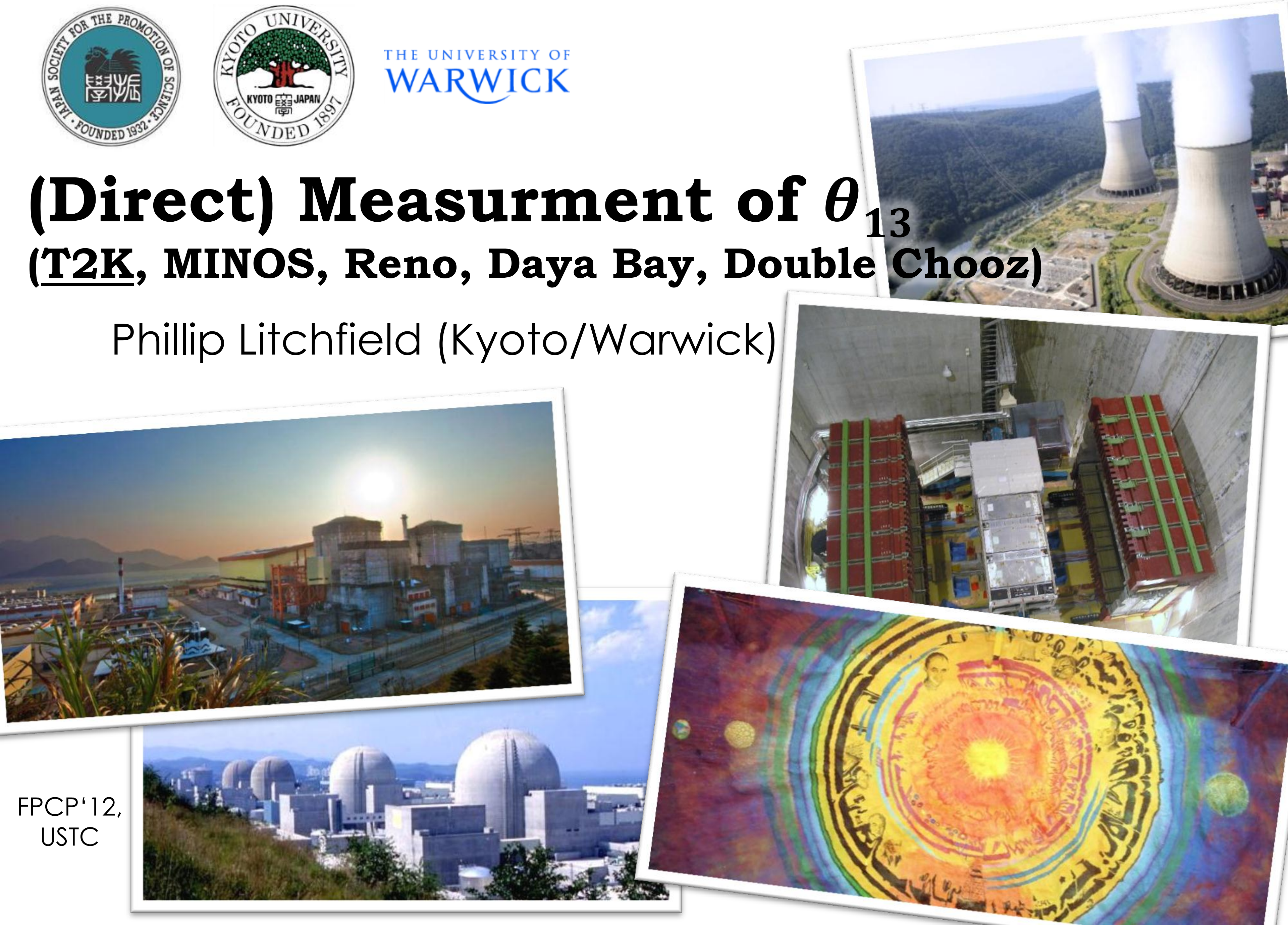
(Direct) Measurment of θ_{13}

(T2K, MINOS, Reno, Daya Bay, Double Chooz)

Phillip Litchfield (Kyoto/Warwick)



FPCP'12,
USTC

Outline

- **Role and significance of θ_{13}**
- **Long-baseline experiments**

MINOS T2K

- **Reactor experiments**

RENO DOUBLE Chooz

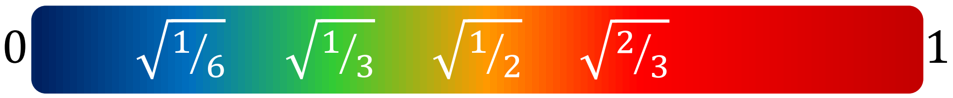
- **Next talk [Jianglai LIU]**

Daya Bay

Neutrino mixing

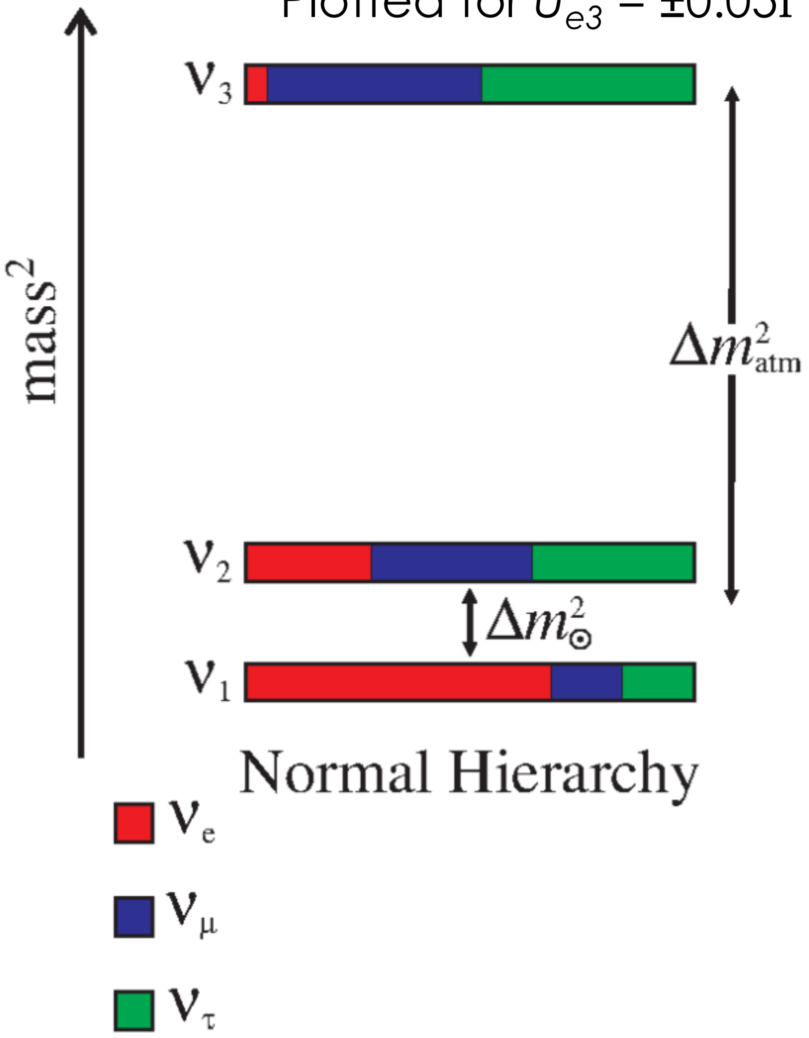
Neutrino mixing (PMNS) matrix is:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & \boldsymbol{U_{e3}}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



- Very different from CKM matrix
- 8 large elements
- $\boldsymbol{U_{e3}}$ is significant as the smallest element, and the last to be measured.

*Plotted for $U_{e3} = \pm 0.05i$



Angle parameterisation

The mixing matrix is commonly parameterised as the product of two rotations and a unitary transformation. Writing $\mathrm{s}_{ij} = \sin\theta_{ij}$, and $\mathrm{c}_{ij} = \cos\theta_{ij}$:

$$\begin{pmatrix} \mathrm{c}_{12} & \mathrm{s}_{12} & 0 \\ -\mathrm{s}_{12} & \mathrm{c}_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \mathrm{c}_{13} & 0 & \mathrm{s}_{13}\mathrm{e}^{\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -\mathrm{s}_{13}\mathrm{e}^{-\mathrm{i}\delta} & 0 & \mathrm{c}_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{c}_{23} & \mathrm{s}_{23} \\ 0 & -\mathrm{s}_{23} & \mathrm{c}_{23} \end{pmatrix}$$

The choice of parameterisation is convenient as the **solar** and **atmospheric** disappearance amplitudes are well approximated as functions of $\boldsymbol{\theta_{12}}$ and $\boldsymbol{\theta_{23}}$, respectively.

This approximation only works because the third angle $\boldsymbol{\theta_{13}}$ is small.

The role of θ_{13}

In the standard parameterisation, it turns out that

$$U_{e3} = \sin\theta_{13}\, e^{-i\delta}, \quad \text{and therefore} \quad \sin\theta_{13} = |U_{e3}|.$$

The value of $\sin\theta_{13}$ is particularly significant because a zero element in the mixing matrix would eliminate the possibility of (KM-mechanism) leptonic CP violation.

The future program of neutrino physics is strongly dependent on a non-zero measurement (→ size) of $\boldsymbol{\theta_{13}}$.

To study, need channels involving $\langle \upsilon_e | \upsilon_3 \rangle$. The most accessible are $\bar{\nu}_e \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ at first 'atmospheric' maximum (*L*/m ~ 500 × *E*/MeV)

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- **Long-baseline experiments**
- Reactor experiments
- Next talk [Jianglai LIU]

$\nu_\mu \rightarrow \nu_e$ appearance probability

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 $\sin 2\theta_{13}$:

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

$$+ T_{\alpha\theta}\alpha \sin 2\theta_{13} \frac{\sin([1-A]\Delta)}{(1-A)} \frac{\sin(A\Delta)}{A} \cos(\delta + \Delta)$$

where

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

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

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; MINOS $|A| \sim 0.3$, T2K$|A| \sim 0.07$

ν_e appearance measurements

Two experiments have recently published results from the $\nu_\mu \rightarrow \nu_e$ channel: **MINOS** and **T2K**.

MINOS is an older experiment, not optimised for ν_e appearance, but has been running for years.

