Neutrino Detectors for future facilities

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What do neutrinos look like?

- Neutrino detectors are built to detect the particles produced when neutrinos interact with nuclei.

- As such we will need to understand:
  - Some basics of neutrino interactions and event topologies.
  - Some basics of the topologies of the particle produced by neutrino interactions.
\[ N_{\text{obs}} = \left[ \int \mathcal{F}(E_\nu)\sigma(E_\nu, \ldots)\epsilon(E_\nu, \ldots)dE_\nu d\ldots \right] \frac{M}{A m_N} T \]

- \( N_{\text{obs}} \): number of neutrino events recorded
- \( \mathcal{F} \): Flux of neutrinos (\#/cm\(^2\)/s)
- \( \sigma \): neutrino cross section per nucleon \( \approx 0.7 \frac{E_\nu}{[\text{GeV}]} \times 10^{-38} \text{cm}^2 \)
- \( \epsilon \): detection efficiency
- \( M \): total detector mass
- \( A \): effective atomic number of detector
- \( m_N \): nucleon mass
- \( T \): exposure time

**Typical “superbeam” flux at 1000 km**

**Need detector masses of** \( 10^6 \text{ kg} = 1 \text{ kton} \) **to get in the game**

**Challenge to the experimentalist:** maximize efficiency and detector mass while minimizing cost

**Work at high energies if you can**

**Push this as high as you can**
Current and future facilities “Super-beams”

- Super-beams are produced by
  \[ p + A \rightarrow \pi^\pm + K^\pm \ldots \]
  \[ \pi \rightarrow \mu + \nu_\mu \]

- Typical energies: 1-10 GeV
- Typical fluxes:
  - 90% \( \nu_\mu \)
  - 9% anti-\( \nu_\mu \)
  - 1% \( \nu_e \) + anti-\( \nu_e \)
- In anti-neutrino focus right sign/wrong sign ration worsen due to \( \pi^+ / \pi^- \) ratio and detection cross-section
- Search for:
  - \( \nu_\mu \rightarrow \nu_\mu \)
  - \( \nu_\mu \rightarrow \nu_e \)
  - \( \nu_\mu \rightarrow \nu_\tau \)
Current and future facilities
Beta-beams

• Beta-beams are produced by beta decay of relativistic ions in a storage ring. For example:

\[ ^{6}\text{He}^{++} \rightarrow ^{3}\text{Li}^{+++}e^{-}\bar{\nu}_{e}. \]
\[ ^{18}\text{Ne} \rightarrow ^{18}_{9}\text{Fe}^{+}\nu_{e}. \]

• Typical energies are lower than super-beams (<1 GeV) but higher energies are thought possible (1-5 GeV)

• Pure beam of \(\nu_{e}\) or anti-\(\nu_{e}\)

• Search for \(\nu_{e} \rightarrow \nu_{e}\)
\(\nu_{e} \rightarrow \nu_{\mu}\)
Current and future facilities
Neutrino factories

- Fluxes from neutrino factory are produced by decay of relativistic muons in a storage ring: \( \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \)
- Typical energies 10-50 GeV. Low energy (~4 GeV) options also thought possible
- Mixed beam of \( \nu_e \) and anti-\( \nu_\mu \) (or anti-\( \nu_e \) and \( \nu_\mu \))
- Search for:
  - \( \nu_e \rightarrow \nu_e \) \( \nu_\mu \rightarrow \nu_\mu \)
  - \( \nu_e \rightarrow \nu_\mu \) \( \nu_\mu \rightarrow \nu_e \)
  - \( \nu_e \rightarrow \nu_\tau \) \( \nu_\mu \rightarrow \nu_\tau \)
Neutrino detection channels

Charged-current

- Electron shower
- Hadrons
- Muon track
- Neutrino tagged as $\nu_e, \nu_\mu, \nu_\tau$
- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - In the case of $\nu_\tau$, the presence of a $\tau$ must be deduced from the $\tau$ decay products
- In CC events nearly all the neutrino energy is deposited in the detector
- CC rates are affected by oscillations

Neutral-current

- Electron shower
- Hadrons
- Muon track
- Neutrino tagged as $\nu_e, \nu_\mu, \nu_\tau$
- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available
- NC rates are not affected by oscillations
  - In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes
Production thresholds

\[ l = e \quad m_e = 0.511 \text{ MeV} \quad P_{\text{thresh}} = 0.511 \text{ MeV} \]

\[ l = \mu \quad m_\mu = 106 \text{ MeV} \quad P_{\text{thresh}} = 112 \text{ MeV} \]

\[ l = \tau \quad m_\tau = 1.78 \text{ GeV} \quad P_{\text{thresh}} = 3.47 \text{ GeV} \]
What’s going on in this event?

