Double Chooz
double-detector results

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ICNFP 2017
OAC, 28.08.2017
Content

• $\theta_{13}$ Experiments
• Double Chooz Detectors
  - Setup
  - Selection
  - Datasets
• Latest $\theta_{13}$ result
• Beyond $\theta_{13}$
• Summary/Outlook
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Reactor Neutrino $\theta_{13}$ Experiments

- Systematic uncertainties below 1% required to measure small $\theta_{13}$ oscillation
- Can not use reactor flux prediction only
- Several identical detectors at different distances
  - Near detector measures unoscillated flux
  - Far detector measures energy dependent deficit due to disappearance
  - Identical detector design cancels systematics!

Three major experiment: Double Chooz, RENO, Daya Bay

Double Chooz
Chooz reactors
France / Ardenne

RENO
YonGwang reactors
South Korea

Daya Bay
Daya Bay reactors
South China (close Hong Kong)
Comparision of Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Thermal Power (GW)</th>
<th>Distance Near/Far (m)</th>
<th>Depth Near/Far (mwe)</th>
<th>Target mass (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>8.5</td>
<td>400/1050</td>
<td>120/300</td>
<td>8/8</td>
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<tr>
<td>RENO</td>
<td>16.8</td>
<td>290/1380</td>
<td>120/450</td>
<td>16/16</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>17.4</td>
<td>360(500) /1985(1613)</td>
<td>260/860</td>
<td>40x2/80</td>
</tr>
</tbody>
</table>

Very similar design
Highest statistics for Daya Bay (by far)
Note, at the end of the day the systematics is limiting
Two event coincidence:

i) prompt signal:
   - positron annihilation

ii) delayed signal:
   - n-capture on H or Gd after n-thermalization
   - char. energy deposit of 8.0 MeV (Gd)/ 2.2 MeV (H)
   - char. delay time $\Delta T \sim 30 \mu s$ (Gd)/ 220 $\mu s$ (H)
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Near detector
- Operating since Jan 2015
- Baseline ~ 400 m
- Overburden ~ 120 m

Far detector
- Operating since Apr 2011
- Baseline ~ 1050 m
- Overburden ~ 300 m

Reactor B1
- 4.27 GW

Reactor B2
- 4.27 GW

Experimental site
$P_{e\rightarrow \bar{e}} \approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right)$

$\Delta m_{ee}^2 = \cos^2 \theta_{12} \cdot \Delta m_{31}^2 + \sin^2 \theta_{12} \cdot \Delta m_{32}^2$

$|\Delta m_{ee}^2| \approx |\Delta m_{31}^2| \approx |\Delta m_{32}^2|$

matter effects safely negligible!

Double Chooz is optimized for $\theta_{13}$ measurement ($\Delta m_{31}$)
\[ P_{\bar{e} \rightarrow \bar{e}} \approx 1 - \sin^2(2 \theta_{13}) \sin^2 \left( \frac{\Delta m^2_{ee} L}{4E} \right) \]

\[ \Delta m^2_{ee} = \cos^2 \theta_{12} \cdot \Delta m^2_{31} + \sin^2 \theta_{12} \cdot \Delta m^2_{32} \]

\[ |\Delta m^2_{ee}| \approx |\Delta m^2_{31}| \approx |\Delta m^2_{32}| \]

\[ \text{FD: } L \sim 1050 \text{m} \]

\[ \text{ND: } L \sim 400 \text{m} \]

:= anti electron neutrino surv. prob.

matter effects safely negligible!
Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture
Detector

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

gamma catcher (GC)
stainless steel vessel holding 390 PMTs
inner veto (IV)
glove box (GB)
one lower OV
buffer (B)
acrylic vessels
steel shielding
v-target (NT)
**Neutrino Target (NT)**
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture

**Gamma Catcher (GC)**
Liquid Scintillator (22 m³)
Measures γ escaping the target

**Buffer (B)**
Non-scintillating mineral oil (110 m³)
390 10" PMT
Shielding against external γ

**Neutrino Target (NT)**
Gd loaded (1 g/l) liquid scint. (10 m³)
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Detector

Neutrino Target (NT)
- Gd loaded (1 g/l) liquid scint. (10 m³)
- IBD interactions on Gd capture

