The Emerging Picture of Neutrino Oscillation

Ed Kearns

Boston University

11th International Workshop on Neutrino Factories, Superbeams and Beta Beams

NuFact09

Outline:

Our standard picture of neutrino oscillation physics

Some recent results

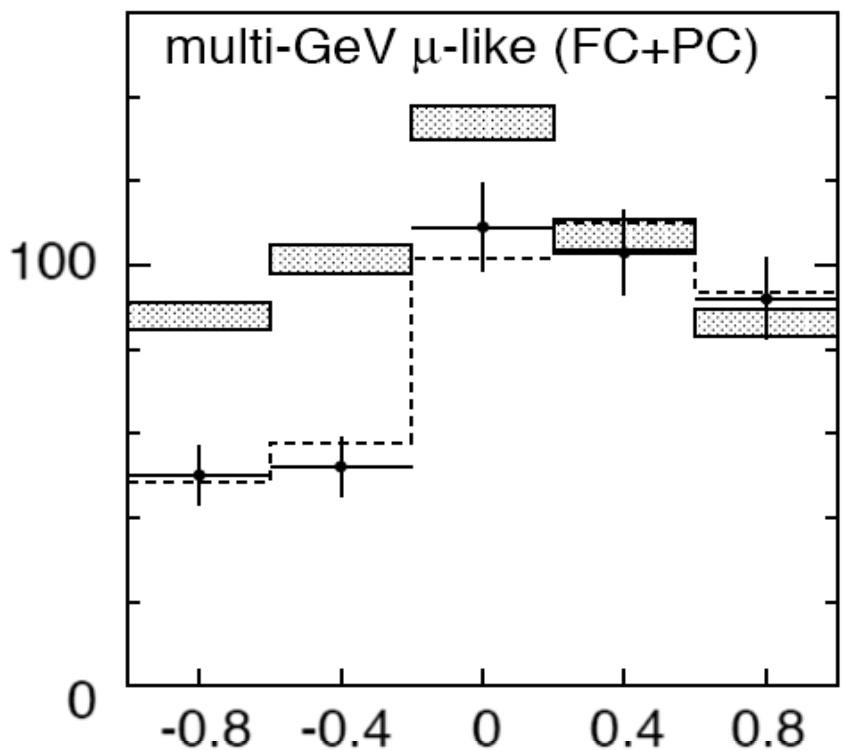
Approved experiments about to run

Future experiments that we dream about at night

Neutrinos Change Flavor in Flight

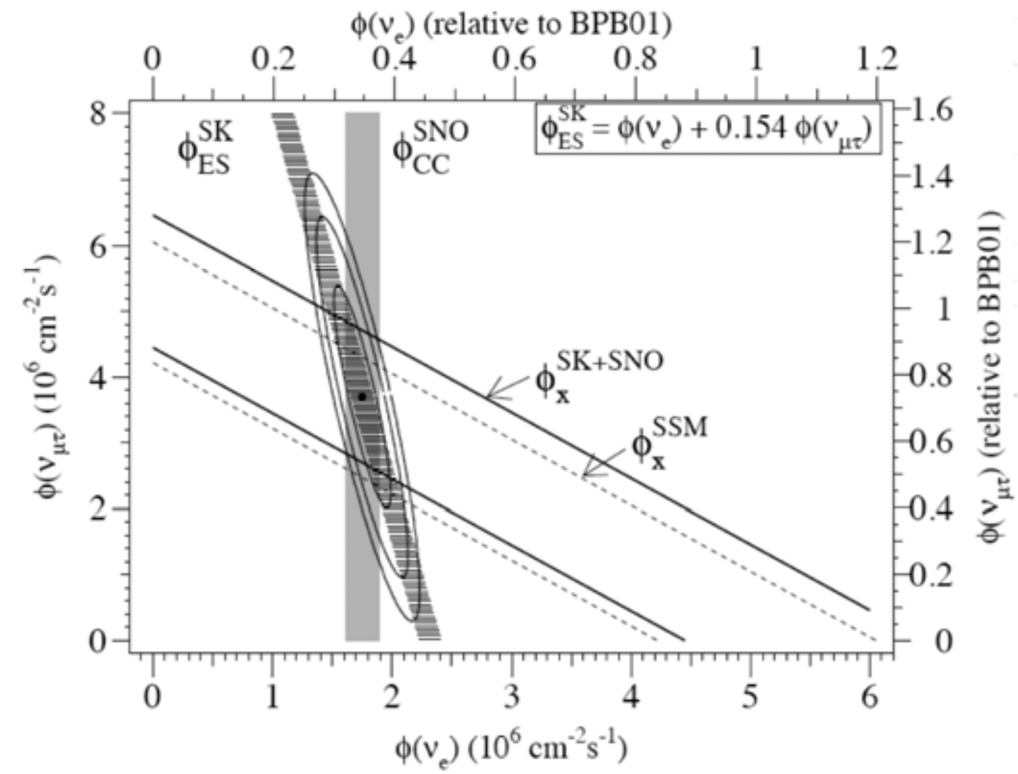
Implying that neutrinos have mass

Atmospheric Neutrinos (1997)



Super-K 414 days

Solar Neutrinos (2001)

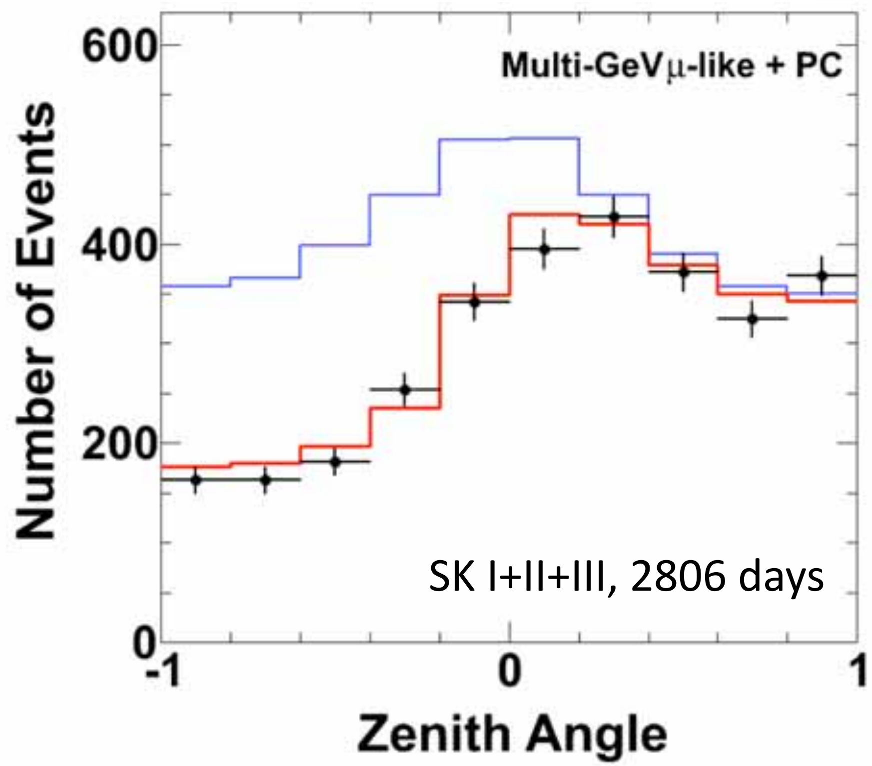


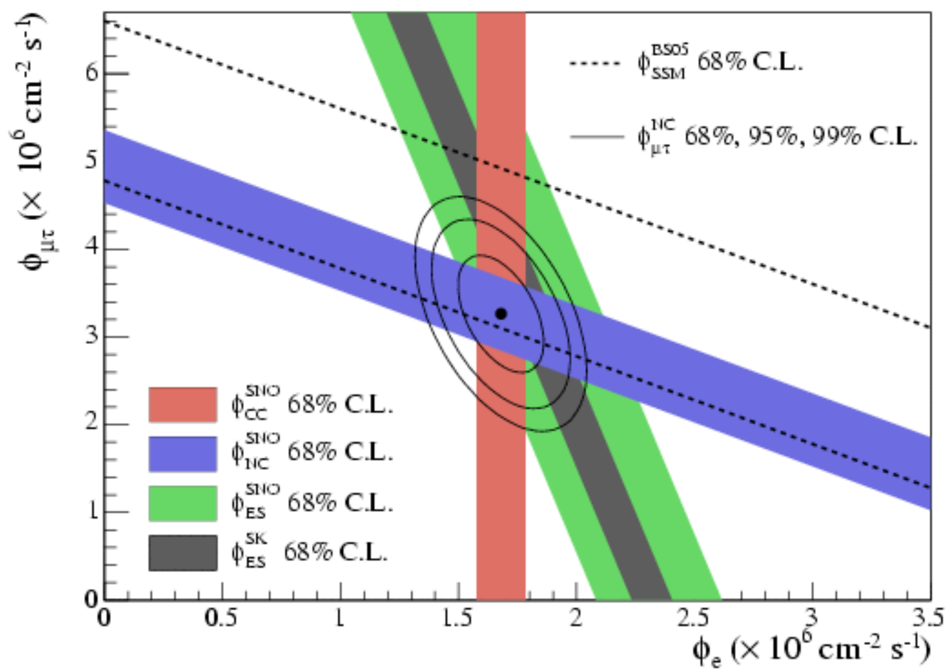
SNO Heavy water only

Neutrinos Change Flavor in Flight

Implying that neutrinos have mass

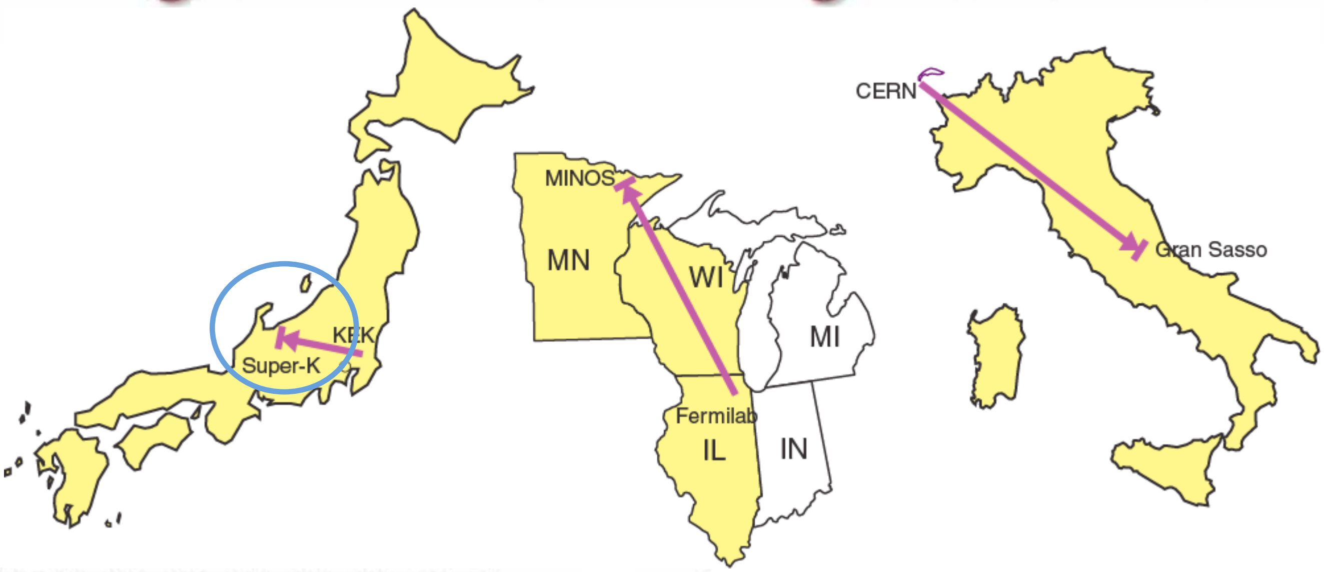
Confirmations: MACRO, Soudan 2, K2K, MINOS, KamLAND,
with high precision by MINOS and KamLAND



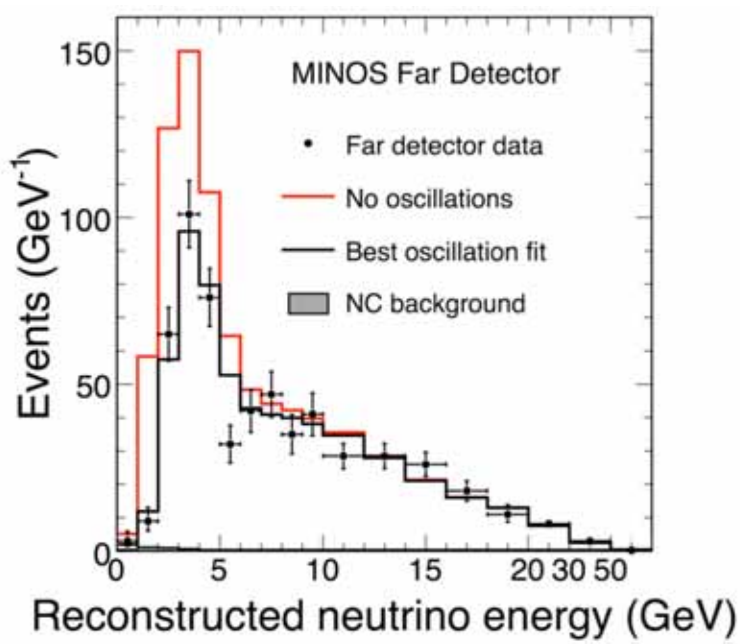


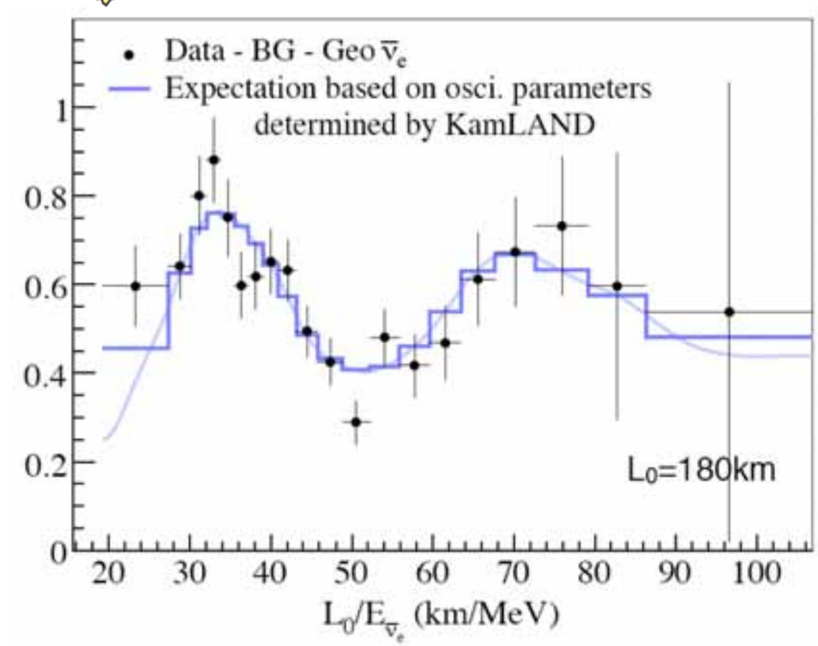
$$\Phi(\nu_e) < \Phi(\nu_e + \nu_\mu + \nu_\tau) \approx \Phi(\mathrm{SSM})$$

Confirming and Measuring Neutrino Mixing

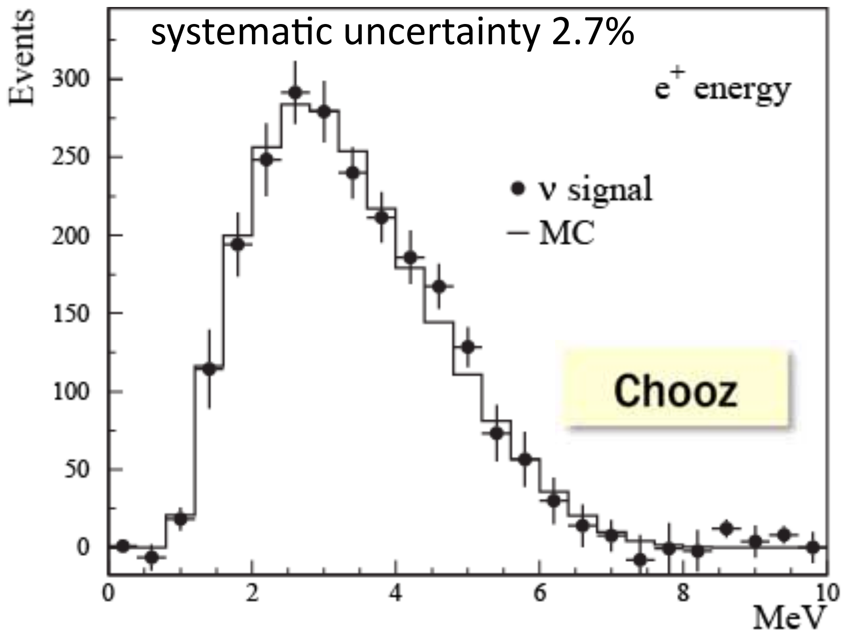


τ appearance





plus an important constraint from the absence of (detected) effect:



No evidence for reactor neutrino disappearance over ~ 1 km

The Neutrino Matrix

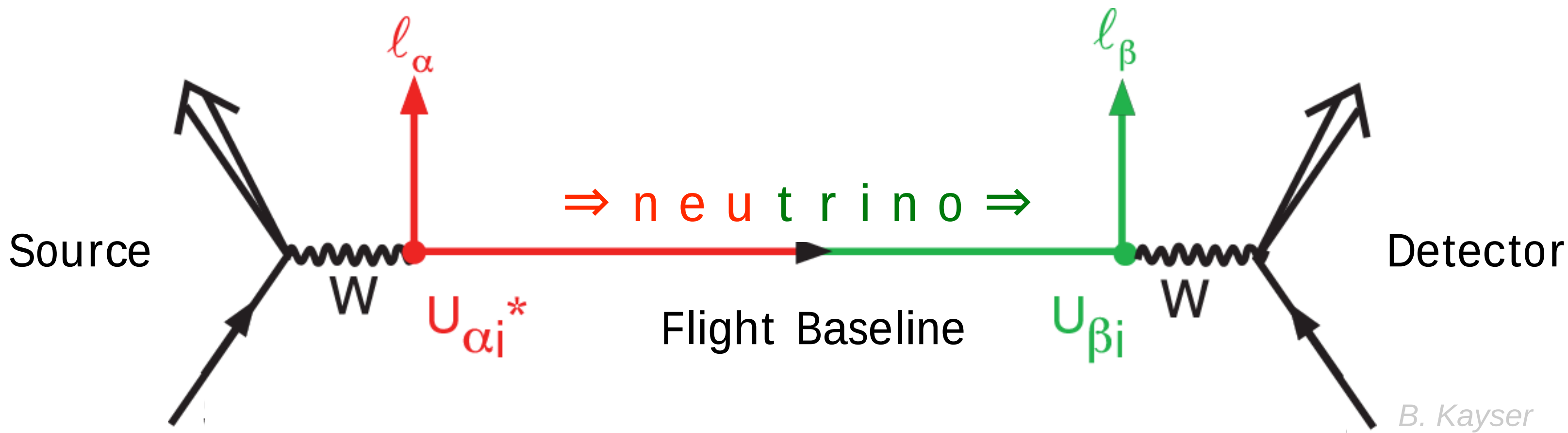
Pontecorvo-Maki-Nakagawa-Sakata Matrix (PMNS or MNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor

mass

Neutrino flavor mixing



$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

$$\pm 2\sum_{i>j} \mathrm{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin\left(\Delta m_{ij}^2 \frac{L}{2E}\right)$$

Mass-squared splittings. $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

The Neutrino Matrix -- Expanded

$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$

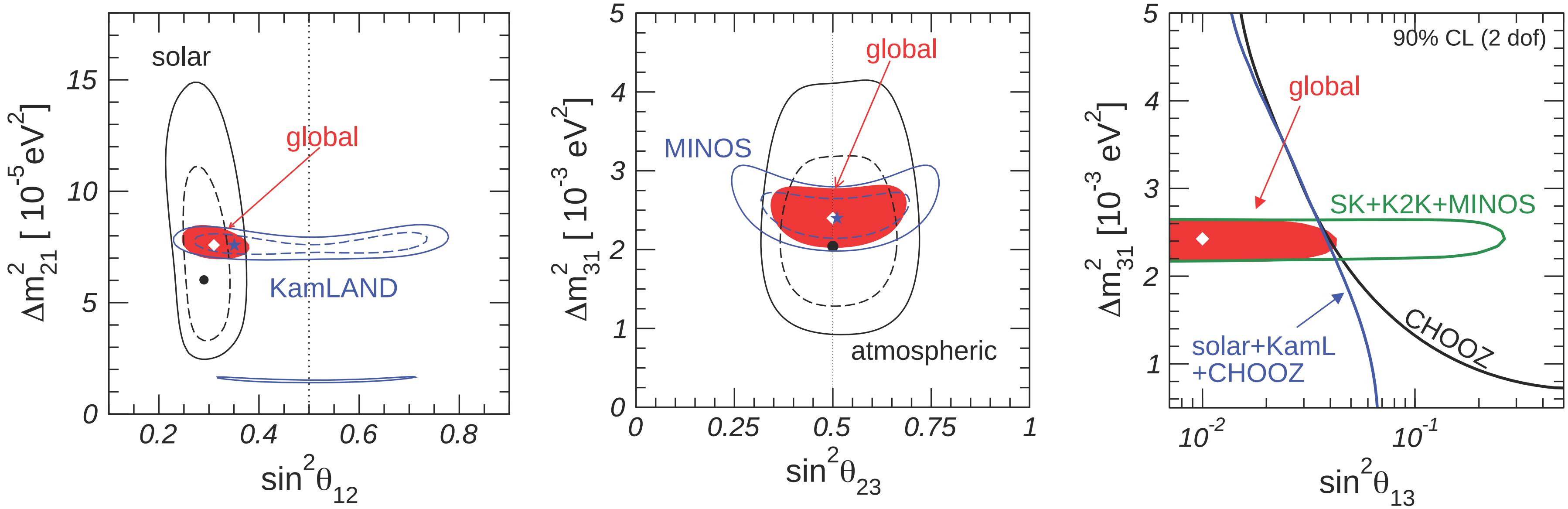
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

