detectors: ND280 and INGRID





J-PARC

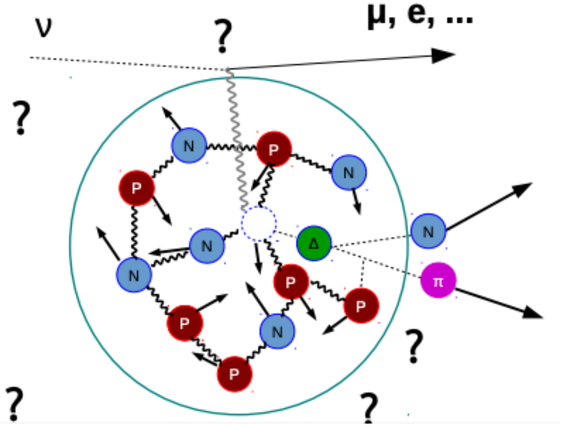




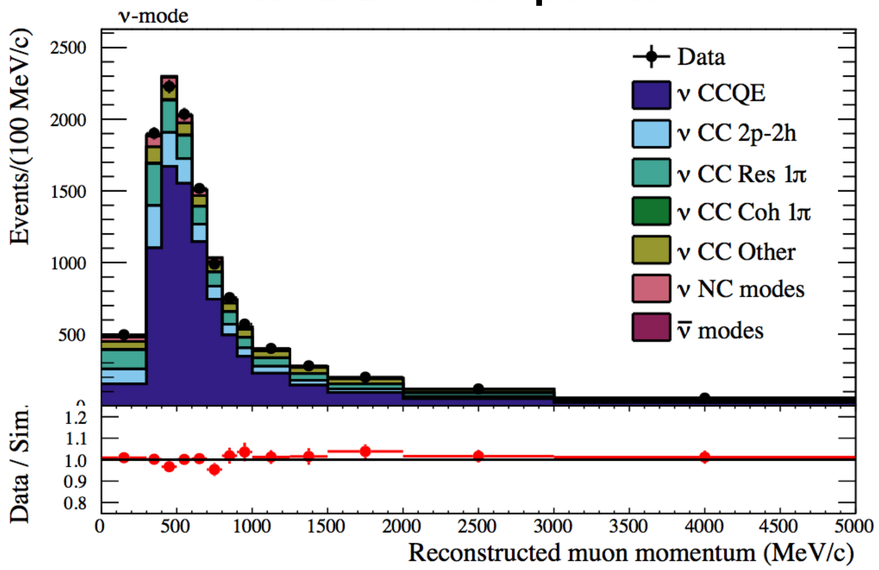
Challenge of Modeling Neutrino Interactions

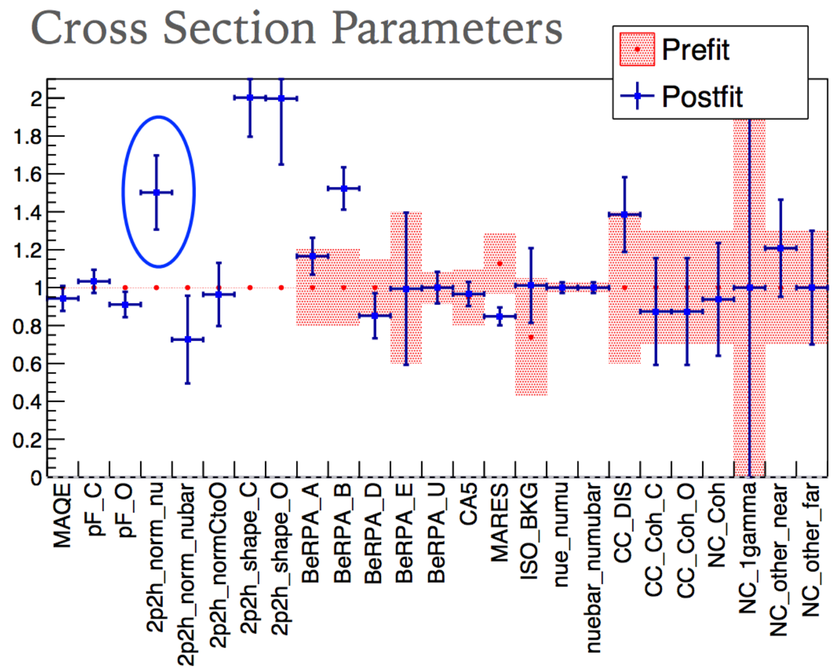
The modeling of neutrino beams and interactions with complicated nuclei create a challenge for oscillation measurements

