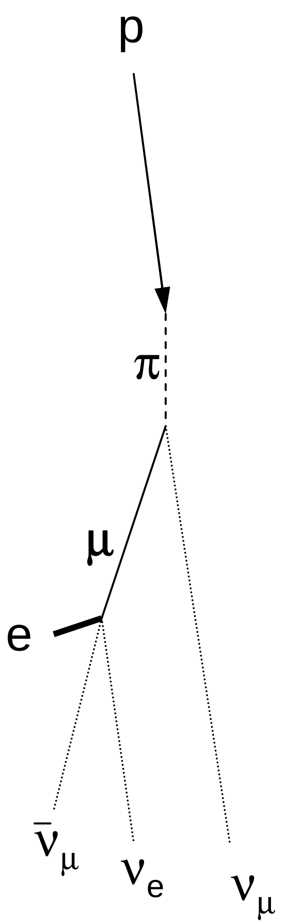
Atmospheric muons & neutrinos in neutrino telescopes

- Neutrino oscillations
- Muon & neutrino beams
- Muons & neutrinos underground

Atmospheric neutrinos

- Produced by cosmic-ray interactions
  - Last component of secondary cosmic radiation to be measured
  - Close genetic relation with muons
    - $p + A \rightarrow \pi^{\pm}\ (K^{\pm}) +$ other hadrons
    - $\pi^{\pm}\ (K^{\pm}) \rightarrow \mu^{\pm} + \nu_{\mu}\ (\bar{\nu}_{\mu})$
    - $\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}\ (\nu_{\mu}) + \nu_{e}\ (\bar{\nu}_{e})$



Historical context

Detection of atmospheric neutrinos

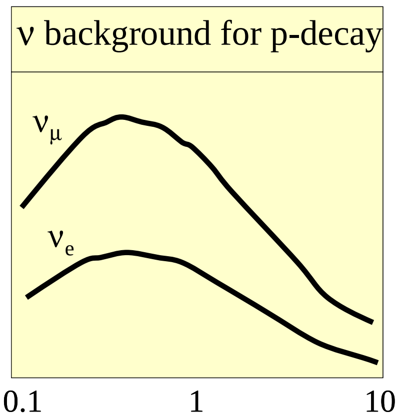
- Markov (1960) suggests Cherenkov light in deep lake or ocean to detect atmospheric ν interactions for neutrino physics
- Greisen (1960) suggests water Cherenkov detector in deep mine as a neutrino telescope for extraterrestrial neutrinos
- First recorded events in deep mines with electronic detectors, 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

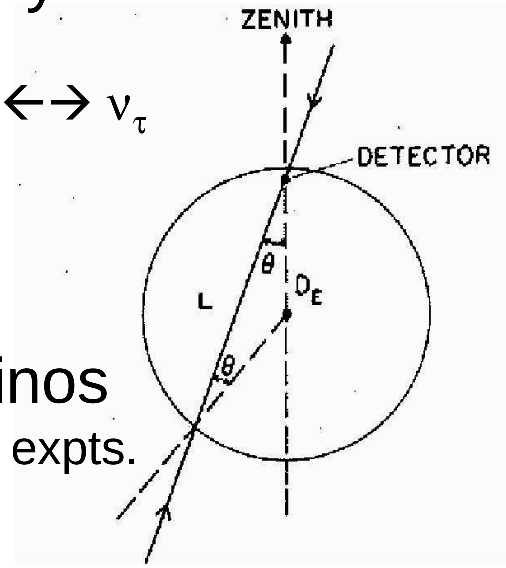


Historical context (cont'd)

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



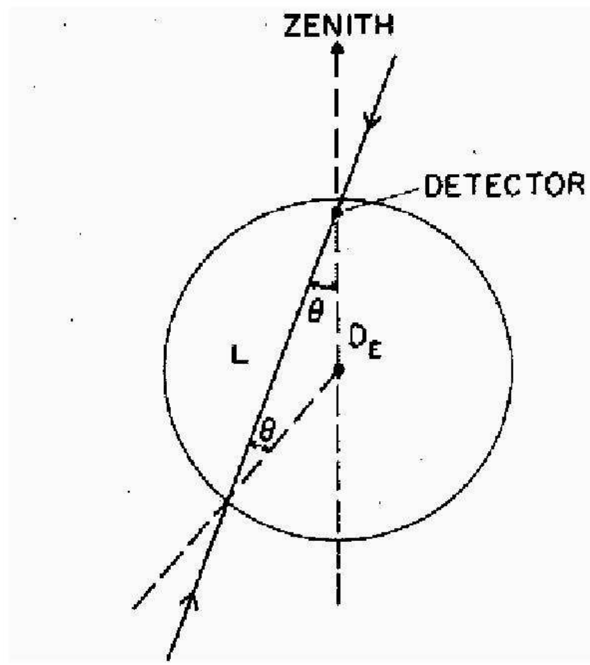
- Super-K: "Evidence for neutrino oscillations" at Neutriino 98
- Subsequent increasingly detailed analyses from Super-K: $\nu_\mu \leftrightarrow \nu_\tau$
- Confirming evidence from MACRO, Soudan, K2K, MINOS
- Analyses based on **ratios** comparing to 1D calculations
- Compare up vs down

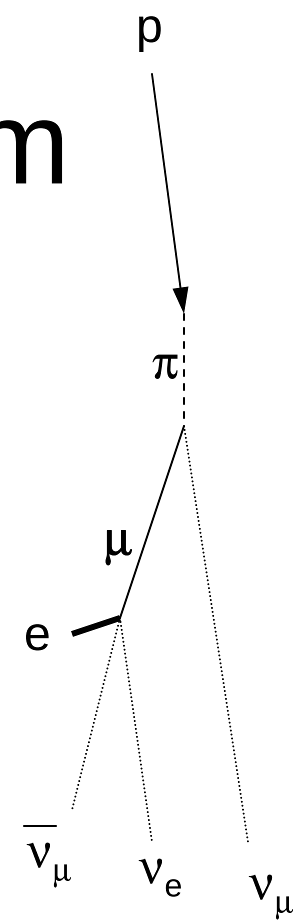
Parallel discovery of oscillations of Solar neutrinos

- Homestake 1968-1995, SAGE, Gallex … chemistry counting expts.
- Kamioka, Super-K, SNO … higher energy with directionality
- $\nu_e \leftrightarrow (\nu_\mu, \nu_\tau)$

Atmospheric neutrino beam

- Cosmic-ray protons produce neutrinos in atmosphere
- $\nu_\mu / \nu_e \sim 2$ for $E_\nu <$ GeV
- Up-down symmetric
- Oscillation theory:
  - Characteristic length ($E/\delta m^2$)
  - related to $\delta m^2 = m_1^2 - m_2^2$
  - Mixing strength ($\sin^2 2\theta$)
- Compare 2 pathlengths
  - Upward: 10,000 km
  - Downward: 10 – 20 km





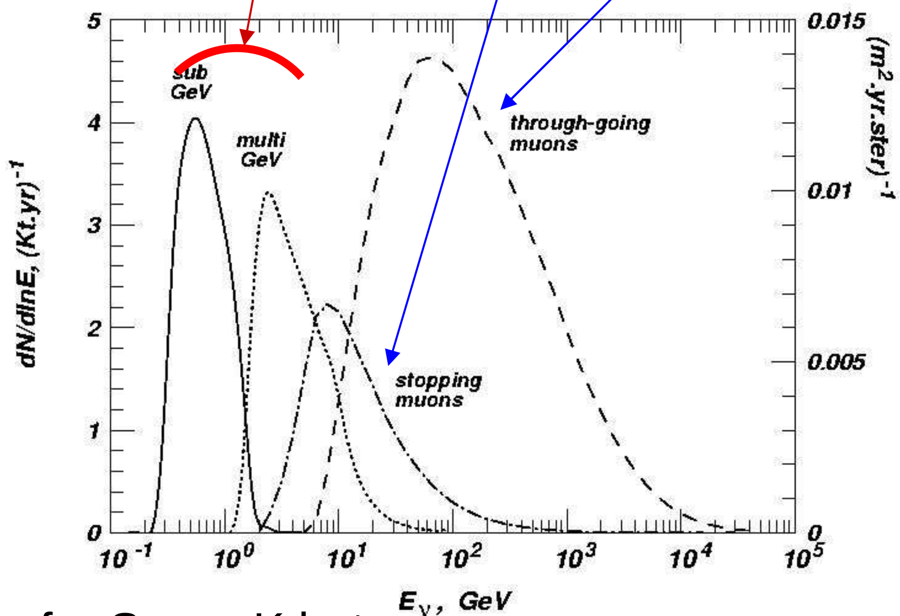
$$P(\nu_\mu \longleftrightarrow \nu_\tau) = \sin^2 2\theta \, \sin^2 \left(\frac{1.27\, L(\text{km})\, \delta m^2(\text{eV}^2)}{E_\nu(\text{GeV})} \right)$$

Wolfenstein; Mikheyev & Smirnov

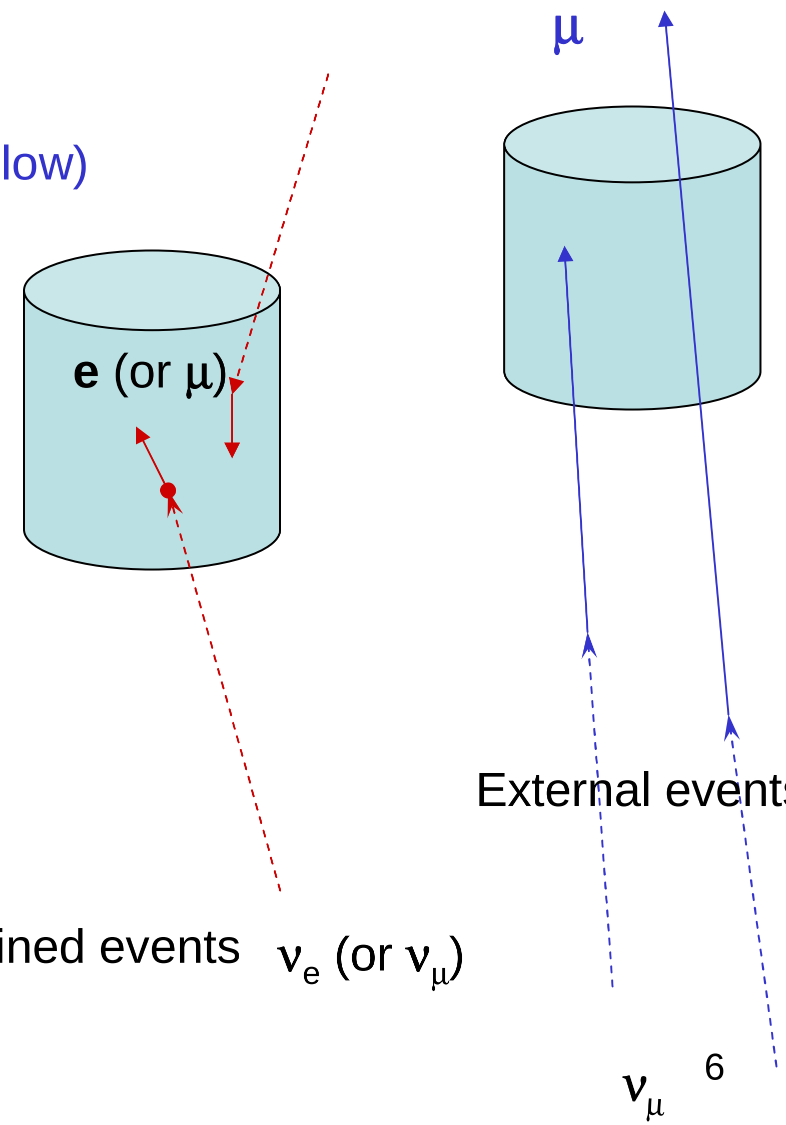
Classes of atmospheric ν events

Contained (any direction)

ν-induced μ (from below)



