Summary
on
Recent Reactor θ_{13} Measurements

Topical Conference Talk
in
SLAC Summer Institute 2013

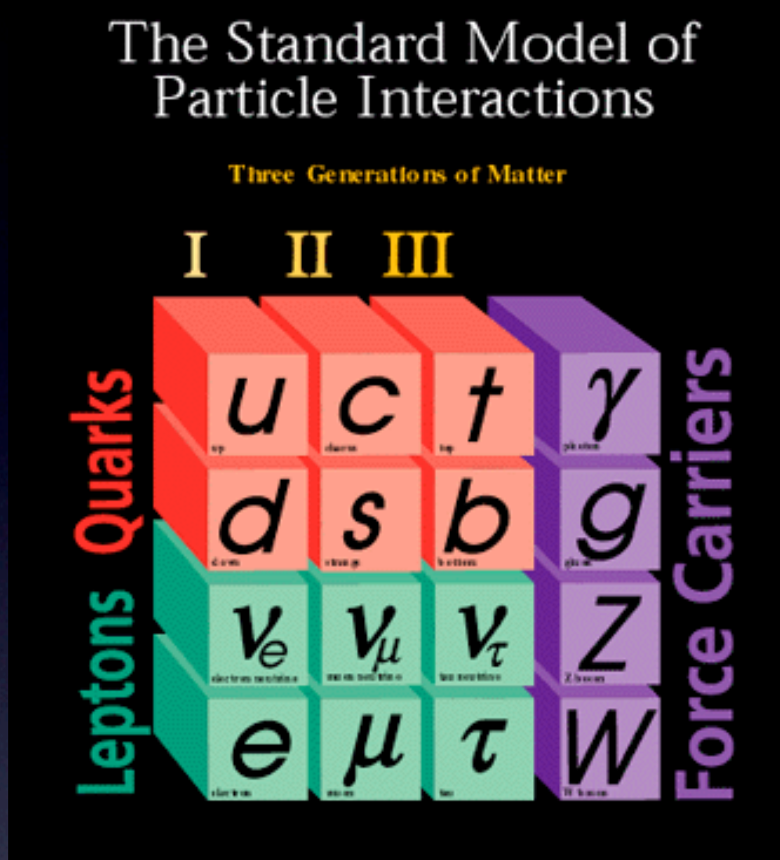
Kazuhiro Terao @ Columbia Nevis Lab

Outline

- Neutrino Mixing Angle, θ_{13}
  - Neutrino oscillation
  - θ_{13} measurement as a milestone
- Measurement of θ_{13}
  - Reactor experiments & their concept
  - Recent results
- What now?

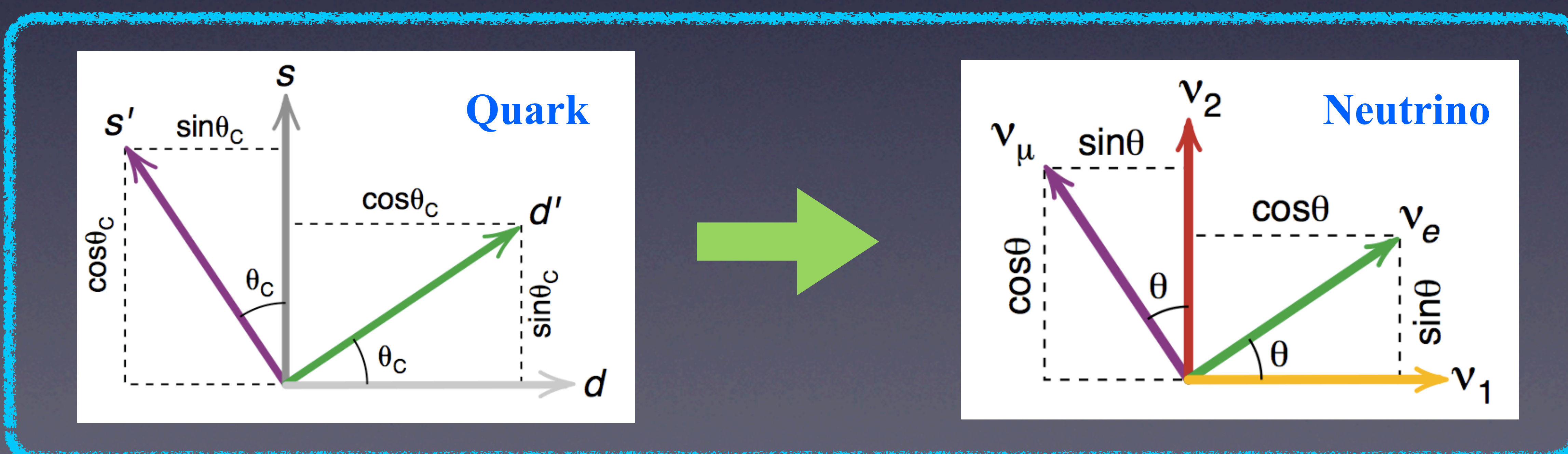
Neutrino Oscillation
and
Measurement of θ_{13}

Neutrino Flavor Mixing



What we know about neutrinos

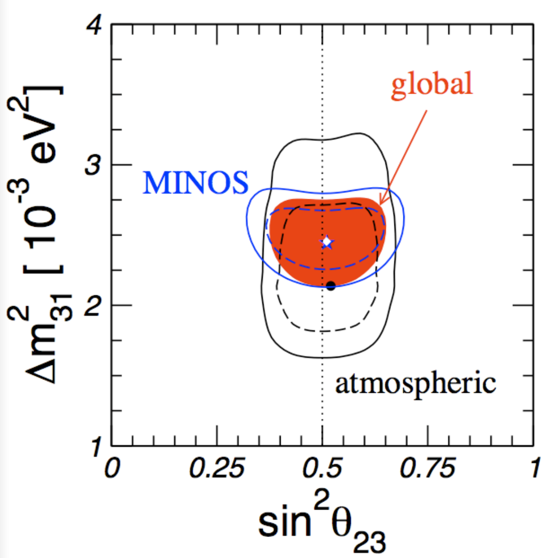
- Neutral, spin 1/2 lepton
- 3 weakly interacting flavors
- At least 3 non-degenerate mass eigenstates
- Very, very tiny mass
- Flavor mixing!



What We Already Know

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

Accelerator & Atmospheric



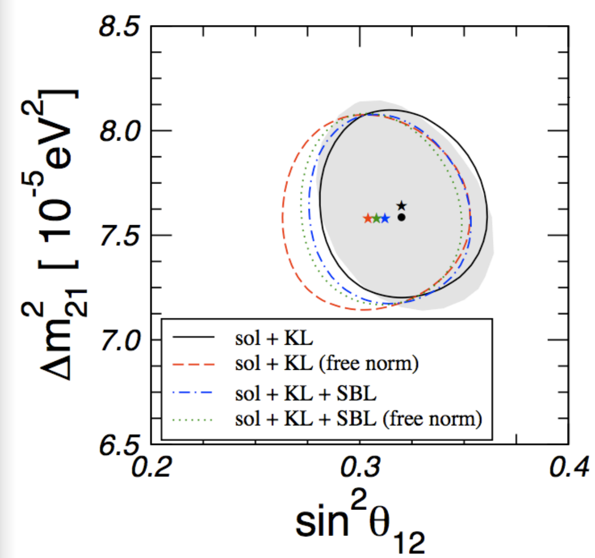
$\Delta m_{31}^2 = 2.35 \times 10^{-3}$ eV^2
$\sin^2\theta_{23} = 0.42$

Long-Baseline Appearance
+
Reactor Disappearance

Last Mixing Angle θ_{13}
+
CP Phase, δ

Schwetz et al. arXiv:1103.0734
and
Particle Data Group

KamLAND & Solar



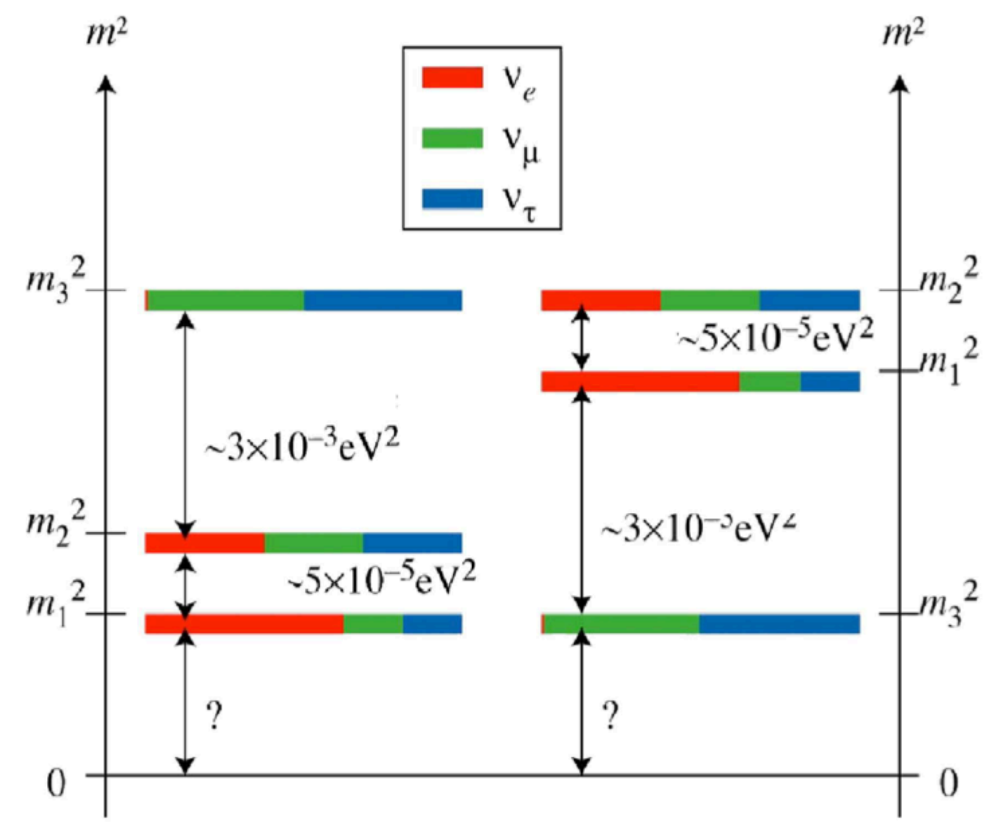
$\Delta m_{21}^2 = 7.58 \times 10^{-5}$ eV^2
$\sin^2\theta_{12} = 0.306$

What We Still Need to Determine

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

In addition to angles ...

- CP violation
- Mass hierarchy
- Dirac vs. Majorana
- Sterile neutrinos



Measurement of θ_{13} as a Milestone

Why is θ_{13} measurement important?

- Obviously, **we want to know the last mixing angle!**
  - For a long time, only clue was the upper bound from Chooz
- Affects ease of a **mass hierarchy** & **CP violation** measurement
  - **Value of θ_{13} may tell us what to tackle next**

How can we measure it?

- "**Appearance Accelerator Measurement**" ... **$P(\nu_\mu \rightarrow \nu_e)$**
  - Coupled with δ_{CP}, mass hierarchy
- "**Disappearance Reactor Measurement**" ... **$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$**
  - Clean & simple θ_{13} measurement

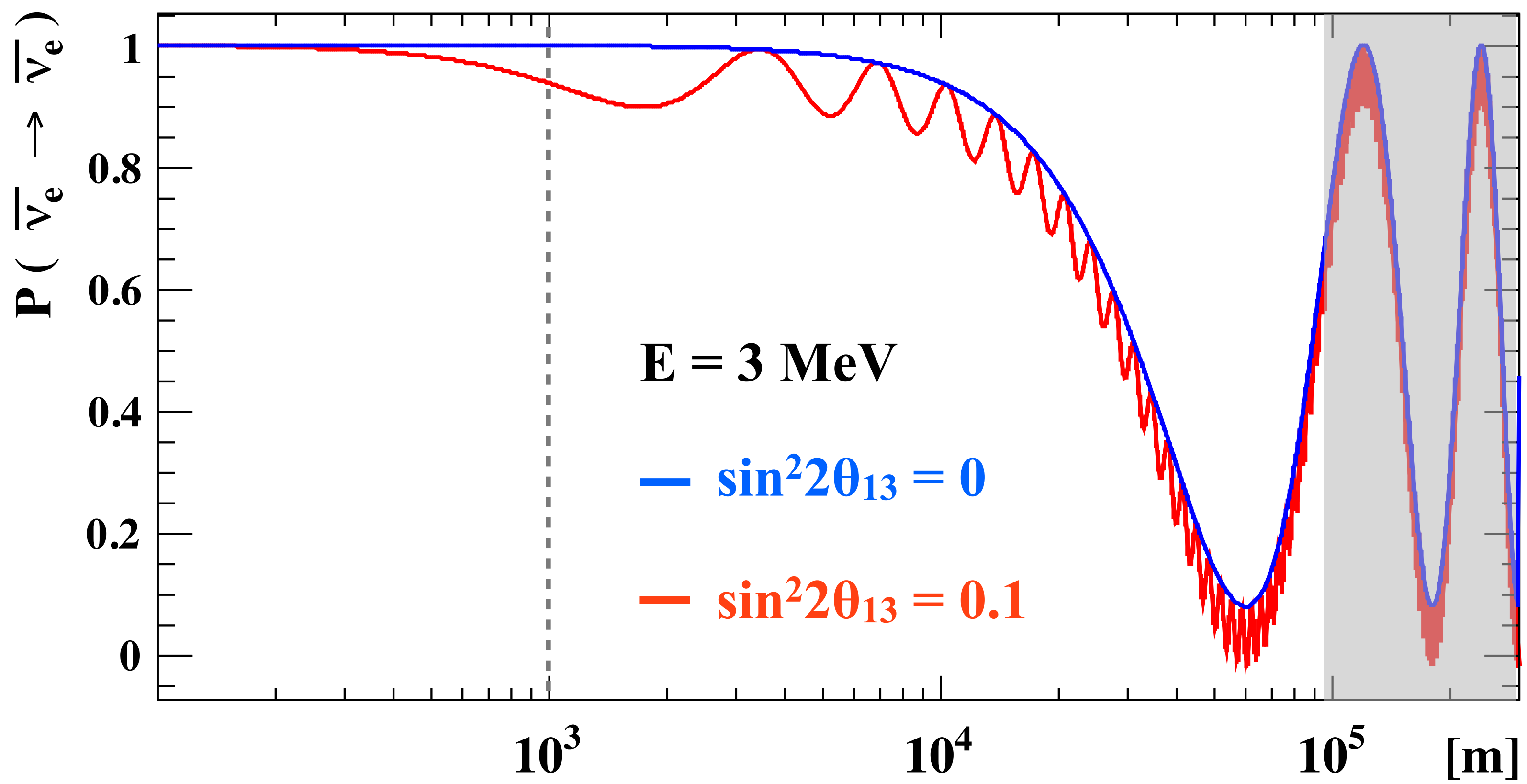
Reactor Experiments
for
Measurement of θ_{13}

Reactor θ_{13} Experiments

Why reactor experiment?

