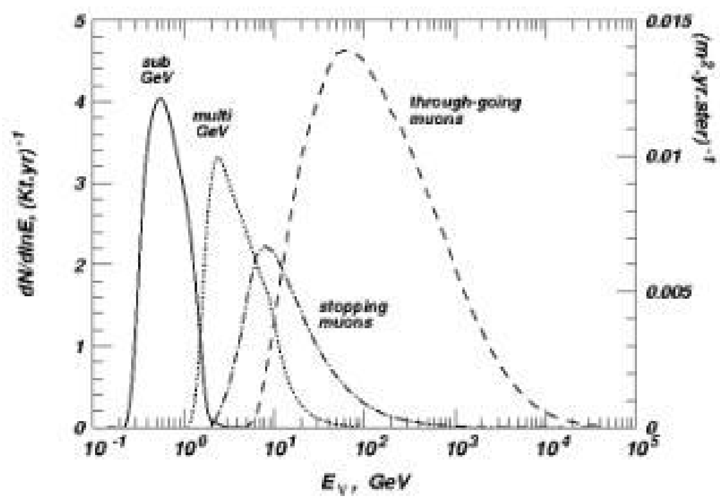
Atmospheric neutrino fluxes

Status of the calculations

based on work with M. Honda

Outline

- Overview of calculations
- E_ν < 10 GeV (contained)
  - Geomagnetic effects
  - Response functions
  - Primary spectrum
  - Hadronic interactions
  - Comparison of calculations
  - 3 D effects
- High energy
  - Importance of kaons
  - Dependence of ν_μ / ν_e ratio on energy and angle
  - Calibration of ν - telescopes
  - Prompt background
- Summary



Distribution of E_ν for 4 classes of events

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

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

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

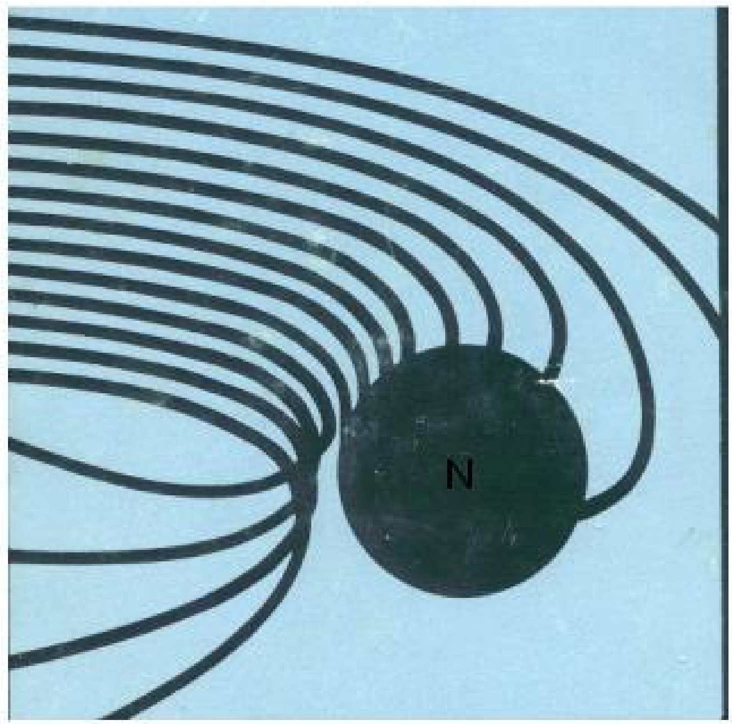
Calculations of atmospheric ν

- 1 dimensional
  - *Bartol flux: V. Agrawal et al., Phys. Rev. D53 (1996) 1314
  - *HKKM: M. Honda et al.: Phys. Rev. D52 (1995) 4985
  - TKG et al., Hamburg ICRC (2001) p. 1381
  - HKKM, Hamburg ICRC (2001) p. 1162
  - Fiorentini, Naumov, Villante, Phys. Lett. B510 (2001) 173
  - * Used in analysis of Super-K
- 3 dimensional
  - G. Battistoni et al., Astropart. Phys. 12 (2000) 315 -- first 3D calculation
  - Y. Tserkovnyak et al., Hamburg ICRC (2001) p. 1196
  - J. Wentz, Hamburg, p. 1167 (complete but preliminary)
  - Y. Liu et al., Hamburg, p. 1033 (low result ?)
  - V. Plyaskin, Phys. Lett. B516 (2001) 213 (just revised)

See poster session

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



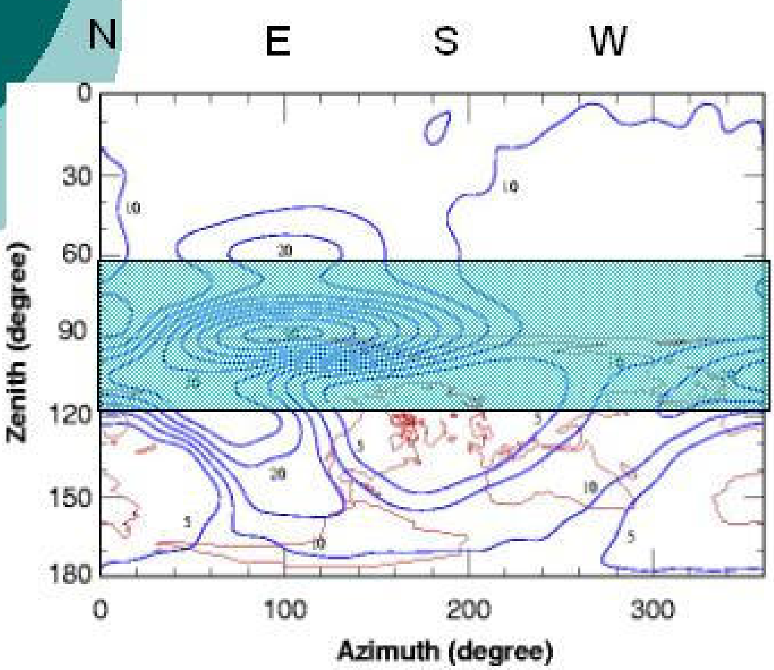
From cover of "*Cosmic Rays*" by A.M. Hillas (1972)

