θ_{13} at Double Chooz

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Brief Neutrino Oscillation Review

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 $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$.

Current Oscillation Knowledge

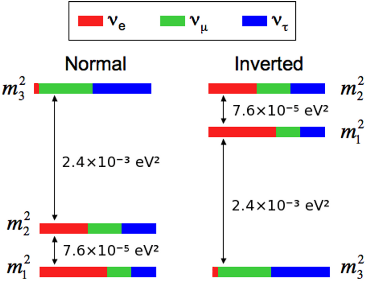
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

We have observed three left-handed weak flavor eigenstates which are non-trivial superpositions of three mass eigenstates. This mixing is parameterized by:

- 3 Euler 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).

Current Oscillation Knowledge



- Knowns: $|\Delta m^2_{32}| \approx |\Delta m^2_{31}|$, 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}

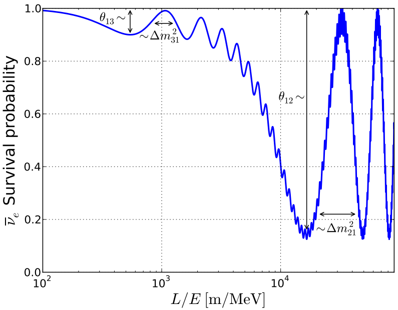
- One way to measure θ_{13} is to look at $\overline{\nu}_e$ survival probability for small L/E:

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

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

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

- $E_{e^+} = E_{\bar{\nu}_e} + T_n - 0.8$ MeV, however since T_n small, $E_{e^+} \simeq E_{\bar{\nu}_e} - 0.8$ MeV



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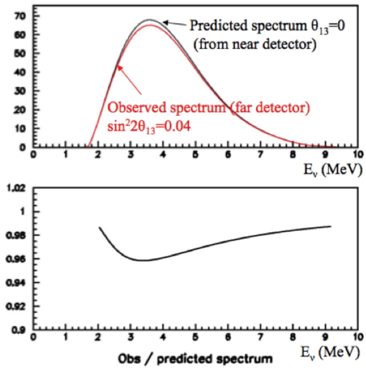


Double Chooz Overview

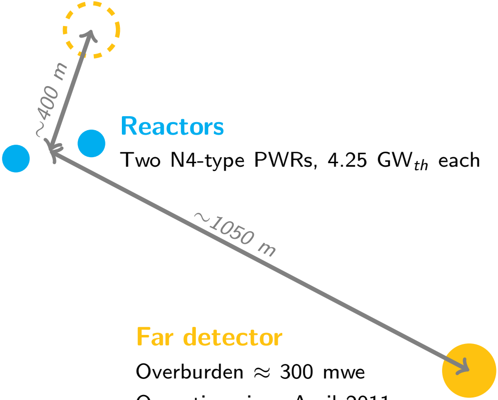
Double Chooz Experiment

Site Layout

Near detector

Overburden ≈ 120 mwe

Commissioning now



Reactors

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

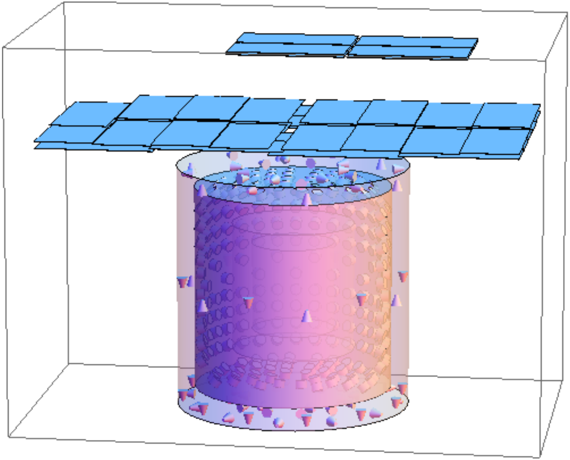
Far detector

Overburden ≈ 300 mwe

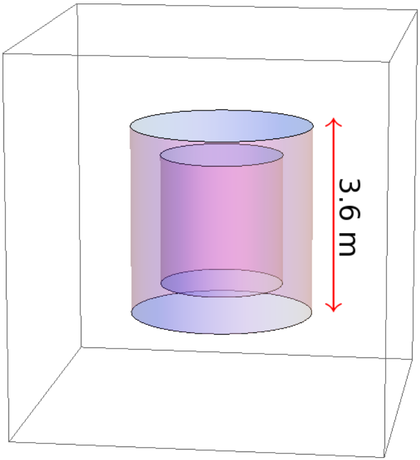
Operating since April 2011

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.

