Status of the Double Chooz Experiment

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Yale WIDG Seminar
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Neutrino Oscillations

- First proposed by Pontecorvo in 1957, but only thoroughly confirmed in the late 1990s/early 2000s.
- Two different sets of eigenstates are required for neutrino oscillation:
  - Flavor states ν_e, ν_μ, ν_τ (Greek indices ν_α)
  - Mass states ν_1, ν_2, ν_3 (Latin indices ν_i)

  which are related by:

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

- Neutrinos are produced and detected in flavor states (e.g. $\pi^+ \to \mu^+ \, \nu_\mu$), but they propagate as mass states.
- Oscillation probabilities are given by $P_{\alpha\to\beta} = \langle \nu_\alpha | \nu_\beta \rangle$:

$$P_{\alpha\to\beta} = \sum_j \left| U_{\beta j} \right|^2 \left| U_{\alpha j} \right|^2 + 2 \sum_{j \neq k} \left| U_{\beta j} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k} \right| \cos\left(\frac{\Delta m^2_{jk} L}{2E} - \phi_{\alpha\beta jk} \right)$$

where $\phi_{\alpha\beta jk} \equiv \arg(U_{\beta j} U^*_{\alpha j} U_{\alpha k} U^*_{\beta k})$ and $\Delta m^2_{ij} \equiv m^2_i - m^2_j$.

Oscillation Parameters

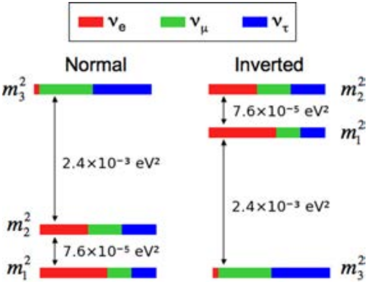
$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

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

In nature we have observed three flavor states, so the relevant oscillation parameters are:

- 3 mixing angles: θ_{23}, θ_{12}, and θ_{13}
- 3 mass squared differences: Δm^2_{32}, Δm^2_{31}, and Δm^2_{21}
- One Dirac CP phase δ and possibly two Majorana phases (not shown).

Oscillation Parameters



- Knowns: $\left|\Delta m^2_{32}\right| \approx \left|\Delta m^2_{31}\right|$, Δm^2_{21}, θ_{12} ($\sim 30^\circ$), θ_{23} ($\sim 40^\circ$), and now θ_{13} ($\sim 10^\circ$)
- Unknowns: CP phase δ and mass hierarchy

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Measuring θ_{13}

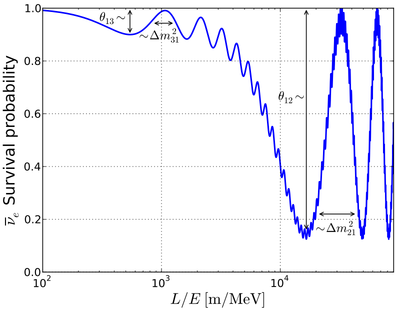
- One way to measure θ_{13} is to look at $\overline{\nu}_e$ survival probability for small L/E:

$$P_{\overline{\nu}_e \to \overline{\nu}_e} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(1.267 \Delta m^2_{31} \frac{L}{E}\right)$$

- Nuclear reactors produce copious $\overline{\nu}_e$ with $\mathcal{O}$(MeV) energy
- Inverse beta decay (IBD) reactions are only initiated by electron flavor $\overline{\nu}_e$:

$$\overline{\nu}_e + p \to e^+ + n$$

- A detector searching for IBD ~1 km away from a nuclear reactor will measure θ_{13} if it sees $\overline{\nu}_e$ disappearance



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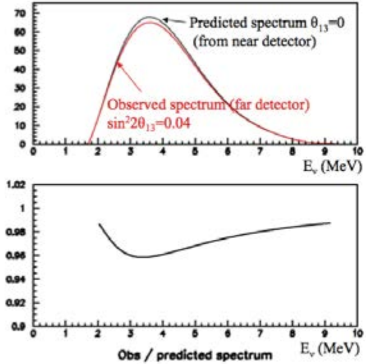


Double Chooz Overview

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 Tbingen
MPIK Heidelberg
RWTH Aachen
TU Mnchen
U. Hamburg

Japan
Tohoku U.
Tokyo I. T.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima I. T.

Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

United States
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
UCLA
Drexel U.
U. Hawaii
IIT
Kansas State
LLNL
MIT
U. Notre Dame
SNL
U. Tennessee
Virginia Tech

Spokesperson: H. de Kerret (IN2P3) **Project manager:** Ch. Veyssière (CEA-Saclay)
Website: www.doublechooz.org