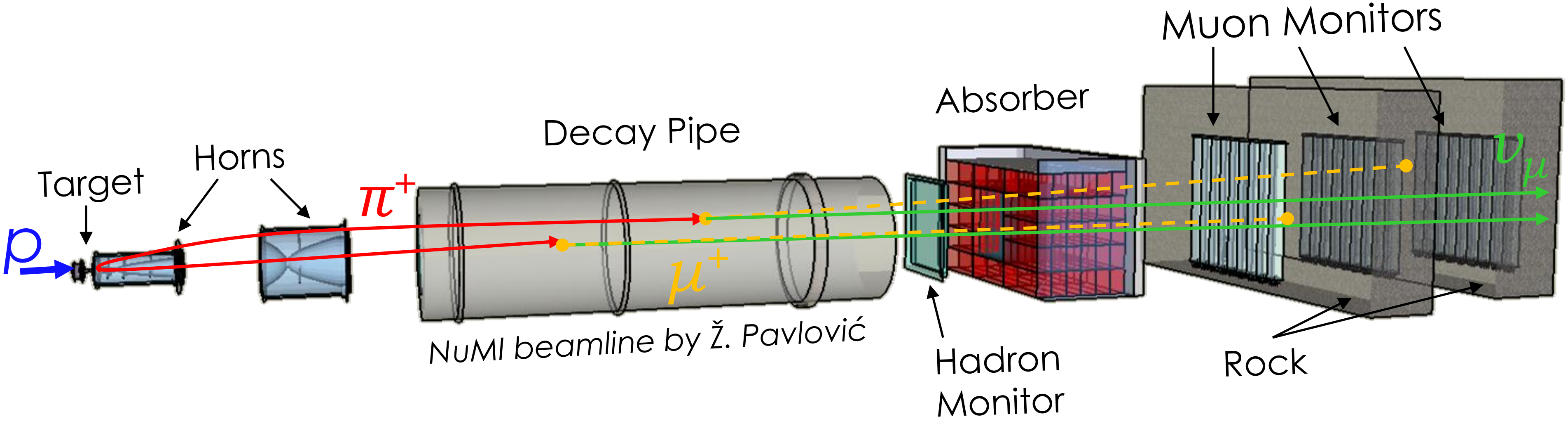
T2K is newer & will be much more sensitive, but so far has only a small fraction of its planned integrated luminosity.

Both experiments follow the same basic principle:

- A beam ν_μ of from pion decay.
- A near detector to measure interaction rates
- A far detector to look for oscillations

Muon neutrino beams.

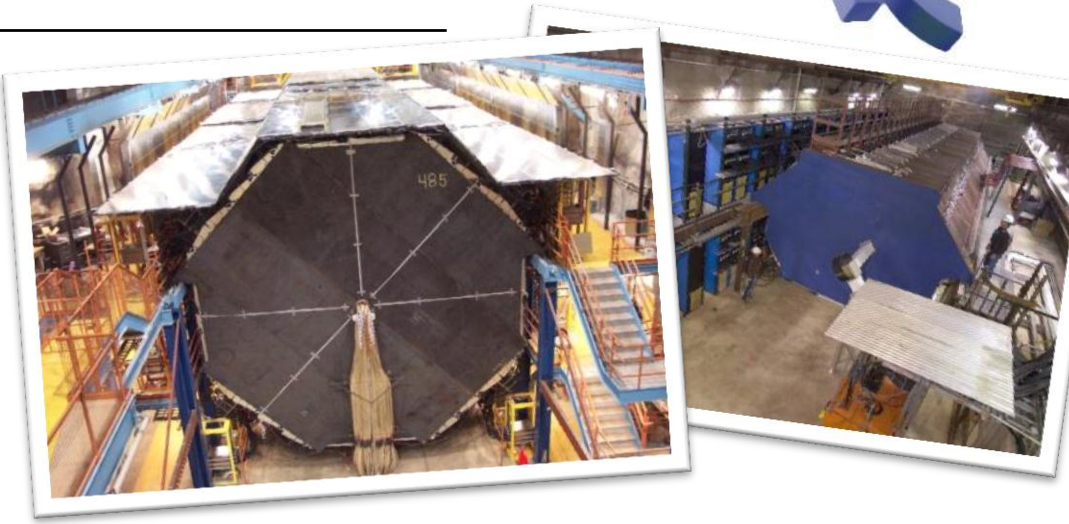
- ν_μ from pion decay.
- Pions produced in proton interactions on a target, and focussed by magnetic horns (NuMI/MINOS: 2, T2K: 3)
- Horn current and geometry most important in determining (on-axis) spectrum
- Wrong sign (anti-ν) and ν_e backgrounds are ~ few %

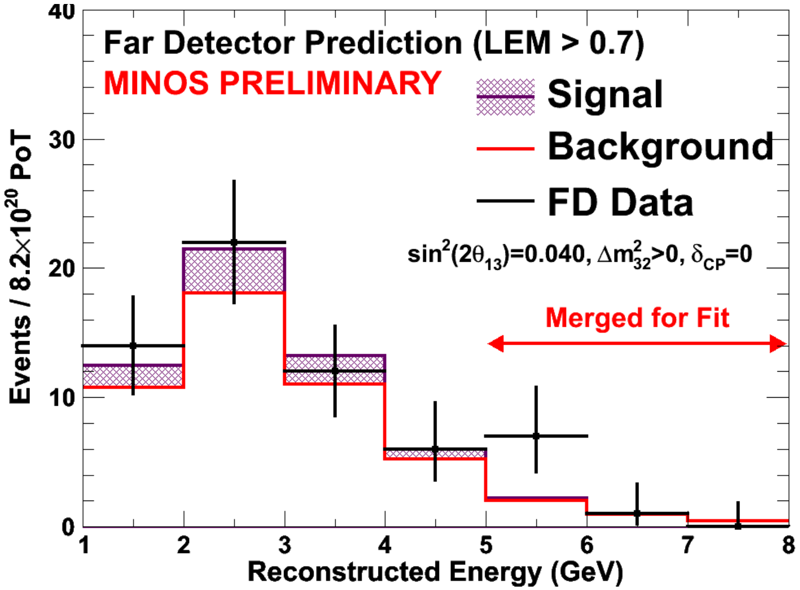


NuMI beamline by Ž. Pavlović

MINOS analysis

- Both MINOS detectors are steel/scintillator tracking calorimeters.
- At peak energy (~3GeV) ν_e signal events appear as small, tight showers.



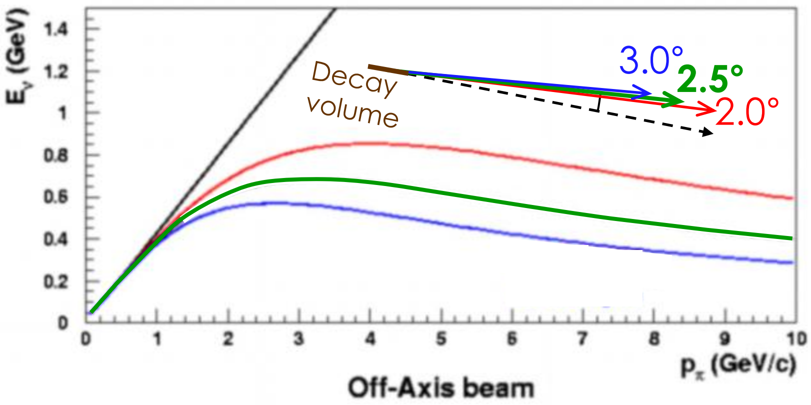


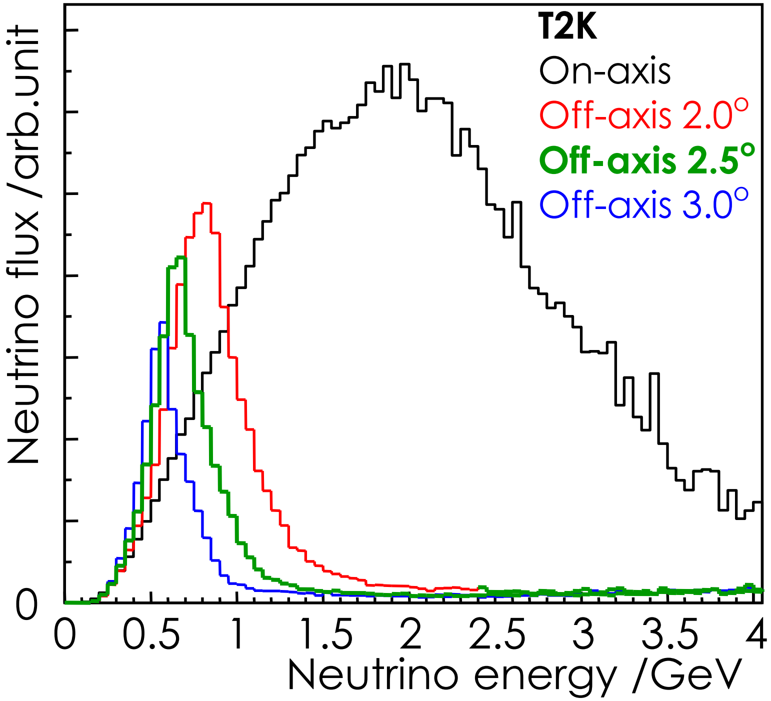
- Analysis approach uses the fact both detectors are functionally identical.
- NC interactions of higher energy neutrinos are the major background: well-controlled, but limits sensitivity because of its size.

T2K: The Off-axis ‘trick’

T2K is the first experiment to have its detectors off-axis

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

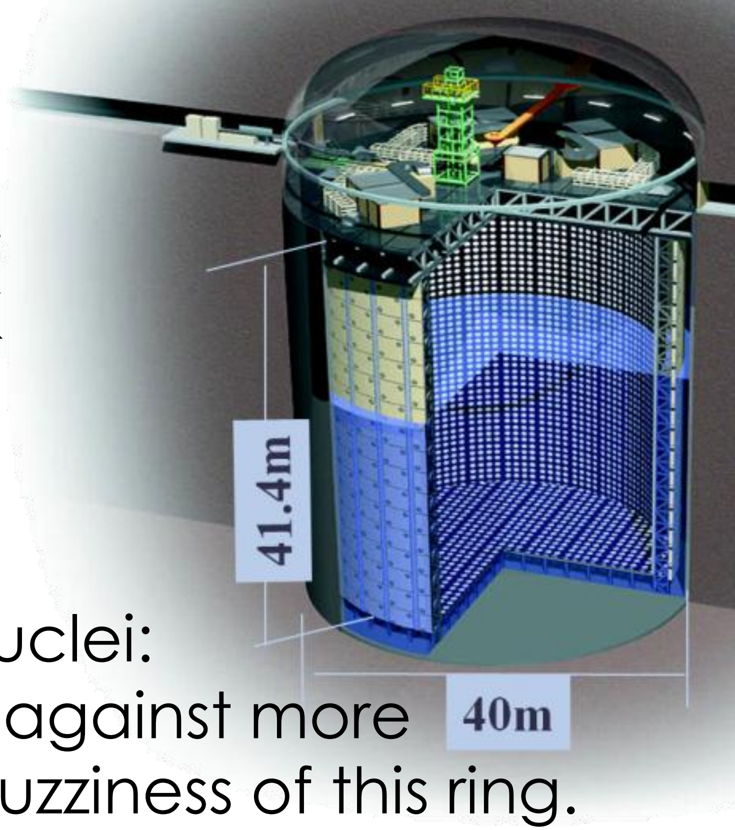




Gives slightly narrower flux peak, and **drastically reduces high energy tail**.

