Atmospheric Neutrino Fluxes

• Historical introduction
• Sub-GeV $\nu$ in three dimensions
• Multi-GeV and $\nu$-induced upward $\mu$
• Atmospheric $\nu$ as background & calibration 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

Tom Gaisser
August 20, 2004
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
• 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
Atmospheric neutrino beam

- Up-down symmetric except for geomagnetic effects
- One detector for both
  - long baseline
  - short baseline
- $1 < L/E < 10^5$ km/GeV
- $\nu_\mu/\nu_e \sim 2$ for $E_\nu < \text{GeV}$

D. Ayres, A.K. Mann et al., 1982
Also V Stenger, DUMAND, 1980
## Summary of Atmospheric Neutrino Calculations

<table>
<thead>
<tr>
<th>Contributors</th>
<th>Journal and Year</th>
<th>Neutrino Flavor</th>
<th>Methodology</th>
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<tbody>
<tr>
<td>Zatsepin, Kuz’m’in</td>
<td>SP JETP 14:1294(1961)</td>
<td>Mu</td>
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<td>Many calculations</td>
<td>~ 1965 --- ~1990</td>
<td>1D</td>
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<tr>
<td>Honda, Kajita, Kasahara, Midorikawa</td>
<td>PRD 52: 4985 (1995)</td>
<td>1D * FRITIOF</td>
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<td>Agrawal, Gaisser, Lipari, Stanev</td>
<td>PRD 53: 1314 (1996)</td>
<td>1D * Target</td>
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<tr>
<td>Wentz et al</td>
<td>PRD 67 073020 (2003)</td>
<td>3D</td>
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<td>Liu, Derome, Buénerd</td>
<td>PRD 67 073022 (2003)</td>
<td>3D</td>
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<tr>
<td>Favier, Kossalsowski, Vialle</td>
<td>PRD 68 093006 (2003)</td>
<td>3D</td>
<td>GFLUKA</td>
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<tr>
<td>Barr, Gaisser, Lipari, Robbins, Stanev</td>
<td>PRD 70 023006 (2004)</td>
<td>3D Target</td>
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<tr>
<td>Honda, Kajita, Kasahara, Midorikawa</td>
<td>PRD 64 053011 (2001)</td>
<td>3D ** DPMJET</td>
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<td>astro-ph/0404457 to PRD</td>
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* Used for analysis of Super-K data in publications before 2004; ** used now
Overview of the calculation

\[ \phi_{\nu_i} = \text{primary flux} \otimes \text{cutoffs} \otimes \text{Yield} \]

\[ = \phi_p \otimes R_p \otimes Y_{p \to \nu_i} + \sum_A \left\{ \phi_A \otimes R_A \otimes Y_{A \to \nu_i} \right\} \]

\[ \sum \text{protons} \]

\[ \sum \text{nuclei} \]

Yield: \( p \to \pi^+ (k^+) \to \mu^+ + \nu_\mu (\bar{\nu}_\mu) \)

\[ \to \bar{\nu}_\mu (\nu_\mu) + \nu_e (\bar{\nu}_e) + e^+ \]

[Signal \sim \phi_{\nu_i} \otimes \sigma_{\nu_i}]
Primary spectrum

- Largest source of overall uncertainty
  - 1995: experiments differ by 50% (see lines)
  - Present: AMS, BESS within 5% for protons
  - discrepancy for He larger, but He only 20% of nucleon flux
  - CAPRICE lower by 15-20%
Primary spectrum: new standard?

Tom Gaisser
August 20, 2004

Atmospheric Neutrino Fluxes
Primary spectrum

- Compare 3 fits using same event generator (Target 2.1)
  - AGLS = PRD 53: 1996
  - Hamburg = TG et al., ICRC 2001 p. 1643 used for comparisons
  - $1.7 \times E^{-2.7}$ (c.g.s.) for analytic estimates

Note change of scale

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August 20, 2004

Atmospheric Neutrino Fluxes
Hadronic interactions

- Sub-GeV $\nu$ depend most on treatment of $\pi$ production
- $K^+$ dominate $E_\nu > 100$ GeV
- Compare 5 calculations:
  - Bartol (Target-1, 2.1)
  - Honda et al. (1995: Fritiof; present: Dpmjet3)
  - Battistoni et al. (Fluka)
- Uncertainties from interactions $\sim +/-15\%$
Hadronic interactions

Example: Compare original Target 1 with Target 2.1 (Target 3D): pions down, kaons up
Comparison (using same flux)

- New calculations lower than old, e.g.:
  - Target-2.1 / -1
  - Dpmjet3 / HKKM
  - 3 new calculations agree at Kamioka but less well at Soudan/SNO

- Larger uncertainty at high geomagnetic $\lambda$
  - Interactions $< 10$ GeV are important
Super-K atmospheric neutrino data (T. Kajita)

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 $\mu$-like, $P < 400$ MeV/c
- Multi-ring Sub-GeV $\mu$-like
- Multi-ring Multi-GeV $\mu$-like
- Upward stopping $\mu$
- Upward through-going $\mu$

1489 day FC+PC data + 1646 day upward going muon data
Flavor ratio at production

- $r = \nu_\mu / \nu_e$ at production sets background for search for effects of solar and $s_{13}$ mixing
- $\Delta_e = P_2(r \cos^2 \theta_{23} - 1)$
  Peres & Smirnov, 2004
- \[ \to 0 \] for $r = 2, \theta_{23} = 45^\circ$
- $r_{\text{sub-GeV}} \sim 2.04 - 2.1$
New hadro-production data expected

