Comparing Reactor Sites for a Future Reactor Neutrino Experiment to Measure $\theta_{13}$
A Comparison of Sites

Not a sensitivity study, detector design and systematics will determine $\sin^2 2\theta_{13}$ sensitivity

- Reactor Power
- Baseline
- Detector Size
- Overburden

Some sites place constraints on detector size:

- Chooz
  - horizontal tunnel sites if detectors movable
Issues and Questions

1. What are the minimum overburden requirements for near and far detector?
   Overburden requirements as a function of
   - distance
   - power
   - size
   - muon veto efficiency

2. What (if anything) do we gain from having the same overburden at near and far detector?

3. Baseline and physics potential

4. Will it be possible to measure backgrounds? Can we measure during refueling period? How does it work for multiple reactors?

5. Are any of the proposed projects limited by signal statistics?
FOM Components I

Signal

\[ S_\nu = S_\nu [P, d] \]

Backgrounds

I) Limit absolute background contribution to < 1%

\[ \frac{B_\mu}{S_\nu} = \frac{B_{\mu [depth, A_{det}]} }{S_\nu [P, d]} < 0.01 \]

II) Measure backgrounds to < 1% and subtract

\[ \frac{\sigma_{B_\mu}}{S_\nu} = \frac{\sqrt{B_\mu}}{S_\nu} = \frac{\sqrt{B_{\mu [depth, A_{det}]} }}{S_\nu [P, d]} < 0.01 \]
FOM Components II

Deadtime Due to Spallation Cuts

\[ D_\mu = D_\mu [\text{depth}, A_{det}] \]

\[ D_\mu = D_{\text{Chooz}} \frac{\mu [\text{depth}, A_{det}]}{\mu [\text{depth}_{\text{Chooz}}, A_{\text{Chooz}}]} \]

Oscillation Effect

\[ O_\nu [d_{\text{near}}, d_{\text{far}}] = 1 - \frac{\Phi_{\nu_e} [d_{\text{far}}]}{\Phi_{\nu_e} [d_{\text{near}}]} / \frac{\Phi_{\nu_e} [d_{\text{min}}]}{\Phi_{\nu_e} [0]} \]
Detector Size

Statistical Error

\( \sigma_{\text{stat}} \sim 0.5\% \) for \( \mathcal{L} = 300\text{t-yr} \)

Nominal data taking: 3 years (?)

Interaction rate: 300 /yr/ton at 1.8 km

Fiducial volume > 30 ton at 1.8 km
Overburden

Chooz candidate events
reactor on 2991
reactor off 287

Chooz has 9.5% irreducible background, presumably
- fast neutrons, and
- spallation backgrounds.

Minimum overburden

![Graph showing background versus depth]

scaling Chooz background with muon spectrum that generates spallation backgrounds

<table>
<thead>
<tr>
<th>bkgd</th>
<th>depth (mwe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>300</td>
</tr>
<tr>
<td>&lt; 5%</td>
<td>&gt; 400</td>
</tr>
<tr>
<td>&lt; 2%</td>
<td>&gt; 560</td>
</tr>
<tr>
<td>&lt; 1%</td>
<td>&gt; 730</td>
</tr>
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</table>
Muon Veto and Efficiency

Chooz have 98% (?)
> 99.5% possible (?)

event candidates
reactor on 2991
reactor off 287

Improvement in muon veto can reduce backgrounds.
Muon Flux and Deadtime

Muon veto requirements increase with volume, reduce with depth

\[ D_\mu = D_\mu [\text{depth}, A_{\text{det}}] \]

\[ D_\mu = D_{\text{Chooz}} \frac{\mu [\text{depth}, A_{\text{det}}]}{\mu [\text{depth}_{\text{Chooz}}, A_{\text{Chooz}}]} \]

Chooz 2% deadtime

For a target of ~50 t perhaps we want 2 x 25 t detectors?
Double Chooz

Near Detector

critical issues:
- stability
- muon veto efficiency

dead time $\sim 50\%$
Can we measure backgrounds?

