Atmospheric Neutrinos

Theory and experimental data of atmospheric neutrino production
Outline

• Historical introduction

• Atmospheric $\nu$ beam for particle physics
  – Uncertainties in calculated neutrino fluxes
  – Relation to studies of neutrino oscillations

• Atmospheric $\nu$ as foreground for astrophysical neutrinos
  – Extension to very low and very high energy
    • Background for diffuse, relic SNR neutrinos
    • Background for indirect searches for WIMPs
    • Background for neutrino telescopes
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
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 Neutriino 98
- Subsequent increasingly detailed analyses from Super-K 1998…
- Confirming evidence from MACRO and Soudan
- Analyses based on ratios comparing to 1D calculations

Need for precise, complete, accurate, 3D calculations
- $\Theta \sim P_T / E$ is large for sub-GeV neutrinos
- Bending of muons in geomagnetic field important for $\nu$ from $\mu$ decay
- Complicated angular/energy dependence of primaries (AMS measurement)
- Use improved primary spectrum and hadroproduction information

ν 2006 June 16, Santa Fe
(MZhg)ZK

- Basic features of neutrino flux calculated and known since 1961
<table>
<thead>
<tr>
<th>Name</th>
<th>Journal/Details</th>
<th>1D/3D</th>
<th>Target</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zatsepin, Kuz’min</td>
<td>SP JETP 14:1294 (1961)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Many calculations</td>
<td>~ 1965 ---- ~1990</td>
<td>1D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agrawal, Gaisser, Lipari, Stanev</td>
<td>PRD 53: 1314 (1996)</td>
<td>1D</td>
<td></td>
<td>Target</td>
</tr>
<tr>
<td>P. Lipari</td>
<td>Asp. Phys 14:171 (2000)</td>
<td>3D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V. Plyaskin</td>
<td>PL B516:213 (2001)</td>
<td>3D</td>
<td></td>
<td>GHEISHA</td>
</tr>
<tr>
<td></td>
<td>hep-ph/0303146</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wentz et al</td>
<td>PRD 67 073020 (2003)</td>
<td>3D</td>
<td></td>
<td>Corsika: DPMJET VENUS, UrQMD</td>
</tr>
<tr>
<td>Liu, Derome, Buénerd</td>
<td>PRD 67 073022 (2003)</td>
<td>3D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Favier, Kossalsowski, Vialle</td>
<td>PRD 68 093006 (2003)</td>
<td>3D</td>
<td></td>
<td>GFLUKA</td>
</tr>
<tr>
<td>Barr, Gaisser, Lipari, Robbins, Stanev</td>
<td>PRD 70 023006 (2004)</td>
<td>3D</td>
<td>C</td>
<td>Target</td>
</tr>
<tr>
<td>Honda, Kajita, Kasahara, Midorikawa</td>
<td>PRD 64 053011 (2001)</td>
<td>3D</td>
<td></td>
<td>DPMJET</td>
</tr>
<tr>
<td></td>
<td>PRD 70 043008 (2004)</td>
<td></td>
<td></td>
<td>A</td>
</tr>
</tbody>
</table>
Comparison of 3 calculations used by Super-K

Differences ~ 10%
( using similar primary spectra )
Classes of atmospheric $\nu$ events

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

# Graph

- $dN/dE$ vs. $E_{\nu}$, GeV
  - sub GeV
  - multi GeV
  - through-going muons
  - stopping muons

# Equation

$$\nu_e \text{ (or $\nu_\mu$)}$$

$\nu^8$
Super-K atmospheric neutrino data (hep-ex/0501064)

CC $\nu_e$
- Sub-GeV e-like $P < 400$ MeV/c
- Sub-GeV $\mu$-like $P < 400$ MeV/c
- Multi-GeV e-like
- Multi-GeV $\mu$-like

CC $\nu_\mu$
- Sub-GeV e-like $P > 400$ MeV/c
- Sub-GeV $\mu$-like $P > 400$ MeV/c
- Multi-GeV $\mu$-like
- Multi-ring Sub-GeV $\mu$-like
- Multi-ring Multi-GeV $\mu$-like
- PC

1489day FC+PC data + 1646day upward going muon data
Super-K adjust atmospheric $\nu$ parameters in their fit

Atmospheric parameters only

Effective flux including shifts in neutrino cross sections, etc.
A priori analysis of uncertainties
Giles Barr et al., 2006

Uncertainties in
\[ p + A \rightarrow \pi \, (K) + X \]

Assume 9 (\( \pi \)) + 4(K) independent regions

<table>
<thead>
<tr>
<th>( E_i ) (GeV)</th>
<th>Pions</th>
<th></th>
<th>Kaons</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;8</td>
<td>10%</td>
<td>30%</td>
<td>40%</td>
</tr>
<tr>
<td>8–15</td>
<td>30%</td>
<td>10%</td>
<td>30%</td>
</tr>
<tr>
<td>15–30</td>
<td>30</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>30–500</td>
<td>30</td>
<td>15%</td>
<td>10%</td>
</tr>
<tr>
<td>&gt;500</td>
<td>30</td>
<td>15%+Energy dep.</td>
<td>30%</td>
</tr>
</tbody>
</table>