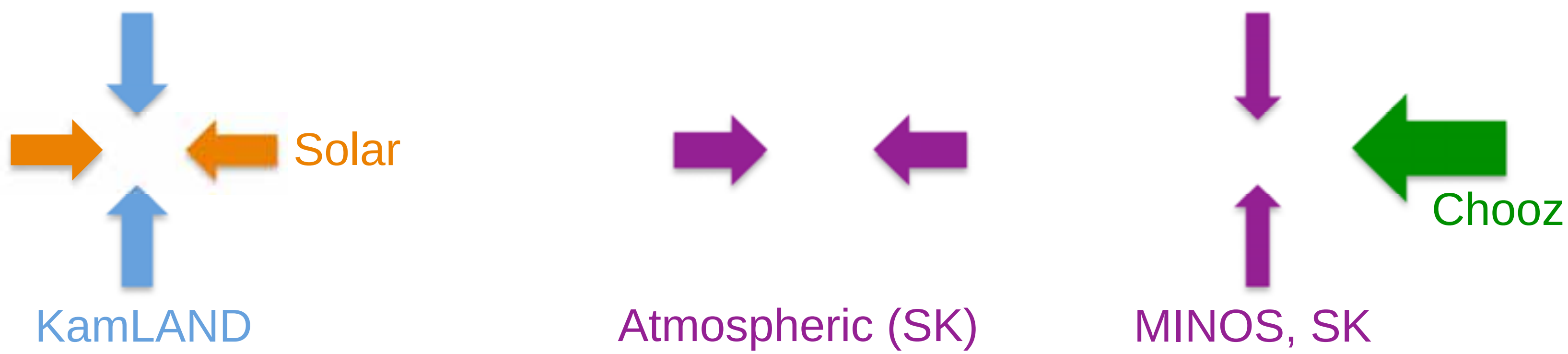
Atmospheric

Solar

Global Fits to Neutrino Data

arXiv:0812.3161 Maltoni and Schwetz





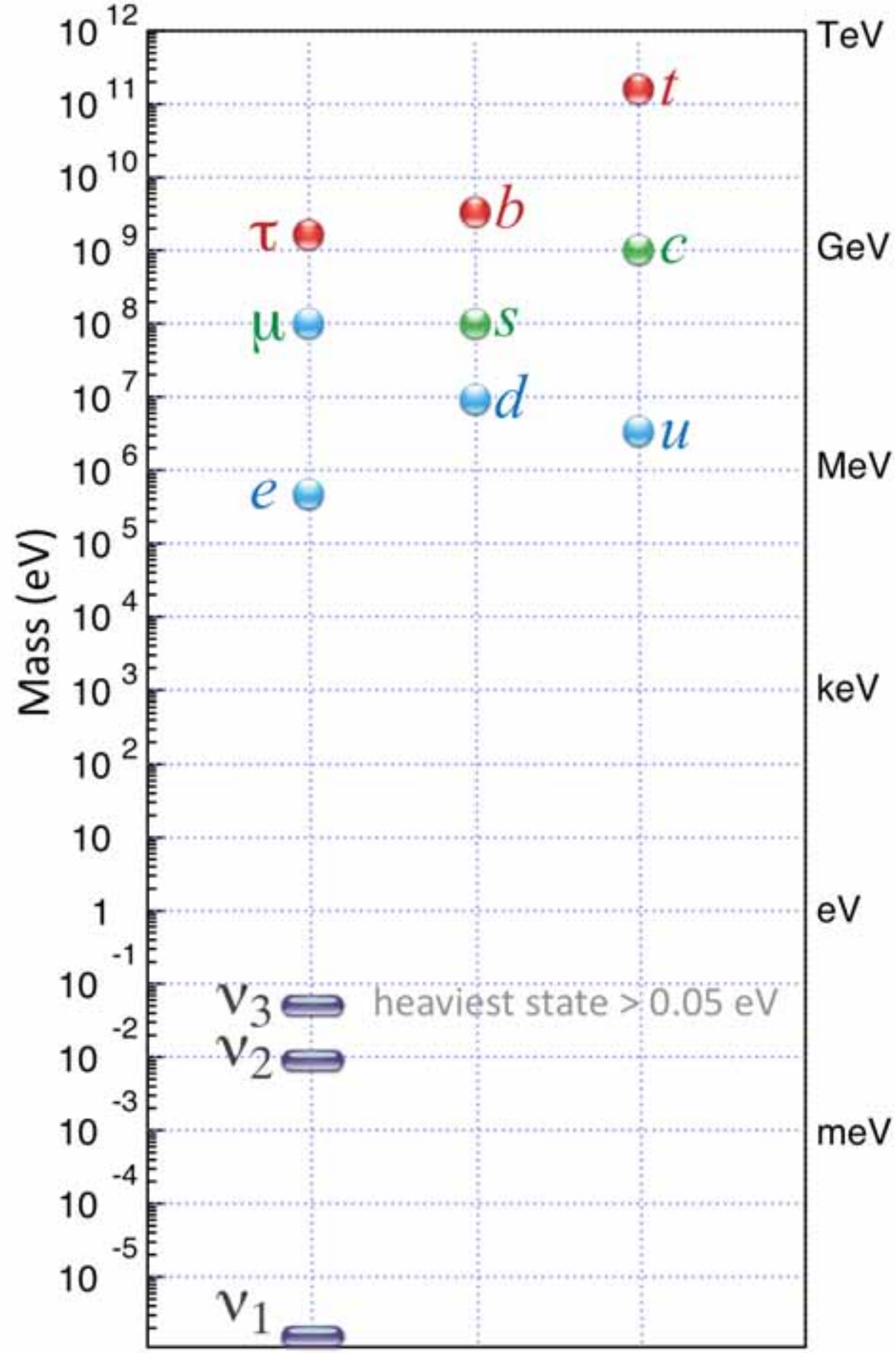
What we know (and don't know) about masses:

$$\Delta m^2_{23} = 2.4 \pm 0.3 \times 10^{-3}\ \text{eV}^2$$

$$\Delta m^2_{12} = 7.7 \pm 0.2 \times 10^{-5}\ \text{eV}^2$$

$$m_2 > m_1$$

maybe … Hierarchical normal ordering (2-3)



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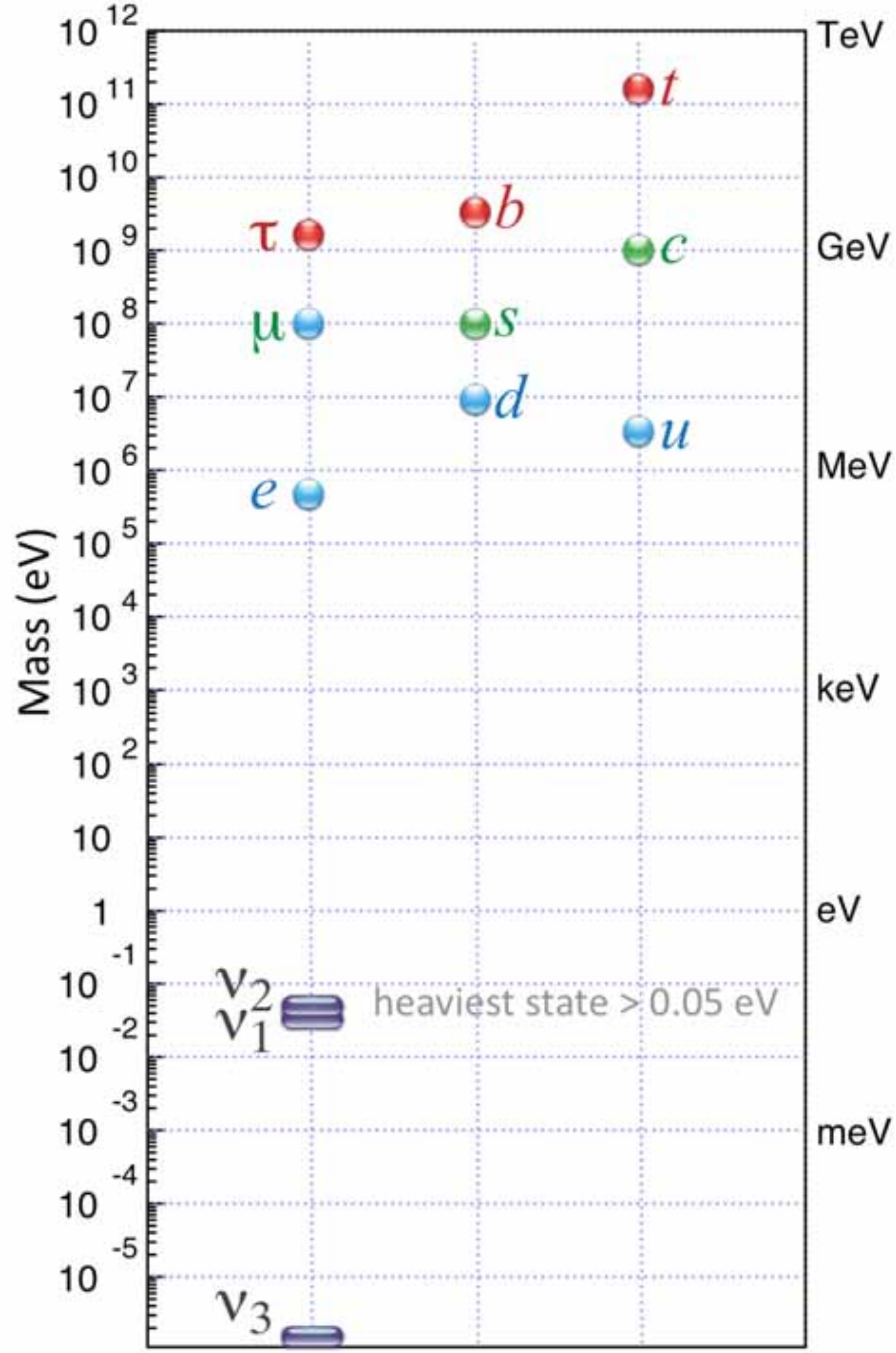
maybe … Hierarchical inverted ordering



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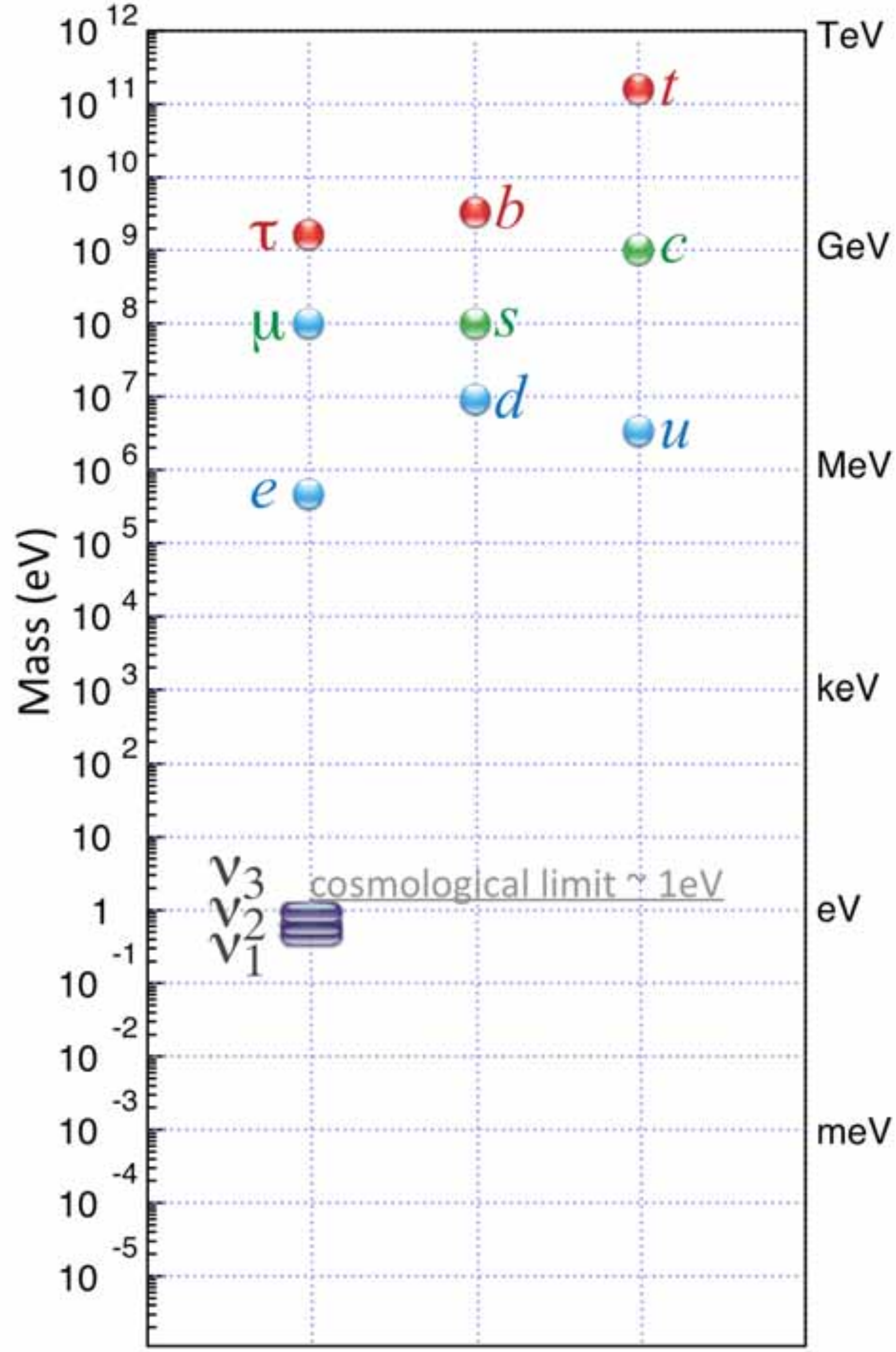
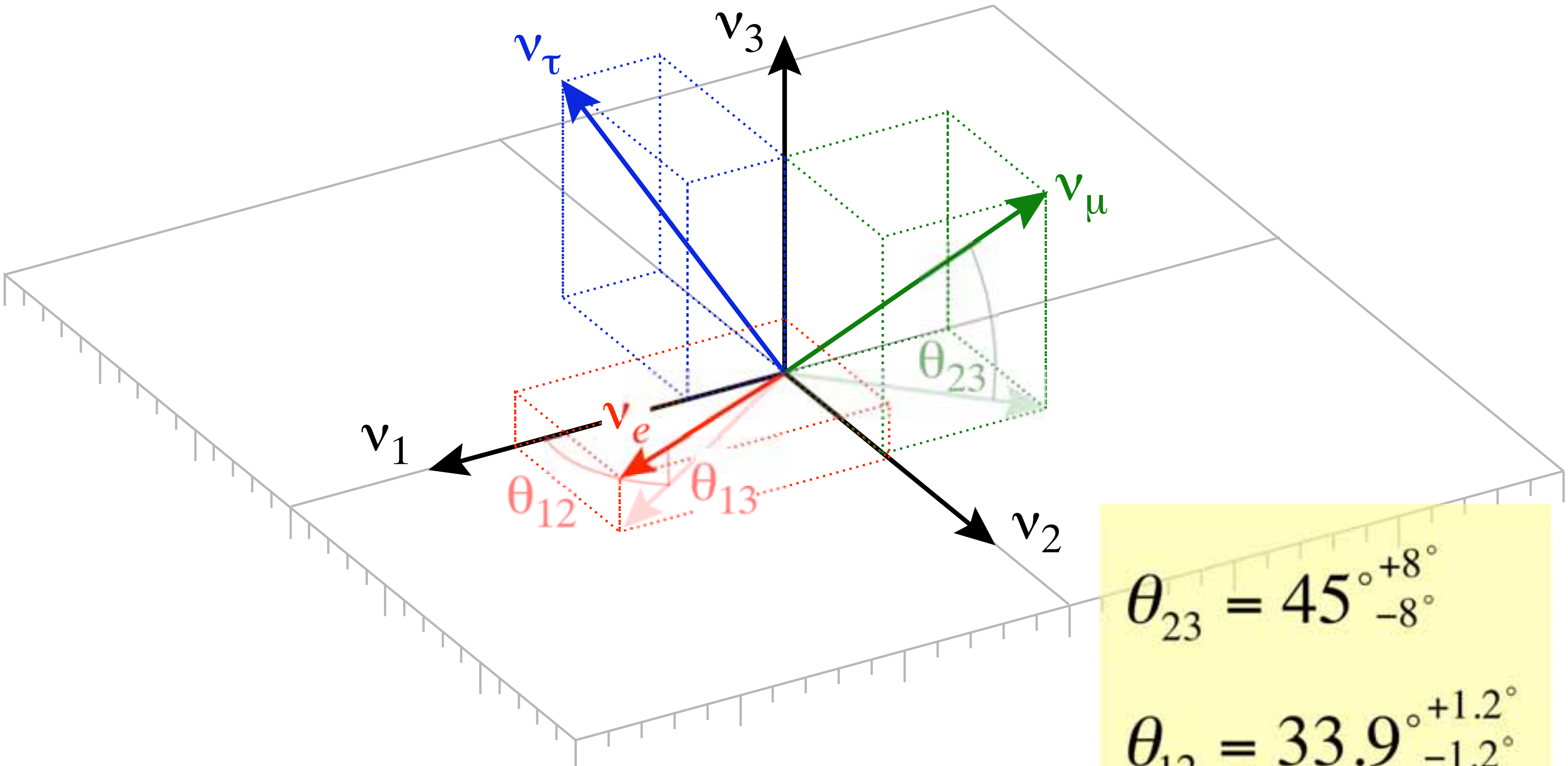
$$\Delta m_{12}^2 = 7.7 \pm 0.2 \times 10^{-5}\ \text{eV}^2$$

$$m_2 > m_1$$

maybe … Degenerate normal (or inverted) ordering



What we know (and don't know) about angles:



$$\theta_{23} = 45^{\circ}{}^{+8^{\circ}}_{-8^{\circ}}$$

$$\theta_{12} = 33.9^{\circ}{}^{+1.2^{\circ}}_{-1.2^{\circ}}$$

$$\theta_{13} < 13^{\circ}$$

The Experimental Program for Neutrino Oscillation Physics

- **Observe all predicted effects:**
  oscillation pattern, tau appearance, matter effects ...
- **Constrain non-standard effects:**
  sterile neutrinos, neutrino decay, decoherence, MaVaNs, LIV, NSI, CPT violation...

