Recent Results from Double Chooz

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Feb. 24th ~ Mar. 2nd, 2013

@Les Rencontres de Physique de la Vallee d'Aoste (La Thuile)

Outline

- Neutrino Oscillation
- The Double Chooz Experiment
- Measurement of $\sin^2 2\theta_{13}$ with Neutron Capture on Gadolinium
- Measurement of $\sin^2 2\theta_{13}$ with Neutron Capture on Hydrogen
- Other Physics Studies:

  -- Direct Background Detection During 2 Reactors OFF

  -- Lorentz Violation Study with Reactor Neutrinos
- Summary

Neutrino Oscillation

- Neutrino Oscillation as a Result of Non-zero Mass & Mixing of Mass Eigenstates & Flavor Eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

Solar Reactor Atmospheric

<Neutrino Oscillation in 2 Flavor Scheme>

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2[eV^2]L[m]/E[MeV])$$

- θ_{13}: Only Not-Yet Observed Mixing Angle Until Recently. Finally Discovered by Reactor Neutrino Experiments.

➔ Now in the Stage of Its Precise Measurement.

➔ Also Important to Discover CP Violation Phase in Combination with Accelerator Experiments.

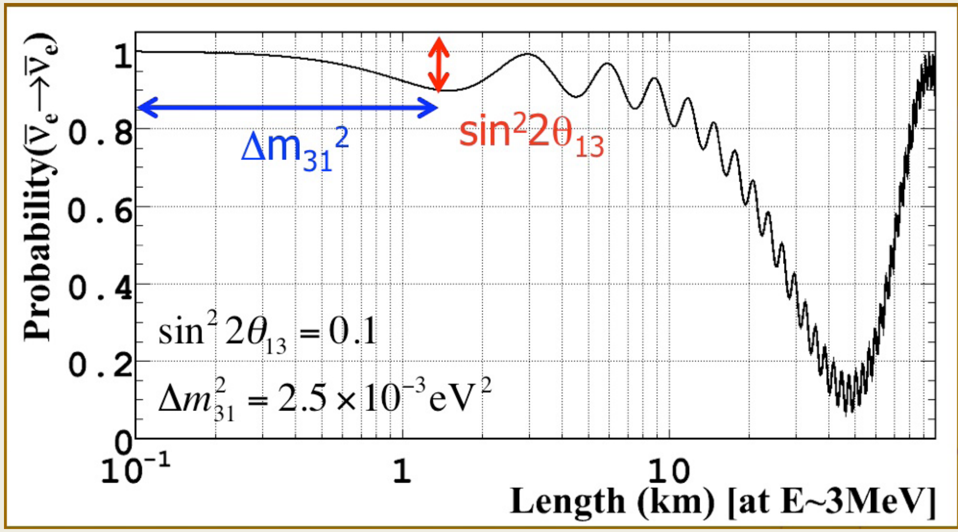
About Double Chooz

The Double Chooz Experiment

Motivation of Double Chooz

➔ Precise Measurement of θ_{13} Using Reactor Neutrinos at Short Distance (~ 1 km).

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} L/E)$$



➔ Simple 2 Flavor ν Osc. Formalism

-- Survival Probability $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ as a Function of Δm^2_{31} and θ_{13}.

-- Matter Effect Negligible.

-- Independent of CP-Violation Phase.

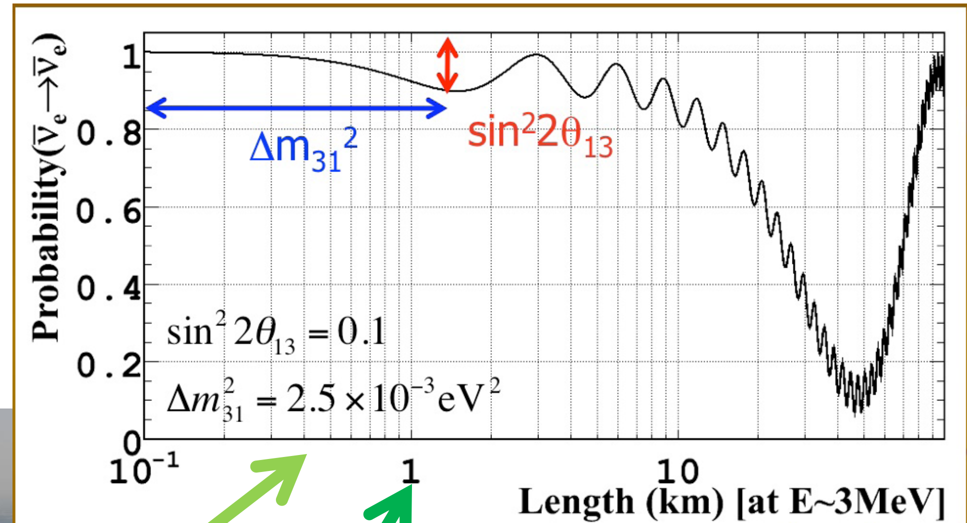
★ Capability of Clean Observation of θ_{13}.

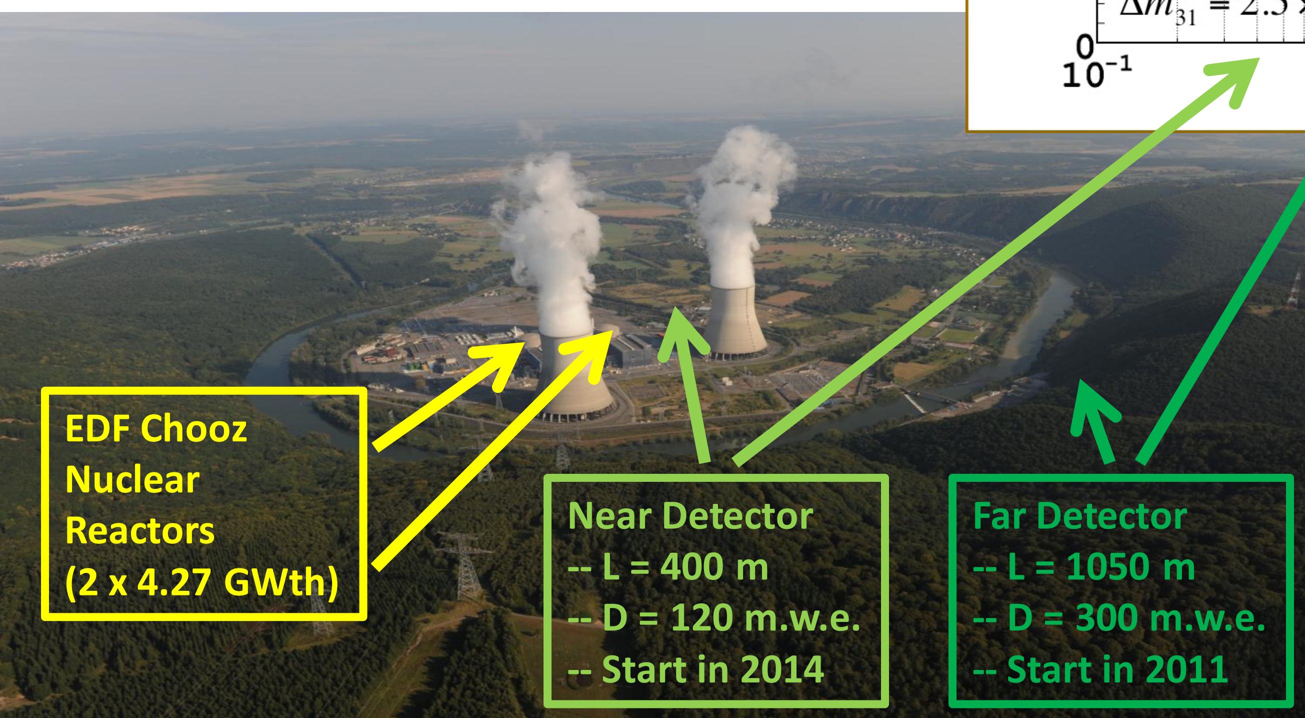
Experimental Site & Technique

Construction of 2 Identical Detectors at Different Baselines:

(Near = No Osc. & Far = 1st Osc.)

➔ Cancellation of Systematics on ν Flux, Cross Section, Detection Efficiency, Number of Target Protons.





The Double Chooz Collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB/VUB

Germany
EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

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Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
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Hiroshima Inst. Tech.

