Recent Results On θ_{13} From Reactor- and Accelerator-based Neutrino Oscillation Experiments

BENE 2012

M. Toups, MIT

Outline

- Neutrino Mixing and θ_{13} (Up to 2010)
- Hints on the value of θ_{13} (2011)
- Measurements of θ_{13} (2012)

The Standard 3ν Oscillation Picture circa 2010

$$\left|\nu_\alpha\right\rangle = U_{\alpha i}\left|\nu_i\right\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2 2\theta_{23} > 0.92$ (90% C.L.)

$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2$

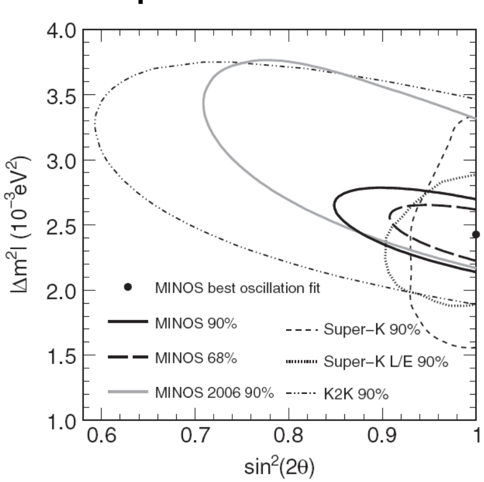
$\sin^2 2\theta_{13} < 0.15$ (90% C.L.)

CHOOZ

$\sin^2 2\theta_{12} = 0.861\ ^{+0.026}_{-0.022}$

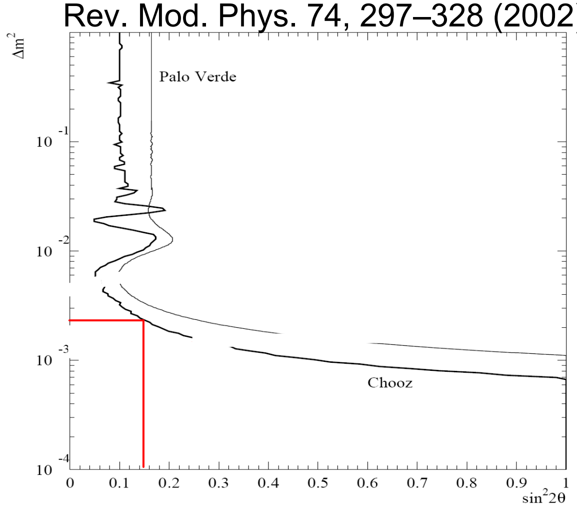
$\Delta m^2_{21} = (7.50 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2$

Super-K + MINOS



PRL 101, 131802 (2008)

Rev. Mod. Phys. 74, 297–328 (2002)



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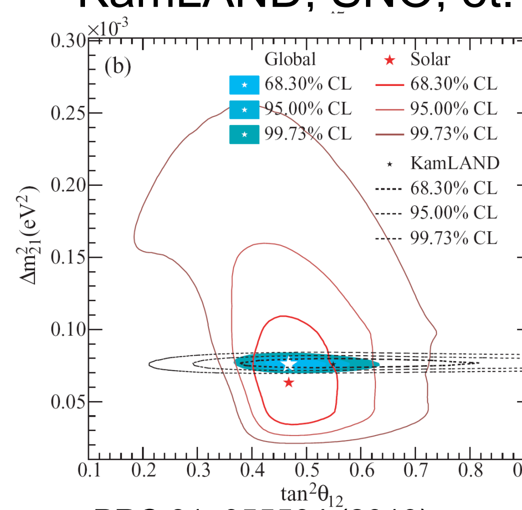
KamLAND, SNO, et. al.



PRC 81, 055504 (2010)

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Dirac CP-violating phase?

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Mass hierarchy? Maximal Mixing? Magnitude of θ_{13}?

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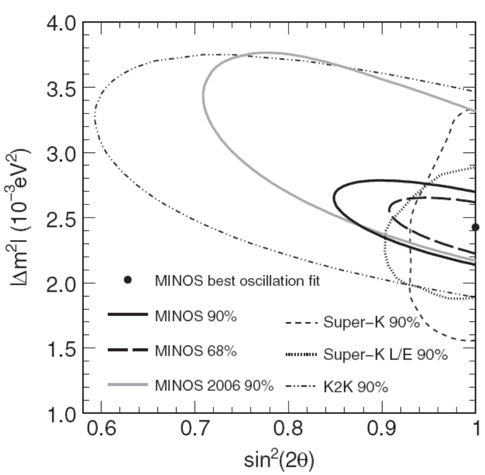

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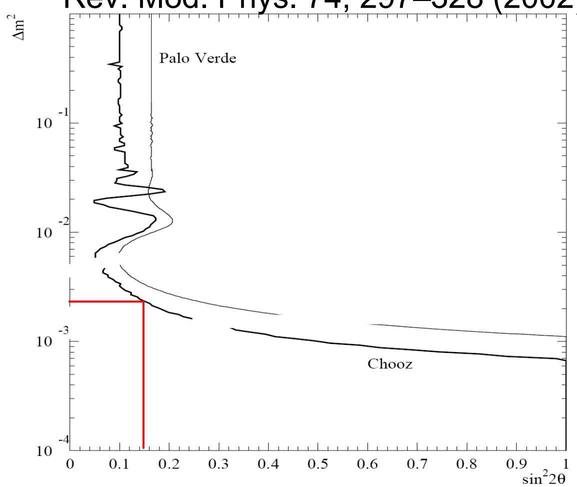

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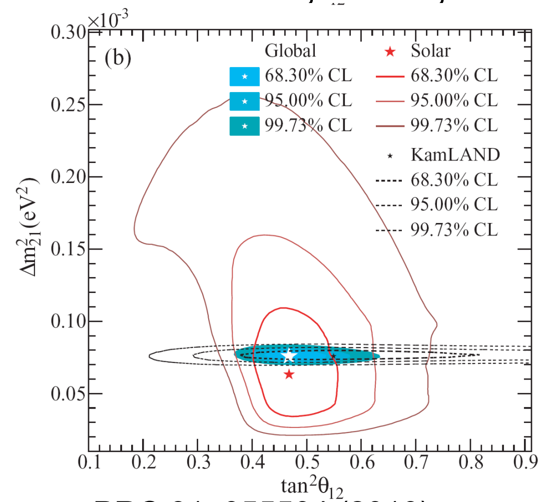

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Mass hierarchy?

Maximal Mixing?

Magnitude of θ_{13}?

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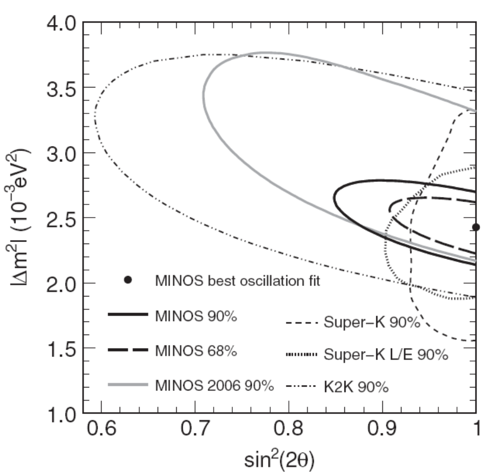

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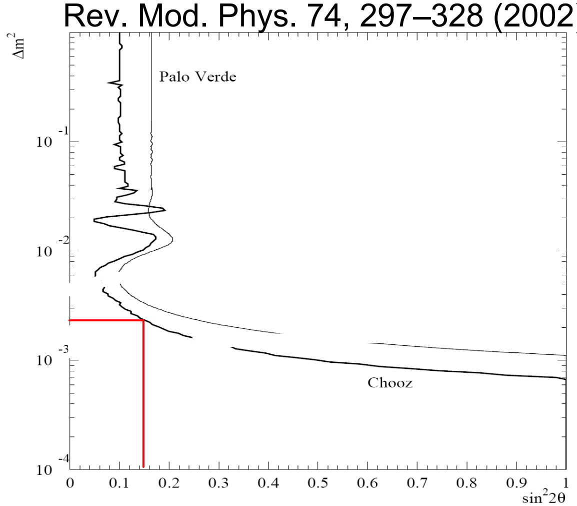

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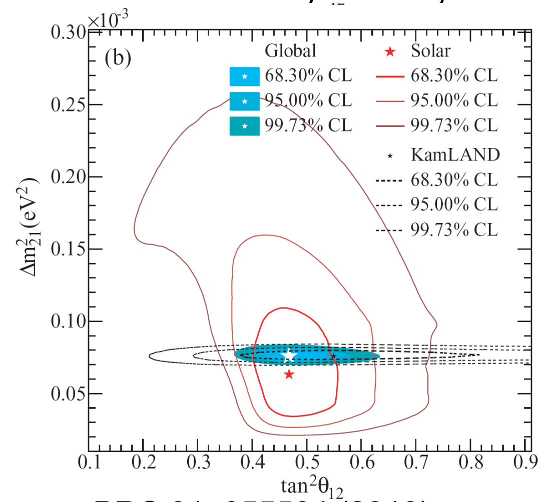


PRC 81, 055504 (2010)

ν Oscillation Probabilities

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2)
\end{aligned}
$$

$\Rightarrow$ These extra dependencies are both a "curse" and a "blessing"

Reactor Disappearance Experiments

- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \ small\ terms$$

Experimental Methods to Measure the "Little Mixing Angle", θ_{13}

- Long-Baseline Accelerators: Appearance ($\nu_\mu \to \nu_e$) at $\Delta m^2 \approx 2.4\times10^{-3}$ eV^2
  - Look for appearance of ν_e in a quite pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

MINOS:
$E_\nu \sim 3$ GeV
L = 735 km

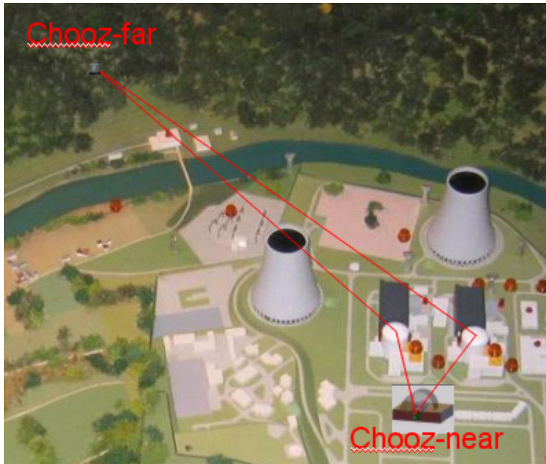
T2K:
$E_\nu \sim 0.6$ GeV
L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \not\to \bar{\nu}_e$) at $\Delta m^2 \approx 2.4\times10^{-3}$ eV^2
  - Look for a change in $\bar{\nu}_e$ flux as a function of L and E
    - Use near detector to measure the unoscillated flux
    - Look for a non- $1/r^2$ behavior of the $\bar{\nu}_e$ rate

