First Results from Double Chooz

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• Current Status of Neutrino Oscillations and $\theta_{13}$
• Recent Double Chooz Results

On behalf of the Double Chooz Collaboration
MIAMI 2011 Conference
December 16th 2011
Double Chooz Collaboration

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Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.in2p3.fr
Oscillations

- PMNS matrix describing the relationship between mass and flavor eigenstates.
- $\theta_{12}$, $\theta_{23}$, $\Delta m^2_{21}$, and $\Delta m^2_{31}$ oscillation parameters are now experimentally known.

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

Atmospheric
Super Kamiokanda & MINOS

Solar
SNO & KamLand

$\theta_{13}$ parameter is small making measurements difficult

$$s_{23}^2 = \sin^2 \theta_{23} = 0.50^{+0.07}_{-0.06}$$

$$|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2$$

$$s_{12}^2 = \sin^2 \theta_{12} = 0.318^{+0.019}_{-0.016}$$

$$\Delta m^2_{21} = 7.59^{+0.23}_{-0.18} \times 10^{-5} \text{ eV}^2$$
Measuring $\theta_{13}$

- From reactor neutrino experiments looking for survival of electron anti-neutrinos.
  
  $$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2 \left( \frac{\Delta m^2_{31} \cdot L}{4E} \right) - \cos^4 \theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2 \left( \frac{\Delta m^2_{21} \cdot L}{4E} \right)$$

- From accelerator neutrino experiments looking for appearance of electron neutrinos from muon neutrino beams.
  
  $$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 (\Delta_{31} - \alpha L)}{(\Delta_{31} - \alpha L)^2} \Delta_{31}^2 + 2 \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos \theta_{13} \frac{\sin (\Delta_{31} - \alpha L)}{(\Delta_{31} - \alpha L)} \Delta_{31}$$

  $$\ast \frac{\sin(\alpha L)}{\alpha L} \Delta_{21} \cdot (\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta) + \cos^4 \theta_{13} \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 (\alpha L)}{(\alpha L)^2} \Delta_{21}^2$$
Reactor Neutrinos

- Much cleaner measurement.

\[
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2 \left( \frac{\Delta m_{31}^2 \cdot L}{4E} \right) + \cos^4 \theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2 \left( \frac{\Delta m_{21}^2 \cdot L}{4E} \right)
\]

Black \( \sin^2 2\theta_{13} = 0 \)

Red \( \sin^2 2\theta_{13} = 0.1 \)

Ev = 4MeV  \( \Delta m_{13}^2 = 2.5 \times 10^{-3} \text{eV}^2 \)
The original CHOOZ Experiment was designed to measure $\theta_{13}$. First results in 1998.

Due to limited statistics and high systematic uncertainty of the absolute neutrino flux, only upper limits were set for $\sin^2 2\theta_{13}$. 

$$\sin^2 2\theta_{13} < 0.19 \land \Delta m^2_{13} = 2.0 \times 10^{-3} \, \text{eV}^2$$

M. Apollonio [CHOOZ Collaboration], PLB 466 1999 415
New Generation of Reactor Experiments

• Near and Far detectors are used in the new generation of detectors.
• The relative rates between near and far will eliminate the reactor flux uncertainty.

Double Chooz: Far detector data taking since April 2011
First results presented at LowNu11 in November 2011
Near detector running early 2013

Reno: Both near and far detectors running since August 2011

Daya Bay: First Near Hall running since August 2011
Full running Summer 2012
Accelerator Neutrino Experiments

- T2K: Running (delayed now due to the earthquake and tsunami)
- MINOS: Running
- Nova: Under Construction
Double Chooz

- Double Chooz was designed on improvements of the first CHOOZ experiment.
- Two identical detectors will be deployed, one at the previous CHOOZ site (~1.05km from reactors) and a near detector (~400m from reactors).
Detector Design

- Reactor electron anti-neutrinos are detected by inverse beta decay reactions inside the target area.