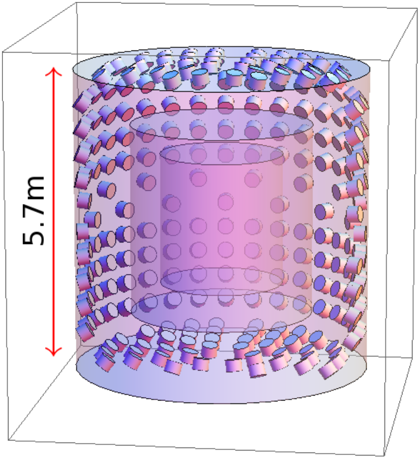


Target and Gamma Catcher



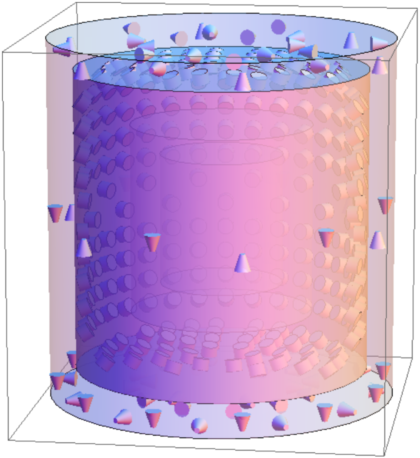
- Target is 10 m^3 (8.3 tons) of liquid scintillator doped with 1 g/L Gd.
  - $\sim$ 85% of neutrons in target capture on Gd.
- Gamma Catcher is 550 mm shell of liquid scintillator around target (no Gd).
  - Nearly all gammas released by n+Gd are contained in scintillator $\rightarrow$ reliable 8 MeV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

Buffer



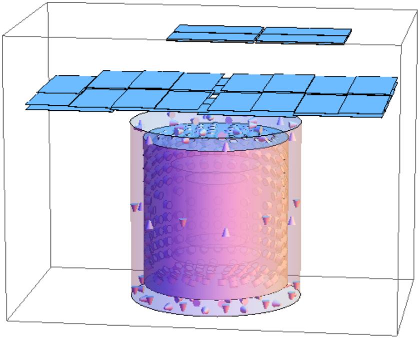
- Target and gamma catcher are surrounded by the buffer.
- Filled with non-scintillating mineral oil
- 390 low-activity Hamamatsu 10" PMTs
- Shields scintillator from PMT glass radioactivity, surrounding rock radioactivity, and neutrons.

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.

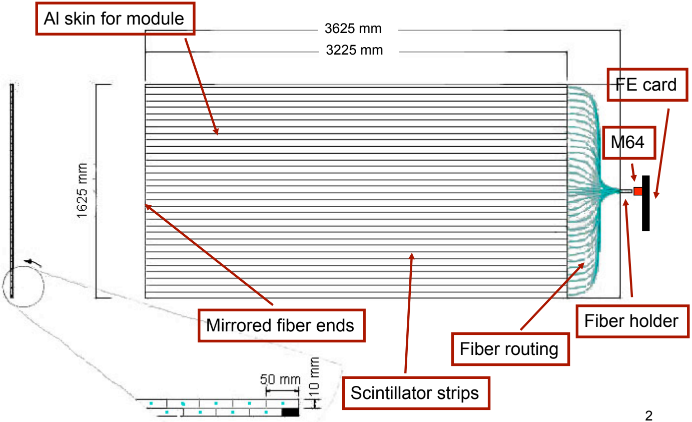
Outer Veto



- 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.

