Long Baseline Neutrino Experiments

-Phill Litchfield

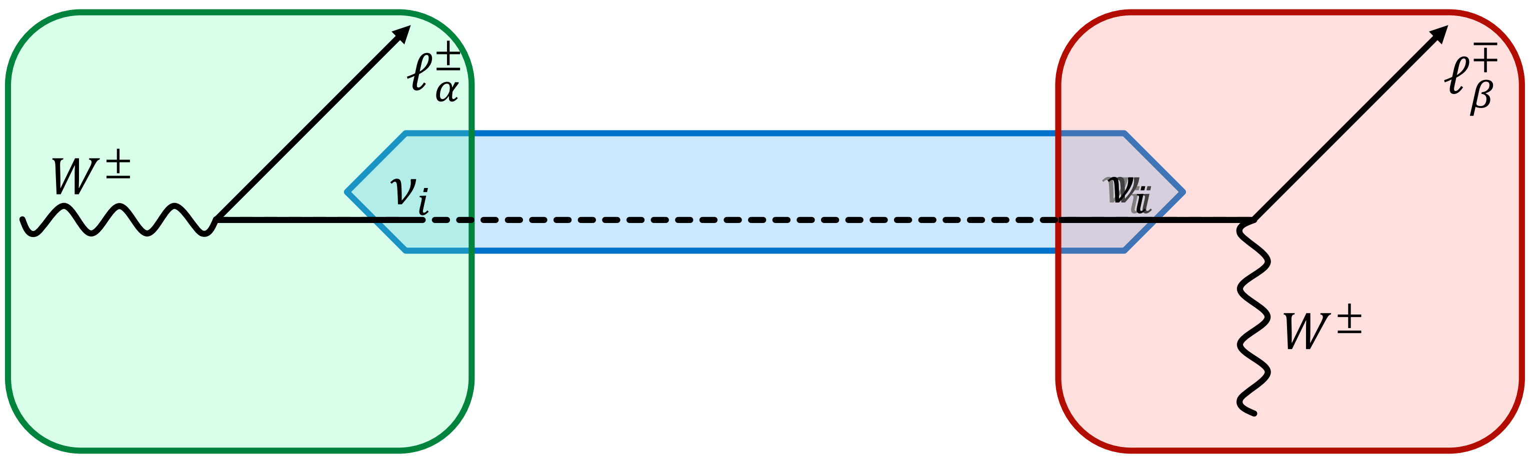
T2K

Hyper-Kamiokande

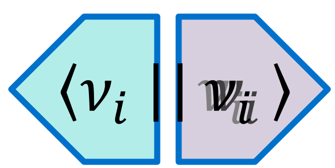
Neutrino mixing

Neutrinos are **produced** and **detected** as weak states $\nu_\alpha = \{\nu_e, \nu_\mu, \nu_\tau\}$ which is (very) different from **propagation** basis $\nu_i = \{\nu_1, \nu_2, \nu_3\}$

- In vacuum, **propagation basis ≡ mass basis**



Propagation states eventually get out of phase



- The superposition resolves as a different weak *flavour*

The oscillation probability

For neutrinos of energy E, oscillation probabilities can be written (e.g. for $\nu_\mu \rightarrow \nu_e$):

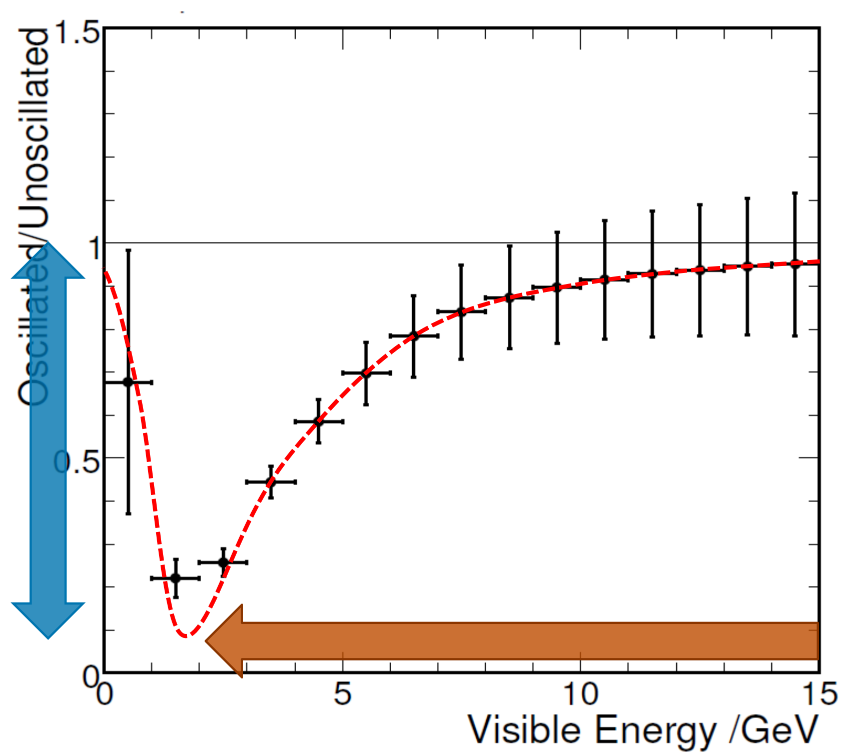
$$P(\nu_\mu \rightarrow \nu_e) = \sum \underbrace{A_{ij}} \underbrace{\mathbb{O}_{ij}} \left(\Delta m^2_{ij} \frac{L}{E} \right)$$

The A_{ij} are amplitudes that depend on a mixing matrix U_{PMNS}

The $\mathbb{O}_{ij}$ are oscillating functions

- e.g. $\sin^2(\Delta m^2_{ji} L/4E)$

where $\Delta m^2_{ij} = m^2_i - m^2_j$



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If the mixing matrix U_{PMNS} is *complex*, it can have complex elements → $e^{i\delta}$. In that case:

- There will be terms where the (real) amplitudes $A_{ij} \propto \sin\delta$
- **Such sin $\boldsymbol{\delta}$ terms have opposite sign for $\boldsymbol{\nu}$ / $\boldsymbol{\bar{\nu}}$ ⇒ CP violation**

Also, propagation in matter modifies both the amplitude ($\boldsymbol{A_{ij}}$) and frequency ($\mathbb{O}_{ij}$)

− Differently for ν and $\bar{\nu}$ → mimics CPv

+ Depends on whether $\boldsymbol{\Delta m^2_{ji}}$ is +ive or −ive

Appearance probability

The ν_e appearance probability can be approximated as an interfering sum-squared of atmospheric and solar scale terms:

$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e\right) \approx T_{\mathrm{atm}}^2 \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + \alpha^2 T_{\mathrm{sol}}^2 \frac{\sin^2(A\Delta)}{A^2}$$
$$\mp 2\alpha T_{\mathrm{atm}}\, T_{\mathrm{sol}} \frac{\sin([1-A]\Delta)}{[1-A]} \frac{\sin(A\Delta)}{A} \sin\Delta \sin\delta$$
$$+2\alpha T_{\mathrm{atm}}\, T_{\mathrm{sol}} \frac{\sin([1-A]\Delta)}{[1-A]} \frac{\sin(A\Delta)}{A} \cos\Delta \cos\delta$$

where

$$T_{\mathrm{atm}} = \sin 2\theta_{13} \sin\theta_{23}; \qquad T_{\mathrm{sol}} = \sin 2\theta_{12} \cos\theta_{23} \cos\theta_{13},$$

and

$$\Delta = \frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2}; \qquad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \approx 1/32; \qquad A = \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m_{31}^2}$$

NOνA: $|A| \sim 0.2$, T2K: $|A| \sim 0.07$

Angle parameterisation of U_{PMNS}

Mixing must be unitary; decompose in terms of $\{c, s\}_{ij} = \{\cos, \sin\}\,\theta_{ij}$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Knowledge of U_{PMNS}

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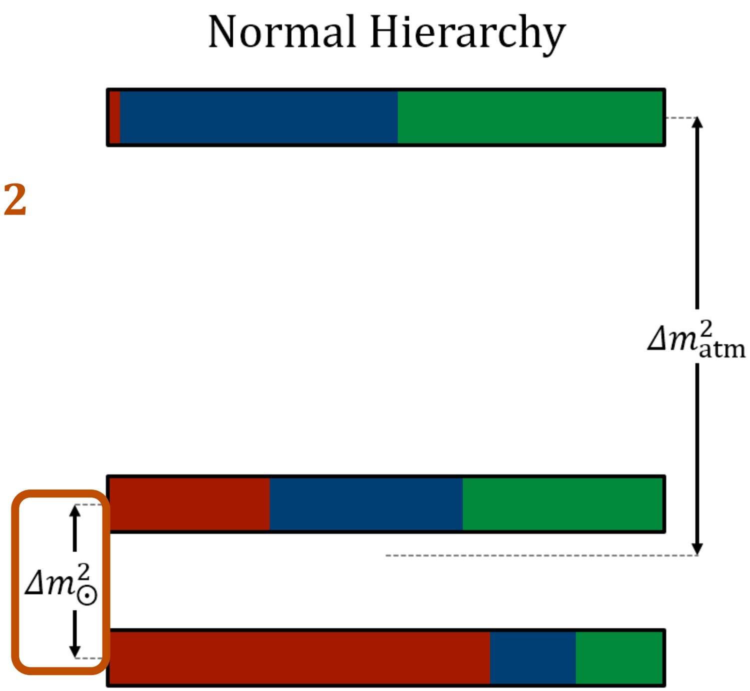
Historically useful:

- ν_e disappearance in **solar** neutrinos from $\boldsymbol{\theta_{12}}$ mixing and splitting $\boldsymbol{\Delta m^2_{21} = m^2_2 - m^2_1}$



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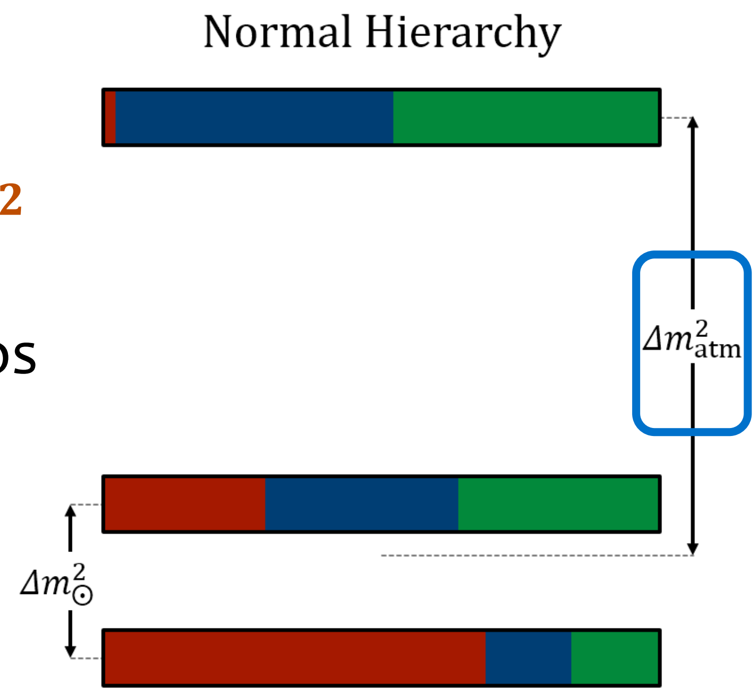
- ν_e disappearance in **solar** neutrinos from $\boldsymbol{\theta_{12}}$ mixing and splitting $\boldsymbol{\Delta m^2_{21} = m^2_2 - m^2_1}$
- $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in **atmospheric** neutrinos from $\boldsymbol{\theta_{23}}$ mixing and splitting $\boldsymbol{\Delta m^2_{3i}}$



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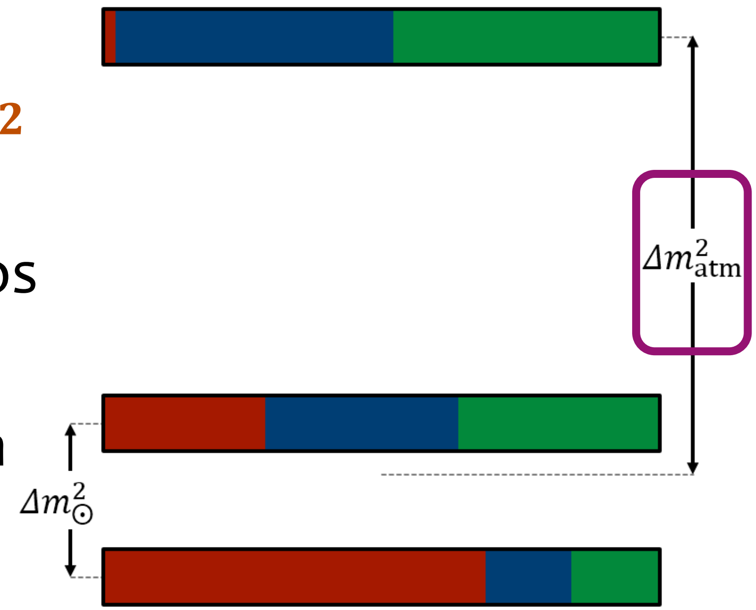
It also works out that **reactor** neutrinos at 1km are sensitive to $\boldsymbol{\theta_{13}}$ and $\boldsymbol{\Delta m^2_{3i}}$ only

Normal Hierarchy

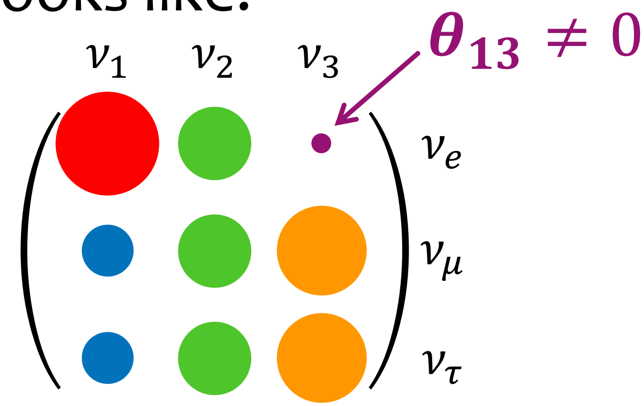


Open questions

Now: precision measurement — can't approximate as a single sub-matrix.

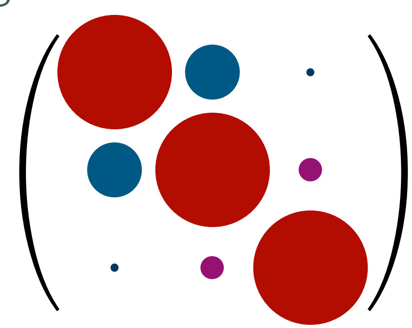
- We know fairly well what the mixing matrix looks like:

$$|U_{\mathrm{PMNS}}|^2 \simeq$$



and it's nothing like the CKM matrix

$$|V_{\mathrm{CKM}}|^2 \simeq$$



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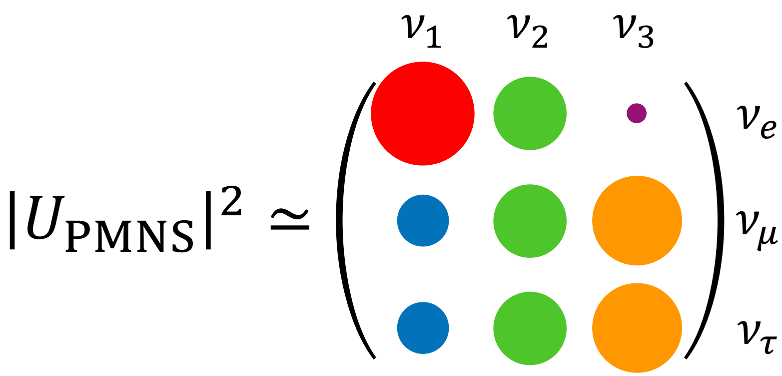
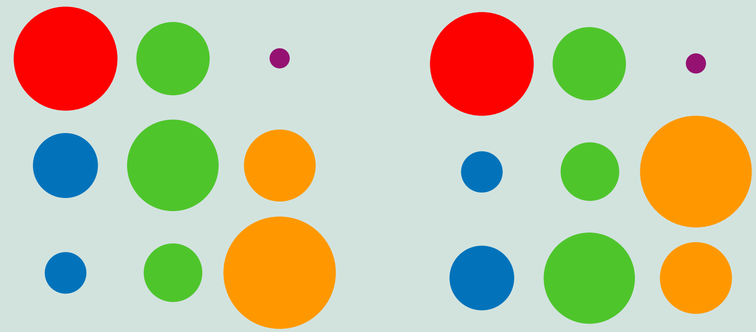
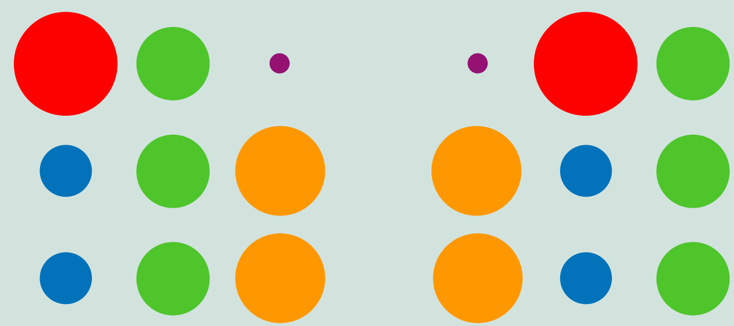


Octant degeneracy



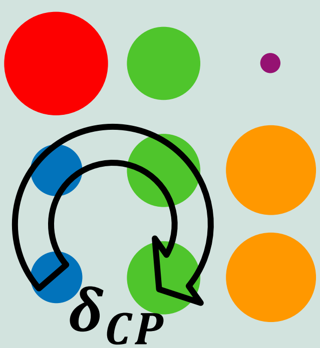
Lower ($\theta_{23} < 45°$) Upper ($\theta_{23} > 45°$)

Mass Ordering [Hierarchy]



Normal (NO) Inverted (IO)

