$\nu_\mu$ appearance measurement in a SK-like detector for a beta-beam

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Pure $\nu_e$ or $\overline{\nu}_e$ beam could be produced at the Beta-beam facility.

The golden signal is a $\nu_\mu$ appearance channel.

Because the beam contains only one type neutrino, it is not necessary to identify the charge. Therefore, a very massive Water Cherenkov detector could be a good candidate as the far detector.

Here, we studied the efficiencies and the backgrounds of $\nu_\mu$ appearance in a Water Cherenkov detector with the proposed beta beams, based on our experiences of the SK analysis.
Beta-beam facility

Beta-beam facility is determined by following;
- Type of ion ($E_0$)
- Relativistic $\gamma (=E/m)$ of ion
- Baseline L

$L/E_{\nu}$ should be near the oscillation maximum
- LE: $\gamma = 100$, $L = 130$ km (ex. CERN → Frejus)
- HE: $\gamma = 350$, $L = 700$ km (ex. CERN → Gran-Sasso)

Choice of isotope
- CERN-SPS: $\gamma(\text{He}) \sim 150$, $\gamma(\text{Ne}) \sim 250$
- Refurbished SPS: $\gamma(\text{He}) \sim 350$, $\gamma(\text{Ne}) \sim 580$
  → choose He and Ne

1 year operation = $2.9 \times 10^{18}$ decays (He)
  = $1.1 \times 10^{18}$ decays (Ne)

We assume these 4 beta-beam setups
Neutrino measurement in SK-like detector

1. Detection of a Cherenkov ring of a lepton produced by the neutrino interaction.
2. Identification of particle type (e or μ) by the ring pattern.
3. Reconstruction of the lepton momentum with the observed charge.

### Momentum threshold

<table>
<thead>
<tr>
<th></th>
<th>Cherenkov radiation</th>
<th>Analysis threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>0.57 (MeV/c)</td>
<td>100 (MeV/c)</td>
</tr>
<tr>
<td>muon</td>
<td>118 (MeV/c)</td>
<td>200 (MeV/c)</td>
</tr>
<tr>
<td>proton</td>
<td>1 (GeV/c)</td>
<td></td>
</tr>
</tbody>
</table>

700MeV muon

500MeV electron
Performance of the detector (1)

Angular resolution

- **electron (1-ring, e-like)**
  - Momentum (GeV/c)
    - <1GeV: 27.3
    - >1GeV: 48.9

- **muon (1-ring, μ-like)**
  - Momentum (GeV/c)
    - <1GeV: 23.9
    - >1GeV: 23.8

Momentum resolution

- **electron (1-ring, e-like)**
  - Momentum (GeV/c)
    - <1GeV: 27.3
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Vertex resolution

<table>
<thead>
<tr>
<th></th>
<th>electron</th>
<th>muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1GeV</td>
<td>27.3</td>
<td>23.9</td>
</tr>
<tr>
<td>&gt;1GeV</td>
<td>48.9</td>
<td>23.8</td>
</tr>
</tbody>
</table>
Performance of the detector (2)

Neutrino energy resolution for CCQE

**νe**
(1-ring, e-like, CCQE)

**νμ**
(1-ring, μ-like, CCQE)

CCQE ($\nu_\mu + n \rightarrow \mu^- + p$)

\[
E_{\nu}^{\text{rec}} = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + P_\mu \cos \theta_\mu}
\]

- $m_N$: nucleon mass
- $E_\mu$: muon energy
- $m_\mu$: muon mass
- $P_\mu$: muon momentum
Overview of this study

This study is motivated to understand the detection efficiencies and the backgrounds of $\nu\mu$ appearance from beta-beam in the Water Cherenkov detector. The study is based on the current SK Monte-carlo simulation and the analysis tools.

**contents**

- expected $\nu$ flux
- Event Selection
  - 1-ring selection
  - PID selection
  - Decay electrons selection
- Background
Expected neutrino energy spectra in WC 1Mton-year (flux*cross-section)

\[ P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

\[ P(\nu_e \rightarrow \nu_\mu) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

\[ \sin^2 2\theta_{13} = 0.15, \sin^2 \theta_{23} = 0.5 \]
\[ \Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \theta_{12} = 0, \delta = 0, \text{ no matter effect} \]

Beta-beam flux
Neutrino interaction mode after the simple reductions

Expected neutrino interaction rates after the simple cuts: Fully-contained selection, vertex in the fiducial volume, visible energy>30MeV. Non-QE and NC interactions are increased with in the HE beam.
Expected CC signal and selections

Open
reconstructed muon momentum
(CC events, FVFC)

Hatch
after selection

Selection criteria;
- 1-ring
- μ-like ring
- with 1-decay electron
“1-ring” selection is to select CCQE events.