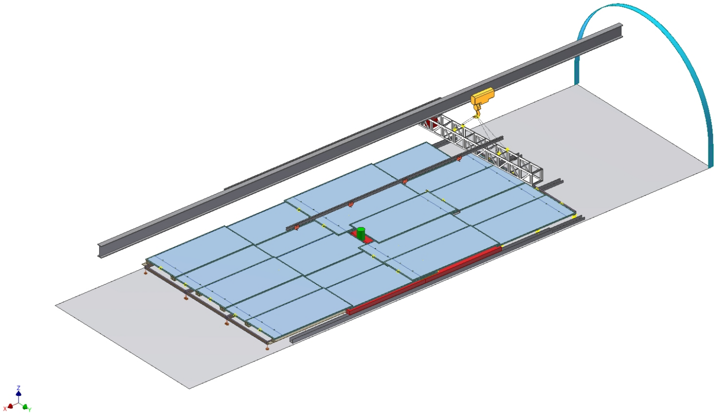
Outer Veto Module Schematic

- Two layers of 32 scintillating strips each
- Wavelength shifting fibers in center bring light to PMT
- Module dimensions: 2 cm × 1.6 m × (3.2 m or 3.6 m)
- Built 130 modules in total; all tested in ACC high bay



Installation

Lower OV consists of two layers.



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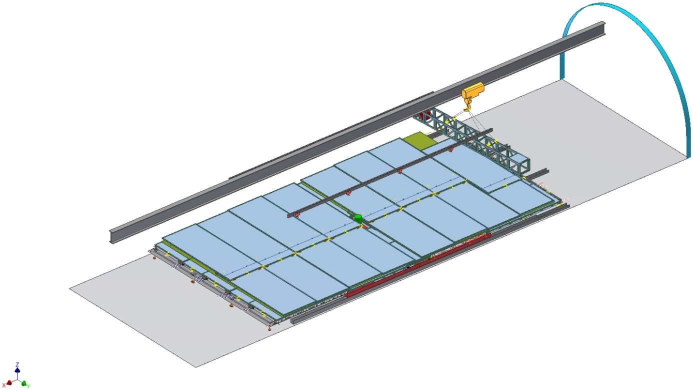
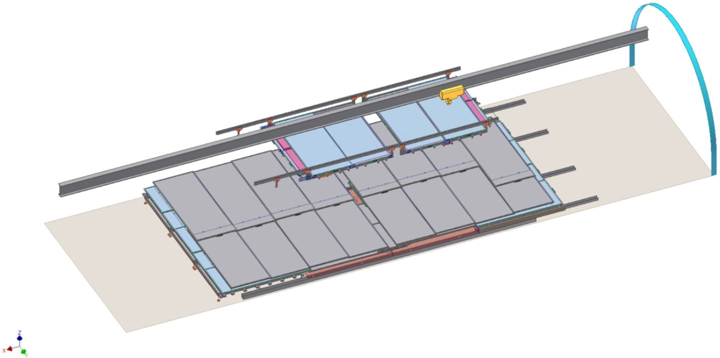


Installation

Lower OV installed in spring 2011.

Installation

Upper OV also consists of two layers.

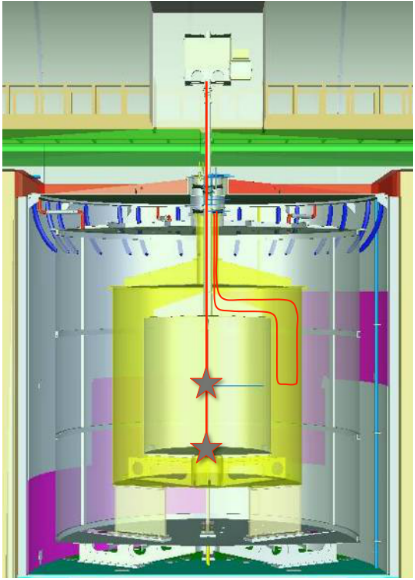


Installation

Upper OV installed in summer 2012.