12 foot bubble chamber,
Argonne National Lab.
Nov. 13, 1970
What's going on in this event?

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12 foot bubble chamber, Argonne National Lab.
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Abb. 15: Ein Kandidat für die Reaktion $(\nu n + \nu n \pi^0)$. Im Gegensatz zum Normalfall wird das Neutron durch inelastische Reaktion strahlabwärts.
Neutrino detection channels

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Muons

- Muons in the energy regions of interest for current and future neutrino facilities (0.1-100 GeV) lose their energy almost entirely through ionization:
  - Radiative loses (delta rays and bremsstrahlung) are important only above $E_{\mu c} \sim 100$ GeV
  - Nuclear loses are important only below 1 MeV
  - Ionization loses are given by the Bethe-Bloch equation at right
  - Typical value: 2 MeV cm$^2$/g

![Plot of Muon Stopping Power](http://pdg.lbl.gov/)

available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

\[
-dE \over dx = K z^2 Z \frac{1}{A \beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{\gamma^2} \right] - \beta^2 - \frac{\delta(\beta \gamma)}{2}
\]
Range

As seen in the plot at the right, the range of a particle with momentum in the GeV range has roughly a power law dependence:

\[
\frac{R}{M} \left[ \frac{g}{\text{cm}^2 \text{ GeV}} \right] = C \left( \frac{p}{M} \right)^n
\]

Above \(\beta \gamma = 5\):
\[n = 1, C = \frac{A}{Z} (210 + 38 \log Z)\]

Below \(\beta \gamma = 1\):
\[n = 3, C = \frac{A}{Z} (39 + 13 \log Z)\]

In between \(\beta \gamma = 1\) and 5 choosing the smaller of the two calculations overestimates the range by as much as 30%

Figure 27.4: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a \(K^+\) whose momentum is 700 MeV/c, \(\beta \gamma = 1.42\). For lead we read \(R/M \approx 396\), and so the range is 195 g cm\(^{-2}\).
Multiple scattering

- As charged particles pass through matter they experience Rutherford scattering off of nuclei.

- Typically there are a large number of scatters which all go more-or-less in the forward direction. Given the large number of scatters it is common to work in a Gaussian approximation.

- Affects path length through material and can make measurements of curvature difficult.

\[ \theta_0 = \frac{13.6 \ \text{MeV}}{\beta CP} z \sqrt{x/X_0} \left[ 1 + 0.038 \ln(x/X_0) \right] \]

\[ \theta_0 = \theta_{\text{rms plane}} = \frac{1}{\sqrt{2}} \theta_{\text{rms space}} \]

\[ \psi_{\text{rms plane}} = \frac{1}{\sqrt{3}} \theta_{\text{rms plane}} = \frac{1}{\sqrt{3}} \theta_0 , \]

\[ y_{\text{rms plane}} = \frac{1}{\sqrt{3}} x \theta_{\text{rms plane}} = \frac{1}{\sqrt{3}} x \theta_0 , \]

\[ s_{\text{rms plane}} = \frac{1}{4\sqrt{3}} x \theta_{\text{rms plane}} = \frac{1}{4\sqrt{3}} x \theta_0 . \]
Multiple scattering

<table>
<thead>
<tr>
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<th>$X_0$ [cm]</th>
<th>$p = 1$ GeV/$c$</th>
<th>$p = 10$ GeV/$c$</th>
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<td></td>
<td></td>
<td>$x=1$ cm</td>
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<td>1.97</td>
<td>6.84</td>
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<tr>
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<td>2.80</td>
<td>9.7</td>
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<tr>
<td>LqAr</td>
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<td>3.29</td>
<td>11.4</td>
</tr>
<tr>
<td>Fe</td>
<td>1.76</td>
<td>10.1</td>
<td>34.7</td>
</tr>
</tbody>
</table>

Multiple scattering of angles in mrad of 1 and 10 GeV muons for various materials of thicknesses of 1, 10, and 100 cm
Q: What is the minimum muon energy required to pass from the beam line to the detector?

B, C, D vetos against entering tracks

FIG. 1. Plan view of AGS neutrino experiment.

FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and $\delta$ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/$c$; (C) $p_\mu > 440$ with $\delta$ ray.
Q: What is the minimum muon energy required to pass from the beam line to the detector?