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U. Tennessee

Web Site: www.doublechooz.org/

Spokesperson:
H. de Kerret (IN2P3)
Project Manager:
C. Veyssière (CEA-Saclay)

Double Chooz Detector

Four-Layer Liquid Structure

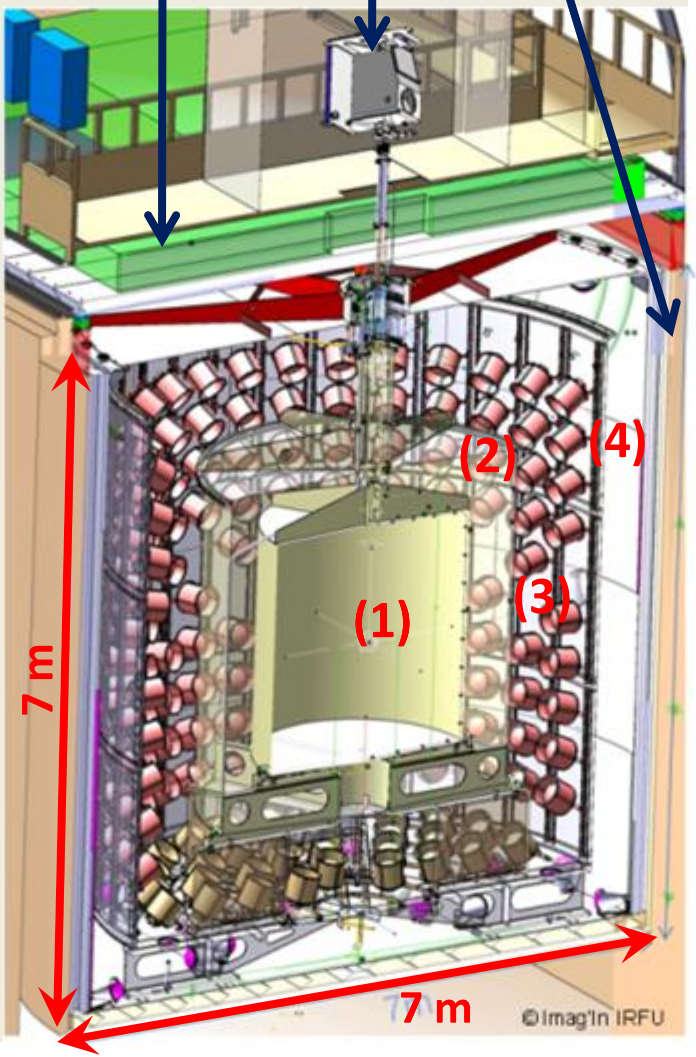
(1) Neutrino Target (ν-Target)
-- 10.3 m³ Gadolinium-Loaded Liquid Scintillator.
➔ Target for $\overline{\nu}_e$'s.

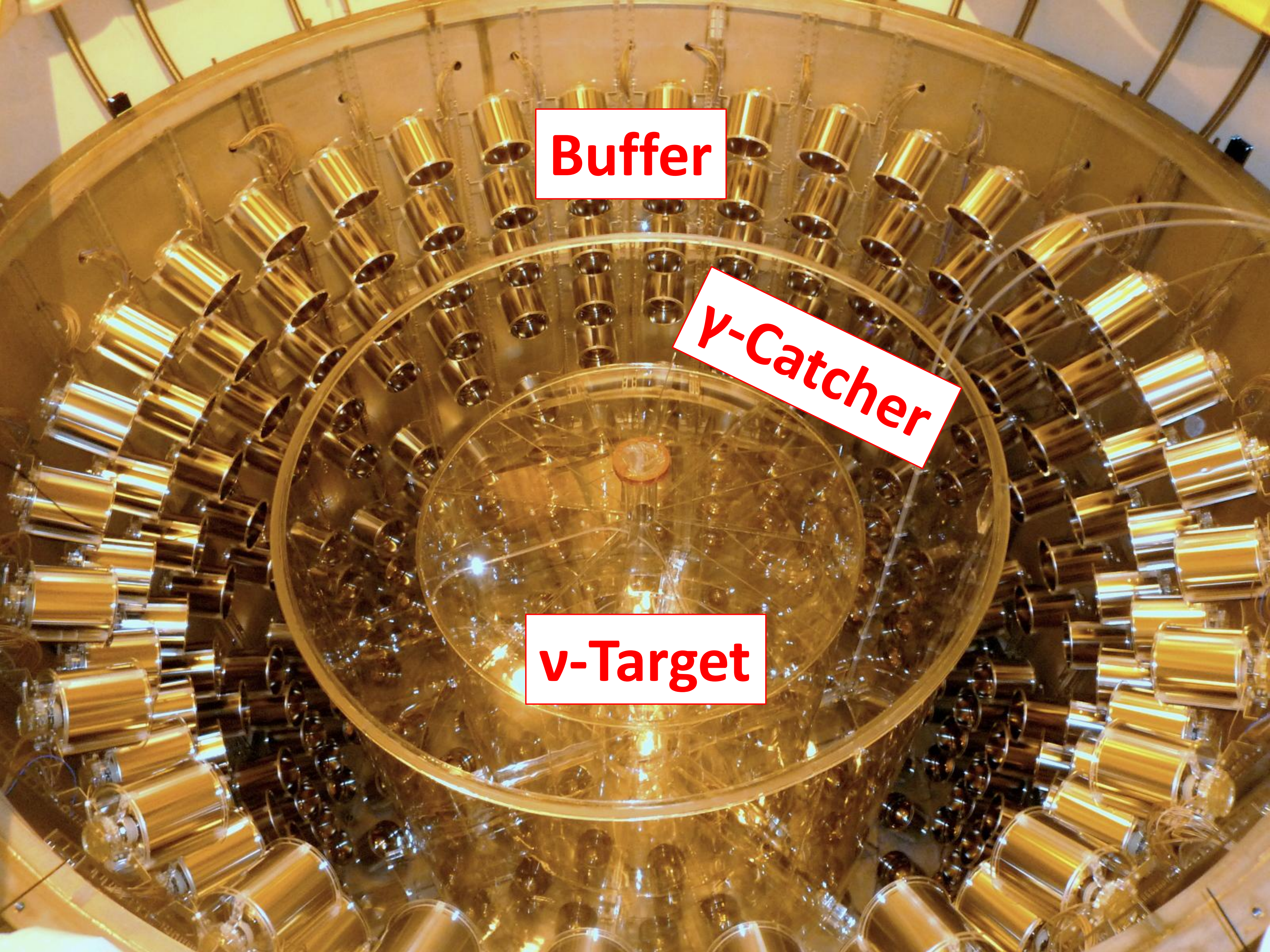
(2) Gamma Catcher (γ-Catcher)
-- 22.3 m³ Liquid Scintillator w/o Gadolinium.
➔ Energy Recovery of Escaping Gammas of Annihilation or Following Neutron Capture on Gadolinium, from ν-Target.

(3) Buffer
-- 110 m³ Non-Scintillating Mineral Oil w/ 390 10-inch PMTs Mounted.
➔ Shield of Environmental γ's & Neutrons.

Inner Detector (ID)

(4) Inner Veto (IV)
-- 90 m³ LAB-Based Liquid Scintillator w/ 78 8-inch PMTs Mounted.
➔ Veto of Cosmic-ray Muons.




Buffer
γ-Catcher
ν-Target


Outer Veto

Milestone in Double Chooz

- May 2008 ~ Oct. 2010: Far Detector Constructed.
- Dec. 2010: Liquid Filling at Far Detector Completed.
- Apr. 2011: Far Detector Commissioned.
  Physics Data-taking & Near Laboratory Construction Started.
- Jul. 2011: Outer Veto Commissioned.
- Nov. 2011: FIRST RESULTS Released (PRL 108, 131801 (2012)).
- Jul. 2012: 2nd Results Released with Neutron Capture on Gadolinium (PRD 86, 052008 (2012)).
- Sep. 2012: First Test of Lorentz Violation with Reactor Neutrinos Released (PRD 86, 112009 (2012)).
- Oct. 2012: Directly Measured Background Results During 2 Reactors Off Released (PRD 87, 011102 (2013)).
- Jan. 2013: Results from Neutron Capture on Hydrogen Released (arXiv:1301.2948).
- Mar. 2013: Near Laboratory to be Delivered.
- 2014: Near Detector Expected to Start Data Taking with Two Detectors.

