Water Cherenkov Detector and Neutrino Oscillation Experiments Using $\nu_\mu \rightarrow \nu_e$

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Cherenkov radiation

- Water Cherenkov Detector a la SK

\[ L_c = \frac{c}{n} \cdot t \]

\[ L = v \cdot t \]

\[ \cos \theta_c = \frac{1}{n\beta} \leq 1 \]

Threshold p: muon 121 MeV/c
pion 160 MeV/c
proton 1070 MeV/c

\[ \frac{d^2 N}{dx d\lambda} = \frac{2\pi \alpha}{\lambda^2} \left(1 - \frac{1}{n^2 \beta^2}\right) \]

390 photons per 1 cm
(300 nm < \lambda < 700 nm)

\[ \lambda = \text{wavelength}, \ n = \text{index of refraction} \]
\[ \beta = \frac{v}{c}, \ v = \text{speed of charged particle} \]
Time of photon generation $t_i$ for a photon detected by PMT I at time $t^0_i$

Estimator to be maximized

$$G_p = \frac{1}{N_{hit}} \sum_i \exp \left[ - \frac{1}{2} \left( \frac{t_i - t_0}{1.5\sigma} \right)^2 \right], \quad <t_i> = t_0$$

$\sigma \sim 2.5 \text{ nsec}$

Vertex fit (I) : Point-fit

Good for a point source such as electron ring
Ring edge: 
\[
\theta_{\text{edge}} > \theta_{\text{peak}} \quad \text{and} \quad \left. \frac{d^2 PE(\theta)}{d\theta^2} \right|_{\theta_{\text{edge}}} = 0
\]

Particle direction: 
\[
\vec{d}_p = \sum_i q_i \frac{\vec{P}_i - \vec{O}_0}{|\vec{P}_i - \vec{O}_0|}, \quad q_i = \text{charge in PMT } i
\]

Estimator (maximized by changing \( d_p \)) 
\[
Q(\theta_{\text{edge}}) = \frac{\int_{\theta_{\text{edge}}}^{\theta} \frac{PE(\theta)d\theta}{\sin \theta_{\text{edge}}} \left( \frac{dPE(\theta)}{d\theta} \right)_{\theta_{\text{edge}}}^2}{\exp \left[ -\frac{(\theta_{\text{edge}} - \theta_p)^2}{2\sigma_\theta^2} \right]}
\]
**Vertex fit (II): TDC-fit - track length and scattered light effect included**

**Time residual:**

\[ t_i = t_i^0 - \frac{1}{c} \left| \vec{X}_i - \vec{O} \right| - \frac{n}{c} \left| \vec{P}_i - \vec{O} \right| \]

for PMTs inside Cherenkov edge

\[ t_i = t_i^0 - \frac{1}{c} \left| \vec{X}_i - \vec{O} \right| \]

for PMTs outside Cherenkov edge

**Estimators:**

\[ G_I = \sum_i \frac{1}{\sigma_i^2} \exp \left[ -\frac{1}{2} \left( \frac{t_i - t_0}{1.5\sigma} \right)^2 \right] \]

for PMTs inside

\[ G_{O_1} = G_{O_1}(t_i) \text{ for PMTs outside and } t_i > t_0 \]

\[ G_{O_2} = G_{O_2}(t_i) \text{ for PMTs outside and } t_i < t_0 \]

**Final estimator to be maximized:**

\[ G_T = \frac{G_I + G_{O_1} + G_{O_2}}{\sum_i \frac{1}{\sigma_i^2}} \]

by changing vertex position and cone direction
Likelihood function for N+1 rings:

\[ L_{N+1} = \sum_i \log\left[ \text{prob}\left(q_{i}^{\text{obs}}, \sum_n^{N+1} \alpha_n \cdot q_{i,n}^{\text{exp}}\right) \right] \]

\[ \text{prob}(q_{i}^{\text{obs}}, q_{i}^{\text{exp}}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[ -\frac{(q_{i}^{\text{obs}} - q_{i}^{\text{exp}})^2}{2\sigma^2} \right] \text{ for } q_{i}^{\text{exp}} > 20 \text{ pe} \]

= convolution of a single pe  
for \( q_{i}^{\text{exp}} < 20 \text{ pe} \)  
dist. and a Poisson dist.

