Atmospheric Neutrino Fluxes

- Historical introduction
- Sub-GeV ν in three dimensions
- Multi-GeV and ν-induced upward μ
- Atmospheric ν as background & calibration for neutrino telescopes

Historical context

Detection of atmospheric neutrinos

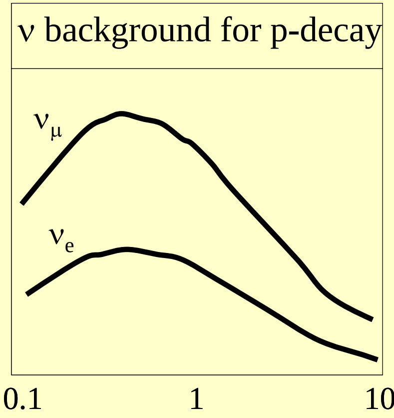
- Markov (1960) suggests Cherenkov light in deep lake or ocean to detect atmospheric ν interactions for neutrino physics
- Greisen (1960) suggests water Cherenkov detector in deep mine as a neutrino telescope for extraterrestrial neutrinos
- First recorded events in deep mines with electronic detectors,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

Two methods for calculating atmospheric neutrinos:

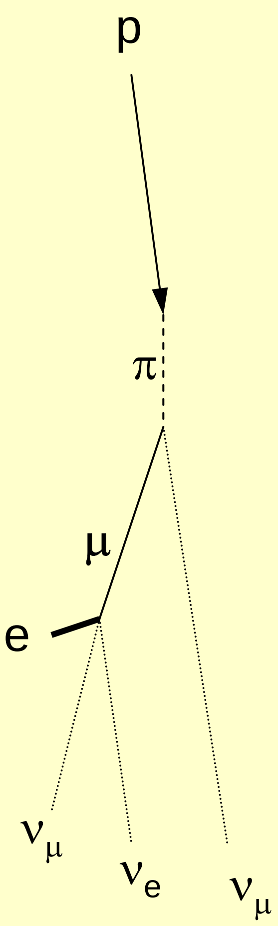
- From muons to parent pions infer neutrinos (Markov & Zheleznykh, 1961; Perkins)
- From primaries to π, K and μ to neutrinos (Cowsik, 1965 and most later calculations)
- Essential features known since 1961: Markov & Zheleznykh, Zatsepin & Kuz'min
- Monte Carlo calculations follow second method

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
- Hint of pathlength dependence from Kamioka, Fukuda et al., 1994

Discovery of atmospheric neutrino oscillations by S-K

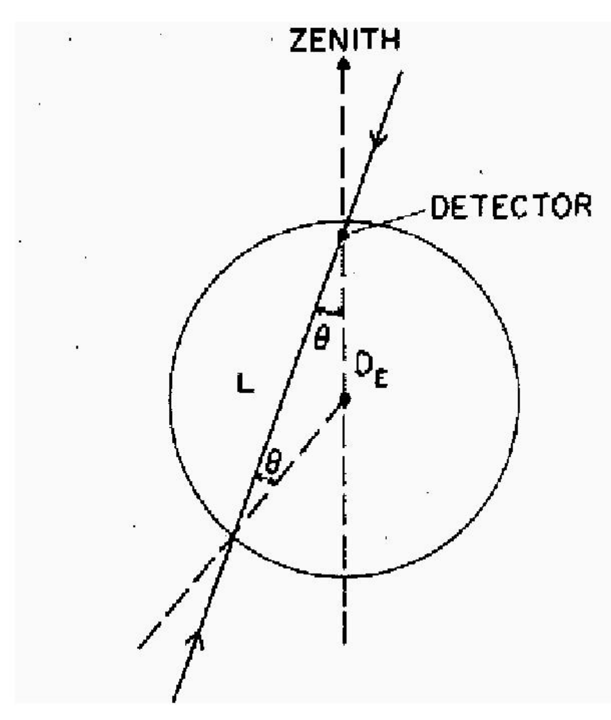
- Super-K: “Evidence for neutrino oscillations” at Neutriino 98
- Subsequent increasingly detailed analyses from Super-K 1998…
- Confirming evidence from MACRO and Soudan
- Analyses based on **ratios** comparing to 1D calculations

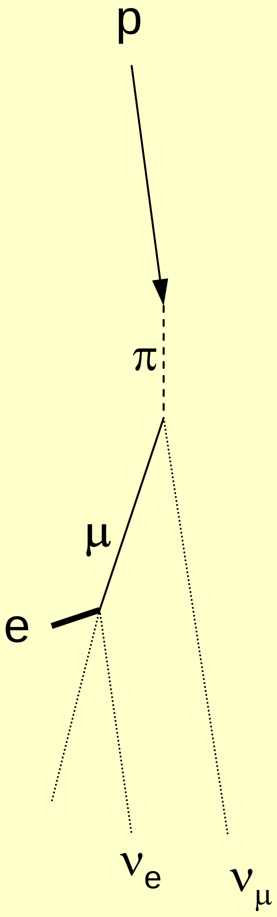
Need for precise, complete, accurate, 3D calculations

- $\Theta \sim P_T / E$ 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

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

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		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		Target
Honda, Kajita, Kasahara, Midorikawa	PRD 64 053011 (2001) astro-ph/0404457 to PRD	3D	** **	DPMJET

∗ Used for analysis of Super-K data in publications before 2004; ** used now

Overview of the calculation

ϕ_{ν_i} = primary flux ⊗ cutoffs ⊗ 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

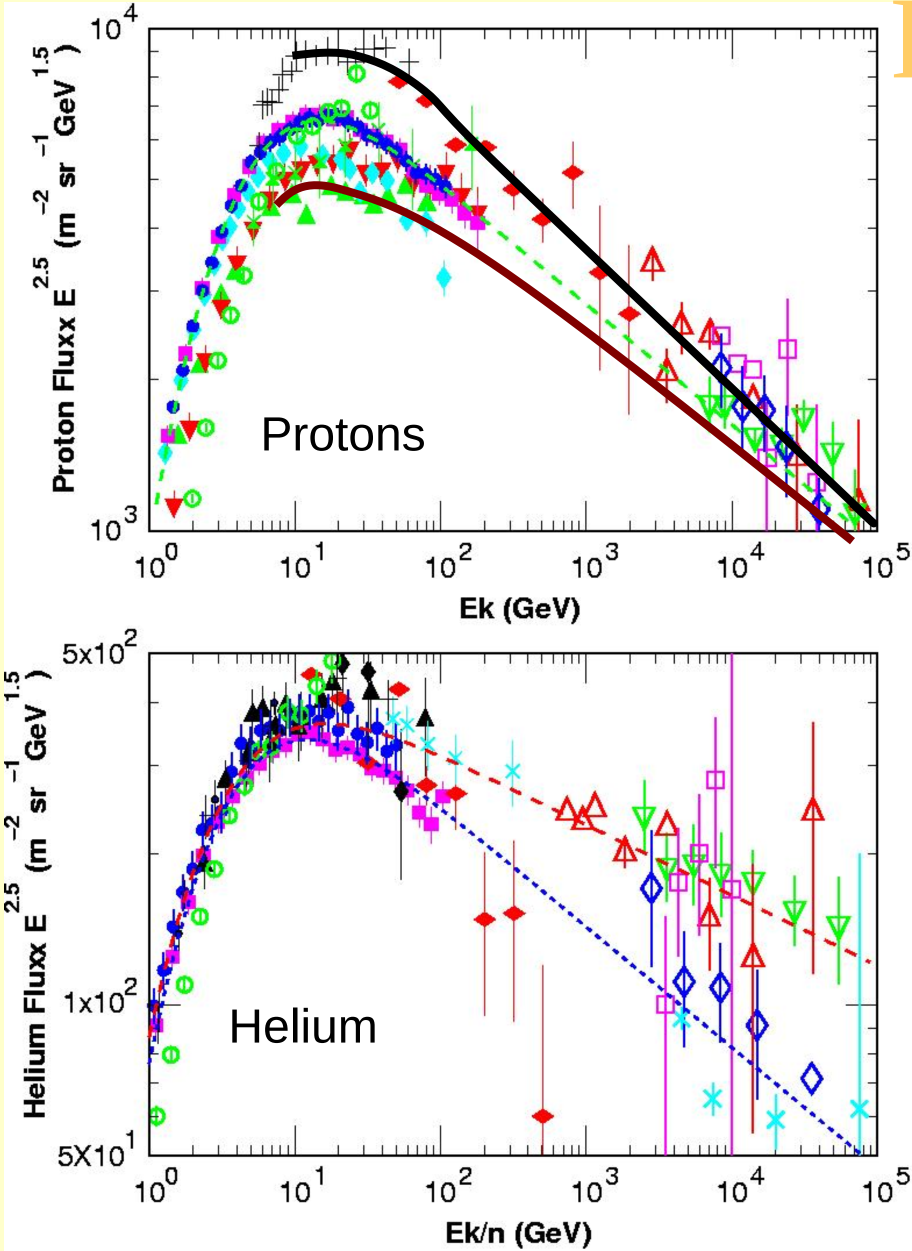
↑ nuclei

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

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

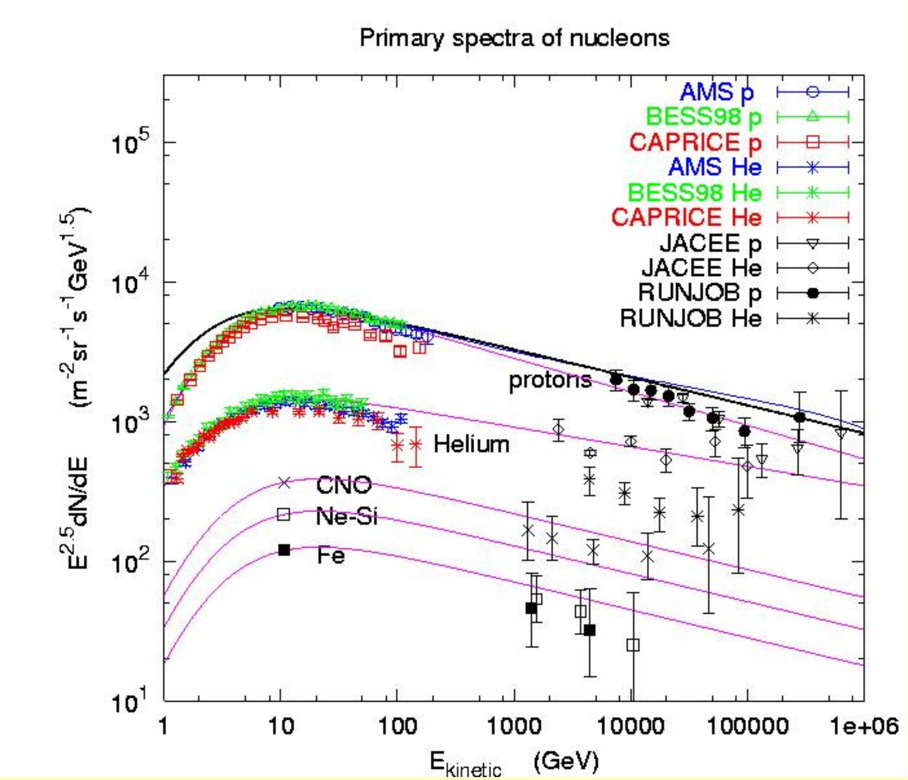
[Signal ~ $\phi_{\nu_i} \otimes \sigma_{\nu_i}$]

