Long-baseline and atmospheric neutrino experiments

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T2K

Introduction

- How do neutrino oscillation analyses work?
- Reminder of long-baseline and atmospheric experiments
- Introduction to each of the currently running experiments and what's new recently
- Highlights of recent results

PMNS matrix

- Ignoring overall phase, general 3x3 unitary matrix can be broken down into 3 rotation matrices and a complex phase

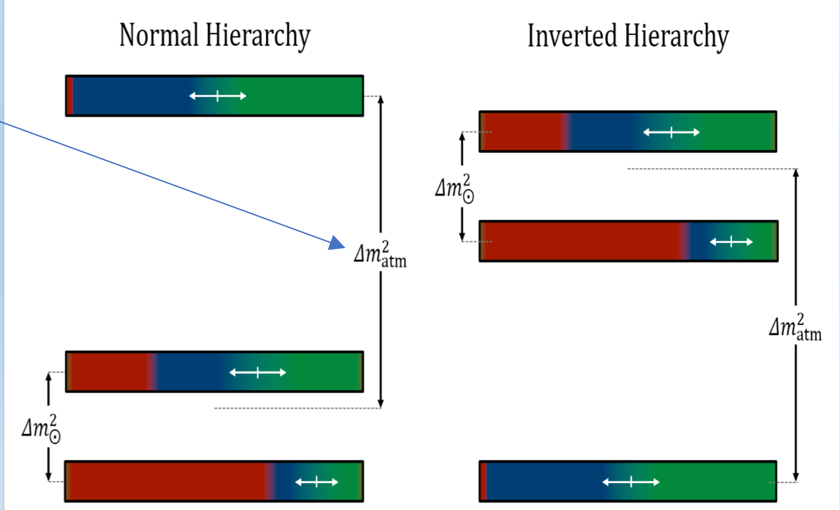
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Oscillation probability in vacuum given by:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

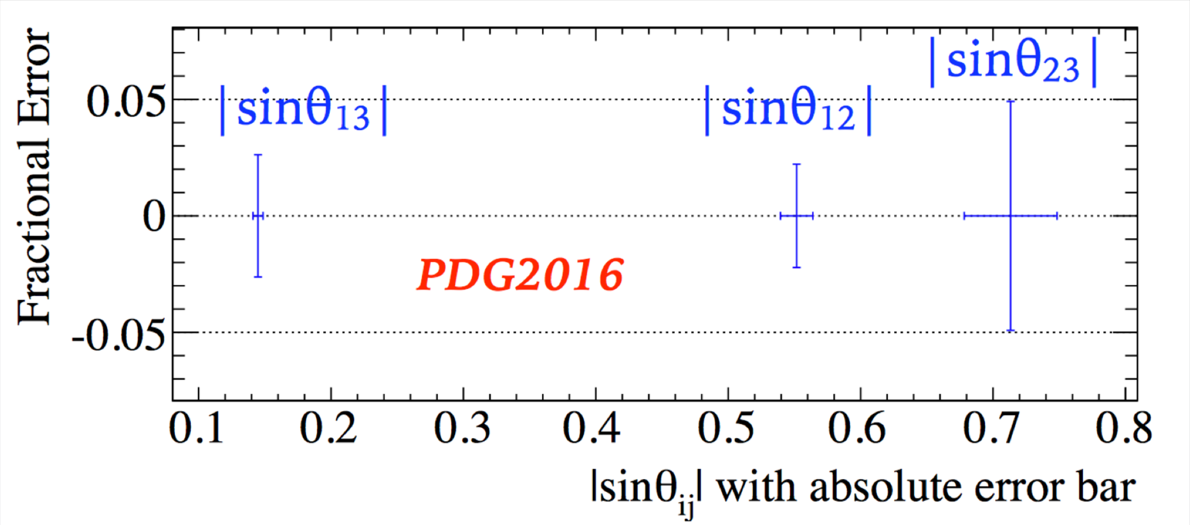
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

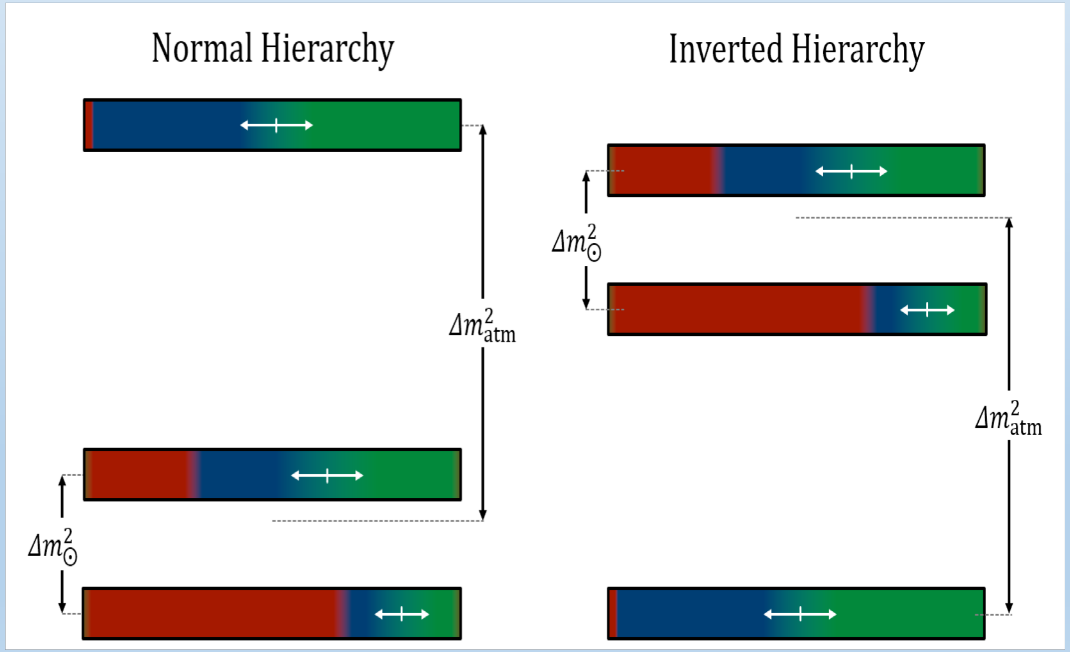
- Distance scale of oscillation set by squared mass difference and energy
  - For few GeV energies anything with ν_3 leads to O(100-1000 km) oscillations
- Amplitude of oscillation decided by mixing angles
- CPT symmetry implies $P(\alpha\rightarrow\beta) = P(\bar{\beta}\rightarrow\bar{\alpha})$
- Non-zero complex phase, δ_{CP}, would lead to CP violation



State of measurements

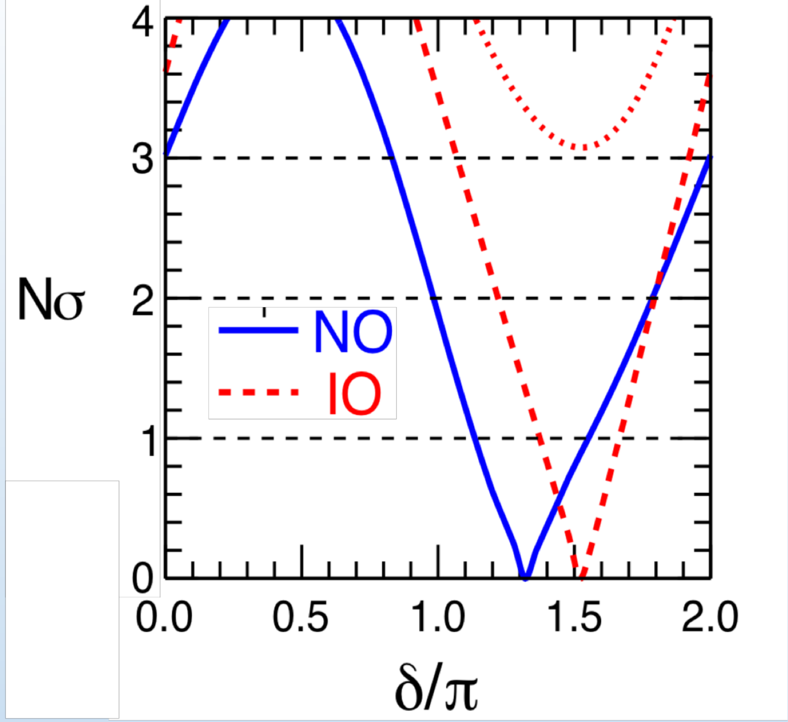
- Sine of mixing angles measured to better than 5%
- Whether $\sin^2\theta_{23}$ is maximal is an area of interest
- Mass hierarchy not yet known
  - Matter effect alters vacuum oscillation probability giving long-baseline/atmospheric experiments sensitivity to hierarchy



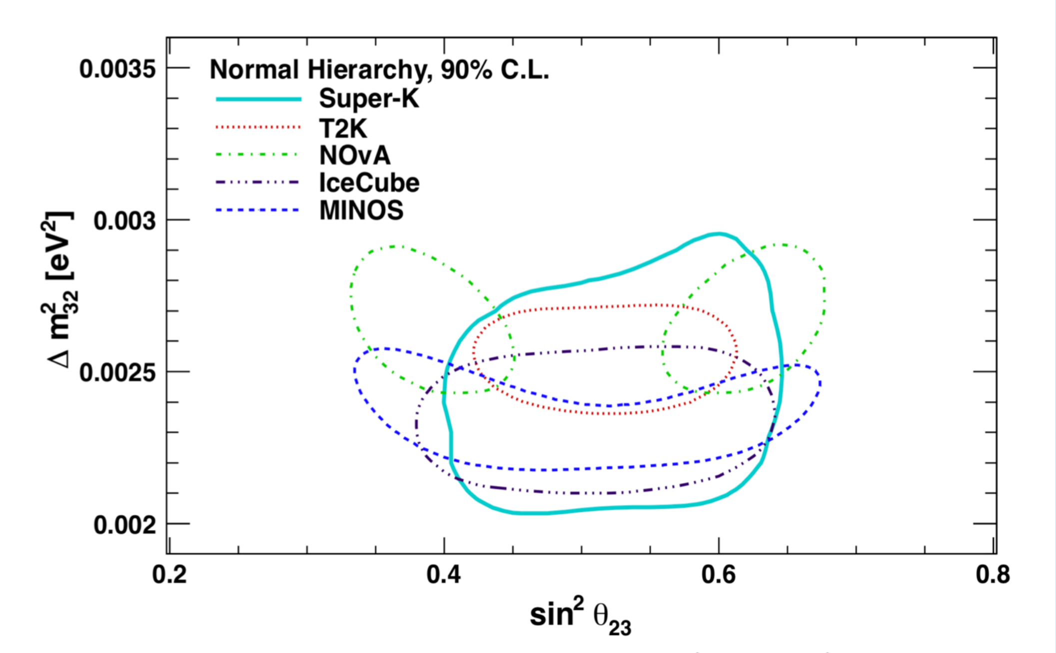


State of measurements

- δ_{CP} as yet unmeasured
  - Will show hints from long-baseline results of preference for non-zero δ_{CP}
- Atmospheric and long baseline experiments lead measurements in $\sin^2\theta_{23}$, Δm^2_{32} and δ_{CP}