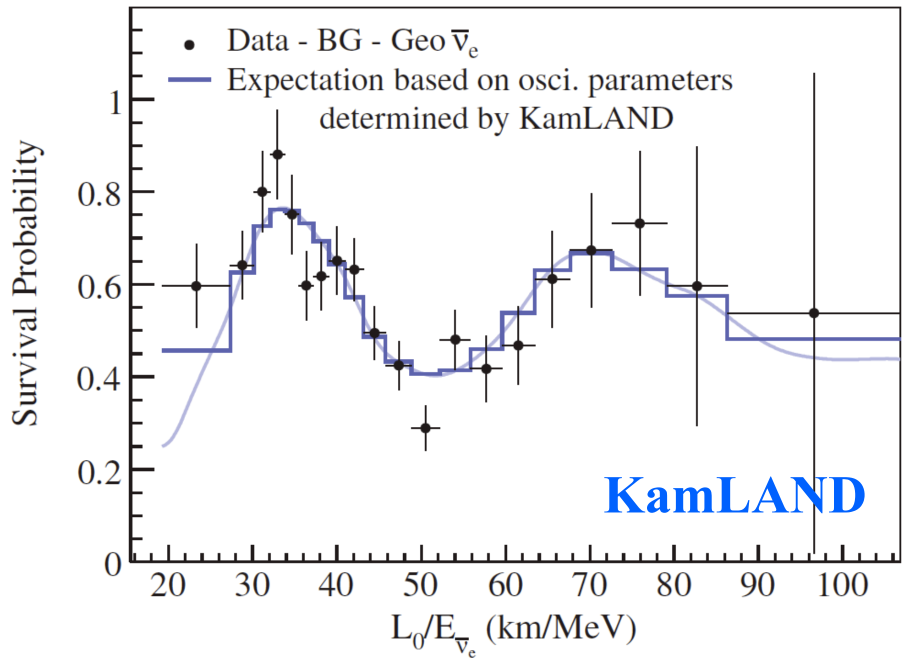
- Free & rich source of $\bar{\nu}_e$
- "Simple" measurement of θ_{13}
  - @ L ≃ 1 km, oscillation only depends on θ_{13} & Δm_{13}^2

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{31}^2 L}{E}\right) - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E}\right)$$



Reactor ν_e disappearance tells us...

- θ_{13} at small L/E
- θ_{12} at large L/E

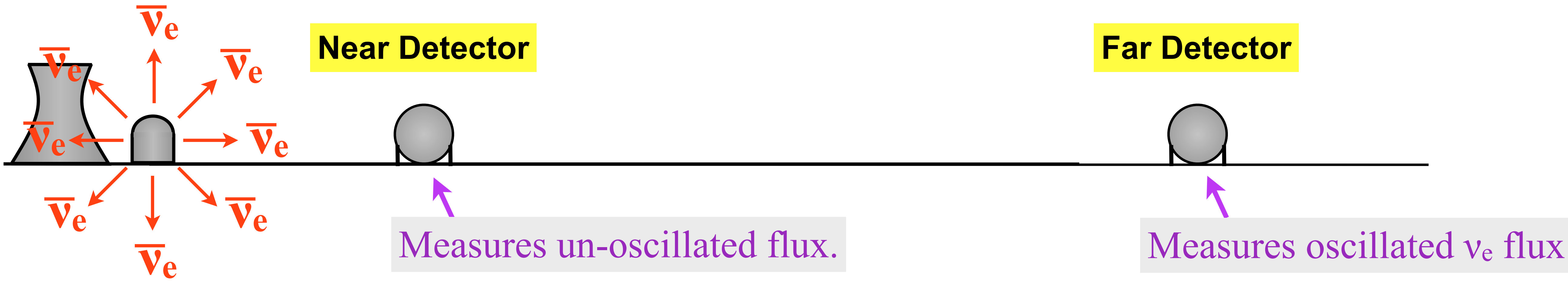


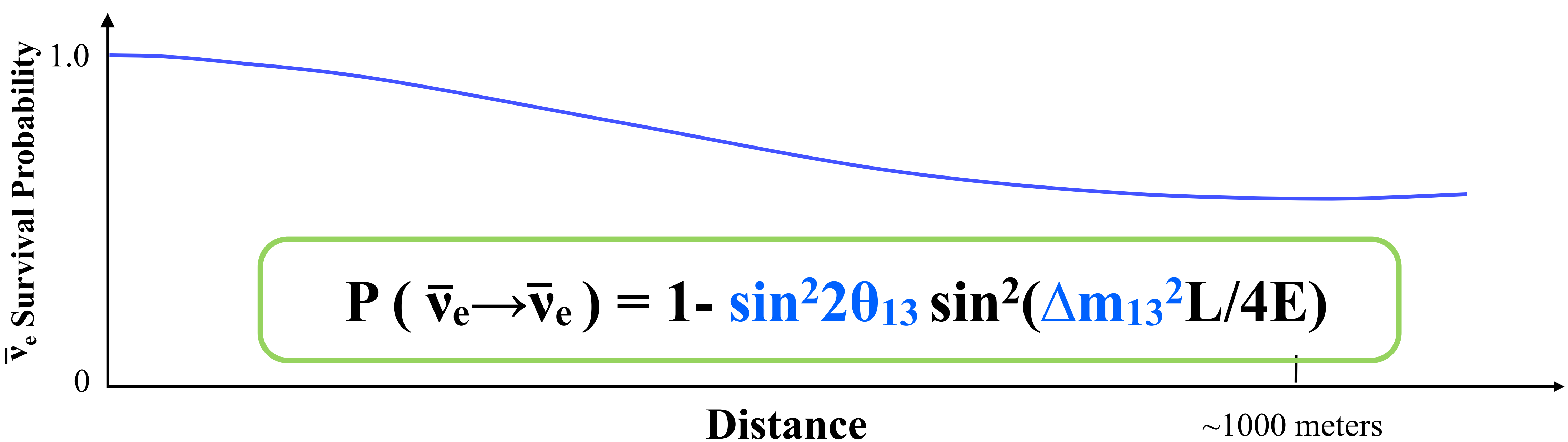
PRL 100 (20): 221803

Reactor θ_{13} Experiments

Why reactor experiment?

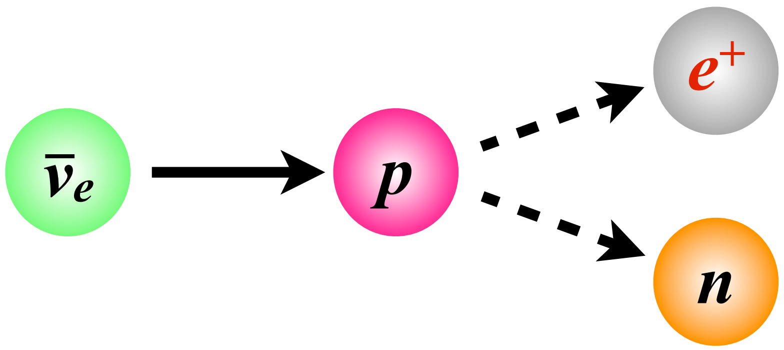
- Free & rich source of $\bar{\nu}_e$
- "Simple" measurement of θ_{13}
  - **@ L ≃ 1 km**, oscillation only depends on θ_{13} & Δm_{13}^2





$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{13}^2 L/4E)$$

How to Detect Signal?



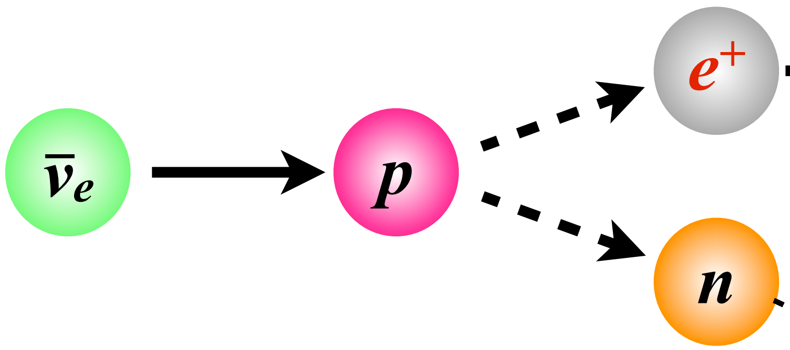
$$\bar{\nu}_e + p \longrightarrow n + e^+$$

(Energy Thres. 1.8 MeV)

Inverse Beta Decay

- **Target** = **Free protons**
- **Signal** = **Inverse Beta Decay**
  - e^+ and neutron
- **Detector** = **Liquid Scintillator** + **PMT**
  - Scintillation light emission through EM int.

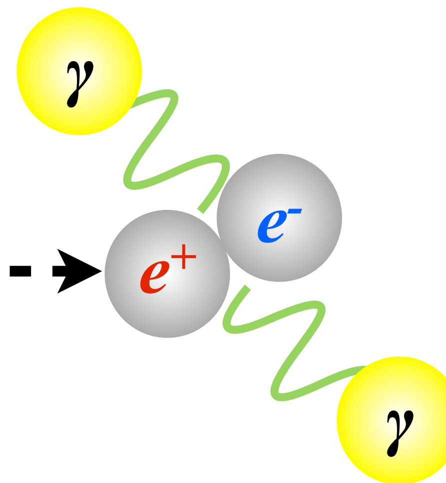
How to Detect Signal?



$$\bar{\nu}_e + p \longrightarrow n + e^+$$

(Energy Thres. 1.8 MeV)

Inverse Beta Decay

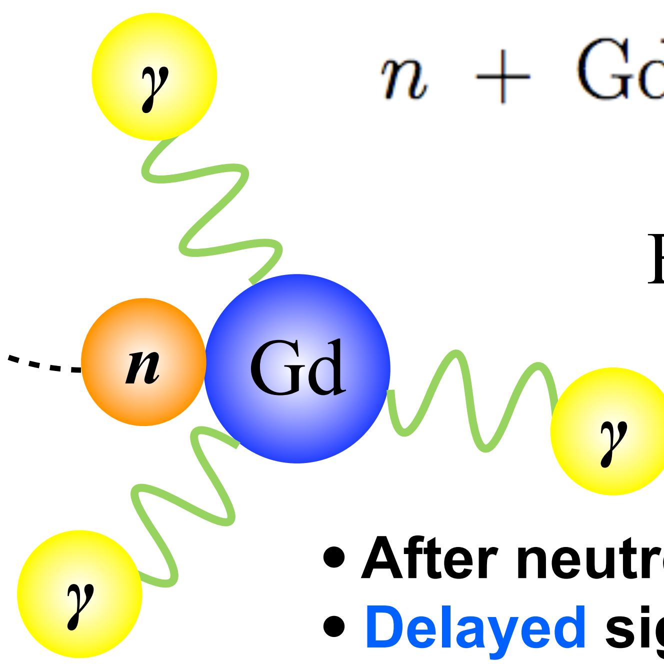


$$e^+ + e^- \longrightarrow 2\gamma$$

Energy ≈ E_ν - 0.8 MeV

- **Immediately after IBD**
- **Prompt signal**

e^+e^- Annihilation



$$n + \mathrm{Gd} \longrightarrow \sum_i \gamma_i$$

Energy ≈ 8 MeV

- **After neutron thermalization**
- **Delayed signal**

Neutron Capture on Gadolinium

- **Target** = **Free protons**
- **Signal** = **Inverse Beta Decay**
  - e^+ and neutron
- **Detector** = **Liquid Scintillator** + **PMT**
  - Scintillation light emission through EM int.

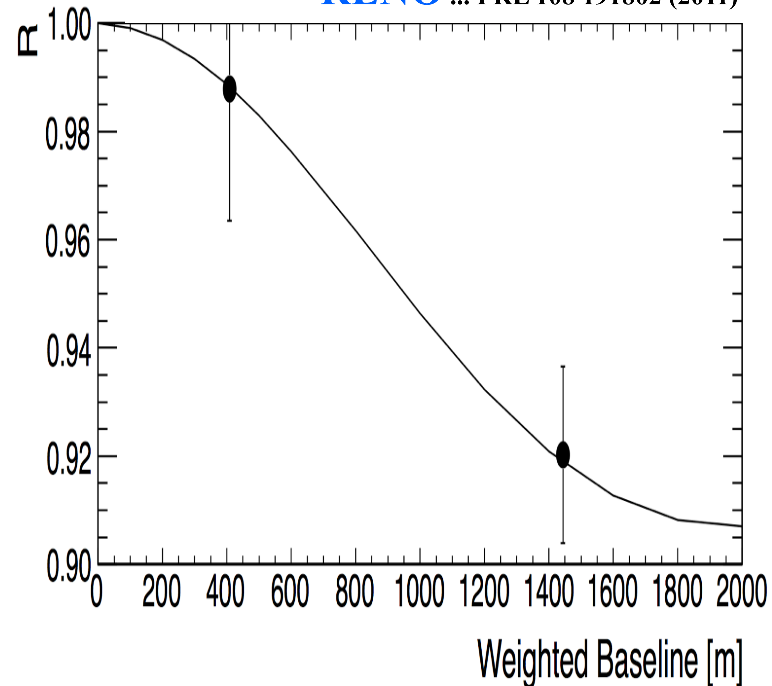
n-Gd capture cross-section much larger than n-H

How To Measure θ_{13}

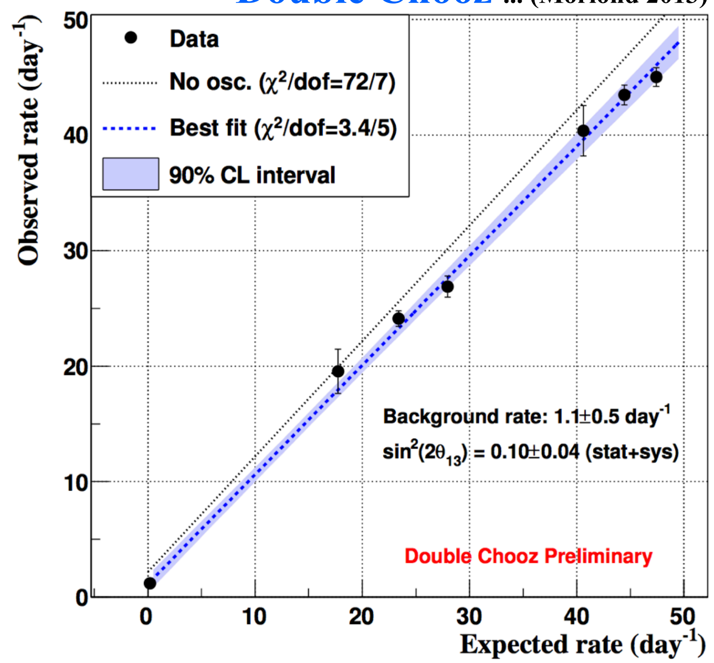
General Approach

- **“Rate” analysis ... counting ν_e**
    - Disappearance = #(Near) - #(Far)
        - Multiple detector fit
        - Reactor-Rate-Modulation fit

