New measurements of reactor $\bar{\nu}_e$ disappearance

with the Double Chooz far detector

Rachel Carr, Columbia University

on behalf of the Double Chooz collaboration

DPF | UC Santa Cruz | August 16, 2013

Outline

I. Experiment overview

II. Latest Double Chooz results
- Reactor-off background measurements
- First combined Gd+H fit
- Reactor rate modulation analysis

III. Future of Double Chooz

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III. Future of Double Chooz

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

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

Chooz, France

Designed to measure $\sin^2 2\theta_{13}$ via reactor $\bar{\nu}_e$ disappearance:

$$\mathbf{P}_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(1.27\, \Delta m^2_{31}\, L/E\right)$$

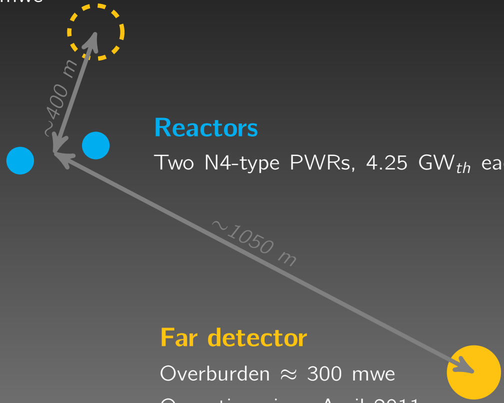
$[\Delta m^2_{31}]$ = eV^2, $[L]$ = m, $[E]$ = MeV

Site layout

Near detector

Overburden ≈ 120 mwe

Ready in mid-2014



Reactors

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

Far detector

Overburden ≈ 300 mwe

Operating since April 2011

Inverse β decay signal

Prompt signal:

e^+ scintillation and annihilation

$E_{prompt} \approx E_{\bar{\nu}_e} - 0.8$ MeV

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

Delayed signal:

n capture on Gd
$\hookrightarrow \gamma$ cascade

$E_{delayed} \approx 8$ MeV

$\Delta T \approx 30\ \mu s$

OR

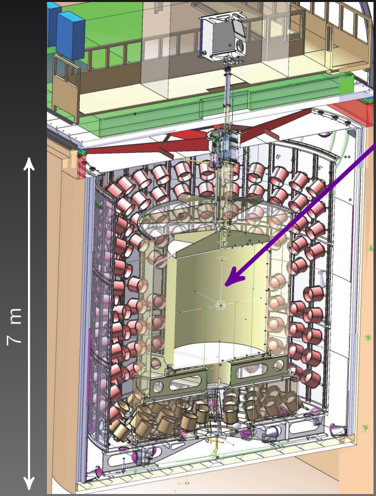
n capture on H
$\hookrightarrow$ single γ

$E_{delayed} = 2.2$ MeV

$\Delta T \approx 200\ \mu s$

Unique to Double Chooz!

Detector design

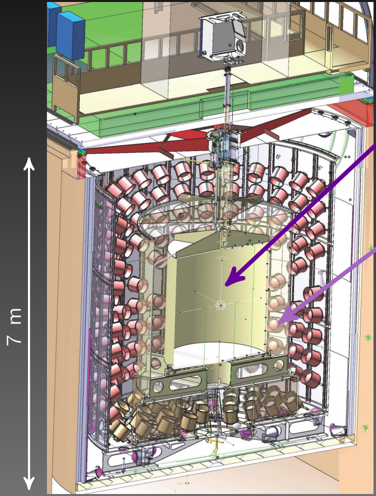


Inner detector:

Neutrino target

Gd-doped liquid scintillator (8.3 tons)

Detector design



Inner detector:

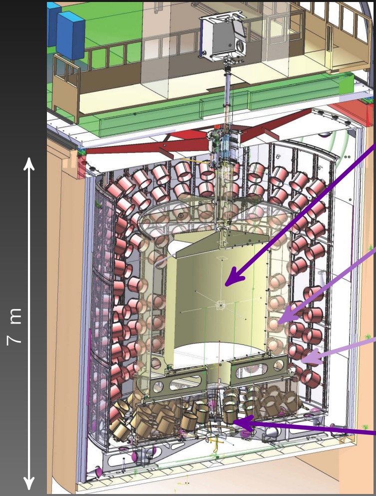
Neutrino target

Gd-doped liquid scintillator (8.3 tons)

