Status of Double Chooz experiment

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Measurement of $\theta_{13}$ with Double Chooz

- non vanishing last mixing angle $\theta_{13}$ (Nov. 2011) → input for next generation experiments: mass hierarchy, CP violation, etc.
- direct measurement of $\theta_{13}$ through disappearance $\bar{\nu}_e$ from nuclear reactors:
  \[
P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) + O(10^{-3})
\]
- 2 identical detectors for high precision (detection+flux systematics reduction)
Double Chooz detectors layout

**INVERSE BETA DECAY on proton (threshold > 1.8 MeV)**

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

**prompt signal:** scintillation + e\(^+\) annihilation  
E\(_{\text{prompt}} \approx E(\nu_e) - 0.8 \text{ MeV} \]

**delayed signal:** γ ray(s) from neutron capture  
n-Gd  
E\(_{\text{delayed}} \approx 8.0 \text{ MeV} \)  \( \Delta T \approx 30 \mu s \)
or n-H  
E\(_{\text{delayed}} \approx 2.2 \text{ MeV} \)  \( \Delta T \approx 200 \mu s \)

**Neutrino target:** liquid scintillator PXE + Gd

**Gamma catcher:** liquid scintillator PXE (no Gd)

**Buffer volume:** transparent mineral oil  
with 390 x 10'' PMTs assembly

**Inner Veto:** liquid scintillator (LAB)  
with 78 x PMTs 8''

**Outer Veto:** plastic scintillator strips
Background

COSMOGENETIC
long lifetime $\beta$-n emitter
(mainly $^9$Li)

CORRELATED
fast neutrons from $\mu$ spallation,
stopping-$\mu$ (acceptance hole)

ACCIDENTALS
natural radioactivity: $^{40}$K, $^{208}$Tl
$\rightarrow$ dominant in H-analysis

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Visible Energy (MeV)

BACKGROUND SPECTRUM
(ARBITRARY UNIT)

neutrino signal
cosmogenetic
correlated
accidentals

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Visible Energy (MeV)
new analysis with opened selection (more signal) + new vetos (less background)

- excellent spectral distortion in $0.5 - 4$ MeV region constraining $\theta_{13}$ fit

$$\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$$

- previous Gd results: $0.109 \pm 0.039$

- unexpected E/L structure $> 4$ MeV (only published experimental observation)

Alternative channel to Gd (main) with independant data sample

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt Energy</td>
<td>0.7 – 12.2 MeV</td>
<td>1.0 – 20 MeV</td>
</tr>
<tr>
<td>Delayed Energy</td>
<td>1.5 – 3.0 MeV</td>
<td>1.3 – 3 MeV</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>10 – 600 $\mu$s</td>
<td>0.5 – 800 $\mu$s</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>&lt; 0.9 m</td>
<td>&lt; 1.2 m</td>
</tr>
<tr>
<td>isolation window</td>
<td>[-600, +1000] $\mu$s</td>
<td>[-800, +900] $\mu$s</td>
</tr>
</tbody>
</table>

- muon veto: $\Delta t_{\text{last}} - \mu > 1.25$ ms
- OV veto: no OV hit coincident with prompt
- $^9\text{Li}$ veto: likelihood method trained with $^{12}\text{B}$
- “FV” veto: reject stopping muons
- IV veto: reject fast-neutrons and accidentals
- ANN: reject accidentals *NEW*
- MPS veto: reject fast-neutrons *NEW*

H-III analysis benefits previous improvement from last Gd analysis (2014)
Neural Network for accidental background rejection (ANN)

- **multiple variable analysis** instead of cut-based approach
- input: delayed energy, time and space correlation
- maximise signal/background for unprecedented accidental reduction
Neural Network for accidental background rejection (ANN)

- **multiple variable analysis** instead of cut-based approach
- input: delayed energy, time and space correlation
- maximise signal/background for unprecedented accidental reduction

\[ \text{H-II:} \quad 73.45 \pm 0.16 \ \text{events/day} \]
\[ \text{H-III:} \quad 4.334 \pm 0.011 \ \text{events/day} \quad (17x \ less) \]
Multiplicity Pulse Shape veto (MPS)