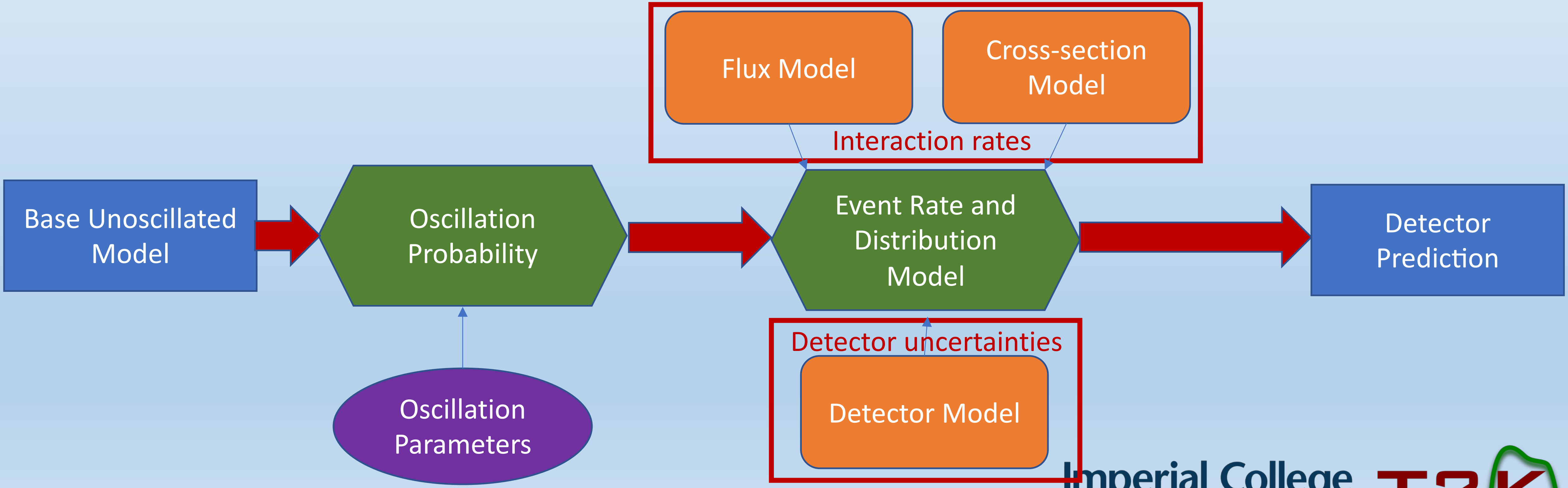


Capozzi et al, arxiv:1804:09678



How to do a neutrino oscillation analysis

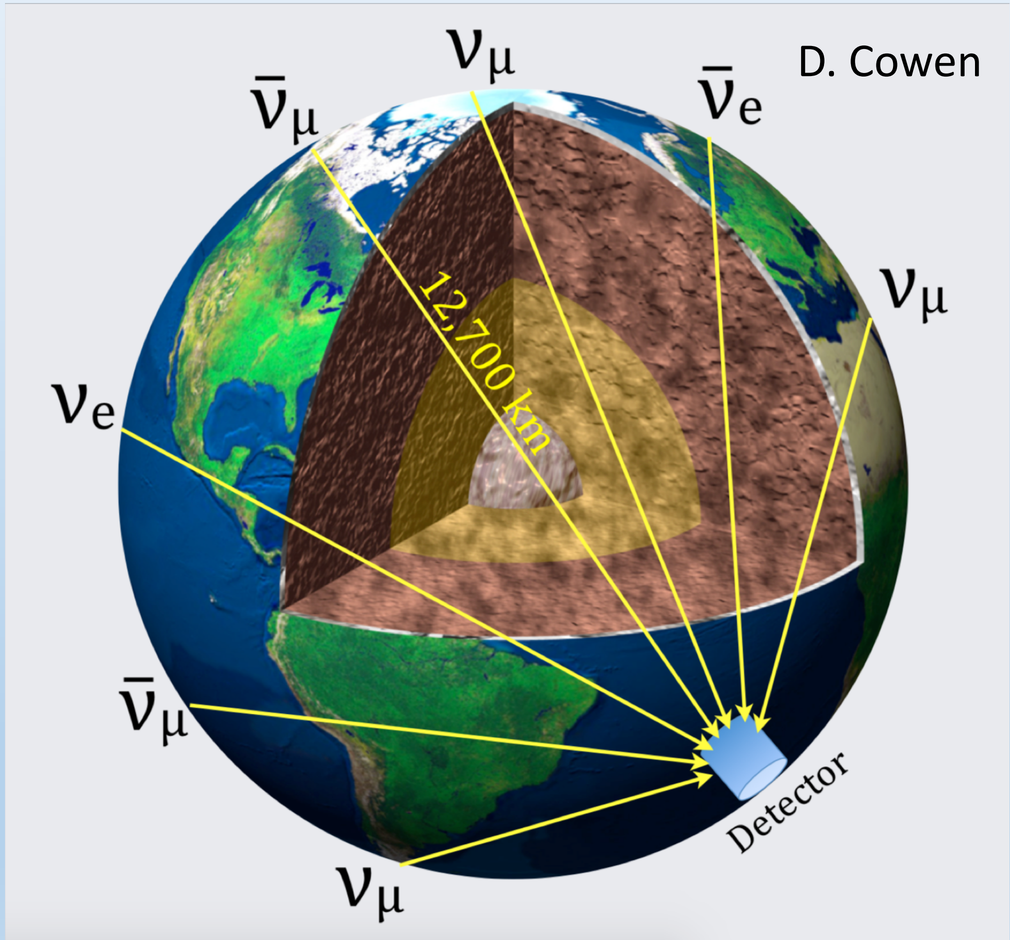
- Like any particle physics experiment make prediction and compare to data
- Need to ensure experiment can constrain non-oscillation elements of model
  - Cross-section model highly dependent on nuclear effects (see K. Mcfarland's talk)
  - Incoming neutrino energy not known in data on an event by event basis $E_{reco} \rightarrow E_{true}$ mapping important (can go wrong due to e.g. multinucleon interactions)



Atmospheric oscillations

Overview of atmospheric experiments

- Cosmic ray interactions in the atmosphere create particle showers including neutrinos
- Oscillation baseline depends on zenith angle
- Most oscillations are $\nu_\mu \rightarrow \nu_\tau$
- Large number of events allows sub-dominant effects to be studied



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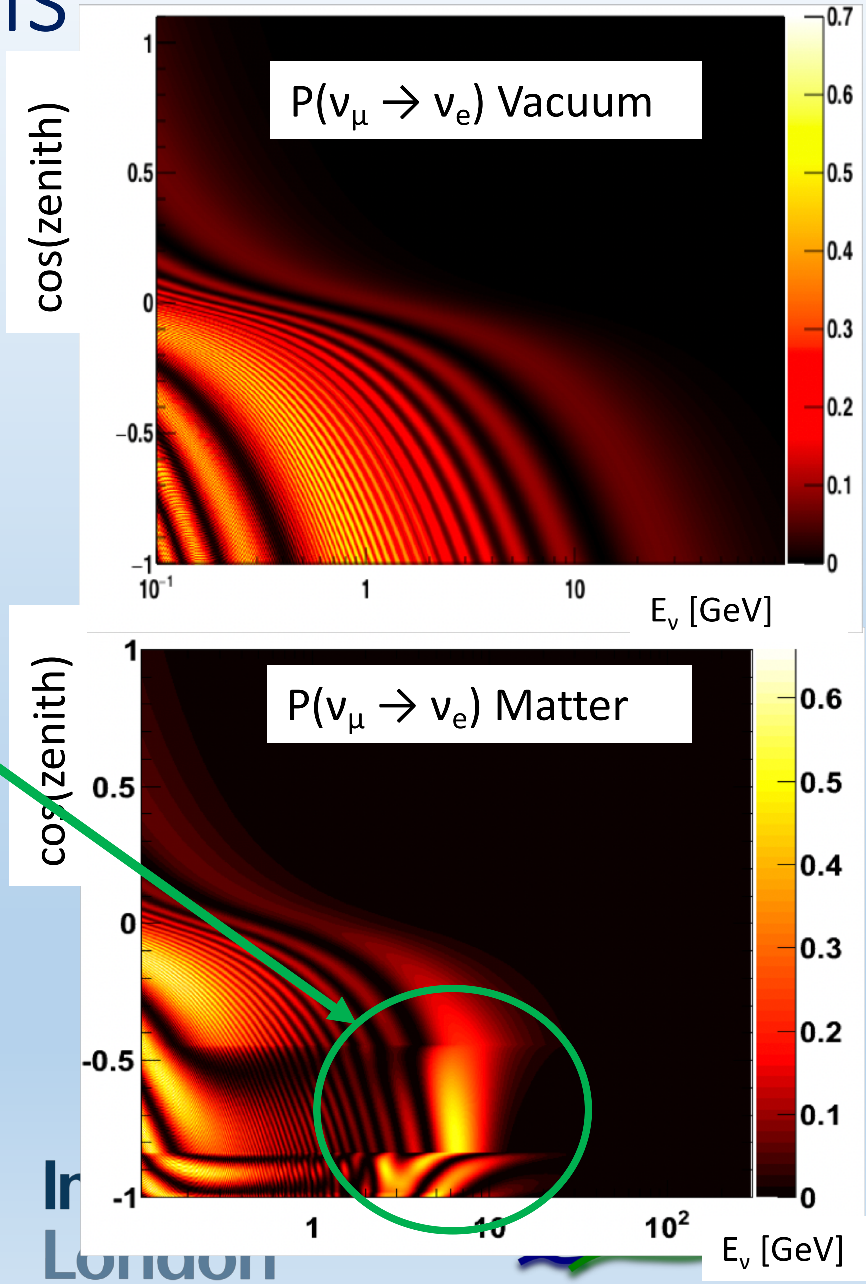
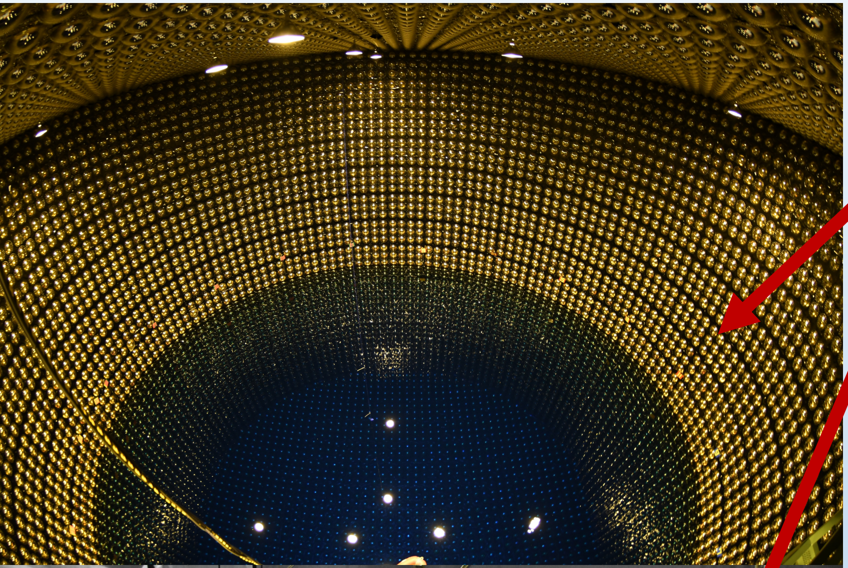
What do atmospheric oscillations look like?

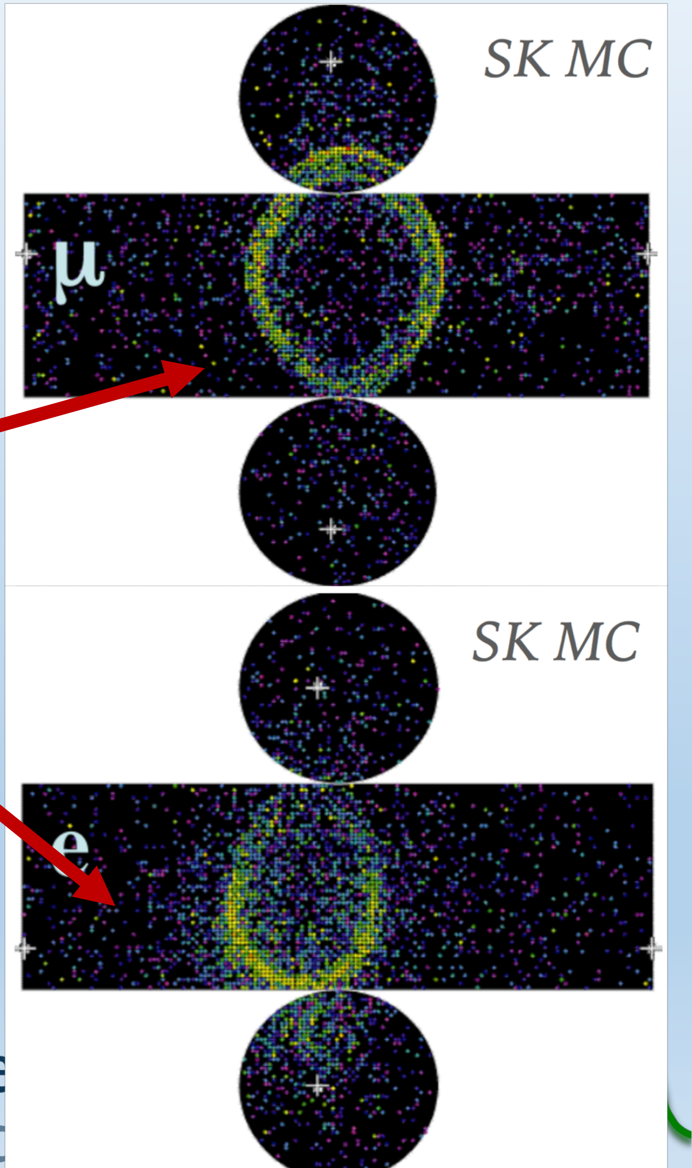
- Oscillation frequency determined by Δm^2_{32}
- Resonant effects from matter effects
  - Only for ν in normal hierarchy
  - Only for $\bar{\nu}$ in inverted hierarchy
- Size of the effect is $\sin^2(\theta_{23})$ dependent



Super-K

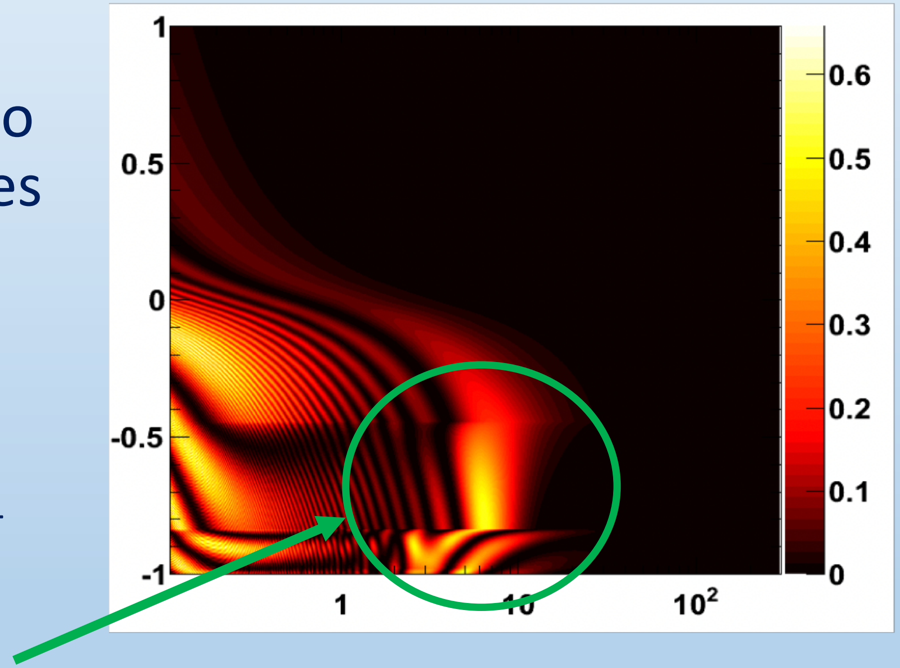


- 50kt Water-Cherenkov detector
- ~11,000 20” PMT inner detector
  - 40% photo-coverage
- ~2000 8” PMT outer detector
- Not magnetised
- Particle ID via Cherenkov ring pattern:
  - Muons produce sharp rings
  - Electrons scatter more → fuzzier rings
- Hadronic part of interaction usually not seen
  - Neutrino energy reconstructed kinematically
  - Gd being loaded into SK for neutron tagging next year



SK recent updates

- Main recent update is improved "fitqun" reconstruction
  - Uses full charge and time information from each PMT to do a likelihood fit to different reconstruction hypotheses
  - Improved background rejection allows 32% larger detector volume to be used
- At higher energies additional pions often created
  - π^- from $\bar{\nu}$ more likely to be captured on Oxygen than π^+
  - $\bar{\nu}$ events less likely to have a Michel electron
  - Use to make $\nu/\bar{\nu}$ enriched samples for better hierarchy sensitivity



