Atmospheric muons & neutrinos in neutrino telescopes

• Neutrino oscillations
• Muon & neutrino beams
• Muons & neutrinos underground
Atmospheric neutrinos

- Produced by cosmic-ray interactions
  - Last component of secondary cosmic radiation to be measured
  - Close genetic relation with muons
    - $p + A \rightarrow \pi^\pm (K^\pm) + \text{other hadrons}$
    - $\pi^\pm (K^\pm) \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$
    - $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu (\nu_\mu) + \nu_e (\bar{\nu}_e)$
Historical context

Detection of atmospheric neutrinos

- Markov (1960) suggests Cherenkov light in deep lake or ocean to detect atmospheric $\nu$ interactions for neutrino physics
- Greisen (1960) suggests water Cherenkov detector in deep mine as a neutrino telescope for extraterrestrial neutrinos
- First recorded events in deep mines with electronic detectors, 1965: CWI detector (Reines et al.); KGF detector (Menon, Miyake et al.)

Two methods for calculating atmospheric neutrinos:

- From muons to parent pions infer neutrinos (Markov & Zheleznykh, 1961; Perkins)
- From primaries to $\pi$, K and $\mu$ to neutrinos (Cowsik, 1965 and most later calculations)
- Essential features known since 1961: Markov & Zheleznykh, Zatsepin & Kuz’min
- Monte Carlo calculations follow second method

Stability of matter: search for proton decay, 1980’s

- IMB & Kamioka -- water Cherenkov detectors
- KGF, NUSEX, Frejus, Soudan -- iron tracking calorimeters
- Principal background is interactions of atmospheric neutrinos
- Need to calculate flux of atmospheric neutrinos

Berlin, 1 October 2009

Tom Gaisser
Historical context (cont’d)

Atmospheric neutrino anomaly - 1986, 1988 …
• IMB too few $\mu$ decays (from interactions of $\nu_\mu$) 1986
• Kamioka $\mu$-like / e-like ratio too small.
• Neutrino oscillations first explicitly suggested in 1988 Kamioka paper
• IMB stopping / through-going consistent with no oscillations (1992)
• Hint of pathlength dependence from Kamioka, Fukuda et al., 1994

Discovery of atmospheric neutrino oscillations by S-K
• Super-K: “Evidence for neutrino oscillations” at Neutrino 98
• Subsequent increasingly detailed analyses from Super-K: $\nu_\mu \leftrightarrow \nu_\tau$
• Confirming evidence from MACRO, Soudan, K2K, MINOS
• Analyses based on ratios comparing to 1D calculations
• Compare up vs down

Parallel discovery of oscillations of Solar neutrinos
• Kamioka, Super-K, SNO … higher energy with directionality
• $\nu_e \leftrightarrow (\nu_\mu, \nu_\tau)$
Atmospheric neutrino beam

- Cosmic-ray protons produce neutrinos in atmosphere
- $\nu_\mu/\nu_e \sim 2$ for $E_\nu < \text{GeV}$
- Up-down symmetric
- Oscillation theory:
  - Characteristic length ($E/\delta m^2$)
  - related to $\delta m^2 = m_1^2 - m_2^2$
  - Mixing strength ($\sin^2 2\theta$)
- Compare 2 pathlengths
  - Upward: 10,000 km
  - Downward: 10 – 20 km

$$P(\nu_\mu \leftrightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left( \frac{1.27 L(\text{km}) \delta m^2(\text{eV}^2)}{E_\nu(\text{GeV})} \right)$$

Wolfenstein; Mikheyev & Smirnov
Classes of atmospheric $\nu$ events

- Contained (any direction)
- $\nu$-induced $\mu$ (from below)

Plot is for Super-K but the classification is generic

Berlin, 1 October 2009    Tom Gaisser
Super-K atmospheric neutrino data (hep-ex/0501064)

CC $\nu_e$

Sub-GeV e-like $P < 400$ MeV/c

Number of Events

Sub-GeV $\mu$-like $P < 400$ MeV/c

Multi-ring Sub-GeV $\mu$-like

Multi-GeV $\mu$-like

Upward through-going $\mu$

CC $\nu_\mu$

Sub-GeV e-like $P > 400$ MeV/c

Number of Events

Sub-GeV $\mu$-like $P > 400$ MeV/c

Multi-ring Multi-GeV $\mu$-like

Upward stopping $\mu$

Multi-GeV e-like

Number of Events

Multi-GeV $\mu$-like

PC

1489 day FC+PC data + 1646 day upward going muon data
Atmospheric $\nu$

$\nu_\mu \leftrightarrow \nu_\tau$, $\delta m^2 = 2.5 \times 10^{-3}$ eV$^2$  
maximal mixing