- Refine measurements, especially: is $\theta_{23} \neq 45°$?
- Measure θ_{13} – **is it greater than zero?**

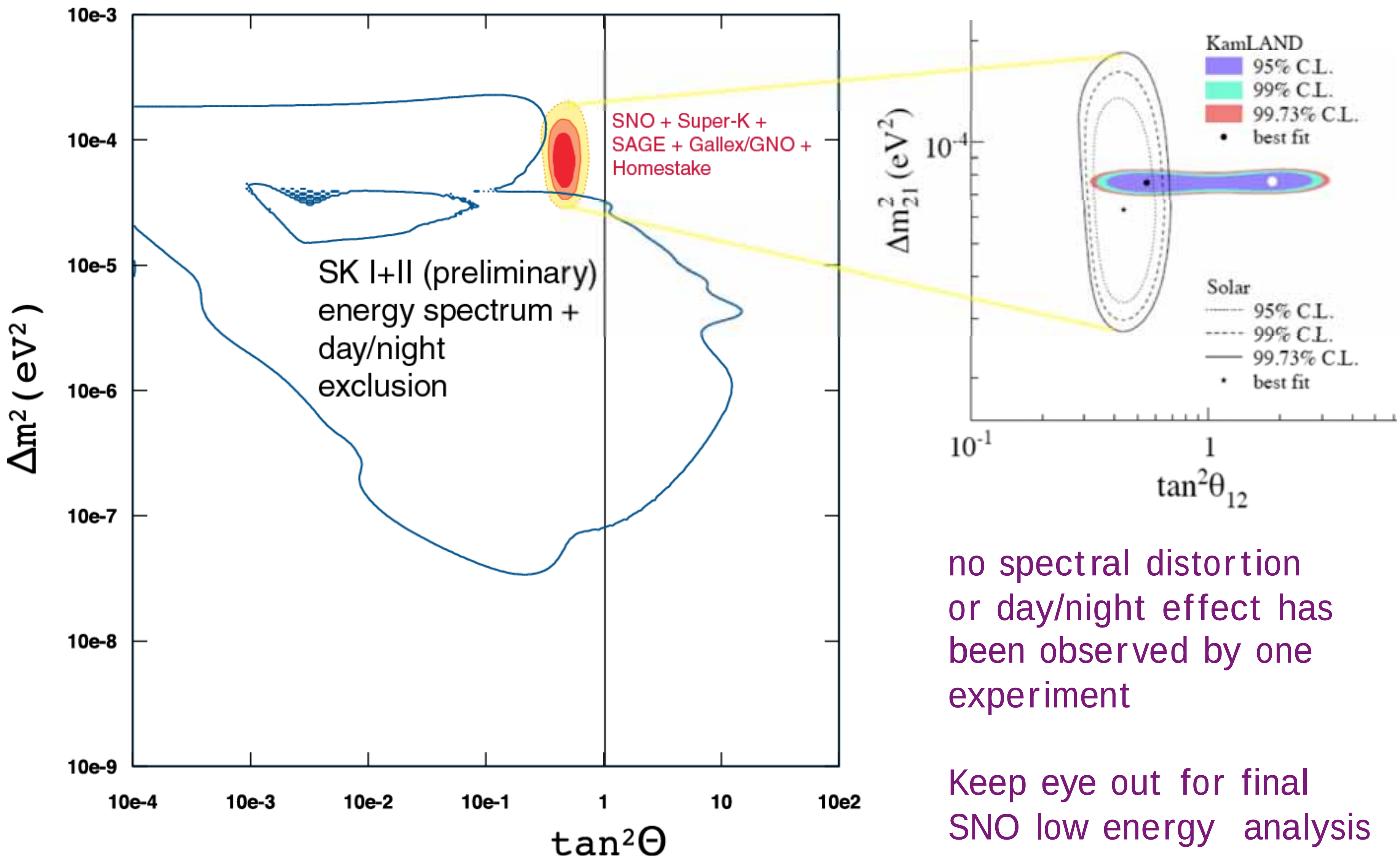
upcoming generation of experiments

- Determine the 2-3 mass hierarchy*
- Measure phase δ – **seek CP violation**

future generation being planned

* possible with upcoming NOνA experiment under some circumstances

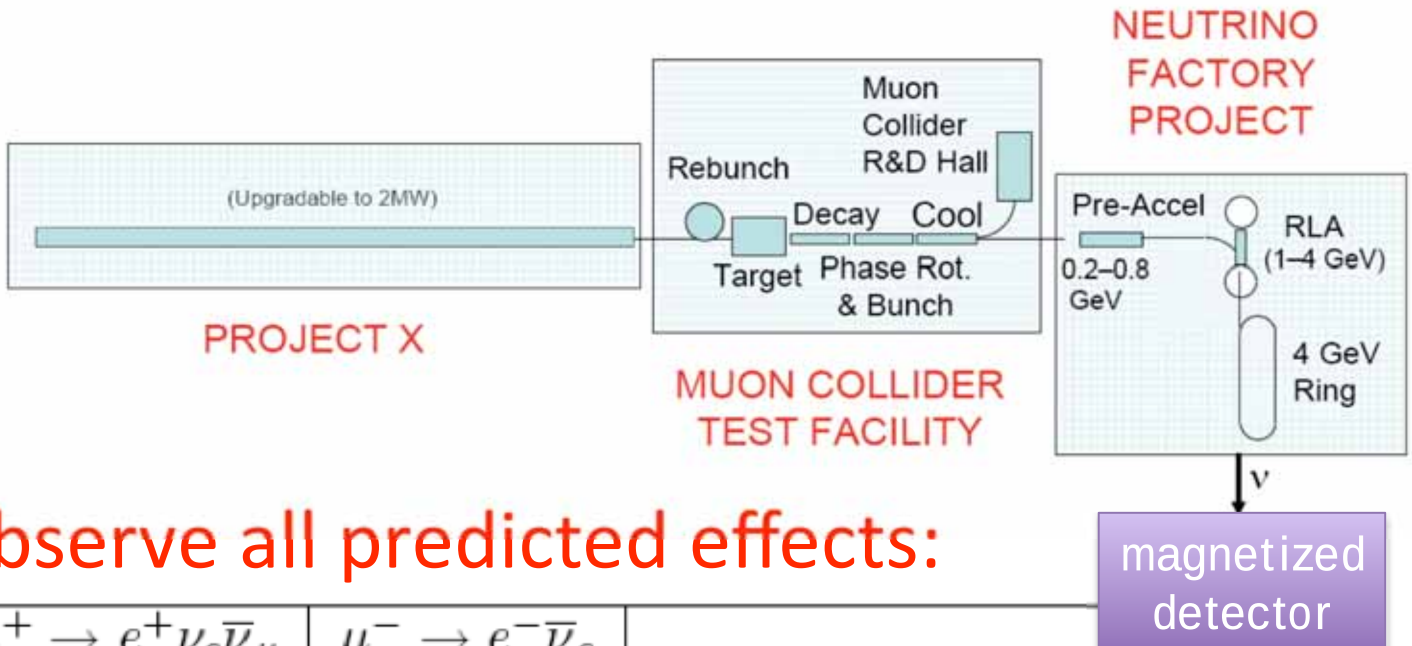
observe all effects!



no spectral distortion or day/night effect has been observed by one experiment

Keep eye out for final SNO low energy analysis

The NuFACT Connection



- Observe all predicted effects:

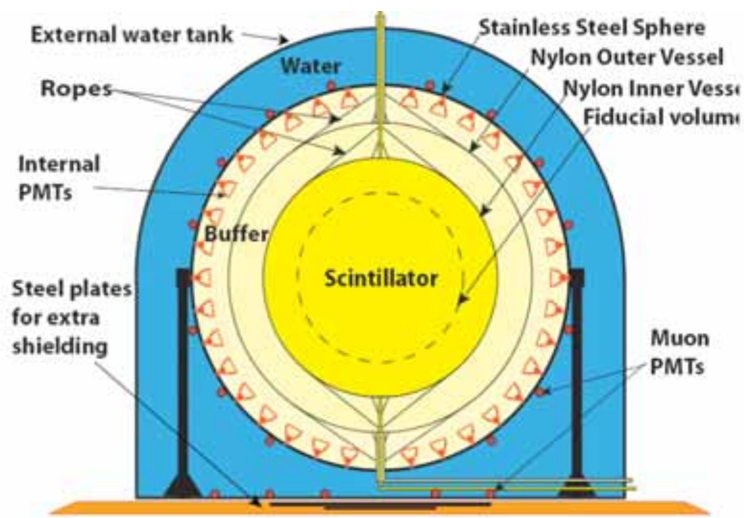
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

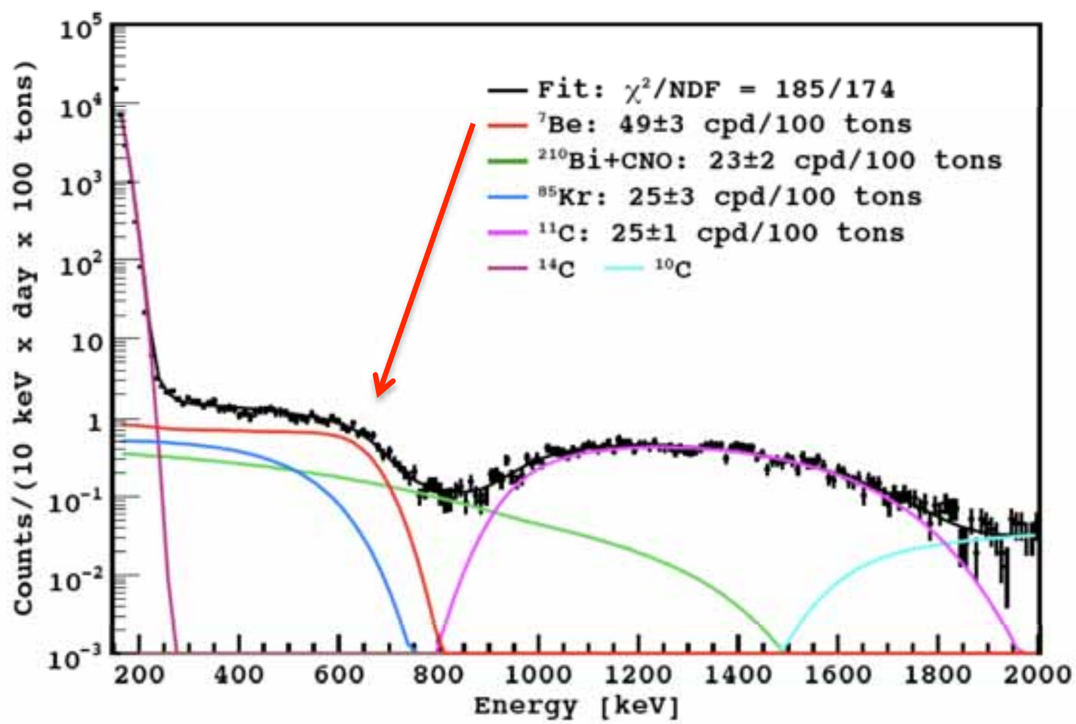
also, excellent at resolving degenerate solutions


What's new?
Recent results...

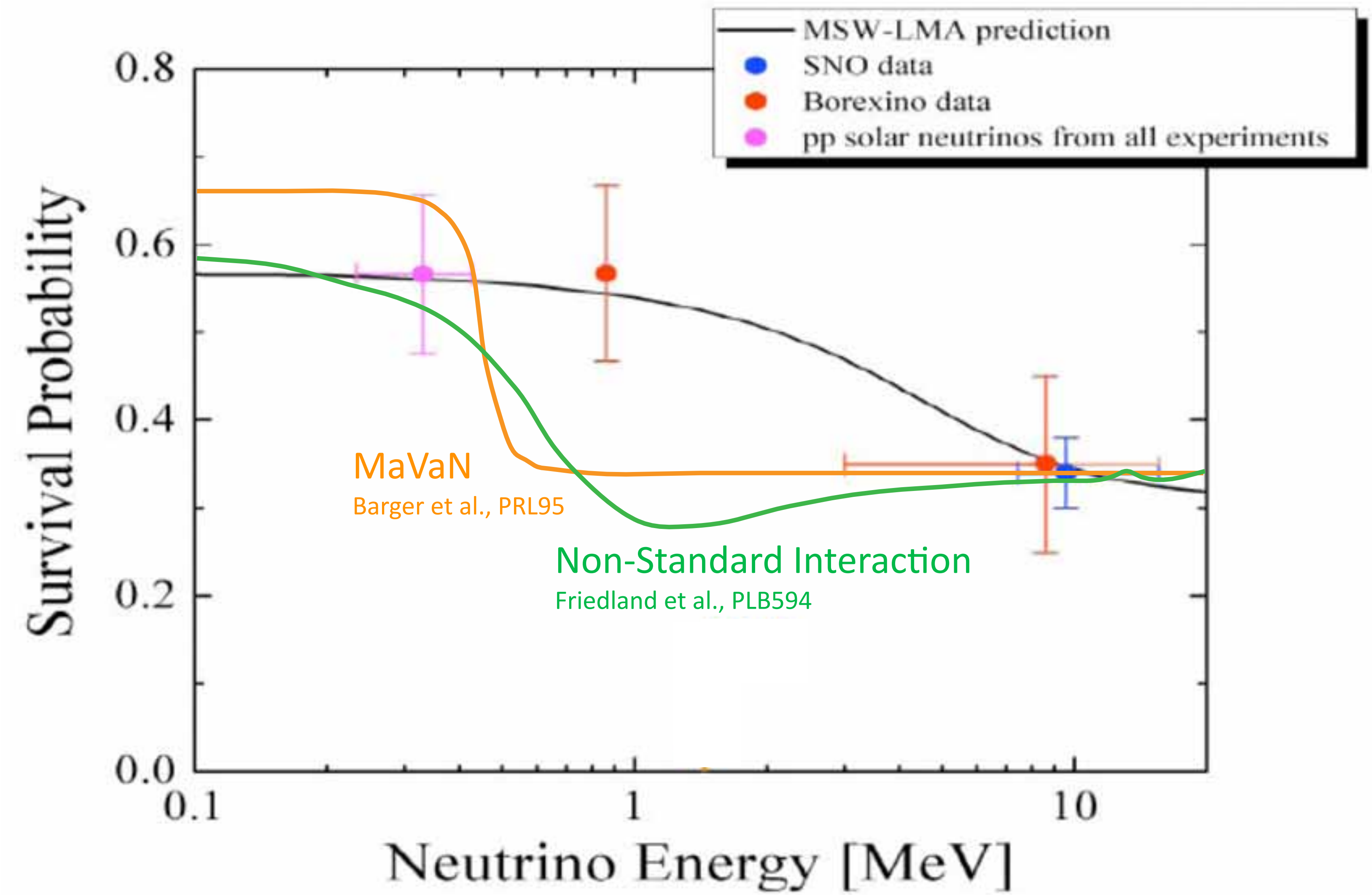
Borexino

neutrino-electron elastic scattering, goal is 862 keV ^{7}Be line
extremely low radioactive contamination
278 tons, 100 tons fiducial of scintillator doped mineral oil





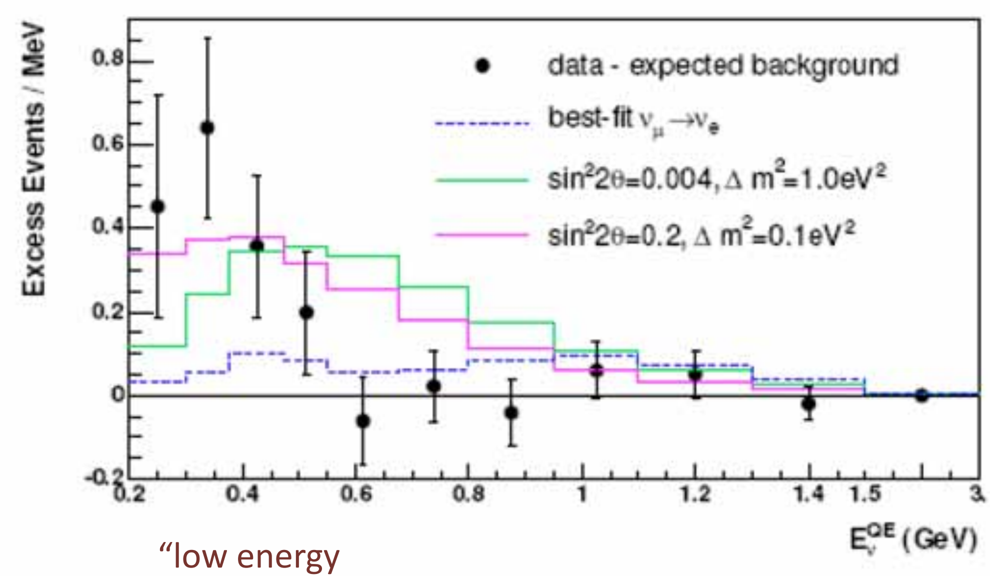
Borexino Oscillation Result



Mini-BooNE

L = 540 m (10× LSND)
E = 500 MeV (10× LSND)

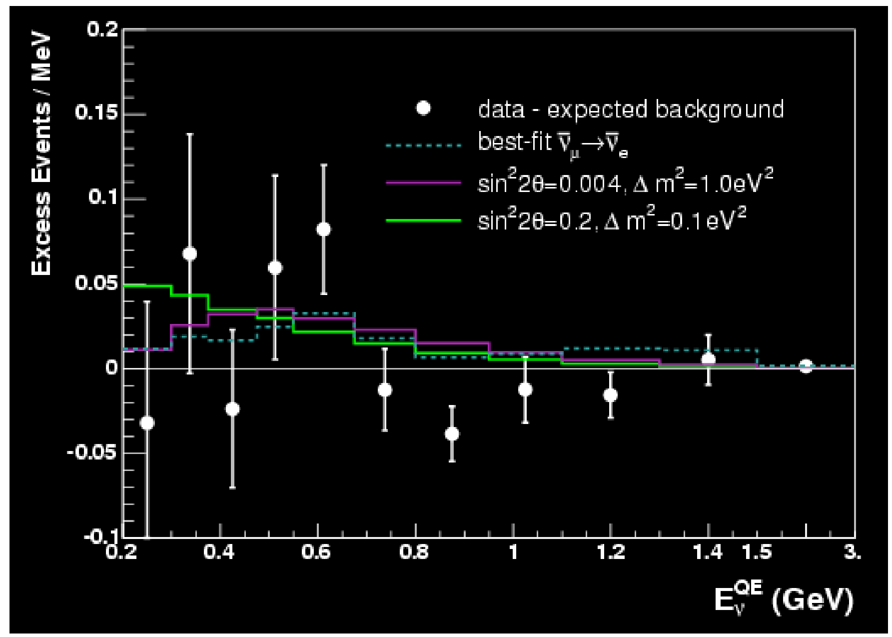
neutrinos



"low energy
Mini-BooNE excess"

anti-neutrinos

Karagiorgi FNAL Seminar



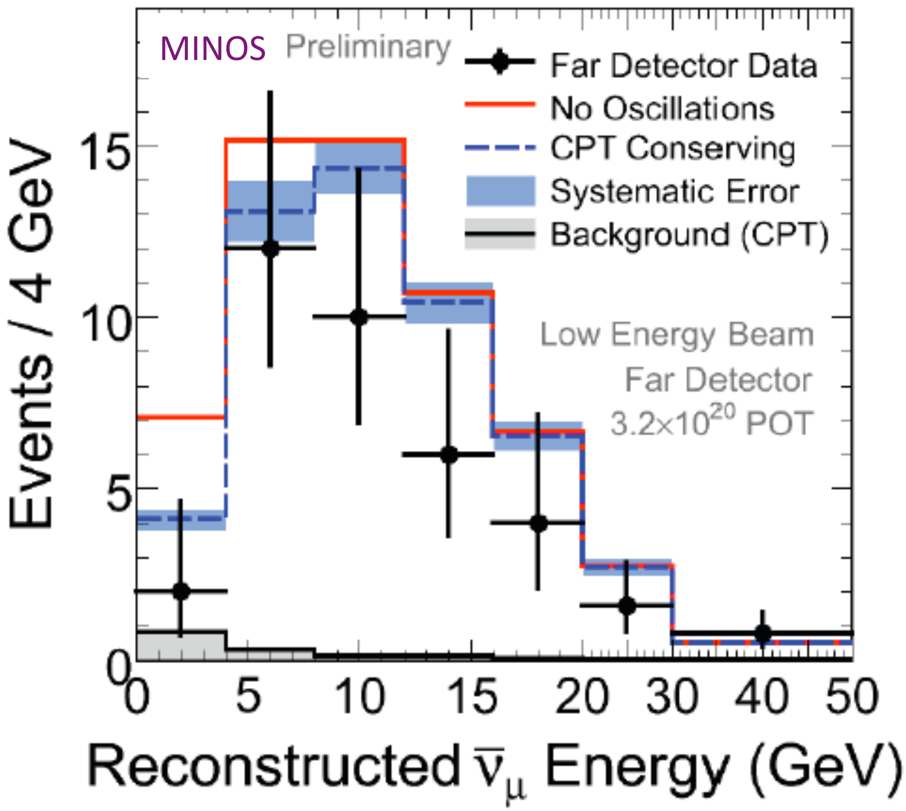
no evidence for LSND-like oscillation at 1 GeV^2 scale

