Neutrino detectors for future facilities - II

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Neutrino detectors optimized for electron reconstruction

$\nu_\mu \rightarrow \nu_e$ and/or $\nu_e \rightarrow \nu_e$
Neutrino detectors optimized for $\nu_x \rightarrow \nu_e$

- I’ve put three basic detector technologies into this category
  - Water Cherenkov: T2K experiment
  - Totally Active Scintillator Detector (“TASD”): NOvA experiment
  - Liquid Argon Time Projection Chambers: ICARUS and future facilities

- The main focus of these experiments is electron neutrino appearance in muon neutrino beam.

- However, they can, of course, measure muons and in general have good performance for muon detection! I’ll comment in the next lecture on questions about measuring the sign of the muons. The experiments listed above do not plan to run these detectors with magnetic fields and hence don’t have sensitivity to the sign of muons.
The basic problem for $\nu_\mu \rightarrow \nu_e$ detection at a “Super Beam” facility

- In muon neutrino beams, an electron neutrino signal competes with many backgrounds
- Need large mass to get signal up
- Need fine granularity to distinguish muon neutrino and neutral-current event topologies from electron neutrino event topologies
- Need good energy resolution to home in on signal energy window
Water Cherenkov
Super-Kamiokande

Kamioka-Mozumi zinc mine
Mozumi, Japan
1 km rock overburden
(2.7 km water equivalent)
50 kt total mass 50 kt
22.5 kt fiducial mass: 22.5 kt
Inner detector: 11,146 50 cm PMTs
Outer detector: 1800 20 cm PMT’s
Cherenkov effect

- If speed of charged particle exceeds speed of light in a dielectric medium of index of refraction $n$, a “shock wave” of radiation develops at a critical angle:

$$\cos \theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}$$

- Threshold for Cherenkov radiation:

$$K = m \left( \frac{n}{\sqrt{n^2 - 1}} - 1 \right)$$

| $\theta_C | \beta=1.0$ | $\theta_C | \beta=0.9$ |
|----------------|----------------|----------------|
| 42°            | 33°            |

For water, $n=1.33$

<table>
<thead>
<tr>
<th>$K_{thresh}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
</tr>
<tr>
<td>$\mu$</td>
</tr>
<tr>
<td>$\tau$</td>
</tr>
<tr>
<td>$\pi$</td>
</tr>
<tr>
<td>$p$</td>
</tr>
</tbody>
</table>

- $m$: particle mass [GeV]
- $p$: particle momentum [GeV]
- $E$: particle total energy [GeV]
- $K$: particle kinetic energy [GeV]
- $\beta$: particle velocity/c
- $n$: index of refraction
- $\theta_C$: Cherenkov angle

PMT's mounted on wall of detector
Photomultiplier tubes

Photon incident on the photocathode produces a photoelectron via the photoelectric effect. Probability to produce a photoelectron is called the quantum efficiency of the PMT.

Output signal is seen as a current delivered to the anode. Typical gains are $10^6$ yielding pC-scale currents.

A series of plates called dynodes are held at high voltage by the base such that electrons are accelerated from one dynode to the next. At each stage the number of electrons increases. Probability to get first electron from the photocathode to the first dynode is called the collection efficiency.

Wavelength of Cherenkov photons in water
General performance

- Sensitive to a wide range of energies. Capable of electron and photo detection down to ~5 MeV.

- Tracks produce rings on the walls. In high multiplicity events overlap of rings makes reconstruction difficult. Typically, analyses focus on quasi-elastic events which are very often single-track events.

- For single track QE events, neutrino energy reconstructed from kinematics (see next slide).

- Events with pions (and other tracks) that are below Cherenkov threshold lead to backgrounds for the quasi-elastic selection.