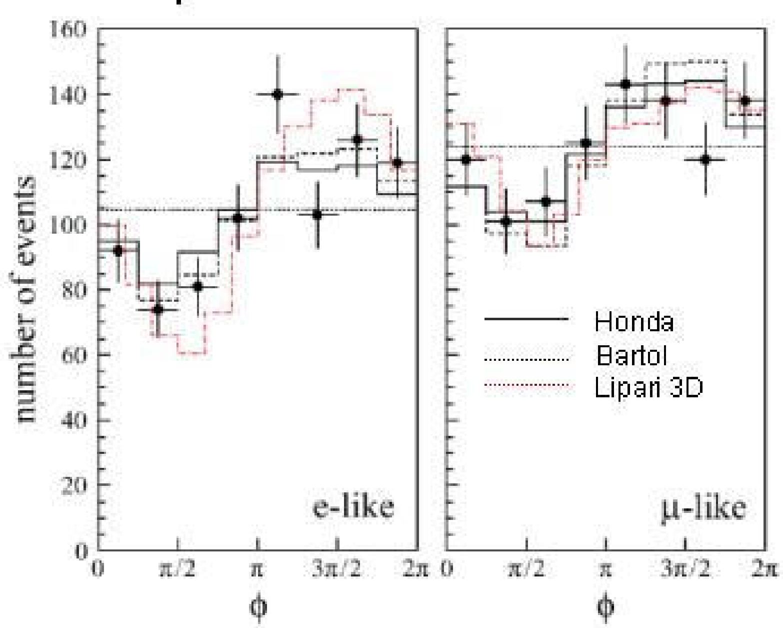
Cutoffs at Super-K

ν flux, $0.4 < E_\nu < 3$ GeV

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

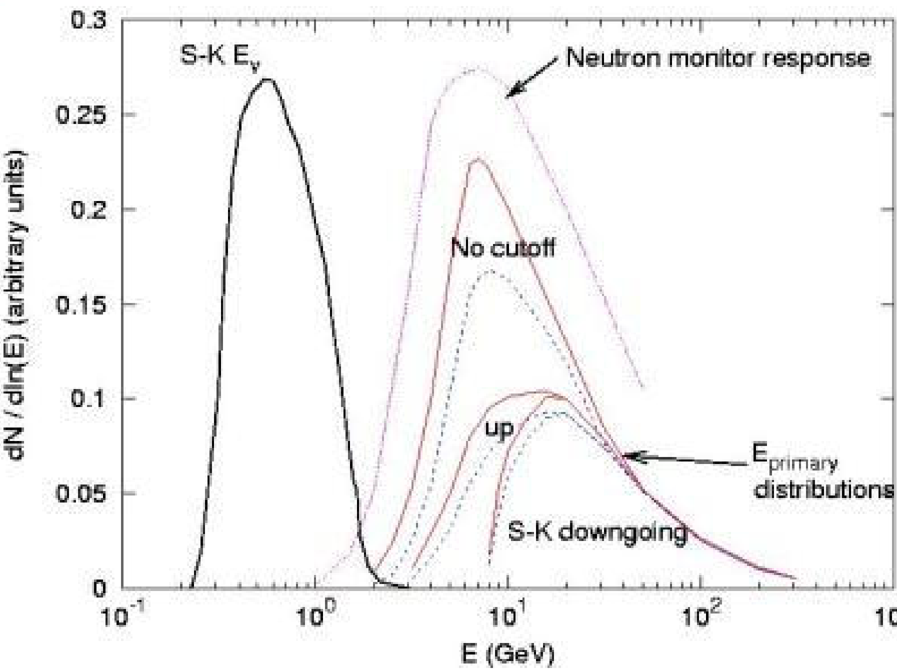
measured by Super-K and compared to 3 calculations

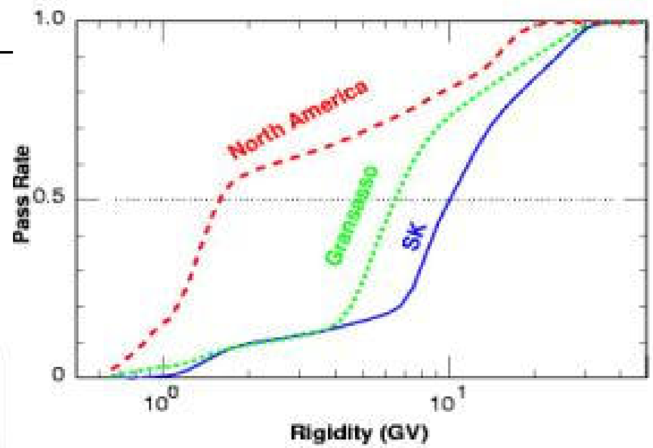


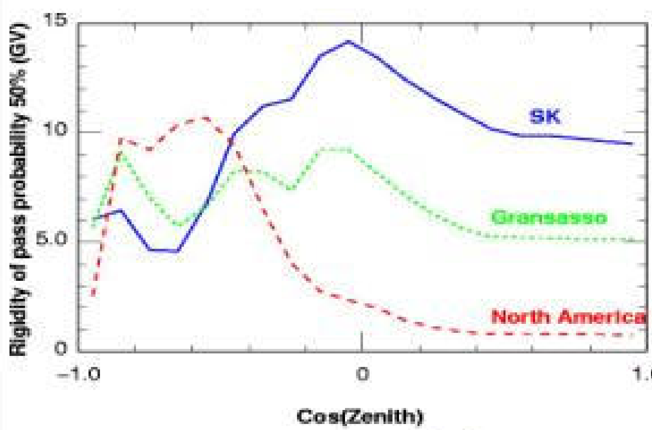


Response functions, sub-GeV ν

- $E_{primary} \sim (10) \times E_\nu$
- Up/down ratio opposite at Kamioka vs Soudan/SNO



