Atmospheric Neutrinos

Physics signal,
Astrophysics calibration & background

Outline

- Historical introduction
- Atmospheric ν beam for particle physics
  - Comparison of calculations with data
  - Discovery of neutrino oscillations
- Atmospheric ν as foreground for astrophysical neutrinos
  - Extrapolation to high energy
  - Comments on calibration
  - Prompt neutrino background vs diffuse signal

Historical context

Detection of atmospheric neutrinos

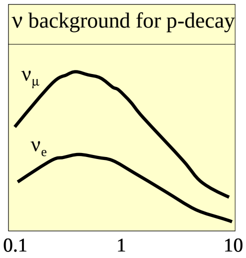
- Markov (1960) suggests Cherenkov light in deep lake or ocean to detect atmospheric ν interactions for neutrino physics
- Greisen (1960) suggests water Cherenkov detector in deep mine as a neutrino telescope for extraterrestrial neutrinos
- First recorded events in deep mines with electronic detectors,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

Two methods for calculating atmospheric neutrinos:

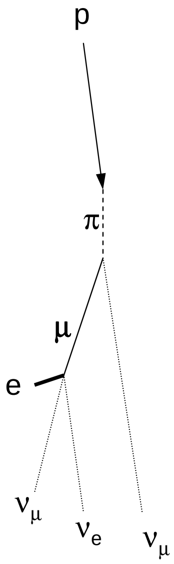
- From muons to parent pions infer neutrinos (Markov & Zheleznykh, 1961; Perkins)
- From primaries to π, K and μ to neutrinos (Cowsik, 1965 and most later calculations)
- Essential features known since 1961: Markov & Zheleznykh, Zatsepin & Kuz'min
- Monte Carlo calculations follow second method

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 μ decays (from interactions of ν_μ) 1986
- Kamioka μ-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 ν from μ decay
- Complicated angular/energy dependence of primaries (AMS measurement)
- Use improved primary spectrum and hadroproduction information

Overview of the calculation

ϕ_{ν_i} = primary flux $\otimes$ cutoffs $\otimes$ Yield

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

↖ protons ↖ nuclei

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

$\hookrightarrow \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) + e^\pm$

[Signal ~ $\phi_{\nu_i} \otimes \sigma_{\nu_i}$]

Summary of Atmospheric Neutrino Calculations

Zatsepin, Kuz'min	SP JETP 14:1294(1961)	Mu	🟪	
Many calculations	~ 1965 --- ~1990	1D	🟪	
D.H. Perkins	Asp.Phys. 2: 249 (1994)	Mu	🟪	
Honda, Kajita, Kasahara, Midorikawa	PRD 52: 4985 (1995)	1D	🟪	FRITIOF
Agrawal, Gaisser, Lipari, Stanev	PRD 53: 1314 (1996)	1D	🟪	Target
Battistoni et al	Asp.Phys 12:315 (2000) Asp.Phys 19:269 (2003)	3D	🟩 B	FLUKA
P. Lipari	Asp.Phys 14:171 (2000)	3D	🟩	
V. Plyaskin	PL B516:213 (2001) hep-ph/0303146	3D	🟦	GHEISHA
Tserkovnyak et al	Asp.Phys 18:449 (2003)	3D	🟦	CALOR-FRITIOF GFLUKA/GHEISHA
Wentz et al	PRD 67 073020 (2003)	3D	🟦	Corsika: DPMJET VENUS, UrQMD
Liu, Derome, Buénerd	PRD 67 073022 (2003)	3D	🟦	
Favier, Kossalsowski, Vialle	PRD 68 093006 (2003)	3D	🟦	GFLUKA
Barr, Gaisser, Lipari, Robbins, Stanev	PRD 70 023006 (2004)	3D	🟦 C	Target
Honda, Kajita, Kasahara, Midorikawa	PRD 64 053011 (2001) PRD 70 043008 (2004)	3D	🟦 A	DPMJET

Comparison of 3 calculations used by Super-K

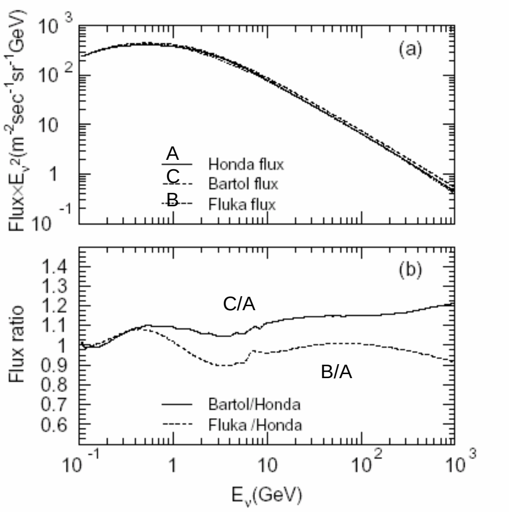


FIG. 2: (a) The direction averaged atmospheric neutrino energy spectrum for $\nu_\mu + \overline{\nu}_\mu$ calculated by several authors are shown by solid line [28], dashed line [29] and dotted line [25]. (b) The ratio of the calculated neutrino flux. The fluxes calculated in [29] (solid line) and [25] (dashed line) are normalized by the flux in [28].

