Water Cherenkov Capabilities

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Introduction

- Set the stage for VLB $\nu_\mu$ appearance

Analysis I

- Comparison between BNL report and my result

Analysis II

- Use of a new likelihood

Analysis III

- With all interactions on

Analysis IV

- Use of off-axis

Conclusions
Introduction

Where we stand:

- $\nu_\mu \rightarrow \nu_\tau$ established
  - $\nu_\mu$ disappearance experiments: SK, K2K, Soudan2, MACRO
  - $\sin^2 2\theta_{23}$ and $\Delta m^2_{\text{atm}} \sim \Delta m^2_{23}$ measured

- $\nu_e \rightarrow \nu_x$ established
  - $\nu_e$ disappearance experiments: Cl, SK, Ga, SNO, KamLAND
  - $\Delta m^2_{12} \ll \Delta m^2_{23} \sim \Delta m^2_{13}$

If $\Delta m^2_{12} \ll \Delta m^2_{23} \sim \Delta m^2_{13} = \Delta m^2_{\text{atm}}$, then

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (1.27 \Delta m^2_{\text{atm}} / E_\nu) + f(\delta_{CP})$$

Observation of $\nu_\mu \rightarrow \nu_e$ will give us info on $\sin^2 \theta_{13}$ and $\delta_{CP}$
How we do that?

- $\nu_\mu \rightarrow \nu_e$ and $\nu_e + N \rightarrow e + N' + (\text{invisible } \pi s)$

- Look for single electron events

- Major background
  - $\nu_\mu + N \rightarrow \nu_\mu + N' + \pi^0 + (\text{invisible } \pi s)$
  - $\nu_e$ contamination in beam (typically 0.7%)

- With a large water Cherenkov detector such as UNO
  - Cheaper for a large volume than other technologies
  - Potentially quite capable of removing background
Introduction

Spectra of on- and off-axis beams

PRD68 (2003) 12002; private communication w/ M.Diwan

![Graph showing spectra of on-axis and off-axis beams](image)

- On-axis beam
- 1° off-axis beam

\[ \nu_{\mu}\rightarrow\nu_{\mu} \text{ (GeV)} \]

\[ N_{\nu_{\mu}/\text{GeV/m}^2/\text{POT}} \]
Monte Carlo Event Generation

- Atmospheric neutrino events in SK-> BNL superbeam

- All ν interactions available
- SK- I geometry/configuration/PMT coverage
- Standard SK-I analysis package + Special π^0 finder (ntuples)
- Neutrino spectrum reweighted for BNL superbeam using all events
- Total number of events normalized with that expected for BNL using QE events (0.5 Mtons, 5 yr running at 2,540 km)
- Δm^2_{21} = 7.3 \times 10^{-5} \text{eV}^2, \Delta m^2_{31} = 2.5 \times 10^{-3} \text{eV}^2
- \sin^2 2\theta_{ij}(12,23,13) = 0.86/1.0/0.04, \delta_{CP} = +45,+135,-45,-135^\circ

Probability tables from Brett Viren of BNL
Interactions included

- **Mode 1**: QE (CC)  *signal*
- **Mode 11-13**: Single $\pi$ from $\Delta$ (CC)
- **Mode 16**: Coherent $\pi^0$ (CC)
- **Mode 21**: Multi $\pi$ ($1.3<W<2.0$ GeV) (CC)
- **Mode 22**: Single $\eta$ (CC)
- **Mode 23**: Single K (CC)
- **Mode 26**: Deep inelastic ($2.0$ GeV < $W$) (CC)
- **Mode 31-34**: Single $\pi$ from $\Delta$ (NC)  *background ($\pi^0$ only)*
- **Mode 36**: Coherent $\pi^0$ (NC)  *background*
- **Mode 41**: Multi $\pi$ ($1.3<W<2.0$ GeV) (NC)
- **Mode 42-43**: Single $\eta$ (NC)
- **Mode 44-45**: Single K (NC)
- **Mode 46**: Deep inelastic ($2.0$ GeV < $W$) (NC)
- **Mode 51-52**: Elastic (NC)
Selection Criteria I  

QE for signal, single pi0 for bkg

- Cut 0:
  - Fiducial volume cut (200 cm inside from PMTs)
  - 2 $\gamma$ s, $E_\gamma > 150$ MeV, $\theta_\gamma > 9^\circ$ \(\rightarrow\) 2 rings