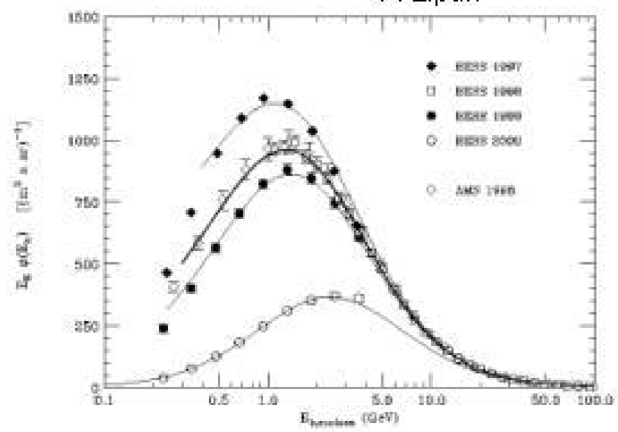




Neutrino 2002 Munich

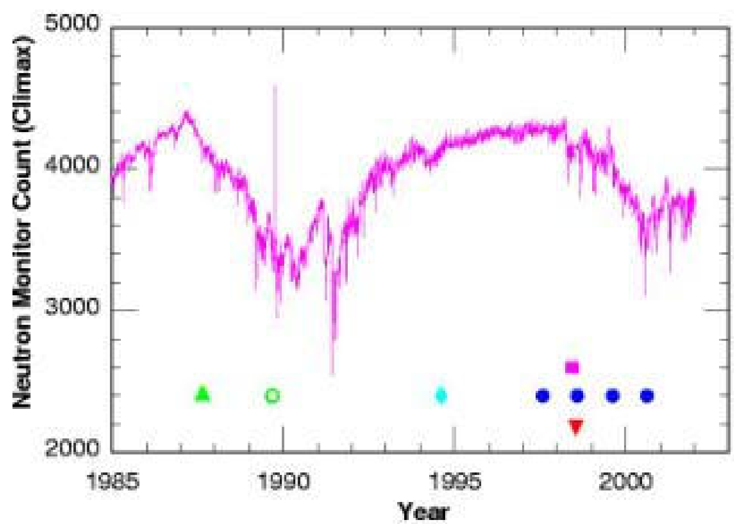
Solar modulation

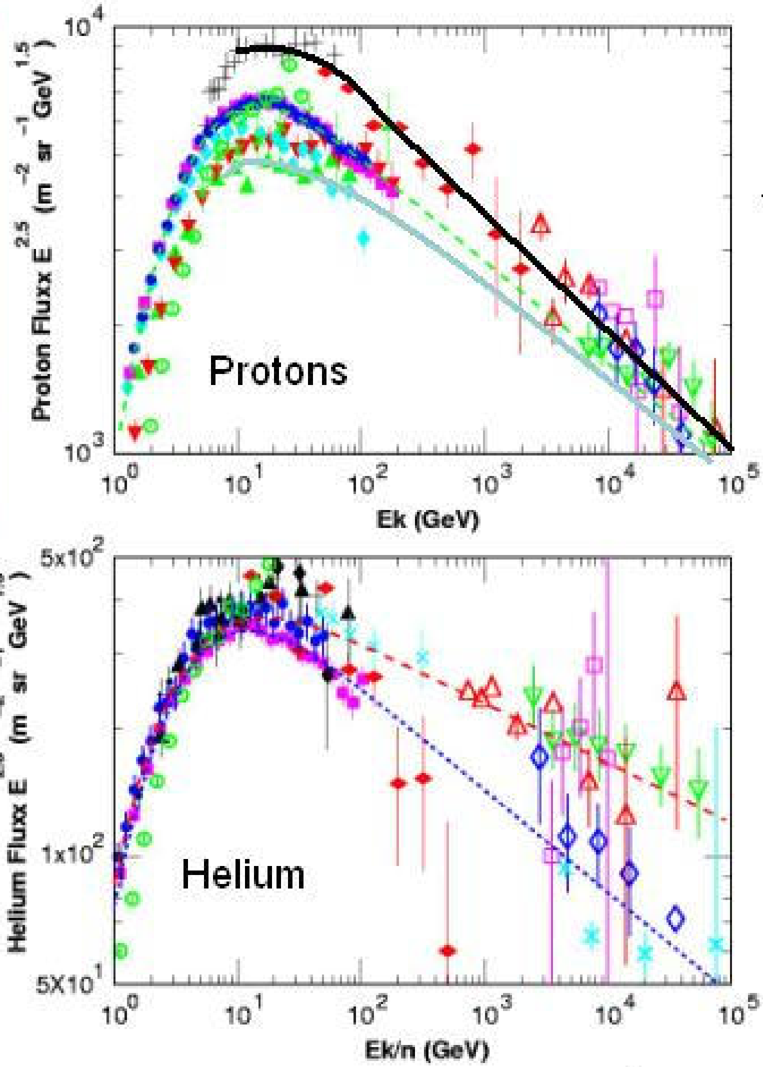
P. Lipari



Neutron monitors

- well correlated with cosmic-ray flux
- provide continuous monitor
- response like sub-GeV neutrinos with no cutoff
- SNO, Soudan: <20% variation
- Kamioka: <5% (10 %) for downward (upward)



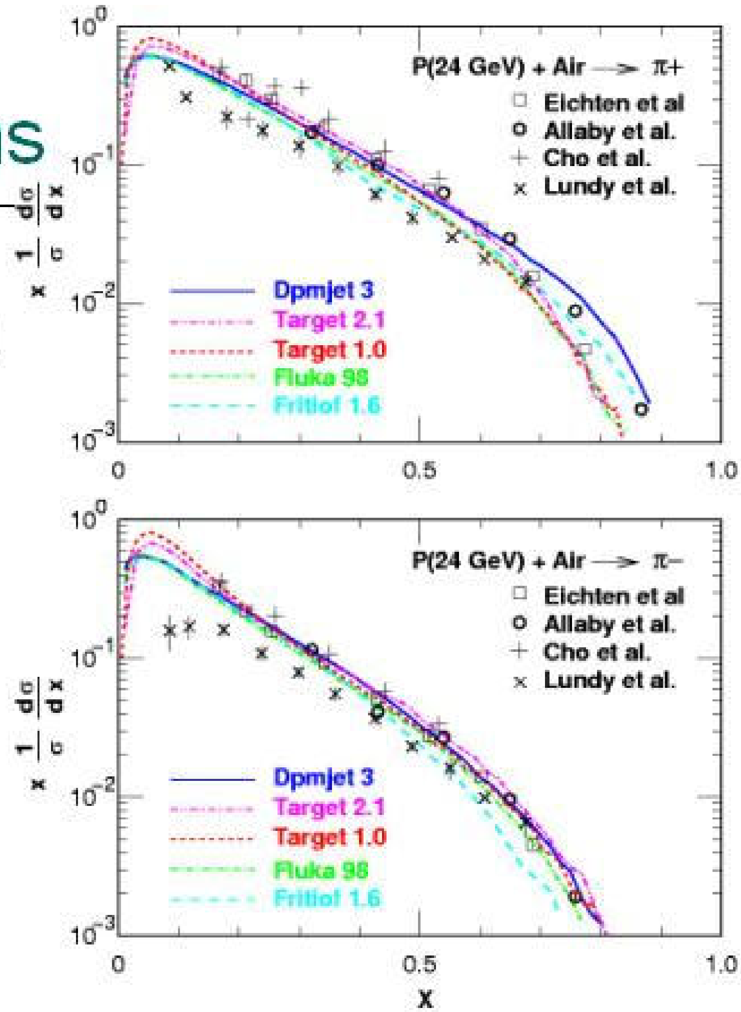


Primary spectrum

- 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
  - overall range (neglect highest and lowest):
    - +/-15%, E < 100 GeV
    - +/- 30%, E ~ TeV