Reactor Neutrino Prediction & Detector Calibration

Predicted Number of Neutrinos

- $\overline{\nu}_e$ Emitted from Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu & ^{241}Pu
- Expected Number of Neutrinos:

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

-- N_p: Number of Protons in Detector

-- ε: Detection Efficiency; -- L: Baseline

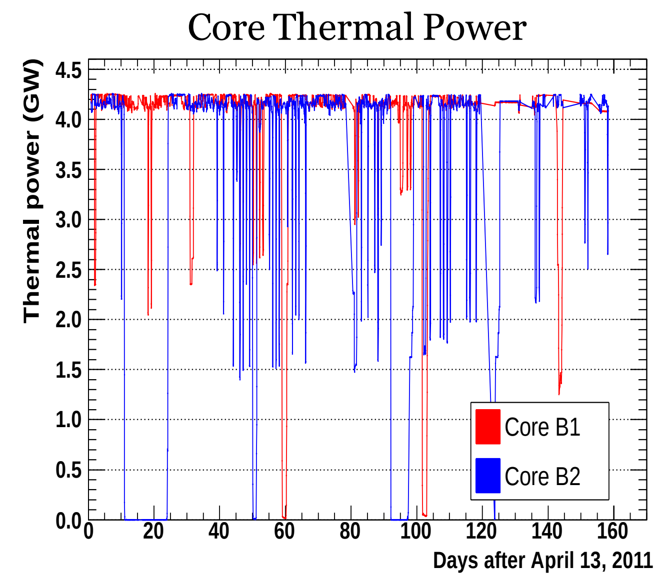
-- $P_{th}(t)$: Thermal Power ($\delta P_{th}/P_{th}$ = 0.46 %)

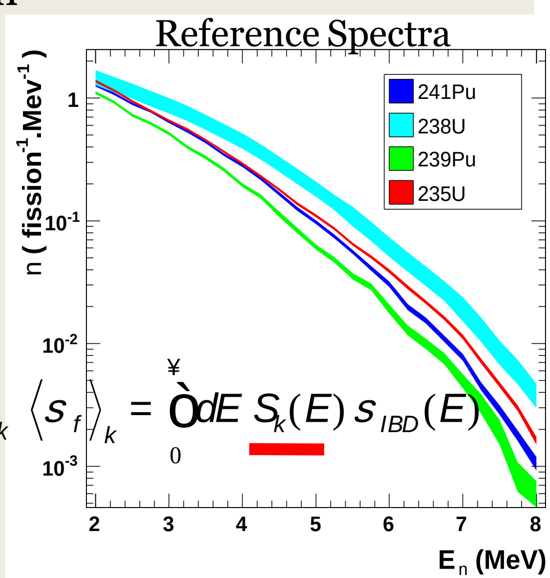
-- $\langle E_f \rangle$: Mean Energy per Fission

-- $\langle \sigma_f \rangle$: Mean Cross Section per Fission Anchored at Bugey4 Measurement

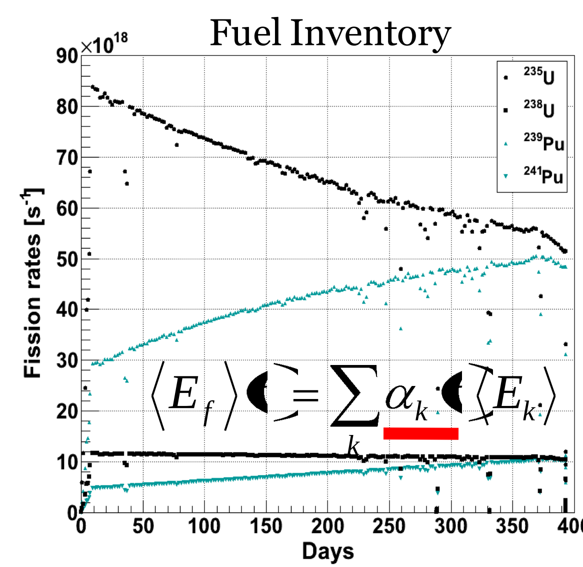
★ Reduction of Reactor Systematics (2.70 → 1.76 %)

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





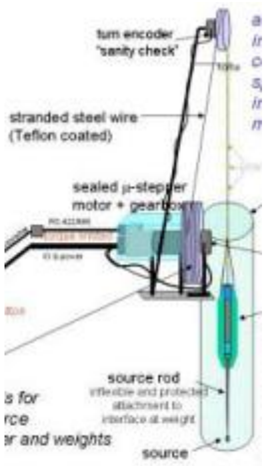
$$\langle \sigma_f \rangle_k = \int_0^{\infty} dE\, S_k(E)\, \sigma_{IBD}(E)$$



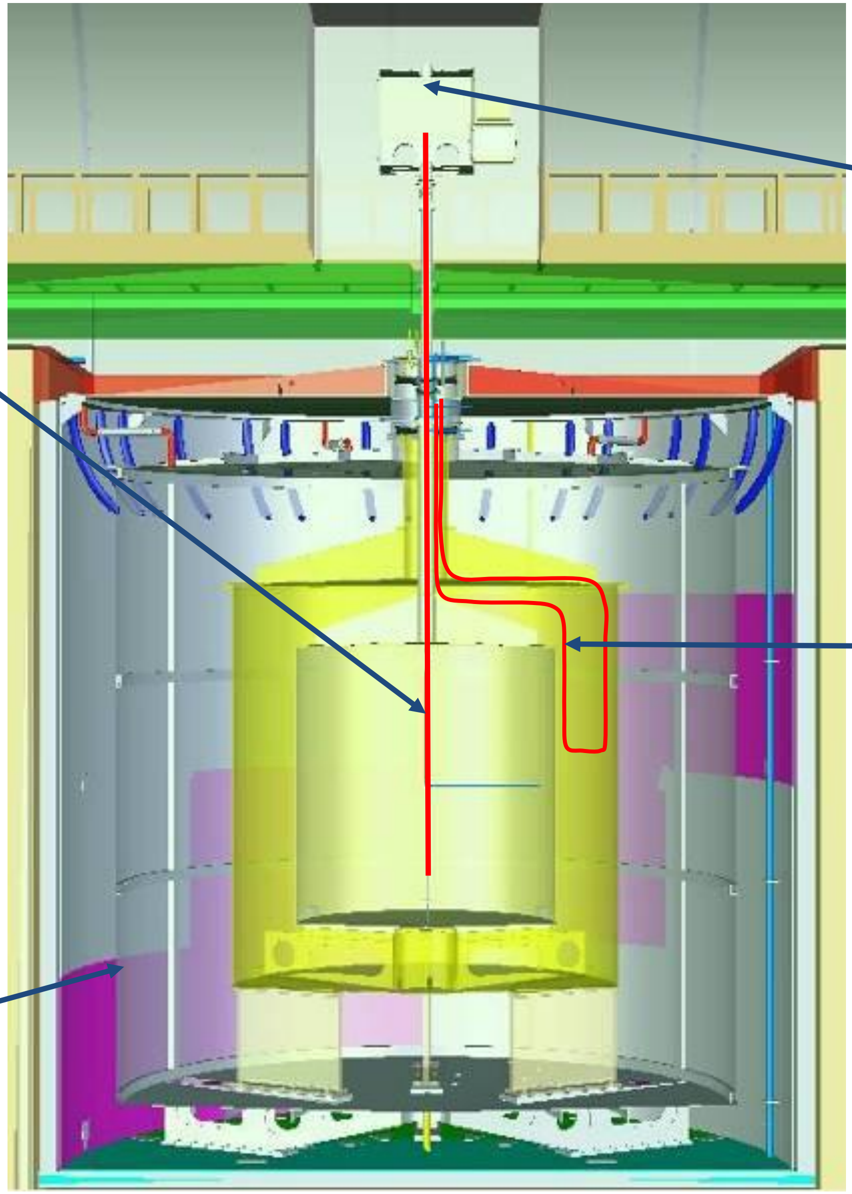
$$\langle E_f \rangle(t) = \sum_k \alpha_k(t) \langle E_k \rangle$$

Double Chooz Calibration System

Z-Axis System

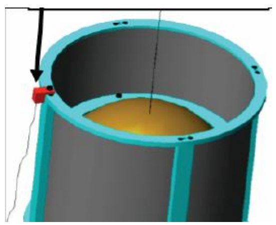


Glove Box



GC Guide Tube

Embedded LED System
λ = 385, 420, 470 nm



Detector Calibration

- **Energy Calibration**

(1) PMT & Electronics Gain Non-linearity Calibration

➔ LED Light Injection System

(2) Position Dependence Correction

➔ Spallation Neutron Capture on Hydrogen (H)

(3) Correction of Time Variation

➔ Spallation Neutron Capture on Gadolinium (Gd)