Modeling and systematic uncertainties constrained using **near detector**



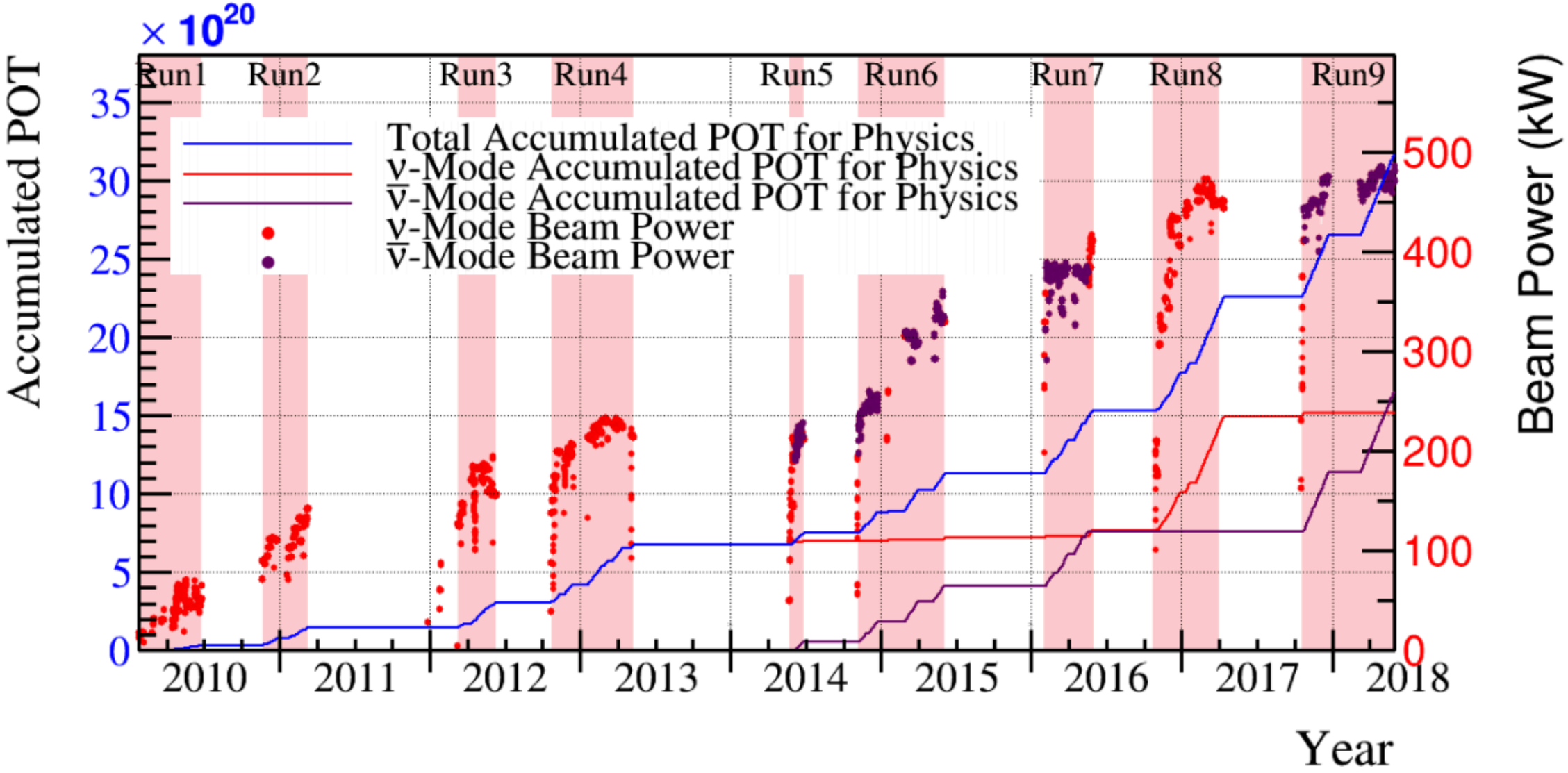
Near Detector post fit





T2K selected samples in ND based on lepton plus number of pions or tracks which match samples which they select in Super-K

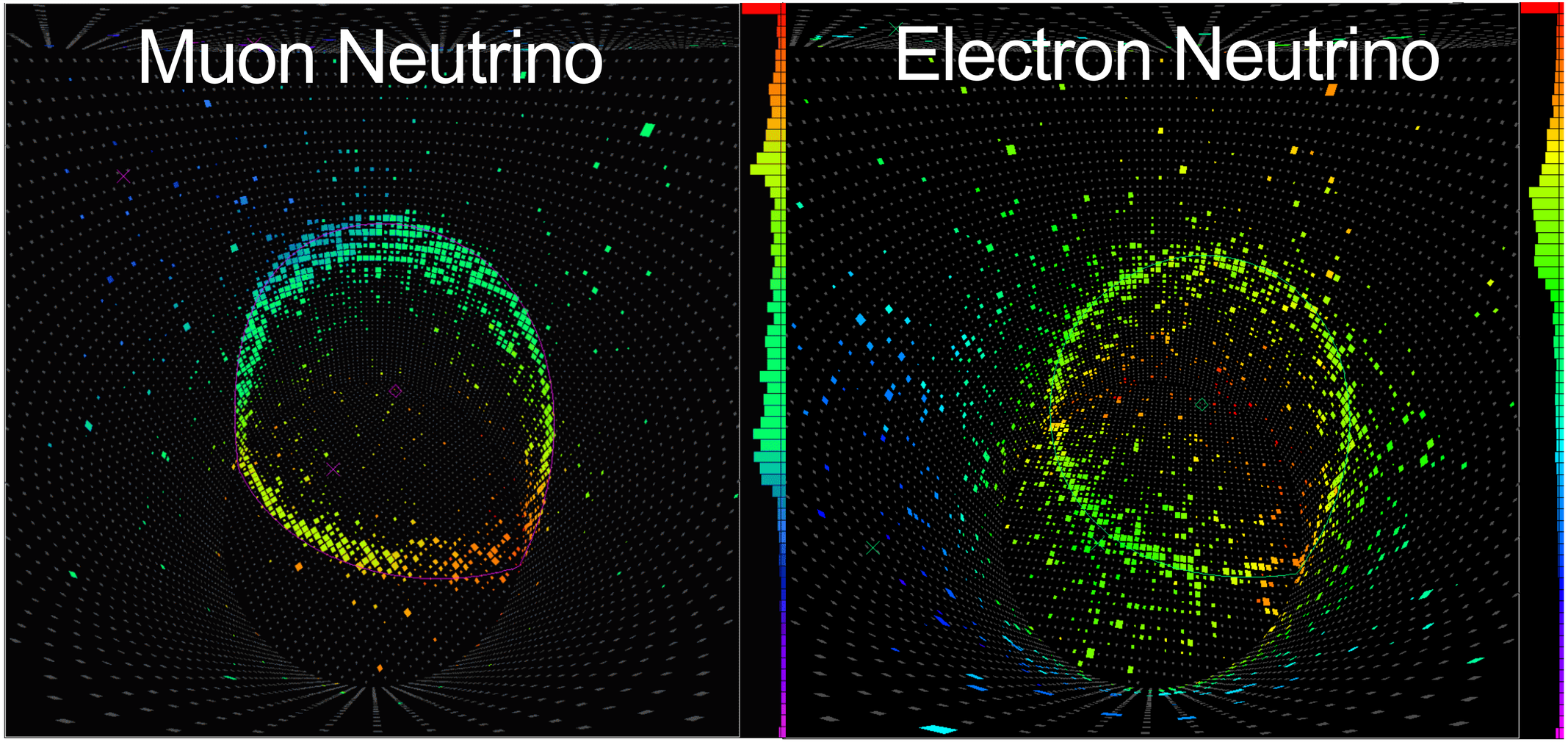
Used large number of parameters to both fit near detector data to produce central value for Super-K prediction and to constrain the systematic uncertainties