- $\mu$ producing multiple fast-neutrons in rocks
- proton recoil mimics prompt signal
- additional pulses (low energy p-recoil) recorded within 256 ns $\rightarrow$ exploit power of FADC

IBD event

fast neutron event

MPS veto rejects $\sim 25\%$ of fast-neutron background
H-III neutrino candidates, background and systematics

- Expected $\nu$ rate
- Measured candidates rate

### DC-III (n-H) Preliminary
- Average Rate: $68.9 \pm 0.4$ day$^{-1}$
- MC Average Rate: $64.9 \pm 0.0$ day$^{-1}$

### Background

<table>
<thead>
<tr>
<th>Source</th>
<th>H-II (d$^{-1}$)</th>
<th>H-III (d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental</td>
<td>$73.45 \pm 0.16$</td>
<td>$4.33 \pm 0.01$</td>
</tr>
<tr>
<td>Cosmogenic $^9$Li/$^8$He</td>
<td>$2.8 \pm 1.2$</td>
<td>$0.95^{+0.57}_{-0.33}$</td>
</tr>
<tr>
<td>Fast-n + Stopping muons</td>
<td>$3.17 \pm 0.54$</td>
<td>$1.55 \pm 0.15$</td>
</tr>
<tr>
<td>Total</td>
<td>$79.4 \pm 1.3$</td>
<td>$6.83^{+0.59}_{-0.36}$</td>
</tr>
</tbody>
</table>

### Source Uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor flux</td>
<td>1.73%</td>
</tr>
<tr>
<td>Statistics</td>
<td>0.60%</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>1.00%</td>
</tr>
<tr>
<td>Accidental BG</td>
<td>0.02%</td>
</tr>
<tr>
<td>$^9$Li + $^8$He BG</td>
<td>$+0.86% / -0.50%$</td>
</tr>
<tr>
<td>Fast-n and stop-$\mu$ BG</td>
<td>0.23%</td>
</tr>
<tr>
<td>Total</td>
<td>$+2.28% / -2.18%$</td>
</tr>
</tbody>
</table>
H-III $\theta_{13}$ MEASUREMENT
H-III rate + shape result

\[
\sin^2(2\theta_{13}) = 0.124^{+0.030}_{-0.039}
\]

Gd-III: 0.090^{+0.032}_{-0.029}

H-II: 0.097 \pm 0.048

deviation in 4–6 MeV similar with the Gd-III one reported

(result for cross-check only)
H-III Reactor Rate Modulation (RRM) result

- independent measurement of $\theta_{13}$ (slope)
- constraint with background model to increase precision

\[
\sin^2(2\theta_{13}) = 0.098^{+0.038}_{-0.039} \quad \text{background} = 7.29 \pm 0.49 \text{ /day}
\]

Livetime: 462.72 days

1σ error defined as $\Delta \chi^2 = 1.0$
H-III Reactor Rate Modulation (RRM) result

- independent measurement of $\theta_{13}$ (slope)
- constraint with background model to increase precision

$$\sin^2(2\theta_{13}) = 0.098 \pm 0.038$$

background = 7.29 ± 0.49 /day

- combination Gd-III + H-III: $\sin^2(2\theta_{13}) = 0.090 \pm 0.033$
- Gd-III only: $\sin^2(2\theta_{13}) = 0.090 \pm 0.034$
Conclusion and outlook

New analysis with n-H channel (far detector only)

- validation and cross-check of Gd-III measurement (2014)
- RRM analysis: $\sin^2(2\theta_{13}) = 0.098 \pm 0.038$
- combined fit Gd+H RRM: $\sin^2(2\theta_{13}) = 0.090 \pm 0.033$
- verification of E/L distortion with independent data set and detection volume