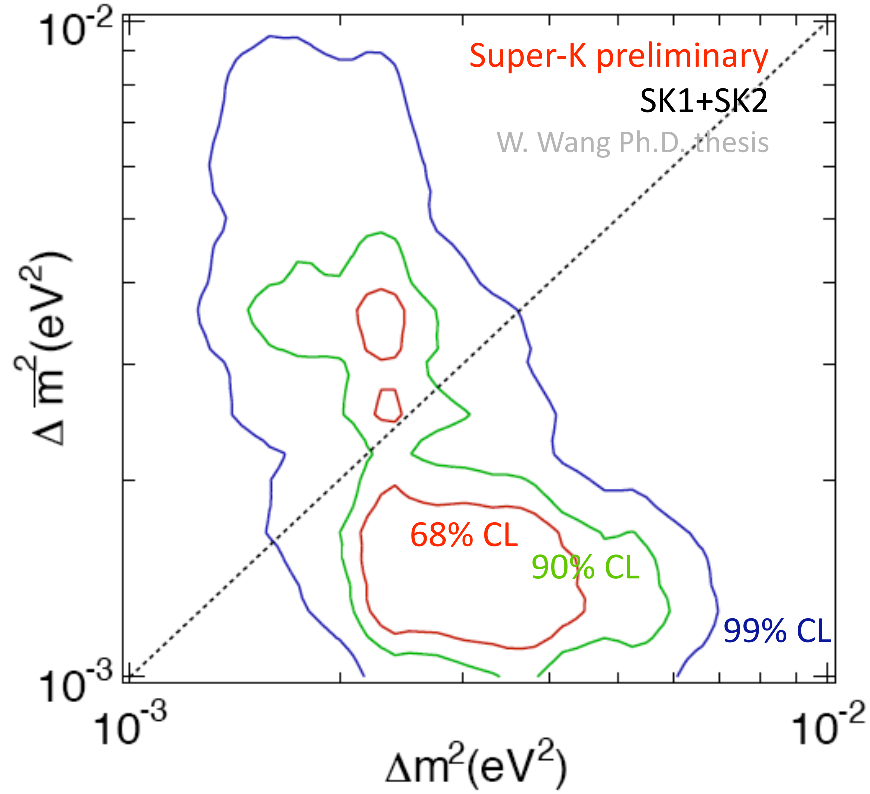
Neutrinos and Anti-Neutrinos

MINOS: unique ability to measure ±charge

$\nu_\mu \rightarrow \bar{\nu}_\mu$ appearance limited < 2.6%

Is $\Delta m^2 = \Delta \bar{m}^2$?   42 events detected, 58.3±8.4 expected



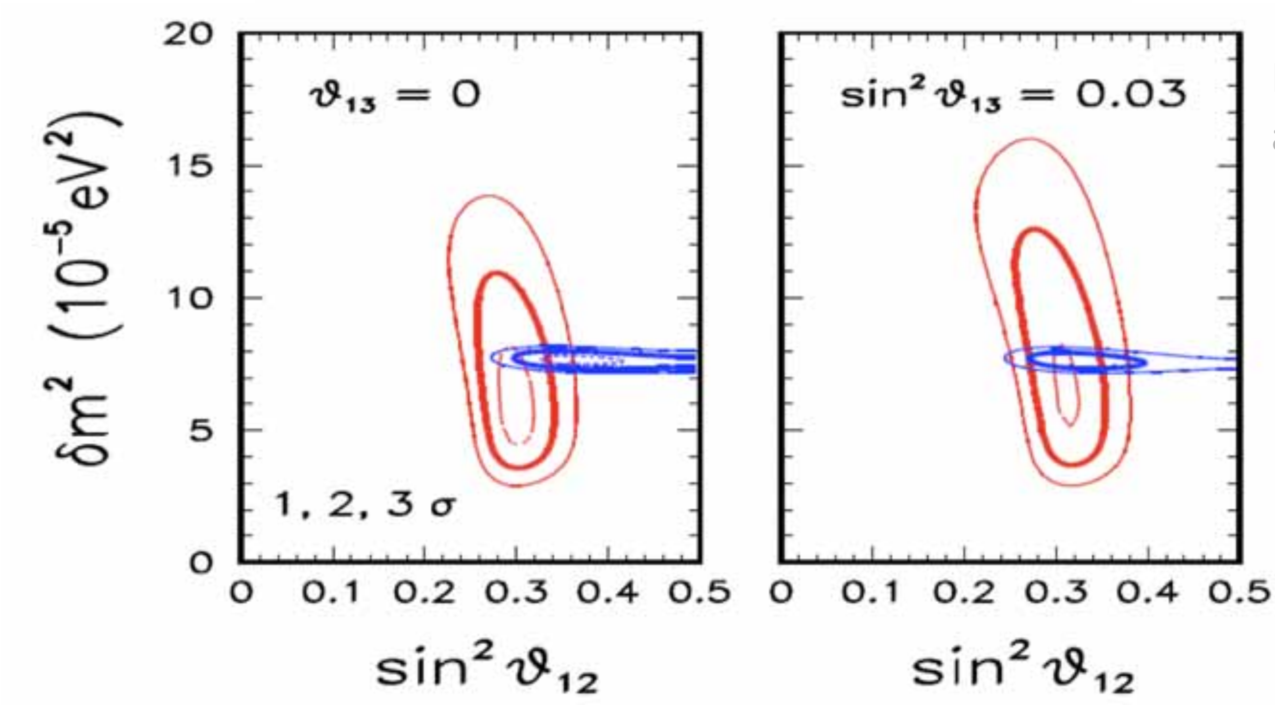


Super-K atmospheric neutrinos:

no event-by-event determination

statistical sensitivity from different fluxes, cross sections

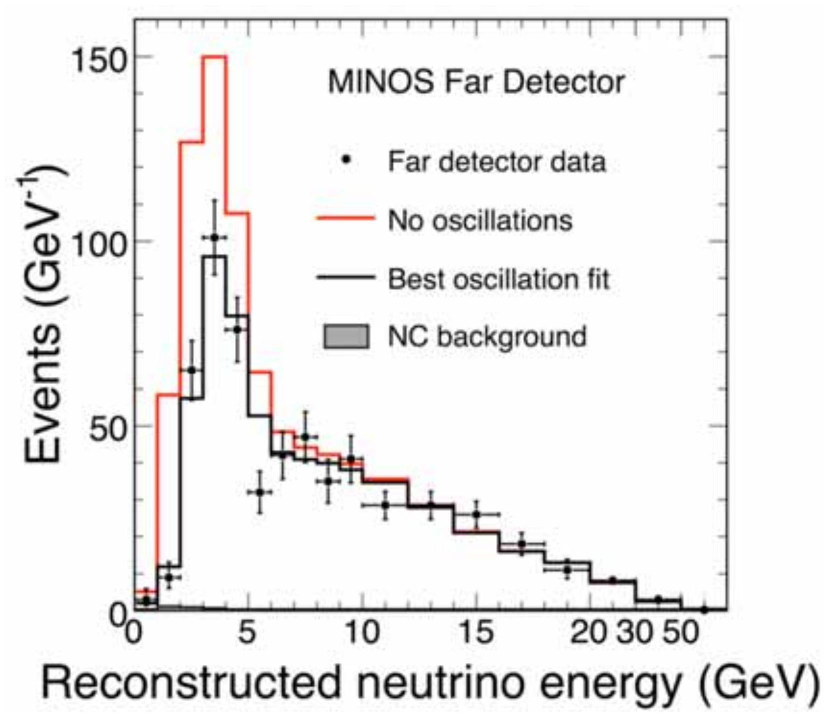
Any hints on θ_{13}?



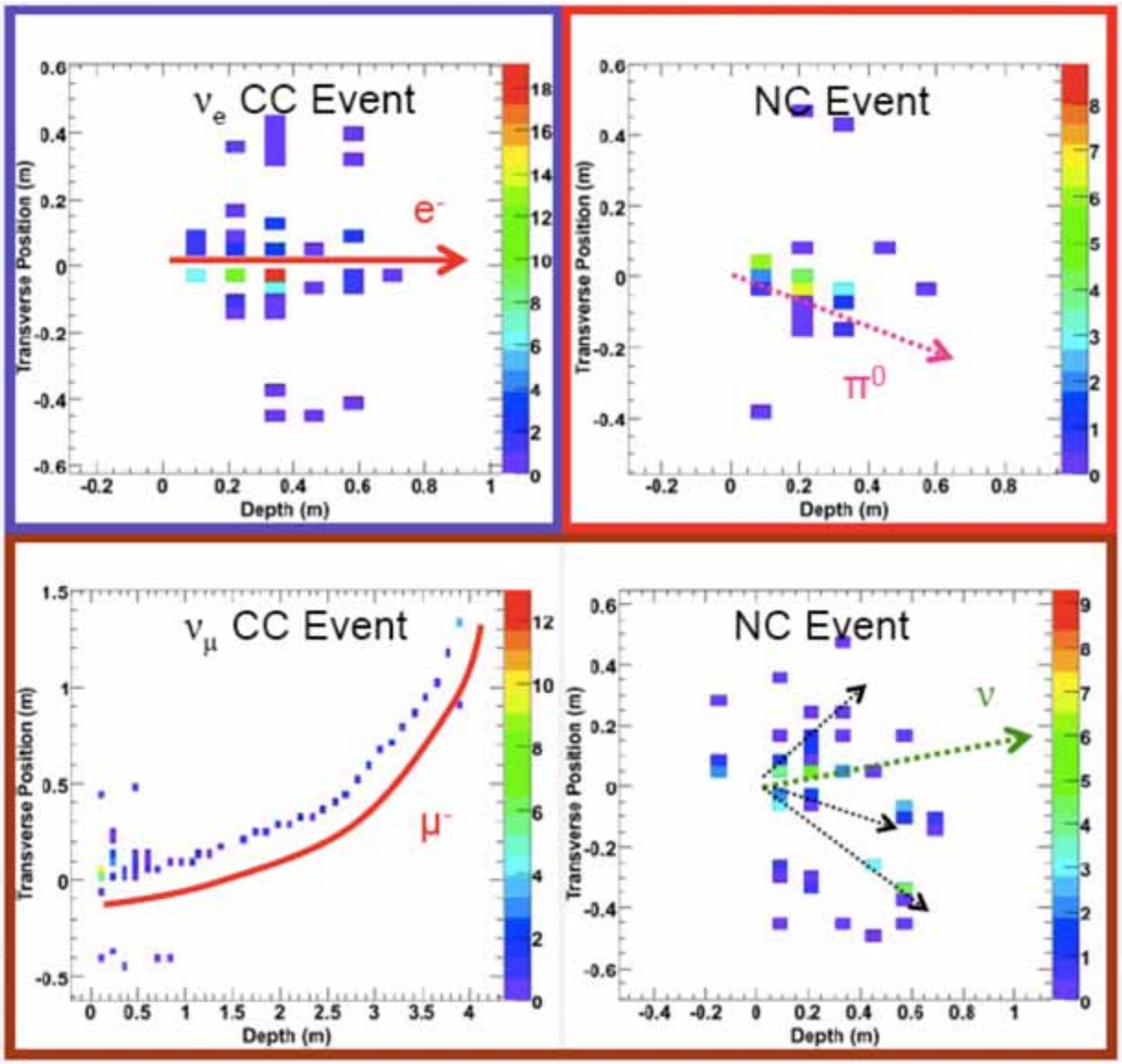
Fogli et al., arXiv:0905.3549

MINOS

- Fermilab-Soudan, 735 km
- 5.4 kton far detector, 1 kton near
- **2.54 cm thick steel plates (1.4X_0)**
- 1.2 T solenoidal magnetic field

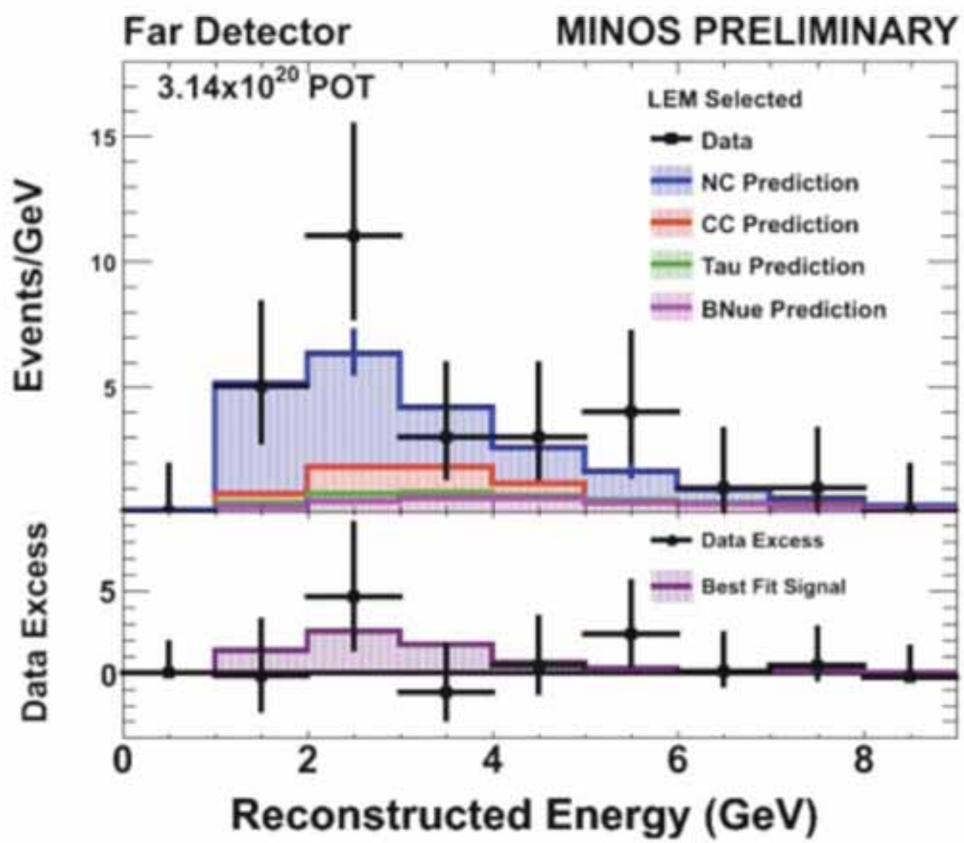


EM Showers in MINOS



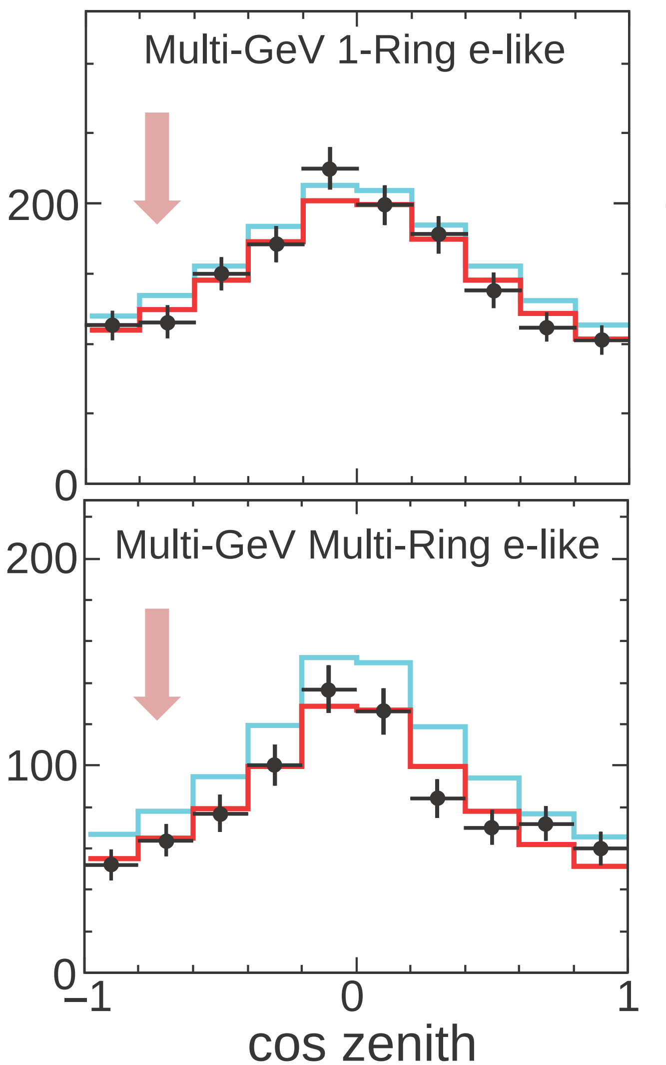
M. Sanchez

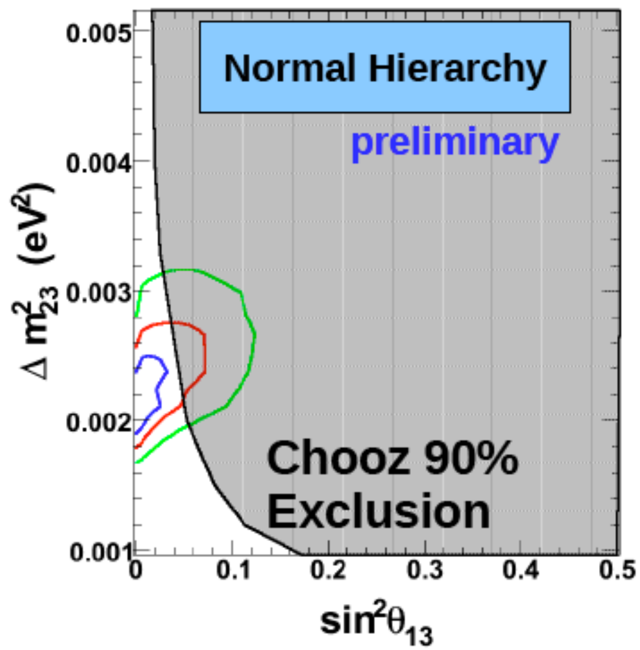
MINOS First ν_e Appearance Search

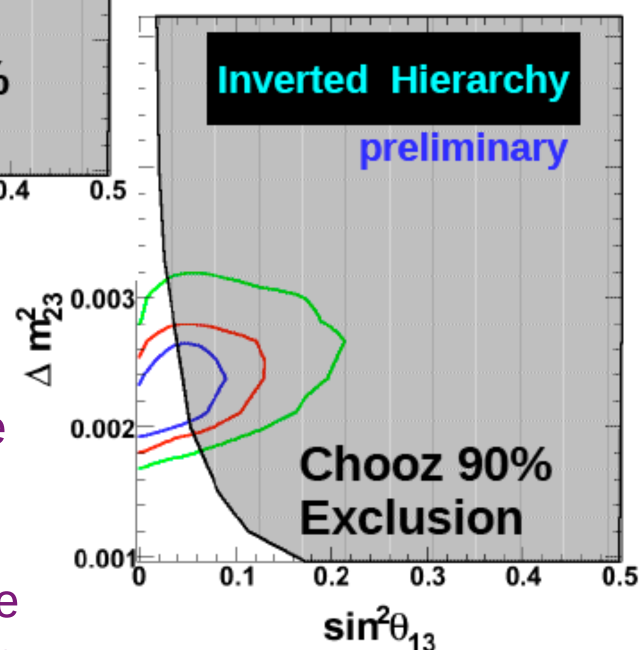


Observed: 35 events
Expected background: 27±5(stat)±2(sys)
1.5σ excess

Super-K Atmospheric Neutrinos







No evidence of (matter enhanced) upward ν_e appearance

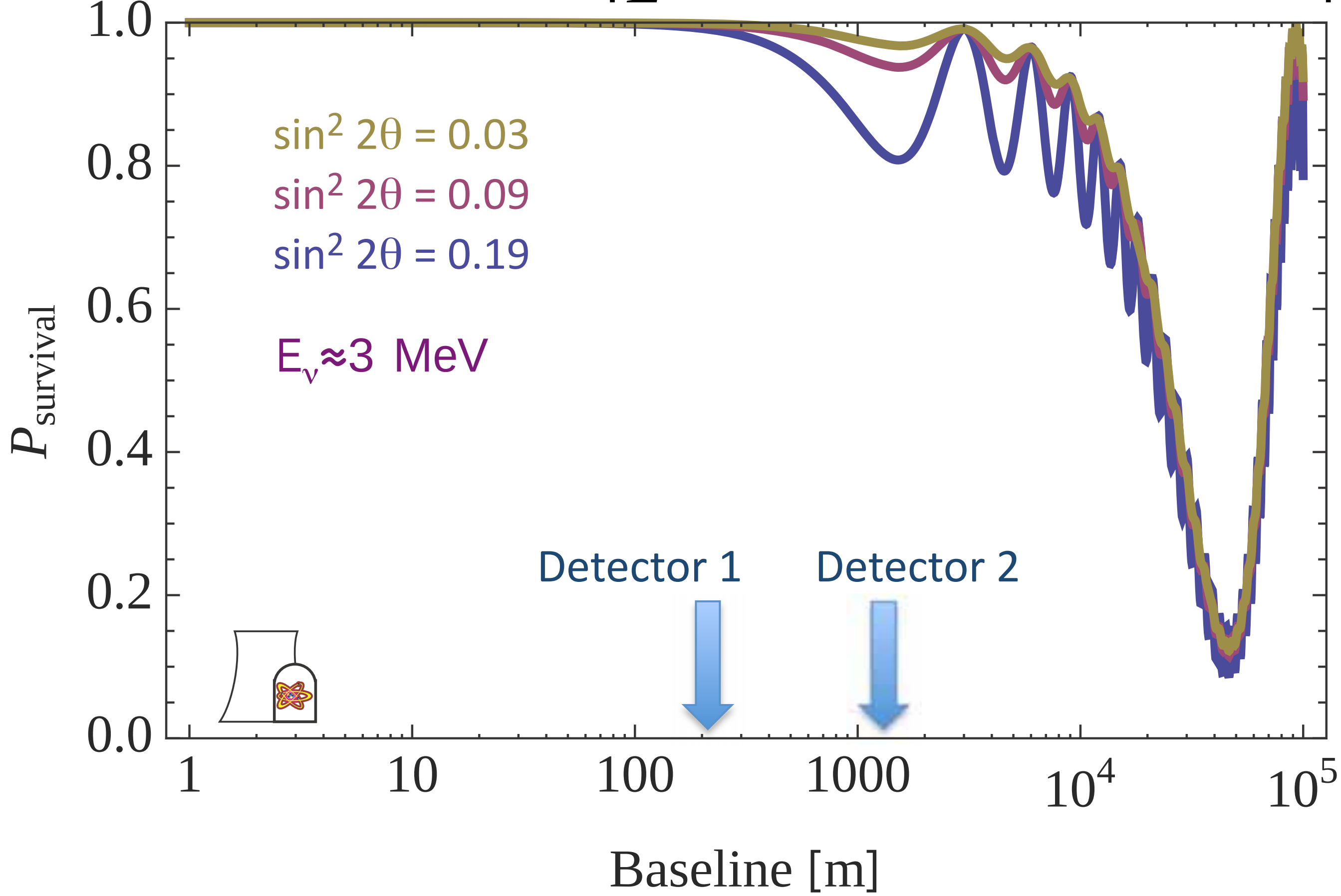
analysis assumes Δm^2_{12} = 0; next update will include solar term

What's coming up?