**Target area:** 10.3m³ liquid scintillator doped with Gd

**Gamma Catcher:** 22.3m³ liquid scintillator

**Buffer Area:** 110m³ non-scint. mineral oil

**Outer Muon Veto:**
- Scintillator Plastic
- 15cm Steel Shielding

**Inner Veto:** 90m³ liquid scintillator
Detecting Reactor Anti-Neutrinos

- The electron anti-neutrinos are detected with inverse beta decay reactions.

\[ \overline{\nu}_e + p = n + e^+ \]

\[ \Delta t \approx 30 \mu s \]
Reactor Spectrum

Thermal Power from EDF

Time Evolved Fission Rates

- P. Huber, Phys. Rev. C84 (2011) 024617
Calibration Data

$^{68}$Ge
In Gamma Catcher
$^{252}$Cf Source

Spontaneous fission neutrons deployed in Target

Preliminary Data
Far Detector Outer Veto

Outer Veto and Chimney

Muons tagged by OV and Inner Detector

Preliminary
Inner Veto

Muon rates from Inner Veto

Michel Electrons after tagged stopping Muons

Detector Timing working well down to the $\mu$s level
Events Following Muons

Visible Energy Spectrum

Rate of neutron capture on Hydrogen following Muons

Preliminary
Backgrounds

Accidental:
Gamma from radioactive contamination followed by a thermalized neutron from an untagged muon.
  Rate $0.332 \pm 0.004$ day$^{-1}$

Long lived Muon induced isotopes:
  Beta + n decay of $^9$Li and $^8$He
  Rate $2.3 \pm 1.2$ day$^{-1}$

Muon induced fast neutrons:
  Recoil proton followed by thermalized neutron.
  Rate $0.7 \pm 0.5$ day$^{-1}$
Two Reactors Off Data

- Double Chooz had the unique opportunity to have ~1 day of running with both reactors off.

Preliminary

- Two recorded events during this time within IBD prompt visible energy:
  - 9.8 MeV (200ms after high energy Muon)
  - 4.8 MeV (241ms after high energy Muon)

Consistent with background estimations from data
Inverse Beta Decay

- Neutrino event candidates via Inverse Beta Decay Reactions:
  - Prompt Event (0.7-12 MeV visible energy)
  - Delay Event (6-12MeV visible energy)
  - Delta T between prompt and delay(2-100µs)
  - Veto events 1ms after tagged muons.
- Multiplicity conditions
  - No event 100µs before prompt events
  - Only delay event 400µs after prompt events
- Cut of PMT spontaneous light emission
  - Ratio of max charge/total charge
  - RMS of PMT hit time
Timing and Spatial Distribution

- Distance between Prompt and Delay events

- Time between Prompt and Delay events
Candidate Position Reconstruction

- No Cuts made on position
- Cuts are made for delay events to capture on Gd
- Well contained in target
Inverse Beta Decay Rates

Neutrino rate (background subtracted)

Neutrino Rate Data-MC ratio (background subtracted)
Visible Energy Spectraums

Rate + Shape Analysis

\[ \sin^2 2\theta_{13} = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst}) \]

Rate Only Analysis

\[ \sin^2 2\theta_{13} = 0.093 \pm 0.029(\text{stat}) \pm 0.073(\text{syst}) \]
Results Presented

First at LowNu11 Conference
November 2011

More recently presented on CBS
“The Big Bang Theory”
December 2011

Episode: “The Speckerman Recurrence”
Images Copyright CBS
http://www.cbs.com/shows/big_bang THEORY/video
A non-zero $\theta_{13}$ value above $3\sigma$. 

Combined Results

\[ \Delta m_{\text{DC}}^2 = 2.35 \times 10^{-3} \text{ eV}^2 \]

curves: T2K+MINOS +CHOOZ
shaded: T2K+MINOS +CHOOZ+DC
Comparison to Theory
Conclusion

• Double Chooz Far Detector has been running stably since April of this year, publication coming soon.
• Double Chooz will continue to run with the Far detector as the Near detector is built (completed 2013).
• A “clean” measurement of a large $\theta_{13}$ will impact current and future accelerator neutrino experiments probing for CP-violating phase and mass hierarchy.

