# Neutrino Oscillations Present

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University of London

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# Open Questions in ν Oscillations

CP phase: key to understand the origin of matter-dominated Universe

*Unknown*

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

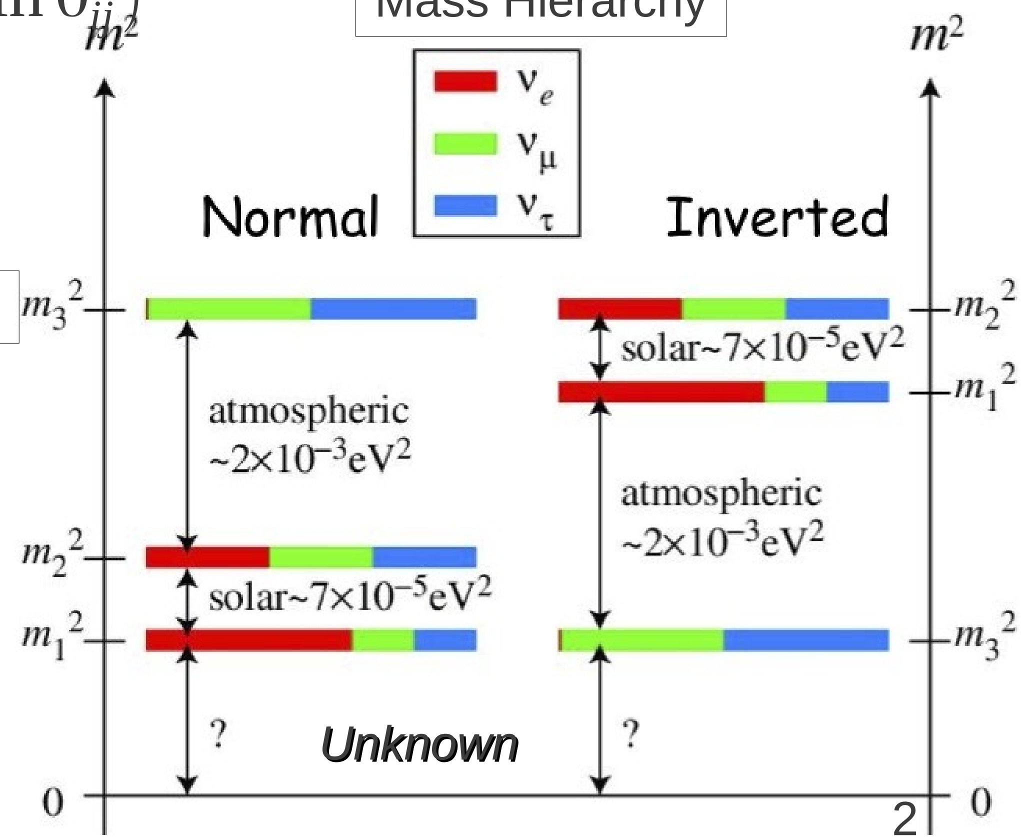
$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

$\theta_{12} = 34^o \pm 1^o$

$\theta_{23} = 40^o + 5^o / -2^o$ — How close to 45°?

$\theta_{13} = 9.1^o \pm 0.6^o$ — Reactor experiments

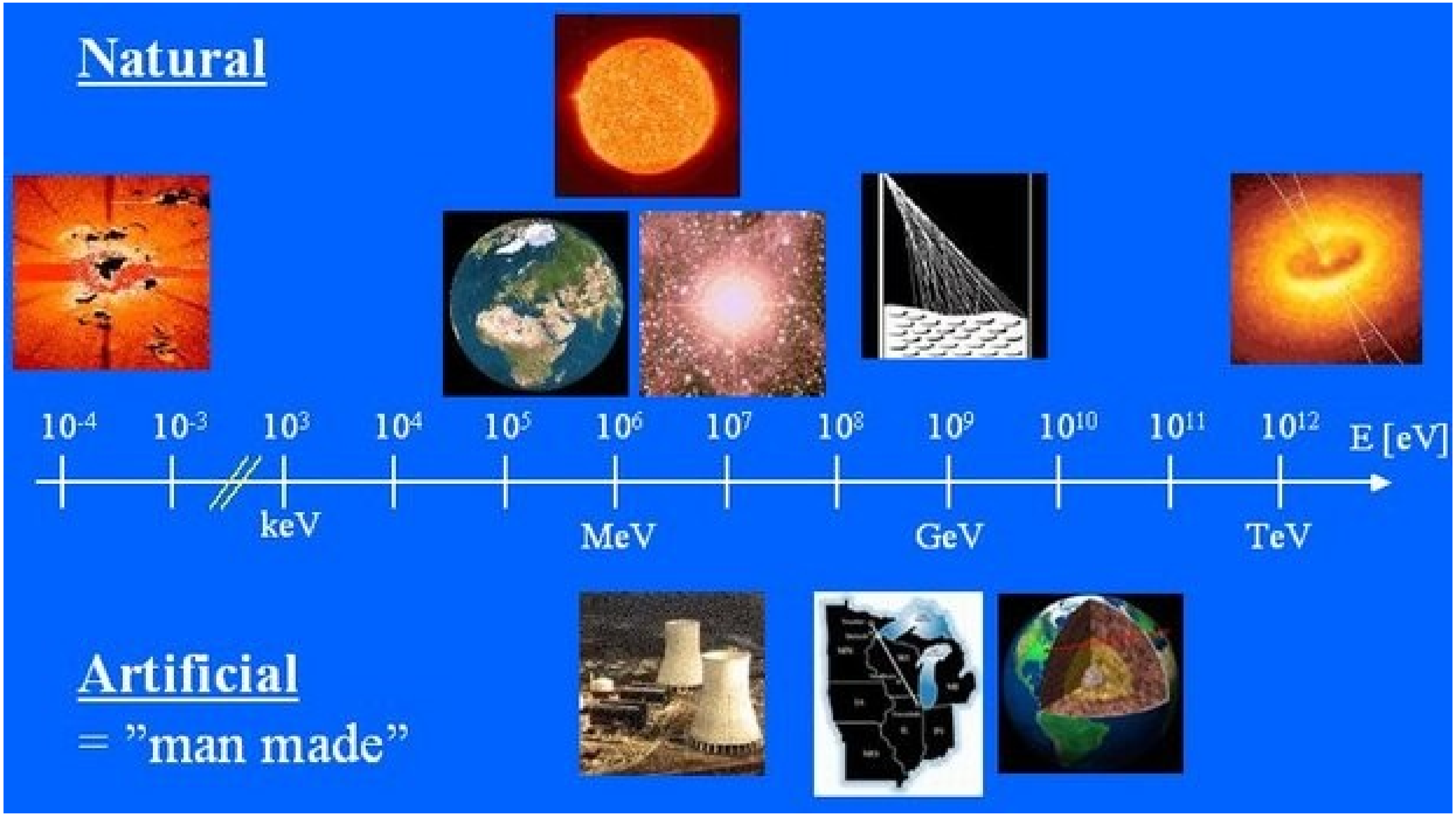
Mass Hierarchy




*Unknown*

Big impact on 0ν double-β decay search (hence on Majorana ν confirmation)

# Neutrino Sources




- We will address both artificial (accelerators, reactors) and natural (atmospheric, solar) sources

# Outline

- Measurements:
  - $\nu_e$ appearance
  - $\bar{\nu}_e$ disappearance
  - $\nu_\mu$ disappearance
  - Atmospheric Neutrinos
  - Solar neutrinos

Caveat: this is a not exaustive list of current undergoing measurements. Sterile neutrinos, cross section measurements, hadron production, etc. are not included.

# Latest News on $\nu_e$ Appearance Results

# Leading Term in Oscillation Equat.

$$\boxed{\Delta m^2_{32}\frac{L}{4E}\sim\Delta m^2_{31}\frac{L}{4E}\sim\frac{\pi}{2},\Delta m^2_{21}\frac{L}{4E}\sim 0}$$

- $\theta_{23}$: $\nu_\mu$ disappearance

Close to 1

$$P_{\mu\to\mu}\sim 1-\sin^2 2\theta_{23}\sin^2(\Delta m^2_{32}L/2E)$$

Mainly go to $\nu_\tau$. Since $\tau$ production is high it disappeares in CC current interaction.

Common

- $\theta_{13}$: $\nu_e$ appearance

$$P_{\mu\to e}\sim\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta m^2_{31}L/2E)$$

Close to 0.5

# $\nu_\mu \rightarrow \nu_e$ Probability

$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$

$\Phi = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

$$P(\nu_\mu \rightarrow \nu e) = \boxed{4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}}$$ **Leading term** $\boxed{\theta_{13}}$

$$+8C_{13}^2 S_{12} S_{13} (C_{12} C_{13} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{32} \sin\Phi_{21}$$ CPC

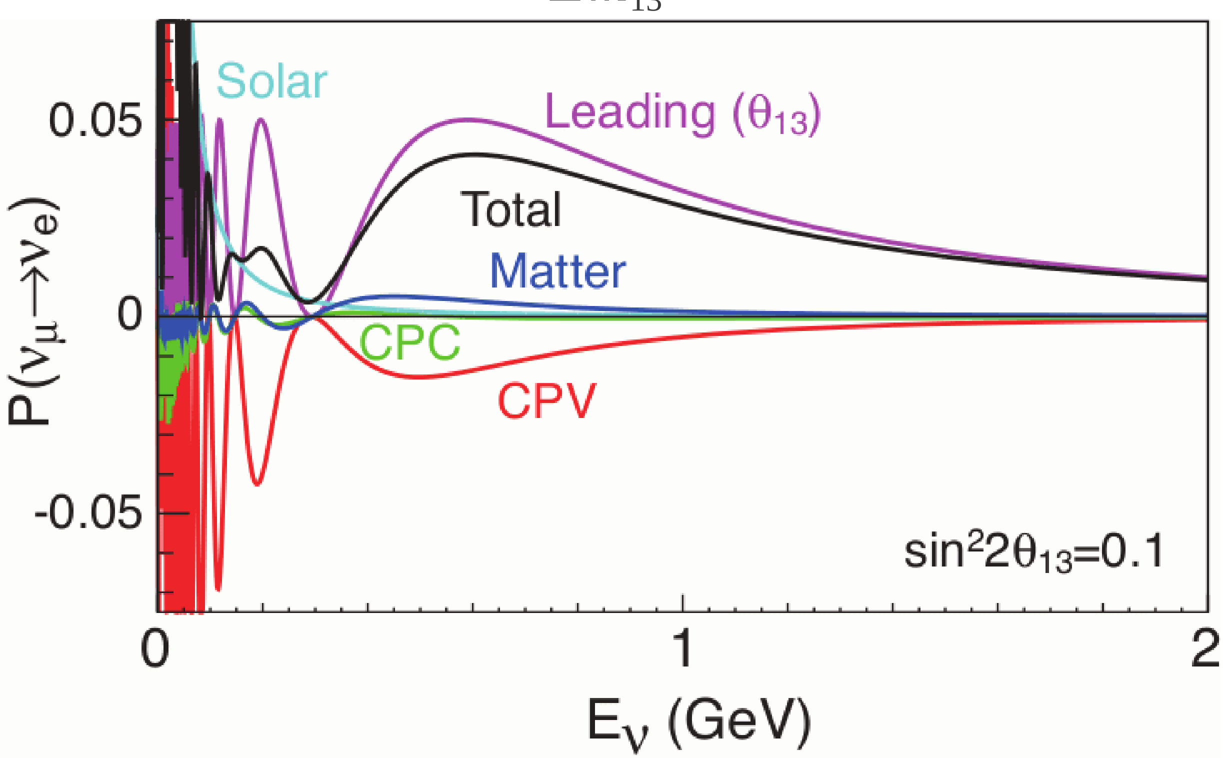
$$\boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}}$$ $\boxed{\text{CPV}}$

$\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$ Solar

$$\left.\begin{aligned} &-8C_{13}^2 S_{12} S_{23}^2 \frac{aL}{4E_\nu}(1-2S_{13}^2)\cos\Phi_{32}\sin\Phi_{31} \\ &+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1-2S_{13}^2)\sin^2\Phi_{31} \end{aligned}\right\}$$ $\boxed{\text{Matter Effect}}$

$a = 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} eV^2 \frac{\rho}{gcm^{-3}} \frac{E}{GeV}$




Leading Term μ $\sin^2 2\theta_{13}$

CPV Term μ $\sin 2\theta_{13}$

Matter Effect μ $\sin^2 2\theta_{13}$

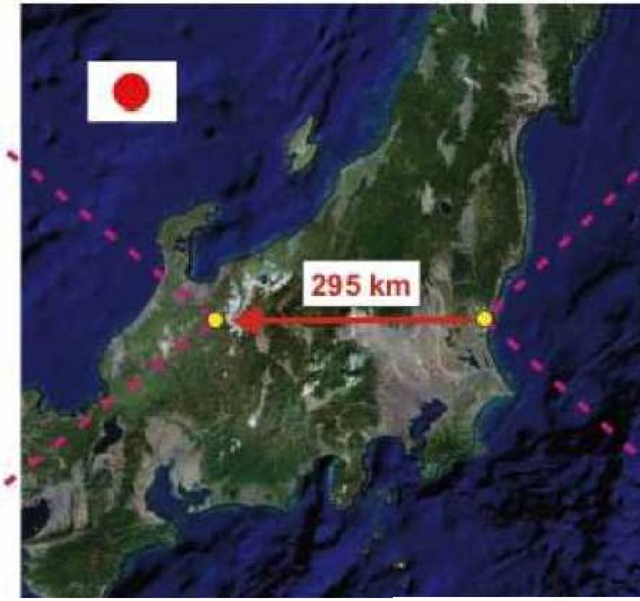
For large $\sin^2 2\theta_{13}$:

Signal ↑, CP Asymmetry ↓,

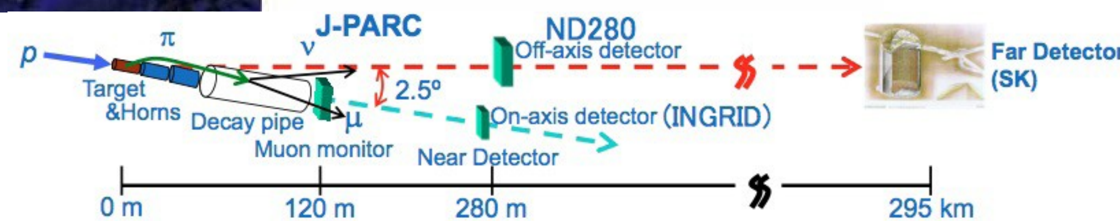
Matter/CP ↑

# Tokai-2-Kamioka (T2K)

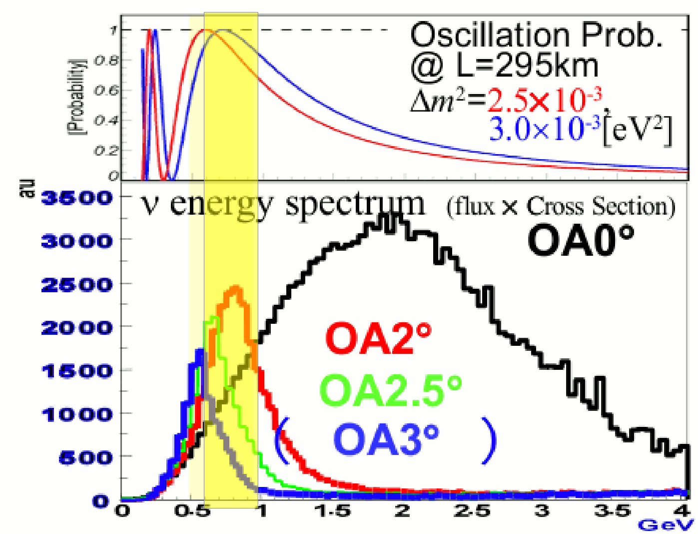
Far detector:
Super-Kamiokande
located near Kamioka




Beam source and near detectors:
J-PARC accelerator complex
located in Tokai-mura

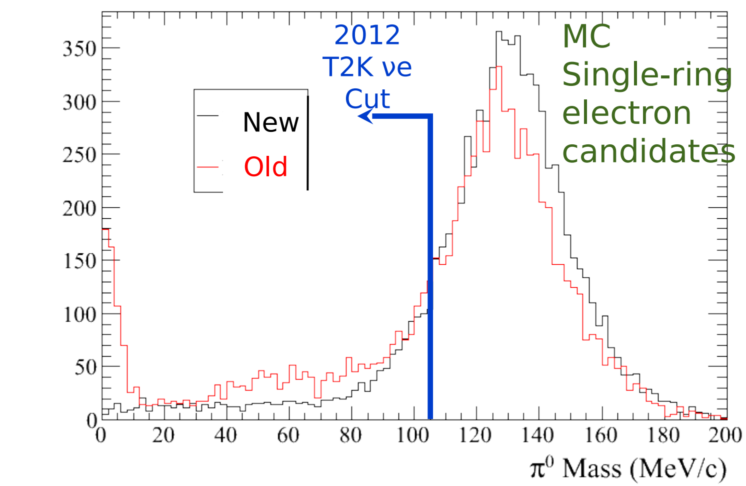



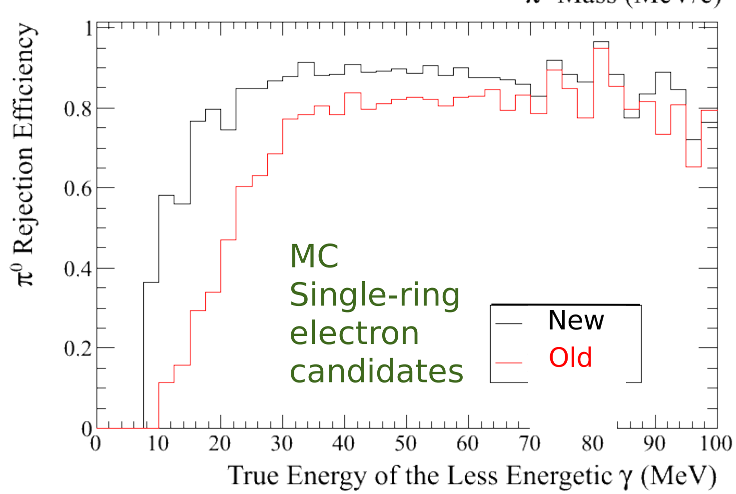

- Baseline 295 km
- Off-axis beam at 2.5°, concentrate at oscillation maximum →
- Suite of new detectors
- Far detector is SuperKamiokande (50kton water Cherenkov detector)



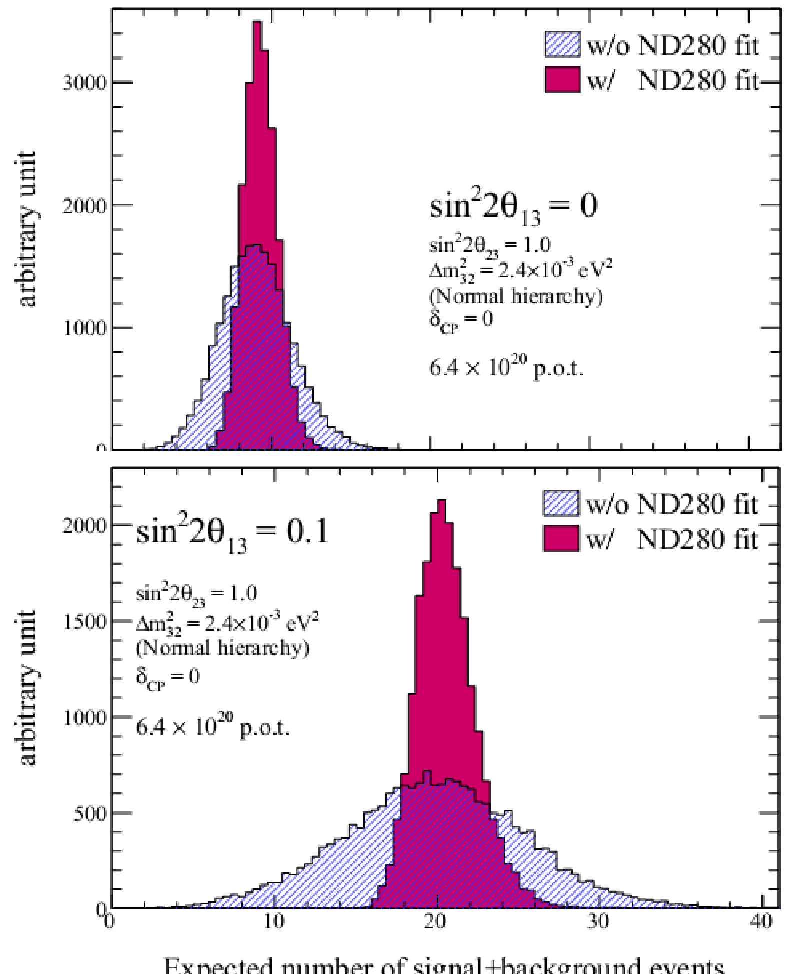
# T2K $\nu_e$ Appearance 2013 Results

- The background rejection cut is improved using a new SK reconstruction algorithm. The number of expected background events is reduced from 6.4 to 4.6.



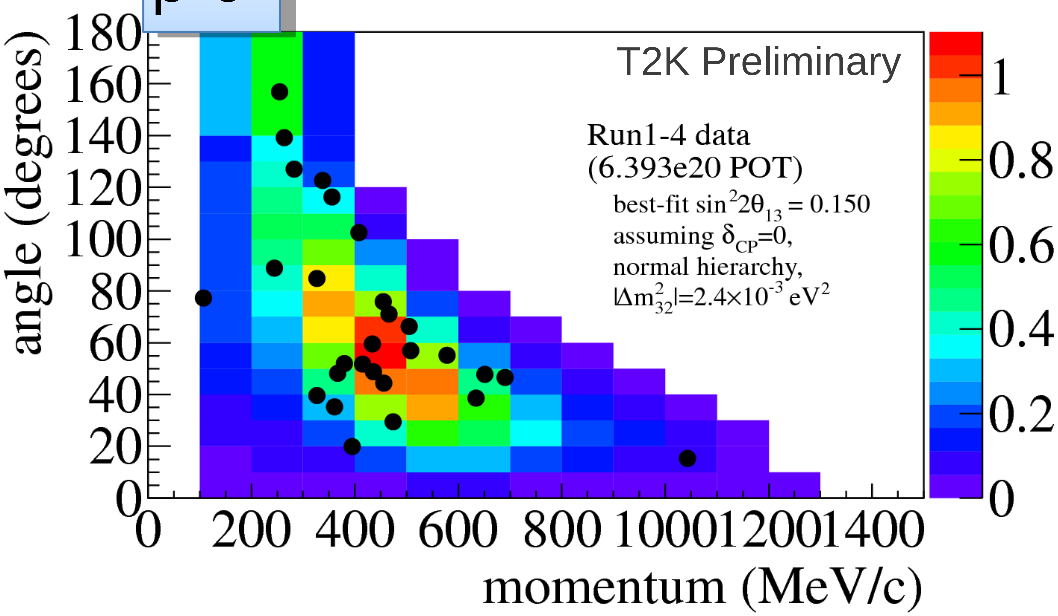

- The near detector measurement is improved using more topological categories.
- Predicted number of events error reduction due to ND280:



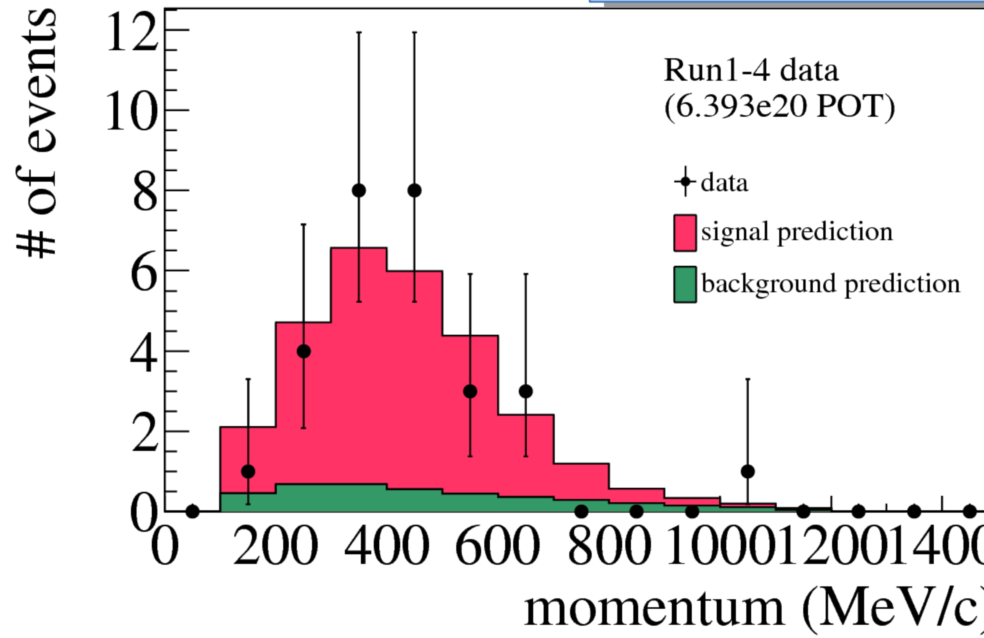

T2K Preliminary

# Results

p-θ




momentum




**Predicted # of events w/ 6.4×10²⁰ POT**

| Event category | $\sin^2 2\theta_{13}$=0.0 (0.1) |
|---|---|
| $\nu_e$ signal | 0.38 (16.42) |
| $\nu_e$ background | 3.17 (2.93) |
| $\nu_\mu$ background (mainly NC$\pi^0$) | 0.89 (0.89) |
| $\nu_\mu + \nu_e$ background | 0.20 (0.19) |
| Total | 4.64 (20.44) |
| Total (w/ 2012 flux & cross section parameters) | 5.15 (21.77) |

**Systematic uncertainties**

| Error source | $\mathrm{Sin}^2 2\theta_{13}$=0.0 (0.1) |
|---|---|
| Beam flux + $\nu$ int. in T2K fit | 4.9 % (3.0 %) |
| $\nu$ int. (from other exp.) | 6.7 % (7.5 %) |
| Far detector (+FSI+SI+PN) | 7.3 % (3.5 %) |
| Total | 11.1 % (8.8 %) |
| Total (2012) | 13.0 % ( 9.9 %) |

# T2K $\nu_e$ Appearance Fit Results

- Fit using (p,θ) distributions
- Note $\sin^2\theta_{23}$ is fixed to 0.5 in the fit.
- Best fit value w/ 68% CL error @ $\delta_{CP}$ = 0.

