Double Chooz Measurement of $\theta_{13}$ and Beyond

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Neutrino Oscillations and $\theta_{13}$

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{-i\delta} & 0 & c_{12}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

$\theta_{23} \sim 45^\circ$ \hspace{1cm} $\theta_{13}$ & "dirac" $\delta_{CP}$ \hspace{1cm} $\theta_{12} \sim 33^\circ$

PMNS

\[\begin{array}{ccc}
\nu_1 & \nu_2 & \nu_3 \\
\nu_e & \nu_\mu & \nu_\tau
\end{array}\]

Driven by $\theta_{13}$

CKM

\[\begin{array}{ccc}
d & s & b \\
u & c & t
\end{array}\]
3 ν Oscillation Status (Marrone et al)

Oscillation parameters: $\theta_{13}$, $\theta_{12}$, $\theta_{23}$, $\Delta m^2$, $\delta m^2$, $\delta_{\text{CP}}$

→ Remarkable precision, even a hint for $\delta_{\text{CP}}$
3ν Oscillation Status (Marrone et al)

Knowledge on 3ν oscillation model depends on $\theta_{\text{13}}$

$\theta_{\text{13}}$ vs $\delta_{\text{CP}}$
$\rightarrow$ Maximal CP?

$\theta_{\text{13}}$ vs “octant”
$\rightarrow$ do we know anything?

$\theta_{\text{13}}$ measurement (value & error) w/ critical implication
ex. Predict CPV correct?
Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

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

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

Japan
Tohoku U.
Tokyo Inst. Tech.
IPPC RAS
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

Russia
INR RAS
RRC
Kurchatov

Spain
CIEMAT-Madrid

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/
Precision measurement of $\theta_{13}$

- Direct measurement of $\theta_{13}$ from energy dependent deficit
  - No parameter degeneracy/matter effects
- Suppression of systematic uncertainties ($<< 1\%$) with multi-detectors at different baselines

**Survival probability of reactor neutrinos**

$$P[\bar{\nu}_e \rightarrow \bar{\nu}_e] \equiv 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \quad \ldots$$

Simple two flavor oscillation formula is valid at $L \sim 1\text{km}$

- Reactor $\theta_{13}$ (most precise) used as reference in current and future projects which aim to search for CP violation and mass hierarchy in neutrino sector.
Double Chooz Detectors

- **Outer Veto (OV)**
  - Plastic scintillator strips

- **Inner Detector (ID)**
  - **ν-target (NT)**
    - Gd loaded liquid scintillator (10m³)
  - **γ-catcher (GC)**
    - Liquid scintillator (22m³)

- **Buffer**
  - Mineral oil (110m³)
  - 390 10-inch PMT

- **Inner Veto (IV)**
  - Liquid scintillator (90m³)
  - 78 8-inch PMT
Single detector analysis

Bugey4 (virtual) provides reactor flux normalization

Reactor B1

FD-I
461 days
Detection Mode

- Inverse Beta Decay (IBD):
  - $\bar{\nu}_e + p \rightarrow n + e^+$
- Prompt signal: $E_{e^+} +$ annihilation $\gamma$'s
  (1 $\sim$ 9 MeV, $E_{\text{vis}} \approx E_{\bar{\nu}_e} - 0.8\,\text{MeV}$)
- Delayed signal: $\gamma$'s from neutron capture on Gd
- Delayed coincidence

Gd channel

Time scale:
- 8 MeV
- $\sim 30\mu$s
IBD coincidence condition

Delayed signal energy
\[ 4 < E_{\text{vis}} < 10\text{MeV} \]
Correlation time
\[ 0.5 < \Delta T < 150\mu\text{sec} \]
Correlation distance
\[ \Delta R < 100\text{cm} \]

\( \Rightarrow \) Remaining BG

Cosmogenic \( \beta \)-n emitter:
\[ ^9\text{Li} \rightarrow \alpha + \alpha + e^- + \nu + n \]

Fast neutron:
\[ n + p \rightarrow p + n \]

Stop-\( \mu \):
\[ \mu \rightarrow e^- + \nu + \nu \]

Accidental coincidence:
\[ \text{e.g. } \gamma + \text{spallation} n \]

FD-I
Background and other uncertainties constrained by shape information

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

Unexpected spectrum distortion observed at 4-6MeV

- Negligible impact to $\theta_{13}$ measurement
- Magnitude of excess proportional to reactor power
- Same distortion later confirmed by RENO, Daya Bay and n-H capture in DC
Detector and background uncertainties are suppressed to per-mille level by analysis improvements

