

Atmospheric muons & neutrinos

Overview of current topics

Workshop on Muon and Neutrino Radiography, Clermont-Ferrand, 17-20/04/2012

Outline

- Introduction
 - Analytic approximations
 - Primary spectrum
- Muon charge ratio (also $\nu/\bar{\nu}$ ratio)
 - K/ π ratio
- Seasonal effects
- Prompt leptons
- Atmospheric neutrinos above 100 TeV

Atmospheric leptons (μ and ν)

- Primary cosmic-ray spectrum
 - A mixture of protons and nuclei
 - π , K, D, ... produced at the level of nucleons (p, n)
 - Decays of charged pions, kaons and charmed hadrons produce μ and ν
 - Processes are identical until the last step:
 - $\pi^\pm \rightarrow \nu \neq \pi^\pm \rightarrow \mu$ (different energy fractions)
 - More massive mesons (K,D) divide energy almost equally between μ and ν

High-energy atmospheric neutrinos

Primary cosmic-ray spectrum $\phi_N(E_N) = E_N \frac{dN}{dE_N} \approx KE^{-\gamma}$
 (nucleons) $\gamma \approx 1.7$

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

$$\epsilon_\mu = 1 \text{ GeV}$$

$$\epsilon_\pi = 115 \text{ GeV}$$

$$\epsilon_K = 850 \text{ GeV}$$

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

$$\phi_\nu(E_\nu) = \phi_N(E_\nu)$$

$$\begin{aligned} \text{pions} &\longrightarrow \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos \theta E_\nu / \epsilon_\pi} \right. \\ \text{kaons} &\longrightarrow + \frac{A_{K\nu}}{1 + B_{K\nu} \cos \theta E_\nu / \epsilon_K} \\ \text{charmed hadrons} &\longrightarrow \left. + \frac{A_{C\nu}}{1 + B_{C\nu} \cos \theta E_\nu / \epsilon_C} \right\} \end{aligned}$$

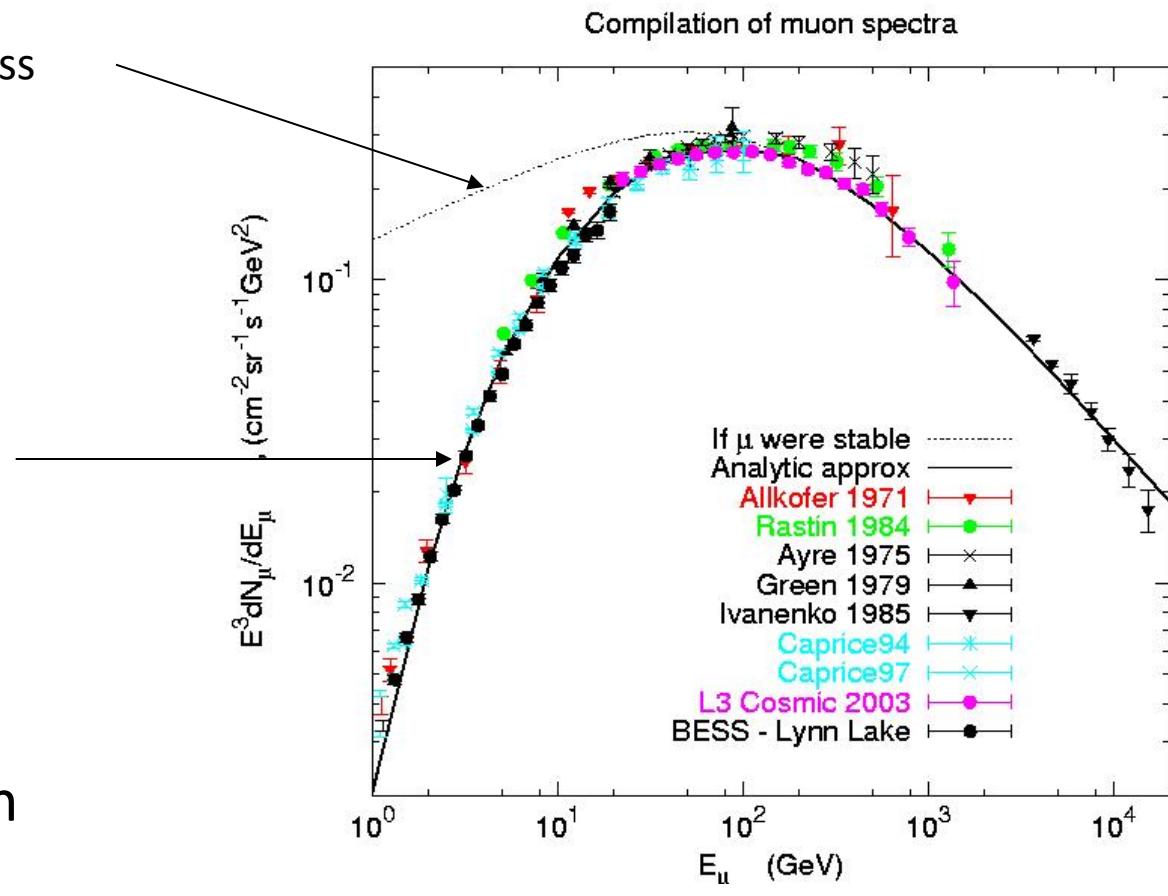
Same form for muons

Similar analysis for atmospheric μ

Account for μ energy loss

Account for μ decay

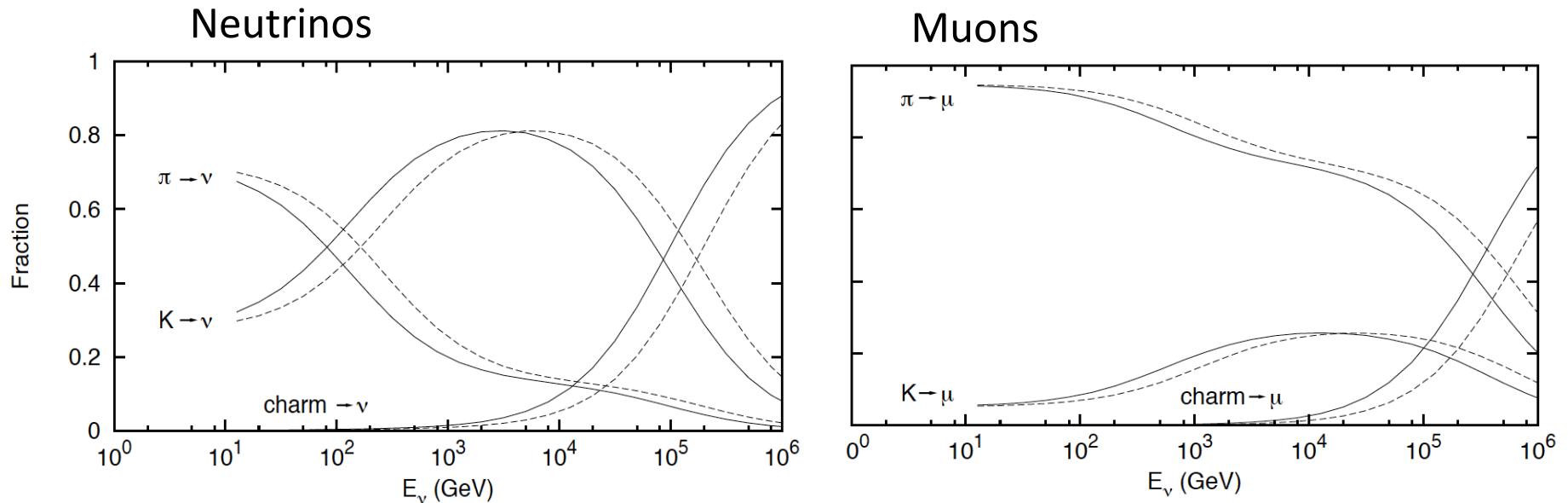
Analytic approximation
works well!



Vertical spectrum $\times E^3$

Kinematic differences for μ, ν (K, π)

- Flux(ν) < Flux(μ) from pion decay
- Kaons therefore more important for ν than for μ
- Charm contribution same for ν and μ
 - Therefore charm relatively more important for ν
 - Charm contribution isotropic (compared to secant θ effect for $>\text{TeV}$ leptons from decay of π and K)