CP Violation



Complex mixing of these 4 elements causes

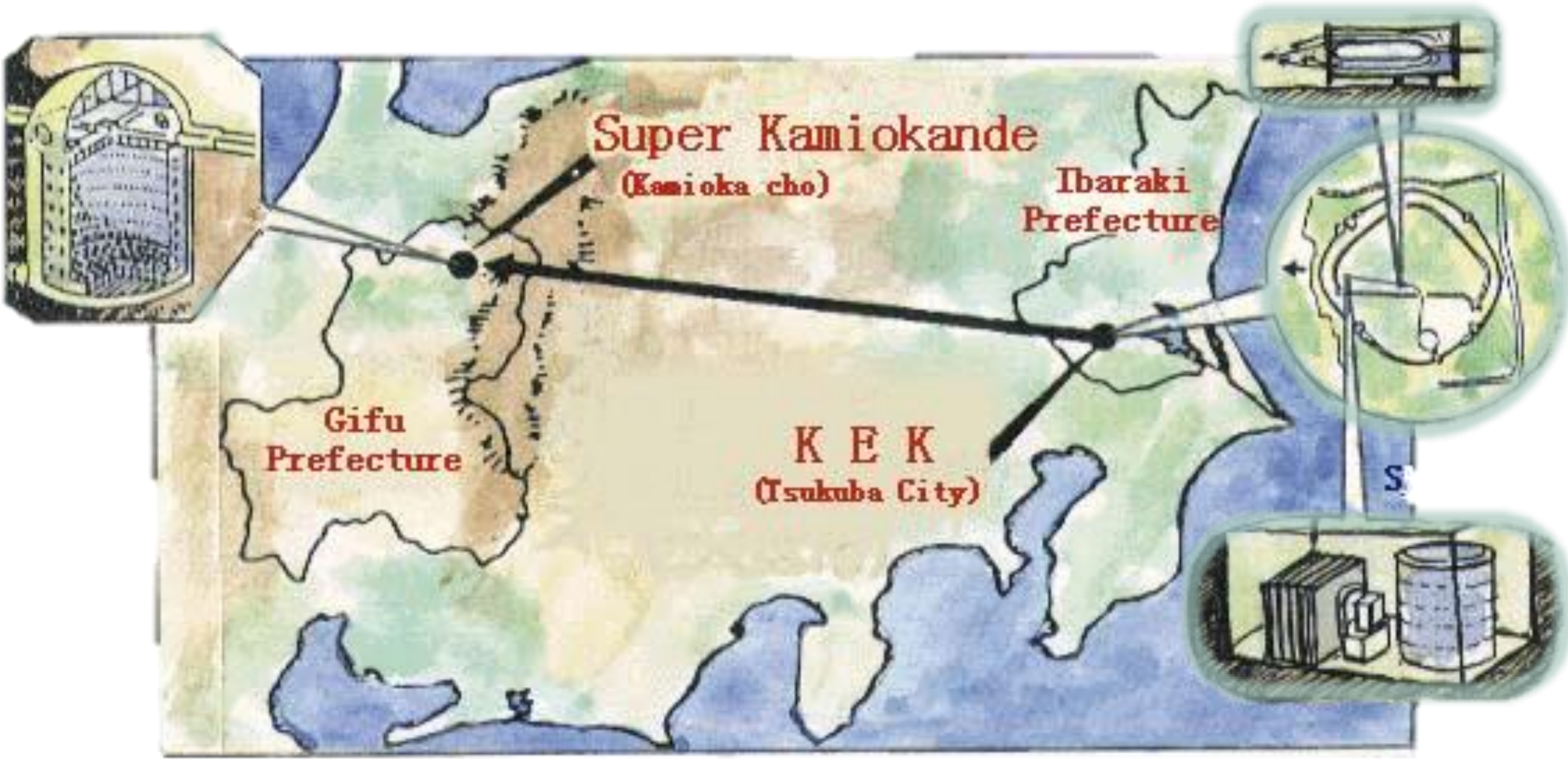
$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Key parameter: $\boldsymbol{\delta_{CP}}$

University of Glasgow

Experiment set-up

General features



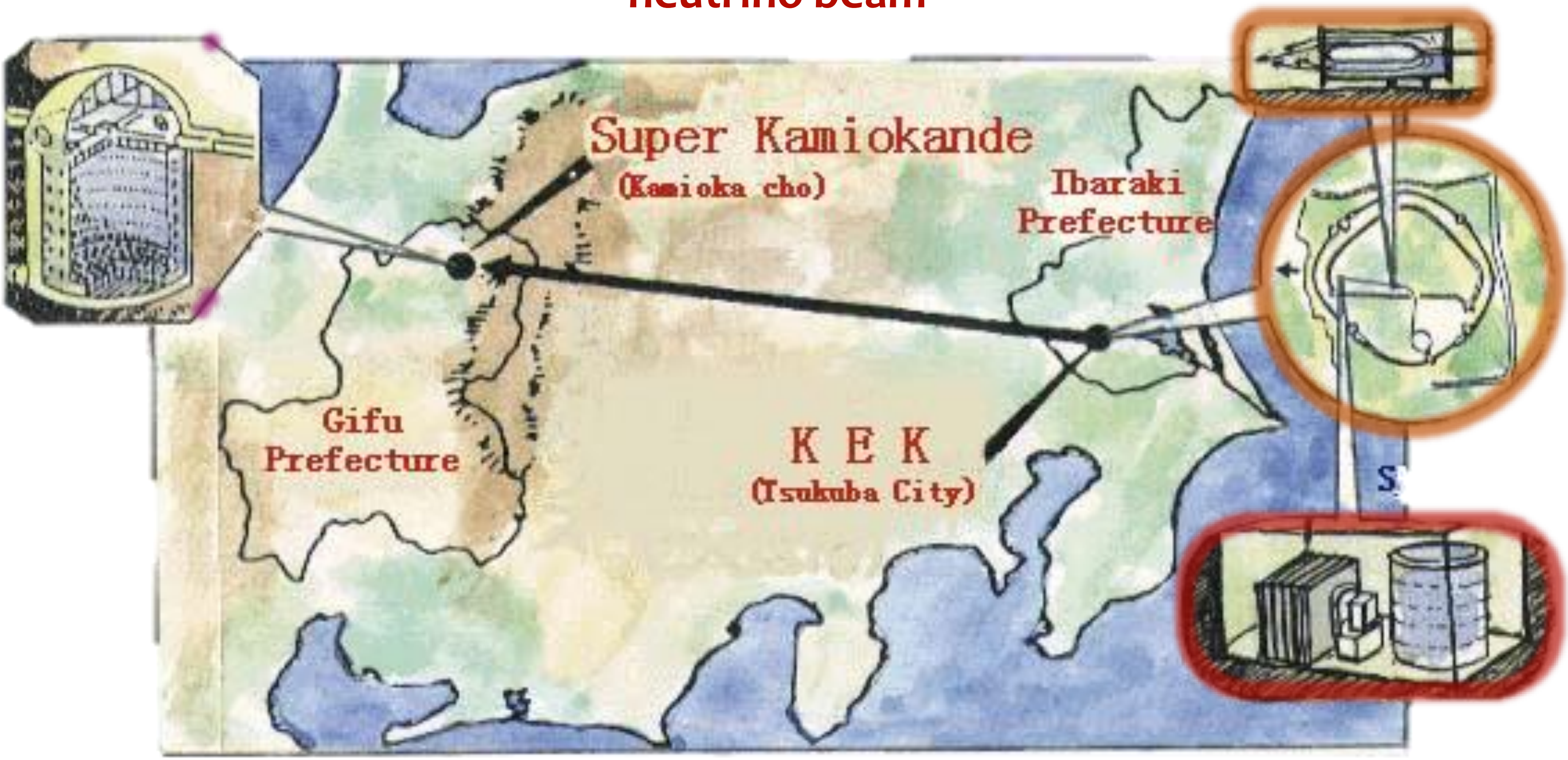
First LBL experiment was **K2K.** Modern examples are very similar.

General features

Far Detector measures the oscillations

Near Detector(s) characterise the initial neutrino beam

Muon neutrinos created at proton accelerator



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LBL Experiments: *L* and *E*

Next Generation

DUNE

Hyper-Kamiokande

T2K

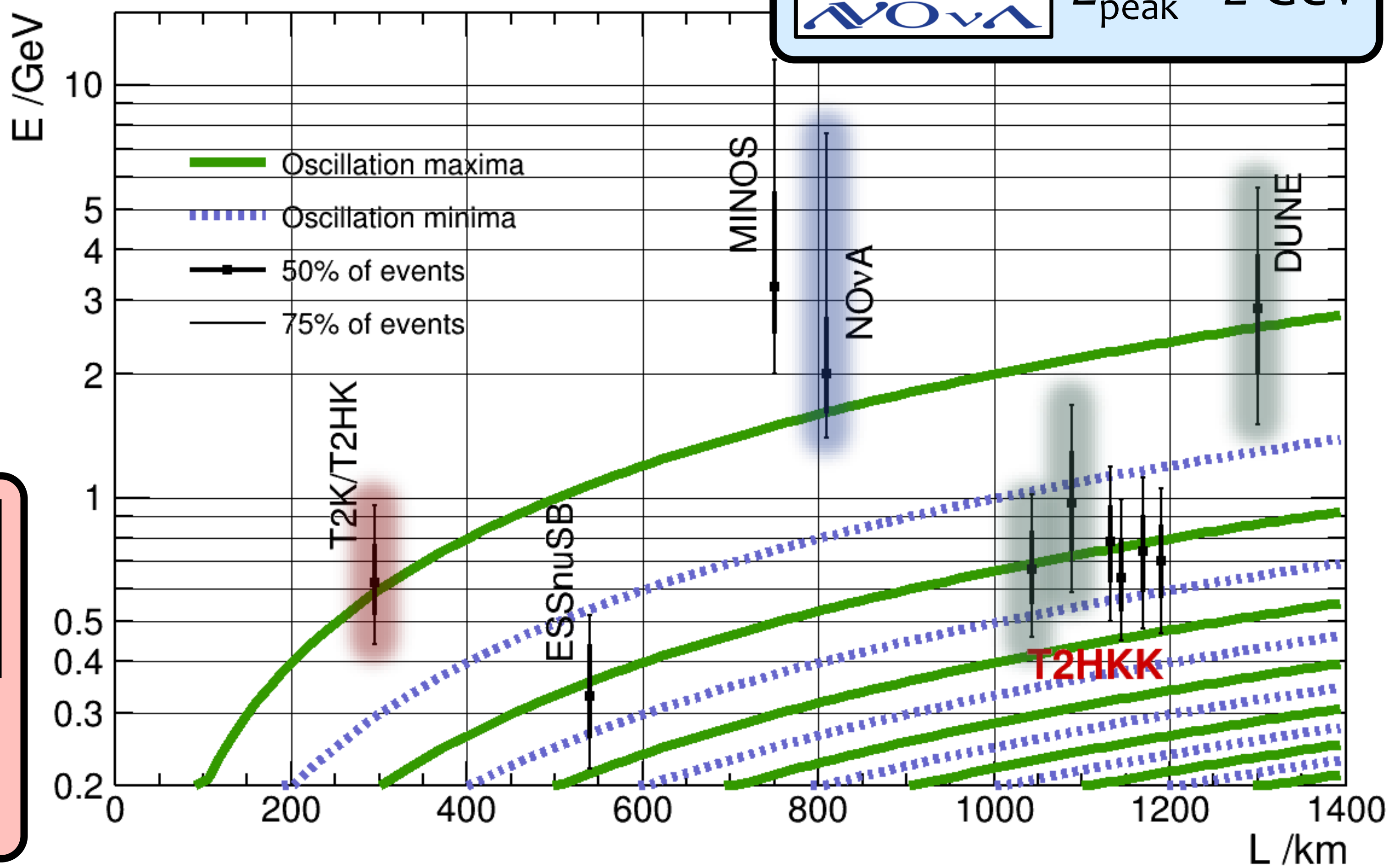
L = 295 km

E_{peak} =0.6 GeV

NOvA

L = 810 km

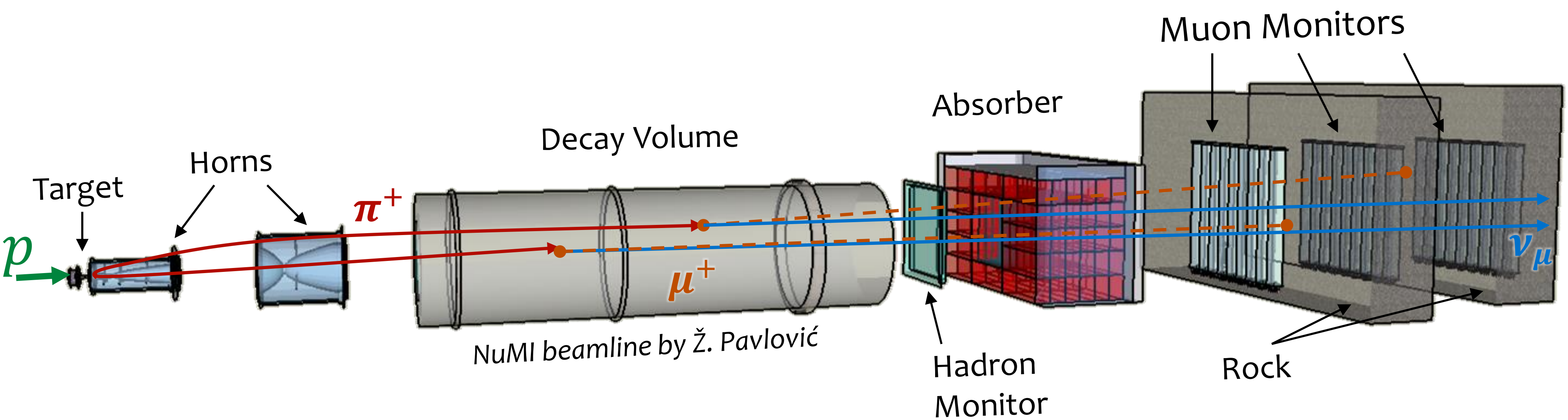
E_{peak} =2 GeV



Making the beam

Basic idea: ν_μ from pion decay.

- Pions produced in proton interactions on a target
- Secondary beam focussed by magnetic horns (NuMI/NOνA: 2, T2K: 3)
- Horn current & geometry determine (on-axis) spectrum
- Wrong sign ($\overline{\nu}$) and ν_e backgrounds are ~ few %
- Can reverse horn current to get $\overline{\nu}$ beam, but B/G is larger



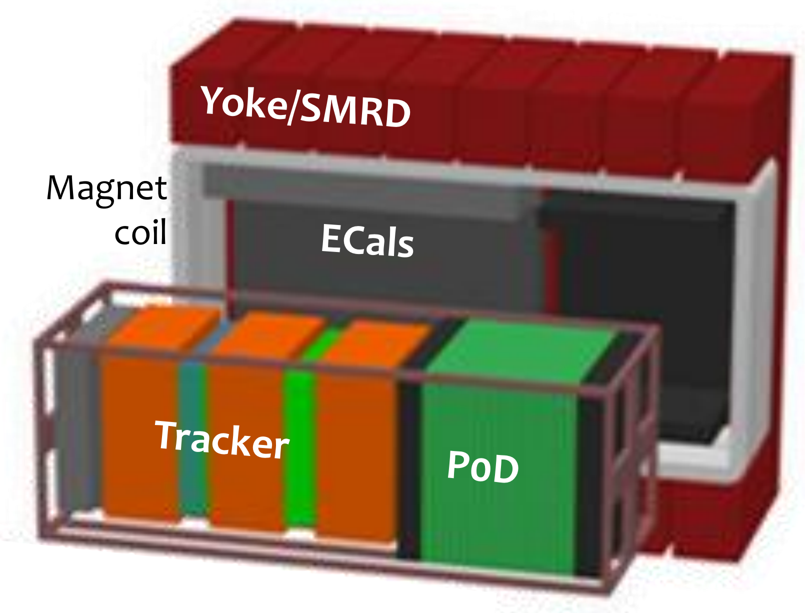
Near detectors

Vital to understand the **beam flux** and the **neutrino interactions**

Otherwise can't correctly interpret Far Detector data

Consensus:

- Understanding of **fluxes** has steadily improved
- Modelling **neutrino interactions** has improved but **remains difficult.**



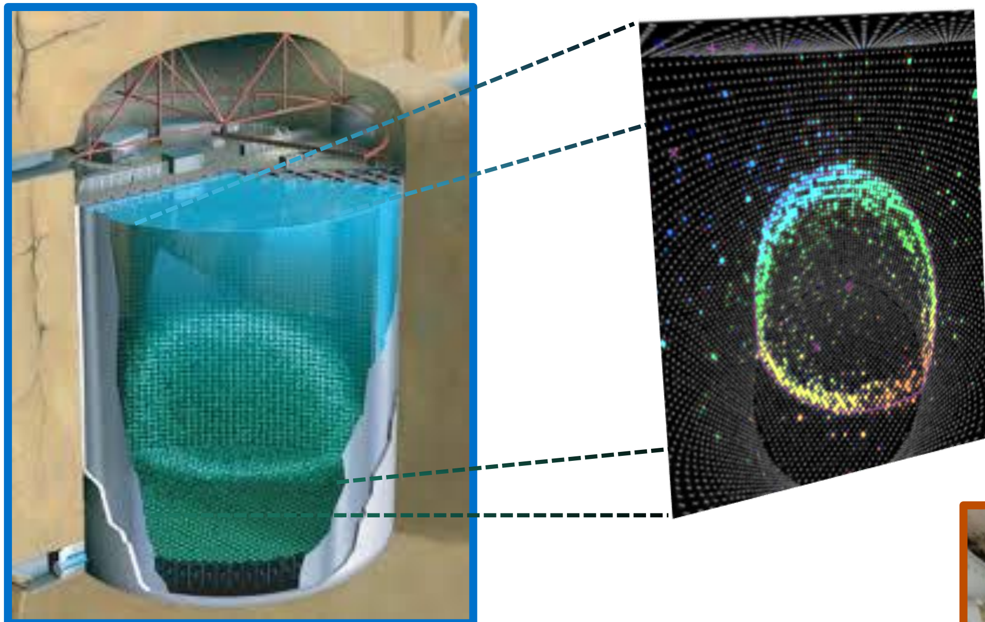
◀ **T2K ND280**

- Small scintillator target regions &TPCs to maximise information
- B-field to get charge sign information
- General concept: **Improve the models!**

NOνA ND built the same way as FD

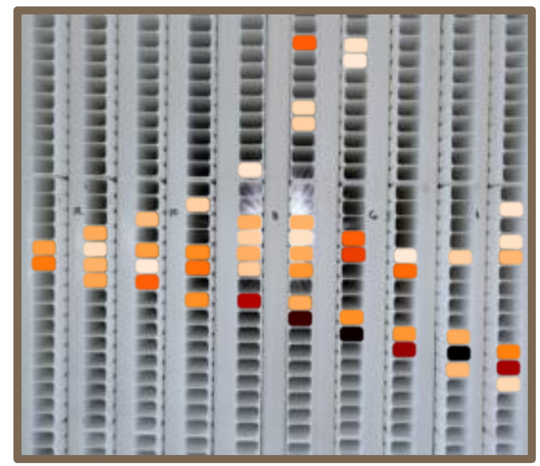
- Aim to **minimise differences**

Far detectors



NOνA detectors use a crossed scintillator tracker geometry.