Double Chooz Experiment

Site Layout

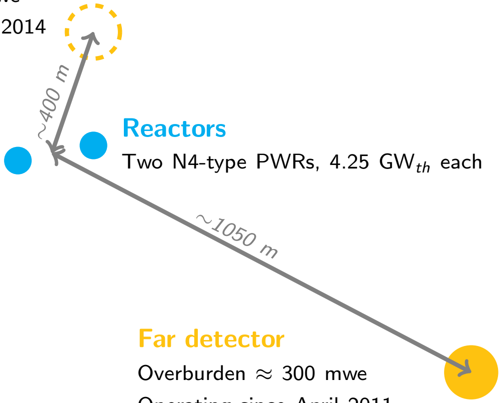
Near detector

Overburden ≈ 120 mwe

Data taking: summer 2014

Reactors

Two N4-type PWRs, 4.25 GW_{th} each



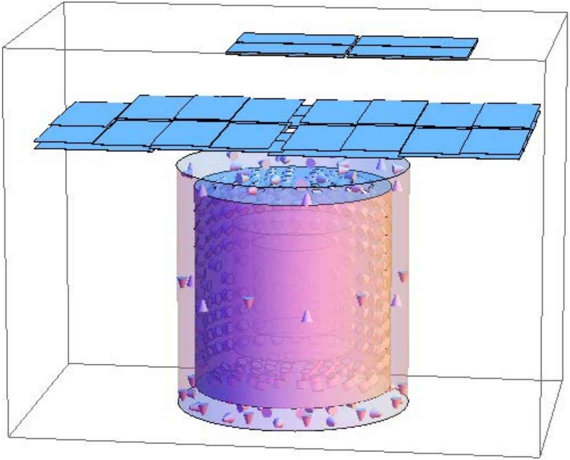
Far detector

Overburden ≈ 300 mwe

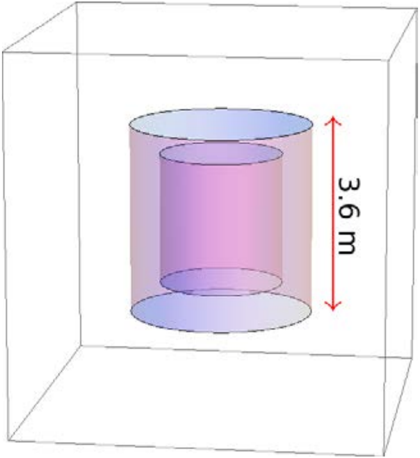
Operating since April 2011

Double Chooz Far Detector

Double Chooz has an inner detector of three nested cylinders, which is further encased by an inner veto. The outer veto modules sit above the inner detector and inner veto.

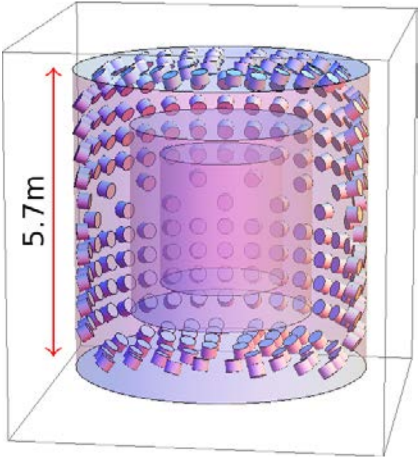


Target and Gamma Catcher



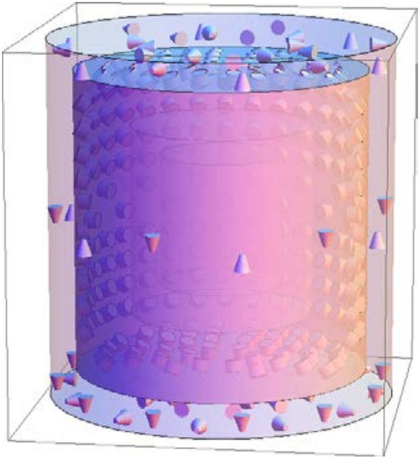
- Target is $10\,m^3$ (8.3 tons) of liquid scintillator doped with 1 g/L Gd.
  - $\sim 85\%$ of neutrons in target capture on Gd.
- Gamma Catcher is 550 mm shell of liquid scintillator around target (no Gd).
  - Nearly all gammas released by n+Gd are contained in scintillator $\rightarrow$ reliable 8 MeV signal.
  - GC has twice the volume of target.

Buffer



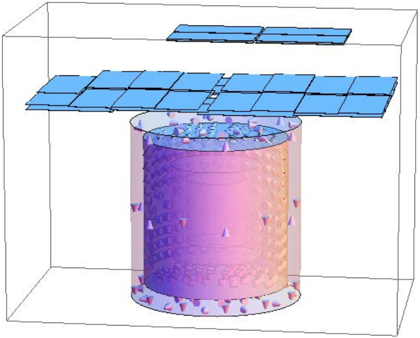
- Target and gamma catcher are surrounded by the buffer.
- Filled with non-scintillating mineral oil
- 390 low-activity Hamamatsu 10" PMTs
- Shields scintillator from PMT glass radioactivity, surrounding rock radioactivity, and neutrons.

Inner Veto



- Buffer vessel sits inside Inner Veto.
- IV is filled with liquid scintillator and instrumented with 78 Hamamatsu 8" PMTs.
- Used to veto muons and other cosmogenic backgrounds.
- Inner Veto surrounded by 15 cm thick steel shielding.

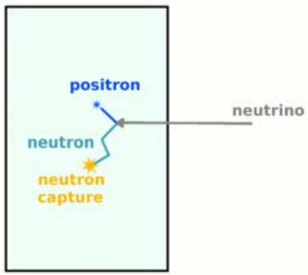
Outer Veto



- Active muon veto above main detector.
- Modules have long strips of plastic scintillator.
- Both Upper and Lower OV have two layers each of transverse strips to allow tracking.
- Module construction and installation performed by University of Chicago group.

Signal and Backgrounds

Neutron capture on Gd and H



- First analyses used IBD neutrons capturing on Gd.
- Neutrons capture on H as well:
  - Longer capture lifetime: $\tau_{\text{n-Gd}} \simeq 30\mu s < \tau_{\text{n-H}} \simeq 200\mu s$
  - Lower capture energy: $E_{\text{n-Gd}} \simeq 8MeV > E_{\text{n-H}} \simeq 2MeV$
- Natural γ background from U and Th tops out at $\sim$3 MeV (^{208}Tl).
- Capture events in GC lose energy due to spill-out.
- GC has $\sim$twice the mass of target.
- H captures $\sim$13% of neutrons in target.
- Semi-independent cross check of n-Gd analysis.