Daya Bay:
<L> = 1642 m

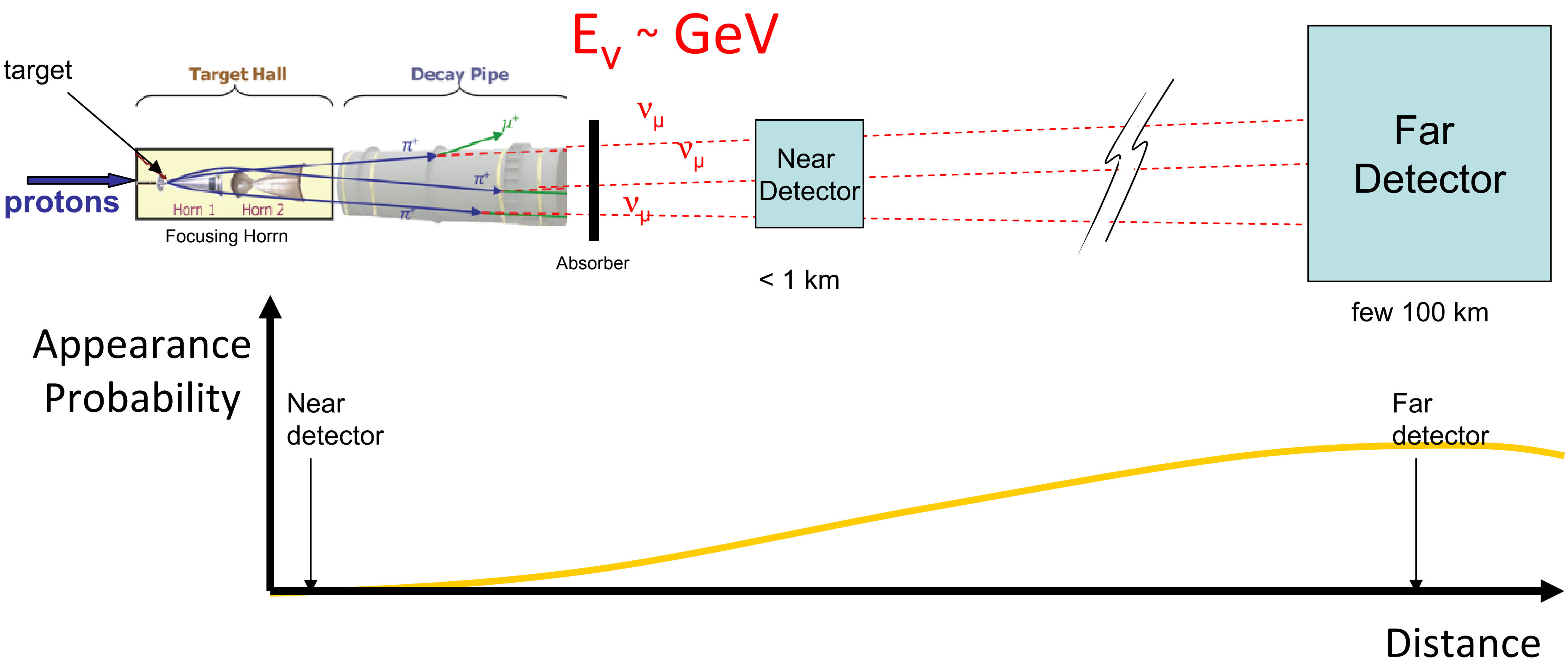
RENO:
<L> = 1444 m

Double Chooz:
<L> = 1050 m



Accelerator-based ν Oscillation Experiment

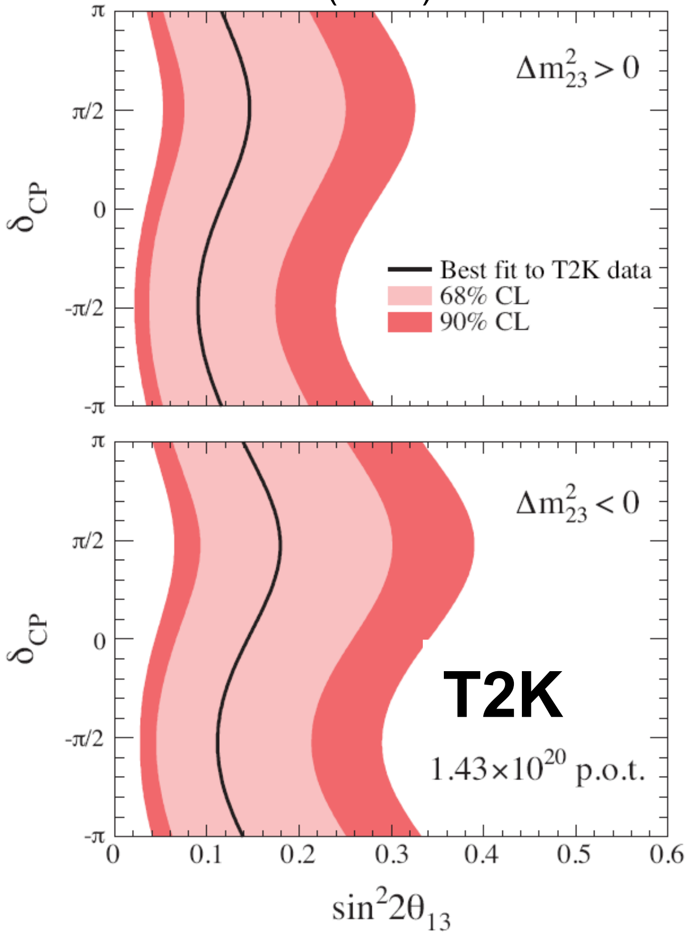
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right)$$



Extrapolate signal/background flux measured in near detector to far detector

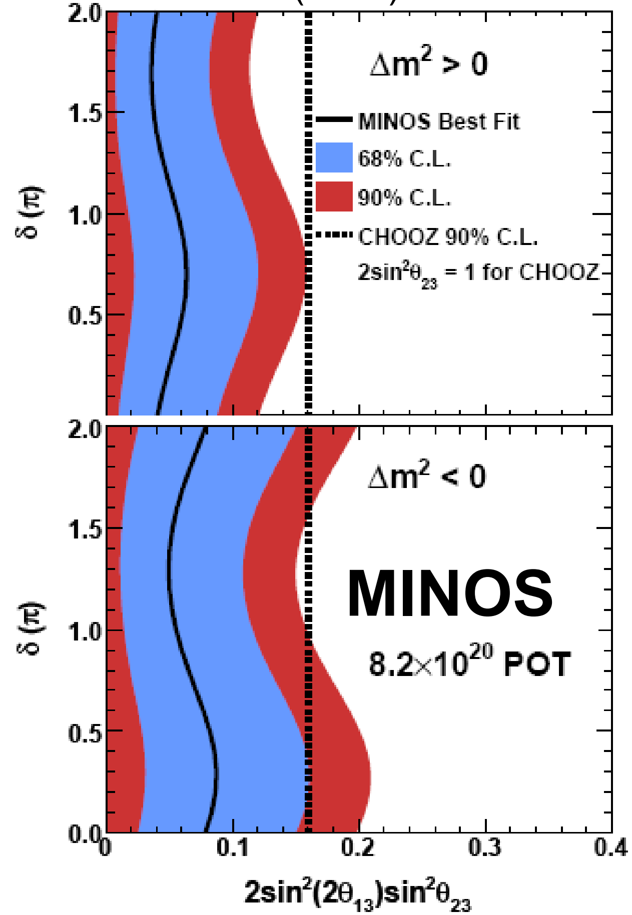
Indications of Nonzero θ_{13} From Accelerator Experiments in 2011:

PRL 107 (2011) 041801



Expected (no oscillations): 1.5 ± 0.3 events
Observed: 6 events (2.5σ significance)

PRL 108 (2012) 191801

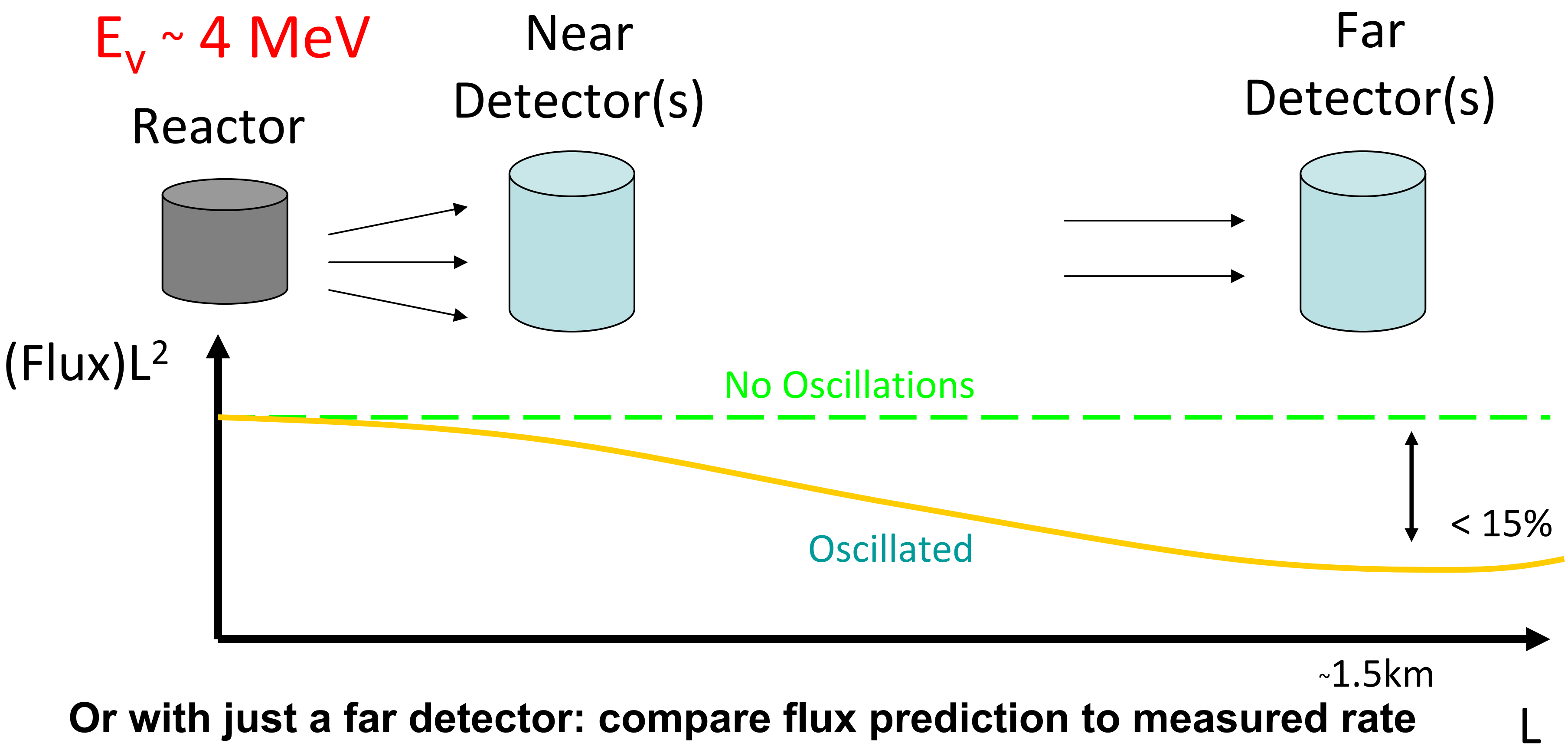


In signal enhance region:

- Expected (no osc) 49.6 ± 7.0 (stat.)± 2.7 (syst.)
- Observed: 62 events
- θ_{13} = 0 disfavored at 89% CL

Reactor ν Oscillation Experiment

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\,\Delta m^2_{13} L}{E_\nu}\right)$$

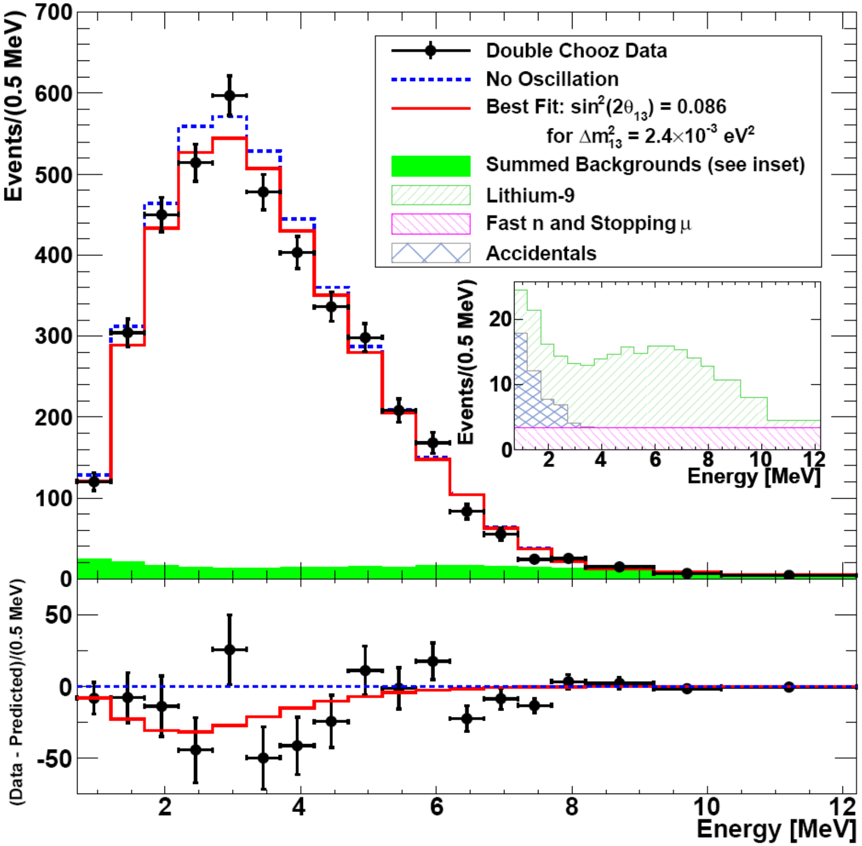


Or with just a far detector: compare flux prediction to measured rate

→ **CHOOZ and Double Chooz first results**

Indications of Nonzero θ_{13} From Reactor Experiment in 2011:

Double Chooz



PRL 108 (2012) 131801

Far detector only fit to rate and energy spectrum (101 days of data):

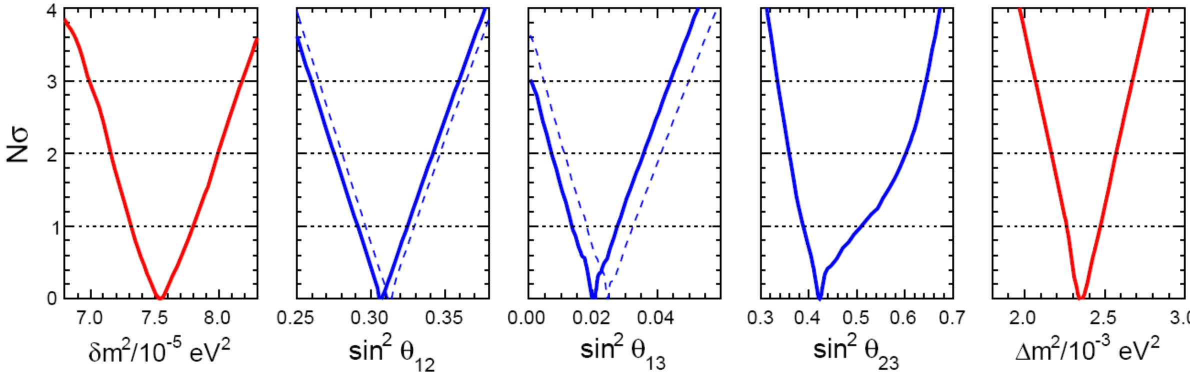
- 4344 ±165 sig + bkg expected (no osc.)
- 4121 candidate events observed

$\sin^2 2\theta_{13} = 0.086 \pm 0.041$ (stat) ± 0.030 (syst)

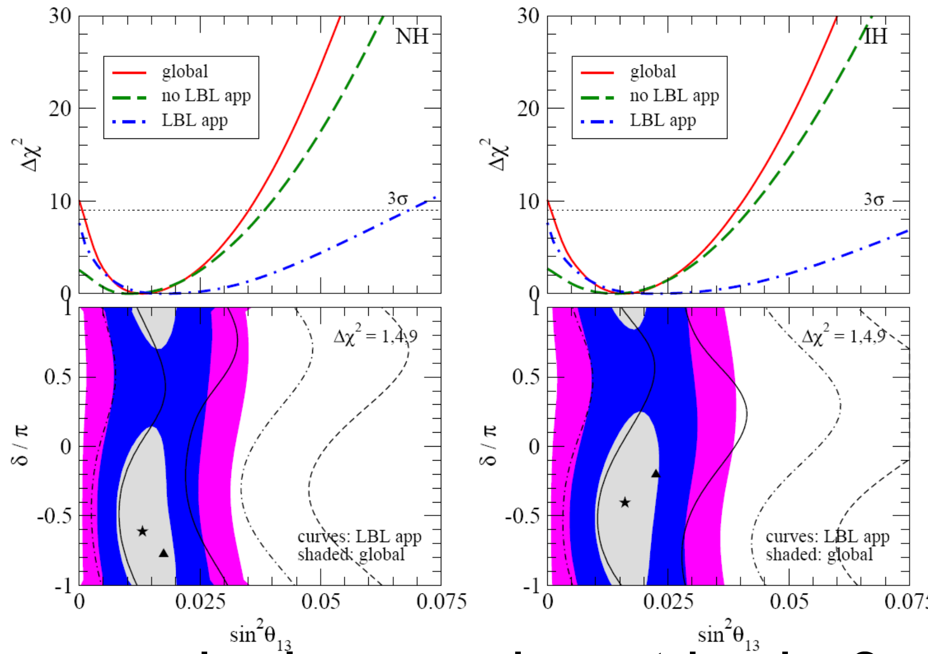
χ^2/d.o.f. = 23.7/17

Frequentist study indicated no-oscillation hypothesis ruled out at 94.6% C.L.