Solar neutrinos

$\nu_e \leftrightarrow \{\nu_\mu, \nu_\tau\}$, $\delta m^2 \sim 10^{-4}$ eV$^2$  
large mixing

3-flavor mixing

Flavor state $|\nu_\alpha\rangle = \Sigma_i U_{\alpha i} |\nu_i\rangle$, where $|\nu_i\rangle$ is a mass eigenstate
High-energy Neutrino telescopes

<table>
<thead>
<tr>
<th>Detector</th>
<th>Number of OMs</th>
<th>Enclosed volume (Megatons)</th>
<th>Depth (m.w.e)</th>
<th>Status</th>
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<td>15</td>
<td>1350-1850</td>
<td>2000-2009</td>
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<td>IceCube</td>
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<td>km$^3$</td>
<td>2300-3300 (NEMO)</td>
<td>Design study</td>
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<tr>
<td></td>
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<td>3000-4000 (NESTOR)</td>
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<tr>
<td></td>
<td></td>
<td>km$^3$</td>
<td>1400-2400 (ANTARES site)</td>
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</tr>
<tr>
<td>GVD (future Baikal)</td>
<td>~2500</td>
<td>km$^3$</td>
<td>800-1300</td>
<td>Design study</td>
</tr>
</tbody>
</table>

Table 4: Parameters of existing and proposed neutrino neutrino telescopes in water and ice.

Large volume--coarse instrumentation--high energy (> TeV) as compared to Super-K with 40% photo-cathode over 0.05 Mton
Detecting neutrinos in H$_2$O

Proposed by Greisen, Markov in 1960

Heritage:
- DUMAND
- IMB
- Kamiokande

Super-K
SNO
IceCube
ANTARES
The neutrino landscape

Lines show atmospheric neutrinos + antineutrinos

Expected flux of relic supernova neutrinos

Astrophysical neutrinos (WB “bound” / 2 for osc)

Solar $\nu$

Prompt $\nu$

Slope = 3.7

Slope = 2.7

RPQM for prompt $\nu$ from charm
Bugaev et al., PRD58 (1998) 054001

Cosmogenic neutrinos

Berlin, 1 October 2009

Tom Gaisser
The atmosphere (exponential approximation)

Pressure = \( X_v = X_0 \exp\left\{ -h_v / h_o \right\} \), where \( h_o = 6.4 \) km for \( X_v < 200 \) g / cm\(^2\) and \( X_0 = 1030 \) g / cm\(^2\)

Density = \( \rho = -dX_v / dh_v = X_v / h_o \) \( X_v \sim p = \rho RT \rightarrow h_o \sim RT \)

\[
X_v \approx h \cos \theta + \frac{1}{2} \frac{h^2}{R_\theta} \sin^2 \theta \approx h \cos \theta
\]

Slant depth \( X = \int_1^\infty \rho(l) \, dl \approx X_v / \cos \theta \)

\( h = h_v / \cos \theta \)
Cascade equations

For hadronic cascades in the atmosphere

\[ \frac{dN_i(E, X)}{dX} = -\left( \frac{1}{\lambda_i} + \frac{1}{d_i} \right) N_i(E, X) + \sum_j \int \frac{F_{ji}(E_i, E_j)}{E_i} \frac{N_j(E_j)}{\lambda_j} dE_j, \]

\( X = \) depth into atmosphere \( d = \) decay length

\( \lambda = \) Interaction length

\[ F_{ac}(E_c, E_\alpha) \equiv E_c \frac{d\eta_c(E_c, E_\alpha)}{dE_c} \]

- \( F_{ji}(E_i, E_j) \) has no explicit dimension, so \( F \rightarrow F(\xi) \)
  - \( \xi = E_i/E_j \) & \( \int \ldots F(E_i, E_j) \, dE_j / E_i \rightarrow \int \ldots F(\xi) \, d\xi / \xi^2 \)
  - Small scaling violations from \( m_i, \Lambda_{\text{QCD}} \sim \text{GeV} \), etc
  - Still... a remarkably useful approximation
Boundary conditions