Gamma catcher

Undoped liquid scintillator (18 tons)

Detector design



Inner detector:

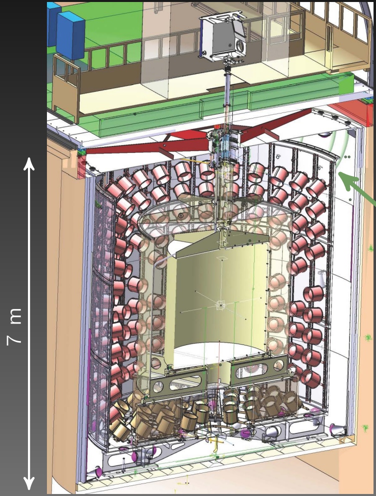
Neutrino target
Gd-doped liquid scintillator (8.3 tons)

Gamma catcher
Undoped liquid scintillator (18 tons)

Buffer
Non-scintillating mineral oil (80 tons)

390 PMTs
installed on stainless steel tank

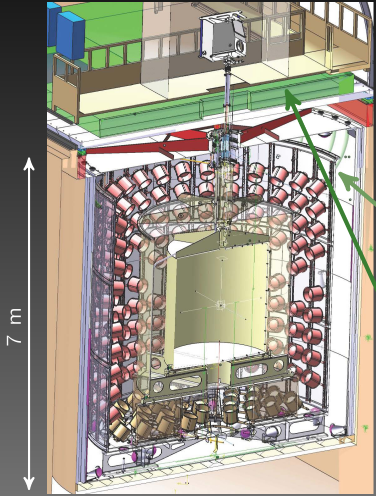
Detector design



Cosmic ray veto systems:

Inner veto
Undoped liquid scintillator (70 tons)
+ 78 PMTs

Detector design



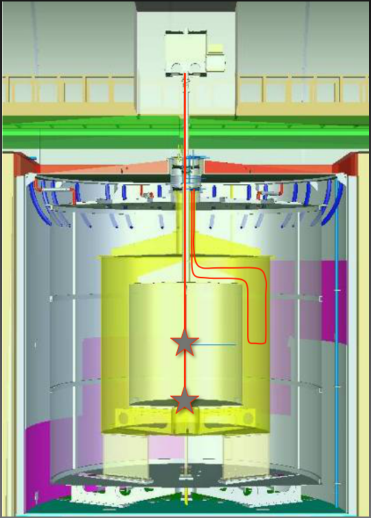
Cosmic ray veto systems:

Inner veto
Undoped liquid scintillator (70 tons)
+ 78 PMTs

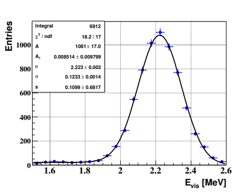
Outer veto
Array of plastic scintillator strips
13 m × 7 m

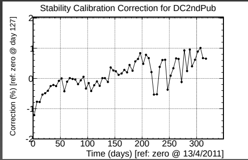
Calibration

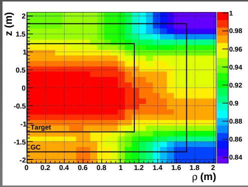
- **Source deployments:**
  ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
  - Z-axis
  - Guide tube
  - Fall 2013: Articulated arm
- **Spallation neutrons**
  generated by cosmic rays
- **LED injection system**



Energy reconstruction







- **q → PE**, correcting for gain nonlinearity
  PE → MeV, using H capture peak
- **Correction for time instability,**
  using Gd capture peak variation
- **Correction for detector inhomogeneity,**
  using H capture map