Calibration and Energy Scale

- **Source deployments:**
  ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
    - Z-axis
    - Guide tube
- **LED injection system**
- **Spallation neutrons**
  generated by cosmic rays
- **Energy scale fractional uncertainty:** $\sim 1\%$
- θ_{13} **fit treatment:**
  $E_{vis}^{MC} \longrightarrow a' + b' \cdot E_{vis}^{MC} + c' \cdot (E_{vis}^{MC})^2$
  where $b' \sim 1$ and $a', c' \sim 0$



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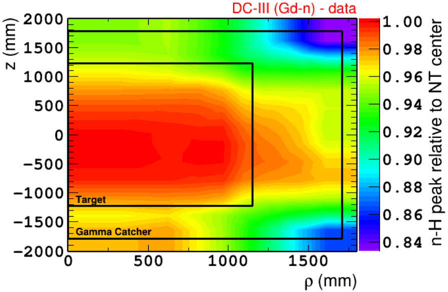

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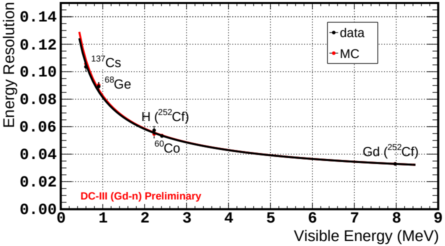
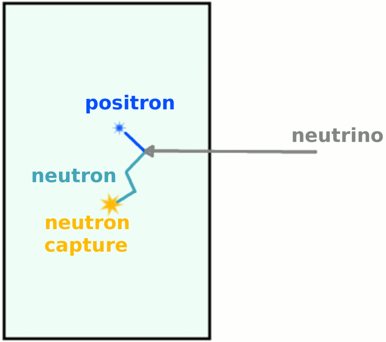


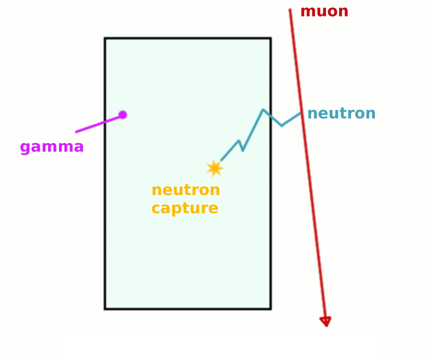
Signal and Backgrounds

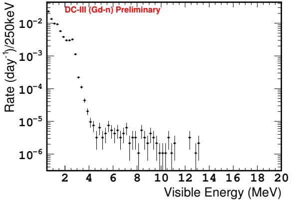
$\overline{\nu}_e$ Signal in Double Chooz



- Look for e^+ followed by neutrons captured by Gd.
  - $E_{\text{n-Gd}} \simeq 8$ MeV, $\tau_{\text{n-Gd}} \simeq 30\mu s$.
- Natural γ background from U, Th, and K tops out at $\sim$3 MeV (^{208}Tl).
  - Singles rate: 13 Hz.
- Cuts on: E_{prompt}, E_{delayed}, Δt, ΔR, various muon vetoes, light topology
- Backgrounds $\sim$ exclusively from cosmics.

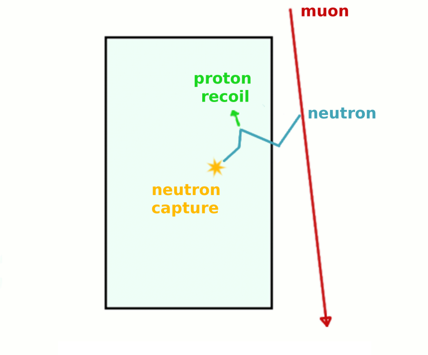
Backgrounds

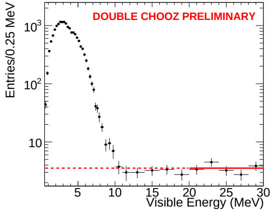




- **Uncorrelated Background**
  - *Accidentals*: precisely measured using off-time windows.