Boundary condition for inclusive flux

\[ N(E, 0) = N_0(E) = \frac{dN}{dE} \approx 1.8 \times 10^{-2.7} \text{ nucleons} \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{GeV/A} \]
Uncorrelated fluxes in atmosphere

Example: flux of nucleons
Approximate: $\lambda \sim$ constant, leading nucleon only

$$\frac{dN(E,X)}{dx} = - \frac{N(E,X)}{\lambda_N} + \frac{1}{\lambda_N} \int_0^1 N\left(\frac{E}{\bar{E}},X\right) F_{NN}(\bar{E}) \frac{d\bar{E}}{\bar{E}^2}$$

Separate X- and E-dependence; try factorized solution, $N(E,X) = f(E) \cdot g(X)$,

$$f(E) \sim E^{-(\gamma+1)}$$

$$\frac{g'(x)}{g(x)} = - \frac{1}{\lambda_N} + \frac{1}{\lambda_N} \int_0^1 f\left(\frac{E}{\bar{E}}\right) F_{NN}(\bar{E}) \frac{d\bar{E}}{\bar{E}^2}$$

Separation constant $\Lambda_N$ describes attenuation of nucleons in atmosphere

$$\frac{g'(x)}{g(x)} = \frac{d \ln g(x)}{dx} = - \frac{1}{\Lambda_N}$$

$$g(x) = a e^{-x/\Lambda_N}$$
Nucleon fluxes in atmosphere

Evaluate $\Lambda_N$:

\[-\frac{1}{\Lambda_N} = -\frac{1}{\lambda_N} + \frac{1}{\lambda_N} \frac{E}{b} \int_0^1 b \left( \frac{E}{E} \right) f_{\text{num}}(\frac{E}{E}) \frac{dE}{E} \]

\[\int_0^1 f_{\text{num}}(\frac{E}{E}) \frac{dE}{E} = Z_{\text{num}} \approx 0.3 + \Lambda_N = \frac{\lambda_N}{1 - Z_{\text{num}}}\]

Flux of nucleons:

\[N(E, X) = g(x)f(E) = ab e^{-\frac{x}{\Lambda_N}} e^{-x} + ab = K\]

$$N(E, X) = N(E, 0) \times \exp\{-X/\Lambda_N\}$$

K fixed by primary spectrum at $X = 0$
Comparison to proton fluxes

Account for $p \rightarrow n$

\[ \frac{p}{N} = \frac{1 + \delta_0 e^{-x/\lambda^\prime}}{2} \]

\[ \lambda_N = 84 \, g/cm^2, \quad \Lambda_N = 120 \, g/cm^2 \]

\[ \delta_0 = \frac{P_0 - n_0}{N} = 0.77 \]

\[ \lambda^\prime = \frac{\lambda_N}{2} = 42 \, g/cm^2 \]

CAPRICE98 (E. Mocchiutti, thesis)

![Graph showing proton flux as a function of kinetic energy and depth in atmosphere.]
$\pi^\pm$ in the atmosphere

\[
\frac{d\Pi}{dX} = -\Pi(E, X) \left( \frac{1}{\Lambda_\pi} + \frac{\epsilon_\pi}{EX \cos \theta} \right) + \frac{Z_{N\pi} \lambda_N}{\lambda_N} N_0(E) e^{-X/\Lambda_N}.
\]

\[
\Pi(E, X) = e^{-(X/\Lambda_\pi)} \frac{Z_{N\pi}}{\lambda_N} N_0(E) \int_0^X \exp \left[ \frac{X'}{\Lambda_\pi} - \frac{X'}{\Lambda_N} \right] \left( \frac{X'}{X} \right)^{\frac{\epsilon_\pi}{E \cos \theta}} dX',
\]

(3.30)

\[
Z_{ac} \equiv \int_0^1 (x_L)^{\gamma-1} F_{ac}(x_L) dx_L,
\]

\[
\frac{1}{d_\pi} = \frac{m_\pi c^2 h_0}{E c \tau_\pi X \cos \theta} \equiv \frac{\epsilon_\pi}{EX \cos \theta}.
\]

$pion$ decay probability

$\pi$ decay or interaction more probable for $E < \epsilon_\pi$ or $E > \epsilon_\pi = 115$ GeV
\( \pi^\pm (K^\pm) \) in the atmosphere