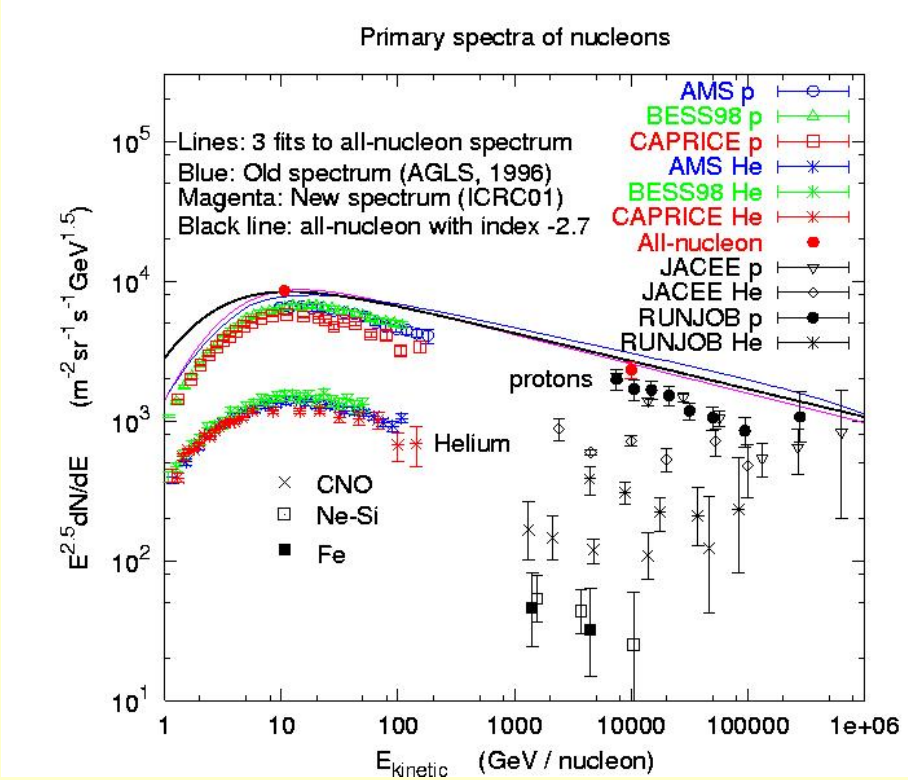
Primary spectrum



- 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?

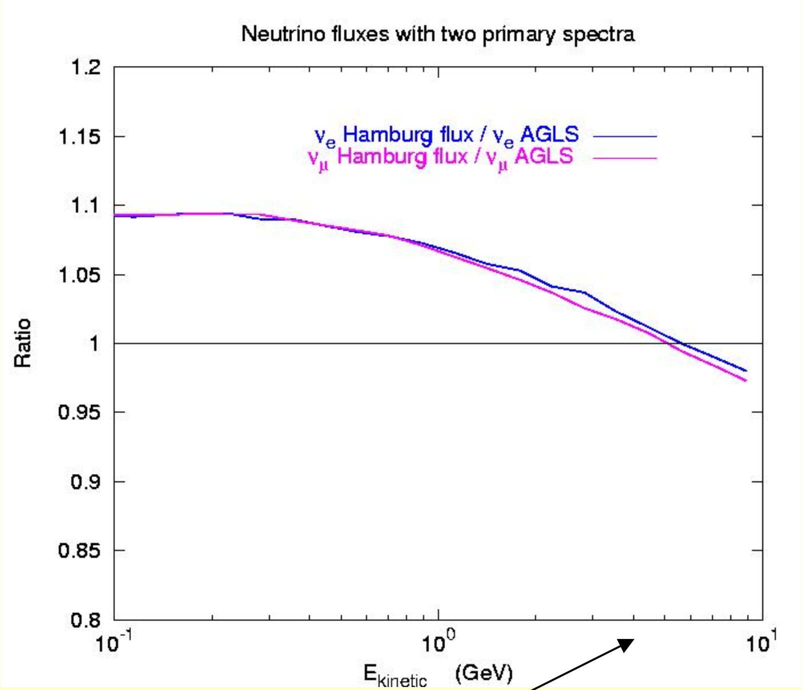


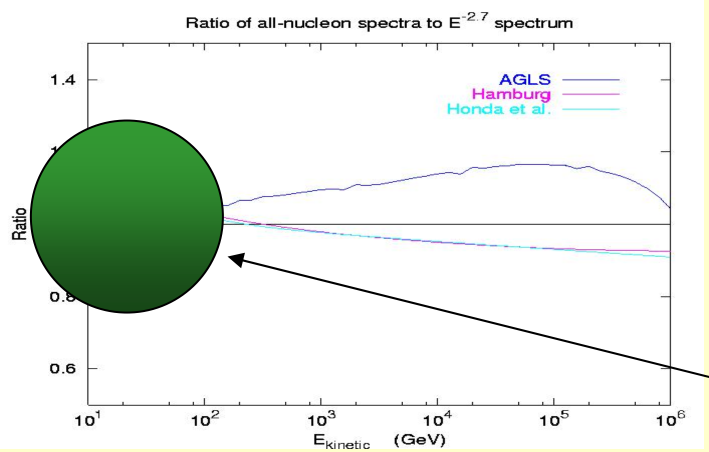


Lines: 3 fits to all-nucleon spectrum
Blue: Old spectrum (AGLS, 1996)
Magenta: New spectrum (ICRC01)
Black line: all-nucleon with index -2.7

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 x $E^{-2.7}$ (c.g.s.) for analytic estimates