- FD around 14kt
- Reconstruct non-QE events using calorimetry for hadronic shower



T2K uses the 50 kt Super-Kamiokande detector

- Water-Cherenkov is mostly sensitive to outgoing lepton
- Excellent reconstruction of QE $(\nu + n \to \ell + p)$ interactions

Analysis and results

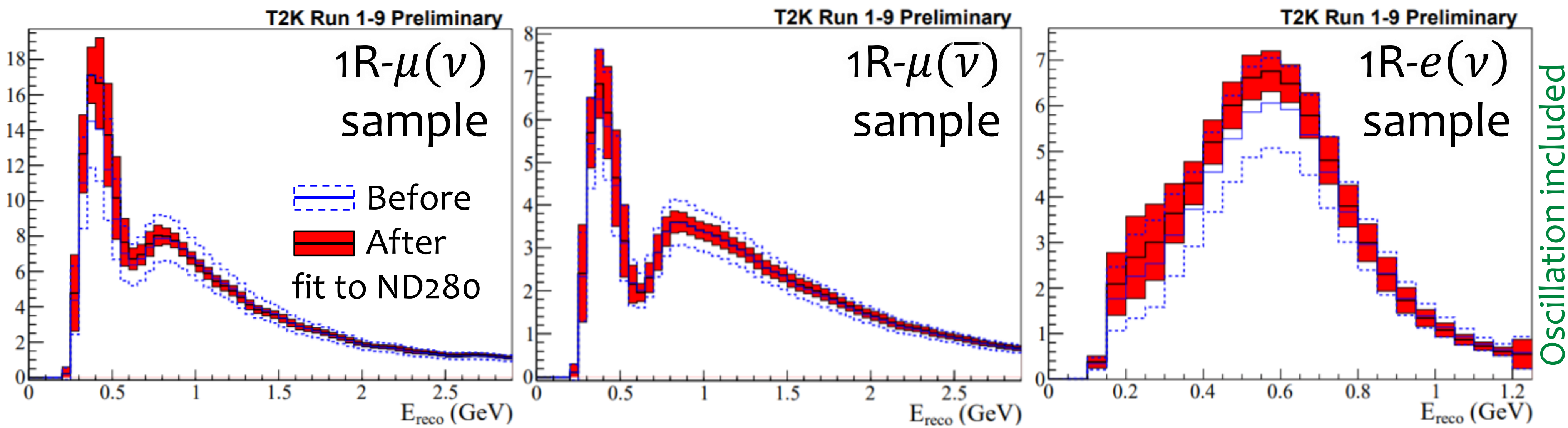
Winter 2018

T2K prediction

T2K makes a tunable MC model,with a large number of parameters adjusting the flux and cross-section.

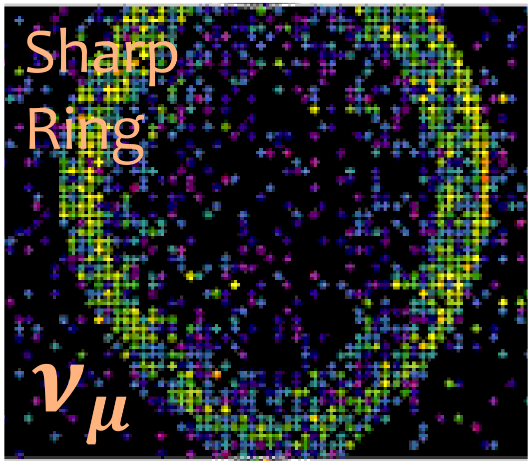
- Variations are sampled according to how well they fit the ND280 data samples (**likelihood score**) × **prior constraints**

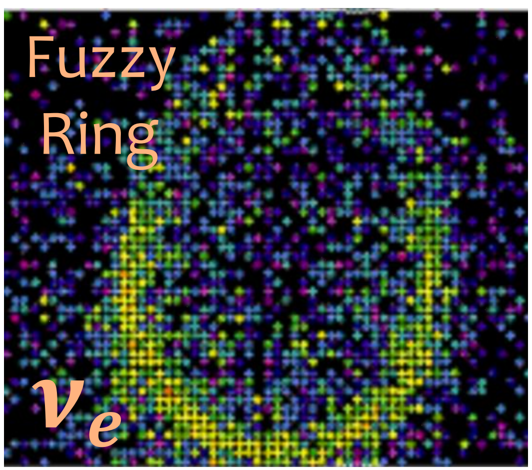
[Some parameters (e.g. SK detector effects) will only have a prior]



The ND280-consistent ensemble is used to provide a prediction of the spectrum at SK, with systematic errors

Super-Kamiokande samples





1R-μ

1R-e

1R-e + d.e.

ν from π^+	$\bar{\nu}$ from π^-

Disappearance of $\boldsymbol{\nu_\mu}$ constrains the parameters $\boldsymbol{\Delta m^2_{3i}}$ and $\boldsymbol{\theta_{23}}$ [up to a degeneracy around 0.5]

Appearance of $\boldsymbol{\nu_e}$ sensitive to $\boldsymbol{\theta_{13}}$, $\boldsymbol{\Delta m^2_{3i}}$ & $\boldsymbol{\theta_{23}}$.

But primary use is to measure $\boldsymbol{\delta_{CP}}$ and **look for CPV**

New sample with a late decay electron corresponds to:

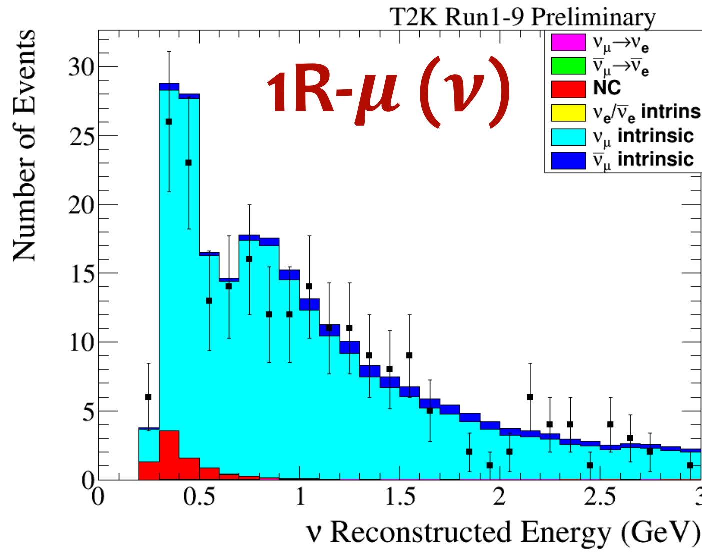
$$\nu_e + n\ (\rightarrow \Delta^+) \rightarrow e^- + n + \pi^+$$

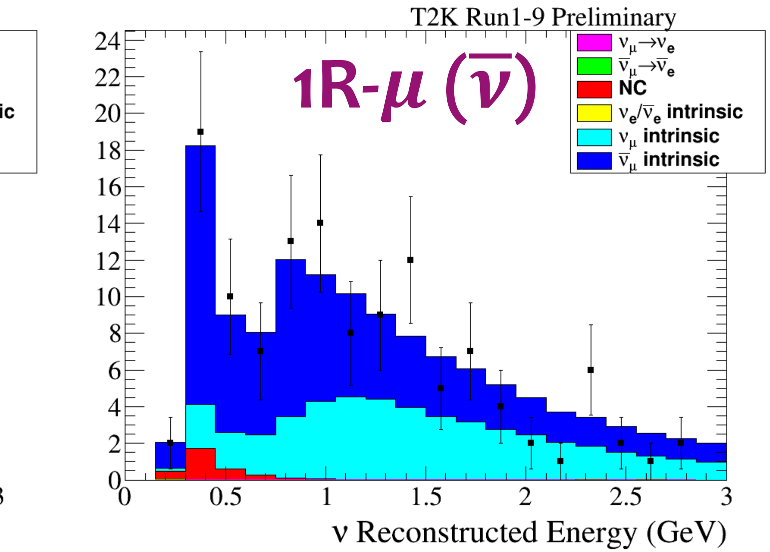
$\bar{\nu}_e - \nu_e$ rate asymmetry should be proportional to **$\sin \delta_{CP}$**

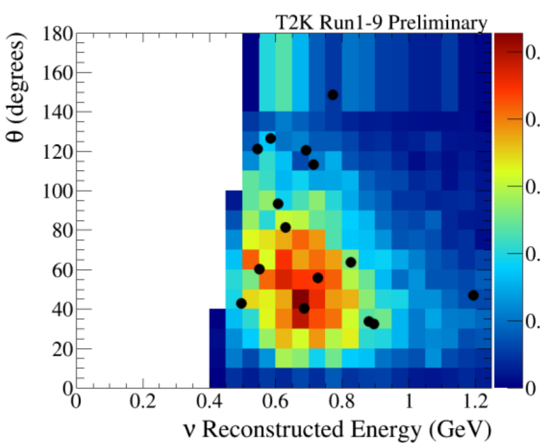
T2K data distributions

ν_μ data is analysed as a function of E_ν

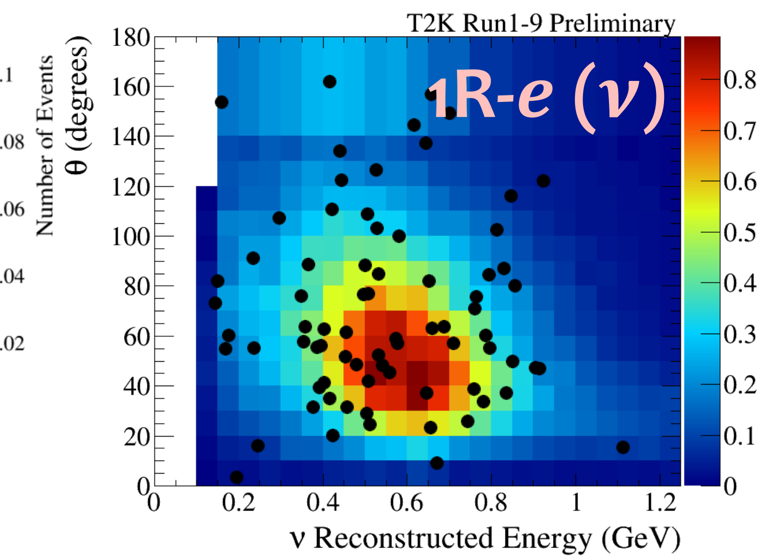
ν_e data is analysed as a function of E_ν and $\theta_{e\nu}$

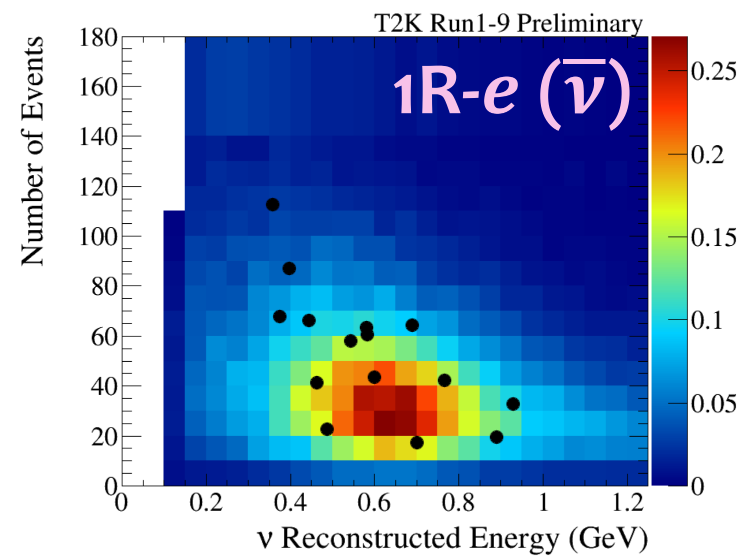






1R-e (ν) with d.e.



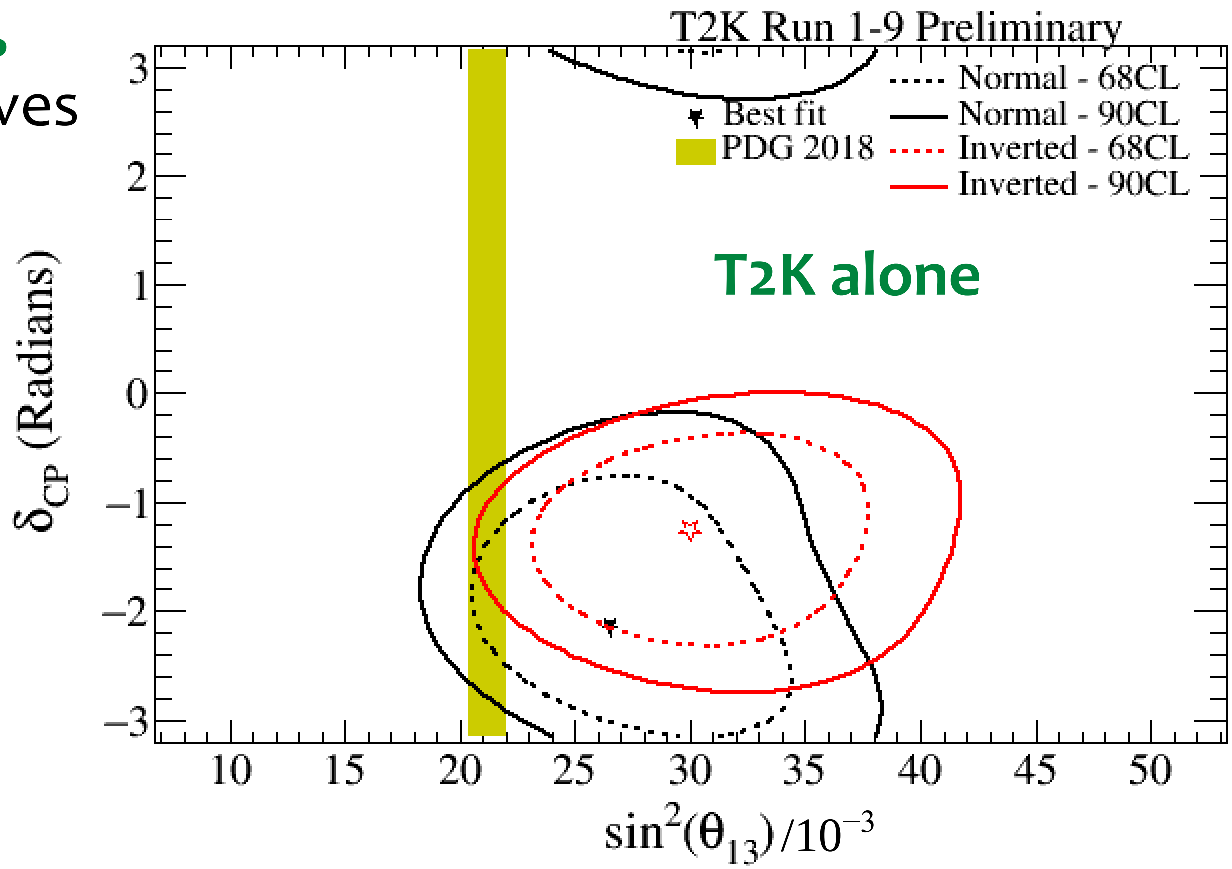


T2K appearance* results

T2K interval in $\sin^2\theta_{13} - \delta_{CP}$ plane is intersection of S-curves

- One curve for ν mode, another for $\bar{\nu}$ mode

- **Inverted Ordering** needs slightly larger $\sin^2\theta_{13}$



*Uses ν_μ data; marginalises over relevant parameters

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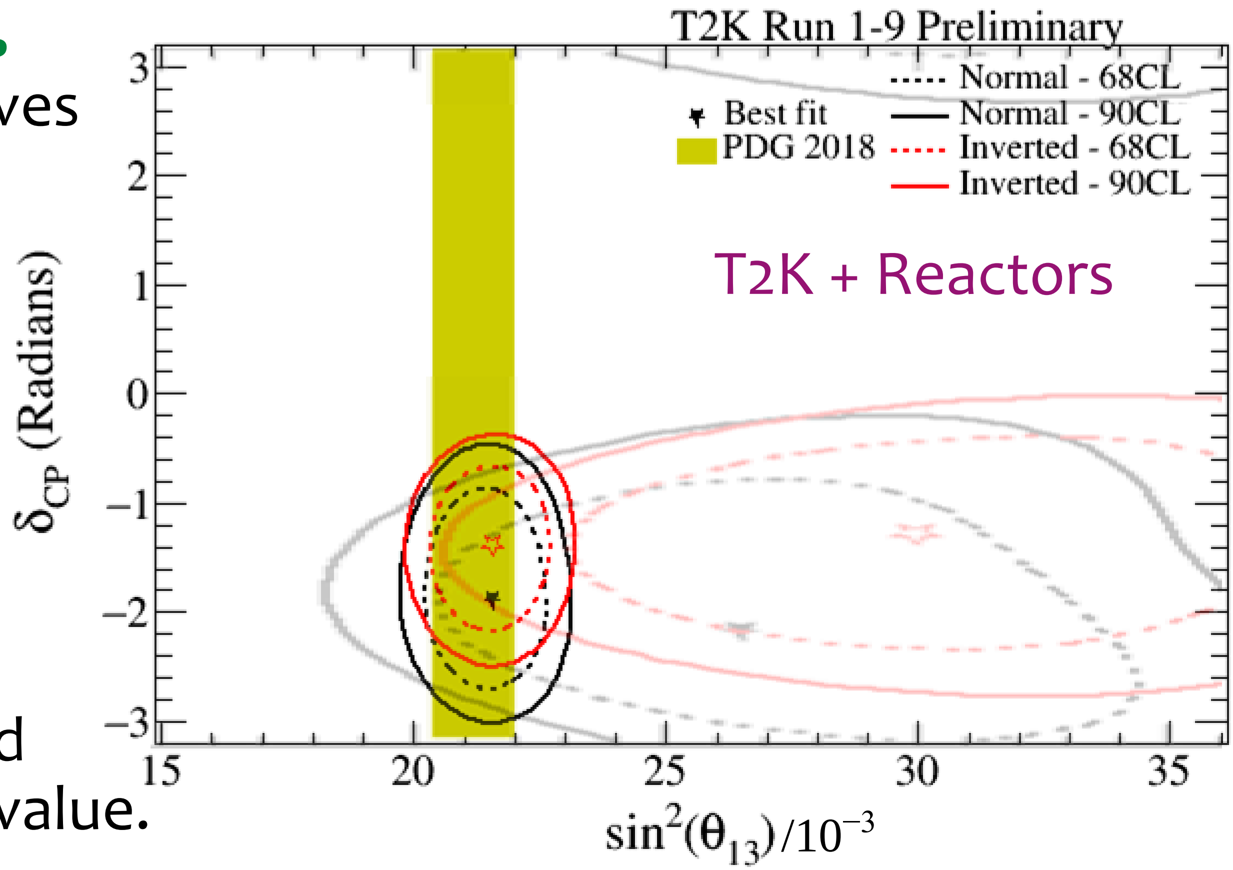


δ_{CP} constraint then improved by intersection with reactor value.