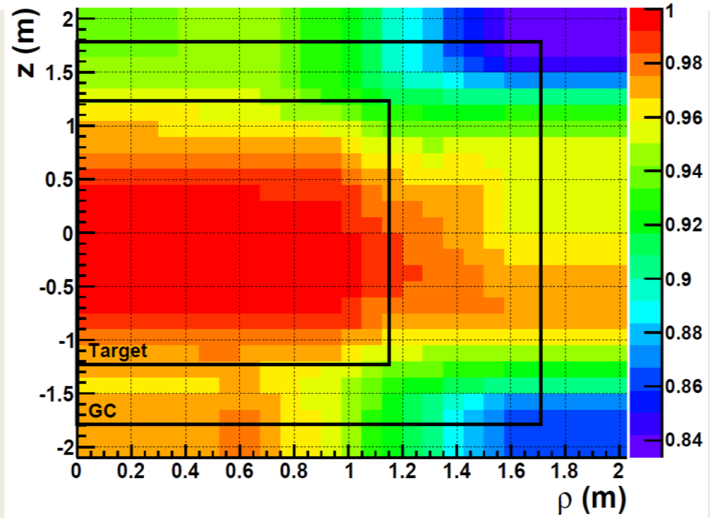
(4) Energy scale

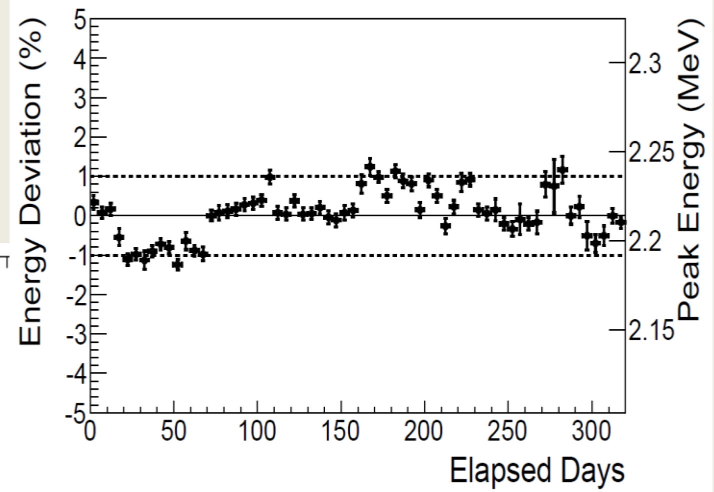
➔ Radioactive Sources Deployment into ν-Target & γ-Catcher

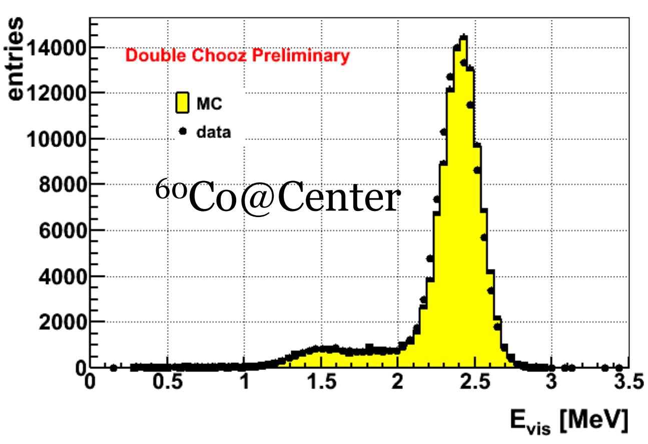
- **Neutron Detection Efficiency**

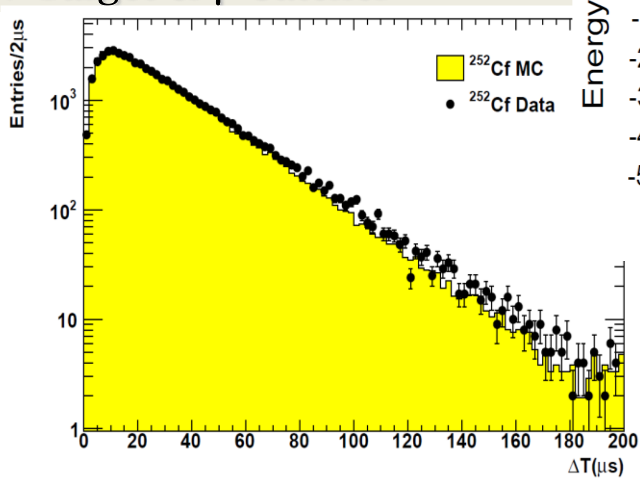
-- Energy & Time Window, Gd Fraction, Spill in/out Effects

➔ ^{252}Cf Source Deployment into ν-Target & γ-Catcher









Measurement of $\sin^2 2\theta_{13}$ from Analysis with Neutron Capture on Gadolinium (nGd Analysis) / Hydrogen (nH Analysis)

Principle of Neutrino Observation

Usage of Delayed Coincidence Technique

- → Detecting Both e^+ (Prompt Events) & n (Delayed Events) Produced at Inverse Beta Decay (E_{th} = 1.806 MeV).
- → Neutrons Found by ΣE_γ ~ 8 MeV of Thermalized n Capture on Gd @ν-Target (τ ~ 30 μs) [nGd],

or

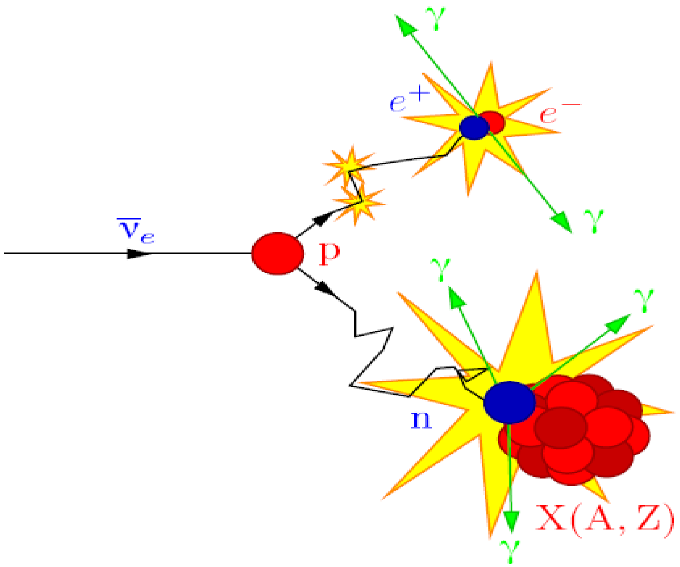
of E_γ = 2.2 MeV on H @ν-Target & Mostly @γ-Catcher (τ ~ 200 μs) [nH].

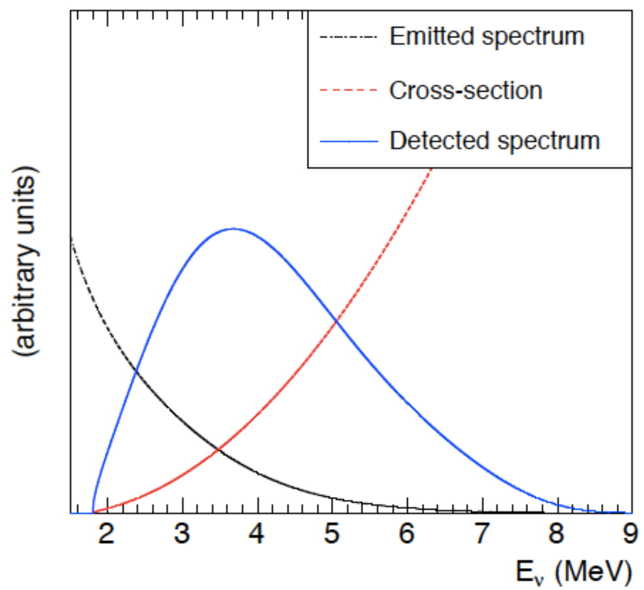
$\bar{\nu}_e + p \rightarrow e^+ + n$

$n + p \rightarrow \ldots \rightarrow n + Gd \rightarrow Gd + \gamma$'s

or

$n + p \rightarrow \ldots \rightarrow n + p \rightarrow d + \gamma$





Importance of Hydrogen Capture Event Analysis (nH)

Independent Cross-check from $\sin^2 2\theta_{13}$ Results by Gd Capture Analysis:

➔ Statistically Different Datasets
(3 Times Larger Volume Available with Gamma Catcher)

➔ Different Systematics

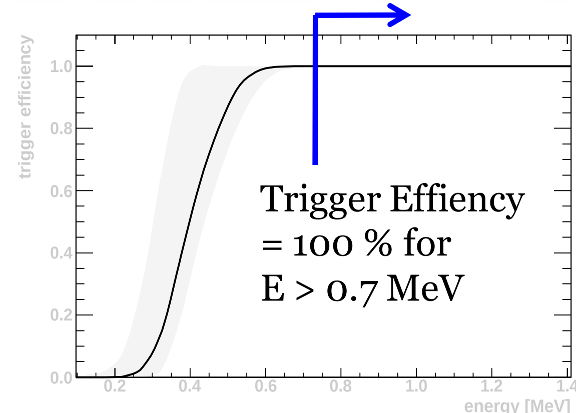
★Combined Results of Gd & H Capture Analyses Prospected in Future with Improved Understanding of Systematics & Their Correlations.