Gamma Catcher (GC)
- Liquid Scintillator (22 m³)
- Measures γ escaping the target

Buffer (B)
- Non-scintillating mineral oil (110 m³)
- 390 10" PMT
- Shielding against external γ

Inner Veto (IV)
- Liquid Scintillator (90 m³)
- 78 8" PMT
- Vetos atmospheric μ and neutrons
- Shielding

Gamma Catcher (GC)
- Liquid Scintillator (22 m³)
- Measures γ escaping the target

Neutrino Target (NT)
- Gd loaded (1 g/l) liquid scint. (10 m³)
- IBD interactions on Gd capture
Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

Buffer (B)
Non-scintillating mineral oil (110 m³)
390 10" PMT
Shielding against external γ

Outer Veto (OV)
Plastic scintillator strips
Vetos atmospheric μ

Inner Veto (IV)
Liquid Scintillator (90 m³)
&78 8" PMT
Vetos atmospheric μ and neutrons

Shielding

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture
IBD Selection

Gd

- Selecting n-Gd capture in Neutrino Target only
  - less statistics
  - less background
  - spilling relevant

Gd++

- Selecting n-Gd and n-H capture in Neutrino Target and Gamma Catcher
  + more statistics
  - more background
  + spilling irrelevant
IBD Selection

Gd

- Selecting n-Gd capture in Neutrino Target only

Gd++

- Selecting n-Gd and n-H capture in Neutrino Target and Gamma Catcher
Datasets

Before 2015

Bugey 4 used as virtual ND (baseline 15 m)

FDI  455 days lifetime
+ 7 days lifetime reactor off

Since 2015

ND  258 days lifetime
FDII  363 days lifetime

Double Chooz is expected to operate 3 years in full configuration until end 2017

Datasets can be combined!
Datasets

FDII (FD parallel to ND) 363 days lifetime
Rate[1/day] vs. time

FDI (FD before ND existed) 455 days lifetime + 7 days lifetime reactor off
Rate[1/day] vs. time

ND 258 days lifetime
Rate[1/day] vs. time

Rates with 2 reactors on:
ND: ~ 900/ day
FD: ~ 130/ day

2 Reactors
1 Reactor
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Latest $\theta_{13}$ Results (Sep 2016)

Rate+ Shape $\chi^2$-fit of data to prediction:

$$\sin^2(2\theta_{13})=(0.119\pm0.016)$$ with $\chi^2 / \text{ndf}: 236.2 / 114$

- Cross checked by Data-Data fits
- Cross checked by three groups
- Not optimal $\chi^2$ due to data-prediction mismatch observed with both detectors
Latest $\theta_{13}$ Results (Sep 2016)

Double Chooz
JHEP 1410, 086 (2014)

Preliminary
(CERN seminar 2016)

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)
$\Delta m^2_{32} > 0$
$\Delta m^2_{32} < 0$

Difference to Daya Bay 2.2 $\sigma$
Difference to RENO 1.8 $\sigma$
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$$P_{\bar{e} \rightarrow \bar{e}} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \sin^2(2\theta_{14}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

:= anti electron neutrino surv. prob.

FD: $L \approx 1050m$
Sterile Signatures

\[ P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) \sin^2(2\theta_{14}) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ := \text{anti electron neutrino surv. prob.} \]

\[ \sin^2 2\theta_{13}, \sin^2 2\theta_{14}, L, \Delta m_{ee}^2, \Delta m_{41}^2 \]

FD: \( L \approx 1050 \text{m} \)

ND: \( L \approx 400 \text{m} \)

- Repeating signature, which is different for ND and FD
  - hard to be matched by any single systematic effect
Spectral Distortion

\[ \sin^2(2\theta_{13}) = (0.119 \pm 0.016) \]
with \( \chi^2 / \text{ndf} = 236.2 / 114 \)

Spectral distortion cancels out in FD/ND ratio
\( \Rightarrow \) can not be explained by sterile neutrinos
Spectral Distortion vs. Reactor Power

Excess/deficit is consistent to be proportional to reactor power
Spectral Distortion Seen by Other Experiments