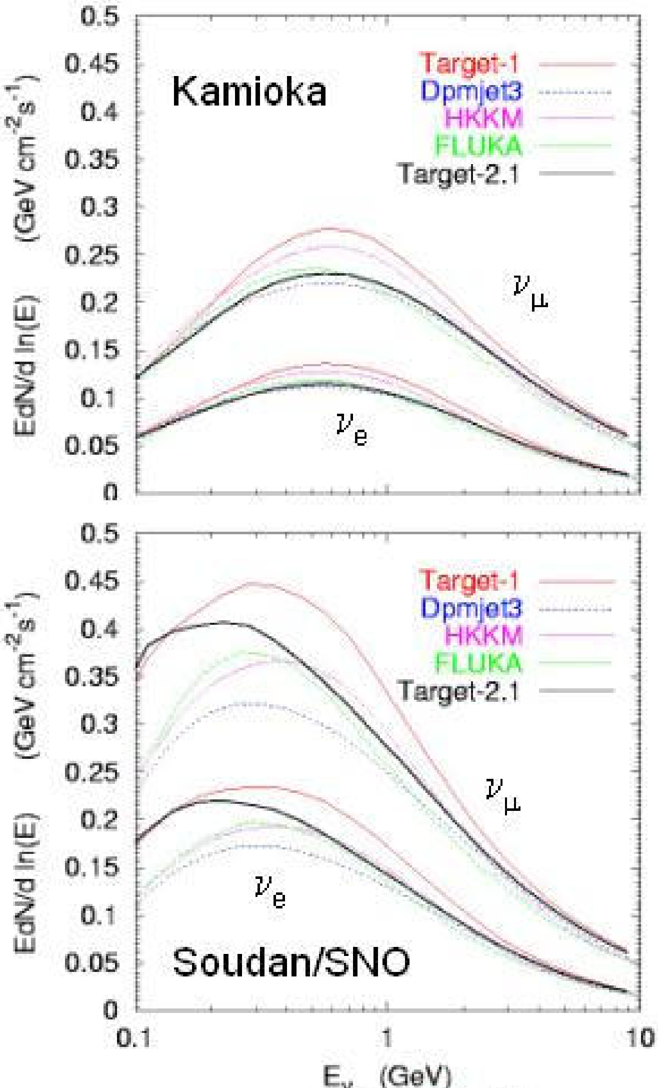
Hadronic interactions

- ν-yields depend most on treatment of π production
- Compare 3 calculations:
  - Bartol (Target)
  - Honda et al. (1995: Fritiof; present: Dpmjet3)
  - Battistoni et al. (Fluka)
- Uncertainties from interactions ~ +/-15%



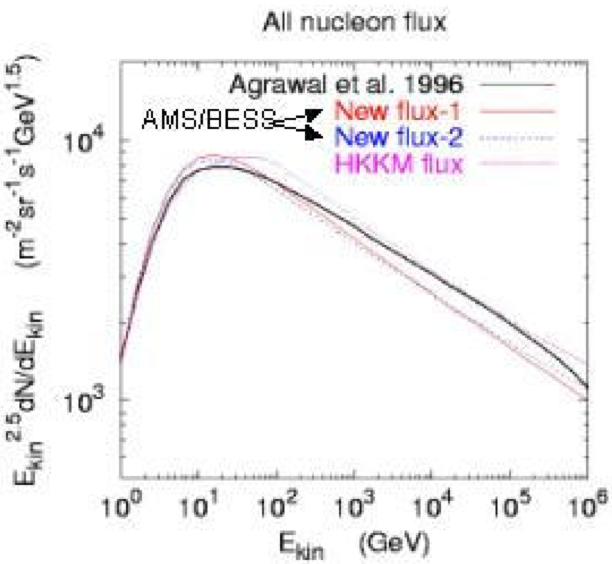
Comparison (using same flux)

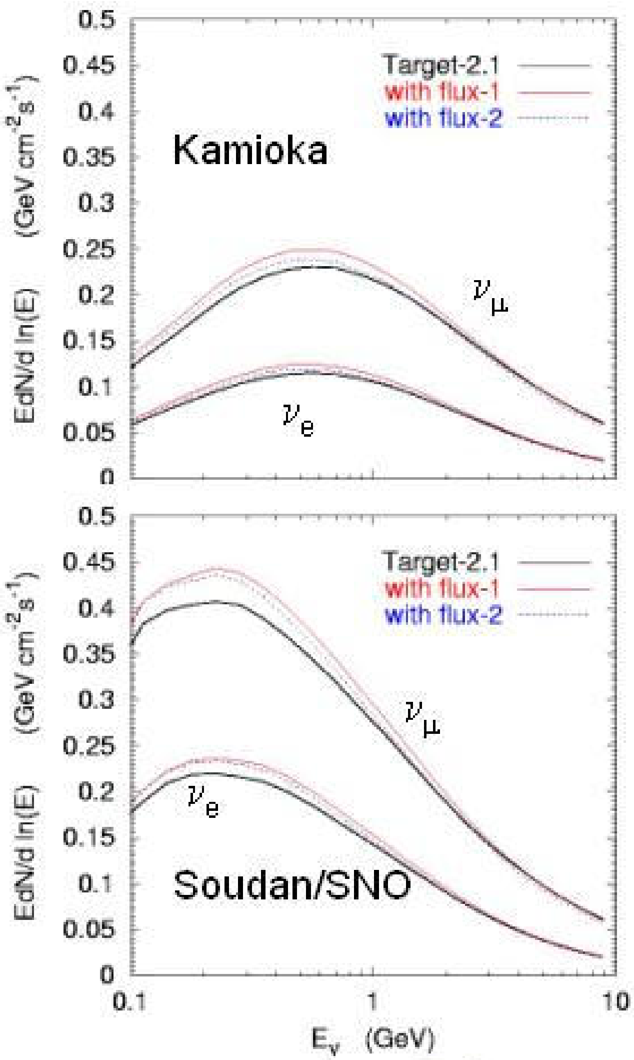
- New calculations lower than old, e.g.:
  - Target-2.1/ -1
  - Dpmjet3 / HKKM
  - 3 new calculations agree at Kamioka but not for Soudan/SNO
- Larger uncertainty at high geomagnetic λ
  - Interactions < 10 GeV are important