- Cut 1:
  - 1 ring and e- like

- Cut 2:
  - $E_{\text{ring}} > 100$ MeV and no decay electrons

- Cut 3: (\(\pi^0\) finder info used)
  - $80 < m_{\gamma\gamma} < 160$ MeV/c\(^2\) \(\text{invariant mass btwn primary ring and an extra ring found by } \pi^0\text{ finder}\)
  - $E_{\text{vis}} > 500$ MeV
  - $\cos \theta_{\text{ring}} > 0.5$
  - 2 $\gamma$ s, $E_\gamma > 150$ MeV, $\theta_\gamma > 9^\circ$ \(\rightarrow\) 2 rings

BNL report requirements (PRD68,2003,p12002)

To remove invisible $\pi/\mu$

BNL report requirements (PRD68,2003,p12002)
**π^0** finder

- **π^0** detection efficiency with standard SK software
- **π^0** detection efficiency with **π^0** finder

Always finds an extra ring in a single ring event

**m_γγ (MeV/c^2)**

- Opening angle measured (deg)
- Efficiency
- True opening angle (deg)

inefficiency overlap
inefficiency weak 2^{nd} ring

Single e-like events from single **π^0** int.

All the single **π^0** int.
Analysis I

$\pi^0$ finder

$\pi^0$ detection efficiency with standard SK + $\pi^0$ finder

All the single $\pi^0$ int.

- True opening angle (deg)
- With atmospheric neutrino spectrum
- $\pi^0$ mass cut: 1- and 2-ring events
- $\pi^0$ mass cut: 2-ring events

With $\pi^0$ finder

Without $\pi^0$ finder
Detection Efficiencies and Background Rejection I

- $\pi^0 \rightarrow e$ probability

- BNL report

- This study

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>~20%</td>
</tr>
<tr>
<td>2</td>
<td>~50%</td>
</tr>
<tr>
<td>1</td>
<td>~7.5%</td>
</tr>
<tr>
<td>2</td>
<td>~20%</td>
</tr>
</tbody>
</table>

$E_{\pi}$ (GeV)

- ~7.5% at 1 GeV
- ~20% at 2 GeV

$E_{\pi}$ (MeV)

- ~20% at 1 GeV
- ~50% at 2 GeV
Detection Efficiencies and Background Rejection I

- $\nu_e$ QE efficiency

- BNL report

- This study

Electron eff. vs energy

<table>
<thead>
<tr>
<th>$E_e$ (GeV)</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>~75% at 1 GeV</td>
<td>$\sim 0.75$</td>
</tr>
<tr>
<td>~95% at 2 GeV</td>
<td>$\sim 0.95$</td>
</tr>
</tbody>
</table>

~50% at 1 GeV
~60% at 2 GeV
### Analysis I

#### BNL report

**Before any cut**

<table>
<thead>
<tr>
<th></th>
<th>Signal Events</th>
<th>Background Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>no OSC</td>
<td>13,290</td>
<td>4,238</td>
</tr>
<tr>
<td>w/ OSC</td>
<td>6,538</td>
<td>4,238</td>
</tr>
</tbody>
</table>

**Normalization**

<table>
<thead>
<tr>
<th></th>
<th>Signal Events</th>
<th>Background Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>no OSC</td>
<td>13,260</td>
<td>3,628</td>
</tr>
<tr>
<td>w/ OSC</td>
<td>6,143</td>
<td>3,628</td>
</tr>
</tbody>
</table>

**6% less 14% less**

#### This study

**Signal** 242 events

- All bkg 380
  - (324 from $\pi^0$)
  - (56 from $\nu_e$)

**Compare** with

**Signal** 303 events

- All bkg 146
  - (76 from $\pi^0$)
  - (70 from $\nu_e$)
Number of signal and background events

BNL report

- Signal: 303 events
- All backgrounds: 146
  - 76 from $\pi^0$
  - 70 from $\nu_e$

Study by B.Viren

- Signal: 255 events
- All backgrounds: 308
  - 292 from $\pi^0$
  - 30 from $\nu_e$

This study

- Signal: 242 events
- All events: signal + background
- All backgrounds: 380
  - 324 from $\pi^0$
  - 56 from $\nu_e$
**Improve**

- Software – More cuts and better pattern recognition
- Some possible variables to be used for additional cuts

Signal: QE  
Background: NC $\pi^0$

- Fraction of energy $E_2/(E_1+E_2)$
- $\cos\theta$ of 1st ring
- $\pi^0$ likelihood
- $e$-like  
- Pid (e/mu)
Define likelihood using fraction of $2^{nd}$ $\gamma$ energy, $\cos \theta$ of $1^{st}$ ring, $\pi^0$-likelihood, pid, and $\pi^0$ mass. But…