Antineutrino data: ~15×10^{20} Protons-on-Target

Neutrino data: ~31×10^{20} Protons-on-Target collected to date

Steadily increasing beam power, beam nominally running now at 500 kW



Far Detector, Super-Kamiokande, is water Cherenkov detector
Stainless-steel tank, 39.3m diameter and 41.4m tall, filled with 50,000 tons of ultra pure water

Detector provides excellent e/μ separation and π^0 rejection.
Select 1-ring, Charged Current Quasi-Elastic enriched sample, and a CC1π+ sample for ν_e appearance.

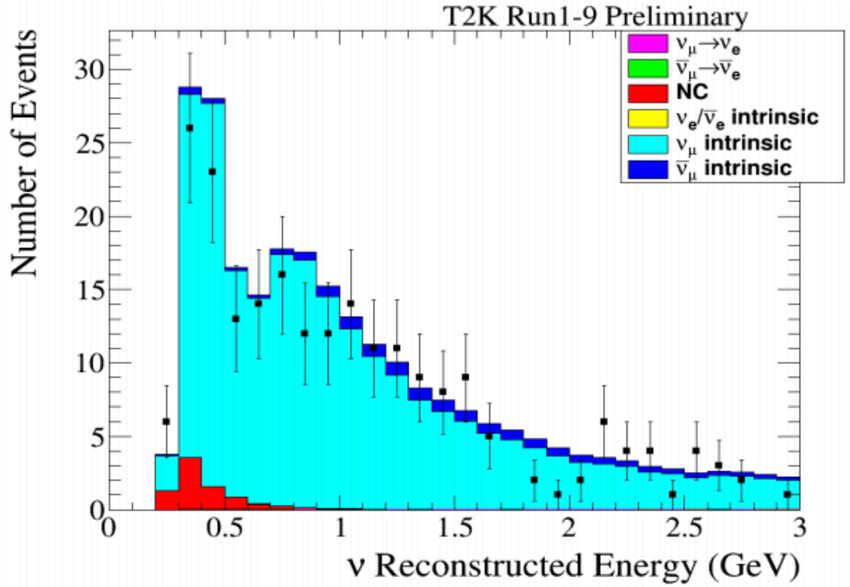
Super-Kamiokande events

In neutrino mode the deficit of μ-like events is compatible with statistical and systematic uncertainties

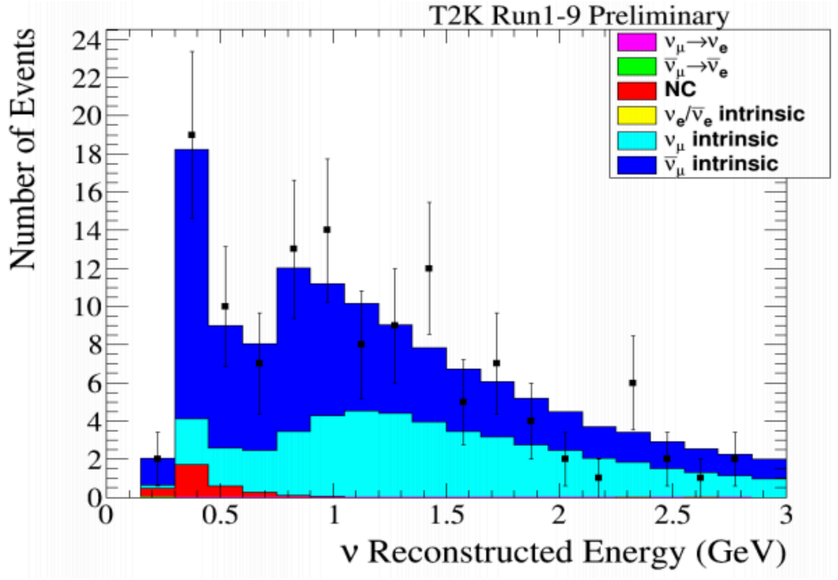
sample	δ = - π /2	δ = 0	δ = + π /2	δ = π	Data
neutrino μ CCQE	272.4	272.0	272.4	272.8	243
anti neutrino μ CCQE	139.2	139.2	139.5	139.9	140
neutrino e CCQE	74.4	62.2	50.6	62.7	75
neutrino e CC1π+	7.02	6.10	4.94	5.87	15
anti-neutrino e CCQE	17.1	19.4	21.7	19.3	15