Comparison (using same event generator)

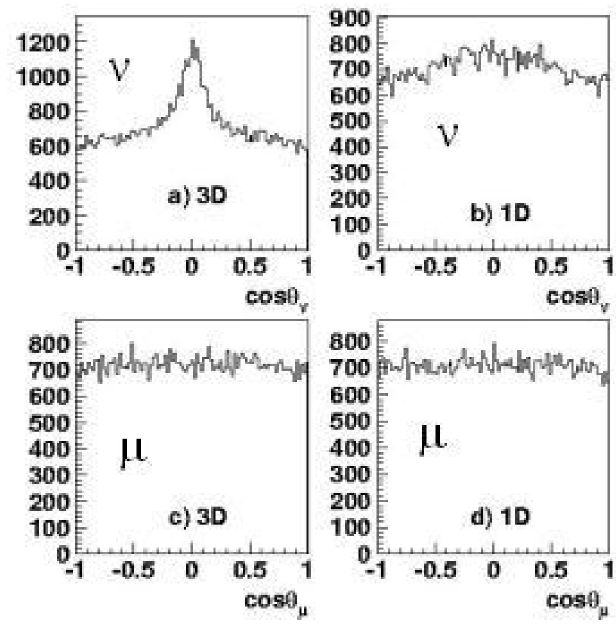
- sub GeV flux increases slightly using new flux from AMS & BESS
  - (starting from Agrawal)





3-dimensional effects

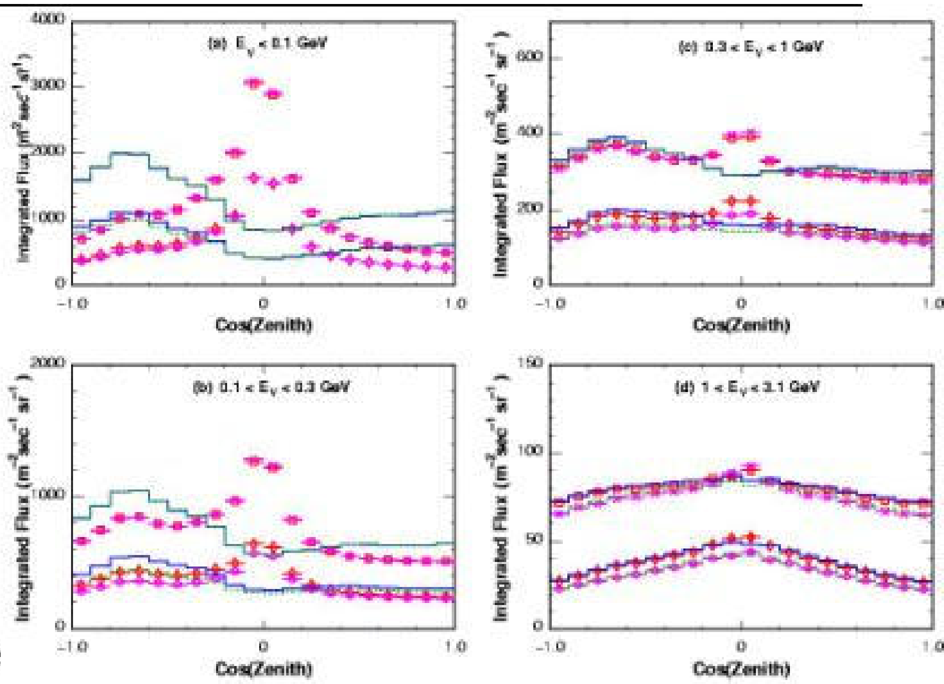
- Characteristic 3D feature:
  - excess of ν near horizon
  - shown in top, left panel
  - lower panels show directions of μ and e
  - cannot see 3D effect directly; however:
- Horizontal excess is associated with a change in path-length distribution



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

3-dimensional effects

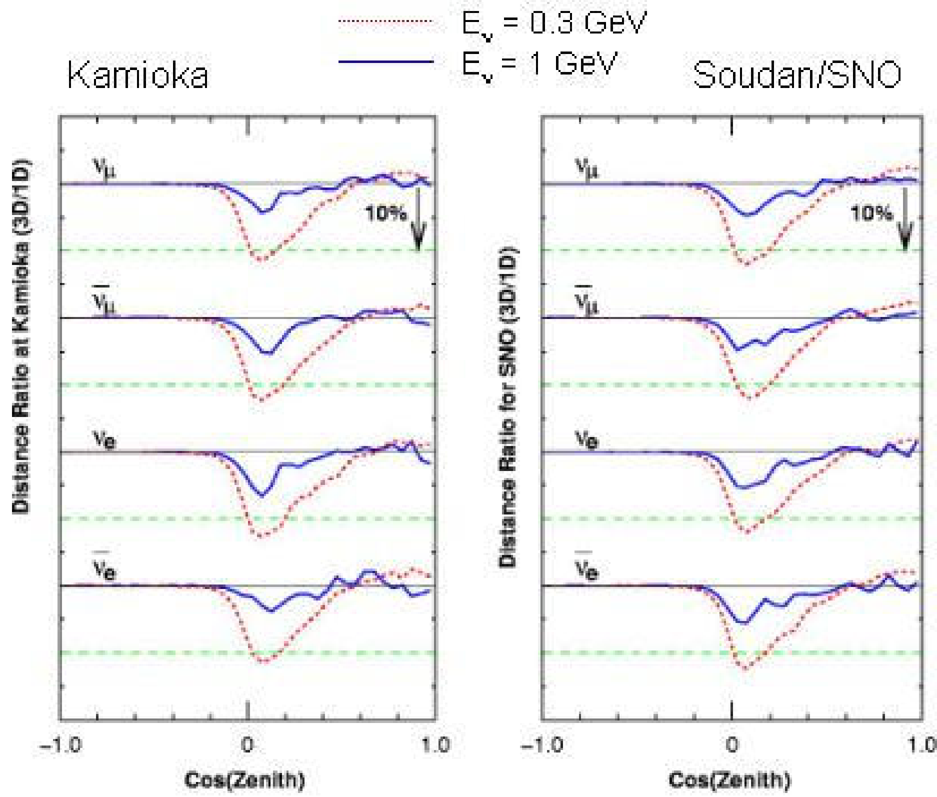
- 3D vs 1D comparison at Kamioka (3D:pink; 1D: blue/green)
- Dip near horizon (1D):
  - due to high local horizontal cutoffs
- Size of effect:
  - $p_T(\pi)/E_\pi$ sets scale
  - ~ 0.1 GeV / E_ν
  - therefore negligible for E_ν > 1 GeV