Backgrounds





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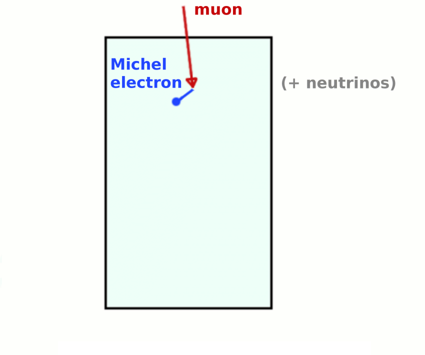

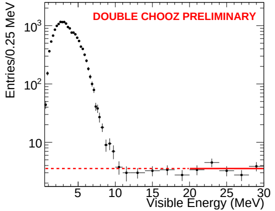

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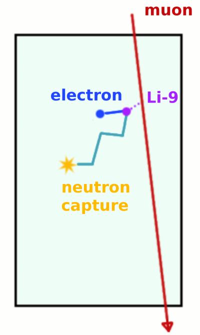

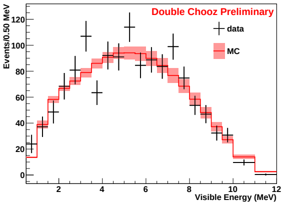

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  - *Stopping muons*: also ∼flat and measured by tagging low E IV events.
  - $^{9}Li/^{8}He$: resembles IBD, larger spectral unc. than other backgrounds; rate and shape measured from time corr. with showering muons.

Double Chooz θ_{13} Fit

Normalization Uncertainties

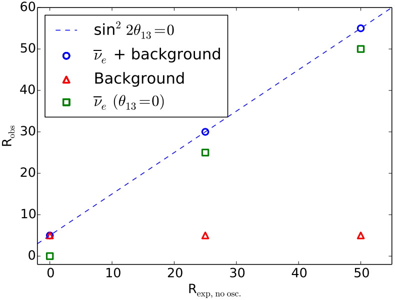
Source	Uncertainty (%)	Improvement
Reactor flux	1.7	None
Backgrounds	0.8	-50%
Detection eff.	0.6	-40%
Statistics	0.8	-30%
Total	2.1	-20%

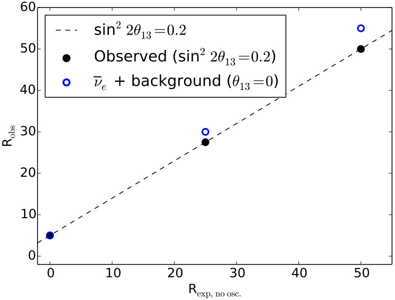
This shows the uncertainty relative to the signal prediction. Improvement column shows improvement from previous DC publication.

Reactor Rate Modulation Fit

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

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





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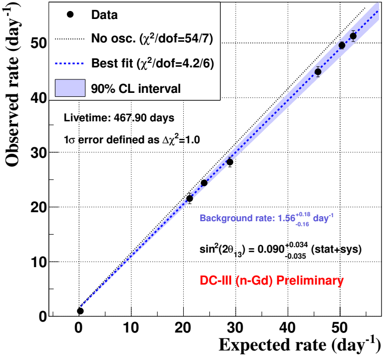
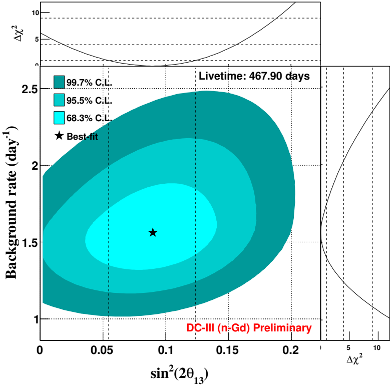


Valuable features:

- Uses DC's relative simple reactor setup
- Use of background model optional
- Leverage from reactor-off data

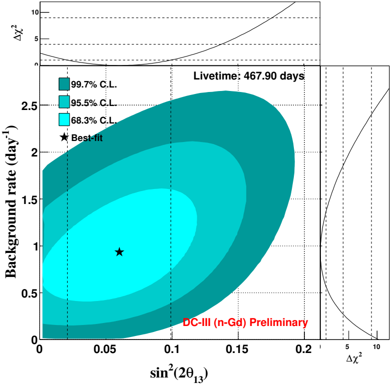
Reactor Rate Modulation Results

RRM with background constraint



- $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$ (stat+sys)
- $B = 1.56^{+0.18}_{-0.16}$ day^{-1}