Results from nGd Analysis

Selection of Neutrino Candidates in nGd

Item	Criteria
Muon Background Reduction	ΔT_{μ} > 1 ms
Prompt Events	0.7 MeV < E < 12.2 MeV
Delayed Events	6.0 MeV < E < 12.0 MeV
Time Correlation Between Prompt & Delayed Events	2 μs < ΔT_{dp} < 100 μs
Light Noise Elimination	PMT Hits Homogeneous & Coincident in Time
Multiplicity Cuts	No Further Events Around Signal
Further Background Rejection	ΔT_{μ} > 500 ms for E_{μ} > 600 MeV, No Coincidence with OV

➔ 8249 $\overline{\nu}_e$ Candidates in 227.93 Livedays.



Backgrounds in nGd

(I) Accidentals

-- Caused by Gammas from Natural Radioactivities & Spallation Neutron Capture.

-- Measurement with Off-time Window Sampling.

➔ 0.261±0.002 Events/Day

(II) Cosmogenic ^{9}Li

-- Created by Muon Spallation to Emit β-n.

-- Measured by Spatial Time Correlation with Muons.

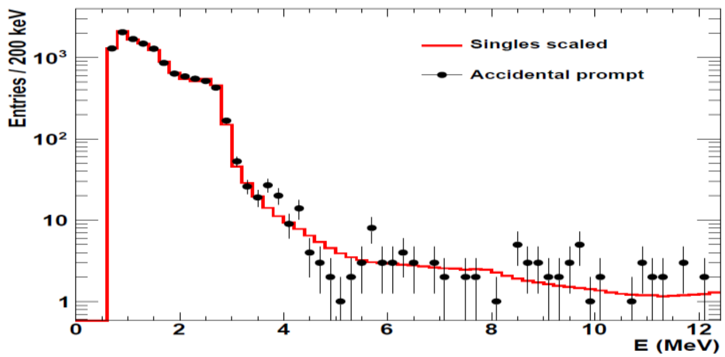
➔ 1.25±0.54 Events/Day

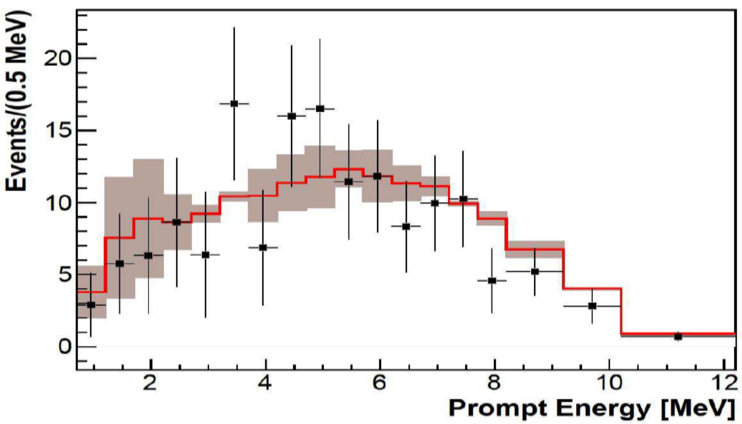
(III) Fast Neutrons & Stopping Muons

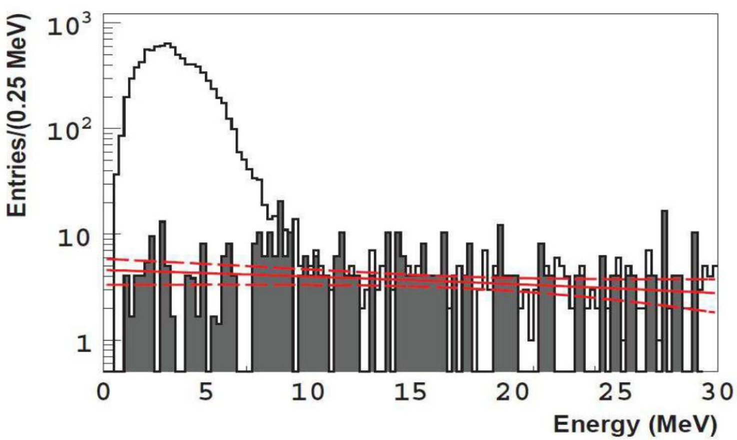
-- Created by Proton Recoil + Neutron Capture (FN) & Muon Track + Muon Decay.

-- Measured with Higher Energy Spectrum.

➔ 0.67±0.20 Events/Day





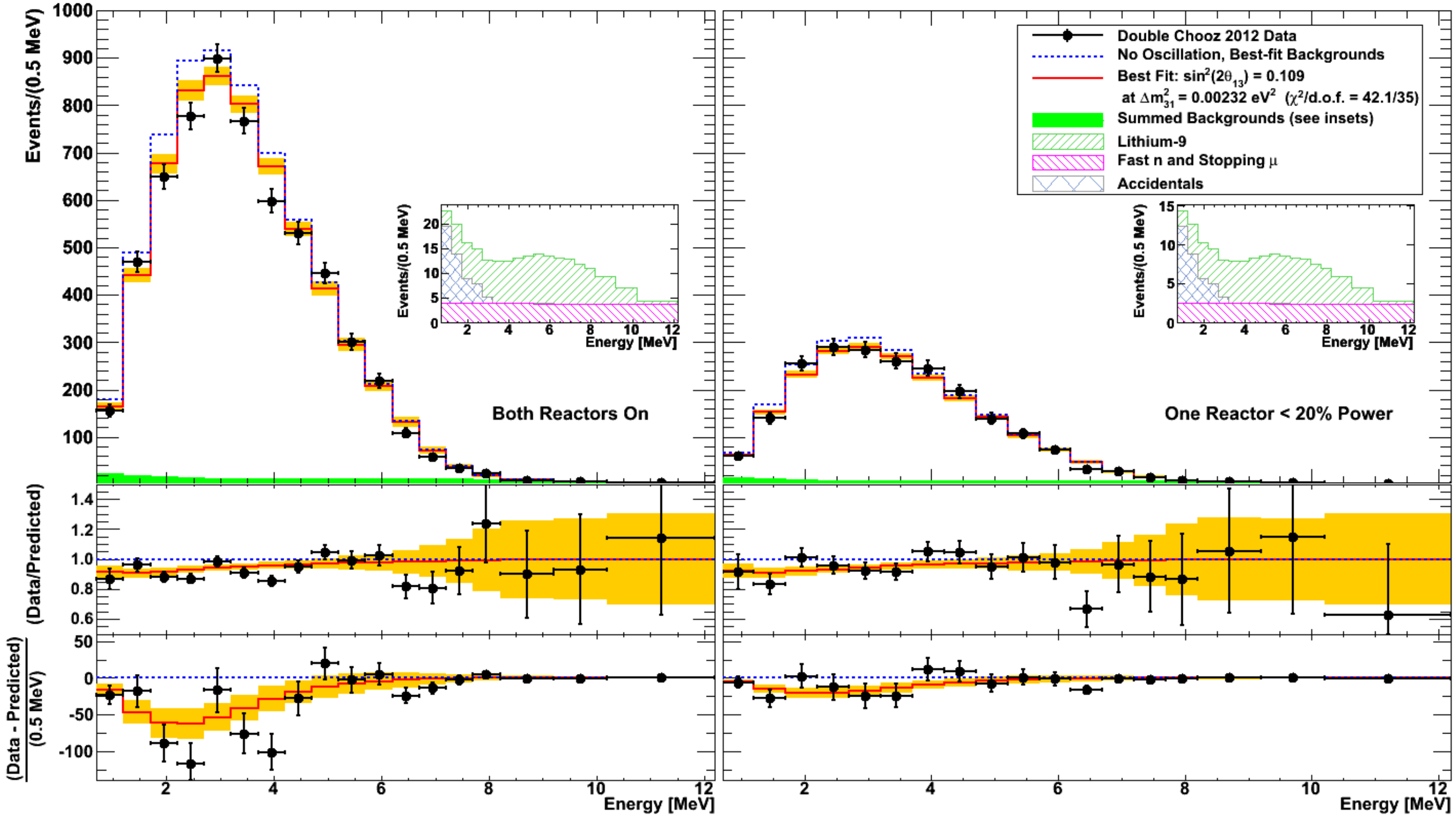


Summary of Uncertainties in nGd

Source	Uncertainty [%]
Reactor Flux	1.67
Statistics	1.06
Accidentals	0.01
Cosmogenic ^{9}Li	1.38
Fast Neutrons/Stopping Muons	0.51
Energy Scale	0.32
Detection Efficiency	0.95
Total	2.66