Y. Ashi et al. (Super-K Collaboration)
hep-ex/0501064

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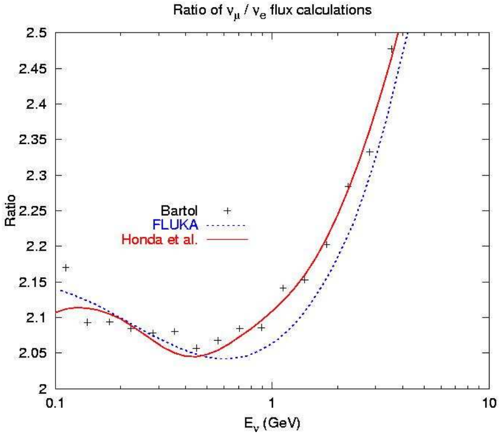
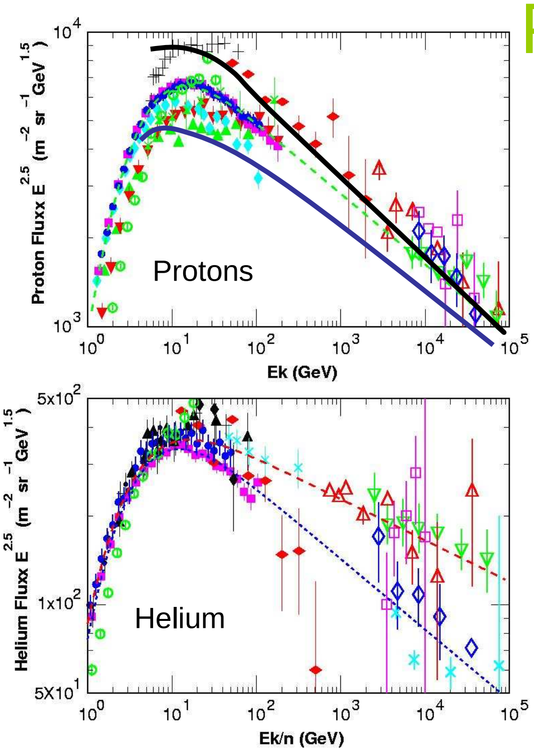
Flavor ratio at production

- uncertainties ~cancel in ratios (e.g. ν_μ/ν_e)
- ν_μ/ν_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
- → 0 for $r = 2$, $\theta_{23}=45^o$
- $r_{\text{sub-GeV}} \sim 2.04 - 2.1$

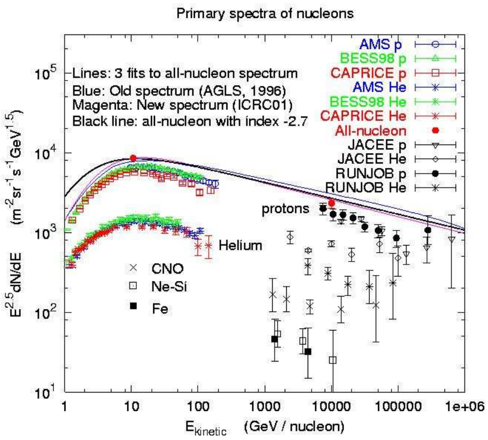




Primary spectrum

- 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%

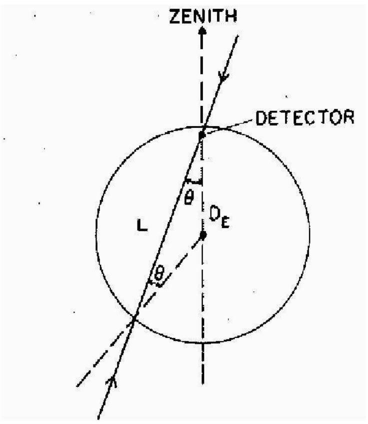
Primary spectrum: new standard?

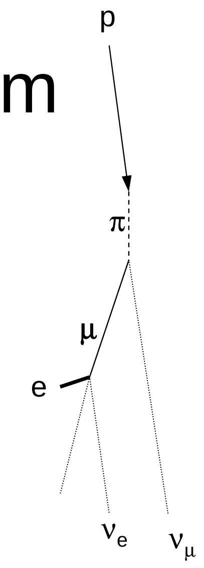


- Fit BESS and AMS
- Include small contributions from heavy elements
- Extrapolate to high E
- Use μ measurements as a constraint