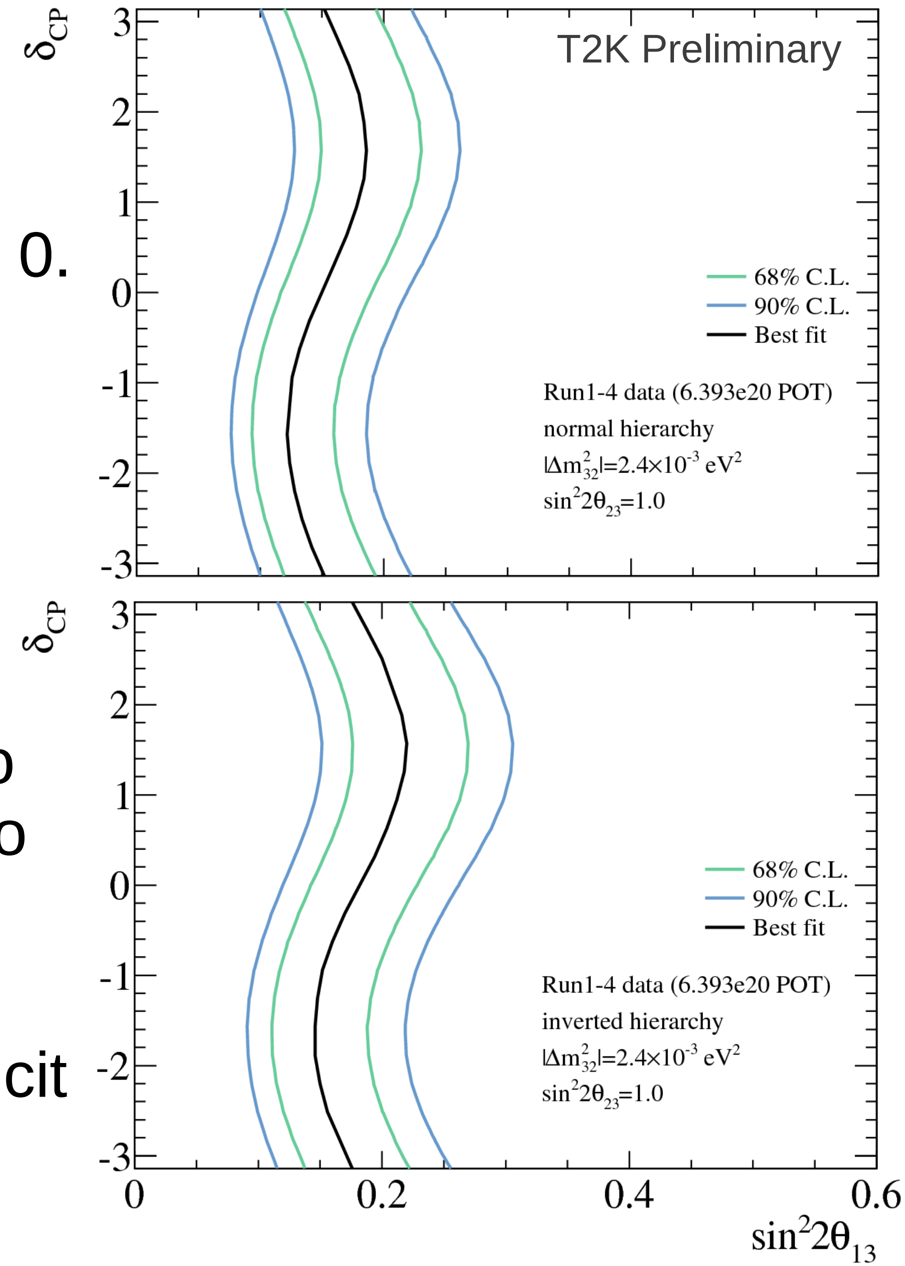
**normal hierarchy:**

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

**inverted hierarchy:**

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

- Comparing the best p-θ fit likelihood to null hypothesis gives a 7.4σ for non-zero $\theta_{13}$ - for $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy.
- First ever observation (>5σ) of an explicit ν appearance channel




NB: These are 1D contours for values of $\delta_{CP}$, not 2D contours in $\delta_{CP}$-$\theta_{13}$ space

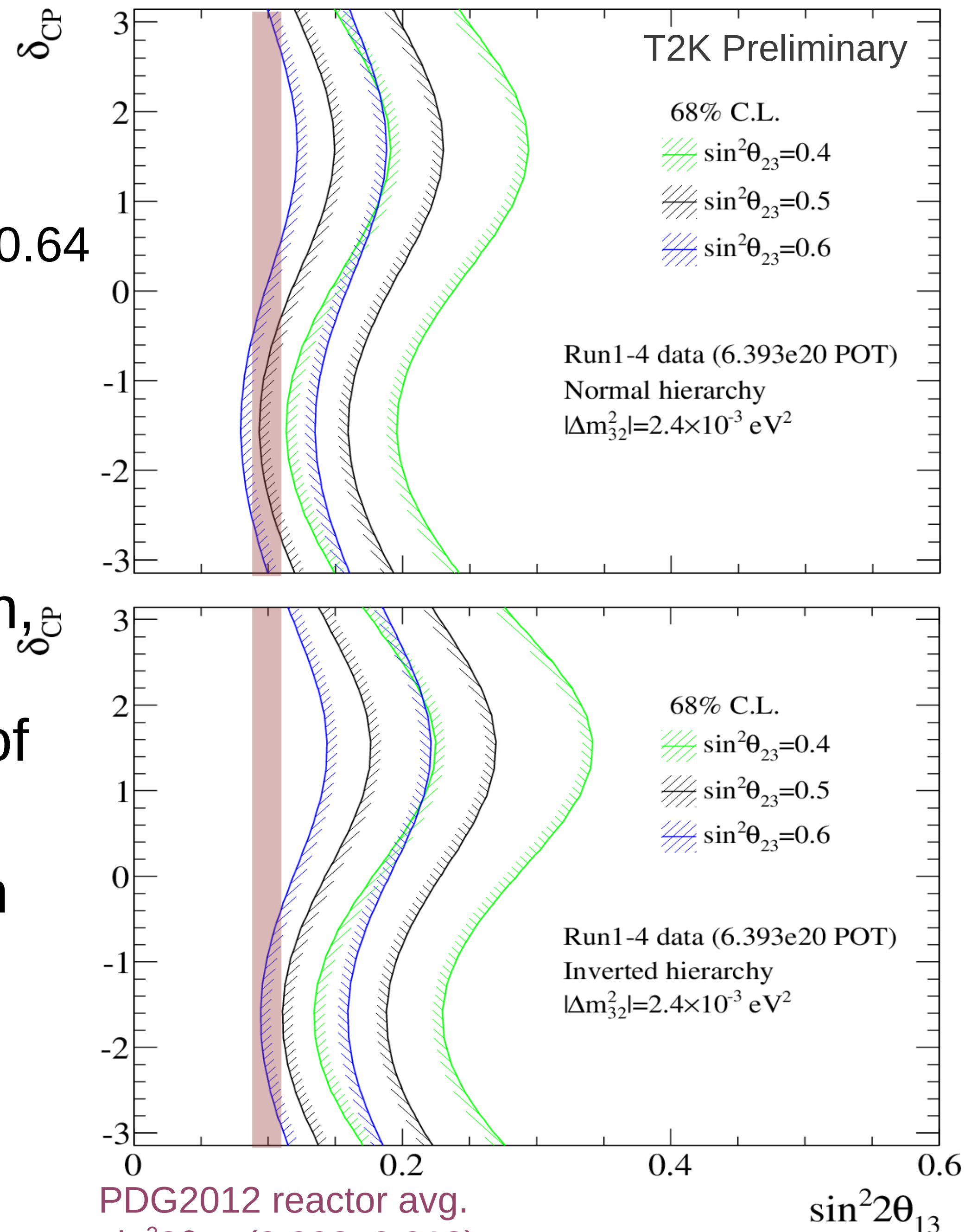
# $\delta_{CP}$ vs $\sin^2 2\theta_{13}$ for different $\theta_{23}$

$$P_{\mu \to e} \sim \boxed{\sin^2 2\theta_{13} \sin^2 \theta_{23}} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

+ (solar term) + (CP interference term) + (matter term)

Note: PDG 2012 2σ region for $\sin^2\theta_{23}$: 0.34-0.64

- $\nu_e$ appearance probability also depends on the value of $\theta_{23}$
- If $\theta_{23}$ is fixed at values near the edge of the current allowed region, the fit contours shift.
- Future improved measurements of $\theta_{23}$ will be important to extract information about other oscillation parameters (including $\delta_{CP}$) in long baseline experiments
- A T2K combined $\nu_e$+$\nu_\mu$ analysis is underway



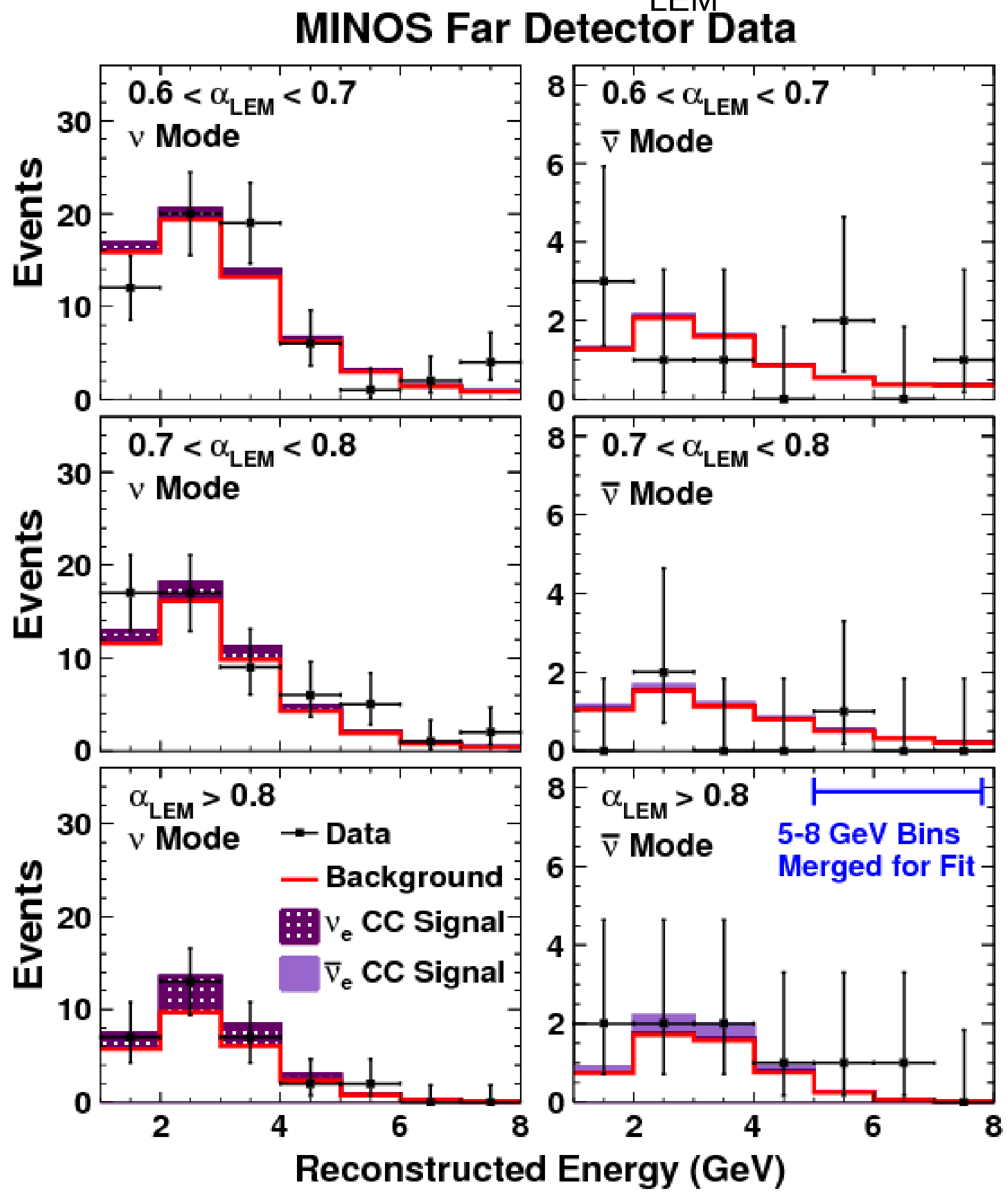

PDG2012 reactor avg.
$\sin^2 2\theta_{13}$=(0.098±0.013)

# MINOS $\nu_e$ Appearance Results

PRL 110, 171801(2013)

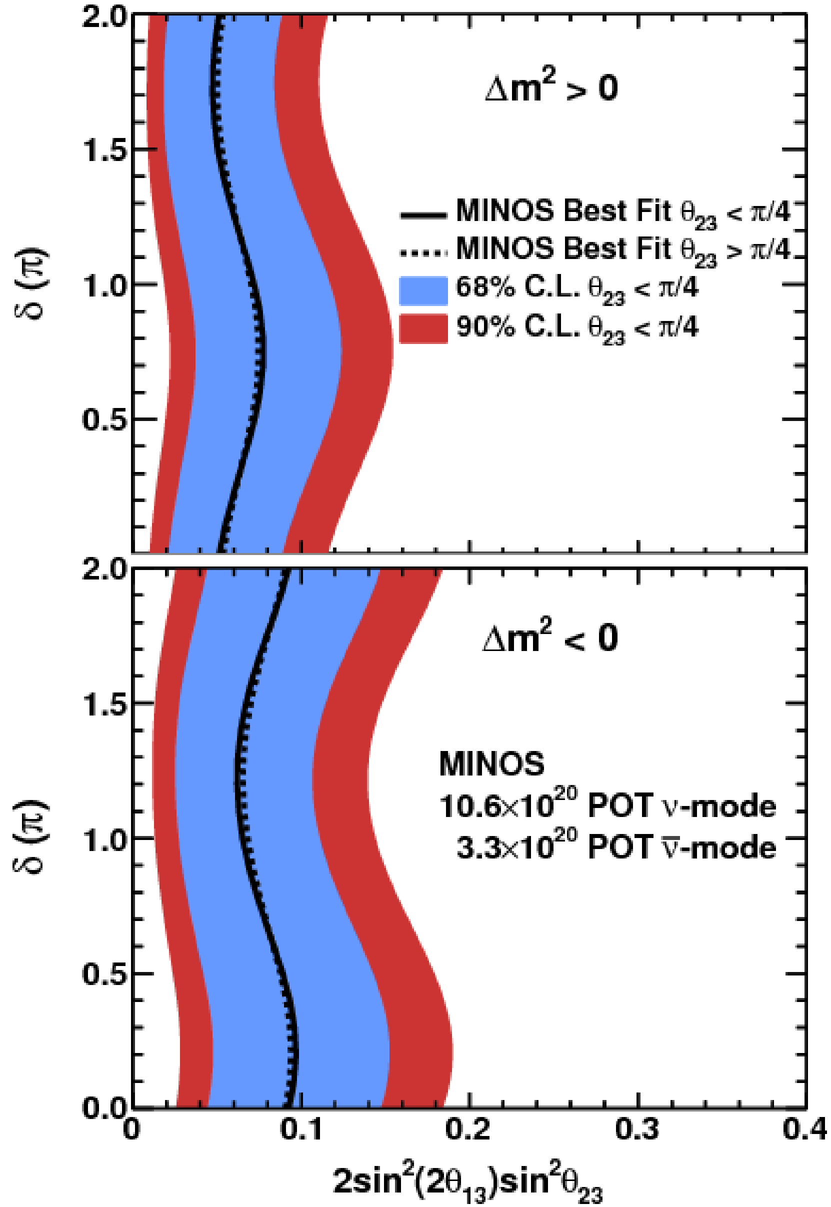

| Event Type | $\nu$ beam mode | $\bar{\nu}$ beam mode |
|---|---|---|
| NC | 89.4 | 13.9 |
| $\nu_\mu$-CC and $\bar{\nu}_\mu$-CC | 21.6 | 1.0 |
| Intrinsic $\nu_e$-CC and $\bar{\nu}_e$-CC | 11.9 | 1.8 |
| $\nu_\tau$-CC and $\bar{\nu}_\tau$-CC | 4.8 | 0.8 |
| $\nu_\mu \to \nu_e$-CC | 33.0 | 0.7 |
| $\bar{\nu}_\mu \to \bar{\nu}_e$-CC | 0.7 | 3.2 |
| Total | 161.4 | 21.4 |
| Data | 152 | 20 |

Reconstructed energy $\alpha_{LEM}$ ranges.

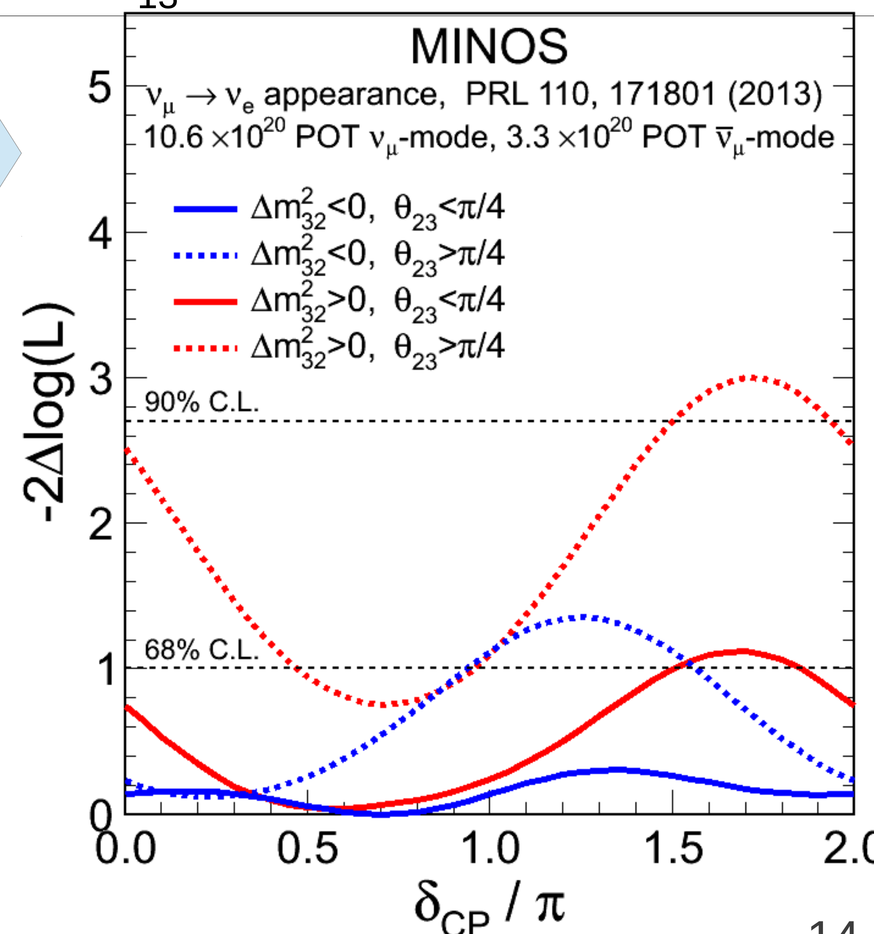


# MINOS $\nu_e$ Appearance Results

Confidence intervals of allowed values for $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ as a function of $\delta$.