**Ring counting technology**

- Ring candidate search
  - Hough transformation method
- Ring candidate test
  - Likelihood method

The efficiency for identifying CCQE events as 1-ring is 94.2\% for atm ν.
The fraction goes down with increasing neutrino energy. Because CC non-QE neutrino interactions (multi-ring events) is getting larger over ~1GeV.
Event selection 2: PID

**PID technology**

- Classification of the rings into two types by the likelihood method.

- The misidentifying probabilities are \(~1\%\) for atmospheric $\nu_{e}$ and $\nu_{\mu}$ of CCQE events.

![PID likelihood (FVFC, 1-ring)]
Selection probability is \(~90\%\) for \(<400\text{MeV}\), \(~95\%\) for \(>400\text{MeV}\) energy region.
Event selection 3: decay electrons

- Select events with 1 decay-e to increase the fraction of CCQE interactions and to reduce NC and $\nu_e$ BG.
- The efficiency of detecting decay-e are 80% for $\mu^+$ and 63% for $\mu^-$. 

### CCQE purity:

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>0 dcy-e</th>
<th>1 dcy-e</th>
<th>2 dcy-e</th>
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</thead>
<tbody>
<tr>
<td>70%</td>
<td>69%</td>
<td>75%</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing number of decay-e events](image)
Decay electron selection probability

LE $\nu_e$ beam

HE $\nu_e$ beam

1-ring + $\mu$-like + dcye=1

$\mu^+$

$\mu^-$
### Summary of event selection

Summary of the event selection efficiencies (probabilities) for both CC $\nu_e$ and CC $\nu_\mu$ in each beam.

<table>
<thead>
<tr>
<th></th>
<th>LE beam</th>
<th>HE beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\overline{CC \nu_e}$</td>
<td>$\overline{CC \nu_e}$</td>
</tr>
<tr>
<td>FC, FV, evis</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>1-ring</td>
<td>94.8</td>
<td>81.3</td>
</tr>
<tr>
<td>m-like</td>
<td>1.2</td>
<td>0.9</td>
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<tr>
<td>dcy-e</td>
<td>&lt;0.0</td>
<td>6.6</td>
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<tr>
<td>Final sample</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
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</table>

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<td>$CC \nu_e$</td>
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</tr>
<tr>
<td>FC, FV, evis</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>1-ring</td>
<td>94.4</td>
<td>72.7</td>
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<tr>
<td>m-like</td>
<td>1.2</td>
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<td>dcy-e</td>
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<td>15.1</td>
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<tr>
<td>Final sample</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
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<td>$CC \overline{\nu_e}$</td>
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<tr>
<td>FC, FV, evis</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>1-ring</td>
<td>96.6</td>
<td>79.6</td>
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<tr>
<td>m-like</td>
<td>95.7</td>
<td>98.8</td>
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<tr>
<td>dcy-e</td>
<td>81.4</td>
<td>66.7</td>
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<tr>
<td>Final sample</td>
<td>75.3</td>
<td>52.5</td>
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<table>
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<th>LE beam</th>
<th>HE beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$CC \nu_\mu$</td>
<td>$CC \nu_\mu$</td>
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<tr>
<td>FC, FV, evis</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>1-ring</td>
<td>95.8</td>
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<tr>
<td>Final sample</td>
<td>59.4</td>
<td>36.4</td>
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</table>
Background in selected events (1)

\( \nu_e \) NC events is significant BG in HE beam. Mainly \( \pi \)s from NC single-\( \pi \) production make \( \mu \)-like events.

**HE ve beam**
- \( \nu_e \) BG: 8.9%
- BG: 25.5%

**LE ve beam**
- \( \nu_e \) BG: 1.1%
- BG: 3.1%
Background in selected events (2)

\[
\sin^2 2\theta_{13} = 0.15
\]

\[
\sin^2 2\theta_{13} = 0.01
\]

The reconstructed neutrino energy of the NC events are peaked at lower energy.

It’s difficult to see $\nu_\mu$ signal in HE beam if $\sin^2 2\theta_{13} = 0.01$.
The selection efficiencies are 75.3%, 59.4% for $\bar{\nu}_\mu$, $\nu_\mu$ from LE beam and 52.5%, 36.4% for $\nu_\mu$, $\bar{\nu}_\mu$ from HE beam.

1-ring selection probabilities are >95% for LE beam and 78%(68%) for $\nu_\mu$($\bar{\nu}_\mu$) from HE beam

Already exists very precise PID software (>95% probability).

Decay-electron selection will increase a purity of CCQE and reject $\nu_e$ BG events.

**BG**

Small fraction of BG in the LE beams is expected.

For HE beams, CC non-QE, NC and $\nu_e$ events are contaminated. NC $\pi$ production could be the dominant background.

It could be possible to reduce NC events by using the reconstructed neutrino energy.
True $E_{\nu e}$ spectrum

Reconstructed $E_{\nu e}$

$\nu_\mu$
+NC
+CC non-QE
+CCQE

True $E_{\nu e}$ (GeV)

Reconstructed $E_{\nu e}$ (GeV)