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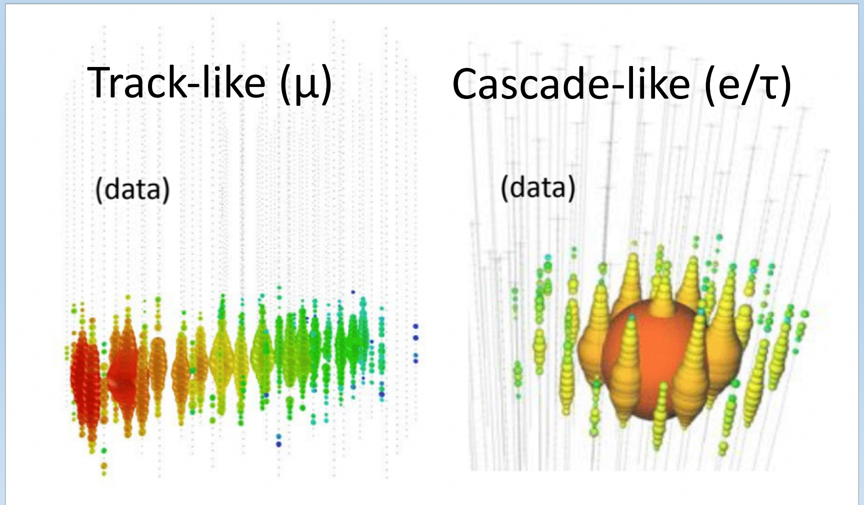
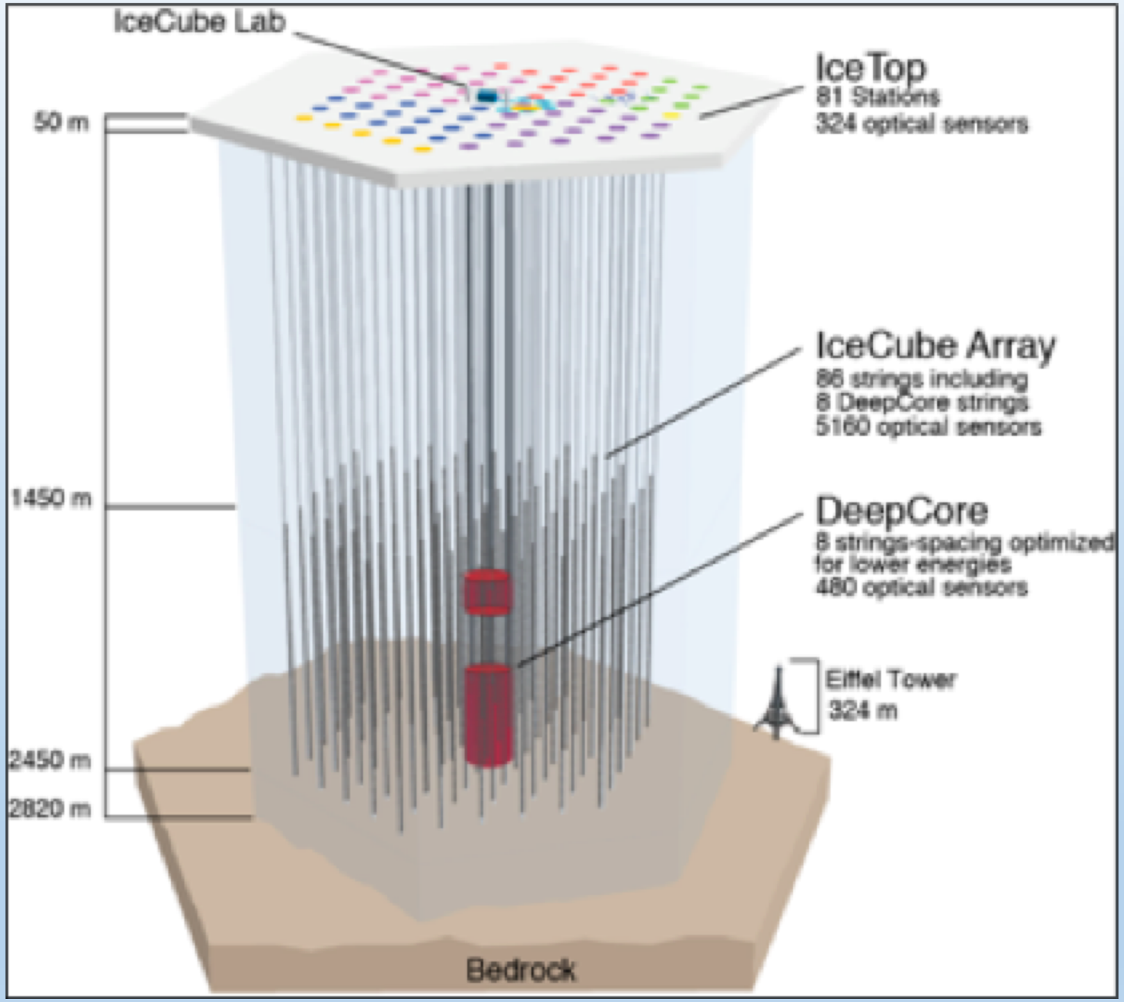
IceCube/DeepCore

- 5,160 PMT modules on strings in ice
- DeepCore is a more densely instrumented region at bottom center
  - Below 2100m where ice is clearer
- Surrounding IceCube strings provide active veto
- Particle ID by track/cascade like





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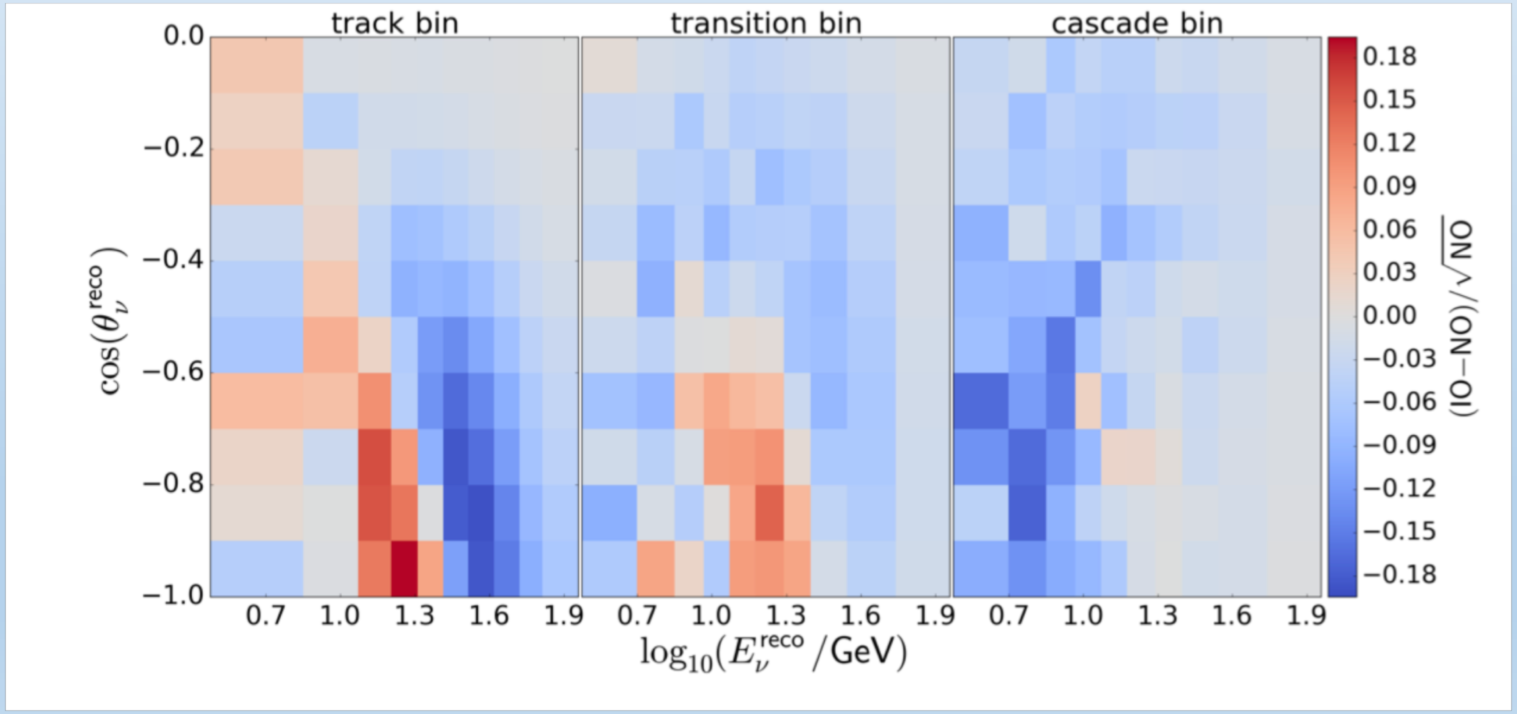
Icecube recent updates

- New mass hierarchy focused analysis performed including improved cross-section systematic uncertainties



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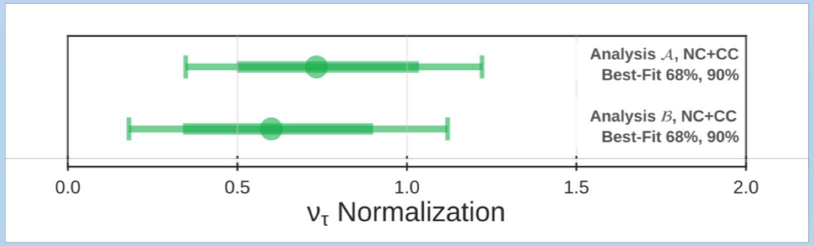
Atmospheric ν_τ appearance

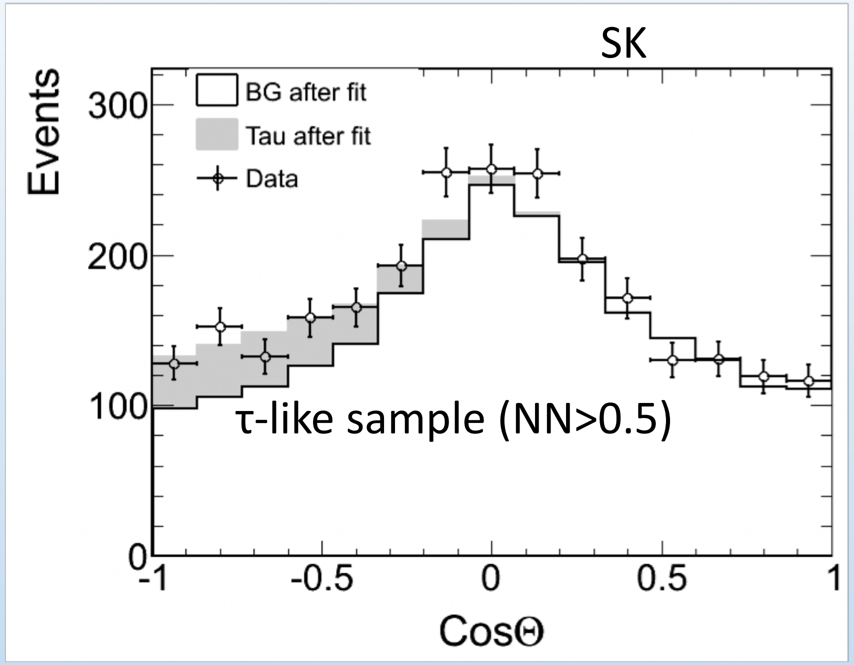
- Most oscillations are $\nu_\mu \rightarrow \nu_\tau$
  - Interactions disfavoured by cross-section and neutrino flux lower above τ mass energy
- Important closure test of PMNS oscillations

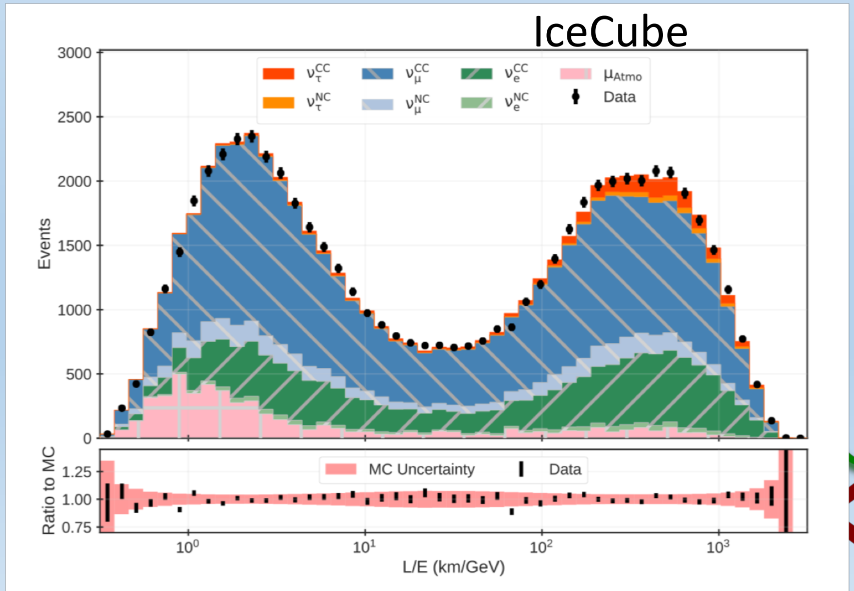
SK

Hierarchy	Signal strength	Significance
Normal	1.47 ± 0.32	4.6σ
Inverted	1.57 ± 0.31	5.0σ