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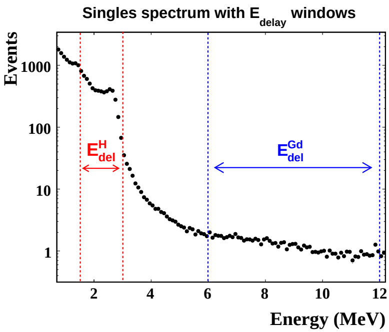

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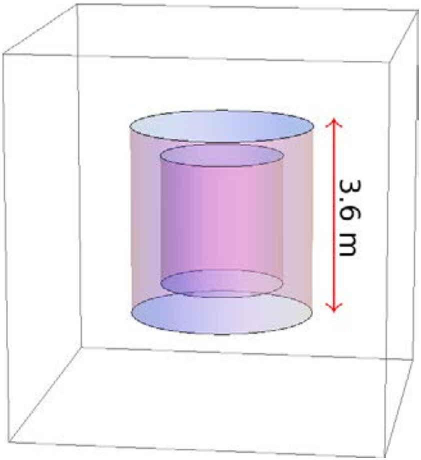

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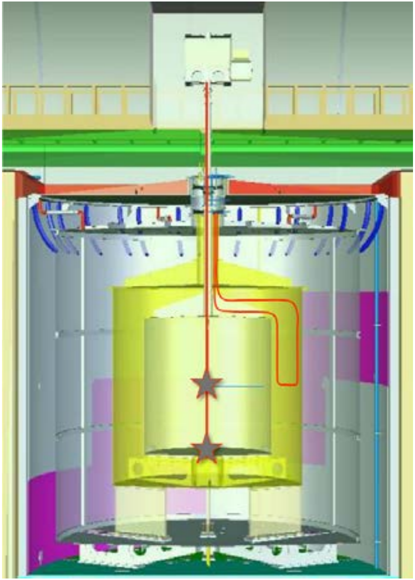
- Natural γ background from U and Th tops out at ~3 MeV (^{208}Tl).
- Capture events in GC lose energy due to spill-out.
- GC has ~twice the mass of target.
- H captures ~13% of neutrons in target.
- Semi-independent cross check of n-Gd analysis.

Calibration and Energy Scale

- **Source deployments:** ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
  - Z-axis
  - Guide tube
  - Future: articulated arm
- **LED injection system**
- **Spallation neutrons** generated by cosmic rays
- **Energy scale fractional uncertainty:** 1-2%
- θ_{13} **fit treatment:** A linear energy scale parameter is allowed to float as a nuisance parameter in the fit.



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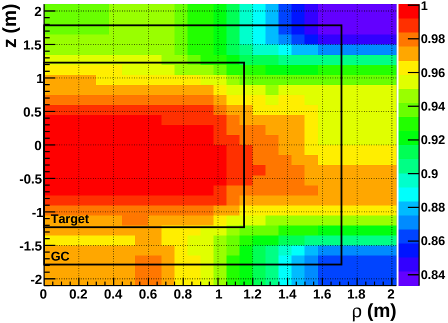
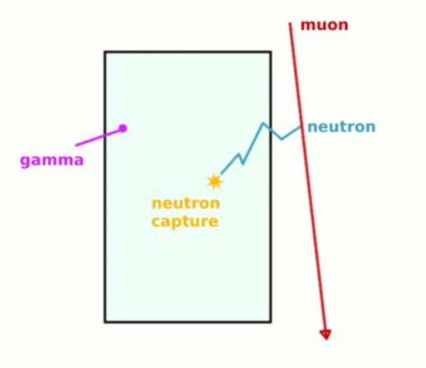
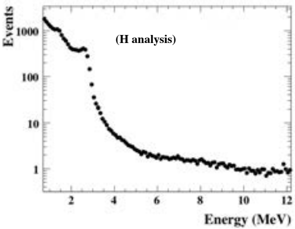


Backgrounds





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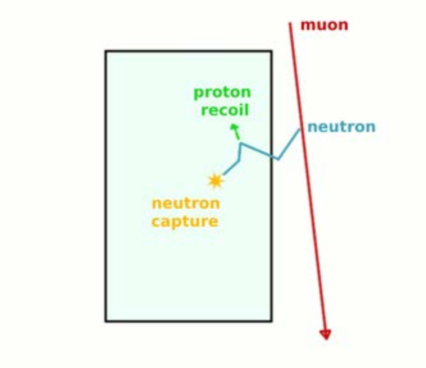

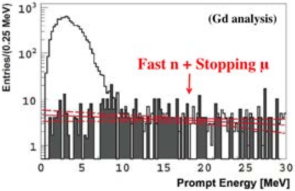

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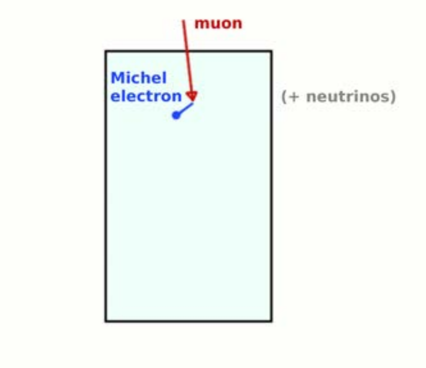

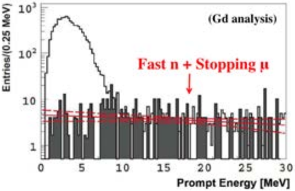

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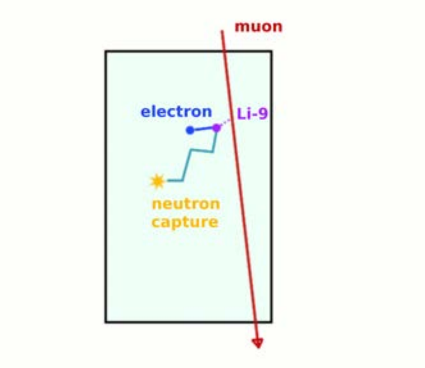