RRM without background constraint



- $\sin^2 2\theta_{13} = 0.060 \pm 0.039$ (stat+sys)
- $B = 0.93^{+0.43}_{-0.36}$ day^{-1}

Rate+Shape Fit

Double Chooz fit strategy:

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

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

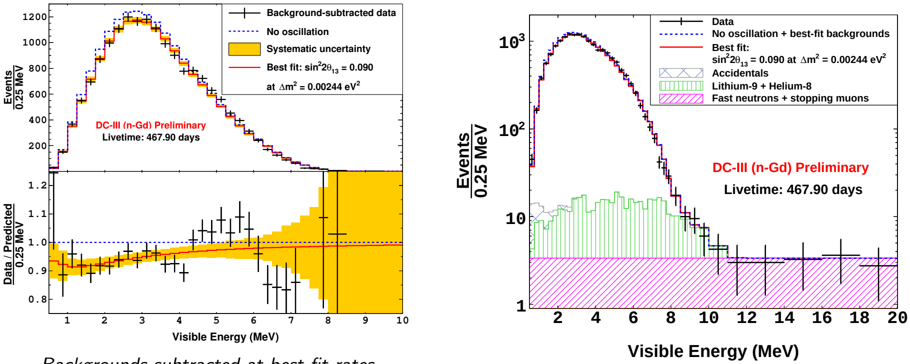
B = number of energy bins = 40

M = covariance matrix, including spectrum shape uncertainties

N^{pred} adjusted for value of θ_{13} and nuisance parameters:

^{9}Li rate, FN + SM rate, energy scale, Δm^2, off-off period

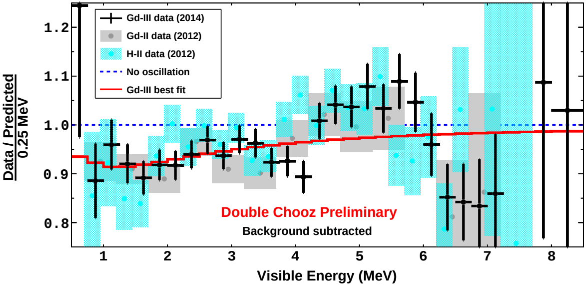
Rate+Shape Results



Backgrounds subtracted at best fit rates.

$$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029} \text{ (stat+sys)} \qquad \chi^2_{\text{min}}/\text{d.o.f.} = 52.2/40$$

Spectrum Distortion

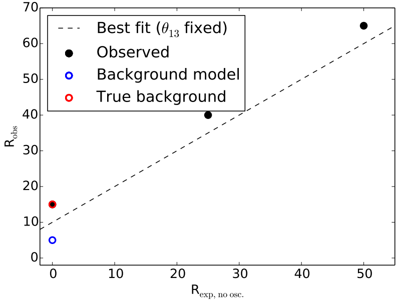


- A distortion between 4 and 8 MeV is visible
- Cross-checks have confirmed:
  - θ_{13} measurement unaffected
  - Unknown Gaussian background disfavored
  - Energy scale near 5 MeV not likely cause (n-^{12}C peak)
- RRM fit on different E_{pr} ranges differentiate reactor from background effects

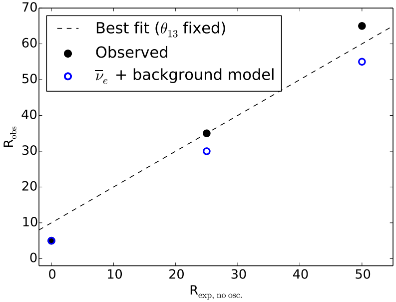
Spectrum Distortion

$\sin^2 2\theta_{13}$ fixed, background fixed to model.

Underestimated background



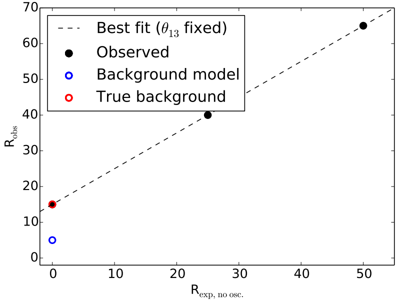
Underestimated flux



Spectrum Distortion

$\sin^2 2\theta_{13}$ fixed, background model floating.