>3σ Evidence of Nonzero θ_{13} From 3ν Global Fits in 2011:



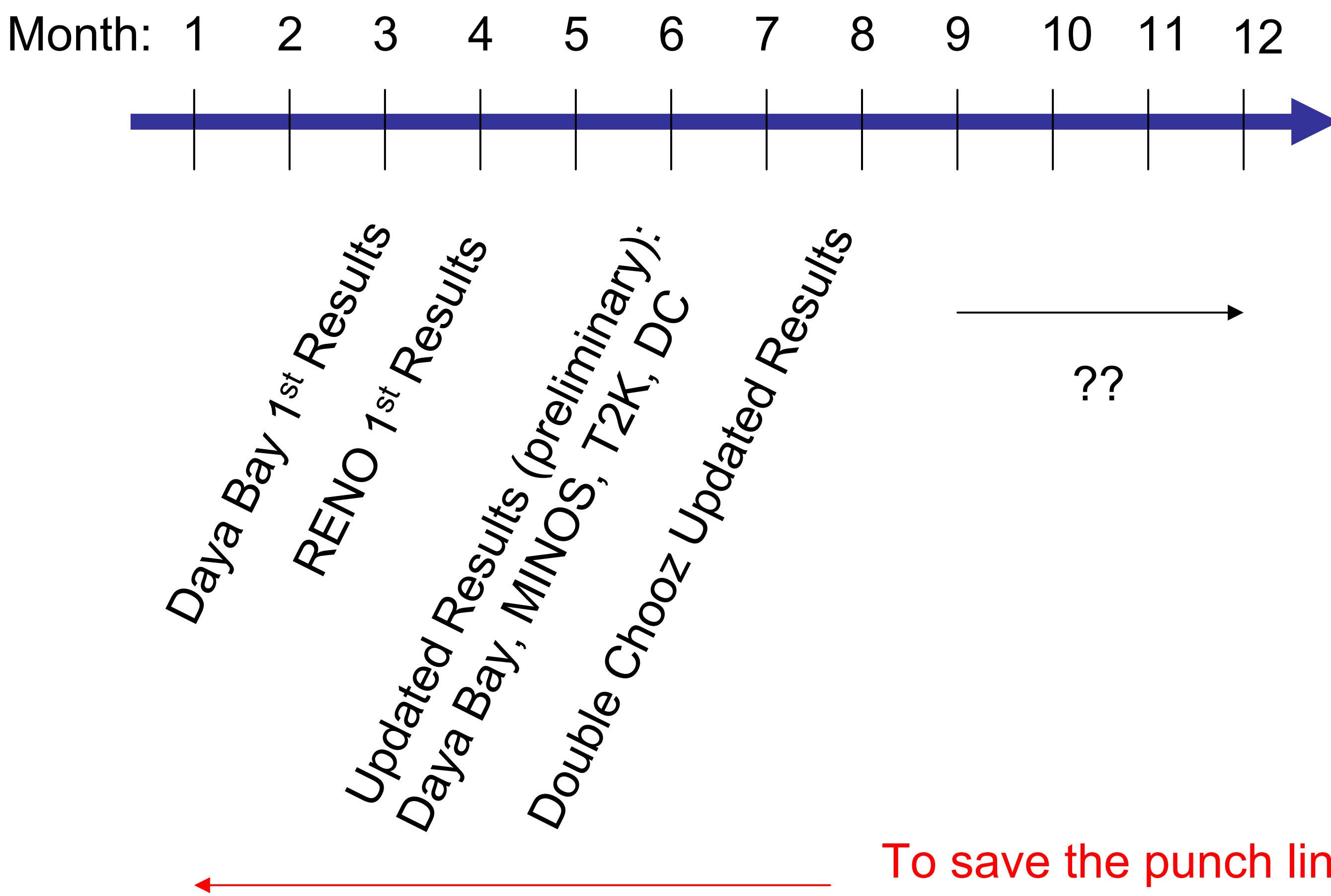
PRD 84 (2011) 053007



New J. Phys. 13 (2011) 109401

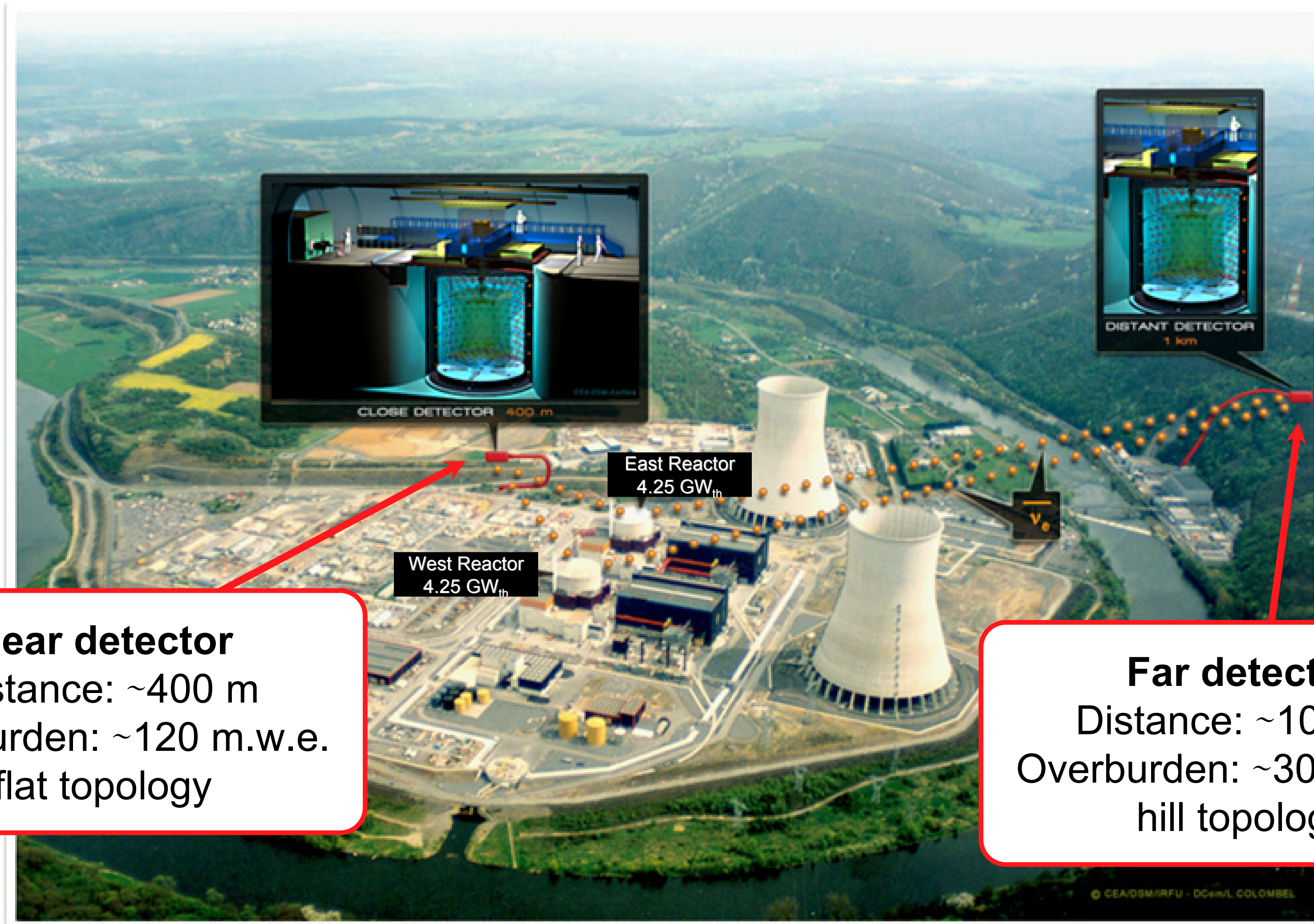
However, no <u>single experiment</u> had >3σ evidence for $\theta_{13} \neq 0$

2012: A Flurry of Results on θ_{13}



To save the punch line for the end,
I will work backwards

Double Chooz Site in Ardennes, France



Near detector
Distance: ~400 m
Overburden: ~120 m.w.e.
flat topology

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e.
hill topology

The Double Chooz Detector

(Typical of multi-zone detectors used by reactor neutrino experiments)

Outer Veto (OV)
plastic scintillator strips

Outer Shielding
250t steel shielding (15 cm)

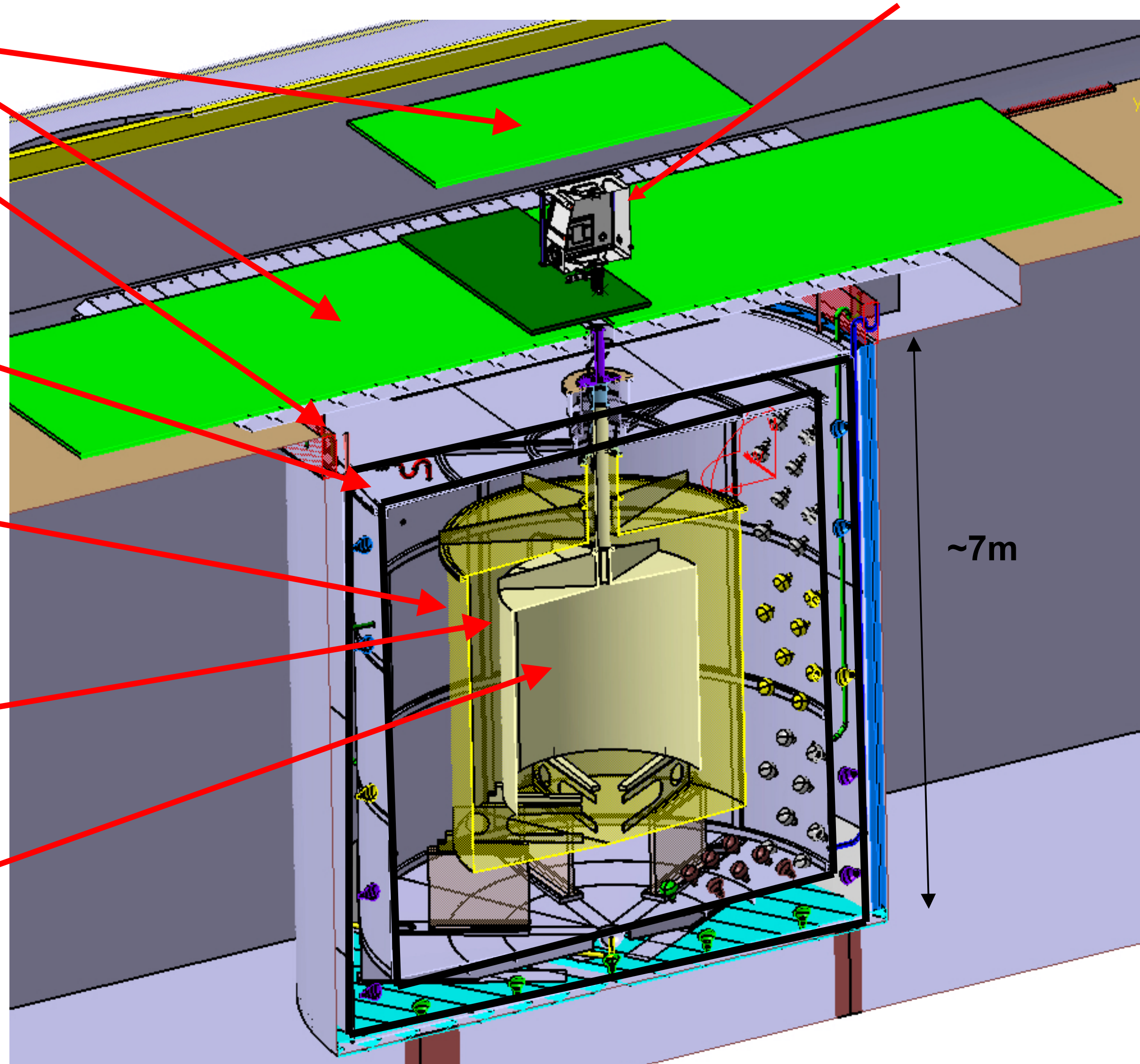
Inner Veto (IV)
90m^3 of scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Buffer
110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 in.)