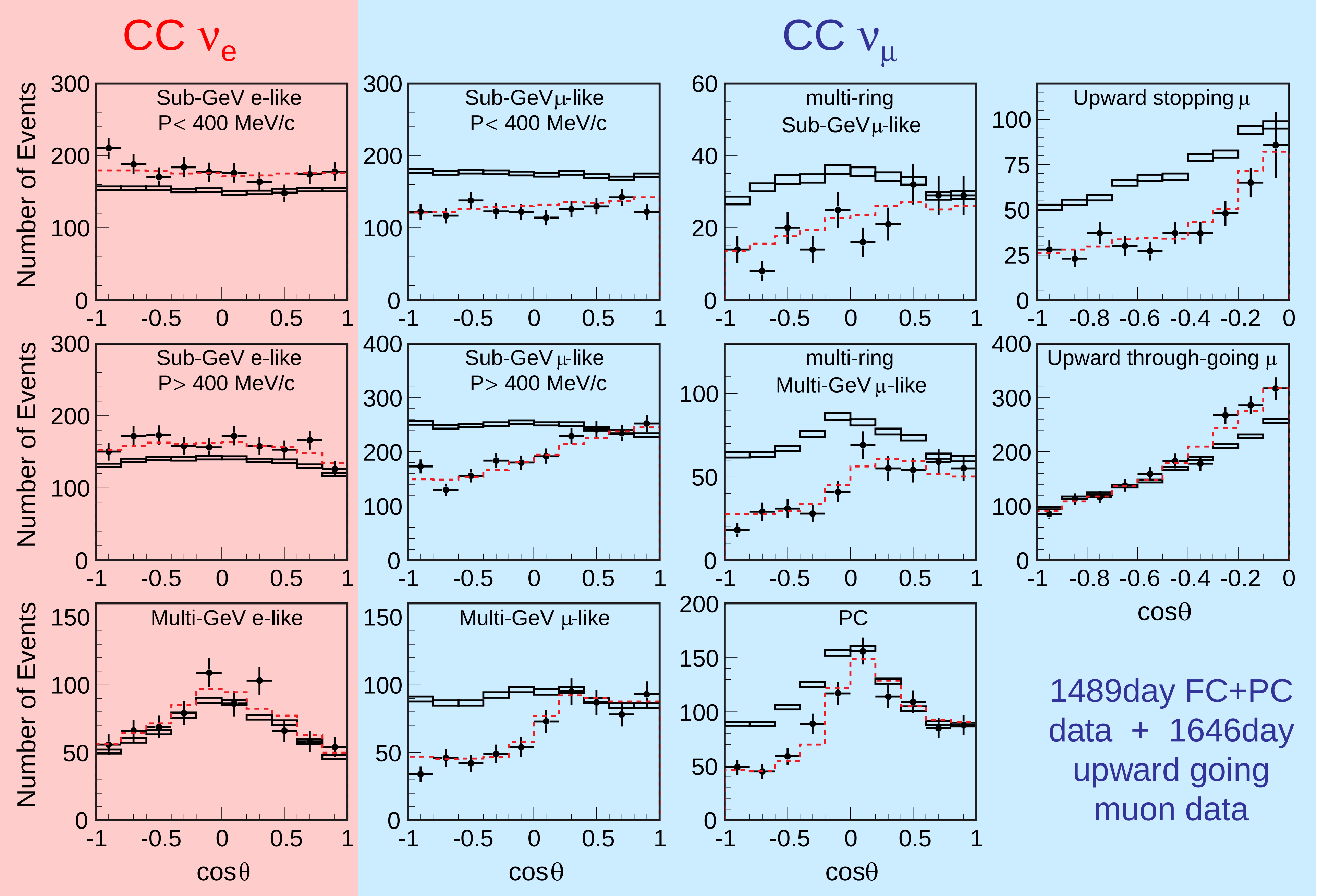
Plot is for Super-K but
the classification is generic



Contained events

External events

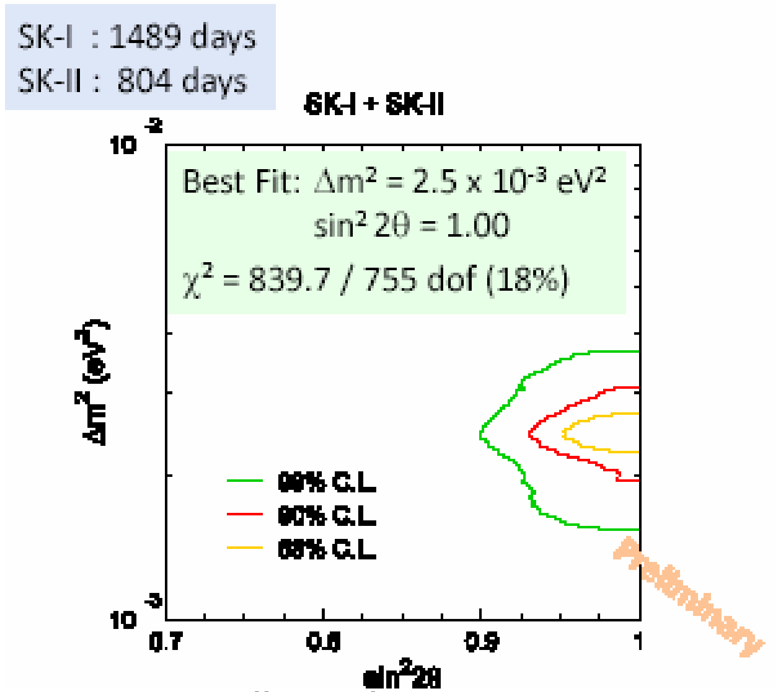
Super-K atmospheric neutrino data (hep-ex/0501064)



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

Atmospheric ν

$\nu_\mu \leftrightarrow \nu_\tau$, $\delta m^2 = 2.5 \times 10^{-3}$ eV^2
maximal mixing



Yumiko Takenaga, ICRC2007

Solar neutrinos

$\nu_e \leftrightarrow \{\nu_\mu,\nu_\tau\}$, $\delta m^2 \sim 10^{-4}$ eV^2
large mixing

3-flavor mixing

Flavor state $|\,\nu_\alpha\,) = \Sigma_i\, U_{\alpha i}\,|\,\nu_i\,)$, where $|\,\nu_i\,)$ is a mass eigenstate

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13} \\ 0 & 1 & 0 \\ -S_{13} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"atmospheric"

$C_{13} \sim 1$
S_{13} small

"solar"

High-energy Neutrino telescopes

Detector	Number of OMs	Enclosed volume (Megatons)	Depth (m.w.e)	Status
Baikal (NT200+)	230	10	1100-1310	Operating
AMANDA	677	15	1350-1850	2000-2009
ANTARES	900	10	2050-2400	Operating
IceCube	3540	500	1350-2250	Operating, 2009
	5160	900	1350-2250	2011
KM3Net	$\sim$10,000	km^3	2300-3300 (NEMO)	Design study
		km^3	3000-4000 (NESTOR)	
		km^3	1400-2400 (ANTARES site)	
GVD (future Baikal)	$\sim$2500	km^3	800-1300	Design study

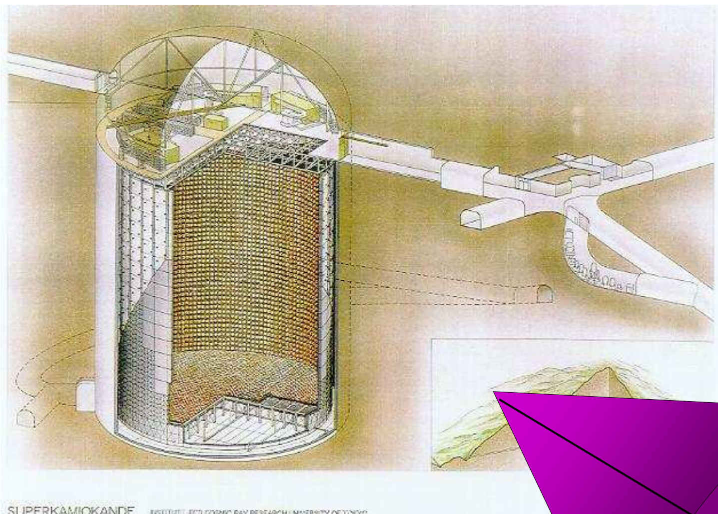
Table 4: Parameters of existing and proposed neutrino neutrino telescopes in water and ice.

Large volume--coarse instrumentation--high energy (> TeV)