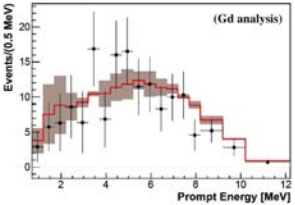

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  - ^{9}Li: resembles IBD, larger spectral unc. than other backgrounds; rate measured by time correlation with muons, shape from MC

Signal Prediction

Far detector-only analyses rely on $\overline{\nu}_e$ rate prediction:

$$N = \frac{\epsilon N_p}{4\pi} \sum_{R=1,2} \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \langle \sigma_f \rangle_R$$

ϵ	=	detection efficiency
N_p	=	number of protons in fiducial volume
L_R	=	distance between reactor and far detector
P_{th}^R	=	thermal power of reactor (time-dependent)
$\langle E_f \rangle_R$	=	average energy per fission (time-dependent)
$\langle \sigma_f \rangle_R$	=	average cross section per fission (time-dependent), "anchored" to Bugey4 measurement at L = 15 m

IBD Selection

Parameter	n-Gd Selection	n-H Selection
$\mathbf{E}_{Prompt}$	0.7 – 12.2 MeV	
$\mathbf{E}_{Delay}$	6 – 12 MeV	1.5 – 3 MeV
Δ**T**	2 – 100 μsec	10 – 600 μsec
Δ**R**	N/A	$<$ 90 cm

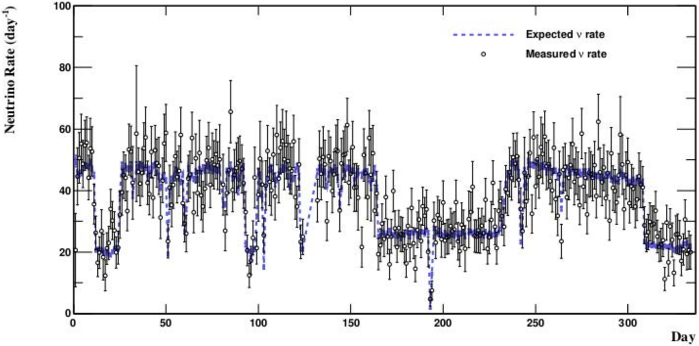
Further cuts

Muon veto	No muon 1 msec before prompt	
Showering muon veto	No μ with E $>$ 600 MeV in 0.5 sec before prompt	N/A
No extra trigger	$[t_{\text{pr}} - 100\ \mu\text{s}, t_{\text{pr}} + 400\ \mu\text{s}]$	$[t_{\text{pr}} - 600\ \mu\text{s}, t_{\text{pr}} + 1000\ \mu\text{s}]$
OV tag	Prompt can't be coincident with OV	
Light noise	Scintillation must be isotropic, arrive ∼simultaneously at PMTs	

Data/MC Comparison

April 2011 – March 2012

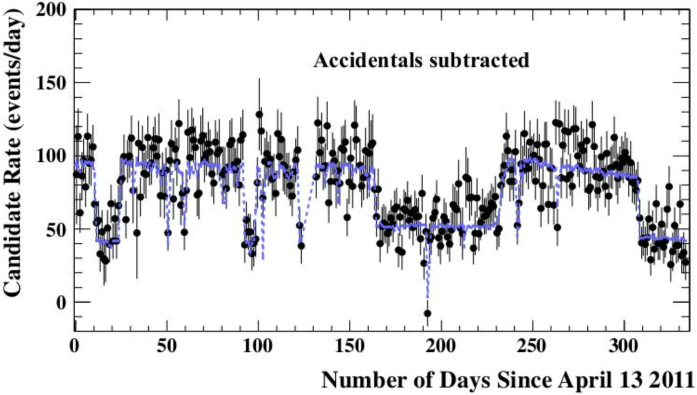
n-Gd selection, 227.9 days live time



Data/MC Comparison

April 2011 – March 2012

n-H selection, 240.1 days live time



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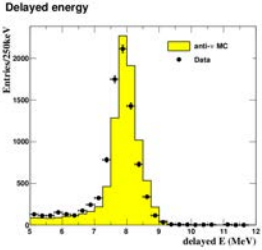
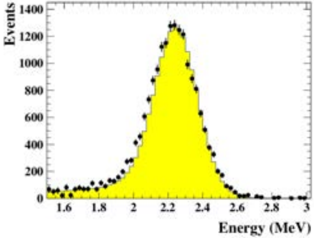
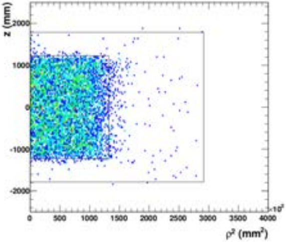
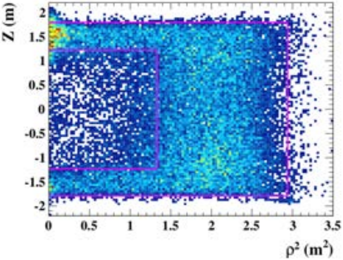








Double Chooz's θ_{13} Analyses

Rate+Shape fit

Double Chooz fit strategy:

- Improves upon rate-based analysis by adding spectrum information
- Constrains backgrounds
- Fits data with specific oscillation shape

$$\chi^2_{Rate+Shape} = \sum_{i,\,j}^{B} \left(N_i^{obs} - N_i^{pred}\right) M_{ij}^{-1} \left(N_j^{obs} - N_j^{pred}\right)^T + \text{ nuisance parameters}$$

$$\text{B} = \text{number of energy bins} = \begin{cases} 18, & \text{for Gd} \\ 31, & \text{for H} \end{cases}$$