RENO ... PRL 108 191802 (2011)

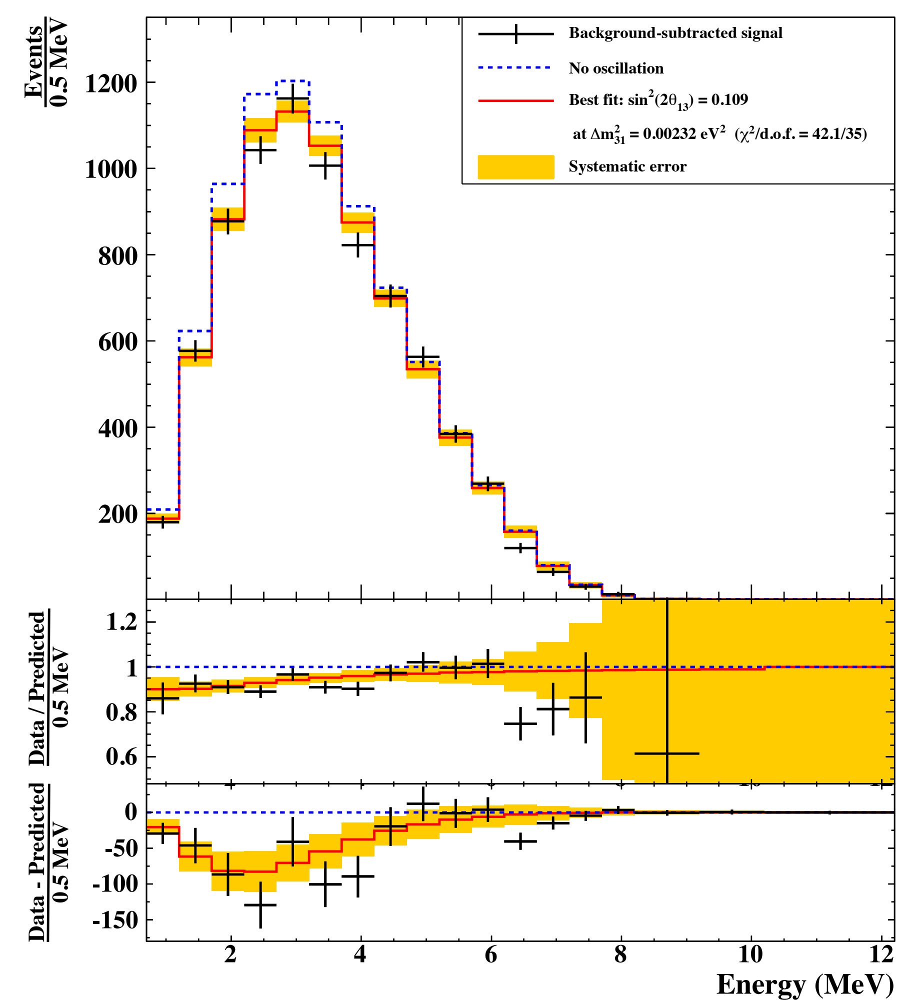


Double Chooz ... (Moriond 2013)



- **“Shape” analysis ... fitting e^+ spectrum**
    - Determine signal/BG component from spectrum shape
    - Compare near vs. far signal component
- **“Rate + Shape” analysis**
    - Input signal / BG rate + constrain from shape
    - Most powerful & robust
        - **Sensitive to shape distortion**
- **Extra handles...**
    - “Reactor Off data” ... BG-only data
        - **DOI: 10.1103/PhysRevD.87.011102**
    - “n-H data” ... use of separate ν_e signal sample
        - **DOI: 10.1016/j.bbr.2011.03.031**

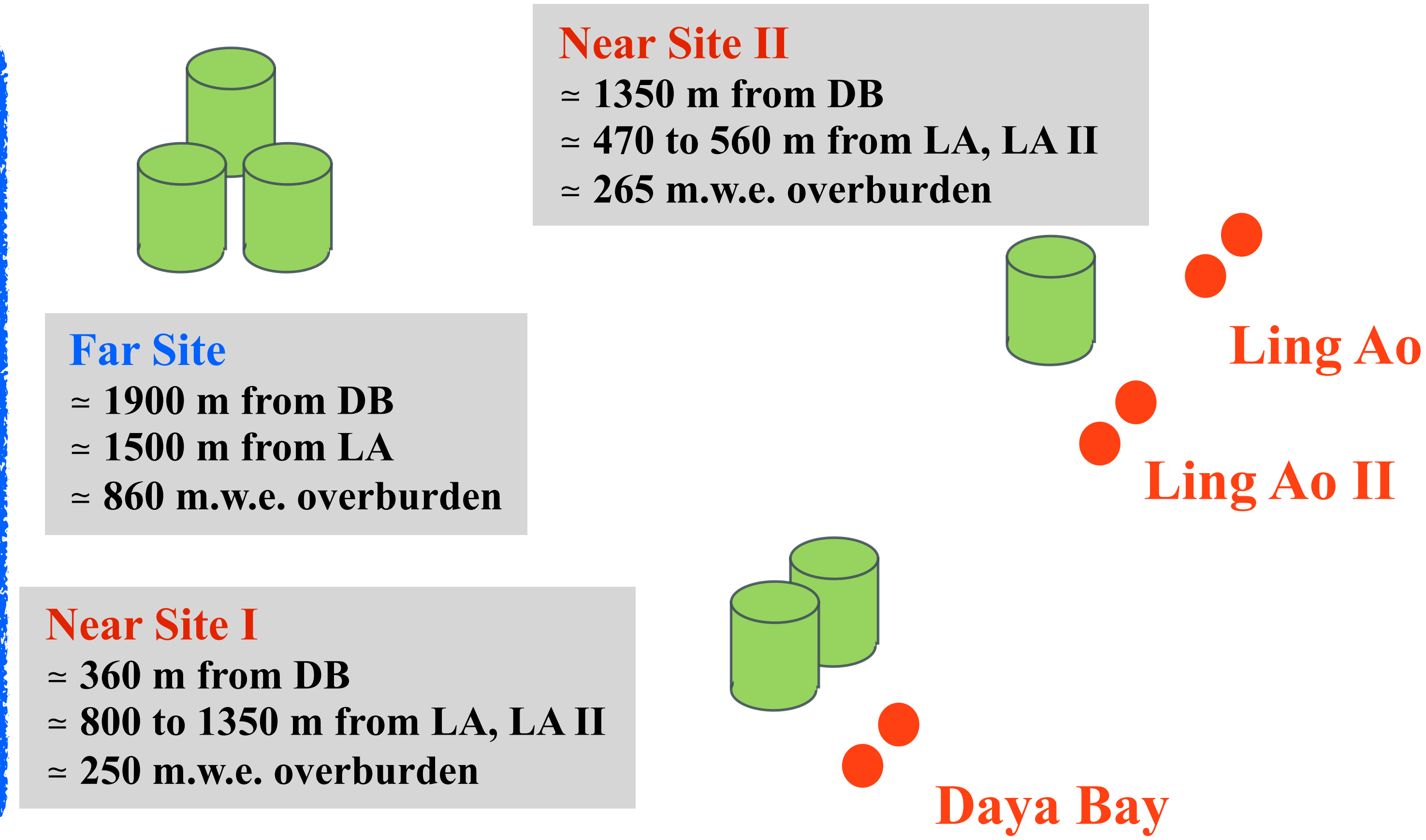
Double Chooz ... PRD 86, 052008 (2012)



Currently Running Reactor Experiments

Daya Bay, China

- Data taking since late 2011
- 6 x 2.9 GW_{th} cores
- 6 detectors (20 t each)
  - Target = LS + 0.1 % Gd
  - 3 far detectors
  - 2 + 1 near detectors



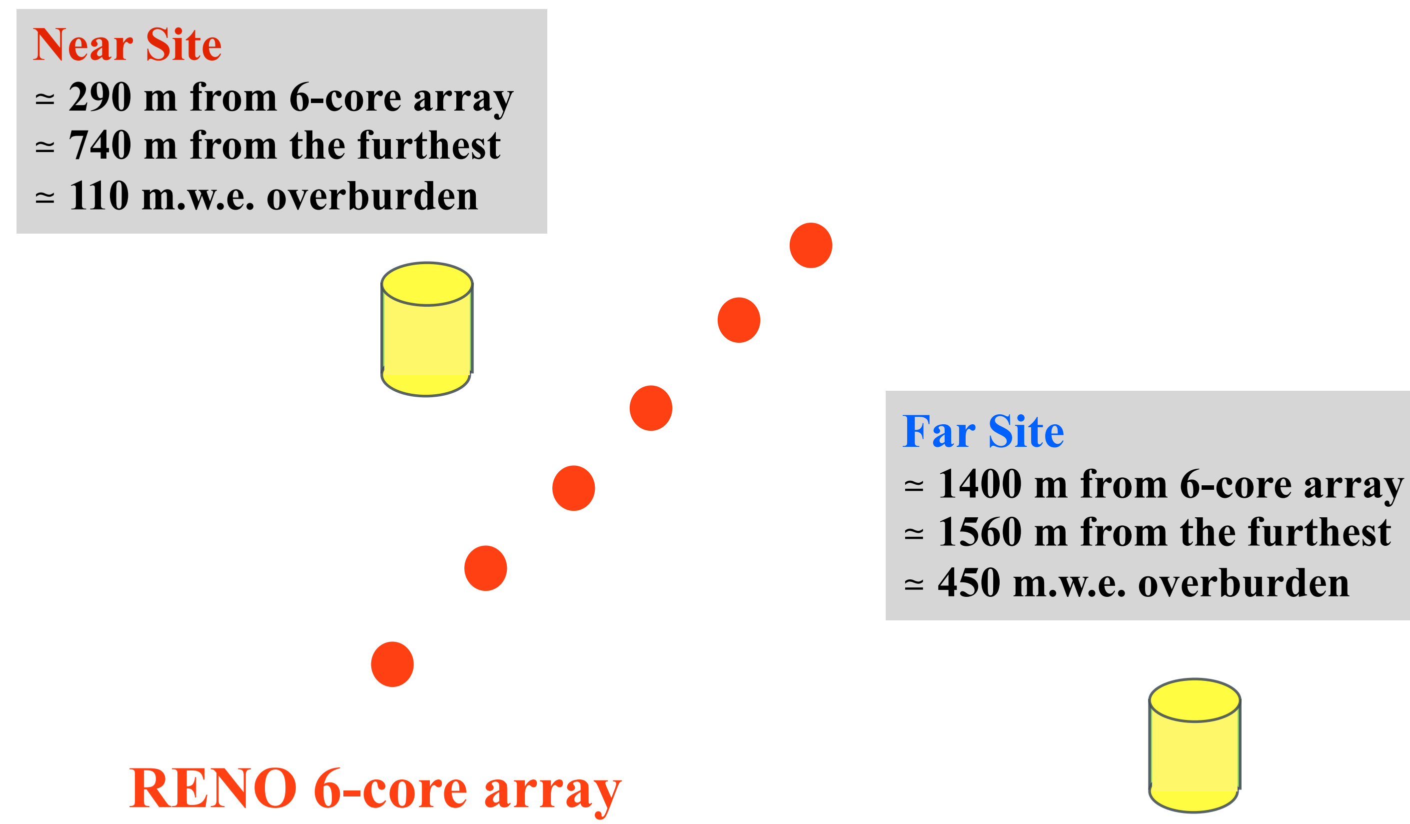
Currently Running Reactor Experiments

Daya Bay, China

- Data taking since late 2011
- **6 x 2.9 GW_{th} cores**
- **6 detectors (20 t each)**
  - Target = LS + 0.1 % Gd
  - 3 far detectors
  - 2 + 1 near detectors

RENO, Korea

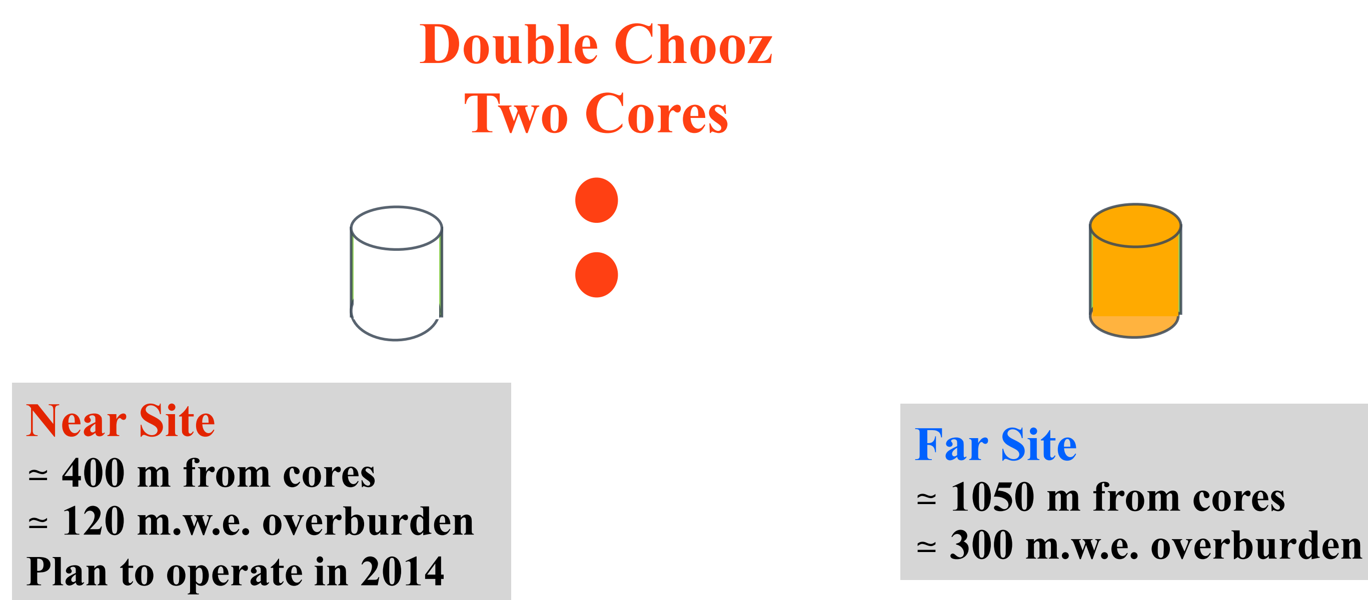
- Data taking since Fall 2011
- **6 x 2.7 GW_{th} cores**
- **2 detectors (16 t each)**
  - Target = LS + 0.1 % Gd
  - 1 far detectors
  - 1 near detectors