Precision Reactor Experiments

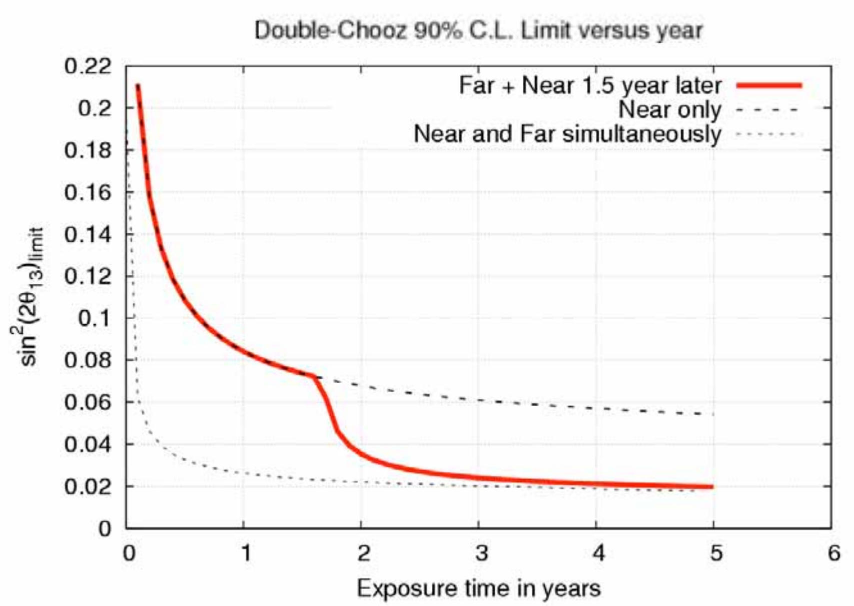
L. Mikaelyan, arXiv:hep-ex/0008046v2 (Krasnoyarsk)

$$P \cong 1 - \sin^2 2\theta_{13} \sin^2 \Delta m^2_{13} \frac{L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m^2_{12} \frac{L}{4E}$$



build nearly identical detectors with nearly identical efficiency

Double Chooz and Daya Bay



Double Chooz (France):

- 2 x 4 GW reactor cores
- 50-300 mwe overburden
- 0.3/1 km baseline
- Existing infrastructure – early start
- 2x10 ton modules – fixed
- Goal of 0.6% systematics
- Reach $\sin^2 2\theta$ ~ 0.03

- Start: early 2010 (far detector only)

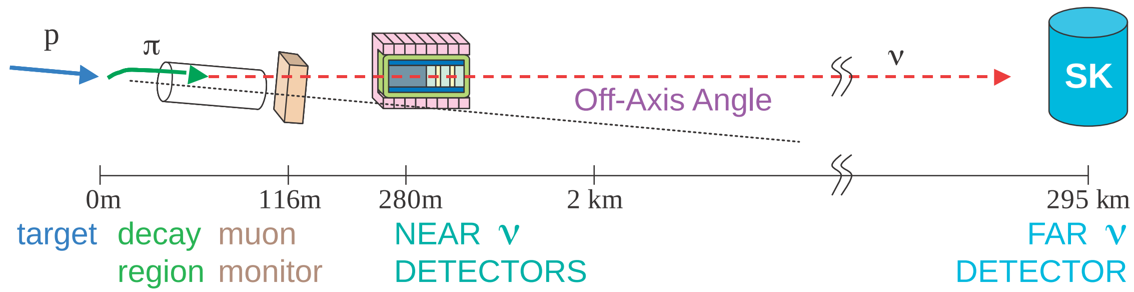
Daya Bay (Hong Kong):

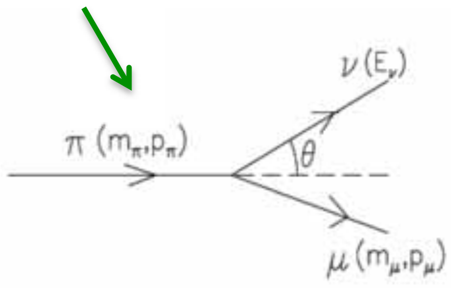
- 6 reactor cores, 17 GW total
- 200-1000 mwe overburden
- 0.3/1.8-2.2 km baseline
- Construct tunnels and labs (above)
- 8x20 ton modules – moveable
- Goal of 0.36% systematics
- Reach $\sin^2 2\theta$ ~ 0.01

- Start: 2011 (also 2 new cores then)

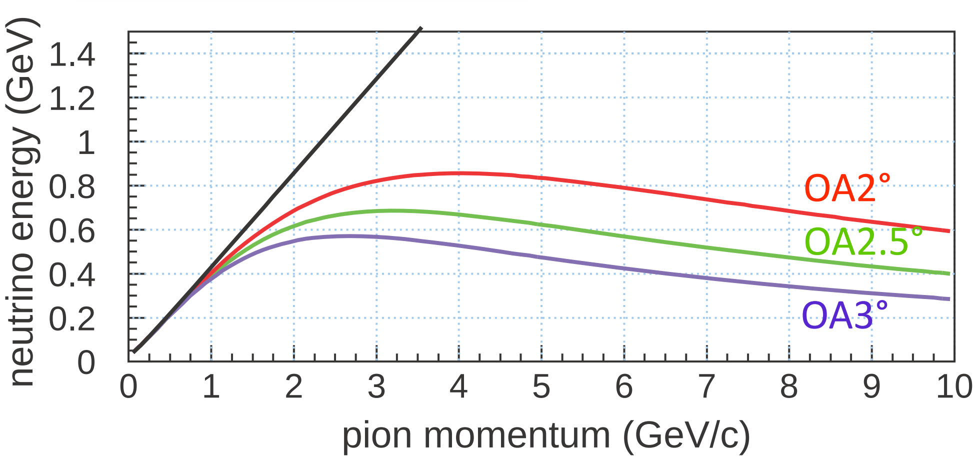
Off-Axis Super-Beams

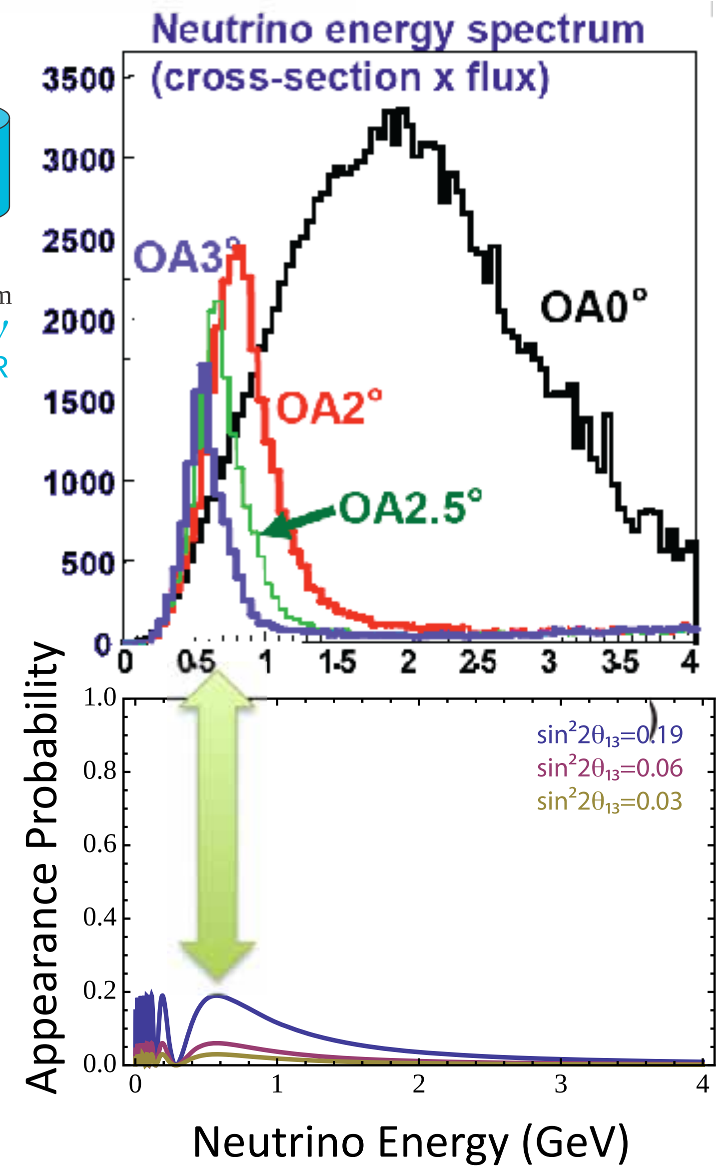
AGS Proposal E-889 BNL-52459 (1995)





$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$





Three Flavor Neutrino Oscillation in Matter

$$P(\nu_\mu \to \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \underline{\sin 2\theta_{13}} + T_3 \alpha \underline{\sin 2\theta_{13}} + T_4 \alpha^2$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

atmospheric
$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

interference
$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

solar
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \Delta m^2_{31} L/4E \qquad x = 2\sqrt{2} G_F N_e E/\Delta m^2_{31} \cong E/12 \text{ GeV}$$

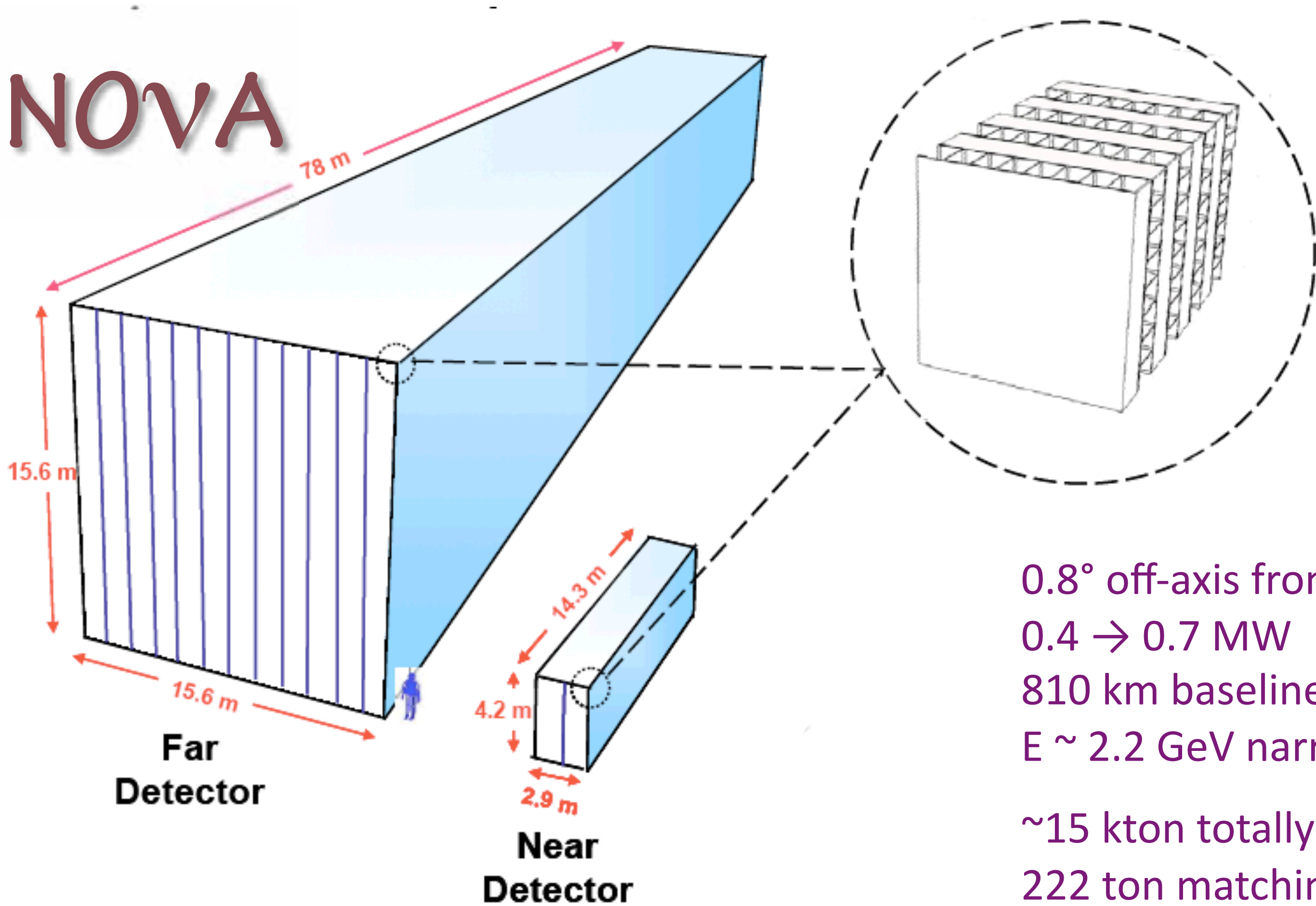
matter effects: for anti-neutrinos, sign of x and sin δ_{cp} is changed
hierarchy inversion also exchanges rol of anti-neutrinos and neutrinos

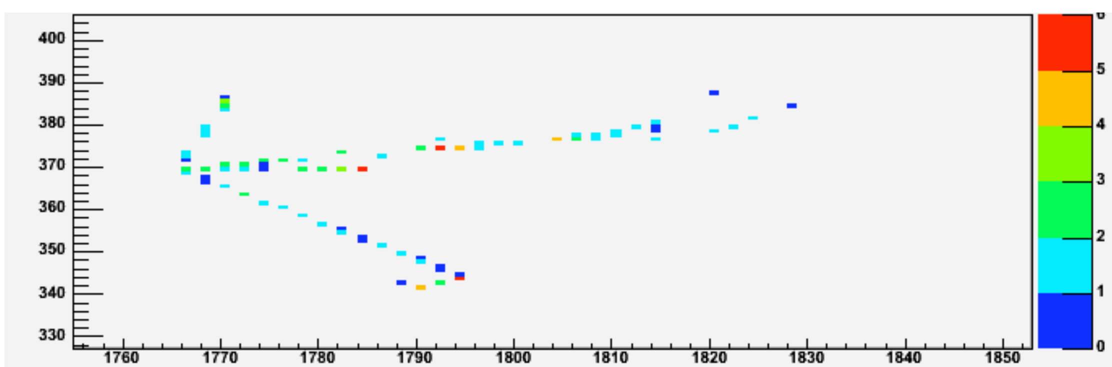
T2K

2.5 degrees off-axis from J-PARC beam
295 km baseline
E ~ 0.75 GeV narrow band

22.5 kton Super-Kamiokande far detector; hybrid magnetized near detector at 280m

NOvA





4cm×6cm cells

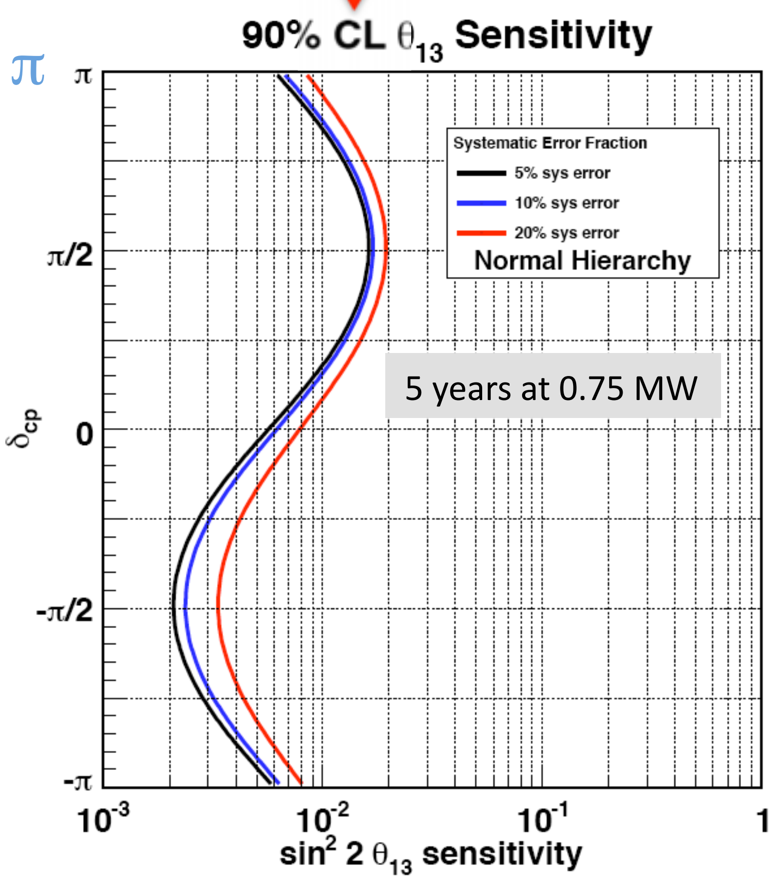
0.8° off-axis from NuMI beam
0.4 → 0.7 MW
810 km baseline
E ~ 2.2 GeV narrow band

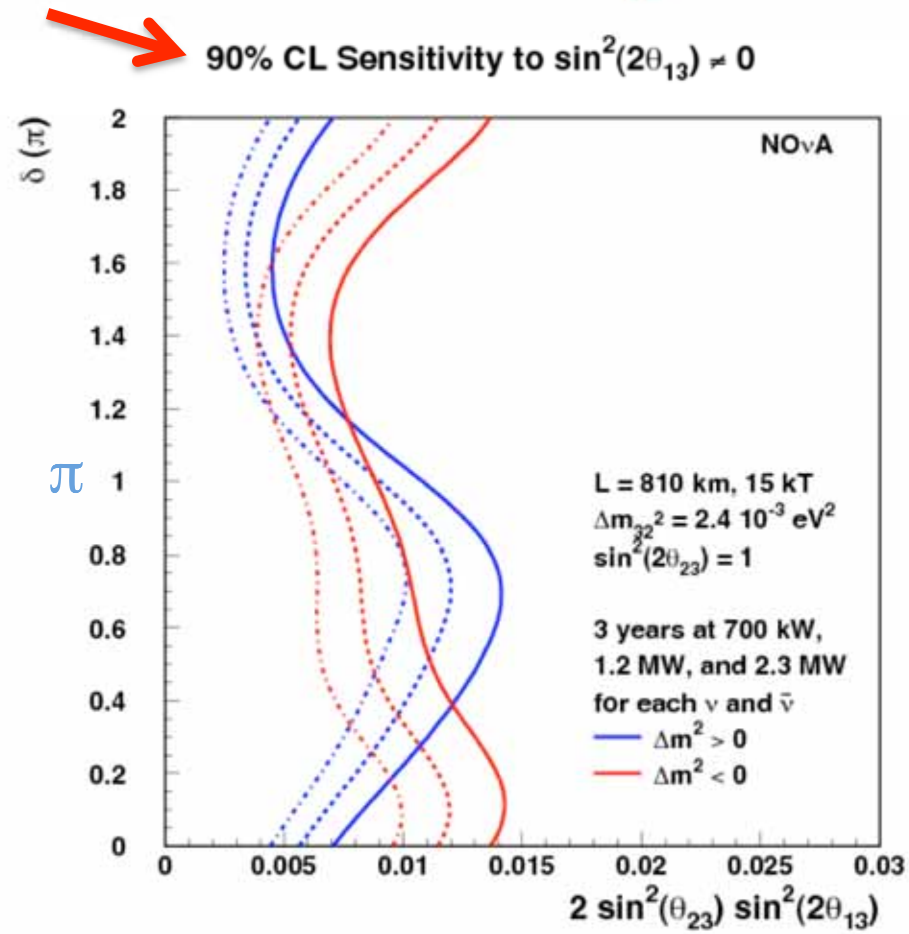
~15 kton totally active detector
222 ton matching near detector

Planes of liquid scintillator (mineral oil) read by WLS fiber and APD

Surface detector with small overburden.