Daya Bay \textit{arXiv:1607.05378}

NEOS \textit{arXiv:1610.05134}

Reno \textit{arXiv:1610.04326}

Spectral distortion seen by several experiments
Sensitivity to $\theta_{14}$

- Sensitivity with Gd++ selection much better than with Gd selection
- Sensitivity valley around $4 \times 10^{-2} \text{ eV}^2$ due to canceling of oscillation signatures of neutrino flux from reactor B1 and B2

Graphs showing sensitivity with CERN data set (15 month GD++ selection) and Gd++ selection vs. Gd selection.
Sensitivity to $\theta_{14}$

- Statistics in final Double Chooz dataset is going to be higher (x2)

Double Chooz
- 2 reactors
- $8.5 \text{ GW}_{\text{th}}$
- 2 det.
- $8T$ (30t) each

Daya Bay
- 6 reactors
- $17.4 \text{ GW}_{\text{th}}$
- 8 det.
- 20t each

Reno
- 6 reactors
- $16.8 \text{ GW}_{\text{th}}$
- 2 det.
- 16t (45t) each
Summary

- Reactor neutrino IBD detection using n-Gd and n-H capture
- Sensitivity to $\theta_{13}$ and $\theta_{14}$
- Latest result: $\sin^2(2\theta_{13}) = 0.119 \pm 0.016$
- Energy shape distortion between 4-6 MeV observed by reactor neutrino experiments
- Biggest uncertainty (proton number) is most likely going to be reduced
- Double Chooz is sensitive to light sterile neutrino ($|\Delta m^2_{41}| \sim 0.005-0.1$ eV²)
Thanks for your attention!
Backup
Background Model

**Accidental**

- Rate and shape measured with offtime method
- Rate and shape constraint in fit using cov. matrix from measurement

**Lithium**

- Lithium likelihood based on distance between vertex and next μ track and number of neutron candidates within 1ms after that μ
- Rate unconstrained in fit
- Shape constraint in fit using cov. matrix from measurement

\[ f(E_{vis}) = p_0 \cdot \exp(p_1 \cdot E_{vis}) + p_2 + p_3 \cdot E_{vis} \]

**Fast n + stopping μ**

- Empirical function
- Sample from IV tagged events
- Dominant at high energies
- Rate estimated using 20-100 MeV prompt energy window

All backgrounds constraint with reactor off sample
Inputs

1 rate + 43 eff. free shape par. + osc. par.

Reactor neutrino flux

3 energy scale par.

Accidental backgr.

1 rate + 40 shape nuis. par.

Li9 backgr.

1 rate + 40 shape nuis. par.

Fast neutron + stopping muon bckgr.

1 rate nuis. par.
DC Sensitivity

\[ 1\sigma \sin^2 \theta_{13} \]

- Today's result
- Nominal running (3 years ND:FD)
- A priori unknown improvement (working)

DC-IV @ CERN Configuration
Improved Proton# Uncertainty

PRELIMINARY

seminar@CERN
Calibration

• two systems for calibration source deployment in the GC/ along the z-axis
• 252-Cf used as neutron source
• Characteristic energy deposit of n-Gd and n-H capture during source deployment used to set energy scale
• Two light injection systems for regular monitoring of PMTs/scintillators
Gd++ Dataset

- Accidental contamination at low energies (1 order of magnitude more than Gd)
- Energy window on purpose extended to background dominated regions
  - Up to 8 MeV signal dominated
  - 8-12 MeV Lithium dominated
  - >12 MeV fast n + stopping µ dominated
- => background estimate for fit
Accidental rejection

- Artificial neuronal network (ANN) using time and space difference and visible delayed energy => signal to background ratio increase > 7 on H data (arXiv:1510.08937)
Uncorrelated Backgrounds

Accidentals
- due to natural radioactivity
- random coincidence

Light Noise
- Light emission by the PMTs themselves
- PMTs mostly light up themselves
  => easy to reject
Muon induced Backgrounds

Crossing muon
- large energy deposit => efficiently rejected

Fast neutrons (FN)
- induced by spallation due to atm. µ (cf. µ₁)
- protein recoil and n-capture may mimic IBD signal

Stopping Muons (SM)
- May enter in particular through the chimney (cf. µ₂)
- end off the µ-track mimics prompt event
- Michel electron mimics delay event

Lithium (Li)
- atm. µ produce long lived β-n decay isotopes ⁹Li, ⁸He (257 ms resp. 172 ms mean live time)
- electrons cannot be distinguished from positrons
Backgrounds