Neutrinos from the Sun

Preliminary

<table>
<thead>
<tr>
<th>SK-III 289 days</th>
<th>Full Final sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5 - 20 MeV, 22.5 kton</td>
<td></td>
</tr>
</tbody>
</table>

Signal: \(3378.9 \pm 82.7\) stat. only

\(\cos \theta_{\text{sun}}\)

- **Data**
- **Background**
- **Best fit \(^{8}\text{B MC + background}\)**
Water Cherenkov: Ring Counting

If you know the pattern you are looking for (line, circle, oval, etc.) the Hough transform is a method for converting a pattern recognition problem to a peak finding problem.
Ring counting likelihood

log of likelihood ratio

Single-ring

Multi-ring

CCQE
Super-Kamiokande
Run 4168 Event 1350418

Resid(ns)
- > 182
- 160– 182
- 137– 160
- 114– 137
- 91– 114
- 68– 91
- 45– 68
- 22– 45
- 0– 22
- -22– 0
- -45– -22
- -68– -45
- -91– -68
- -114– -91
- -137– -114
- <=-137

Times (ns)
Quasi-elastic reconstruction

\[ E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos \theta_l} \]

From 2 body kinematics

Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for \( \nu_\mu \) events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of \( \nu_\mu \) events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.
Water Cherenkov: \( e/\mu \) identification

- At low momenta, one can correlate the particle visible energy with the Cherenkov angle. Muons will have "collapsed" rings while electrons are ~always at 42°.

- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are "crisp", electron showers are "fuzzy". See plots and figures at the right.

Figures from M. Earl's PhD Thesis

Figures from [http://hep.bu.edu/~superk/atmnu/](http://hep.bu.edu/~superk/atmnu/)
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Useful trick: Count decay electrons from π→μ→e decay. Good way to count π’s and μ’s that are below threshold.

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- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42°.

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Super-Kamiokande
Run 4234 Event 367257
97-06-26 12:32:31
Detector 1904 hits, 5779 g/s
omitted 5 hits, 2 g/s (time-range)
Trigger 7000 ns
B wall 895.6 cm
PE mm-350, p = 760.0 mV/c

Results
• > 157
• 120 – 157
• 95 – 120
• 65 – 95
• 50 – 65
• 35 – 50
• 25 – 35
• 17 – 25
• 12 – 17
• 8 – 12
• 54 – 8
• 50 – 54
• 45 – 50
• 40 – 45
• 150
c-140

Times (ns)

Useful trick: Count decay electrons from π→μ→e decay. Good way to count π’s and μ’s that are below threshold.

Super-Kamiokande
Run 4260 Event 7809021
97-04-28 23:30:15
Detector 2022 hits, 5741 g/s
omitted 3 hits, 2 g/s (time-range)
Trigger 7000 ns
B wall 895.6 cm
PE mm-350, p = 760.0 mV/c

Results
• > 157
• 120 – 157
• 95 – 120
• 65 – 95
• 50 – 65
• 35 – 50
• 25 – 35
• 17 – 25
• 12 – 17
• 8 – 12
• 54 – 8
• 50 – 54
• 45 – 50
• 40 – 45
• 150
c-140

Times (ns)
Notice: NC events much more likely to be e-like than $\mu$-like due to $\pi^0$ production.

Additional selections:

- no decay electrons:  CC $\nu_\mu$ NC CC $\nu_e$ 14% 19% 76%
- signal energy window (T2K) 1% 16% 58%
- $\pi^0$ likelihood fit 0.4% 10% 42%
Pushing the technology: Sub-GeV to Multi-GeV

wble060 disappearance 1300km / 0km

100 kt water detector in multi-GeV 2 MW wide band beam Fermilab to Homestake
2 GeV visible energy
One is signal, the other background

$\pi^0$ decay at high energy

\[ \pi^0 \rightarrow \gamma \rightarrow \pi^0 \rightarrow \gamma \rightarrow \gamma \]

\[ \text{boost} \]

\[ \text{boost} \]
2 GeV visible energy
One is signal, the other background

$\pi^0$ decay at high energy

$\nu_e$ CC

$\pi^0$ decay at high energy

NC $\pi^0$
US DUSSEL Underground lab

Hyper-Kamiokande

Megaton Scale
Water Cherenkov Detectors

Fréjus

MEMPHYS
**20% or 40% Photocathode coverage?**

PMT’s cost ~$3K USD and are one of the schedule drivers for construction of very large water Cherenkov detectors. Can you live with fewer?