IceCube





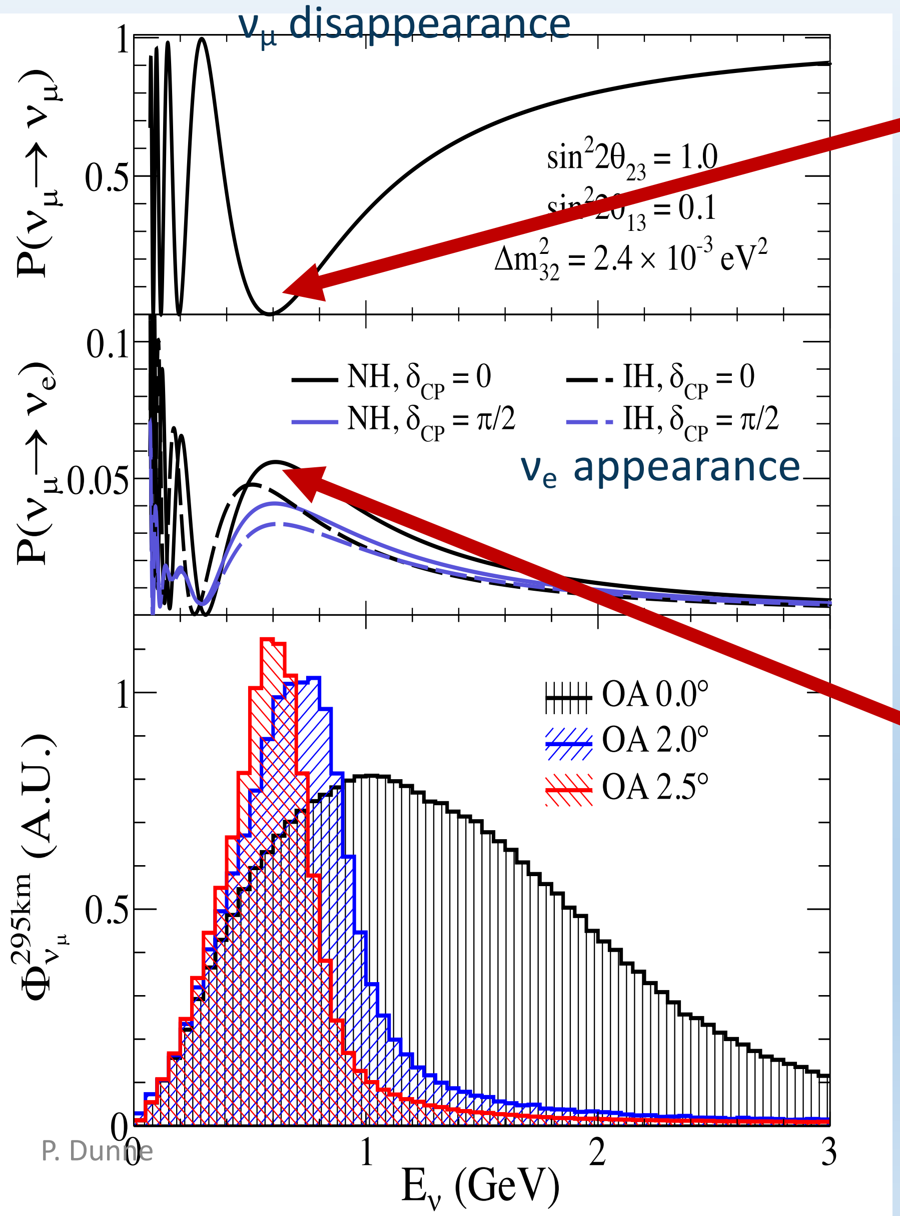


Long baseline oscillations

Long baseline neutrino experiments

- Muon (anti) neutrino beam generated
- Near detector complex measures beam before oscillation (reduce flux and cross-section uncertainty)
- Beam travels O(100s km) to large far detector to be measured after oscillations
- NOvA and T2K are currently running
    - see D. Harris talk for future experiments

Neutrino oscillations at long baseline experiments



- Muon (anti)neutrino disappearance:
  - Location of dip determined by Δm^2_{32}
  - Depth of dip determined by $\sin^2(2\theta_{23})$
- Electron (anti)neutrino appearance:
  - Leading term depends on $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$ and Δm^2_{32}
  - Sub-leading δ_{CP} dependance (up to 45% on event rate)
    - $\delta_{CP} = \pi/2$: fewer neutrinos, more anti-neutrinos
    - $\delta_{CP} = -\pi/2$: more neutrinos, fewer anti-neutrinos
  - Matter effects give dependence on mass hierarchy (~10%)
- For 295km (810km) baseline first oscillation maximum is at 0.6 GeV (1.6 GeV)

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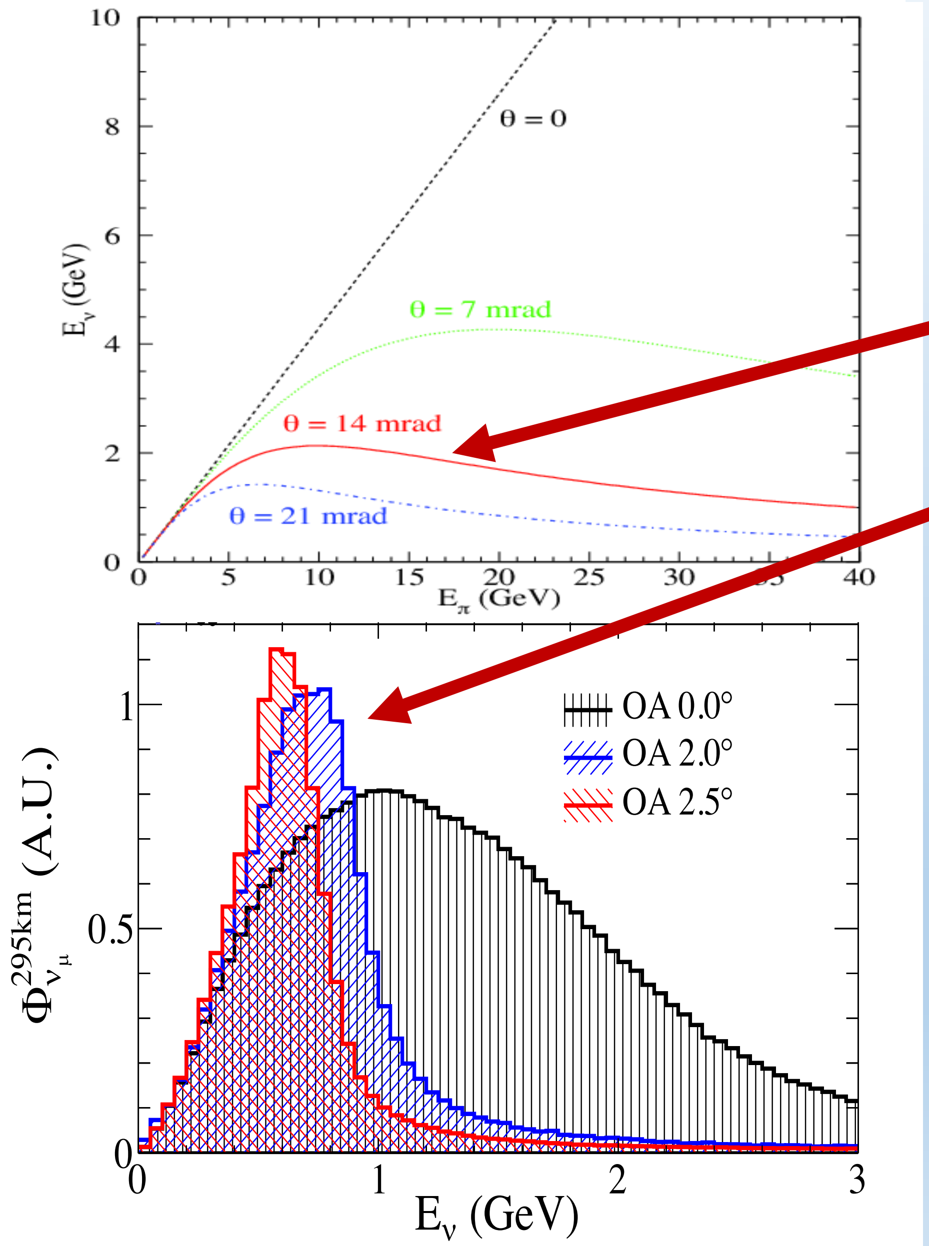
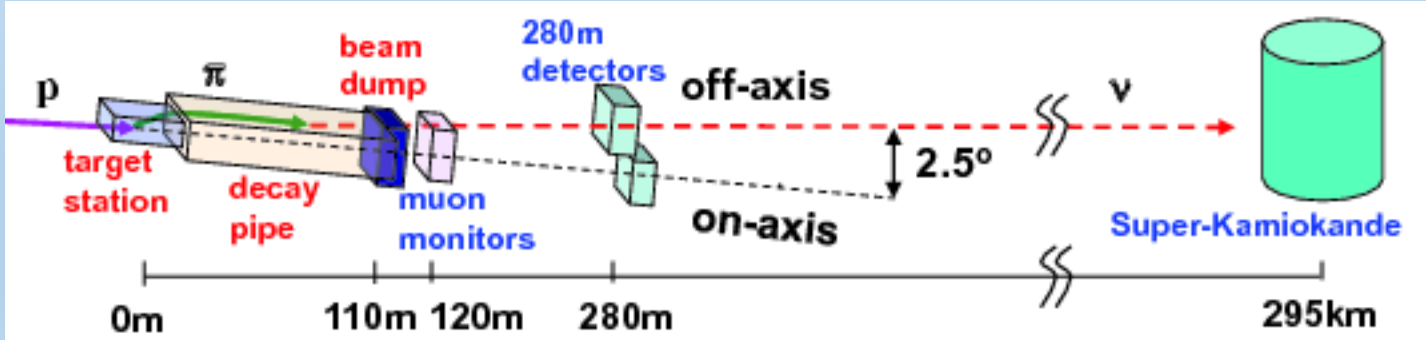
Off-axis beam concept



- Want as much flux as possible at oscillation peak
- Both NOvA and T2K use off-axis beam:
  - Kinematics of pion decay give maximum energy of neutrino at a given angle when off-axis
  - Gives narrower peak in flux
  - Removal of high-energy component suppresses backgrounds from neutral current (NC) interactions



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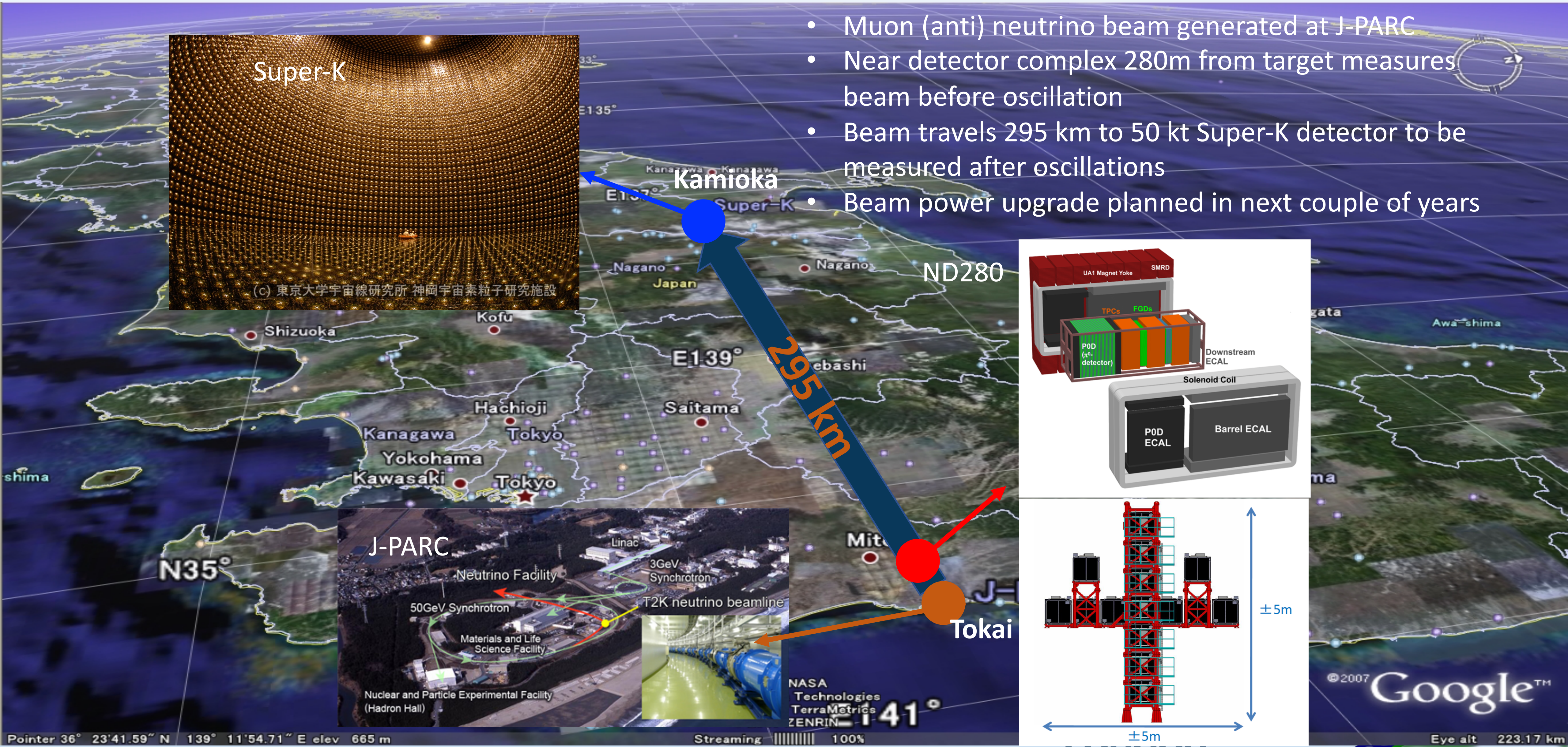
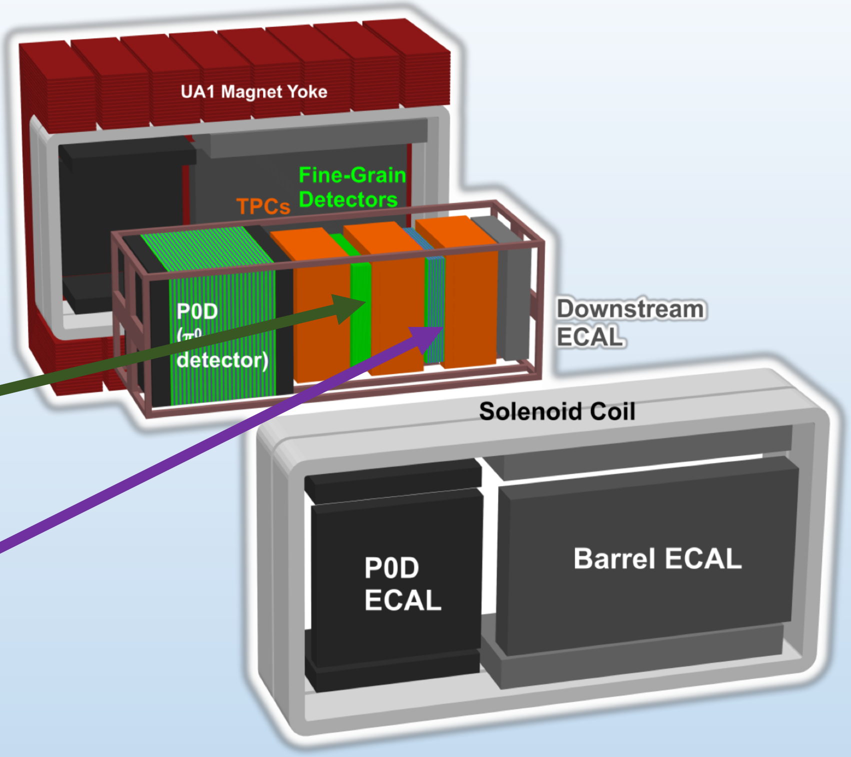
The T2K Experiment