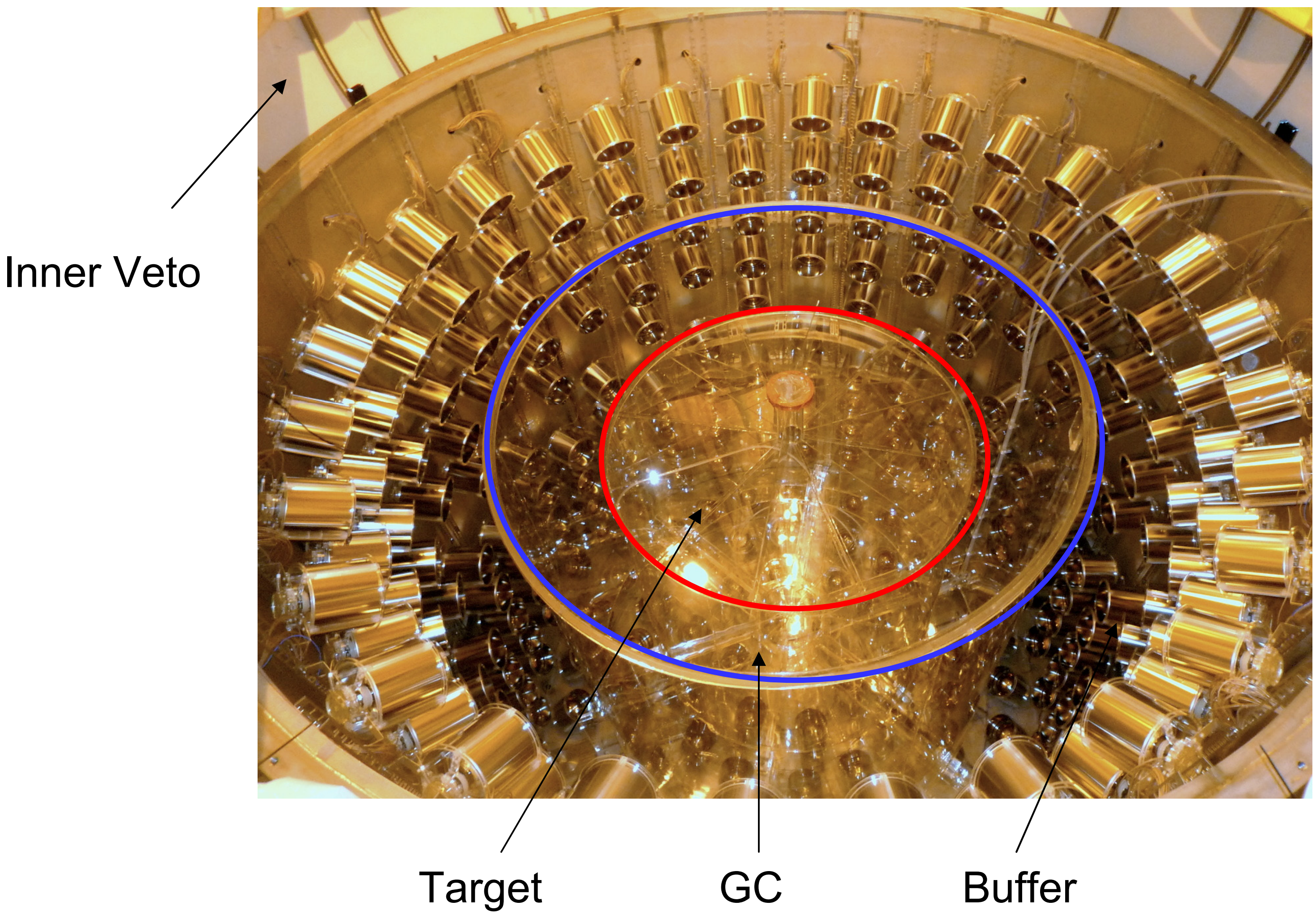
γ-Catcher (GC)
22.3 m^3 scintillator in an acrylic vessel (12 mm)

Target
10.3 m^3 scintillator doped with 1g/l of Gd compound in an acrylic vessel (8 mm)

Calibration Glove Box



The Double Chooz Detector



Experimental Signal For Reactor Neutrino Experiments

- The reaction process is inverse β-decay followed by neutron capture
  - Two part coincidence signal is crucial to reduce background

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\hookrightarrow n \;\; capture$$

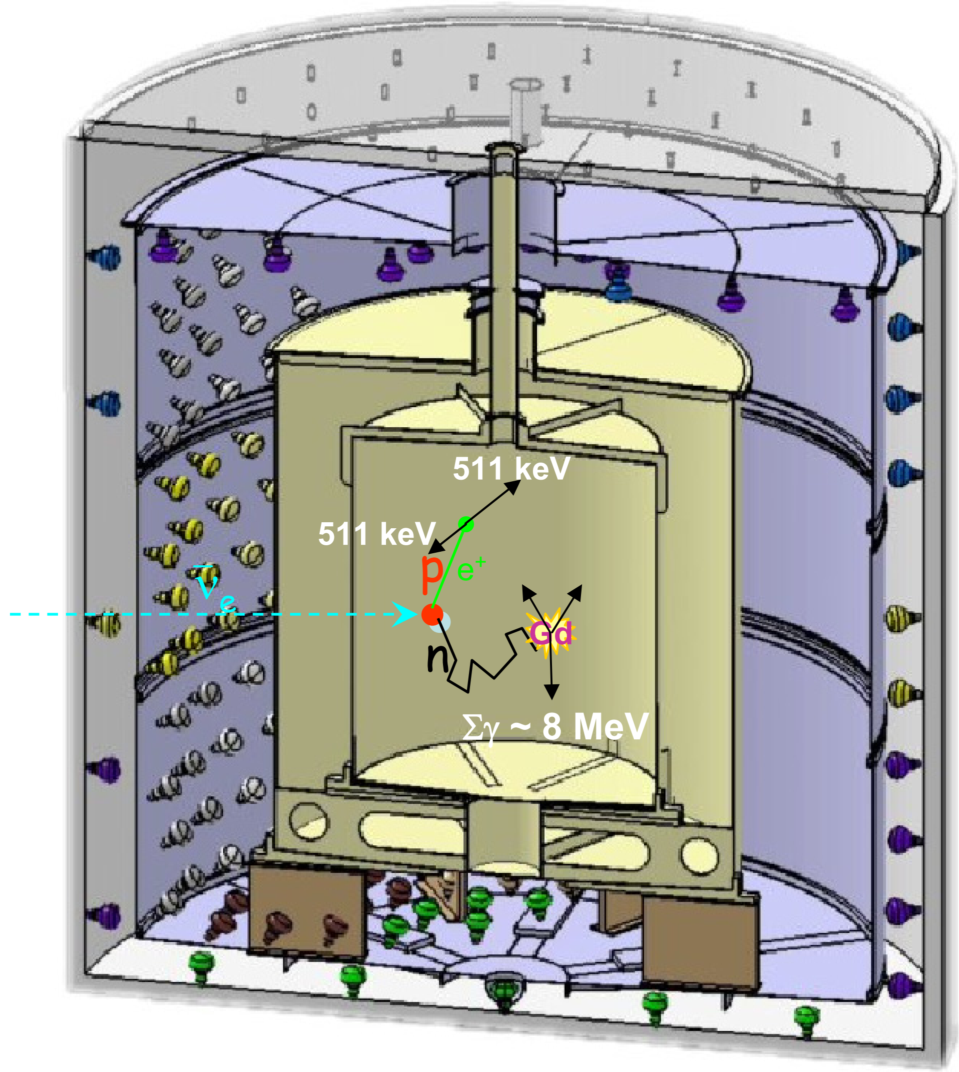
- Positron energy spectrum implies the neutrino spectrum

$$E_\nu = E_{vis} + 1.8\text{ MeV} - 2m_e$$

- The scintillator is doped with gadolinium to enhance capture

$$n\ {}^{m}Gd \rightarrow {}^{m+1}Gd\ \gamma\text{'s (8 MeV)}$$

- Veto system for cosmic–ray muons



Signal = Positron signal + Neutron signal after an average of ~30 μsec

Double Chooz Far Detector Only Analysis

- Simultaneous fit to two far detector spectra—low and high reactor power samples

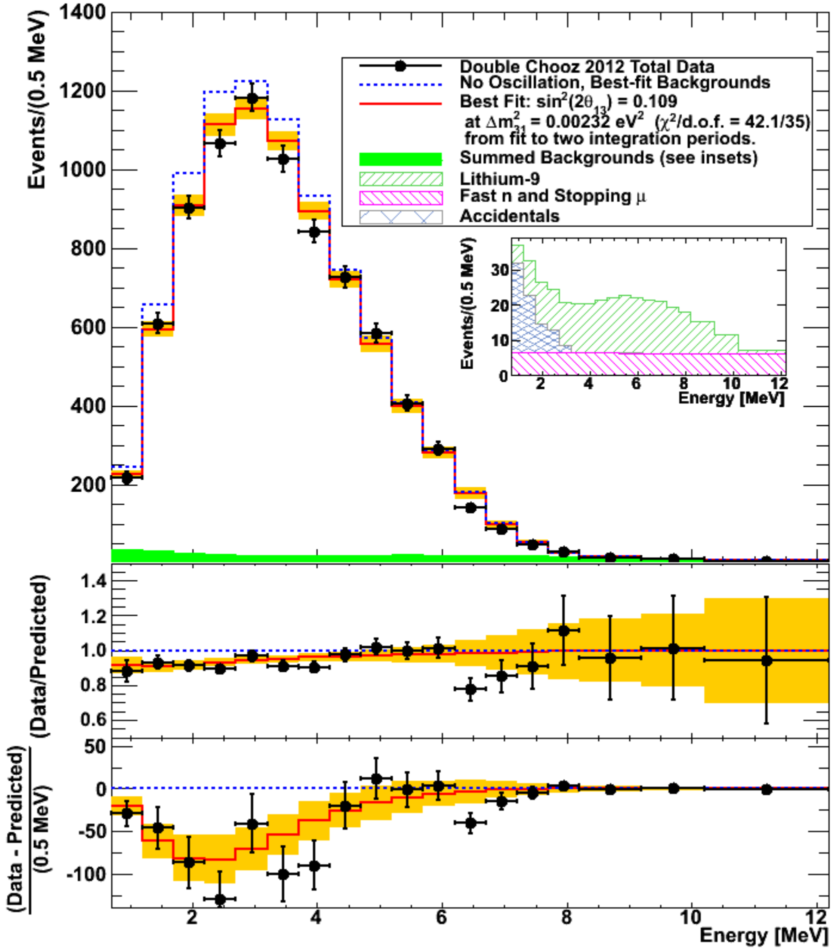
- No near/far comparison—far detector spectrum is compared to MC prediction
  - Flux normalization taken from Bugey4 + corrections

- Rate and spectral shape fit to positron spectrum

$$\chi^2 = \sum_{i,j}^{36} \left(N_i - N_i^{pred}\right)^T M_{ij}^{-1} \left(N_j - N_j^{pred}\right) + \sum_k \frac{\left(\alpha_k - 1\right)^2}{\sigma_k^2} + \frac{\left(\Delta m_{31}^2 - \Delta m_{MINOS}^2\right)^2}{\sigma_{MINOS}^2}$$

- First publication showed that background rate measurements agreed with data taken with both reactors off
  - Additional week of reactor off data in the can

Double Chooz Oscillation Fit Results



Rate-only:
$\sin^2 2\theta_{13}$ = 0.170 ± 0.035 (stat.) ± 0.040 (syst.)

Rate+Shape:
$\sin^2 2\theta_{13}$= 0.109 ± 0.030 (stat.) ± 0.025 (syst.)
χ^2/d.o.f. = 42.1/35

Frequentist analysis:
$\sin^2 2\theta_{13}$ = 0 excluded at 99.8% (2.9σ)

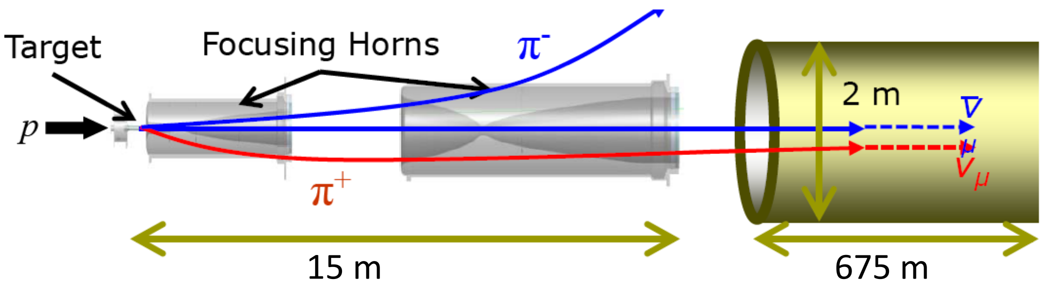
Presented in arXiv:1207.6632, accepted by PRD

Double Chooz Near Detector

Expected to start taking data at the end of 2013

The MINOS Experiment

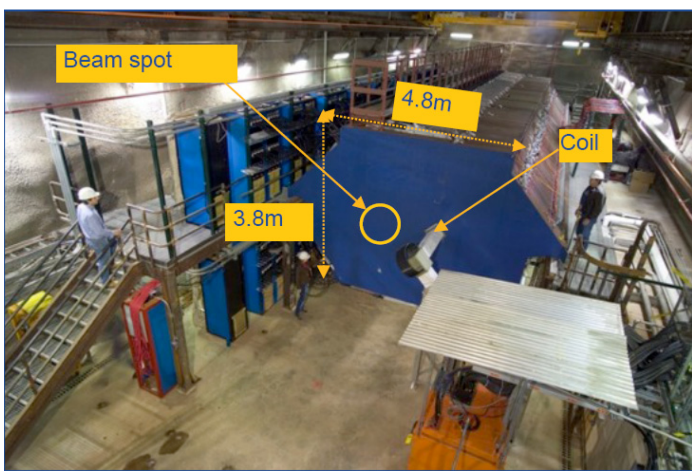
Fermilab
NUMI beam line



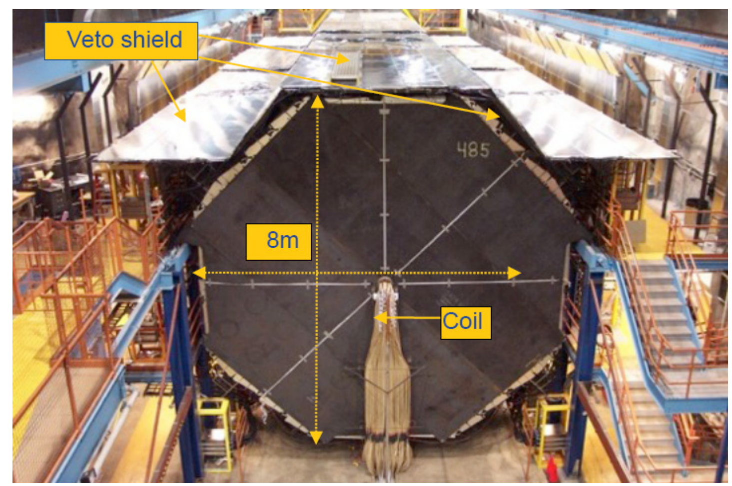
Positively (negatively) focused pions produce ~3 GeV ν_μ ($\bar{\nu}_\mu$)