If \( L_{N+1} > L_N \), several conditions are checked and a decision is made on how many rings there are.
Sub-GeV: $E_{vis} < 1.33 \text{ GeV}$, Multi-GeV: $E_{vis} > 1.33 \text{ GeV}$

- Ring count
Ring fitter example \( p \rightarrow e^+ \pi^0 (\pi^0 \rightarrow \gamma \gamma) \)
How do we detect muon and electron neutrinos?

Major interactions:

\[ \nu_e + n \rightarrow p + e^- \]

\[ \nu_\mu + n \rightarrow p + \mu^- \]

Most of time invisible
Particle ID

Likelihood and probabilities

\[ L_n(e \text{ or } \mu) = \prod_{\theta_i < 1.5 \theta_c} \text{prob}(q_{i,\text{obs}}^{e}, q_{i,n}^{\exp}(e \text{ or } \mu) + \sum_{n' \neq n} q_{i,n'}^{\exp}) \]

\[ \chi_n^2(e \text{ or } \mu) = -2 \log L_n(e \text{ or } \mu) + \text{const} \]

\[ P_n^{\text{pattern}}(e \text{ or } \mu) = \exp \left[ -\frac{(\chi_n^2(e \text{ or } \mu) - \min(\chi_n^2(e), \chi_n^2(\mu)))^2}{2\sigma_{\chi_n^2}^2} \right] \]

\[ P_n^{\text{angle}}(e \text{ or } \mu) = \exp \left[ -\frac{(\theta_n^{\text{obs}} - \theta_n^{\exp}(e \text{ or } \mu))^2}{2\sigma_{\theta}^2} \right] \]

Probability

\[ P_1(e \text{ or } \mu) = P_1^{\text{pattern}}(e \text{ or } \mu) \times P_1^{\text{angle}}(e \text{ or } \mu) \text{ for a single - ring event} \]

\[ P_n(e \text{ or } \mu) = P_n^{\text{pattern}}(e \text{ or } \mu) \text{ for a multi - ring event} \]

\[ P \equiv \sqrt{- \log P(\mu)} - \sqrt{- \log P(e)} \]
Particle ID ($\mu$-like vs. e-like)

(a) $\nu_e$ Q.E.  
$> 5$ GeV/c

(b) $\nu_\mu$ Q.E.  
$> 5$ GeV/c

Lepton Momentum (MeV/c)
Vertex fit (III) : MS-fit – Timing and charge info used for a single ring event

- A vertex shift along a track changes the TOF of each hit by almost equal amount

Bad vertex resolution along the track

- Ring pattern (charge distribution) gives additional handle to improve vertex resolution along the track
Vertex fit (III) : MS-fit – Timing and charge info used for a single ring event

(a) Sub-GeV e-like
1 ring

\[ \sigma = 28 \text{ cm} \]

(b) Sub-GeV \( \mu \)-like
1 ring

\[ \sigma = 24 \text{ cm} \]

(c) Multi-GeV e-like
1 ring

\[ \sigma = 47 \text{ cm} \]

(d) Multi-GeV \( \mu \)-like
1 ring

\[ \sigma = 23 \text{ cm} \]
Momentum measurement

- pe vs. momentum
- momentum resolutions

Graphs showing the corrected total p.e.s. versus momentum (MeV/c) and momentum resolutions for electrons and muons.
Angular resolutions

(a) Sub-GeV e-like
Q.E. 1 ring
\(\sigma = 3.2^\circ\)

(b) Sub-GeV \(\mu\)-like
Q.E. 1 ring
\(\sigma = 1.9^\circ\)

(c) Multi-GeV e-like
Q.E. 1 ring
\(\sigma = 1.6^\circ\)

(d) Multi-GeV \(\mu\)-like
Q.E. 1 ring
\(\sigma = 0.8^\circ\)
$\pi^0$ finder: Motivation and strategy

- $\pi^0$ reconstruction efficiency with standard SK software
  - Inefficiency due to overlap
  - Inefficiency due to a week 2\textsuperscript{nd} ring
  - Inefficiency in between

- Needs a smart algorithm to increase efficiency

- POLfit (Pattern Of Light fit)
  - Always looks for an extra ring in a single e-like ring event
  - Observed light pattern is compared with templates
  - Scattered light due to processes such as Mie scattering taken into account
  - Outputs: Likelihoods in addition to information of the extra-photon are provided

- Inefficiency due to overlap
- Inefficiency due to weak 2\textsuperscript{nd} ring
- Inefficiency in between

