Latest Results from Double Chooz

EPS-HEP

Philipp Soldin
for the Double Chooz collaboration

Physics Institute III B
RWTH Aachen University
July 11th 2019
Double Chooz

$\theta_{13}$ Measurement

Fit Results

Spectral Distortion Discussion
Double Chooz

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Double Chooz

- Two nuclear cores with a thermal output of 4.27 GW
- Near detector with a distance of $\sim 400$ m
- Far detector with a distance of $\sim 1$ km
- Data taking since April 2011
- The near detector was installed afterwards in 2015
- Double Chooz is no longer taking data and will be dismantled
Neutrinos are measured by the signature of the inverse beta decay (IBD)

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

The signature consists of a prompt annihilation signal and a delayed neutron capture event.

The neutron is captured by either Gd (8 MeV, \( \nu \)-Target) or H (2.2 MeV, \( \gamma \)-Catcher)
Double Chooz Detector

Onion like structure

- upper OV
- glove box (GB)
- outer veto (OV)
- inner veto (IV)
- buffer (B)
- stainless steel vessel holding 392 PMTs
- gamma catcher (GC)
- acrylic vessels
- v-target (NT)
- steel shielding
Double Chooz Detector

- Onion like structure
- **Neutrino Target (NT)**
  - $1 \text{ g l}^{-1}$ Gd doped LS ($10 \text{ m}^3$)
Double Chooz Detector

- Onion like structure
- **Neutrino Target (NT)**
  - $1 \text{ g} \cdot \text{l}^{-1}$ Gd doped LS ($10 \text{ m}^3$)
- **Gamma Catcher**
  - Undoped LS ($22 \text{ m}^3$)
  - Measures $\gamma$'s, that leave the NT
Double Chooz Detector

- Onion like structure
- **Neutrino Target (NT)**
  - 1 g l⁻¹ Gd doped LS (10 m³)
- **Gamma Catcher**
  - Undoped LS (22 m³)
  - Measures γ’s, that leave the NT
- **Buffer**
  - Non scintillating mineral oil (110 m³)
  - 390 10” PMTs
Double Chooz Detector

- Onion like structure
- **Neutrino Target (NT)**
  - 1 g l$^{-1}$ Gd doped LS (10 m$^3$)
- **Gamma Catcher**
  - Undoped LS (22 m$^3$)
  - Measures $\gamma$’s, that leave the NT
- **Buffer**
  - Non scintillating mineral oil (110 m$^3$)
  - 390 10” PMTs
- **Veto**
  - Plastic scintillator for atm. $\mu$ veto
  - PMTs in liquid scintillator outside the buffer
Total neutron Capture (TnC)

- Increase detection efficiency
- Increase of active detector volume (\(\sim 30 \text{ t}\))
- TnC (Total neutron Capture) improves statistics by factor 2.5
- Immune to liquid exchange between ND neutrino target and \(\gamma\) catcher
**Measured Data**

**Double Chooz IV: Near (258 live-days)**

- ND Data
- No-oscillated MC
- Accidental
- $^9$Li
- Fast Neutrons

**Double Chooz IV: Far (818 live-days)**

- FD Data
- No-oscillated MC
- Accidental
- $^9$Li
- Fast Neutrons

**~ 210k IBD events**

**~ 90k IBD events**

<table>
<thead>
<tr>
<th></th>
<th>FD $\text{d}^{-1}$</th>
<th>ND $\text{d}^{-1}$</th>
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<td>IBD candidates</td>
<td>112</td>
<td>816</td>
</tr>
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<td>Cosmogenic BG ($^9$Li)</td>
<td>$2.62 \pm 0.27$</td>
<td>$14.52 \pm 1.48$</td>
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Well understood Background
Signal to Background ratio $> 10$
\[-2 \ln \left( L \left( \bar{n}_{\text{meas}} | \bar{a} \right) \right) = \sum_{d \in \{\text{FD1, FD2, ND}\}} \left[ \left( -2 \sum_{i=1}^{38} n_i^{\text{meas}} \cdot \ln \left( n_i^{\exp} (\bar{a}) - n_i^{\exp} (\bar{a}) \right) \right) + \sum_{i=1}^{38} n_{\text{offOff},i}^{\text{meas}} \cdot \ln \left( n_{\text{offOff},i}^{\exp} (\bar{a}) - n_{\text{offOff},i}^{\exp} (\bar{a}) \right) + \sum_{j} \begin{cases} g_{c}(j) & j \text{ vector of correlated par.} \\ g(j) & j \text{ single uncorrelated par.} \end{cases} \right] \]

- $\theta_{13}$ is acquired with a fit of the disappearance effect
- This is done with a $\chi^2$ and a poissonian likelihood (my work) approach
- A model is constructed for every parameter set and compared
- In LLH fit, one correlated parameter for every energy bin as norm. $\rightarrow$ independent of input spectrum
Fit Results

- Bugey 4 normalisation used for MC-Data fit
- Best fit result: \( \sin^2 (2\theta_{13}) = 0.105 \pm 0.014 \)
- Clear visible distortion in the energy region [4, 6] MeV
Fit Results