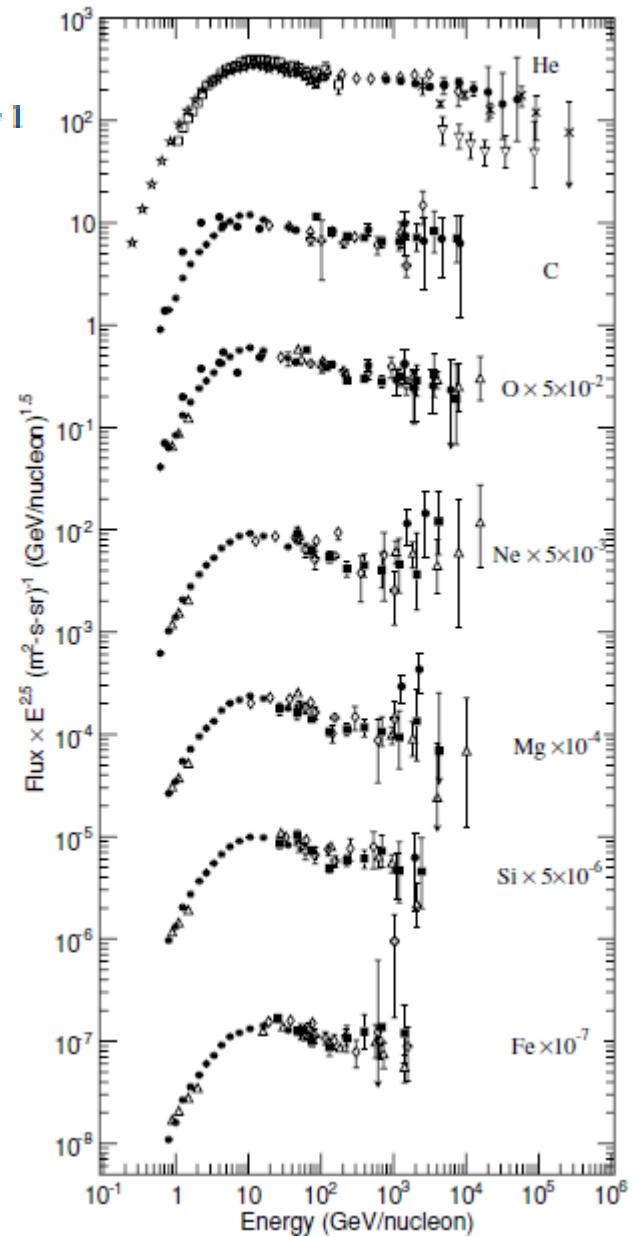
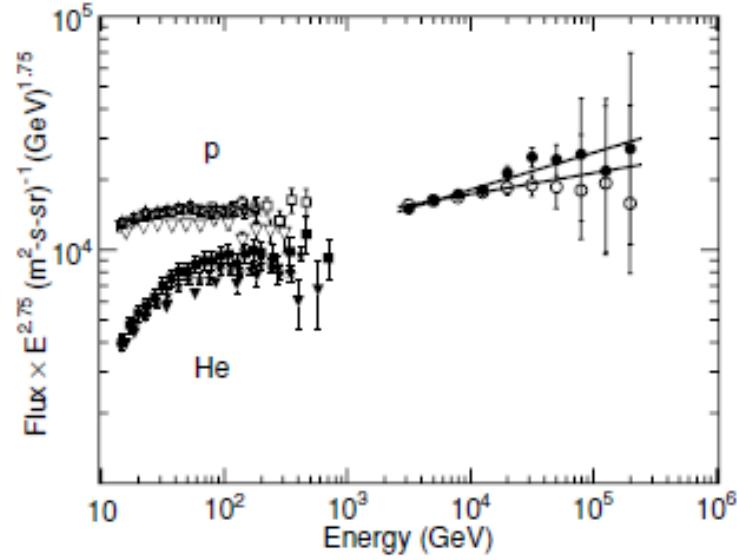


Primary spectrum

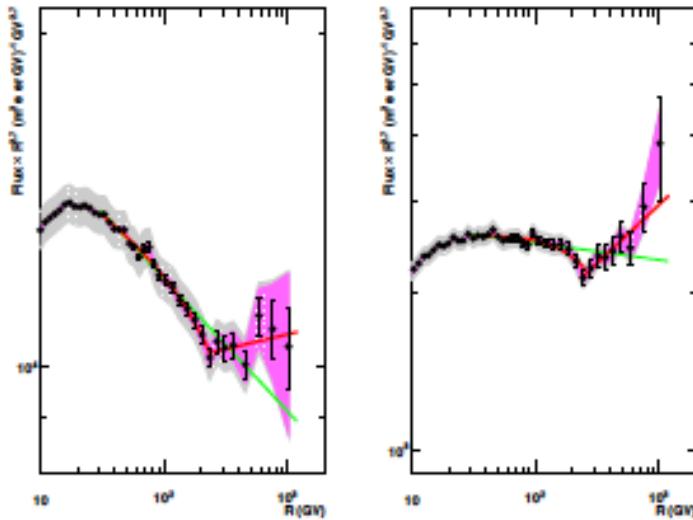
- Combine information
 - from direct measurements < 100 TeV
 - with air shower measurements of all-particle spectrum at higher E
- Assumptions:
 - 5 nuclear groups: p, He, CNO, Mg-Si, Fe
 - 3 populations: SNR, Hillas' Galactic component B, extra-galactic
 - All features depend on rigidity, $R = P_c / Z_e$
- Requirements
 - Consistency with air shower measurements of the all-particle spectrum
 - Anchor to composition from direct experiments below 100 TeV
- Goals
 - derive spectrum of nucleons to > 10 PeV (beyond the knee)
 - Calculate atmospheric muons and neutrinos to PeV

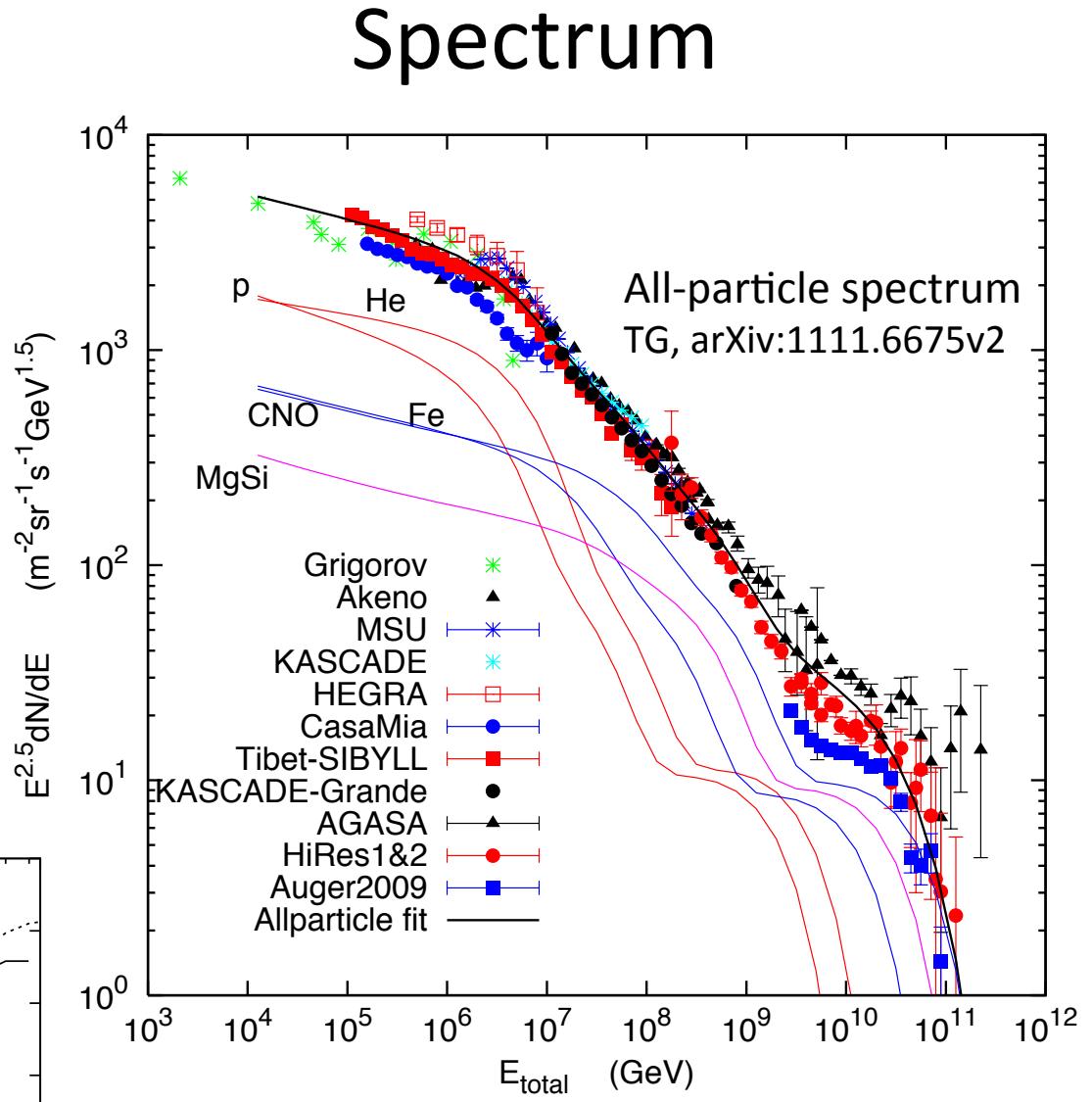
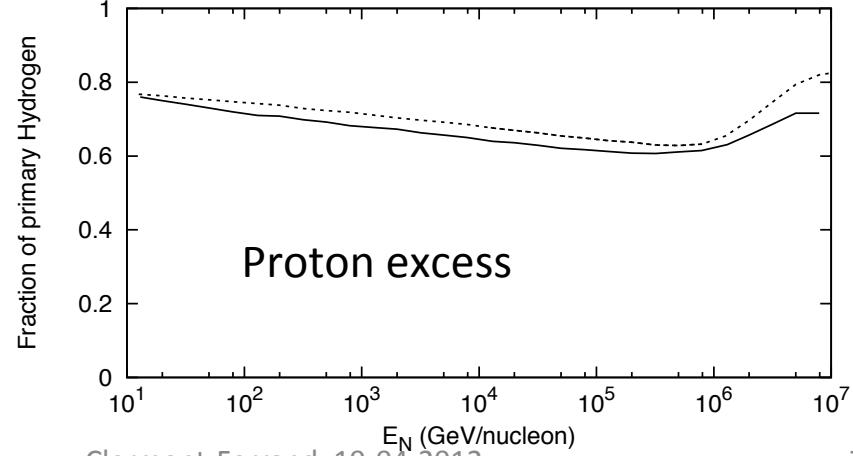
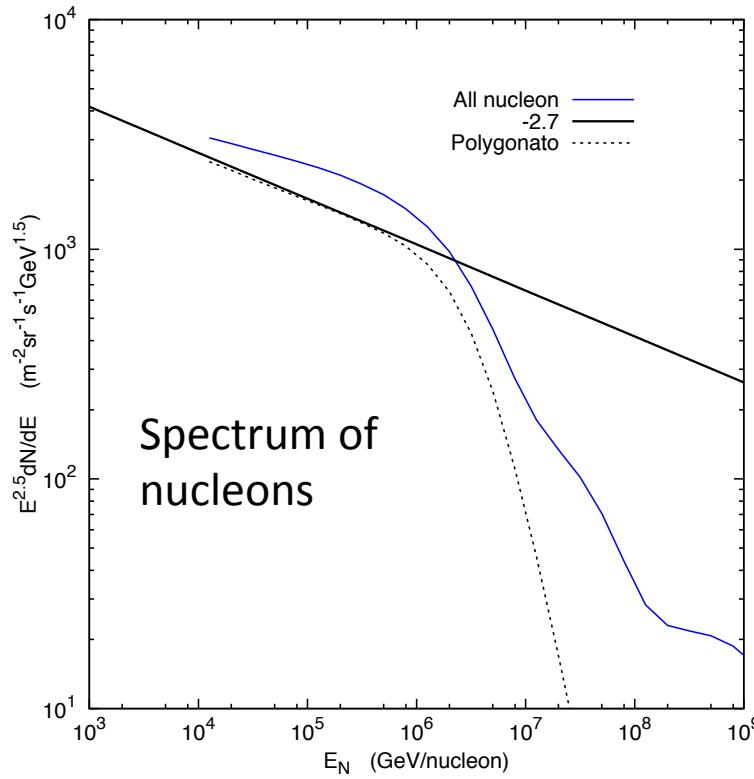
CREAM