Underestimated background



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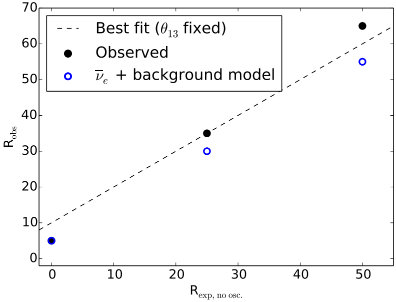
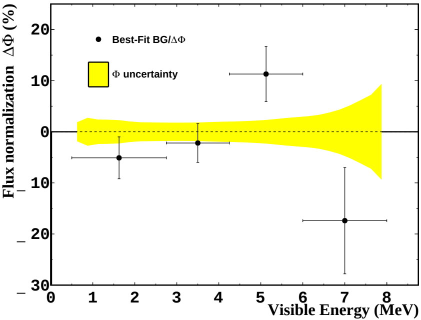


Spectrum Distortion

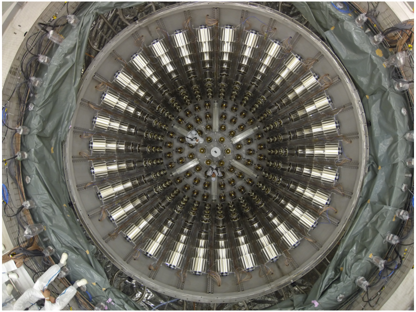
Fixed $\sin^2 2\theta_{13} = 0.090^{+0.009}_{-0.008}$ *(Daya Bay).*



- RRM fits in wide energy bins with θ_{13} fixed, flux floating or background floating
- Much more tension when flux constrained
- Excess significant at 3σ level; deficit 1.6σ
- Seen in Daya Bay and RENO too
- New flux calculation points to reactor as cause (arXiv:1407.1281)

Conclusions

- Near detector being commissioned
- First reactor experiment to present distortion
- New θ_{13} results (arxiv:1406.7763):
  - Rate+shape: $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$
  - RRM: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$, $B = 1.56^{+0.18}_{-0.16}$ day^{-1}
  - RRM (no bkgd model): $\sin^2 2\theta_{13} = 0.060 \pm 0.039$, $B = 0.93^{+0.43}_{-0.36}$ day^{-1}
- Hydrogen-capture analysis underway
- Long-term 1σ error $\lesssim 10\%$



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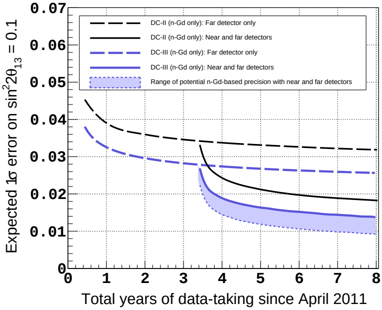
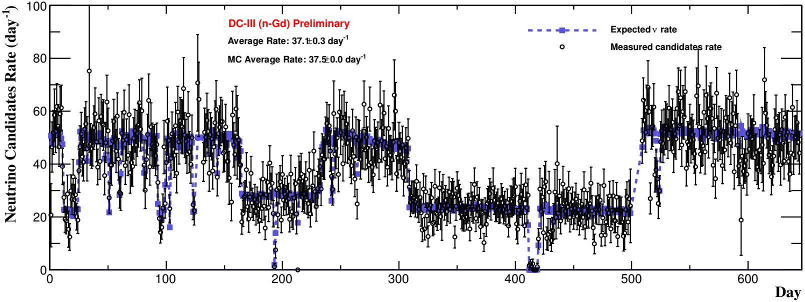
- Hydrogen-capture analysis underway
- Long-term 1σ error $\lesssim 10\%$