Three different horn configurations allow separation of background

- Neutral current, ν_μ charged-current, intrinsic ν_e charged-current



Near detector



Far detector

Functionally identical, magnetized, steel-scintillator tracking calorimeters

MINOS $\nu_\mu \rightarrow \nu_e$ Appearance Analysis

MINOS detectors optimized to look for ν_μ disappearance

- Difficult to identify ν_e events
- Instead use MC library event matching technique to statistically separate ν_e / bkg

Neutrino mode

- No oscillation expectation: 128.6 events
- Observe 152 events

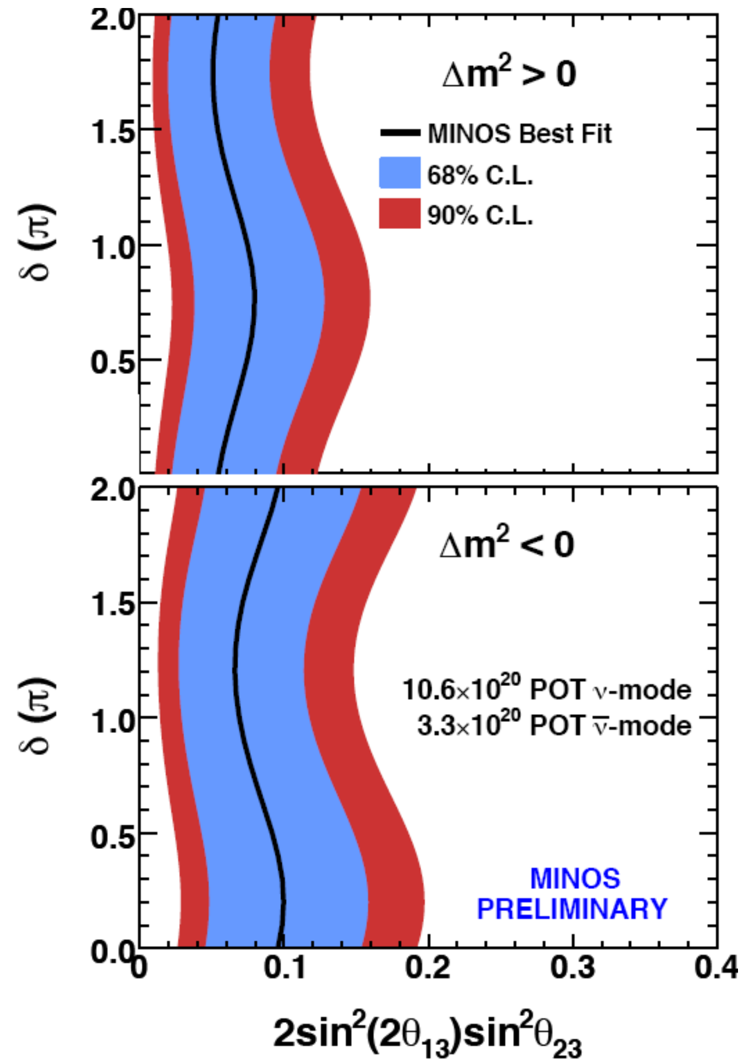
Antineutrino mode

- No oscillation expectation: 17.5 events
- Observe 20 events

Two neutrino fit

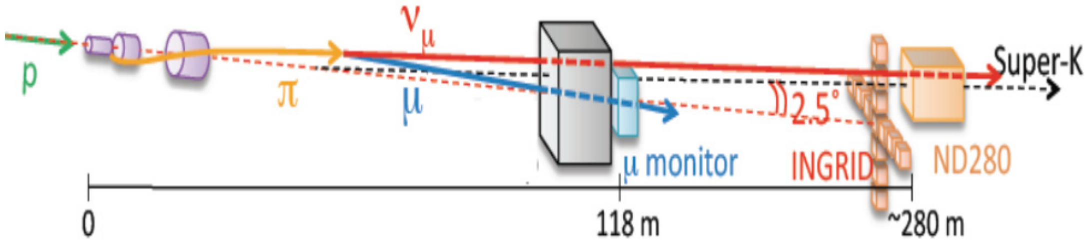
- $\theta_{13} \neq 0$ at 96% C.L. for $\Delta m^2 > 0$, $\delta_{CP} = 0$

Final three neutrino fit expected soon

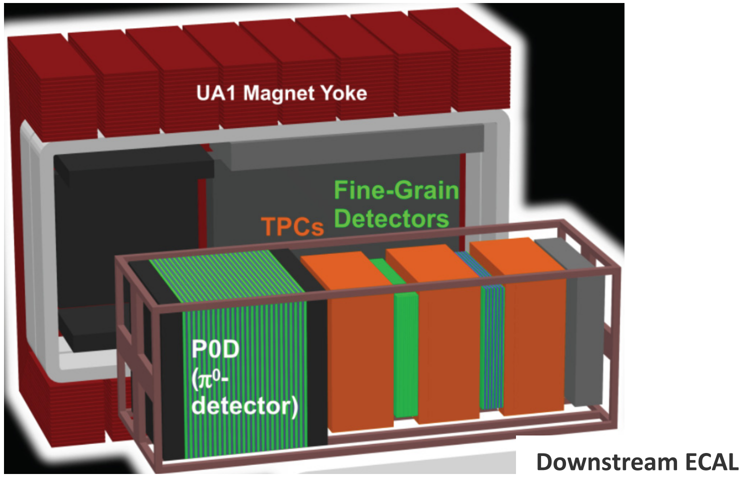


R. Nichol, Neutrino 2012

The T2K Experiment



Positively (negatively) focused pions produce ~0.6 GeV ν_μ ($\bar{\nu}_\mu$)



Near detector (ND280)

Far detector (Super-K)

- 22.5 kt water Cerenkov detector
- ~11,000 ID 20" PMTs
- Identify ν_e charged-current interactions from electron-like single ring events

Roughly doubled the POT used in the 2011 ν_e appearance results

T2K $\nu_\mu \rightarrow \nu_e$ Appearance Analysis

No oscillation expectation: 3.22 ± 0.43 events

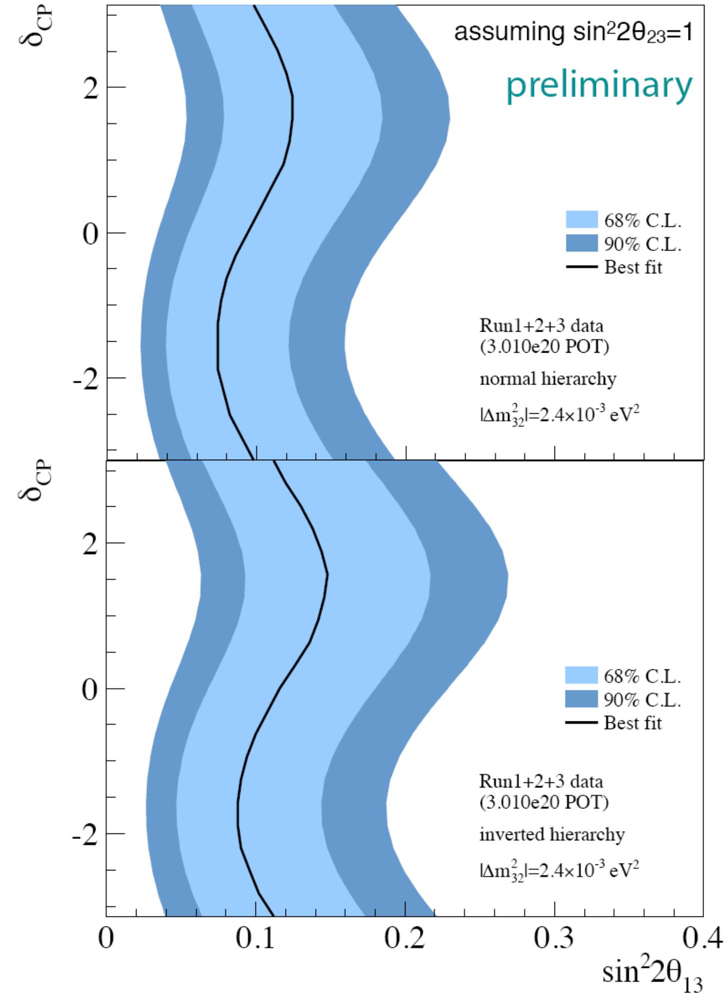
Observed events: 11

Probability to observe 11 or more events given no oscillation expectation is 0.08% (3.2σ)

Three different analysis methods used yielding consistent results

- Main analysis uses maximum likelihood fit to signal + 4 background pdfs is (p_e, θ_e) bins

Latest results consistent with 2011 results, but more precise



M. G. Catanesi, NOW 2012

→ Plan to achieve 5σ significance of nonzero θ_{13} in coming years

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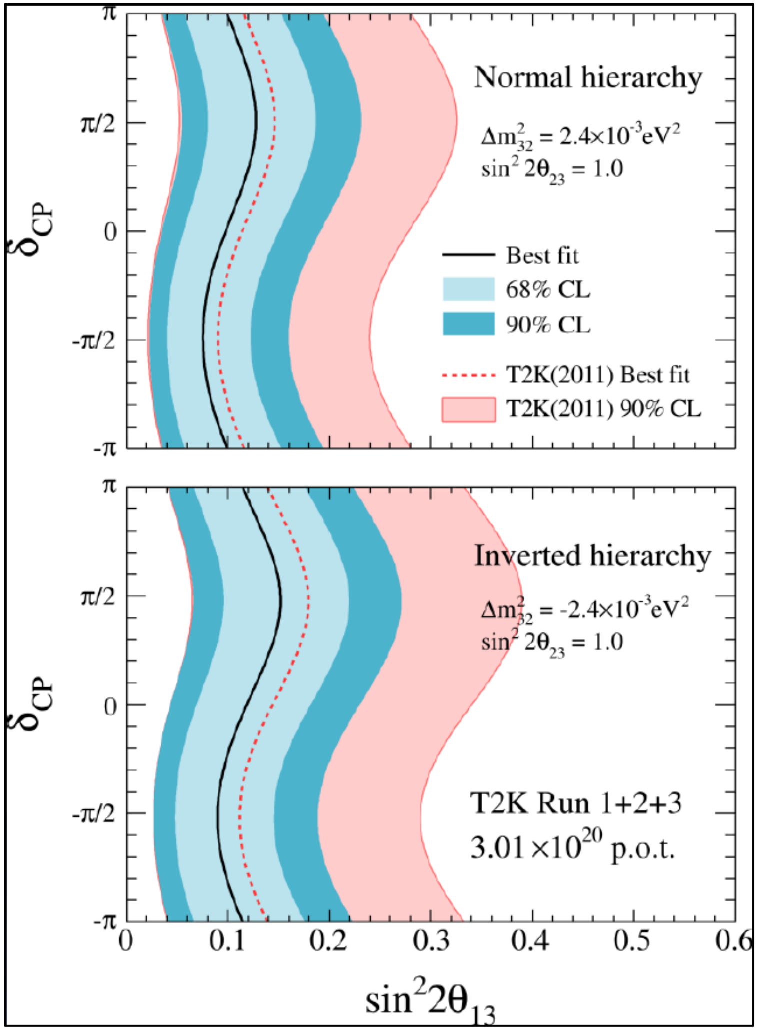