Diagram: For all single $\pi^0$ interactions, SK atm. neutrino spectra

- Efficiency due to overlap
- True opening angle (deg)

Table:

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Value</th>
<th>RMS</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>45</td>
<td>0.55</td>
<td>0.88</td>
</tr>
<tr>
<td>R1</td>
<td>40</td>
<td>0.30</td>
<td>0.68</td>
</tr>
<tr>
<td>R2</td>
<td>35</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>
π⁰ finder: Performance

- Measured opening angle vs. π⁰ mass using π⁰ finder
- $\pi^0$ finder: “Efficiency”

- $\pi^0$ “reconstruction efficiency” with standard SK + $\pi^0$ finder

All NC single $\pi^0$ int.

$\pi^0$ mass cut: 1- and 2-ring events

With atmospheric neutrino spectra

with $\pi^0$ finder

w/o $\pi^0$ finder

$\pi^0$ mass cut: 2-ring events
ντ event identification (I)

A τ event at SK (simulation)
In addition to traditional SK variables, new variables such as sphericity and aplanarity that describe topology of events are also used to define a likelihood to distinguish \( \tau \) events from others.

- **Sphericity ("roundness")**
  
  \[ 0 < S < 1 : S = 1 \text{ if the event is spherically symmetric.} \]

- **Aplanarity ("flatness")**
  
  \[ 0 < A < 1/2 : A = 0 \text{ if the event is planar.} \]
ντ event identification (III)
ντ event identification (VI) After some cuts plus a cut on likelihood

Excess of events *i.e.* τ appearance
Very Long Baseline Neutrino Oscillation Experiment

Setting the stage

- A half megaton F.V. water Cherenkov detector, for example UNO at 2,540 (BNL-HS) km and 1,480 km (Fermilab-Henderson) from the beam source
- BNL very long baseline wide band neutrino beam
- VLB neutrino oscillation experiment $\nu_\mu \rightarrow \nu_e$

See, for example, PRD68 (2003) 12002 by BNL group for physics argument. But it is based on 4-vector level MC and on very optimistic assumptions.

How do we find the signal for $\nu_\mu \rightarrow \nu_e$

- $\nu_\mu \rightarrow \nu_e$ and $\nu_e + N \rightarrow e + \text{invisible } N' + (\text{invisible } n \pi^\pm s, n \geq 0)$
- Look for single electron events

- Major background
  - $\nu_{\mu,\tau,e} + N \rightarrow \nu_{\mu,\tau,e} + N' + \pi^0 + (\text{invisible } n \pi^\pm s, n \geq 0)$
  - $\nu_e$ contamination in beam (typically 0.7%)
Neutrino spectra of on- and off-axis BNL Superbeams

PRD68 (2003) 12002; private communication w/ M.Diwan
How is analysis done?

- Use of SK atmospheric neutrino MC
  - Standard SK analysis package + special $\pi^0$ finder
  - Flatten SK atm. $\nu$ spectra and reweight with BNL beam spectra
  - Normalize with QE events: 12,000 events for $\nu_\mu$, 84 events for beam $\nu_e$ for 0.5 Mt F.V. with 5 years of running, 2,540 (1,480) km baseline
    
    $2500 \text{ kt} \cdot \text{MW} \cdot 10^7 \text{ sec}$
    $\text{BNL 30 GeV AGS}$
    
    - Reweight with oscillation probabilities for $\nu_\mu$ and for $\nu_e$

- Oscillation parameters used:
  - $\Delta m^2_{21} = 7.3 \times 10^{-5} \text{ eV}^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$
  - $\sin^2 2\theta_{ij}(12,23,13) = 0.86/1.0/0.04$, $\delta_{CP} = 0, +45, +135, -45, -135^\circ$

  Probability tables from Brett Viren of BNL
Selection criteria used to improve

Initial cuts: Traditional SK cuts only

- One and only one electron-like ring with energy and reconstructed neutrino energy more than 100 MeV without any decay electron

\[ E_v^{\text{rec}} = \frac{m_N E_e}{m_N - (1 - \cos \theta_e) E_e} \]

To reduce events with invisible charged pions

Likelihood analysis using the following 9 variables: With \( \pi^0 \) finder

- \( \pi^0 \) mass (pi0mass)
- energy fraction (efrac)
- costh
- \( \pi^0 \)-likelihood (pi0-like)
- e-likelihood (e-like)
- \( \Delta \log \pi^0 \)-likelihood (\( \Delta \log \text{pi0like} \))
- single ring-ness (dlfct)
- total charge/electron energy (poa)
- Cherenkov angle (ange)
How well can we measure neutrino energy?