- Ideal for ν_e appearance (much reduced NC BG)

T2K analysis



T2K uses the 22.5 kt (fiducial) Super-K water Čerenkov detector to look for ν_e appearance.

Signal is $\nu, n \rightarrow p, e^-$ (CCQE) on ^{16}O nuclei:
Results in a fuzzy Čerenkov ring. PID against more common μ^- events is based on the fuzziness of this ring.

Other important backgrounds from

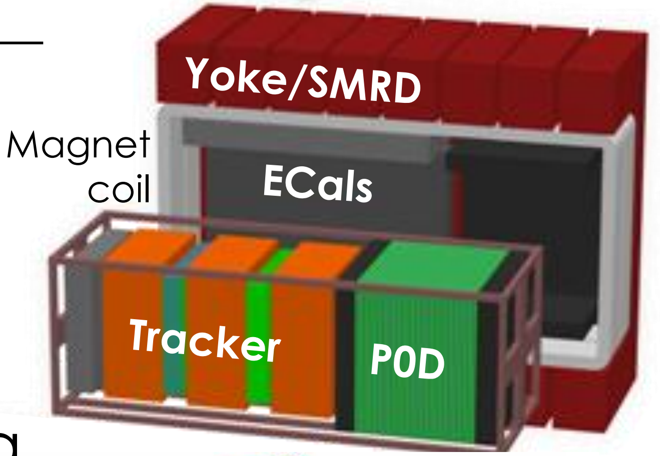
- Beam ν_e contamination (removed by energy cut)
- NC-π^0 events (removed by fitting for a 2nd γ ring)

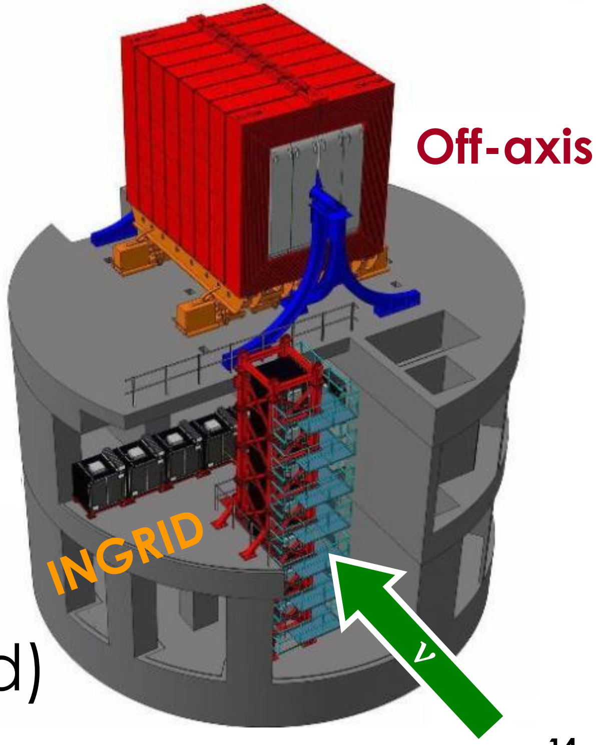
T2K uses exclusive channels, so need good understanding of cross-sections → drives design of the Near Detector.

T2K-ND280 near detectors

Off-axis detector uses fine-resolution scintillator detectors and TPCs for momentum measurement and PID.

- Much better estimate of interaction rates than using MC dead-reckoning
- Extensive program of cross-section measurements to improve future MC





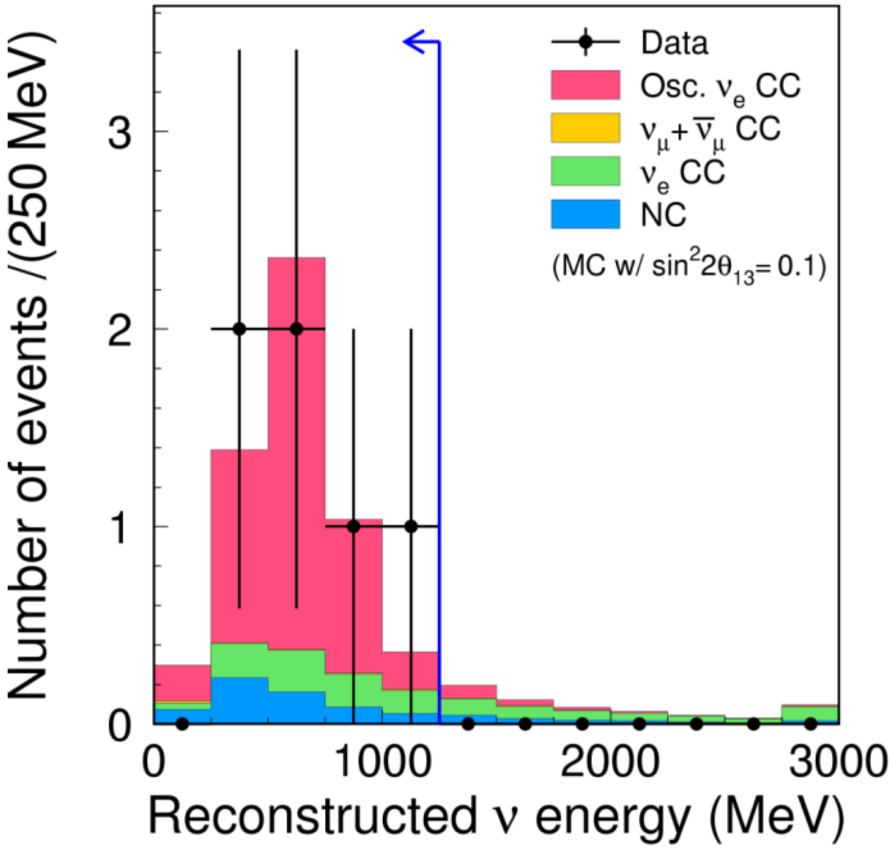
INGRID: A cross arrangement of iron-scintilator detectors, centred on the beam axis, to check beam direction.

- Stable to better than required (1mrad)

T2K data

Current results dominated by statistical error.

(Data set up to 11/03/11 earthquake)



Backgrounds are much smaller than MINOS,
↳ sensitive measurement with only six FD events.

Current results use ND280 for rate normalisation.

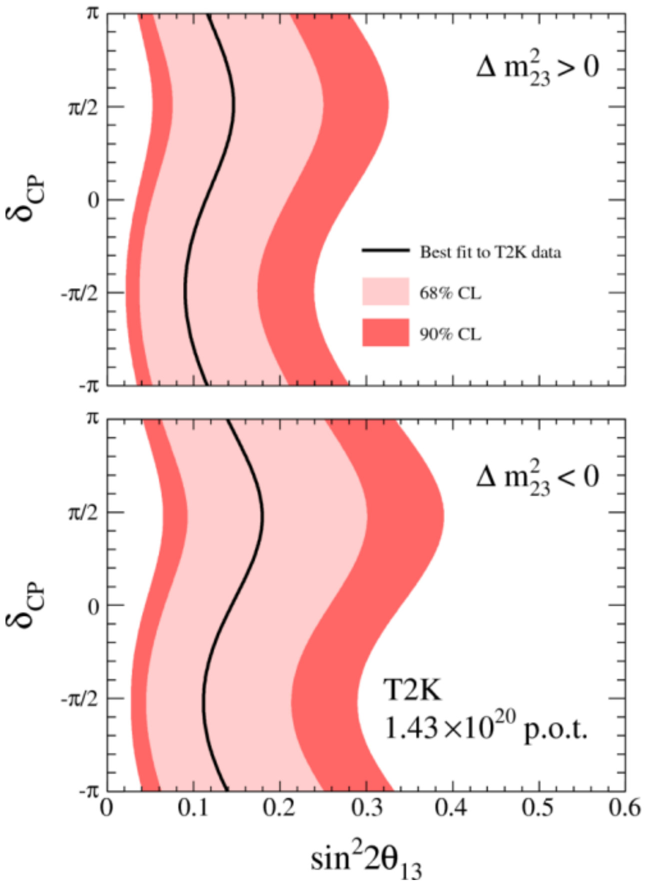
Future results will need the improved constraints from detailed ND820 analyses

T2K & MINOS: side-by-side

T2K	**MINOS**
Small data sample, but very low background.	Large data sample, but high backgrounds.
Systematics controlled by high-resolution Near Detector measurements.	Many systematics cancel out because of similarity of Near & Far detectors.
Precise flux inputs from NA61 experiment.	Flexible beam helps separate flux from cross-section errors.
Exclusive analysis in sub-GeV region.	Inclusive analysis in few-GeV region.
New experiment, much more (stats, analysis) to come!	Mature—data taking finished last month.

Although experiments are similar in principle, in practice their analyses & systematics are quite different.

Results from T2K & MINOS



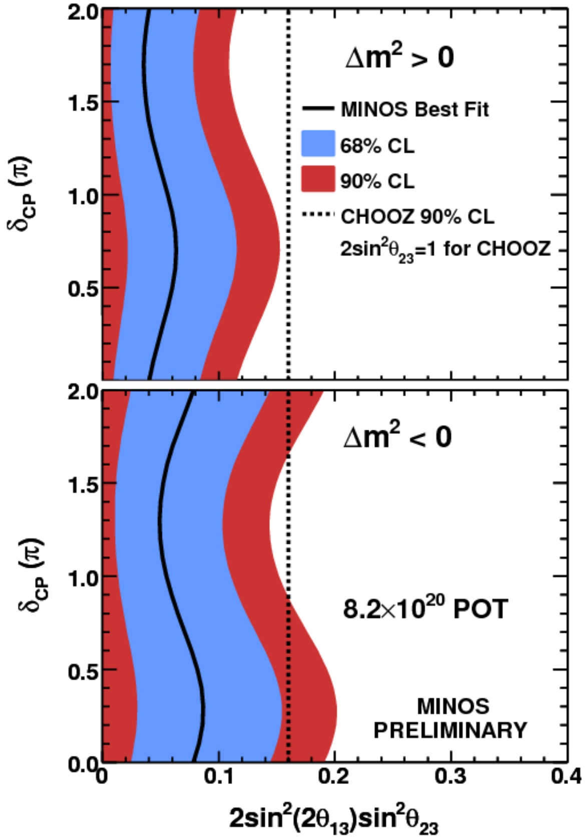
Results vs δ

▶ **MINOS**

◀ **T2K**

Note:
y-axes are offset by π

Note:
T2K holds $\theta_{12,}$ $\theta_{23,}$ & Δm^2 fixed; MINOS varies within global errors. Difference is small.