Currently Running Reactor Experiments

Daya Bay, China

- Data taking since late 2011
- **6 x 2.9 GW_{th} cores**
- **6 detectors (20 t each)**
  - Target = LS + 0.1 % Gd
  - 3 far detectors
  - 2 + 1 near detectors



RENO, Korea

- Data taking since Fall 2011
- **6 x 2.7 GW_{th} cores**
- **2 detectors (16 t each)**
  - Target = LS + 0.1 % Gd
  - 1 far detectors
  - 1 near detectors

Double Chooz, France

- Data taking since Spring 2011
- **2 x 4.3 GW_{th} cores**
- **1 detector (8.3 t)**
  - Target = LS + 0.1 % Gd
  - 1 far detectors
  - no near detector yet

Recent Results

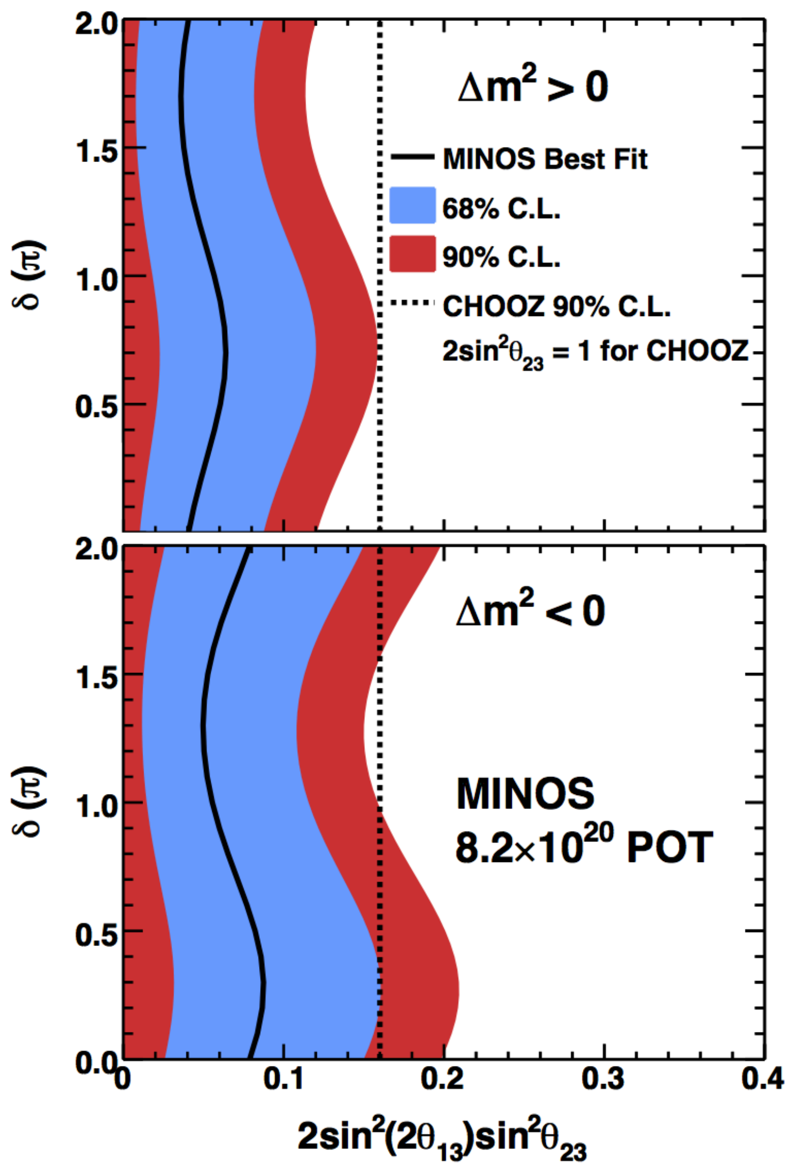
from

2011 ~ 2012: Year of θ_{13}

2011 ~ 2012 ... The Year of θ_{13}

First indication of non-zero θ_{13} ... Summer 2011

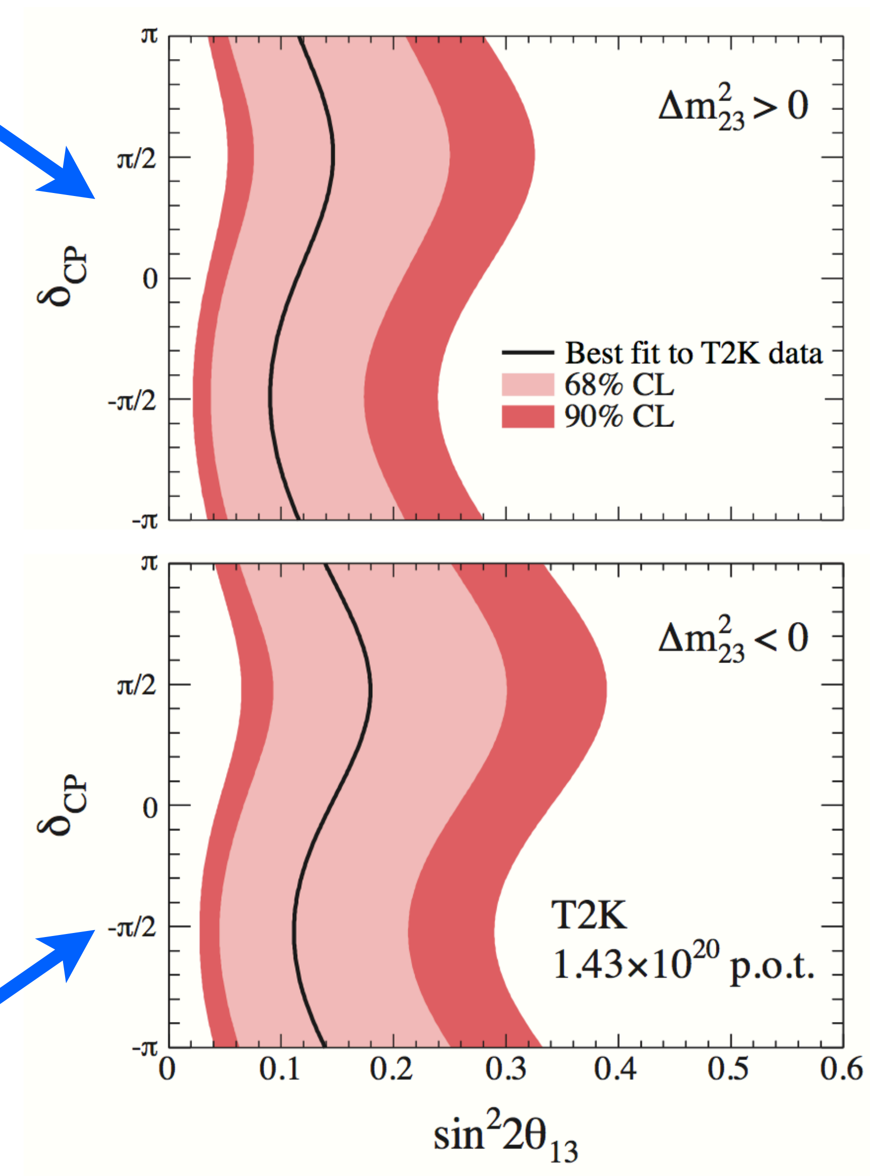
- T2K and MINOS from $\nu_\mu \rightarrow \nu_e$ oscillation



MINOS Collaboration
PRL 107 181802, 2011

Normal Hierarchy

Inverted Hierarchy



T2K Collaboration
PRL 107 041801, 2011

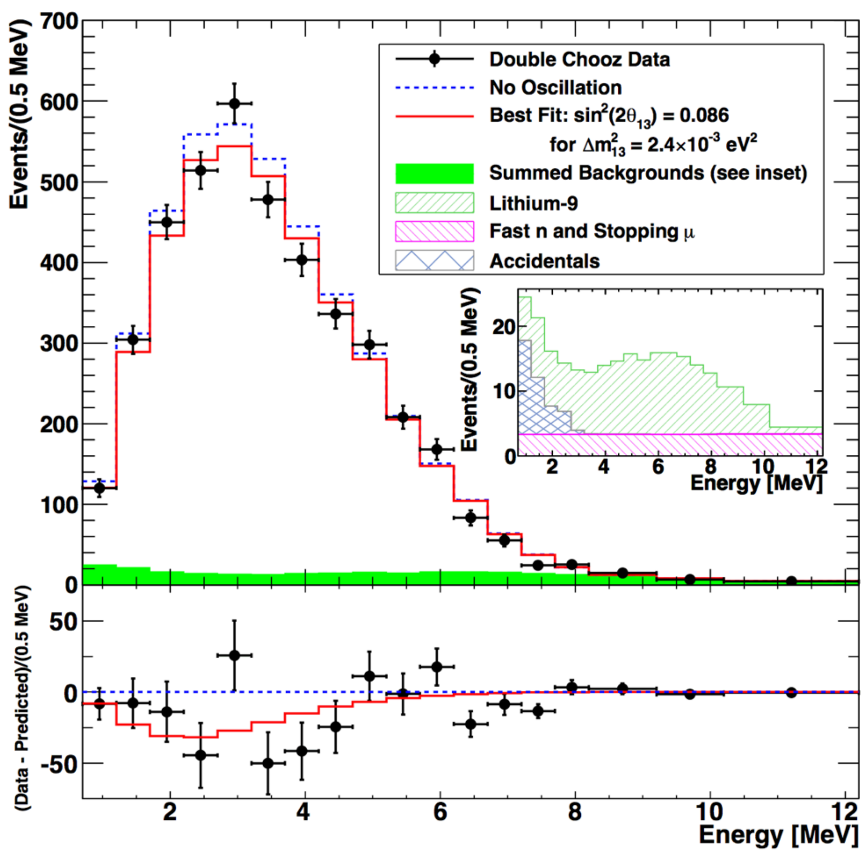
2011 ~ 2012 ... The Year of θ_{13}

First indication of non-zero θ_{13} ... Summer 2011

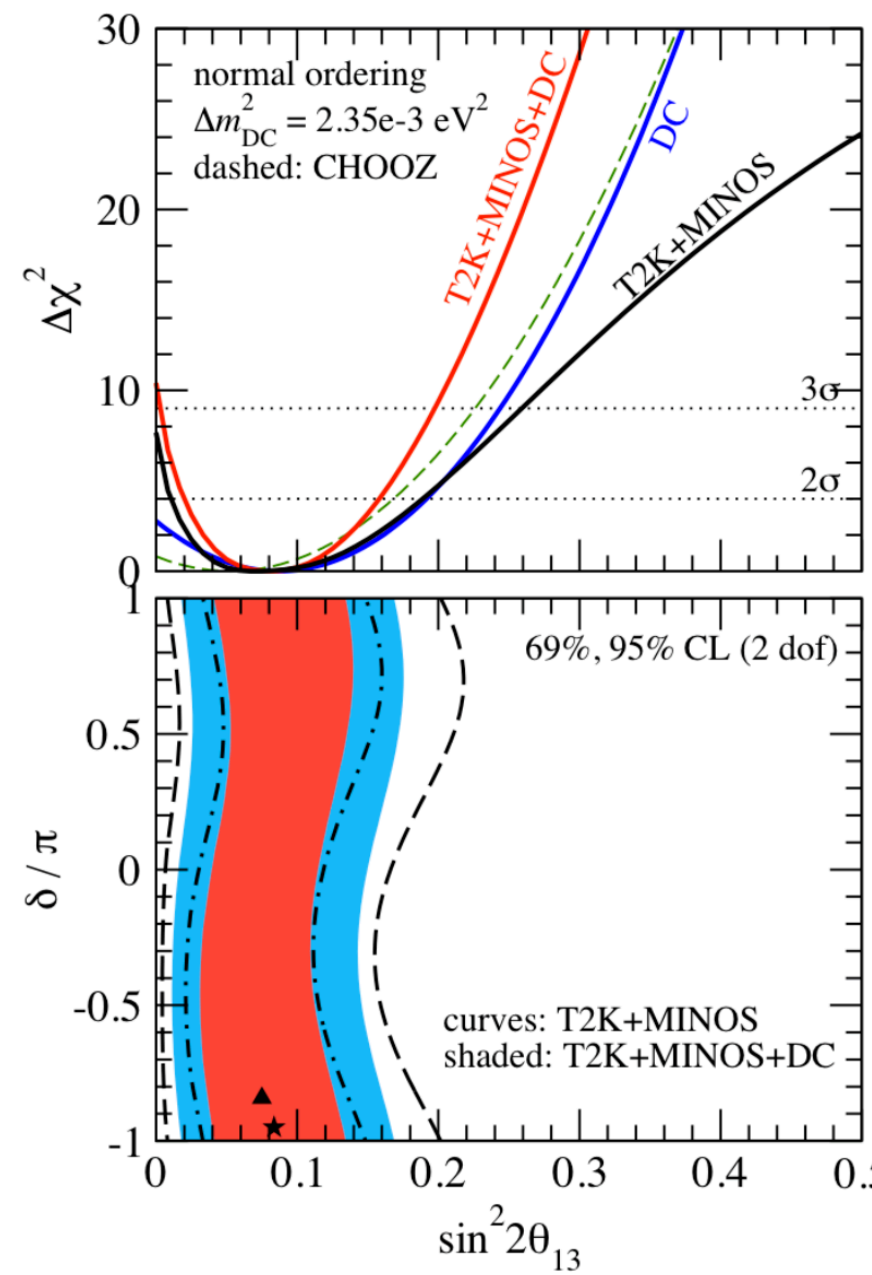
- T2K and MINOS from $\nu_\mu \to \nu_e$ oscillation

First result from Double Chooz ... Nov. 2011

- T2K + MINOS + DC = 3σ exclusion of $\theta_{13} = 0$
  - $\sin^2 2\theta_{13} = 0.086 \pm 0.041$ (stat) ± 0.030 (syst)