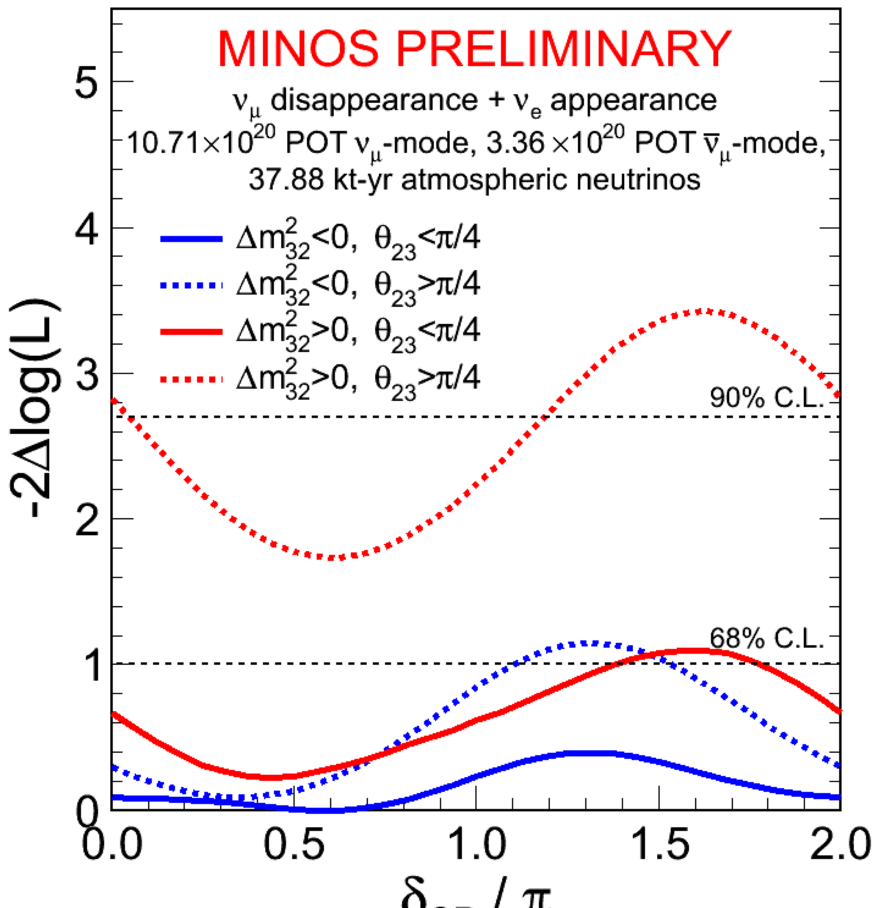


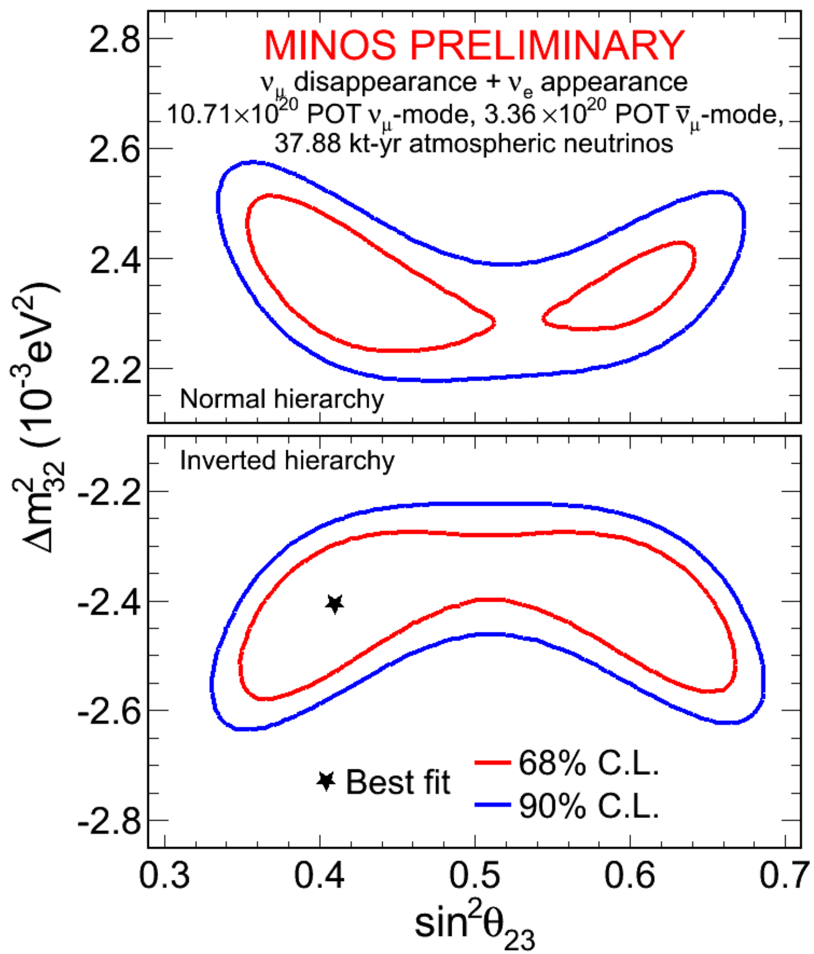

- Three flavour elec. neutr. appearance
- Fit both $\nu_e$ and $\bar{\nu}_e$:
  - $\sin^2 2\theta_{13} = 0.053$ (0.094)
  - $\sin^2 2\theta_{13} > 0$ (96%)



# Appearance & Disappearance Results

- Combine the information from both fits
  - Each provides a 4D likelihood surface in $\Delta m^2_{32}$, $\sin^2\theta_{23}$ $\sin^2\theta_{13}$, and $\delta_{CP}$
- Systematics assumed to be uncorrelated.




- Normal hierarchy, upper octant case is now further disfavoured.
  - At least 90% C.L for half $\delta_{CP}$ range.
- Slight preference for the inverted hierarchy
- Normal hierarchy, higher octant disfavoured

# Appearance & Disappearance Results

- Combine the information from both fits
  - Each provides a 4D likelihood surface in $\Delta m^2_{32}$, $\sin^2\theta_{23}$ $\sin^2\theta_{13}$, and $\delta_{CP}$
- Systematics assumed to be uncorrelated
- The four local best fit points:

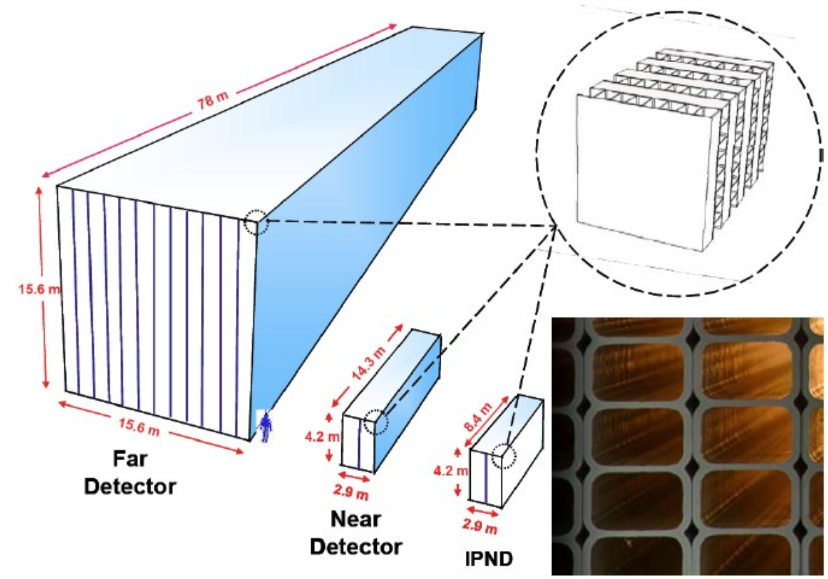
| Hierarchy | Octant | Best fit parameters | | | | $-2\Delta\log(L)$ |
|---|---|---|---|---|---|---|
| | | $\Delta m^2_{32}/10^{-3}eV^2$ | $\sin^2\theta_{23}$ | $\sin^2\theta_{13}$ | $\delta_{CP}/\pi$ | |
| Normal | Lower | 2.37 | 0.41 | 0.0242 | 0.44 | 0.23 |
| Normal | Higher | 2.35 | 0.61 | 0.0238 | 0.62 | 1.74 |
| Inverted | Lower | -2.41 | 0.41 | 0.0243 | 0.62 | - |
| Inverted | Higher | -2.41 | 0.61 | 0.0241 | 0.37 | 0.09 |

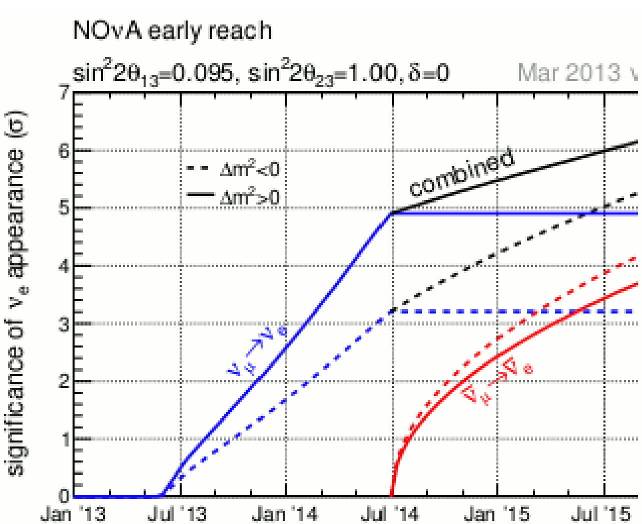
| Hierarchy | $\Delta m^2_{32}$ / $10^{-3}$ eV$^2$ | $\sin^2\theta_{23}$ (90% C.L.) |
|---|---|---|
| Normal | $2.37^{+0.09}_{-0.09}$ | $0.35 < \sin^2\theta_{23} < 0.65$ |
| Inverted | $-2.41^{+0.12}_{-0.09}$ | $0.34 < \sin^2\theta_{23} < 0.67$ |

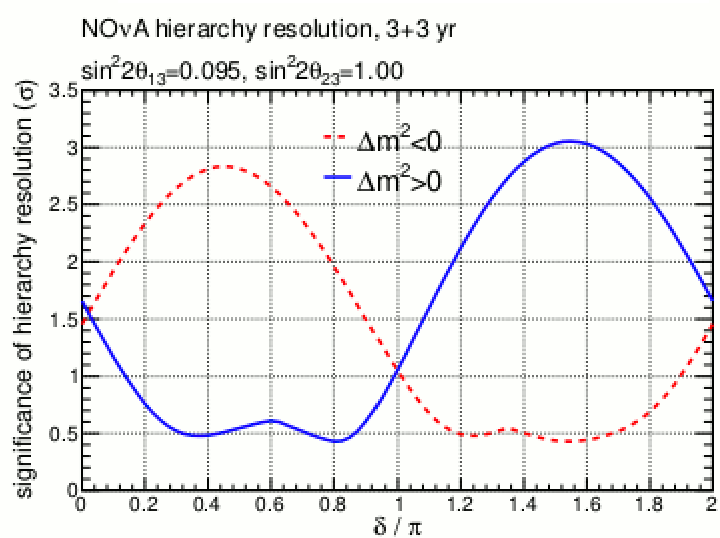
- Prefer non-maximal mixing at 76%.

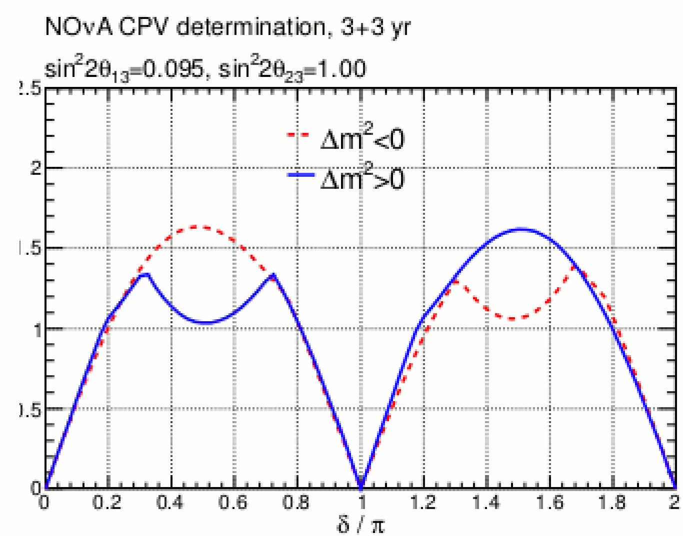
# NOvA


- Currently taking data. ND will be finished to be built next year.
- Main physics goals:
  - Mass hierarchy
  - Observe $\nu_\mu \rightarrow \nu_e$ and first observation of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



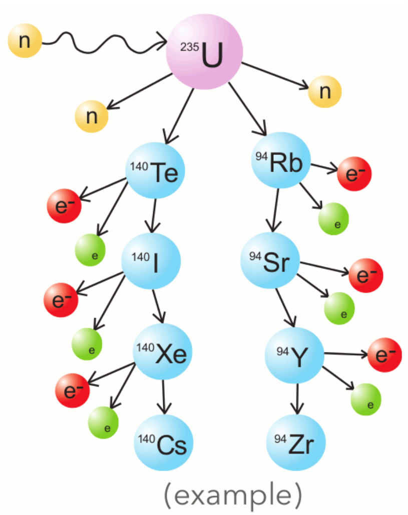



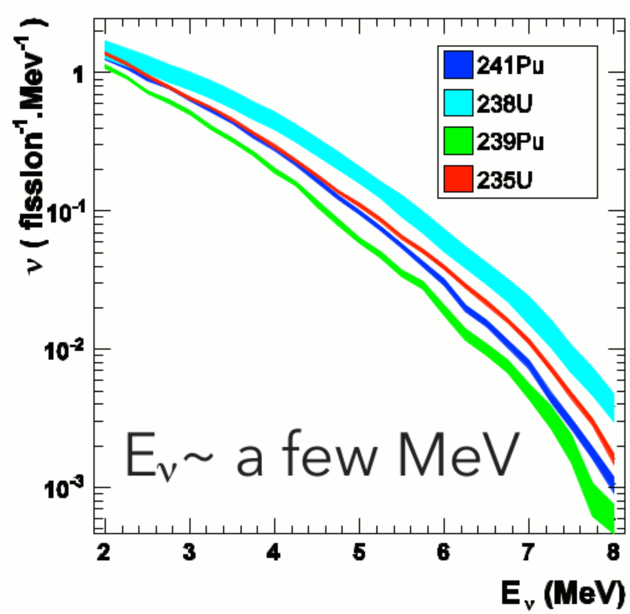



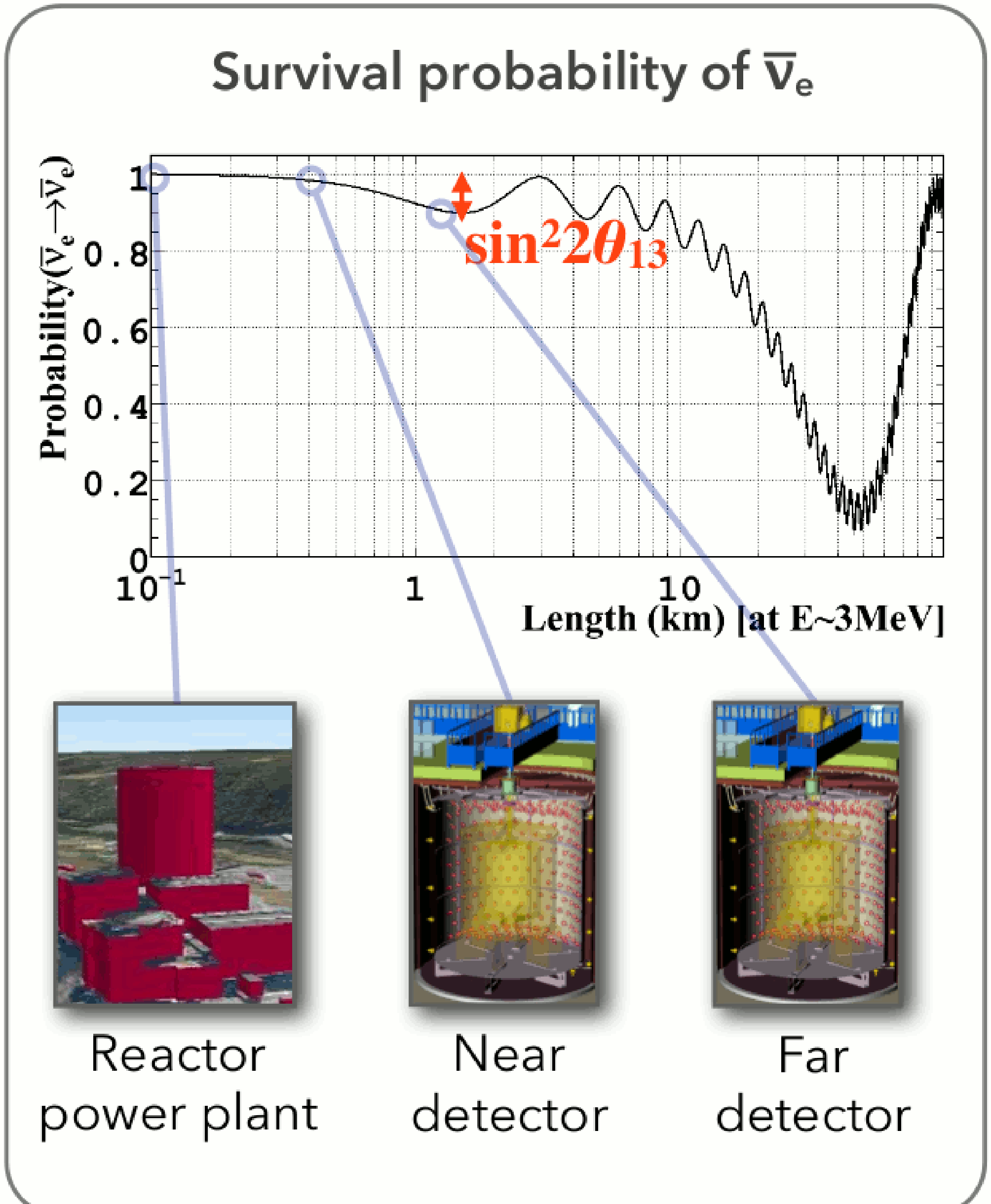
# Principle of Reactor $\theta_{13}$ Measurement

- Reactors are powerful and "free" sources of low-energy (isotropic) neutrinos.
- Electron antineutrinos emitted through decays of fission products of $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu.

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O\,10^{-3}$$



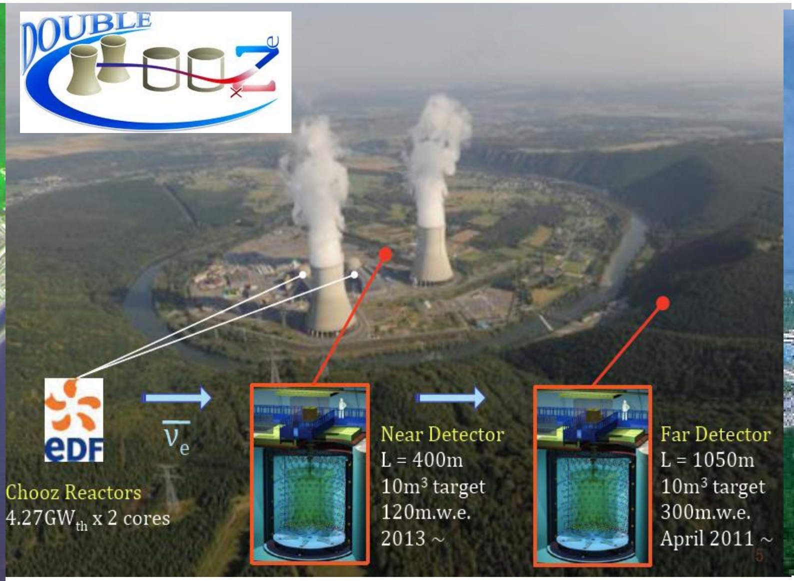




Th. A. Mueller et al., Phys. Rev. C83 (2011) 054615
P. Huber, Phys. Rev. C84 (2011) 024617

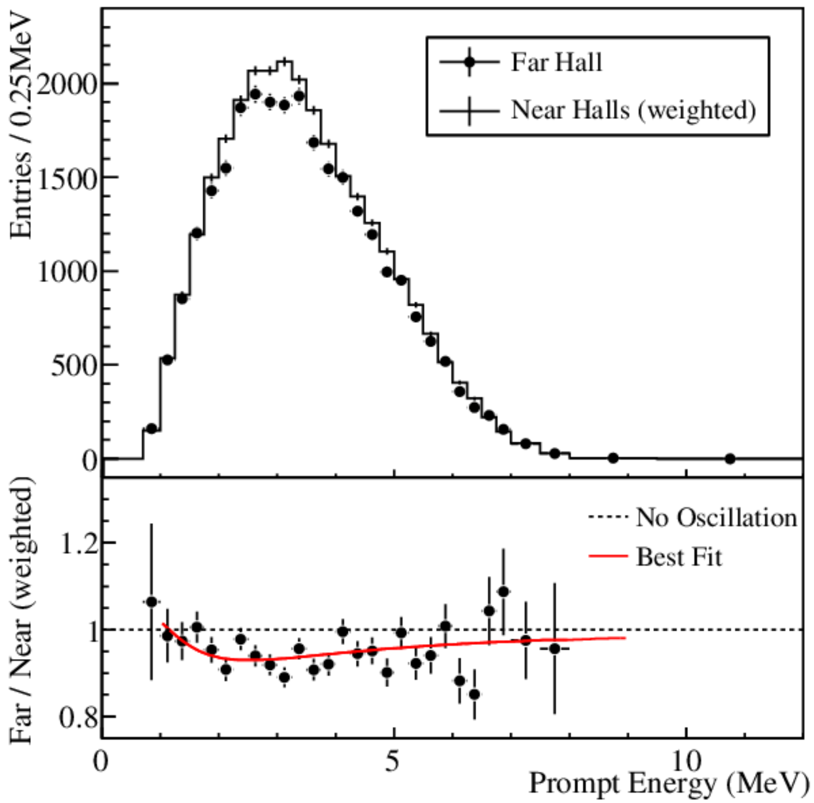
# Reactor experiments for $\theta_{13}$

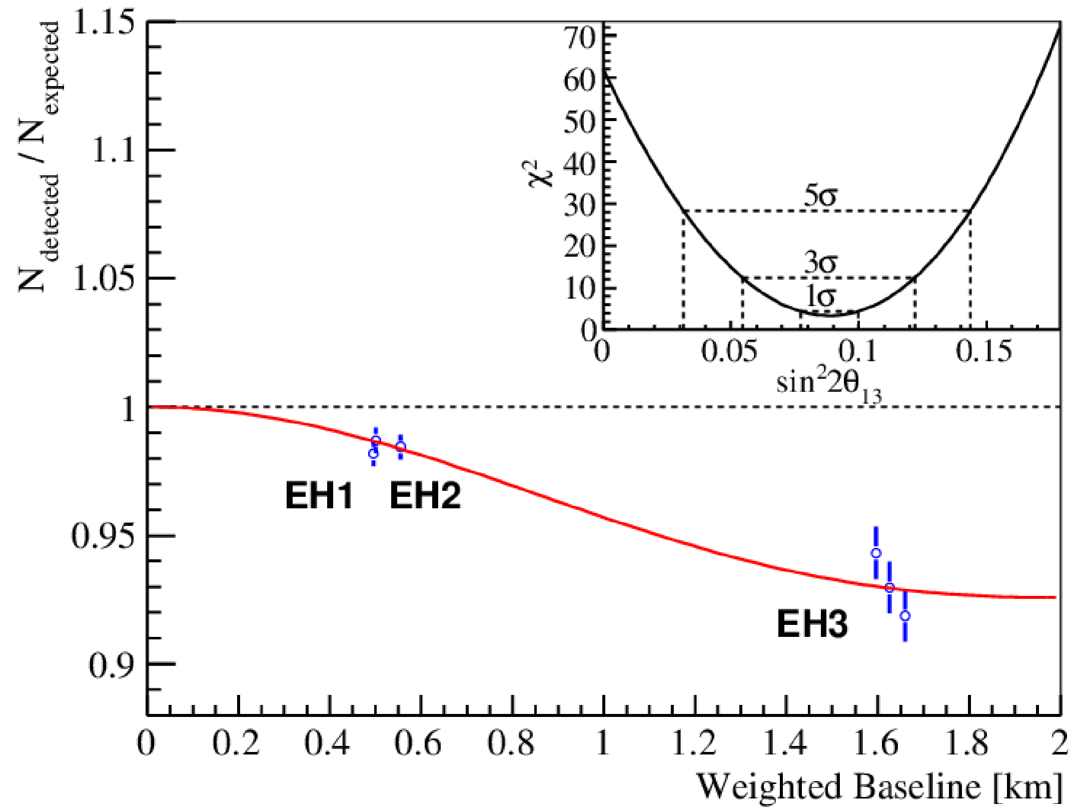
| Experiment | Power (GW) | Baseline (m) Near/Far | Detector (t) Near/Far | Overburden (MWE) Near/Far | Designed Sensitivity (90% CL) |
|---|---|---|---|---|---|
| Daya Bay | 17.4 | 470/576/1650 | 40/40/80 | 250/265/860 | ~0.008 |
| Double Chooz | 8.5 | 400/1050 | 8.2/8.2 | 120/300 | ~0.03 |
| Reno | 16.5 | 409/1444 | 16/16 | 120/450 | ~0.02 |


# Daya Bay Rate-Only Results

F.P. An et al., Chin. Phys.C 37(2013) 011001



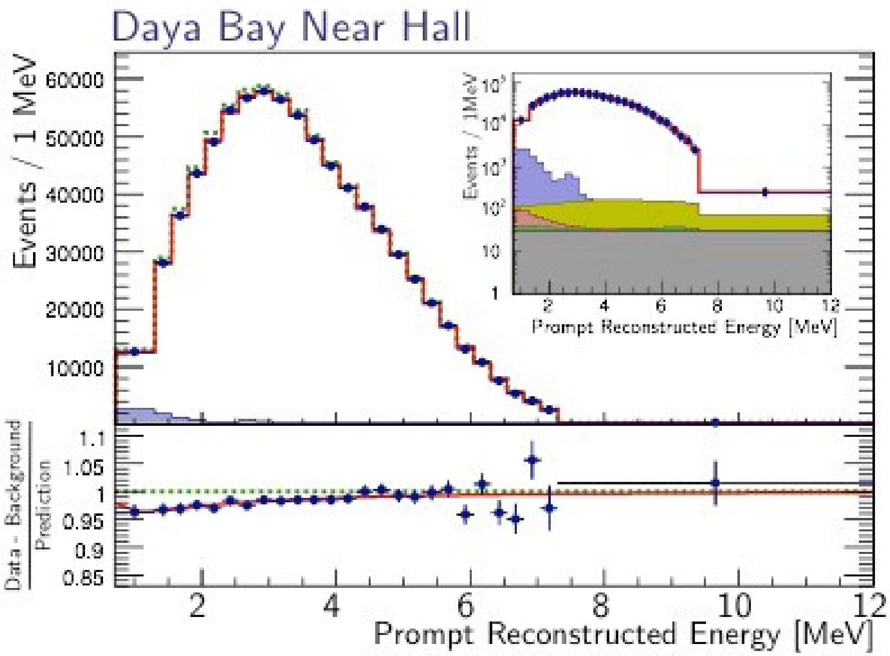

R= 0.944 ± 0.007 (stat) ± 0.003 (syst)