T2K: $\sin^2(2\theta_{13}) = 0$ disfavoured at 99.3%

MINOS: $\sin^2(2\theta_{13}) = 0$ disfavoured at 89%

arXiv:1106.2822

arXiv:1108.0015

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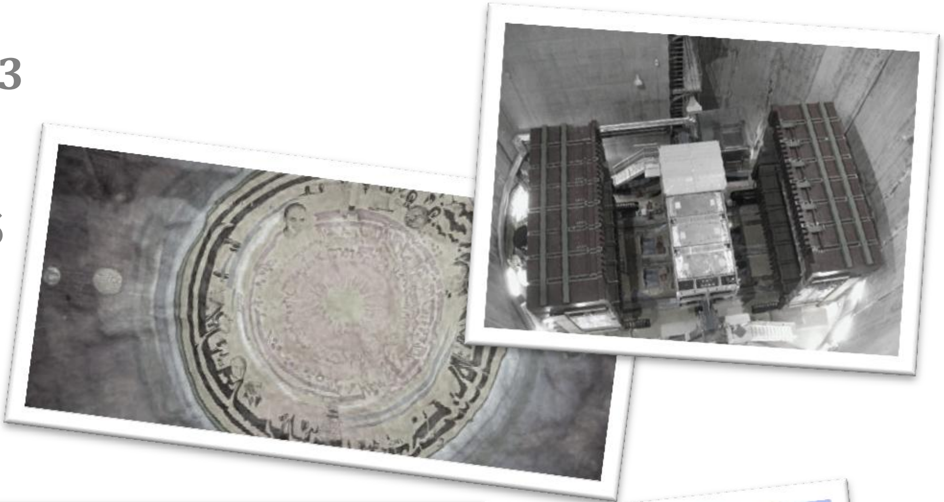
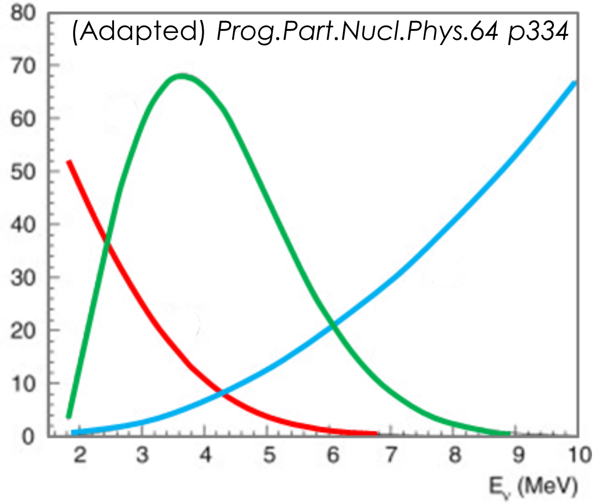
- Next talk [Jianglai LIU]



$\bar{\nu}_e \to \bar{\nu}_e$ survival

Disappearance channel. Electron is light enough that we can use nuclear reactors.

- Cheap, intense source.
- Interaction rate peaks at 3~4 MeV (falling flux × rising cross-section)


(Adapted) *Prog.Part.Nucl.Phys.64 p334*

(Some) previous reactor experiments:

- **Savannah River:** first $\bar{\nu}_e$ detection
- **CHOOZ**: previous best measurement of $\sin 2\theta_{13}$
- **KamLAND**: same channel on longer baseline measures Δm^2_{21} and $\sin 2\theta_{12}$

New generation of reactor experiments provide much better sensitivity through control of systematics.

$\bar{\nu}_e$ survival probability

For reactor antineutrinos in the earth's crust we can ignore matter effects, and the probability is very simple:

$$P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \alpha\Delta$$

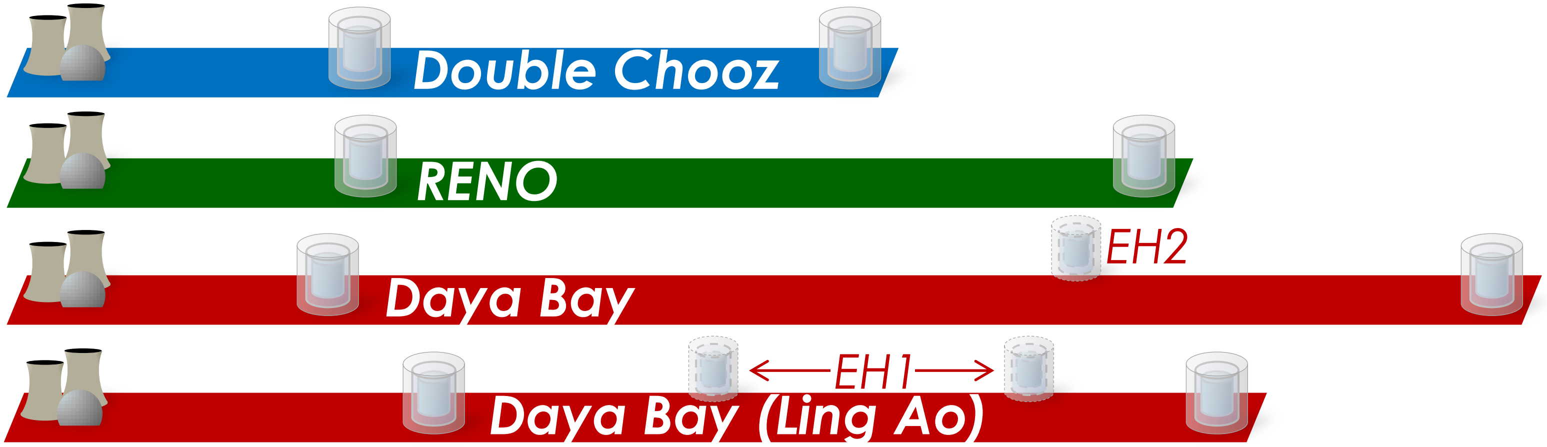
On a ~1km baseline the 3rd solar-scale term is small, (around 0.001) so the survival probability allows **direct access** to the parameter $\sin^2 2\theta_{13}$.

In contrast with the appearance channel, $\bar{\nu}_e$ disappearance at reactors gives a **theoretically clean determination of $\sin^2 2\theta_{13}$** but, on it's own, **cannot determine the mass hierarchy or look for CP violation**.

New reactor experiments

Three new reactor experiments turned on in 2011:
Double Chooz (France), **RENO** (S.Korea), **Daya Bay** (China)
Basic design is very similar among all three, differences are mostly in detector mass & reactor flux.

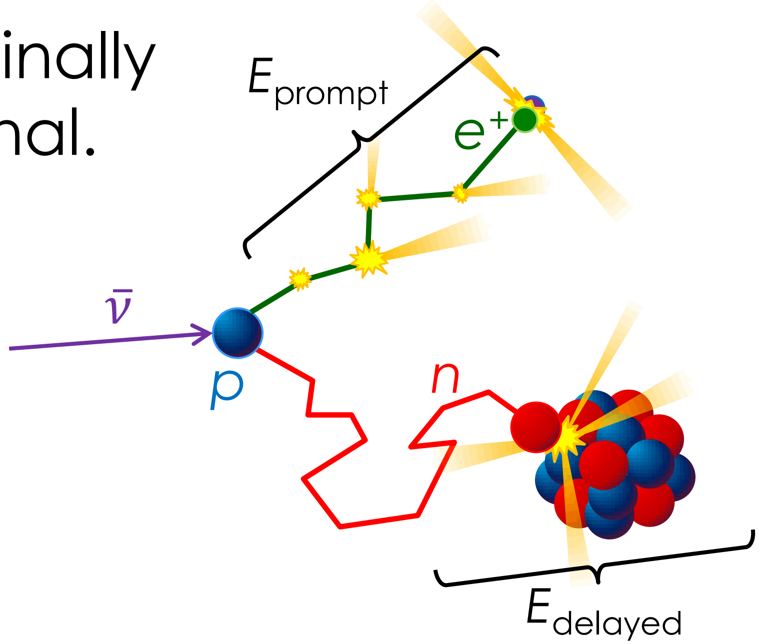
- But backgrounds, calibration systems, photosensor coverage (etc.) will affect ultimate performance.
- All experiments use a ***near detector*** to reduce systematics.



Principles of $\bar{\nu}_e$ detection

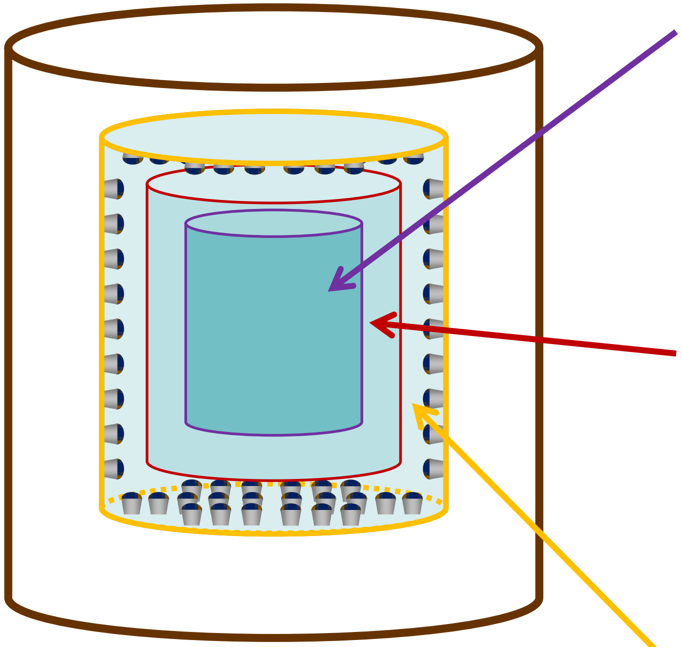
Anti-neutrino interacts on protons in a liquid scintillator target (inverse beta decay)

- Positron excites scintillator and finally annihilates, giving a prompt signal.
- Neutron is detected using Gadolinium dopant (Gd has high neutron capture cross section); this gives a large delayed coincidence signal.



The delayed coincidence signal heavily suppresses backgrounds, so the same principle is used by all three of the new generation reactor experiments.