Accidentals
- due to natural radioactivity
- random coincidence
Fast neutrons (FN)
- induced by spallation due to atm. $\mu$ (cf. $\mu_1$)
- protein recoil and n-capture may mimic IBD signal

Stopping Muons (SM)
- May enter in particular through the chimney (cf. $\mu_2$)
- end off the $\mu$-track mimics prompt event
- Michel electron mimics delayed event
Backgrounds

**Lithium (Li)**
- atm. µ produce long lived β-n decay isotopes $^9$Li, $^8$He (257 ms resp. 172 ms mean live time)
- electrons cannot be distinguished from positrons

**Fast neutrons (FN)**
- induced by spallation due to atm. µ (cf. $\mu_1$)
- protein recoil and n-capture may mimic IBD signal

**Stopping Muons (SM)**
- May enter in particular through the chimney (cf. $\mu_2$)
- end off the µ-track mimics prompt event
- Michel electron mimics delayed event
Spectral distortion observed in both detectors
=> very unlikely to be a sterile signature
Mass orderings

\[ \Delta m_{41} \]

a) 

b) 

c) 

d)
PMNS Matrix

\[ U = R_{34}R_{24}R_{23}R_{14}R_{13}R_{12} \]

\[ U_{e1} = \cos \theta_{14} \cos \theta_{13} \cos \theta_{12} \]
\[ U_{e2} = \cos \theta_{14} \cos \theta_{13} \sin \theta_{12} \]
\[ U_{e3} = \cos \theta_{14} \sin \theta_{13} \]
\[ U_{e4} = \sin \theta_{14} \]

\[ P_{ee} = 1 - \sum_{i<j} 4 |U_{ei}|^2 |U_{ej}|^2 \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E_\nu} \right) \]
IBD selection

Single event selection
- Not light noise, muon, or random trigger
- Not within 1.25 ms after a muon

IBD prompt-delayed pair selection
- $E_{\text{prompt}}$, $E_{\text{delayed}}$, $\Delta T$, $\Delta R$

Background rejection:
- Multiplicity cut
- No IV, OV coincidence
- Artificial neuronal network (ANN) using $E_{\text{delayed}}$, $\Delta T$, $\Delta R$
- Stopping $\mu$ veto cut
- Lithium veto cut
IBD selection

Single event selection
- Not light noise, muon, or random trigger
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IBD prompt-delayed pair selection
- $E_{\text{prompt}}, E_{\text{delayed}}, \Delta T, \Delta R$

Background rejection:
- Multiplicity cut
- No IV, OV coincidence
- Artificial neuronal network (ANN) using $E_{\text{delayed}}$, $\Delta T$, $\Delta R$
- Stopping $\mu$ veto cut
- Lithium veto cut

Inverse beta decay IBD

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

$10 \sin^2 2\theta_{13}$

- today's result
- nominal running (3 years ND:FD)
- a priori unknown improvement (working)

PRELIMINARY seminar@CERN
Full oscillation prob.

\[ P_{ee} = P_{\bar{e}e} = 1 - 4 \sum_{i<j} |U_{ei}|^2 |U_{ej}|^2 \sin^2 \left( \frac{\Delta m^2_{ji} L}{4E_\nu} \right) \]

\[ P_{ee} = 1 - c_{14}^4 s_{12}^2 \sin^2 2\theta_{13} \sin^2 \Delta_{32} - c_{14}^4 c_{12}^2 \sin^2 2\theta_{13} \sin^2 \Delta_{31} - c_{14}^4 c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{12} \]

\[ - s_{13}^2 \sin^2 2\theta_{14} \sin^2 \Delta_{43} - c_{13}^2 s_{12}^2 \sin^2 2\theta_{14} \sin^2 \Delta_{42} - c_{13}^2 c_{12}^2 \sin^2 2\theta_{14} \sin^2 \Delta_{41} \]

\[ U_{e1} = \cos \theta_{14} \cos \theta_{13} \cos \theta_{12} \]
\[ U_{e2} = \cos \theta_{14} \cos \theta_{13} \sin \theta_{12} \]
\[ U_{e3} = \cos \theta_{14} \sin \theta_{13} \]
\[ U_{e4} = \sin \theta_{14} \]

Small anyway