I) Measure background spectrum correlated with muon flux and neutron background

- high muon veto efficiency
- stability
- background statistics

II) Direct measurement during reactor refueling time:

3-4 weeks
every 12-18 months

4-8% time for background measurement

An optimistic estimate

<table>
<thead>
<tr>
<th>No of Reactors</th>
<th>$\sigma_B/S$</th>
<th>$\rightarrow$ 0.013 for 100k events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4.15/$\sqrt{S_v}$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6/$\sqrt{S_v}$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.8/$\sqrt{S_v}$</td>
<td></td>
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</tbody>
</table>
Oscillation Effect

Baseline and Physics Sensitivity

\[
O_\nu [d_{\text{near}}, d_{\text{far}}] = 1 - \frac{\Phi_{\bar{\nu}_e}[d_{\text{far}}]}{\Phi_{\bar{\nu}_e}[d_{\text{near}}]} / \frac{\Phi_{\bar{\nu}_e}[d_{\text{min}}]}{\Phi_{\bar{\nu}_e}[0]}
\]

measured osc

max osc

measured oscillation

max oscillation
## Requirements for Near and Far Detector

<table>
<thead>
<tr>
<th>Detector</th>
<th>Description</th>
<th>Mathematical Expression</th>
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</thead>
<tbody>
<tr>
<td>Near</td>
<td>Measurement of backgrounds non-trivial</td>
<td></td>
</tr>
</tbody>
</table>
|            | Dead time may be significant                      | \[
|            | Signal/background critical (> 100)               | \[
|            | Baseline and oscillation sensitivity             | \[
|            | Include dead time                                | \[
| Far        | Signal/background important (> 100)              | \[
|            | Baseline and oscillation sensitivity             | \[
|            | Include dead time                                | \[

\[
\frac{S_v}{B_\mu} \times D_\mu \times O_v
\]
Thermal Reactor Power

Reactor Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Thermal Power (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angra des Reis</td>
<td>4.1</td>
</tr>
<tr>
<td>Braidwood</td>
<td>6.5</td>
</tr>
<tr>
<td>Chooz</td>
<td>8.4</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>11.6</td>
</tr>
<tr>
<td>Diablo Canyon</td>
<td>6.4</td>
</tr>
<tr>
<td>Kashiwazki</td>
<td>24.3</td>
</tr>
<tr>
<td>Krasnoyarsk</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Detector Volumes

Volume assumptions based on recent talks, papers, and discussions.
Baselines

<table>
<thead>
<tr>
<th>Location</th>
<th>Near</th>
<th>Far</th>
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</thead>
<tbody>
<tr>
<td>Krasnoyarsk</td>
<td>115</td>
<td>885</td>
</tr>
<tr>
<td>Kashiwazki</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>Diablo Canyon</td>
<td>400</td>
<td>1400</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>300</td>
<td>1500</td>
</tr>
<tr>
<td>Chooz</td>
<td>200</td>
<td>850</td>
</tr>
<tr>
<td>Braidwood</td>
<td>200</td>
<td>1300</td>
</tr>
<tr>
<td>Angra des Reis</td>
<td>300</td>
<td>1000</td>
</tr>
</tbody>
</table>

Distance from Reactor (m)
Site Comparison

Signal x Deadtime/Background

![Bar chart showing site comparison with data points for Angra des Reis, Braidwood, Chooz, Daya Bay, Diablo Canyon, Kashiwazaki, and Krasnoyarsk. The chart indicates differences in FOM2 for near and far sites.](chart.png)
Site Comparison

Far Detector Performance with and without Oscillation Effect

![Bar Chart]

- Angra des Reis: w/out oscillation (9.87), w/ oscillation (6.44)
- Braidwood: w/out oscillation (10.77), w/ oscillation (7.12)
- Chooz: w/out oscillation (6.44), w/ oscillation (7.12)
- Daya Bay: w/out oscillation (6.7), w/ oscillation (9.85)
- Diablo Canyon: w/out oscillation (7.8), w/ oscillation (13.6)
- Kashiwazaki: w/out oscillation (15.27), w/ oscillation (16.69)
- Krasnoyarsk: w/out oscillation (15.27), w/ oscillation (16.69)