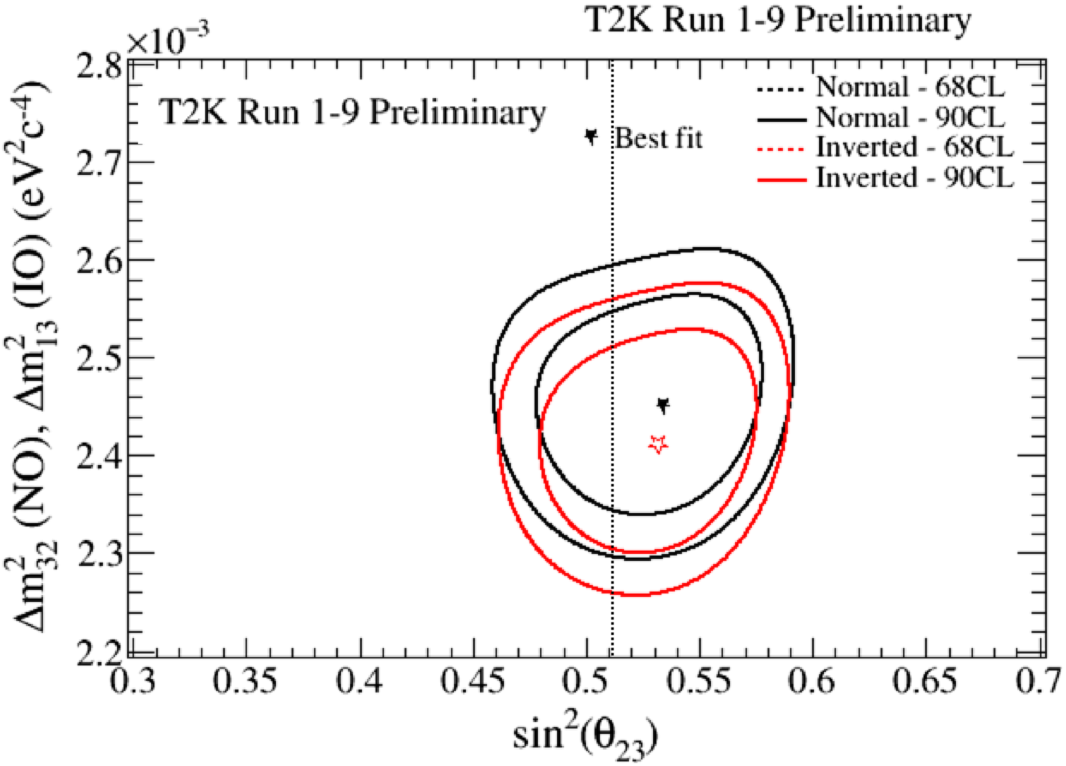
- More tension in Inverted Ordering, leading to stronger than expected preference for Normal Ordering

T2K disappearance* results

Δm^2_{32}, $\sin^2\theta_{23}$ results mostly dependent on the $\nu_\mu/\bar{\nu}_\mu$ data.

Low **observed/expected** ratio so expect maximal disappearance…

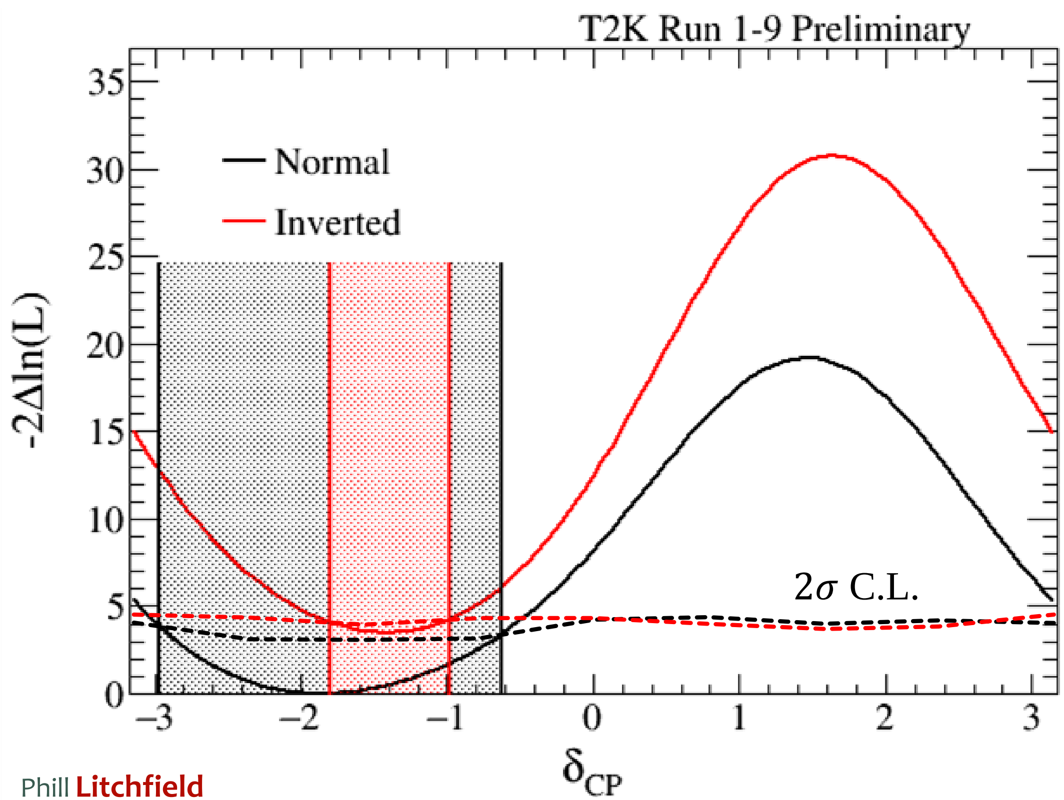
- This happens for $\sin^2\theta_{23} \simeq 0.51$ ∴ small preference for *Upper octant* from disappearance alone

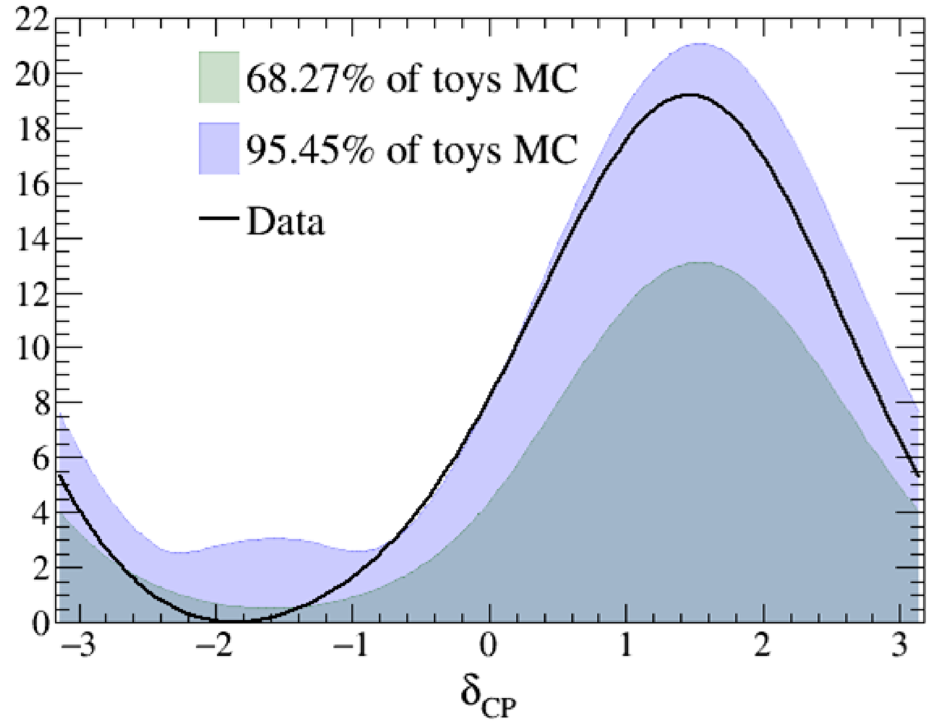


- But larger values of $\sin^2\theta_{23}$ also enhance *appearance* rates and improve fit to ν_e appearance.

Constraint on δ_{CP}

- Marginalise over everything except δ_{CP}
- Compare to critical values from toys
- Exclude CP conservation at $> 2\sigma$ C.L.
- Inverted ordering only just $< 2\sigma$ C.L.





Stronger than expected

- In toy experiments at best fit, 2σ exclusion of $\delta = \{0, \pi\}$ occurs in 25% of cases

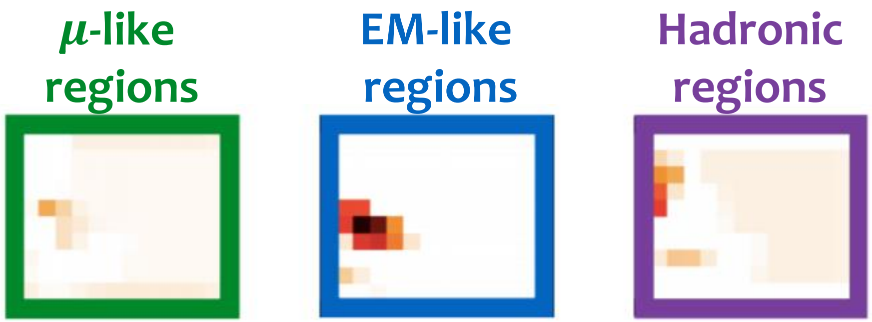
Analysis and results

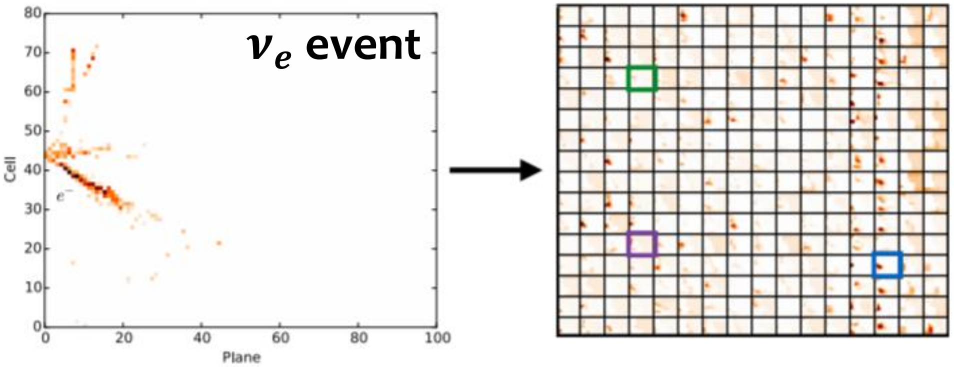
June 2019

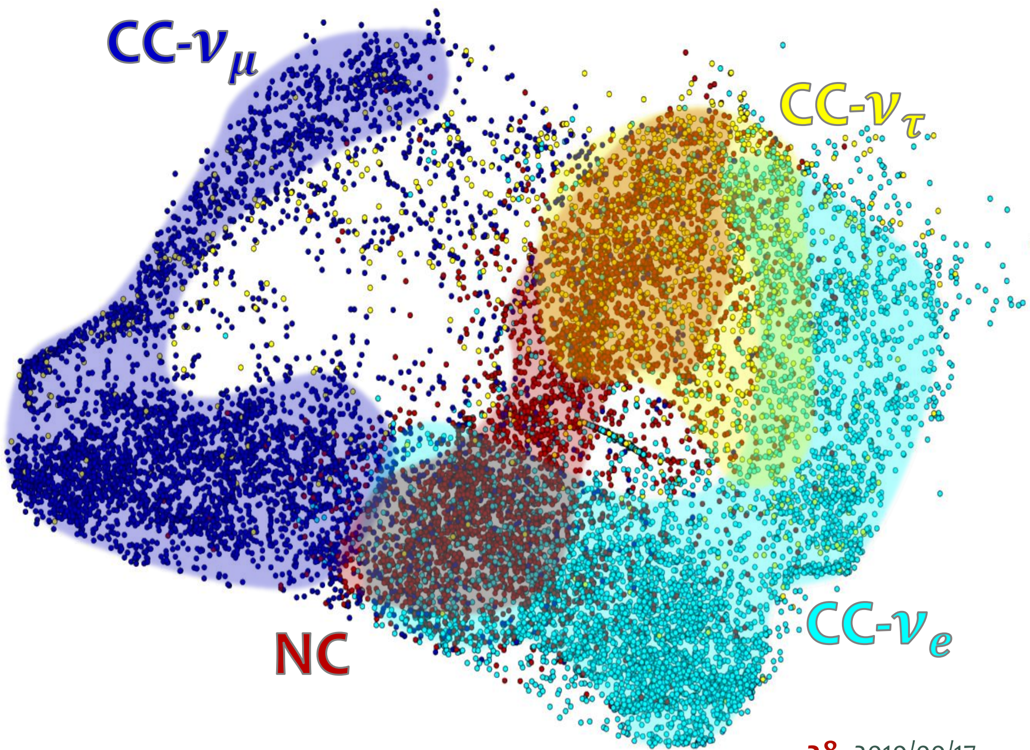
NOνA selection

Uses a modern Convolutional Visual Network

- Acts on hits directly
- Effectively recognises regions dominated by different kinds of activity
- Then classifies based on distribution of such regions



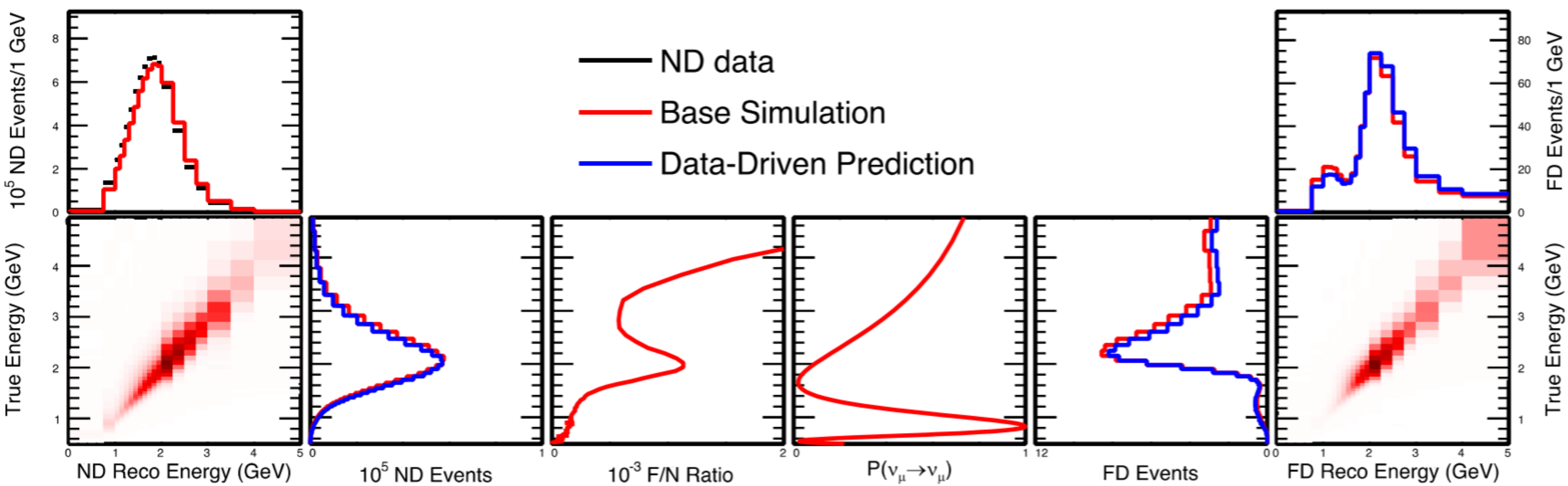




NOνA prediction

NOνA relies on a ‘free’ prediction of FD spectrum from ND data

- All ND deviations from nominal MC are mapped to the FD prediction
- Validity rests on similarity of the two detectors
- MC model still matters because of “Reco ↔ True” conversions

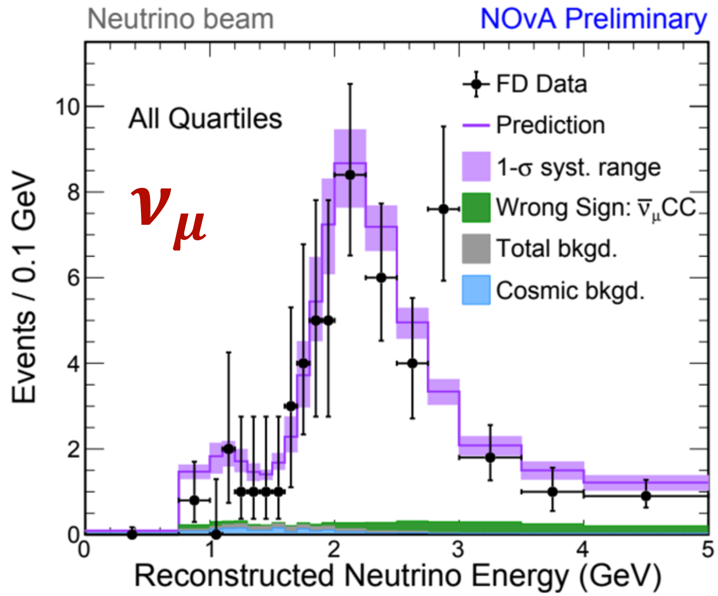


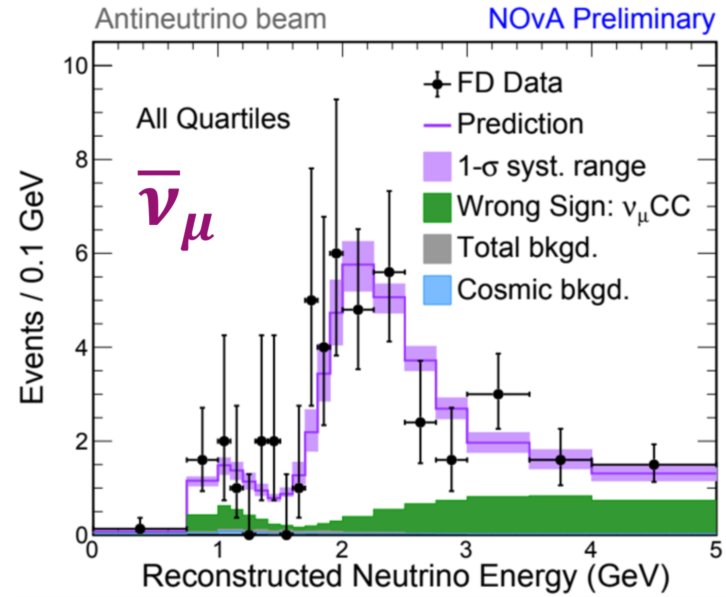
NOνA data distributions

ν_μ events analysed in 4 bins of energy resolution

- $E_\mu/(E_\mu + E_{\text{had}})$

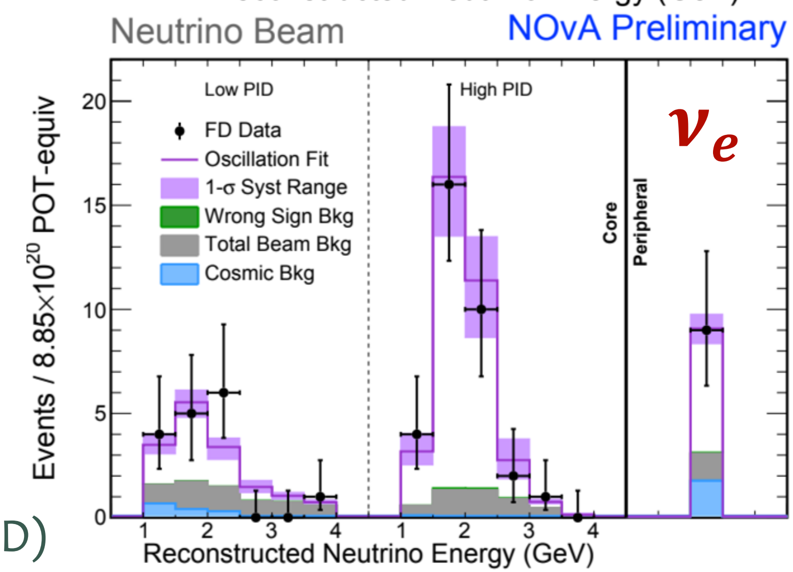
  [muons have better resolution]