"**Rate + Shape**" from **Double Chooz**



T2K + MINOS + Double Chooz

2011 ~ 2012 ... The Year of θ_{13}

First indication of non-zero θ_{13} ... Summer 2011

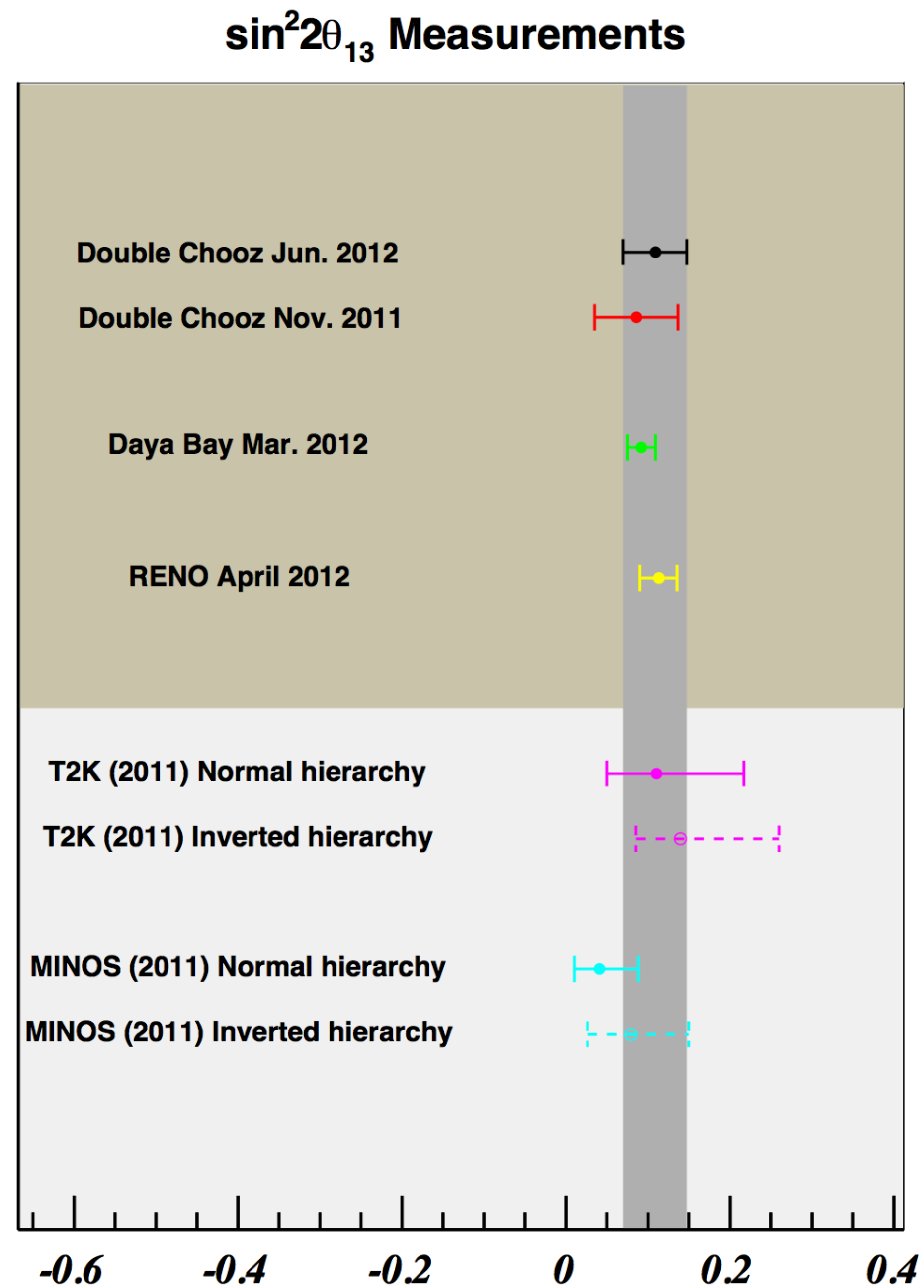
- T2K and MINOS from $\nu_\mu \rightarrow \nu_e$ oscillation

First result from Double Chooz ... Nov. 2011

- T2K + MINOS + DC = 3σ exclusion of $\theta_{13} = 0$

Grand Finale ... Spring to Summer 2012

- Double Chooz ... **PRD 86, 052008 (2012)**
  - $\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat) ± 0.025 (syst)
- RENO ... **PRL 108, 191802 (2012)**
  - $\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat) ± 0.019 (syst)
- Daya Bay ... **PRL 108 171803 (2012)**
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)



PRD 86, 052008 (2012)

2011 ~ 2012 ... The Year of θ_{13}

First indication of non-zero θ_{13} ... Summer 2011

- T2K and MINOS from $\nu_\mu \rightarrow \nu_e$ oscillation

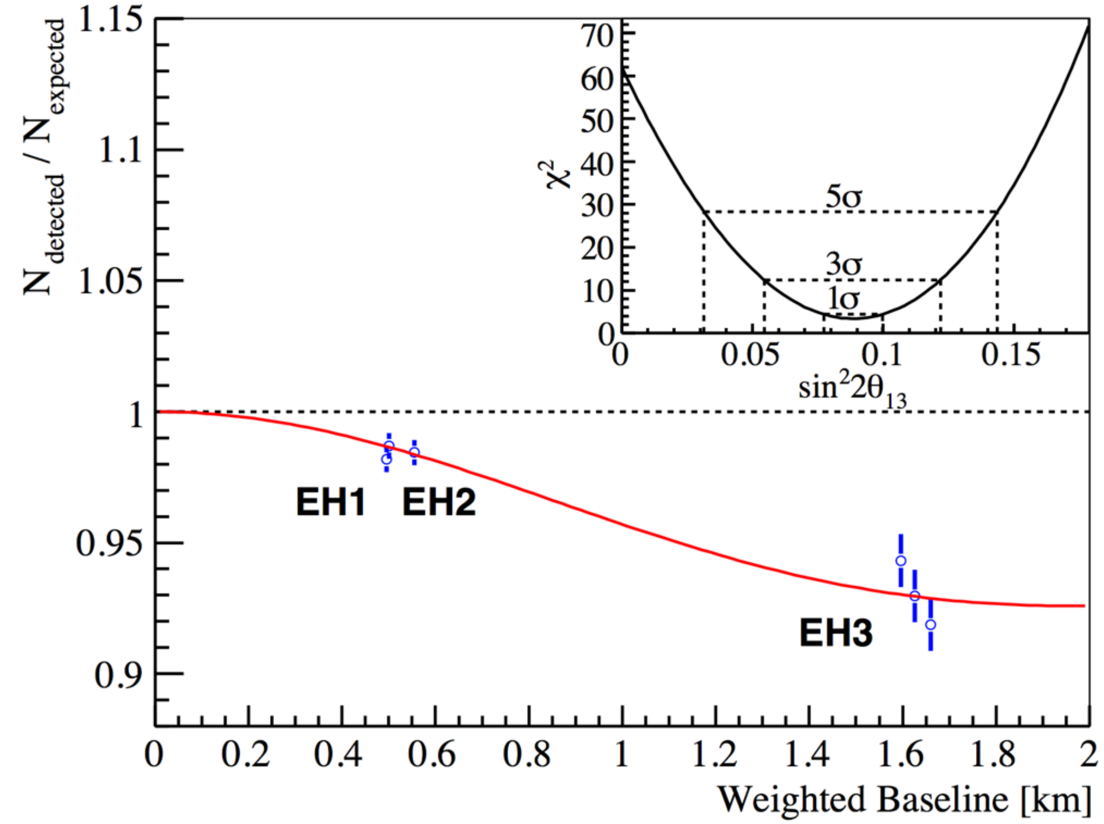
First result from Double Chooz ... Nov. 2011

- T2K + MINOS + DC = 3σ exclusion of $\theta_{13} = 0$

Grand Finale ... Spring to Summer 2012

- Double Chooz ... **PRD 86, 052008 (2012)**
  - $\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat) ± 0.025 (syst)
- RENO ... **PRL 108, 191802 (2012)**
  - $\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat) ± 0.019 (syst)
- Daya Bay ... **PRL 108 171803 (2012)**
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

Daya Bay Best Fit
Near vs. Far "Rate" Analysis



Best result to date ... by single experiment

- Daya Bay ... $\mathbf{\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005}$ ... **(Chin.Phys. C37 (2013) 011001)**

****Congratulations****

to

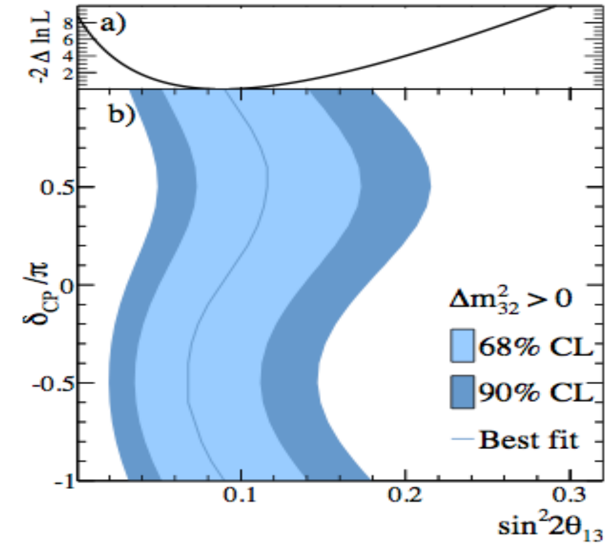
everyone involved!

- Great precision achieved in incredibly short time!
- θ_{13} became from the least to the best known angle!
- All measurements are consistent within errors

What Now?

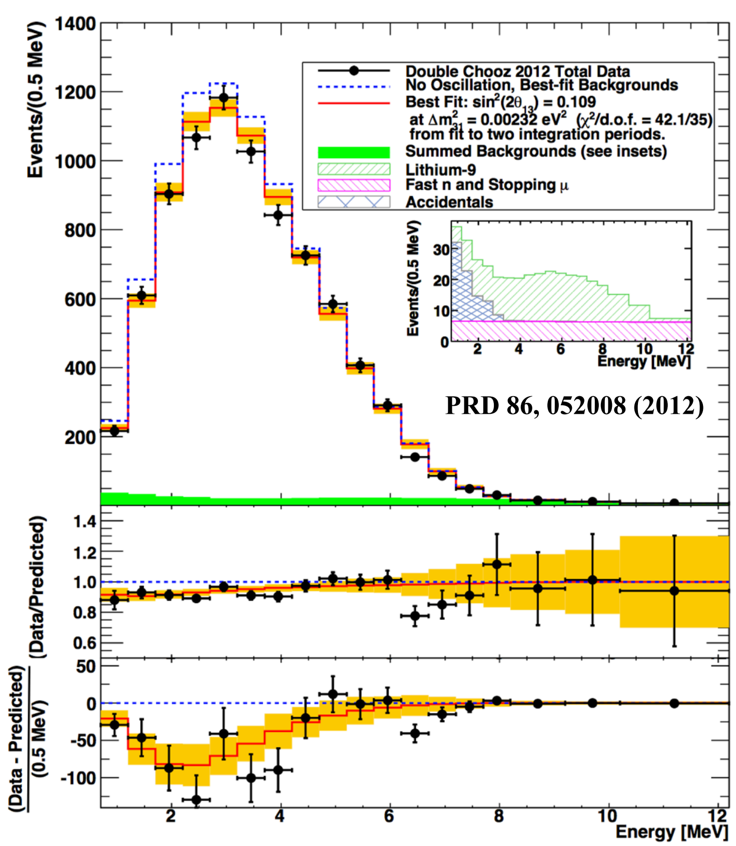
Reactor Experiments ... What Now?

T2K Update
Arxiv 1304.0841

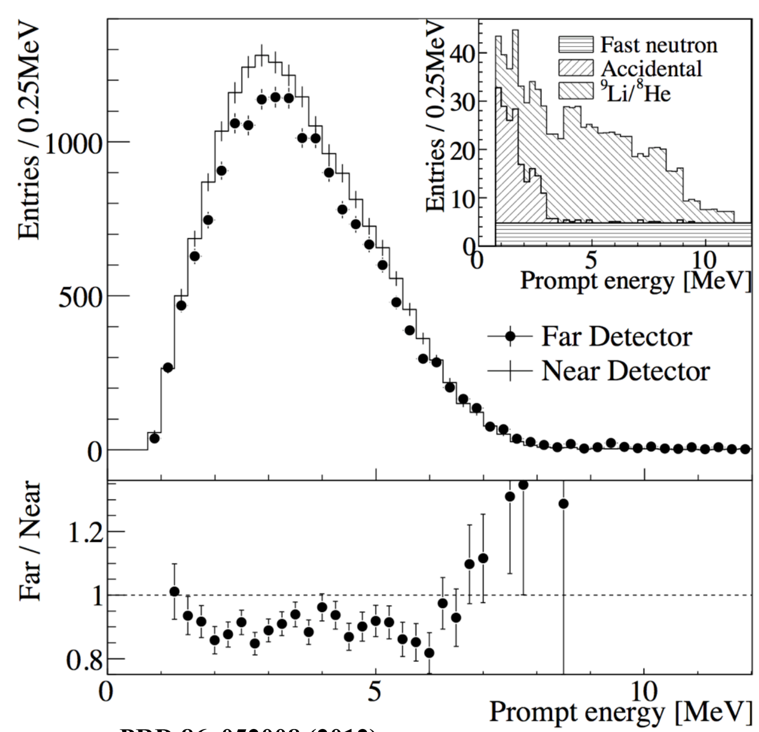


More to say on θ_{13}?

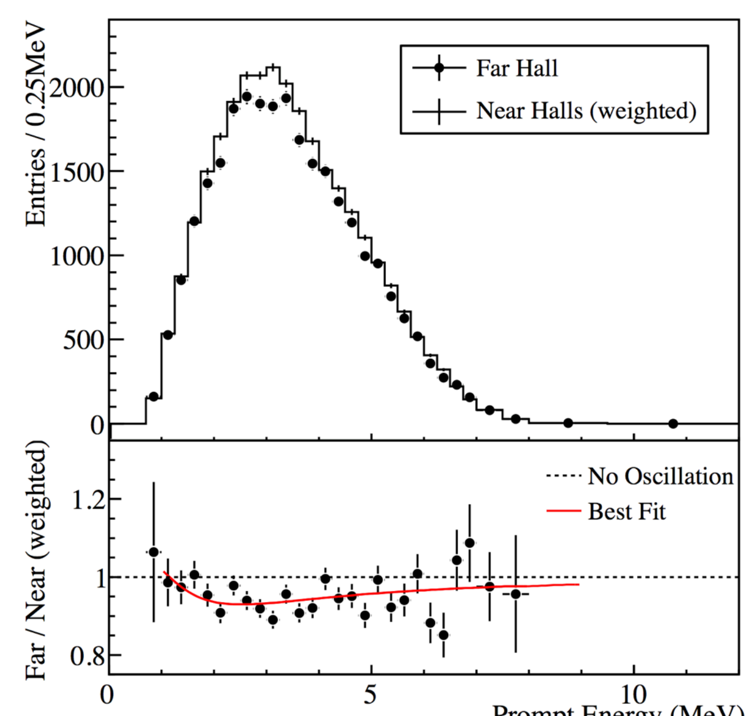
- Cross-checks are important
- **Rate + Shape analysis** by Daya Bay & RENO
  - **Does that affect the value/uncertainty of θ_{13}?**
    - **IMPORTANT** ... θ_{13} is an input value for δ_{CP} and mass hierarchy measurements



"**Rate + Shape**"
by Double Chooz



PRD 86, 052008 (2012)



Chin. Phys. C37 (2013) 011001

RENO (left) and **Daya Bay** (right) e+ spectrum
High statistics = small error bar in each bin
Great sample for "Rate + Shape" fit! (**not done yet**)

Reactor Experiments ... Outside θ_{13}

Other Physics?