A $\bar{\nu}_e$ detector



Veto tank

Pure water & PMTs to veto cosmics and external radioactivity

Target region, Liquid Scintillator (LS) doped with Gd. Around 2~3m (diameter & height)

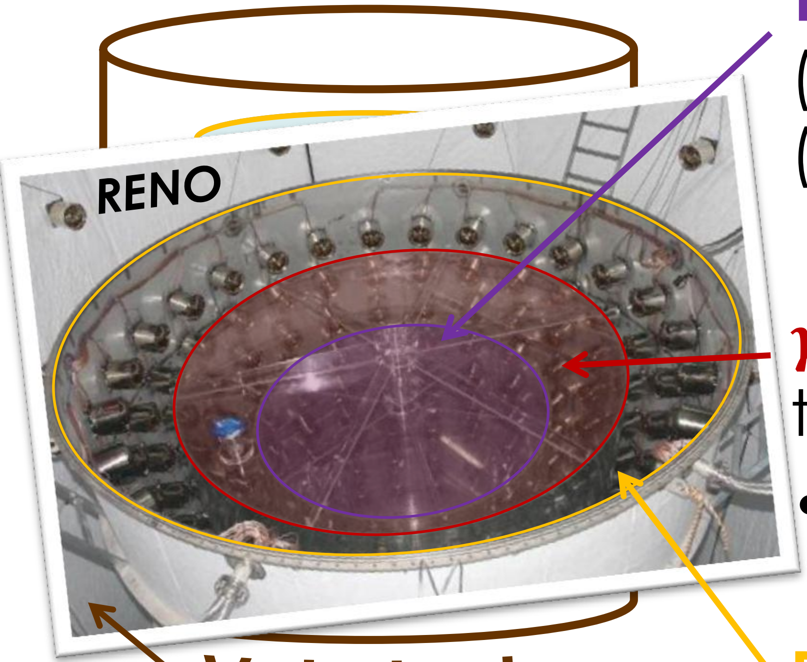
γ-catcher, LS without Gd doping, typically about 50cm thick

- Improves energy resolution.

Buffer region, Mineral oil without scintillator, up to ~1m thick

- Shields active regions

A $\bar{\nu}_e$ detector



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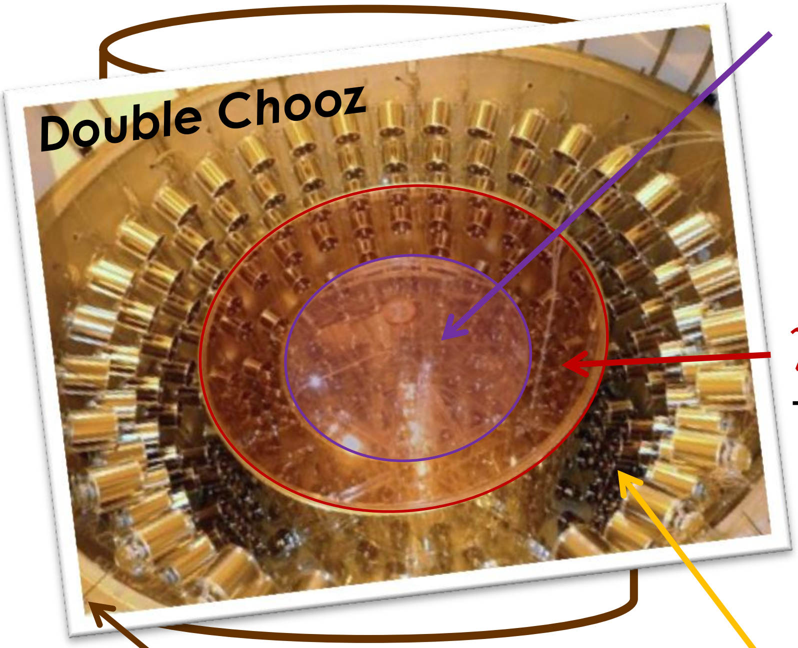

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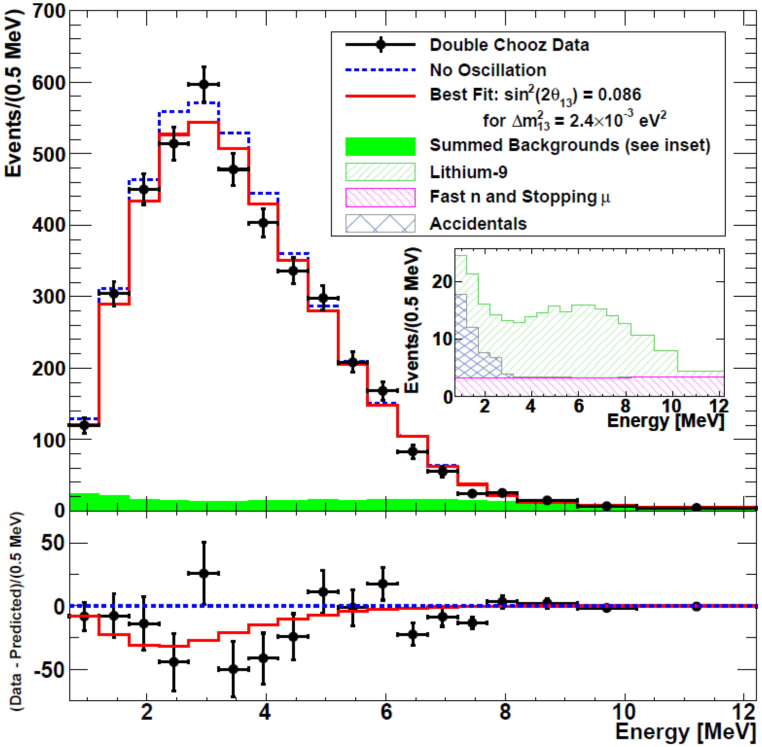
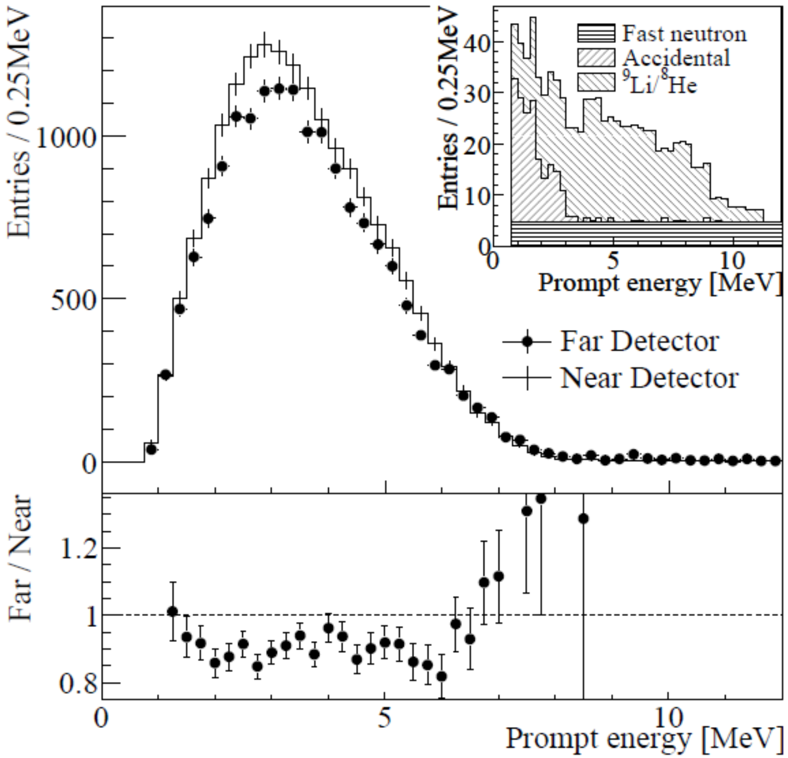
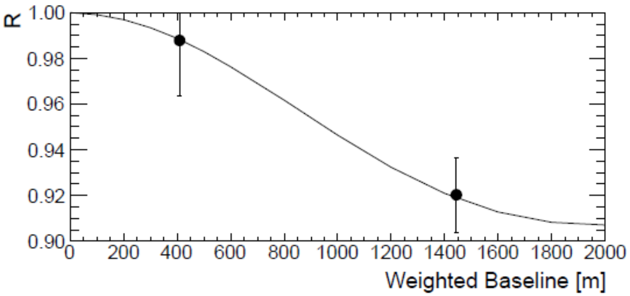
Results from DC and RENO





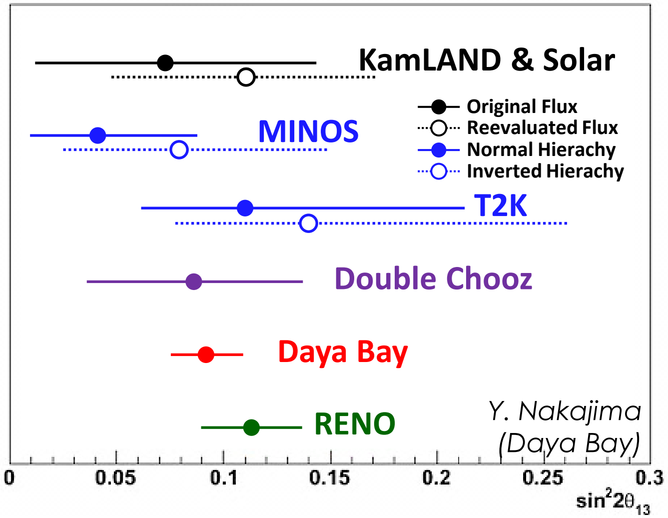
- ▲ Double Chooz result from 1050m only period (2011)
  - No oscillation disfavoured at 94.6%
- ▶ RENO results with two detectors.
  - No oscillation disfavoured at 4.9σ