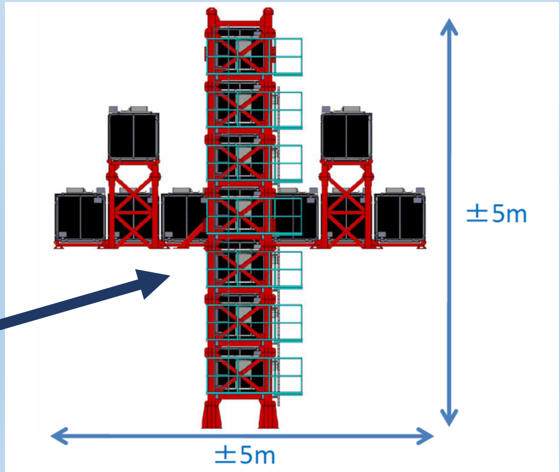
- Muon (anti) neutrino beam generated at J-PARC
- Near detector complex 280m from target measures beam before oscillation
- Beam travels 295 km to 50 kt Super-K detector to be measured after oscillations
- Beam power upgrade planned in next couple of years



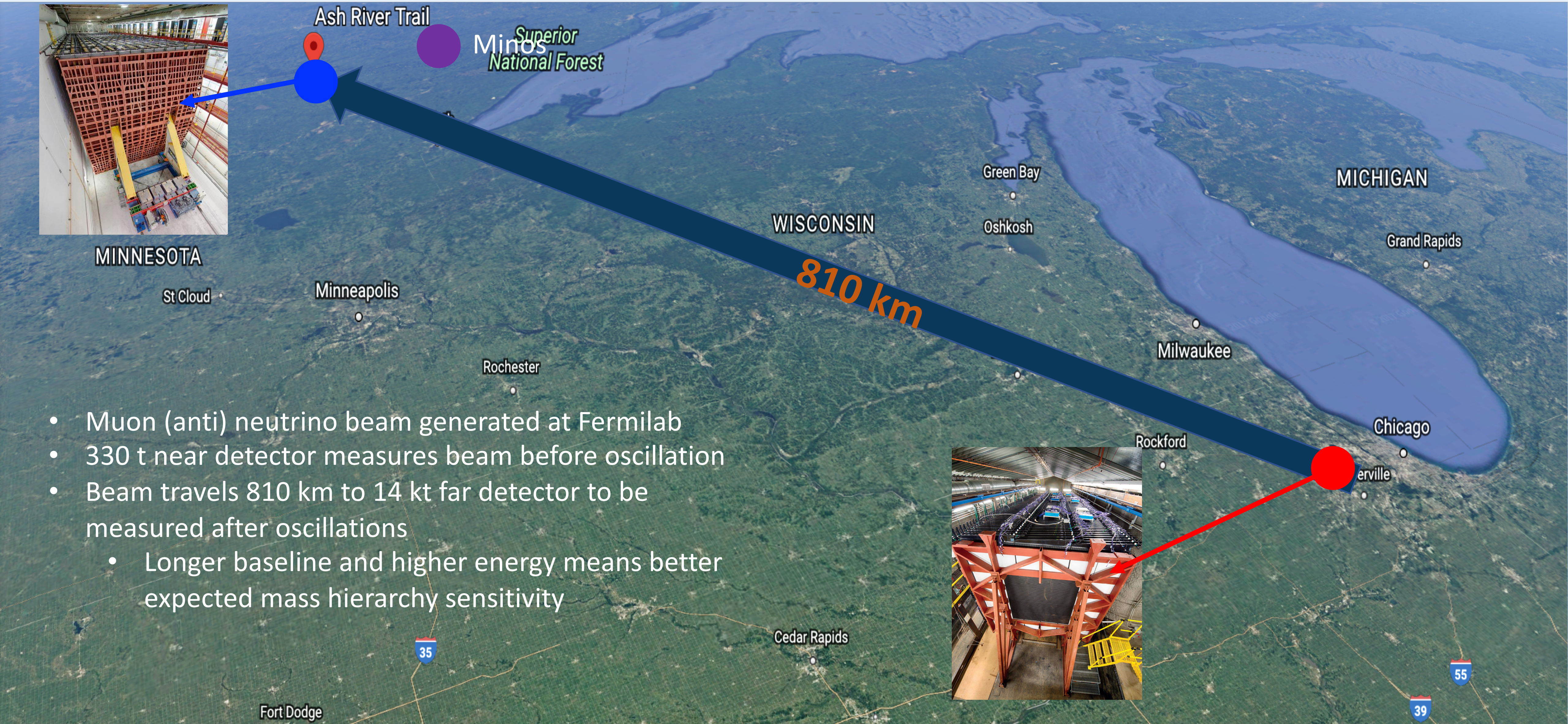
T2K Near Detector - ND280

- Near and far detector are very different
- Two fine-grained detector (FGD) targets
    - FGD1 – Active carbon target
    - FGD2 – Active carbon and passive water layers (same nucleus as SK)
- Magnet + three TPCs
    - Particle charge + momentum from curvature
    - Particle ID From dE/dx – 0.2% mis-ID rate
- INGRID detector on-axis for beam monitoring





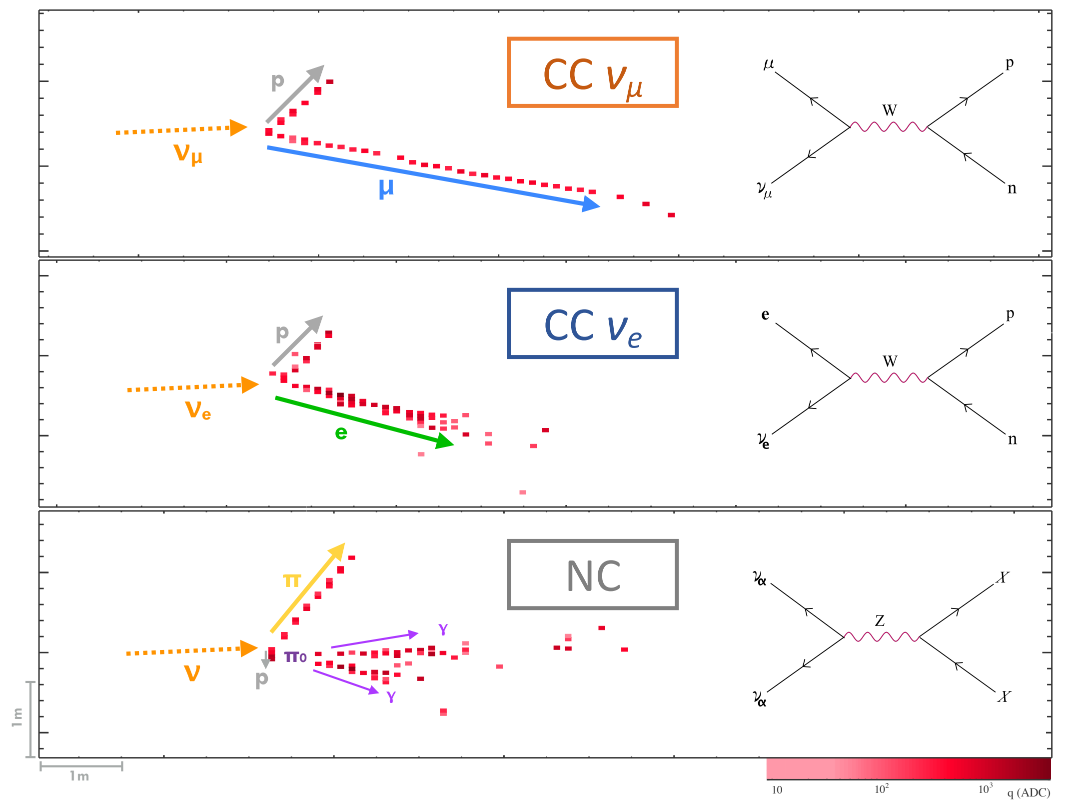
The NOvA Experiment



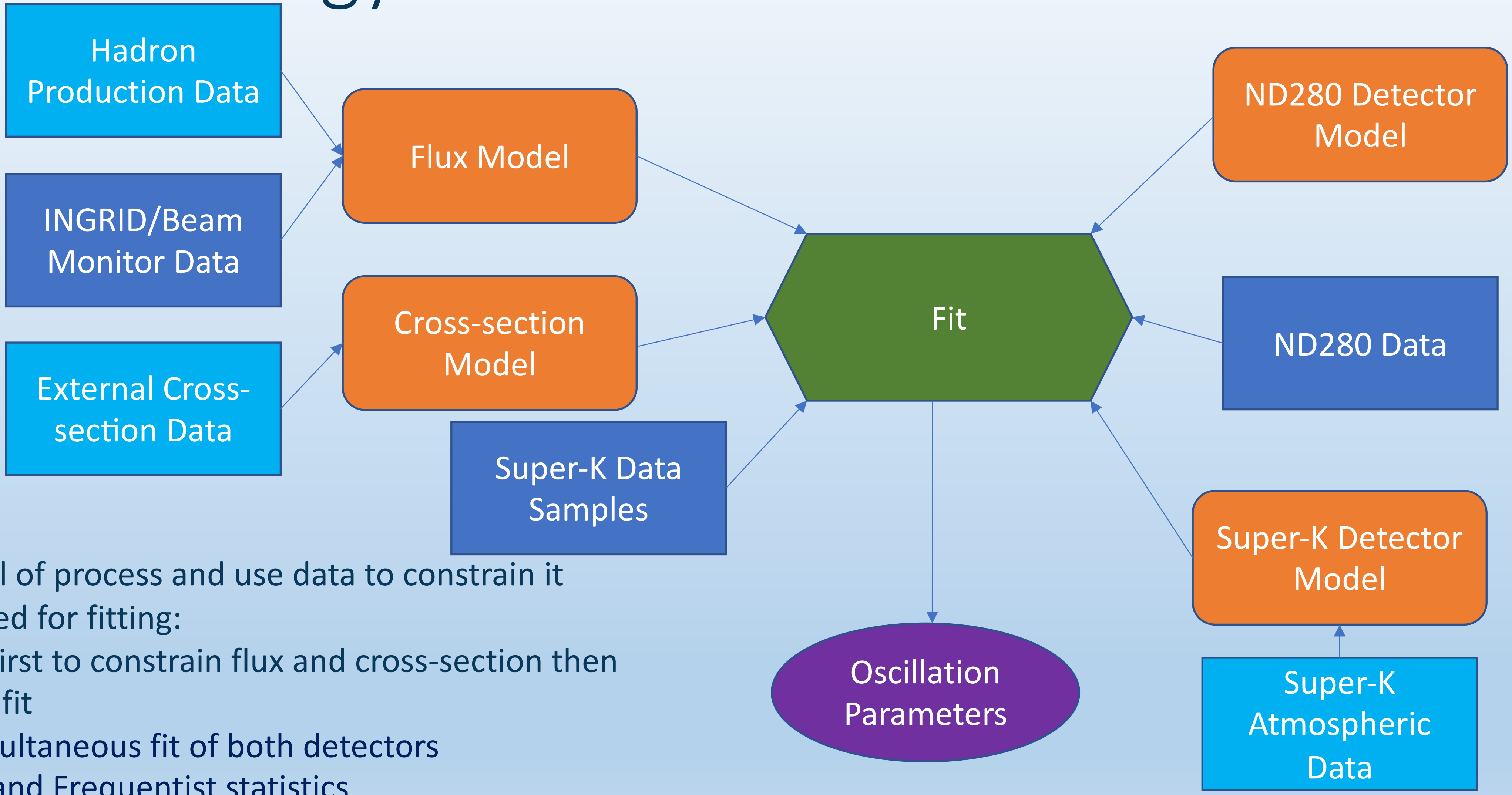
- Muon (anti) neutrino beam generated at Fermilab
- 330 t near detector measures beam before oscillation
- Beam travels 810 km to 14 kt far detector to be measured after oscillations
    - Longer baseline and higher energy means better expected mass hierarchy sensitivity

The NOvA Experiment

- Near and far detectors both use horizontal-vertical alternating liquid scintillator filled bars
- Particle identification uses machine learning
- Neutrino energy reconstructed calorimetrically