T2K and NOνA Sensitivity

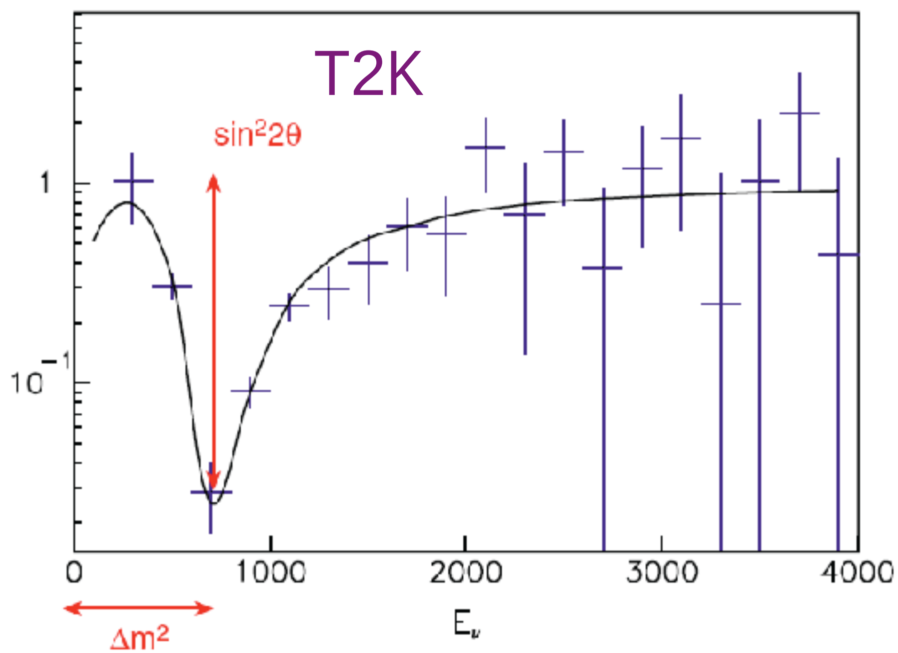


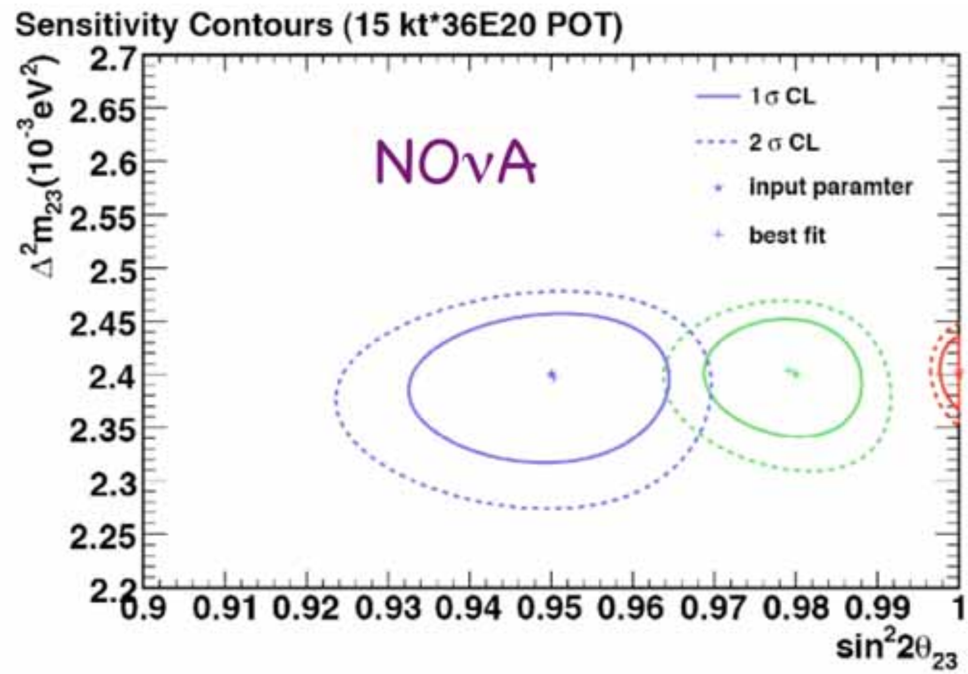


Sensitivity around 1% appearance probability.

Is θ_{23} Maximal?

Both experiments also excellent for Δm^2_{23} and $\sin^2 2\theta_{23}$.

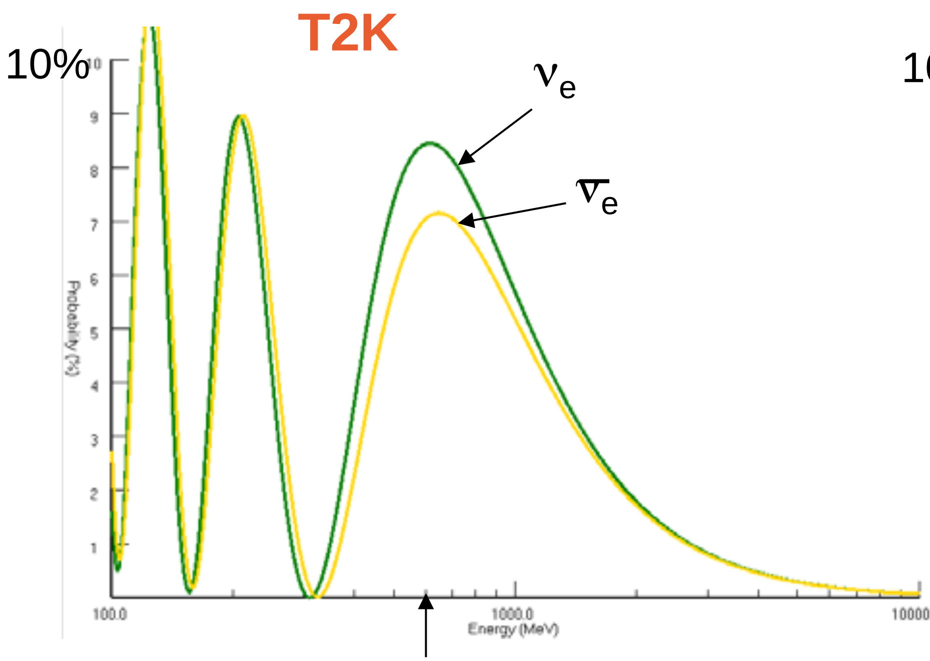




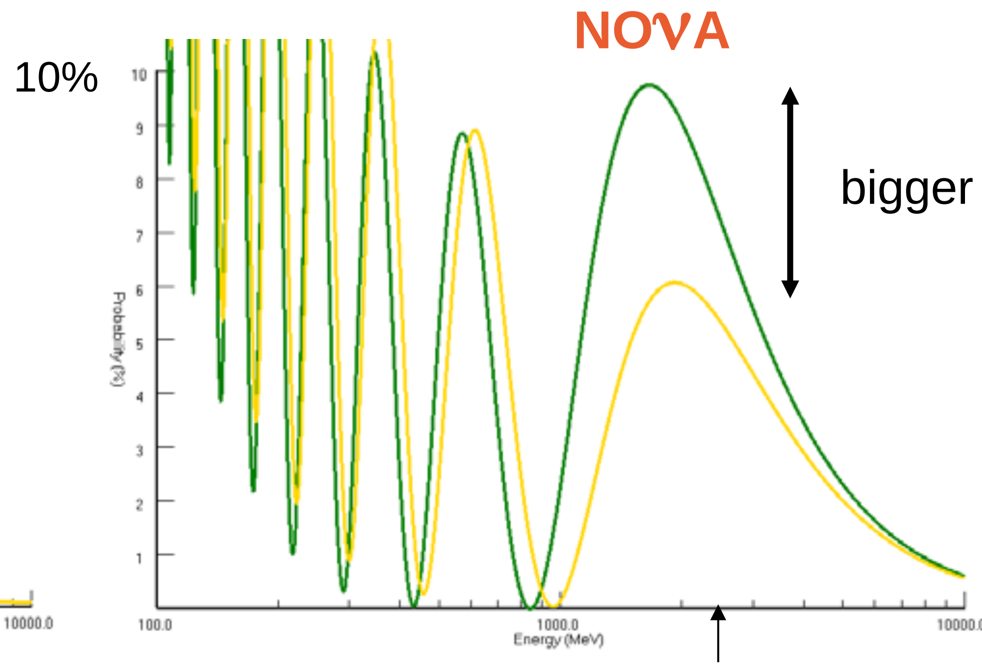
current SK 90% CL
from atmospheric ν

Resolving the Mass Hierarchy

Matter effect enhances ν_e appearance for normal hierarchy
Effect is reversed (enhanced anti-ν_e) for inverted hierarchy



600 MeV
290 km



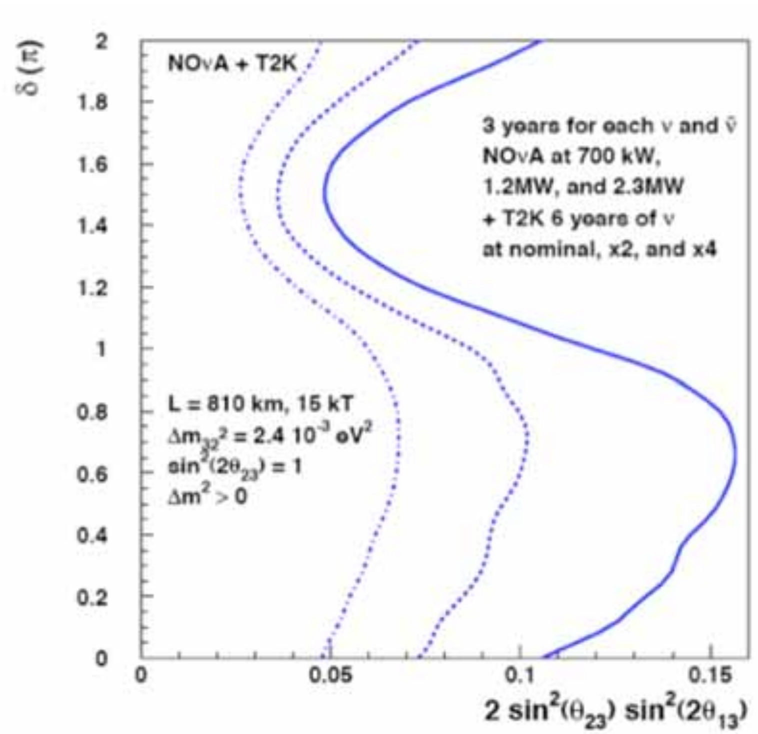
2.3 GeV
820 km

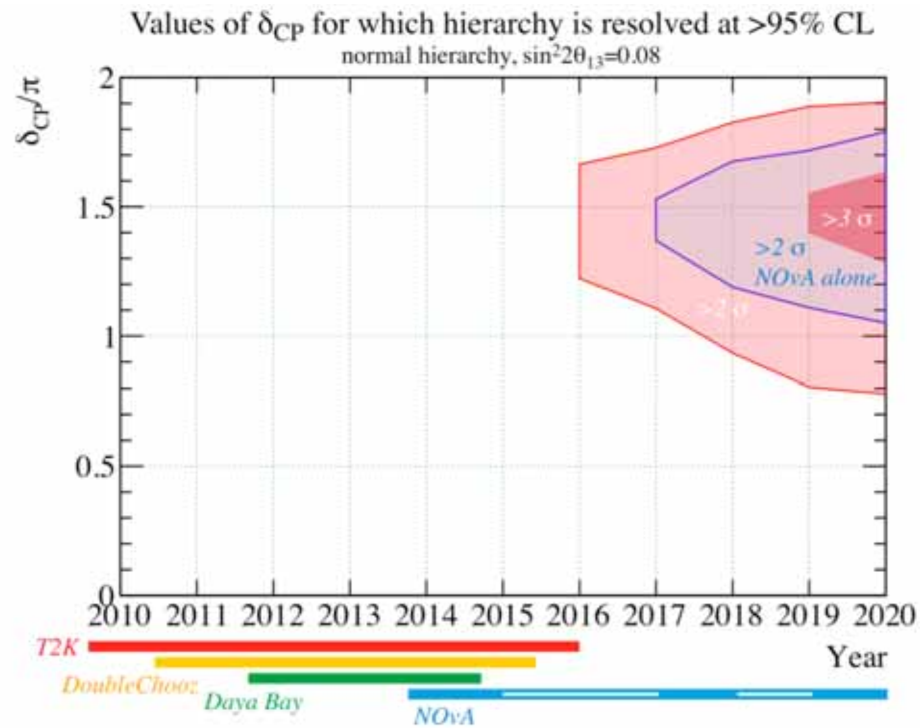
$\delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\sin^2 2\theta_{23}=1.0$

$\delta m^2_{12}=7.1\times10^{-5}$ eV^2 $\sin^2 2\theta_{12}=0.81$

$\sin^2 2\theta_{13}=0.16$

NOνA and Mass Hierarchy





Chooz limit

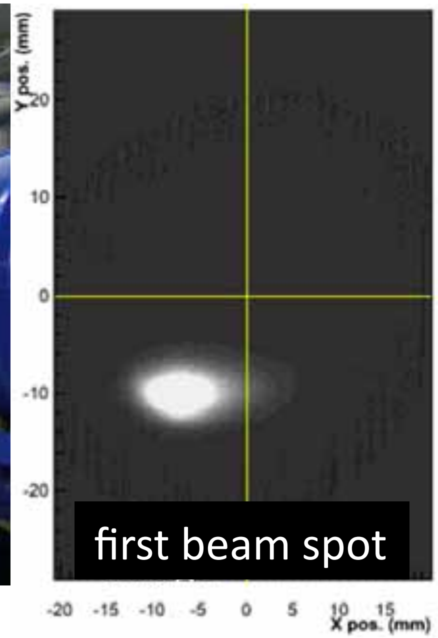
combining
T2K, Double Chooz, Daya Bay,
and NOνA

NOvA and T2K: construction progress

far site preparation at Ash river

detector plane production

neutrino beamline at JPARC



first beam spot

ND280 construction

The quest for θ_{13} – circa 2012

- Double Chooz adds second detector
- Daya Bay reactor experiment has early results
- T2K long baseline experiment is midway
- NOνA (U.S.) experiment will start data taking

If $\theta_{13} > 2.9^\circ$ ($P_{appear} \geq 1\%$),
we can contemplate going after δ.
CP VIOLATION

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


Thinking big...
next generation experiments

Three Flavor Neutrino Oscillation in Matter

$$P(\nu_\mu \rightarrow \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2\alpha \underline{\sin 2\theta_{13}} + T_3\alpha \sin 2\theta_{13} + T_4\alpha^2$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

CP violating $$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

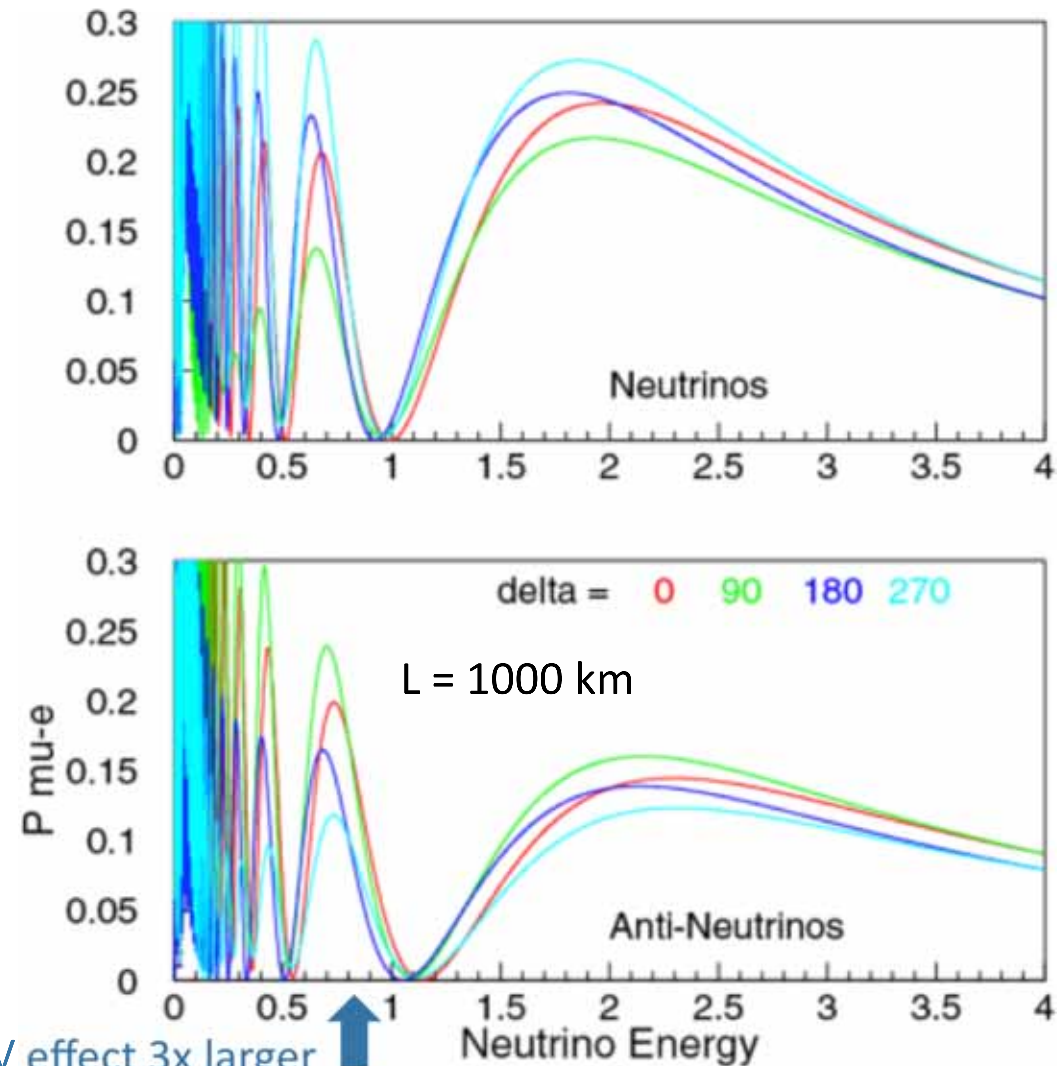
CP conserving $$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \Delta m^2_{31} L/4E \qquad x = 2\sqrt{2} G_F N_e E/\Delta m^2_{31} \cong E/12 \text{ GeV}$$

for anti-neutrinos, sign of x and $\sin\delta_{cp}$ is changed

CP Violating Neutrino Oscillation



CPV effect 3x larger at 2nd maximum than 1st

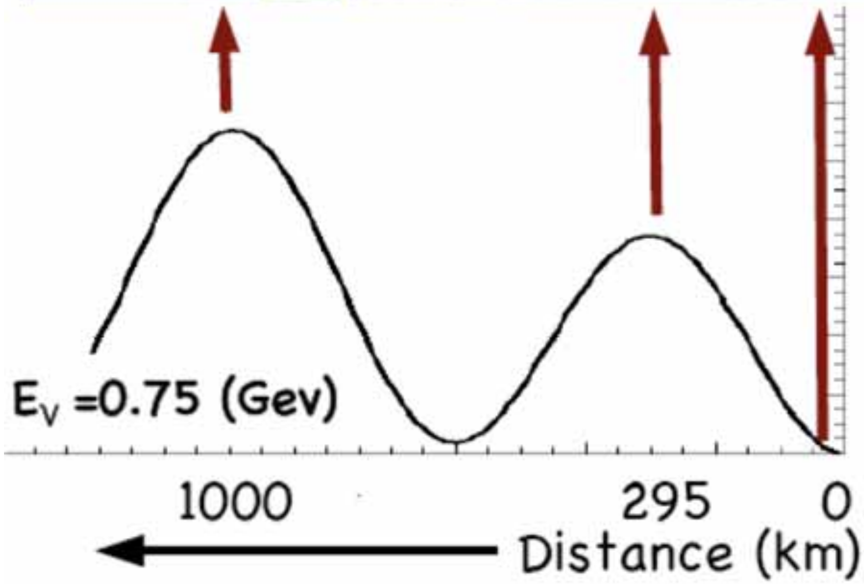
Neutrinos and anti neutrinos reverse places with neutrino mass hierarchy.