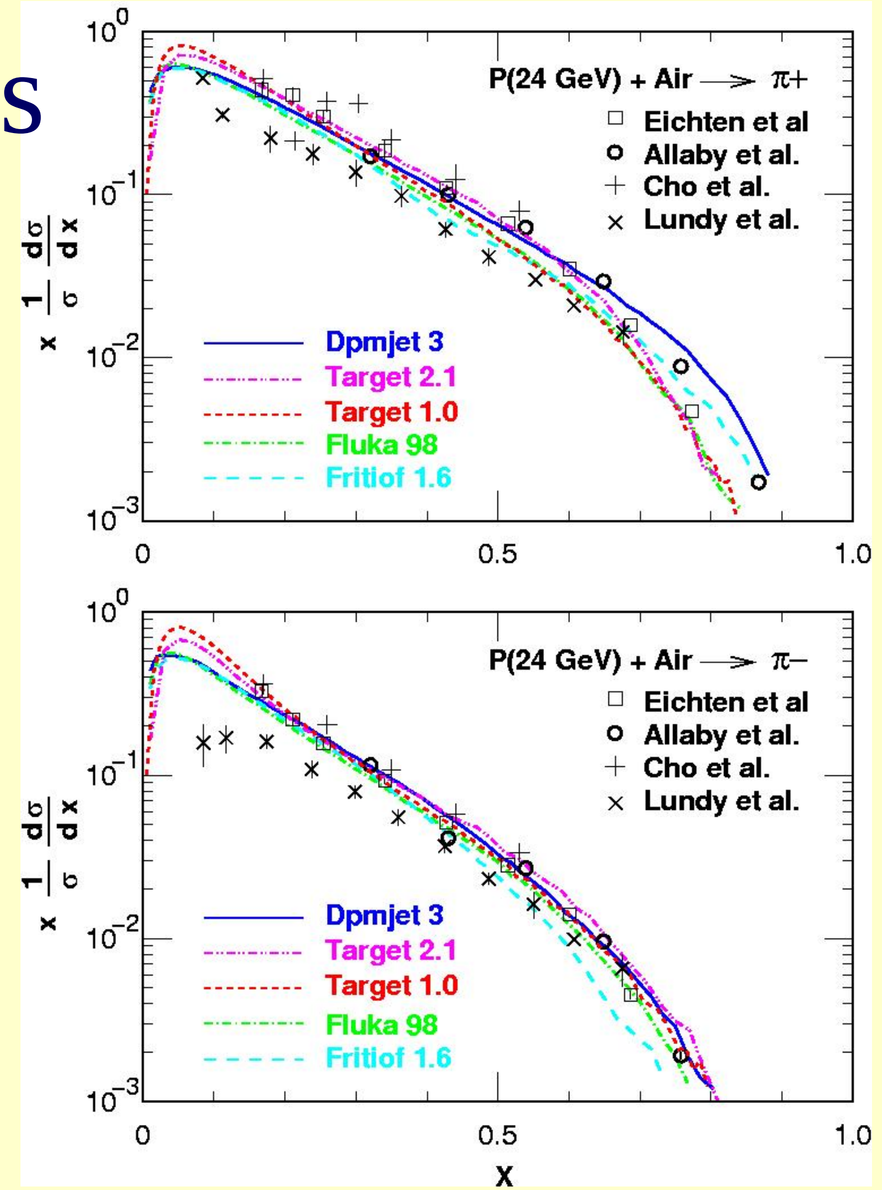




Note change of scale

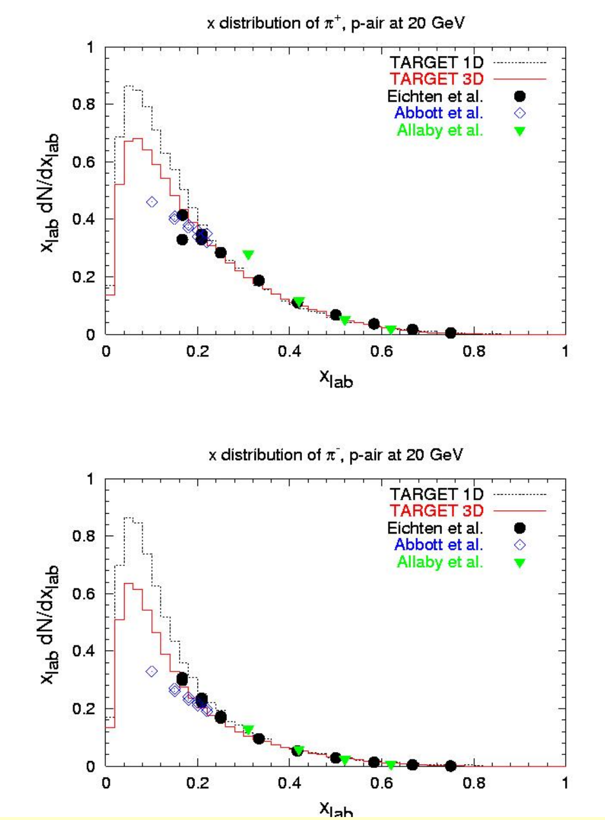
Hadronic interactions

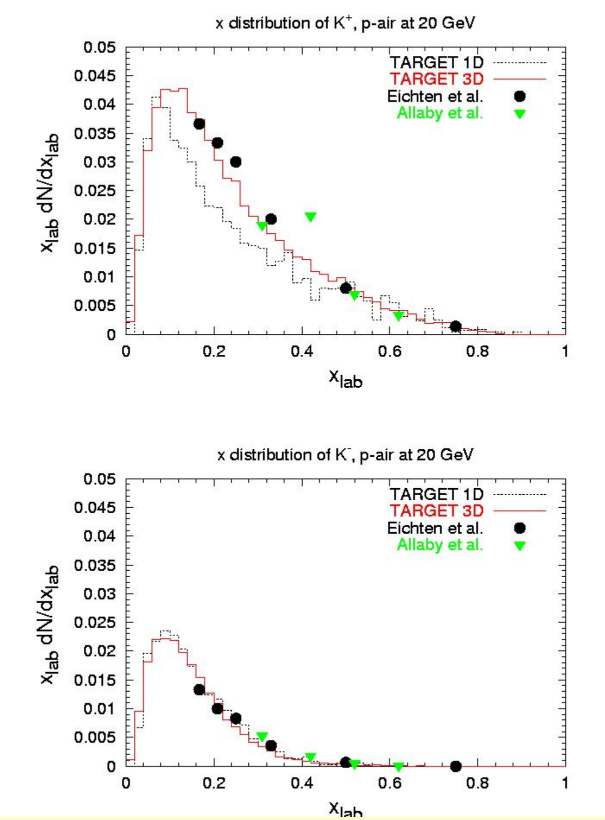
- Sub-GeV ν depend most on treatment of π production
- K^+ dominate $E_\nu > 100$ GeV
- Compare 5 calculations:
  - Bartol (Target-1, 2.1)
  - Honda et al. (1995: Fritiof; present: Dpmjet3)
  - Battistoni et al. (Fluka)
- Uncertainties from interactions ~ +/-15%



Hadronic interactions

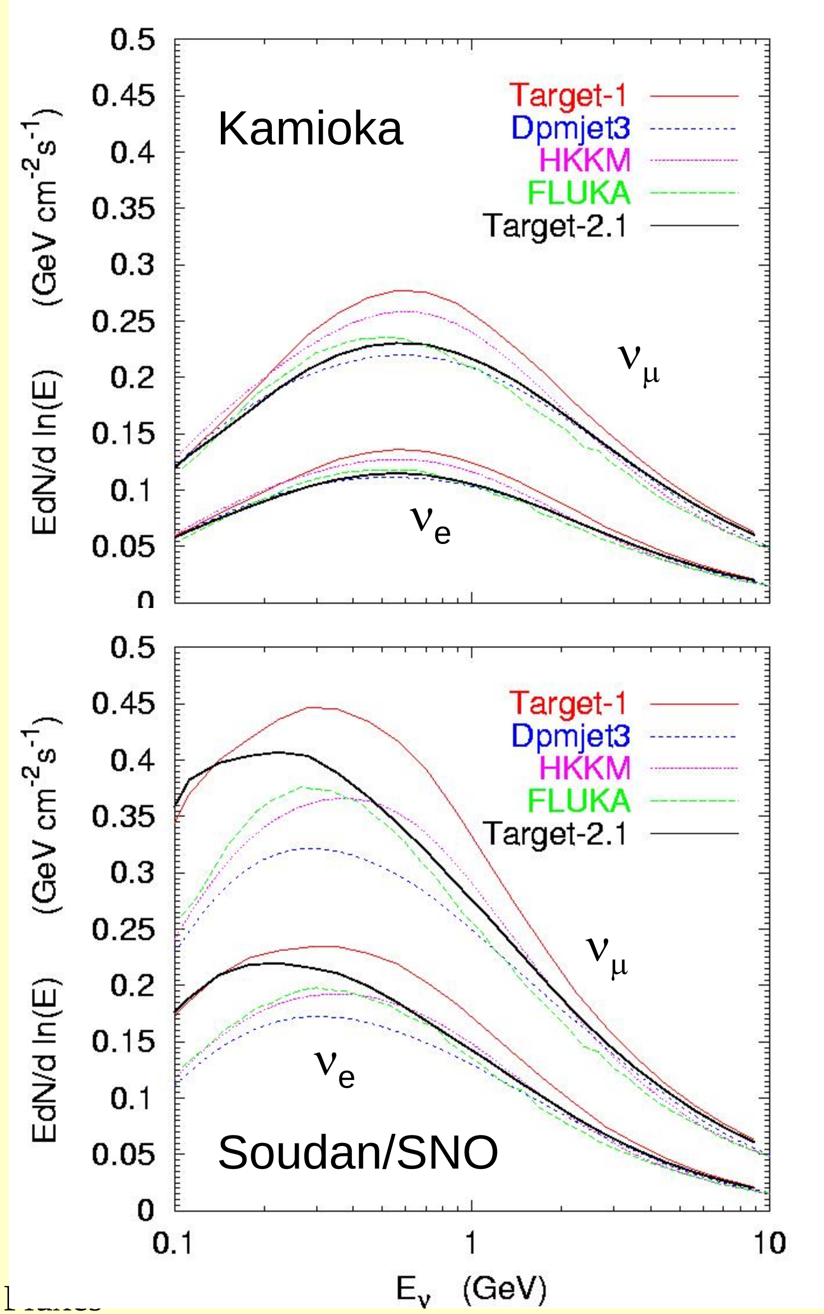
Example: Compare original Target 1 with Target 2.1 (Target 3D): pions down, kaons up



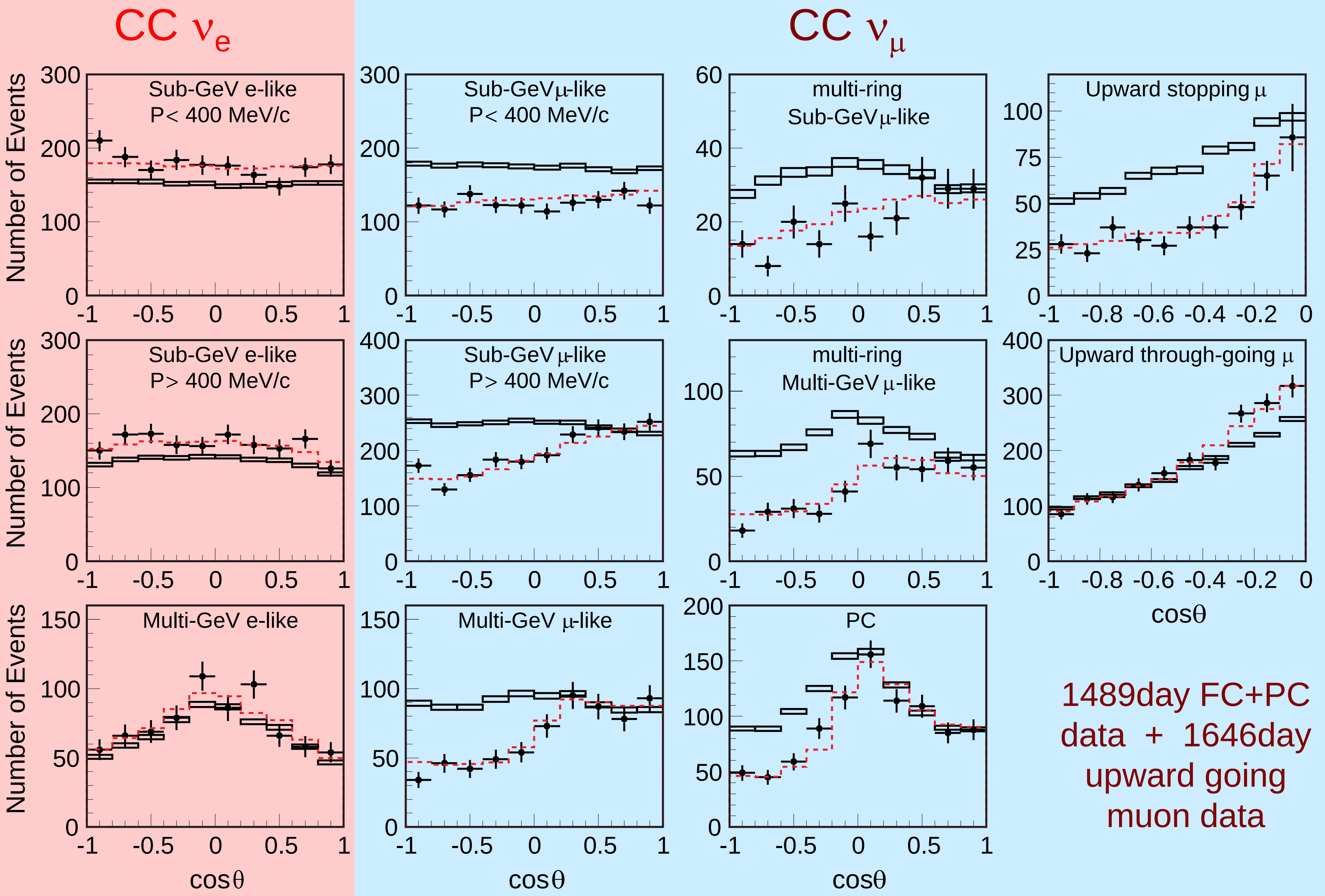


Comparison (using same flux)

- 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 λ
  - Interactions < 10 GeV are important