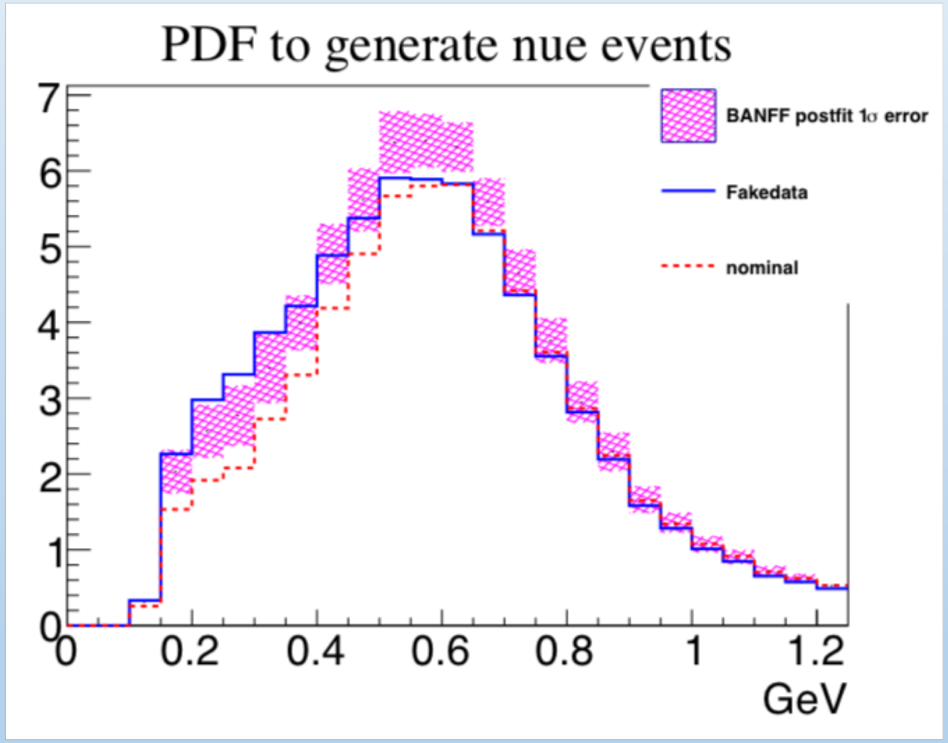
T2K Analysis Strategy



- Model fit:
  - Define a model of process and use data to constrain it
- Two approaches used for fitting:
  1. ND-only fit first to constrain flux and cross-section then far detector fit
  2. Perform simultaneous fit of both detectors
- Use both Bayesian and Frequentist statistics

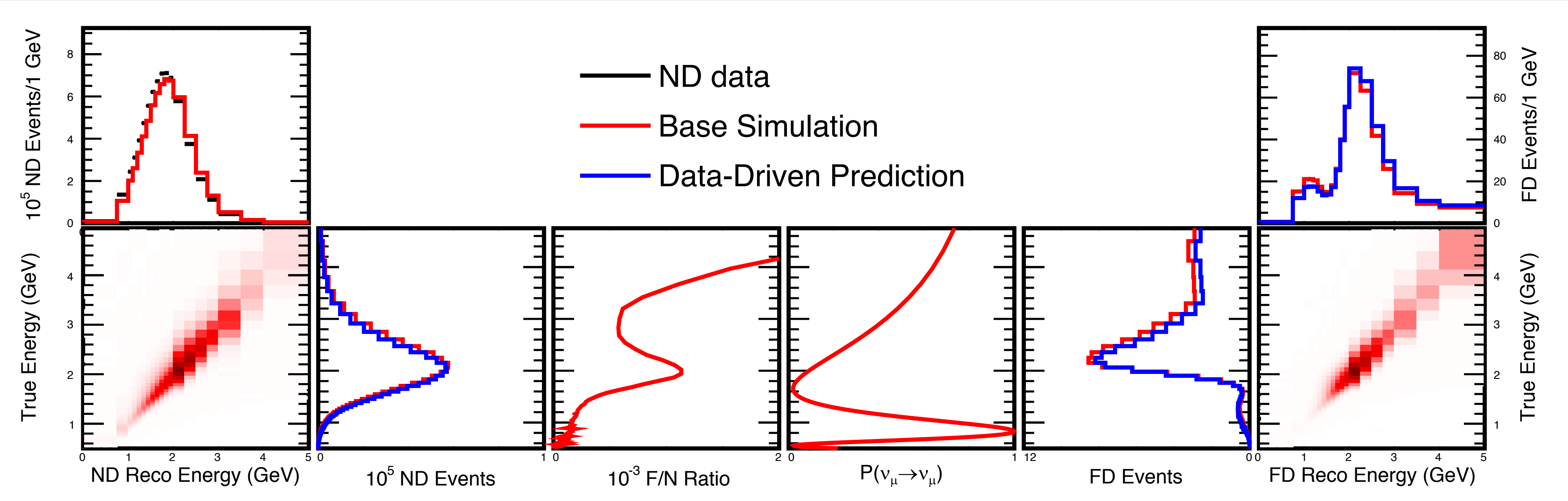
T2K recent updates

- Like SK, moved to improved fitqun reconstruction
- 20% larger fiducial volume
- Added a ν_e with additional pion sample:
  - Increase of 10% in ν_e events
- Wider range of models tested
  - T2K perform fits to 'mock data' with different simulated models to make sure incorrect choice doesn't bias result
  - New cross-section uncertainties added to mitigate biases found (e.g. nucleon removal energy)



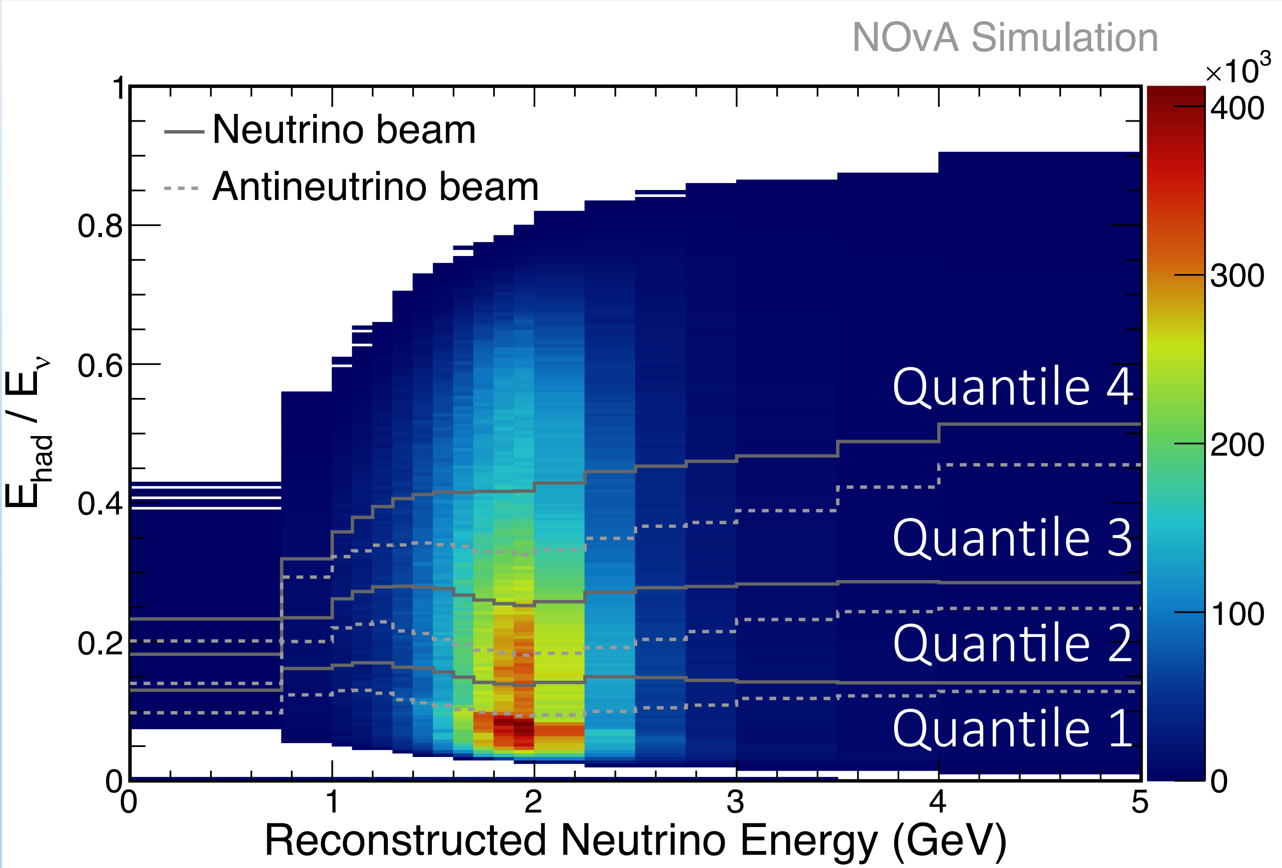
NOvA Analysis Strategy

- Extrapolation:
  - Take near detector data and use a model to do reconstructed to true mapping then propagate to far detector



NOvA updates for recent analysis

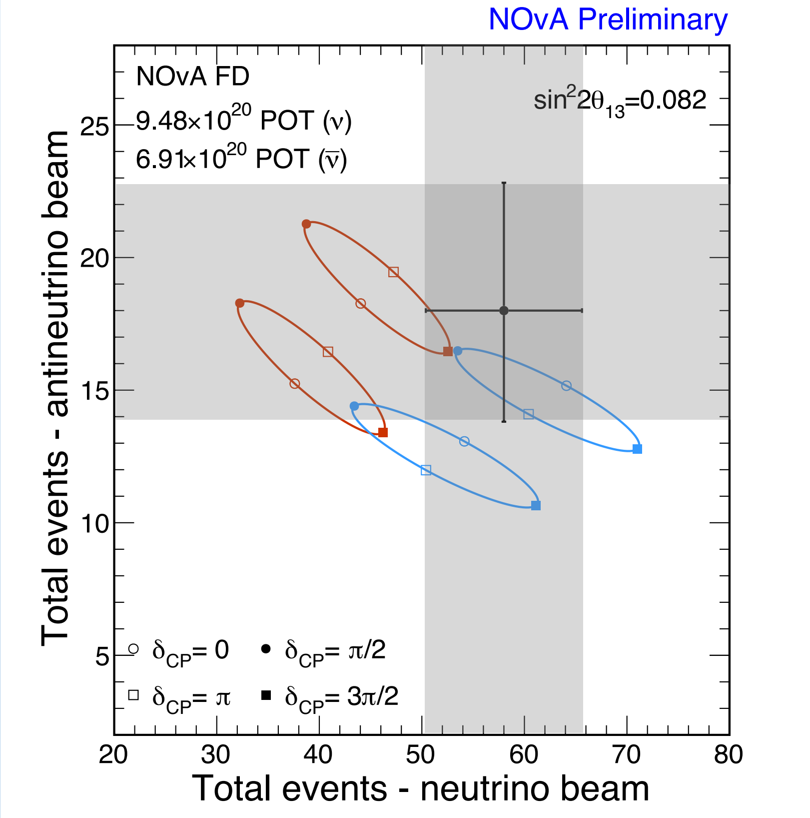
- First analysis including antineutrino data
- Improved scintillator model with better Cherenkov light treatment
- Improvements to machine learning and new signal categorization by energy resolution

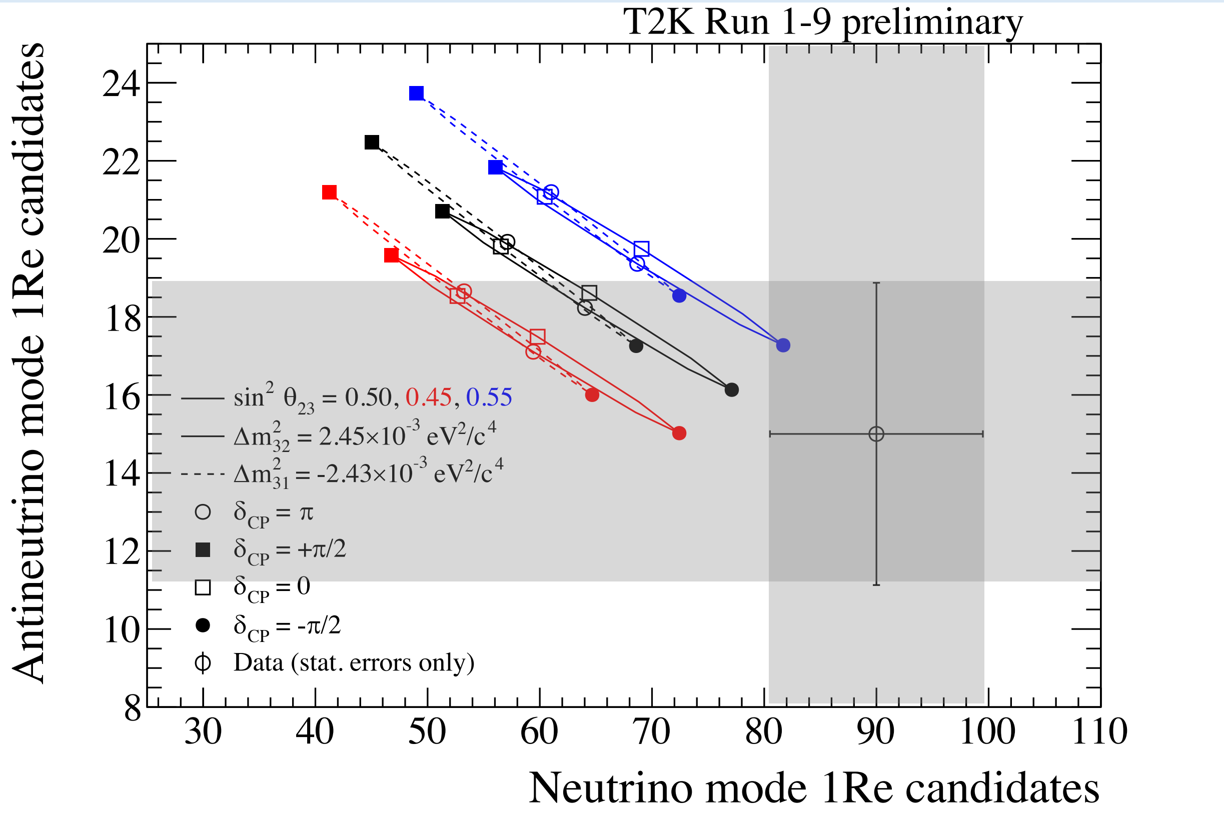


Oscillation Results

Long baseline event rates

- Long-baseline experiment sensitivity to hierarchy and δ_{CP} driven by electron event rates
- Compatible at 1σ level
- Results are complementary