Difference is greater for longer baselines (matter effects)

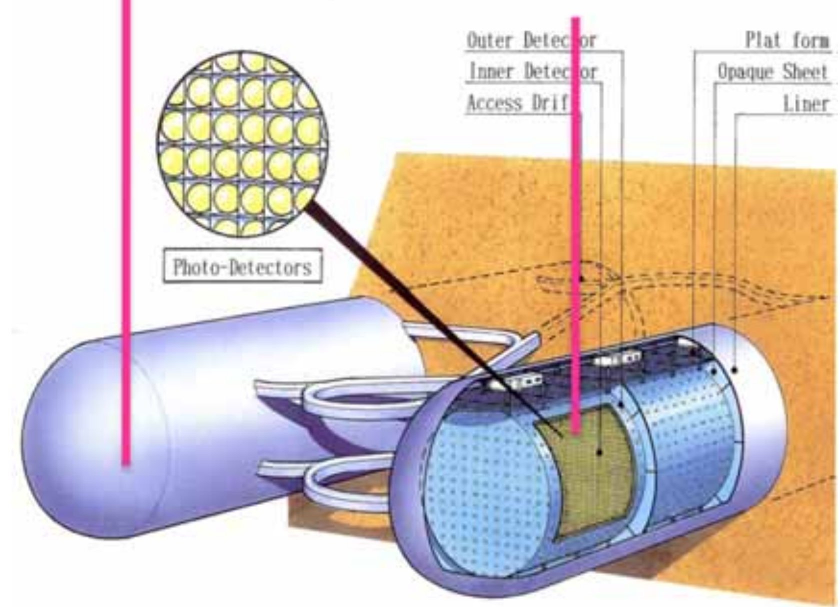
To measure these two probabilities, need large statistical sample

Upgrades in Japan

Also increase J-PARC beam power: benchmark = 1.66 MW



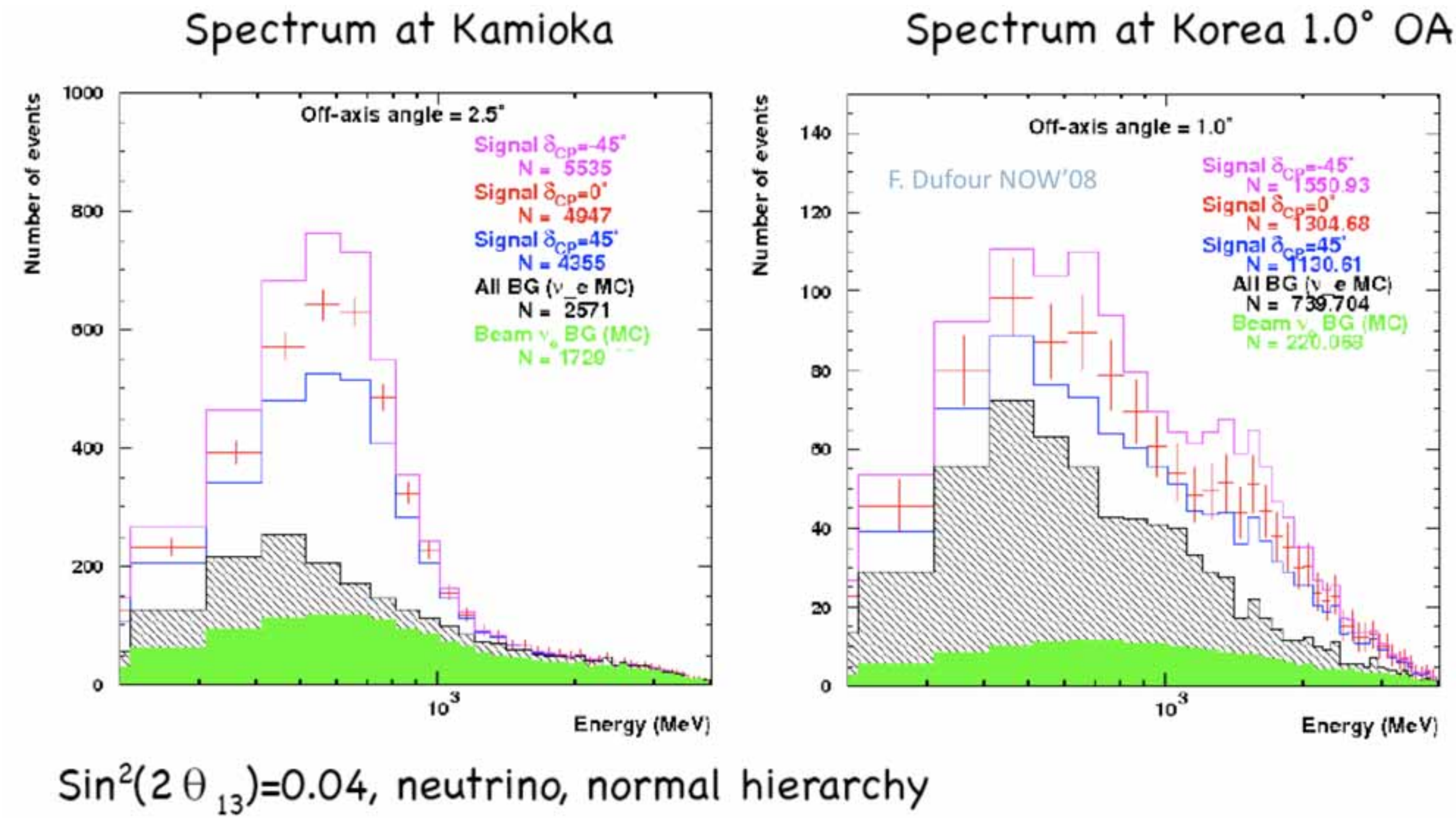
Hyper-Kamiokande



- Measure both first and second maximum
- 270 kton + 270 kton fiducial mass
- Eliminates many degeneracies
- Controls systematic uncertainty.

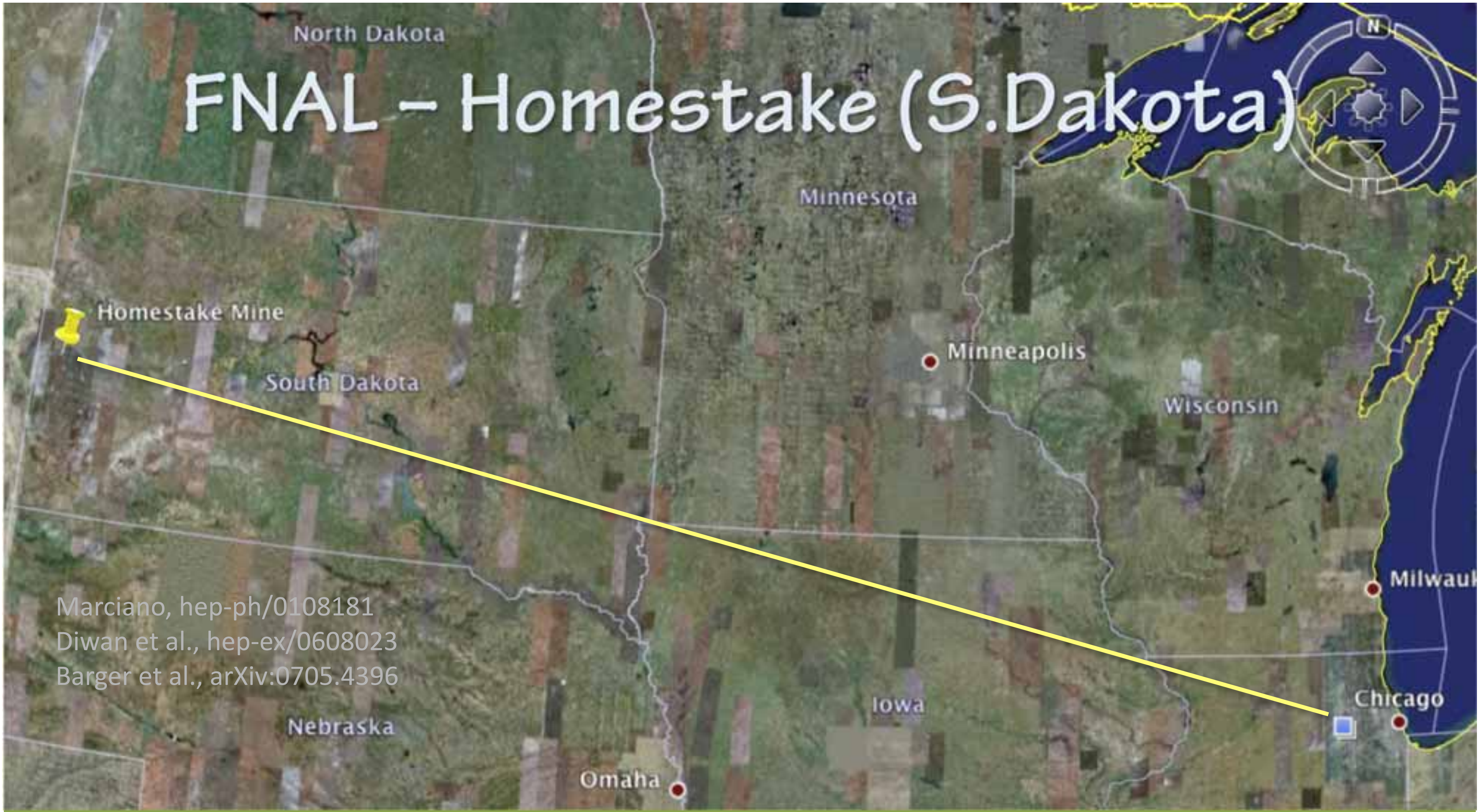
M. Ishitsuka et al., Phys.Rev.D72:033003,2005

Example Simulated Data from T2KK



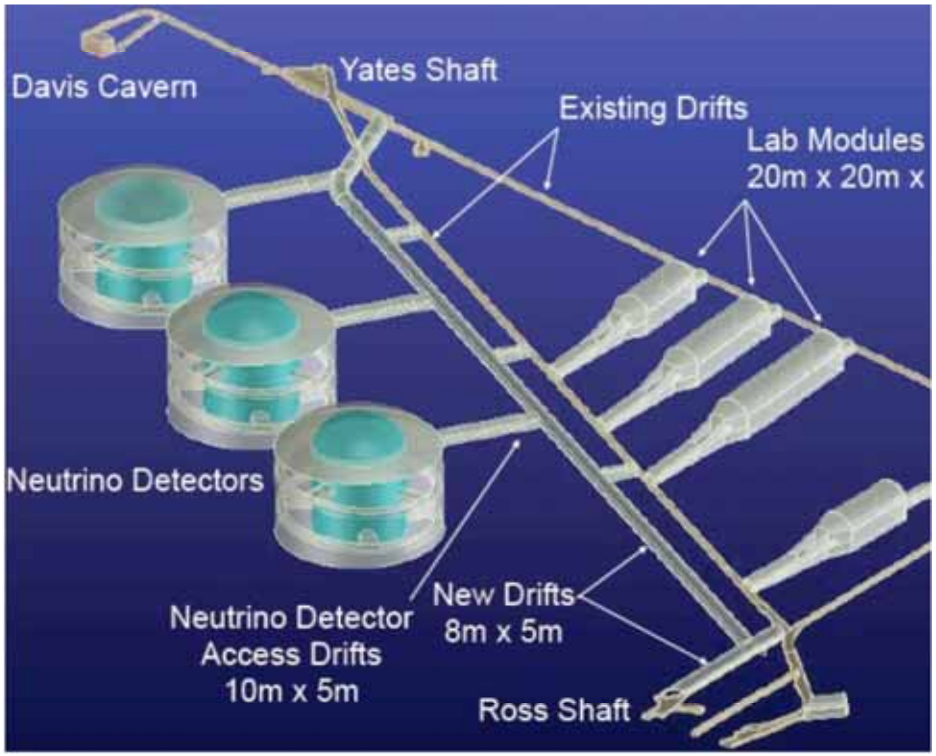
Narrow band, off axis

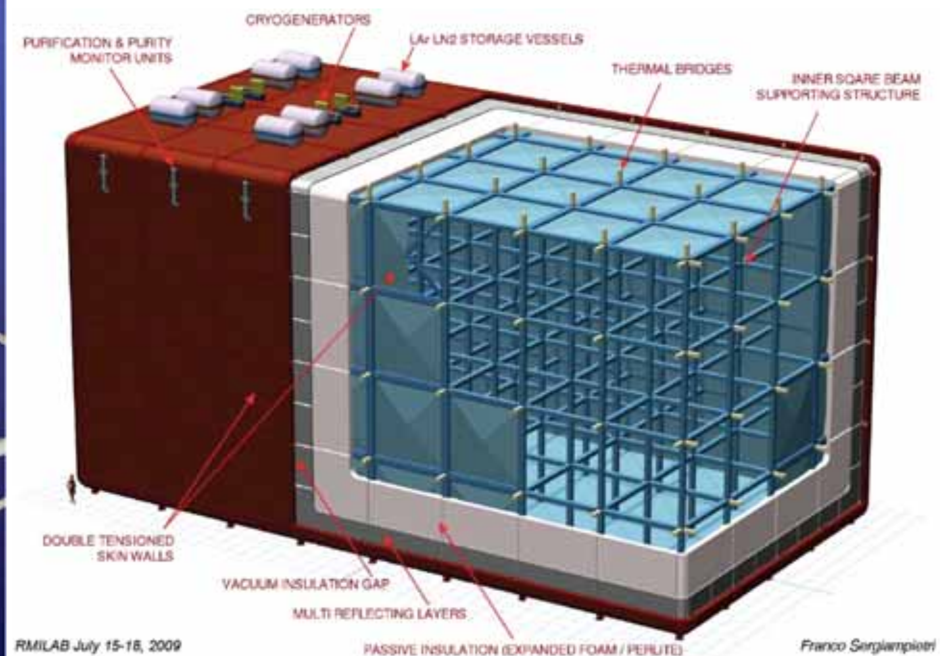
semi Wide-band, more on axis



- In post-Tevatron era, Fermilab's long range plan is converging on the high intensity frontier.
- The flagship project would be a new 1-2 MW beam towards DUSEL .
- Unique feature is longest baseline being considered (1300 km).
- 60 – 120 GeV protons fed by Project X.
- 300-500 kton Water Cherenkov and/or 20 kton (or larger?) LAr TPC.

Water Cherenkov vs Liquid Argon





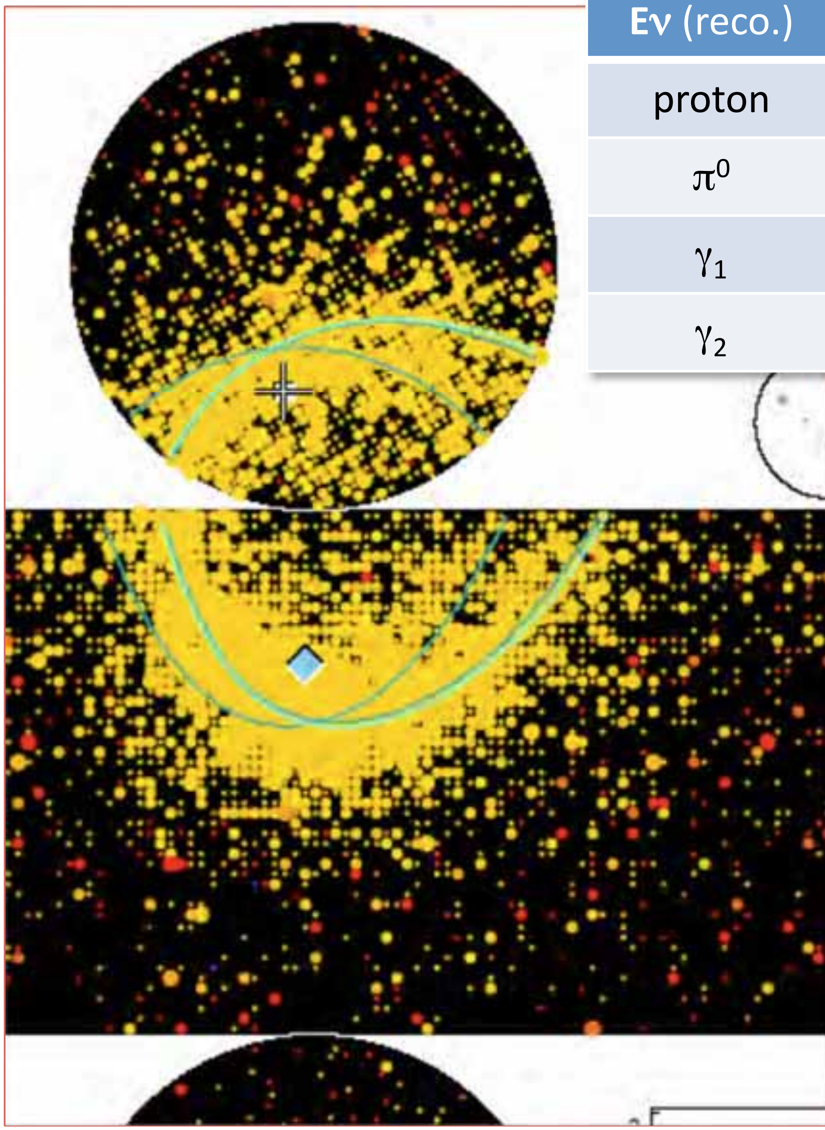
planning is getting underway

a lot of R&D is needed

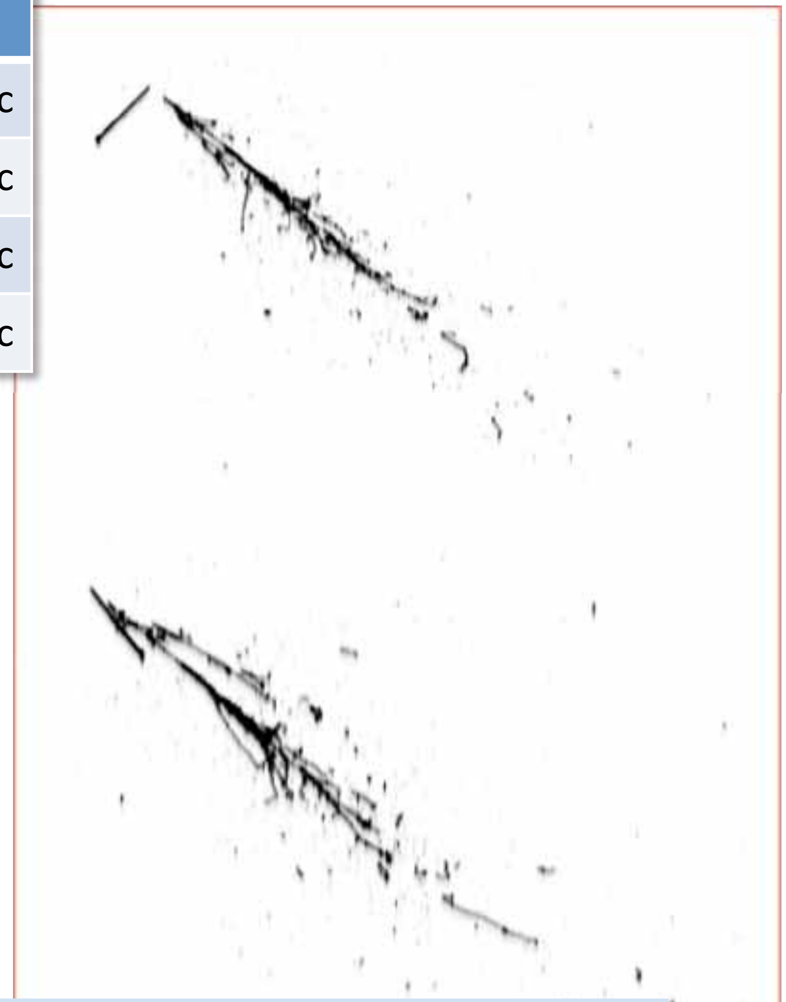
there are good reasons to build both

there is also invaluable non-accelerator physics: supernova and proton decay

Example: WC vs LAr (Background Event)



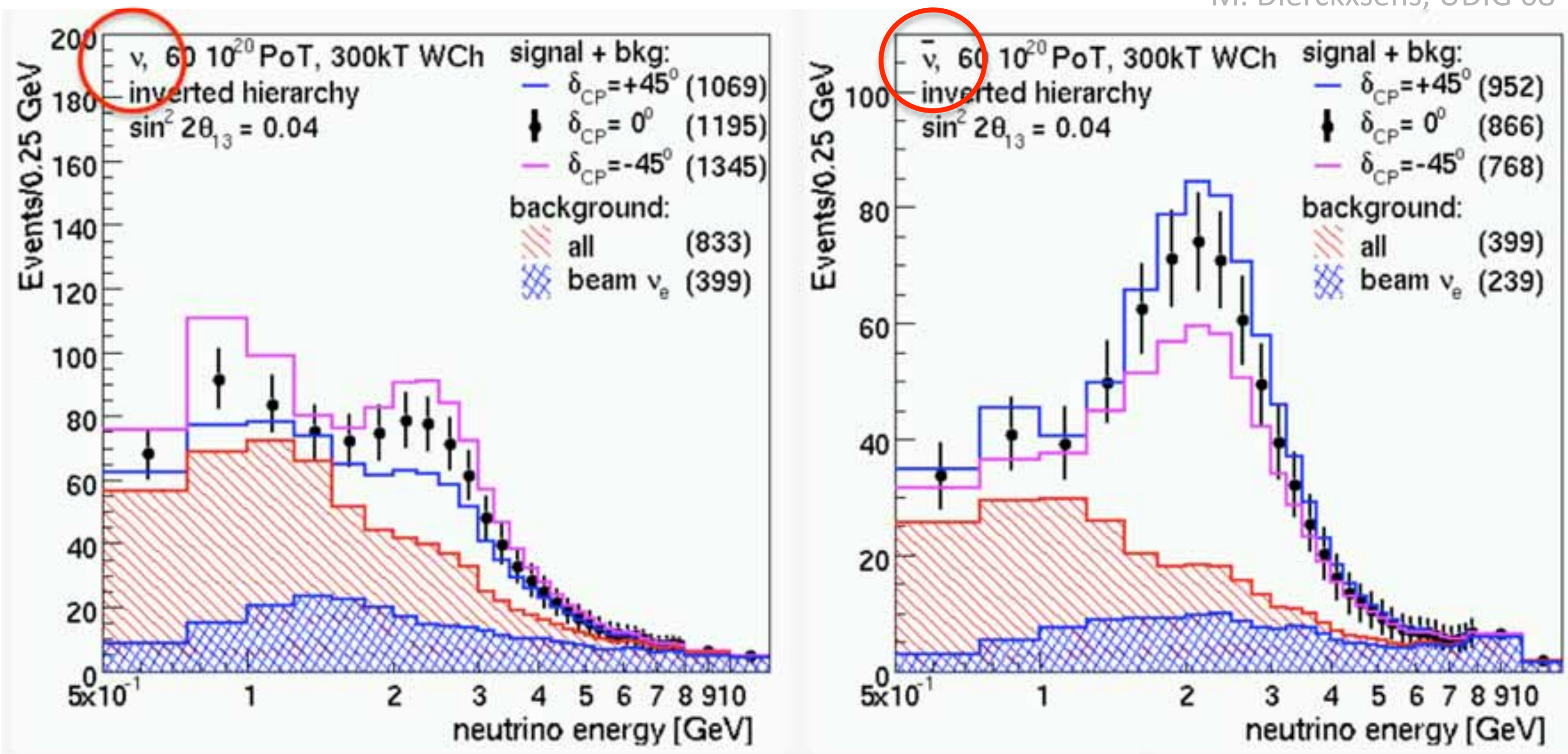
Eν (reco.)	1.7 GeV
proton	691 MeV/c
π^0	1442 MeV/c
γ_1	1204 MeV/c
γ_2	245 MeV/c



Sensitivity studies suggest a factor of 3-6× in equivalent mass for LAr over WC.