Simple guess:

\[(2 \text{ MeV cm}^2/\text{g} \times 7.87 \text{ g/cm}^3 \times 1350 \text{ cm}) = 21 \text{ GeV}\]

15 GeV proton beam

Be target

B, C, D vetos against entering tracks

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\[
\frac{R}{M} = (7.87 \text{ g/cm}^3) \times (1350 \text{ cm} / 0.106 \text{ GeV}) = 100,000 \text{ g/cm}^2/\text{GeV}
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which is off the plot on the previous page. So all we can say from the plot is that \( p > 10 \text{ GeV}. \)

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From previous page: For \( A=55.8, Z=26, C=566 \)

\[ p = \rho R/C = (7.87 \text{ g/cm}^3) \times (1350 \text{ cm})/(566 \text{ g/cm}^2/\text{GeV}) \]

\[ p = 19 \text{ GeV} \]
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\]

\[
p = 19 \text{ GeV}
\]

Paper says 17.5 GeV
Neutrino detection channels

### Charged-current

- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - In the case of $\nu_\tau$, the presence of a $\tau$ must be deduced from the $\tau$ decay products.
- In CC events nearly all the neutrino energy is deposited in the detector.
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### Neutral-current

- In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes.
**Electromagnetic showers**

**Simple model of shower development:**

- $e^+/e^-$'s with $E > E_c$ travel one $X_0$ then brems a $\gamma$ with energy $E/2$. $E_c$ is a “critical energy” at which energy losses due to brems and ionization are equal. Typically $E_c \approx 20$ MeV.
- $\gamma$s with $E > E_c$ travel ~one $X_0$ then pair produce $e^+/e^-$ each with energy $E/2$
- When $E < E_c$ electrons lose their energy through collisions and don’t radiate

This model is simple and useful. However, it does have limitations:

I) You may be tempted to assume that the number of particles at some particular depth obeys Poisson statistics. However, fluctuations in the particle numbers at any given layer are correlated with what happens in previous layers.

II) Fluctuations occur such that a certain point in the shower there may only be only $\gamma$s creating gaps in the shower, an effect which this model fails to capture.
Electrons: Critical energy

Due to their relatively small mass, energy losses due to bremsstrahlung ("brems") are more important for electrons than for muons.

Above a critical energy, $E_c$, electrons lose energy mostly to brems. Ionization losses are only important below the critical energy.

Approximately:

$$E_c = \frac{800 \text{ MeV}}{Z + 1.2}$$

Figure 27.12: Two definitions of the critical energy $E_c$.

$$(\frac{dE}{dx})_{\text{rad}} = (\frac{dE}{dx})_{\text{col}} \text{ seems to be in more common usage}$$
Electrons: Radiation length and Moliere radius

- The radiation length, $X_0$, of a material is defined as the distance over which an electron loses $1/e$ of its energy via radiation. $X_0$ is measured in cm or in $\text{g/cm}^2$.
- Roughly speaking, an electron emits one photon through bremsstrahlung for every $1 X_0$ traversed.
- $X_0$ also controls the distance over which photons pair produce
- Approximate formula for $X_0$:
  \[
  X_0 = \frac{716.4 A}{Z(Z + 1) \ln(287/\sqrt{Z})} \left[ \frac{\text{g}}{\text{cm}^2} \right]
  \]
- Development in the transverse direction scales with the Moliere radius:
  \[
  R_M = X_0 \frac{21.2 \text{ MeV}}{E_C}
  \]
- If the shower longitudinal shower profile is measured in units of $X_0$ transverse profile is measured in units of $R_M$ then (roughly speaking) all showers look the same independent of material and energy.
Effective Z and A

• For mixtures, one can compute an effective Z and A based on the fraction by weight of each of the component elements:

\[ A_{\text{eff}} = p_i A_i \]
\[ Z_{\text{eff}} = p_i Z_i \]

\[ p_i \quad : \quad \text{fraction by weight of element } i \]
\[ A_i \quad : \quad \text{atomic mass of element } i \]
\[ Z_i \quad : \quad \text{atomic number of element } i \]
Electrons: Radiation length and Moliere radius

<table>
<thead>
<tr>
<th>Material</th>
<th>Radiation length $g/cm^2$</th>
<th>Radiation length $cm$</th>
<th>Moliere radius $g/cm^2$</th>
<th>Moliere radius $cm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>liquid H$_2$</td>
<td>61.28</td>
<td>866</td>
<td>3.57</td>
<td>50.49</td>
</tr>
<tr>
<td>liquid Ar</td>
<td>19.55</td>
<td>14.0</td>
<td>9.95</td>
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<tr>
<td>C</td>
<td>42.70</td>
<td>18.8</td>
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<td>Fe</td>
<td>13.84</td>
<td>1.76</td>
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<td>SiO$_2$</td>
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<td>Polystyrene scintillator</td>
<td>43.72</td>
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<td>8.25</td>
</tr>
<tr>
<td>Liquid scintillator</td>
<td>51.07</td>
<td>43.9</td>
<td>8.93</td>
<td>7.68</td>
</tr>
</tbody>
</table>

A sample of radiation lengths and Moliere radii for materials common in neutrino detectors.
Topology of electromagnetic showers:
Longitudinal development

Shower maximum occurs at

\[ t_{max} = \frac{a - 1}{b} = \ln \frac{E_0}{E_C} + C_i \]

where \( C_{i=e} = -0.5 \) for electron showers and \( C_{i=\gamma} = +0.5 \) for gamma showers.