- Reactor flux uncertainty (1.7%) dominant in last FD-only analysis

⇒ Reactor flux and detection systematics to be suppressed with two detectors
Mult-detectors analysis

- FD-I (single detector) 461 days
- FD-II (multi-detectors) 212 days
- Reactor B1
- Bugey4 (virtual)
- ND (multi-detectors)

DC: most iso-flux setup ⇒ reactor flux error highly suppressed with multi-detectors
The Largest Single $\theta_{13}$ Target

IBD (Gd)

Target: $\sim 8t$ (smallest $\theta_{13}$ target)
The Largest Single $\theta_{13}$ Target

IBD (Gd)

Target: $\sim 8t$ (smallest $\theta_{13}$ target)

IBD (Gd+H)

Target: $\sim 30t$ (largest $\theta_{13}$ single detector target)
Detection Mode

- Inverse Beta Decay (IBD):
  - $\nu_e + p \rightarrow n + e^+$
- Prompt signal: $E_{e^+} + \text{annihilation } \gamma's$
  - $(1 \sim 9 \text{ MeV}, E_{vis} \approx E_{\nu_e} - 0.8 \text{ MeV})$
- Delayed signal: $\gamma's$ from neutron capture on Gd or H
- Delayed coincidence

\[ \begin{align*}
\text{Gd channel} & : 8 \text{ MeV} \\
\text{H channel} & : 2.2 \text{ MeV} \\
\text{time} & \sim 30 \mu s \\
\text{time} & \sim 200 \mu s
\end{align*} \]
ANN Accidental BG Rejection

IBD (signal) (correlated)

Accidental BG (Random) (i.e. longer $\Delta t$, $\Delta R$)
IBD(Gd+H) definition: Multi-variable cut

- $\Delta R$ (prompt:delay)
- $\Delta t$ (prompt:delay)
- $\Delta R$ (prompt:delay)
- $E_{\text{vis}}$ (delay)
- ANN
Energy Spectrum IBD(Gd+H) Selection

AccBG: ~4day\(^{-1}\) (FD/ND)

IBD(Gd+H+C): \leq 140day\(^{-1}\) (FD)
\leq 1000day\(^{-1}\) (ND)

\sim 2.5 \times IBD(Gd)

IBD(Gd+H) integrates over all captures
IBD (Gd+H) and IBD (Gd) vs Time

\[
\text{IBD(Gd)} \lesssim 50 \text{day}^{-1} @ \text{FD} \\
\sigma_{\text{stat}} = 0.56\% \text{now}
\]

\[
\text{IBD(Gd+H)} \lesssim 140 \text{day}^{-1} @ \text{FD} \\
\sigma_{\text{stat}} = 0.35\% \text{now}
\]

\[\Rightarrow \sim 0.2\%_{\text{stat \; final}}\]
BG rejection: $\Delta t(e^+ : n)$ view

$\Delta t$(prompt:delay) vetoes rejection impact (demonstration $>10^3$ range)

ND $\approx$ FD(both) (after vetoes)


JHEP 1410 (2014) 086

Systematic error evolution

proton# (full volume) is largest uncertainty
(beyond DC-IV) dedicated campaign proton#
(analysis@hardware→ even decommissioning)
\( \theta_{13} \) fits (R+S & RRM) fold all information simultaneous

- MD(FD-II:ND) \( \oplus \) SD(FD-I:FD-II:ND) [SD uses MC\( \rightarrow \) minimal impact]
  \( \Rightarrow \) MC-e+ non-linearity model [NT vs NT\( \oplus \)GC volume]
- each BG (\(^9\)Li measurement \( \gtrsim 7\)MeV) \( \oplus \) reactor-OFF constraint
  - full flux error w/ and w/o Bugey4 constraint
  - all correlations energy\( \oplus \)reactors\( \oplus \)detectors\( \oplus \)backgrounds

(R+S Fit) All Detector Spectra
$\theta_{13}$ R+S Fit Result

$\sin^2(2\theta_{13})^{R+S} = (0.119 \pm 0.016)$ with $\chi^2 / \text{ndf}: 236.2 / 114$

(marginalised over $\Delta m^2 = (2.44 \pm 0.09)\text{eV}^2$

Parke et al. arXiv:1601.07464)
$\theta_{13}$ Fit Validation

Data | MC

Data | Data

$\sin^2(2\theta_{13}) = (0.119 \pm 0.016)$

(spectral distortions cancel across ND:FD)

$\sin^2(2\theta_{13}) = (0.123 \pm 0.023)$
Comparison with others

Double Chooz
JHEP 1410, 086 (2014)

Preliminary
(CERN seminar 2016)
\[\sin^2(2\theta_{13}) = (0.119 \pm 0.016)\]

Daya Bay
PRL 115, 111802 (2015)

RENO
PRL 116 211801(2016)

T2K
PRD 91, 072010 (2015)
\[\Delta m^2_{32} > 0\]
\[\Delta m^2_{32} < 0\]

NOvA
Preliminary (private communication)
\[\Delta m^2_{32} > 0\]
\[\Delta m^2_{32} < 0\]

\[\Delta(DYB:DC) \sim 2.2\sigma's\]

DC-IV-PRELIMINARY

Example: NOvA

DC & beams might prefer a higher \(\theta_{13}\)?