From now on only single e-like events after initial cuts will be used.

Oscillation effect on with CPV+45° at 2,540 km

Reconstructed and true energy

QE events only before likelihood cut

- Ev
- Erec

All CC events (=signal) before likelihood cut

- Ev
- Erec

All CC events that survive the initial cuts are signals.
• Useful Variables to form likelihood function

• $\pi^0$ mass

All the distributions of useful variables are obtained with neutrino oscillation “on” with CPV phase angle $+45^0$
Energy fraction of 2nd ring: Fake ring has less energy than real one.
• Difference between log of two $\pi^0$-likelihoods (wide vs. forward) from POLfit

- One algorithm optimized to find an extra ring near the primary ring (forward region)
  This algorithm practically gives likelihood how likely the event is single e-like
- Another algorithm optimized to find an extra ring in wider space (wide region)
- See the difference log $\pi^0$-likelihood (forward) - log $\pi^0$-likelihood (wide)
Difference between log of two $\pi^0$-likelihood (wide vs. forward) from POLfit
\[ \cos \theta = \cos \theta_e \]
Trained with $\nu_e$ CC events for signal, $\nu_\mu$ CC/NC & $\nu_{e,\tau}$ NC for bkg

- $\Delta$ log likelihood distributions
  - log likelihood ratio (signal vs. background)

0 < $E_{\text{rec}}$ < 0.5 GeV

- $\Delta$ log likelihood

0.5 < $E_{\text{rec}}$ < 1.0 GeV

- $\Delta$ log likelihood

1.0 < $E_{\text{rec}}$ < 1.5 GeV

- $\Delta$ log likelihood

1.5 < $E_{\text{rec}}$ < 2.0 GeV

- $\Delta$ log likelihood

2.0 < $E_{\text{rec}}$ < 3.0 GeV

- $\Delta$ log likelihood

3.0 GeV < $E_{\text{rec}}$

- $\Delta$ log likelihood
Trained with $\nu_e$ CC events for signal, $\nu_\mu$ CC/NC & $\nu_{e,\tau}$ NC for bkg

- Efficiency of a cut on $\Delta \log$ likelihood (signal vs background)

0 < $E_{\text{rec}}$ < 0.5 GeV  
0.5 < $E_{\text{rec}}$ < 1.0 GeV  
1.0 < $E_{\text{rec}}$ < 1.5 GeV  
1.5 < $E_{\text{rec}}$ < 2.0 GeV  
2.0 < $E_{\text{rec}}$ < 3.0 GeV  
3.0 GeV < $E_{\text{rec}}$
BNL-Homestake (2540 km)

Effect of cut on $\Delta$ log likelihood

No $\Delta$ log likelihood cut (100% signal retained after initial cuts)

TRADITIONAL ANALYSIS
( $\epsilon$~80-90% for QE)

Preliminary

Signal + backgrounds

Background from $\pi^0$

$\nu_e$ background

Effect of cut on $\Delta$ log likelihood

$\nu_e$ CC for signal; all $\nu_{\mu,\tau,e}$ NC, $\nu_e$ beam for background

$\Delta$ log likelihood cut (~50% signal retained)

Signal 700 ev  Bkgs 2004
(1877 from $\pi^0$+others)
(127 from $\nu_e$)

Signal 350 ev  Bkgs 169
(147 from $\pi^0$+others)
(61 from $\nu_e$)
Effect of cut on $\Delta$ log likelihood

Effect of cut on $\Delta$ log likelihood cut (40% signal retained)

- Signal 280 ev
- Bkgs 136
  - (87 from $\pi^0$+others)
  - (49 from $\nu_e$)

Effect of cut (~40% signal retained)

- Signal 158 ev
- Bkgs 135
  - (87 from $\pi^0$+others)
  - (48 from $\nu_e$)

$\nu_e$ CC for signal; all $\nu_{\mu,\tau,e}$ NC, $\nu_e$ beam for backgrounds

BNL-Homestake (2540 km)
BNL-Homestake (2540 km)

Effect of cut on $\Delta$ log likelihood

$\Delta$ log likelihood cut (40% signal retained)