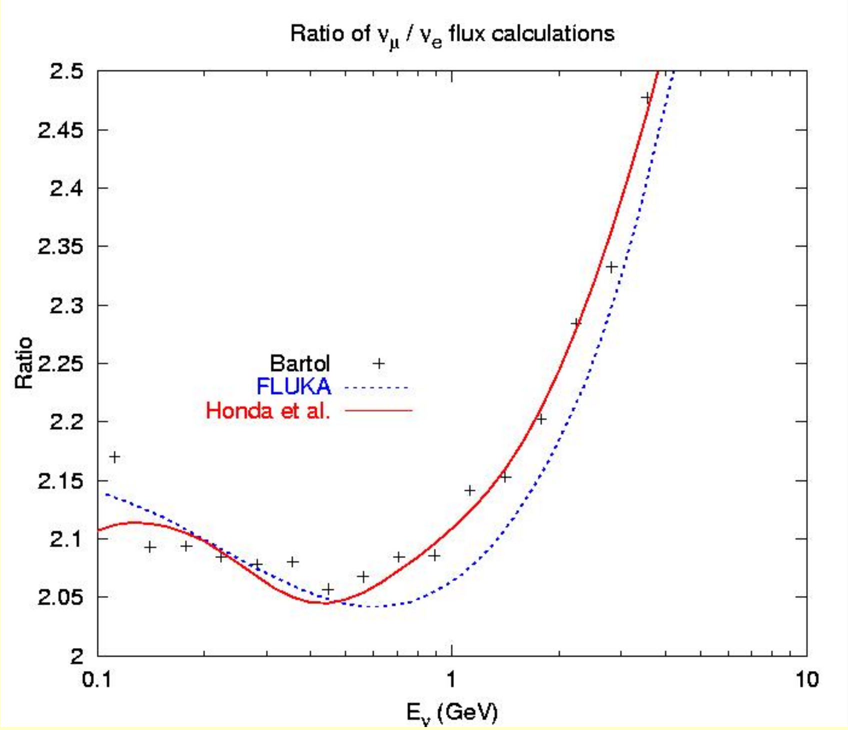
Super-K atmospheric neutrino data (T. Kajita)



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

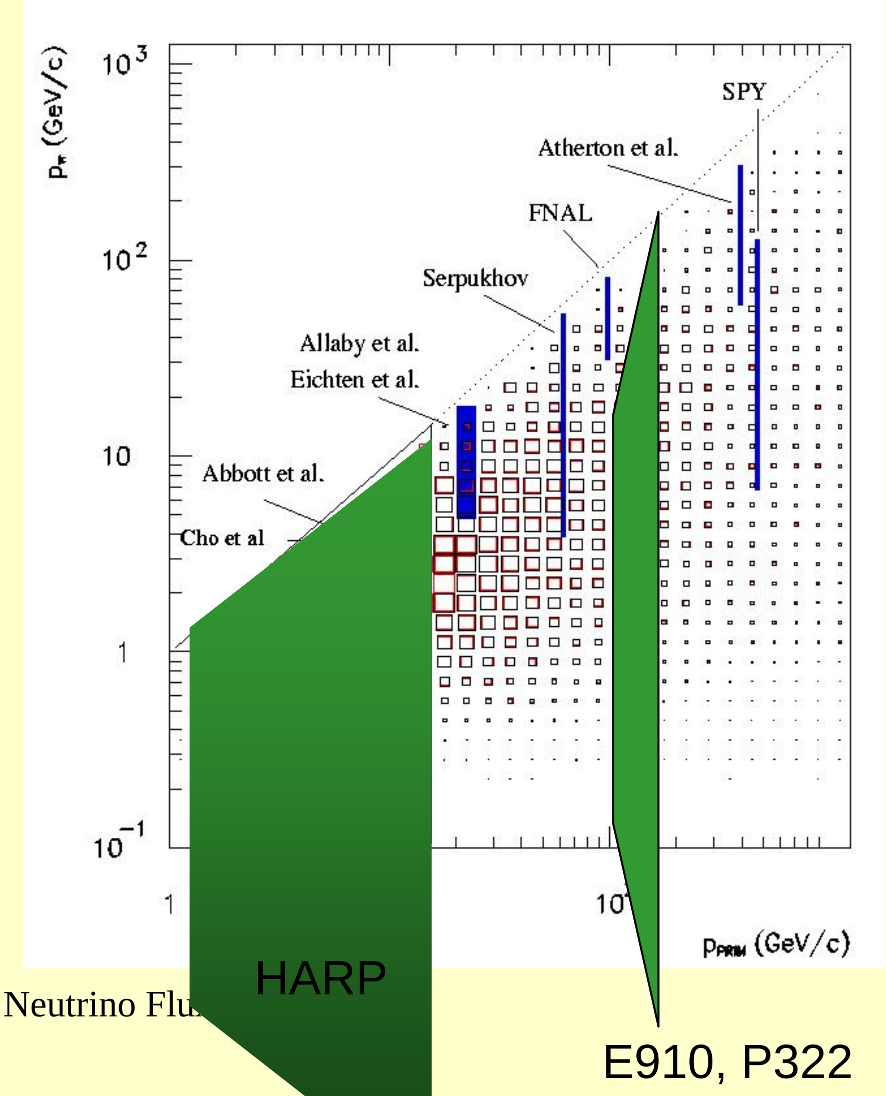
Flavor ratio at production

- $r = \nu_\mu / \nu_e$ 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
- $\rightarrow 0$ for $r = 2$, $\theta_{23} = 45^o$
- $r_{\text{sub-GeV}} \sim 2.04 - 2.1$



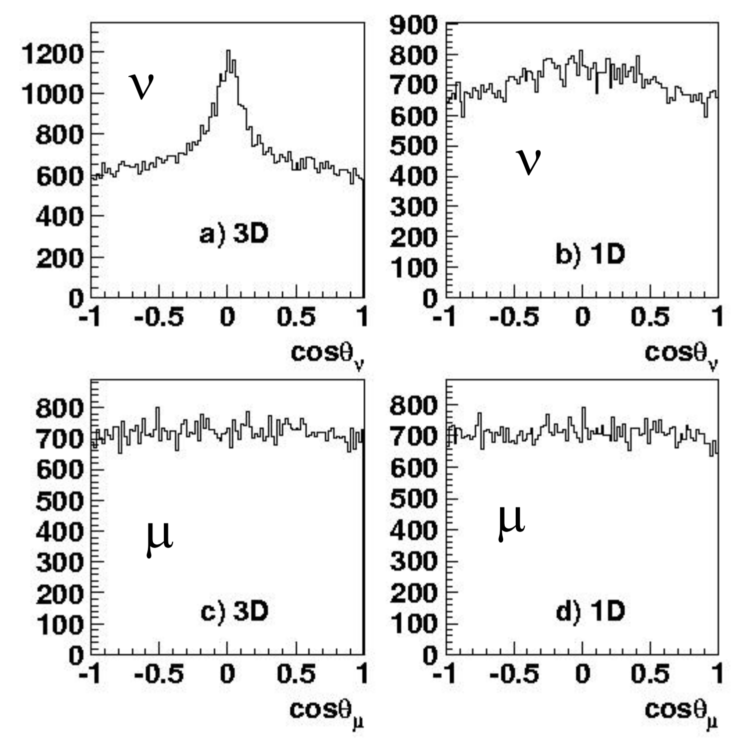
New hadro-production data expected

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



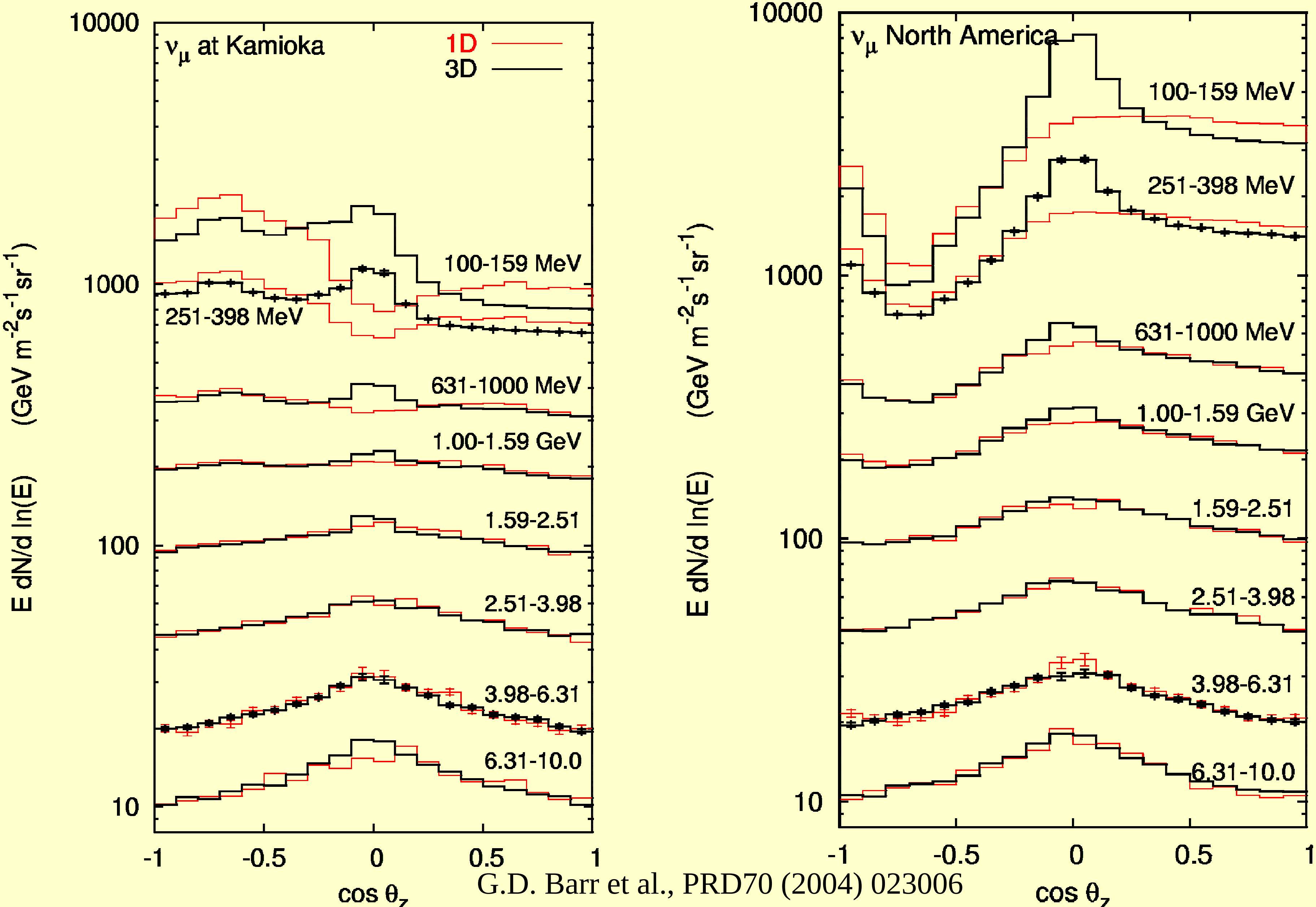
3-dimensional effects

- Characteristic 3D feature:
  - excess of ν near horizon
  - shown in top, left panel
  - lower panels show directions of μ and e
  - cannot see 3D effect directly; however:
- Horizontal excess is associated with a change in path-length distribution