as compared to Super-K with 40% photo-cathode over 0.05 Mton

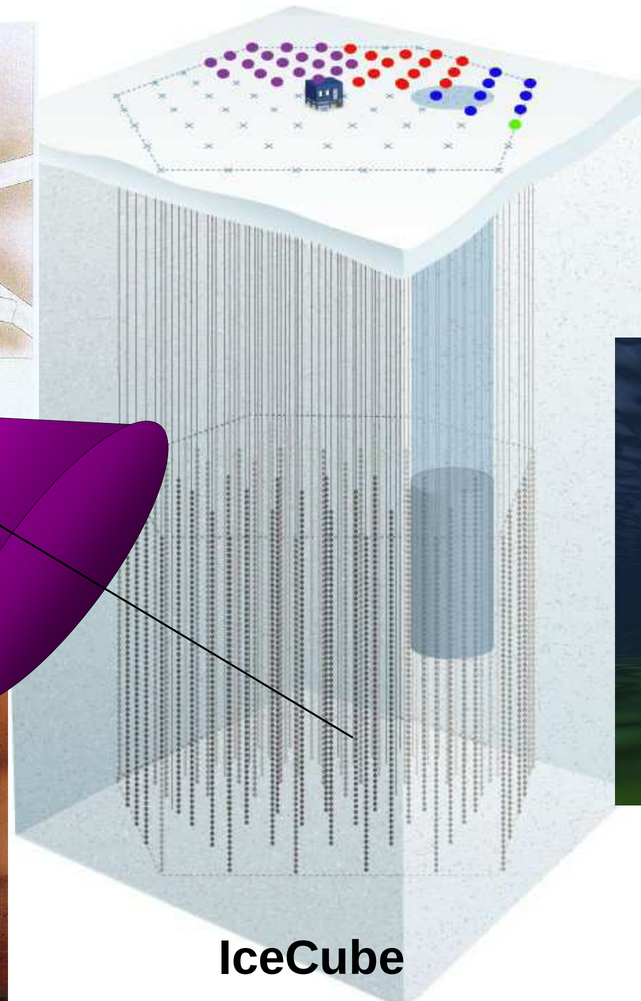
Detecting neutrinos in H_20

Proposed by Greisen, Markov in 1960



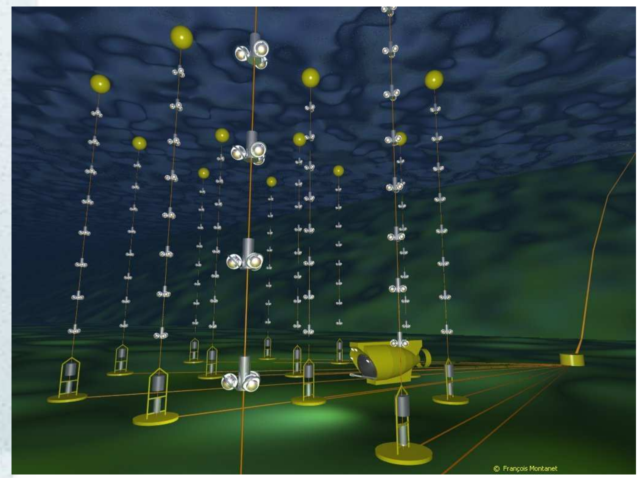
Super-K

SNO



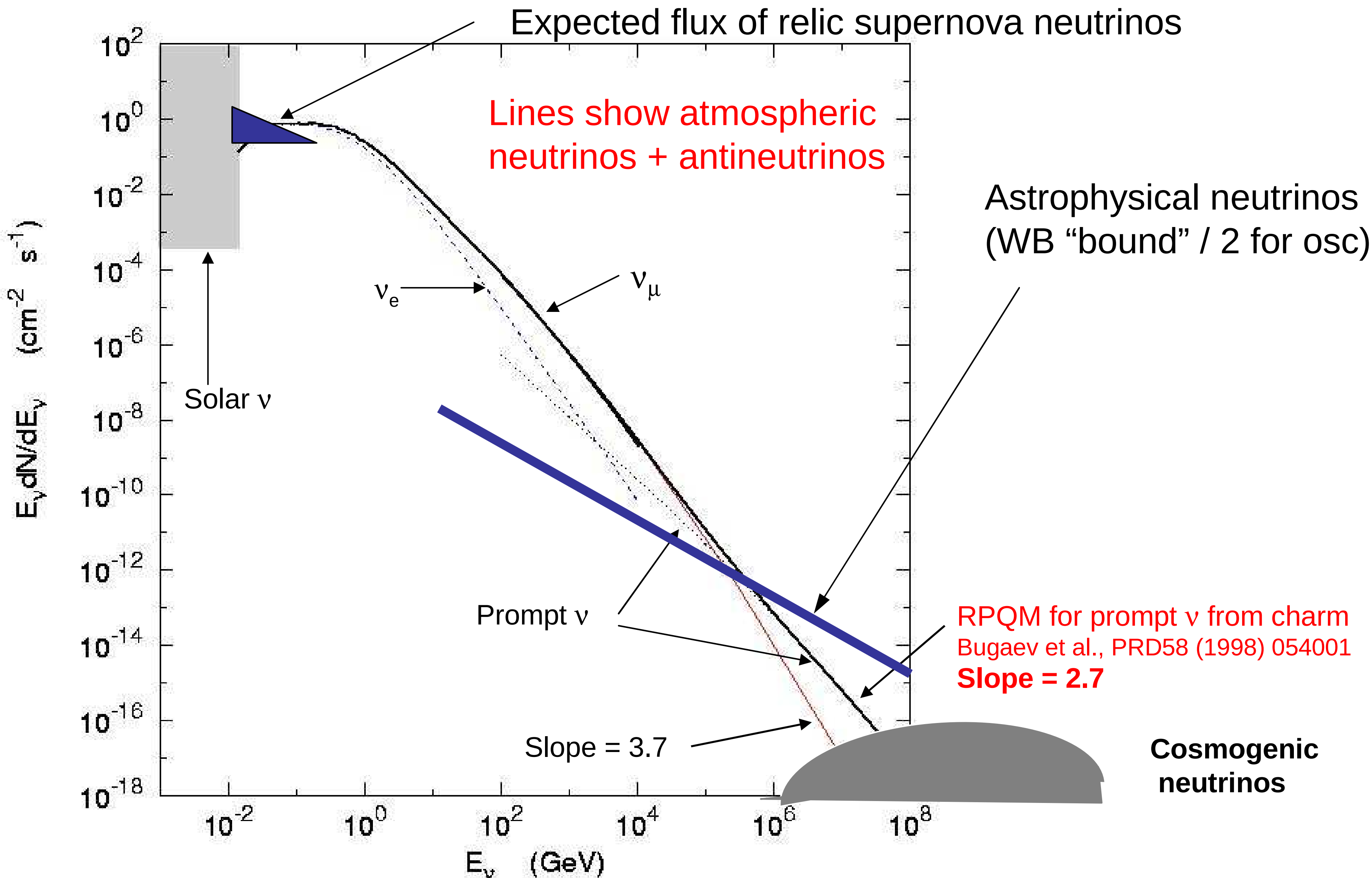
IceCube

Heritage:
- DUMAND
- IMB
- Kamiokande



ANTARES

The neutrino landscape

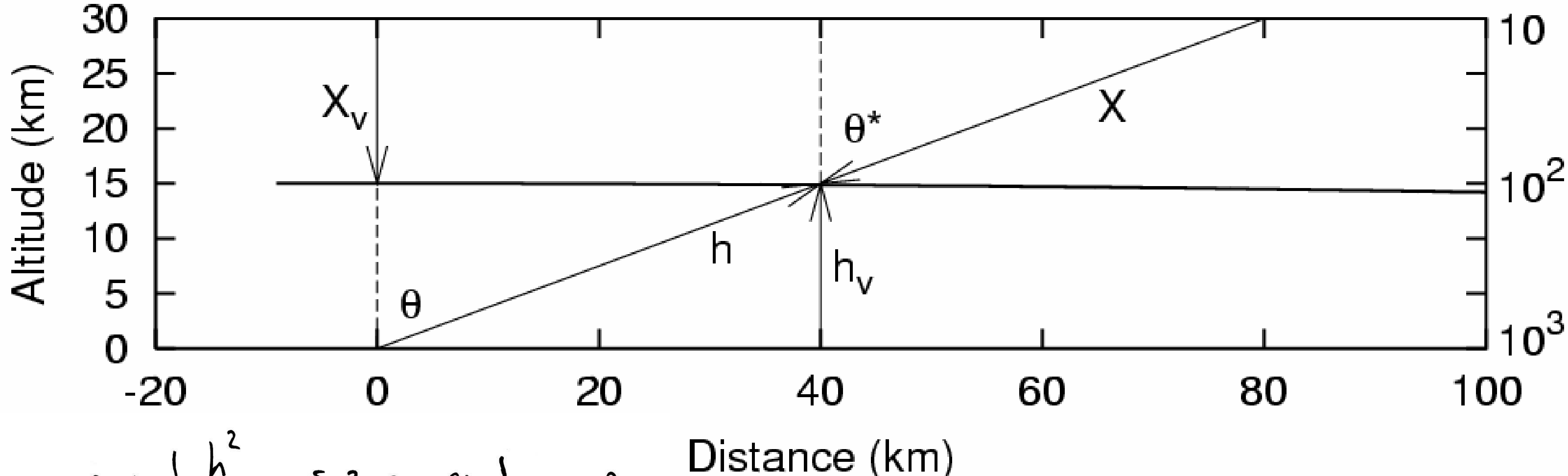


The atmosphere (exponential approximation)

Pressure = $X_v = X_o \exp\{-h_v / h_o\}$, where $h_o = 6.4$ km for $X_v < 200$ g / cm^2

and $X_0 = 1030$ g / cm^2

Density = $\rho = -dX_v / dh_v = X_v / h_o$ $\quad X_v \sim p = \rho RT \rightarrow h_o \sim RT$



$h_v \cong h\cos\theta + \frac{1}{2}\frac{h^2}{R_\oplus}\sin^2\theta \cong h\cos\theta$

Slant depth $X = \int_{h = h_v/\cos\theta}^{\infty} \rho(l)\, dl \cong X_v/\cos\theta$

Cascade equations

For hadronic cascades in the atmosphere

$$\frac{\mathrm{d}N_i(E,X)}{\mathrm{d}X} = -\left(\frac{1}{\lambda_i} + \frac{1}{d_i}\right) N_i(E,X) + \sum_j \int \frac{F_{ji}(E_i,E_j)}{E_i} \frac{N_j(E_j)}{\lambda_j} \mathrm{d}E_j,$$

X = depth into atmosphere

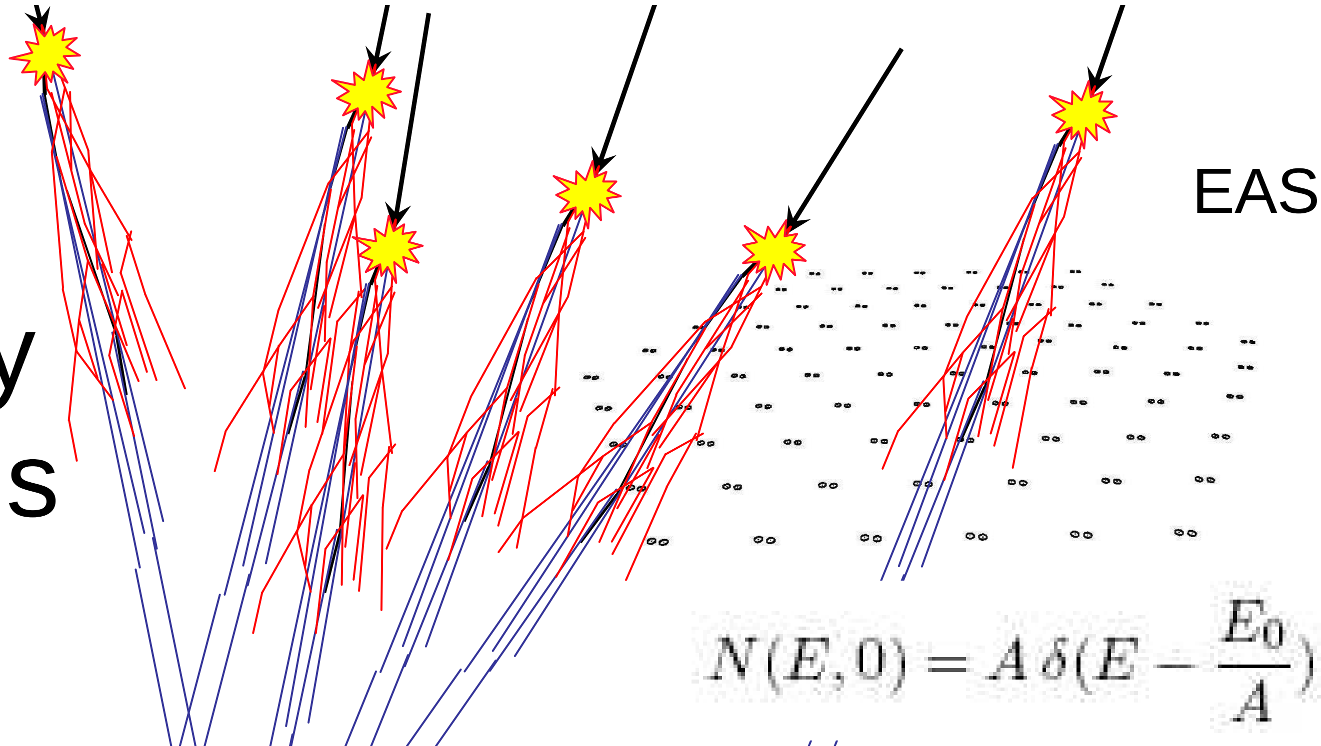
d = decay length

λ = Interaction length

$$F_{ac}(E_c,E_a) \equiv E_c \frac{\mathrm{d}n_c(E_c,E_a)}{\mathrm{d}E_c}$$

- $F_{ji}(E_i,E_j)$ has no explicit dimension, so F → F(ξ)
  - $\xi = E_i/E_j$ & $\int \ldots F(E_i,E_j)\, dE_j / E_i \rightarrow \int \ldots F(\xi)\, d\xi / \xi^2$
  - Small scaling violations from m_i, Λ_{QCD} ~ GeV, etc
  - Still… a remarkably useful approximation

Boundary conditions



$$N(E,0) = A\,\delta(E - \frac{E_0}{A}),$$

Boundary condition
for inclusive flux

$$N(E,0) = N_0(E) = \frac{\mathrm{d}N}{dE} \approx 1.8\,E^{-2.7}\,\frac{\mathrm{nucleons}}{\mathrm{cm}^2\,\mathrm{sr\,s\,GeV}/A}$$

Uncorrelated fluxes in atmosphere

Example: flux of nucleons
Approximate: λ ~ constant, leading nucleon only

$$\frac{dN(E,X)}{dX} = -\frac{N(E,X)}{\lambda_N} + \frac{1}{\lambda_N}\int_0^1 N\left(\frac{E}{\xi},X\right) F_{NN}(\xi)\frac{d\xi}{\xi^2}$$

Separate X- and E-dependence; try factorized solution, $N(E,X) = f(E) \cdot g(X)$, $f(E) \sim E^{-(\gamma+1)}$

$$\frac{g'(X)}{g(X)} = -\frac{1}{\lambda_N} + \frac{1}{\lambda_N}\frac{1}{f(E)}\int_0^1 f\left(\frac{E}{\xi}\right) F_{NN}(\xi)\frac{d\xi}{\xi^2}$$

Separation constant Λ_N describes attenuation of nucleons in atmosphere

$$\frac{g'(X)}{g(X)} = \frac{d\ln g(X)}{dX} = -\frac{1}{\Lambda_N} \qquad g(X) = a\,e^{-X/\Lambda_N}$$

Nucleon fluxes in atmosphere

Evaluate Λ_N:

$$-\frac{1}{\Lambda_N} = -\frac{1}{\lambda_N} + \frac{1}{\lambda_N}\frac{E^{\gamma+1}}{b}\int_0^1 b\left(\frac{\xi}{E}\right)^{\gamma+1} F_{NN}(\xi)\frac{d\xi}{\xi^2}$$

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

Flux of nucleons:

$$N(E,X) = g(X)f(E) = ab\,e^{-X/\Lambda_N} E^{-(\gamma+1)} \quad \therefore ab = K$$

$$\boxed{N(E, X) = N(E, 0) \times \exp\{-X/\Lambda_N\}}$$

K fixed by primary spectrum at X = 0

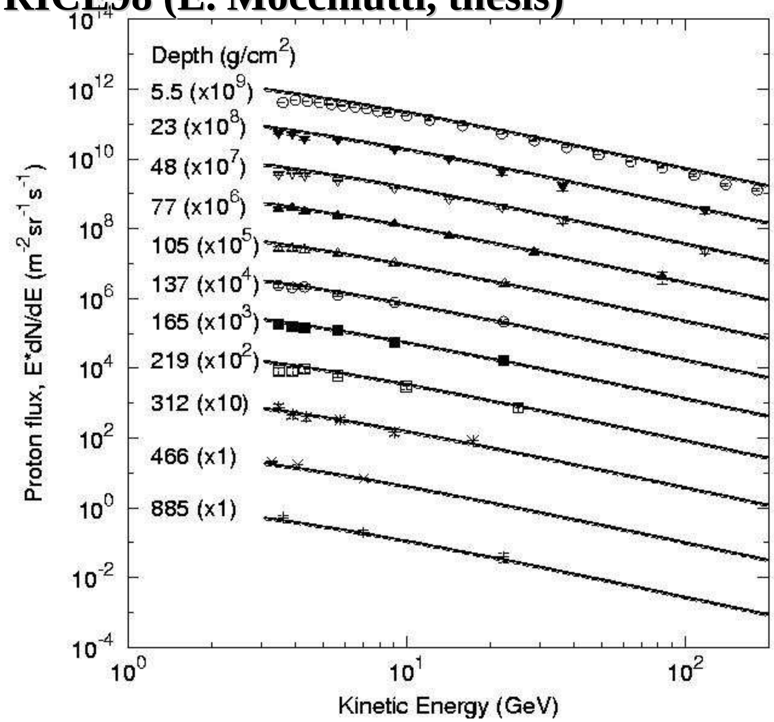
Comparison to proton fluxes

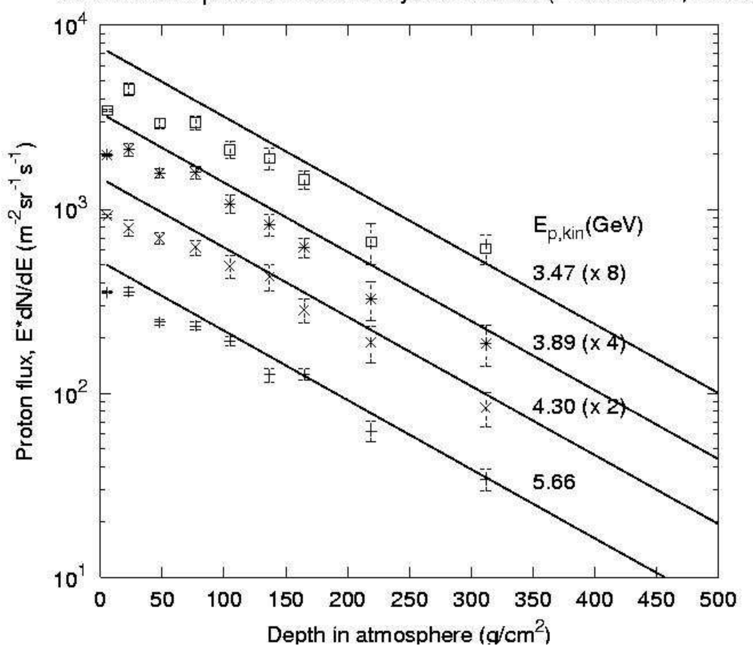
Account for p → n

$$\frac{p}{N} = \frac{1 + \delta_0 e^{-X/\Lambda^*}}{2}$$

$$\begin{cases} \lambda_N \cong 84\ \mathrm{g/cm^2},\ \Lambda_N \cong 120\ \mathrm{g/cm^2} \\ \delta_0 = \dfrac{P_0 - n_0}{N} = 0.77 \\ \Lambda^* = \lambda_N / 2 Z_{pn} = 1200\ \mathrm{g/cm^2} \end{cases}$$