THE ASTROPHYSICAL JOURNAL LETTERS, 714:L89–L93, 2010 May 1



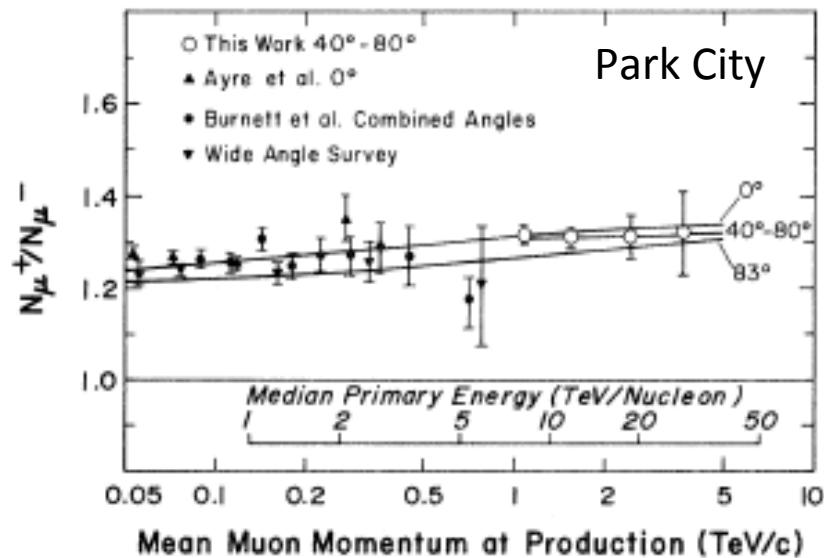
PAMELA





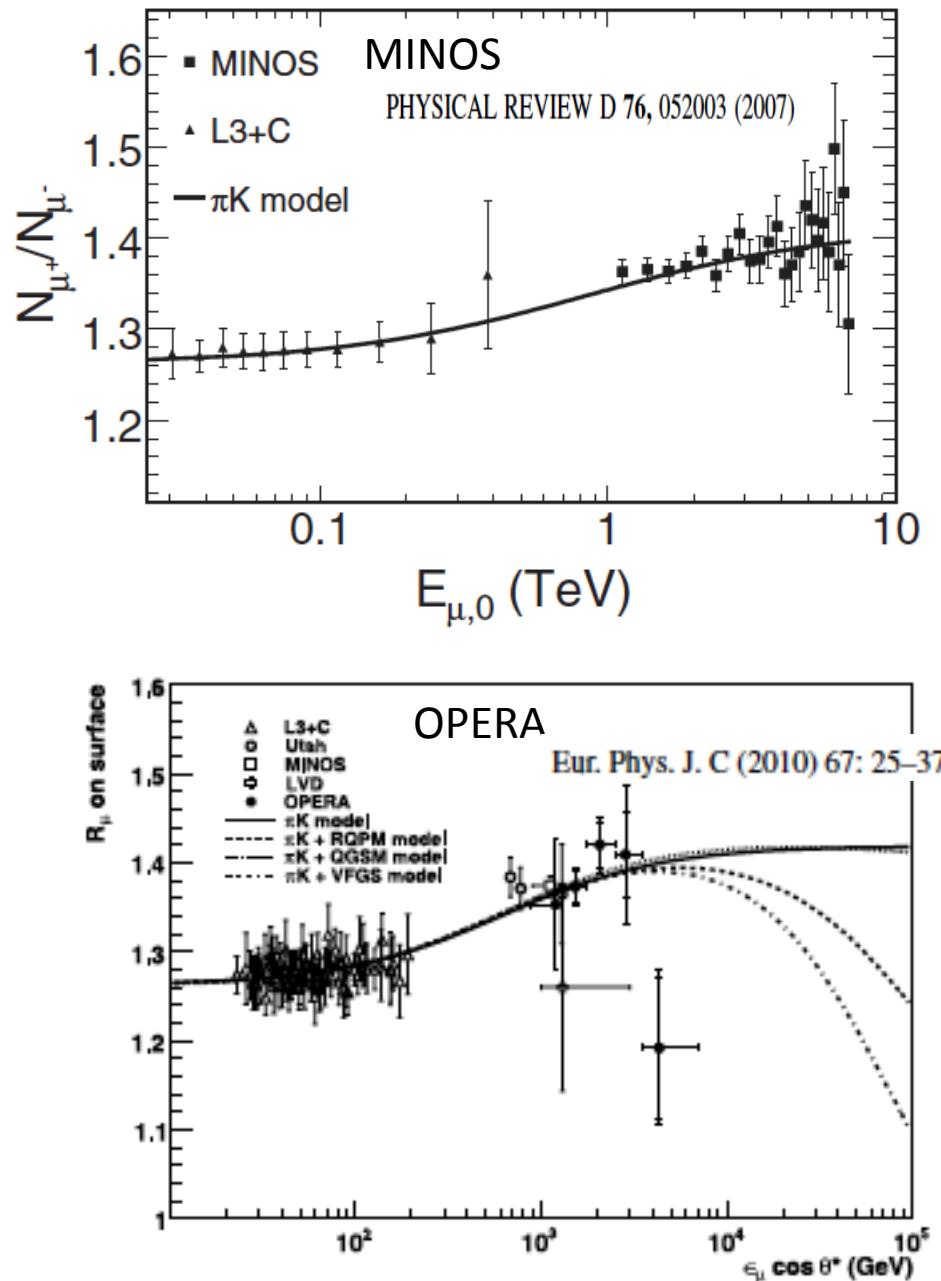
Tom Gaisser

Muon charge ratio



Ashley, Elbert, Keuffel, Larsen, Morrison, PRL 31(1973) 1091

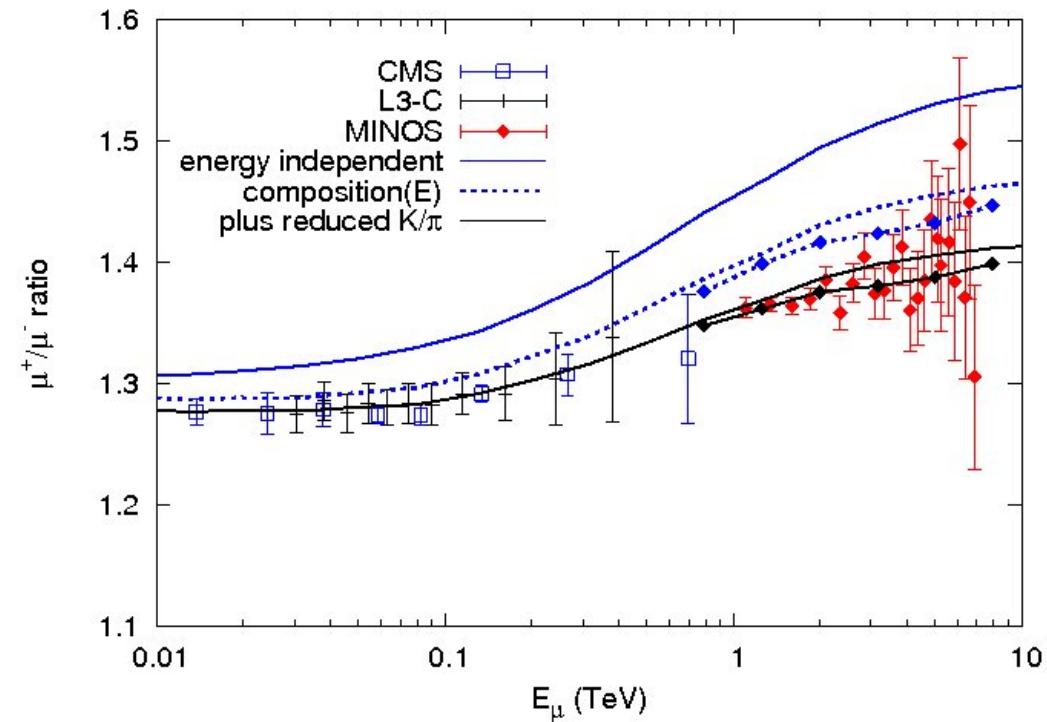
- Ratio due to excess of p over n in primary CR + steep spectrum which favors $p \rightarrow \pi^+$ over $p \rightarrow \pi^-$
- Rise at TeV due to increased importance of Kaons (especially K⁺)