... Final energy scale uncertainty: 1-2%

Signal selection

Parameter	Gd selection	H selection
E_{prompt}	0.7 – 12.2 MeV	0.7 – 12.2 MeV
$E_{delayed}$	6.0 – 12.0 MeV	1.5 – 3.0 MeV
ΔT	2 – 100 μs	10 – 600 μs
ΔR	—	< 90 cm

Further requirements for background reduction:		
Parameter	**Gd selection**	**H selection**
Multiplicity	No additional triggers in 500 μs surrounding prompt	No additional triggers in 1600 μs surrounding prompt
Muon veto	No muon in ID or IV in 1 ms before prompt	
Showering muon veto	No muon depositing $>$ 600 MeV in 0.5 s before prompt	—
OV veto	No OV hit coincident with prompt	
Light noise rejection	Passes cuts on PMT charge isotropy and pulse simultaneity	

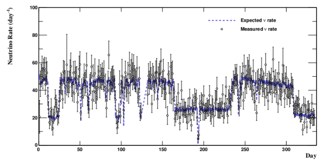
Predicted no-oscillation signal in April 2011–March 2012 dataset:

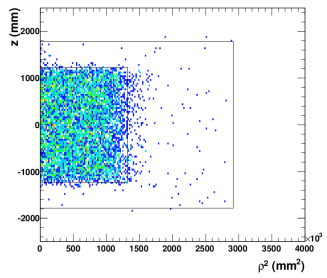
Gd selection: 8,440 H selection: 17,690

IBD candidates

Gd selection

April 2011 – March 2012

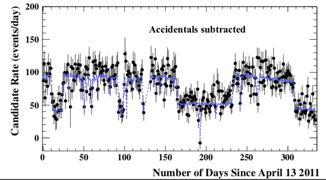


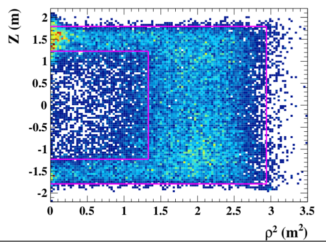


Live time: 227.9 days
Candidates: 8,249

H selection

April 2011 – March 2012

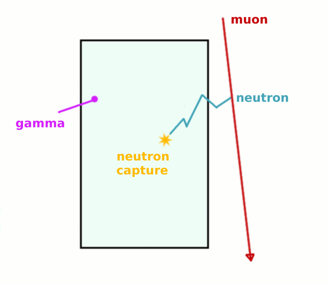


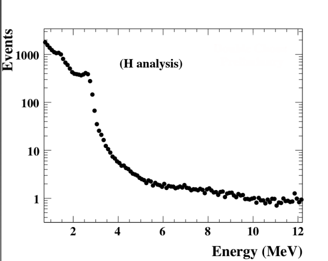


Live time: 240.1 days
Candidates: 36,284

Backgrounds

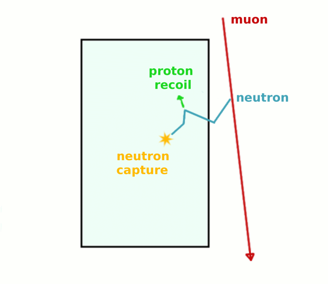
- **Accidentals**
  - Gd: $0.3\ \mathrm{d}^{-1}$ (error $\ll 0.1\ \mathrm{d}^{-1}$)
  - H: $73.5 \pm 0.2\ \mathrm{d}^{-1}$

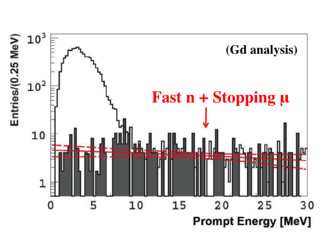




Backgrounds

- **Accidentals**
  - Gd: 0.3 d^{-1} (error $\ll$ 0.1 d^{-1})
  - H: 73.5 $\pm$ 0.2 d^{-1}
- **Fast neutrons + stopping muons**
  - Gd: 0.7 $\pm$ 0.2 d^{-1}
  - H: 2.5 $\pm$ 0.5 d^{-1} (all fast n)