CAPRICE98 (E. Mocchiutti, thesis)





$\pi^{\pm}$ in the atmosphere

$$\frac{\mathrm{d}\Pi}{\mathrm{d}X} = -\Pi(E,X)\left(\frac{1}{\Lambda_\pi} + \frac{\epsilon_\pi}{E\,X\,\cos\theta}\right) + \frac{Z_{N\pi}}{\lambda_N} N_0(E)\, e^{-X/\Lambda_N},$$

$$\Pi(E,X) = e^{-(X/\Lambda_\pi)} \frac{Z_{N\pi}}{\lambda_N} N_0(E) \int_0^X \exp\left[\frac{X'}{\Lambda_\pi} - \frac{X'}{\Lambda_N}\right]\left(\frac{X'}{X}\right)^{\epsilon_\pi/E\cos\theta} \mathrm{d}X'. \tag{3.30}$$

$$Z_{ac} \equiv \int_0^1 (x_L)^{\gamma-1} F_{ac}(x_L)\,\mathrm{d}x_L, \qquad \frac{1}{d_\pi} = \frac{m_\pi c^2 h_0}{E\,c\,\tau_\pi X\,\cos\theta} \equiv \frac{\epsilon_\pi}{E\,X\,\cos\theta}.$$

pion decay probability

π decay or interaction more probable for $E < \epsilon_\pi$ or $E > \epsilon_\pi = 115$ GeV

$\pi^{\pm}$ ($K^{\pm}$) in the atmosphere

- Low-energy limit: $E_\pi < \varepsilon_\pi \sim 115$ GeV

$$\Pi(E,X) \Rightarrow N(E)\,\frac{Z_{N\pi}}{\lambda_N}\, e^{-X/\Lambda_N}\;\frac{X\,E\cos\theta}{\epsilon_\pi}$$

$$\mathcal{D}_\pi(E,X) = \frac{\epsilon_\pi}{X\,E\cos\theta}\,\Pi(E,X) = N(E)\,\frac{Z_{N\pi}}{\lambda_N}\, e^{-X/\Lambda_N}$$

Production spectrum

$$P_\mu(E_\mu, X) = \int \frac{dn}{dE_\mu}(E_\mu, E_\pi)\,\mathcal{D}_\pi(E_\pi, X)\,dE_\pi$$

$\pi^{\pm}$ ($K^{\pm}$) in the atmosphere

- High-energy limit: $E_\pi > \varepsilon_\pi \sim 115$ GeV

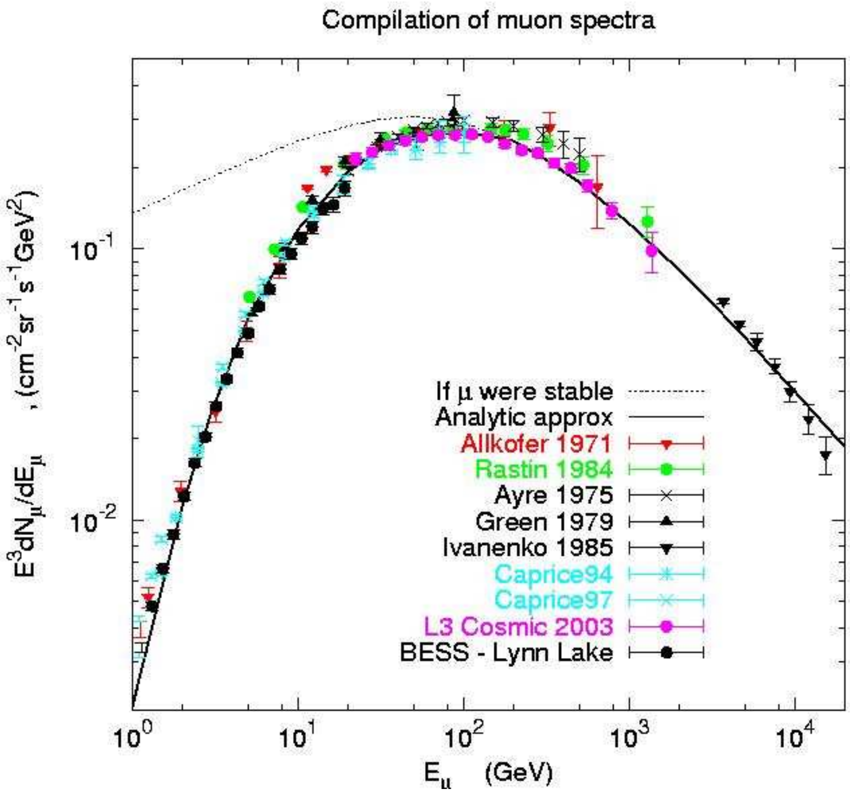
$$\Pi(E,X) \rightarrow N(E)\,\frac{Z_{N\pi}}{1-Z_{NN}}\,\frac{\Lambda_\pi}{\Lambda_\pi-\Lambda_N}\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)$$

$$\mathcal{D}_\pi(E,X) = \frac{\epsilon_\pi}{X\,E\cos\theta}\,\Pi(E,X)$$

Spectrum of decaying pions one power steeper for $E_\pi >> \varepsilon_\pi$

μ and ν_μ in the atmosphere

- To calculate spectra of μ and ν
  - Multiply Π(E,X) by
    pion decay probability
  - Include contribution of kaons
    - Dominant source of neutrinos
  - Integrate over kinematics
    of $\pi \rightarrow \mu + \nu_\mu$
    and $K \rightarrow \mu + \nu_\mu$
  - Integrate over the
    atmosphere (X)
  - Good description of data



2-body decays of $\pi^{\pm}$ and $K^{\pm}$

SCHÖNERT, GAISSER, RESCONI, AND SCHULZ

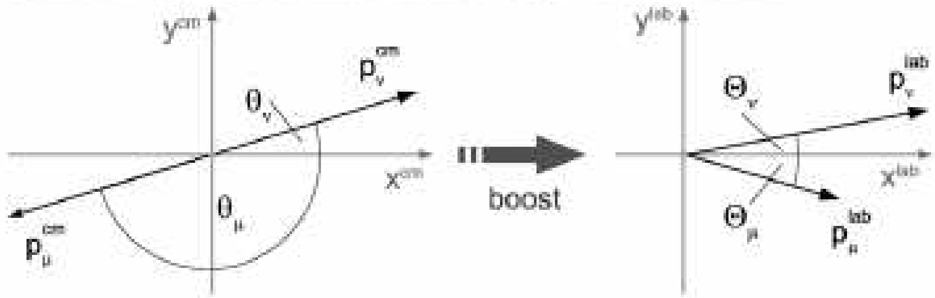


FIG. 1. Two-body decay of the parent meson into muon and neutrino. The left figure displays the back-to-back kinematics in the meson cm frame. The right figure shows the momenta after Lorentz transformation into the laboratory frame.

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ 99.99%

$K^+ \rightarrow \mu^+ + \nu_\mu$ 63.44%

also for negative mesons
to produce anti-neutrinos

In rest frame of parent μ and ν have equal and opposite 3 momentum **p**
CM energy of neutrino = $p = |\mathbf{p}| = E_\nu^* = (M^2 - \mu^2) / (2\,M)$
CM energy of muon $= p^2 + \mu^2 = E_\mu^* = (M^2 + \mu^2) / (2\,M)$
M = mass of parent meson, μ = mass of muon

For both μ and ν : $E_{LAB} = \gamma\, E^* + \beta\, \gamma\, p \cos(\theta)$

Momentum distributions for π, K

$E_{LAB} = \gamma E^* + \beta \gamma p \cos(\theta)$

$\gamma = E_M / M$ and assume $E_{LAB} >> M$ so $\beta \rightarrow 1$

Then $(E^* - p) / M < E_{LAB} / E_M < (E^* + p) / M$ because $-1 < \cos(\theta) < 1$

Also, decay is isotropic in rest frame so $dn / d\cos(\theta)$ = constant

But $d E_{LAB} = d \cos(q)$, so $dn / d E_{LAB}$ = constant

Normalization requires exactly one μ or ν so the normalization gives

$(\text{constant})^{-1} = E_M (1 – r)$ where $r = \mu^2 / M^2$ for both μ and ν

Note: $r_\pi = 0.572$ while $r_K = 0.0458$, an important difference !

Compare μ and ν

$$(E^* - p)/M < E/E_M < (E^* + p)/M$$

muons : $r < E_\mu/E_M < 1 \Rightarrow \langle x_\mu \rangle = \frac{1+r}{2}$

neutriños $0 < E_\nu/E_M < 1-r \Rightarrow \langle x_\nu \rangle = \frac{1-r}{2}$

$r_\pi = 0.572 \;, \quad r_K = 0.0458$

$\pi^\pm \to \mu\ \nu \quad \langle x_\mu \rangle = 0.79 \quad \langle x_\nu \rangle = 0.21$

$K^\pm \to \mu\ \nu \quad \langle x_\mu \rangle = 0.523 \quad \langle x_\nu \rangle = 0.477$

μ and ν_μ differ only by kinematics of $\pi^\pm$ and $K^\pm$ decay

$$\frac{dN_\mu}{dE_\mu} \simeq \frac{N_0(E_\mu)}{1-Z_{NN}} \left\{ \mathcal{A}_{\pi\mu}\frac{1}{1+\mathcal{B}_{\pi\mu}\cos\theta E_\mu/\epsilon_\pi} + 0.635\,\mathcal{A}_{K\mu}\frac{1}{1+\mathcal{B}_{K\mu}\cos\theta E_\mu/\epsilon_K} \right\}.$$

$$\frac{dN_\nu}{dE_\nu} \simeq \frac{N_0(E_\nu)}{1-Z_{NN}} \left\{ \frac{\mathcal{A}_{\pi\nu}}{1+\mathcal{B}_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + 0.635\,\frac{\mathcal{A}_{K\nu}}{1+\mathcal{B}_{K\nu}\cos\theta\, E_\nu/\epsilon_K} \right\}$$

$$\mathcal{A}_{\pi\mu} \equiv Z_{N\pi}\left[1-(r_\pi)^{\gamma+1}\right](1-r_\pi)^{-1}(\gamma+1)^{-1}$$

$$\mathcal{A}_{\pi\nu} \equiv Z_{N\pi}\frac{(1-r_\pi)^\gamma}{\gamma+1}$$

$$\mathcal{B}_{\pi\mu} \equiv \frac{(\gamma+2)}{(\gamma+1)}\,\frac{1-(r_\pi)^{\gamma+1}}{1-(r_\pi)^{\gamma+2}}\,\frac{\Lambda_\pi-\Lambda_N}{\Lambda_\pi\ln(\Lambda_\pi/\Lambda_N)}$$

$$\mathcal{B}_{\pi\nu} \equiv \left(\frac{\gamma+2}{\gamma+1}\right)\left(\frac{1}{1-r_\pi}\right)\left(\frac{\Lambda_\pi-\Lambda_N}{\Lambda_\pi\ln(\Lambda_\pi/\Lambda_N)}\right)$$

$$\frac{dN_\mu}{dE_\mu} \approx \frac{0.14\,E^{-2.7}}{\mathrm{cm^2\,s\,sr\,GeV}}\left\{\frac{1}{1+\frac{1.1\,E_\mu\cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054}{1+\frac{1.1E_\mu\cos\theta}{850\ \mathrm{GeV}}}\right\}$$

$$\frac{dN_\nu}{dE_\nu} \cong 0.018\,E_\nu^{-2.7}\left\{\frac{1}{1+\frac{2.77\,E_\nu\cos\theta}{115\ \mathrm{GeV}}} + \frac{0.367}{1+\frac{1.18\,E_\nu\cos\theta}{850\ \mathrm{GeV}}}\right\}$$

Spectrum-weighted moments

$$Z_{ab} \equiv \int \xi^{(\gamma-1)} F_{ab}(\xi)\, d\xi$$

projectile	p	π^+	K^+
p	0.263	-	-
n	0.035	-	-
π^+	0.046	0.243	0.030
π^-	0.033	0.028	0.022
π^0	0.039	0.098	0.026
K^+	0.0090	0.0067	0.211
K^-	0.0028	0.0067	0.012

Interaction vs. decay

X_v = 100 g / cm^2 at 15 km altitude

which is comparable to interaction lengths of hadrons in air

Table 5.1: Interaction lengths of hadrons (g/cm^2).

$E_{\rm Lab}$(TeV)	$p-p$	p–air	$\pi-p$	π–air	$K-p$	K–air
0.1	53	86	82	116	96	138
1.0	49	83	[74]	[107]	-	-
1000	30	60	[41]	[70]	-	-
10^6	[15]	[43]	[26]	[50]	-	-

Relative magnitude of $\lambda_{\mathbf{i}}$ and $\mathbf{d_i}$ = X cosθ (E / ε_i) determines competition between interaction and decay

Table 3.1: Decay constants.