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - \alpha L)}{(\Delta_{31} - \alpha L)^2} \Delta_{31}^2 \]

\[ + 2 \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos \theta_{13} \frac{\sin(\Delta_{31} - \alpha L)}{(\Delta_{31} - \alpha L)} \Delta_{31} \]

\[ \ast \frac{\sin(\alpha L)}{(\alpha L)} \Delta_{21} \cdot (\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta) \]

\[ + \cos^4 \theta_{13} \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\alpha L)}{(\alpha L)^2} \Delta_{21}^2 \]
Thank You
Backup Slides
Readout Threshold

Preliminary
Data Analysed
Spontaneous Light Emission Cut

preliminary
Prompt vs Delay

$E_{\text{prompt}}$ vs $E_{\text{delayed}}$

Double Chooz preliminary
Background

There are unavoidable events that can mimic inverse beta decay in our detector.

Much care was taken in the detector construction to limit these events.

We must carefully determine the rate and energy spectrum of these events to get a pure anti-neutrino spectrum.

\[
\bar{\nu}_e + p = n + e^+ \\
\Delta t \approx 30 \mu s
\]
Accidental Background

- Accidental background events come from prompt-like signal from radioactivity.
- Muon induced long lived isotopes resulting in beta + n.
- Fast Neutrons with recoil protons
Accidental BG

- Accidental events are found by using an off time window between prompt and delay events of $\Delta t$ 1-100ms.
- Rate $0.332 \pm 0.004 \text{ day}^{-1}$
Correlated BG $^9$Li

- For $^9$Li events, look for time since last high energy muon to prompt event.

Rate $2.3 \pm 1.2$ day$^{-1}$

Preliminary
Correlated BG Fast Neutrons

- For Fast Neutron events, look at high energy prompt spectrum above neutrino signal energy range.

Rate $0.7 \pm 0.5$ day$^{-1}$
• A total reactor errors of 1.74% remains for a far detector analysis only.

• Having two identical detectors will cancel these uncertainties.
Preliminary Data

- Stable Data taking at the Far Detector began April 13, 2011

Now over 100 days of physics data analyzed.

~75% physics data efficiency
~10% calibration data
For accelerator experiments compare appearance rates for neutrinos and anti-neutrinos.

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e) \]

Figure 36: The bi-probability \( P(\nu_\mu \rightarrow \nu_e) \) diagram for NO\(\nu\)A including matter effects.

Nova: Beam from Fermi Lab to detector in Ash River MN  Baseline 810km
Two Reactors Off Data

- Due to one reactor undergoing two month refueling period and tests to the second reactor, one day of data was taken with both reactors off.

- Three recorded events during this time with prompt visible energy < 30MeV
  - 2 events with prompt visible energy within the IBD spectrum range (9.8 and 4.8 MeV).
  - 1 event with high prompt visible energy (26.5 MeV)