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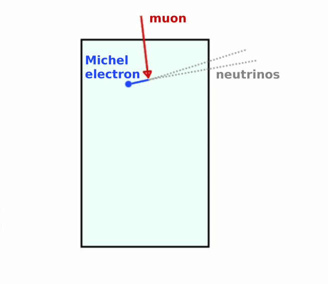
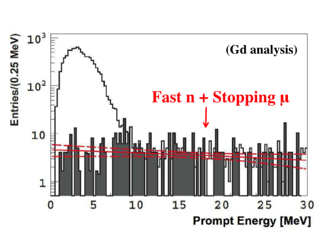
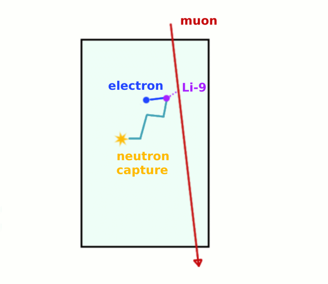


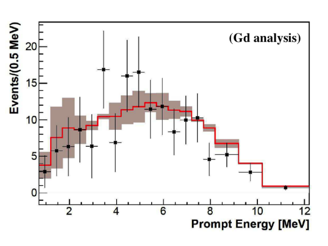


Backgrounds

- **Accidentals**
  - Gd: 0.3 d^{-1} (error $\ll$ 0.1 d^{-1})
  - H: 73.5 $\pm$ 0.2 d^{-1}
- **Fast neutrons + stopping muons**
  - Gd: 0.7 $\pm$ 0.2 d^{-1}
  - H: 2.5 $\pm$ 0.5 d^{-1} (all fast n)
- **Cosmogenic isotopes, mainly ^{9}Li**
  - Gd: 1.3 $\pm$ 0.5 d^{-1}
  - H: 2.8 $\pm$ 1.2 d^{-1}

Rates of ^{9}Li and FN + SM are further constrained in final fit.





$\bar{\nu}_e$ flux prediction

Far detector-only analyses rely on $\bar{\nu}_e$ 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*

Uncertainties

Normalization uncertainties (relative to signal):

Source	Gd selection	H selection
Reactor $\bar{\nu}_e$ flux	1.8%	1.8%
Efficiency	1.0%	1.6%
^{9}Li rate	1.5%	1.6%
Fast n + stopping μ rate	0.5%	0.6%
Accidentals rate	<0.1%	0.2%
Total statistical error	1.1%	1.1%

Spectrum shape uncertainties:

- Reactor $\bar{\nu}_e$ spectrum
- Energy scale
- ^{9}Li spectrum
- Fast n + stopping μ spectrum

Rate+Shape fit

Unique Double Chooz fit strategy:

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

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

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

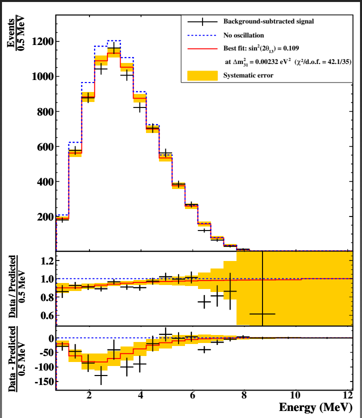
M = covariance matrix, including spectrum shape uncertainties

Pull terms on ^{9}Li rate, FN + SM rate, energy scale, Δm^2

Published Rate+Shape fits

Gd analysis, June 2012

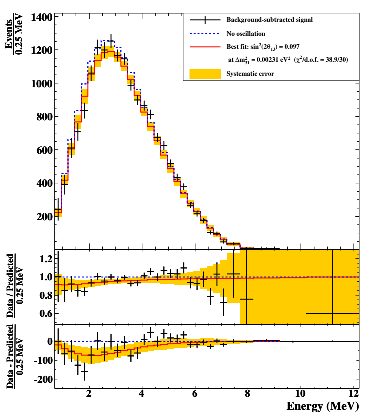
Phys. Rev. D 86 (2012)