- Low-energy limit: \( E_\pi < \varepsilon_\pi \sim 115 \text{ GeV} \)

\[
\Pi (E, x) \rightarrow N(E) \frac{Z_{\pi}^N}{\lambda_N} e^{-x/\lambda_N} \frac{xE_{\text{Earth}}}{\varepsilon_\pi}
\]

\[
\mathcal{O}_\pi (E, x) = \frac{E_\pi}{xE_{\text{Earth}}} \quad \Pi (E, x) = N(E) \frac{Z_{\pi}^N}{\lambda_N} e^{-x/\lambda_N}
\]

Production spectrum

\[
\mathcal{P}_\mu (E_\mu, x) = \int \frac{dN}{dE_\mu} (E_\mu, E_\pi) \mathcal{O}_\pi (E_\pi, x) dE_\pi
\]
\( \pi^\pm (K^\pm) \) in the atmosphere

- High-energy limit: \( E_\pi > \varepsilon_\pi \sim 115 \text{ GeV} \)

\[
\Pi(E, x) \rightarrow N(E) \frac{Z_{\nu\pi}}{1 - Z_{\nu\pi}} \frac{\Lambda^\pi}{\Lambda^\pi - \Lambda_N} \left( e^{-x/\Lambda^\pi} - e^{-x/\Lambda_N} \right)
\]

\[
\Omega_\pi(E, x) = \frac{E_\pi}{X \text{ Eareas}} \Pi(E, x)
\]

Spectrum of decaying pions one power steeper for \( E_\pi \gg \varepsilon_\pi \)
μ and ν_μ in the atmosphere

• To calculate spectra of μ and ν
  – Multiply Π(E,X) by pion decay probability
  – Include contribution of kaons
    • Dominant source of neutrinos
  – Integrate over kinematics of π → μ + ν_μ
c  and K → μ + ν_μ
  – Integrate over the atmosphere (X)
  – Good description of data
2-body decays of $\pi^\pm$ and $K^\pm$

In rest frame of parent $\mu$ and $\nu$ have equal and opposite 3 momentum $\mathbf{p}$

CM energy of neutrino $= p = |\mathbf{p}| = E_{\nu}^* = (M^2 - \mu^2) / (2 M)$

CM energy of muon $= p^2 + \mu^2 = E_{\mu}^* = (M^2 + \mu^2) / (2 M)$

$M =$ mass of parent meson, $\mu =$ mass of muon

For both $\mu$ and $\nu$ : $E_{LAB} = \gamma E^* + \beta \gamma p \cos(\theta)$
Momentum distributions for $\pi, K$

$$E_{\text{LAB}} = \gamma E^* + \beta \gamma p \cos(\theta)$$

$$\gamma = E_M / M \quad \text{and assume } E_{\text{LAB}} >> M \quad \text{so } \beta \to 1$$

Then $$(E^* - p) / M < E_{\text{LAB}} / E_M < (E^* + p) / M \quad \text{because} \quad -1 < \cos(\theta) < 1$$

Also, decay is isotropic in rest frame so $$\frac{dn}{d \cos(\theta)} = \text{constant}$$

But $$d E_{\text{LAB}} = d \cos(q) \quad \text{so} \quad \frac{dn}{d E_{\text{LAB}}} = \text{constant}$$

Normalization requires exactly one $\mu$ or $\nu$ so the normalization gives

$$(\text{constant})^{-1} = E_M \left( 1 - r \right) \quad \text{where} \quad r = \frac{\mu^2}{M^2} \quad \text{for both } \mu \text{ and } \nu$$

Note: $$r_{\pi} = 0.572 \quad \text{while} \quad r_K = 0.0458, \quad \text{an important difference!}$$
Compare $\mu$ and $\nu$

$$\frac{(E^* - p)}{M} < \frac{E}{E_m} < \frac{(E^* + p)}{M}$$

**muons**

$$r < \frac{E}{E_m} < 1 \Rightarrow \langle x_\mu \rangle = \frac{1 + r}{2}$$

**neutrinos**

$$0 < \frac{E_\nu}{E_m} < 1 - r \Rightarrow \langle x_\nu \rangle = \frac{1 - r}{2}$$

$$\nu_\pi = 0.572, \quad \nu_K = 0.0458$$

$$\pi^\pm \rightarrow \mu \, \nu \quad \langle x_\mu \rangle = 0.79 \quad \langle x_\nu \rangle = 0.21$$

$$K^\pm \rightarrow \mu \, \nu \quad \langle x_\mu \rangle = 0.523 \quad \langle x_\nu \rangle = 0.477$$
μ and νμ differ only by kinematics of π± and K± decay