FNAL-DUSEL Water Cherenkov

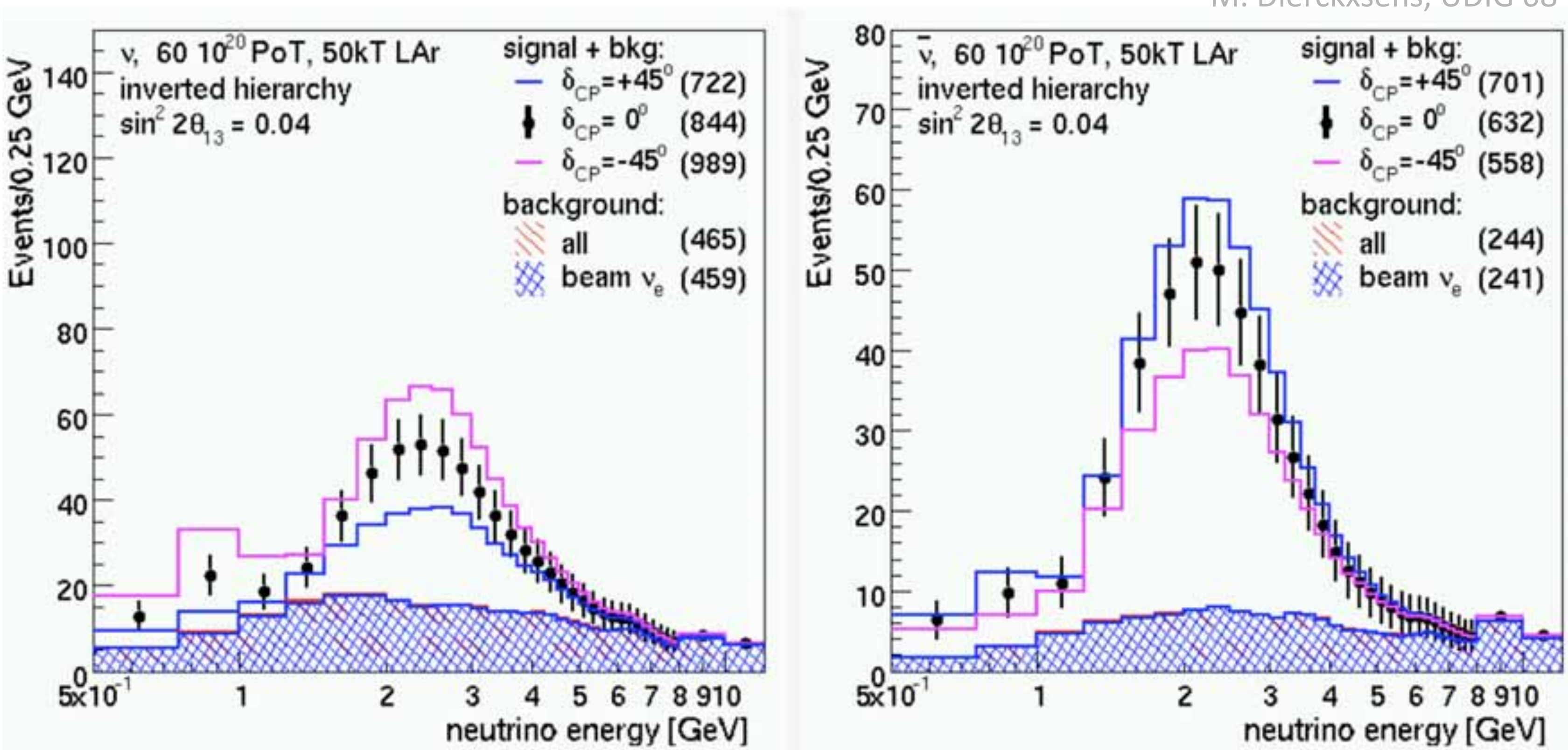
M. Dierckxsens, UDIG 08



- Neutrino and antineutrino running

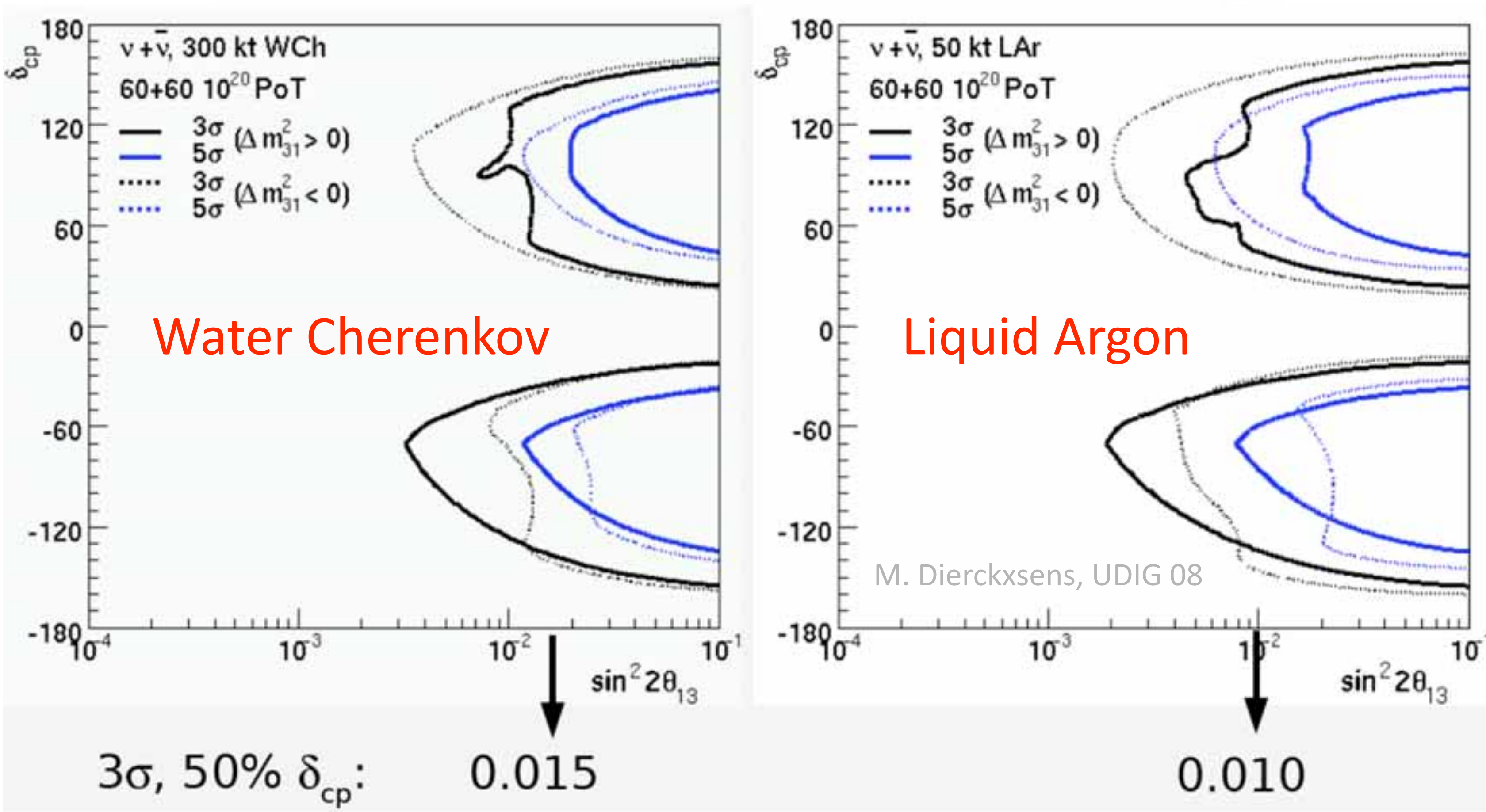
FNAL-DUSEL Liquid Argon

M. Dierckxsens, UDIG 08



It is assumed that NC BG is completely removed for LAr.
Remains to be demonstrated!

FNAL-DUSEL Sensitivity



Sensitivity to CPV: > 50% δ-coverage (3σ) for $\sin^2 2\theta_{13} > 0.015$

- 3+3 years running
- BG uncertainty = 5%; assume perfect BG rejection for LAr (80% signal efficiency)

In summary:

A standard picture of 3-flavor neutrino oscillation exists.

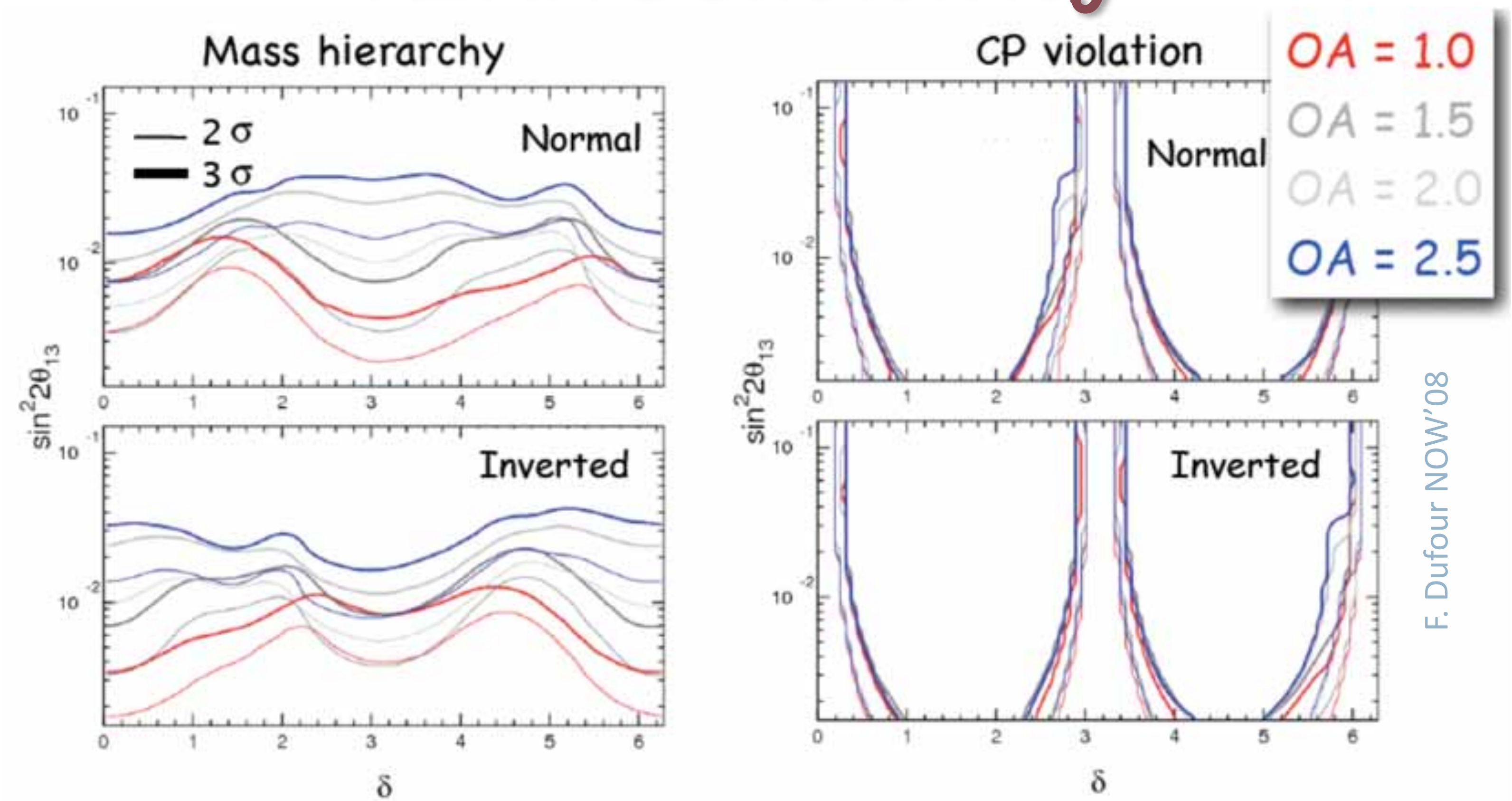
Numerous experiments are poking and prodding at it now.
More beyond are being built and proposed.

We should look for every feature we expect ...
... and keep our eyes out for the unexpected.

The critical parameter is θ_{13}, which will be explored to an oscillation appearance level of 1% over the next 5 years.

If θ_{13} is large enough, the gateway is opened for CP violation.

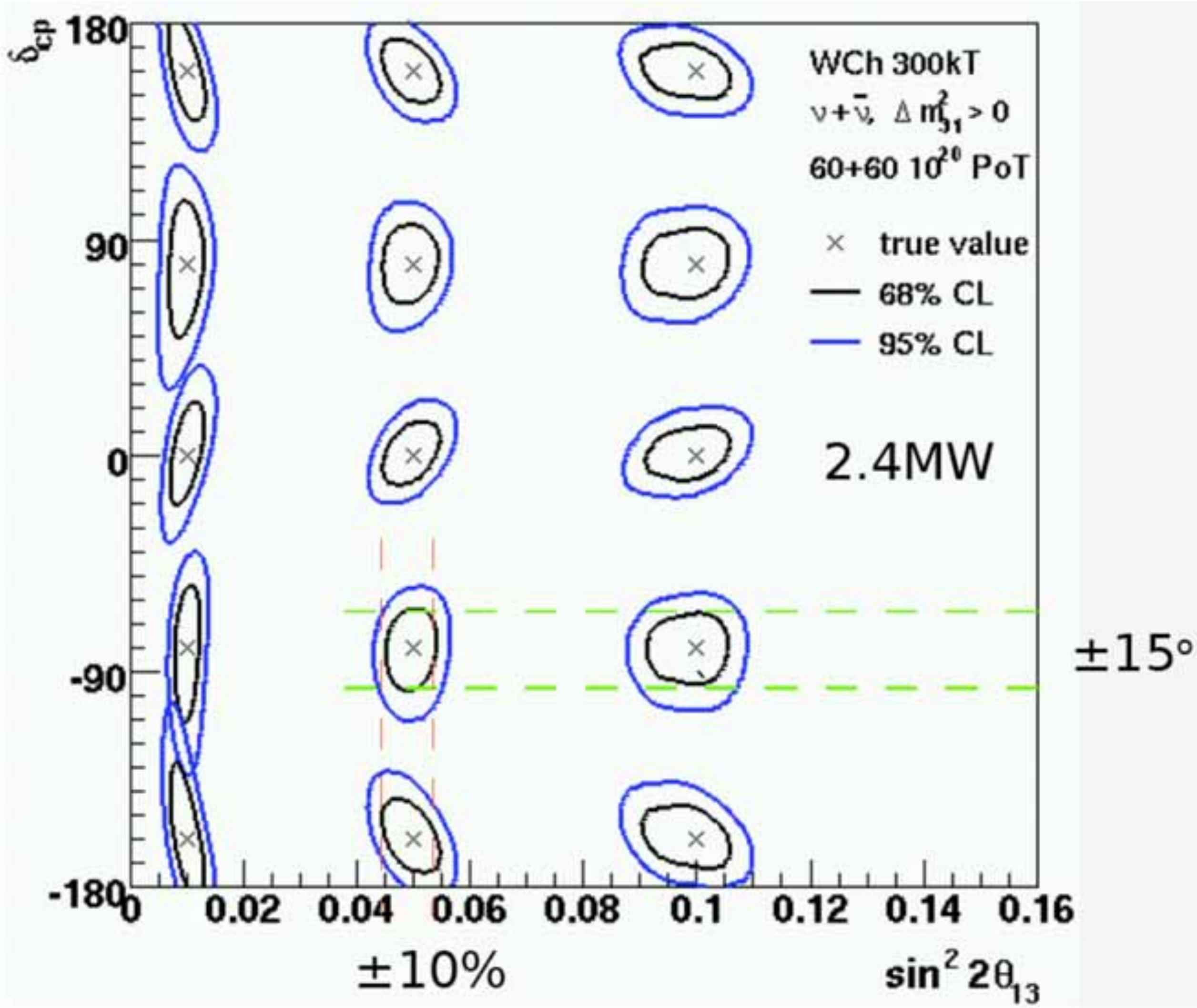
T2KK Sensitivity



Sensitivity to CPV: > 70% δ-coverage (3σ) for $\sin^2 2\theta_{13} > 0.01$

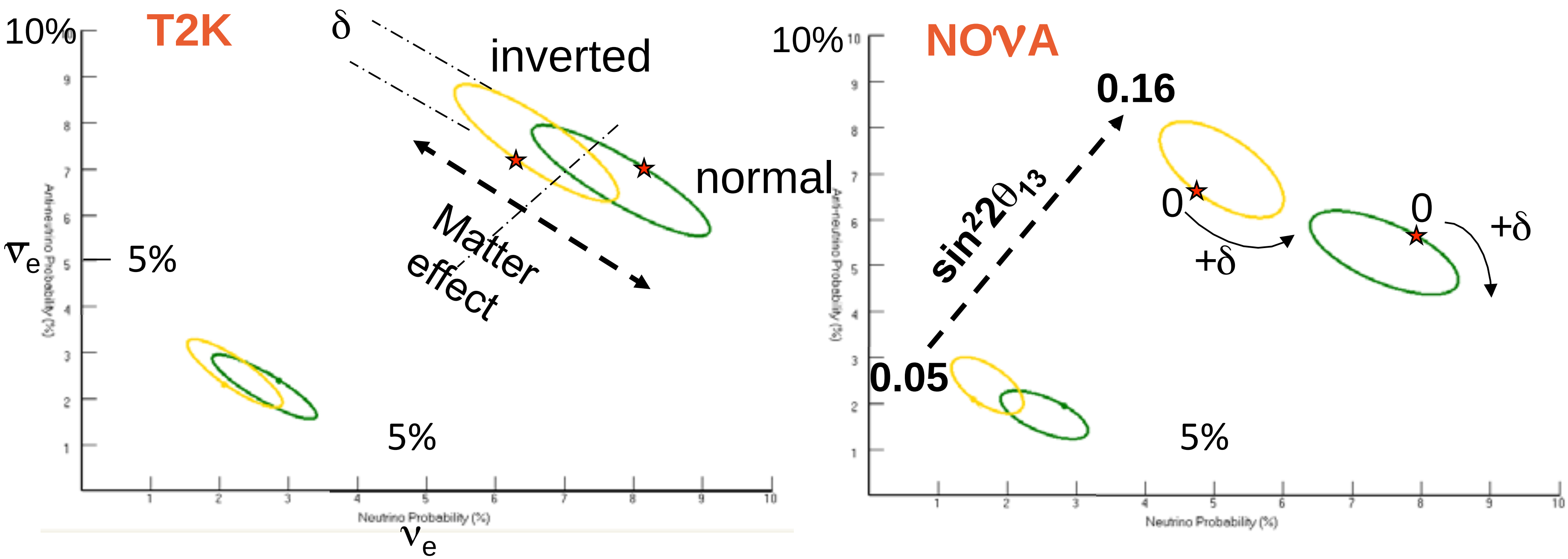
- 10 years running
- 15 systematic uncertainty terms, most = 5%; 20% in normalization > 1.2 GeV
- CPV reach insensitive to angle, but 1˚OA quasi-WBB benefits hierarchy study

FNAL-DUSEL Precision



M. Dierckxsens, UDIG 08

Degeneracies and CPV



$$P_{matt\pm}[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)] = \pm \cos 2\theta_{13} \sin^2 2\theta_{13} s_{23}^2 \left(\frac{2Ea(x)}{\Delta m_{13}^2}\right) \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)$$
$$\mp \frac{a(x)L}{4} \sin^2 2\theta_{13} \cos 2\theta_{13} s_{23}^2 \sin\left(\frac{\Delta m_{13}^2 L}{2E}\right),$$

$$a(x) = \sqrt{2} G_F N_e(x)$$