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

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. $= 2 \times 18 - 1$

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%)**	$\rightarrow$	1.0 ± 0.3 d^{-1} **(30%)**
	FN + SM rate	0.7 ± 0.2 d^{-1} **(30%)**	$\rightarrow$	0.6 ± 0.1 d^{-1} **(20%)**
H	^{9}Li rate	2.8 ± 1.2 d^{-1} **(40%)**	$\rightarrow$	3.9 ± 0.6 d^{-1} **(15%)**
	FN + SM rate	2.5 ± 0.5 d^{-1} **(20%)**	$\rightarrow$	2.6 ± 0.4 d^{-1} **(15%)**

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

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- First combined Gd+H fit
- Reactor rate modulation analysis

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Reactor-off background measurements

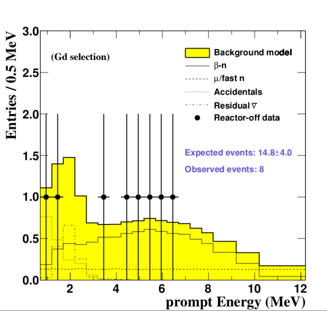
Analyzed 7.5 days of data with both reactors off.

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



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

Combined Gd+H fit results

PRELIMINARY:

Rate+Shape:	$\mathbf{\sin^2 2\theta_{13} = 0.109 \pm 0.035}$	$(\chi^2/\text{d.o.f.} = 61.2/50)$
Rate-Only:	$\sin^2 2\theta_{13} = 0.107 \pm 0.045$	$(\chi^2/\text{d.o.f.} = 6.1/3)$

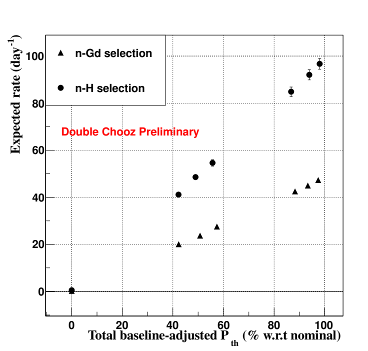
Compare to Gd-only analysis of same dataset (June 2012):

Rate+Shape:	$\sin^2 2\theta_{13} = 0.109 \pm 0.039$	$(\chi^2/\text{d.o.f.} = 42.1/35)$
Rate-Only:	$\sin^2 2\theta_{13} = 0.170 \pm 0.052$	$(\chi^2/\text{d.o.f.} = 0.5/1)$

Reactor rate modulation analysis

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

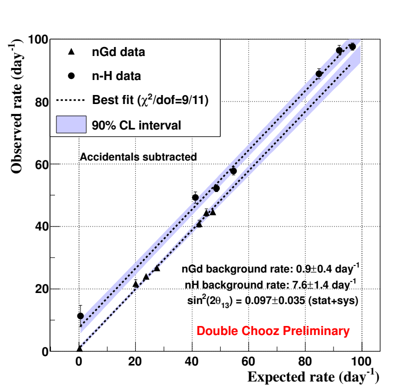
$$R^{obs} = B + \left(1 - \sin^2 2\theta_{13} \langle \sin^2(1.27\Delta m^2 L/E) \rangle\right) R^{exp,\, no\ osc}$$

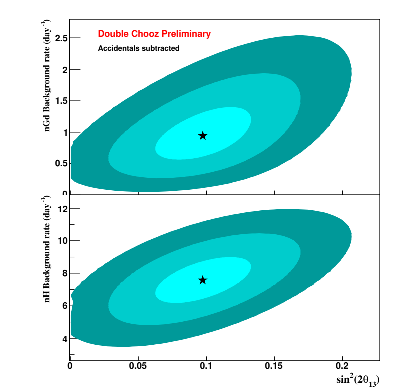


Valuable features:

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

Reactor rate modulation results





Best fit: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$

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Near detector

Construction ongoing!

Near detector expected to begin taking data in spring of 2014.