(beam “handicapped” by unknowns(\(\delta_{CP}\)) / uncertainties)

reactor- \(\theta_{13}\) key to solve CP-violation & mass hierarchy\(\rightarrow\) redundancy fundamental

(reactor- \(\theta_{13}\) experiments work together to resolve)
Prospects to the Future

DC largely dominated by proton#→ improvement possibility?

collaboration is committed improve to resolve (internally & together with DYB+RENO)
Beyond $\theta_{13}$

Reactor spectral characterization
High Precision Reactor-IBD Rate (world ref. Bugey4)

\[ \langle \sigma_f \rangle = \frac{n_\nu}{N_p \times \epsilon} \times \frac{1}{\sum_{p=1}^{2} \langle P_{th} \rangle_p \times 4\pi R_p^2} \]

\( n_\nu \): IBD rate \textit{without} oscillation [\( \bar{\nu}_e, \text{s}^{-1} \)]

\( p \): iterator over the reactor B1 & B2

DC expected to supersede Bugey4 (world reference today)

precision limit \( \langle \sigma_f \rangle^{DC} \): total error \( \approx \) reactor error (irreducible)

(Reactor Thermal Power \( \sim 0.47\% \) @ Chooz)
(2014) Reactor- $\theta_{13}$ found spectral distortions

1σ of $\delta(\text{flux}) \rightarrow \pm 3\%$ (DYB & RENO) & $\pm 1.7\%$ (DC⊕Bugey4)

3 different experiments in agreement (not trivial→ not identical fuels)

**MAIN ISSUE**
features $>1\sigma(\text{flux})$ ILL-based prediction uncertainties ⇒ error is (likely) underestimated (hard to believe otherwise)

**QUESTION**
why Bugey3 data did not see it? (best world shape reference) [DC⊕B3 working to reconcile]

⇒**LIMITATION?**
our ability to address $\nu(\text{sterile})$ hypothesis with reactor-data (single detector)

DC first paper on the subject @JHEP 1410 (2014) 086

claimed uncertainty $\sim 3\%$ positron energy (MeV)
Consistency between Double Chooz and Daya Bay results!
→ not trivial: $\theta_{13}$ correction, background, energy, ...

- Due to the normalization used, RENO points are close to 1 up to 4 MeV
- But good agreement with RENO when area are normalized to 1 for $E < 4.5$ MeV
- Some discrepancy remains with RENO around 5 MeV:
  → DC and DB reactors are similar (Areva), not Reno reactors
  → Reactor fuels? Other?
Distortion analysis with ND rate+shape

test the existence of features not biased by shape-only assumption (i.e. smaller errors)

shape-only≈Bugey4 (consistency of Bugey4?)

non-statical features
• which is deficit?
• which excess?
• which is OK?
⇒ less evident!!

careful analysis before stating the “trouble region” is bump problem really? (maybe no bump whatsoever)

(bias question⇒bias answer)
DC-IV Preliminary

DC first results with new IBD(Gd+H+C) selection [big challenge]
  · largest-single-\(\theta_{13}\) -target now [statistics comparable to \sim 2x DYB-FD’s & 2x larger than RENO]
  · DC will NOT be limited by statistics: systematics challenge
  · conservative systematic scenario adopted \rightarrow expected to improve (ongoing work)

DC-IV PRELIMINARY results
  · new \(\sin^2(2\theta_{13}) = (0.119\pm0.016)\) [many cross-checks: all consistent all across to our best ability]
    · non-statistical discrepancy @ \sim 2.2\sigma \rightarrow must address internally & reactor-\(\theta_{13}\) forum
  · new reactor spectrum characterization (rate@shape) major improvement
    · most precise reactor normalization & rate@shape analyses: intriguing spectral distortions
    · DC-ND superseding world best reactor references Bugey4 & Bugey3
  · DC questions ILL-based prediction error budget: limitation to reactor single-detectors to yield (some) fundamental particle physics issue: neutrino(sterile) hypothesis?