Observed events at Super-K. predictions assuming Normal Hierarchy reactor constant on θ_{13}

Muon neutrino: Charged current quasi-elastic sample



Muon antineutrino: Charged current quasi-elastic sample



Super-Kamiokande events

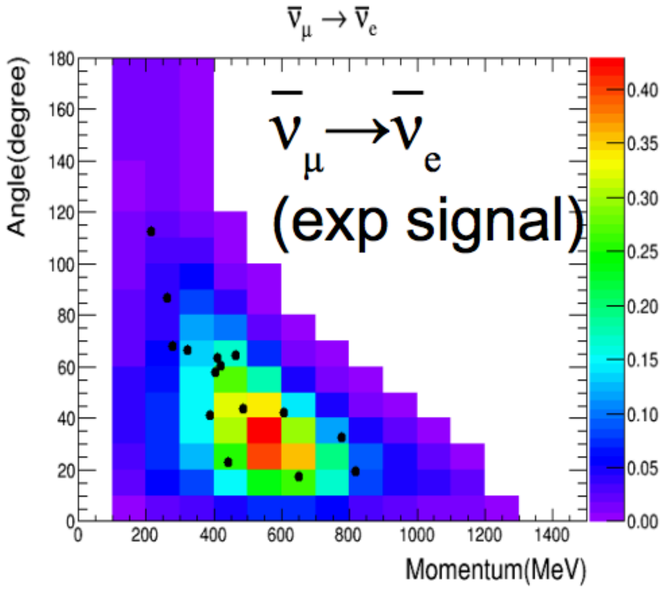
CC1π+ sample, 15 events with prediction of 7.02 max. p-value for fluctuation this significant in any one of the five samples is 12%

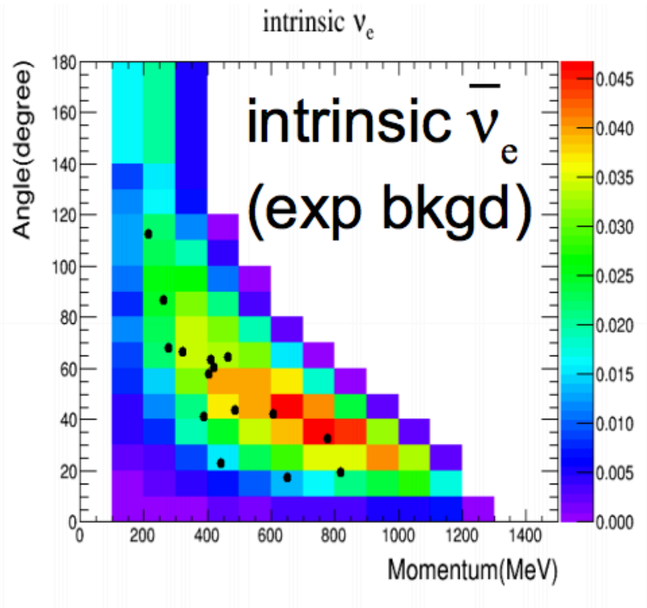
sample	δ = - π /2	δ = 0	δ = + π /2	δ = π	Data
neutrino μ CCQE	272.4	272.0	272.4	272.8	243
anti neutrino μ CCQE	139.2	139.2	139.5	139.9	140
neutrino e CCQE	74.4	62.2	50.6	62.7	75
neutrino e CC1π+	7.02	6.10	4.94	5.87	15
anti-neutrino e CCQE	17.1	19.4	21.7	19.3	15

Observed events at Super-K. predictions assuming Normal Hierarchy reactor constant on θ_{13}