<table>
<thead>
<tr>
<th></th>
<th>Super-K I (40% coverage)</th>
<th>Super-K II (20% coverage)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-GeV vertex resolution</strong></td>
<td>26 cm (e-like) / 23 cm (μ-like)</td>
<td>30 cm (e-like) / 29 cm (μ-like)</td>
</tr>
<tr>
<td><strong>Sub-GeV particle mis-ID</strong></td>
<td>0.81% (e-like) / 0.70% (μ-like)</td>
<td>0.69% (e-like) / 0.96% (μ-like)</td>
</tr>
<tr>
<td><strong>Sub-GeV momentum resolution</strong></td>
<td>4.8% (e-like) / 2.5% (μ-like)</td>
<td>6.3% (e-like) / 4.0% (μ-like)</td>
</tr>
<tr>
<td><strong>p→e⁺π⁰ signal efficiency</strong></td>
<td>40.8±1.2 ±6.1%</td>
<td>42.2±1.2 ±6.3%</td>
</tr>
<tr>
<td><strong>p→e⁺π⁰ background</strong></td>
<td>0.39(±35%) events/100kty</td>
<td>0 events/100kty</td>
</tr>
<tr>
<td><strong>p→K⁺ν, γ tag signal efficiency</strong></td>
<td>8.4±0.1 ±1.7%</td>
<td>4.7±0.1 ±1.0%</td>
</tr>
<tr>
<td><strong>p→K⁺ν, γ tag background</strong></td>
<td>0.72(±28%) events/100kty</td>
<td>1.4(±30%) events/100kty</td>
</tr>
<tr>
<td><strong>p→K⁺ν, π⁺π⁰ signal efficiency</strong></td>
<td>5.5±0.1 ±0.7%</td>
<td>5.7±0.1 ±0.4%</td>
</tr>
<tr>
<td><strong>p→K⁺ν, π⁺π⁰ background</strong></td>
<td>0.59(±28%) events/100kty</td>
<td>1.0(±30%) events/100kty</td>
</tr>
<tr>
<td><strong>T2K CCνₑ likelihood effic.</strong></td>
<td>83.7% (±0.1% stat)</td>
<td>84.8 %</td>
</tr>
<tr>
<td><strong>T2K BG likelihood effic.</strong></td>
<td>21.3 %</td>
<td>21.5 %</td>
</tr>
</tbody>
</table>

*S.T. Clark, Ph.D. Thesis (2006)*  
F. Dufour, T2KK Workshop (2006)

*Preliminary numbers, for comparison purposes. Final published efficiencies and BG may differ.*
Totally Active Scintillator Detector ("TASD")
The NOvA Experiment

- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt “totally active” tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
  - A 215 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km
Top left: extrusions coming off the line
Bottom left: testing compressive strength
Above: Horizontal pieces for IPND

PVC Extrusions
**Detector design**

*Liquid scintillator*
(14.8M liters, 12.6 ktons)
Contained in 3.9 x 6.6 cell cells of length 15.7 m
- 18 m attenuation length
- 5.5% pseudocumene

*Extruded PVC*
(5.4 ktons)
15% anatase TiO$_2$ for high reflectivity

*Wavelength shifting fiber*
(18k km)
- 0.7 mm diameter
- Looped, both ends to same readout pixel

*Avalanche photodiodes (APD)*
(14k boards, 32 channels each)
- 85% quantum efficiency at long wavelengths
- Collect 30 photoelectrons per muon crossing at far end of cell
The high QE of APD's, especially at long wavelength, is crucial to NOvA performance.
Fred Reines and Clyde Cowan. 1995 Nobel to Reines for the detection of the neutrino

Project Poltergeist, 1953
Wall reflectivity

- In NOvA cell, a photon typically bounces off the cell walls 10 times before being captured by a fiber.
- This makes the reflectivity of the cell wall of crucial importance to maximizing light output:
  - $0.8^{10} = 0.11$
  - $0.9^{10} = 0.35$

10% improvement in reflectivity yields factor 3 more light!
Avalanche photo diodes (APD)