DC world best IBD-directionality measurements \rightarrow still improving!
Thank you!
Backup
Double Chooz Read-out

Liquid Scintillator ⊕
10” PMTs ⊕
analogue electronics (clean & μ-handling) ⊕
500MHz FADC readout

Rich off-line reconstruction: energy & BG reduction
  • time, charge [multiple methods] → control of linearity
  • position (x,y,z,t) [multiple methods] → uniformity & BG vetoes
  • PSD & PID [time and frequency domain] → BG vetoes
  • multiplicity & inter-detector-layer correlation → BG vetoes
Prompt energy of $^{252}$Cf data

- $^{252}$Cf emits $\sim 10 \gamma$ with 1MeV in average.
- Comparison of FD and ND data with $^{252}$Cf at the center of detector.
Scintillator accumulates on Buffer top

most $\mu$-decay @ rest ($\text{Michel-}e^{\pm}$)
rate(ND/FD)$\sim 100x$

stopped-$\mu$ (all) contamination  → negligible!!
(ND$\approx$FD after rejection)
## Background Vetoes

### Table: Vetoes and Information Used

<table>
<thead>
<tr>
<th>Cut</th>
<th>Information used</th>
<th>Target of cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ veto</td>
<td>1ms veto after μ</td>
<td>μ, cosmogenic</td>
</tr>
<tr>
<td>Multiplicity</td>
<td>unity condition</td>
<td>multiple-n</td>
</tr>
<tr>
<td>FV veto</td>
<td>vertex likelihood</td>
<td>chimney stop-μ</td>
</tr>
<tr>
<td>IV veto</td>
<td>IV activity</td>
<td>fast n, stop-μ, γ scattering</td>
</tr>
<tr>
<td>OV veto</td>
<td>OV activity</td>
<td>fast n, stop-μ</td>
</tr>
<tr>
<td>Li veto</td>
<td>Li-likelihood</td>
<td>cosmogenic</td>
</tr>
<tr>
<td>LN cut</td>
<td>PMT hit pattern &amp; time</td>
<td>light emission from PMT</td>
</tr>
</tbody>
</table>

### Diagram:

- **FV veto**: fast neutron, stop-μ
- **OV veto**: fast neutron, stop-μ, γ scattering
- **Li veto**: cosmogenic $^9$Li
- **IV veto**: fast neutron, stop-μ, γ scattering

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**Legend:**
- $^9$Li: Cosmogenic $^9$Li
- n: Neutron
- γ: Gamma ray
- μ: Muon
Precious reactor-off data

Rejection Power estimation (total and per-veto)

IBD(Gd+H): 158x (6:1000 selection) & efficiency≈(95.00±0.03)
[IBD(Gd): 11x (9:100 selected)]

IBD(Gd+H) allows BG strategy validation of IBD(Gd) by an one extra order of magnitude

BG-model inclusiveness validation [next]
**Remaining BG Measurement**

**BG model:** $\text{BG}(\Sigma) = \text{BG(accidental)} + \text{BG(fast-neutron)} + \text{BG($^{9}\text{Li}$)}$

**BG(acc):** via OFF-time coincidence $[\sigma(\text{BG})/S \rightarrow \sim 0\%]$  
**BG(fast-n):** via $\mu$-detector tagging (IV checked by OV) up to 100MeV $[\sigma(\text{BG})/S: \sim \text{small}]$  
**BG($^{9}\text{Li}$):** via $\mu$-spallation correlated production ($\leq 50\%$ vetoed) $[\sigma(\text{BG})/S: \sim \text{dominant}]$

$\sigma(\text{BG})/\text{Signal} \approx 0.2\% (\text{FD})$

$\text{BG}(\Sigma)^{\text{exclusive}} \approx \text{BG(reactor-OFF)}^{\text{inclusive}} \Rightarrow \text{BG-model is complete}$

(implies $\text{BG(stopped-}\mu), \text{BG}(^{12}\text{B}), \text{BG(BiPo), BG(multi-captures): all negligible!!}$)
Reactor spectral distortions (shape only)

**shape-only analysis (i.e. norm integral = 1)**

- non-statical features
  - lowest bin: high?
  - deficit [2,4]MeV
  - excess [4,6]MeV
  - (non-trivial)

ND ≈ FD: same features (possible combination)

Note: significance and interpretation depends highly on the normalization strategy
⇒ shape-only likely incomplete (no physical motivation)
Features scaling with reactor

features scaling fractionally constant with reactor\# (i.e. reactor power)
- deficit $[2,4]$ MeV
- excess $[4,5]$ MeV