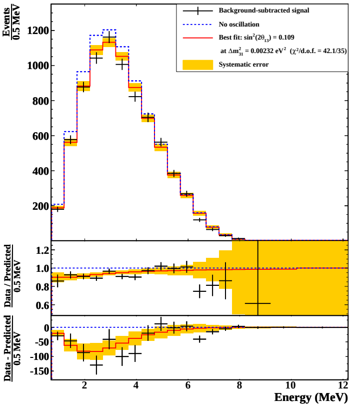
M = covariance matrix, including spectrum shape uncertainties

Nuisance parameters for ^{9}Li rate, FN + SM rate, energy scale, Δm^2

Published Rate+Shape Fits

Gd analysis, June 2012

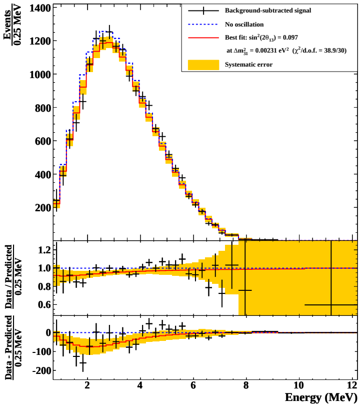
Phys. Rev. D 86 (2012)



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

H analysis, December 2012

Phys. Lett. B 723 (2013)



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

Shown with all backgrounds subtracted. Gd uses two integration periods, yielding d.o.f. = 2 × 18 − 1

Rate+Shape constraints

- **Rate+Shape fit constrains backgrounds:**

		Input (relative uncertainty)		Fit output (rel. unc.)
Gd	^{9}Li rate	1.3 ± 0.5 d^{-1} **(40%)**	→	1.0 ± 0.3 d^{-1} **(30%)**
	FN + SM rate	0.7 ± 0.2 d^{-1} **(30%)**	→	0.6 ± 0.1 d^{-1} **(20%)**
H	^{9}Li rate	2.8 ± 1.2 d^{-1} **(40%)**	→	3.9 ± 0.6 d^{-1} **(15%)**
	FN + SM rate	2.5 ± 0.5 d^{-1} **(20%)**	→	2.6 ± 0.4 d^{-1} **(15%)**

- **Also adjusts energy scale and Δm^2 to reach best fit.**

First combined Gd+H fit

Combining published Gd and H analyses:

- Data set covers April 2011-March 2012
- Fit includes correlation of systematic errors
- Backgrounds constrained by reactor-off measurements

Normalization Uncertainties

Source	n-Gd Unc. [%]	n-H Unc. [%]	Prelim. $\rho_{\mathrm{Gd,H}}$
Reactor Flux	1.8	1.8	1
Efficiency	1.0	1.6	0.09
Cosmogenic rate	1.4	1.6	0.003
Fast n rate	0.5	0.6	0
Accidental rate	0.01	0.2	0
Statistics	1.1	1.1	0
Total	2.7	3.1	

There are also spectral shape uncertainties due to the energy scale, fast neutrons/stopping muons, cosmogenic backgrounds, and the reactor $\overline{\nu}_e$ spectrum.

In order to combine n-H and n-Gd analyses, we needed to evaluate correlations between the analyses. Here $\rho_{\mathrm{Gd,H}}$ for a source of error X is defined as:

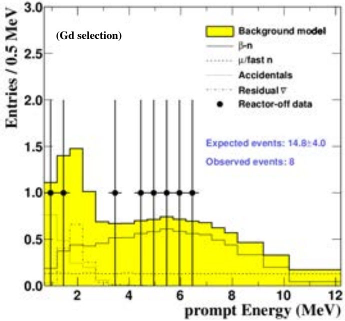
$$\rho_{\mathrm{Gd,H}} \equiv \frac{Cov[X_{\mathrm{Gd}}, X_{\mathrm{H}}]}{\sigma_{\mathrm{Gd}}\sigma_{\mathrm{H}}}$$

Reactor-off background measurements

Analyzed 7.5 days of data with both reactors off.

Phys. Rev. D. 87 (2013)

- Unique Double Chooz capability
- Rate consistent with predictions:
  - Gd selection: 1.0 ± 0.4 day^{-1}
    with residual $\bar{\nu}_e$ subtracted
    (expected 2.0 ± 0.6 day^{-1})
  - H selection: 11.3 ± 3.4 day^{-1}
    with residual $\bar{\nu}_e$ and accidentals subtracted
    (expected 5.8 ± 1.3 day^{-1})
- New constraint for oscillation fits



Combined Gd+H fit results

PRELIMINARY:

Rate+Shape: $\mathbf{\sin^2 2\theta_{13} = 0.109 \pm 0.035}$ (χ^2/d.o.f. = 61.2/50)

Rate-Only: $\sin^2 2\theta_{13} = 0.107 \pm 0.045$ (χ^2/d.o.f. = 6.1/3)

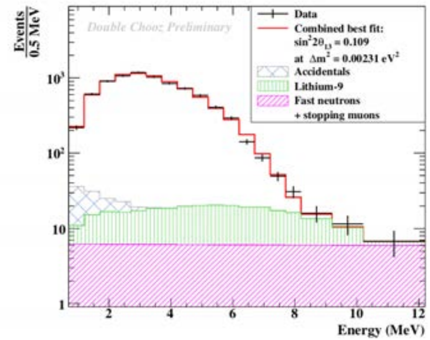
Compare to Gd-only analysis of same dataset (June 2012):