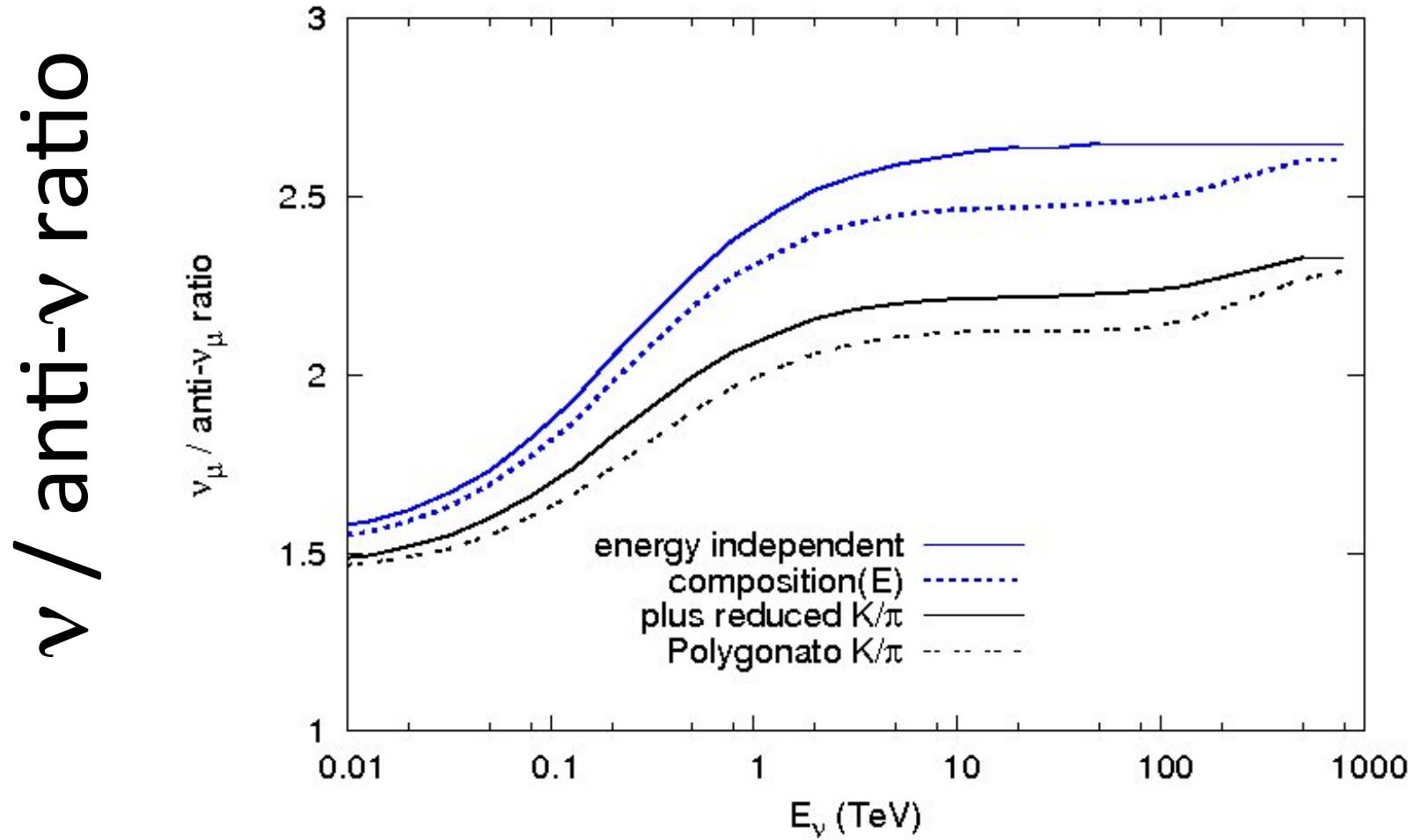


3 fits to μ^+/μ^- ratio:

1. $\delta_0 = \frac{p(0) - n(0)}{p(0) + n(0)} = \text{constant} = 0.76$
2. δ_0 energy-dependent from fit to CREAM, etc.
3. δ_0 energy-dependent + decrease K^+

K/π decreased from
0.149 to 0.135





Note that Polygonato δ_0 gives different ratio for ν
 It is tuned to the same μ^+/μ^- ratio with a different Z_{pK^+}

Seasonal variations of μ in IceCube and K/ π ratio

This work is in progress in IceCube. Preliminary results were shown by Paolo Desiati at ICRC 2011 (arXiv:1111.2735, with TKG, T. Kuwabara).

See also S.Tilav et al., ICRC 2009 (arXiv:1001.0776)

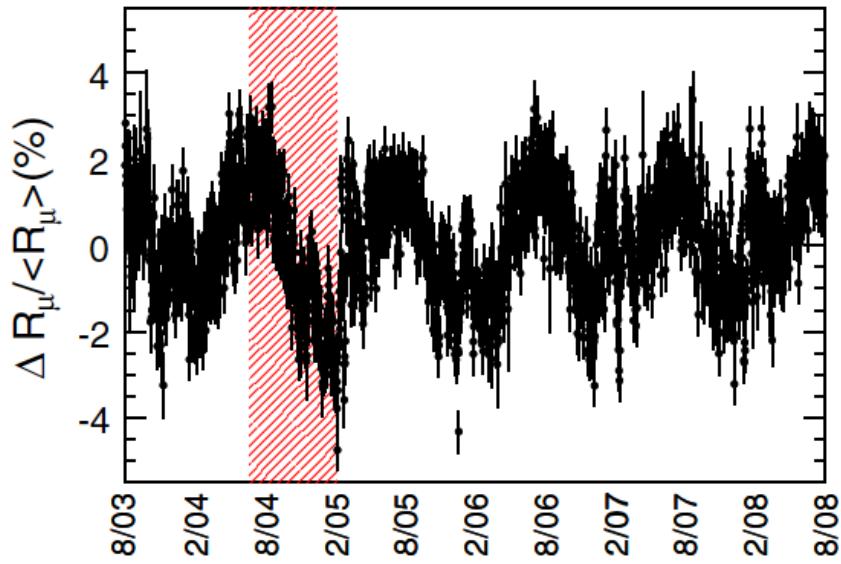
History

- Cornell
 - P.H. Barret et al., Refs. Mod. Phys. 24 (1952) 133
- MACRO
 - M. Ambrosio et al., Astropart. Phys. 7 (1997) 109
- LVD
 - M. Selvi, Proc. 31st ICRC (2009)
- AMANDA
 - A. Bouchta, Proc. 26th ICRC (1999)
- MINOS
 - P. Adamson et al., Phys. Rev. D81 (2010) 012001
- IceCube
 - S. Tilav et al., Proc 31st ICRC (2009)
 - P. Desiati et al., Proc. 32nd ICRC (2011)

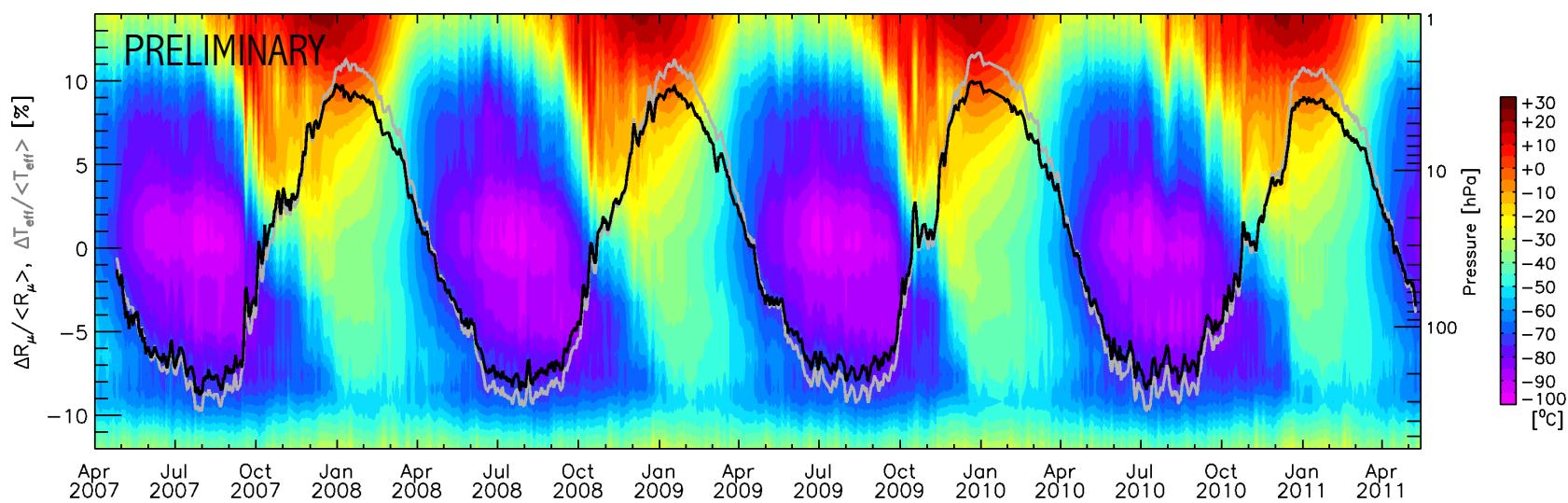
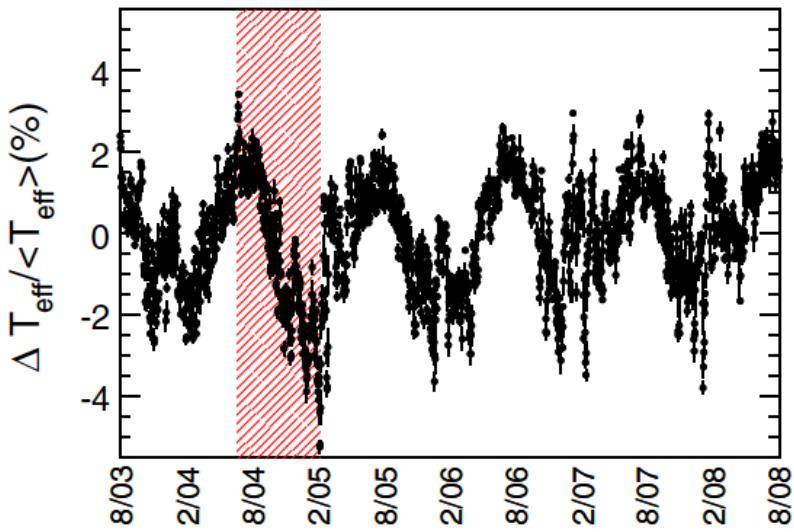
Rate

MINOS/IceCube

PHYSICAL REVIEW D 81, 012001 (2010)