Assumed uncertainties in phase space

<table>
<thead>
<tr>
<th>( E_i ) (GeV)</th>
<th>Pions</th>
<th></th>
<th>Kaons</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;8</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>8–15</td>
<td>D</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>15–30</td>
<td>G</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>30–500</td>
<td>H + I(Energy dep.)</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>&gt;500</td>
<td>I</td>
<td>J</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainty in flux of \( \nu_\mu \) broken down by source (red: primary spectrum)

Tom Gaisser
Flavor ratio at production

- uncertainties \( \sim \) cancel in ratios (e.g. \( \nu_\mu/\nu_e \) differences < 1.5 %)
- \( r = \nu_\mu/\nu_e \) at production sets background for search for effects of solar & \( s_{13} \) mixing and the octant of \( \theta_{23} \) e.g.,
- \( N_e/N_e^{(0)} - 1 = P_2(r \cos^2 \theta_{23} - 1) \)
  - Peres & Smirnov, 2004
- \( \to 0 \) for \( r = 2, \theta_{23} = 45^\circ \)
- \( r_{\text{sub-GeV}} \sim 2.04 - 2.1 \)
- \( r \) larger for vertically upward

Near vertically up (\( \cos \theta < -0.5 \))

Neutrino flavor ratio (\( \nu_\mu/\nu_e \))

All directions
Analysis of uncertainties in ratios
Barr et al.

(a) $\nu_e / \bar{\nu}_e$
$E_\nu \, 0.3 - 3 \text{ GeV}$

(b) $\nu_e / \bar{\nu}_e$
$E_\nu \, 3 - 30 \text{ GeV}$
New measurements in progress

HARP
E910
NA49
MIPP

For example:
New results from NA49
p C → π⁺⁻ X at 158 GeV/c
hep-ex/0606028

Figure 18: Invariant cross section as a function of $x_F$ at fixed $p_T$ for a) $\pi^+$ and b) $\pi^-$ produced in p+C collisions at 158 GeV/c
Atmospheric neutrinos as background for astrophysical neutinos

• Some examples
  – Diffuse neutrinos from relic supernovae
    • anti-$\nu_e$, 20-50 MeV
  – Neutrinos from WIMP annihilation
    • 10 -1000 GeV
    • directional source (e.g. Sun) above atmospheric background
  – High energy neutrinos
    • Talk of Gary Hill Monday
Diffuse, relic supernova neutrinos

• Super-K limit is from $\bar{\nu}_e + p \rightarrow n + e^+$
• Neutron not detected in current Super-K
• Backgrounds:
  – atmospheric $\nu_e$ and $\bar{\nu}_e$
  – solar $\nu_e$ and reactor $\bar{\nu}_e$
  – atmospheric $\nu_\mu \rightarrow \mu$
    $(E_\mu < 50 \text{ MeV})$

Stopped $\mu$ below threshold
Improvement with tagged neutron

Prescribe gadolinium additive to detect neutrons and select anti-$\nu_e$ only

Beacom & Vagins, PRL 93 (2004) 171101
Calculations of anti-$\nu_e$ background
10-100 MeV

Note dependence on phase of solar cycle:

- 10 – 20% variation a signature of background, not of signal
- similar to response of neutron monitors

FLUKA 10-100 MeV

ν 2006 June 16, Santa Fe  
Tom Gaisser
Variation with solar cycle

McMurdo, Antarctica, Neutron Monitor
Bartol Research Institute, University of Delaware
27-day Averages - data through April 2006

RP, May 2006
Indirect limits on WIMPs in Sun

From $\nu_\mu$-induced upward muons

$\sim 5 \times 10^{-15} \text{ cm}^{-2}\text{s}^{-1}$


- disfavored out by direct searches
Time signature of background

Flux of atmospheric $\nu_{\mu}$
- higher from near horizon
- lower from near vertical
- parent mesons more likely to decay in less dense atmosphere

→ Lowest from direction of sun at local midnight

→ Possible signature to enhance sensitivity of search for WIMPs

\[ \nu \text{ 2006 June 16, } \text{Santa Fe} \]
Global view of atmospheric $\nu$ spectrum

Plot shows sum of neutrinos + antineutrinos

Possible $E^{-2}$ diffuse astrophysical spectrum (WB bound / 2 for osc)

RPQM for prompt $\nu$
Bugaev et al., PRD58 (1998) 054001
Slope = 2.7
Concluding comments

- Uncertainty in calculated $\nu$ fluxes at production ($0.1 < E_\nu < 10$ GeV)
  - Calculations differ by ~10%
  - $\nu_\mu/\nu_e \sim 2.1$ for sub-GeV; differences < 2%
  - a priori estimate: uncertainty in $\nu_\mu/\nu_e \sim 1$
  - HARP, E910, NA49, MIPP → further reductions?

- Properties of atmospheric $\nu$ distinguish signal from background:
  - Known secular and directional variations
  - Low content of $>\text{TeV} \ \nu_e, \nu_\tau$ compared to
    - Astrophysical $\nu_\mu: \nu_e: \nu_\tau \sim 1:1:1$