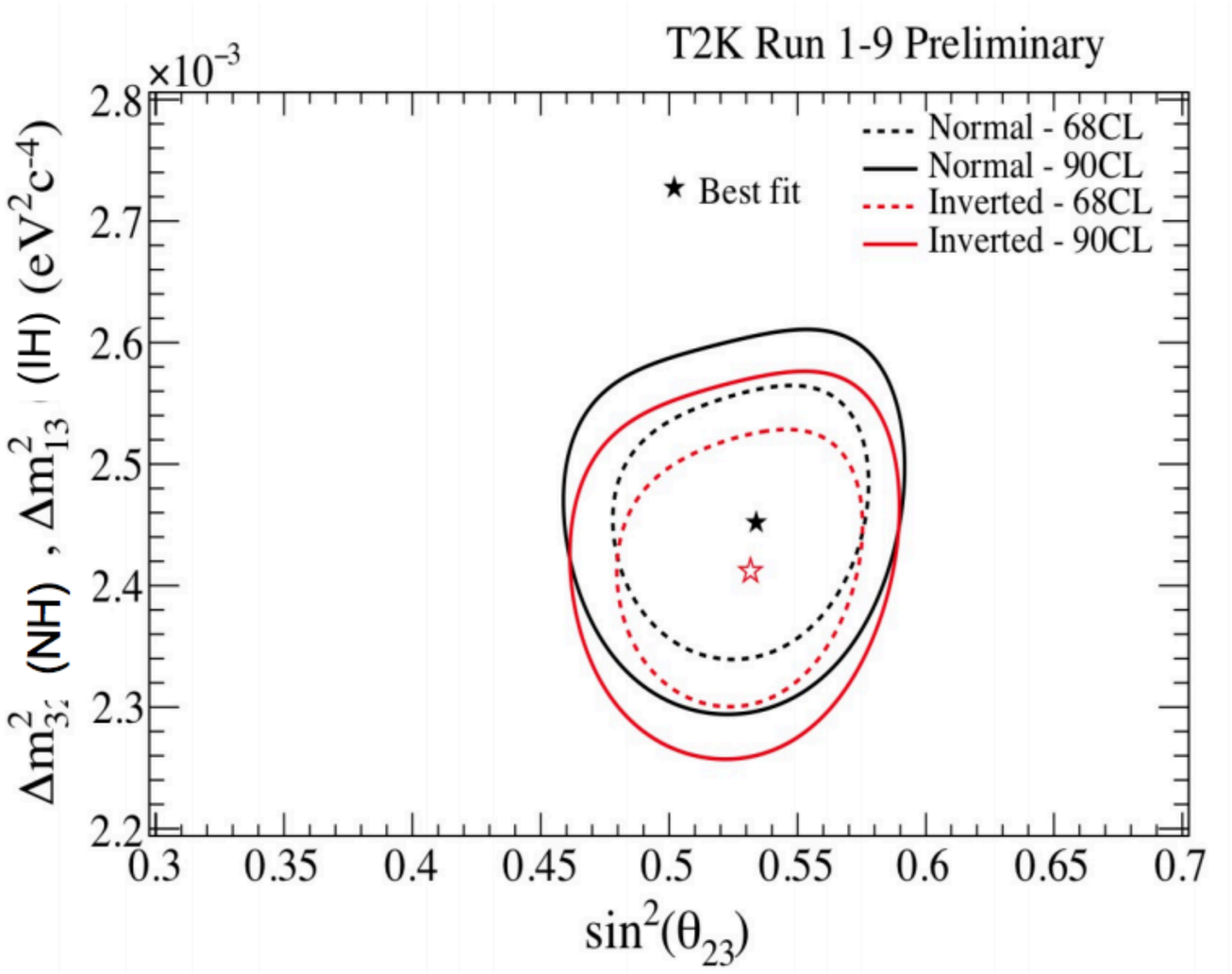
Electron antineutrino results
Expect 9.4 events in the case of no ν_e appearance, and observed 15 events.

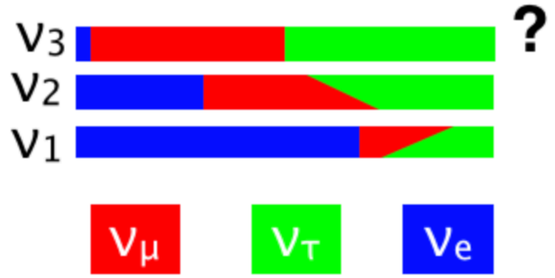
No $\bar{\nu}_e$ appearance excluded at 2σ