Temperature



Clermont-Ferrand, 19-04-2012

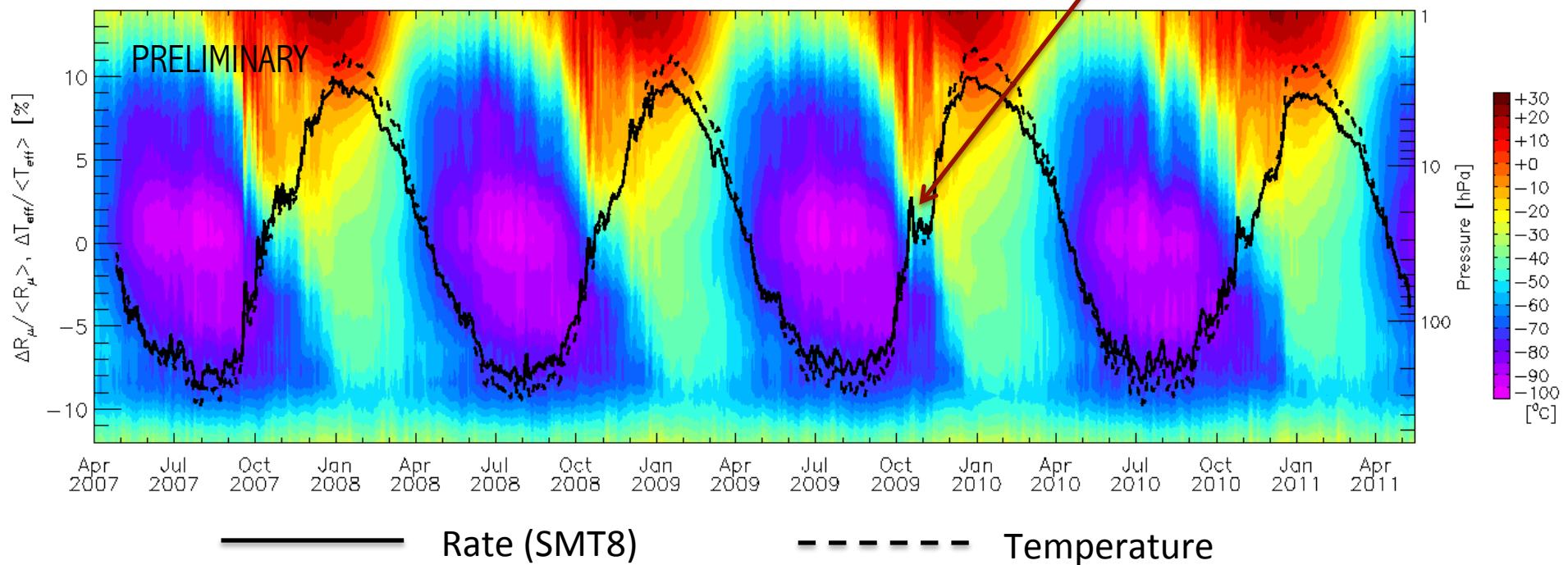
Tom Gaisser

15

Correlation coefficient relates Rate & T

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T^{exp} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

High statistical precision of IceCube allows detailed study of sudden changes



α depends on K/π

$$\phi_\mu(E_\mu, \theta) = \phi_N(E_\mu) \times \left\{ \frac{A_{\pi\mu}}{1 + B_{\pi\mu} \cos \theta E_\mu / \epsilon_\pi} + \frac{A_{K\mu}}{1 + B_{K\mu} \cos \theta E_\mu / \epsilon_K} \right\}$$

$$E_{\text{critical}} = \frac{\epsilon_\pi}{\cos \theta^*} = \frac{m_i c^2 h_0}{\cos \theta^* c \tau_i} = \frac{\epsilon_{\pi,0}}{\cos \theta^*} \times \frac{T}{T_0}$$

$$\alpha_\mu(E_\mu, \theta) = T \frac{1}{\phi_\mu(E_\mu, \theta)} \frac{d\phi_\mu(E_\mu, \theta)}{dT}$$

See Desiati & TKG

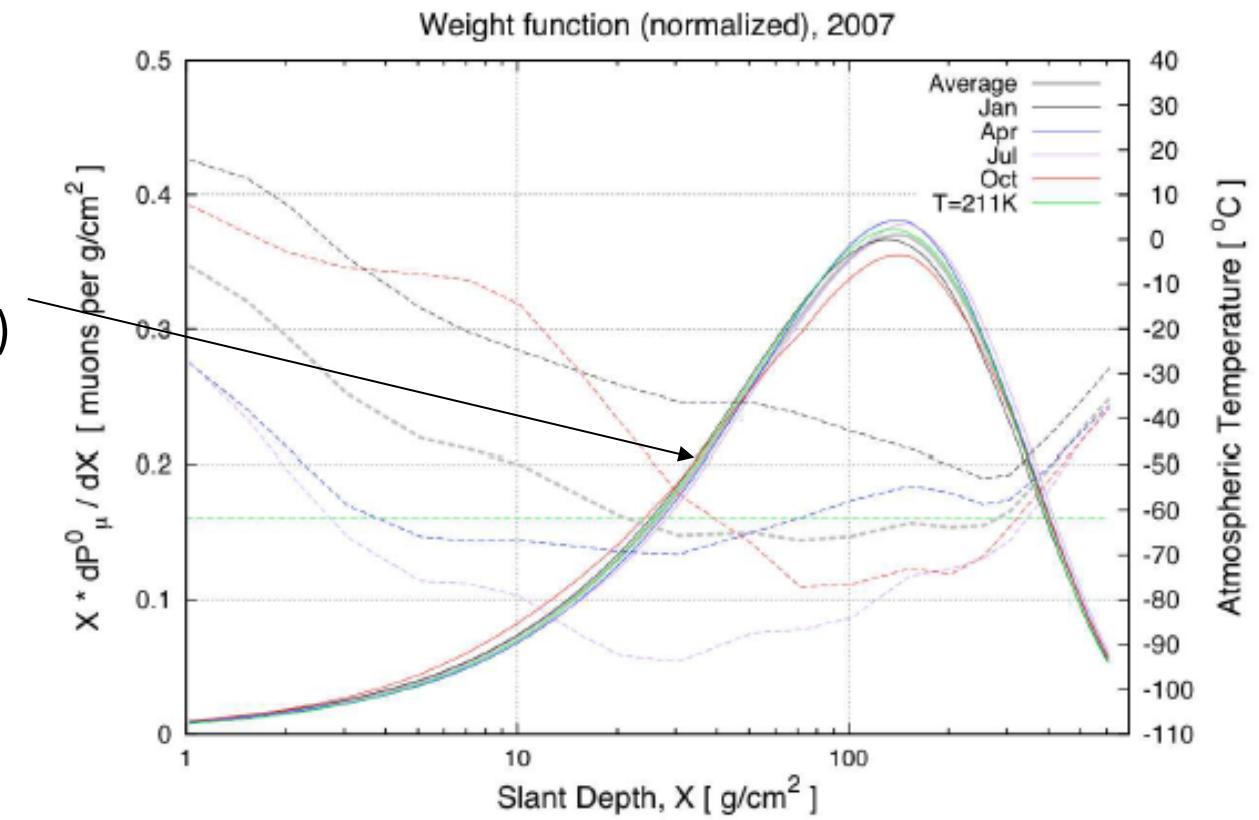
PRL **105**, 121102 (2010)

$$T \frac{d}{dT} \frac{A_{\pi\mu}}{1 + B_{\pi\mu} \cos \theta E_\mu / \epsilon_\pi} = \frac{A_{\pi\mu} B_{\pi\mu} \cos \theta E_\mu / \epsilon_\pi}{(1 + B_{\pi\mu} \cos \theta E_\mu / \epsilon_\pi)^2}$$

$$\alpha_\iota(\theta) = \frac{T}{\int dE \phi_\iota(E, \theta) \times A_{\iota, \text{eff}}(E, \theta)} \times \frac{d}{dT} \int dE \phi_\iota(E) \times A_{\iota, \text{eff}}(E, \theta).$$

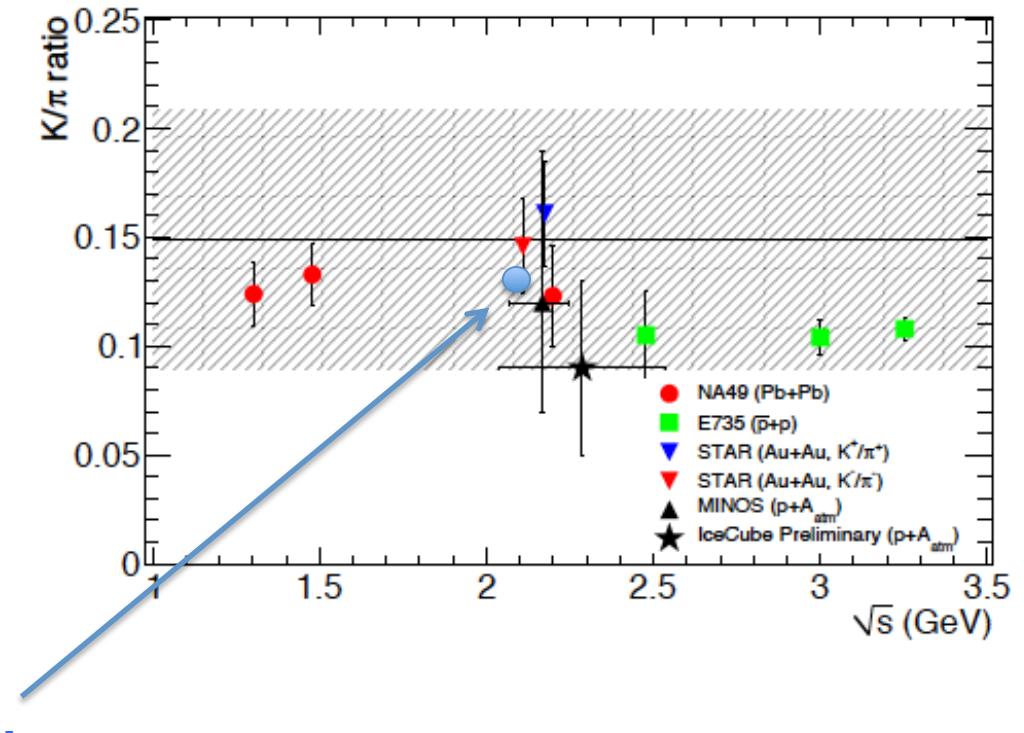
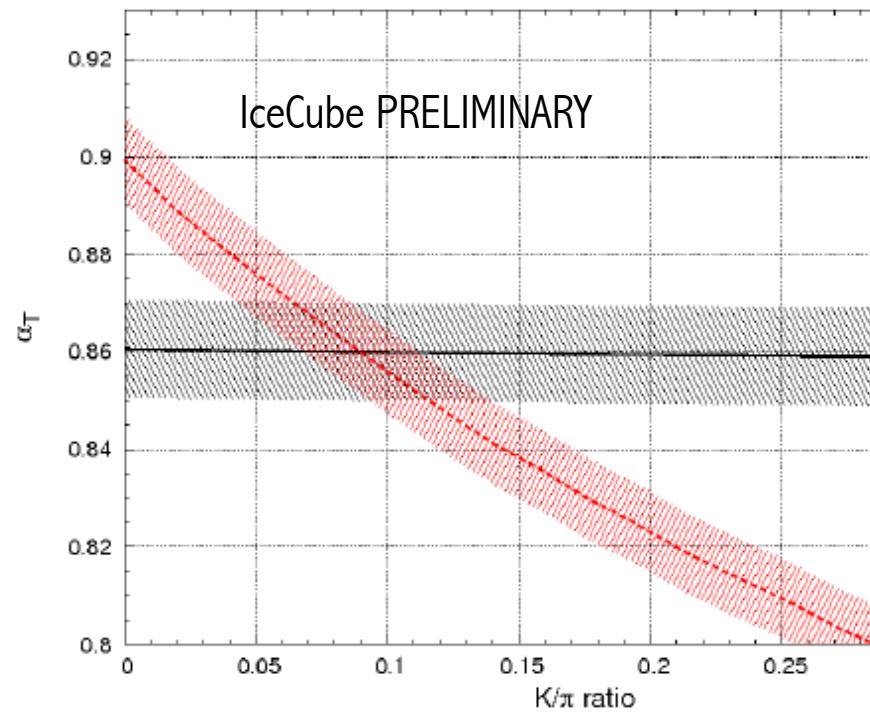
T_{eff}