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.039$ (χ^2/d.o.f. = 42.1/35)

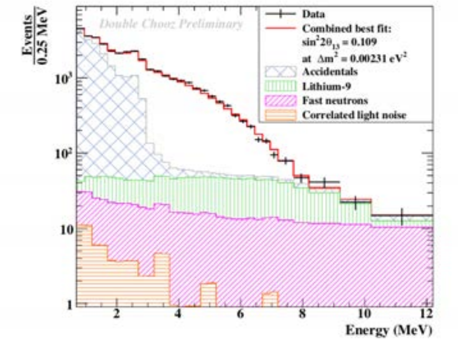
Rate-Only: $\sin^2 2\theta_{13} = 0.170 \pm 0.052$ (χ^2/d.o.f. = 0.5/1)

Gd and H prompt spectra, with backgrounds

Gd selection



H selection



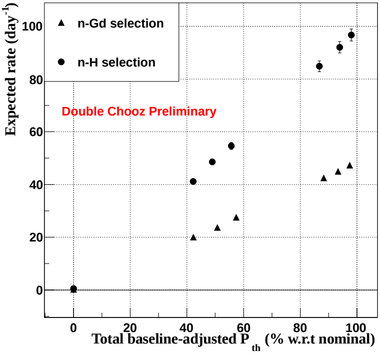
Red line is combined Gd+H Rate+Shape best fit.

Backgrounds shown at best-fit rates.

Reactor rate modulation analysis

Fit observed rates for $\sin^2 2\theta_{13}$ and total background rate, B:

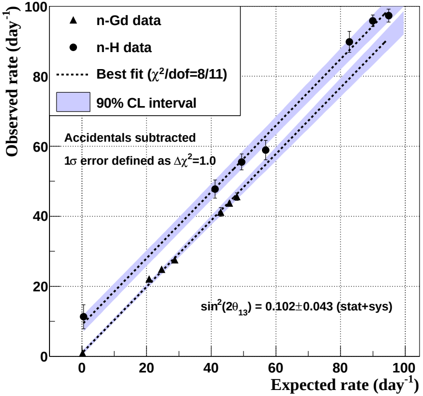
$$R^{obs} = B + \left(1 - \sin^2 2\theta_{13} \langle \sin^2(1.267 \Delta m^2 L/E) \rangle \right) R^{exp,\, no\ osc}$$

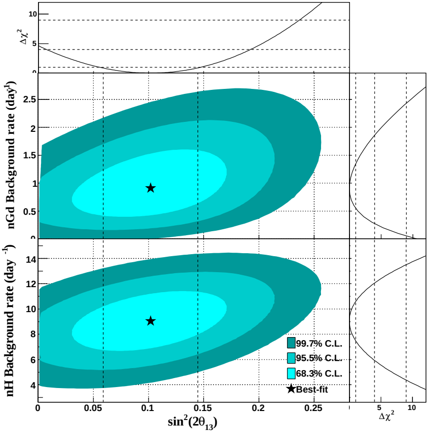


Valuable features:

- No *a priori* background model
- Combines Gd and H selections
- Leverage from reactor-off data

Reactor rate modulation results





Best fit: $\mathbf{\sin^2 2\theta_{13} = 0.102 \pm 0.043}$

arXiv:1401.5981, submitted to PLB

Double Chooz Outlook

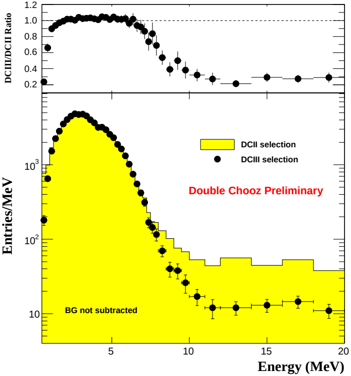
Near detector

Construction ongoing

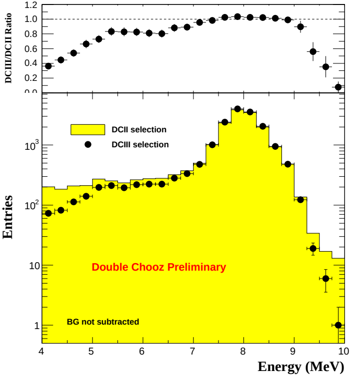
Near detector to begin taking data in summer of 2014.

Enhanced Selection

Ratio of new/old prompt E



Ratio of new/old delayed E



We have also improved our energy scale and reduced other systematic errors.

Future Double Chooz Results

Expanded far detector-only θ_{13} analysis

- $\sim 2\times$ more statistics + optimized selection
- Reduced systematic errors
- Projected $\sin^2 2\theta_{13}$ sensitivity: $\sigma \approx 0.03$

Two-detector θ_{13} analysis

- Reactor uncertainties nearly drop out
- Projected $\sin^2 2\theta_{13}$ sensitivity: $\sigma \approx 0.01$

Other Analyses

- Various background studies
- Lorentz violation (DC Coll., PRD 86, 112009, 2012)
- Ortho-positronium observation (DC, La Thuile 2014)
- Δm^2_{31} (arXiv:1304.6259)
- Reactor physics (with ND)

Summary

- **Multiple analyses with just far detector**
  - Two signal channels: Gd, H
  - Two oscillation analyses: R+S, RRM
  - Reactor-off background measurements

- **Newest results**
  - Gd+H Rate+Shape fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
  - Gd+H Reactor rate modulation: $\sin^2 2\theta_{13} = 0.102 \pm 0.043$

- **Future prospects**
  - Improved single-detector analysis
  - First two-detector analysis
  - Several non-θ_{13} analyses, too

Backups

Gd, H, and combined fit results

Rate+Shape:

	Individual fit results		Combined fit, Jul. 2013	
Fit parameter	**Gd, Jun. 2012**	**H, Dec. 2012**	**Gd selection**	**H selection**
Energy scale	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
FN+SM rate (d^{-1})	0.6 ± 0.1	2.6 ± 0.4	0.6 ± 0.1	2.6 ± 0.4
Li-9 rate (d^{-1})	1.0 ± 0.3	3.9 ± 0.6	0.9 ± 0.2	3.9 ± 0.6
Δm^2 (10^{-3}eV^2)	2.32 ± 0.12	2.32 ± 0.12	2.31 ± 0.12	
$\sin^2 2\theta_{13}$	0.109 ± 0.039	0.097 ± 0.048	0.109 ± 0.035	
χ^2/d.o.f.	42.1/35	38.9/30	61.2/50	

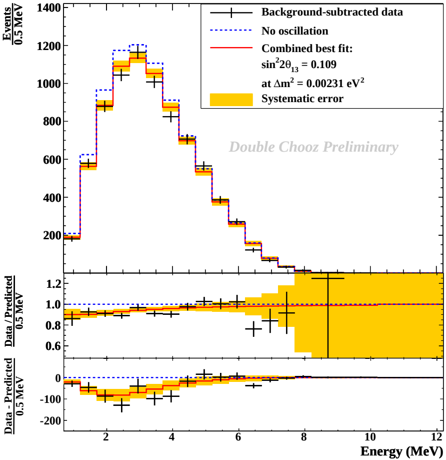
Rate-Only:

	Individual fit results		Combined fit, Jul. 2013	
Fit parameter	**Gd, Jun. 2012**	**H, Dec. 2012**	**Gd selection**	**H selection**
Energy scale	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01	1.00 ± 0.02
FN+SM rate (d^{-1})	0.7 ± 0.2	2.5 ± 0.5	0.6 ± 0.2	2.7 ± 0.5
Li-9 rate (d^{-1})	1.4 ± 0.5	2.8 ± 1.2	0.8 ± 0.4	3.7 ± 1.0
Δm^2 (10^{-3}eV^2)	2.32 ± 0.12	2.32 ± 0.12	2.32 ± 0.12	
$\sin^2 2\theta_{13}$	0.170 ± 0.052	0.044 ± 0.061	0.107 ± 0.045	
χ^2/d.o.f.	0.5/1	0/0	6.1/3	

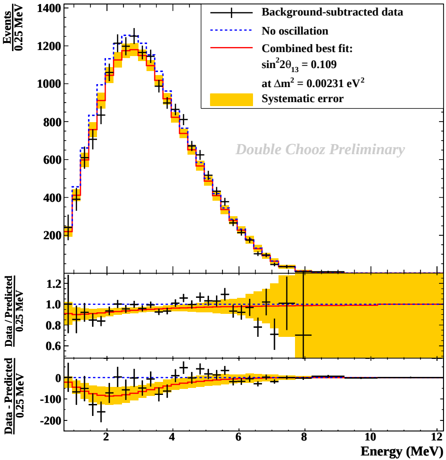
Reactor-off information is not included in individual fits.

Combined Gd+H Rate+Shape fit

Gd selection



H selection



All backgrounds subtracted at best-fit rates.

χ^2 definition for individual Gd and H fits

$$\chi^2_{Rate+Shape} = \sum_{i,j}^{B} \left(N_i^{obs} - N_i^{pred}\right) M_{ij}^{-1} \left(N_j^{obs} - N_j^{pred}\right)^T + \frac{(\alpha_{Li} - 1)^2}{\sigma_{Li}^2} + \frac{(\alpha_{FNSM} - 1)^2}{\sigma_{FNSM}^2} + \frac{(\alpha_E - 1)^2}{\sigma_E^2} + \frac{(\Delta m^2 - \Delta m^2_{MINOS})^2}{\sigma^2_{MINOS}}$$

with covariance matrix:

$$M = M_{stat} + M_{reactor} + M_{acc} + M_{corr\,LN} + M_{Li\,shape} + M_{FNSM\,shape}$$

χ^2 definition for combined Gd+H fit

$$\chi^2 = \sum_{i,\, j}^{B} (N_i^{obs} - N_i^{pred})\; M_{ij}^{-1}\; (N_j^{obs} - N_j^{pred})$$

Inner product with covariance matrix, as defined on previous slide

$$+\frac{(\Delta m^2 - \Delta m^2_{MINOS})^2}{\sigma^2_{MINOS}}$$

Mass splitting nuisance parameter

$$+\left[(\alpha_{li}^{Gd} - 1),\ (\alpha_{fn}^{Gd} - 1),\ (\alpha_{e}^{Gd} - 1),\ (\alpha_{li}^{H} - 1),\ (\alpha_{fn}^{H} - 1),\ (\alpha_{e}^{H} - 1)\right]$$

$$\times \begin{bmatrix} (\sigma_{li}^{Gd})^2 & 0 & 0 & \rho_{li}\sigma_{li}^{Gd}\sigma_{li}^{H} & 0 & 0 \\ 0 & (\sigma_{fn}^{Gd})^2 & 0 & 0 & \rho_{fn}\sigma_{fn}^{Gd}\sigma_{fn}^{H} & 0 \\ 0 & 0 & (\sigma_{e}^{Gd})^2 & 0 & 0 & \rho_{e}\sigma_{e}^{Gd}\sigma_{e}^{H} \\ \rho_{li}\sigma_{li}^{H}\sigma_{li}^{Gd} & 0 & 0 & (\sigma_{li}^{H})^2 & 0 & 0 \\ 0 & \rho_{fn}\sigma_{fn}^{H}\sigma_{fn}^{Gd} & 0 & 0 & (\sigma_{fn}^{H})^2 & 0 \\ 0 & 0 & \rho_{e}\sigma_{e}^{H}\sigma_{e}^{Gd} & 0 & 0 & (\sigma_{e}^{H})^2 \end{bmatrix}^{-1}$$

$$+\left[(\alpha_{li}^{Gd} - 1),\ (\alpha_{fn}^{Gd} - 1),\ (\alpha_{e}^{Gd} - 1),\ (\alpha_{li}^{H} - 1),\ (\alpha_{fn}^{H} - 1),\ (\alpha_{e}^{H} - 1)\right]^T$$