T2K Atmospheric mixing angle limits, θ_{23}





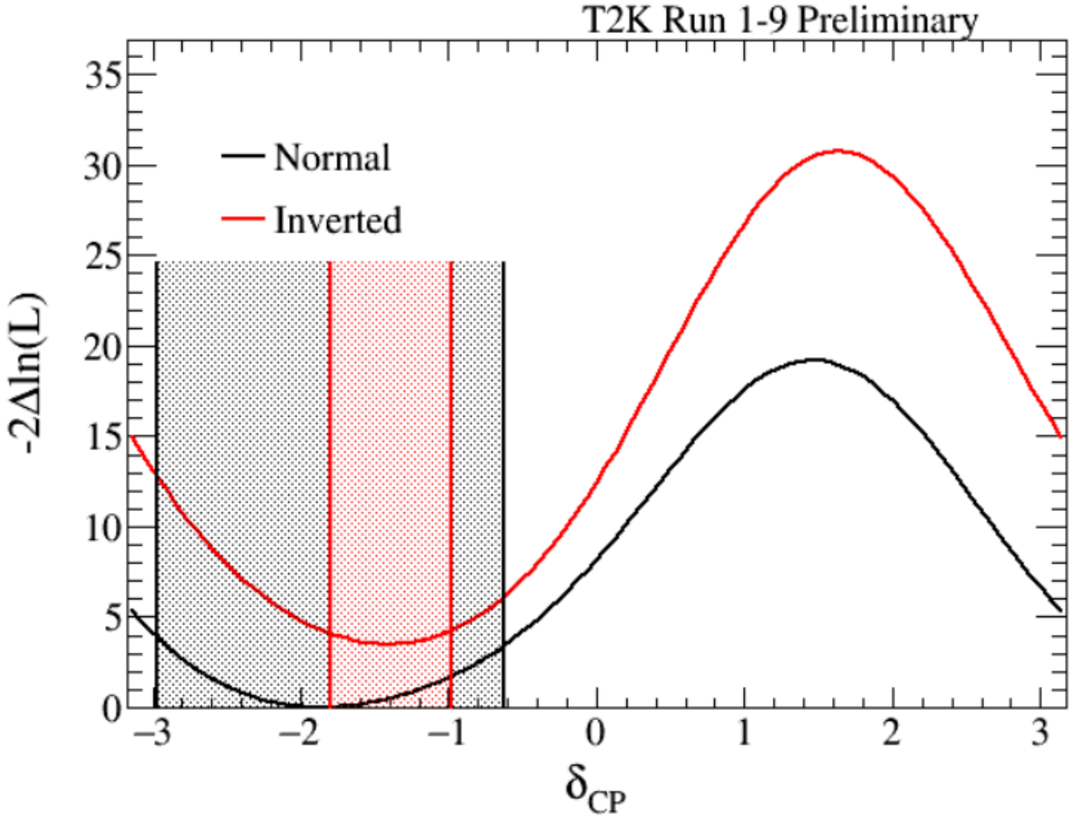
T2K data compatible with maximal mixing

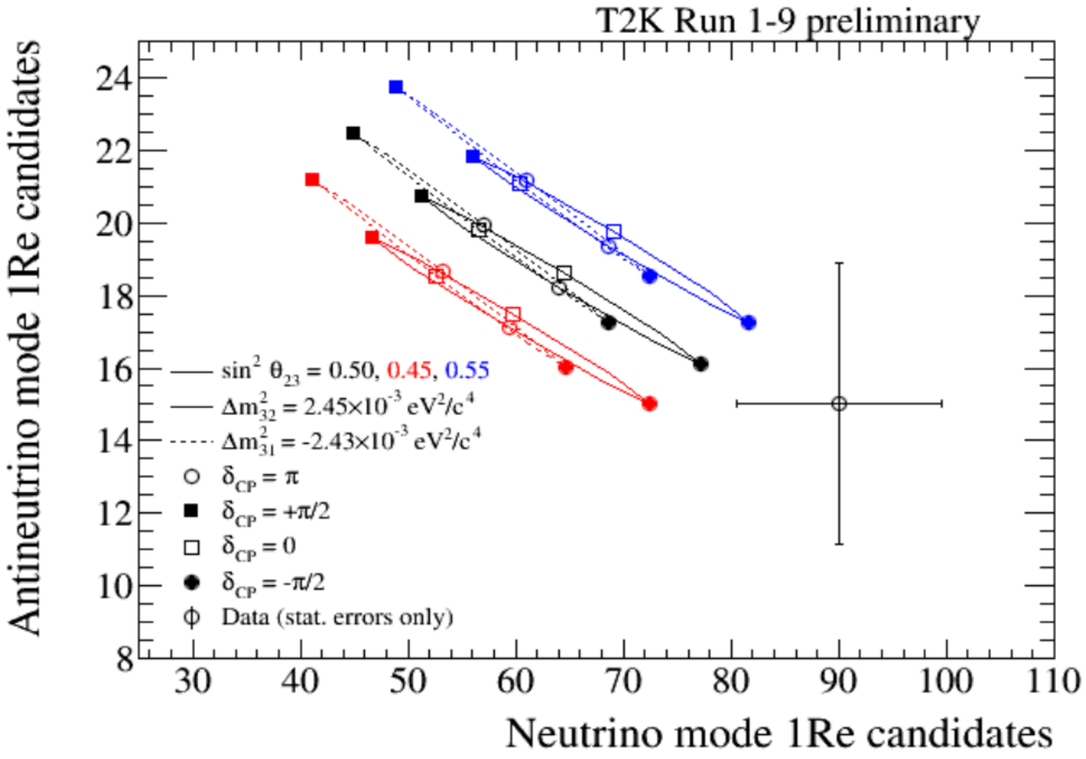
Parameter	Best Fit NH (HI)	±1σ NH (IH)
$\sin^2\theta_{32}$	0.54 (0.53)	[0.490,0.558] ([0.496,0.560])
$\lvert\Delta m^2_{32}\rvert$ (10^{-3}eV²/c⁴)	2.46 (2.43)	[2.370,2.498] ([2.362,2.502])
$\sin^2\theta_{13}$	0.0268 (0.0305)	[0.0222,0.0319] ([0.0253,0.0369])

Includes reactor constraint

CP phase, δ_{CP}, at T2K

The vertical lines show the corresponding allowed 95% confidence interval





T2K data prefer values of δ_{CP} ~-π/2

Mostly driven by the large number of events observed in the e-like sample in neutrino mode