- High (80%) quantum efficiency even into UV
- Large dark currents - must be cooled to -15°C to get noise down to ~10 pe equivalent
- Low gains, x100
Electron neutrino signal event

$\nu_e (2.4 \text{ GeV}) + N \rightarrow e^- (1.8 \text{ GeV}) + X \ (\text{Res})$

Color code for hits:
- $e$
- $\mu$
- $p$
- $\pi$

<table>
<thead>
<tr>
<th>MC Truth</th>
<th>Detector response</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="chart1.png" alt="" /></td>
<td><img src="chart2.png" alt="" /></td>
</tr>
<tr>
<td><img src="chart3.png" alt="" /></td>
<td><img src="chart4.png" alt="" /></td>
</tr>
</tbody>
</table>

Electron and pion tracks reconstructed
Sample signal and background events in NOvA
Sample signal and background events in NOvA

\[ \nu_\mu N \rightarrow \nu_\mu p\pi^0 \]

- \( E_\nu = 10.6 \text{ GeV} \)
- \( E_p = 1.04 \text{ GeV} \)
- \( E_{\pi^0} = 1.97 \text{ GeV} \)

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

- \( E_\nu = 2.5 \text{ GeV} \)
- \( E_e = 1.9 \text{ GeV} \)
- \( E_p = 1.1 \text{ GeV} \)
- \( E_{\pi^+} = 0.2 \text{ GeV} \)
Particle ID

21 event shape variables input to artificial neural net
<table>
<thead>
<tr>
<th></th>
<th>Neutrino Running</th>
<th>Antineutrino Running</th>
<th>Total</th>
<th>Efficiency (Includes fiducial cut)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ signal</td>
<td>75.0</td>
<td>29.0</td>
<td>104</td>
<td>36%</td>
</tr>
<tr>
<td><strong>Backgrounds:</strong></td>
<td></td>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$ NC</td>
<td>6.0</td>
<td>3.6</td>
<td>9.6</td>
<td>0.23%</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>0.05</td>
<td>0.48</td>
<td>0.53</td>
<td>0.004%</td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>8.4</td>
<td>3.4</td>
<td>11.8</td>
<td>14%</td>
</tr>
<tr>
<td><strong>FOM</strong></td>
<td>19.8</td>
<td>10.5</td>
<td>22.1</td>
<td></td>
</tr>
</tbody>
</table>

Numbers generated assuming:
$\sin^2(2\theta_{13}) = 0.10$, $\sin^2(2\theta_{23}) = 1.0$, and $\Delta m_{32}^2 = 0.0024 \text{ eV}^2$

Optimizing event selection

Calculations based on $\sin^22\theta_{13}=0.1$ with matter effects turned off. 2 GeV NBB beam.
Quasi-Elastic Event

Color code for hits:
- e
- μ
- p
- π

Monte Carlo “Truth”

Detector response
\( \nu_\mu (1.4 \text{ GeV}) + N \rightarrow \mu^- (1.0 \text{ GeV}) + X (\text{QEL}) \)

Monte Carlo "Truth"

Detector response

Color code for hits:

- e
- \( \mu \)
- p
- \( \pi \)

\( \nu_\mu \) Quasi-Elastic Event
$\nu_\mu$ quasi-elastic event

Color code for hits:
- e
- \(\mu\)
- p
- \(\pi\)

Monte Carlo “Truth”

Proton ID from \(dE/dx\)

$\nu_\mu$ quasi-elastic event
Liquid Argon Time Projection Chamber
Liquid Argon TPC: Concept

Charge yield \( \sim 6000 \) electrons/mm
\(~ 1 \text{ fC/mm} \)

Charge readout planes: \( Q \)

UV Scintillation Light: \( L \)

Light yield \( \sim 5000 \gamma/\text{mm} \)
The ICARUS LqAr Detector

Figure 2.4: Picture of the open T300 ICARUS module during assembly.
What’s going on in this event?
Recorded by 50L LqAr detector in WANF beam
What’s going on in this event?
Recorded by 50L LqAr detector in WANF beam
What’s going on in this event?
*Recorded by 50L LqAr detector in WANF beam*