Production profile
of muons (and ν_μ)



$$T_{\text{eff}}(E_\mu, \theta) = \frac{\int_0^X dX T(X) \mathcal{P}_\mu(E_\mu, \theta, X)}{\int_0^X dX \mathcal{P}_\mu(E_\mu, \theta, X)}$$

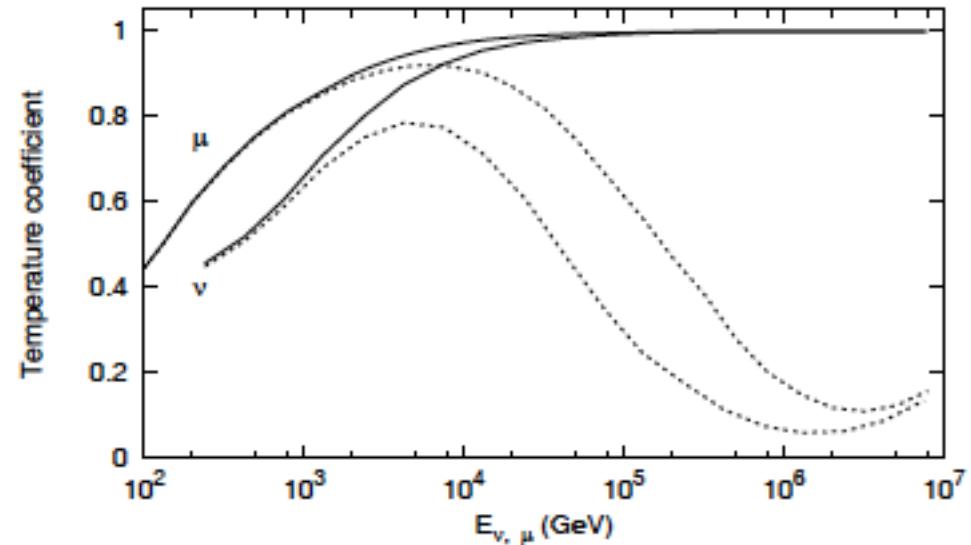
K/π ratio



Result from μ^+/μ^-

Can we use seasonal variations to see prompt leptons from charm decay?

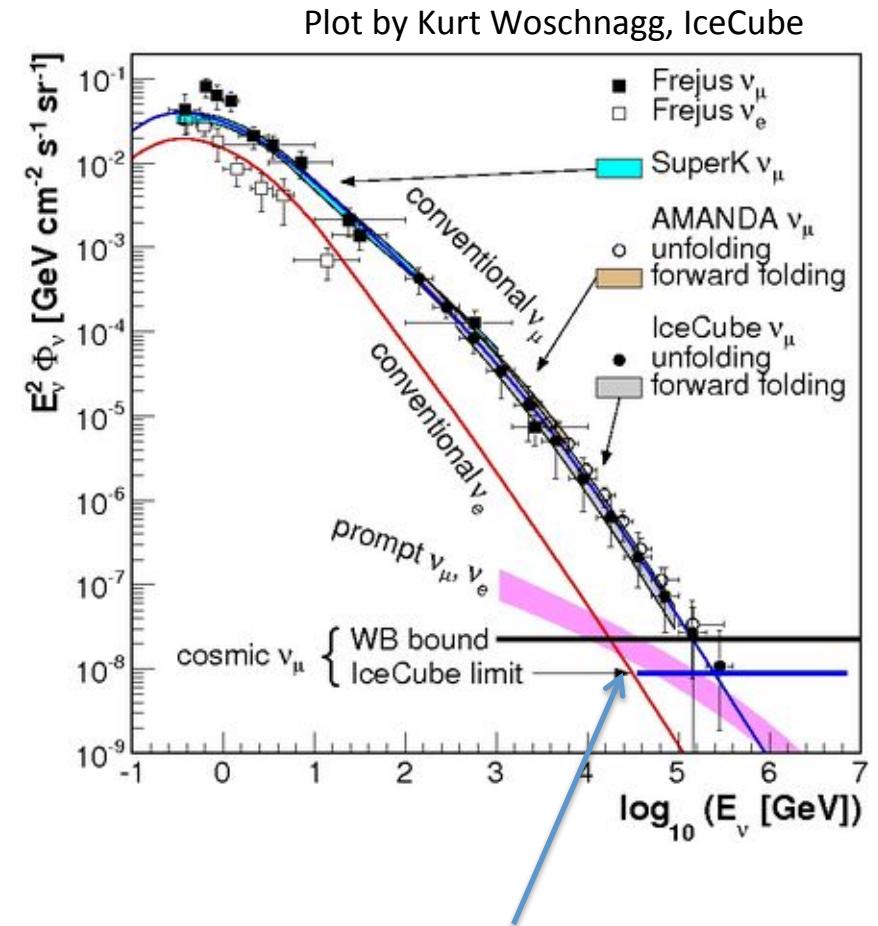
- Look for charm as temperature-independent component
- Also isotropic
- Need 100 TeV μ with high statistics
- Expect $\sim 10^5 \mu$ per year in IceCube with $E_\mu > 100 \text{ TeV}$



P. Desiati & TG, PRL 105 (2010) 121102

Atmospheric ν for $E_\nu > 100$ TeV

- This is the current range of interest for IceCube looking for a diffuse flux of astrophysical neutrinos above the background of atmospheric neutrinos
- Need to account for knee in primary spectrum
- Also relevant for ν tomography (K. Hoshina)



Current IceCube limit:
Phys. Rev. D84 (2011) 082001

Neutrino yield

$$\varphi_\nu(E_\nu, \theta) = \int dE_0 \Phi_N(E_0) Y_\nu(E_\nu, E_0, \theta)$$

If the yield per nucleon (Y_ν) is known, we can calculate ν (or μ) flux numerically for an arbitrary primary spectrum. For a power-law spectrum, the neutrino spectrum is known (see slide 4), so the yield can be obtained by inverting the following integral equation (inverse Mellin transform):

$$\varphi_\nu(E_\nu, \theta) = \int dE_0 K E_0^{-\alpha} Y_\nu(E_\nu, E_0, \theta)$$

Elbert formula for yields of μ and ν

Lipari showed that the Elbert formula for muons approximates the Mellin transform of the elementary solution (Astropart. Phys. 1 (1993) 399):

$$N_\mu(>E_\mu) = \frac{A \mathcal{E}_\mu^*}{E_\mu \cos \theta} \left(\frac{E_0}{AE_\mu} \right)^p \left(1 - \frac{AE_\mu}{E_0} \right)^q$$