\[
\frac{dN_\mu}{dE_\mu} \approx \frac{N_0(E_\mu)}{1 - Z_{NN}} \left\{ \frac{1}{A_{\pi\mu}} \frac{1}{1 + B_{\pi\mu} \cos \theta E_\mu/\epsilon_\pi} + 0.635 A_{K\mu} \right. \frac{1}{1 + B_{K\mu} \cos \theta E_\mu/\epsilon_K} \left. \right\}
\]

\[
A_{\pi\mu} \equiv Z_{N\pi} \left[ 1 - (r_\pi)^{\gamma+1} \right] (1 - r_\pi)^{-1} (\gamma + 1)^{-1}
\]

\[
B_{\pi\mu} = \frac{(\gamma + 2)}{(\gamma + 1)} \frac{1 - (r_\pi)^{\gamma+1}}{1 - (r_\pi)^{\gamma+2}} \frac{\Lambda_\pi - \Lambda_N}{\Lambda_\pi \ln(\Lambda_\pi/\Lambda_N)}
\]

\[
\frac{dN_\mu}{dE_\mu} \approx \frac{0.14}{cm^2 s sr GeV} E^{-2.7} \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115 GeV}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850 GeV}} \right\}
\]

\[
\frac{dN_\nu}{dE_\nu} \approx \frac{N_0(E_\nu)}{1 - Z_{NN}} \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos \theta E_\nu/\epsilon_\pi} + 0.635 \frac{A_{K\nu}}{1 + B_{K\nu} \cos \theta E_\nu/\epsilon_K} \right\}
\]

\[
A_{\pi\nu} \equiv Z_{N\pi} \frac{(1 - r_\pi)^\gamma}{\gamma + 1}
\]

\[
B_{\pi\nu} = \frac{(\gamma + 2)}{(\gamma + 1)} \frac{1}{1 - r_\pi} \left( \frac{\Lambda_\pi - \Lambda_N}{\Lambda_\pi \ln(\Lambda_\pi/\Lambda_N)} \right)
\]
Spectrum-weighted moments

\[ Z_{ab} \equiv \int \xi^{(\gamma-1)} F_{ab}(\xi) \, d\xi \]

<table>
<thead>
<tr>
<th>projectile</th>
<th>( p )</th>
<th>( \pi^+ )</th>
<th>( K^+ )</th>
</tr>
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<tr>
<td>( p )</td>
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<td>( n )</td>
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<td>( \pi^0 )</td>
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<td>( K^+ )</td>
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<tr>
<td>( K^- )</td>
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<td>0.0067</td>
<td>0.012</td>
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</table>
Interaction vs. decay

$X_v = 100 \text{ g/cm}^2$ at 15 km altitude

which is comparable to interaction lengths of hadrons in air

Relative magnitude of $\lambda_i$ and $d_i = X \cos \theta (E / \varepsilon_i)$ determines competition between interaction and decay

<table>
<thead>
<tr>
<th>$E_{\text{Lab}}$(TeV)</th>
<th>$p-p$</th>
<th>$p$-air</th>
<th>$\pi-p$</th>
<th>$\pi$-air</th>
<th>$K-p$</th>
<th>$K$-air</th>
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<td>[50]</td>
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Table 3.1: Decay constants.

<table>
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<tr>
<th>Particle</th>
<th>$c\tau_0$(cm)</th>
<th>$\epsilon$(GeV)</th>
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<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>$6.59 \times 10^4$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>780</td>
<td>115</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>$2.5 \times 10^{-6}$</td>
<td>$3.5 \times 10^{10}$</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>371</td>
<td>850</td>
</tr>
<tr>
<td>$K_S$</td>
<td>2.68</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>$K_L$</td>
<td>1554</td>
<td>205</td>
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<tr>
<td>$D^\pm$</td>
<td>0.028</td>
<td>$4.3 \times 10^7$</td>
</tr>
<tr>
<td>$D^0$</td>
<td>0.013</td>
<td>$9.2 \times 10^7$</td>
</tr>
<tr>
<td>$n$</td>
<td>$2.69 \times 10^{13}$</td>
<td>-</td>
</tr>
</tbody>
</table>
High-energy atmospheric neutrinos

Primary cosmic-ray spectrum (nucleons)

\[ \phi_N(E_N) \equiv E_N \frac{dN}{dE_N} \approx K E^{-1.7} \]

Nucleons produce

- pions
- charmed hadrons

Kaons produce most \( \nu_\mu \) for 100 GeV < \( E_\nu < 100 \) TeV

Eventually “prompt \( \nu \)” from charm decay dominate, ….but what energy?