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

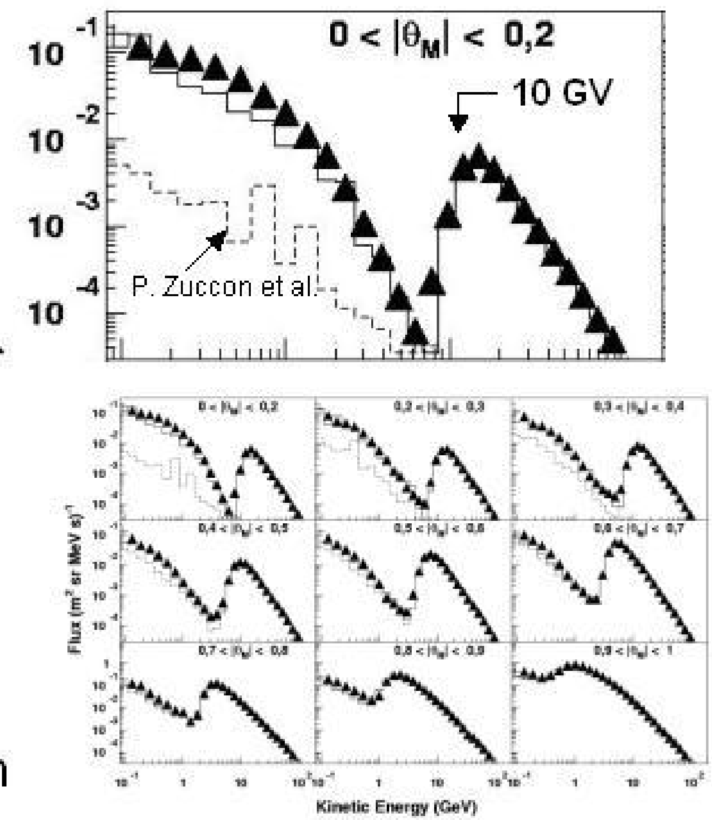
Path-length dependence

- 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_ν ~0.3-1 GeV)
- Effect not yet included in Super-K analysis



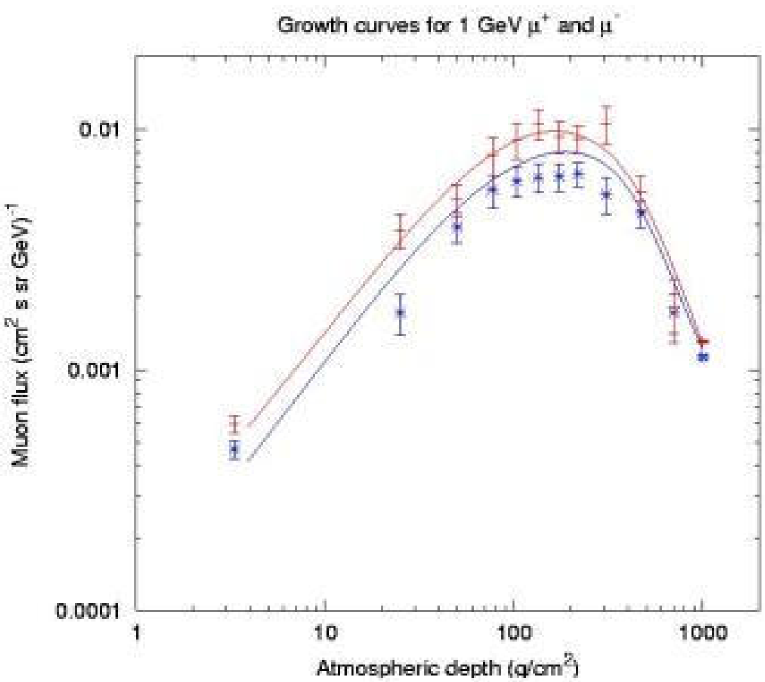
Is the second spectrum important for atmospheric ν?

- Cosmic-ray albedo beautifully measured by AMS at 380 km
- Biggest effect near geomagnetic equator (vertical cutoff ~ 10 GV)
- Albedo: sub-cutoff protons from grazing interactions of cosmic rays > cutoff (S.B. Treiman, 1953)
- trapped for several cycles
- Re-entry rate (dashed line) is lower than rate at 380 km



Comparison to muons

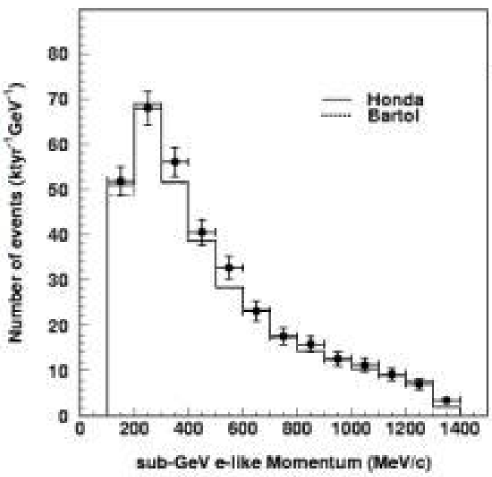
- μ^+, μ^- vs atmospheric depth
- newer measurements lower by 10-15% than earlier
- comparison not completely internally consistent:
  - ascent vs float
  - balloons rise rapidly
  - fraction detected is small compared to μ decayed to ν