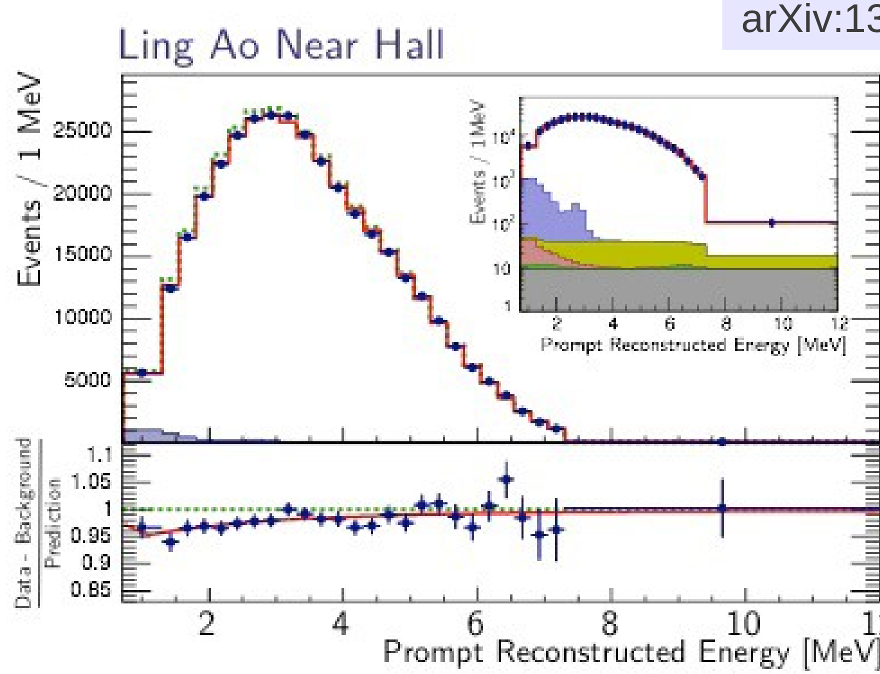
$\sin^2 2\theta_{13}$ = 0.098 ± 0.010 (stat) ± 0.005 (syst)

$\chi^2$/ndof = 3.4/4, 7.7$\sigma$ for non zero $\theta_{13}$

# Dataset for Spectrum Analysis

arXiv:1310.6732



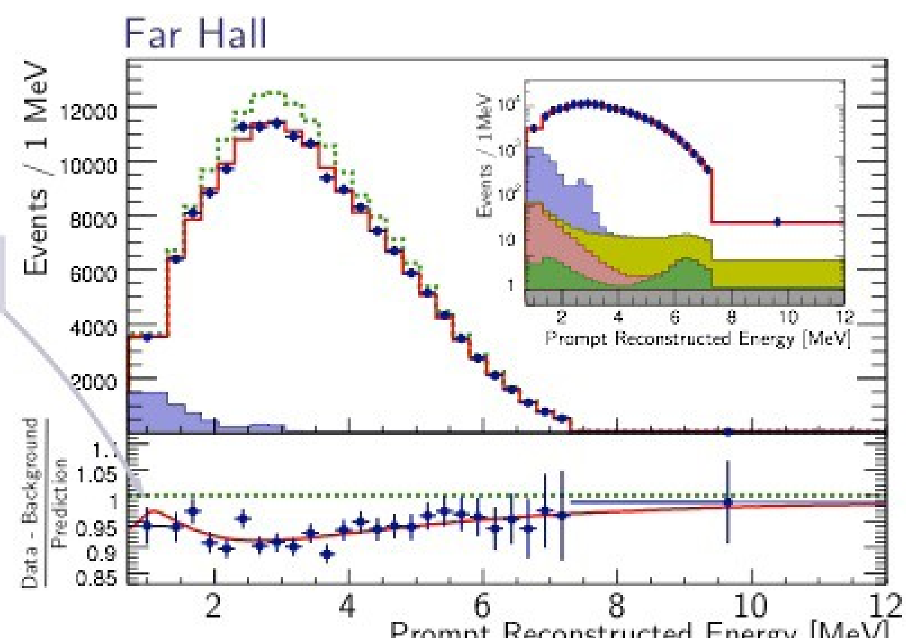





## Spectral distortion consistent with oscillation

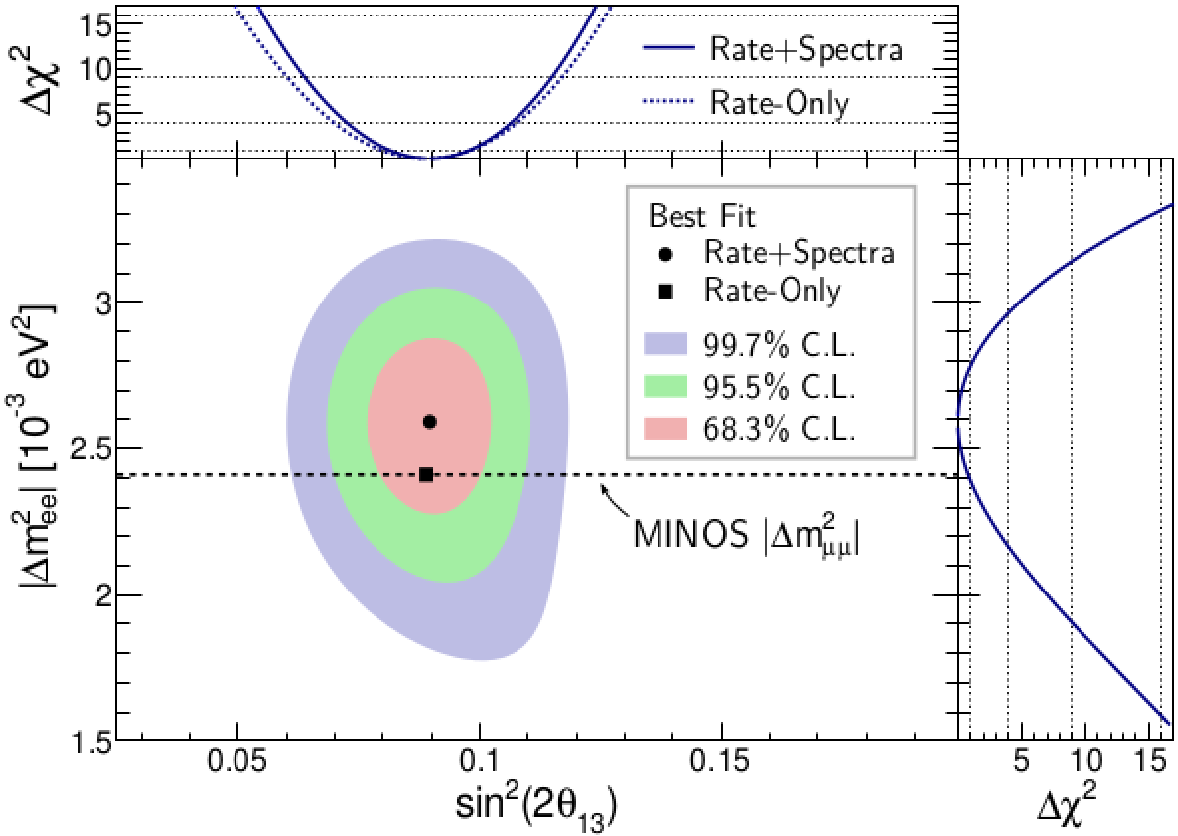
- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

Shape distortion from energy losses in acrylic



# Rate + Spectra Oscillation Results

arXiv:1310.6732




$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\mathrm{eV}^2$$

First Measurement

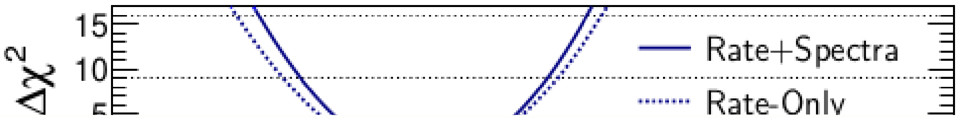
$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$

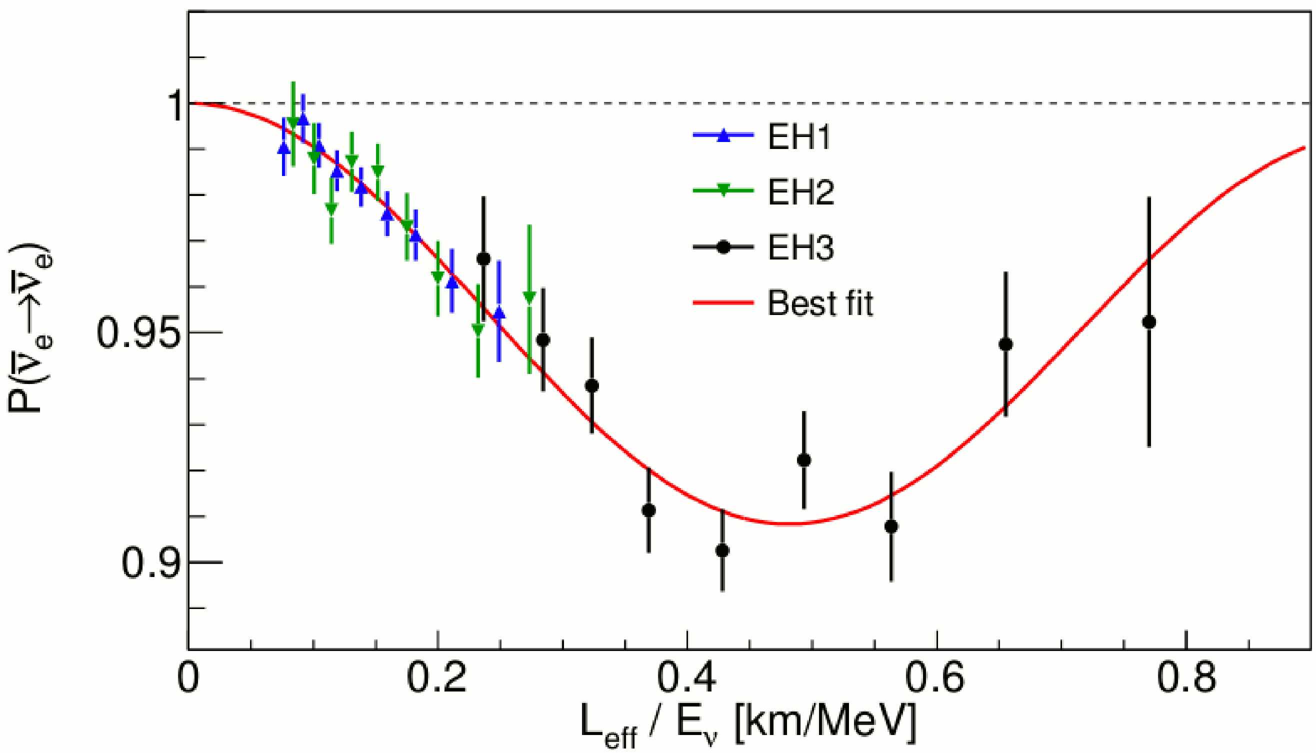
Strong confirmation of oscillation-interpretation of observed $\nu_e$ deficit

| | Normal MH $\Delta m^2_{32}$ [$10^{-3}$eV$^2$] | Inverted MH $\Delta m^2_{32}$ [$10^{-3}$eV$^2$] |
|---|---|---|
| From Daya Bay $\Delta m^2_{ee}$ | $2.54^{+0.19}_{-0.20}$ | $-2.64^{+0.19}_{-0.20}$ |
| From MINOS $\Delta m^2_{\mu\mu}$ | $2.37^{+0.09}_{-0.09}$ | $-2.41^{+0.11}_{-0.09}$ |

# Rate + Spectra Oscillation Results

arXiv:1310.6732




$2\theta_{13} = 0.090^{+0.008}_{-0.009}$

$m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\,\mathrm{eV}^2$

First Measurement

$N_{\mathrm{DoF}} = 162.7/153$

of observed $\nu_e$ deficit

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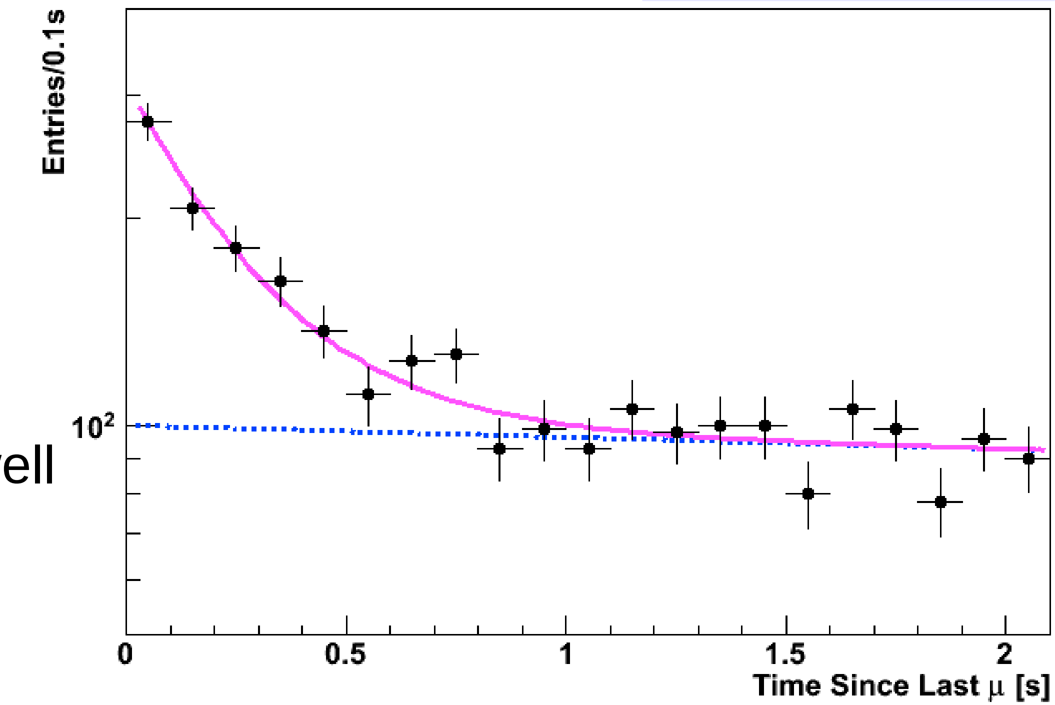
# RENO: Improved $^{9}Li/^{8}He$ Background

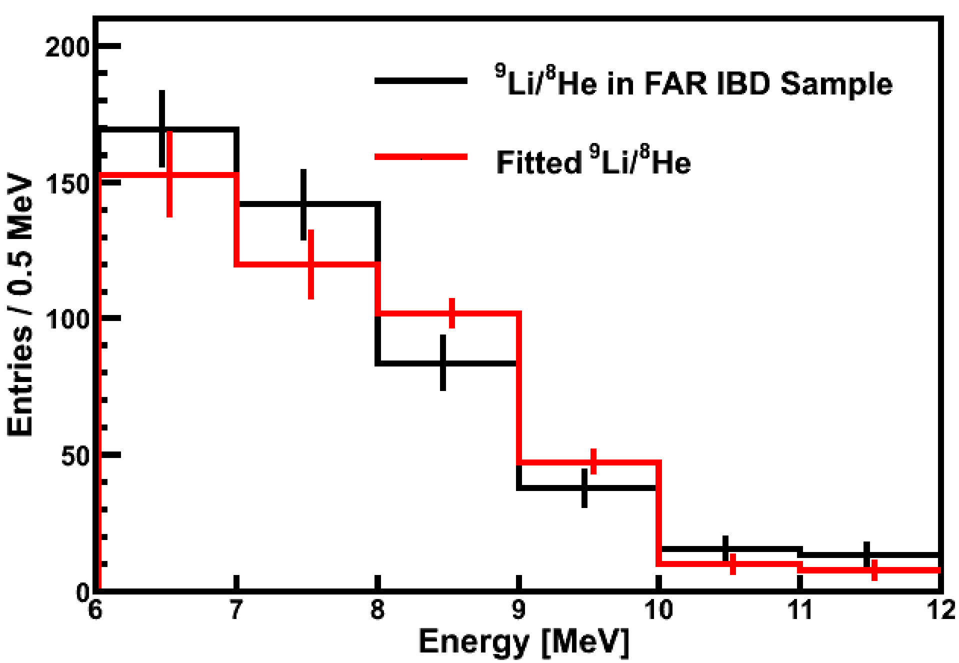
RENO Preliminary

$^{9}Li/^{8}He$ background estimation has been improved.

- fit range: 8 MeV → 6.5 MeV
- increased statistics of BG sample

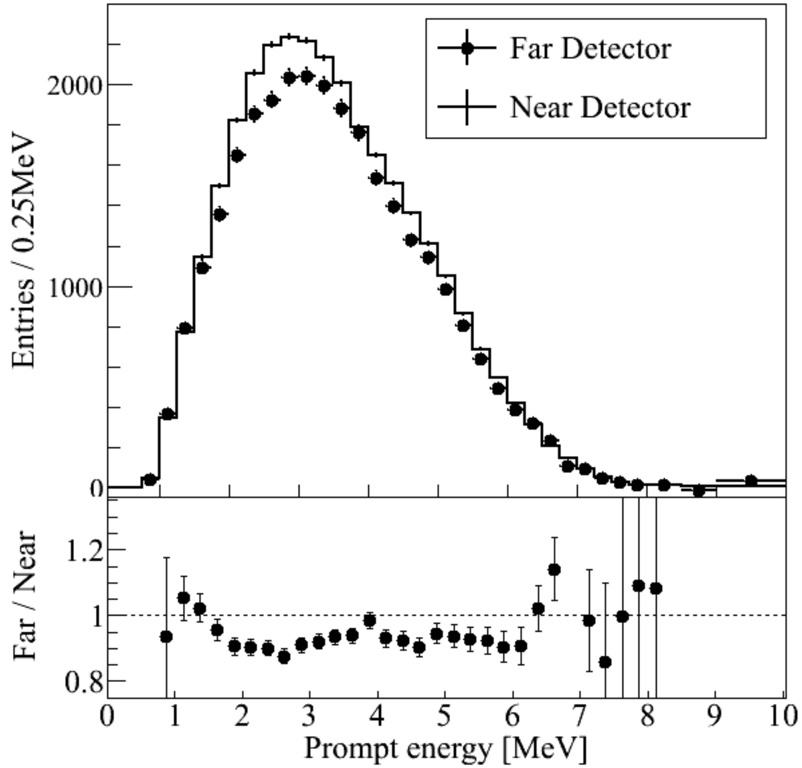



Fitted shape from bkg. sample matches well within the $^{9}Li/^{8}He$ shape contained in IBD sample.




Far
3.61±0.11(stat.)±0.59(sys.) /day
→3.55±0.11(stat.)±0.44(sys.) /day
Near
13.73±0.22(stat.)±2.12(sys.) /day
→13.97±0.22(stat.)±1.52(sys.) /day

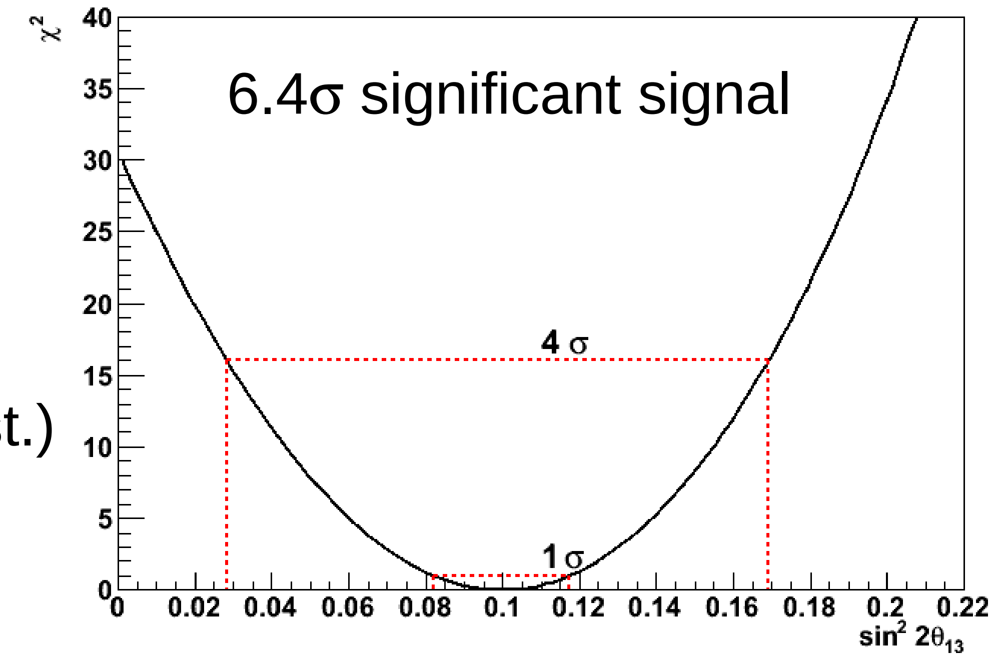
# RENO Results




RENO Preliminary

- A clear deficit in rate (7.0% reduction)
- Consistent with neutrino oscillation in the spectral distortion

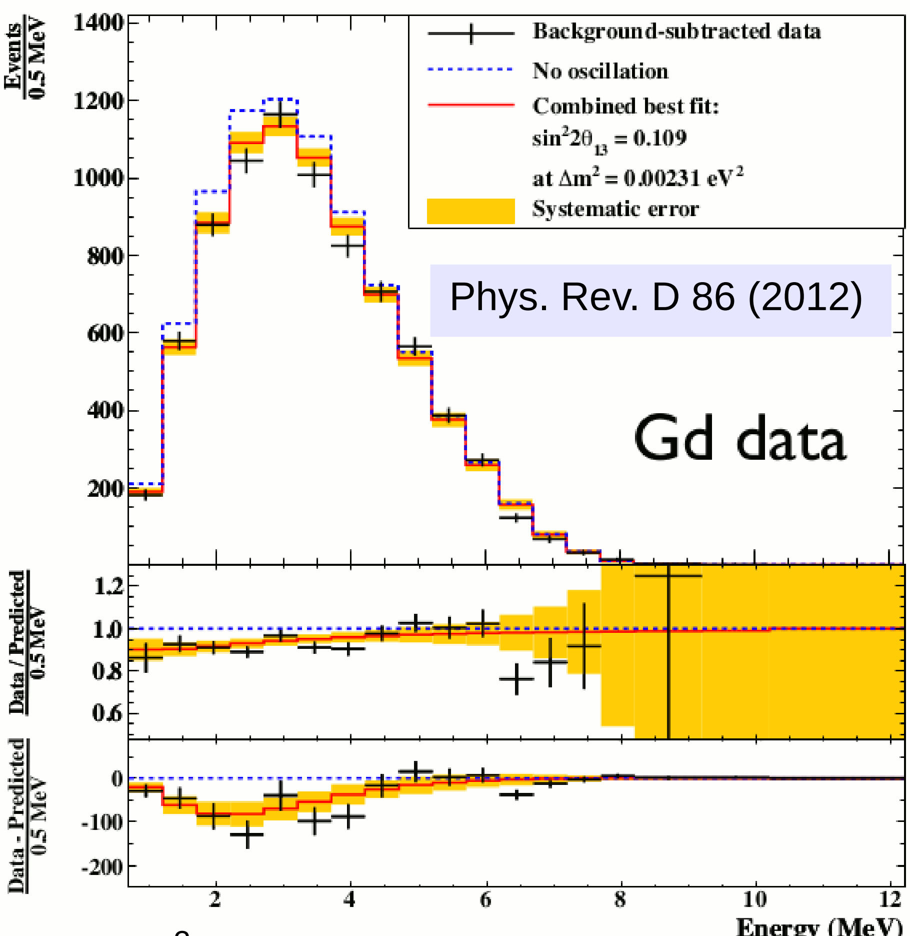
$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006\,(stat.) \pm 0.007\,(syst.)$$