Critical energy \( E_c = m_i c^2 \frac{h_0}{c \tau_i} \)
Importance of kaons at high E

- Importance of kaons
  - main source of $\nu > 100$ GeV
  - $p \rightarrow K^+ + \Lambda$ important
  - Charmed analog important for prompt leptons at higher energy
Neutrinos from kaons

Critical energy $e_i = m_i c^2 \frac{h_o}{c \tau_i}$

- $\epsilon_{\mu} = 1$ GeV
- $\epsilon_{\pi} = 115$ GeV
- $\epsilon_{\text{charm}} \sim 5 \times 10^7$ GeV
- $\epsilon_{KL} = 0.203$ TeV

Critical energies determine where spectrum changes, but $A_{K\nu}/A_{\pi\nu}$ and $A_{C\nu}/A_{K\nu}$ determine magnitudes.

New information from MINOS relevant to $\nu_\mu$ with $E >$ TeV
Electron neutrinos

\[ \phi_{\nu_e} = E^{-1.7} \left[ \frac{A_e}{1 + B_K E \cos^2 \theta / E_K} + \frac{B_e}{1 + B_K E \cos^2 \theta / E_K} \right] \]

\[ \phi_{\bar{\nu}_e} = E^{-1.7} \left[ \frac{c_e}{1 + B_K E \cos^2 \theta / E_K} + \frac{\bar{B}_e}{1 + B_K E \cos^2 \theta / E_K} \right] \]

\[ \phi_{\mu^+} \left[ 1 - e^{-\lambda / E \cos^2 \theta} \right] \]

\[ \phi_{\mu^-} \left[ 1 - e^{-\lambda / E \cos^2 \theta} \right] \]

\[ K^+ \rightarrow \pi^0 \nu_e e^\pm \ (\text{B.R. } 5\%) \]

\[ K_L^0 \rightarrow \pi^\pm \nu_e e \ (\text{B.R. } 41\%) \]

Kaons important for $\nu_e$ down to ~10 GeV

Berlin, 1 October 2009
TeV $\mu^+/\mu^-$ with MINOS far detector

- 100 to 400 GeV at depth $\rightarrow$ > TeV at production
- Increase in charge ratio shows
  - $p \rightarrow K^+ \Lambda$ is important
  - Forward process
  - $s$-quark recombines with leading di-quark
  - Similar process for $\Lambda_c$?

Increased contribution from kaons at high energy
MINOS fit ratios of Z-factors

\[
\frac{Z_{N\pi^+}}{Z_{N\pi^+} + Z_{N\pi^-}} = 0.55
\]

\[
\frac{Z_{NK^+}}{Z_{NK^+} + Z_{NK^-}} = 0.67.
\]

• Z-factors assumed constant for E > 10 GeV

• Energy dependence of charge ratio comes from increasing contribution of kaons in TeV range coupled with fact that charge asymmetry is larger for kaon production than for pion production

• Same effect larger for \(\nu_\mu / \bar{\nu}_\mu\) because kaons dominate
Atmospheric neutrinos – harder spectrum from kaons?

AMANDA atmospheric neutrino
arXiv:0902.0675v1

Re-analysis of Super-K
Gonzalez-Garcia, Maltoni, Rojo JHEP 2007
Signature of charm: $\theta$ dependence

For $\varepsilon_K < E \cos(\theta) < \varepsilon_c$, conventional neutrinos $\sim \sec(\theta)$, but “prompt” neutrinos independent of angle

$$\phi_{\nu}(E_{\nu}) = \frac{\phi_N(E_{\nu})}{1 - Z_{NN}} \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos \theta \frac{E_{\nu}}{E_{\pi}}} + \frac{A_{k\nu}}{1 + B_{k\nu} \cos \theta \frac{E_{\nu}}{E_K}} + \frac{A_{c\nu}}{1 + B_{c\nu} \cos \theta \frac{E_{\nu}}{E_c}} \right\}$$

Uncertain charm component most important near the vertical

Critical energy $\varepsilon_c = m_i c^2 \frac{h_\nu}{c \tau_i}$
Neutrinos from charm

- Main source of atmospheric $\nu$ for $E_\nu > ??$
- ?? > 20 TeV
- Large uncertainty in normalization!