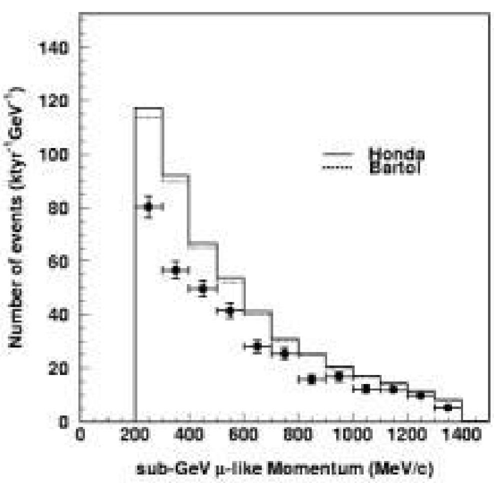


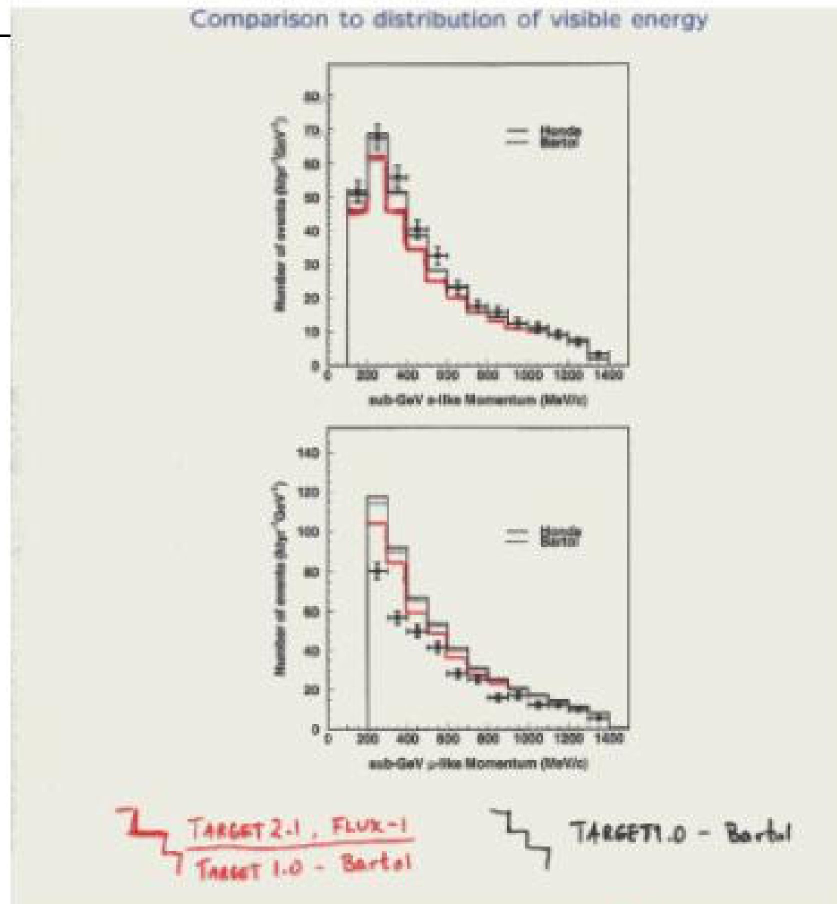
Data from CAPRICE, 3D calculation of Engel et al. (2001)

Absolute comparison

shows new calculation using new flux

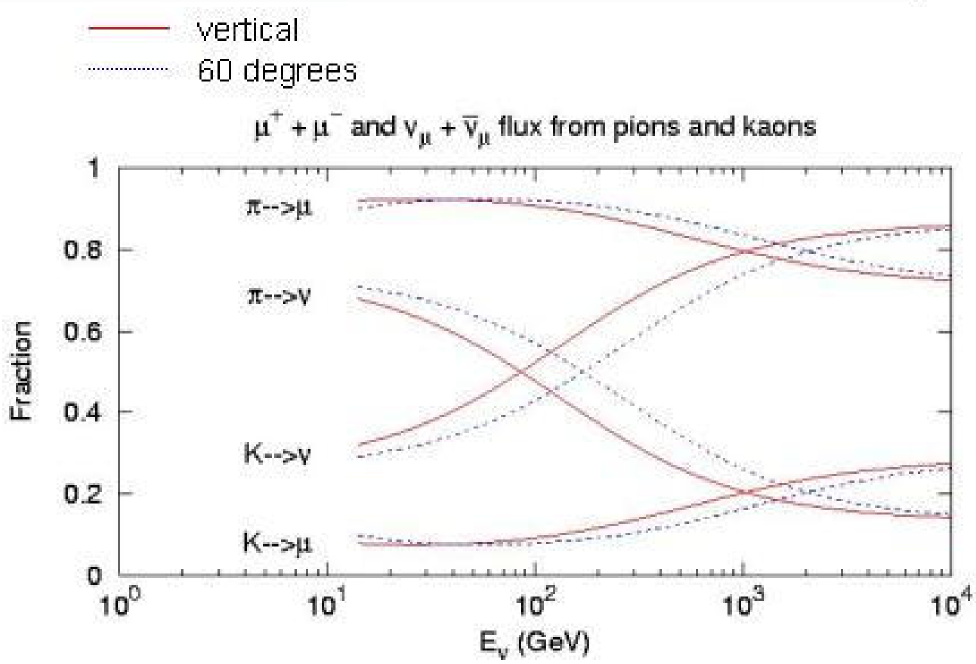






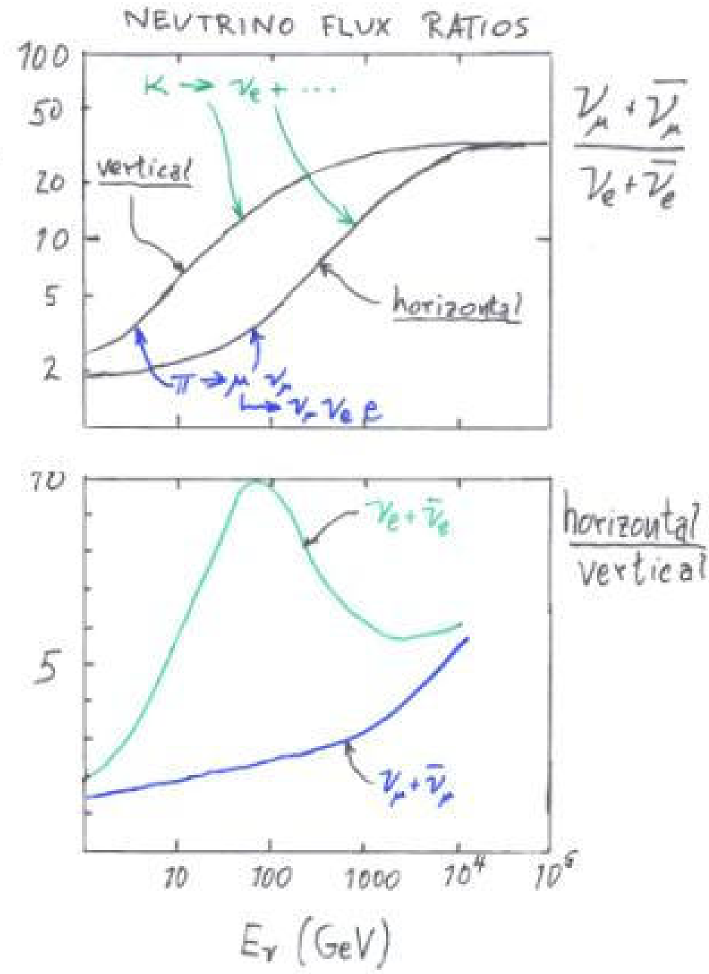
High energy (e.g. $\nu_\mu \rightarrow \mu$)