Instrumentation

- novel powerful techniques for low background IBD selection
- accidentals reduced by $> 10\times$ with negligible impact on syst. and stat. errors
  - Double Chooz demonstrates capability of precision measurement of reactor neutrinos with Hydrogen and narrow overburden (Gd still better)
Conclusion and outlook

- Near detector operating since January 2015
- working on two detector analysis to challenge 10 % $1\sigma$-error within $\sim 3$ years
- more prospects with ND data: one reactor spectrum, cosmogenic isotope, etc.
BACKUP SLIDES
4–6 MeV distortion

- Consistent feature in Gd and H channels (different volume and background)
- Excess in 4–6 MeV region correlated with reactor power
- Ongoing research and discussion in the community
Energy reconstruction

\[ E_{vis} = N_{pe} \times f_u(\rho, z) \times f_{PE/MeV} \times f_{data}^{data}(E_{vis}, t) \times f_{n\ell}^{MC} \]

- \( N_{pe} \): Charge to PE
- \( f_u(\rho, z) \): non-uniformity correction
- \( f_{n\ell}^{MC} \): non linearity correction
Energy reconstruction

\[ E_{\text{vis}} = N_{pe} \times f_u(\rho, z) \times f_{PE/\text{MeV}} \times f_s^{\text{data}}(E_{\text{vis}}, t) \times f_{n\ell}^{\text{MC}} \]

- \( f_{PE/\text{MeV}} \): absolute PE to MeV scale using \(^{252}\text{Cf} \) @ center
- \( f_s^{\text{data}}(E_{\text{vis}}, t) \): time stability correction

![Graphs showing energy reconstruction results](chart.png)
Correlated background

Double Chooz Preliminary DC-III (n-H)

- Data driven measurement
- Exponential shape in H channel (flat for Gd)
- Includes a negligible proportion of stopping muons
H-III OFF-OFF data

- Expected rate: $7.05^{+0.6}_{-0.4}$ events/day (residual neutrino $= 0.33 \pm 0.10$)
- Measured rate: $8.8 \pm 1.1$ events/day
  - Demonstration of the rejection of power of our selection
  - Validation of our background model

<table>
<thead>
<tr>
<th></th>
<th>all events</th>
<th>$\geq 12$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>before vetos</td>
<td>10185</td>
<td>23</td>
</tr>
<tr>
<td>after vetos</td>
<td>63</td>
<td>1</td>
</tr>
<tr>
<td>rejection</td>
<td>160x</td>
<td>23x</td>
</tr>
</tbody>
</table>
Reactor flux prediction

**Thermal power,** $P_{th}$, from reactor operation data

**Simulated fission fractions,** $\alpha_k$, and mean energy, $\langle E_f \rangle$

**Semi-empirical mean cross section per fission,** $\langle \sigma_f \rangle$

(following Huber/Mention et al., 2011)

\[
N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2 \langle E_f \rangle_R} \left( \frac{\langle \sigma_f \rangle_R}{\sum_k \alpha_k^R \langle \sigma_f \rangle_k} \sum_k \alpha_k^R (\sigma_f)_{k,i} \right)
\]

**Bugey4 “anchor”:**

\[
\langle \sigma_f \rangle_R = \langle \sigma_f \rangle_{\text{Bugey}} + \sum_k (\alpha_k - \alpha_k^{\text{Bugey}}) (\sigma_f)_{k}
\]

$i =$ energy bin index, $R =$ {Reactor 1, Reactor 2}, $k =$ \{\(^{235}\text{U}, \ ^{236}\text{U}, \ ^{239}\text{Pu}, \ ^{241}\text{Pu}\}\}

$\epsilon =$ detection efficiency, $N_p =$ number of protons in fiducial volume, $L_R =$ distance between $R^{th}$ reactor and detector
Early uncalibrated ND data demonstrating:

- feasibility of IBD measurement and quality/similarities of the two detectors
- illustration of energy reconstruction (from ND to FD)
- preliminary study of singles in ND indicates a similar rate as in FD
  → goals in term of radiopurity and shielding are achieved