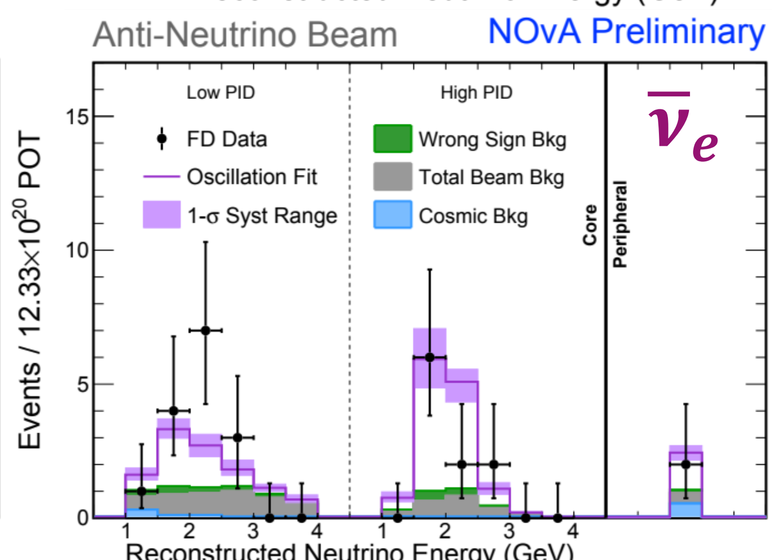




Exposure* for $\bar{\nu}_e$ is ~40% higher than ν_e

Significance of $\bar{\nu}_e$ appearance is 4.4σ

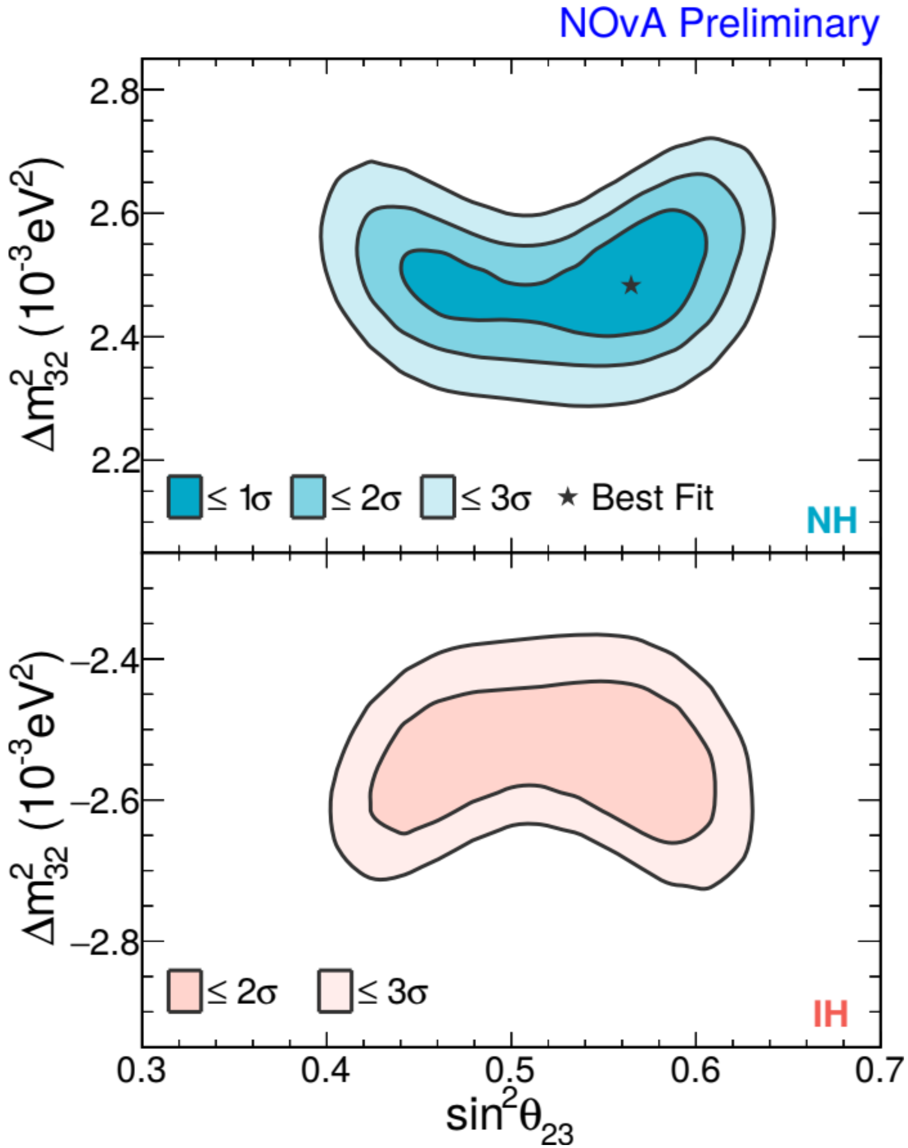




* POT × FD mass

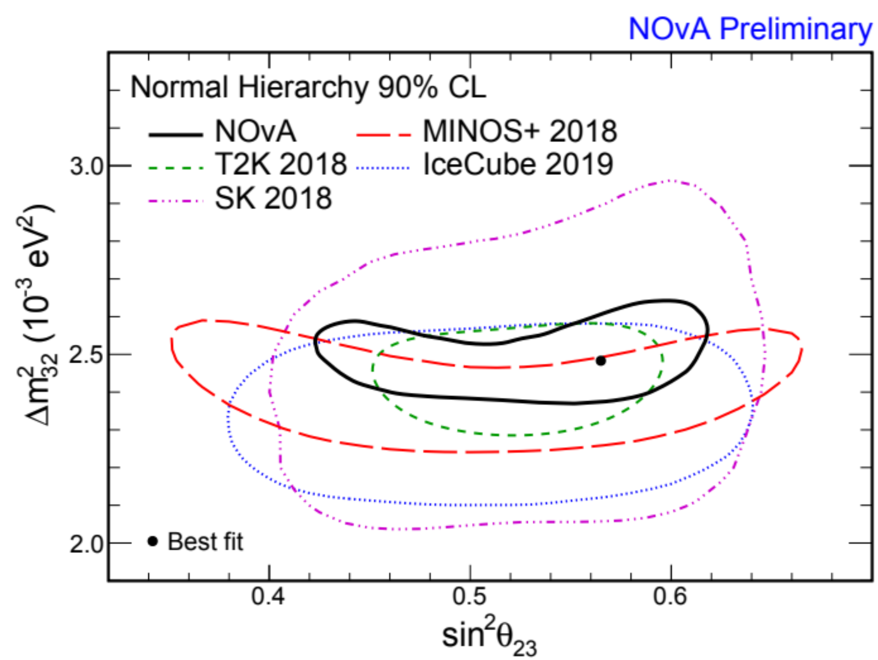
(Started with partial FD)

NOνA disappearance* results



Results consistent with T2K

- Weak preference for non- maximal disappearance
- Preference for **Upper Octant** ($\sin^2 \theta_{23} > 0.5$) and **Normal Ordering**



NOνA appearance* results

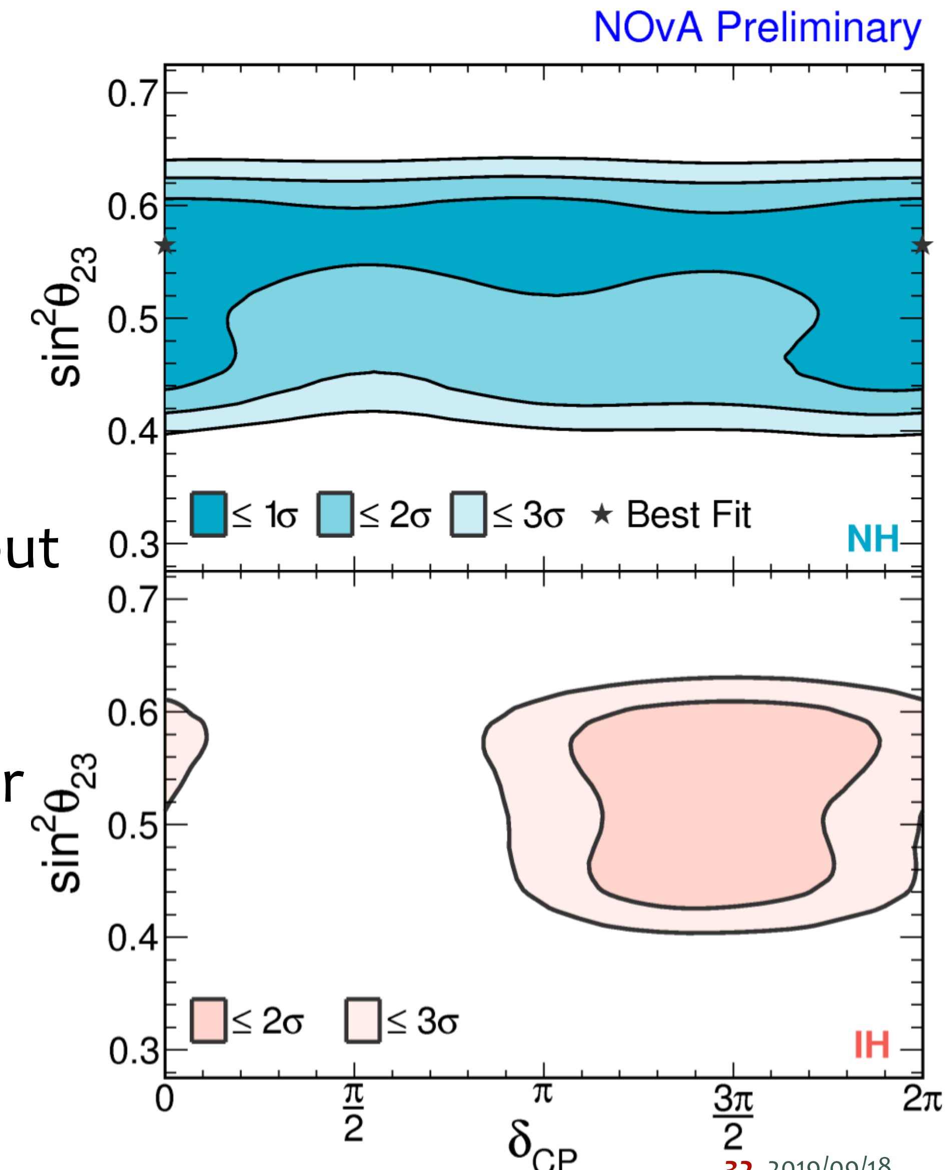
For NOνA, joint interval in $\delta_{CP} - \theta_{23}$ space is quite complicated

- $\delta_{CP} - \theta_{13}$ space is ~~less fun~~ simpler
- NOνA always incorporates reactor constraint

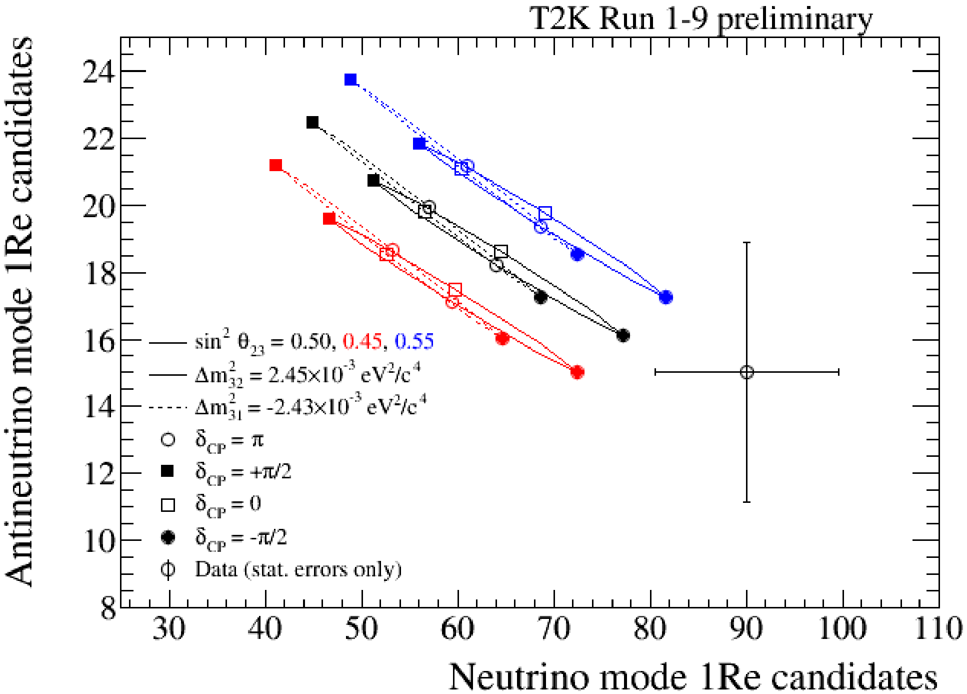
Best fit is very close to CP conserving, but all values are consistent <1σ

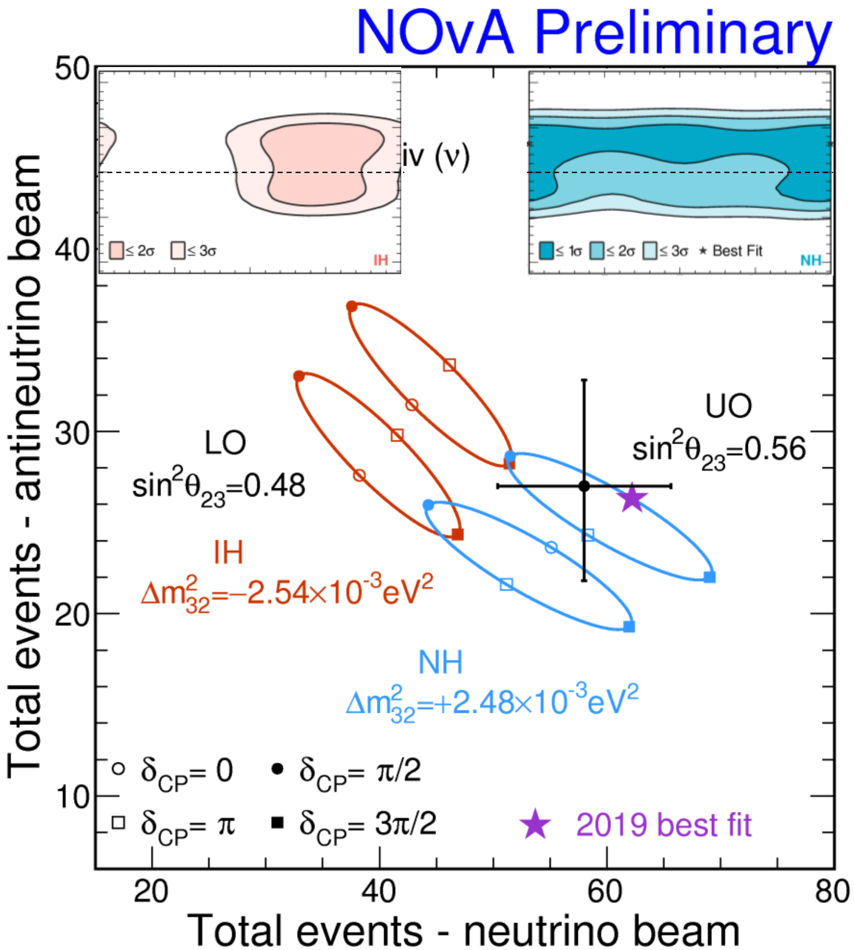
Some δ_{CP} preference if Lower Octant or Inverted Ordering is assumed.

- But not the same in both cases



Comparison of T2K & NOνA results





[This is not how analyses are done]

But In T2K, $\boldsymbol{\delta_{CP}}$ is independent of other factors because data is 'extreme'

NOνA data is more central so conclusion about $\boldsymbol{\delta_{CP}}$, **MO** and **octant** are coupled.

Mass Ordering and Octant

T2K and NOvA data both have some preference in the binary choices:

- **Mass ordering ↔** $\mathbf{sign}\left(\Delta m_{31}^2\right)$
- **Octant ↔** $\mathbf{sign}(\theta_{23} - \pi/4)$

- Both have similar level and pattern [just a coincidence]

T2K uses Bayes Factors, which are not strictly comparable to Frequentist statements

A Bayes Factor of ~10 would be termed "strong", & is roughly equivalent to the common "$p < 0.05$; significant" criterion.