Correlated nuisance parameters on background rates and energy scale

$$+\left[(\alpha_{li}^{Gd} R_{li}^{Gd,\,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}),\ (\alpha_{li}^{H} R_{li}^{H,\,pred} + \alpha_{fn}^{H} R_{fn}^{H,pred} - R_{off}^{H})\right]$$

$$\times \begin{bmatrix} (\sigma_{off}^{Gd})^2 & \rho_{off}\sigma_{off}^{Gd}\sigma_{off}^{H} \\ \rho_{off}\sigma_{off}^{H}\sigma_{off}^{Gd} & (\sigma_{off}^{H})^2 \end{bmatrix}^{-1} \times \begin{bmatrix} (\alpha_{li}^{Gd} R_{li}^{Gd,\,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}) \\ (\alpha_{li}^{H} R_{li}^{H,\,pred} + \alpha_{fn}^{H} R_{fn}^{H,pred} - R_{off}^{H}) \end{bmatrix}$$

Reactor-off rate constraints

Predicted $\bar{\nu}_e$ spectrum

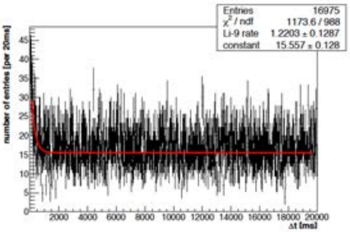
$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \left(\frac{\langle \sigma_f \rangle_R}{\sum_k \alpha_k^R \langle \sigma_f \rangle_k} \sum_k \alpha_k^R \langle \sigma_f \rangle_k^i \right)$$

Bugey4 "anchor": $\langle \sigma_f \rangle_R = \langle \sigma_f \rangle_{Bugey} + \sum_k \left(\alpha_k - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$

... scales predicted $\langle \sigma_f \rangle$ to match $\langle \sigma_f \rangle$ measured at $L = 15$ m, removing sensitivity to $\Delta m^2 \sim 1$ eV^2 oscillations

R	=	{Reactor 1, Reactor 2}
k	=	{^{235}U, ^{238}U, ^{239}P, ^{241}P}
ϵ	=	detection efficiency
N_p	=	number of protons in fiducial volume
L_R	=	distance between R^{th} reactor and far detector
P_{th}^R	=	thermal power of R^{th} reactor (time-dependent)
$\langle E_f \rangle_R$	=	mean energy per fission in R^{th} reactor (time-dependent)
$\langle \sigma_f \rangle_R$	=	mean cross section per fission in R^{th} reactor (time-dependent)
α_k^R	=	fission fraction for k^{th} isotope in R^{th} reactor (time-dependent)
$\langle \sigma_f \rangle_k$	=	mean cross section per fission of k^{th} isotope
$\langle \sigma_f \rangle_k^i$	=	mean cross section per fission of k^{th} isotope in i^{th} energy bin

^{9}Li measurement



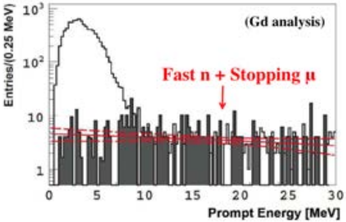
Rate derived from $\Delta t_{\mu} = t - t_{previous\ \mu}$ for IBD candidates:

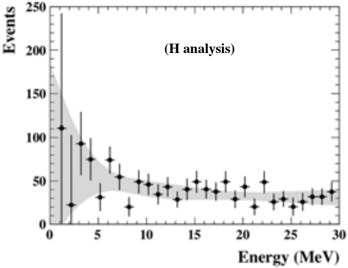
- Δt_{μ} fit with $\tau(^{9}Li) = 257$ ms
  (sample plot show for $E_{\mu} > 600$ MeV)
- Purity increased with $\Delta R_{\mu\ track}$ cuts
- Consistent rates found for Gd and H

Spectrum shape predicted from MC:

- Spectrum uncertainties from uncertainty on ^{9}Li branching ratios
- Data consistent with predicted shape

Fast n + stopping μ measurement





Rough estimate:

- Extrapolate from $E_p \in [12, 30]$ MeV

Refined measurement:

- Pure selection from IV/OV-tagging
  (+ additional cuts, background subtraction)
- Fit with linear/exponential model
- Rate from integrating spectrum fit

All stopping μ removed from
H selection with $\Delta T < 10\ \mu$s cut.

Light noise

Cuts remove almost all light noise, with negligible signal inefficiency:

- **Charge isotropy:** $$\frac{Q_{max}}{Q_{tot}} < \begin{cases} 0.09 & \text{H, Gd prompt} \\ 0.06 & \text{Gd delayed} \end{cases}$$

  Q_{max} = maximum charge seen by single PMT

  Q_{tot} = total charge seen by all PMTs

- **Pulse simultaneity:** $T^{RMS}_{start} < 40$ ns

  T^{RMS}_{start} = RMS of pulse start times, over all PMTs recording pulses

Time-correlated light noise remains in H selection: 0.3 ± 0.1 d^{-1} (included in H fit, but impact is negligible)