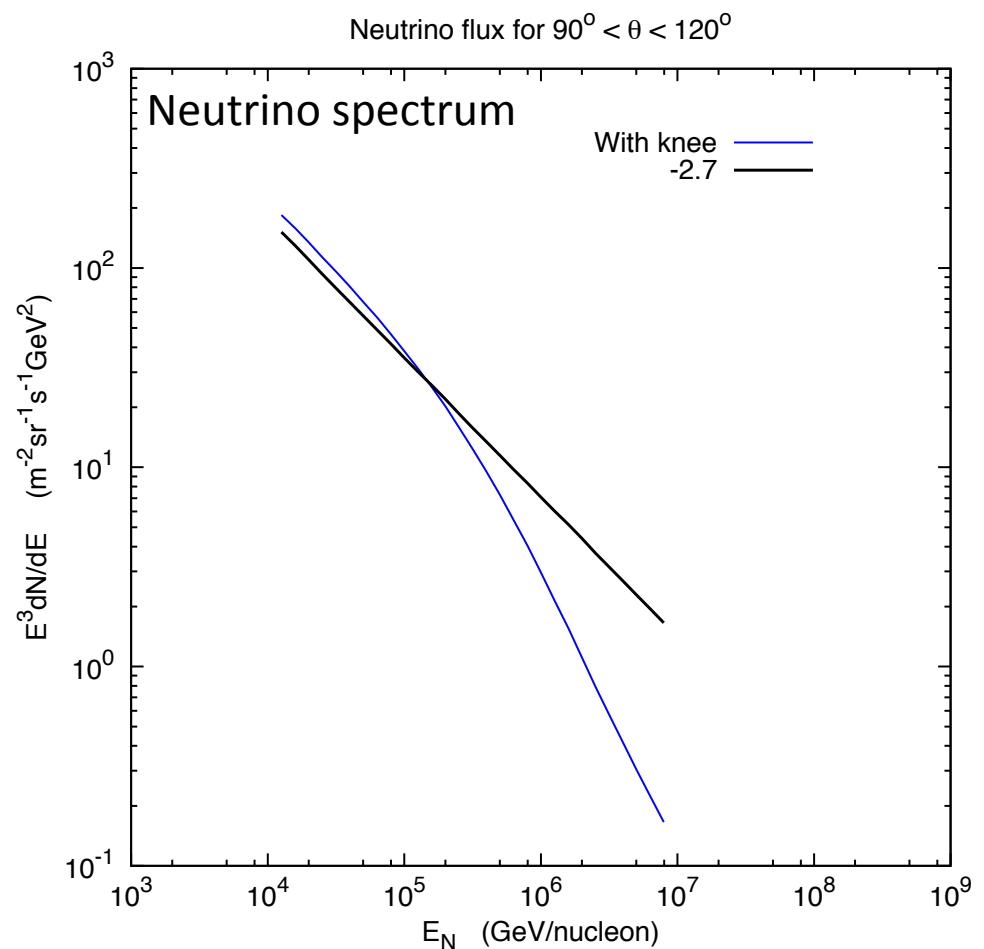
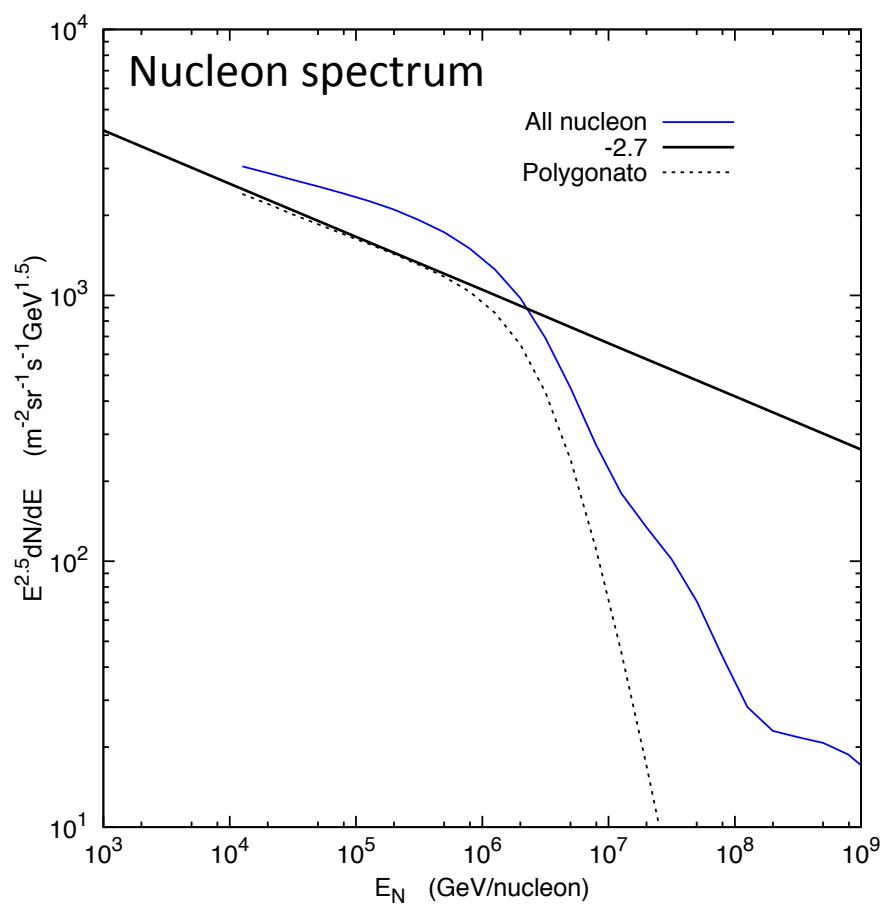
$$\mathcal{E}_\mu^* \approx 14.5 \text{ GeV}, \quad p \approx 0.76 \text{ and } q \approx 5.25$$

The corresponding formula for neutrinos differs only in the decay kinematics of $\pi \rightarrow \nu$ instead of $\pi \rightarrow \mu$

From this I estimate

$$\mathcal{E}_\nu^* \approx 4.8 \text{ GeV}$$

Knee in the neutrino spectrum



Summary remarks

- Analytic approximations
 - Could substitute for CORSIKA etc in μ tomography
- Muon charge ratio refines K/π ratio (and $\nu/\bar{\nu}$)
- Seasonal effects well understood
- Prompt leptons?
- Atmospheric neutrinos above 100 TeV – o.k.

This week in pictures.

From Sven Lidstrom at the South Pole



Moon over South Pole at -100F



ICL in moonlight



Carlos in action on Tuesday



300 club training session



Clermont-Ferrand, 19-04-2012

Walking home



Tom Gaisser

Last of the trace of sunlight in the horizon

Follow the charges

Reference: TKG arXiv:1111.6675v2

$$\phi_N(E) = \phi_N(0) \times \exp\left(-\frac{X}{\Lambda_N}\right) \quad \Delta(X) = \delta_0 \phi_N(0) \times \exp\left(-\frac{X}{\Lambda_-}\right)$$
$$N = p + n \quad \delta_0 = \frac{p(0) - n(0)}{p(0) + n(0)} \quad \frac{1}{\Lambda_-} = \frac{1 - Z_{pp} + Z_{pn}}{1 + Z_{pp} + Z_{pn}} \frac{1}{\Lambda_N}$$

For the pion channel only, the result is (Frazer et al., 1972)

$$\phi_\mu(E_\mu)^\pm = \phi_N(E_\mu) \frac{A_{\pi\mu} \times 0.5(1 \pm \beta\delta_0\alpha_\pi)}{1 + B_{\pi\mu}^\pm E \cos(\theta)E_\mu/\epsilon_\pi}$$

$$\beta = \frac{1 - Z_{pp} - Z_{pn}}{1 - Z_{pp} + Z_{pn}} \approx 0.909 \quad \alpha_\pi = \frac{Z_{p\pi^+} - Z_{p\pi^-}}{Z_{p\pi^+} + Z_{p\pi^-}} \approx 0.165 \quad \alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}}$$

Kaon channel

$$\phi_K(E_\mu)^- = \frac{Z_{NK^-}}{Z_{NK}} \phi_N(E_\mu) \frac{A_{NK}}{1 + B_{K\mu} \cos(\theta) E_\mu / \epsilon_K}.$$

$$\phi_K(E_\mu)^+ = \phi_N(E_\mu) A_{NK} \times \frac{\frac{1}{2}(1 + \alpha_K \beta \delta_0)}{1 + B_{K\mu}^+ \cos(\theta) E_\mu / \epsilon_K}$$

$$p \rightarrow n \pi^+ = n \rightarrow p \pi^- \text{ but } p \rightarrow \Lambda K^+ = n \rightarrow \Lambda K^0 \qquad \alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}}$$

To evaluate the formulas we need the proton excess, $\delta_0 = \frac{p(0) - n(0)}{p(0) + n(0)}$

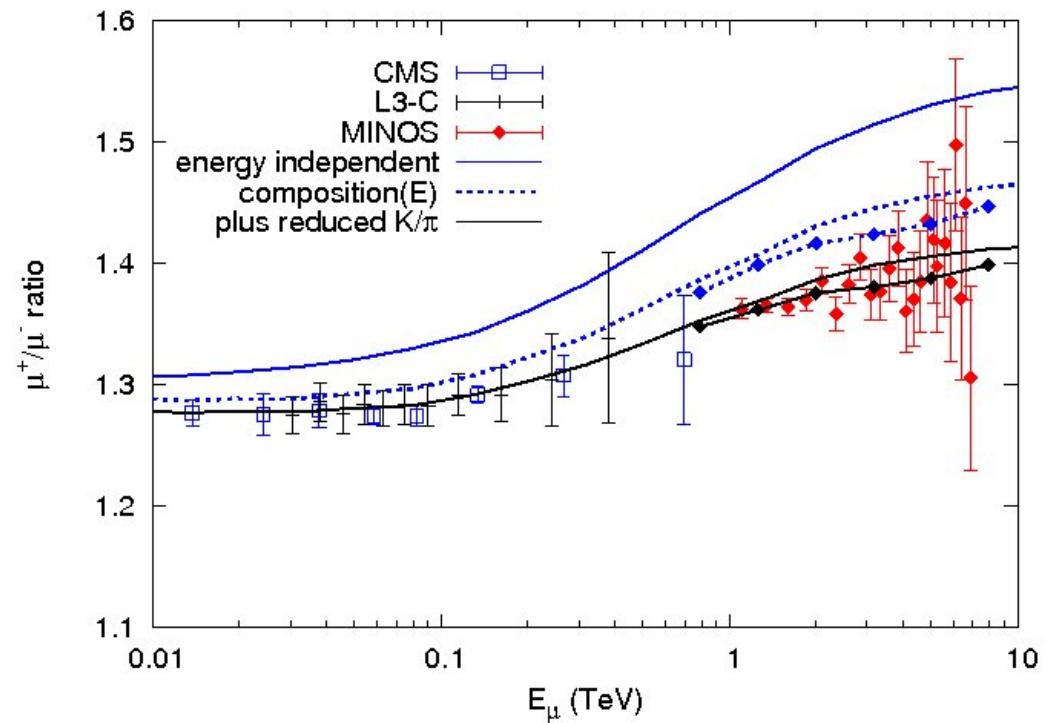
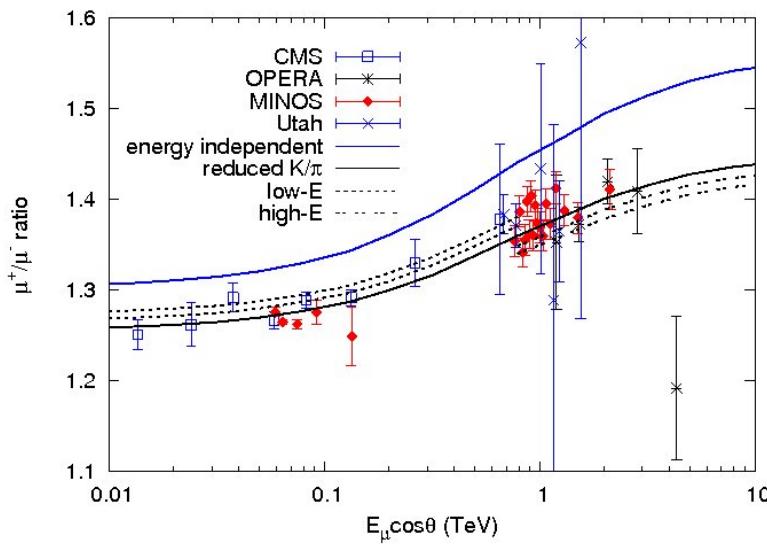
and we need the energy spectrum of nucleons $\phi_N(E_N)$ per GeV/nucleon

3 fits to μ^+/μ^- ratio:

1. $\delta_0 = \frac{p(0) - n(0)}{p(0) + n(0)} = \text{constant} = 0.76$

2. δ_0 energy-dependent from fit to CREAM, etc.