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 $E_\nu <$ GeV





D. Ayres, A.K. Mann et al., 1982

Also V Stenger, DUMAND, 1980

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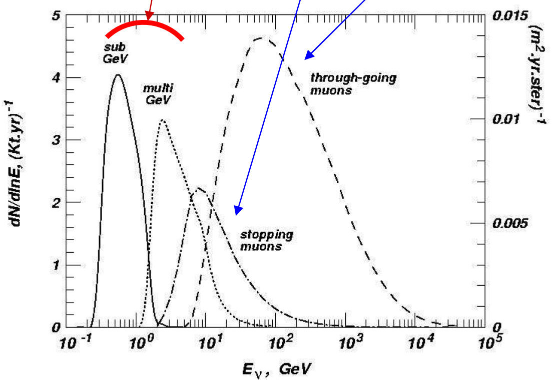
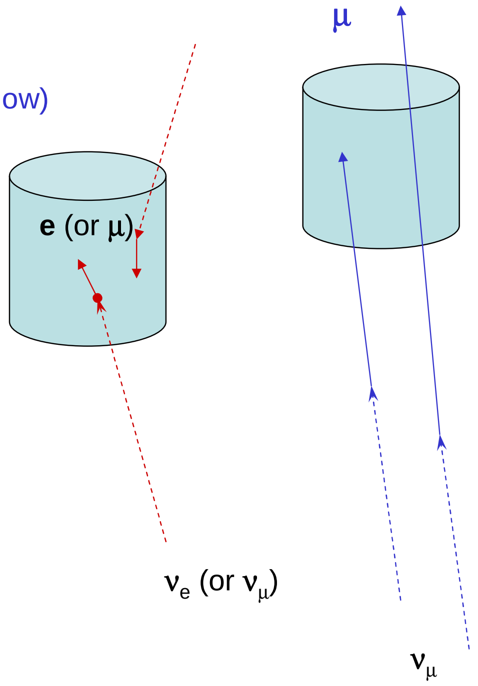
Classes of atmospheric ν events

Contained (any direction)

ν-induced μ (from below)





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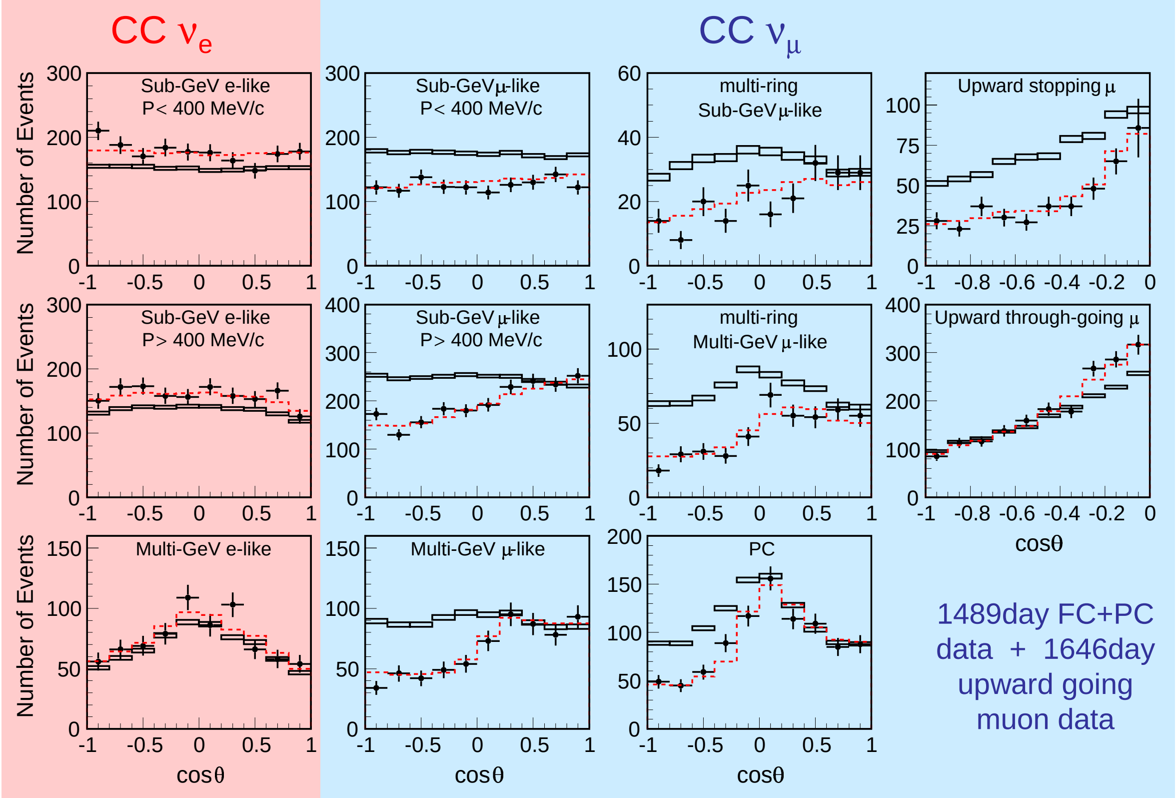
Super-K atmospheric neutrino data (hep-ex/0501064)