Future θ_{13} results

Expanded far detector-only analysis (end of 2013)

- $\sim 2\times$ more statistics + optimized selection
- Reduced systematic errors
- Projected precision: $\sigma \approx 0.03$

Two-detector analysis (2014)

- Reactor uncertainties nearly drop out
- Projected final precision: $\sigma \approx 0.01$
- Ultimately background-limited (especially ^{9}Li)

Summary

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

Summary

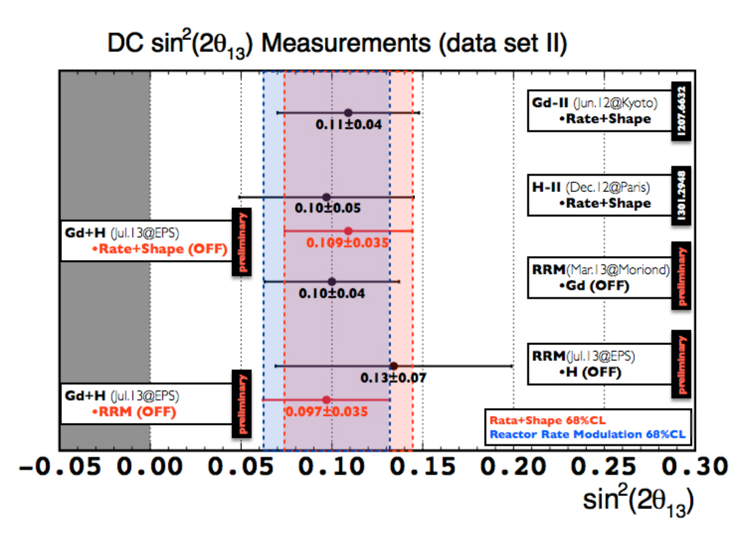
- **Rich, unique program with far detector**
  - Two signal channels: Gd, H
  - Two oscillation analyses: R+S, RRM
  - Reactor-off background measurements
- **New results**
  - Gd+H Rate+Shape fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
  - Reactor rate modulation: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$

Summary

- **Rich, unique program with far detector**
  - Two signal channels: Gd, H
  - Two oscillation analyses: R+S, RRM
  - Reactor-off background measurements
- **New results**
  - Gd+H Rate+Shape fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
  - Reactor rate modulation: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
- **Future prospects**
  - Improved single-detector analysis
  - First two-detector analysis

Additional plots

Summary of Double Chooz results



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	

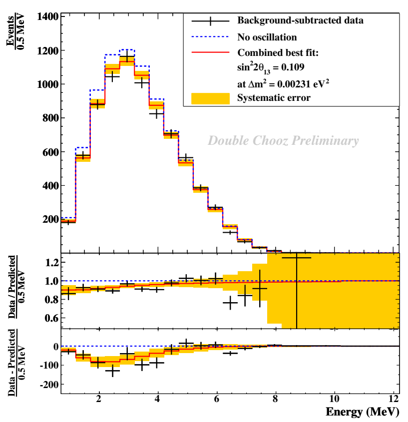
Rate-Only:

	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	

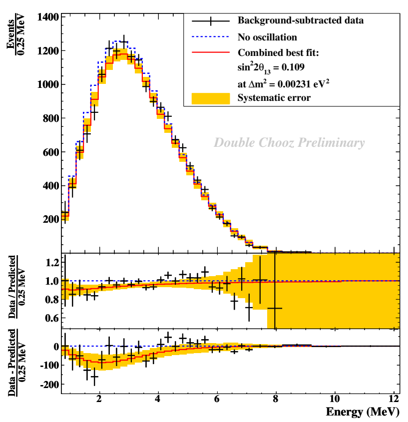
Reactor-off information is not included in individual fits.