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



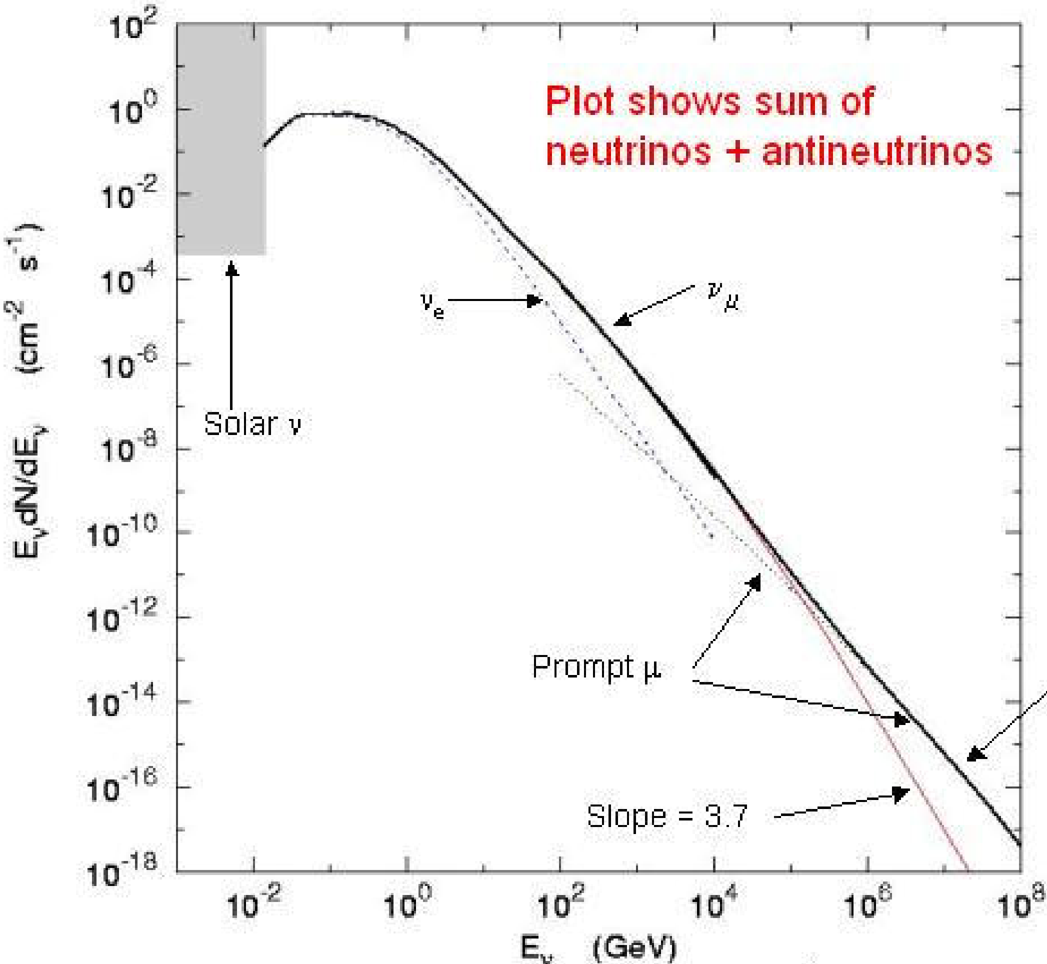
Transition to high energy

- ν_μ / ν_e ratio changes with energy, angle
- K to π^0 e ν_e becomes important
- Calibration of neutrino telescopes
  - Example*** of ν_μ / ν_e
    - flavor ratio
    - angular dependence



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

Global view of atmospheric ν spectrum



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

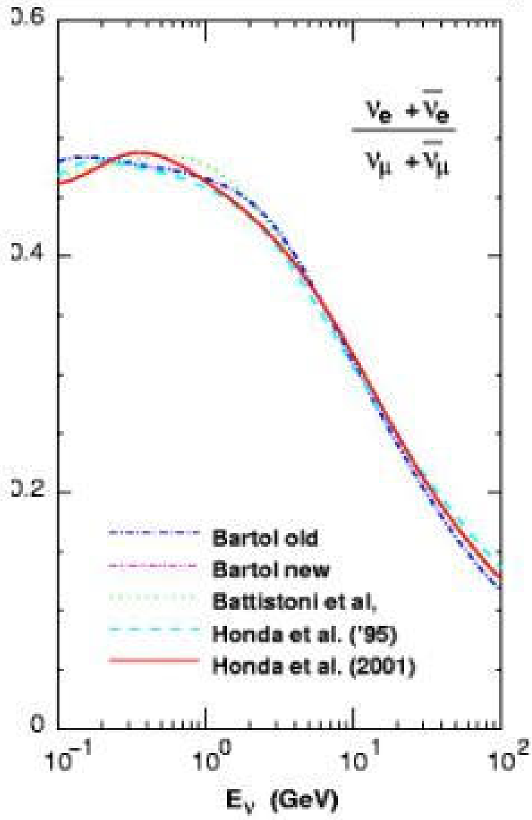
Uncertainties & absolute normalization

- Primary spectrum
  - +/- 10% up to 100 GeV (using AMS, BESS only)
  - +/- 20% below 100 GeV, +/- 30% ~TeV (all data)
  - Note lack of measurements in TeV range
- Hadronic interactions
  - +/- 15% below 100 GeV
  - 1D o.k. for comparing calculations and for tracking effects of uncertainties in input
  - Other sources at per cent level
    - (local terrain, seasonal variations, anisotropy outside heliosphere)
  - New measurements: HARP, E907
- Uncertainty in σ_ν

Summary (low energy)

Evidence for ν oscillation uses ratios:

- Contained events
  - $(\nu_e / \nu_\mu)_{data} / (\nu_e / \nu_\mu)_{calculated}$
  - 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
  - (plots here show ratio at production)
- Observation of geomagnetic effects confirms experiment & interpretation
- Path length dependence of 3D a small effect but needs to be included in analysis

Summary (high energy)

- Kaon decays dominate atmospheric ν_μ, ν_e above 100 GeV
- Well-understood atmospheric ν_μ, ν_e useful for calibration of neutrino telescopes
- Uncertainty in level of prompt neutrinos (from charm decay) will limit search for diffuse astrophysical neutrinos