From Battistoni et al., Astropart. Phys. 12 (2000) 315

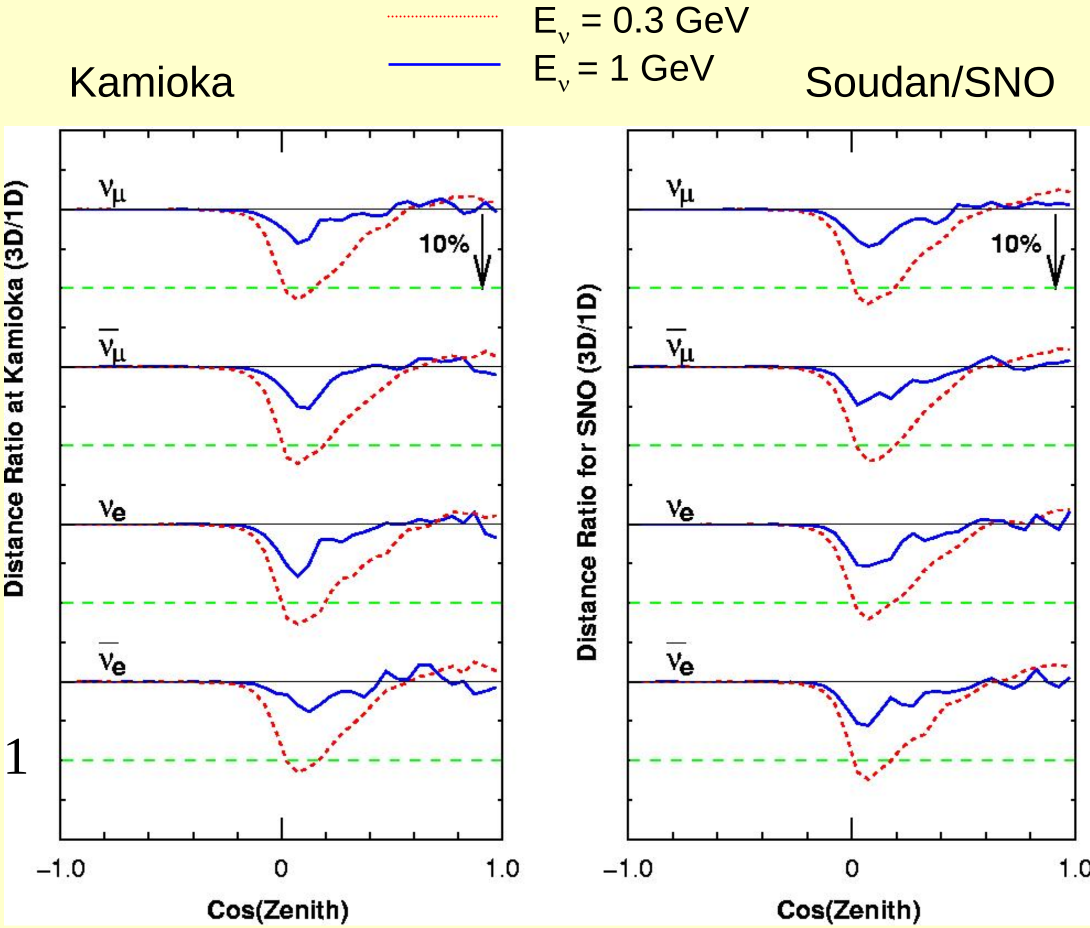
Zenith angle dependence



G.D. Barr et al., PRD70 (2004) 023006

Path-length dependence

- Path length shorter near horizon on average in 3D case
  - cos(θ) > 0 only,
  - phase space favors nearby interaction scattering to large angle
  - 5-10% (E_ν ~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 δm^2 by ~1% ?



from M. Honda et al., Phys. Rev. D64 (2001) 053001

3D orthogonal to S-K L/E analysis

Giles Barr, ν-2004

▲	3D bigger	>30%
▲		10%-30%
△		3%-10%
○		<3%
▽	1D bigger	3%-10%
▼		10%-30%

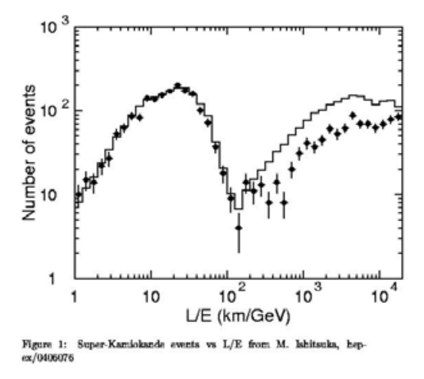
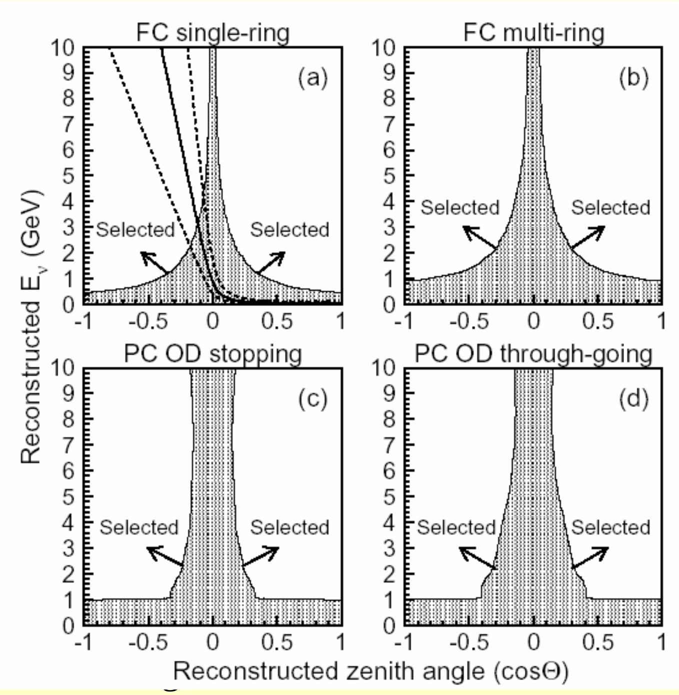
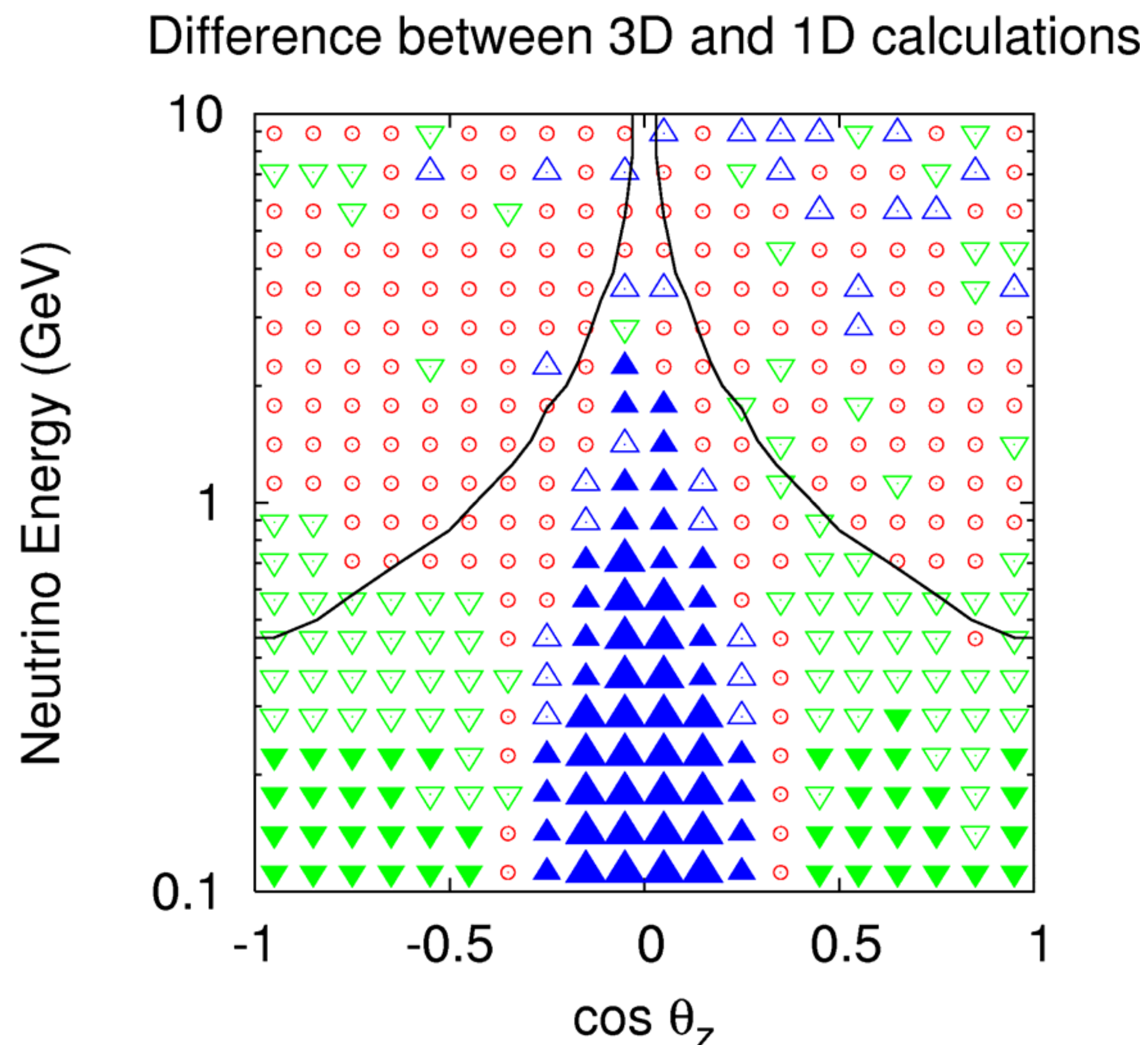