Oscillation Analysis Results in nGd

χ^2 Minimization with Covariance Matrix & Pull Terms



$\chi^2/ndf = 42.1/35$

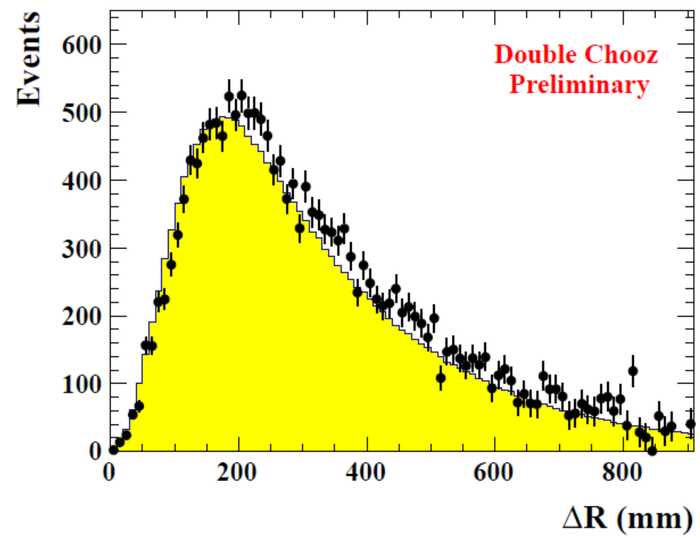
Rate + Shape Fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(stat.) \pm 0.025(syst.)$

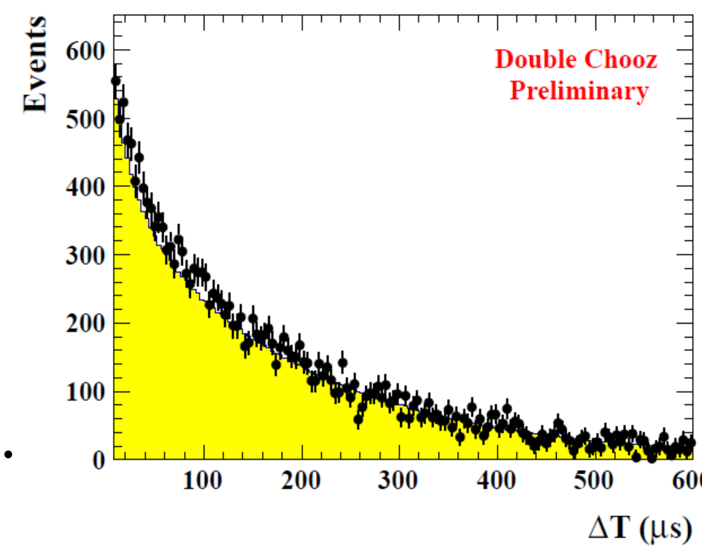
➔ No Oscillation Hypothesis Excluded at 99.8 % C.L. (2.9σ).

Results from nH Analysis

Selection of Neutrino Candidates in nH

Item	Criteria
Muon Background Reduction	$\Delta T_{\mu} > 1$ ms
Prompt Events	0.7 MeV < E < 12.2 MeV
Delayed Events	1.5 MeV < E < 3.0 MeV
Time Correlation Between Prompt & Delayed Events	10 µs < ΔT_{dp} < 600 µs
Spatial Correlation Between Prompt & Delayed Events	ΔR_{dp} < 900 mm
Light Noise Elimination	PMT Hits Homogeneous & Coincident in Time
Multiplicity Cuts	No Further Events Around Signal





➔ 36284 $\overline{\nu}_e$ Candidates in 240.06 Livedays.

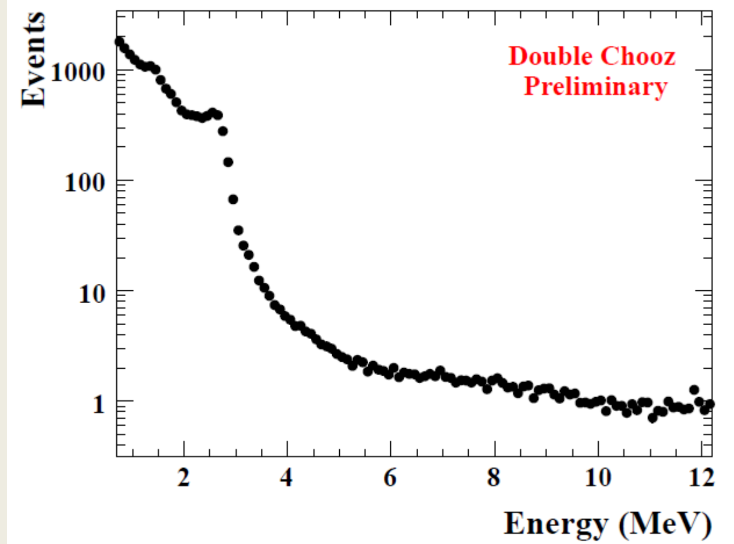
Backgrounds in nH (1)

(I) Accidentals

-- Caused by Gammas from Natural Radioactivities.

-- Measurement with Off-time Window Sampling; Rate Can Be Estimated Precisely by Timing Analysis.

➔ 73.45±0.16 Events/Day

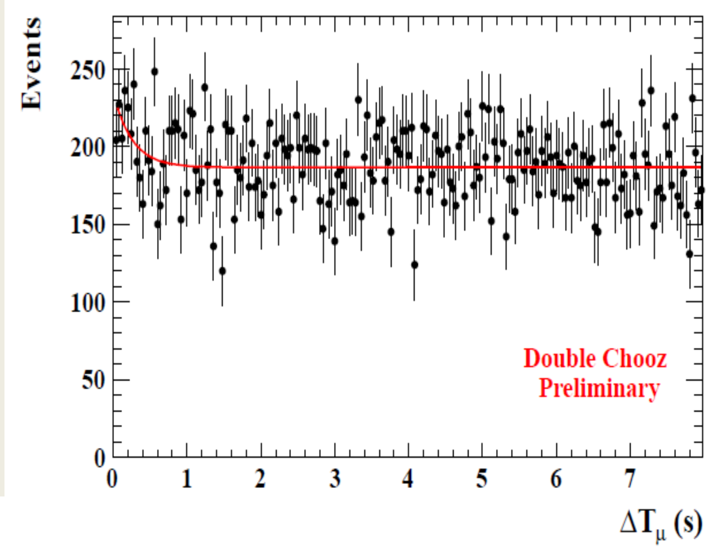


(II) Cosmogenic ^{9}Li

-- Created by Muon Spallation to Emit β-n.

-- Measured by Time Correlation with Muons to Fit with ^{9}Li Lifetime.

➔ 2.84±1.15 Events/Day



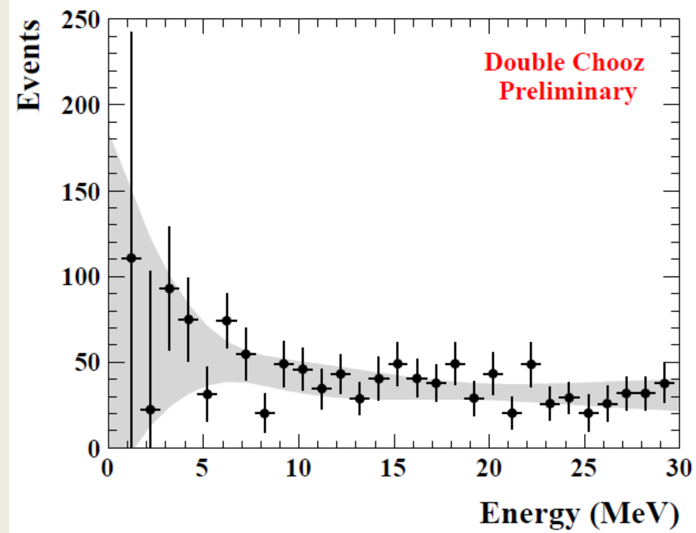
Backgrounds in nH (2)

(III) Fast Neutrons

-- Composed of Recoiled Protons Followed by Neutron Capture.