NOvA	Lower	Upper
Normal	$>1.6\sigma$	Prefer
Inverted	$>2.0\sigma$	$>1.8\sigma$

T2K	Lower	Upper	Sum
Normal	0.184	**0.705**	0.889
Inverted	0.021	0.090	0.111
Sum	0.205	0.795	

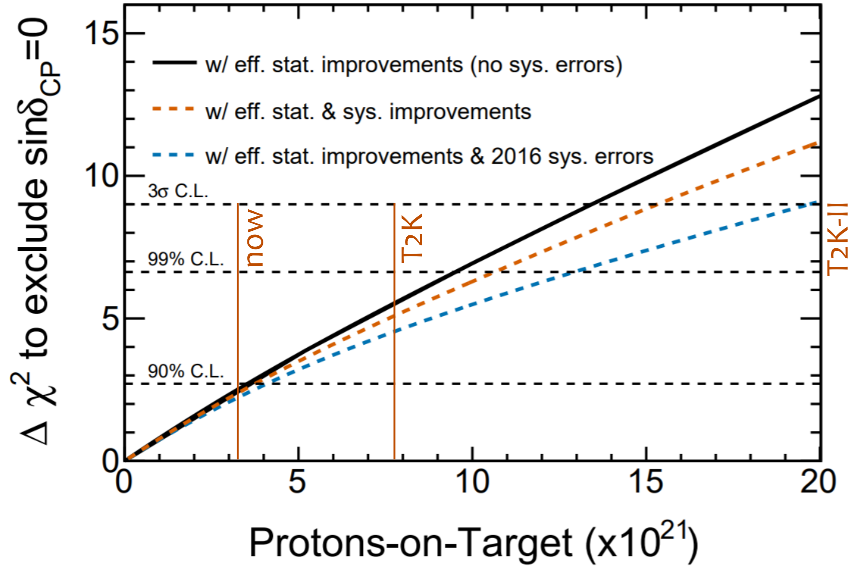
Future experiments

T2K & NOνA future

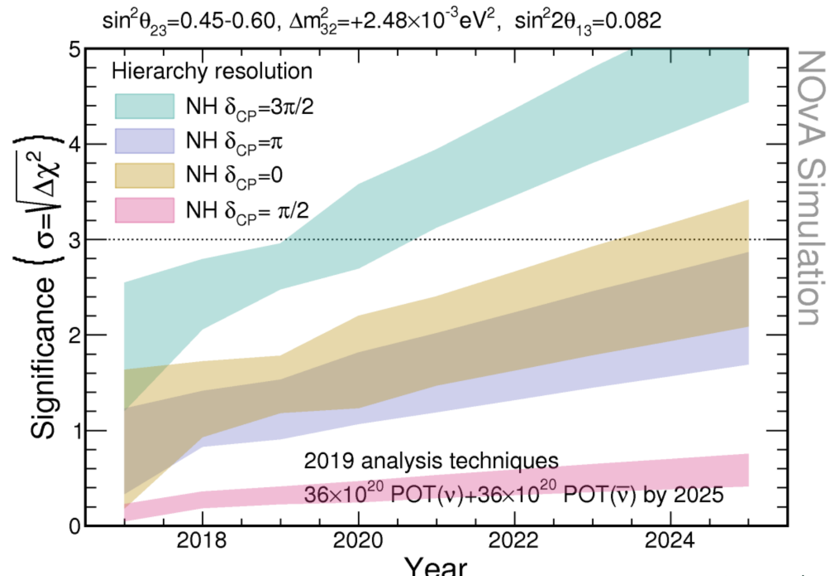
T2K and NOνA are still running

Both hope to be able to make 3σ-level statements:

- T2K focussing on CP violation
  - Plot for $\delta_{CP} = -\pi/2$



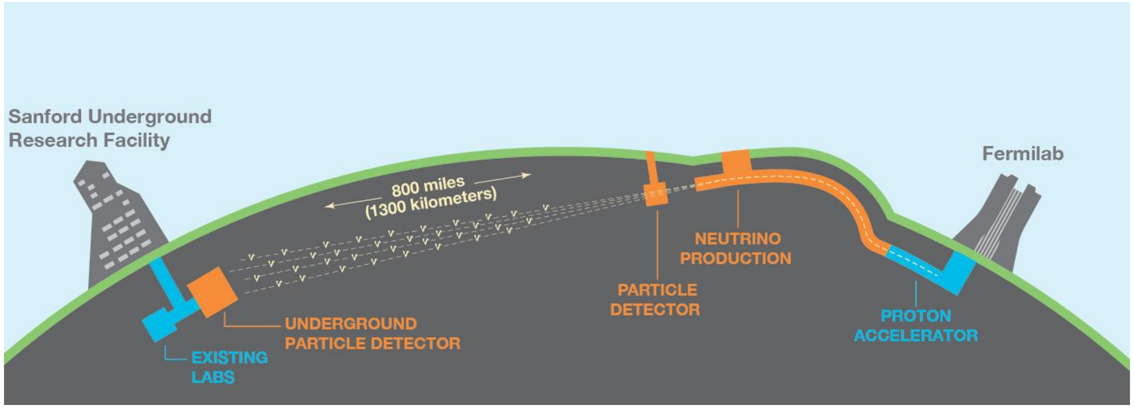
- NOνA focussing on Mass Ordering



Both planning to run until ~2025

- T2K(-II) incorporates continuous increases to beam power (0.5 → 1.3MW)

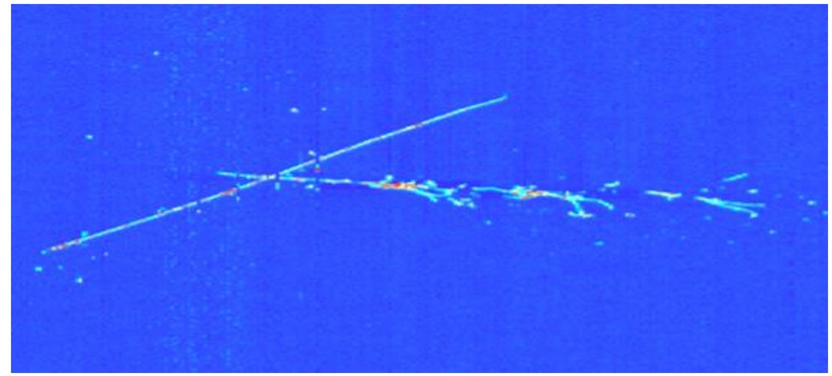
LBNE/DUNE



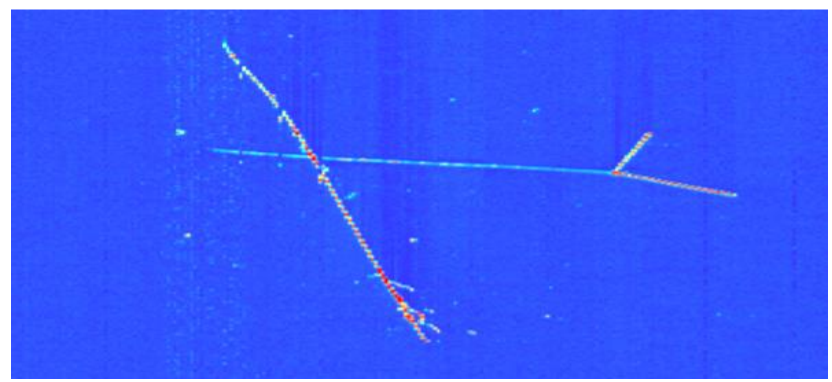
All-new experiment at FNAL.

- $L \sim 1300$ km baseline to Sanford
- Up to 4× 10kt Liquid Argon detectors
- Wide-band beam [1 ~ 4 GeV] allows **mapping of a full oscillation period**
  - Separate CP effects and MO by different E dependence
  - Precision measurement of $\boldsymbol{\delta_{CP}}$

Liquid Argon detectors have potential for very detailed reconstruction



ProtoDUNE-SP events @ 1 GeV

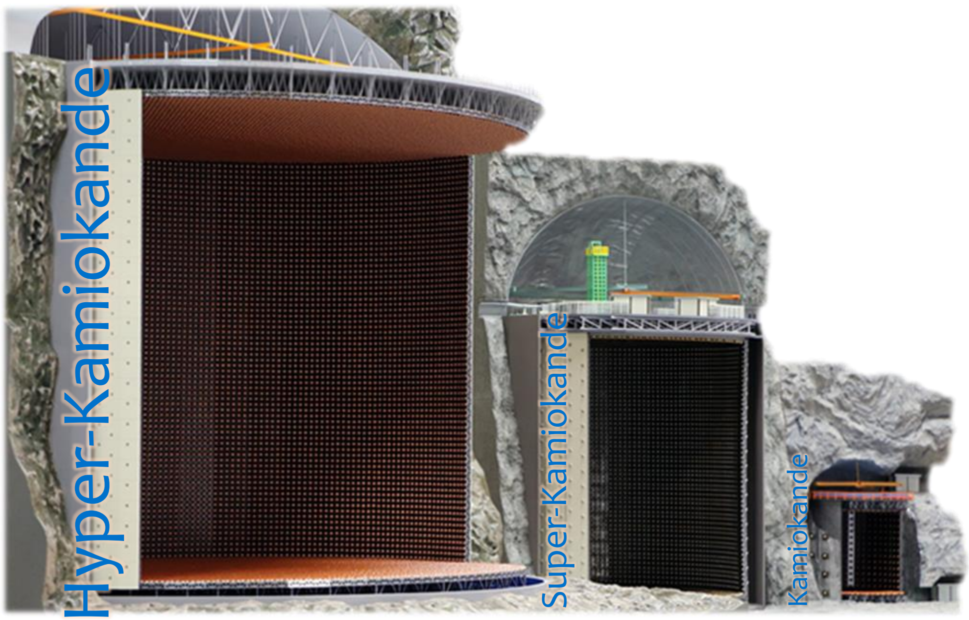


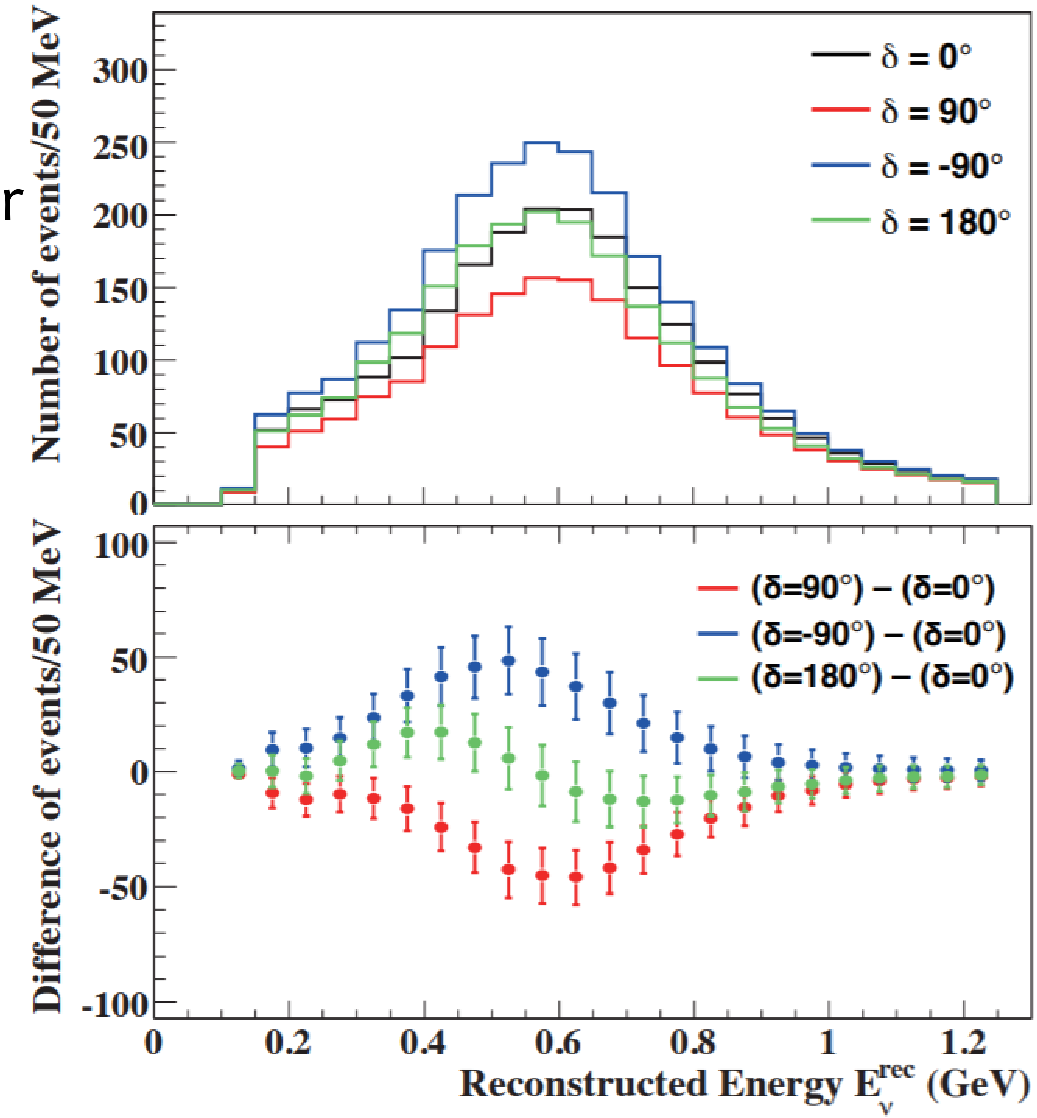
Hyper-Kamiokande

Like Super-Kamiokande, but ~8× bigger, + improved detectors.

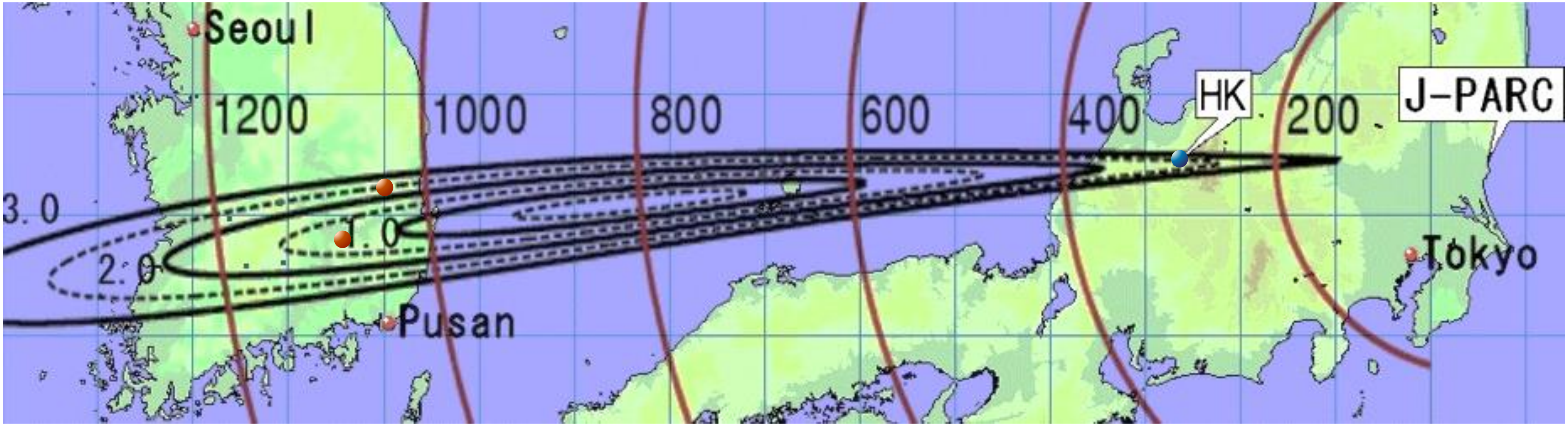
- ~800 ν_e or ~250 $\overline{\nu}_e$ events per year
- **CPC excluded at 3σ (5σ) for 76% (57%) of values**

MO also possible with atmos. ν





Korea Neutrino Observatory



Extension to use same J-PARC beamline at a longer baseline

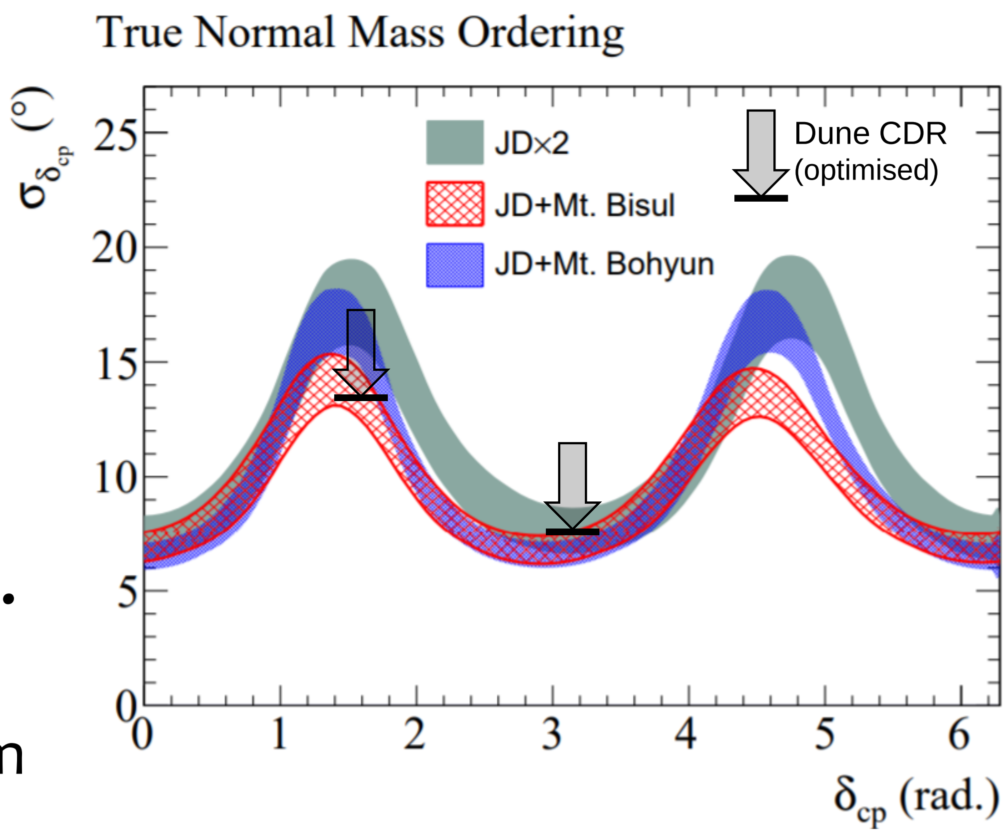
- Measurement **centred on 2nd maximum** at ~1100km
  - Site choice allows either wide-band or Kamioka-like flux (1.5° or 2.2° OA)
- CPV grows with baseline – compensates for $1/L^2$ statistics
- Systematic errors *do not* grow, so effectively supressed by factor ~3
- Precision on δ_{CP} and validation of PMNS model

Precision on δ_{CP}

Different optimisation to discovery of CP violation ($\sin\delta \neq 0$)

- Discovery just needs sensitivity to **$\sin\delta$** terms
- Precision at large $\sin\delta$ requires sensitivity to $\frac{dP}{d\delta} \rightarrow$ **$\cos\delta$** terms

The easier it is to discover $\delta \neq 0$, the harder it will be to measure it.