- **Diagram:**
  - Lego plot shows phase space weighting for sub-GeV events
  - Bars show existing data
- **New sources of data**
  - HARP
  - NA49 (P322)
  - MIPP (E907)
3-dimensional effects

- Characteristic 3D feature:
  - excess of $\nu$ near horizon
  - shown in top, left panel
  - lower panels show directions of $\mu$ and $e$
  - cannot see 3D effect directly; however:

- Horizontal excess is associated with a change in path-length distribution

Zenith angle dependence

G.D. Barr et al., PRD70 (2004) 023006
Path-length dependence

- Path length shorter near horizon on average in 3D case
  - $\cos(\theta) > 0$ only,
  - phase space favors nearby interaction scattering to large angle
  - 5-10% ($E_\nu \sim 0.3-1$ GeV)

- Size of effect not yet known
  - $\delta m^2 L/E$: decrease L by 5% in 1 angular bin out of 20
  - increase $\delta m^2$ by ~1% ?

from M. Honda et al., Phys. Rev. D64 (2001) 053001
3D orthogonal to S-K L/E analysis

S-K: hep-ex/0404034

Giles Barr, v-2004

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<thead>
<tr>
<th>3D</th>
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<td>b</td>
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Difference between 3D and 1D calculations

Neutrino Energy (GeV) vs.\(\cos \theta_z\)
Geomagnetic cutoffs & E-W effect as a consistency check

• Picture shows:
  – 20 GeV protons in geomagnetic equatorial plane
  – arrive from West and from near the vertical
  – but not from East

• Comparison to data:
  – provides consistency test of data & analysis

From cover of “Cosmic Rays” by A.M. Hillas (1972)
Cutoffs at Super-K

Measurement of East-West effect with atmospheric neutrinos--an important confirmation of analysis & interpretation of Super-K data as neutrino oscillations

ν flux, \( 0.4 < E_\nu < 3 \text{ GeV} \)

\(-0.5 < \cos(\theta) < 0.5\)

measured by Super-K and compared to 3 calculations

Tom Gaisser
August 20, 2004

Atmospheric Neutrino Fluxes
Higher energy atmospheric $\nu$

- Mean $E_{\nu} \sim 100$ GeV for $\nu$-induced upward $\mu$
- Note difference in normalization

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Analytic approximation

\[ \nu = \nu_\mu + \bar{\nu}_\mu \]

-- good for \( E_\nu > 10 \text{ GeV} \)

\[ \phi_\nu(E_\nu) = \frac{\phi_\nu(E_\nu)}{1 - Z_{n\nu}} \left\{ \frac{Z_{n\pi} Z_{\pi\nu}}{1 + D_{n\mu} \frac{\cos \theta E_\nu}{E_\pi}} \right\} \]

\[ + B_{k\nu} \frac{Z_{nK} Z_{K\nu}}{1 + D_{K\mu} \frac{\cos \theta E_\nu}{E_K}} \]

\[ Z_{n\pi} = 0.087 \quad Z_{nK} = 0.34 \]

\[ E_\pi = 115 \text{ GeV} \quad E_K = 850 \text{ GeV} \]
High energy (e.g. $\nu_\mu \rightarrow \mu$)

- Importance of kaons
  - main source of $\nu > 100$ GeV
  - $p \rightarrow K^+ + \Lambda$ important
  - Charmed analog important for prompt leptons
Importance of kaon production

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Atmospheric Neutrino Fluxes
Calibration with atmospheric $\nu$

- MINOS, etc.
- Neutrino telescopes
- Example*** of $\nu_\mu / \nu_e$
  - flavor ratio
  - angular dependence

***Note: this is maximal effect: horizontal = 85 - 90 deg in plots
Global view of atmospheric $\nu$ spectrum

Plot shows sum of neutrinos + antineutrinos

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

Uncertainty in level of charm a potential problem for finding diffuse neutrinos

Slope = 3.7

Slope = 2.7

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August 20, 2004

Atmospheric Neutrino Fluxes
Summary - oscillations

• Evidence for $\nu$ oscillation uses ratios:
  – Contained events
    • $\left(\frac{\nu_e}{\nu_\mu}\right)_{\text{data}} / \left(\frac{\nu_e}{\nu_\mu}\right)_{\text{calculated}}$
    • upward / downward
  – Neutrino-induced upward muons
    • stopping / through-going
    • vertical / horizontal
  – Broad response functions minimize dependence on slope of primary spectrum

• Uncertainties tend to cancel in comparison of ratios

• Observation of geomagnetic effects confirms experiment & interpretation
Summary & outlook

• Current generation of calculations is 3D but
  – changes due to improved treatment of primary flux and treatment of hadronic interactions, not primarily to 3D
  – Need further refinements to see sub-dominant aspects of three flavor oscillations in atmospheric neutrinos
  – Calculate $20 < E_\nu < 100 \text{ MeV}$: background for SNR neutrinos. Only FLUKA has done this so far

• Incorporate new hadro-production results
  – HARP below 15 GeV
  – NA 49, MIPP ~ 100 GeV

• Uncertainty in kaon production limits accuracy of flux above 100 GeV

• Uncertainty in charm production (prompt $\nu$) limits sensitivity for diffuse astrophysical ($> \text{TeV}$) neutrinos