Our new knowledge

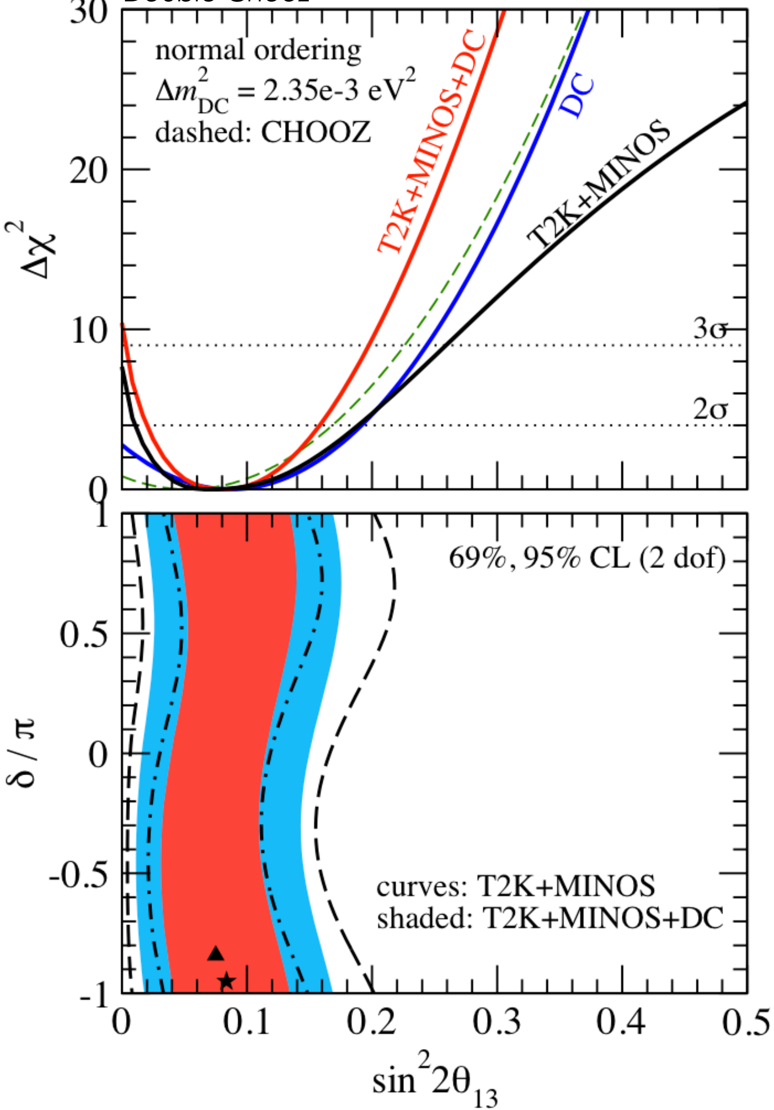
In under a year θ_{13} has gone from unknown to well measured.

- At the top of expected range.
- Focus is rapidly shifting to CP phase and mass-hierachy.
  - Need precision on $|U_{e3}|^2$, but also $|U_{\mu 3}|^2$ and Δm^2_{atm}



Y. Nakajima (Daya Bay)

Double Chooz



Thank you for listening!

Long baseline results

T2K Phys.Rev.Lett.**107** (2011) 041801
arXiv:1106.2822 [hep-ex]

MINOS Phys.Rev.Lett.**107** (2011) 181802
arXiv:1108.0015 [hep-ex]

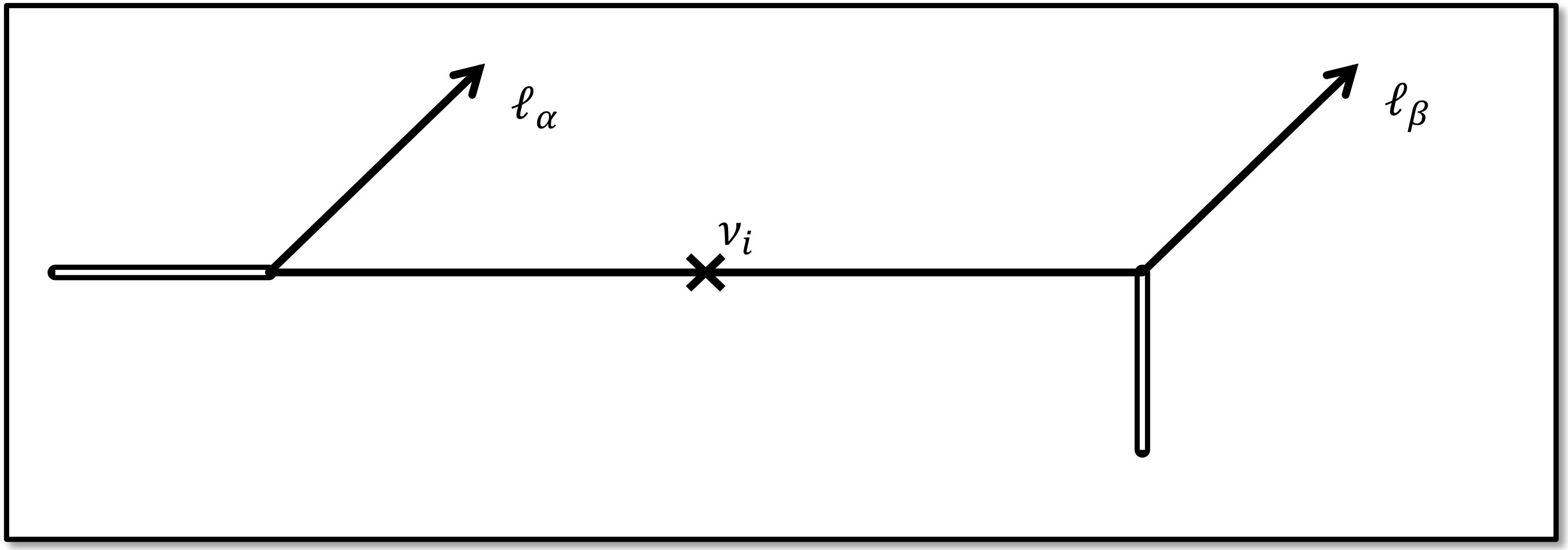
Reactor results

Double Chooz Phys.Rev.Lett.**108** (2012) 131801
arXiv:1112.6353 [hep-ex]

Daya Bay Phys.Rev.Lett.**108** (2012) 171803
arXiv:1203.1669 [hep-ex]

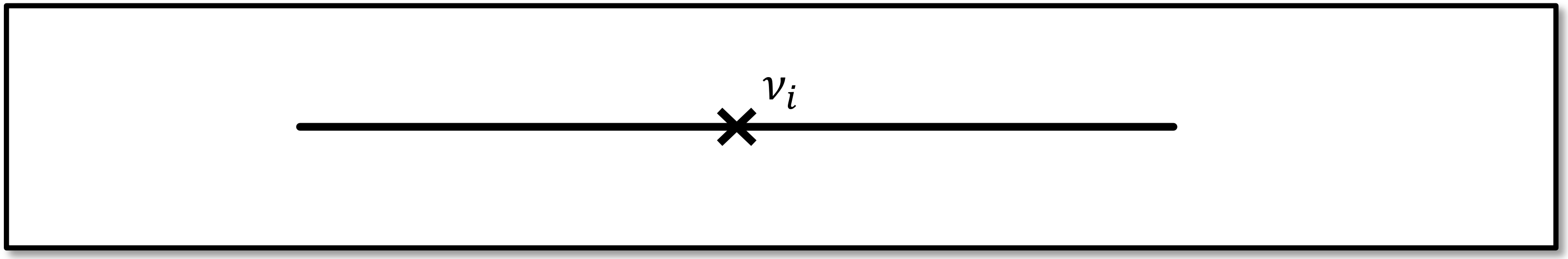
RENO Phys.Rev.Lett.**108** (2012) 191802
arXiv:1204.0626 [hep-ex]

Neutrino ‘box’ diagram



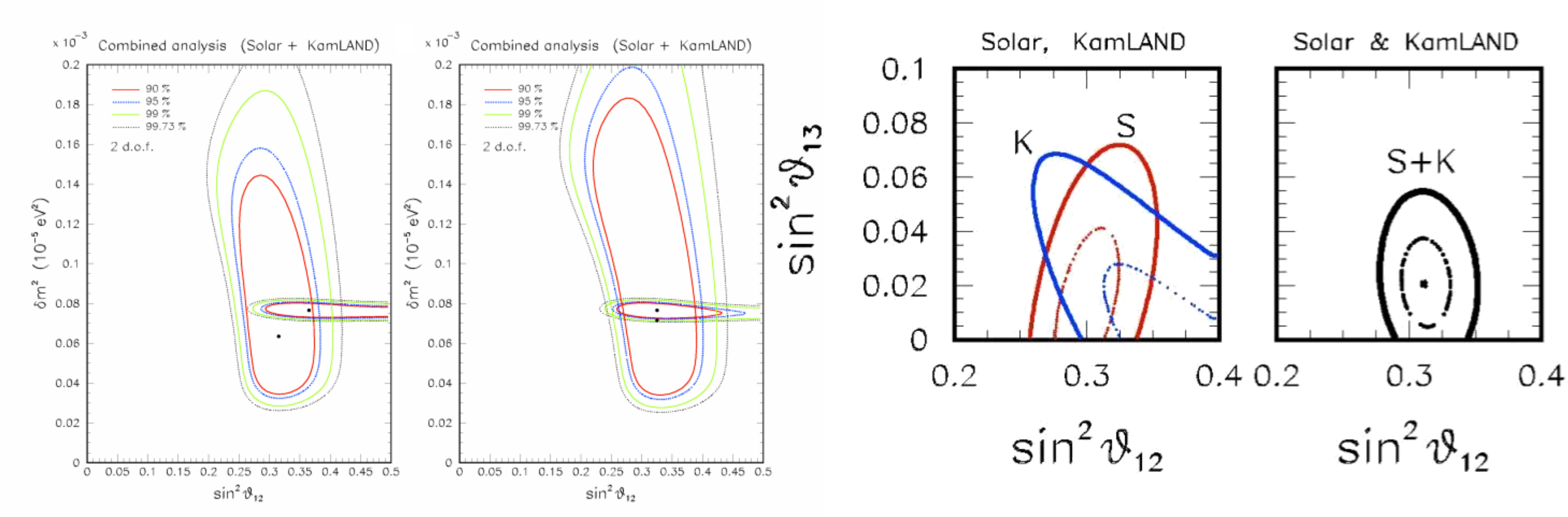
Here is the box

My preferred version:



Extra slides

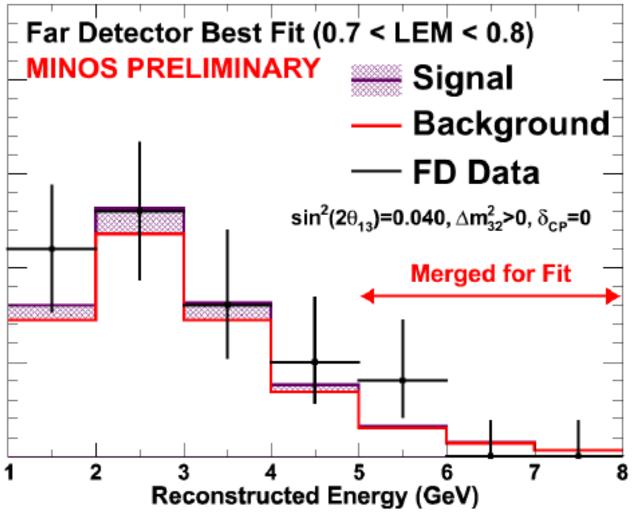
Indirect measurements of θ_{13}

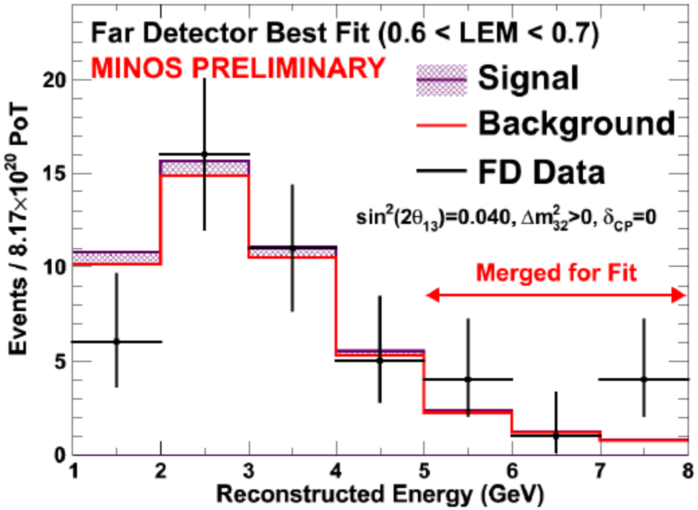


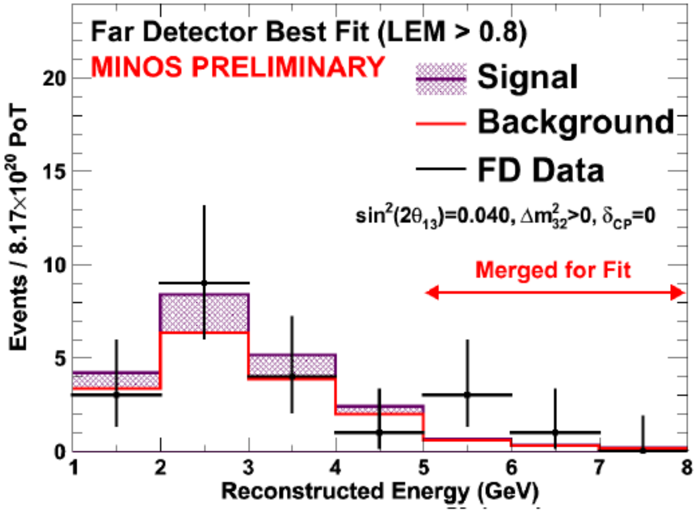
Before recent measurements there was a ~1.5σ hint from combining Solar and KamLAND data.

Turned out to agree very well with new measurements, but weak compared to new data.

Minos results in detail







For LEM>0.7

Expected background events:

49.5 ± 2.8 (syst) ± 7.0 (stat)

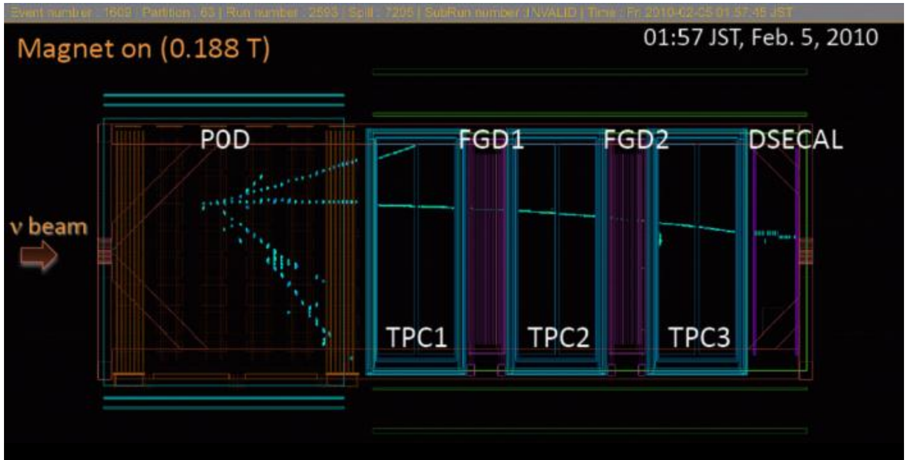
Observed events in FD data:

62

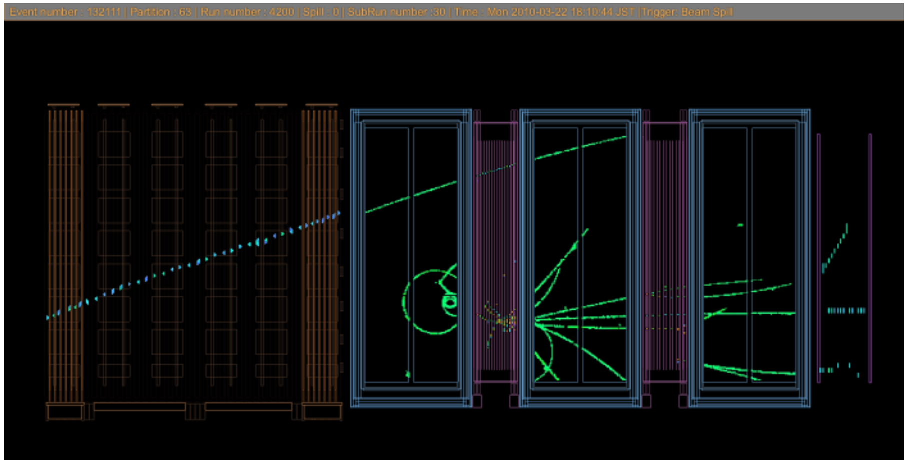
1.7σ excess above background

Example ND280 events

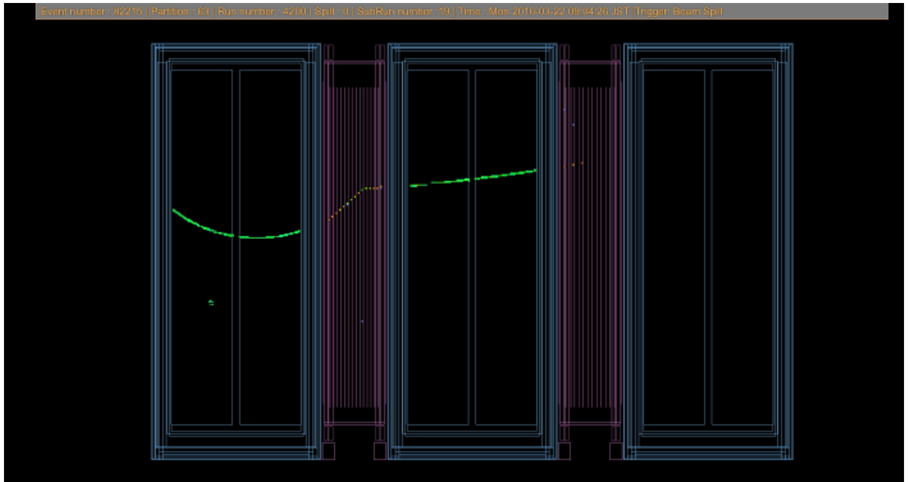
[ND280 Data]



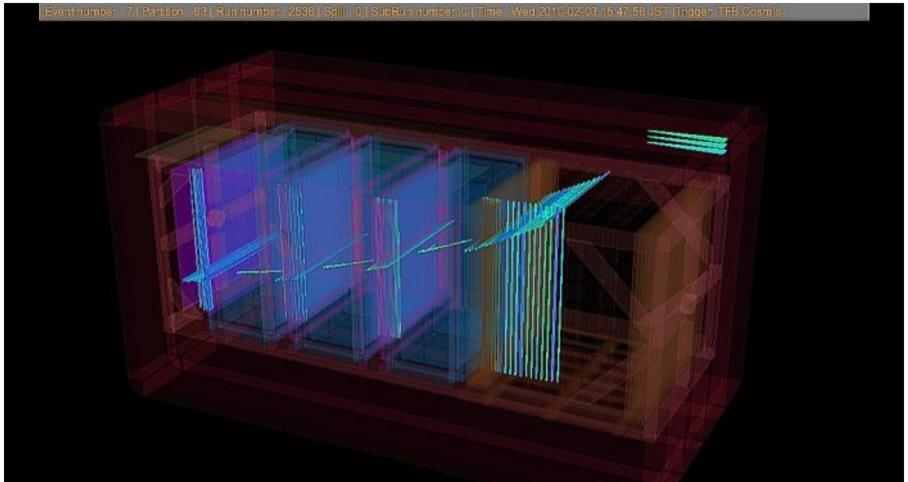
Interaction in P0D: View from (north) side



Sand Muon & FGD interaction

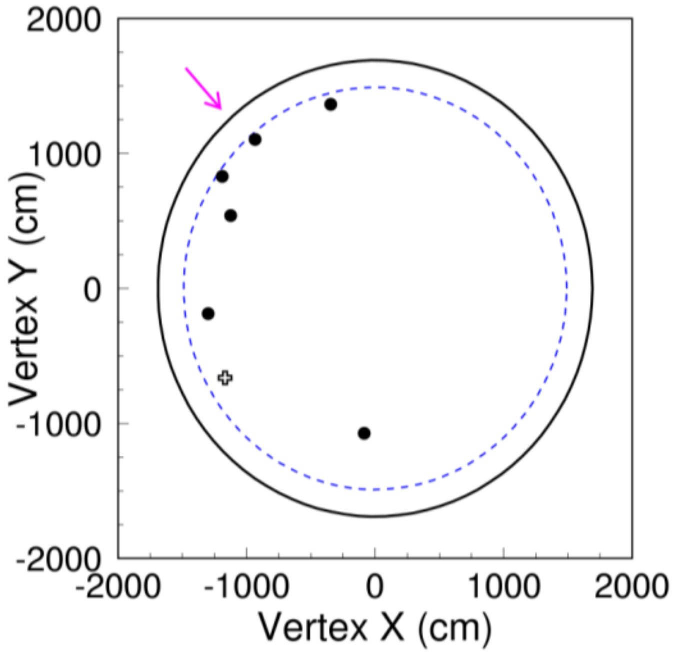


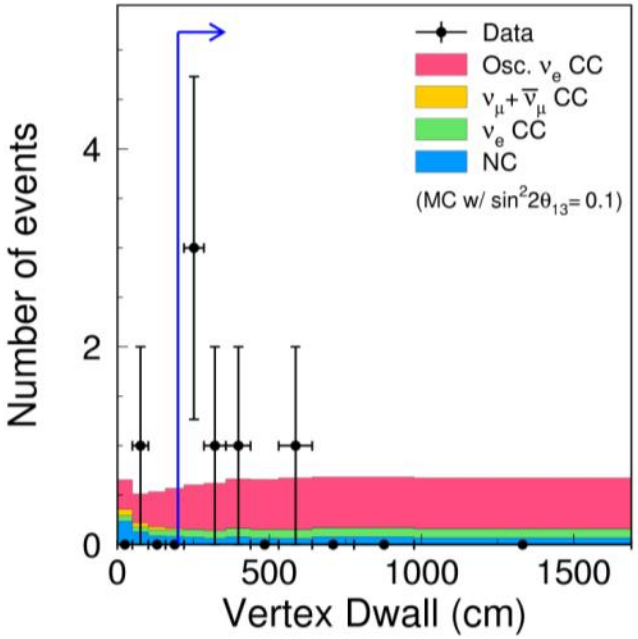
FGD interaction with backward track



Cosmic ray muon

T2K Event distributions





Distribution is unusual: $d_{\text{upstream-wall}}$ prob. is 0.14%,
$d_{\text{nearest-wall}}$ (‘Dwall’) prob. is 3.7%

But, addition of non-fiducial region improves the probabilities, opposite to a ‘leak-in’ hypothesis.