Combined Gd+H Rate+Shape fit

Gd selection



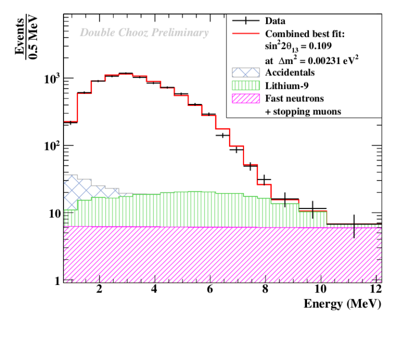
H selection



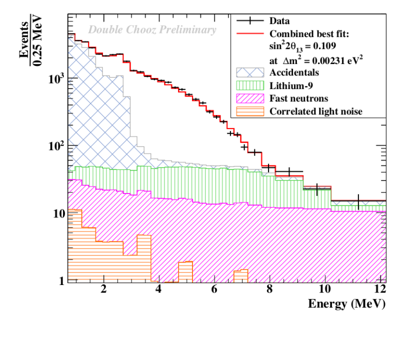
All backgrounds subtracted at best-fit rates.

Gd and H prompt spectra, with backgrounds

Gd selection



H selection



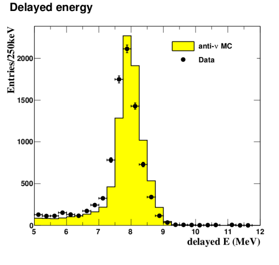
Red line is combined Gd+H Rate+Shape best fit.
Backgrounds shown at best-fit rates.

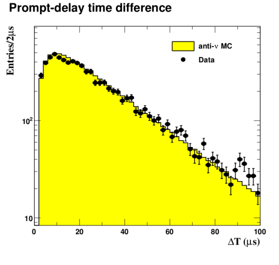
Correlations between Gd and H analyses

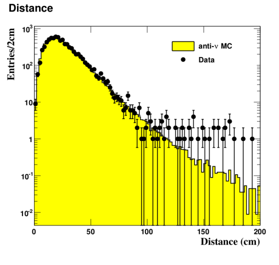
PRELIMINARY

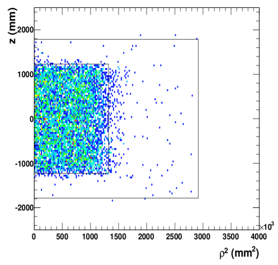
Parameter	$\rho_{Gd,H}$
Accidental rate	0
Correlated light noise	0
Fast n + stopping μ rate	0
^{9}Li rate	0.003
^{9}Li shape	1
Efficiency	0.09
Energy scale	0.4
Reactor	1