-- Measured from Their Spectrum Tagged by Inner Veto and Inner Detector.

➔ 2.50±0.47 Events/Day

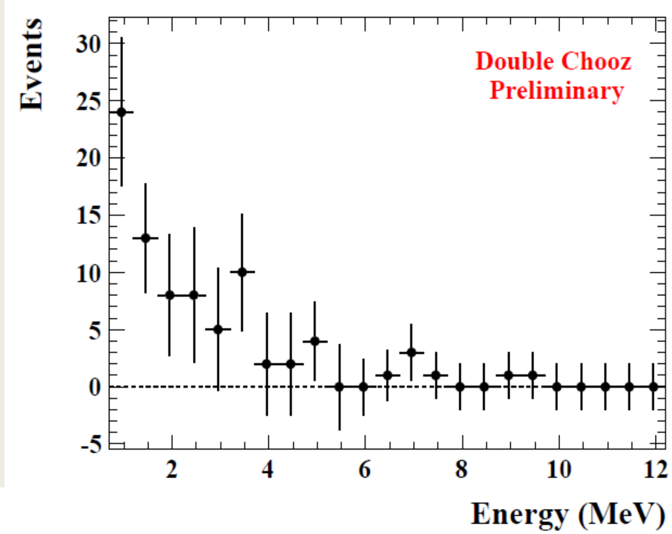


(IV) Correlated Light Noises

-- Generated by Their Two Triggers in Series.

-- Measurement with Volume Cut on Reconstructed Vertex.

➔ 0.32±0.07 Events/Day

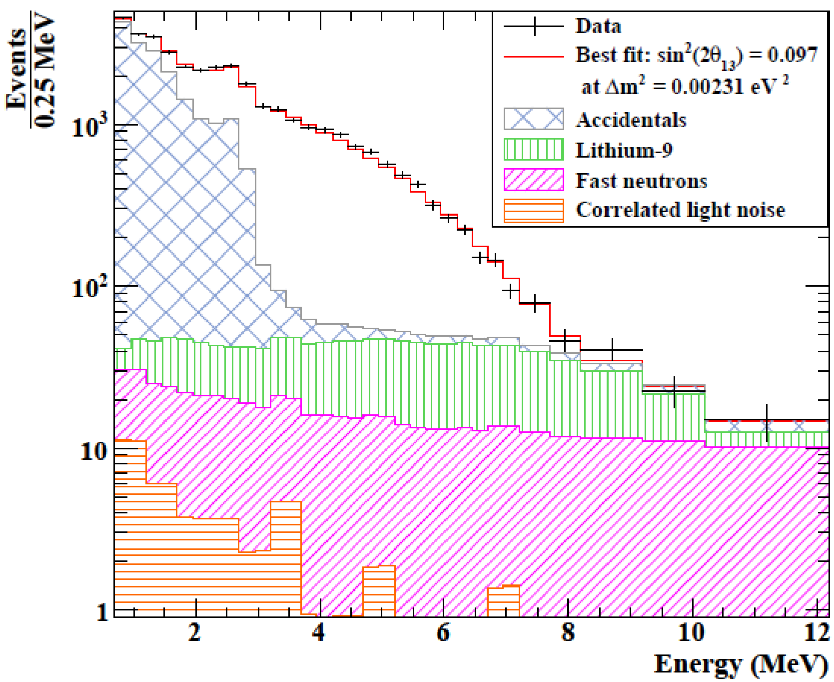


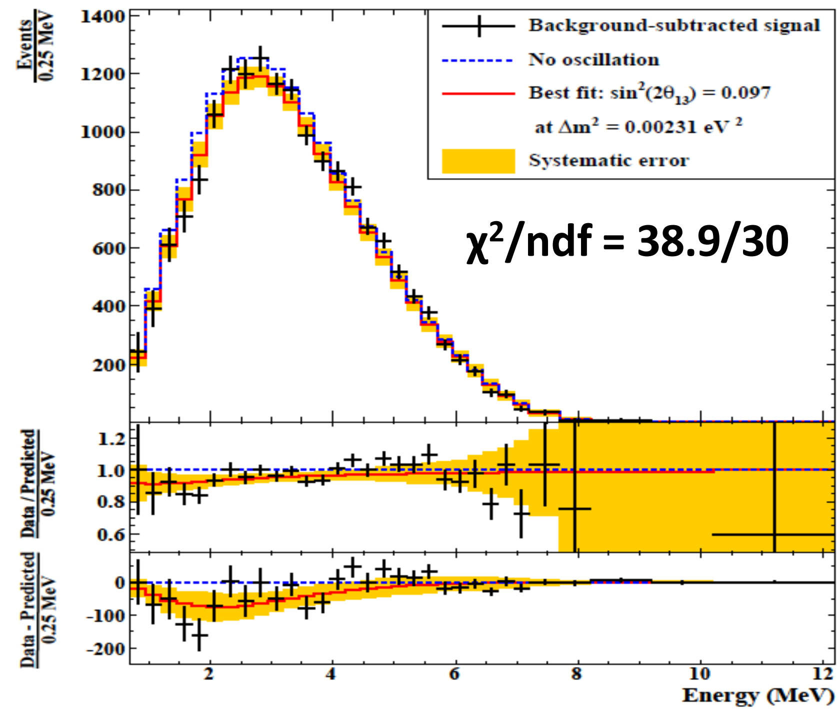
Summary of Uncertainties in nH

Source	Uncertainty [%]
Reactor Flux	1.8
Statistics	1.1
Accidentals	0.2
Cosmogenic ^{9}Li	1.6
Fast Neutrons	0.6
Correlated Light Noises	0.1
Energy Scale	0.3
Detection Efficiency	1.6
Total	3.1

Oscillation Analysis Results in nH

χ^2 Minimization with Covariance Matrix & Pull Terms





Rate + Shape Fit: $\sin^2 2\theta_{13} = 0.097 \pm 0.034(\text{stat.}) \pm 0.034(\text{syst.})$

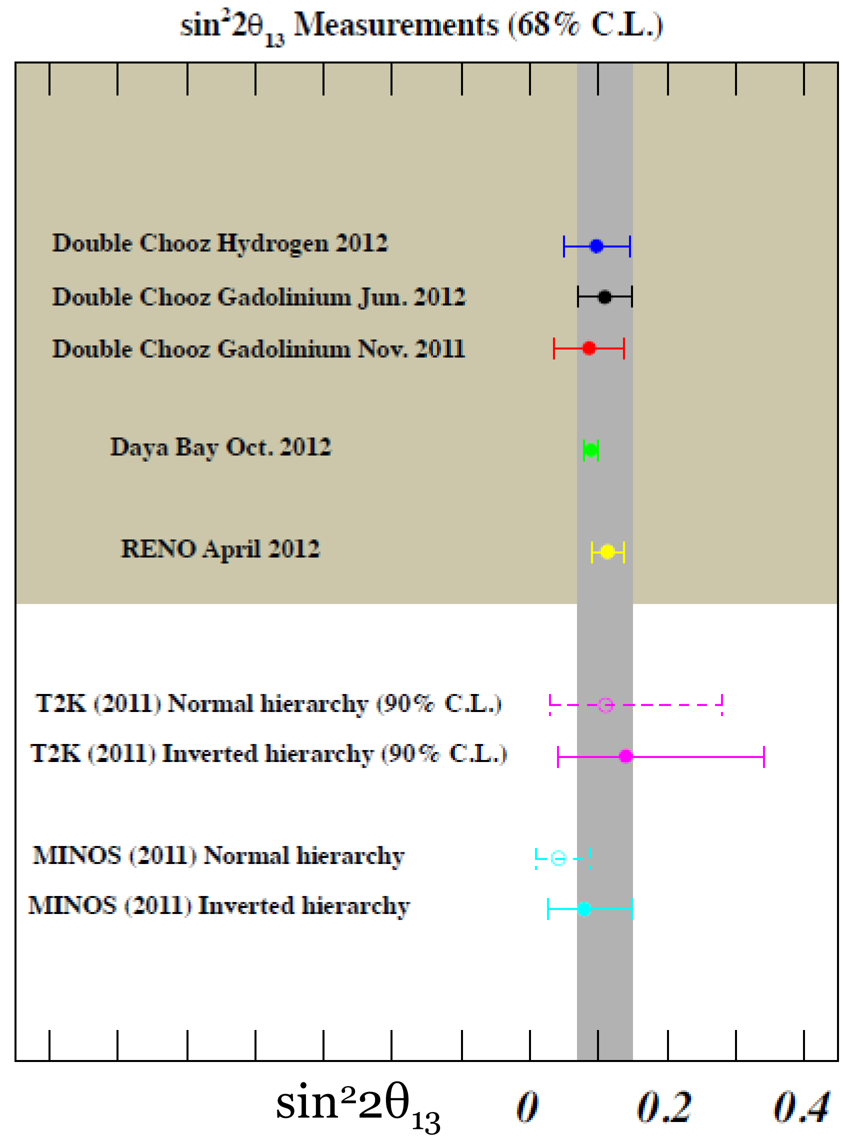
➔ No Oscillation Hypothesis Excluded at 97.4 % C.L. (2.0σ).