Gelmini, Gondolo, Varieschi
Muons & Neutrinos underground

Muon average energy loss:

\[-\frac{dE_\mu}{dX} = a + b E_\mu\]

Table 1.2: Average muon range \( R \) and energy loss parameters calculated for standard rock [53]. Range is given in km-water-equivalent, or \( 10^5 \) g cm\(^{-2}\).

<table>
<thead>
<tr>
<th>( E_\mu ) GeV</th>
<th>( R ) km.w.e.</th>
<th>( a ) MeV g(^{-1}) cm(^2)</th>
<th>( b_{\text{brems}} ) ( 10^{-6} ) g(^{-1}) cm(^2)</th>
<th>( b_{\text{pair}} )</th>
<th>( b_{\text{nucl}} )</th>
<th>( \sum b_i )</th>
<th>( \sum b(\text{ice}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.05</td>
<td>2.17</td>
<td>0.70</td>
<td>0.70</td>
<td>0.50</td>
<td>1.90</td>
<td>1.66</td>
</tr>
<tr>
<td>100</td>
<td>0.41</td>
<td>2.44</td>
<td>1.10</td>
<td>1.53</td>
<td>0.41</td>
<td>3.04</td>
<td>2.51</td>
</tr>
<tr>
<td>1000</td>
<td>2.45</td>
<td>2.68</td>
<td>1.44</td>
<td>2.07</td>
<td>0.41</td>
<td>3.92</td>
<td>3.17</td>
</tr>
<tr>
<td>10000</td>
<td>6.09</td>
<td>2.93</td>
<td>1.62</td>
<td>2.27</td>
<td>0.46</td>
<td>4.35</td>
<td>3.78</td>
</tr>
</tbody>
</table>

from Reviews of Particle Physics, *Cosmic Rays*

Critical energy:

\[\epsilon \equiv \frac{a}{b} \approx 500 \text{ GeV}\]
μ energy spectrum underground

\[
E_\mu = (E_{\mu,0} + \epsilon) e^{-bX} - \epsilon
\]

\[
\frac{dN_\mu (X)}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}} \frac{dE_{\mu,0}}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}} e^{bX}
\]

Shallow:

\[
X \ll b^{-1} \approx 2.5 \text{ km water equivalent}
\]

\[
E_{\mu,0} \approx E_\mu (X) + aX
\]

Deep:

\[
E_{\mu,0} \approx (\epsilon + E_\mu (X)) \exp(bX)
\]
High-energy, deep muons

At large depths \( (bX \gg 1, \; X > 2.5 \text{ km\-w.e.}) \)

\[
\frac{dN_r}{dE_r} \sim \text{constant for } E_r < E = 500 \text{ GeV}
\]

Then

\[
\frac{dN_r}{dE_r} \rightarrow bX \frac{dN_r}{dE_0} \bigg|_{E_0 \sim e^{bX} E_r} \text{ for } E_r \gg E
\]

If surface spectrum is \( K E_0^{-(\gamma(E) + 1)} \)

then

\[
\frac{dN_r}{dE_r} \rightarrow K E^{-bX \gamma(E)} E_r^{-(\gamma(E) + 1)}
\]

\( \gamma(E) \rightarrow 2.7 \) for \( E \gg E_K \)
Differential and integral spectrum of atmospheric muons

Differential

\[ \frac{dN_\mu}{dE_\mu} \approx \frac{0.14}{\text{cm}^2 \text{s sr GeV}} E^{-2.7} \left\{ \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850 \text{ GeV}}} \right\} \]

Integral

\[ N_\mu (> E_\mu) = \frac{840 \text{ m}^{-2} \text{s}^{-1} \text{sr}^{-1}}{E_\mu^{1.7}} \left\{ \frac{1}{1 + \frac{E_\mu \cos \theta}{66 \text{ GeV}}} + \frac{0.054}{1 + \frac{E_\mu \cos \theta}{487 \text{ GeV}}} \right\} \]

Energy loss: \( E_\mu \) (surface) = \( \exp\{ b X \} \cdot (E_\mu + \varepsilon) - \varepsilon \)

Set \( E_\mu = \varepsilon \{ \exp[ b X ] - 1 \} \) in Integral flux to get depth – intensity curve
Plot shows $dN_\mu / d\ln(E_\mu)$
Detecting neutrinos

• Rate =
  Neutrino flux
  x Absorption in Earth
  x Neutrino cross section
  x Size of detector
  x Range of muon (for $\nu_\mu$)