Figure 1: Super-Kamiokande events vs L/E from M. Ishitsuka, hep-ex/0406076

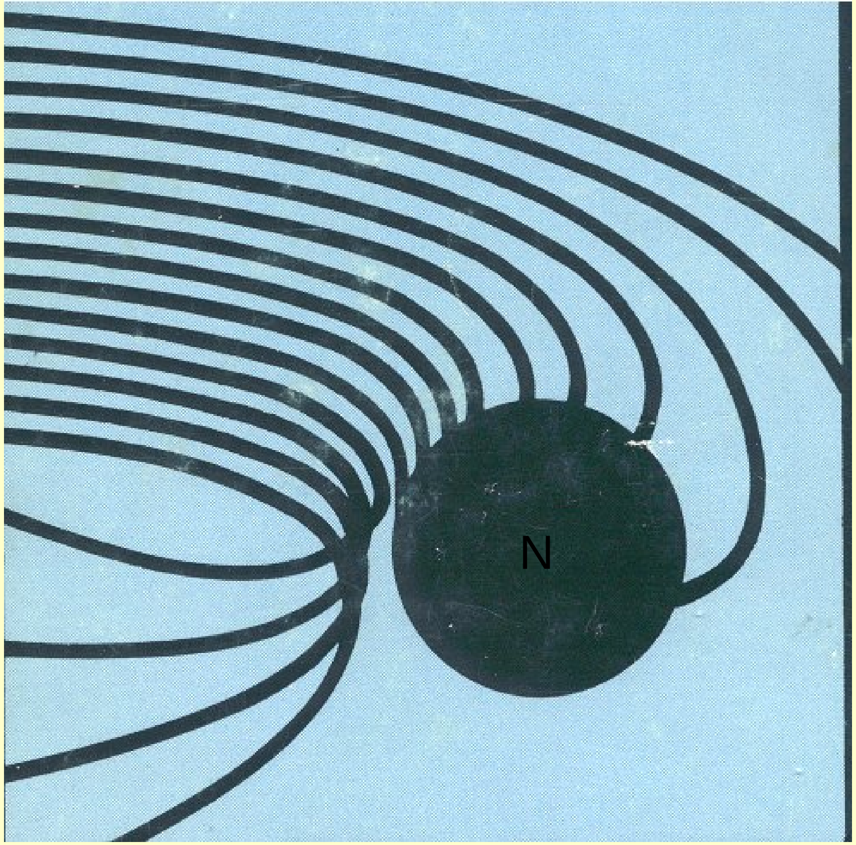
S-K: hep-ex/0404034





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)

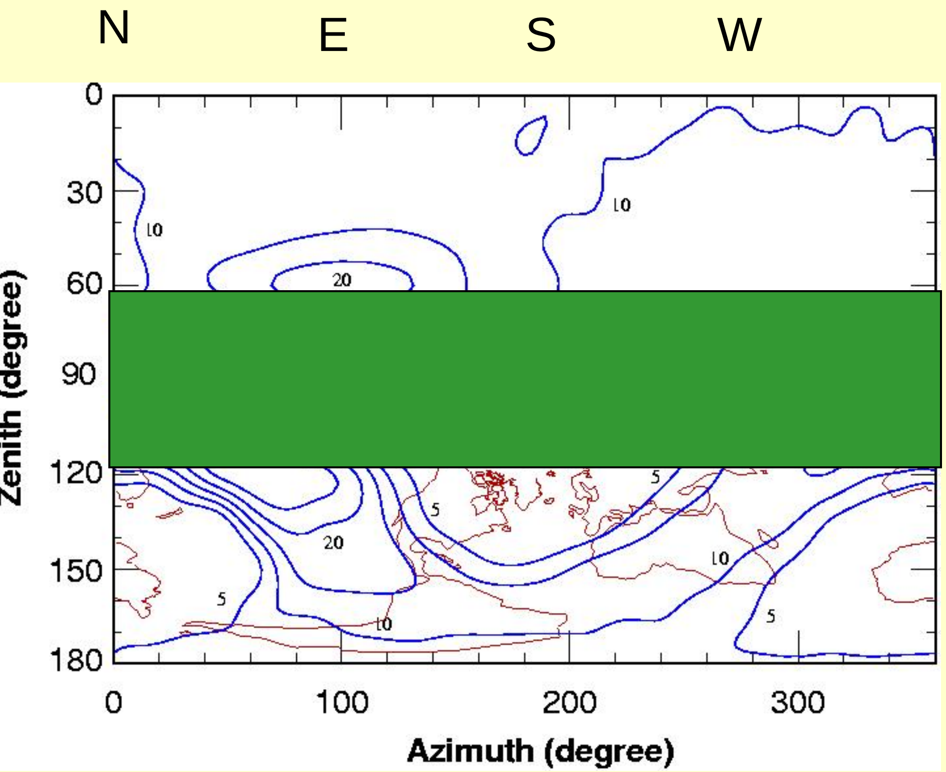
Cutoffs at Super-K

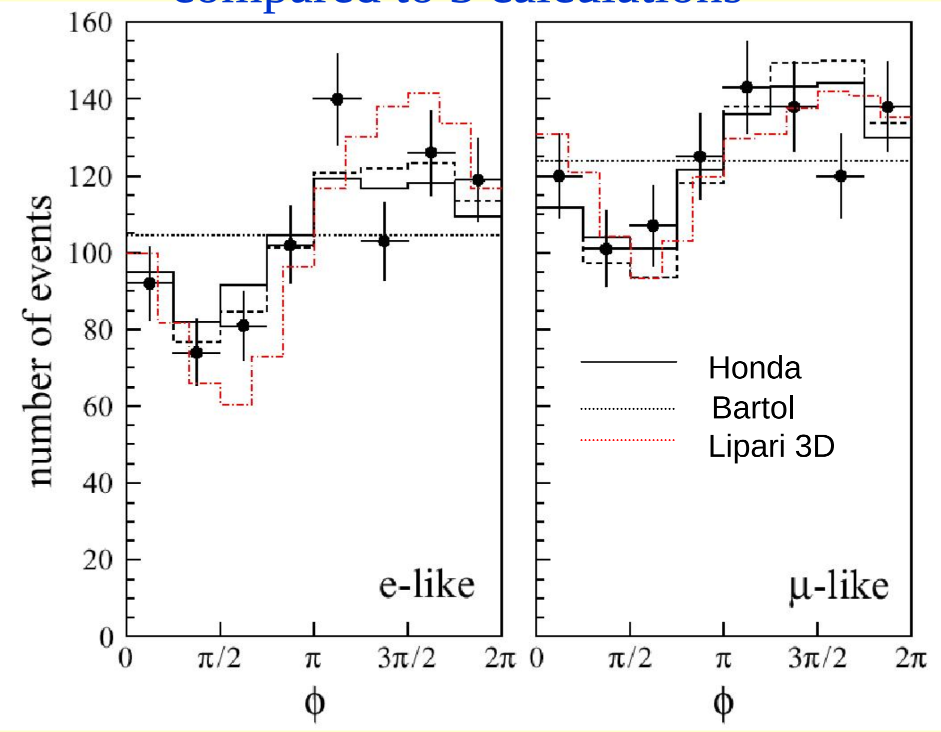
Measurement of East-West effect with atmospheric neutrinos--an important confirmation of analysis & interpretation of Super-K data as neutrino oscillations

ν flux, $0.4 < E_\nu < 3$ GeV

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

measured by Super-K and compared to 3 calculations

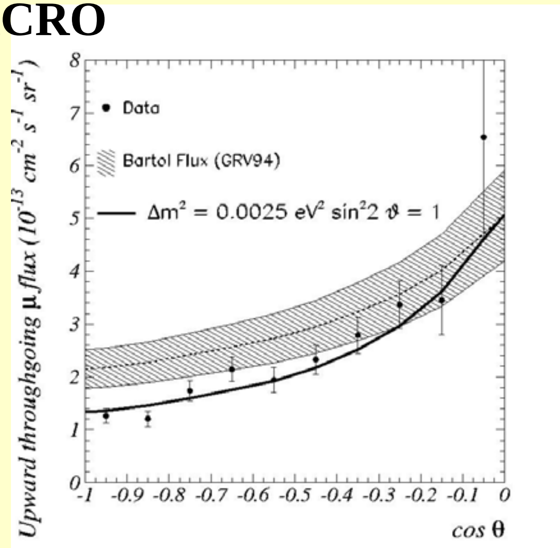


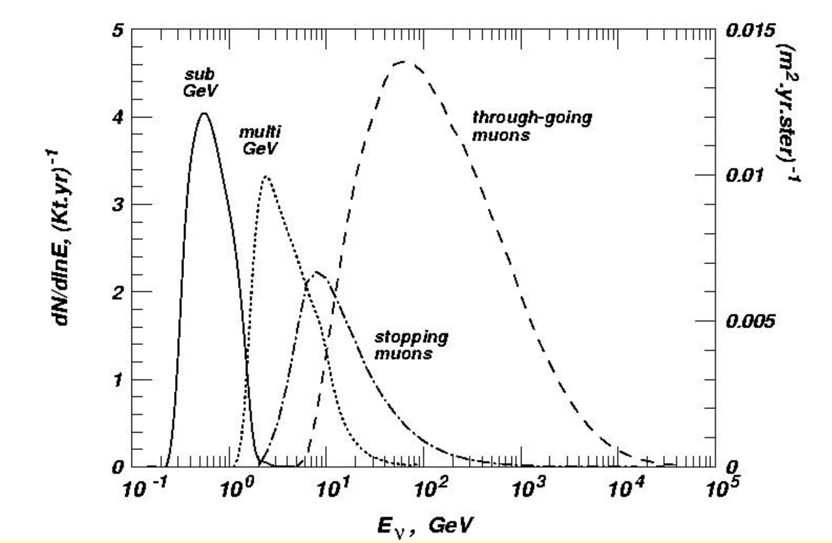


Higher energy atmospheric ν

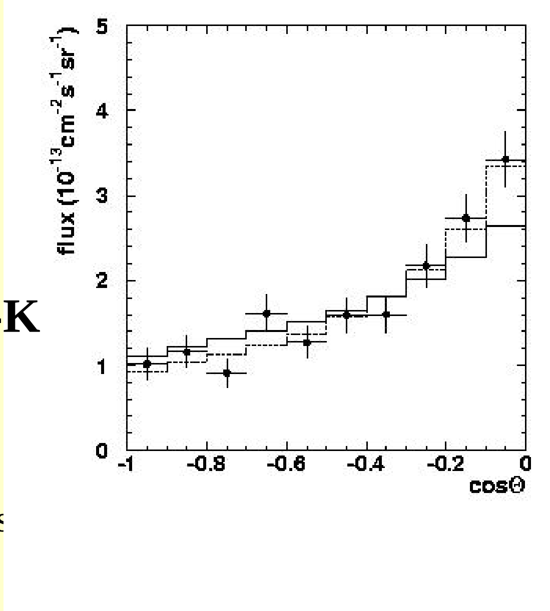
- Mean E_ν ~ 100 GeV for ν-induced upward μ
- Note difference in normalization