**Multi-Detector (MD)**
- DC-IV Rate+Shape (TnC)
  - Rate Only
  - Shape Only
- ND⊕FD-I (Rate+Shape)
- ND⊕FD-II (Rate+Shape)
- Free $\Delta m^2_{ee}$ (Rate+Shape)
- Data-to-Data (Rate+Shape)
- RRM (Rate Only)

**Single-Detector (SD)**
- Rate+Shape (Bugey4⊕4×$\sigma_{shape}$)
- Rate+Shape (Bugey4⊕1×$\sigma_{shape}$)
- DC-III Rate+Shape (Gd-n)

- Rate norm. pushes up
- FD-II Flux compensation pushes up
Mean Cross-Section per Fission

Double Chooz IV (ND)  
TnC (n-H⊕n-C⊕n-Gd)

Bugey4  

Daya Bay  
CPC 41.1.013002(2017)  n-Gd

2011 World Average  

\[<\sigma_t> = (5.71 \pm 0.06) \times 10^{-43} \text{ cm}^2/\text{fission}\]

\[<\sigma_t> = (5.75 \pm 0.08) \times 10^{-43} \text{ cm}^2/\text{fission}\]

\[<\sigma_t> = (5.91 \pm 0.12) \times 10^{-43} \text{ cm}^2/\text{fission}\]

Common Reactor Model  \(\sigma \approx 2.2\%\)
World Comparison

Double Chooz IV
TnC MD (n-H⊕n-C⊕n-Gd)

Daya Bay
PRD 95, 072006 (2017) n-Gd
PRD 93, 072011 (2016) n-H

RENO
PRL 116, 211801(2016) n-Gd

T2K
PRD 96, 092006 (2017)

\[ \Delta m_{32}^2 > 0 \]
\[ \Delta m_{32}^2 < 0 \]

Total Uncertainty
Statistical Uncertainty
\( \sin^2(2\theta_{13}) = 0.105 \pm 0.014 \)
\( \sin^2(2\theta_{13}) = 0.084 \pm 0.003 \)
\( \sin^2(2\theta_{13}) = 0.071 \pm 0.011 \)

Marginalisation \( (\delta_{CP}, \theta_{23}) \)
Double Chooz has the unique property of *only* two nuclear reactors. So one or both can be off at times.

- 8 days of off-off data with only the far detector
- 17 additional off-off days with both detectors
- Data can be used to further constrain the backgrounds
Background Reduction

- Good MC/Data agreement for IBD candidates
- Efficient background suppression with cuts/vetoes
- Off-Off data set as validation
Background Reduction

Cumulative rejection per cut

Average Efficiency ~85%

Total Rejection ND: ×34\(^1\)

Total Rejection FD: ×193\(^1\)

Accidental Background Only
Spectral Distortion Comparison (Shape only)

All reactor neutrino experiments show the same trend.
Spectral Distortion (Rate + Shape)

- Observed distortion in [4, 6] MeV region dissappears in data-data ratio
  - Result from ratio is $\sin^2 (2\theta_{13}) = 0.103 \pm 0.017$
  - Cause is present, correlated in both detectors
  - All reactor neutrino experiments observe this effect
- **Empirical** fit yields a negative slope and a double peak structure
- Width of the distortion is significantly larger than the energy resolution
Summary

- Expanded IBD detection to include Hydrogen via TnC
  - Improved statistics and systematics
  - Previously statistically limited, now systematically

- Background estimation confirmed with reactor off data (S/B > 10)

- New result: $\sin^2 (2\theta_{13}) = 0.105 \pm 0.014$

- Best Mean Cross-Section per Fission results to date:
  $(5.71 \pm 0.06) \cdot 10^{-43} \text{ cm}^2 \text{ fission}$

- Spectral distortion investigation (Rate + Shape)

- Double Chooz is unfortunately decommissioned

- Analyse the remaining data to increase statistics

- Improve systematics by proton number calibration during dismantling
In memory of Hervé de Kerret
Double Chooz collaboration

Brazil
CBPF
UNICAMP
France
APC (IN2P3)
CEA/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CENBG (IN2P3)
LNCA (IN2P3/CEA)
Subatech (IN2P3)
Germany
EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Tokyo U. Science
Kitasato U.
Kobe U.
Russia
INR RAS
RRC Kurchatov
Spain
CIEMAT-Madrid
USA
Alabama U.
ANL
Chicago U.
Drexel U.
Hawaii U.
Notre Dame U.
Virginia Tech.

Spokesperson:
A. Cabrera (IN2P3/CNRS)
Project Manager:
Ch. Veyssière (CEA)

97 scientists 25 institutions (Americas, Asia, Europe)

web: doublechooz.in2p3.fr

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Backup
Double Chooz wants to perform a precise measurement of the neutrino mixing angle $\theta_{13}$. 

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

$\theta_{23} \sim 45^\circ$  
$\theta_{13} & \delta_{\text{CP}}$  
$\theta_{12} \sim 33^\circ$
Double Chooz wants to perform a precise measurement of the neutrino mixing angle $\theta_{13}$.

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} (L, E) \sim 1 - \sin^2 (2\theta_{13}) \sin^2 \left( 1.27 \frac{\Delta m^2_{13} \ [\text{eV}^2]}{E_\nu \ [\text{MeV}]} L \ [\text{km}] \right)$$

Two flavour oscillation is valid for distance $\sim 1 \text{ km}$.
Reactor Model Uncertainty Impact

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