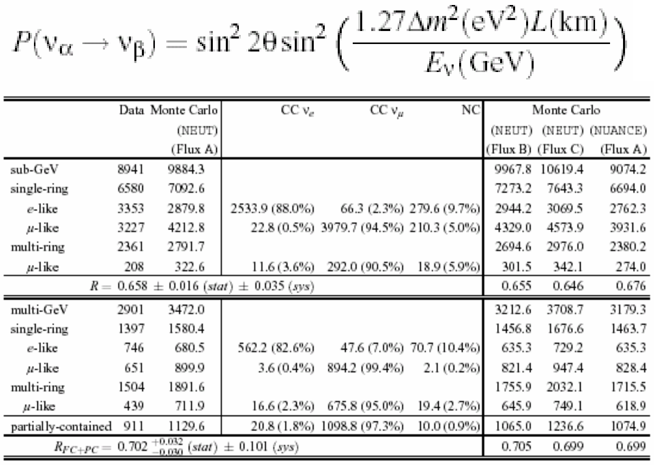


1489day FC+PC data + 1646day upward going muon data

Fit 2 flavor mixing:
$\sin^2\theta_{23} = 1.0$
$\delta m^2 = 2.1\text{x}10^{-3}\ \text{eV}^2$

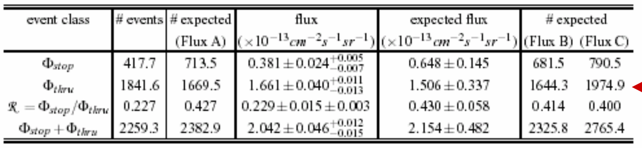
Super-K fits

38 parameters represent uncertainties in flux of atmospheric neutrinos

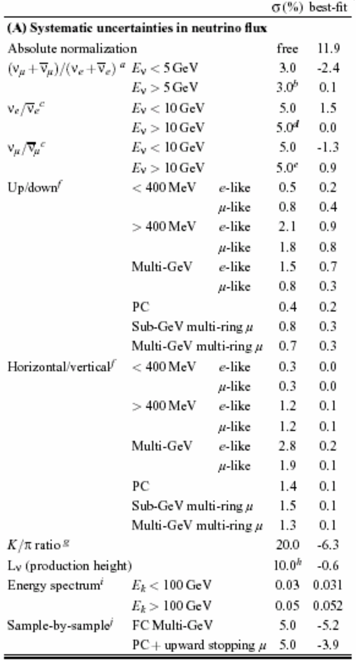


$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\text{eV}^2)L(\text{km})}{E_\nu(\text{GeV})}\right)$$

	Data	Monte Carlo (NEUT) (Flux A)	CC ν_e	CC ν_μ	NC	Monte Carlo (NEUT) (Flux B)	(NEUT) (Flux C)	(NUANCE) (Flux A)
sub-GeV	8941	9884.3				9967.8	10619.4	9074.2
single-ring	6580	7092.6				7273.2	7643.3	6694.0
e-like	3353	2879.8	2533.9 (88.0%)	66.3 (2.3%)	279.6 (9.7%)	2944.2	3069.5	2762.3
μ-like	3227	4212.8	22.8 (0.5%)	3979.7 (94.5%)	210.3 (5.0%)	4329.0	4573.9	3931.6
multi-ring	2361	2791.7				2694.6	2976.0	2380.2
μ-like	208	322.6	11.6 (3.6%)	292.0 (90.5%)	18.9 (5.9%)	301.5	342.1	274.0
$R =$ 0.658 ± 0.016 (*stat*) ± 0.035 (*sys*)						0.655	0.646	0.676
multi-GeV	2901	3472.0				3212.6	3708.7	3179.3
single-ring	1397	1580.4				1456.8	1676.6	1463.7
e-like	746	680.5	562.2 (82.6%)	47.6 (7.0%)	70.7 (10.4%)	635.3	729.2	635.3
μ-like	651	899.9	3.6 (0.4%)	894.2 (99.4%)	2.1 (0.2%)	821.4	947.4	828.4
multi-ring	1504	1891.6				1755.9	2032.1	1715.5
μ-like	439	711.9	16.6 (2.3%)	675.8 (95.0%)	19.4 (2.7%)	645.9	749.1	618.9
partially-contained	911	1129.6	20.8 (1.8%)	1098.8 (97.3%)	10.0 (0.9%)	1065.0	1236.6	1074.9
$R_{FC+PC} = 0.702\,^{+0.032}_{-0.030}$ (*stat*) ± 0.101 (*sys*)						0.705	0.699	0.699