- Signal + backgrounds
- Background from $\pi^0$

$\nu_e$ background

$\nu_e$ CC for signal; all $\nu_{\mu,\tau,e}$ NC, $\nu_e$ beam for backgrounds

$\Delta$ log likelihood cut (~40% signal retained)

<table>
<thead>
<tr>
<th>Signal</th>
<th>Bkgs</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>386 ev</td>
<td>136</td>
<td>89 from $\pi^0$+others, 50 from $\nu_e$</td>
</tr>
<tr>
<td>263 ev</td>
<td>136</td>
<td>87 from $\pi^0$+others, 49 from $\nu_e$</td>
</tr>
</tbody>
</table>
### BNL-Homestake (2540 km)

**Effectiveness of variables**

<table>
<thead>
<tr>
<th>Variable removed</th>
<th>Signal</th>
<th>Bkg</th>
<th>Effic</th>
<th>Signal</th>
<th>Bkg</th>
<th>(\pi^0)</th>
<th>Beam</th>
<th>(v_e)</th>
<th>(S / B(\pi^0))</th>
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</thead>
<tbody>
<tr>
<td>None</td>
<td>(v_e) CC</td>
<td>(v_\mu) all, (v_e, v_\tau) NC</td>
<td>40%</td>
<td>280</td>
<td>87</td>
<td>49</td>
<td>3.22</td>
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<tr>
<td>(\Delta\pi0lh)</td>
<td>(v_e) CC</td>
<td>(v_\mu) all, (v_e, v_\tau) NC</td>
<td>40%</td>
<td>281</td>
<td>102</td>
<td>50</td>
<td>2.75</td>
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<tr>
<td>poa</td>
<td>(v_e) CC</td>
<td>(v_\mu) all, (v_e, v_\tau) NC</td>
<td>40%</td>
<td>281</td>
<td>94</td>
<td>49</td>
<td>2.98</td>
<td></td>
<td></td>
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<tr>
<td>pi0-lh</td>
<td>(v_e) CC</td>
<td>(v_\mu) all, (v_e, v_\tau) NC</td>
<td>40%</td>
<td>278</td>
<td>94</td>
<td>51</td>
<td>2.95</td>
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<tr>
<td>e-lh</td>
<td>(v_e) CC</td>
<td>(v_\mu) all, (v_e, v_\tau) NC</td>
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<td>277</td>
<td>94</td>
<td>46</td>
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<td>costh</td>
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<td>ange</td>
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<td>dlfct</td>
<td>(v_e) CC</td>
<td>(v_\mu) all, (v_e, v_\tau) NC</td>
<td>40%</td>
<td>277</td>
<td>95</td>
<td>49</td>
<td>2.93</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Neutrino oscillation was on to define template distributions. For analysis with CPV=+45°
### Breakdown of interaction mode

<table>
<thead>
<tr>
<th>Interaction mode</th>
<th>$0 &lt; E_{\text{rec}} &lt; 1$ GeV</th>
<th>$1 &lt; E_{\text{rec}} &lt; 2$ GeV</th>
<th>$2 &lt; E_{\text{rec}} &lt; 3$ GeV</th>
<th>$3$ GeV $&lt; E_{\text{rec}}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Sig</td>
<td>Bkg $\pi^0$</td>
<td>Sig</td>
<td>Bkg $\pi^0$</td>
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<tr>
<td>CC QE</td>
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<tr>
<td>$1\pi^0$</td>
<td>82%</td>
<td>7%</td>
<td>69%</td>
<td>1%</td>
</tr>
<tr>
<td>$1\pi^+$</td>
<td>3%</td>
<td>3%</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>DIS</td>
<td>14%</td>
<td>7%</td>
<td>22%</td>
<td>1%</td>
</tr>
<tr>
<td>NC $1\pi^0$</td>
<td>0%</td>
<td>39%</td>
<td>0%</td>
<td>68%</td>
</tr>
<tr>
<td>$1\pi^+$</td>
<td>0%</td>
<td>29%</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>DIS</td>
<td>0%</td>
<td>11%</td>
<td>0%</td>
<td>9%</td>
</tr>
<tr>
<td>Others</td>
<td>0%</td>
<td>3%</td>
<td>1%</td>
<td>10%</td>
</tr>
</tbody>
</table>
BNL-Homestake (2540 km)