Candidates from Gd selection

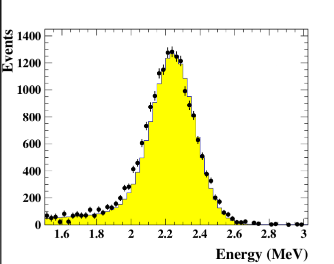


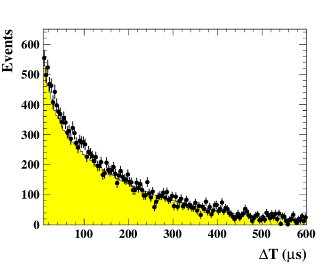


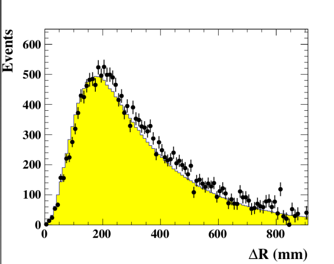


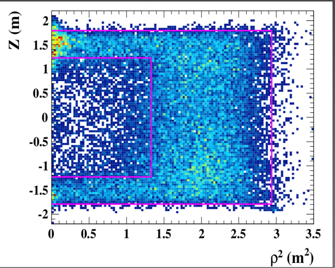


Candidates from H selection









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

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

Inner product with covariance matrix, as defined on previous slide

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

Mass splitting pull term

$$\begin{aligned}
&+ \Big[(\alpha_{li}^{Gd} - 1), (\alpha_{fn}^{Gd} - 1), (\alpha_{e}^{Gd} - 1), (\alpha_{li}^{H} - 1), (\alpha_{fn}^{H} - 1), (\alpha_{e}^{H} - 1)\Big] \\
&\times \begin{bmatrix}
(\sigma_{li}^{Gd})^2 & 0 & 0 & \rho_{li}\sigma_{li}^{Gd}\sigma_{li}^{H} & 0 & 0 \\
0 & (\sigma_{fn}^{Gd})^2 & 0 & 0 & \rho_{fn}\sigma_{fn}^{Gd}\sigma_{fn}^{H} & 0 \\
0 & 0 & (\sigma_{e}^{Gd})^2 & 0 & 0 & \rho_{e}\sigma_{e}^{Gd}\sigma_{e}^{H} \\
\rho_{li}\sigma_{li}^{H}\sigma_{li}^{Gd} & 0 & 0 & (\sigma_{li}^{H})^2 & 0 & 0 \\
0 & \rho_{fn}\sigma_{fn}^{H}\sigma_{fn}^{Gd} & 0 & 0 & (\sigma_{fn}^{H})^2 & 0 \\
0 & 0 & \rho_{e}\sigma_{e}^{H}\sigma_{e}^{Gd} & 0 & 0 & (\sigma_{e}^{H})^2
\end{bmatrix}^{-1} \\
&+ \Big[(\alpha_{li}^{Gd} - 1), (\alpha_{fn}^{Gd} - 1), (\alpha_{e}^{Gd} - 1), (\alpha_{li}^{H} - 1), (\alpha_{fn}^{H} - 1), (\alpha_{e}^{H} - 1)\Big]^T
\end{aligned} \tag{3}$$

Correlated pull terms on background rates and energy scale

$$\begin{aligned}
&+ \Big[(\alpha_{li}^{Gd} R_{li}^{Gd,\,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}), (\alpha_{li}^{H} R_{li}^{H,\,pred} + \alpha_{fn}^{H} R_{fn}^{H,pred} - R_{off}^{H})\Big] \\
&\times \begin{bmatrix}
(\sigma_{off}^{Gd})^2 & \rho_{off}\sigma_{off}^{Gd}\sigma_{off}^{H} \\
\rho_{off}\sigma_{off}^{H}\sigma_{off}^{Gd} & (\sigma_{off}^{H})^2
\end{bmatrix}^{-1} \times \begin{bmatrix}
(\alpha_{li}^{Gd} R_{li}^{Gd,\,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}) \\
(\alpha_{li}^{H} R_{li}^{H,\,pred} + \alpha_{fn}^{H} R_{fn}^{H,pred} - R_{off}^{H})
\end{bmatrix}
\end{aligned} \tag{4}$$

Reactor-off rate constraints

Predicted $\bar{\nu}_e$ spectrum

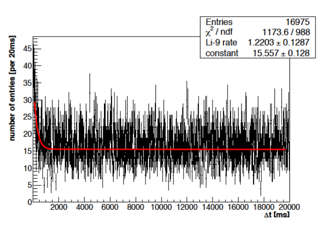
$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \left(\frac{\langle \sigma_f \rangle_R}{\sum_k \alpha_k^R \langle \sigma_f \rangle_k} \sum_k \alpha_k^R \langle \sigma_f \rangle_k^i \right)$$

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



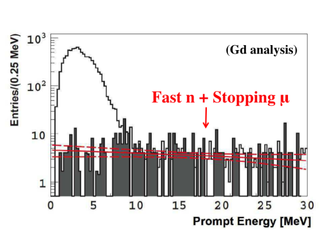
Rate derived from $\Delta t_\mu = t - t_{\text{previous}\,\mu}$ for IBD candidates:

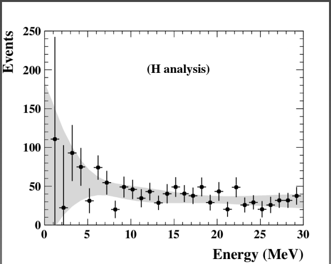
- Δt_μ fit with $\tau(^9Li)$ = 257 ms
  (sample plot show for E_μ > 600 MeV)
- Purity increased with $\Delta R_{\mu\,track}$ cuts
- Consistent rates found for Gd and H

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: $0.3 \pm 0.1\ \mathrm{d}^{-1}$
(included in H fit, but impact is negligible)