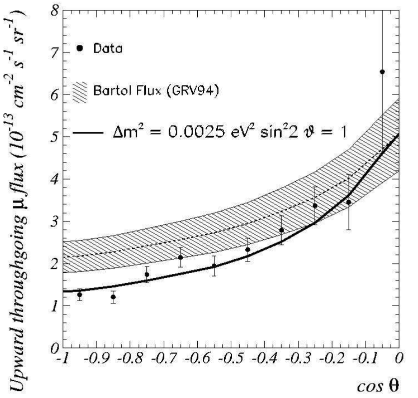


event class	# events	# expected (Flux A)	flux ($\times 10^{-13} cm^{-2}s^{-1}sr^{-1}$)	expected flux ($\times 10^{-13} cm^{-2}s^{-1}sr^{-1}$)	# expected (Flux B)	(Flux C)
Φ_{stop}	417.7	713.5	$0.381 \pm 0.024^{+0.005}_{-0.007}$	0.648 ± 0.145	681.5	790.5
Φ_{thru}	1841.6	1669.5	$1.661 \pm 0.040^{+0.011}_{-0.013}$	1.506 ± 0.337	1644.3	1974.9
$\mathcal{R} = \Phi_{stop}/\Phi_{thru}$	0.227	0.427	$0.229 \pm 0.015 \pm 0.003$	0.430 ± 0.058	0.414	0.400
$\Phi_{stop} + \Phi_{thru}$	2259.3	2382.9	$2.042 \pm 0.046^{+0.012}_{-0.015}$	2.154 ± 0.482	2325.8	2765.4

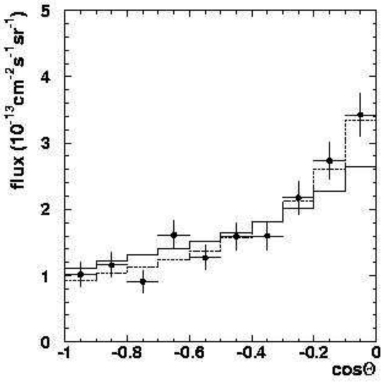


			σ(%)	best-fit
(A) Systematic uncertainties in neutrino flux				
Absolute normalization			free	11.9
$(\nu_\mu+\overline{\nu}_\mu)/(\nu_e+\overline{\nu}_e)$ [a]	$E_\nu < 5$ GeV		3.0	-2.4
	$E_\nu > 5$ GeV		3.0[b]	0.1
$\nu_e/\overline{\nu}_e$ [c]	$E_\nu < 10$ GeV		5.0	1.5
	$E_\nu > 10$ GeV		5.0[d]	0.0
$\nu_\mu/\overline{\nu}_\mu$ [c]	$E_\nu < 10$ GeV		5.0	-1.3
	$E_\nu > 10$ GeV		5.0[e]	0.9
Up/down[f]	< 400 MeV	*e*-like	0.5	0.2
		μ-like	0.8	0.4
	> 400 MeV	*e*-like	2.1	0.9
		μ-like	1.8	0.8
	Multi-GeV	*e*-like	1.5	0.7
		μ-like	0.8	0.3
	PC		0.4	0.2
	Sub-GeV multi-ring μ		0.8	0.3
	Multi-GeV multi-ring μ		0.7	0.3
Horizontal/vertical[f]	< 400 MeV	*e*-like	0.3	0.0
		μ-like	0.3	0.0
	> 400 MeV	*e*-like	1.2	0.1
		μ-like	1.2	0.1
	Multi-GeV	*e*-like	2.8	0.2
		μ-like	1.9	0.1
	PC		1.4	0.1
	Sub-GeV multi-ring μ		1.5	0.1
	Multi-GeV multi-ring μ		1.3	0.1
K/π ratio [g]			20.0	-6.3
L_ν (production height)			10.0[h]	-0.6
Energy spectrum[i]	$E_k < 100$ GeV		0.03	0.031
	$E_k > 100$ GeV		0.05	0.052
Sample-by-sample[j]	FC Multi-GeV		5.0	-5.2
	PC + upward stopping μ		5.0	-3.9

ν_μ-induced upward μ



MACRO



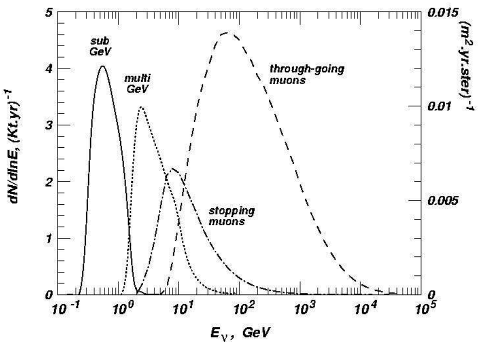
Super-KAMIOKANDE

High-energy ν in Super-K

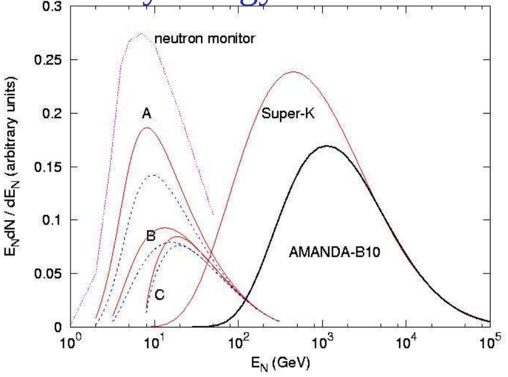
- In Super-K fit, primary spectrum shifts:
  - Overall normalization up 11%
  - Slope < 100 GeV changes: -2.74 → -2.71
  - Slope > 100 GeV changes: -2.71 → -2.66
  - K/p *decreases* by 6%
- Can we use Super-K measurements (together with muon measurements) to constrain extrapolation of neutrino spectrum to high energy?
  - Work in progress with P. Lipari, T. Stanev & G. Barr