  – (Range favors $\nu_\mu$ channel)

$$P_\nu(E_\nu, E_\mu, m_{\nu}) = N_A \int \frac{dE_\mu}{dE_\mu} \frac{d\sigma_\nu(E_\nu)}{dE_\mu} R(E_\mu, E_\mu, m_{\nu})$$

Probability to detect $\nu_\mu$-induced $\mu$
Neutrino effective area

\[ A_{\text{eff}}(\theta, E_\nu) = \varepsilon(\theta) A(\theta) P_\nu(E_\nu, E_\mu, \omega) e^{-\sigma_\nu(E_\nu) N_A X(\theta)} \]

- **Rate:**
  \[ = \int \phi_\nu(E_\nu) A_{\text{eff}}(E_\nu) dE_\nu \]
- **Earth absorption**
  - Starts 10-100 TeV
  - Biggest effect near vertical
  - Higher energy \( \nu \)'s absorbed at larger angles

![Muon-neutrino effective area for an ideal km\(^3\) detector](image.png)

Berlin, 1 October 2009
Neutrino-induced muons

\[
\frac{dN_{\mu}}{dE_{\mu}} = \int_{E_{\nu}}^{\infty} dE_{\nu} \frac{dN_{\nu}}{dE_{\nu}} \int_{E_{\nu}}^{\infty} dE' \frac{d\sigma_{\nu}}{dE'} G(x, E_{\nu}, E_{\nu}') dE'
\]

\[
\frac{d\sigma_{\nu}}{dE_{\nu}} = \frac{1}{E_{\nu}} \int_{0}^{1} \frac{d\sigma_{\nu}}{dxdy} dx \bigg|_y = 1 - E_{\nu}/E_{\nu}
\]

\[
\frac{d^2\sigma}{dx dy} = \frac{G_W^2 ME_{\nu}}{\pi} \frac{1}{\left(1 + Q^2/m_W^2\right)^2} x \left(Q_1 + (1-y)^2 Q_2\right)
\]

cross section per nucleon for $\nu_{\mu} \rightarrow E_{\mu}'$

probability for muon to start with energy $E_{\mu}'$ propagate through $X$ g/cm$^2$ and end up with $E_{\mu}$ to $E_{\mu} + dE_{\mu}$
Atmospheric muons (shape only)
Muons in $\nu$ telescopes

Million to 1 background to signal from above.

→ Use Earth as filter; look for neutrinos from below.

Berlin, 1 October 2009

Tom Gaisser
Muons in IceCube

Downward atmospheric muons

Neutrino-induced muons from all directions

Crossover at ~85° for shallow detectors
~75° for deepest Mediterranean site

→ P. Berghaus et al., ISVHECRI-08 also HE1.5

Berlin, 1 October 2009

Tom Gaisser
Atmospheric $\mu$ and $\nu$ in IceCube

Extended energy reach of km$^3$ detector

4492 events at SBM=1.2

Preliminary

The Atmospheric Muon Spectrum as derived from IceCube data is shown above, compared to previous measurements and various theoretical predictions [3]. The error bars shown do not yet include systematic detector effects. Even though only about 10% of the entire data set has been unblinded, the energy range extends already significantly higher than previous measurements.

Patrick Berkhaus, ICRC 2009

Dmitry Chirkin, ICRC 2009

Currently limited by systematics
Deep muons as a probe of weather in the stratosphere

- Barrett et al.
- MACRO
- MINOS far detector
  - Sudden stratospheric warmings observed
- IceCube
  - Interesting because of unique seasonal features of the upper atmosphere over Antarctica related to ozone hole
- Decay probability \( \sim T \):
  - \( h_0 \sim RT \)

\[
\frac{1}{d_\pi} = \frac{m_\pi c^2 h_0}{E c \tau_\pi X \cos \theta} \equiv \frac{\epsilon_\pi}{E X \cos \theta}.
\]

Pion decay probability
Fig. 1. The temporal behavior of the South Pole stratosphere from May 2007 to April 2009 is compared to IceTop DOM counting rate and the high energy muon rate in the deep ice. (a) The temperature profiles of the stratosphere at pressure layers from 20 hPa to 100 hPa where the first cosmic ray interactions happen. (b) The IceTop DOM counting rate (black - observed, blue - after barometric correction) and the surface pressure (orange). (c) The IceCube muon trigger rate and the calculated effective temperature (red).