Particle	$c\tau_0$(cm)	ϵ (GeV)
$\mu^\pm$	6.59×10^4	1.0
$\pi^\pm$	780	115
π^0	2.5×10^{-6}	3.5×10^{10}
$K^\pm$	371	850
K_S	2.68	1.2×10^5
K_L	1554	205
$D^\pm$	0.028	4.3×10^7
D^0	0.013	9.2×10^7
n	2.69×10^{13}	–

High-energy atmospheric neutrinos

Primary cosmic-ray spectrum (nucleons)

$$\phi_N(E_N) \equiv E_N \frac{dN}{dE_N} \cong K E^{-1.7}$$

Nucleons produce

pions

charmed hadrons

that decay to neutrinos

$$\phi_\nu(E_\nu) = \frac{\phi_N(E_\nu)}{1-Z_{NN}} \left\{ \frac{A_{\pi\nu}}{1+B_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + \frac{A_{c\nu}}{1+B_{c\nu}\cos\theta\, E_\nu/\epsilon_c} \right\}$$

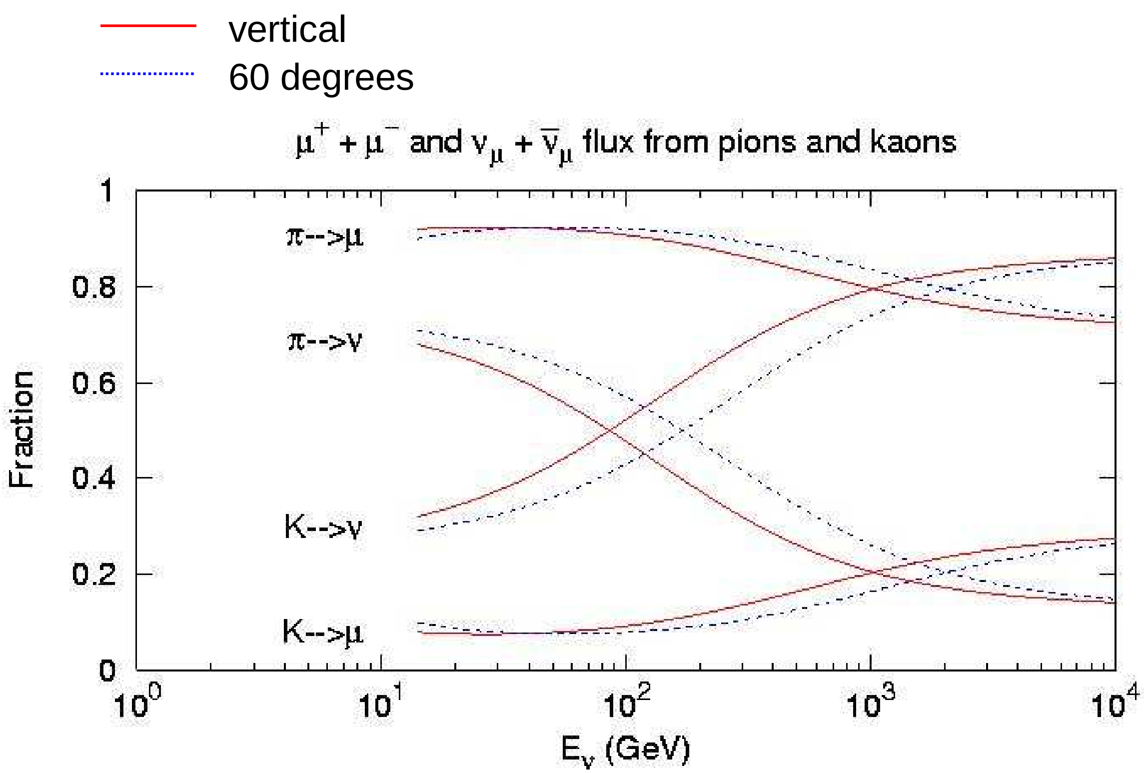
Kaons produce most ν_μ for 100 GeV < E_ν < 100 TeV

Eventually "prompt ν" from charm decay dominate, ….but what energy?

Critical energy $\epsilon_i = m_i c^2 \frac{h_0}{c\tau_i}$

Importance of kaons at high E

- Importance of kaons
  - main source of ν > 100 GeV
  - p → K⁺ + Λ important
  - Charmed analog important for prompt leptons at higher energy



Neutrinos from kaons

Critical energy $\epsilon_i = m_i c^2 \frac{h_0}{c \tau_i}$

$\epsilon_\mu = 1$ GeV

$\epsilon_\pi = 115$ GeV

$\epsilon_{charm} \sim 5 \cdot 10^7$ GeV

$\epsilon_{K_L} = 0.205$ TeV

Critical energies determine where spectrum changes, but $A_{K\nu}$ / $A_{\pi\nu}$ and $A_{C\nu}$ / $A_{K\nu}$ determine magnitudes

New information from MINOS relevant to ν_μ with E > TeV

Electron neutrinos

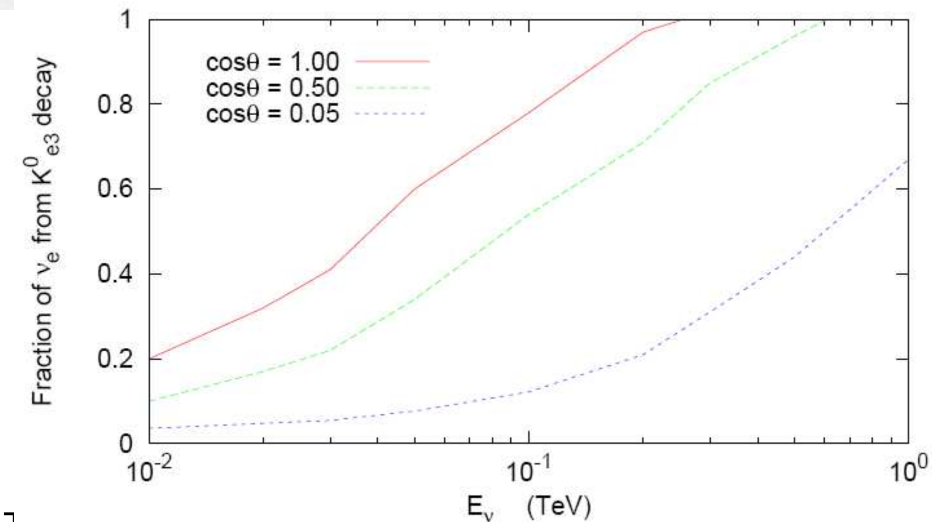
$$\phi_{\nu_e} = E^{-1.7}\left[\frac{A_e}{1 + B_K E \cos^*\theta/\epsilon_K} + \frac{B_e}{1 + B_K E \cos^*\theta/\epsilon_{KL}}\right] + \phi_{\mu^+}\left[1 - e^{-\lambda_\mu/E\cos^*\theta}\right]$$

$$\phi_{\bar{\nu}_e} = E^{-1.7}\left[\frac{C_e}{1 + B_K E \cos^*\theta/\epsilon_K} + \frac{B_e}{1 + B_K E \cos^*\theta/\epsilon_{KL}}\right] + \phi_{\mu^-}\left[1 - e^{-\lambda_\mu/E\cos^*\theta}\right]$$

$K^+ \rightarrow \pi^0 \nu_e e^\pm$ (B.R. 5%)

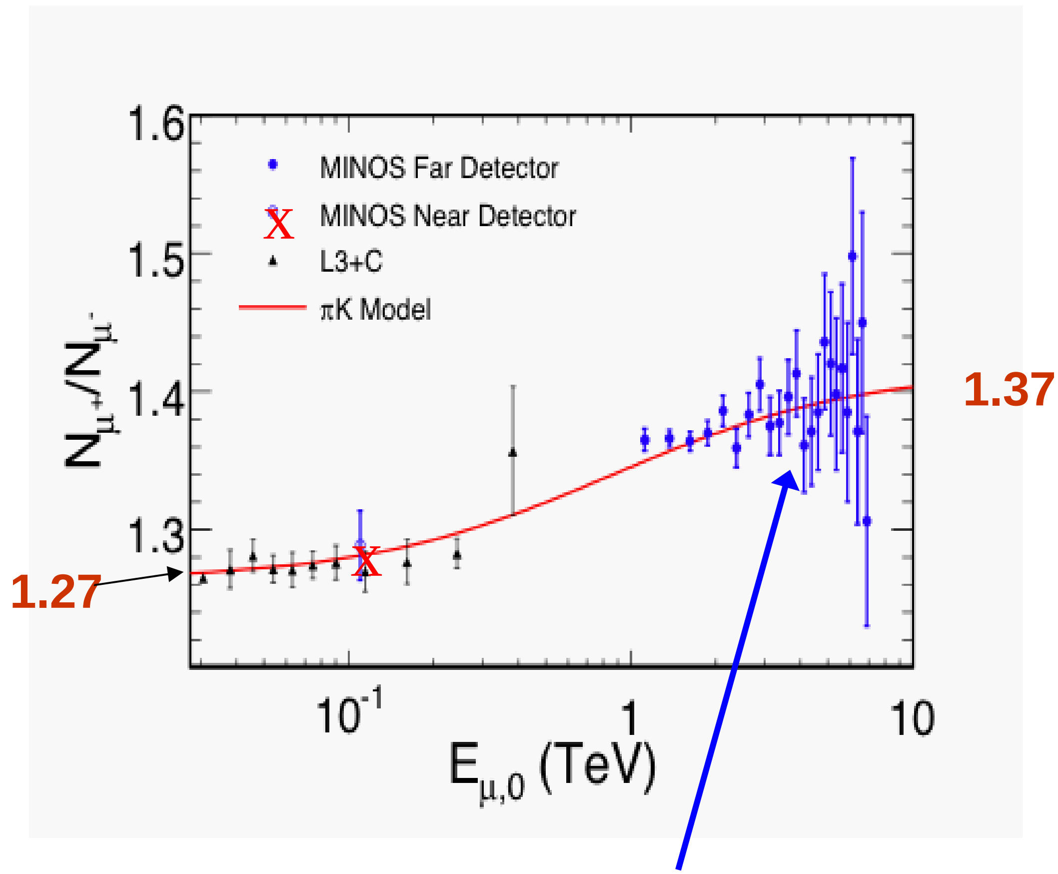
$K_L^0 \rightarrow \pi^\pm \nu_e e$ (B.R. 41%)

Kaons important for ν_e down to ~10 GeV



TeV μ^+/μ^- with MINOS far detector

- 100 to 400 GeV at depth → > TeV at production
- Increase in charge ratio shows
  - p → $K^+ \Lambda$ is important
  - Forward process
  - s-quark recombines with leading di-quark
  - Similar process for Λ_c?



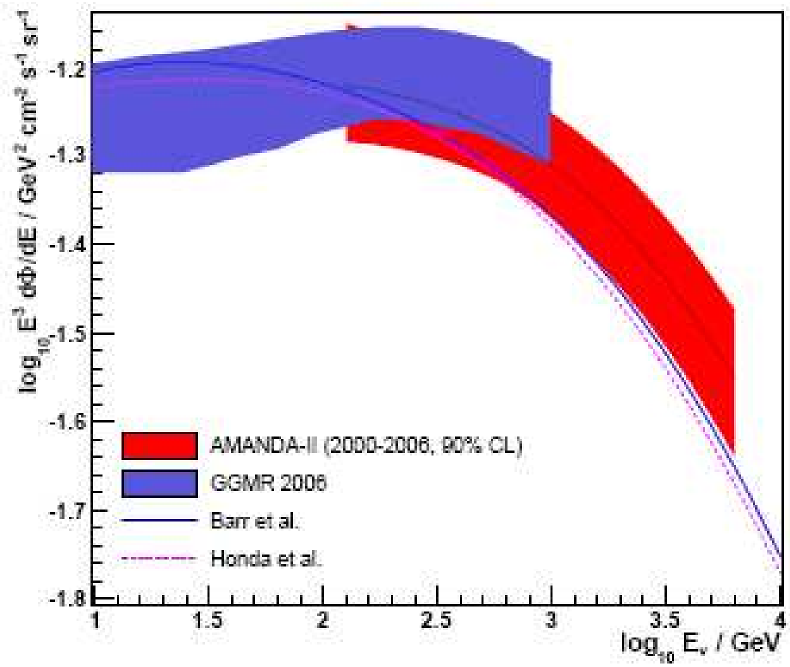
Increased contribution from kaons at high energy

MINOS fit ratios of Z-factors

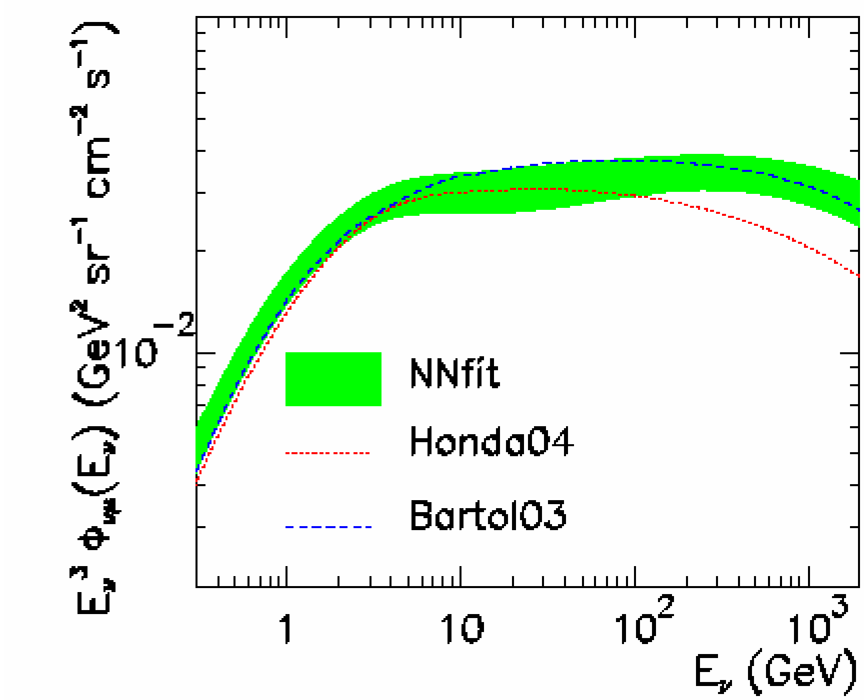
$$\frac{Z_{N\pi^+}}{Z_{N\pi^+} + Z_{N\pi^-}} = 0.55 \qquad \frac{Z_{NK^+}}{Z_{NK^+} + Z_{NK^-}} = 0.67.$$

- Z-factors assumed constant for E > 10 GeV
- Energy dependence of charge ratio comes from increasing contribution of kaons in TeV range coupled with fact that charge asymmetry is larger for kaon production than for pion production
- Same effect larger for ν_μ / $\bar{\nu}_\mu$ because kaons dominate

Atmospheric neutrinos – harder spectrum from kaons?