We can learn a lot from existing data ...

- Baseline dependent Δm_{31}^2 analysis ... **arXiv 1304.6259 (2013)**
- Lorentz violation analysis ... **PRD 86 112009 (2012)**
- Non-proliferation study
- Near vs. far spectral distortion analysis ... beyond θ_{13} effect

Planned / proposed measurement ideas ...

- Mass Hierarchy measurement @ L ≃ 60 km baseline
- Very short baseline measurement: “reactor anomaly”
  - separate physics, no effect on θ_{13} measurement

Summary

Summary

Measurement of θ_{13}

- Hints from accelerator, finale with reactor experiments
  - **All measurements consistent** on the value of θ_{13}
  - Great precision achieved in very short time scale
  - Best single experiment ... **Daya Bay**: $\mathbf{\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005}$ **(Chin.Phys. C37 (2013) 011001)**
- Very important input to plan/review future experiment.
- Important / interesting effort on-going
  - Multiple measurements & cross-checks continues
  - **Spectral distortion?** (non-standard oscillation? new physics??)

What's next?

- Other physics with reactor experiments
- Future deterministic measurement on mass hierarchy and δ_{CP}
  - Measured value of θ_{13} plays an important role

Back Up

Oscillation Physics

Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \end{pmatrix}$$

$$U$$

ν_α → $|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i} e^{-iE_i t} |\nu_i\rangle$ → ν_β

Production
(weak interaction)

Propagation

Detection
(weak interaction)

Probability for detecting ν_β

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$
$$= \sum_{i,j} U^*_{\beta i} U_{\alpha i} U_{\beta j} U^*_{\alpha j} e^{-i(E_i - E_j)t}$$

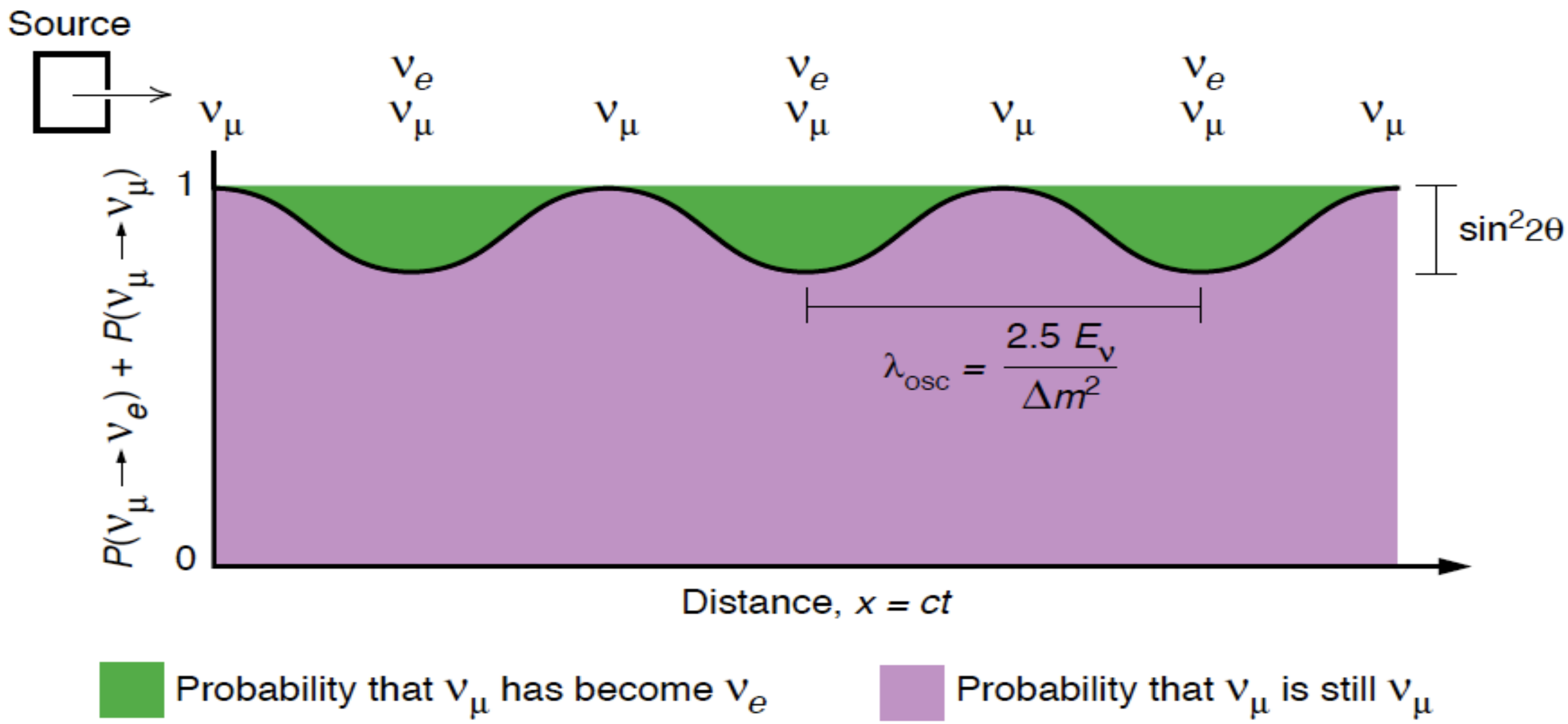
Ultra-relativistic Approx.

$$E_i = \sqrt{\mathbf{p}^2 + m_i^2} \simeq |\mathbf{p}| + \frac{m_i^2}{2|\mathbf{p}|}$$

$$(E_i - E_j) \cdot t = \frac{(m_i^2 - m_j^2)L}{2E} = \frac{\Delta m_{ij}^2 L}{2E}$$

Depends on θ, L, E, and Δm^2

Neutrino Oscillation



Courtesy of "Celebrating Neutrinos" (LANL)

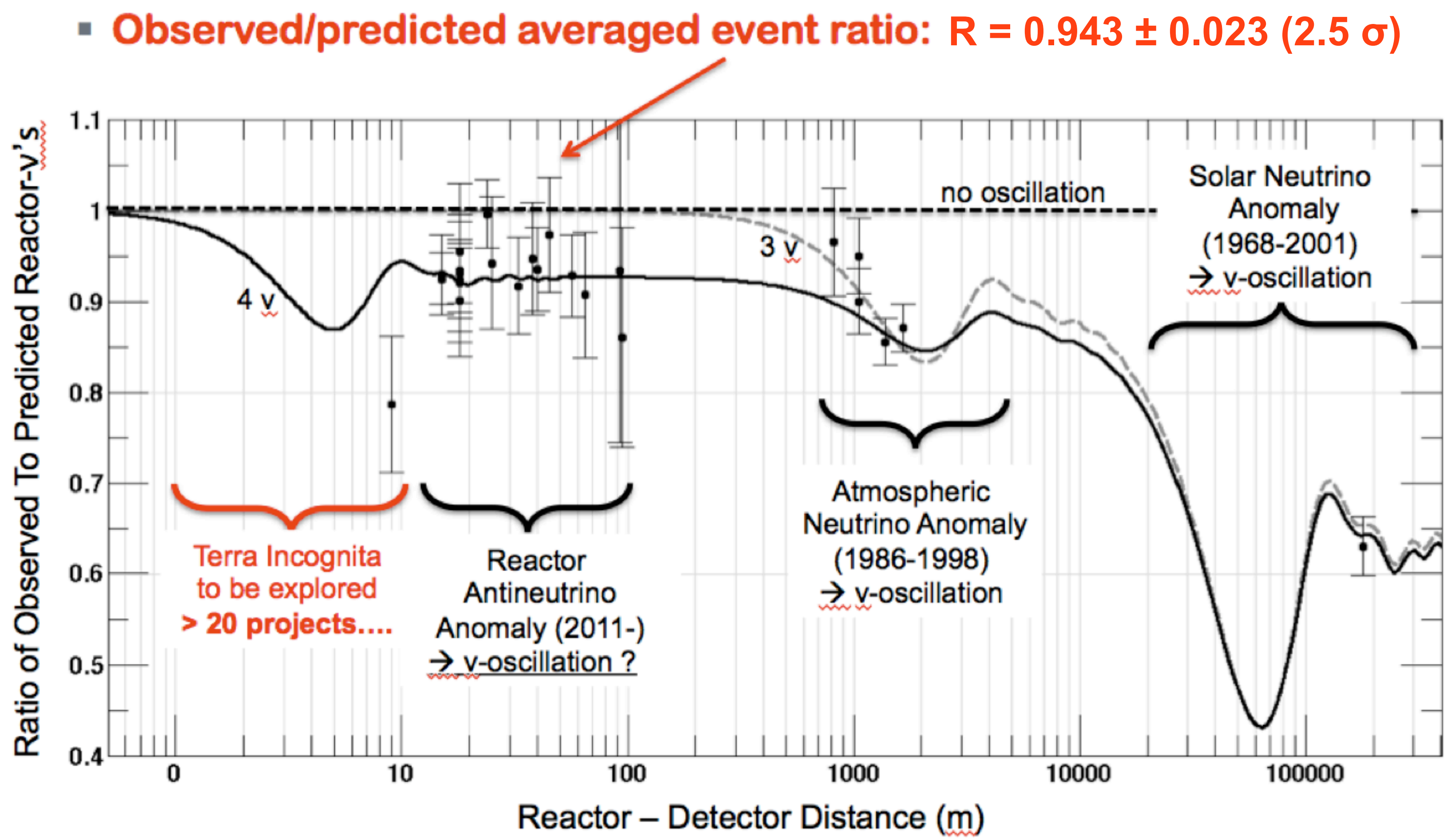
Key points of oscillation experiments

- We produce & detect neutrinos through weak interaction
  - Mixing angle describes initial state
  - We can see either "disappearance" or "appearance" of specific flavor
- Oscillation effect depends on angle, energy, distance, and mass splitting

Reactor Anomaly

Reactor Anomaly

- Recent evaluation in the flux prediction caused anomaly
  - First Reported in Phys. Rev. D 83, 073006 (2011)
  - Updated fission cross section
  - Neutron lifetime changed
    - 885.7 ± 0.8 (2010)
    - 881.5 ± 1.5 (2011)
    - 880.1 ± 1.1 (2012)



  - Latest evaluation by Peter Vogel et al. (arXiv 1303.0900, 03/14/2013)
    - R = 0.959 ± 0.009 (experimental error) ± 0.027 (flux error)
    - 1.4 σ significance

Detector

Detector
(Example: Double Chooz)

Target Volume (10.3 m^3)
- Acrylic vessel filled with LS doped with Gd
- Neutron capture time ≈ 30 μs

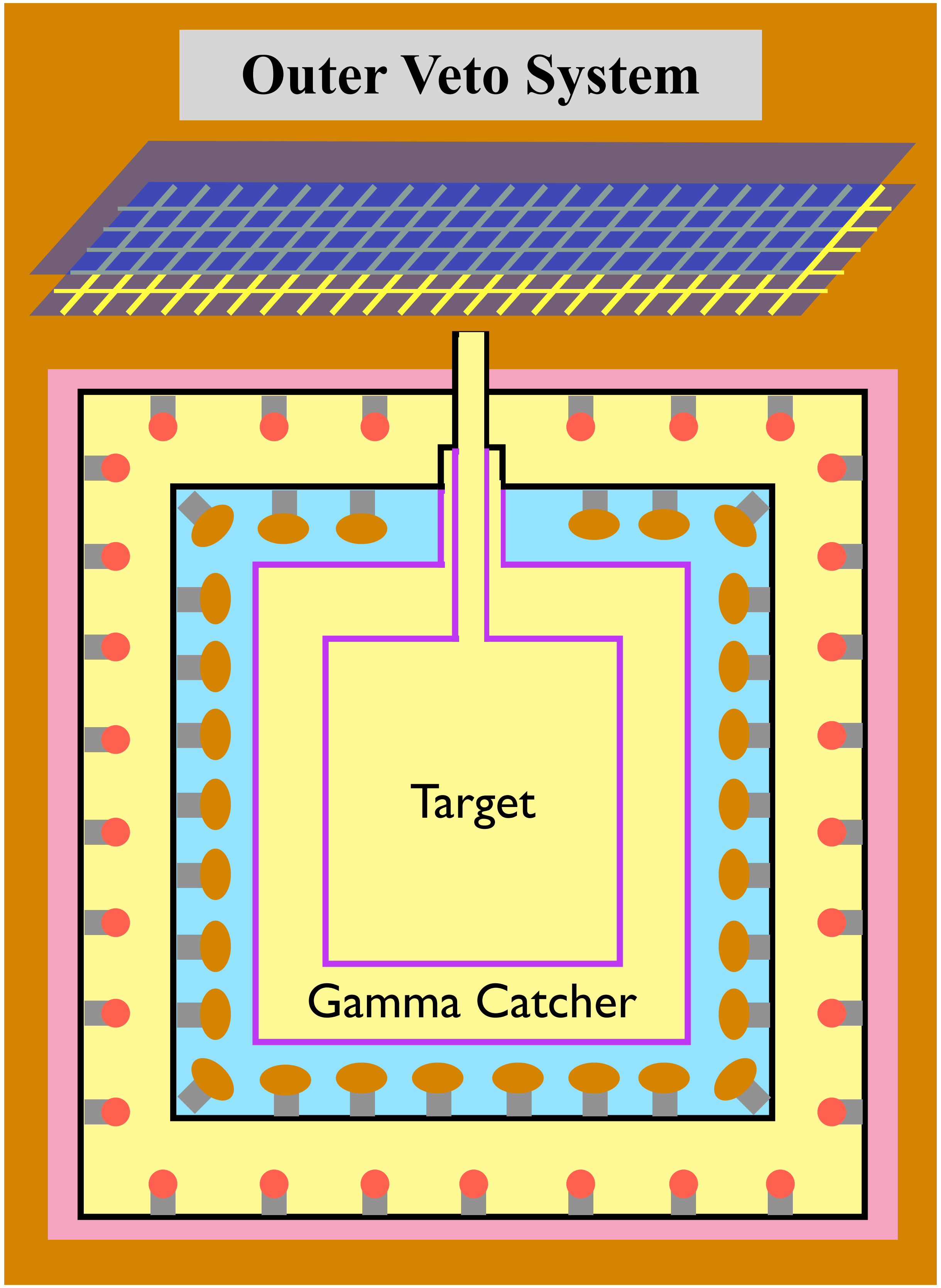
Gamma Catcher (22.6 m^3)
- Acrylic vessel filled with LS
- Neutron capture time ≈ 200 μs

Buffer Tank (98 m^3)
- Stainless-Steel tank filled with mineral oil
- 390 PMTs (10 inch) collecting light