Measuring the appearance spectrum is necessary. Need

- High statistics (T2HK) and/or broad L/E range (DUNE, T2HK-Korea)

Summary & Outlook

T2K and NOνA data **both** prefer
Upper Octant and **Normal Ordering**

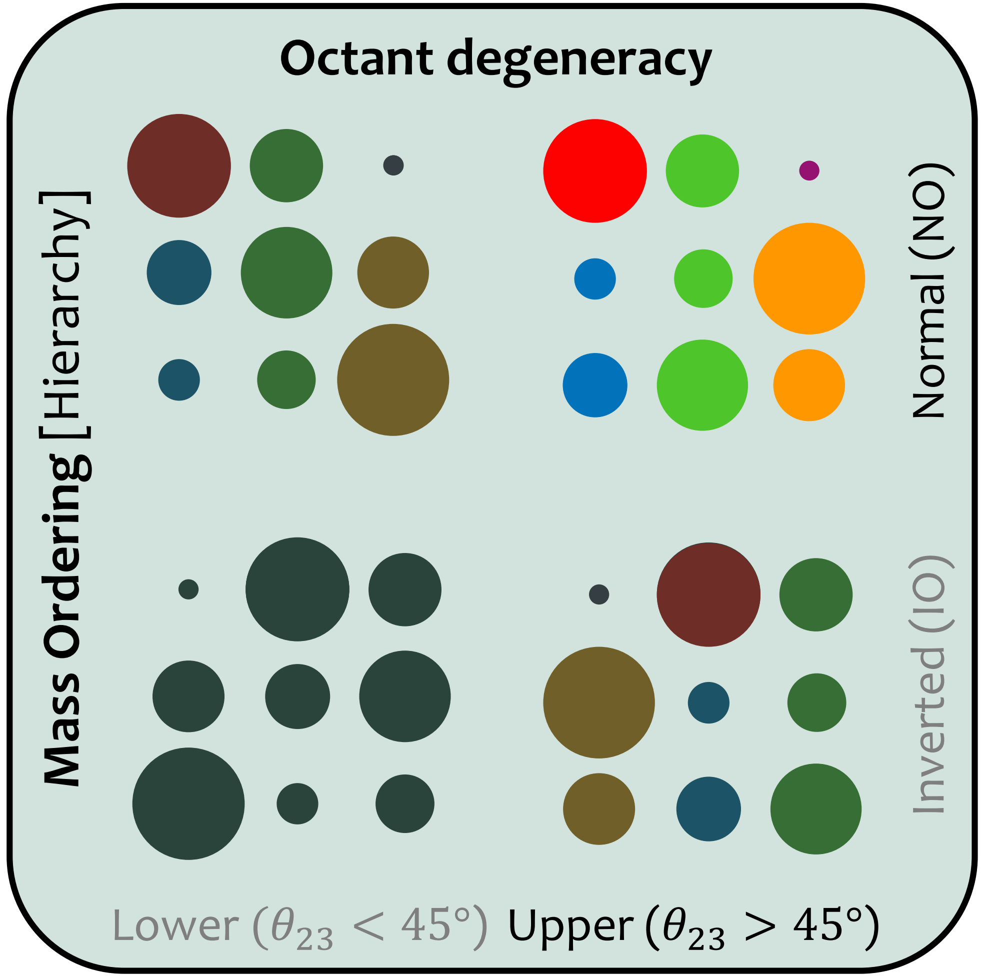
T2K data also point to a large **CP violating** effect ($\delta \sim 3\pi/2$)

If [UO, NO]
NOνA has no preference on δ

More data still to come. **T2HK(-K) and DUNE should be definitive**

+ Precision on leptonic CP δ

+ Start testing the PMNS(-only) model



Extras

The ν_e appearance probability can be written approximately as a sum of terms quadratic in the small parameters $\alpha = \Delta m^2_{21}/\Delta m^2_{31} \approx 1/32$, and $\sin 2\theta_{13}$:

$$P(\nu_\mu \to \nu_e) \approx T_{\theta\theta} \sin^2 2\theta_{13} \frac{\sin^2([1-A]\Delta)}{[1-A]^2} + T_{\alpha\alpha}\alpha^2 \frac{\sin^2(A\Delta)}{A^2} + T_{\alpha\theta}\alpha \sin 2\theta_{13} \frac{\sin([1-A]\Delta)}{[1-A]} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

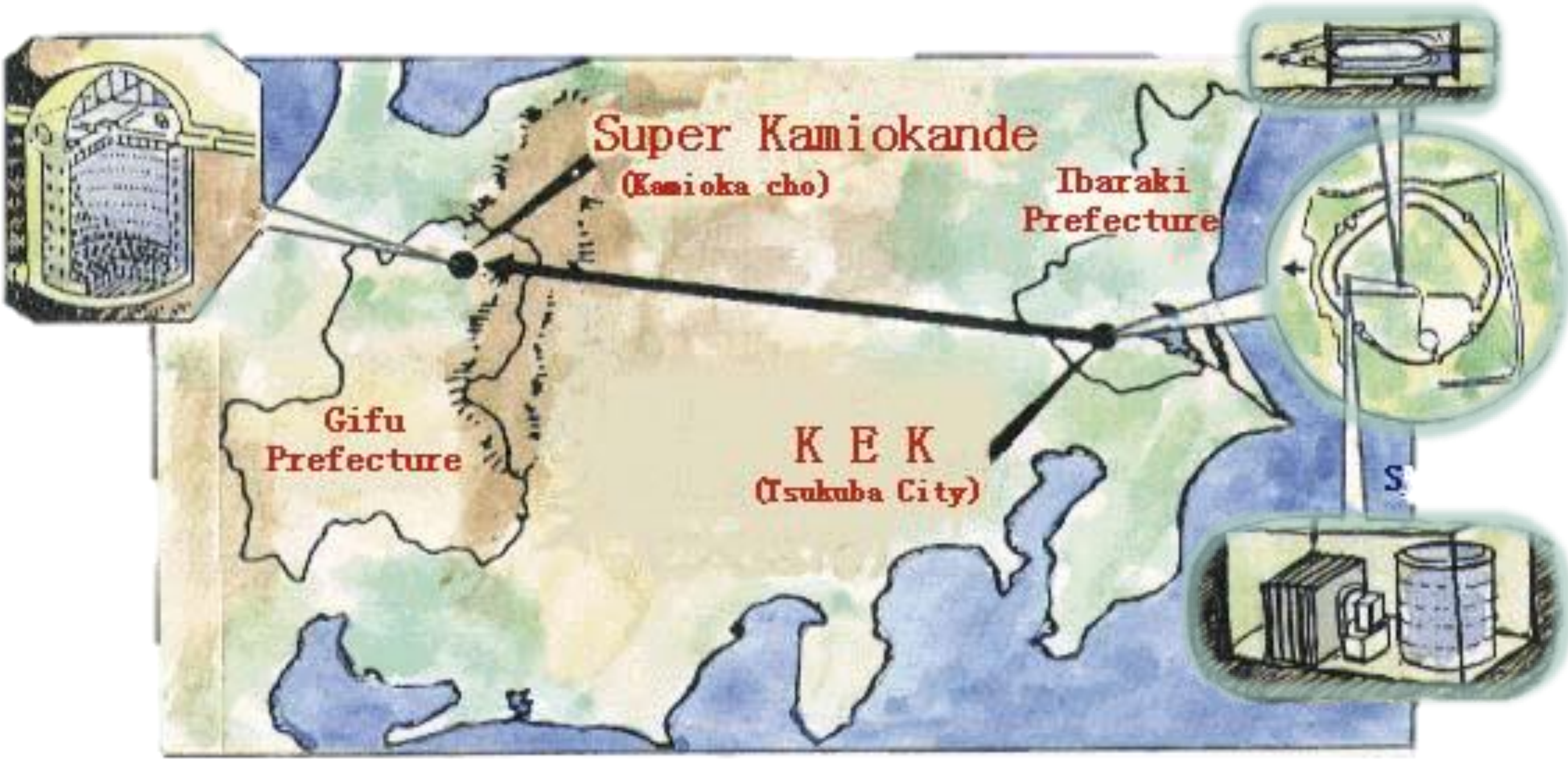
where

$$T_{\theta\theta} = \sin^2\theta_{23}, \qquad T_{\alpha\alpha} = \cos^2\theta_{23}\sin^2 2\theta_{12}, \qquad T_{\alpha\theta} = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$

and $\Delta = \frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$ at 1st osc. maximum.

$A\left(= \pm 2\sqrt{2} G_F n_e E / \Delta m^2_{31}\right)$ is the matter density parameter; NOνA: $|A| \sim 0.2$, T2K: $|A| \sim 0.07$

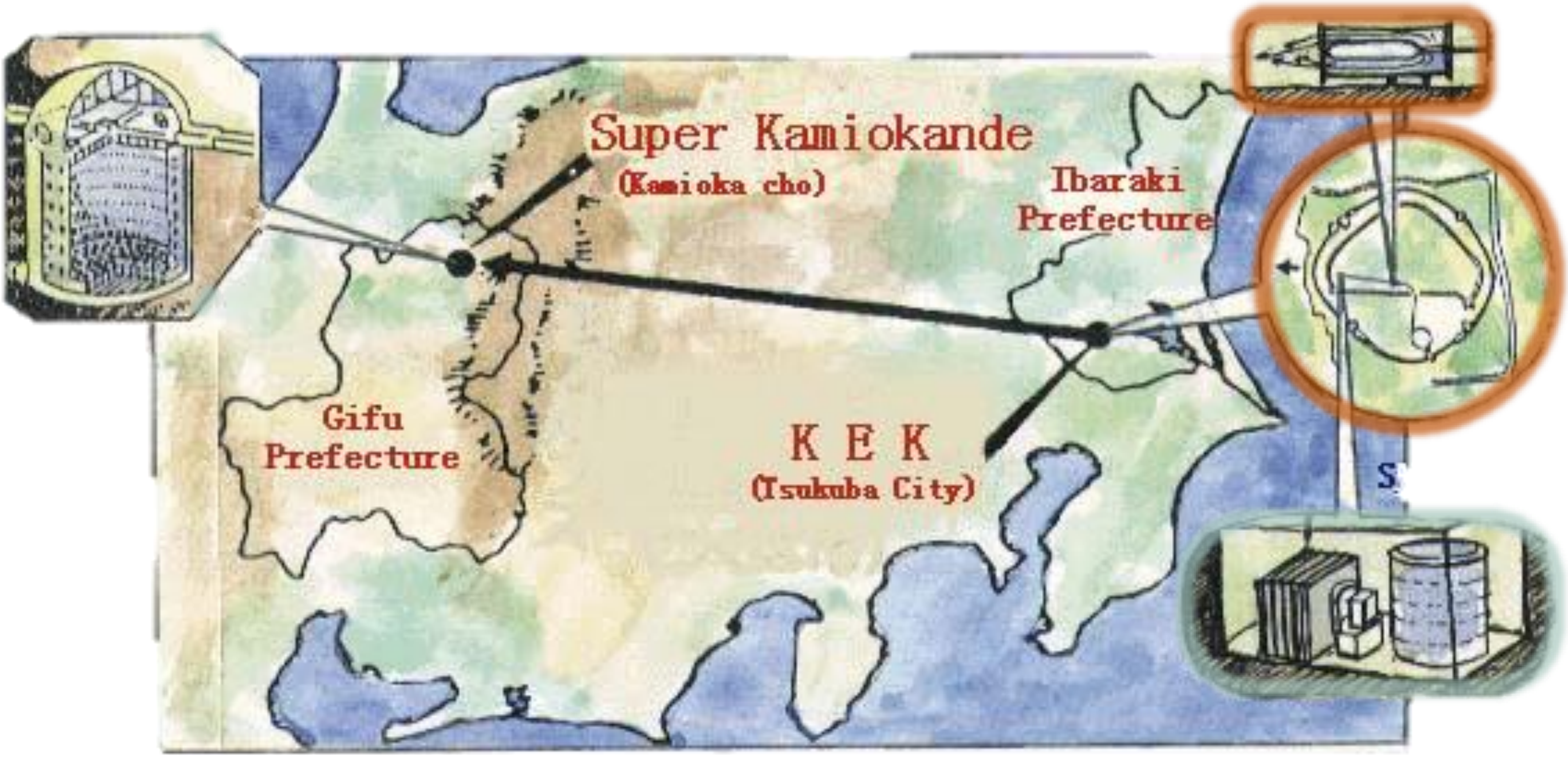
General features



First LBL experiment was **K2K**. Modern examples are very similar.

General features

Neutrinos created at proton accelerator

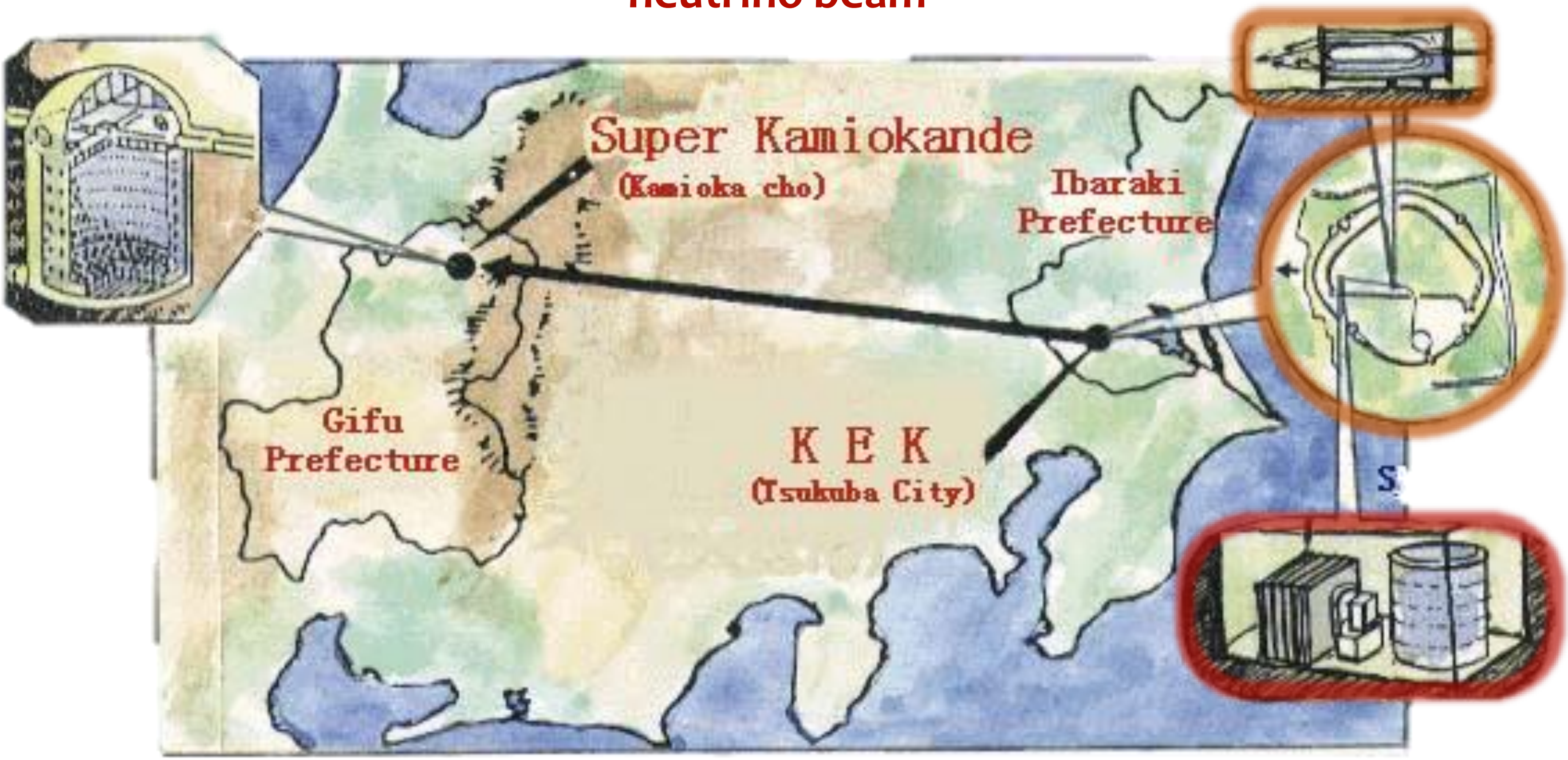


First LBL experiment was **K2K.** Modern examples are very similar.

General features

Near Detector(s) characterise the initial neutrino beam

Neutrinos created at proton accelerator



First LBL experiment was **K2K**. Modern examples are very similar.

General features

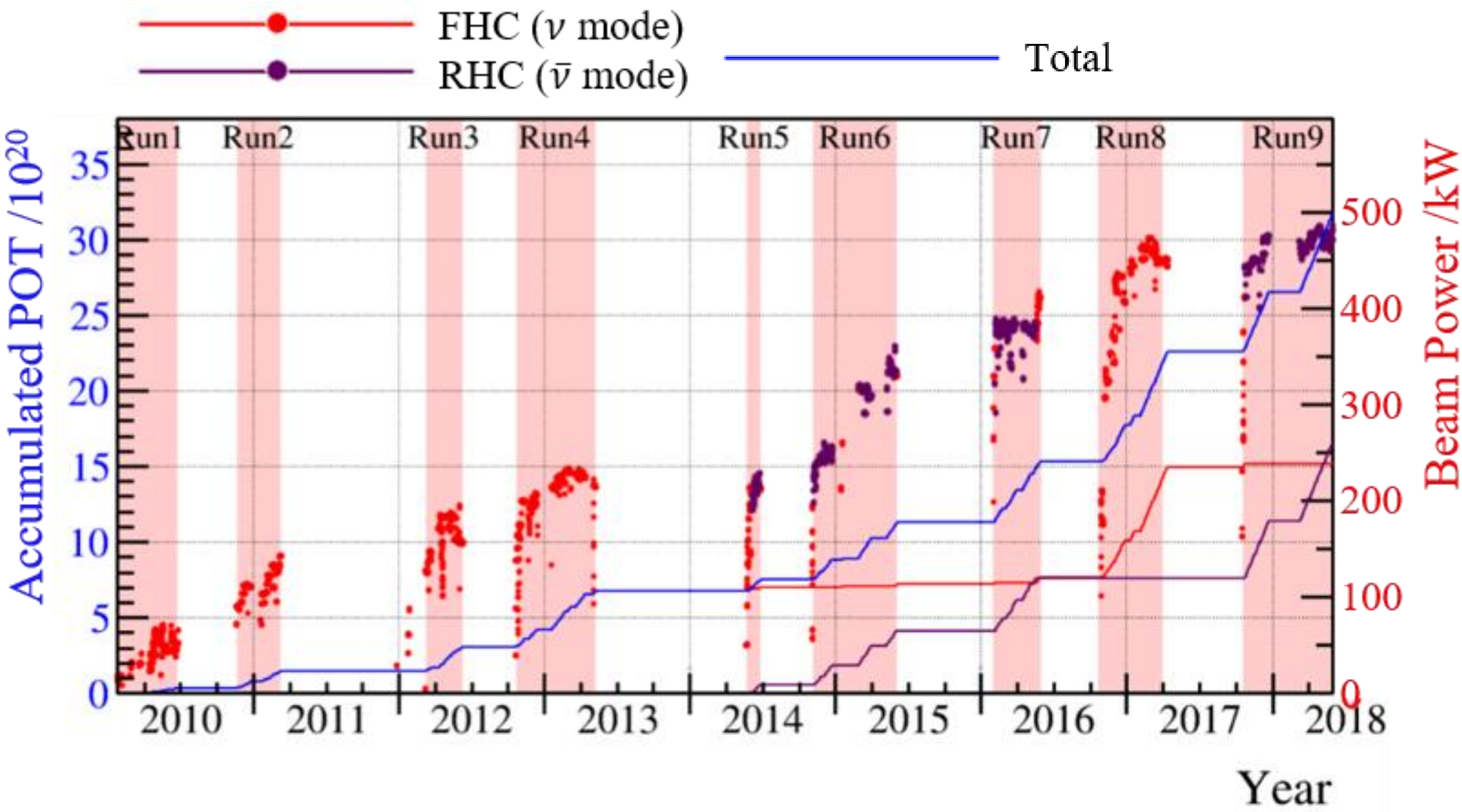
Far Detector measures the oscillations

Near Detector(s) characterise the initial neutrino beam

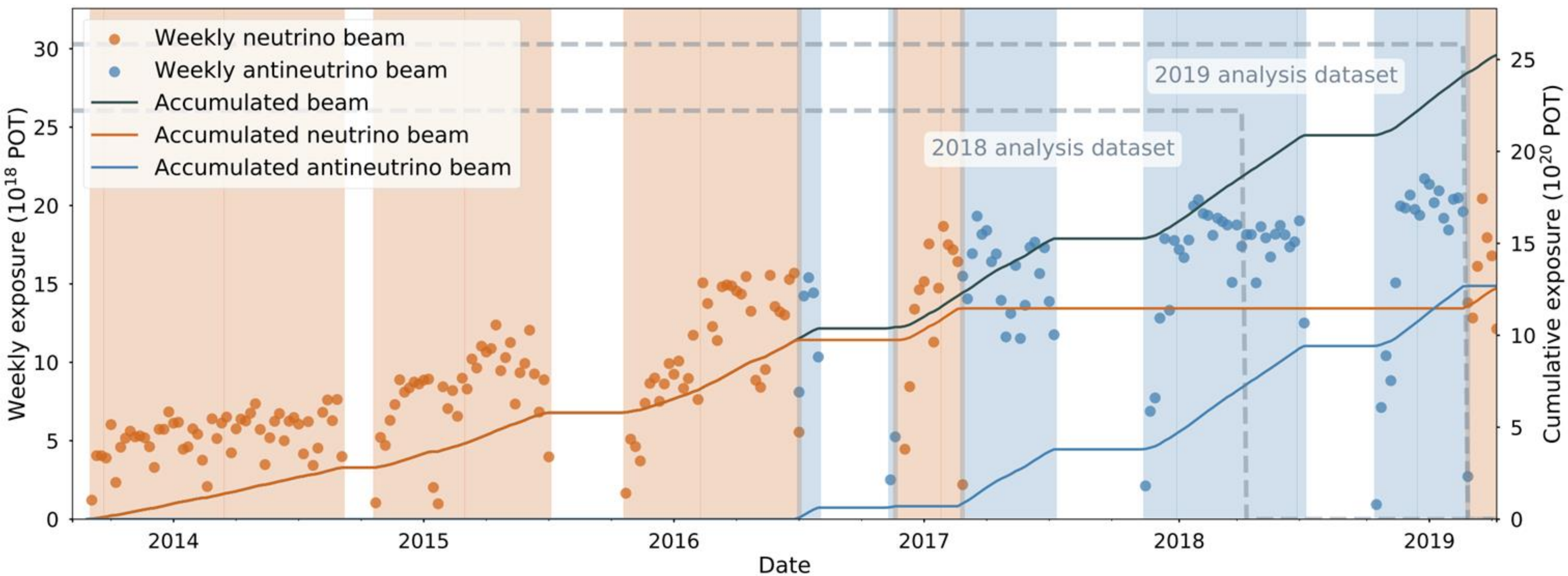
Neutrinos created at proton accelerator

First LBL experiment was **K2K**. Modern examples are very similar.

