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

- $\theta_{13}$ & $\nu$ Oscillations
- Double Chooz Concept and Detector
- Preliminary Results
- Conclusions
θ_{13}

- PMNS Matrix Describes the relationship between neutrino mass and flavor eigenstates.

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\left(
\begin{bmatrix}
e^{i\alpha_1/2} & 0 & 0 \\
0 & e^{i\alpha_2/2} & 0 \\
0 & 0 & 1
\end{bmatrix}
\right)
\]

\[
P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2 \left(\frac{\Delta m^2_{31} \cdot L}{4E}\right) - \cos^4 \theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2 \left(\frac{\Delta m^2_{21} \cdot L}{4E}\right)
\]

- The current limit on θ_{13} comes from the first Chooz experiment.
  \[
  \sin^2 2\theta_{13} < 0.15 \quad @ \quad \Delta m^2_{13} = 2.5 \times 10^{-3} \text{ eV}^2
  \]
Reactor Anti-Neutrinos

- For reactor experiments the source is electron anti-neutrinos from beta decay of unstable fission products.
- For Double Chooz: Two 4.25GW reactors
  \[ \sim 2 \times 10^{21} \ \text{\nu/s} \]
- The electron anti-neutrinos are detected with inverse beta decay reactions.

\[ \bar{\nu}_e + p = n + e^+ \]
Double Chooz

- The Double Chooz concept will build on the previous Chooz experience improving background suppression, systematic and statistical uncertainties.
- Two identical detectors will be built, one at the previous Chooz site (1.05km from reactors) and a near detector (~400m from reactors).

<table>
<thead>
<tr>
<th>Systematic errors</th>
<th>Absolute</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production $\sigma$</td>
<td>1.9 %</td>
<td>-</td>
</tr>
<tr>
<td>Reactor power</td>
<td>0.7 %</td>
<td>-</td>
</tr>
<tr>
<td>Energy per fission</td>
<td>0.6 %</td>
<td>-</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>1.5 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Number of protons</td>
<td>0.8 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Total</td>
<td>2.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Double Chooz Sensitivity

T2K best fit \( \sin^2 2\theta_{13} = 0.11 \)
\( \theta_{23} = 45\text{deg}, \Delta m^2_{13} = 2.5 \times 10^{-3} \text{eV}^2 \)
Detector Design

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

Target area: 10.3m\(^3\) liquid scintillator doped with Gd

Gamma Catcher: 22.3m\(^3\) liquid scintillator

Buffer Area: 110m\(^3\) non-scint. mineral oil

Outer Muon Veto: Scintillator Plastic

Inner Veto: 90m\(^3\) liquid scintillator

15cm Steel Shielding

\[ \bar{\nu}_e p \rightarrow e^- + T_e + 2m_e \]

\[ \Sigma E_\gamma \sim 8 \text{ MeV} \]
Far Detector Construction

Inner Detector PMTs and Acrylic vessel

Outer Veto and Chimney

Buffer Vessel Lid and IV PMTs

Civil Construction of the Near Lab is ongoing
• Stable Data taking at the Far Detector began April 13, 2011

Now over 100 days of physics data.

~75% physics data efficiency
~10% calibration data
Muon Data

- Muon rates from Inner Veto
- Michel Electrons after tagged stopping Muons
Muon Data

- Detector Events following Muons

![Graph showing neutron capture events](image)

- H neutron Capture
- Gd neutron Capture
IBD Candidates by Day

- >4000 Events with background

One reactor off times
Calibration Data

- $^{68}\text{Ge}$ calibration data in Calibration Guide Tube.
- Other Calibrations include:
  - Light injection system
  - Z-axis Deployment
  - $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{252}\text{Cf}$
Conclusion

- Double Chooz Far Detector has been running stable since April of this year.
- The discover potential is promising for far detector data only.
- A “clean” measurement of $\theta_{13}$ will be important for long baseline discoveries.
- First results from Double Chooz are coming soon!
Thank You
Measurement of Theta-13

- Reactor anti-neutrino experiments have the opportunity for a “clean” measurement of $\theta_{13}$.

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

- Accelerator neutrino experiments also have the capability of measuring $\theta_{13}$ but it is coupled with the CP-violating phase and matter effects.

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ 2 \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos \theta_{13} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \frac{\sin(aL)}{(aL)} \Delta_{31} \Delta_{21}$$

$$\times (\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta)$$

$$+ \cos^4 \theta_{13} \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2$$
A measurement of a “large” value for $\theta_{13}$ would impact the potential for mass hierarchy and CP violating phase measurements from accelerator neutrino experiments.
Double Chooz Sensitivity

Fogli, et al., arXiv:0905.3549

- $\sin^2 2\theta_{13} \sim 0.08$
Position Reconstruction

• IBD Delay event reconstructed position.
IBD Delta T

- Delta T between prompt and delay IBD events.

![Prompt - Delayed ΔT Distribution](image)

Double Chooz Preliminary
Delay Events

Delayed Event Charge Distribution

Double Chooz Preliminary