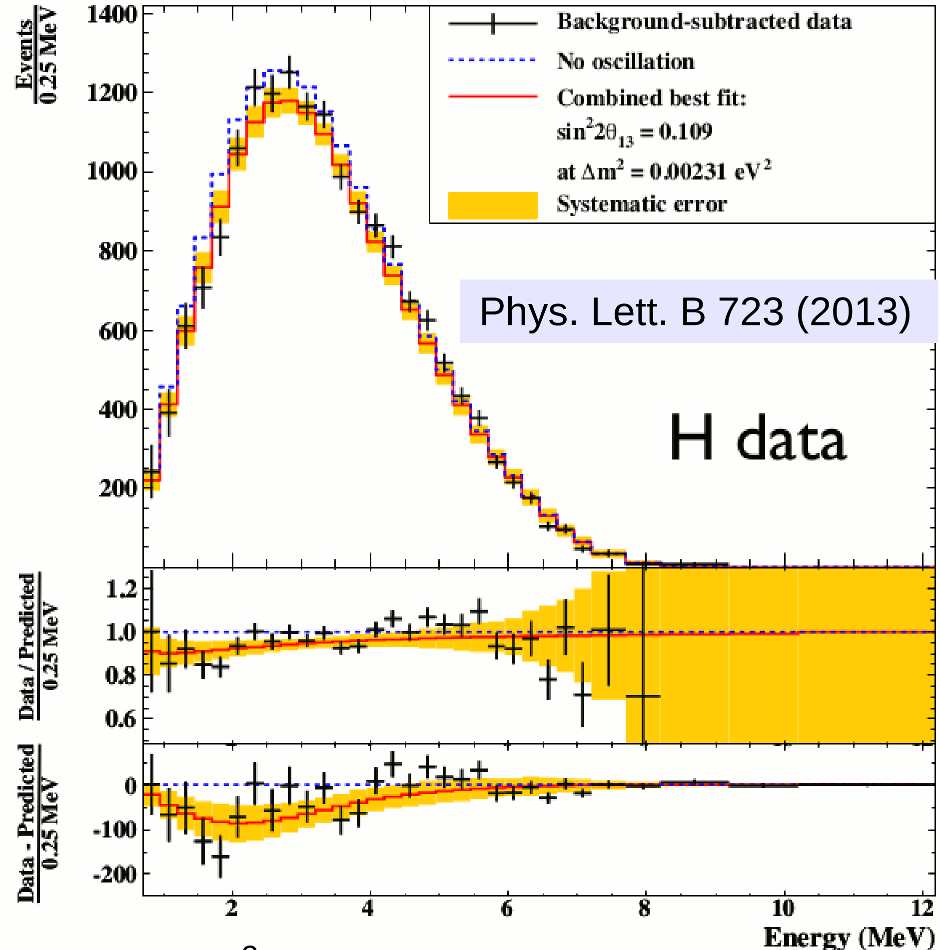

From $\chi^2$ fit:

$\sin^2 2\theta_{13} = 0.100 \pm 0.010(\text{stat.}) \pm 0.012(\text{syst.})$

# Double Chooz Results (Rate+Shape)




$\sin^2 2\theta_{13} = 0.109 \pm 0.039$




$\sin^2 2\theta_{13} = 0.097 \pm 0.048$

Data set: April 2011- March 2012

- Correlations of systematic uncertainties are included in fit
- Reactor off-off data used to constrain BG
- Rate+Shape (Gd & H): $\sin^2 2\theta_{13}$ = 0.109 ± 0.035 (preliminary)

# Reactor-off Background Measurement

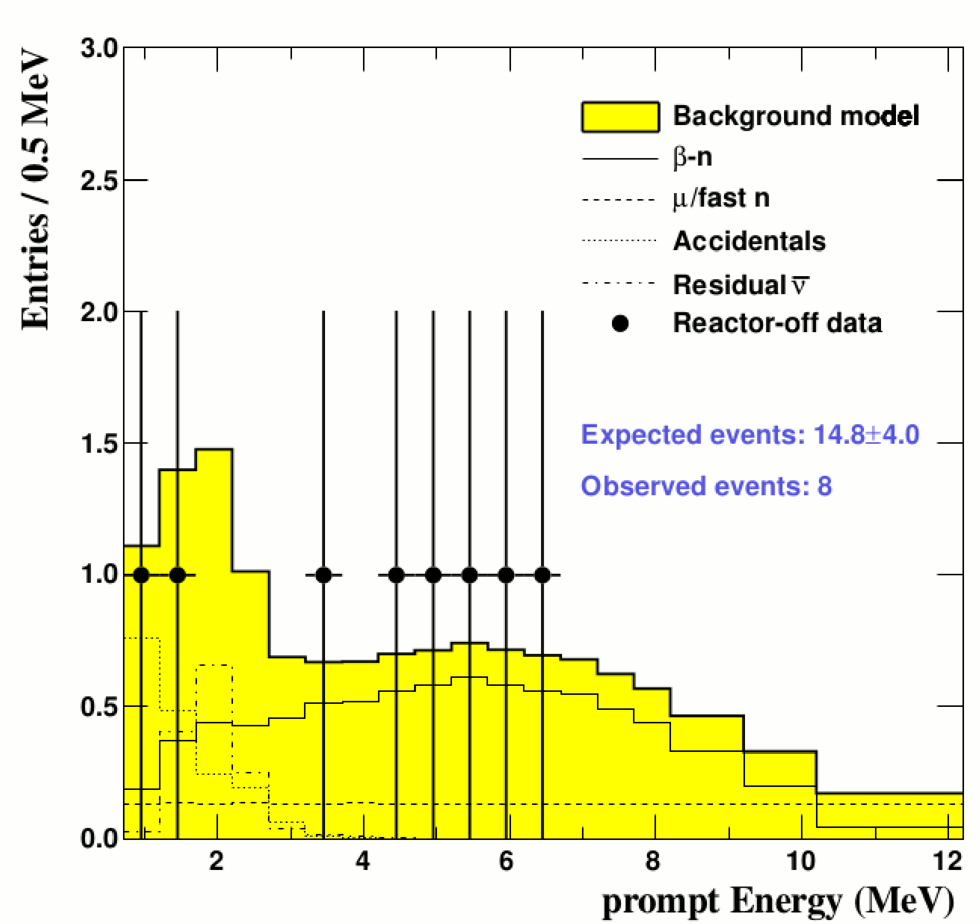
7.5 days of data with both reactors off
→ pure background data

- Unique Double Chooz capability
- Same selection than for Gd analysis.

- Rate consistent with predictions
  Observed: 1.0±0.4 [/day]
  Predicted: 2.0±0.6 [/day]

- New constraint for oscillation fit.

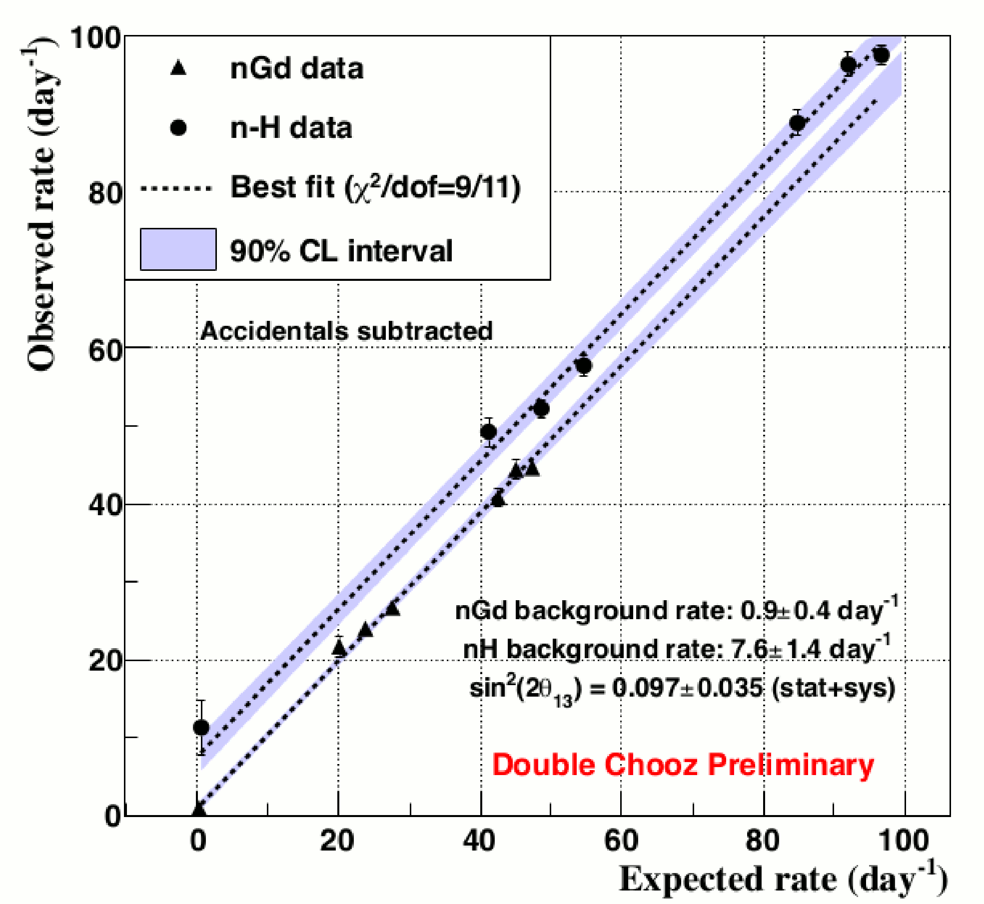
Phys. Rev. D 87 (2013) 011102(R)



# Reactor Rate Modulation analysis

Rate-only background-independent analysis

- Observed vs expected $\nu_e$ rate using different reactor power
  - Fit provides $\sin^2 2\theta_{13}$ and the total background rate
  - No background model assumed includes the reactors-off background

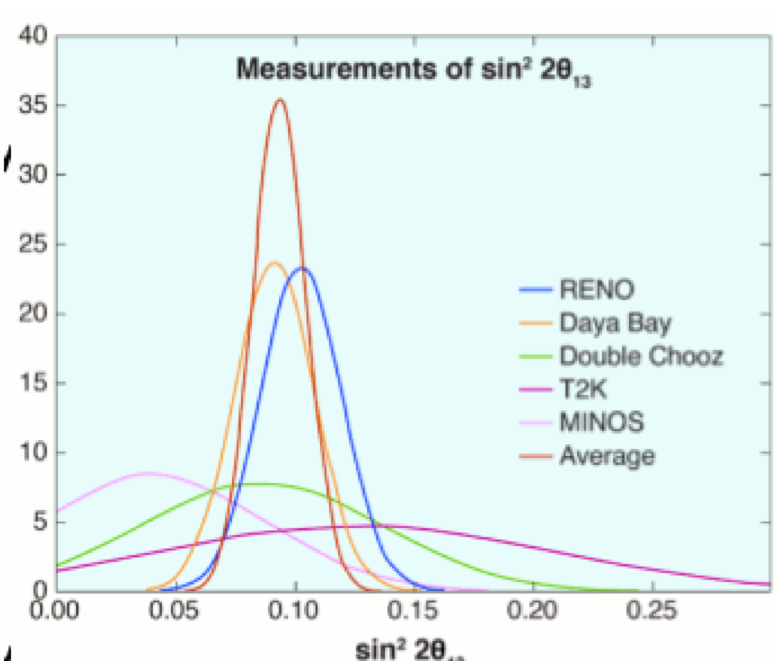



- Measurement Gd+H combined result: $\sin^2 2\theta_{13}$=0.097±0.035 (preliminary)

In agreement (~same precision) with R+S results

# Summary of the Latest Reactor Results

- Daya Bay:
  - Rate+Shape: $\sin^2 2\theta_{13}=0.090^{+0.008}_{-0.009}$
- RENO:
  - Rate: $\sin^2 2\theta_{13}=0.100\pm0.010(\text{stat.})\pm0.012(\text{syst.})$
- Double Chooz:
  - Rate+Shape: $\sin^2 2\theta_{13}= 0.109 \pm 0.035$
  - RRM: $\sin^2 2\theta_{13}= 0.097\pm0.035$




Working towards combined experimental results

I

2012 plot, not updated.

# Latest News on $\nu_\mu$ Disappearance Results

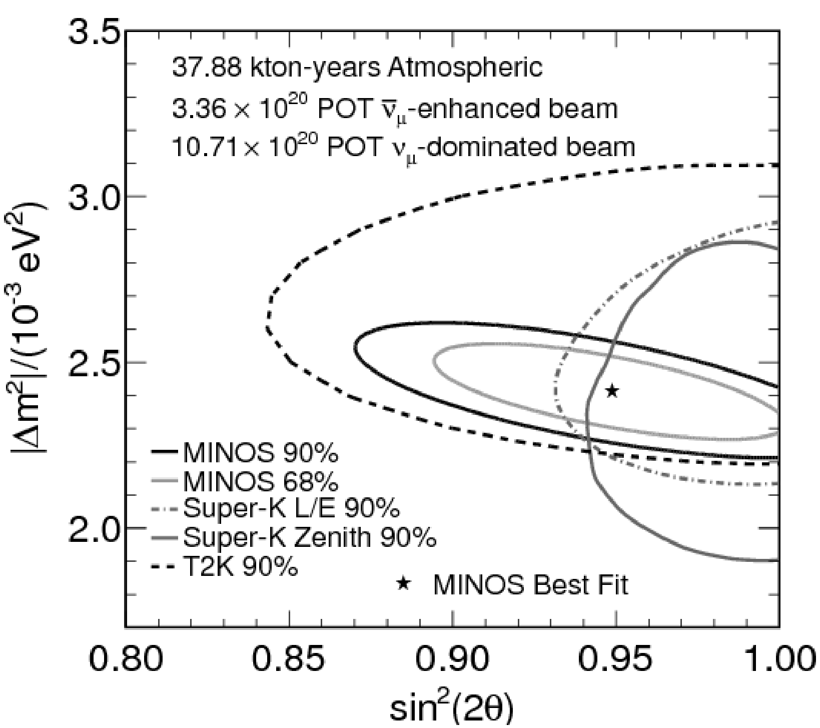
# MINOS $\nu_\mu$ disappearance $\nu$ vs. $\bar{\nu}$

- Leading measurement of $|\Delta m^2_{atm}|$ w/ 4.1% precision using accelerator and atmospheric $\nu$'s and $\bar{\nu}$'s.
- Consistent values for neutrinos and antineutrinos.
- Best- fit parameter values:

<u>Identical $\nu$ and $\bar{\nu}$ oscillations</u>

$$\sin^2\theta_{23} = 0.514 \pm 0.082$$

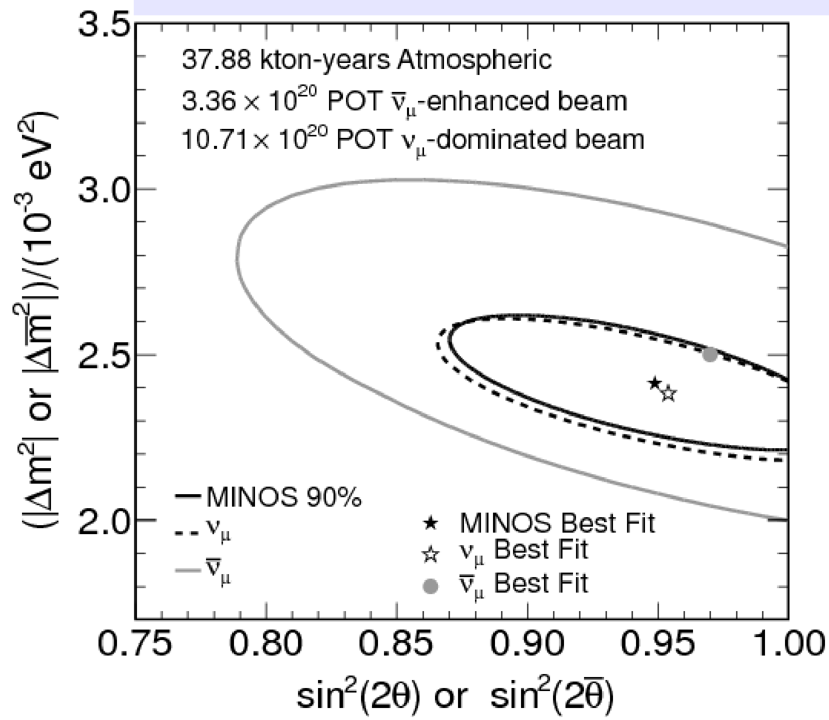
$$\left|\Delta m^2_{32}\right| = 2.41^{+0.10}_{-0.09} \times 10^{-3}\, eV^2/c^2$$




<u>Independent $\nu$ and $\bar{\nu}$ oscillations</u>

$$|\Delta \bar{m}^2| - |\Delta m^2| = 0.12^{+0.24}_{-0.26} \times 10^3\, eV^2$$

Phys. Rev. Lett. 110, 2518011 (2013)

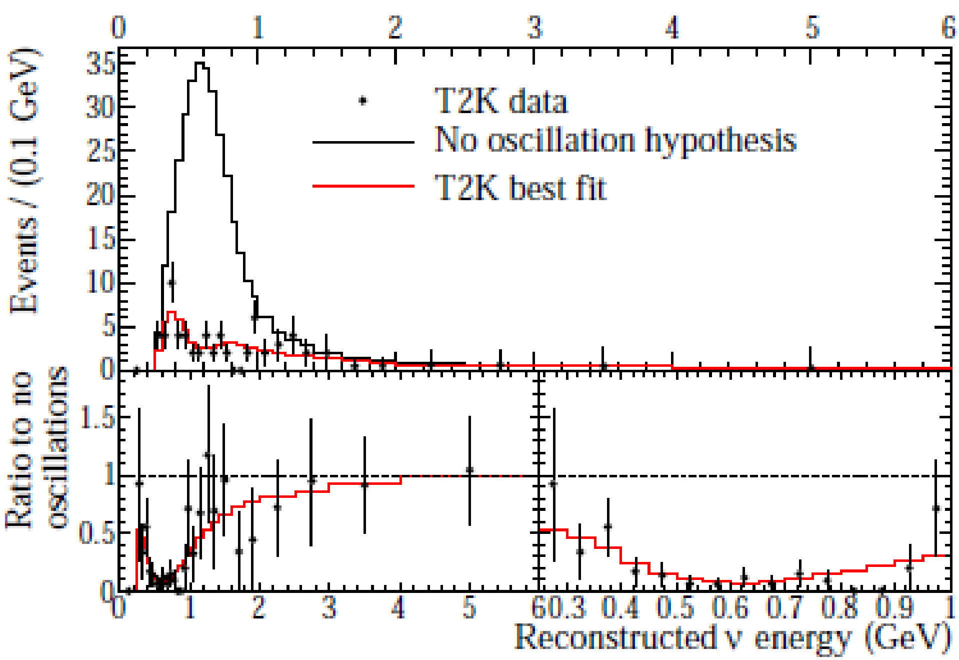


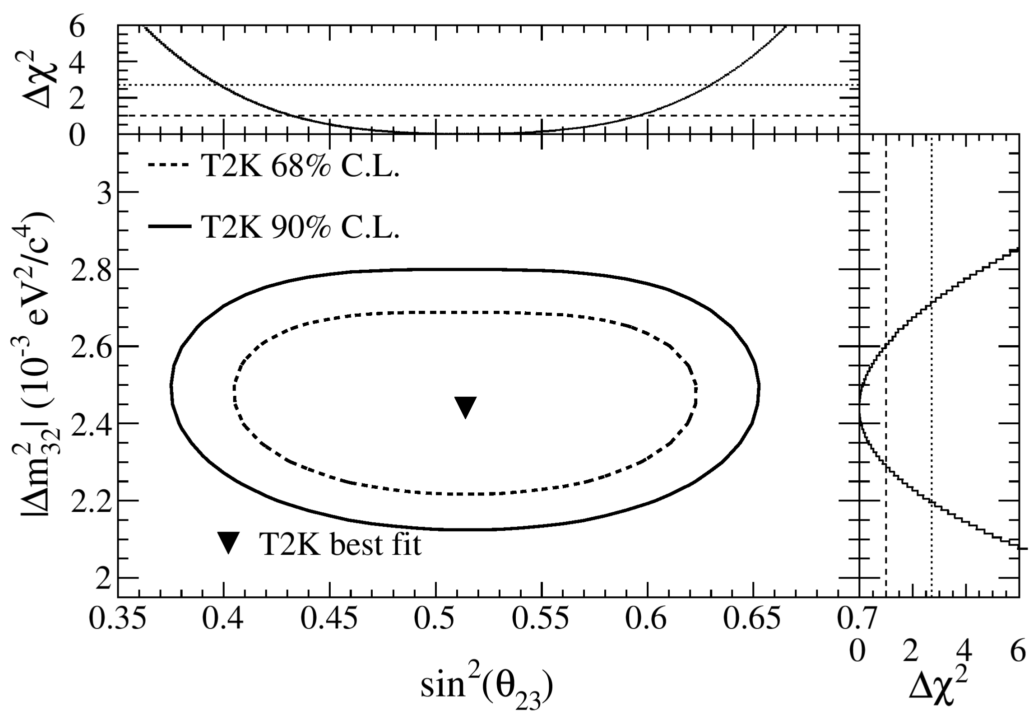
# $\nu_\mu \rightarrow \nu_\mu$ T2K Result

- Best-fit oscillation parameter values:

$$\sin^2\theta_{23} = 0.514 \pm 0.082 \qquad \left|\Delta m^2_{32}\right| = 2.44^{+0.17}_{-0.15} \times 10^{-3}\, eV^2/c^2$$

- Events: 58 (observed), 57.92 (predicted), 205 ± 17(no oscillation)
- Data prefers 2nd $\theta_{23}$ octant
- 1σ confidence intervals are consistent with:
  – Maximal mixing ( $\sin^2\theta_{23}$ )
  – The MINOS result ($\Delta m^2_{32}$)