T2K POT


FHC (ν mode)
RHC ($\bar{\nu}$ mode)
Total
Run1
Run2
Run3
Run4
Run5
Run6
Run7
Run8
Run9
Accumulated POT /10^{20}
Beam Power /kW
0
5
10
15
20
25
30
35
100
200
300
400
500
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year

NOνA POT

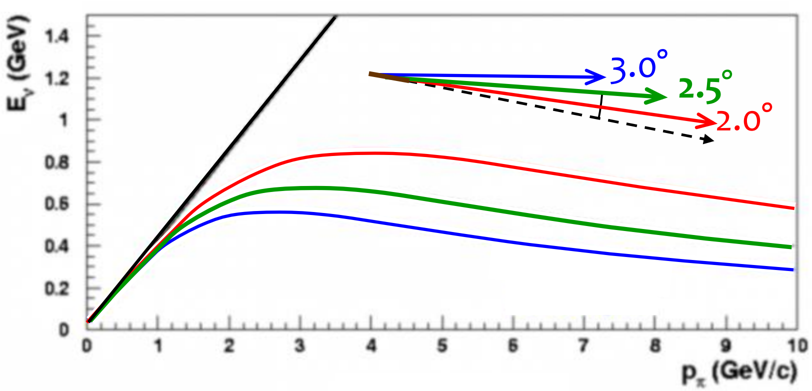


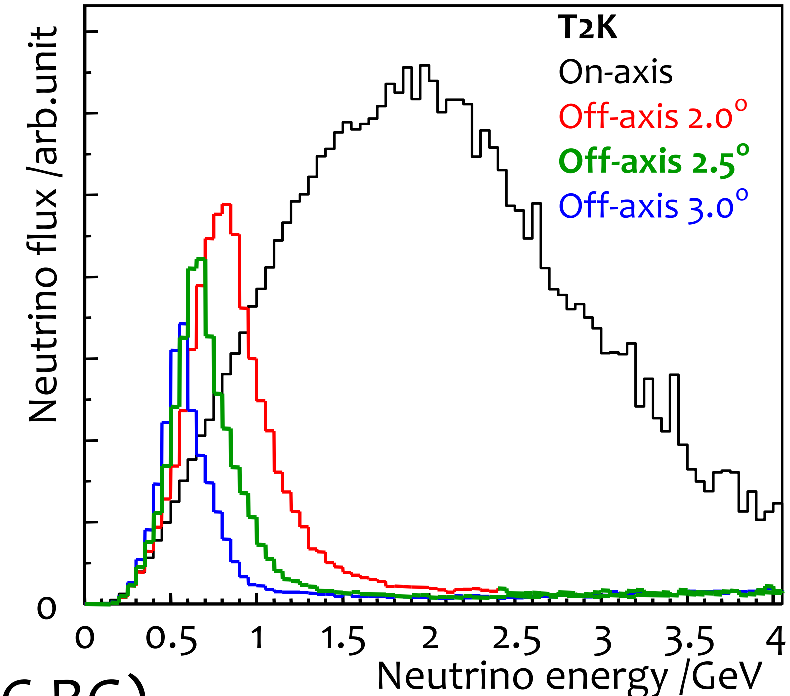
Weekly neutrino beam
Weekly antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam
2019 analysis dataset
2018 analysis dataset
Weekly exposure (10^{18} POT)
Cumulative exposure (10^{20} POT)
Date
0
5
10
15
20
25
30
2014
2015
2016
2017
2018
2019

The off-axis trick

T2K and NOνA both put their far detectors off-axis

Relativistic kinematics → at a small angle to the beam axis, neutrino energy is insensitive to parent pion energy.

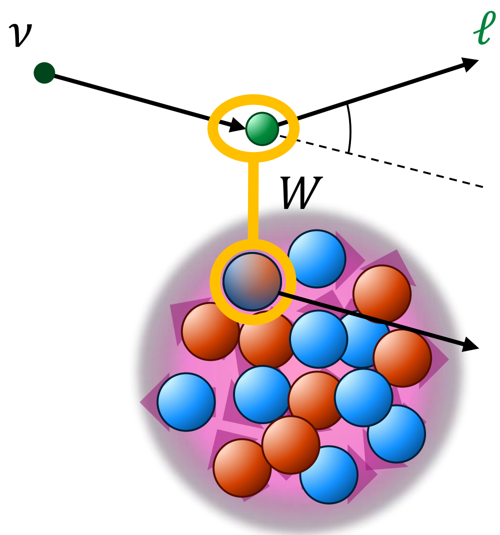




Gives narrower flux peak, and **drastically reduces high energy tail.**

- Ideal for ν_e appearance (reduced NC BG)
- Also helps reach lower energies with existing NuMI beam line (NOνA)

Quasi-elastic events

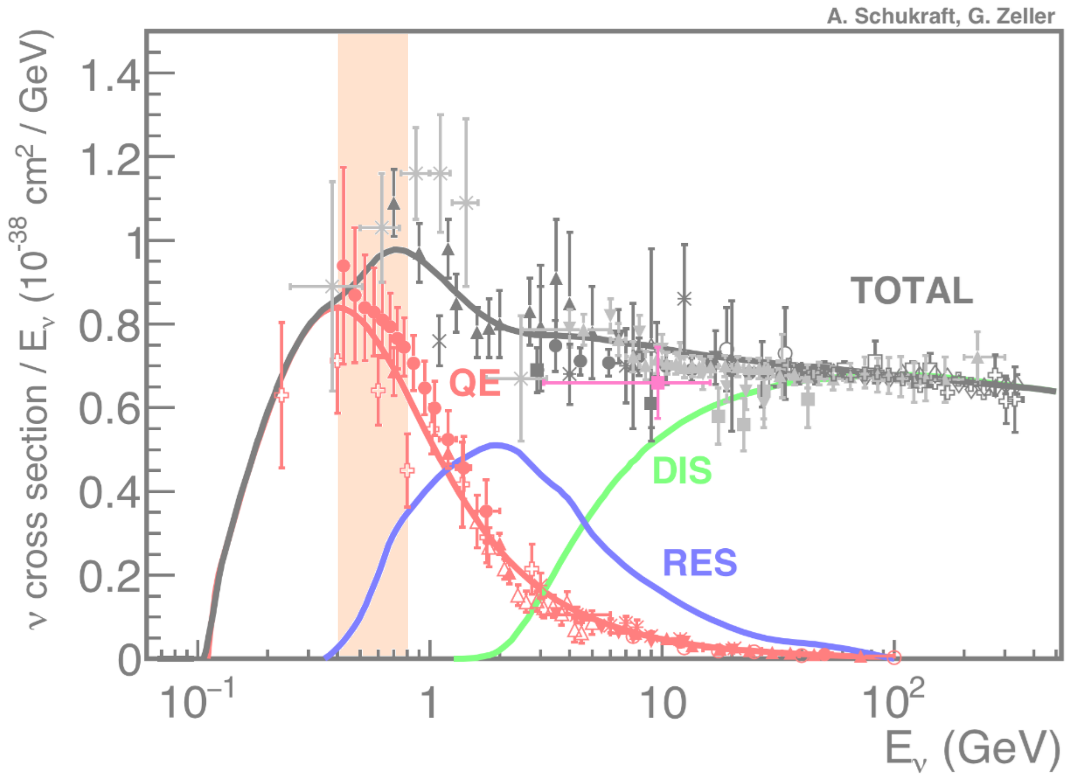


Can’t entirely ignore the nucleus:

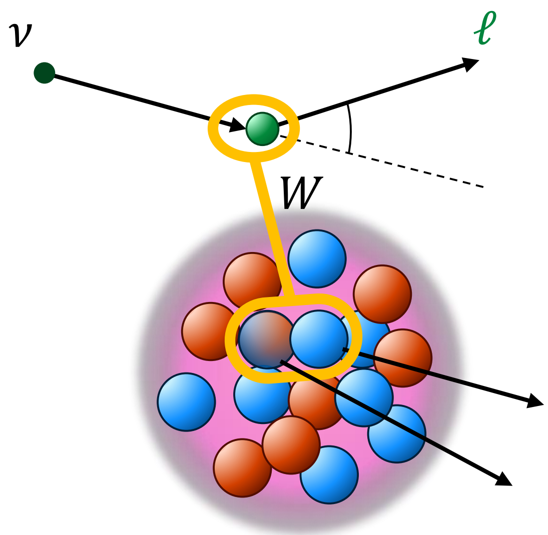
- Nucleons in nuclei are not at rest: **‘Fermi Gas / Spectral Function’**
- Form factors are modified in nuclear medium: **‘Random Phase Approximation’**

Quasi-elastic events are ideal for T2K

- Dominant channel at this energy

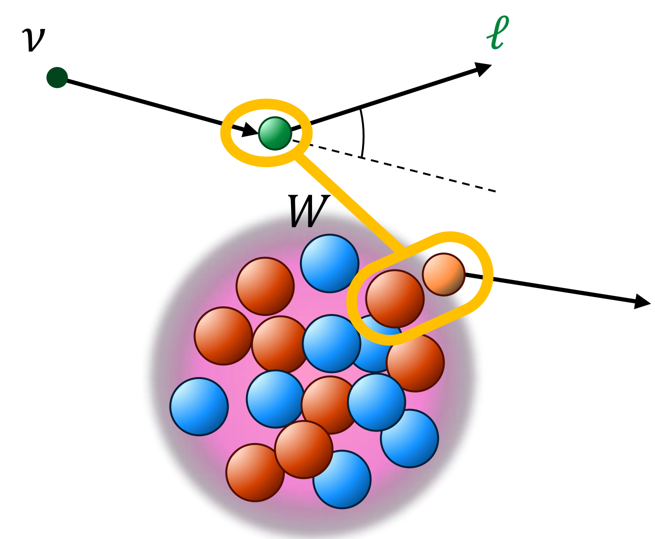


Quasi-elastic events?



Other processes are important as well.

Nucleus is not just a bag of independent nucleons; sometimes you hit a correlated pair. **'2p-2h'**



Can also produce a pion off the nucleus.

- Dominated by $W + N \to \Delta(1232) \to \mathrm{N} + \pi$
- Other resonances are available!
- Non-resonant production available
- **'Rein–Sehgal model'** [Future '**MK-Model**']

Quasi-elastic events?

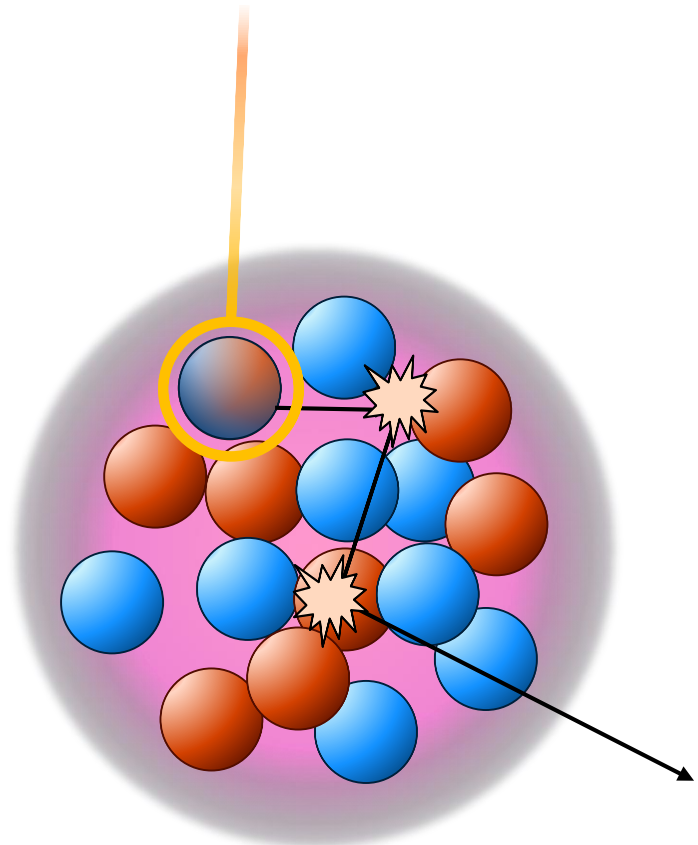
ν ℓ **Other processes are important as well.**

ir.

In all of the previous processes, the hadron(s) must also leave the nucleus.

There is a non-zero chance of reinteraction. Many possible fates for such re-interacting particles. ‘Final State Interactions’

Can both increase or decrease the number of visible particles



Can als

- Domi
- Othe
- Non-
- **‘Rein–Sehgal model’** [Future **‘MK-Model’**]

NOνA appearance* results

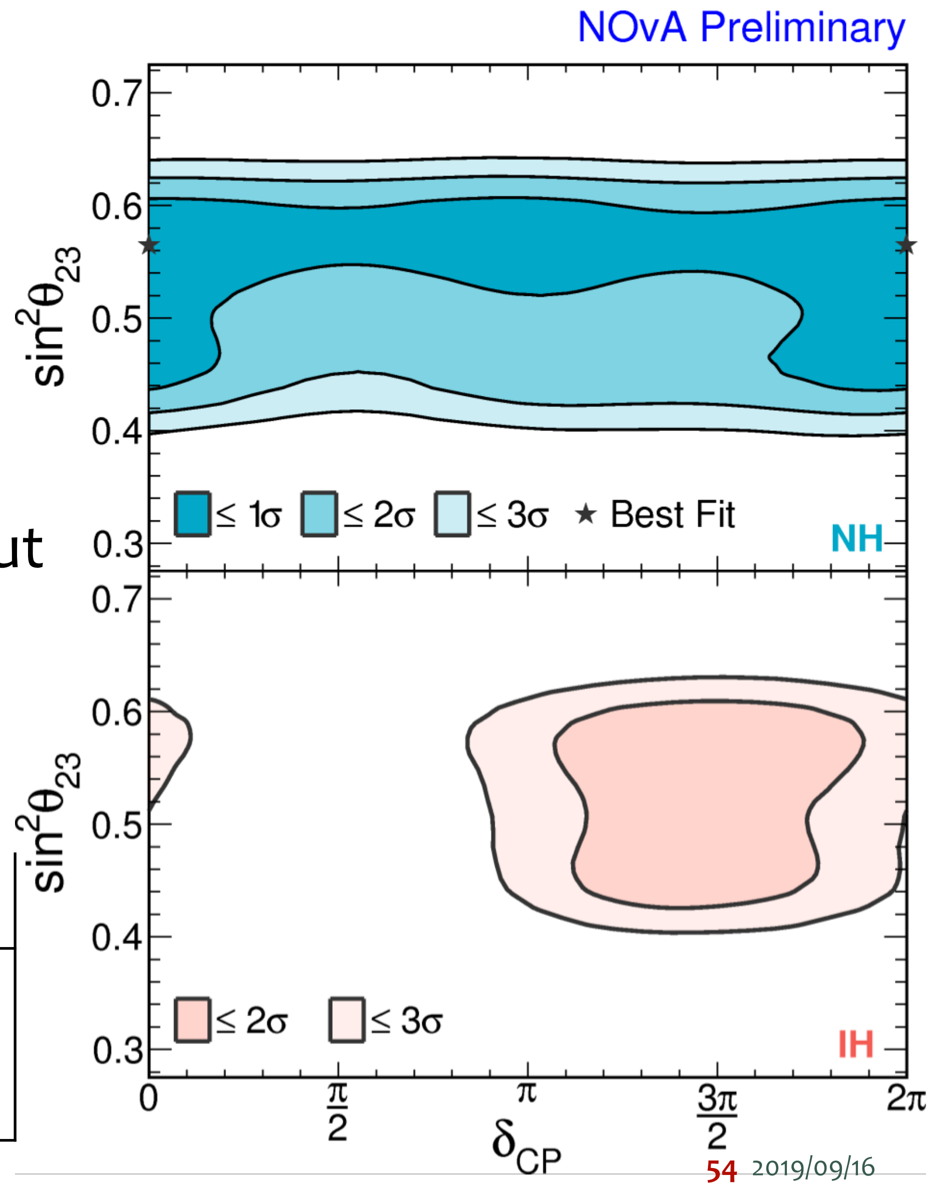
For NOνA, joint interval in $\delta_{\mathrm{CP}} - \theta_{23}$ space is quite complicated.

- $\delta_{\mathrm{CP}} - \theta_{13}$ space is much simpler
- NOνA always incorporates reactor constraint

Best fit is very close to CP conserving, but all values are consistent <1σ (if NH,UO)

Slight preferences w.r.t. the other open questions:

	Normal	Inverted
Upper	Preferred	>1.8σ
Lower	>1.6σ	>2.0σ



Parameter correlations