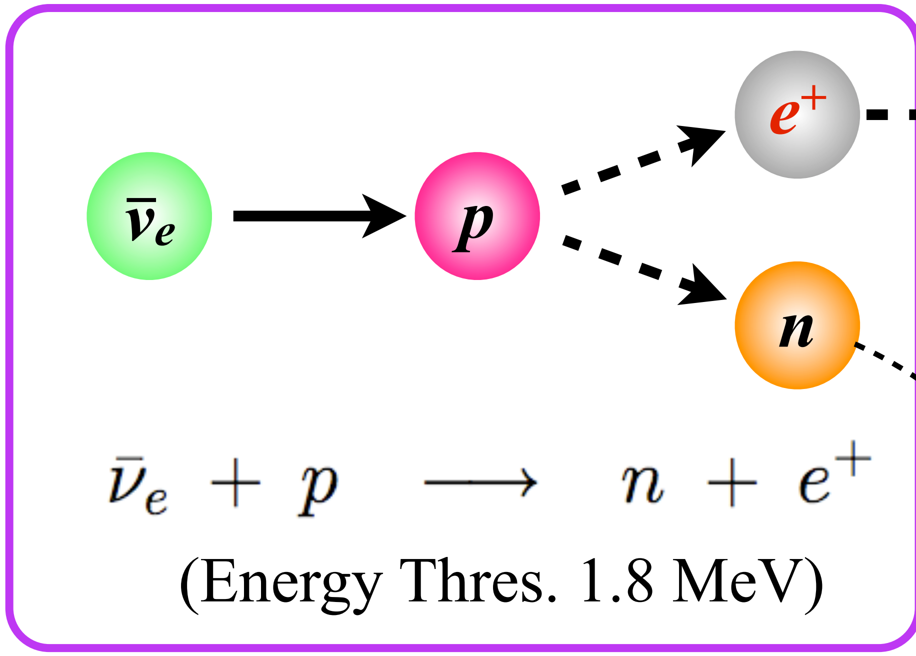
Inner Veto (90 m^3)
- Steel tank filled with LS
- 78 PMTs (8 inch) collecting light

Outer Veto
- Multi-layered scintillator strips (track muons)

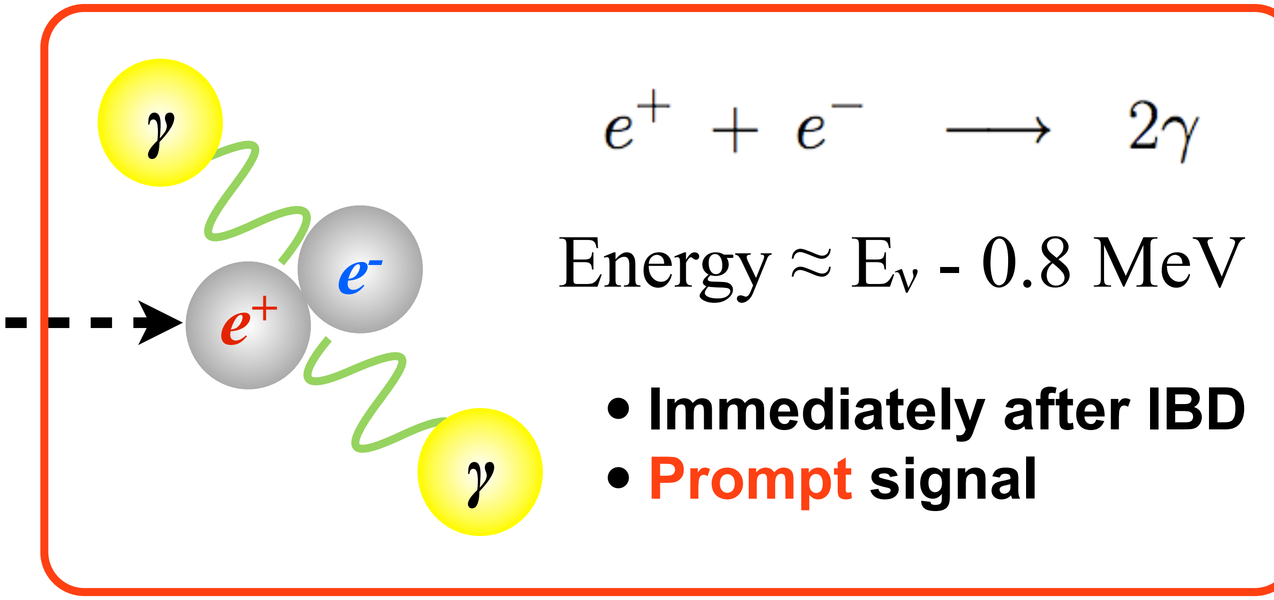
Shielding
- Overburden (300 m.w.e.) + 15 cm steel outside the Inner Veto



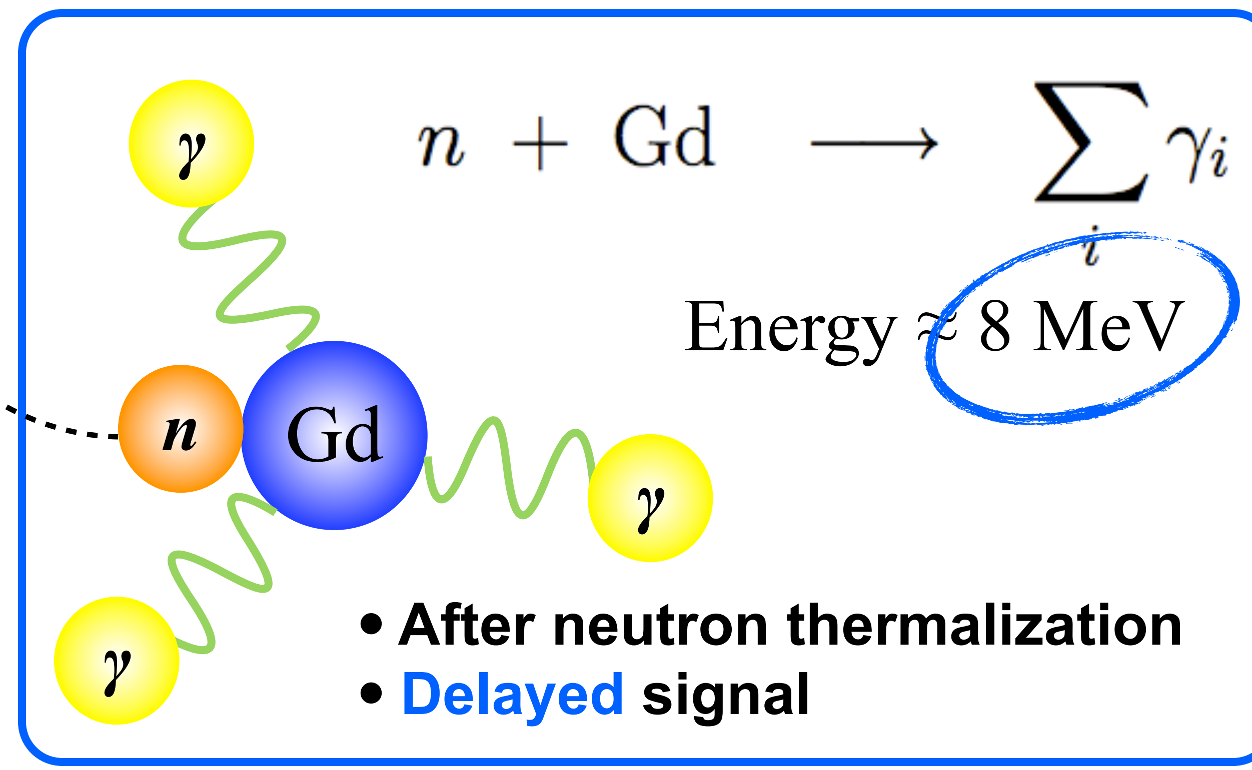
How to Detect Signal?



Inverse Beta Decay

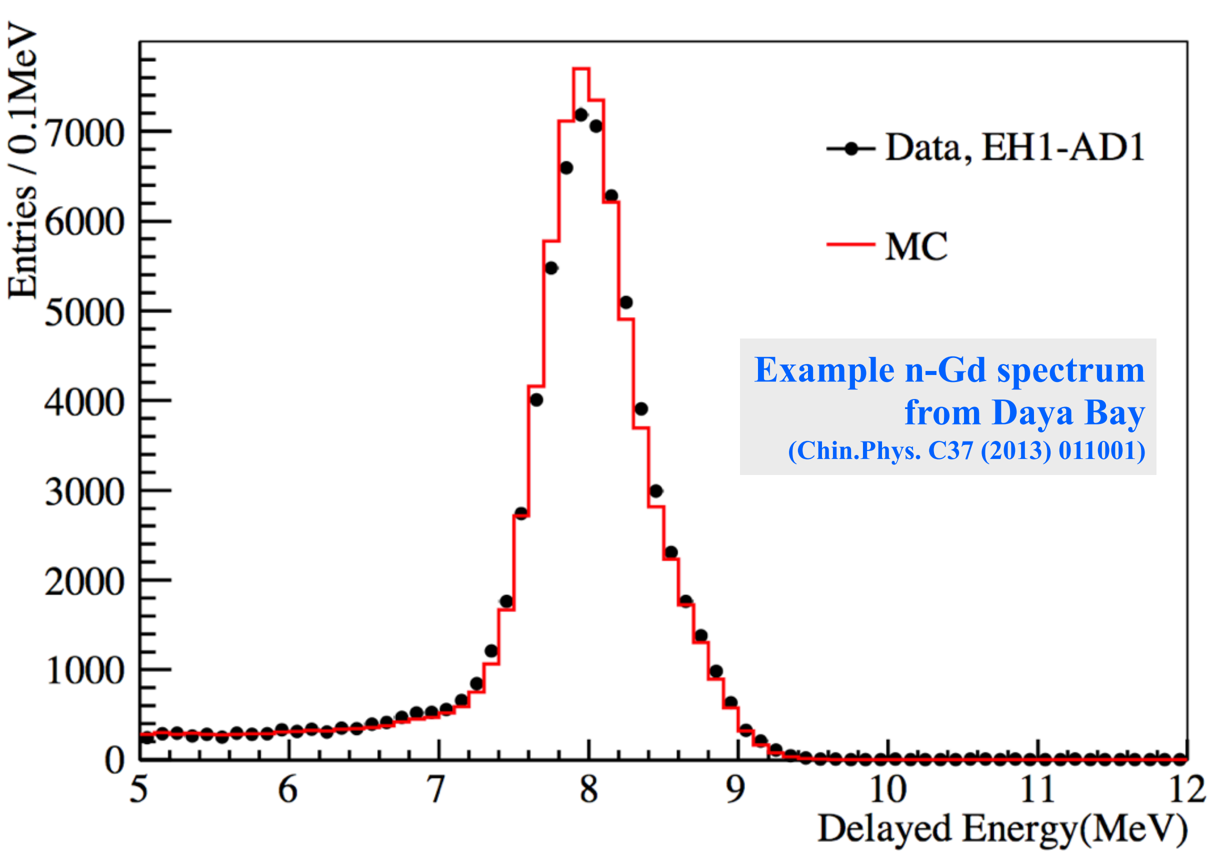


e^+e^- Annihilation



Neutron Capture on Gadolinium

n-Gd capture cross-section much larger than n-H

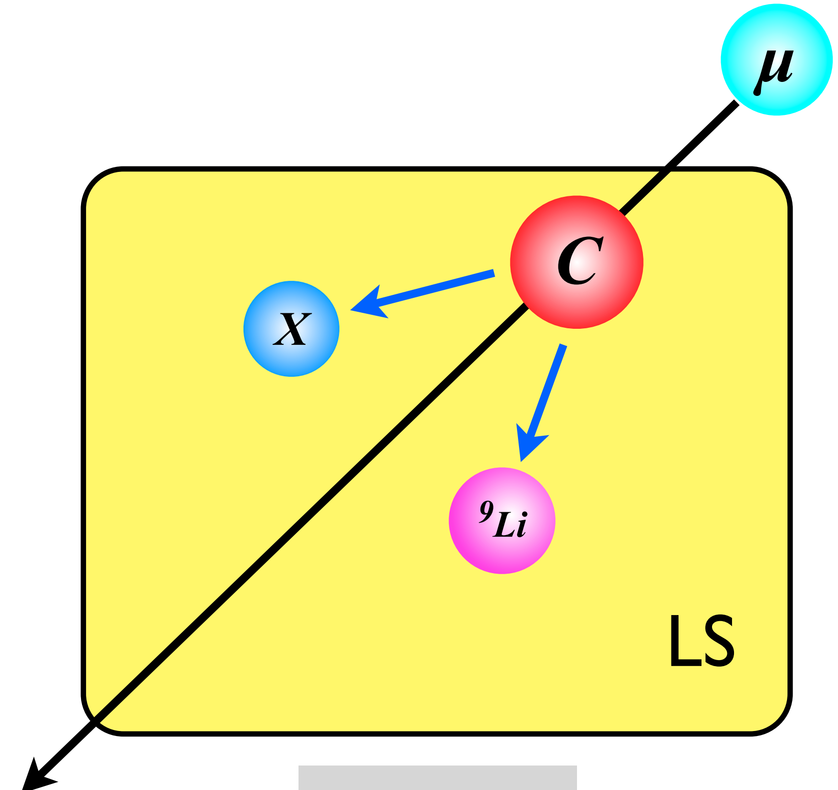


Common Background

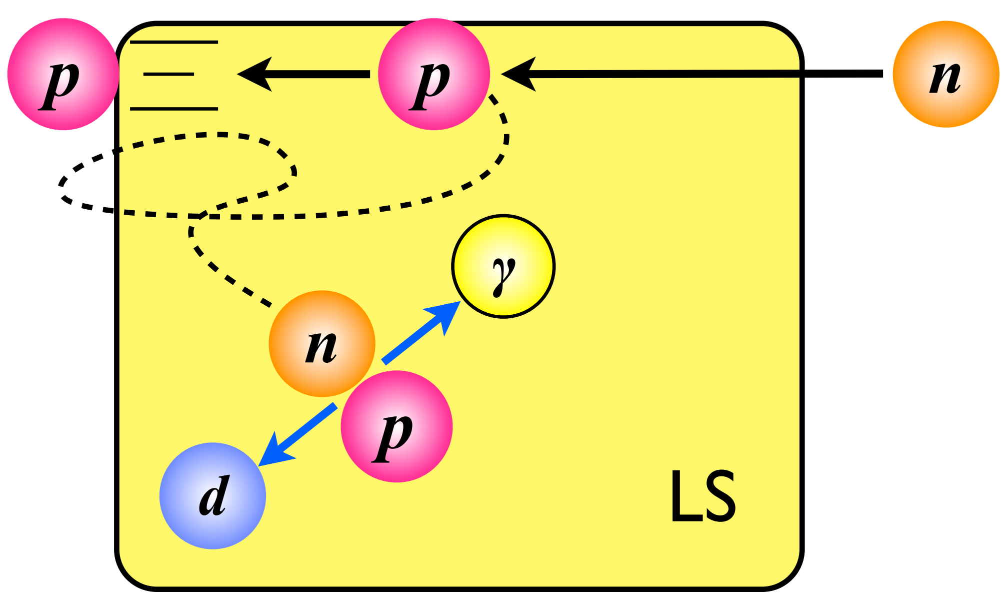
Backgrounds
(Example: Double Chooz)