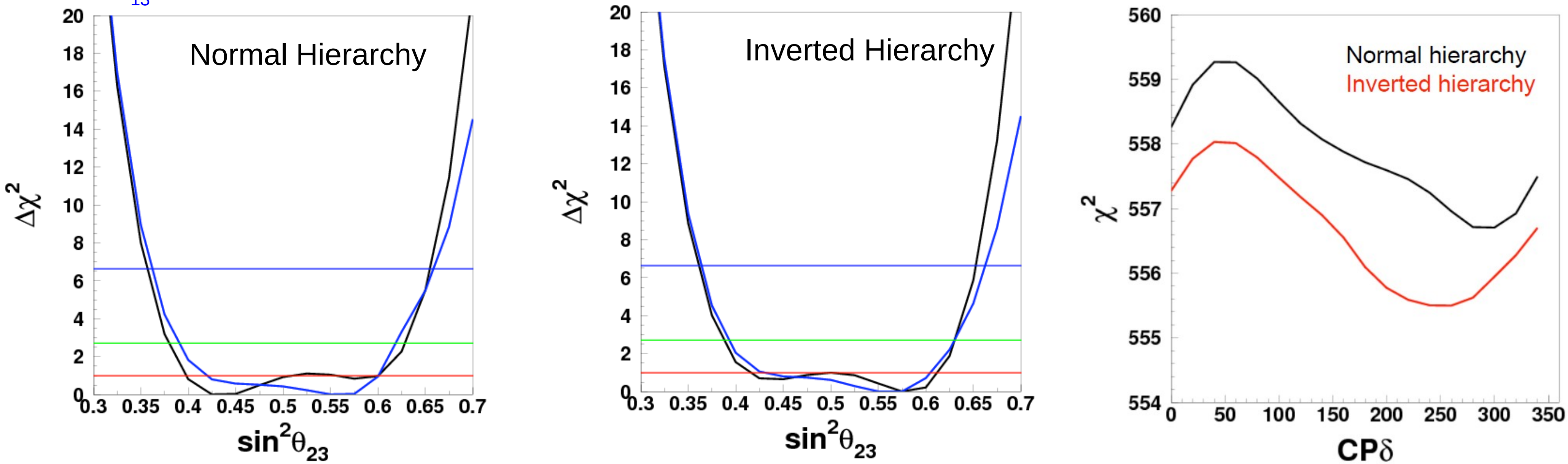



# Recent Atmospheric Neutrinos Results

Super-Kamiokande Preliminary

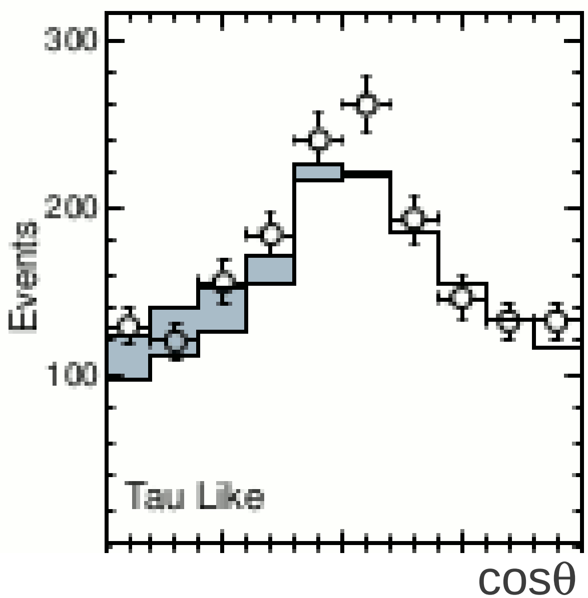
$\Theta_{13}$ Fixed $\sin^2\Theta_{13}$ = 0.025

$\Theta_{13}$ Free




- Normal mass hierarchy: resonance happens for neutrinos
- Inverted mass hierarchy: resonance happens for anti-neutrinos
- Fitting the all Super-K data (~35k data):
  - Both free and constrained fits mostly prefer 2nd octant
  - 1.2σ preference for inverted hierarchy sensitivity is 0.9σ

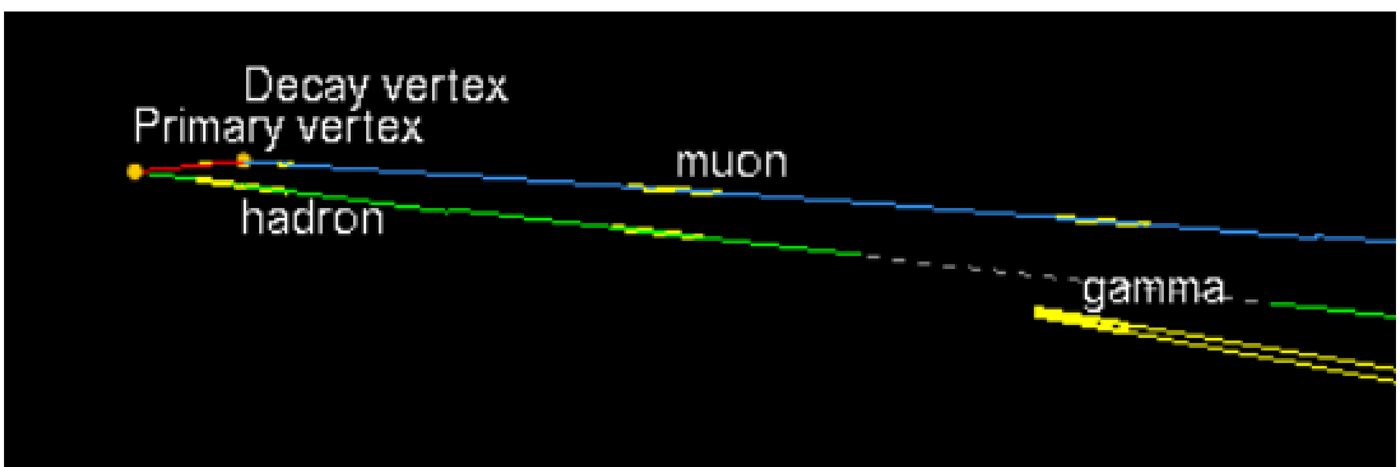
# Confirmation of $\nu_\mu \rightarrow \nu_\tau$




- $3.8\sigma$ $\nu_\tau$ appearance by Super-K atmospheric data (Abe et al., PRL 110, 181802 (2013)) from a sample of enhanced $\tau$-like events.
- A total of $180.1 \pm 44.3(stat.)^{+17.8}_{-15.2}(syst.)$ events observed, and $120.2^{+34.2}_{-34.8}(syst.)$ expected.

Phys. Rev. Lett. 110, 181802 (2013)

- OPERA identifies $\tau$ production in event-by-event basis.




Third $\tau$ candidate taken in March, 2013 w/ ~60% of data analyzed.

- 3 observed events in the $\tau \rightarrow h$, $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels out of 5272 events. Probability to be explained as background = 7 x $10^4$.

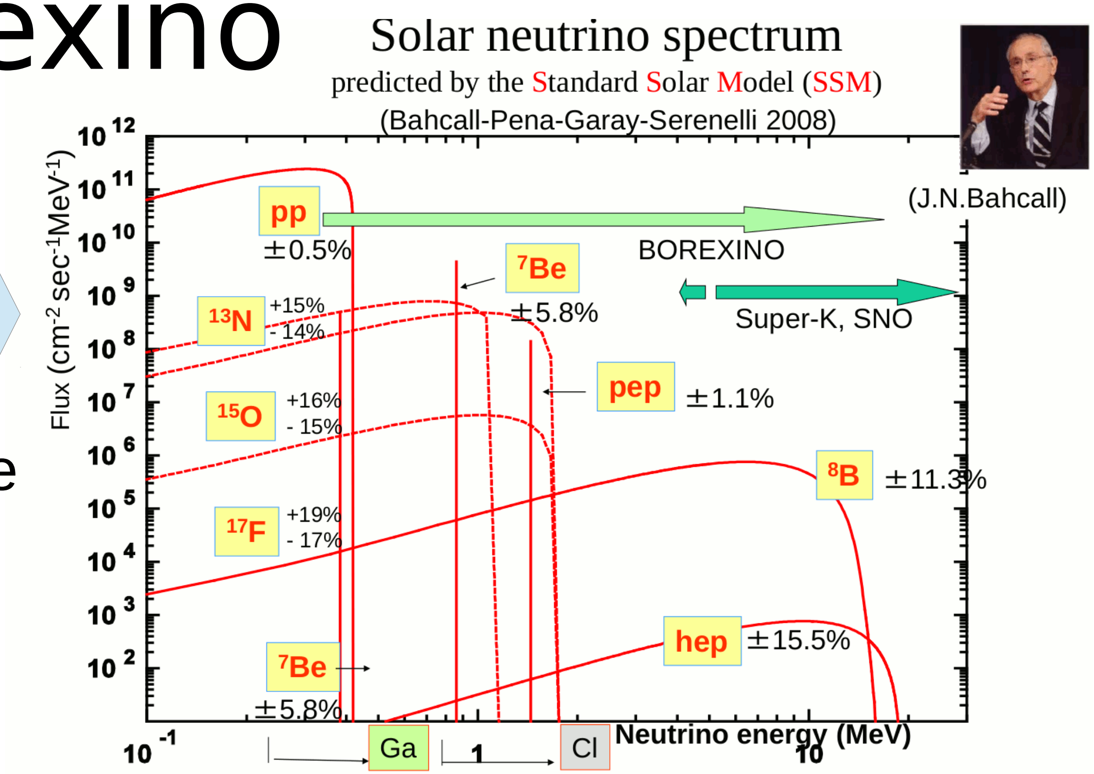
# Solar Neutrinos Status

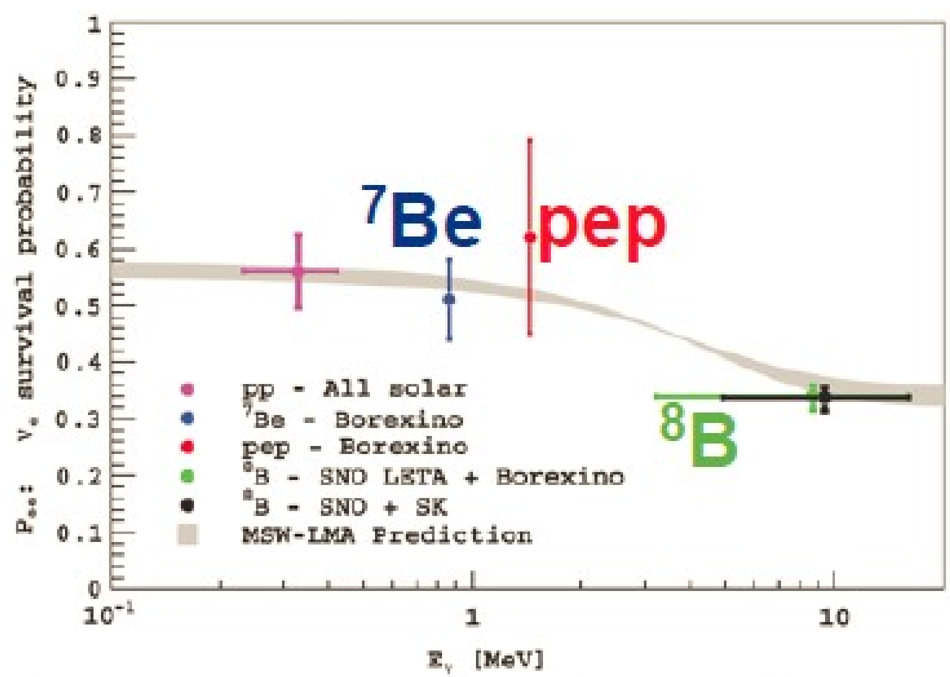
# Borexino

- pep neutrinos are observed for the first time

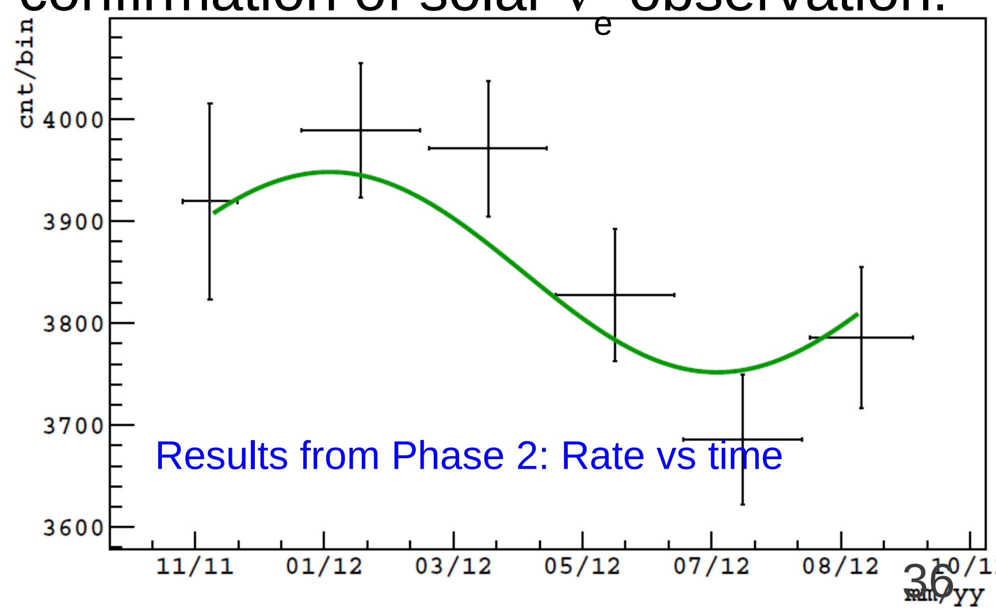
$$\Phi_{pep} = 1.6 \pm 0.3\ 10^8\ cm^{-2}\ s^{-1}$$

- Most of the solar $\nu_e$ components have been seen (except CNO): all in good agreement with SSM and the MSW-LMA solution.




- Seasonal variation: an independent confirmation of solar $\nu_e$ observation:



# Borexino

PRL 108(2012) 051302

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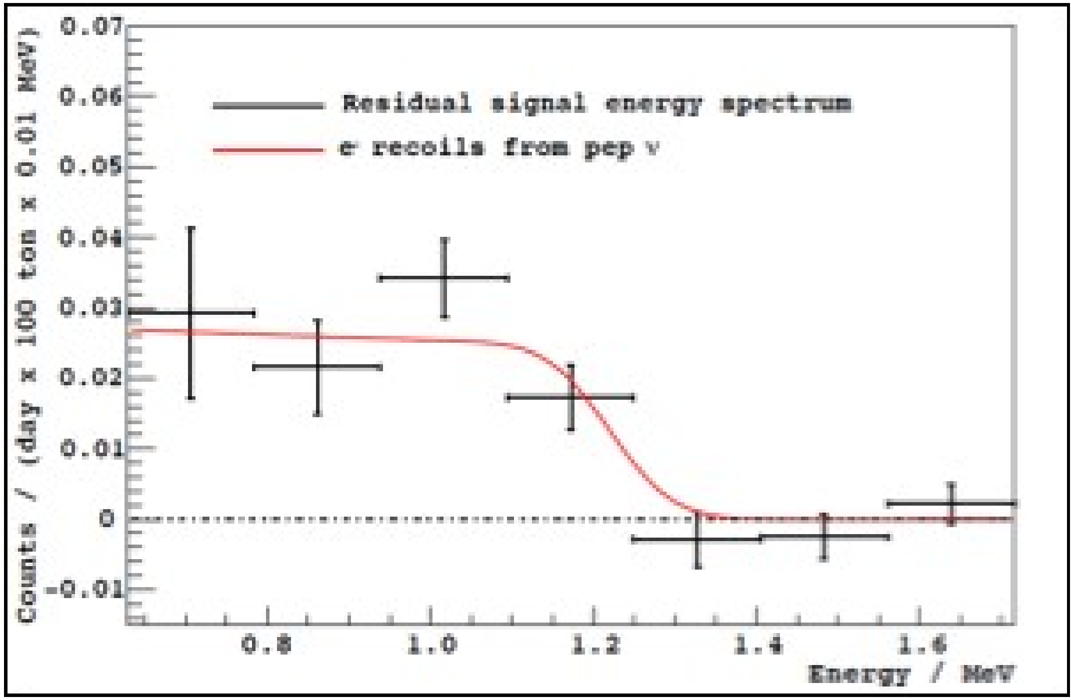


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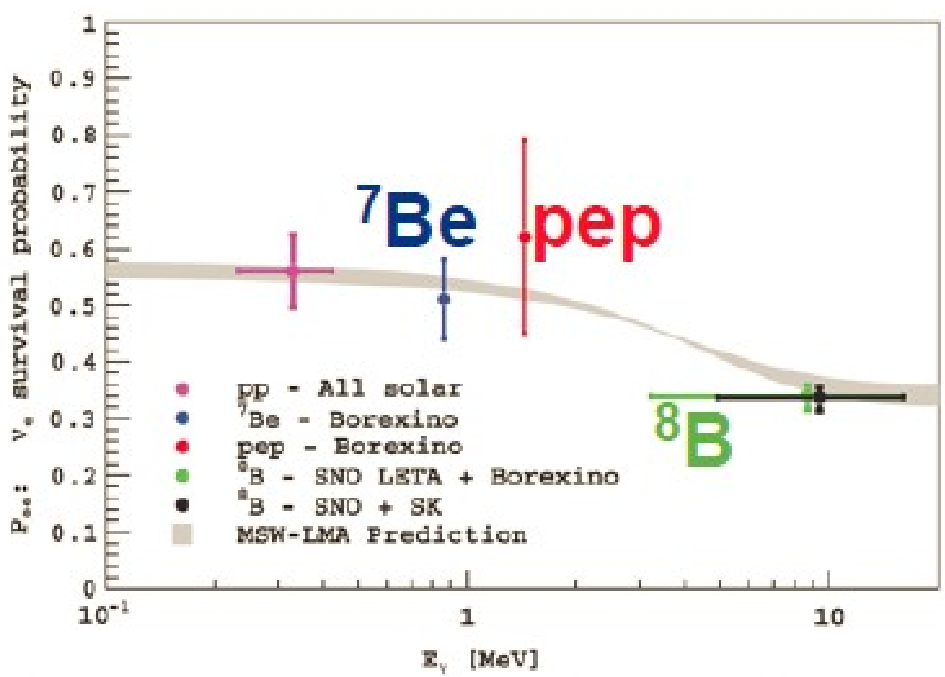


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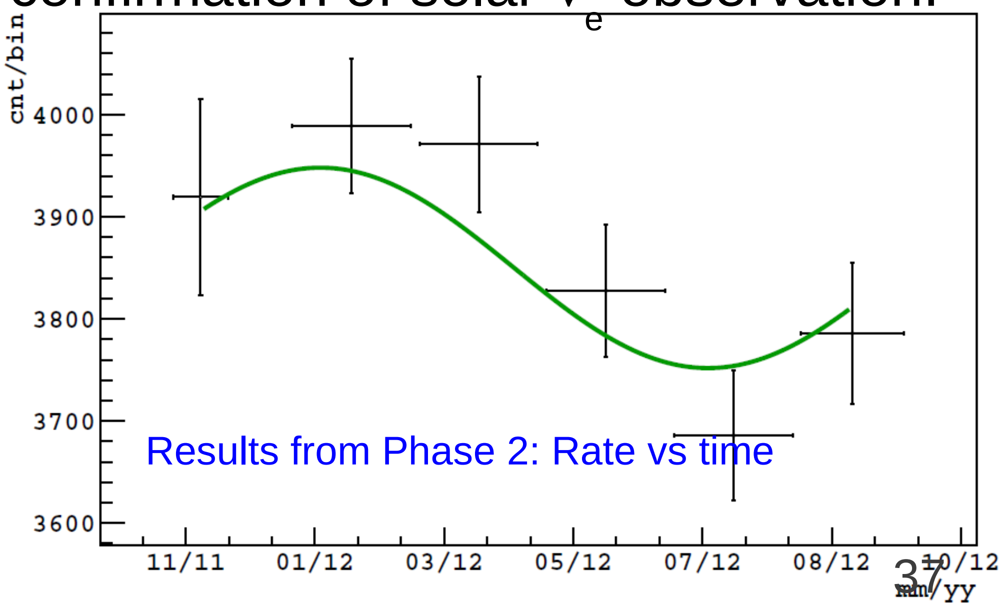
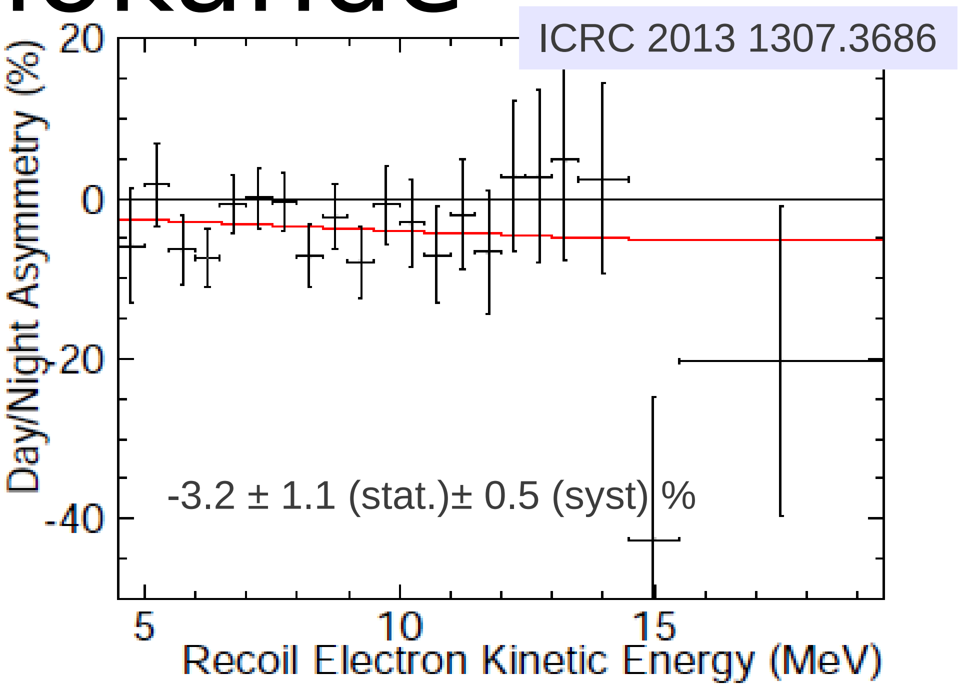
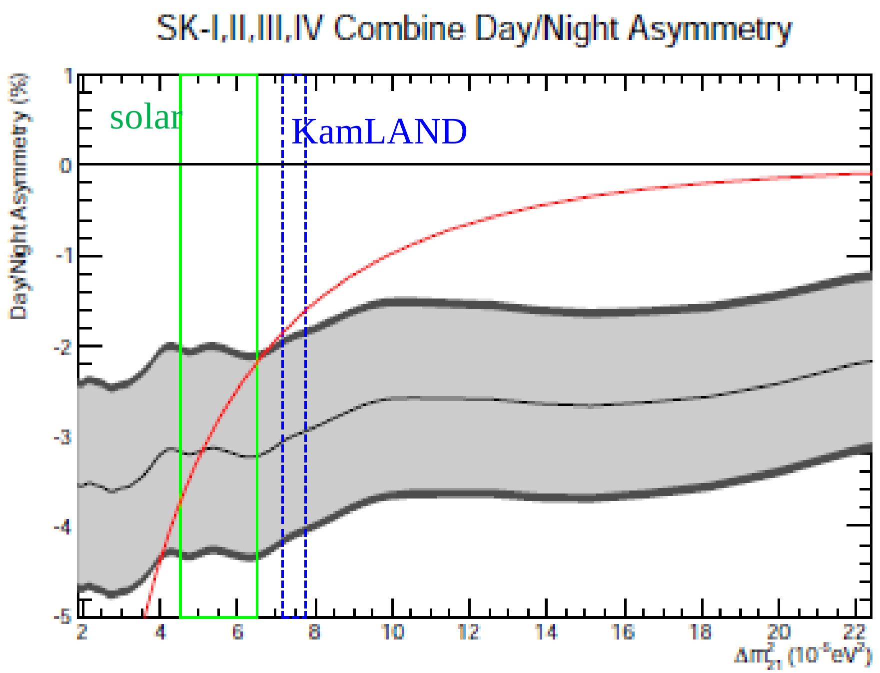


# Super-Kamiokande




- Thanks to new electronics and tight FV cut, $E_{thresh}$ ~ 3.5 MeV.
- A 2.7σ Day-Night asymmetry is observed: indication of the regeneration of $\nu_e$ as they travel through Earth matter.
- In agreement with the expectation.
- Improved $\theta_{12}$ & $\Delta m^2_{12}$ measurements in combination with other solar & KamLAND results:

$$\sin^2\theta_{12} = 0.304 \pm 0.013$$
$$\Delta m^2_{21} = 7.45^{+0.20}_{-0.19} \times 10^{-5} eV^2$$