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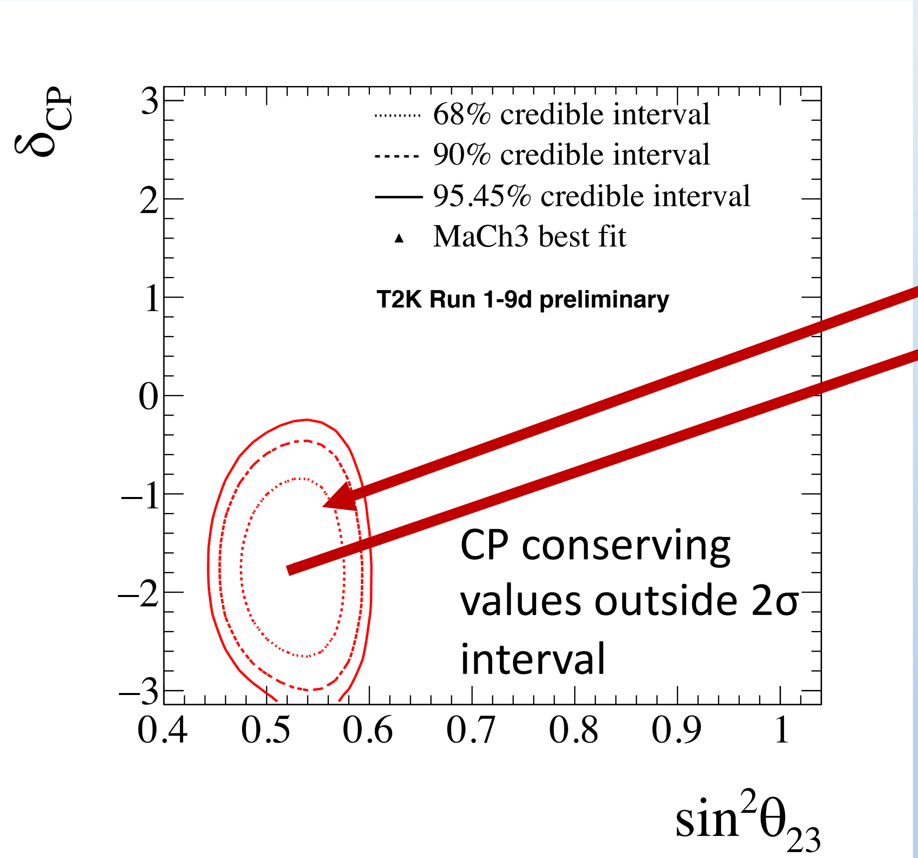
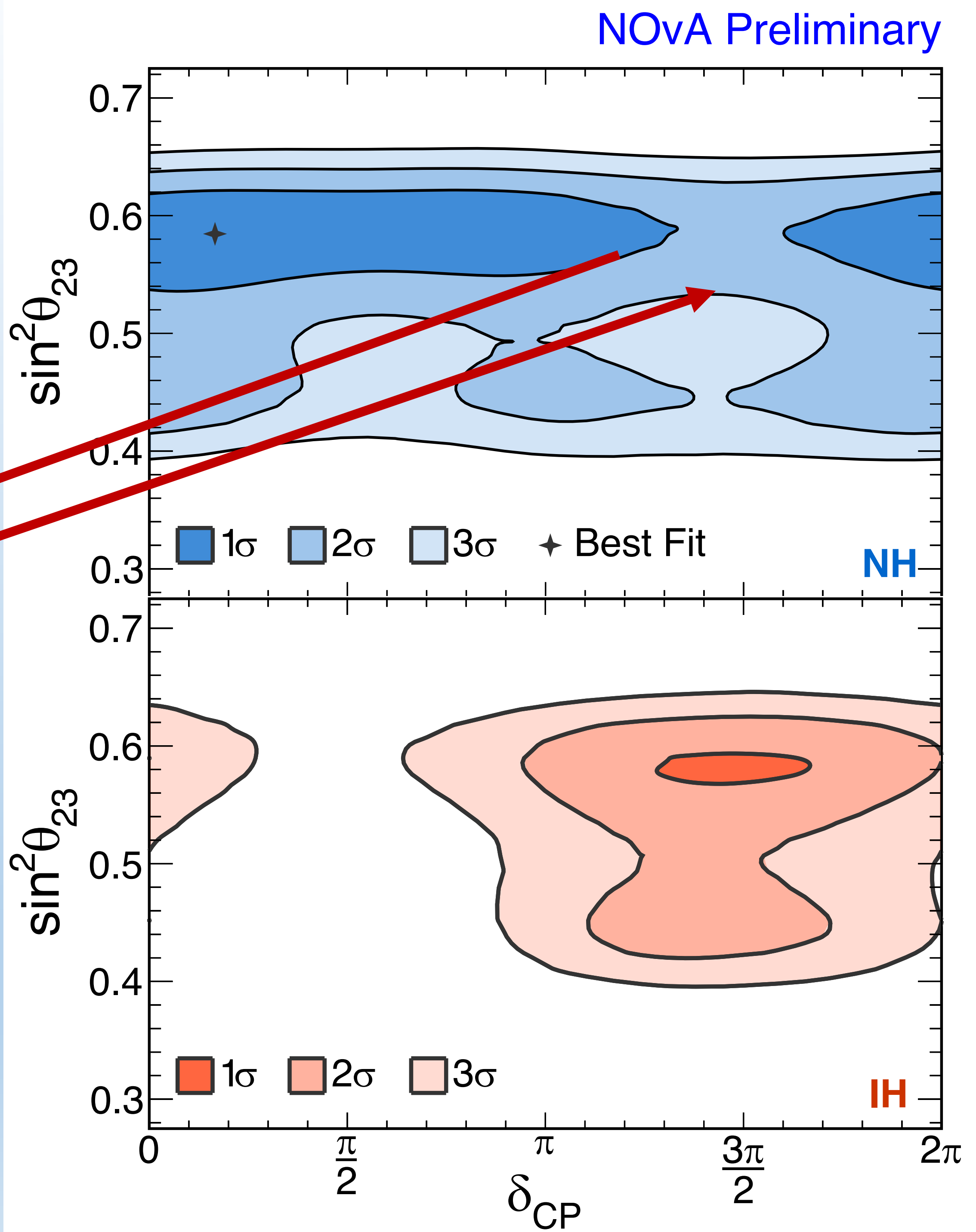
δ_{CP} vs θ_{23}





Both NOvA and T2K use reactor θ_{13} constraint

Hierarchy

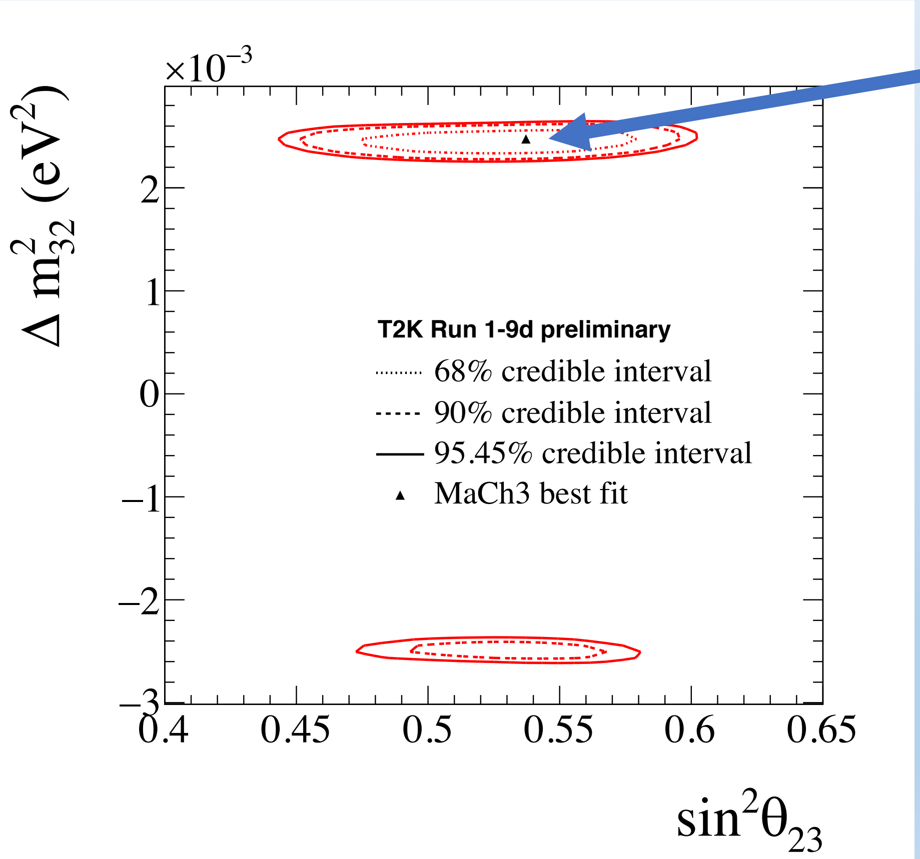
- Most experiments show preference for normal hierarchy
- IceCube has two analyses which show weak preference for opposite hierarchies
- CL_s and Bayes factor used by some experiments to mitigate false significance in case of lack of compatibility with either hierarchy

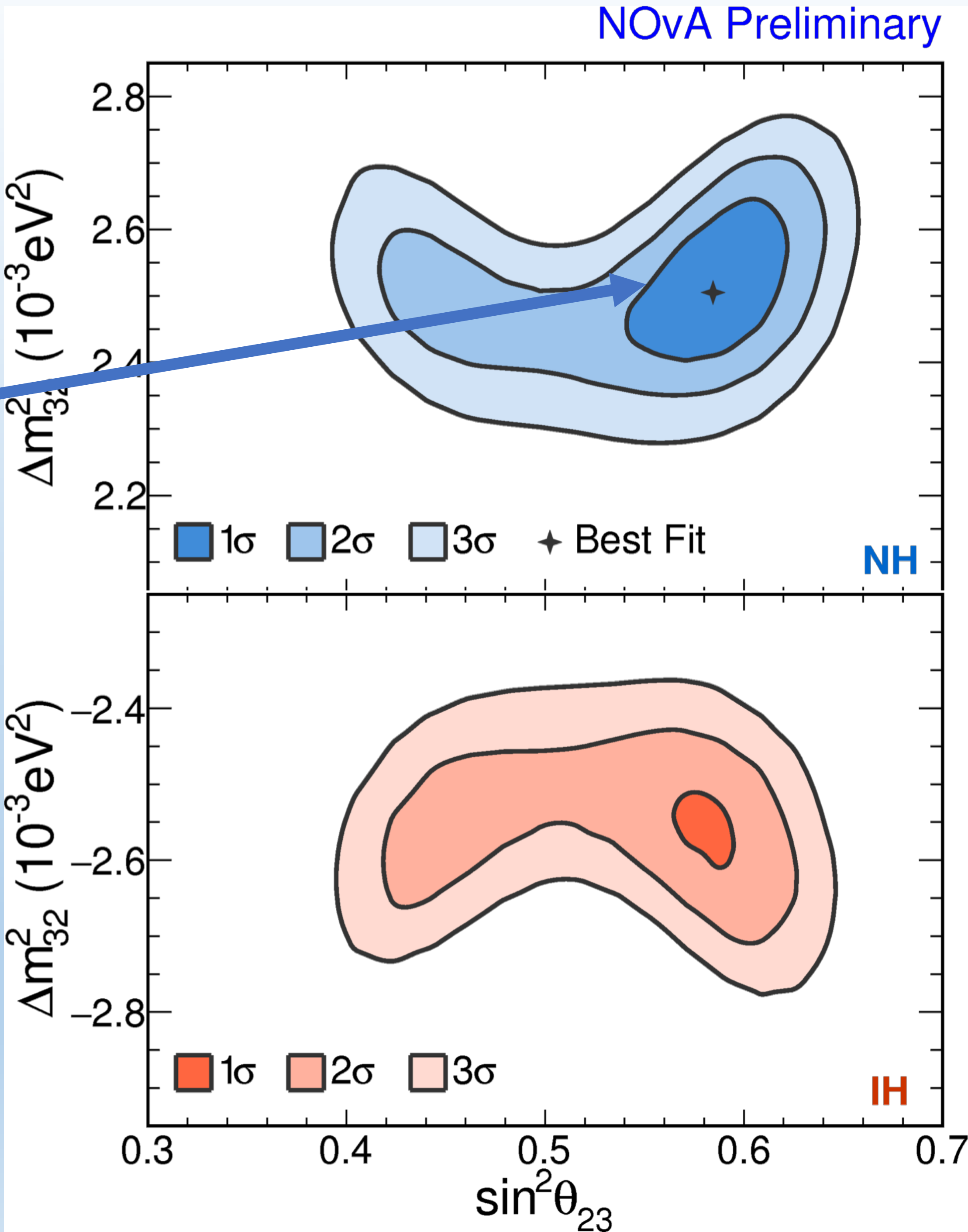
Experiment	IH p-value	CL_s (P(IH)/(1-P(NH))
SK ($\sin^2\theta_{23} = 0.6$)	0.072 ($\sin^2\theta_{23} = 0.6$)	0.143
IceCube Analysis A	0.157	0.533
IceCube Analysis B	0.845	0.954
NOvA	0.076	N/A

Experiment	IH posterior probability	Bayes factor (NH/IH)
T2K	0.111	8.0

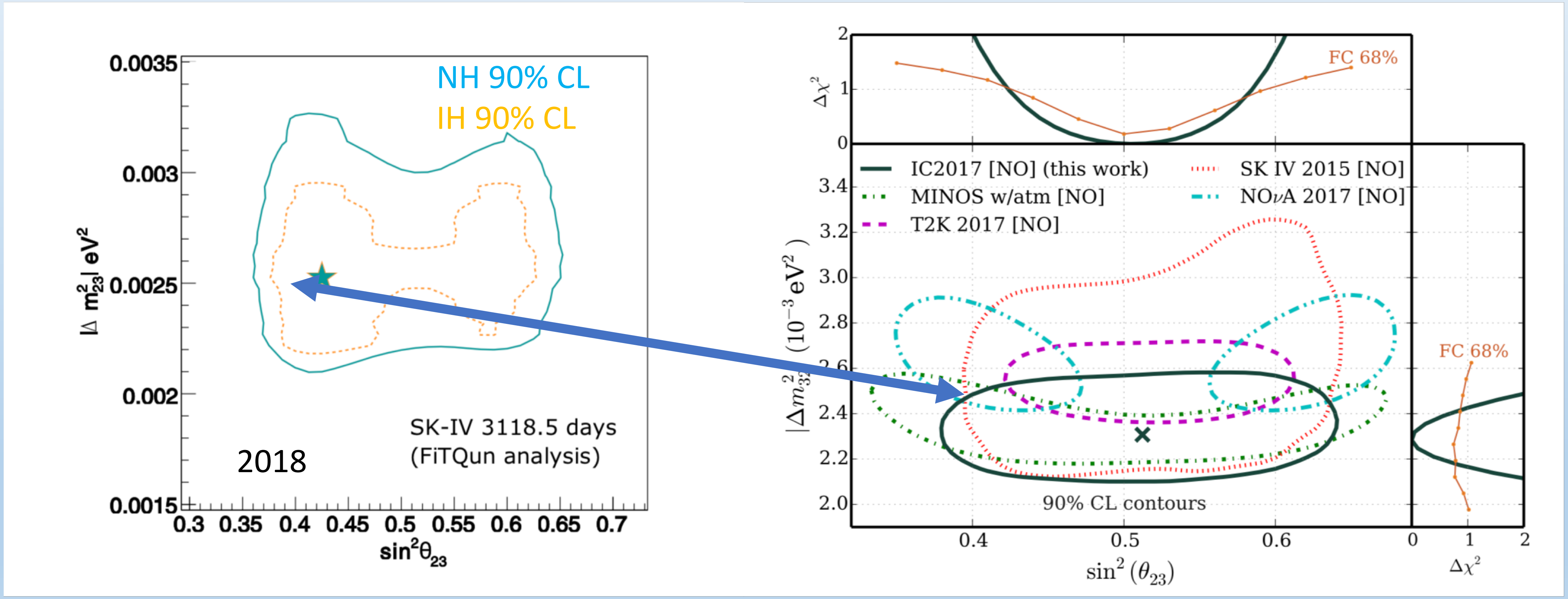
Θ_{23} vs Δm^2_{32}

- Weak upper octant preference (T2K posterior probability 79.5%)