Anything that mimics a coincidence is a background

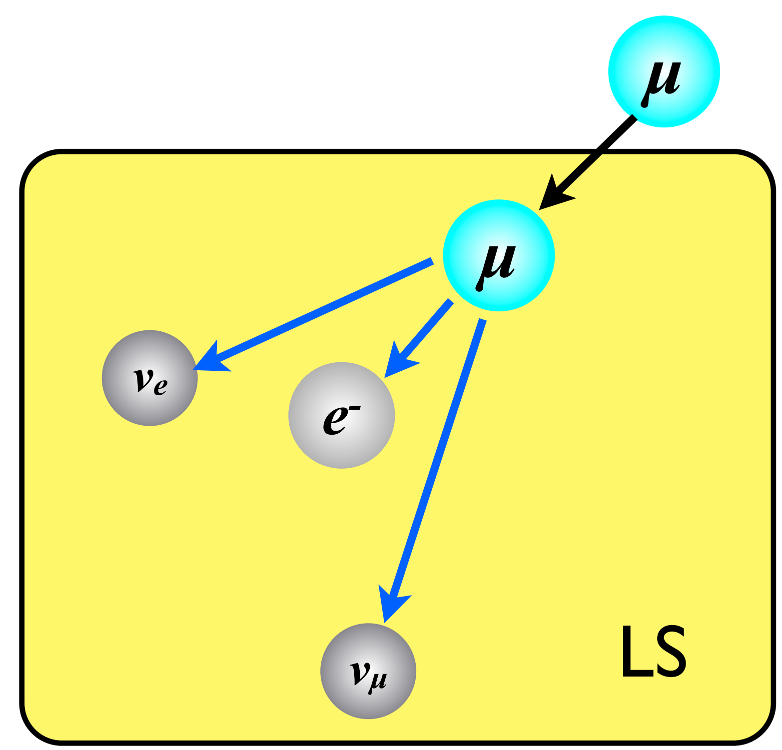
- Accidentals
  - Accidental coincidence of 2 unrelated events
- Long-lived muon spallation isotopes (^{9}Li, ^{8}He)
  - A neutron emitting beta decay
- Stopping muons
  - Muon energy deposition + decay
- Fast neutrons
  - A proton recoil + delayed neutron capture



Lithium-9



Fast Neutrons



Stopping Muon

DC Prediction

Reactor $\bar{\nu}_e$ Flux Prediction

Our Recipe For Prediction

1. **Predict fission rate** using MC with input DATA from EDF
   - Fuel composition + power history from EDF database
   - Two MC (DRAGON & MURE) for cross-checking the precision

2. **Predict Neutrino Spectrum**
   - Use an updated spectrum-per-fission
   - Bugey-4 anchor point to minimize systematics
     - In future use near detector measurement

$$N_\nu^{\exp}(E,t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_f \rangle_k$$

Bugey4 anchor point

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \langle \sigma_f \rangle_k$$

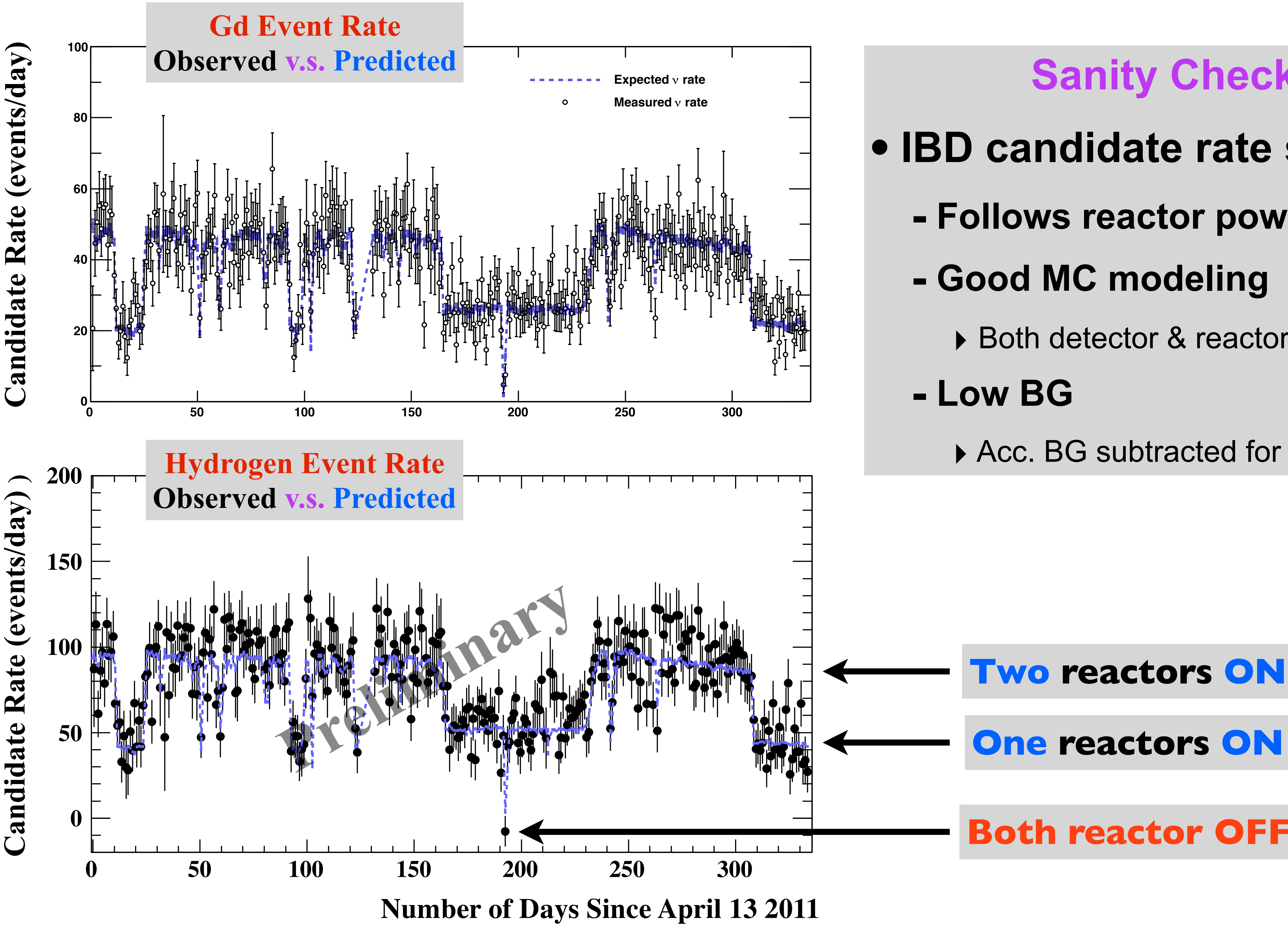
$$\langle \sigma_f \rangle_k = \int_0^\infty dE\; S_k(E)\, \sigma_{IBD}(E)$$

Includes latest neutron life time
τ_n = 881.4 s, PDG2011

Source	Uncertainty [%]
P_{th}	0.5
$\langle \sigma_f \rangle^{Bugey}$	1.4
$S_k(E)\sigma_{IBD}(E_\nu^{true})$	0.2
$\langle E_f \rangle$	0.2
L_R	<0.1
α_k^R	0.9
Total	1.8

≈ 2.7 % w/o Bugey-4

Reactor $\bar{\nu}_e$ Flux Prediction



Sanity Check

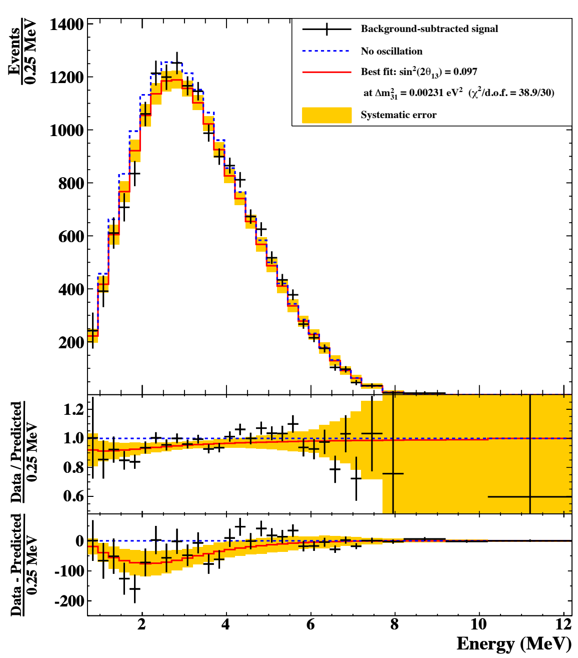
- **IBD candidate rate stability**
  - **- Follows reactor power history**
  - **- Good MC modeling**
    - Both detector & reactor
  - **- Low BG**
    - Acc. BG subtracted for Hydrogen

Reactor Experiments ... What Now?

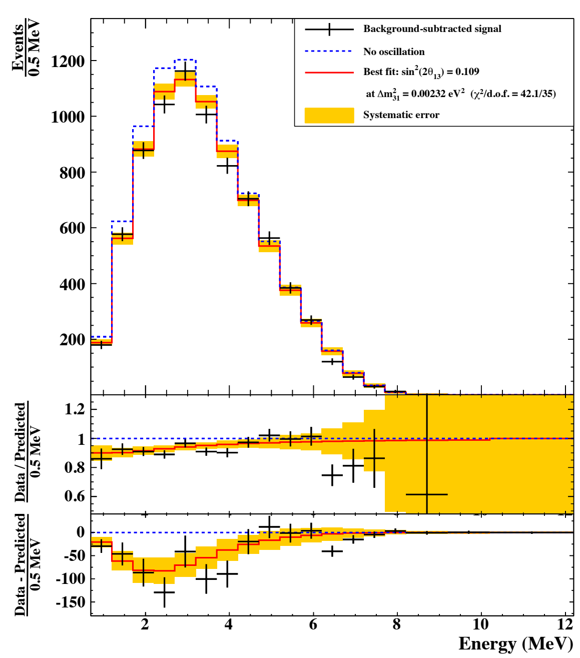
More to say on θ_{13}?

Improvement / Cross-Checks on-going...

- “n-H” analysis ... independent data sample ... **DOI: 10.1016/j.bbr.2011.03.031**
- “Reactor off” data ... pure background measurement ... **DOI: 10.1103/PhysRevD.87.011102**
- Important alternative measurement: Updated T2K result ... **arxiv 1304.0841**



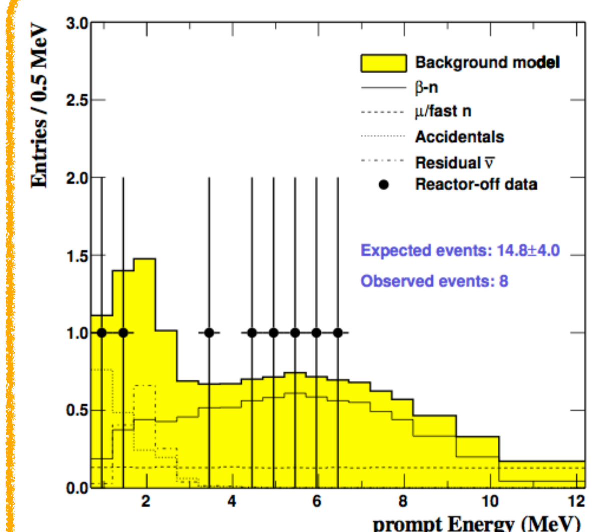
“Rate + Shape” ... n-H
DOI: 10.1016/j.bbr.2011.03.031



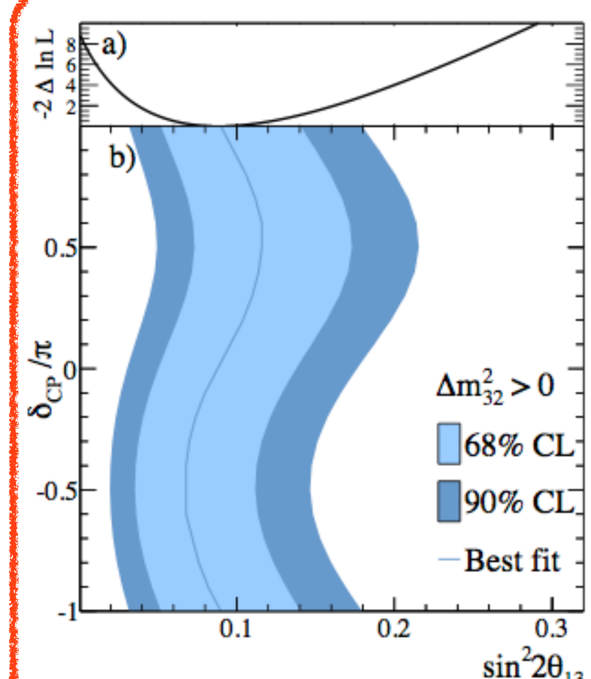
“Rate + Shape” ... n-Gd
DOI: 10.1016/j.bbr.2011.03.031

... Double Chooz “Rate + Shape” analysis result ...

n-H (left) and n-Gd (right) results are consistent



“Reactor - Off”
Pure BG Sample



T2K Updated Result

Global Scope ... What's Next?

With well-measured-relatively-large θ_{13} ...

Accelerator experiments (T2K, NOνA)

- Enhances matter effect term
  - Good for mass-hierarchy measurement
  - Could be 3σ for some value of δ_{CP} (lucky case)
- Weaker enhancement on understanding CP

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \propto 1/\theta_{13}$$

H. Minakata
arxiv 1209.1690

Matter Effect

$$P(\nu_\mu \to \nu_e) = 4\frac{(\Delta m^2_{31})^2}{(\Delta m^2_{31} - a)^2} s^2_{23} s^2_{13} \sin^2\left(\frac{(\Delta m^2_{31} - a)L}{4E}\right)$$

$$+ \quad 8J_r \frac{\Delta m^2_{31} \Delta m^2_{21}}{a(\Delta m^2_{31} - a)} \sin\left(\frac{aL}{4E}\right)$$

$$\times \quad \sin\left(\frac{(\Delta m^2_{31} - a)L}{4E}\right) \cos\left(\delta + \frac{\Delta m^2_{31} L}{4E}\right)$$

$$+ \quad 4\left(\frac{\Delta m^2_{21}}{a}\right)^2 c^2_{12} s^2_{12} c^2_{23} \sin^2\left(\frac{aL}{4E}\right)$$

Access δ_{CP}

For deterministic measurement, we need future experiments!