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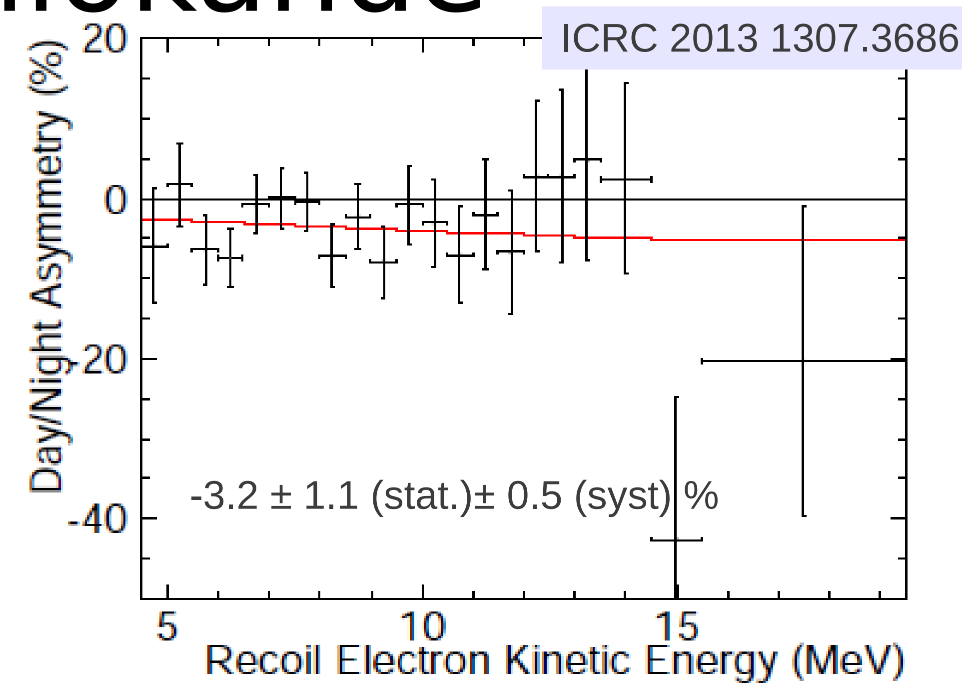
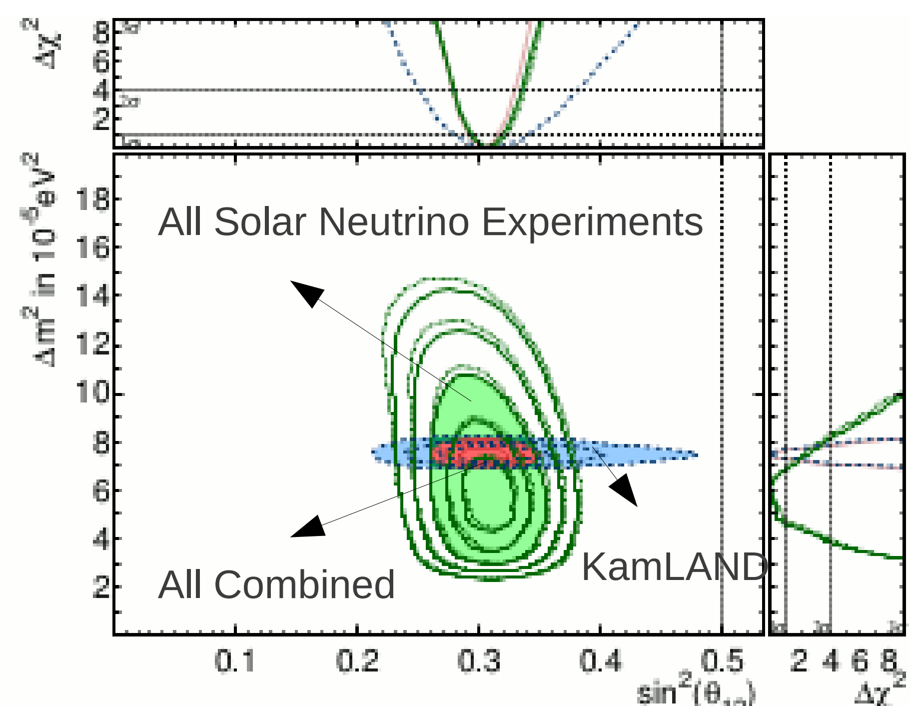
ICRC 2013 1307.3686



# Conclusions

- Lots of progress in the last two years in addressing the measurement of the mixing angles.
- First ever observation (>5σ) of an explicit ν appearance channel
- First ever overvation of antineutrino-electron disappearance in a reactor experiment.
- Improved measurement of the atmospheric neutrino mixing angle.
- Observed tau neutrino appearance from a muon neutrino beam.
- Observed the solar pep flux for the first time.
- Evidence of day/night asymmetry in solar neutrinos.

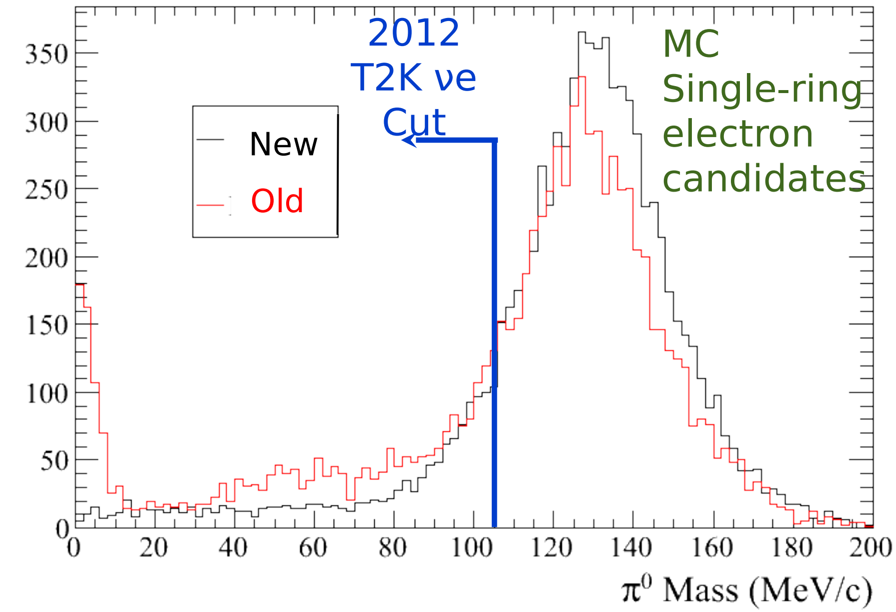
- Stay tuned, lot's of more measurements ahead of us in the next years!

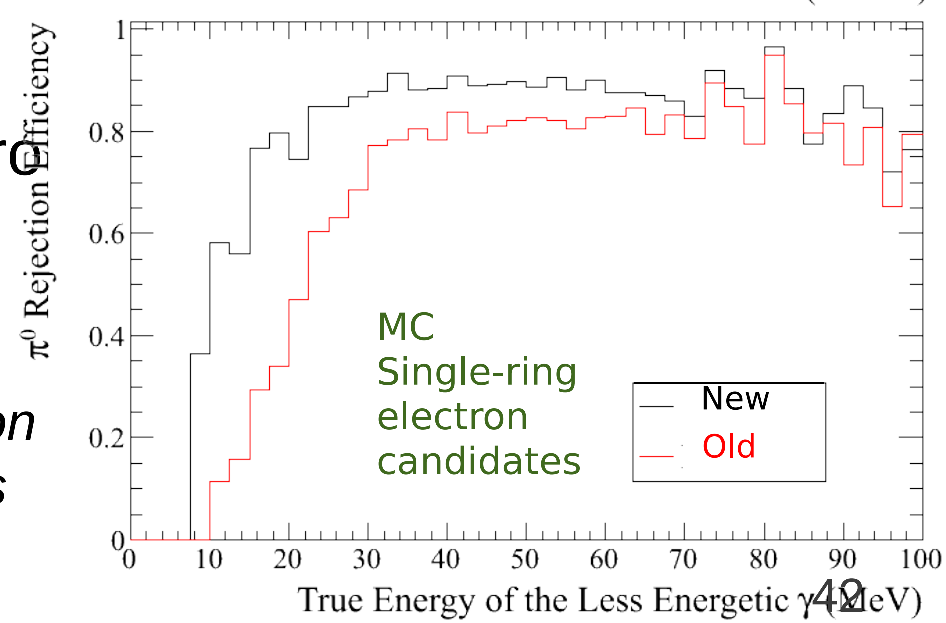
# Backup Slides

# New Cherenkov Ring Reconstruction

- Based on MiniBooNE Likelihood Model [NIM A608, 206 (2009)]
- For given event hypothesis generate charge and time PDF
- Event hypothesis then distinguished by best fit likelihoods.
- New method uses mass of the π0 hypothesis and best-fit likelihood ratio of e- and π0
- Cut removes 70% more π0 background than previous§ method for a 2% added loss of signal efficiency

*§ Previous approach forced the reconstruction to find two rings and then formed a π0 mass under the two-photon hypothesis*



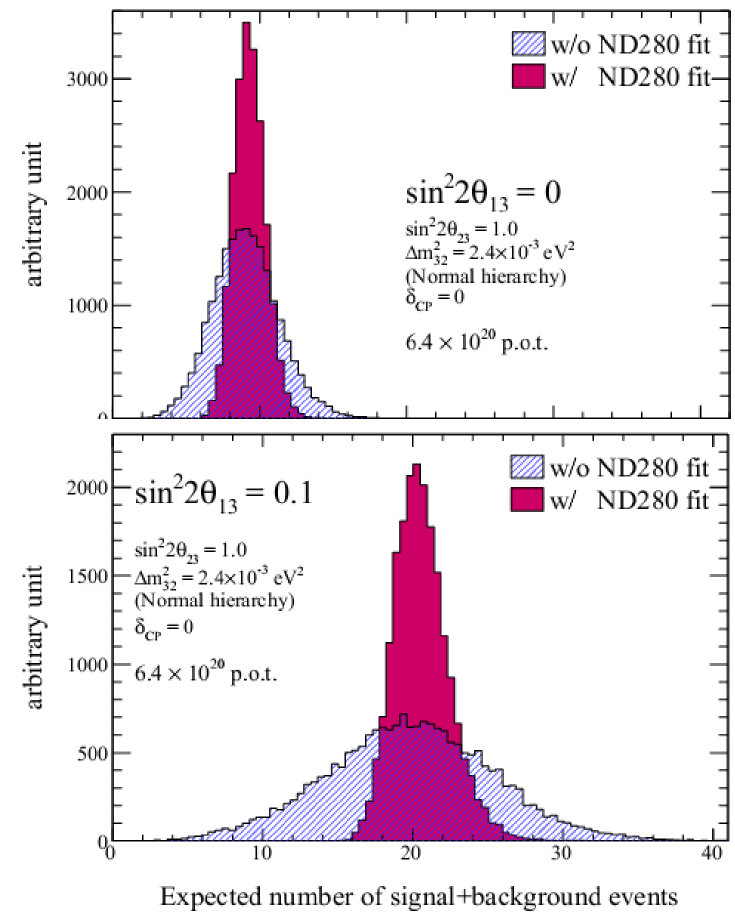
# $\nu_\mu \to \nu_e$ Predicted Number of Events

**Predicted # of events w/ 6.393×1020 POT**

| **Event Category** | **sin22θ13 = 0.0** | **sin22θ13 = 0.1** |
|---|---|---|
| νe signal | 0.38 | 16.42 |
| νe background | 3.17 | 2.93 |
| νμ background (mainly NCπ0) | 0.89 | 0.89 |
| νμ + νe background | 0.20 | 0.19 |
| Total (2013) | 4.64 | 20.44 |
| Total (2012) | 5.15 | 21.77 |

**Systematic Uncertainties**

| **Error Source** | **sin22θ13 = 0.0** | **sin22θ13 = 0.1** |
|---|---|---|
| Beam flux + ν int. T2K fit | 4.9 % | 3.0 % |
| ν int. (other exp.) | 6.7 % | 7.5 % |
| Far detector | 7.3 % | 3.5 % |
| Total (2013) | 11.1 % | 8.8 % |
| Total (2012) | 13.0 % | 9.9 % |

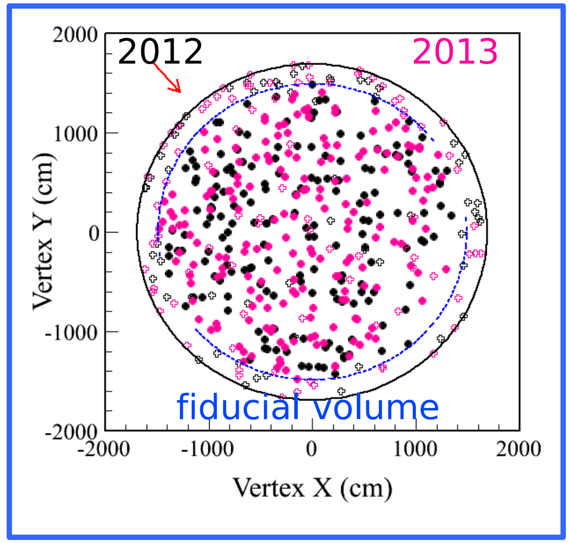


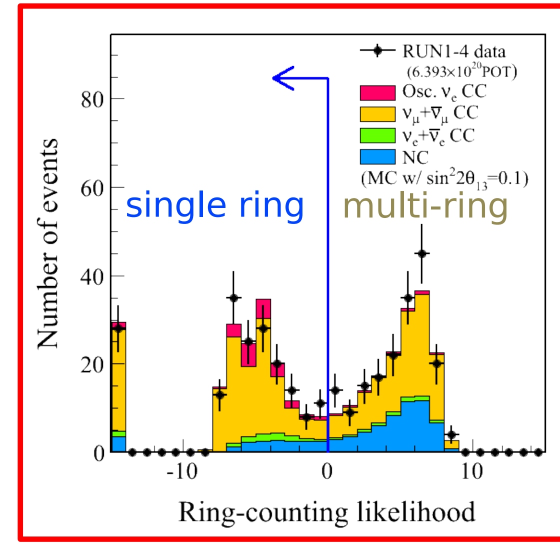

Reduction in errors 2012-2013 mainly due to near detector analysis improvement.

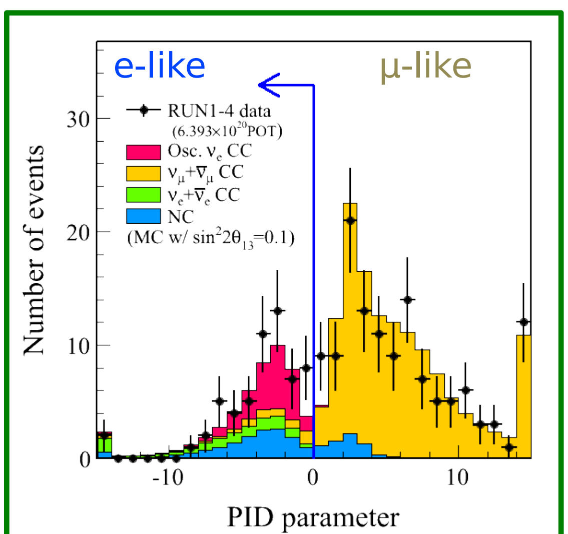
# $\nu_\mu \rightarrow \nu_e$ Event Selection

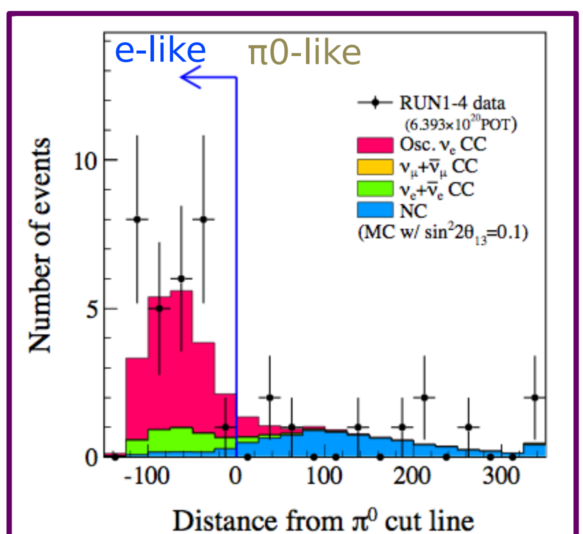
**Event selection:**

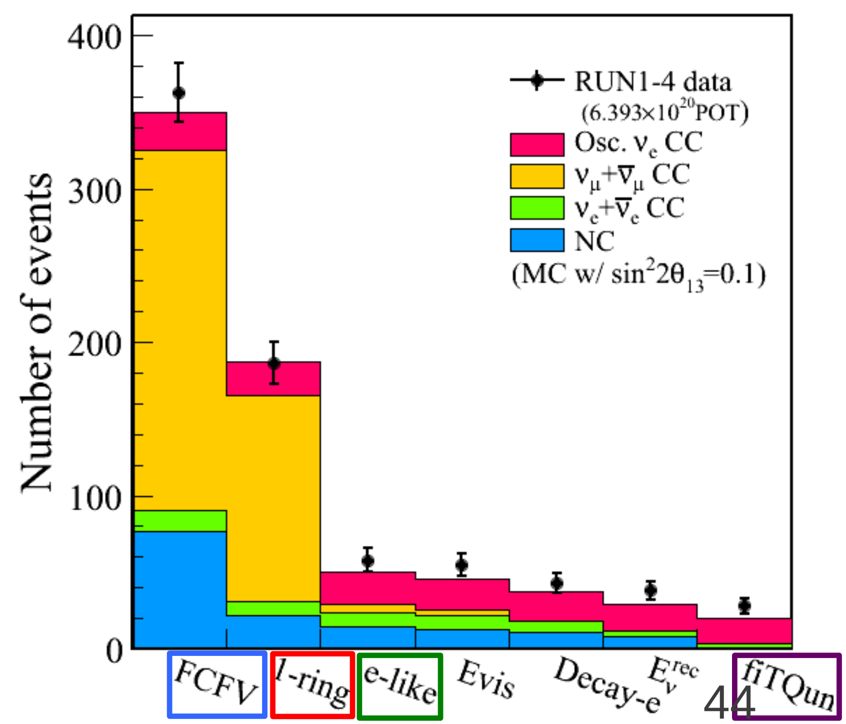
- Fully contained in fiducial volume
- Only one reconstructed rings
- Ring is electron like
- Visible energy > 100MeV
- No Michel Electrons
- Reconstructed energy < 1.25 GeV
- (2013)2D $\pi$0 invariant mass : fiTQun likeli hood cut



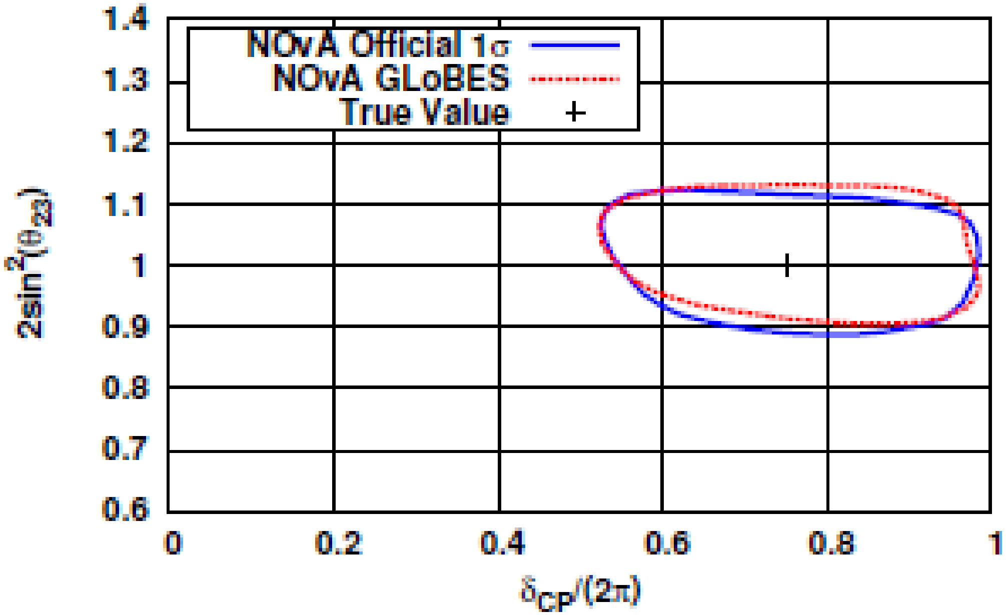



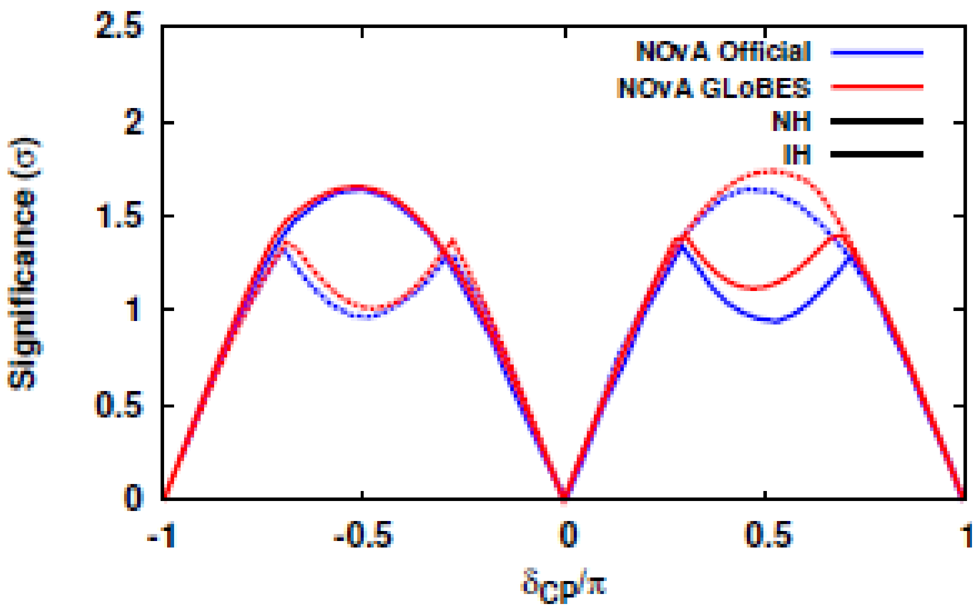



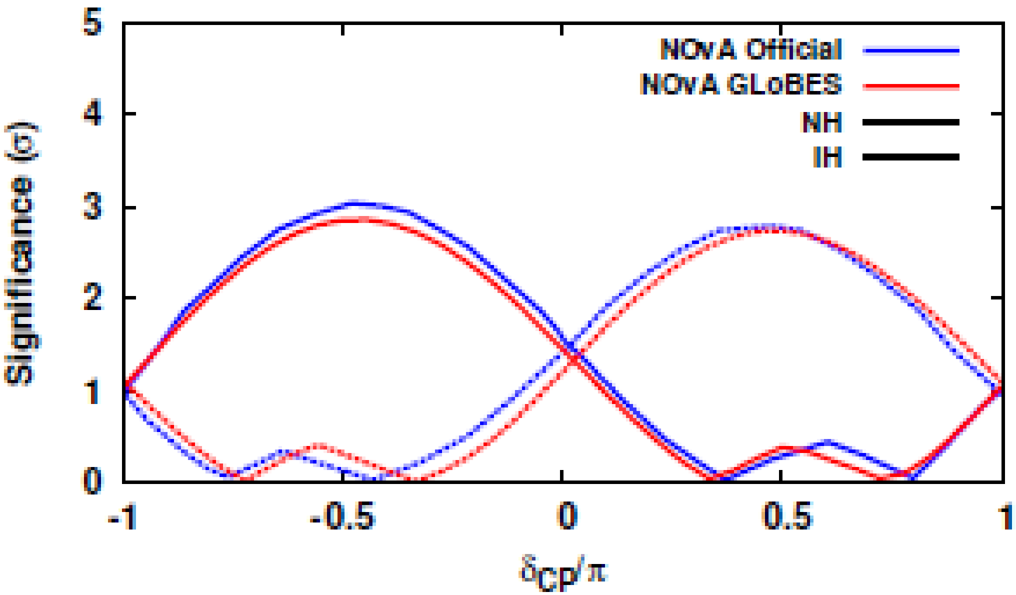



# T2K 50%ν/50%$\bar{\nu}$ + NOvA

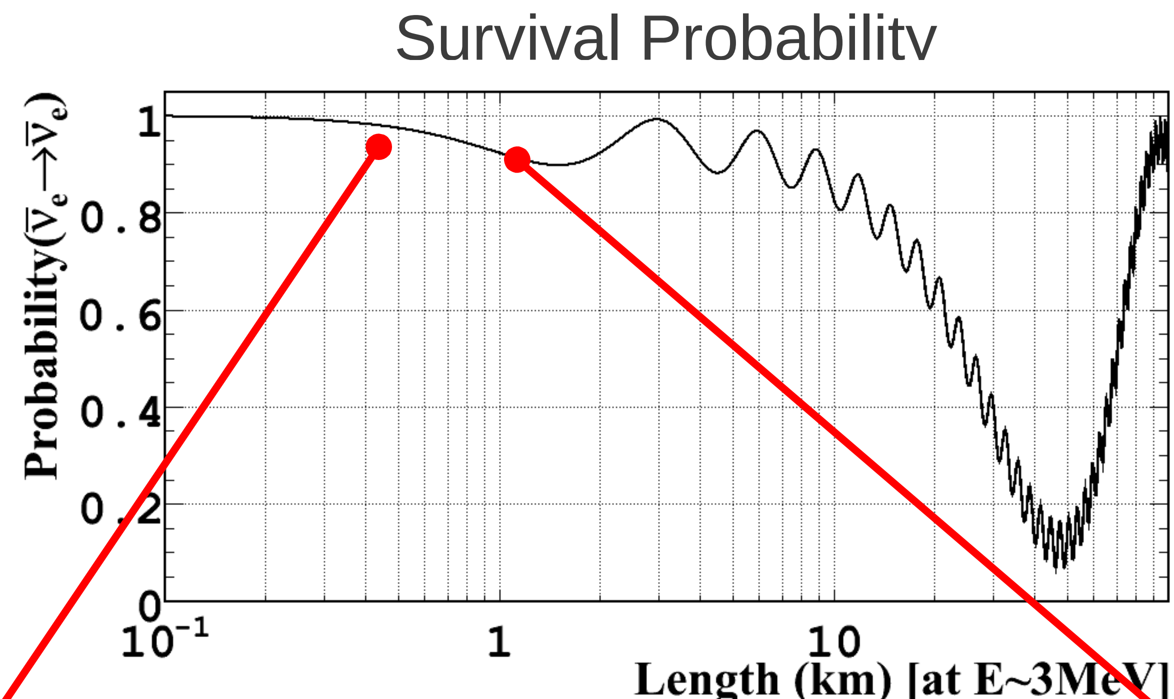
- Ongoing work to estimate the potential of T2K in the future years, including combinations with other experiments.