MACRO

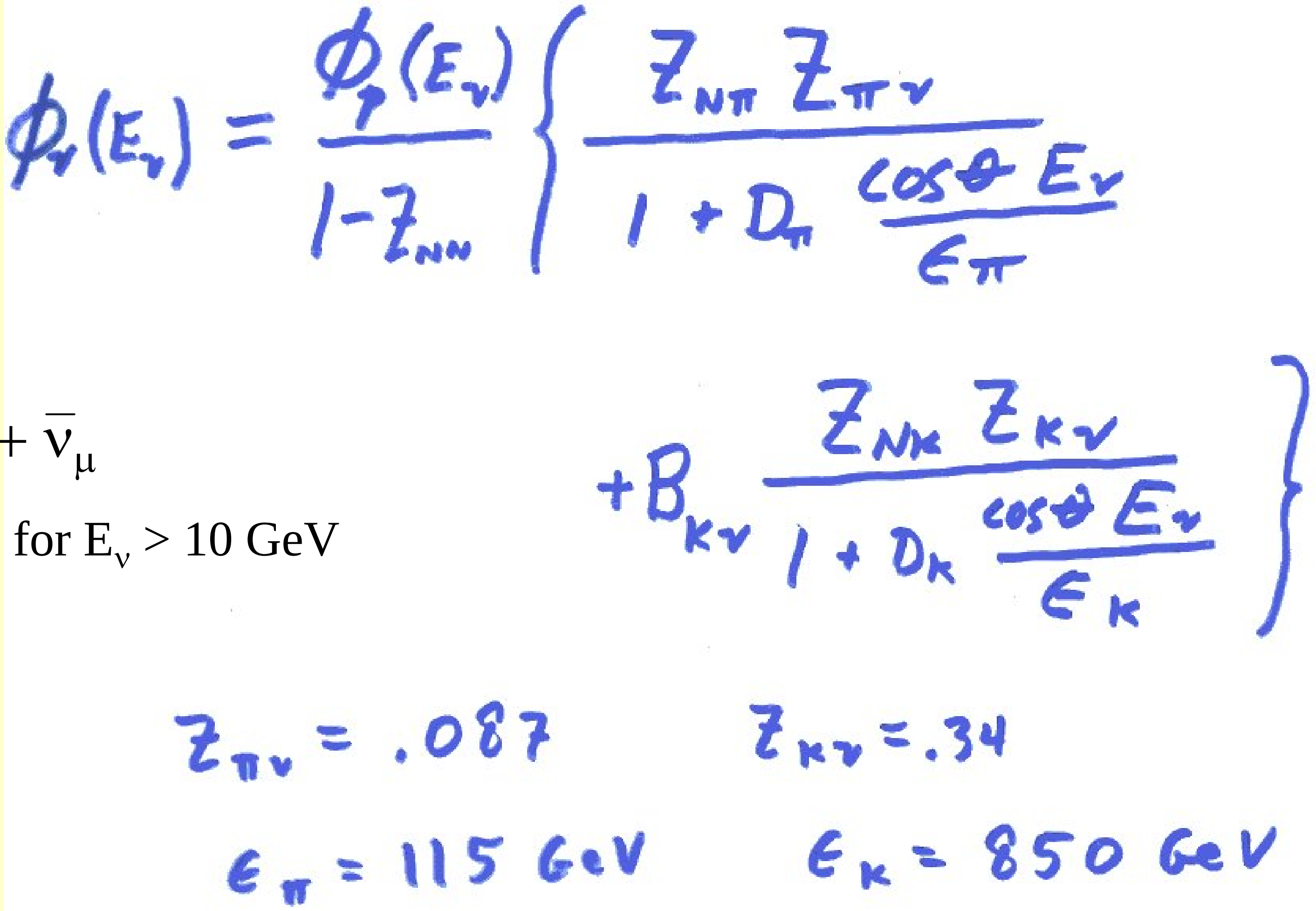




Super-K



Analytic approximation



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

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

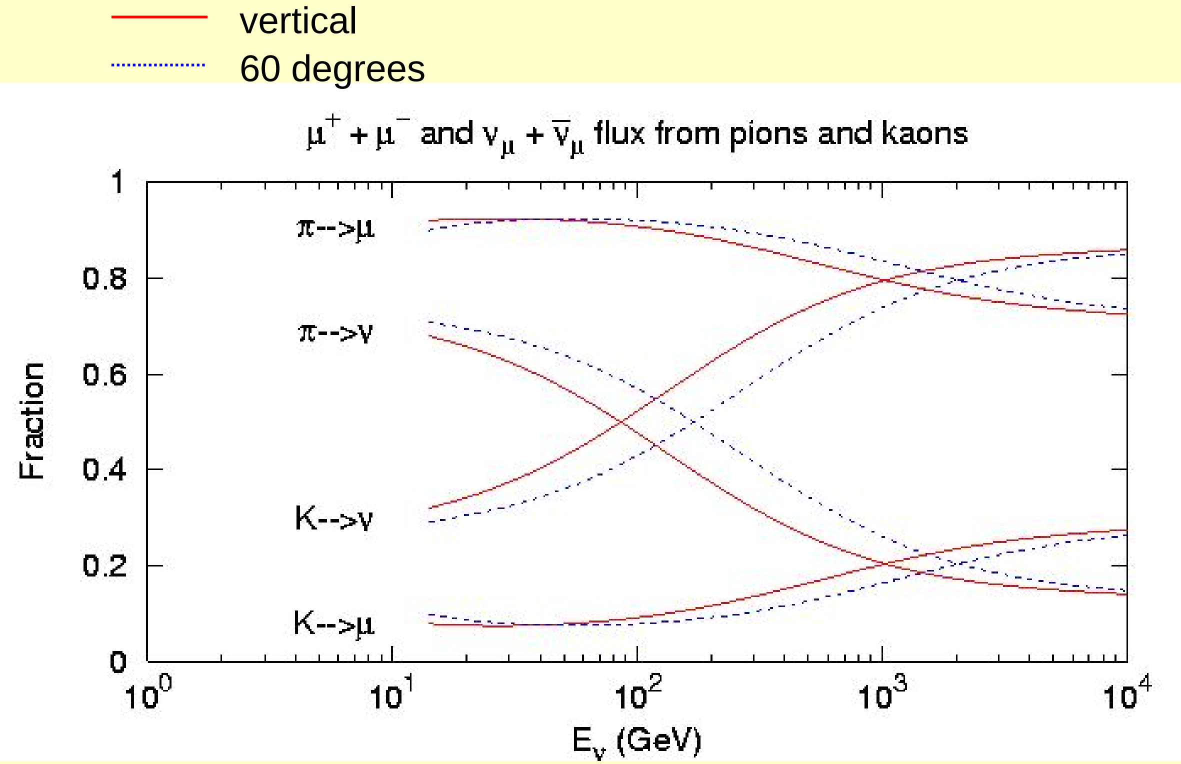
$\epsilon_\pi = 115$ GeV $\quad$ $\epsilon_K = 850$ GeV

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

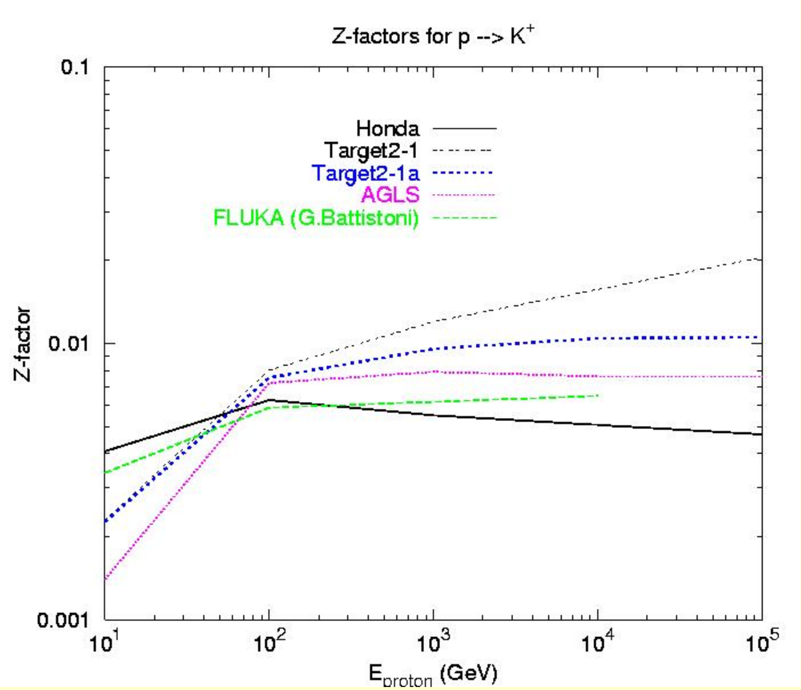
-- good for $E_\nu > 10$ GeV

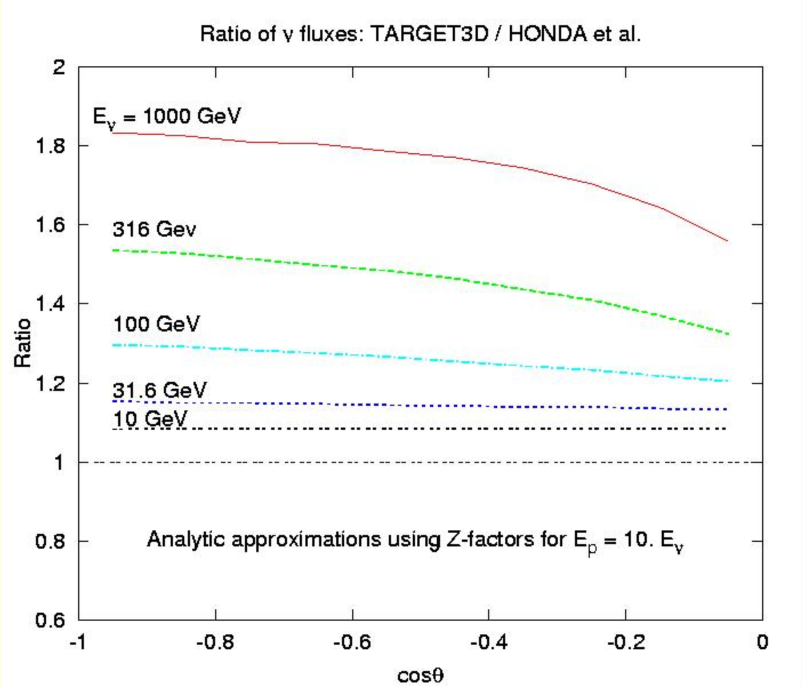
High energy (e.g. $\nu_\mu \rightarrow \mu$)