3. δ_0 energy-dependent + decrease K⁺



Dependence of scale height on T

$$X = X_0 \times e^{-h/h_0}$$

h = altitude

X = column depth (g/cm^2)

X_0 = column depth at sea level

The scale height h_0 is not constant, but it defines an exponential approximation to the atmospheric profile locally at each altitude.

The local density is $\rho = -\frac{dX}{dh} = \frac{X}{h_0}$ and pressure $P = gX$

The ideal gas law relates P and ρ to T by $P = \rho \frac{R}{M} T$ where

$$R = 8.315 \text{ J/(mol} \cdot \text{K}), M = 0.028964 \text{ kg/mol}, g = 9.8 \text{ m/s}^2$$

$$h_0 = \frac{X}{\rho} = \frac{P}{g\rho} = \frac{RT}{Mg} = 6.18 \text{ km for } T = 211^\circ \text{K}$$

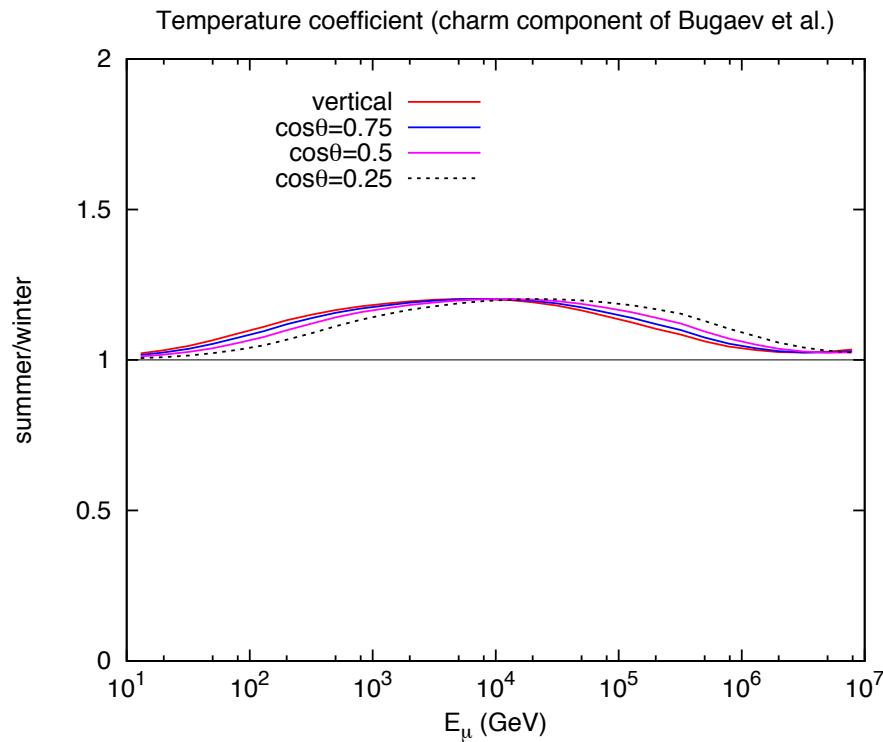
Muons most favorable because of high rate

- Muon energy spectrum by burst method
- Depends on identifying large radiative bursts along muon tracks
 - Measure energy of single burst to select single muon from possible bundle
 - Relate to energy of muon at surface statistically using well-known energy loss theory

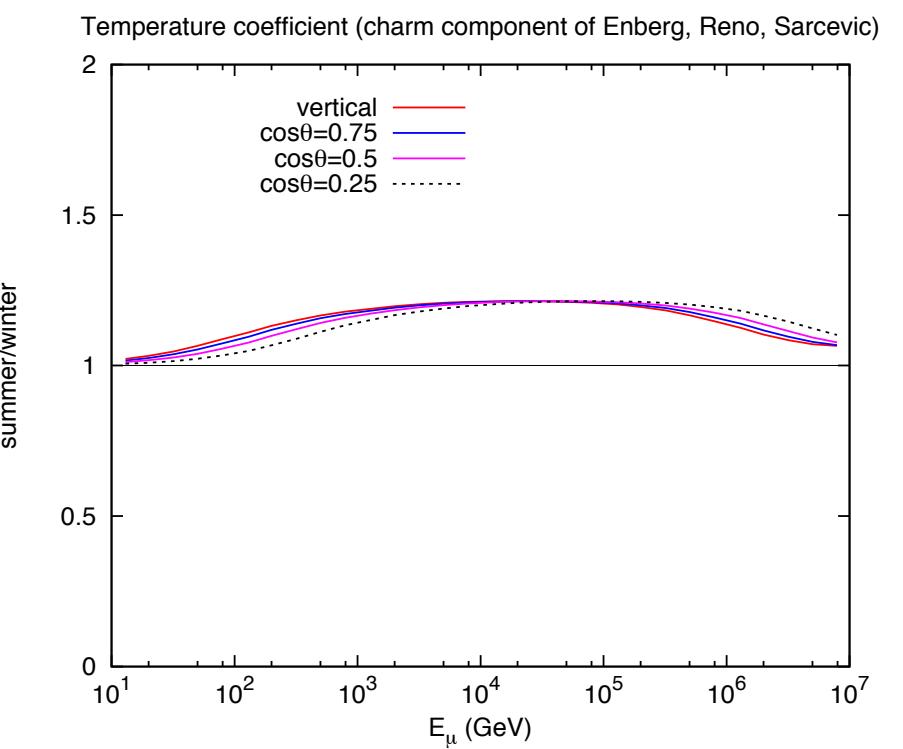
Calculation for 2 different models

Seasonal effect has an angular dependence because $E_{\text{critical}} = \varepsilon_i / \cos\theta$

Bugaev et al. (probably excluded)



Enberg et al.



Elementary solution

Solution for a power law primary spectrum is known.

For example, in the high energy limit for the pion channel,

$$\begin{aligned}\phi_\nu^{(\pi)} &= KE_\mu^{-(\gamma+1)} \frac{Z_{N\pi}(\gamma)}{1 - Z_{NN}} \frac{\Lambda_\pi}{\Lambda_\pi - \Lambda_N} \ln \left[\frac{\Lambda_\pi}{\Lambda_N} \right] \frac{\epsilon_\pi}{E_\nu \cos \theta} \frac{(1 - r_\pi)^{(\gamma+1)}}{\gamma + 2} \\ &= \int dE_0 KE_0^{-\alpha} Y_\nu(E_\nu, E_0, \theta)\end{aligned}$$

Invert the integral (inverse Mellin transform) to find $Y_\nu(E_\nu, E_0, \theta)$
(Note dependence of $Z_{N\pi}$ etc. on γ)

Reference: P. Lipari et al., arXiv:1010.5084

Calculate ν flux from $N_\nu(>E_\nu, E_0, \theta)$

$$\phi_\nu(>E_\nu) = \int dE_0 \Phi_N(E_0) N_\nu(>E_\nu, E_0, \theta)$$

Here the primary spectrum of nucleons can have any shape.
The result is obtained by a simple numerical integration.

Differentiate the integral spectrum to obtain the differential neutrino spectrum

Energy spectrum of atmospheric muons and neutrinos

- At low energy, $\Phi_{\nu,\mu}$ has same spectral index at production as primary spectrum
- $\Phi_{\nu,\mu}$ becomes steeper by one power of energy at high energy
- Critical energy depends on zenith angle:

$$E_{\text{critical}} = \varepsilon_i / \cos\theta$$

5-component model, 3 populations

Hillas model: SNR, Galactic B, extragalactic

All-particle spectrum $\phi_i(E) = \sum_{j=1}^3 a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$

Spectrum of nucleons $\phi_{i,N}(E_N) = A \times \phi_i(A E_N)$

R_c	γ	p	He	CNO	Mg-Si	Fe
γ for Pop. 1	—	1.66	1.58	1.63	1.67	1.63
Population 1: 4 PV	see line 1	7860	3550	2200	1430	2120
Pop. 2: 30 PV	1.4	20	20	13.4	13.4	13.4
Pop. 3 (mixed): 2 EV	1.4	1.7	1.7	1.14	1.14	1.14
" (proton only): 60 EV	1.6	200.	0	0	0	0

Neutrinos from kaons

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

$$\epsilon_\mu = 1 \text{ GeV}$$

$$\epsilon_\pi = 115 \text{ GeV}$$

$$\epsilon_K = 850 \text{ GeV}$$

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

$$\epsilon_{K_L} = 0.205 \text{ TeV}$$

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 $E > \text{TeV}$

Factors in atmospheric ν beam

For each parent $i = \pi^\pm, K^\pm$, charm:

$$A_{n,i} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}}$$

Branching ratio
moment of decay
*Spectrum-weighted moment
of hadron production*

For example, for $N + air \rightarrow K^+ + X$

$$Z_{NK^+} = \frac{1}{\sigma_{N,air}} \int_0^1 x^\gamma \frac{d\sigma_{NK^+}(x)}{dx} dx$$