The parameter \( b \) has been tabulated for several materials:

\[ \frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \]

\( \frac{X_0}{b} \equiv \text{"the shower length"} \)

Figure 27.19: Fitted values of the scale factor \( b \) for energy deposition profiles obtained with EGS4 for a variety of elements for incident electrons with \( 1 \leq E_0 \leq 100 \text{ GeV} \). Values obtained for incident photons are essentially the same.
Topology of electromagnetic showers
Transverse development

• In the transverse direction, shower profiles scale with the Moliere radius $R_M$. Roughly 90% of the energy is located within $2R_M$ of the shower axis.

• The transverse distribution is not Gaussian:

$$f(r) = p \left( \frac{2r R_C^2}{(r^2 + R_C^2)^2} \right) + (1 - p) \left( \frac{2r R_T^2}{(r^2 + R_T^2)^2} \right)$$

Grindhammer and Peters hep-ex/0001020

core dominated
tail dominated
Neutrino detection channels

Charged-current

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Neutral-current
Hadron showers

Hadrons will interact strongly in a material after traversing one “interaction length” $= \lambda_I$

Hadrons can produce tracks or showers depending on the relative importance of energy loss due to collisions and energy loss due to strong interactions. When:
- range due to ionization $< \lambda_I$ $\rightarrow$ track
- range due to ionization $> \lambda_I$ $\rightarrow$ shower

**Simple hadron shower model:**

I) Hadron travels one interaction length and interacts strongly
II) $\sim 1/2$ of the energy is carried by a single secondary hadron
III) Remaining energy carried off by several slow pions
IV) Process continues until secondary hadrons lose all their energy through collisions

Depending on rate of pi0 production, hadron showers will have EM showers embedded in them.
Adding interaction length to our table

<table>
<thead>
<tr>
<th>Material</th>
<th>Radiation length</th>
<th>Moliere radius</th>
<th>Interaction length</th>
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<tbody>
<tr>
<td>liquid H₂</td>
<td>61.28 g/cm²</td>
<td>3.57 g/cm²</td>
<td>50.8 g/cm²</td>
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<tr>
<td>liquid Ar</td>
<td>19.55 g/cm²</td>
<td>9.95 g/cm²</td>
<td>117.2 g/cm²</td>
</tr>
<tr>
<td>C</td>
<td>42.70 g/cm²</td>
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<tr>
<td>Fe</td>
<td>13.84 g/cm²</td>
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</tr>
</tbody>
</table>
Comparison of EM and hadron shower

- Electromagnetic processes tend to be forward peaked
- Hadronic processes typically produce particles with $P_T \approx 300$ MeV/c

→ EM showers tend to be relatively compact in the transverse direction compared to hadron showers which tend to be more diffuse in the transverse direction
- Example at right shows 15 GeV e and π in glass ($Z \approx 11$).

Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.
\( \nu_\mu \) CC event in the NOMAD detector

(1) Veto wall
(2) Drift chambers
(3) Trigger plane
(4) Transition radiation tracker
(5) Trigger plane
(6) Preshower region
(7) Electromagnetic calorimeter
(8) Hadron calorimeter
(9) Muon tracking
(10) Forward calorimeter
(11) Magnet return yoke
(12) Magnet
The MINERvA Detector

MINOS steel/scintillator detector used as muon ranger
Can you classify these events from the MINOS experiment?
Can you classify these events from the MINOS experiment?

- $\nu_\mu$ CC Event
- $\nu^e$ CC Event

*long $\mu$ track+ hadronic activity at vertex*
Can you classify these events from the MINOS experiment?

- $\nu_\mu$ CC Event
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- NC Event
  - short event, often diffuse
Can you classify these events from the MINOS experiment?

$\nu_\mu$ CC Event

- long $\mu$ track + hadronic activity at vertex

$\nu_e$ CC Event

- short, with typical EM shower profile

NC Event

- short event, often diffuse
Tutorials

• For the tutorials, we will be working with neutrino interactions as calculated by the NEUGEN3 program. The interactions are stored as root trees, so you will need access to a computer with root installed.

• Instructions posted at: http://enrico1.physics.indiana.edu/messier/nufact08