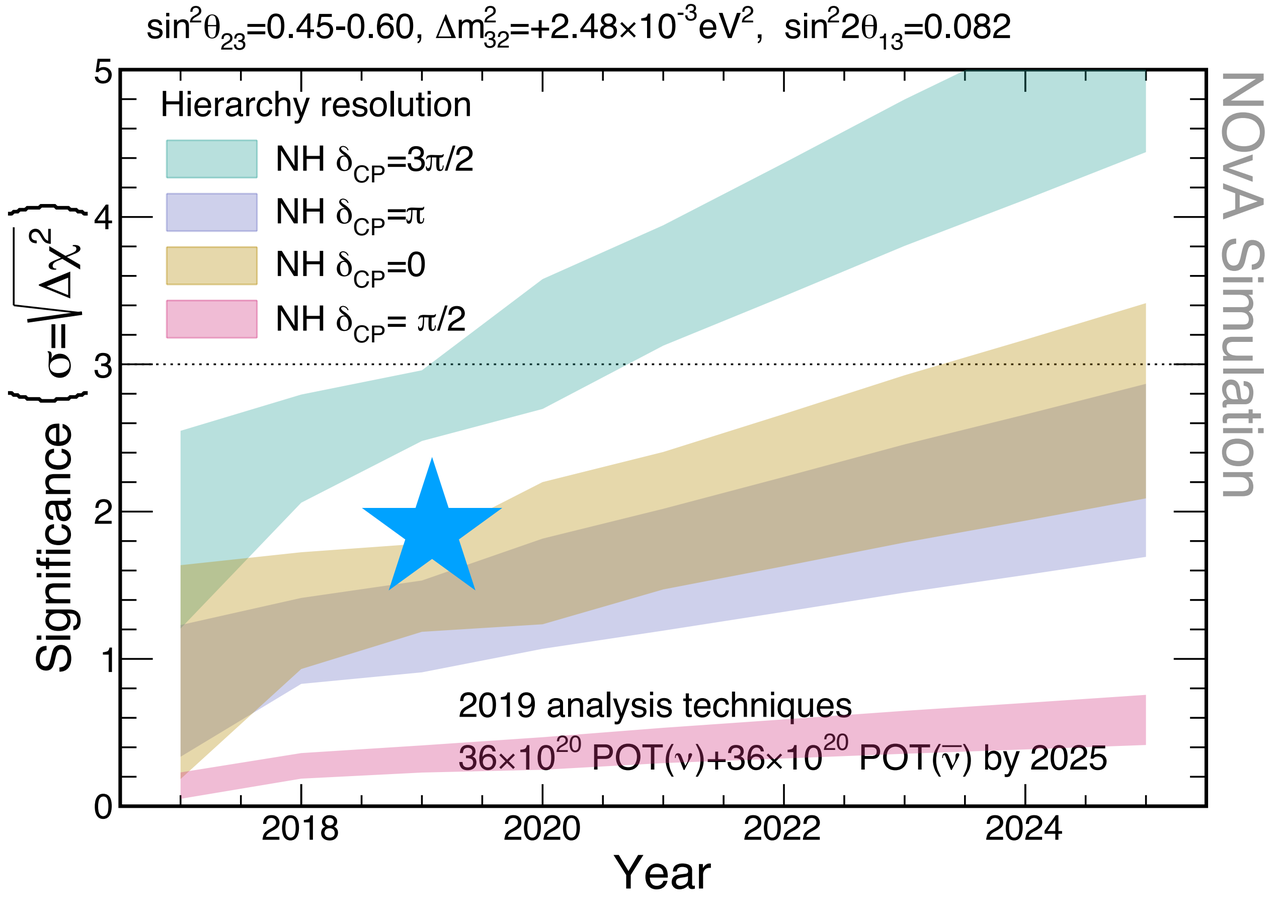
No inverted hierarchy values allowed at < 2σ

CP conservation (δ_{CP} = 0, π) disfavored at 2σ for both mass hierarchies

C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2σ	[-2.97, -0.63]	[-1.78, -0.98]

Looking forward

NOvA will continue take data until ~2025
Plan to run 50% neutrino, 50% anti-neutrino going forward

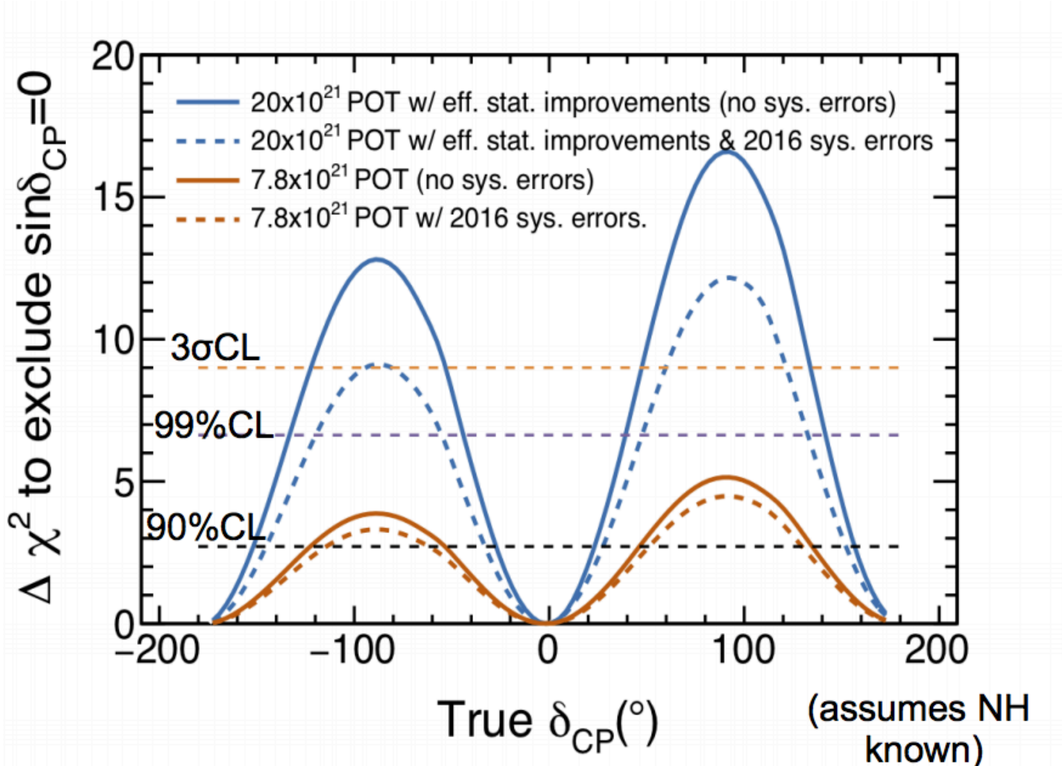


Based on current analysis:
- Potential 3-5σ sensitivity to **hierarchy** with favorable parameters
- Possible >2σ sensitivity to **CP violation**

- Proposed accelerator and beam upgrade projects which will enable beam up to ~1 MW
- Test-beam program underway to improve detector modeling and reduce systematic uncertainties

Looking forward

- Super-K undergoing Gd doping this summer, improves neutron detection capability and may provide wrong sign background constraint in T2K anti-electron data
- T2K initiated Near Detector upgrade project, aim to reduce systematics to 4%
- Approved beam upgrades allow 750 kW operation, with eventual upgrades to 1.3 MW (2021)
- Proposal to collect 8x more data by 2027 (when HK starts), total of 20x10^{21} POT



Enables T2K to have up to 3σ CP violation sensitivity

Sensitivity improves beyond 3σ with reduced systematic errors

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T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2018

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually. The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.