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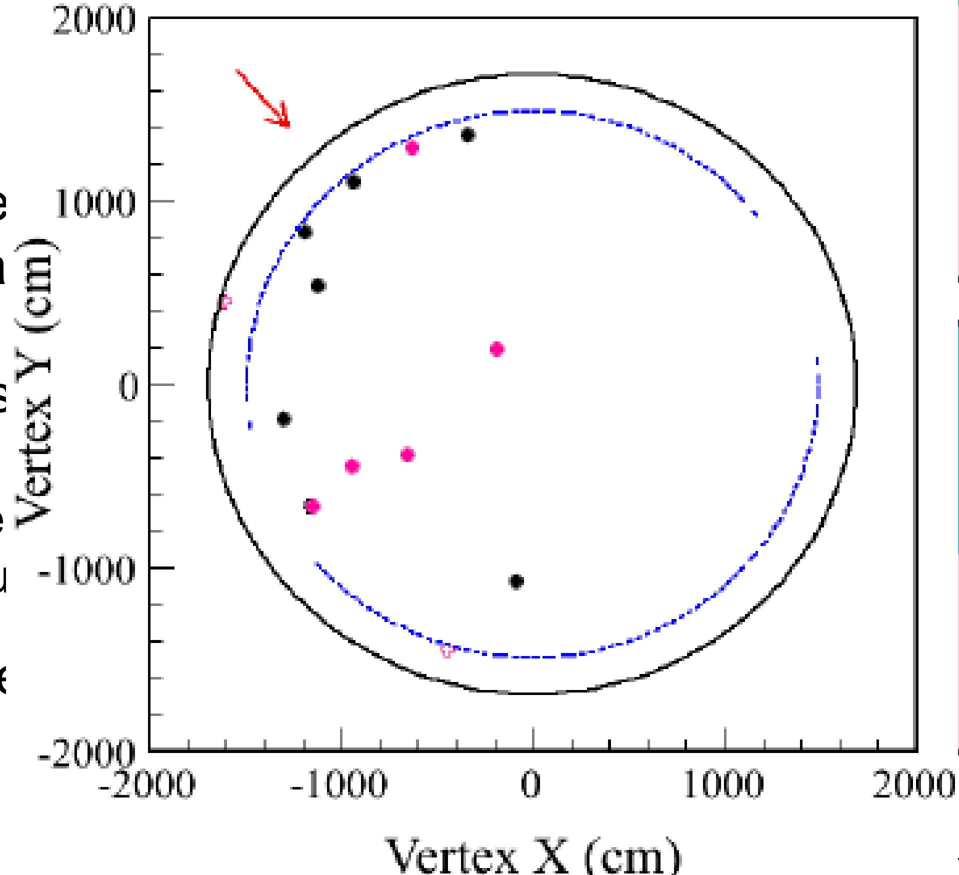
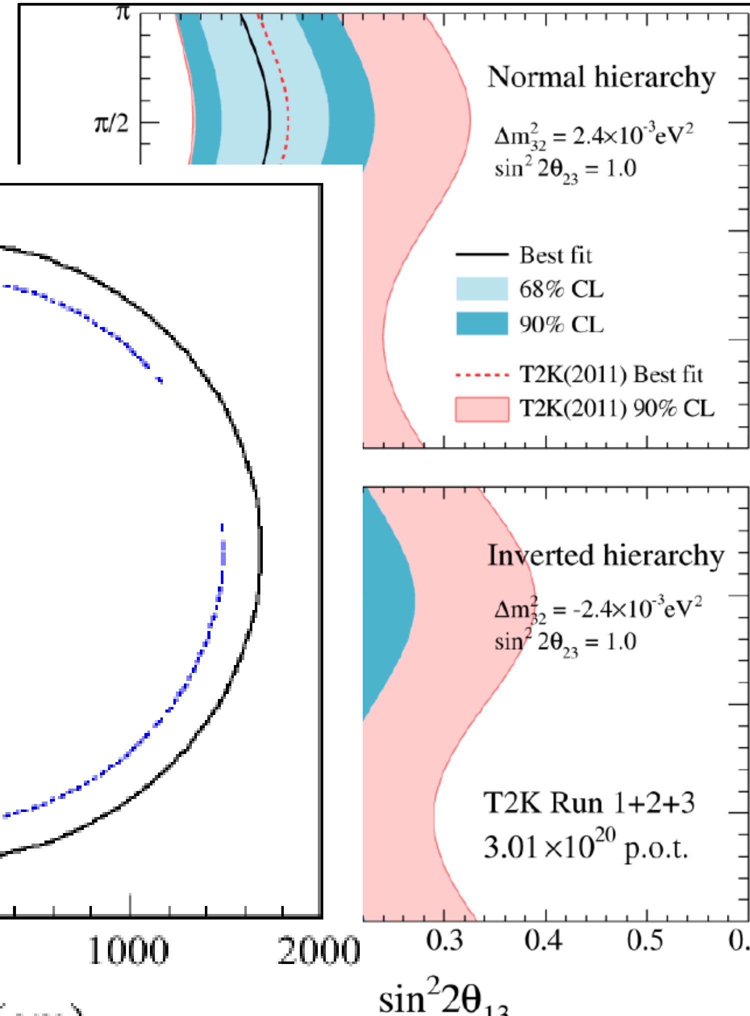


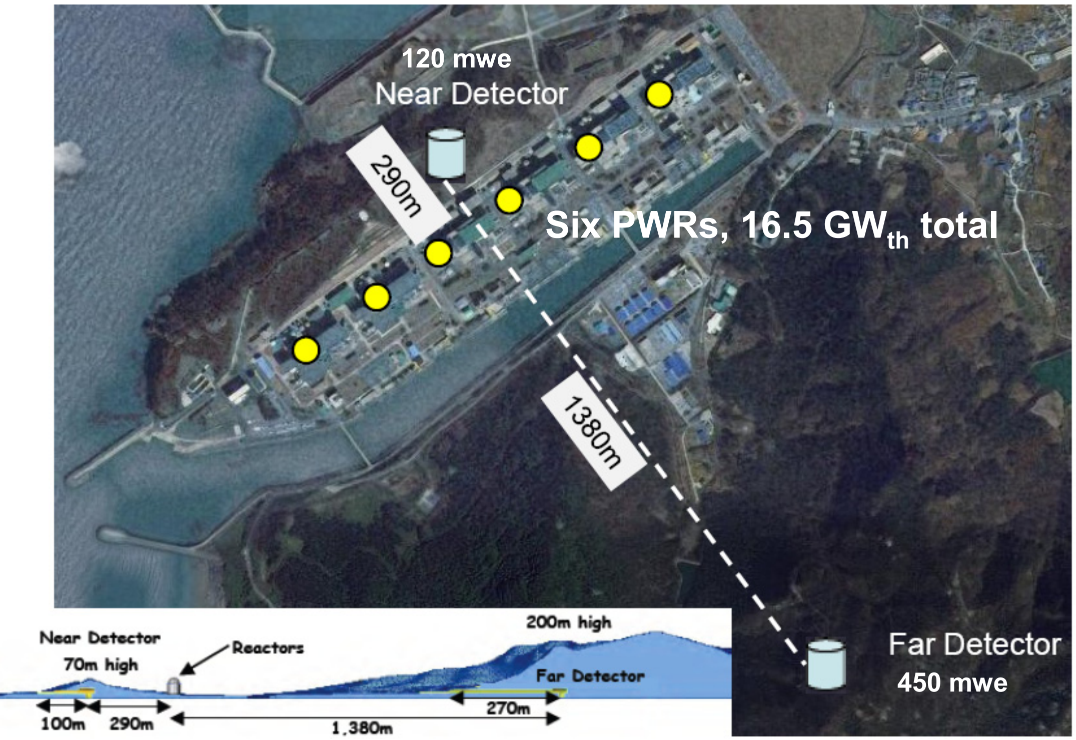


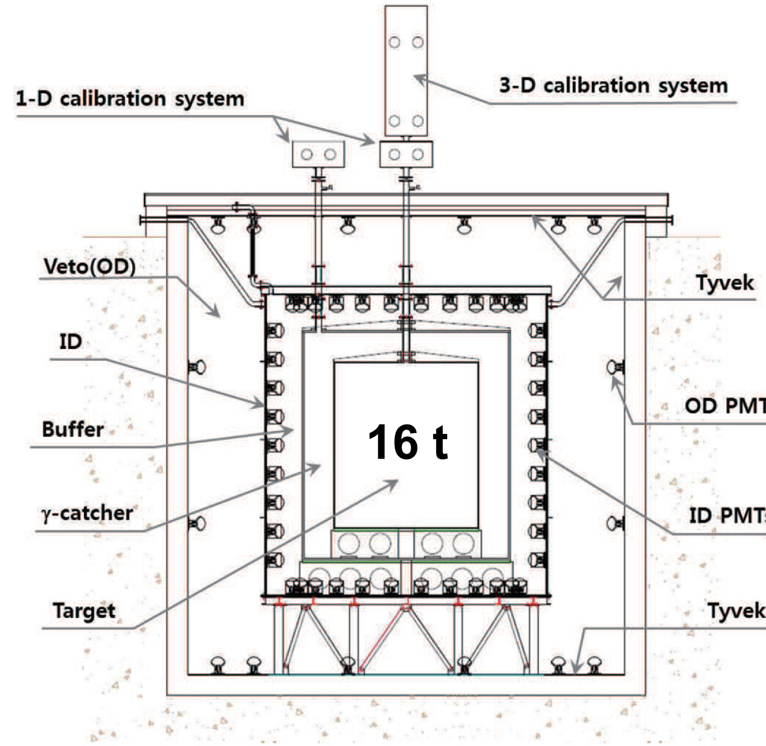
M. G. Catanesi, NOW 2012

⟶ Plan to achieve 5σ significance of nonzero θ_{13} in coming years

The RENO Experiment

Yonggwang Nuclear Power Plant, Korea

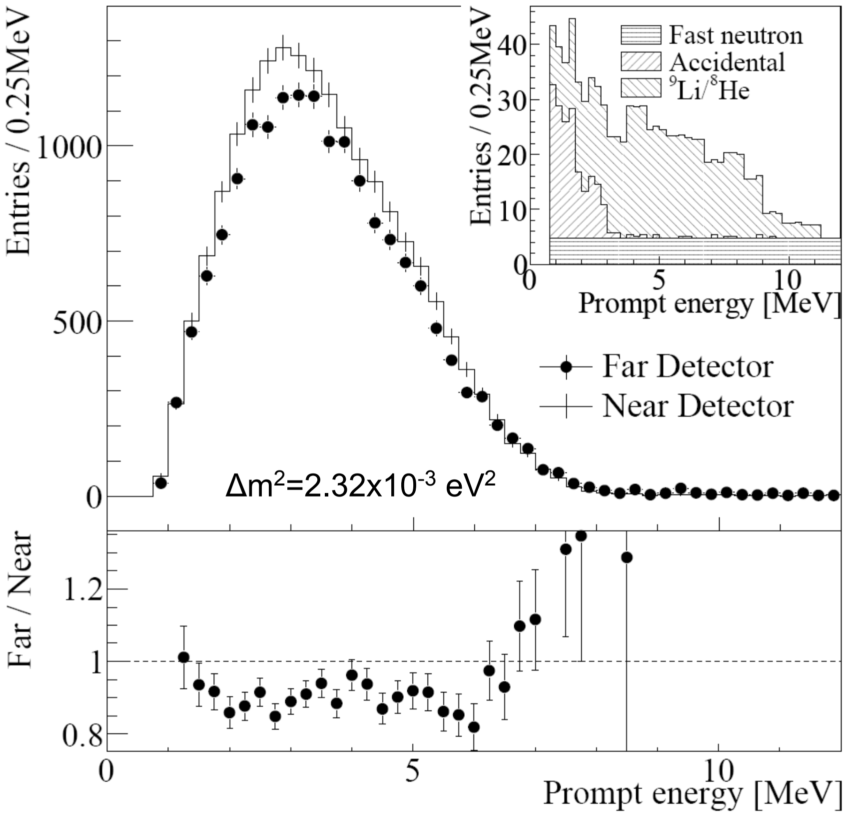




Soo-Bong Kim, Neutrino 2012

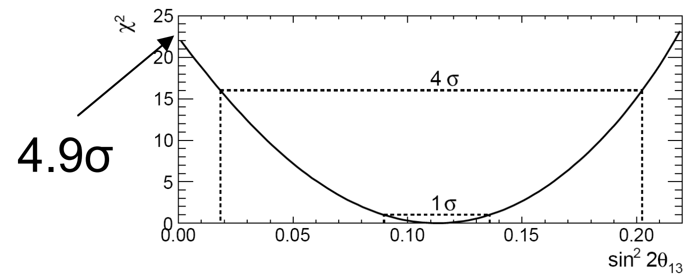
- Started taking data with two detectors in August 2011
- Found 17102 (154088) candidates for 222.06 (192.42) days in the far (near) detector
- Performed rate-only fit with floating normalization

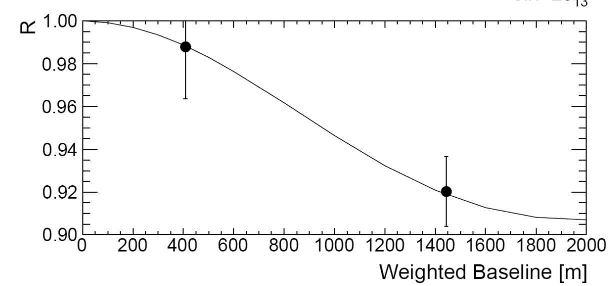
RENO $\overline{\nu}_e$ Disappearance Analysis



PRL 108 (2012) 191802

$$\chi^2 = \sum_{d=N,F} \frac{\left[N^d_{obs} + b_d - (1 + a + \xi_d)\sum_{r=1}^{6}(1+f_r)N^{d,r}_{exp}\right]^2}{N^d_{obs}} + \sum_{d=N,F}\left(\frac{\xi_d^2}{\sigma_d^{\xi 2}} + \frac{b_d^2}{\sigma_d^{b 2}}\right) + \sum_{r=1}^{6}\left(\frac{f_r}{\sigma_r}\right)^2$$



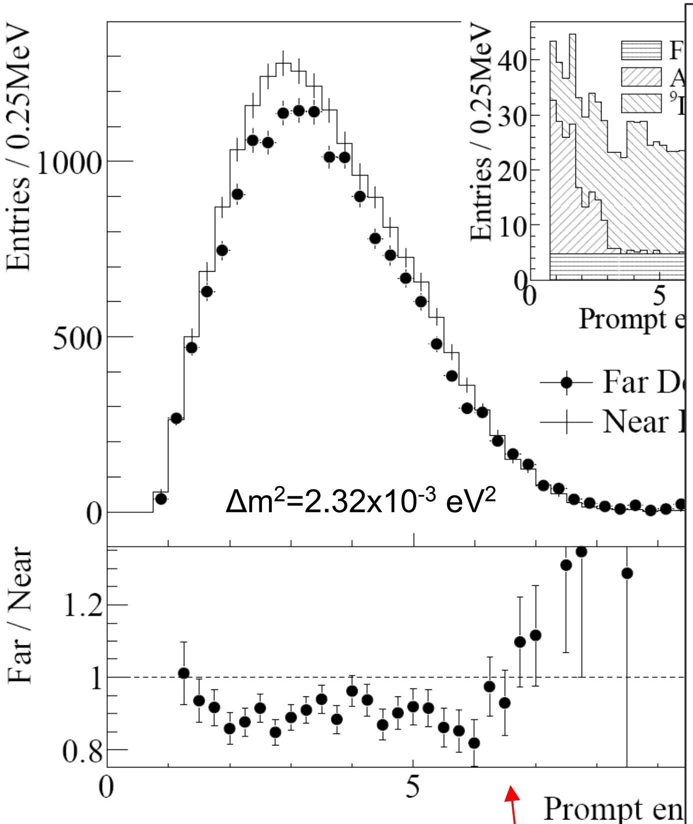


R = 0.920 ± 0.009 (stat.) ± 0.014 (syst.)