- Drop cuts on $\pi^0$ mass, opening angle, and $\cos \theta$
Selection Criteria II

QE for signal, single pi0 for bkg

- **Cut 0:**
  - Fiducial volume cut (200 cm inside from PMTs)

- **Cut 1:**
  - 1 ring and e- like

- **Cut 2:**
  - $E_{\text{ring}} > 100$ MeV and no decay electrons

- **Cut 3:**
  - $E_{\text{rec}} > 500$ MeV  New (Evis->Erec)

- $\Delta \text{likelihood} < 0.4$  New

BNL report requirements

To remove invisible $\pi/\mu$
Signal and Background II

BNL report

Number of signal and background events

This study

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>303</td>
<td>146</td>
</tr>
<tr>
<td>All</td>
<td>76 from $\pi^0$</td>
<td>70 from $\nu_e$</td>
</tr>
<tr>
<td></td>
<td>228</td>
<td>233</td>
</tr>
<tr>
<td>CP+45$^\circ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>180 from $\pi^0$</td>
<td>53 from $\nu_e$</td>
</tr>
</tbody>
</table>
Why don’t we turn on all the interactions?
Then what are signals and what are backgrounds?

Why not accept all CC events as signals?
Analysis III

Selection Criteria III

All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg

all $\nu_\mu$ CC for bkg

- Cut 0:
  - Fiducial volume cut (200 cm inside from PMTs)

- Cut 1:
  - 1 ring and e- like

- Cut 2:
  - $E_{\text{ring}} > 100$ MeV and no decay electrons

- Cut 3:
  - $E_{\text{rec}} > 500$ MeV

$\Delta\text{likelihood}< \text{to be determined}$

BNL report requirements

To remove invisible $\pi/\mu$.

Now this is important to Remove invisible charged Pions.
\[ \Delta \text{likelihood} = \ln[\text{likelihood}(\text{bkg})] - \ln[\text{likelihood}(\text{sig})] \]

- Define likelihood using fraction of 2\textsuperscript{nd} $\gamma$ energy, $\cos \theta$ of 1\textsuperscript{st} ring, $\pi^0$-likelihood, pid, and $\pi^0$ mass. But…

- Drop cuts on $\pi^0$ mass, opening angle, and $\cos \theta$
Number of signal and background events

**BNL report**

- **Signal** 303 events
- **All bkg** 146
  - (76 from $\pi^0$)
  - (70 from $\nu_e$

**This study**

- Out of scale (136 ev)
- $\Delta$likelihood $<-0.8$

- **Signal** 397 events
- **All bkg** 617
  - (527 from $\pi^0$+others)
  - (90 from $\nu_e$)

**Comparing**

- **CP+45°**

- All backgrounds
**Signal and Background III**

- All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg
  - All $\nu_e$ CC for bkg

**Effect of cut on likelihood**

- $\Delta$likelihood $< 0.0$
- $\Delta$likelihood $< -0.4$
- $\Delta$likelihood $< -0.8$

### Analysis III

**Signal**

- 501 events
  - (48% QE events)

**All bkg**

- 1102
  - (90% NC)
  - (971 from $\pi^0$+others)
  - (131 from $\nu_e$)

**Signal**

- 450 events
  - (48% QE events)

**All bkg**

- 853
  - (89% NC)
  - (743 from $\pi^0$+others)
  - (110 from $\nu_e$)

**Signal**

- 397 events
  - (48% QE events)

**All bkg**

- 617
  - (87% NC)
  - (527 from $\pi^0$+others)
  - (90 from $\nu_e$)
Signal and Background III

Effect of cut on likelihood

$\Delta$ likelihood $< -2.0$

All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg

BNL Report

- A tighter cut on likelihood supresses low energy event
- It also modifies energy spectrum very much
- It however improve SN ratio

Signal 303 events
(49% QE events)

All bkgs 253
(86% NC)
(210 from $\pi^0$+others)
(43 from $\nu_e$)

Should we use the tightest cut?