T2K-NOvA Joint Analysis Workshop

25-27 February 2019
Fermilab
US/Central timezone

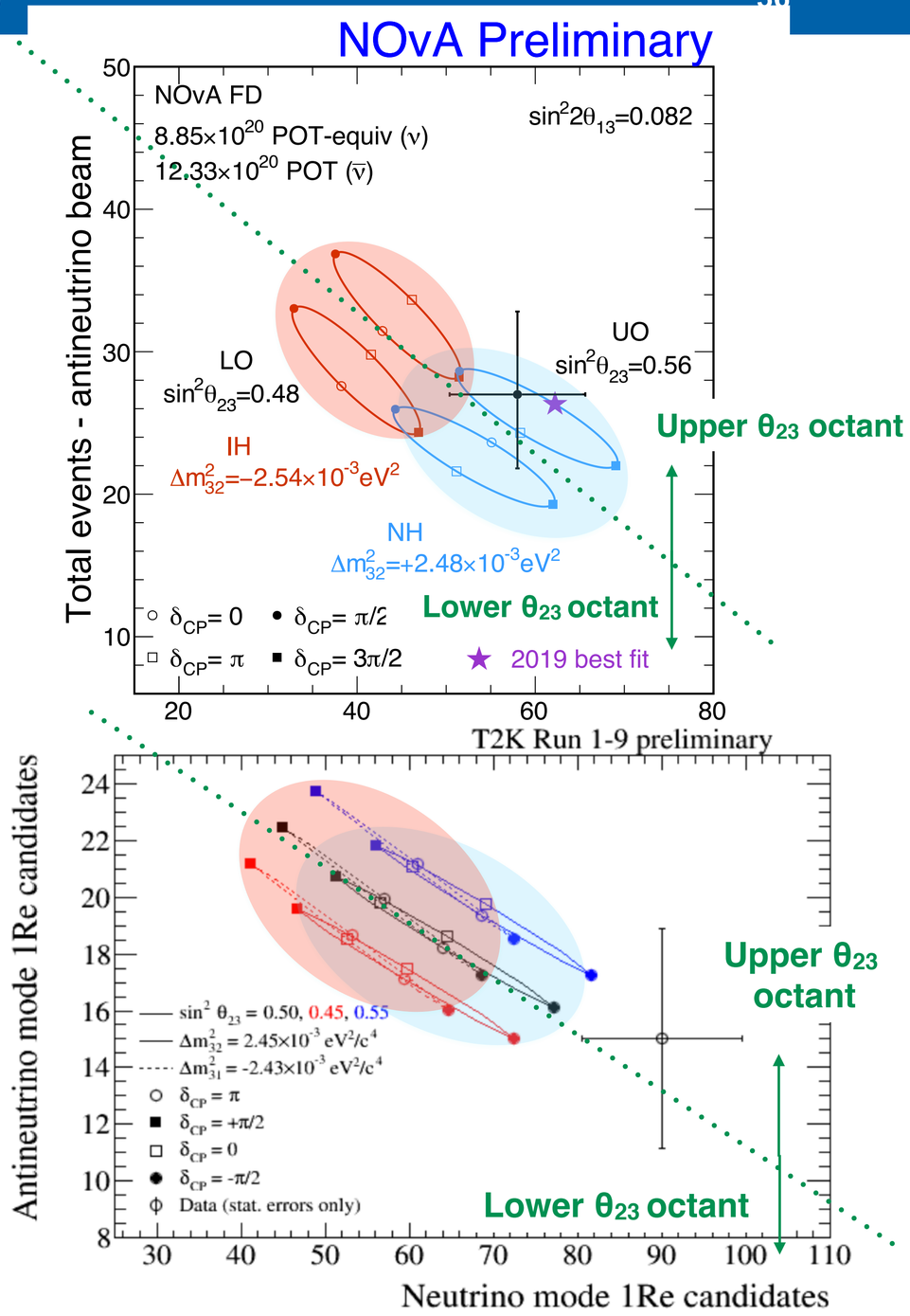
Overview

A 3 day NOvA-T2K joint workshop at Fermilab

Slide from G. Davies

Conclusions

- Exciting active program in long-baseline neutrino physics from both NOvA and T2K
  - Both NOvA and T2K data have preference for Normal Hierarchy over Inverted Hierarchy
  - NOvA and T2K best fit in upper octant of θ_{23}, but at NOvA lower octant and maximal mixing only disfavored at ~1.5σ, and T2K results consistent with maximal mixing
  - At T2K CP conservation ($\delta_{CP} = 0, \pi$) disfavored at 2σ for both mass hierarchies, for NOvA all δ_{CP} values in normal hierarchy upper octant allowed at 1.1σ
  - NOvA antineutrino results 4.4 observation for electron anti-neutrino appearance
- Both experiments have exciting upgrade programs in the works, and are aiming for joint results for 2021



Thanks for all the people I took plots and slides from, including Mayly Sanchez, Morgan Wascko,Ciro Riccio, Jeremy Wolcott and others