Neutrino response to primary spectrum

Neutrino energy



Primary energy / nucleon



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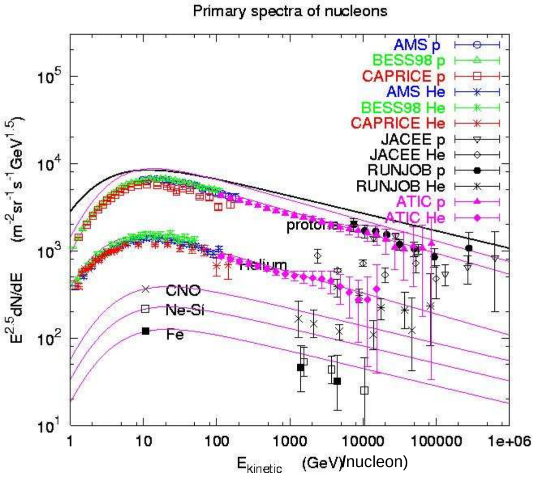
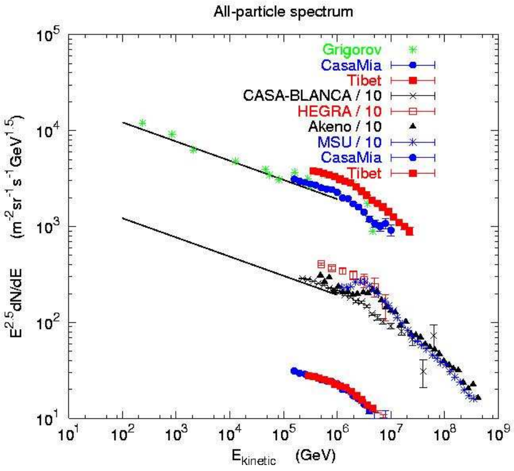
All-nucleon spectrum





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Analytic approximations for E>10 GeV

$$\phi_\nu(E_\nu) = \frac{\phi_p(E_\nu)}{1 - Z_{NN}} \left\{ \frac{Z_{N\pi} Z_{\pi\nu}}{1 + D_\pi \frac{\cos\theta\, E_\nu}{\epsilon_\pi}} + B_{K\nu} \frac{Z_{NK} Z_{K\nu}}{1 + D_K \frac{\cos\theta\, E_\nu}{\epsilon_K}} \right\}$$

$\nu = \nu_\mu + \bar{\nu}_\mu$

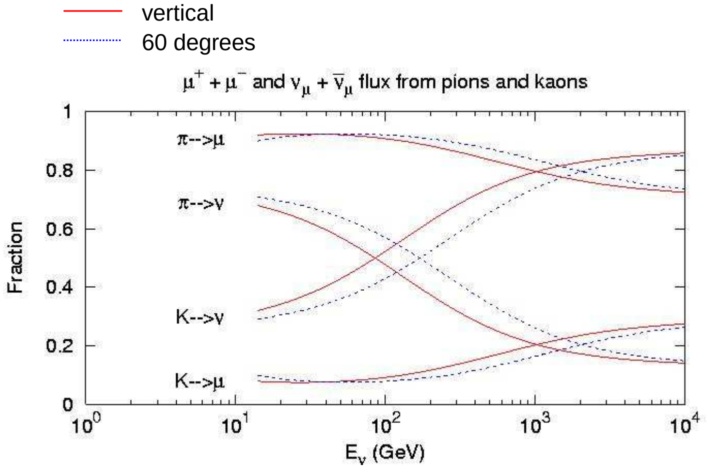
$$\int_0^1 \xi^{\gamma - 1} F_{NN}(\xi)\, d\xi = Z_{NN} \cong 0.3$$

$Z_{\pi\nu} = .087$ $\qquad Z_{K\nu} = .34$

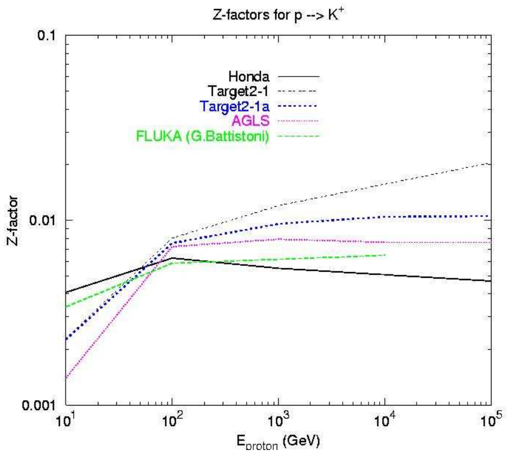
$\epsilon_\pi = 115$ GeV $\qquad \epsilon_K = 850$ GeV