E_{rec} vs. E_\nu

Δlikelihood cut (~40% signal retained)

- Background from π⁰
- CP+45°
- νₑ background
- Signal

Preliminary

Δlikelihood cut (~40% signal retained)
Fermilab-Henderson (1480 km)

Effect of cut on $\Delta$ log likelihood

$\Delta$ log likelihood cut (40% signal retained)

- Preliminary
  - Signal + backgrounds
  - Background from $\pi^0$
  - $\nu_e$ background
  - Signal

$\nu_e$ CC for signal; all $\nu_{\mu,\tau}$ NC, $\nu_e$ beam for backgrounds

$\Delta$ log likelihood cut (~40% signal retained)

- Preliminary
  - CP+45°
  - $\nu_e$ background
  - Signal

Signal 699 ev  Bkgs 373
(233 from $\pi^0$ + others)
(141 from $\nu_e$)

Signal 357 ev  Bkgs 389
(247 from $\pi^0$ + others)
(142 from $\nu_e$)
Fermilab-Henderson (1480 km)

Effect of cut on $\Delta \ln$ likelihood

$\Delta$ log likelihood cut ($\sim$40% signal retained)

Preliminary

Signal + backgrounds

Background from $\pi^0$

$\nu_e$ background

Signal

$\nu_e$ CC for signal; all $\nu_{\mu,\tau,e}$ NC, $\nu_e$ beam for backgrounds

$\Delta$ log likelihood cut ($\sim$40% signal retained)

Preliminary

Signal 645 ev  Bkgs 379

(237 from $\pi^0$+others)

(142 from $\nu_e$)

Signal 609 ev  Bkgs 379

(237 from $\pi^0$+others)

(142 from $\nu_e$)
• Granularity and $\pi^0$ efficiency for same PMT coverage

Expected improvement with UNO? Compared with a smaller detector

- $\pi^0$ efficiency improves when min. distance increases (up to 20%)
- For smaller $\pi^0$ opening angle finer granularity is needed.
- See the power of the $\pi^0$ finder
- What PMT coverage needed? 10, 20, 40% (SK-I has 40% coverage)

$\pi^0$ opening angle 0-20°

More granularity

with $\pi^0$ finder

without $\pi^0$ finder

Minimum distance to wall in $\pi^0$ direction (m)
Conclusions

Realistic MC simulation studies have been performed for the BNL very long baseline scenario with a water Cherenkov detector. It was found that BNL wideband $\nu_\mu$ beam combined with a UNO type detector DO A GREAT JOB whether the baseline is 2,540 km or 1,480 km. – Very exciting news! But always do proper MC simulations!

It was demonstrated that there is room to greatly improve S/B ratio beyond the standard water Cherenkov detector reconstruction codes even with currently available codes.

- We may need further improvement of algorithm/software, which is quite doable.
- Detailed studies on sensitivity on oscillation parameters needed with different neutrino spectrum to optimize the beam spectrum.
- A larger detector such as UNO has an advantage over a smaller detector such as SK (we learned a lesson from 1kt at K2K): Both PMT coverage AND granularity are important.

In collaboration with BNL and Fermilab, proper simulations of a next generation water Cherenkov detector, its optimized design with reasonable $\nu_\mu$ beam will produce sweet fruits for exciting physics.
How do we detect muon and electron neutrinos?

- **Electron-like ring**
- **Muon-like ring**

**Major interactions:**

$$\nu_e + n \rightarrow p + e^-$$

$$\nu_\mu + n \rightarrow p + \mu^-$$

Most of the time invisible
Note: The energy spectrum of $\pi^0$ is that of SK atm. $\nu$ interactions.
What are sources of the signal?

- Neutrino energy reconstruction
  QE events give the best energy resolution but……

\[ E_{\nu}^{\text{rec}} = \frac{m_N E_e}{m_N - (1 - \cos \theta_e) E_e} \]
\[ \text{costh} = \cos \theta_e \]

\[ E_{\nu}^{rec} = \frac{m_N E_e}{m_N - (1 - \cos \theta_e) E_e} \]

It is not clear why the distributions of costh behave as shown in the following. My speculation:

1) The signal events from QE scattering have larger \( \theta_e \) due to the Fermi motion of the target neutron in oxygen in the low energy region.