Δm^2_{32} vs Θ_{23}



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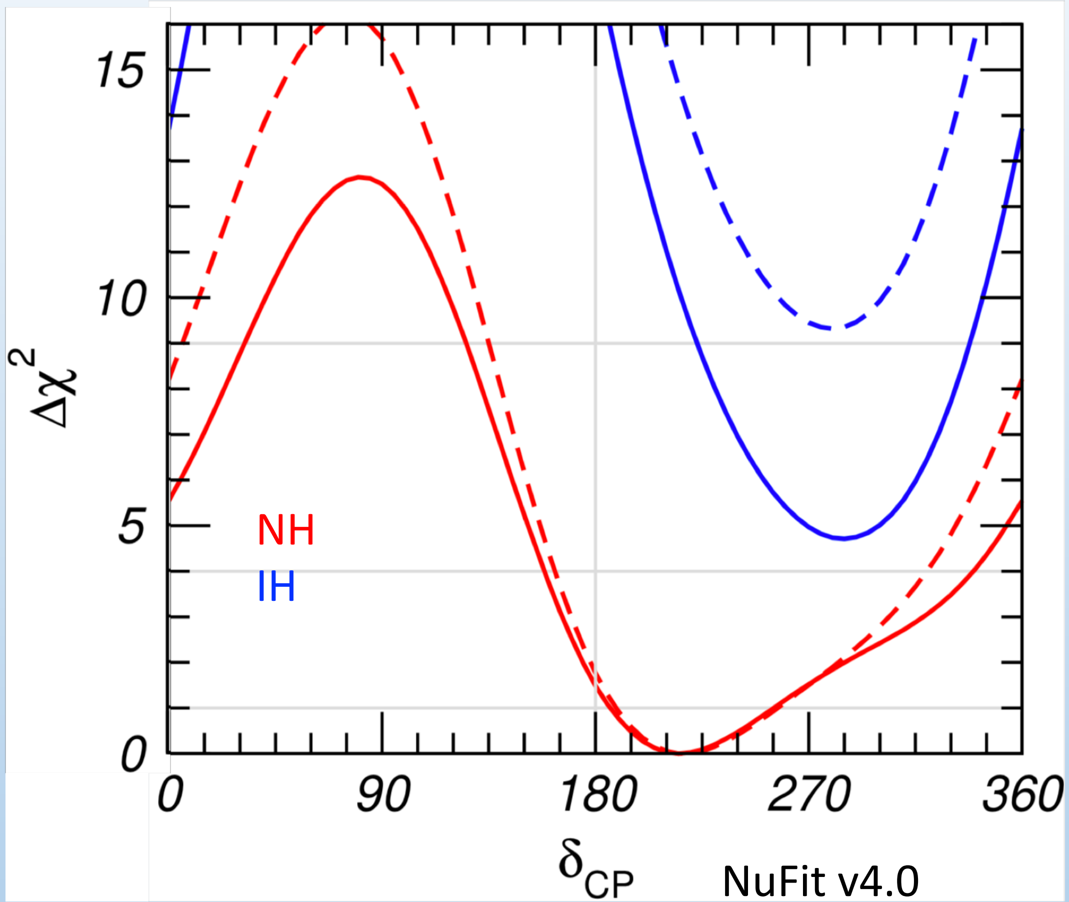
Joint Fits

- All experiments will keep running at least into the mid 2020s e.g. T2K-II but we can do better than statistics only improvements
- Take advantage of complementarity between experiments
  - More robust result
  - Take full advantage of all global data
- Joint fits have been done with publicly available information
  - Not possible to take into account systematic correlations



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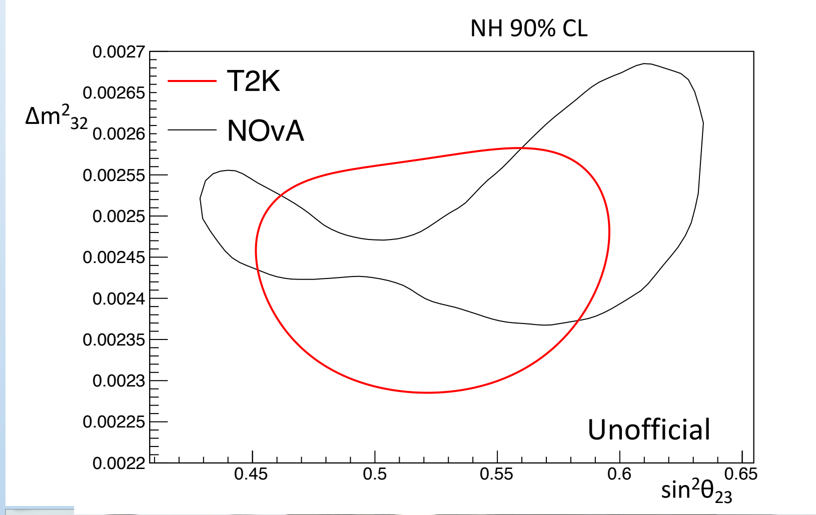
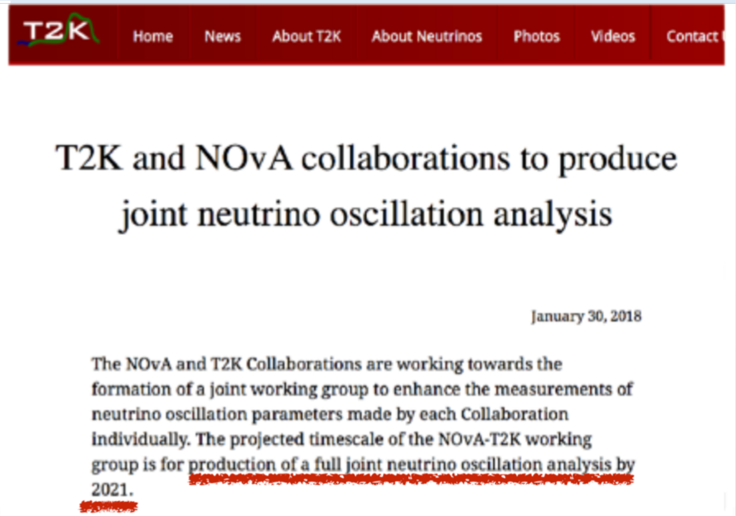
Joint Fits

- Experiments talking to each other to do rigorously correlated joint fits
- Efforts underway to perform joint T2K-NOvA & T2K-SK(atmospheric) fits
  - T2K-NOvA aiming for first result in 2021





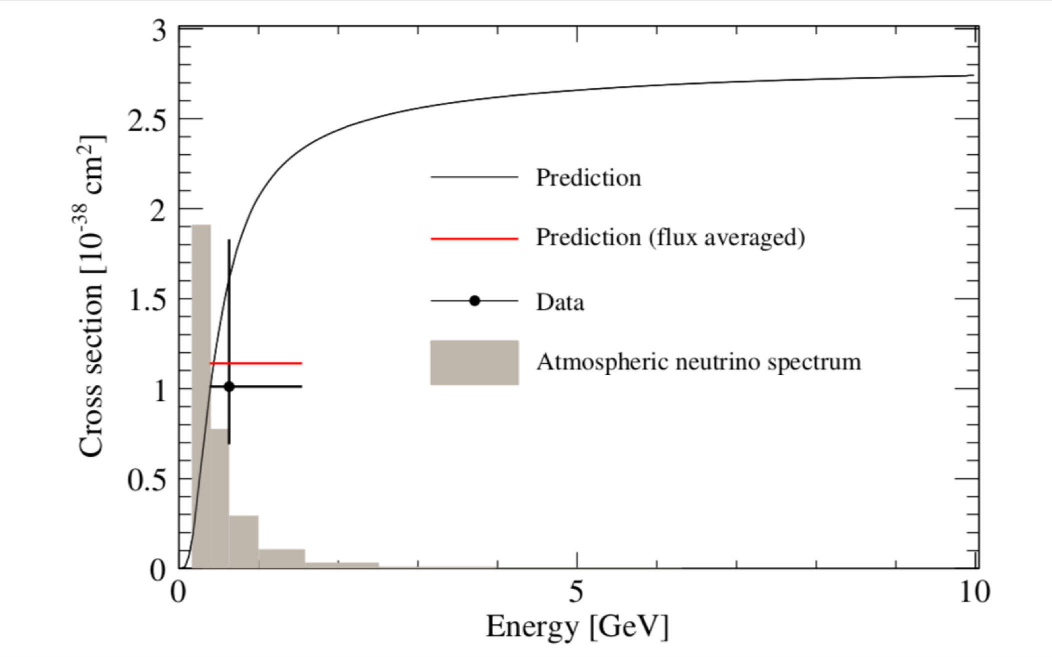
T2K and NOvA collaborations to produce joint neutrino oscillation analysis

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.

Cross-section programme

- Cross-sections are a large systematic in most neutrino experiments
  - Whole talk from Kevin Mcfarland
- Highlight: SK atmospheric Neutral Current Quasi-elastic
  - $\nu + {}^{16}O \rightarrow \nu + {}^{15}O + n + \gamma$
  - Key background for relic supernova neutrino searches
  - Tag events using photon from neutron capture on Hydrogen
  - SK-Gd will help with this measurement in future



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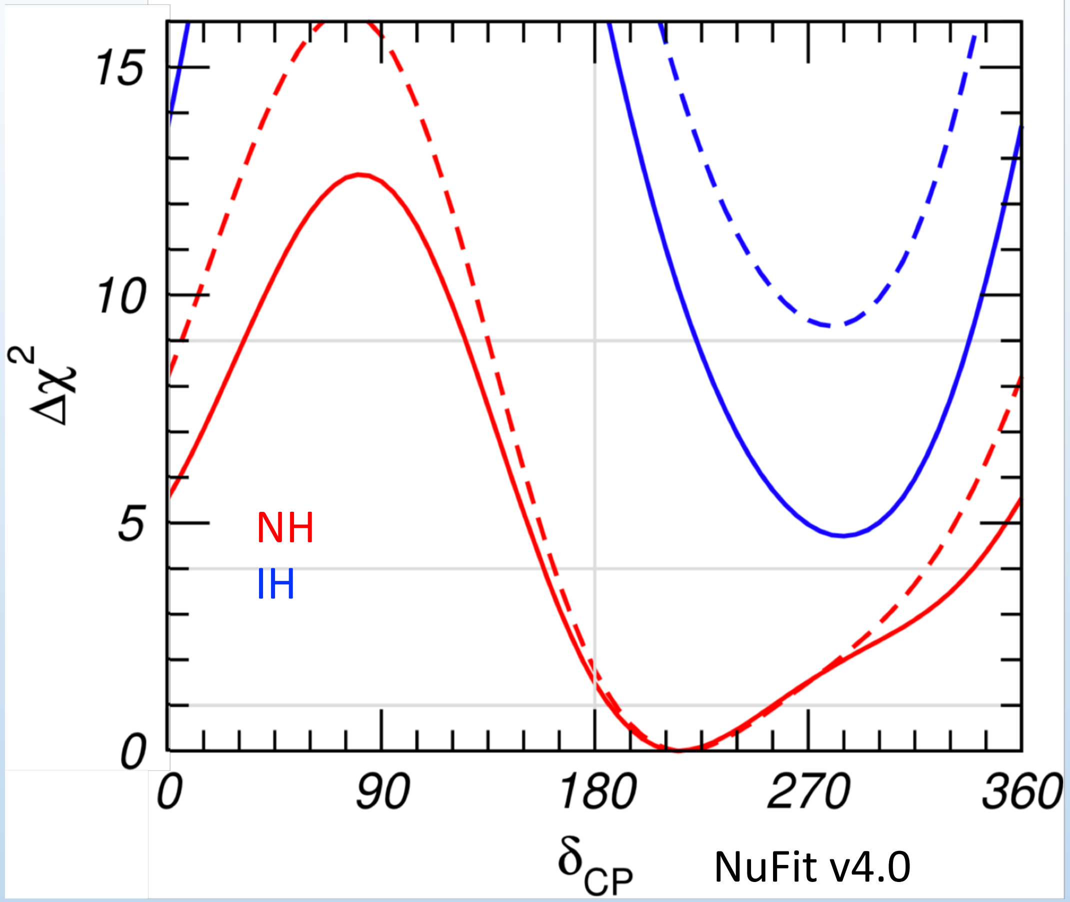
Summary

- Neutrino physics is at an exciting point
- On the cusp of making statements on mass hierarchy and CP violation
- Taking more data and joint fits between the experiments will give us interesting new results in the next few years
- Heard from Debbie Harris yesterday about the future beyond mid 2020s



T2K Preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.184	0.705	0.889
IH ($\Delta m^2_{32} < 0$)	0.021	0.090	0.111
Sum	0.205	0.795	1

Backup