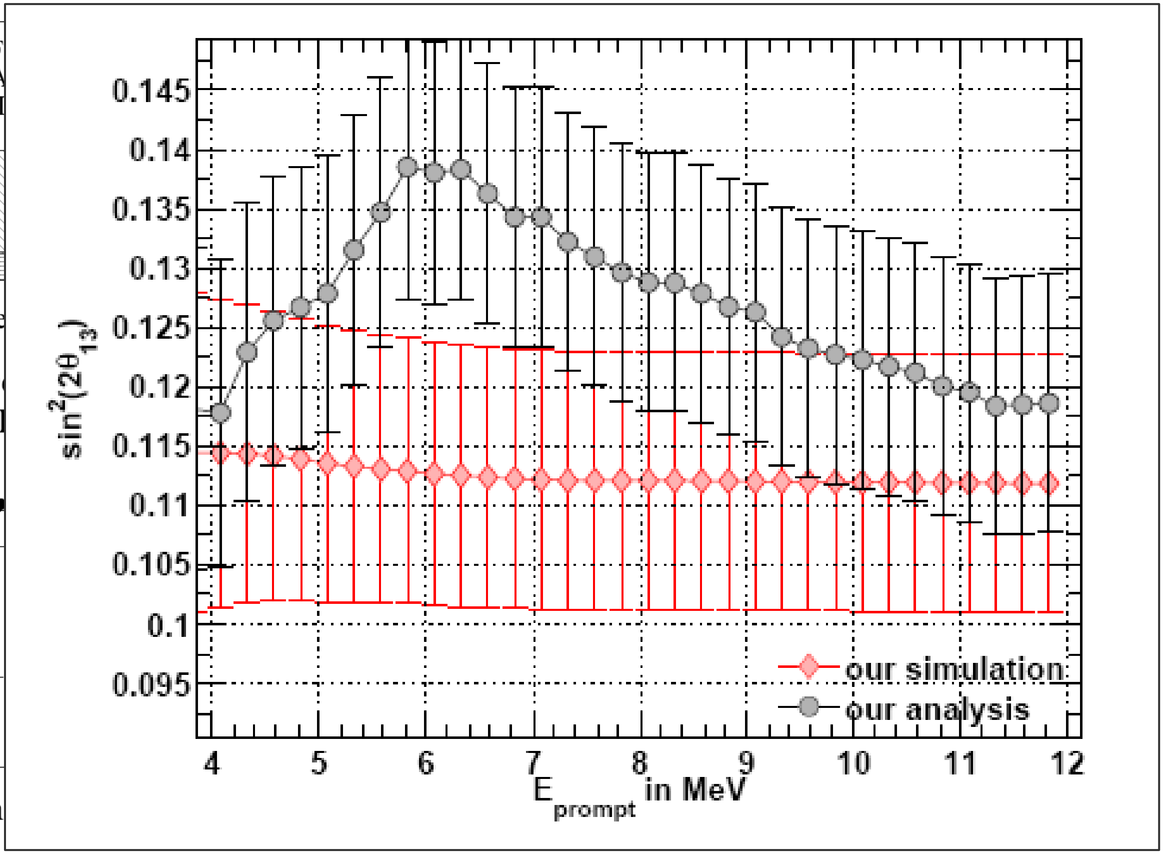
$\sin^2 2\theta_{13}$ = 0.113 ± 0.013 (stat.) ± 0.019 (syst.)

→ Ultimate goal is 5% measurement of θ_{13}

RENO $\bar{\nu}_e$ Disappearance Analysis



PRL 108 (2012) 191802



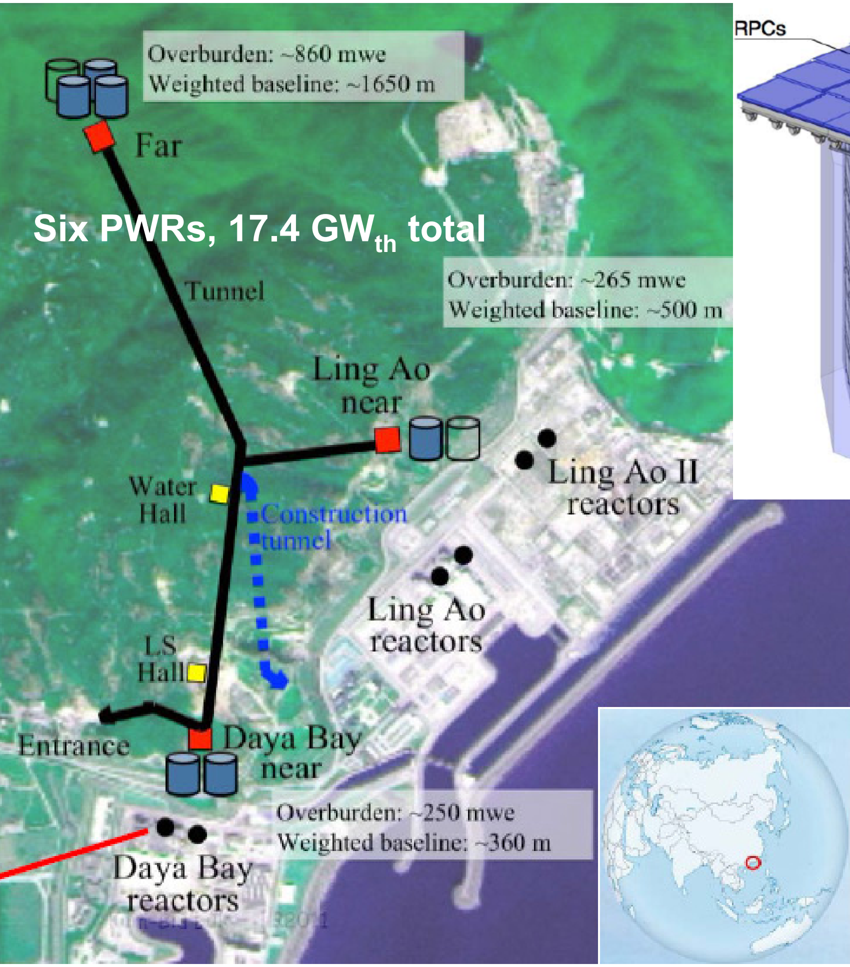
arXiv:1205.5626v1

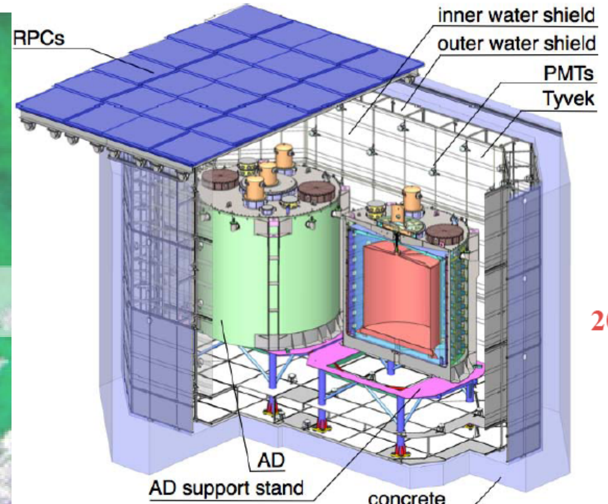
Problem with positron energy spectrum

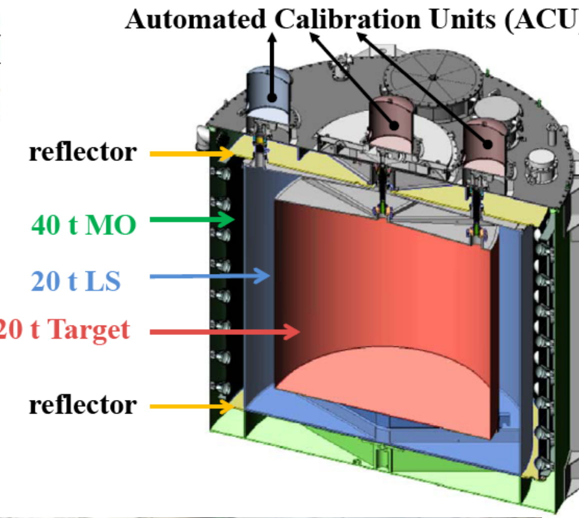
⟶ Measured value of $\sin^2 2\theta_{13}$ depends on upper bound of prompt energy cut

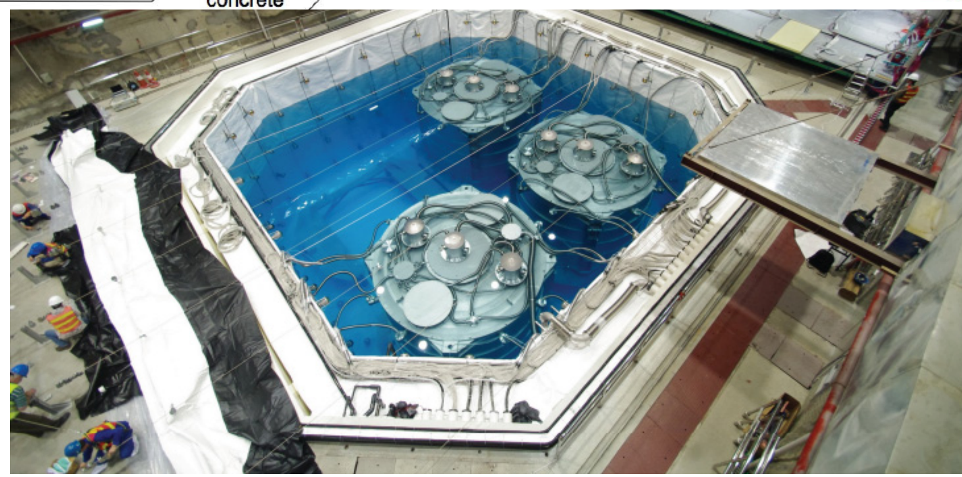
The Daya Bay Experiment

Daya Bay nuclear power complex, China



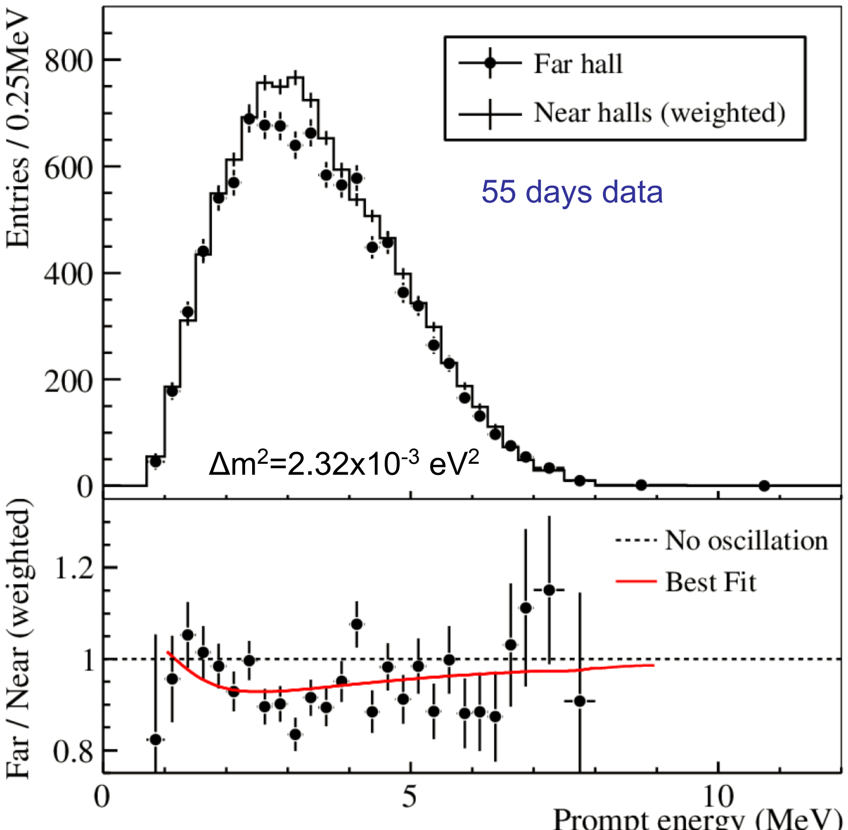






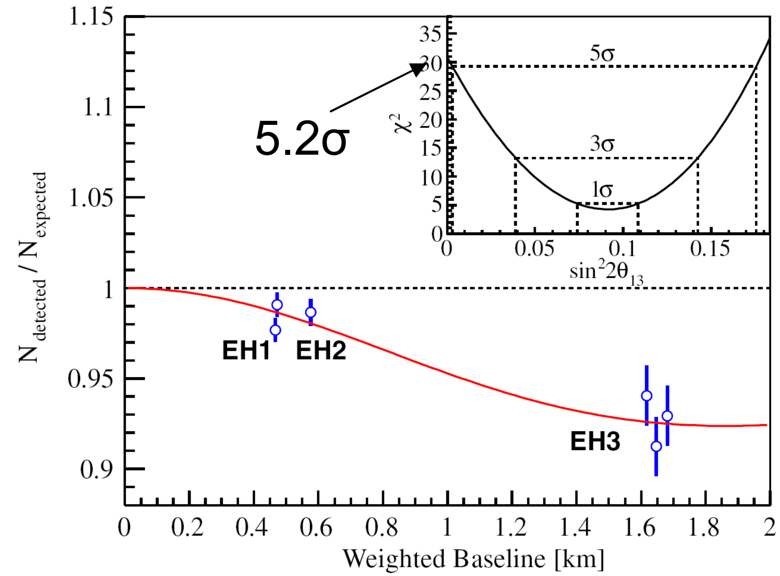
- First results from 55 days of data taking Dec. 24,2011 – Feb.17, 2012
- > 200k antineutrino interactions
- Performed rate-only fit with floating normalization