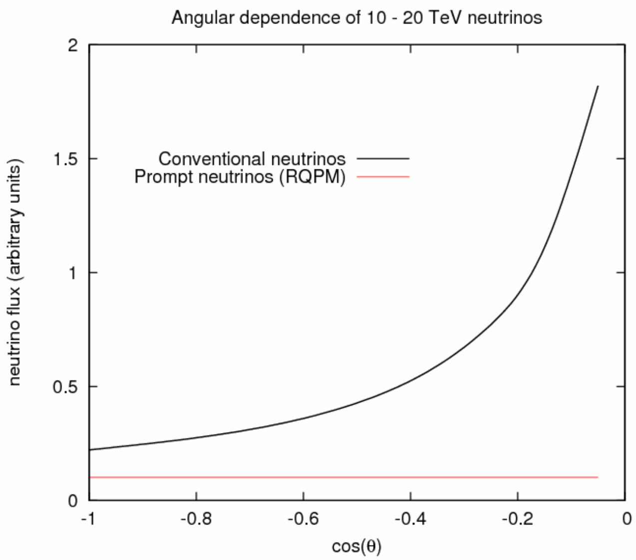
AMANDA atmospheric neutrino
arXiv:0902.0675v1



Re-analysis of Super-K
Gonzalez-Garcia, Maltoni, Rojo JHEP 2007

Signature of charm: θ dependence

For $\varepsilon_K < E\cos(\theta) < \varepsilon_c$, conventional neutrinos ~ sec(θ), but "prompt" neutrinos independent of angle



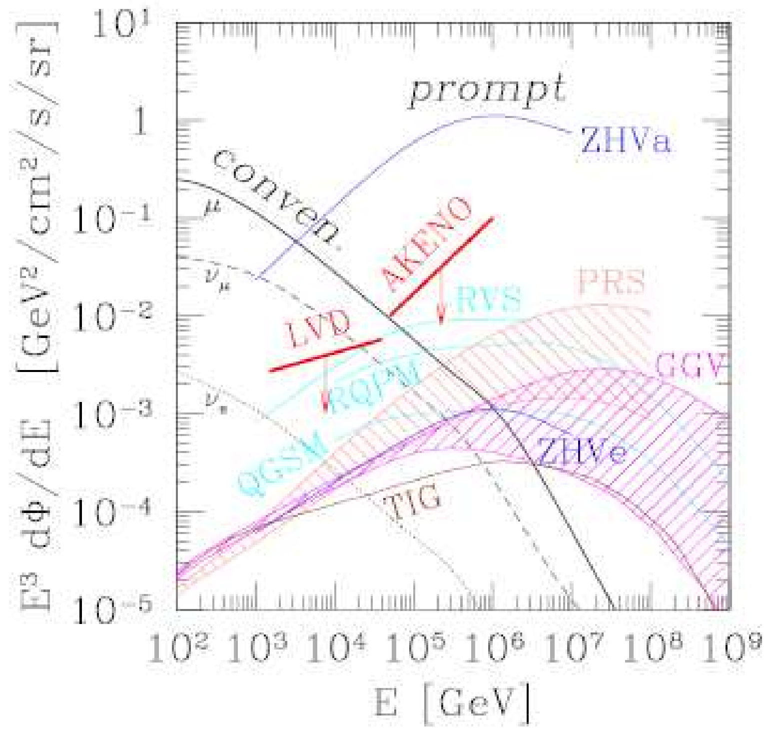
Uncertain charm component most important near the vertical

$$\phi_\nu(E_\nu) = \frac{\phi_N(E_\nu)}{1 - Z_{NN}} \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos\theta\, E_\nu/\epsilon_K} + \frac{A_{c\nu}}{1 + B_{c\nu}\cos\theta\, E_\nu/\epsilon_c} \right\}$$

Critical energy $\epsilon_i = m_i c^2 \frac{h_0}{c\tau_i}$

Neutrinos from charm

- Main source of atmospheric ν for E_ν > ??
- ?? > 20 TeV
- Large uncertainty in normalization!



Gelmini, Gondolo, Varieschi
PRD 67, 017301 (2003)

Muons & Neutrinos underground

Muon average energy loss: $$-\frac{dE_\mu}{dX} = a + b\,E_\mu$$

Table 1.2: Average muon range R and energy loss parameters calculated foı standard rock [53]. Range is given in km-water-equivalent, or 10^5 g cm^{-2}.

E_μ GeV	R km.w.e.	a MeV g^{-1} cm^2	b_{brems}	b_{pair} 10^{-6} g^{-1} cm^2	b_{nucl}	$\sum b_i$	$\sum b(\mathrm{ice})$
10	0.05	2.17	0.70	0.70	0.50	1.90	1.66
100	0.41	2.44	1.10	1.53	0.41	3.04	2.51
1000	2.45	2.68	1.44	2.07	0.41	3.92	3.17
10000	6.09	2.93	1.62	2.27	0.46	4.35	3.78

from Reviews of Particle Physics, *Cosmic Rays*

Critical energy: $\epsilon \equiv a/b \approx 500\ \mathrm{GeV}$

μ energy spectrum underground

Average relation between energy at surface and energy underground

$$E_\mu = \left(E_{\mu,0} + \epsilon\right) e^{-bX} - \epsilon$$

$$\frac{dN_\mu(X)}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}} \frac{dE_{\mu,0}}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}} e^{bX}$$

Shallow: $X \ll b^{-1} \approx 2.5\ \mathrm{km\ water\ equivalent}$

$$E_{\mu,0} \approx E_\mu(X) + aX$$

Deep: $E_{\mu,0} \approx (\epsilon + E_\mu(X))\exp(bX)$

High-energy, deep muons

At large depths $(bX >> 1,\ X > 2.5$ km.w.e.$)$

$\frac{dN_\mu}{dE_\mu} \sim$ constant for $E_\mu < \epsilon = 500$ GeV

Then $\frac{dN_\mu}{dE_\mu} \rightarrow e^{bX} \left.\frac{dN_\mu}{dE_0}\right|_{E_0 \sim e^{bX} E_\mu}$ for $E_\mu >> \epsilon$

If surface spectrum is $K E_0^{-(\gamma(E)+1)}$

then $\frac{dN_\mu}{dE_\mu} \rightarrow K e^{-bX\gamma(E)} E_\mu^{-(\gamma(E)+1)}$

$\gamma(E) \rightarrow 2.7$ for $E >> \epsilon_K$

Differential and integral spectrum of atmospheric muons

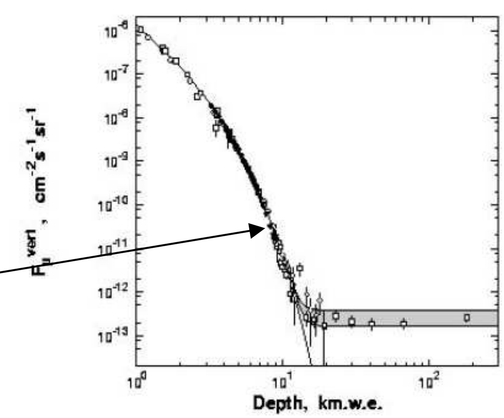
Differential

$$\frac{\mathrm{d}N_\mu}{\mathrm{d}E_\mu} \approx \frac{0.14\,E^{-2.7}}{\mathrm{cm}^2\,\mathrm{s\,sr\,GeV}} \left\{ \frac{1}{1+\frac{1.1\,E_\mu \cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054}{1+\frac{1.1 E_\mu \cos\theta}{850\ \mathrm{GeV}}} \right\}$$

Integral

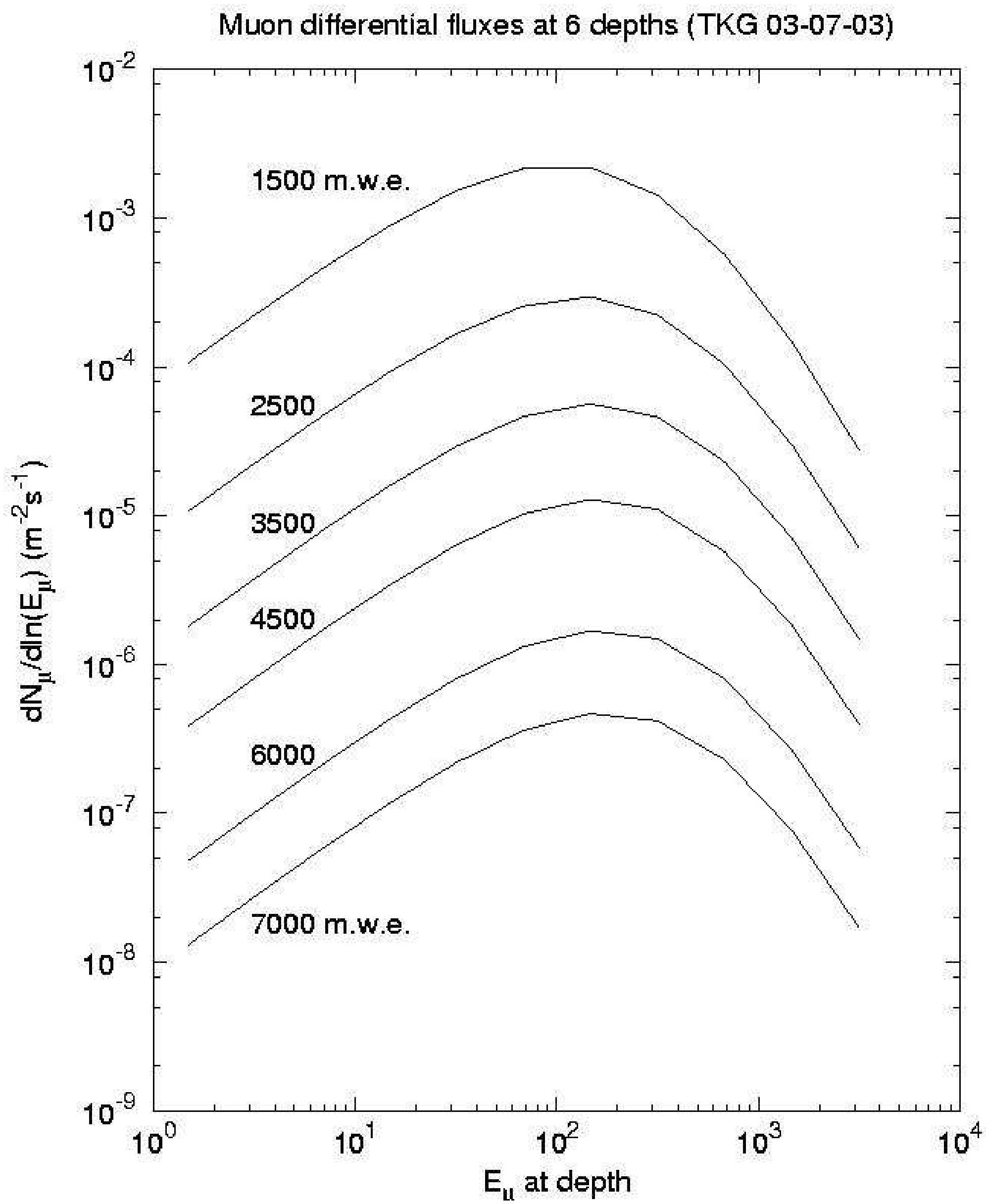
$$N_\mu\,(>E_\mu) = \frac{840\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}}{E_\mu^{\ 1.7}} \left\{ \frac{1}{1+\frac{E_\mu \cos\theta}{66\ \mathrm{GeV}}} + \frac{.054}{1+\frac{E_\mu \cos\theta}{487\ \mathrm{GeV}}} \right\}$$

Energy loss: E_μ (surface) = exp{ b **X** } · (E_μ +ε) - ε



Set E_μ = ε { exp[b **X**] - 1 } in Integral flux
to get depth – intensity curve

Plot shows $dN_\mu / d\ell n(E_\mu)$



Detecting neutrinos

- Rate =

  Neutrino flux

  x Absorption in Earth

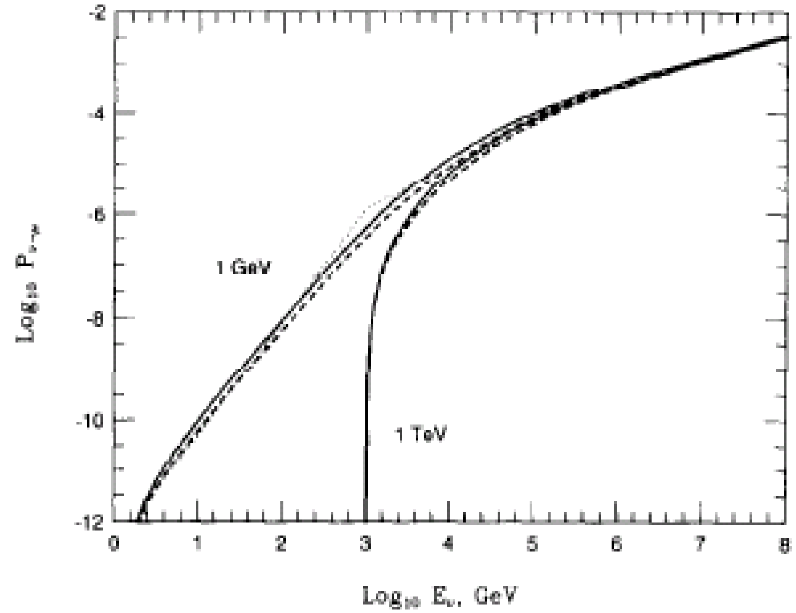
  x Neutrino cross section

  x Size of detector

  x Range of muon (for ν_μ)