Consistent with background estimations from data
<table>
<thead>
<tr>
<th>Reference</th>
<th>$\sin \theta_{13}$</th>
<th>$\sin^2 2\theta_{13}$</th>
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</thead>
<tbody>
<tr>
<td><strong>$SO(10)$</strong></td>
<td></td>
<td></td>
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<tr>
<td>Goh, Mohapatra, Ng [33]</td>
<td>0.18</td>
<td>0.13</td>
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<tr>
<td><strong>Orbifold $SO(10)$</strong></td>
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<tr>
<td>Asaka, Buchmiller, Covi [34]</td>
<td>0.1</td>
<td>0.04</td>
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<tr>
<td><strong>$SO(10)$ + flavor symmetry</strong></td>
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<tr>
<td>Babu, Pati, Wilczek [35]</td>
<td>$5.5 \cdot 10^{-4}$</td>
<td>$1.2 \cdot 10^{-6}$</td>
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<tr>
<td>Blazek, Raby, Tobe [36]</td>
<td>0.05</td>
<td>0.01</td>
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<tr>
<td>Kitano, Mimura [37]</td>
<td>0.22</td>
<td>0.18</td>
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<tr>
<td>Albright, Barr [38]</td>
<td>0.014</td>
<td>$7.8 \cdot 10^{-4}$</td>
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<tr>
<td>Maekawa [39]</td>
<td>0.22</td>
<td>0.18</td>
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<tr>
<td>Ross, Velasco-Sevilla [40]</td>
<td>0.07</td>
<td>0.02</td>
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<tr>
<td>Chen, Mahanthappa [41]</td>
<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td>Raby [42]</td>
<td>0.1</td>
<td>0.04</td>
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<tr>
<td><strong>$SO(10)$ + texture</strong></td>
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<tr>
<td>Buchmüller, Wyler [43]</td>
<td>0.1</td>
<td>0.04</td>
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<tr>
<td>Bando, Obara [44]</td>
<td>0.01 .. 0.06</td>
<td>$4 \cdot 10^{-4}$ .. 0.01</td>
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<tr>
<td><strong>Flavor symmetries</strong></td>
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<td>Grimus, Lavoura [45, 46]</td>
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<td>0</td>
</tr>
<tr>
<td>Grimus, Lavoura [45]</td>
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<td>0.3</td>
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<td>Babu, Ma, Valle [47]</td>
<td>0.14</td>
<td>0.08</td>
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<tr>
<td>Kuchimanchi, Mohapatra [48]</td>
<td>0.08 .. 0.4</td>
<td>0.03 .. 0.5</td>
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<tr>
<td>Ohlsson, Seidl [49]</td>
<td>0.07 .. 0.14</td>
<td>0.02 .. 0.08</td>
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<tr>
<td>King, Ross [50]</td>
<td>0.2</td>
<td>0.15</td>
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<tr>
<td><strong>Textures</strong></td>
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<tr>
<td>Honda, Kaneko, Tanimoto [51]</td>
<td>0.08 .. 0.20</td>
<td>0.03 .. 0.15</td>
</tr>
<tr>
<td>Lebed, Martin [52]</td>
<td>0.1</td>
<td>0.04</td>
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<tr>
<td>Bando, Kaneko, Obara, Tanimoto [53]</td>
<td>0.01 .. 0.05</td>
<td>$4 \cdot 10^{-4}$ .. 0.01</td>
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<tr>
<td>Ibarra, Ross [54]</td>
<td>0.2</td>
<td>0.15</td>
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<tr>
<td>$3 \times 2$ see-saw</td>
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<td></td>
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<tr>
<td>Appelquist, Piria, Shrock [55, 56]</td>
<td>0.05</td>
<td>0.01</td>
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<tr>
<td>Frampton, Glashow, Yanagida [57]</td>
<td>0.1</td>
<td>0.04</td>
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<tr>
<td>Mei, Xing [58]</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>(inverted hierarchy)</td>
<td>&gt; 0.006</td>
<td>&gt; $1.6 \cdot 10^{-4}$</td>
</tr>
<tr>
<td><strong>Anarchy</strong></td>
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<td></td>
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<tr>
<td>de Gouvéa, Murayama [59]</td>
<td>&gt; 0.1</td>
<td>&gt; 0.04</td>
</tr>
<tr>
<td><strong>Renormalization group enhancement</strong></td>
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<tr>
<td>Mohapatra, Parida, Rajasekaran [60]</td>
<td>0.08 .. 0.1</td>
<td>0.03 .. 0.04</td>
</tr>
</tbody>
</table>

Table 11: Incomplete selection of predictions for $\theta_{13}$. 

arXiv:hep-ex/0410081v1
Preliminary Results

\[
\sin^2 2\theta_{13} = 0.085 \pm 0.029\,(stat) \pm 0.042\,(syst)
\]

\[
\sin^2 2\theta_{13} = 0.093 \pm 0.029\,(stat) \pm 0.073\,(syst)
\]