2) For lower energy background events, the minimum opening angle is larger. In those events accepted as signal, \( \pi^0 \) decay is very asymmetric and the primary \( \gamma \) carries most of the energy.
Found as an electron

- Two overlapped e-like rings identified as an e-like ring look like a fuzzier electron than an electron at lower energy.
- At higher energy multiple particles go into a similar direction and identified as an e-like ring – could look less fuzzy than an electron.

Extra energy from an undetected weak ring.
e-likelihood
\( \pi^0 \text{ likelihood} \) tells whether an event is consistent with a single \( \pi^0 \) event.
\pi^0_{\text{like}}
Cherenkov angle (ange)
Total charge/primary ring energy (poa)

Found as an electron

Extra energy from an undetected weak ring
Total charge/primary ring energy (poa)

- $E_{reac} = 0.0 - 0.5$ GeV
- $E_{reac} = 0.5 - 1.0$ GeV
- $E_{reac} = 1.0 - 1.5$ GeV
- $E_{reac} = 1.5 - 2.0$ GeV
- $E_{reac} = 2.0 - 3.0$ GeV
- $E_{reac} = 3.0 - 4.0$ GeV

Events/0.5

Q/E
Single-ring-ness (dlfct)
## Summary of analysis of BNL superbeam@HS

<table>
<thead>
<tr>
<th>CP phase</th>
<th>Signal</th>
<th>Bkg</th>
<th>Effic</th>
<th>Signal</th>
<th>Bkg</th>
<th>Beam</th>
<th>( v_e )</th>
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</thead>
<tbody>
<tr>
<td>0°</td>
<td>( v_e ) CC</td>
<td>( v_\mu ) all, ( v_e ) NC</td>
<td>(~40%)</td>
<td>197</td>
<td>90</td>
<td>48</td>
<td></td>
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<tr>
<td>-135°</td>
<td>( v_e ) CC</td>
<td>( v_\mu ) all, ( v_e ) NC</td>
<td>(~40%)</td>
<td>263</td>
<td>87</td>
<td>49</td>
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<td>+135°</td>
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<tr>
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<td>( v_e ) CC</td>
<td>( v_\mu ) all, ( v_e ) NC</td>
<td>(~40%)</td>
<td>159</td>
<td>87</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>+45°</td>
<td>( v_e ) CC</td>
<td>( v_\mu ) all, ( v_e ) NC</td>
<td>100%</td>
<td>700</td>
<td>1878</td>
<td>127</td>
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</table>

with traditional water Cherenkov cuts

2540 km
Summary of analysis of Fermilab superbeam@HN

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<th>CP phase</th>
<th>Signal</th>
<th>Bkg</th>
<th>Effic</th>
<th>Signal</th>
<th>Bkg</th>
<th>Beam</th>
<th>ν₀</th>
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</thead>
<tbody>
<tr>
<td>0°</td>
<td>νₑ CC</td>
<td>νₘ all, νₑ NC</td>
<td>~40%</td>
<td>498</td>
<td>230</td>
<td>140</td>
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</tr>
<tr>
<td>-135°</td>
<td>νₑ CC</td>
<td>νₘ all, νₑ NC</td>
<td>~40%</td>
<td>609</td>
<td>237</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>+135°</td>
<td>νₑ CC</td>
<td>νₘ all, νₑ NC</td>
<td>~40%</td>
<td>646</td>
<td>238</td>
<td>142</td>
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</tr>
<tr>
<td>-45°</td>
<td>νₑ CC</td>
<td>νₘ all, νₑ NC</td>
<td>~40%</td>
<td>357</td>
<td>247</td>
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<tr>
<td>+45°</td>
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<td>100%</td>
<td>1754</td>
<td>5395</td>
<td>374</td>
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</tbody>
</table>

with traditional water Cherenkov cuts

1480 km
- Future prospect/plans

- All the variables used to define the likelihood seem useful: any more?

- Some variables associated with some pattern recognition such as $\pi^0$-likelihood and $e$-likelihood seem quite useful
  More sophisticated pattern recognition algorithm is desirable and possible

- $\nu_\tau$ CC interactions in water need to be simulated
  My first guess is that the contribution from these interactions is not large because $\tau$ is mostly produced by DIS and in general there are many particles in the event (not a single ring event).

- This kind of analysis can give an insight to optimize neutrino beam spectrum
  Studies on sensitivities to oscillation parameters should be done
  Careful study of the source of background and the associated neutrino energy is needed
  What granularity UNO needs to have?