  – (Range favors ν_μ channel)

T.K. Gaisser et al. / Physics Reports 258 (1995) 173–236



Probability to detect ν_μ-induced μ

$$P_\nu(E_\nu, E_{\mu,min}) = N_A \int_{E_{\mu,min}}^{E_\nu} dE_\mu \frac{d\sigma_\nu(E_\nu)}{dE_\mu} R(E_\mu, E_{\mu,min})$$

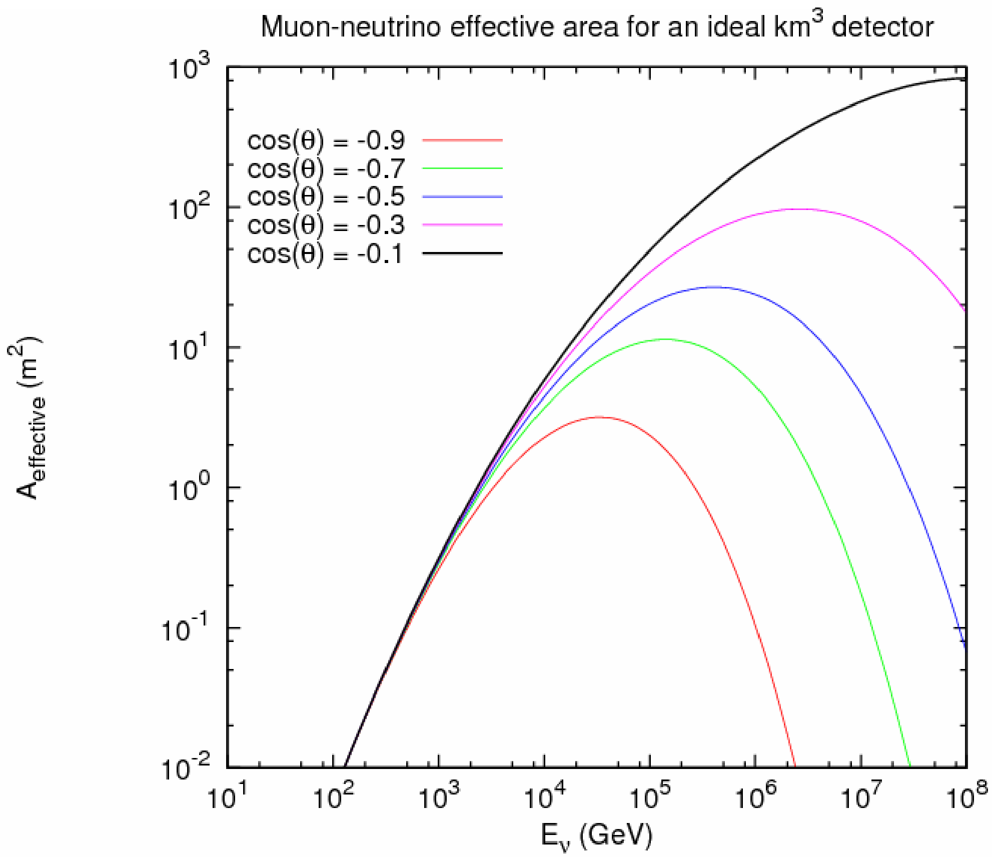
Neutrino effective area

$$A_{eff}(\theta, E_\nu) = \epsilon(\theta) A(\theta) P_\nu(E_\nu, E_{\mu,min}) e^{-\sigma_\nu(E_\nu) N_A X(\theta)}$$

- Rate:

$= \int \phi_\nu(E_\nu) A_{eff}(E_\nu) dE_\nu$

- Earth absorption
  - Starts 10-100 TeV
  - Biggest effect near vertical
  - Higher energy ν's absorbed at larger angles



Neutrino-induced muons

For $\bar{\nu}_\mu$ -induced muons

$$\frac{dN_\mu}{dE_\mu} = \int_{E_\nu}^{\infty} dE_\nu \, \frac{dN_\nu}{dE_\nu} \overbrace{\int_{E_\mu}^{E_\nu} \int_0^{\infty} \underbrace{dX \; N_A}_{\#\,\text{nucleons}/\text{cm}^2} \; \frac{d\sigma_\nu}{dE'_\mu} \; g\left(X, E_\mu, E'_\mu\right) dE'_\mu}^{\frac{dP(E_\nu)}{dE_\mu}}$$

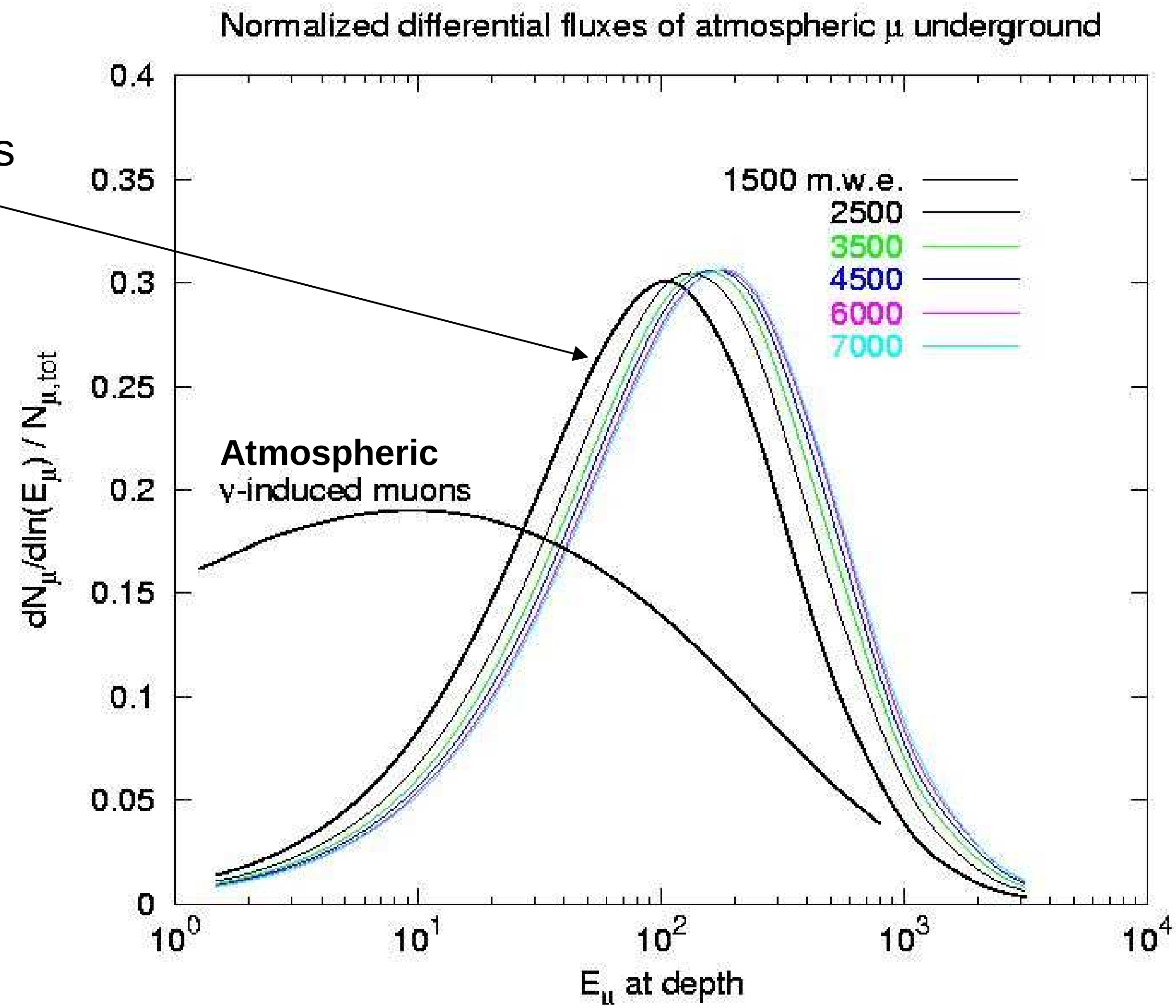
cross section per nucleon for $\nu_\mu \rightarrow E'_\mu$

probability for muon to start with energy E'_μ propagate through X g/cm² and end up with E_μ to $E_\mu + dE_\mu$

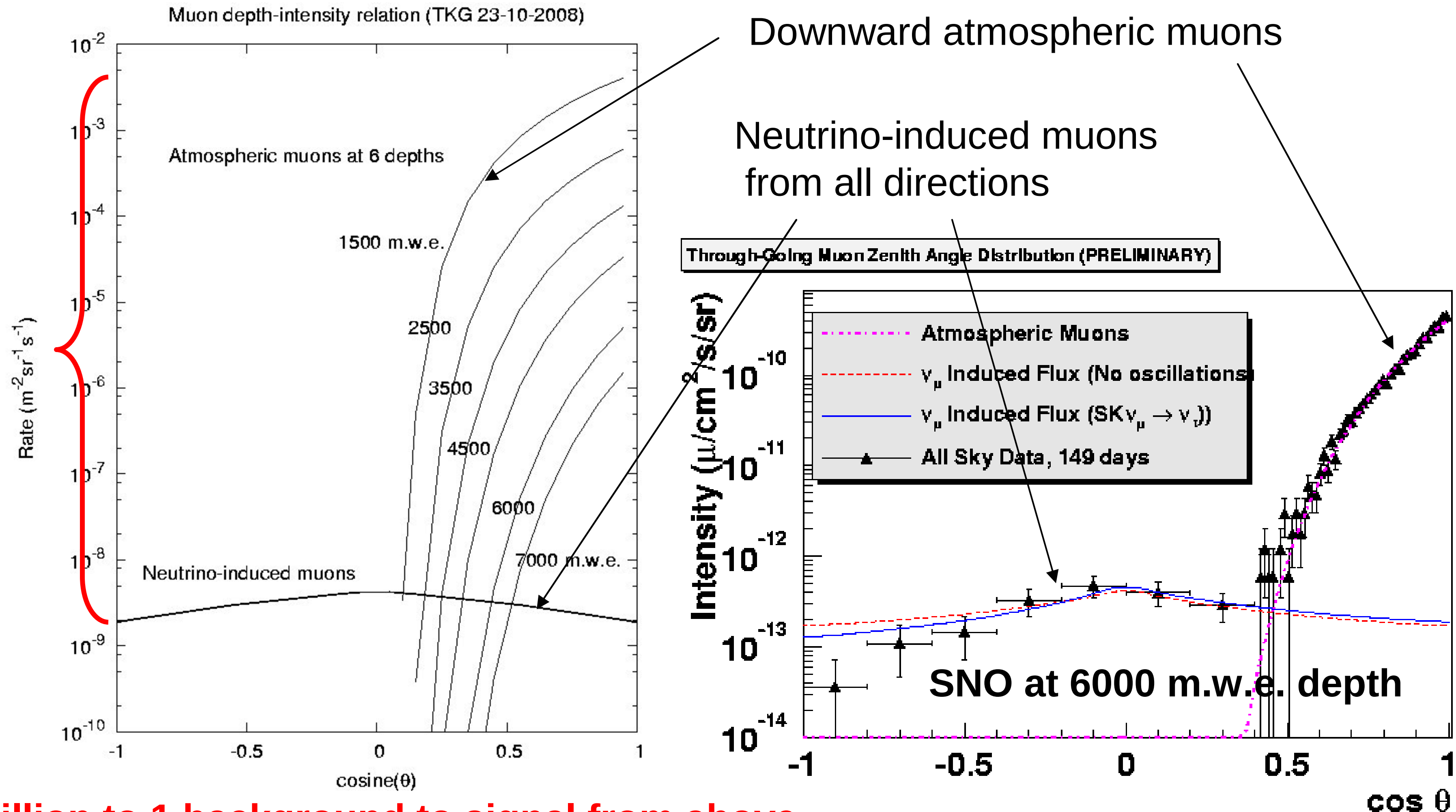
$$\frac{d\sigma_\nu}{dE_\mu} = \frac{1}{E_\nu} \int_0^1 \frac{d\sigma_\nu}{dx\,dy} \, dx \, \Bigg|_{y = 1 - E_\mu/E_\nu}$$

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi} \frac{1}{(1 + Q^2/m_W^2)^2} \, x \, \left(Q_1 + (1-y)^2 Q_2\right)$$

Atmospheric muons
(shape only)



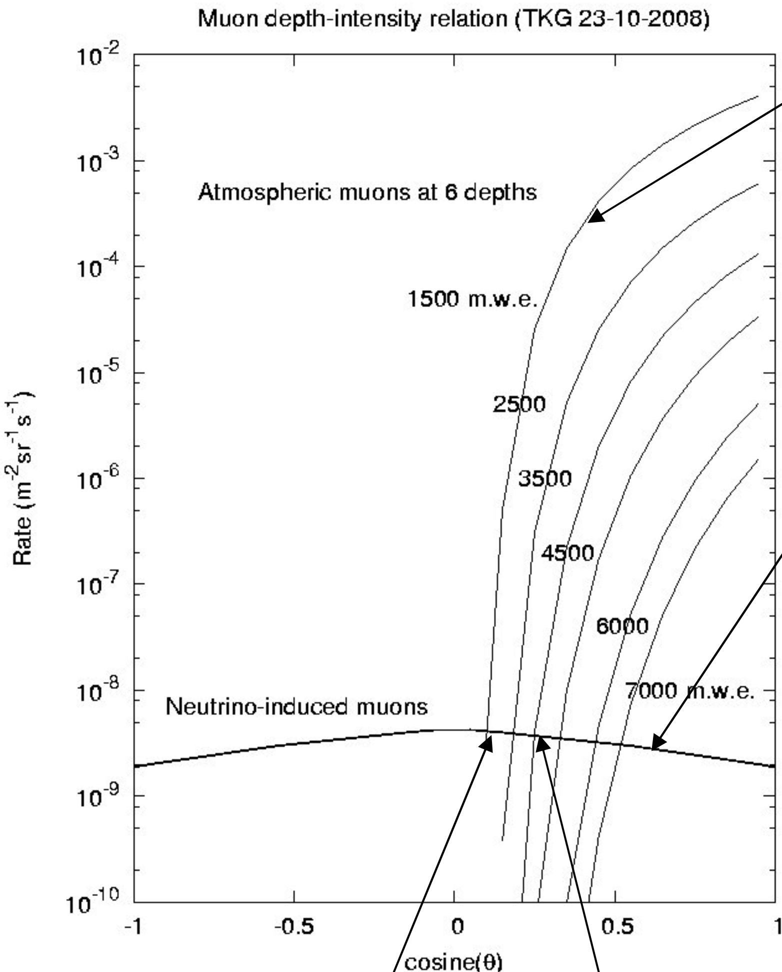
Muons in ν telescopes



Million to 1 background to signal from above.