A.M. de la Ossa Romero, hep-ex/0703026
What’s going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026
What’s going on in this event?
*Recorded by 50L LqAr detector in WANF beam*

Figure 5.21: The raw image of a low multiplicity real event in the collection (left) and induction plane (right). The event is reconstructed as \((\nu_\mu \ n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- \ p \ \pi^0)\) with a mip leaving the chamber, an identified stopping proton and a pair of converted photons from the \(\pi^0\) decay. When these photons escape from the chamber, the event is tagged as a *golden* event.
What’s going on in this event?  
*Recorded by 50L LqAr detector in WANF beam*

---

**Figure 5.21**: The raw image of a low multiplicity plane (right). The event is reconstructed as ($\nu_\mu$; chamber, an identified stopping proton and a pair of these photons escape from the chamber, the event is tagged as a *golden* event.
Electron / Photon Separation

Check dE/dx at start of shower

Monte Carlo

Electron

250 MeV e's and γ's

Monte Carlo

250 MeV e's and γ's

Monte Carlo

γ → e⁺e⁻

π⁰ → γγ

γ → e⁺e⁻
Some possible designs for big detectors

LArTPC: 10-50 kton storage tank. Modular drift regions.

LANDD: Single vessel designed to support vacuum
In gas multiplication region, electrons shower in a region of high electric field. Energy/particle goes up as a result of acceleration in the field.
Path to large detectors (U.S.)

“ArgoNeut” being placed in front of MINOS now

“MicroBooNE” in 8 GeV beamline at Fermilab

LAr5 in NuMI or future DUSEL beamline

Eventual goal: 100 kt

R&D issues

• Are the drift distances required by large detectors achievable in large cryostats?
• Electronic optimization. Multiplexing? Noise?
• Large wire plane construction
Tau neutrinos

- Tau neutrinos are difficult to observe
  - They are difficult to produce. First direct observation (DONUT) was via decays of charmed particles in a beam dump.
  - They are difficult to make interact: Threshold for tau production is 3.5 GeV. This puts them above the oscillation maximum for most beams designed to study oscillations at the atmospheric mass-squared scale. For example, for L=735 km, Emax = 1.5 GeV, which is below threshold
  - They are difficult to detect: The lifetime of the tau is 291 fs; Even when highly boosted, decay length is only a few mm. Required a very finely segmented vertex region

- Tau neutrinos produce backgrounds to electron neutrino searches:

\[
\tau \rightarrow e \, \nu_e \, \nu_\tau
\]
Tau Neutrino Detection

- Several experiments look for tau neutrinos
- Observed by DONUT experiment
- Sought from oscillations by CHORUS and OPERA
- All of the above experiments have used thin films of photographic emulsions placed between target layers
- Use of emulsion allows for resolution of short tau track and search for its decay either through a track kink or to multi-prongs
- Emulsion target followed by other detectors which provide tracking and tell you where you had a neutrino interaction and which emulsions you should develop
Tau Neutrino Detection by DONUT Collaboration

tau decay
to hadrons
OPERA Experiment
In CNGS beam

OPERA uses bricks of lead/emulsion embedded in a solid scintillator-based tracking system + downstream muon spectrometer

<table>
<thead>
<tr>
<th>$\tau$ decay channels</th>
<th>Signal + $\Delta m^2$ (Full mixing)</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2.5 \times 10^{-3}$ (eV$^2$)</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>$3.0 \times 10^{-3}$ (eV$^2$)</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-$</td>
<td>2.9</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau^- \to e^-$</td>
<td>3.5</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau^- \to h^-$</td>
<td>3.1</td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau^- \to 3h$</td>
<td>0.9</td>
<td>0.17</td>
</tr>
<tr>
<td>ALL</td>
<td>10.4</td>
<td>0.76</td>
</tr>
</tbody>
</table>

compatible $\pi^0 \to 2\gamma$;
$\pi^0$ mass: $110 \pm 30$ MeV
While large detectors may not be able to identify tau neutrino events one-by-one, they may be able to separate tau neutrino events from other events statistically.