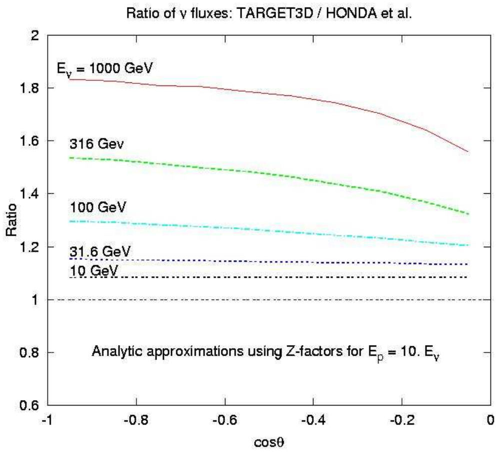
Importance of kaons at high E

- Importance of kaons
  - main source of ν > 100 GeV
  - p → $K^+ + \Lambda$ important
  - Charmed analog important for prompt leptons

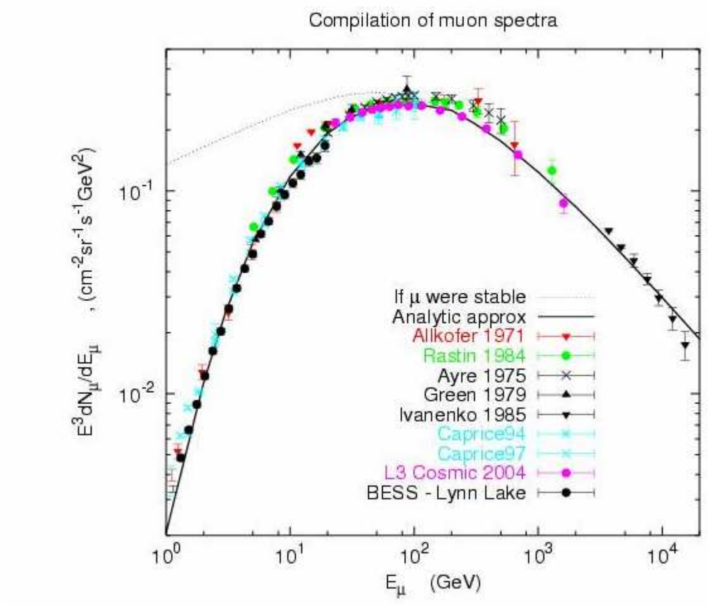


Differences in kaon production



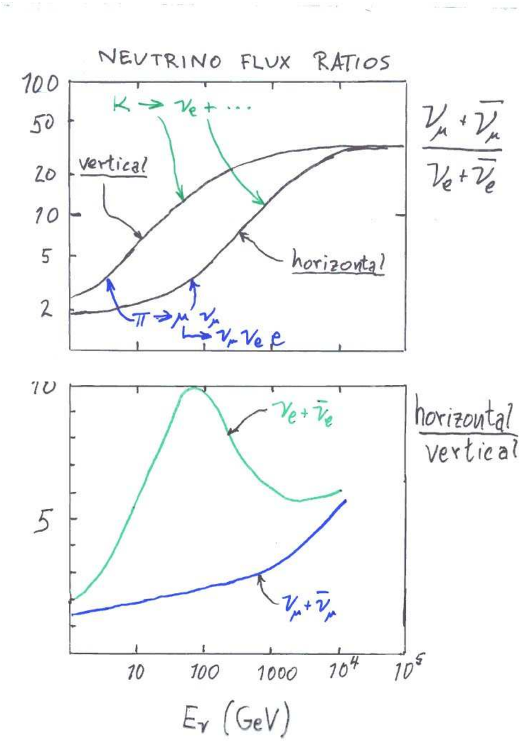


Vertical muon flux



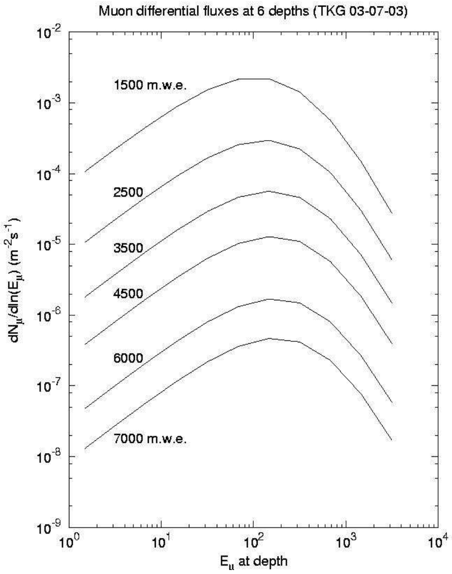
Calibration with atmospheric ν

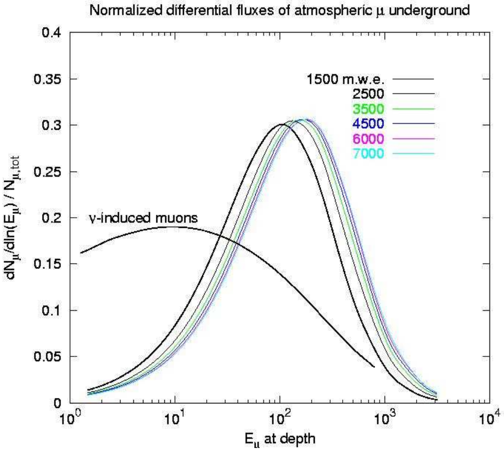
- MINOS, etc.
- Neutrino telescopes
- Example*** of ν_μ / ν_e
  - flavor ratio
  - angular dependence



***Note: this is maximal effect: horizontal = 85 - 90 deg in plots

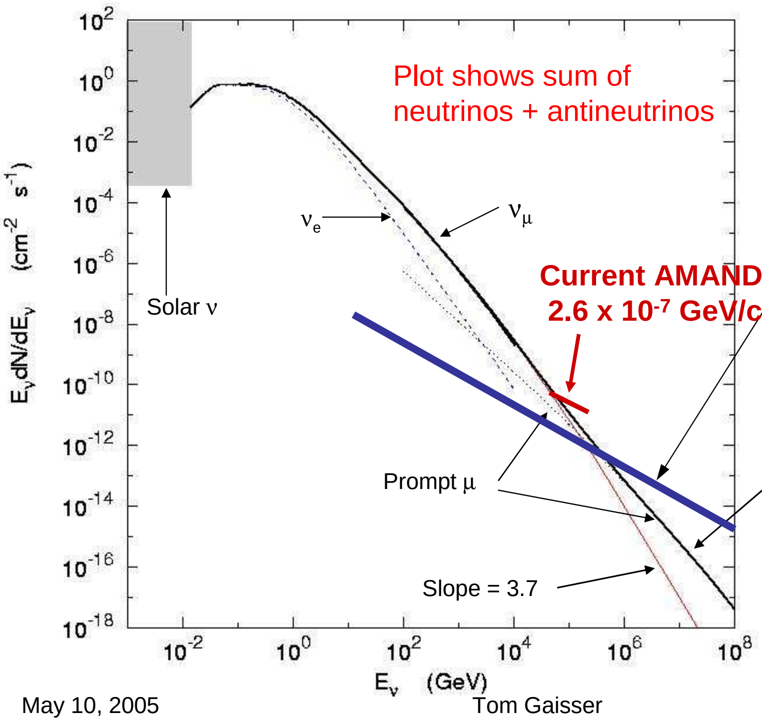
Calibration using ~universal μ energy spectra at depth





See D Chirkin et al. for application to calibrating N_{hit} in AMANDA

Global view of atmospheric ν spectrum



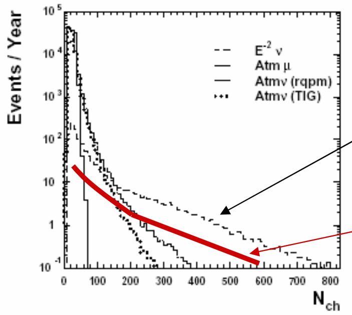
Plot shows sum of
neutrinos + antineutrinos

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

Current AMANDA upper limit
2.6×10^{-7} GeV/cm^2 sr s

RPQM for prompt ν
Bugaev et al., PRD58 (1998) 054001
Slope = 2.7

Diffuse signal vs charmed background in IceCube



E^{-2} “signal” spectrum:
$E^2 dN/dE = 10^{-7}$ GeV/cm^{2}sr s

W-B flux accounting for
oscillations

Fig. 4. Channel multiplicity for different event classes at level 2: For signal from E^{-2} source (dashed), atmospheric neutrinos including the two alternative charm contributions `TIG` (sparse dots) and `rqpm` (dense dots) and CR muon events (full lines).

IceCube Collaboration
J. Ahrens et al., Astropart.Phys. 20 (2004) 507-532

Concluding comments

- Discovery of neutrino oscillations depends on measured ratios; therefore robust
- Super-K fits suggests relatively hard spectrum
- Uncertainty in level of charm production limits sensitivity to diffuse astrophysical neutrinos
- Emphasis on point sources
- Tau-neutrinos (and cascades) important tags
  - $\nu_\mu : \nu_e : \nu_\tau \sim 1 : 0.1 : 10^{-5}$ (high energy atmos.)
  - $\sim 1 : 1 : 1$ for astrophysical