T2K currently judges this to be a chance artefact.

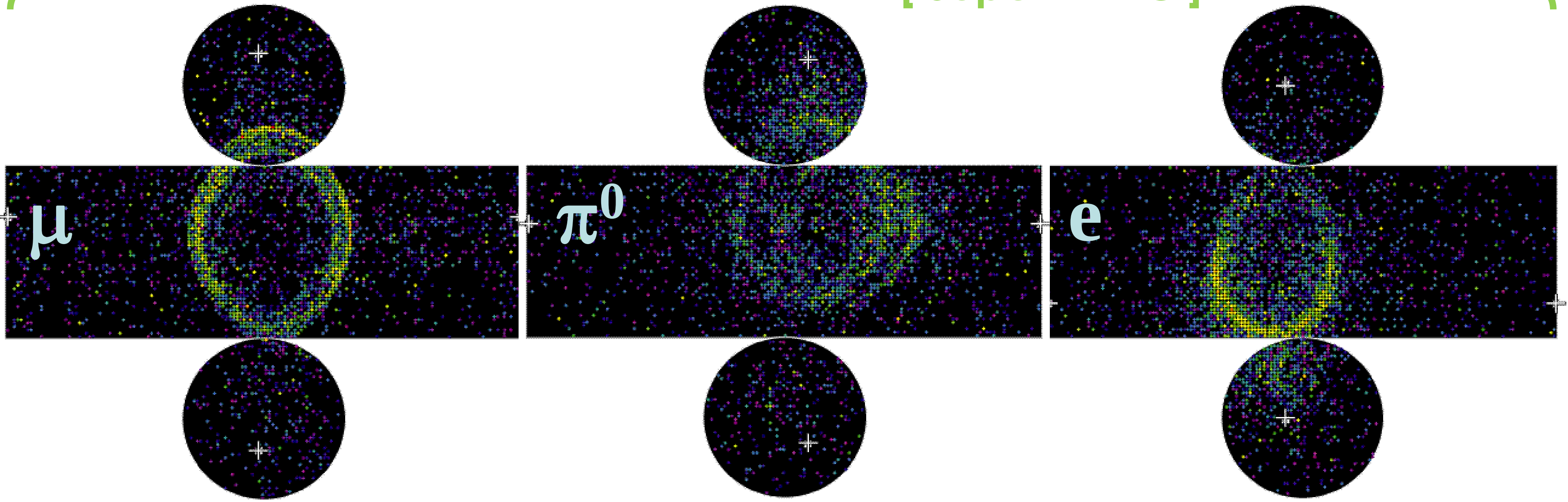
T2K Pi-zero background

Isolated neutral pions from ν_μ-NC events:

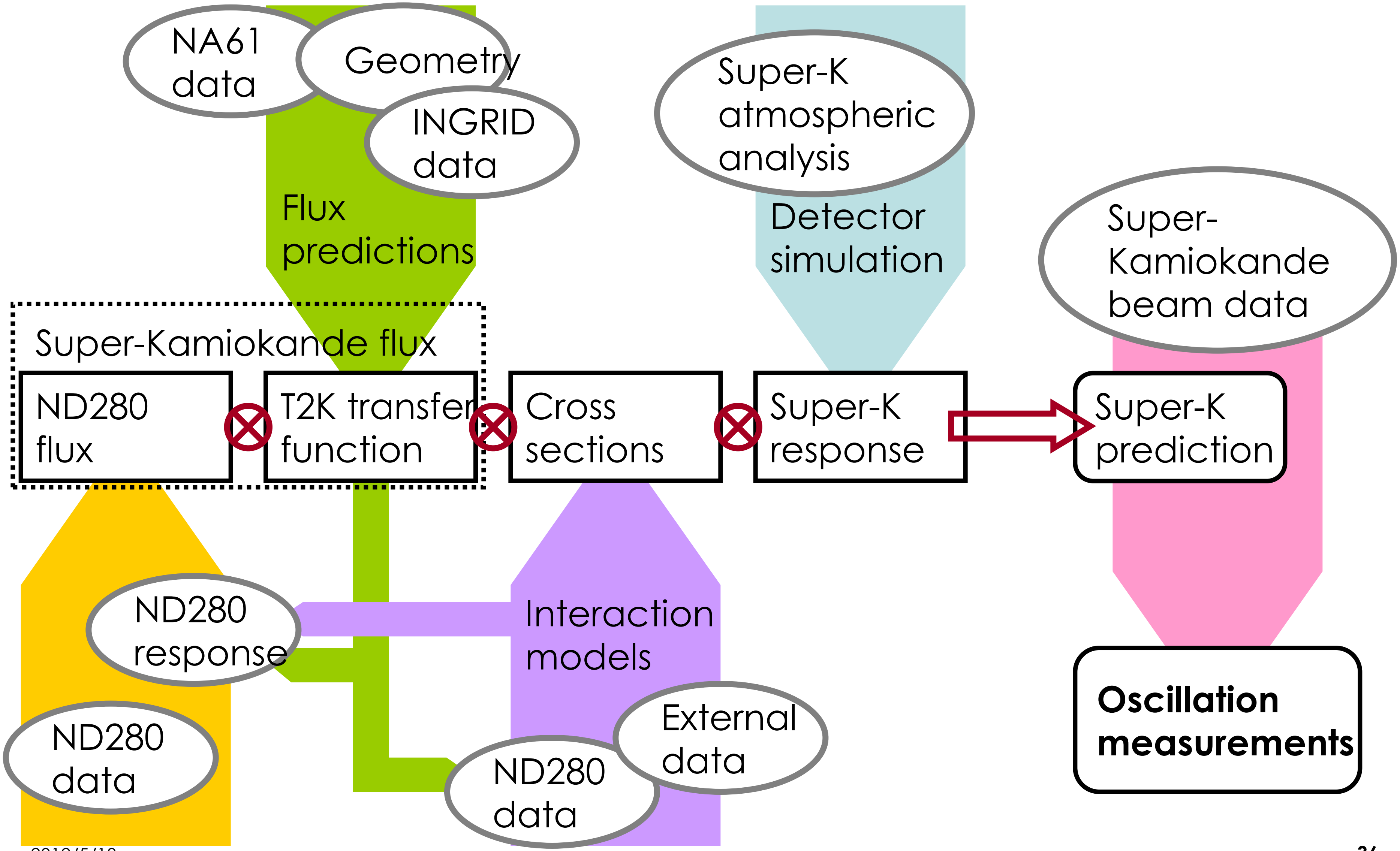
Neutral pion → photon pair → 2 EM showers

- If the EM showers have same direction they mimic a single EM shower (electron signal)

[Super-K MC]



T2K analysis strategy

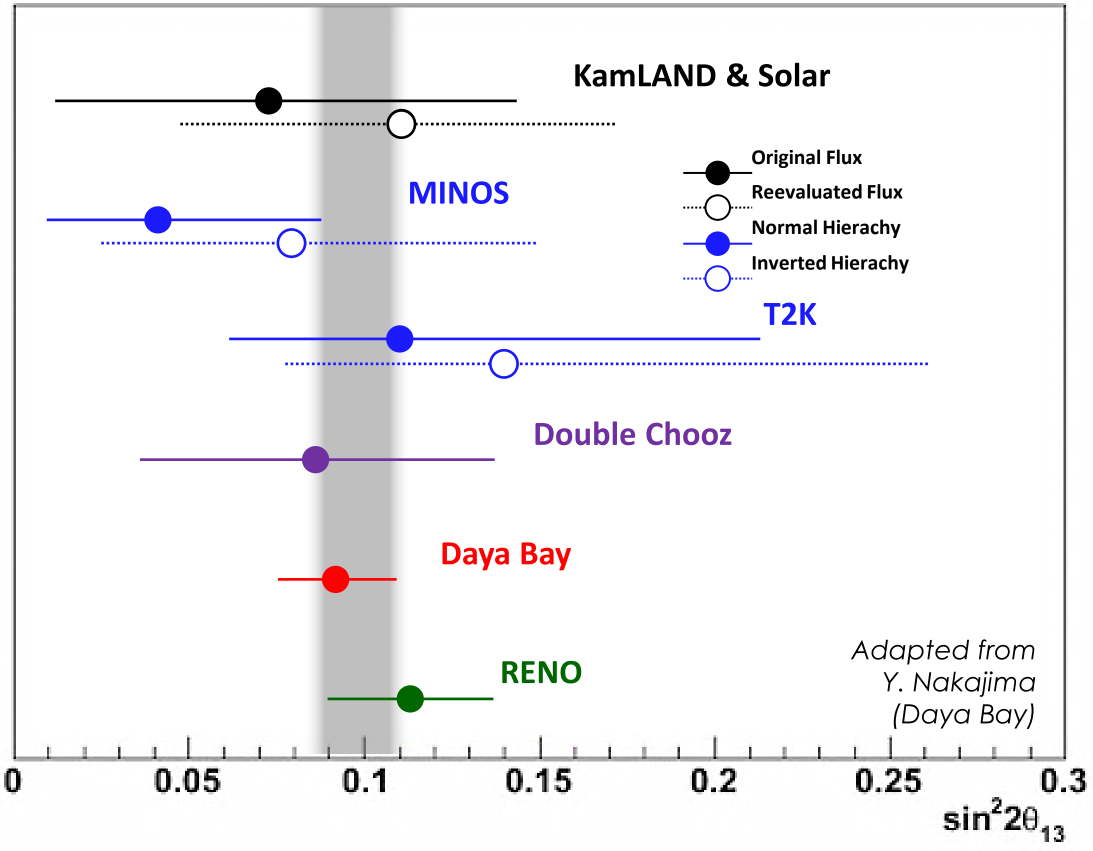


Averaging

LBL experiments hard to include in an average.
(how to interpret..?)

Reactor experiments are cleaner, and likelihood curves are closer to Gaussian.

A simple Gaussian combination (by me!) looks like this:



Adapted from Y. Nakajima (Daya Bay)