# Strategy for $\theta_{13}$ measurement




Near detector

Measure reactor
ν flux & spectrum
before oscillation
(reduce systematic uncertainty)

Far detector

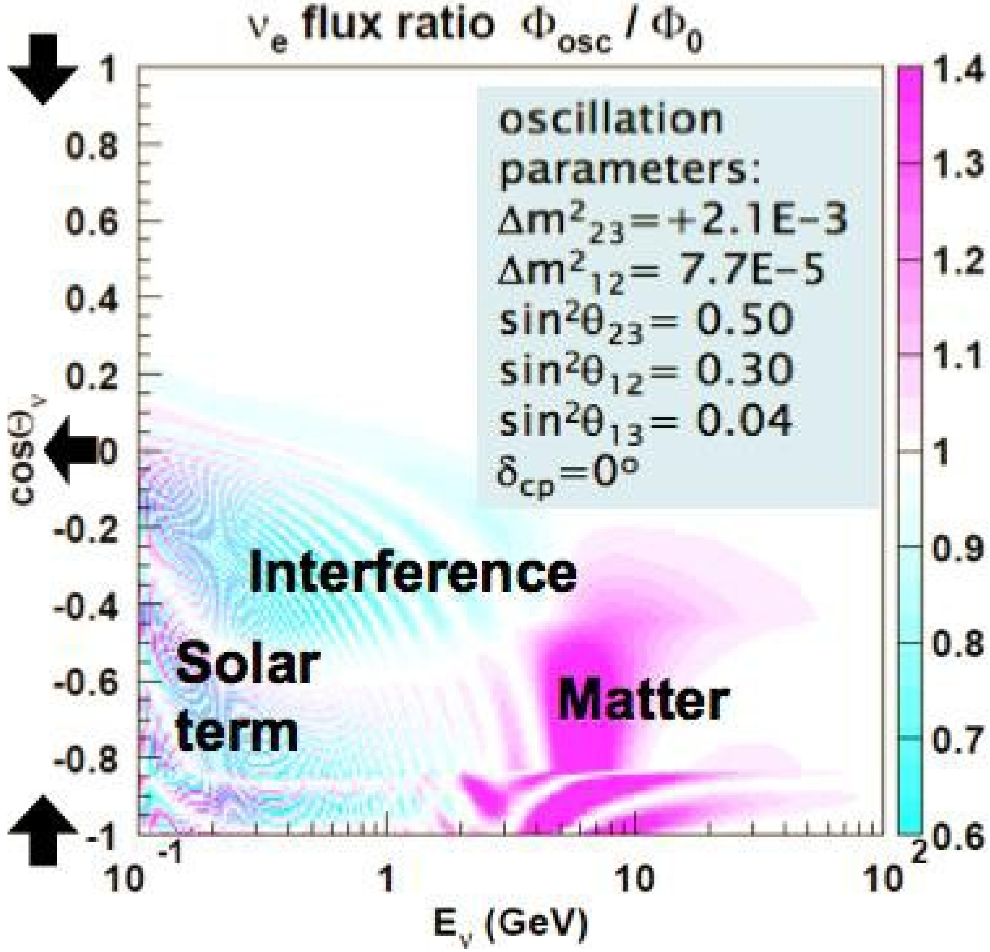
Measure oscillated ν flux & spectrum
(measure $\theta_{13}$)

Same detector type

# Atmospheric Neutrinos

$\nu_e$ appearance and $\nu_\mu$ distortion are expected due to the MSW effect in the Earth's matter.
Thanks to the huge statistics and large $\theta_{13}$, we can look for:

- Mass hierarchy: enhanced high energy upward going $\nu_e$ due to the matter effect
- Octant of oscillation: enhanced low energy $\nu_e$ due to the solar term
- CP phase $\delta$: interference between these two




$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)}-1\sim P_2(r\cos^2\theta_{23}-1)$$ Solar Term

$$-r\sin\tilde{\theta}_{13}\cos^2\tilde{\theta}_{13}\sin 2\theta_{23}(\cos\delta R_2-\sin\delta I_2)$$ Interference

$$+2\sin^2\tilde{\theta}_{13}(r\sin^2\theta_{23}-1)$$ Matter Effect

$P_2=P(\nu_e\rightarrow\nu_{\mu,\tau})$ $R_2$ and $I_2$ are the oscillation amplitudes for CP even and odd terms

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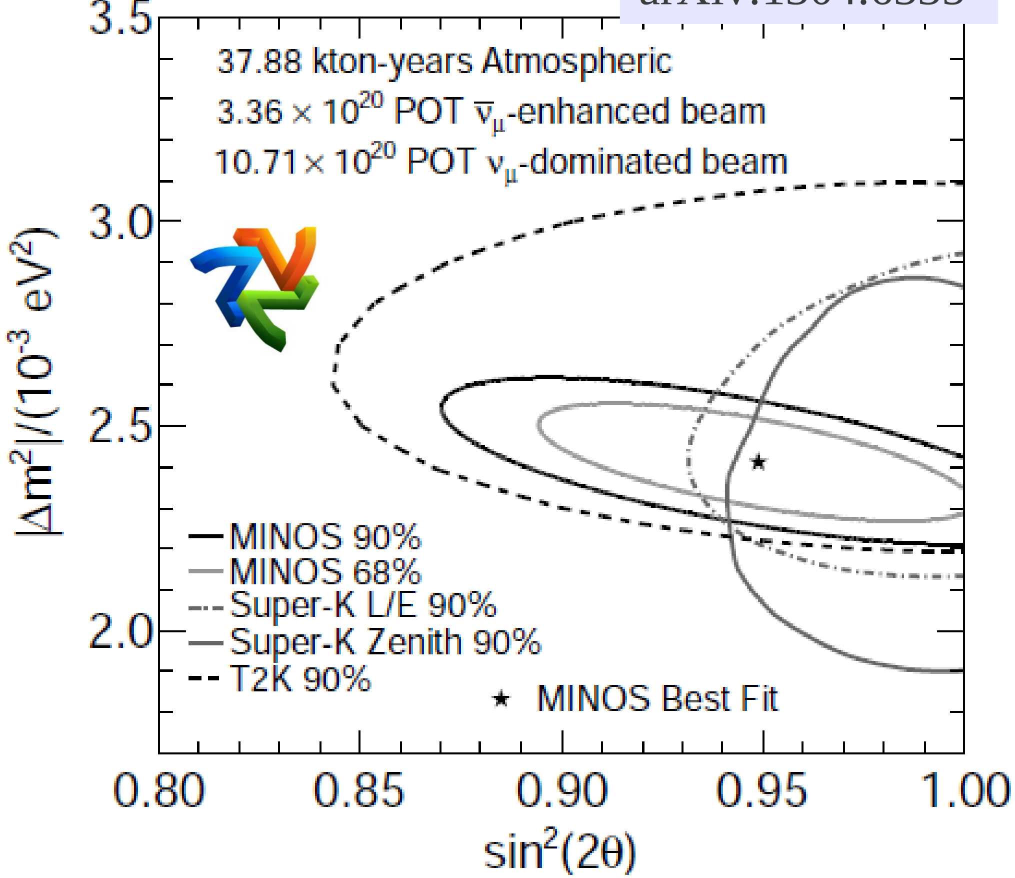
arXiv:1304.6335




$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \sim P_2\left(r\cos^2\theta_{23} - 1\right)$$

Solar Term

$$-r\sin\tilde{\theta}_{13}\cos^2\tilde{\theta}_{13}\sin 2\theta_{23}\left(\cos\delta R_2 - \sin\delta I_2\right)$$

Interference

$$+2\sin^2\tilde{\theta}_{13}\left(r\sin^2\theta_{23} - 1\right)$$

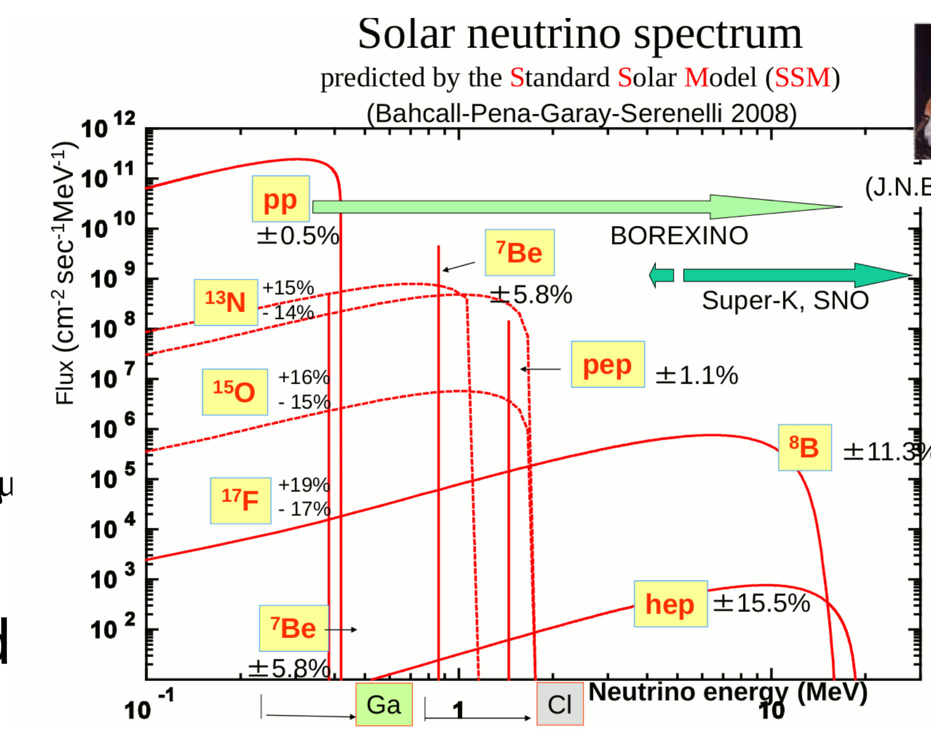
Matter Effect

$P_2 = P(\nu_e \rightarrow \nu_{\mu,\tau})$

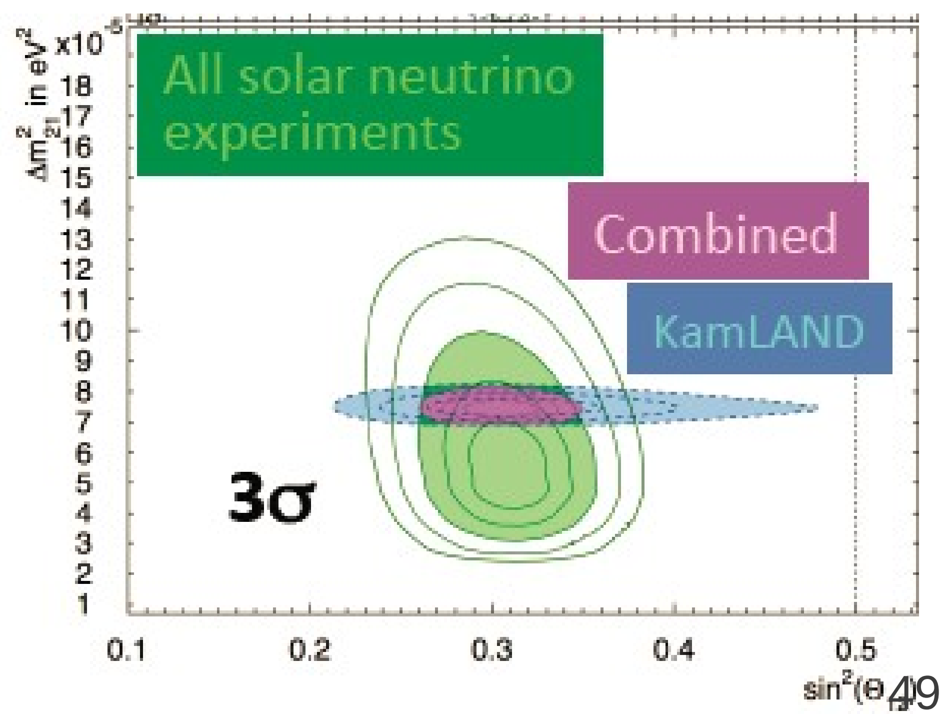
$R_2$ and $I_2$ are the oscillation amplitudes for CP even and odd terms

# Solar Neutrinos

- Solar neutrino oscillation established(00's):
  – SuperK: indication of LMA-MSW
  – SNO： missing $\nu_e$ appeared as $\nu_\mu$
  – KamLAND： $\theta_{12}$ & $\Delta m^2_{12}$
  – Standard Solar Model established
- Current experiments:
  – Borexino
  – SuperKamiokande
- Main issues:
  – Solar related
- Future experiment:
  – SNO+, XMASS, LENA, JUNO…





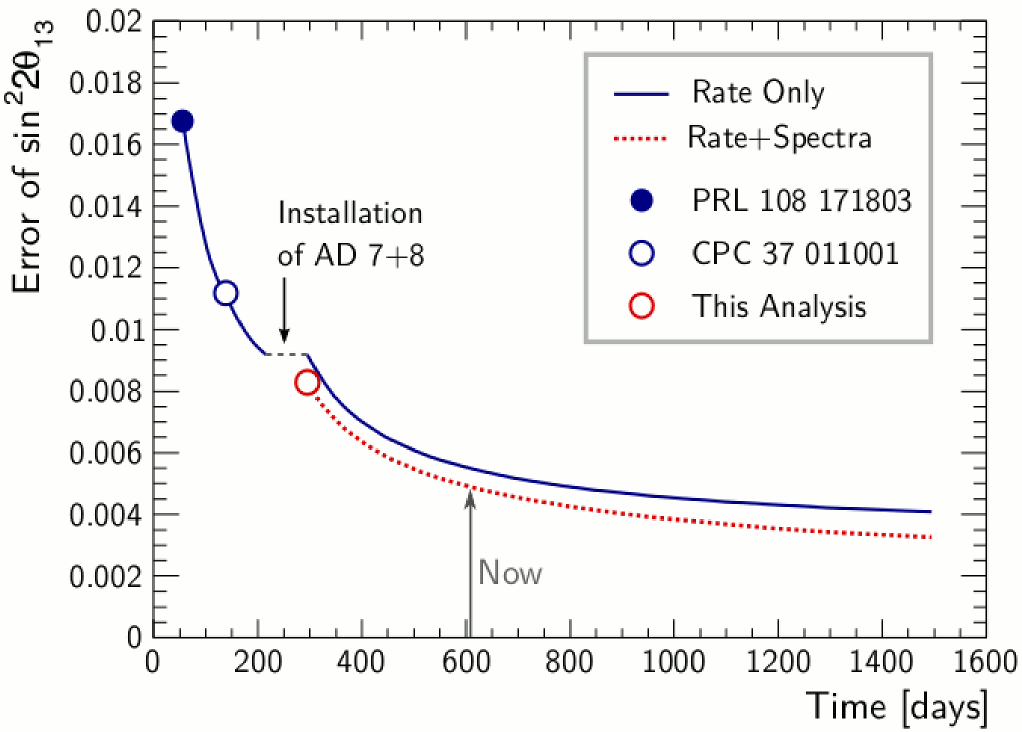


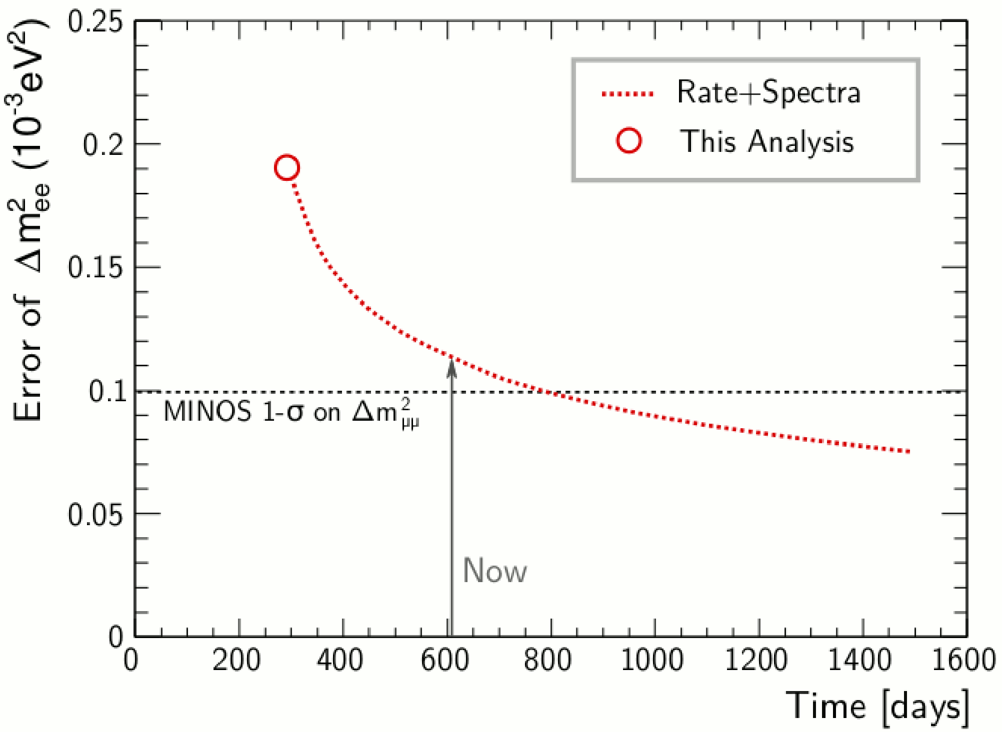
# Prospects

# Prospects from Daya Bay

Increase the precision in oscillation parameters:

- constrains non-standard oscillation models
- improves the reach of next-generation experiments
- absolute reactor neutrino spectrum flux and shape measurement
  - probe reactor models and explore reactor antineutrino anomaly.



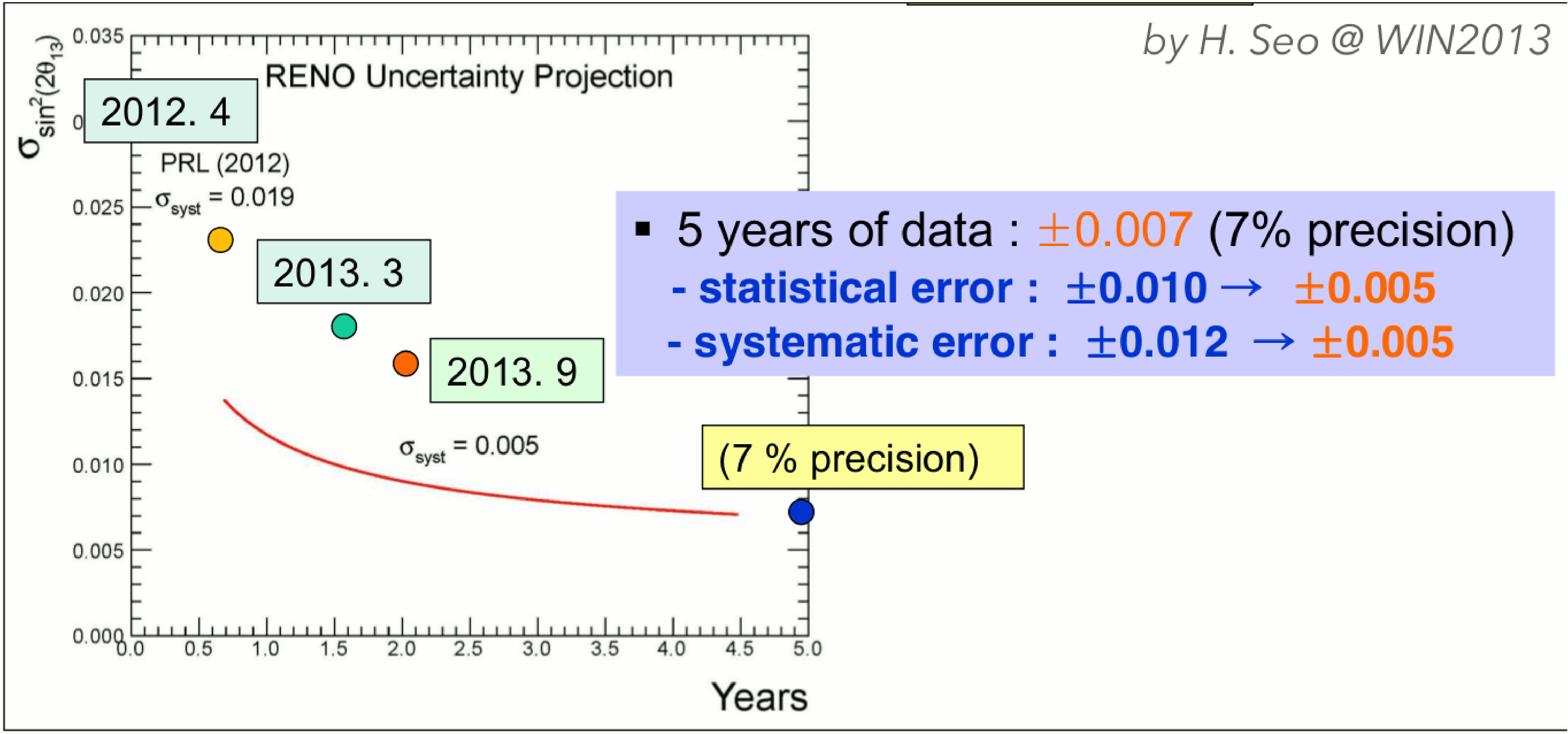



# Prospects from Double Chooz

Currently finishing new improved analysis including...

- Statistics (> 2x)
- Optimized selection to enhance S/B
- Reduced systematics
- Near + Far detector analysis (mid. 2014)
- Reactor flux uncertainty almost cancels
- Projected final precision: ~10%

# Prospects from Reno




Already collected ~700 live days of reactor neutrino data

- new $\theta_{13}$ result with improved energy calibration and bkg. estimation
- direct measurement of $\Delta m^2_{31}$
- precise measurement of reactor neutrino flux and spectrum.

# Reactor Anomaly

Reevaluation of reactor νe spectra and flux

- Th. A. Mueller et al., Phys. Rev. C83 (2011) 054615

Reanalysis of past reactor experiments

- G. Mention et al., Phys. Rev. D83 (2011) 073006
- Reactor anomaly 3σ (new physics??)

Revisited with known θ13

- C. Zhang et al., arXiv:1303.0900 [nucl-ex]
- New world average ~1.4σ lower than unity.