Signal 251 events
(49% QE events)

All bkgs 146
(76 from $\pi^0$)
(70 from $\nu_e$)
Singnal and Background III

All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg

• Effect of cut on likelihood and CPV phase

$\Delta$likelihood $< 0.0$

$\Delta$likelihood $< -0.4$

All events: signal + bkg

<table>
<thead>
<tr>
<th>CPV $\delta$ (deg)</th>
<th>$+45$</th>
<th>$+135$</th>
<th>$-45$</th>
<th>$-135$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>501</td>
<td>660</td>
<td>305</td>
<td>464</td>
</tr>
<tr>
<td>All bkggs</td>
<td>1102</td>
<td>1099</td>
<td>1002</td>
<td>1099</td>
</tr>
<tr>
<td>$\pi^0 +$ others</td>
<td>971</td>
<td>968</td>
<td>971</td>
<td>968</td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>131</td>
<td>131</td>
<td>131</td>
<td>131</td>
</tr>
</tbody>
</table>

Signal

All bkggs

$\pi^0 +$ others

Beam $\nu_e$
Signal and Background III

All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg

- Effect of cut on likelihood and CPV phase

$\Delta$likelihood< -2.0

All events: signal+bkg

$\Delta$likelihood< -0.8

All bkgs

$\pi^0$+others

Beam $\nu_e$

<table>
<thead>
<tr>
<th>CPV $\delta$ (deg)</th>
<th>+45</th>
<th>+135</th>
<th>-45</th>
<th>-135</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>397</td>
<td>501</td>
<td>253</td>
<td>357</td>
</tr>
<tr>
<td>All bkgs</td>
<td>617</td>
<td>615</td>
<td>617</td>
<td>615</td>
</tr>
<tr>
<td>$\pi^0$+others</td>
<td>527</td>
<td>525</td>
<td>527</td>
<td>525</td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Erec (MeV)
- **Off-axis beam**

- Define likelihood using fraction of 2\textsuperscript{nd} $\gamma$ energy, $\cos\theta$ of 1\textsuperscript{st} ring, $\pi^0$-likelihood, pid, and $\pi^0$ mass as for on-axis beam.

- Drop cuts on $\pi^0$ mass, opening angle, and $\cos\theta$

![likelihood(bkg)-likelihood(sig)](image1)

![pi0 mass distribution](image2)

- MeV/c\textsuperscript{2}
Signal and Background IV

All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg

- Effect of cut on likelihood

No contribution from beam $\nu_e$

No $\Delta$likelihood cut

Signal $\quad 310$ events
All bkg$s \quad 403 + ???$
  (403 from $\pi^0$+others)
  (?? from $\nu_e$)

$\Delta$likelihood $< 0.0$

Signal $\quad 199$ events
All bkg$s \quad 131 + ???$
  (131 from $\pi^0$+others)
  (?? from $\nu_e$)
**Analysis IV**

**Signal and Background IV**

- **Effect of cut on likelihood**
  - No contribution from beam $\nu_e$ included
  - $\Delta$likelihood $<-0.4$
  - $\Delta$likelihood $<-0.8$

**Graphs**

- CP+45°
  - All events: signal + bkg
  - All backgrounds

**Event counts**

- **Signal** 153 events
- **All bkg** $85 + ???$
  - (85 from $\pi^0$ + others)
  - (??? from $\nu_e$)

- **Signal** 96 events
- **All bkg** $46 + ???$
  - (46 from $\pi^0$ + others)
  - (??? from $\nu_e$)
Signal and Background III

All $\nu_e$ CC for signal, all $\nu_\mu$ and $\nu_e$ NC for bkg

Effect of cut on likelihood and CPV phase

No contribution from beam $\nu_e$

All events: signal + bkg

$\Delta$likelihood $< -0.4$

<table>
<thead>
<tr>
<th>CPV $\delta$ (deg)</th>
<th>+45</th>
<th>+135</th>
<th>-45</th>
<th>-135</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>153</td>
<td>226</td>
<td>62</td>
<td>140</td>
</tr>
<tr>
<td>Bkg $\pi^0$+others</td>
<td>85</td>
<td>84</td>
<td>85</td>
<td>84</td>
</tr>
</tbody>
</table>

Erec (MeV)
Conclusions

- Realistic MC simulation study was performed for BNL very long baseline with a water Cherenkov detector
  - Estimates on the signal and background level seem optimistic in the BNL report; This was semi-independently confirmed by Brett Viren of BNL

- It was demonstrated that there is some room to improve SN ratio by reducing the background level while keeping a reasonable signal detection efficiency with current available software
  - Further improvement of algorithm/software is essential and possible
  - A larger detector such as UNO has an advantage over a smaller detector such as SK (See C.K. Jung talk)
Conclusions

- The idea of a very long baseline experiment with a large water Cherenkov detector becomes more realistic in terms of physics
  - Further studies are needed