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



Importance of kaon production

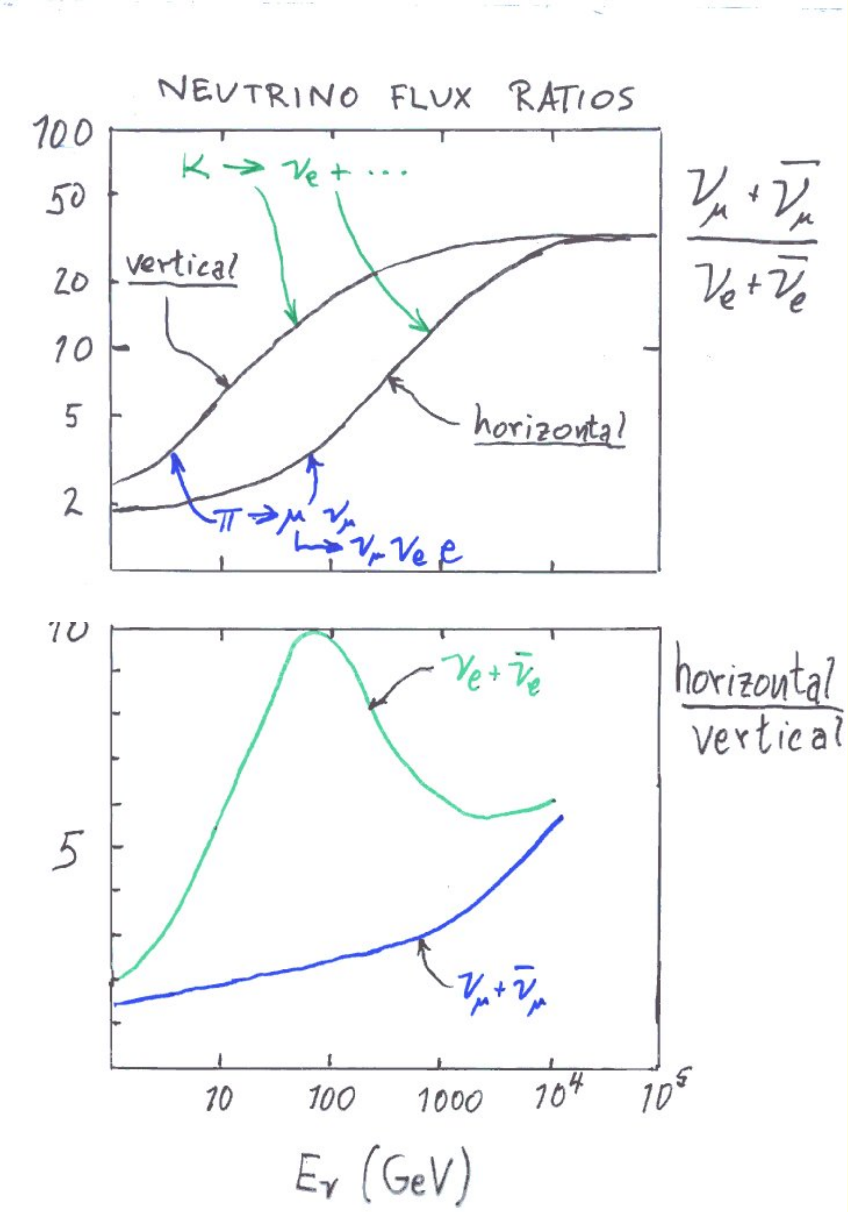




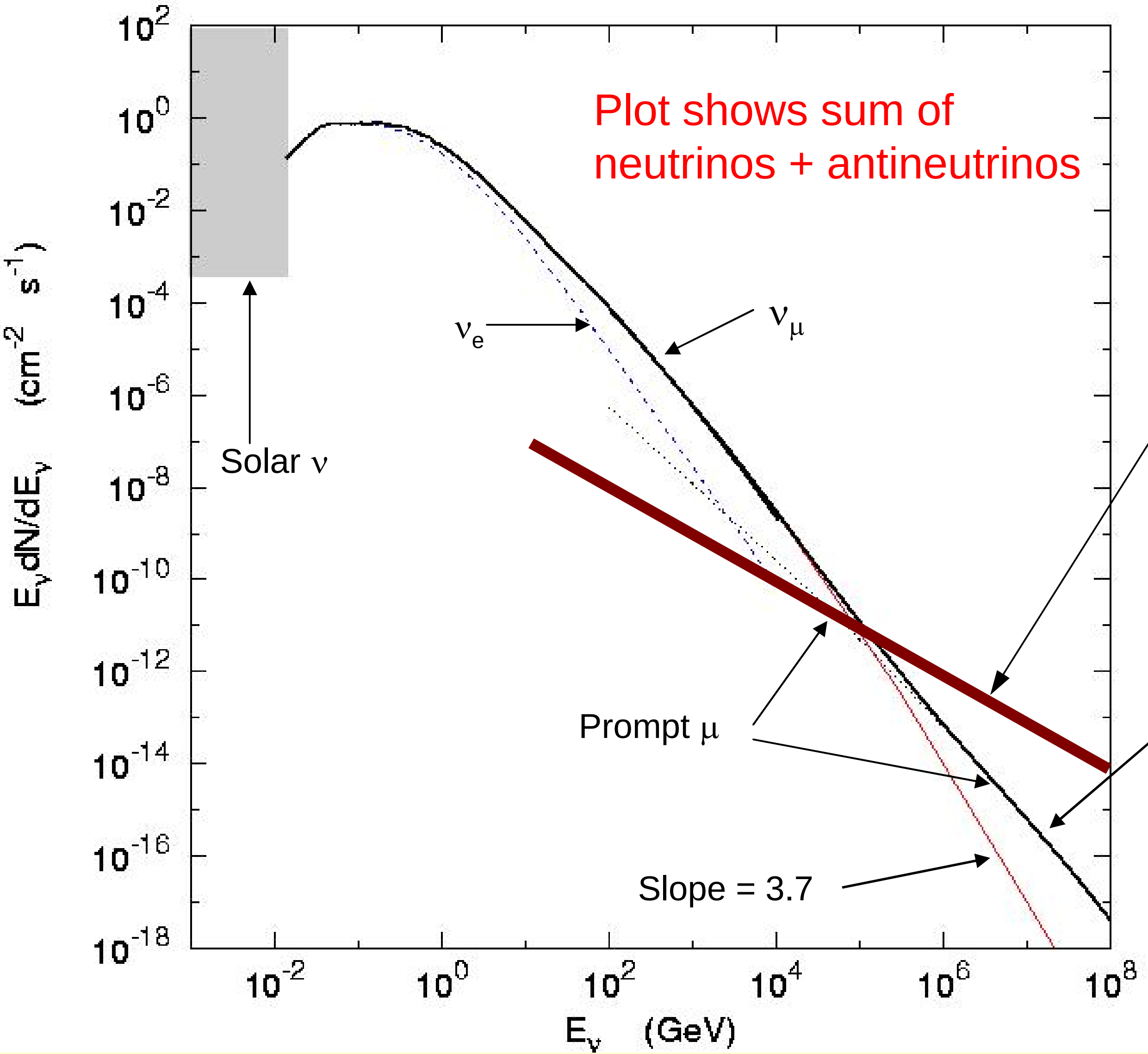
Calibration with atmospheric ν

- 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



Global view of atmospheric ν spectrum



Plot shows sum of neutrinos + antineutrinos

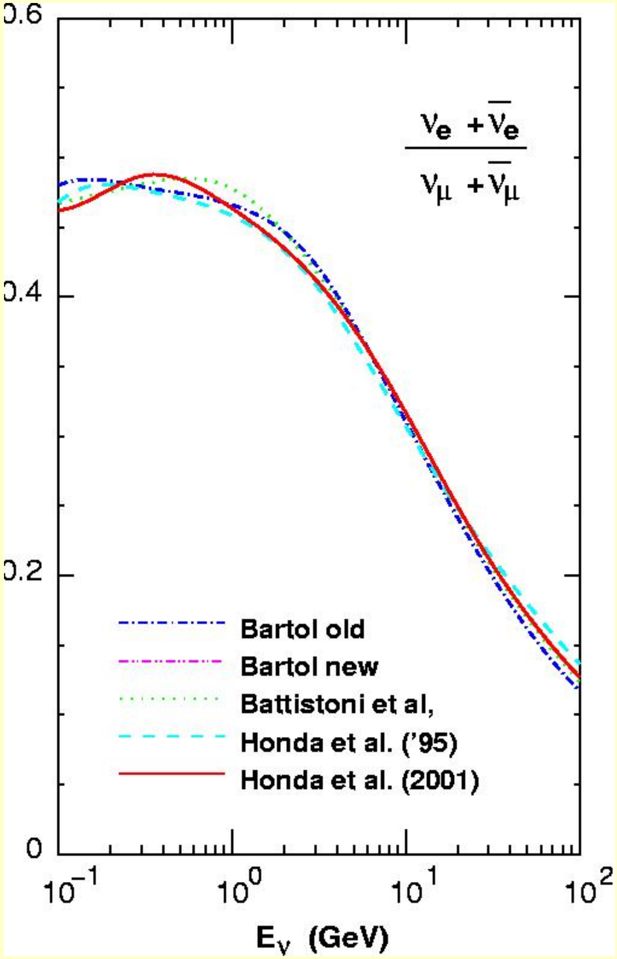
Possible E^{-2} diffuse astrophysical spectrum (WB bound)

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

Slope = 2.7

Summary - oscillations

- Evidence for ν oscillation uses ratios:
  - Contained events
    - $(\nu_\varepsilon / \nu_\mu)_{data} / (\nu_e / \nu_\mu)_{calculated}$
    - 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 $20 < E_\nu < 100$ 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 ν) limits sensitivity for diffuse astrophysical (> TeV) neutrinos