Daya Bay $\bar{\nu}_e$ Disappearance Analysis



PRL 108 (2012) 171803

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2} \right),$$

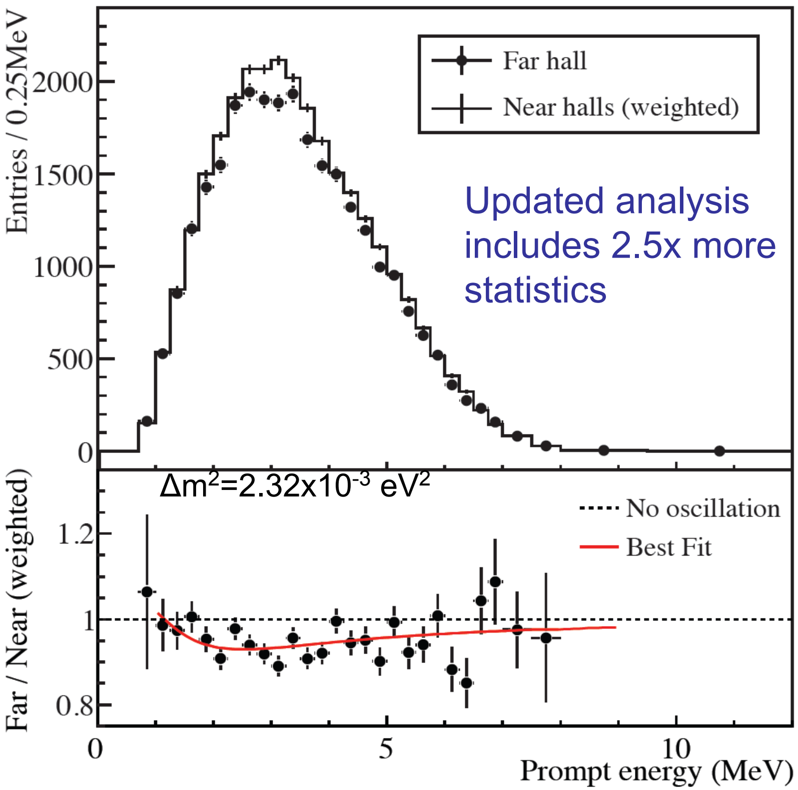


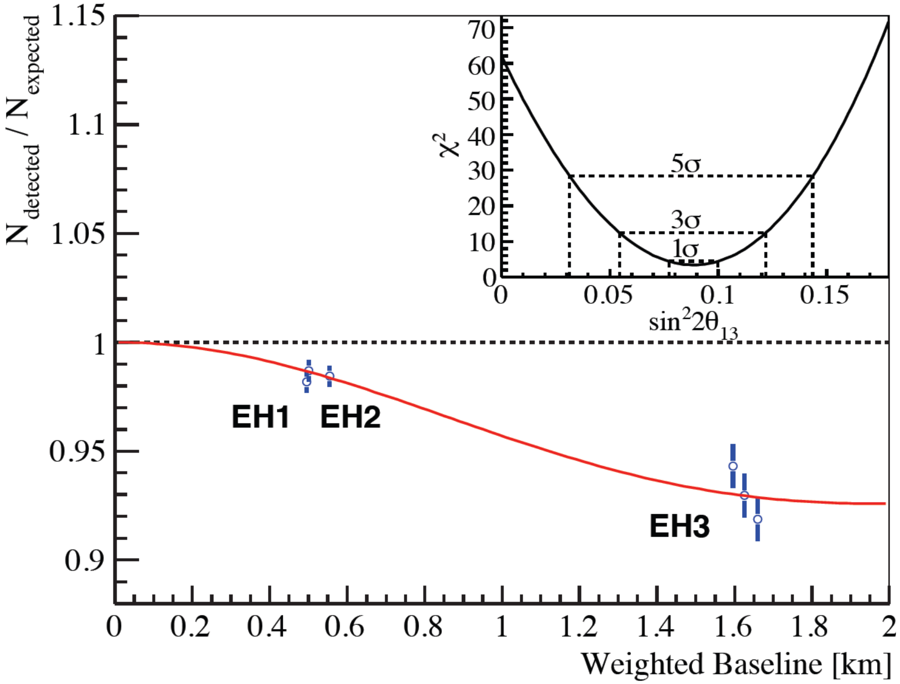
R = 0.940 ± 0.011 (stat.) ± 0.004 (syst.)

$\sin^2 2\theta_{13}$ = 0.0920 ± 0.016 (stat.) ± 0.005 (syst.)

Spectral distortion consistent with oscillation

Updated Daya Bay $\bar{\nu}_e$ Disappearance Analysis





Xiaonan Li, NOW 2012

R = 0.944 ± 0.007 (stat.) ± 0.003 (syst.)

$\sin^2 2\theta_{13}$ = 0.0890 ± 0.010 (stat.) ± 0.005 (syst.)

→ Final two AD's will be installed later this year

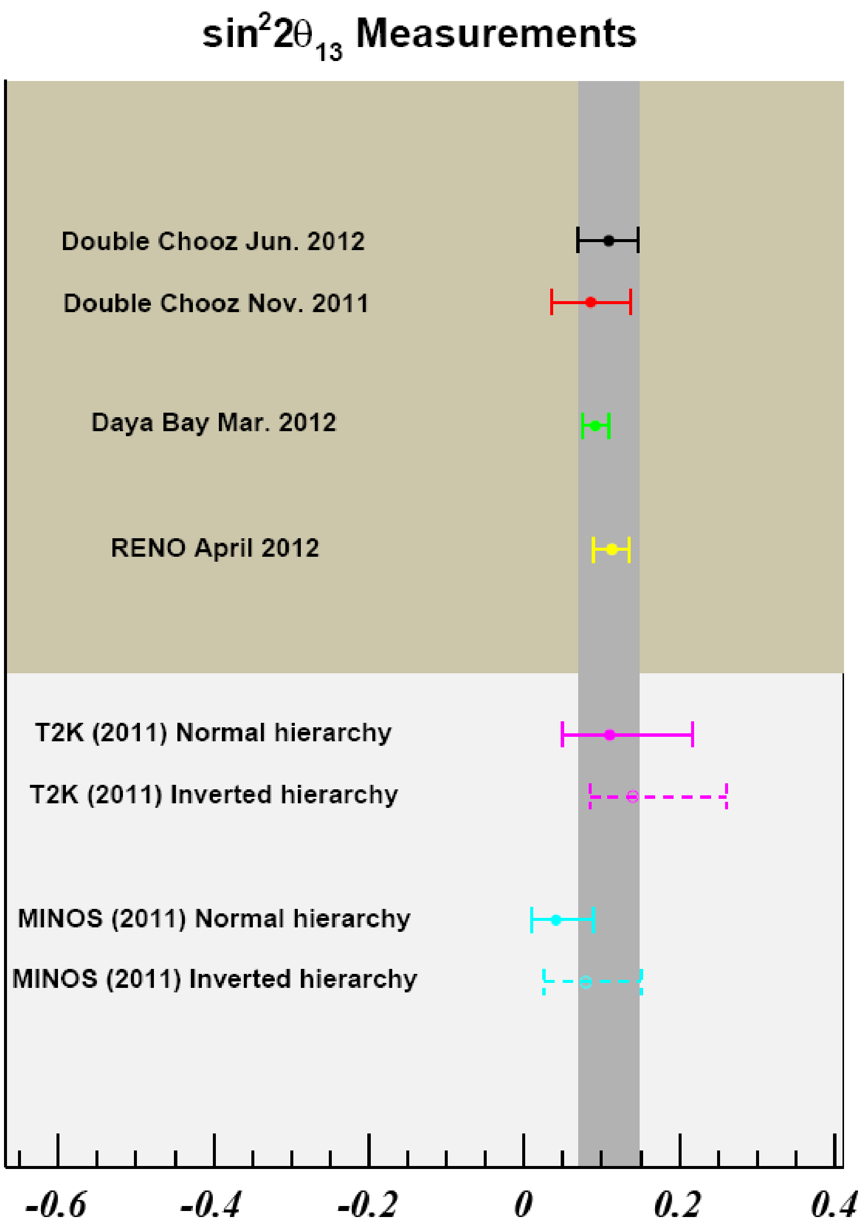
→ Aim to achieve 5% measurement of $\sin^2 2\theta_{13}$ in < 2 years

Conclusions

- Up to 2010 only upper bounds on θ_{13}
- In 2011 we had 3σ evidence for $\theta_{13} \neq 0$ from fits, but not from any one experiment
- The situation in 2012 is completely different:
  - Two accelerator-based experiments see $\nu_\mu \rightarrow \nu_e$ appearance (T2K: 3.2σ)
    - Should also be confirmed in near future by NOvA (not discussed here)
  - Three reactor-based experiments see $\overline{\nu}_e$ disappearance (Daya Bay >> 5σ)
- Measurement of $\sin^2 2\theta_{13}$ to a precision of 5% very likely in the next 2 years

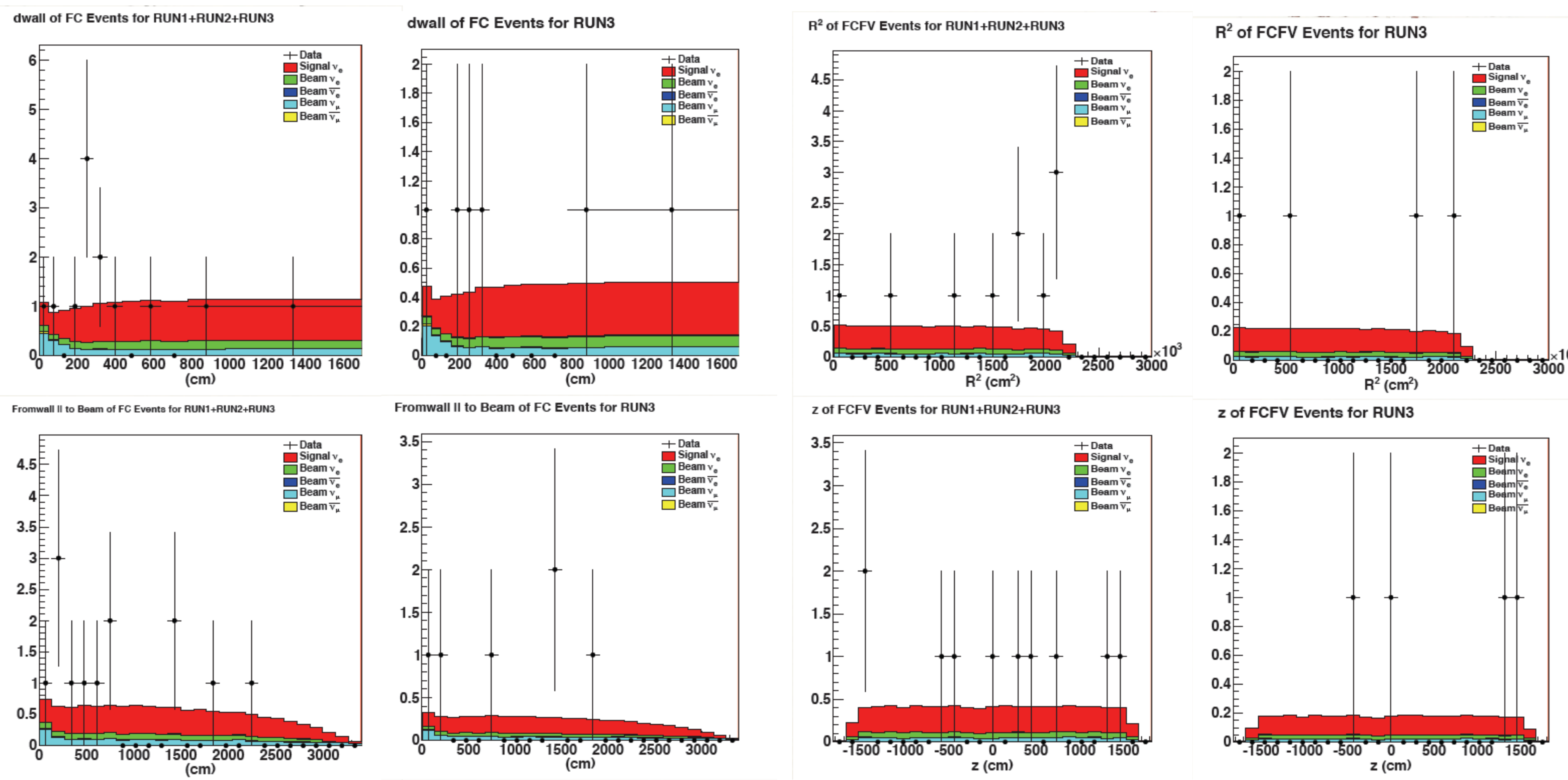
<u>$\sin^2 2\theta_{13}$ is LARGE</u>

→ Good prospect for δ_{CP} searches in next 10-20 years



End.

T2K Vertex Distributions



T. Nakaya, Neutrino 2012

	RUN1+2	RUN3	RUN1+2+3
$Dwall$	22.9%	80.7%	21.5%
$Fromwall$ $\text{beam}_{\parallel}$	1.34%	47.3%	2.64%
$R^2 + Z$	10.5%	66.1%	17.2%