Short Summary on Oscillation Analysis Results

- Results of $\sin^2 2\theta_{13}$ from Two Independent Studies Agree Each Other.

➔ $\sin^2 2\theta_{13}$
= 0.109±0.030(stat.)±0.025(syst.) in nGd, &
= 0.097±0.034(stat.)±0.034(syst.) in nH.

- These Also Consistent with Results from Other Reactor & Accelerator-Based Experiments.



Other Physics Results

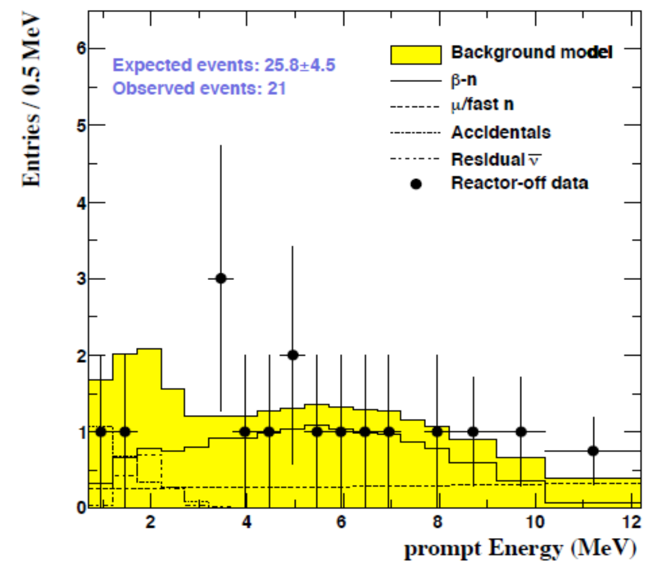
Direct Background Observation During 2 Reactors OFF Period

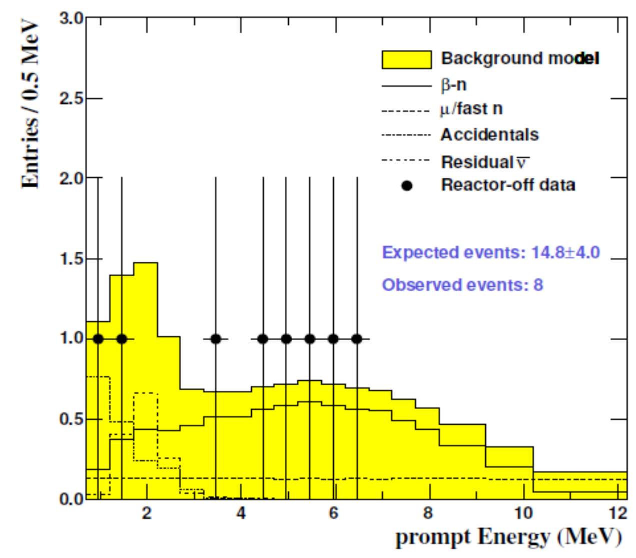
Unique Opportunity for In-situ Background Measurement

-- 2 Reactors Off for 7.53 Days.
-- The Same Event Selection Criteria Applied as in nGd Analysis.

(1) No Cosmogenic Background Rejection & No OV Veto (Top)
➔ 2.7±0.6 (Est. 3.4±0.6) Events/Day
(2) With Cosmogenic Background Rejection & With OV Veto Cut Case (Bottom)
➔ 1.0±0.4 (Est. 2.0±0.6) Events/Day

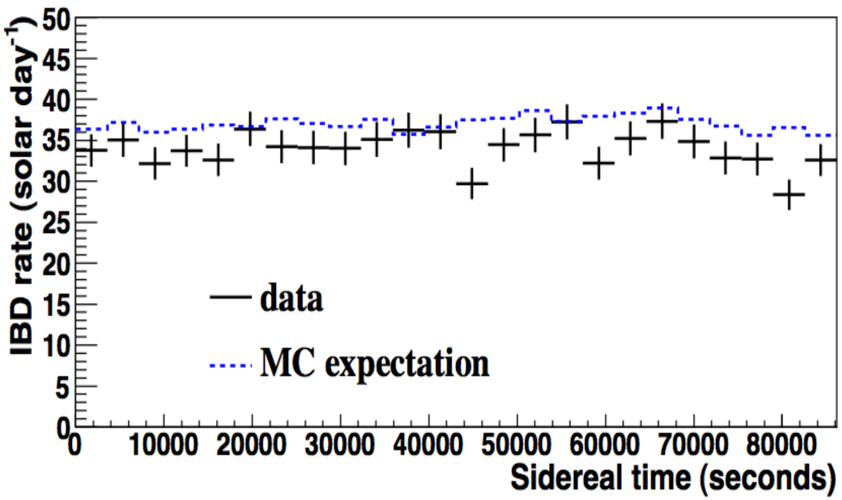
★ Background Rates Consistent with Expectation.

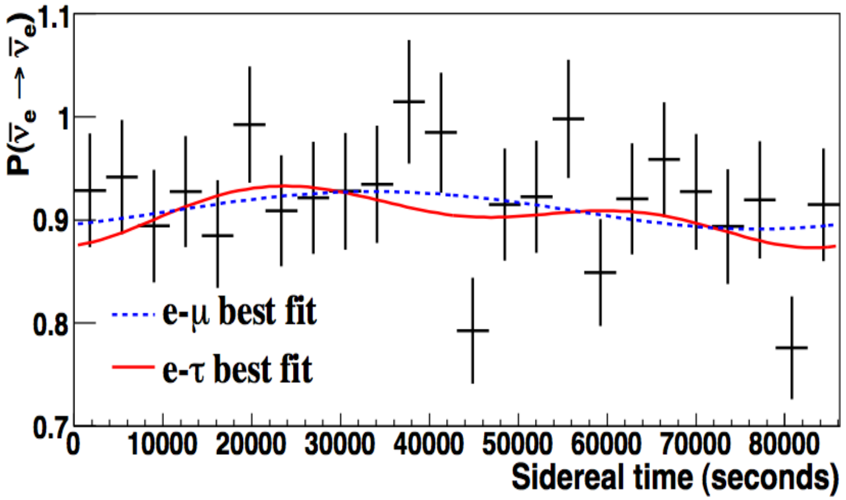




First Test of Lorentz Violation with Reactor Neutrinos

- Search for Sidereal Modulation with the Same Dataset for Oscillation Analysis (8249 ν Candidates).
- Reactor ν Disappearance Experiment Suitable for e-τ Channel.





- No Decisive Events Observed & Results Consistent with Sidereal Time-Independent Neutrino Oscillation.

➔ First Limits Placed on 14 Coefficients (e-τ) + Limits Set on 2 Coefficients (e-μ) in Standard Model Extension.

Summary

- **Observation of Reactor ν Disappearance Using Neutron Capture on Gadolinium:**

➔ $\sin^2 2\theta_{13}$ = 0.109±0.030(stat.)±0.025(syst.).

-- Energy Spectral Information Incorporated as Unique Feature.

- **First Measurement of $\sin^2 2\theta_{13}$ with Analysis of Neutron Capture on Hydrogen:**

➔ Beneficial as Independent Analysis for Cross-check of Gadolinium Analysis.

➔ $\sin^2 2\theta_{13}$ = 0.097±0.034(stat.)±0.034(syst.).

★ Results from Two Analysis Consistent with Each Other.

- **Other Physics Results, i.e.,**

(1) Direct Detection of Backgrounds During 2 Reactors OFF.

(2) First Study of Reactor ν-Based Lorentz Violation Conducted.

- **In Future,**

(1) Combination of Gadolinium & Hydrogen Analysis

➔ Results Prospected with Higher Statistics & Improved Understanding of Systematics.

(2) Data-taking with Near & Far Detectors Leading to Reduction of Systematics.

➔ Improvement of the Precision & Robustness of θ_{13}.