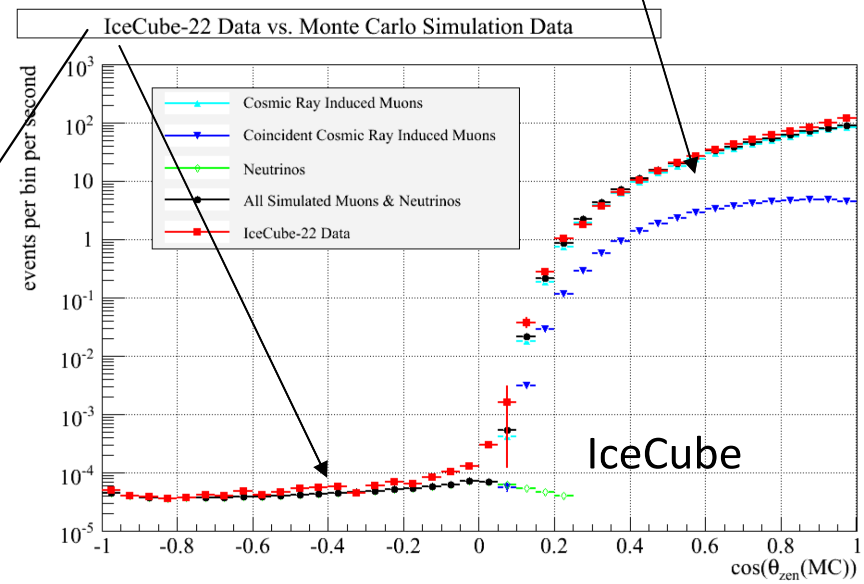
→ Use Earth as filter; look for neurtinos from below.

Muons in IceCube



Downward atmospheric muons

Neutrino-induced muons
from all directions



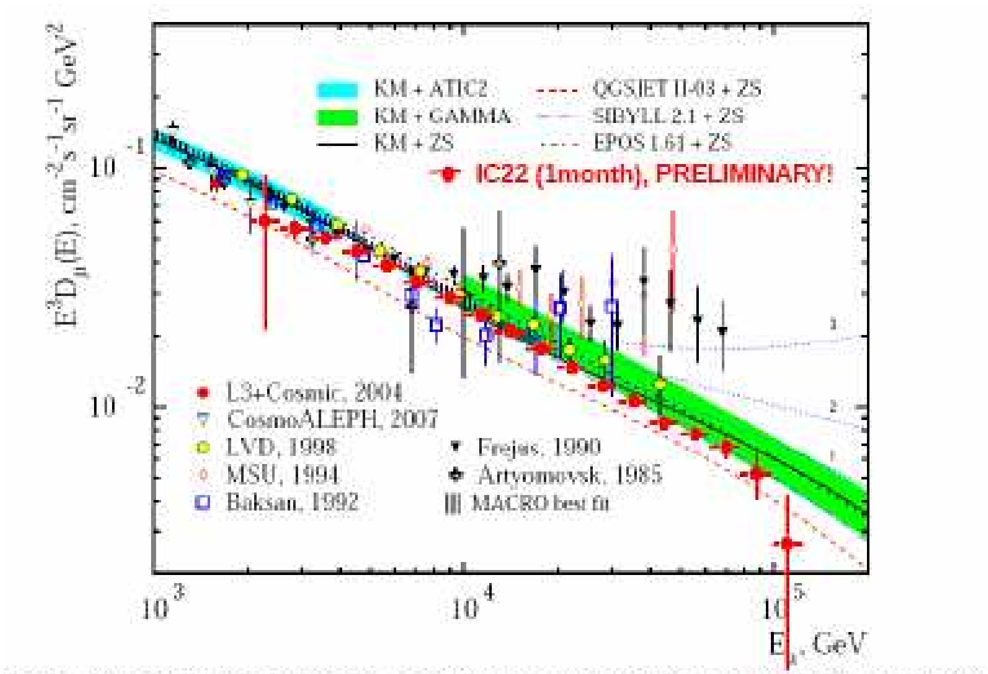
→ *P. Berghaus et al., ISVHECRI-08 also HE1.5*

Crossover at ~85°
for shallow detectors

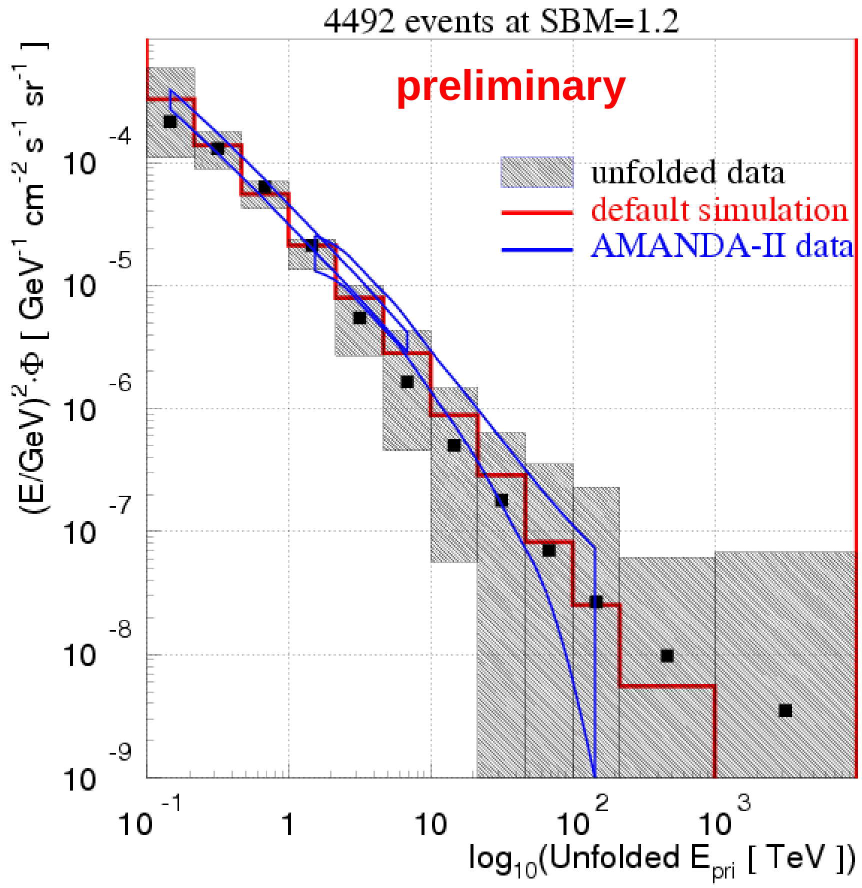
~75°for deepest
Mediterranean site

Atmospheric μ and ν in IceCube

Extended energy reach of km³ detector



The Atmospheric Muon Spectrum as derived from IceCube data is shown above, compared to previous measurements and various theoretical predictions [3]. The error bars shown do not yet include systematic detector effects. Even though only about 10% of the entire data set has been unblinded, the energy range extends already significantly higher than previous measurements.



Patrick Berkhaus, ICRC 2009

Dmitry Chirkin, ICRC 2009
Currently limited by systematics

Deep muons as a probe of weather in the stratosphere

- Barrett et al.
- MACRO
- MINOS far detector
  - Sudden stratospheric warmings observed
- IceCube
  - Interesting because of unique seasonal features of the upper atmosphere over Antarctica related to ozone hole
- Decay probability ~ T:
  - h_0 ~ RT

$$\frac{1}{d_\pi} = \frac{m_\pi c^2 h_0}{E\, c\, \tau_\pi X \cos\theta} \equiv \frac{\epsilon_\pi}{E\, X \cos\theta}.$$

pion decay probability

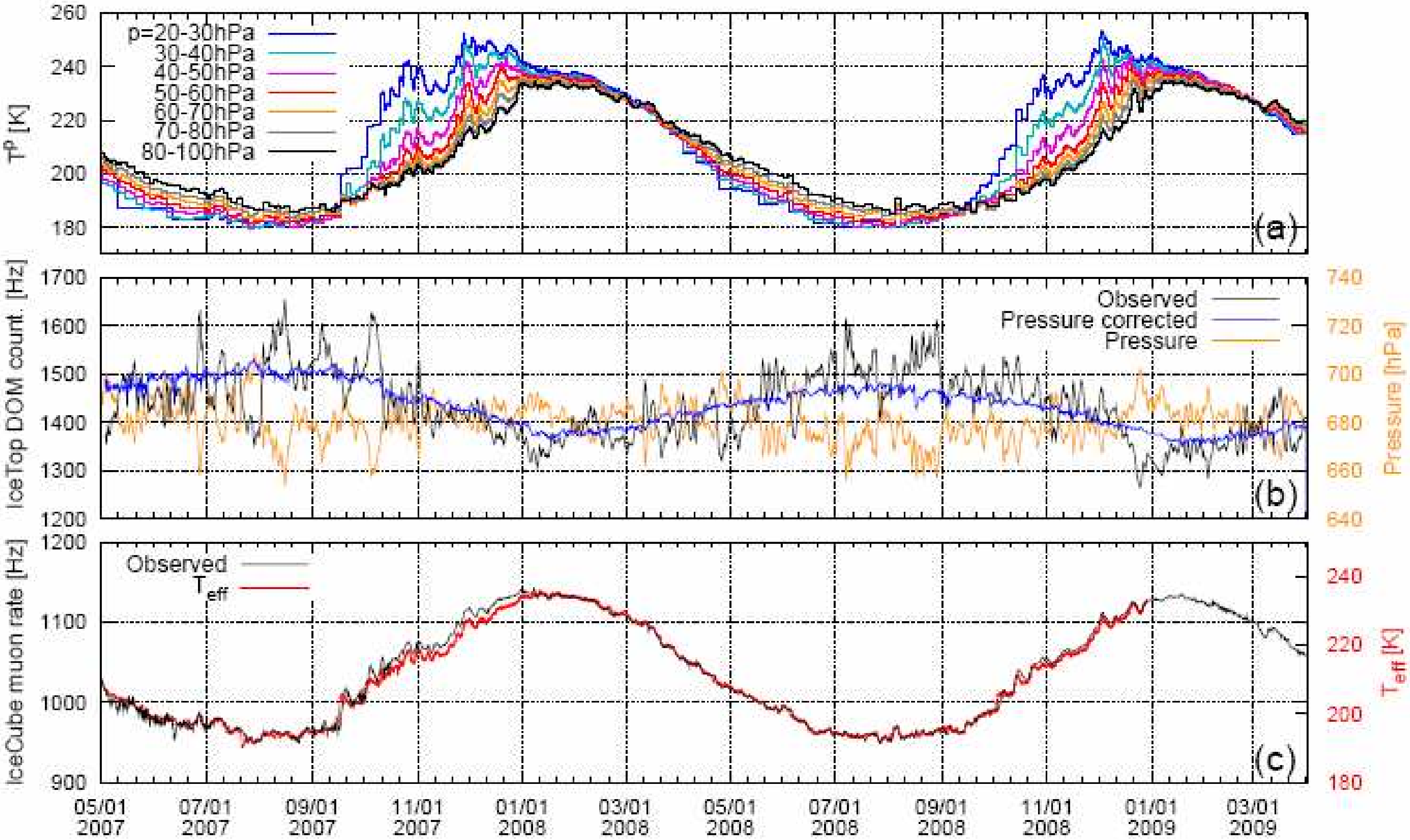


Fig. 1. The temporal behavior of the South Pole stratosphere from May 2007 to April 2009 is compared to IceTop DOM counting rate and the high energy muon rate in the deep ice. (a) The temperature profiles of the stratosphere at pressure layers from 20 hPa to 100 hPa where the first cosmic ray interactions happen. (b) The IceTop DOM counting rate (black -observed, blue -after barometric correction) and the surface pressure (orange). (c) The IceCube muon trigger rate and the calculated effective temperature (red).