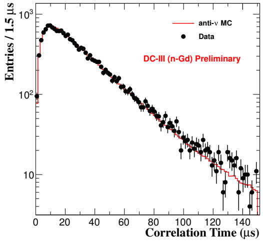
Backups

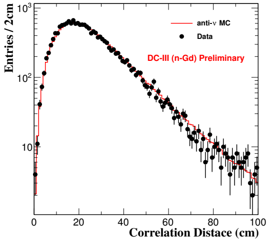
Data/MC Comparison

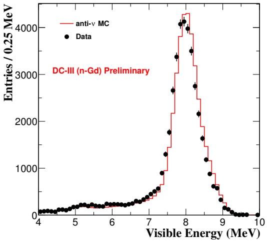
Total live-time: 467.9 days

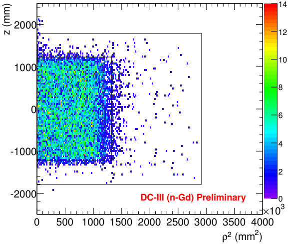


Data/MC Comparison









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

Reactor-off background measurements

Analyzed 7.5 days of data with both reactors off.

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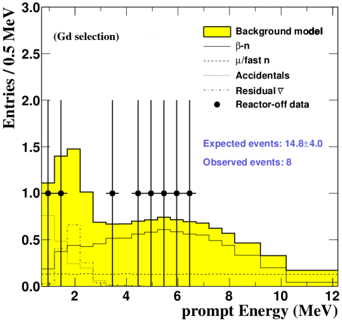
- Unique Double Chooz capability.
- Rate consistent with predictions:
  - Gd selection: 1.0 ± 0.4 day^{-1} with residual $\bar{\nu}_e$ subtracted.

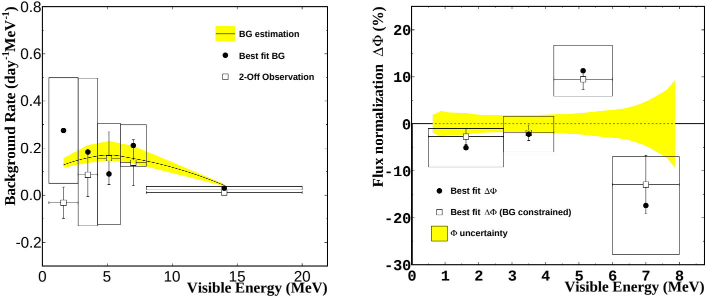
    (expected 2.0 ± 0.6 day^{-1})
  - H selection: 11.3 ± 3.4 day^{-1} with residual $\bar{\nu}_e$ and accidentals subtracted.

    (expected 5.8 ± 1.3 day^{-1})
- New constraint for oscillation fits.



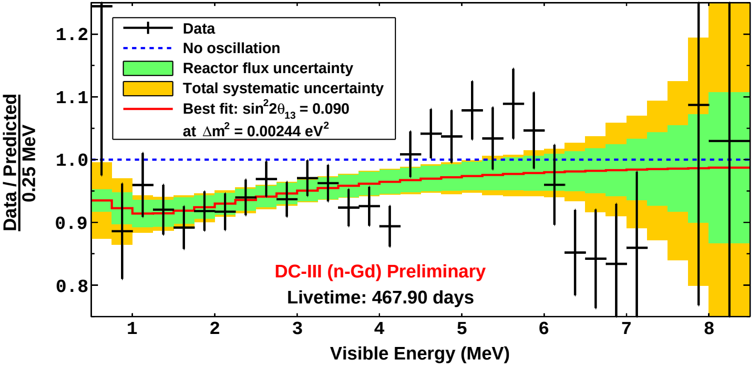
Spectrum Distortion

Fixed $\sin^2 2\theta_{13} = 0.090^{+0.009}_{-0.008}$ *(Daya Bay).*



- RRM fits in wide energy bins with θ_{13} fixed, flux floating (left) or background floating (right).
- Much more tension when flux constrained (right)
- Excess significant at 3σ level; deficit 1.6σ
- New flux calculation points to reactor as cause (arXiv:1407.1281).

Systematic Errors Relative to Distortion



Outer Veto Tracking

- In events with upper and lower OV hits, average muon track resolution improves by factor of 3 ($\sim$ 5 cm resolution)
- OV tracking used as input to ^{9}Li studies
  - We now remove $\sim$ 50% of ^{9}Li shown in these analyses
  - ^{9}Li prompt spectrum now measured directly from data

Visualization of support feet for buffer in IV region: