Cosmic-ray composition

Implications for atmospheric muons and neutrinos up to PeV

Motivation/outline

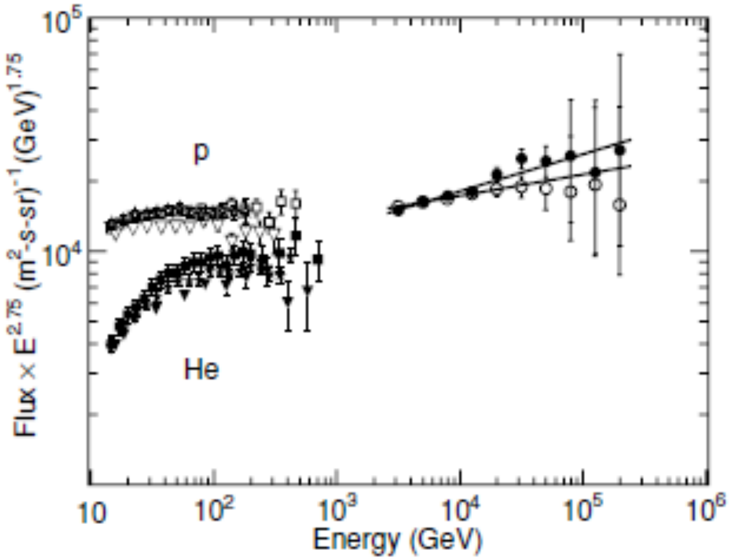
- Spectrum of nucleons is needed to calculate inclusive spectra of μ and ν
- Direct measurements of p, He … only to 100 TeV
- Air shower spectrum is for all particles
  - Suggestions from KASCADE about composition
- Combine information and make a working model consistent with what we know
- Combine with new information from μ^+/μ^-
  - K/π ratio is especially important for ν
  - Seasonal variation of TeV muons also useful

Assumptions for a realistic toy model

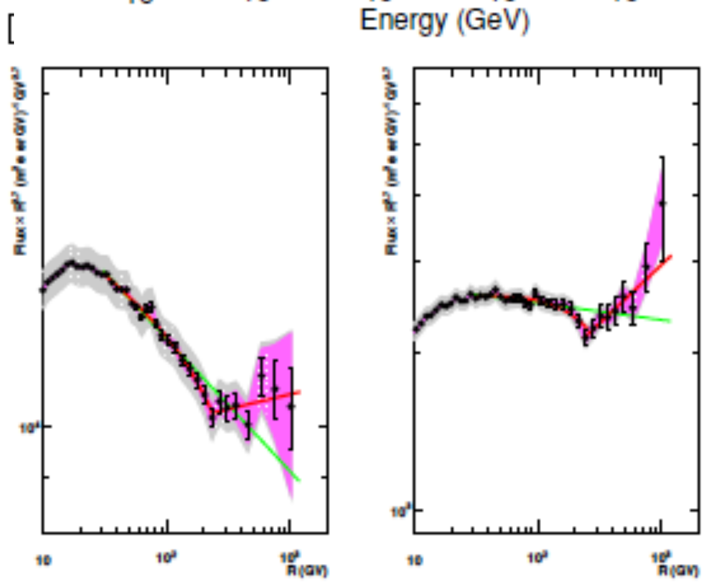
- 5 nuclear groups: p, He, CNO, Mg-Si, Fe
- 3 populations: SNR, Galactic B, extra-galactic
- All features depend on rigidity, R = Pc / Ze
- Requirements
  - Consistency with air shower measurements of the all-particle spectrum
  - Anchor to composition from direct experiments below 100 TeV
- Goals (long-term)
  - derive spectrum of nucleons
  - Calculate atmospheric muons and neutrinos to PeV

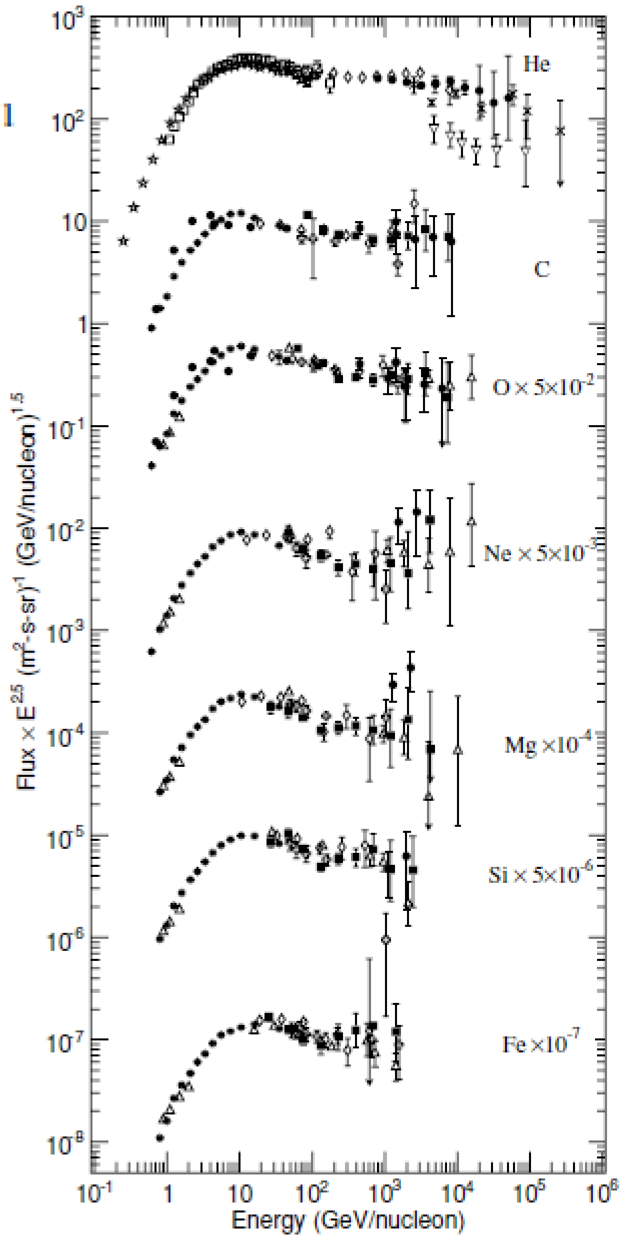
CREAM

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



PAMELA





5-component model, 3 populations

Hillas model: SNR, Galactic B, extragalactic

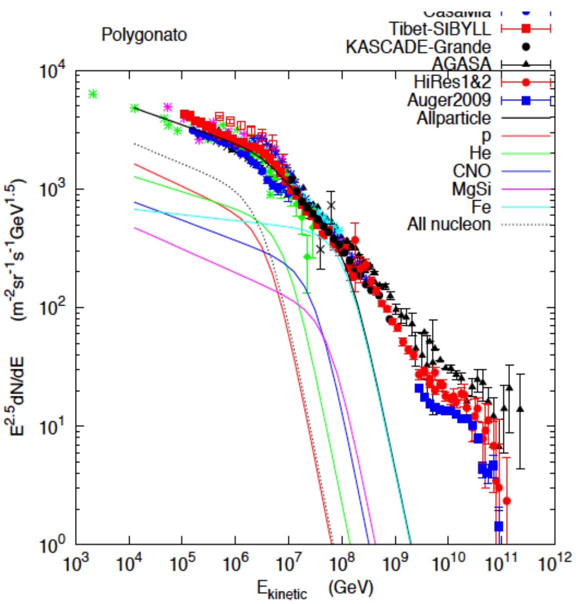
All-particle spectrum $$\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

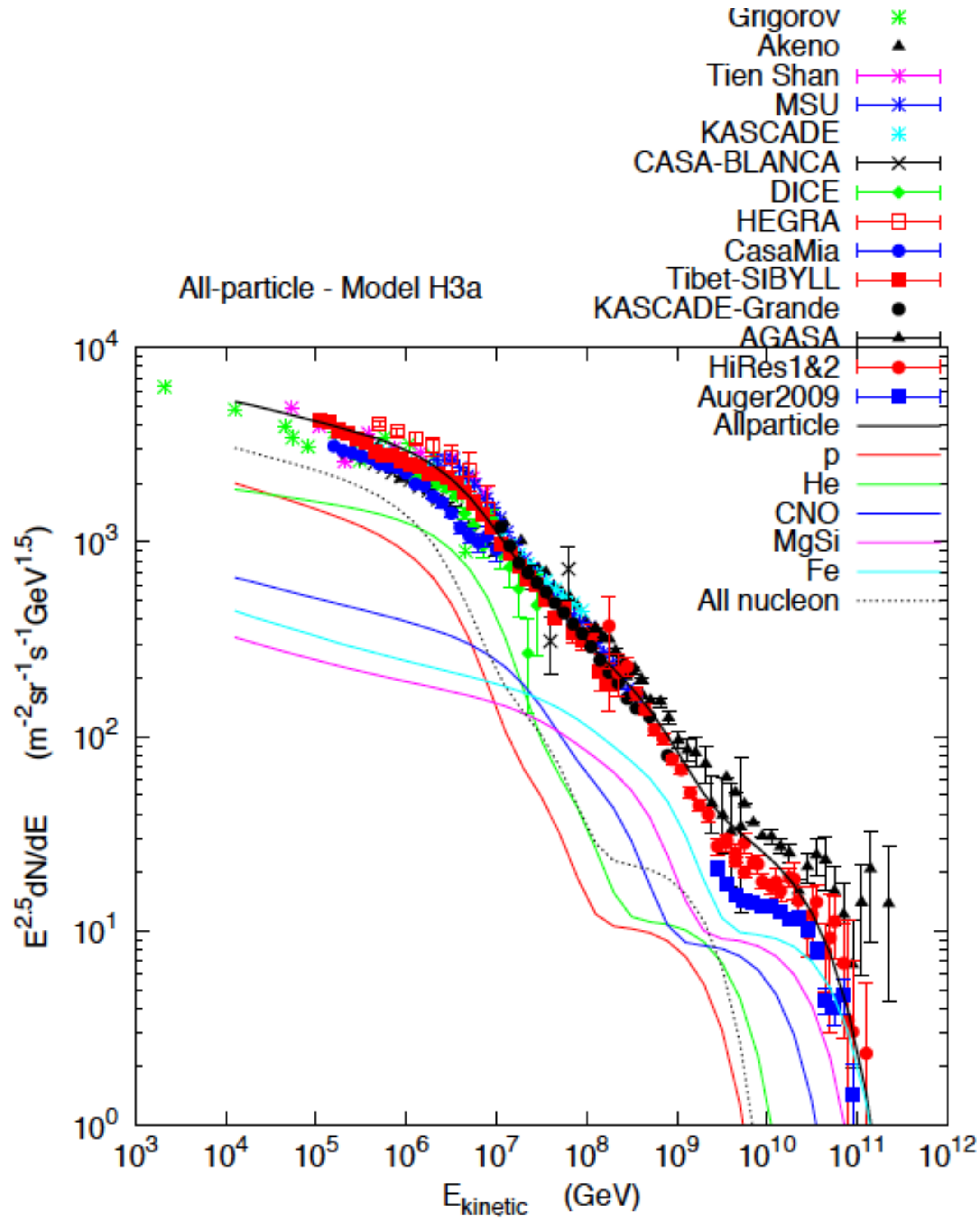
Spectrum of nucleons $$\phi_{i,N}(E_N) = A \times \phi_i(A E_N)$$

R_c	γ	p	He	CNO	Mg-Si	Fe
γ for Pop. 1	—	1.647	1.571	1.634	1.67	1.675
Population 1: 4 PV	see line 1	7860	3550	2200	1430	2120
Pop. 2 (H3a): 30 PV	1.4	20	20	13.4	13.4	13.4
" (H4a): 30 PV	1.4	20	20	13.4	13.4	13.4
Pop. 3 (H3a): 2 EV	1.4	1.7	1.7	1.14	1.14	1.14
" (H4a): 60 EV	1.6	200.	0	0	0	0

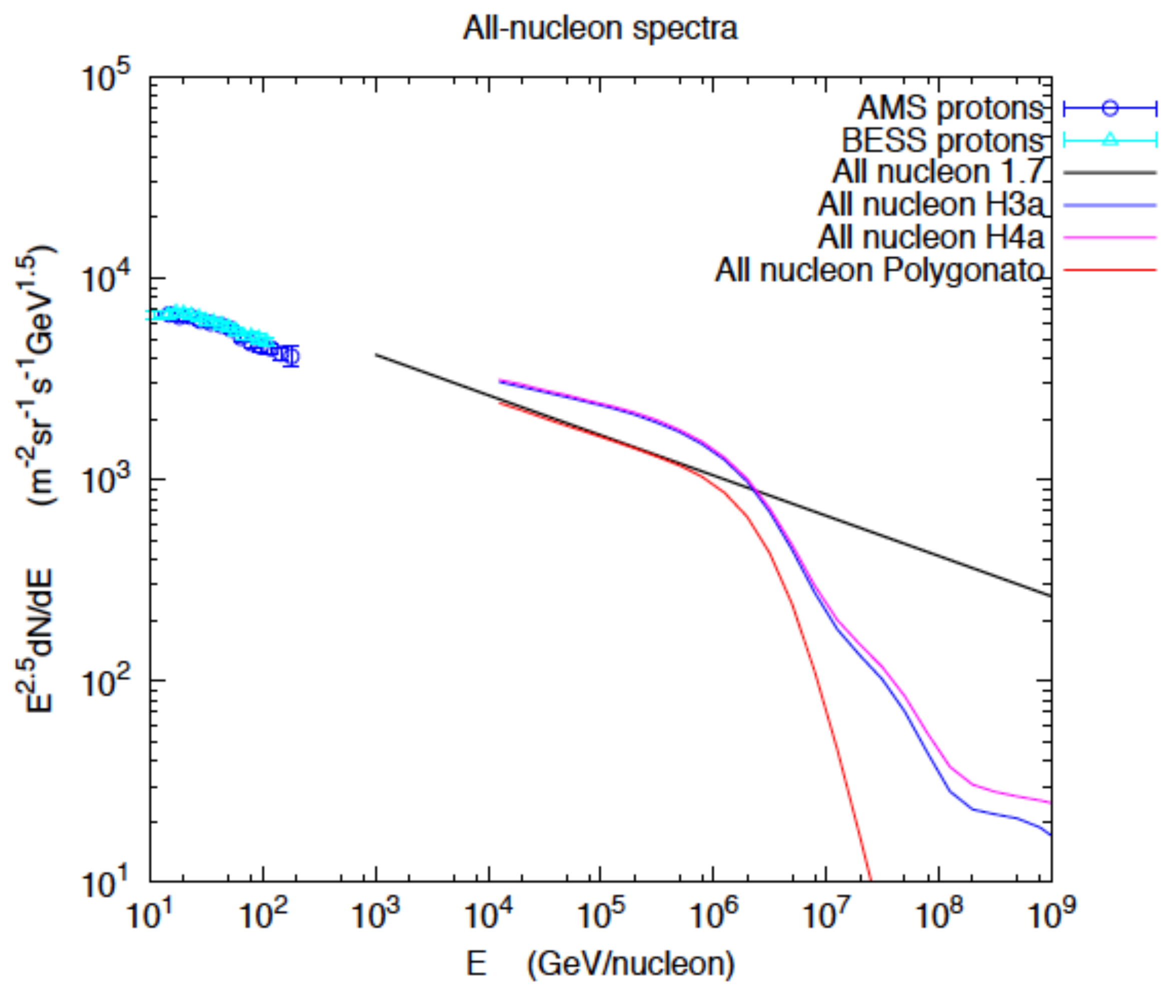
All-particle spectrum

Polygonato, Galactic only





Spectrum of nucleons (GeV/A)

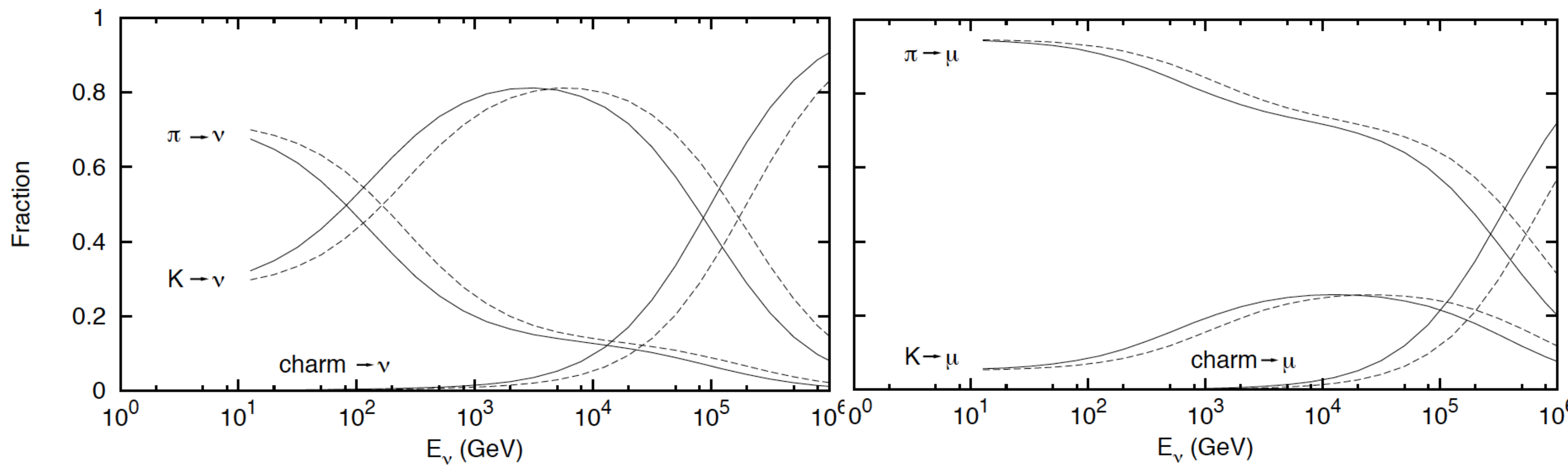


Muons and neutrinos

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

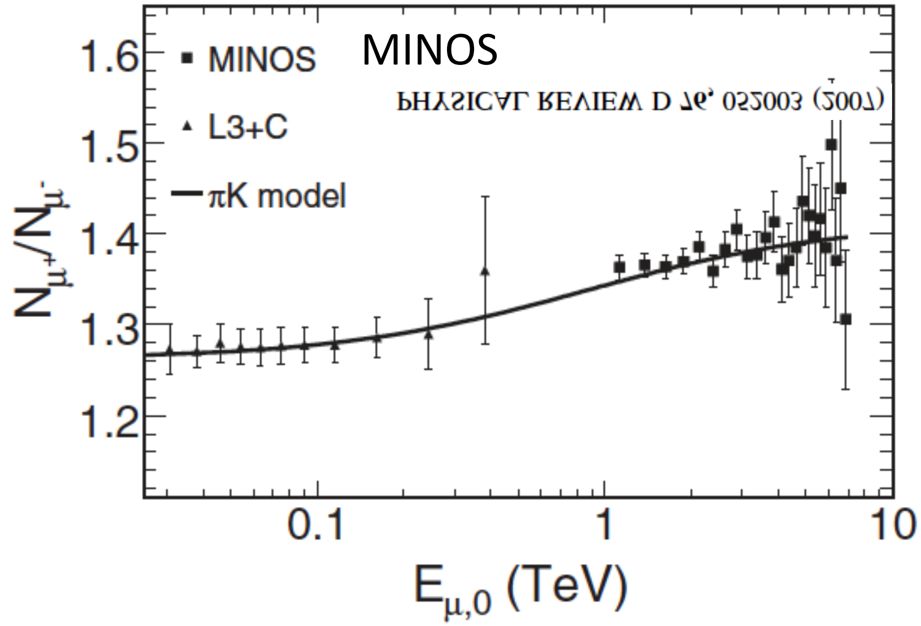
Same form for μ;
Different kinematics
→ μ, ν differences

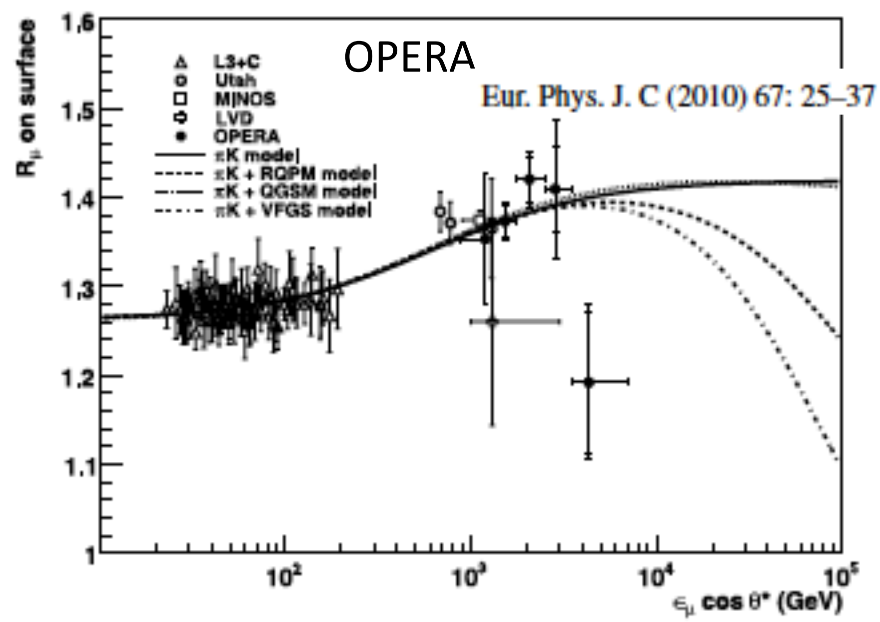
Neutrinos | Muons



Muon charge ratio

- Rise due to increased importance of K
- Calculate charges separately





Follow charges

$$\phi_N(E) \;=\; \phi_N(0) \times exp(-\frac{X}{\Lambda_N}) \qquad \Delta(X) \;=\; \delta_0\, \phi_N(0) \times exp(-\frac{X}{\Lambda_-})$$

N = p + n

$$\delta_0 \;=\; \frac{p(0) - n(0)}{p(0) + n(0)} \qquad \frac{1}{\Lambda_-} \;=\; \frac{1 - Z_{pp} + Z_{pn}}{1 + Z_{pp} + Z_{pn}} \frac{1}{\Lambda_N}$$

Spectrum-weighted moment reflects hadronic physics for each process
Example: p → $K^+ + \Lambda$

$$Z_{pK+} \;=\; \frac{1}{\sigma} \int x^{\gamma} \frac{\mathrm{d}\sigma(x)}{\mathrm{d}x} \mathrm{d}x \qquad x = E_K / E_p$$

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

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

MINOS (OPERA analysis similar)

$$\frac{N_{\mu^+}}{N_{\mu^-}} = \left[\frac{f_{\pi^+}}{1+\frac{1.1E_{\mu^+}\cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054 f_{K^+}}{1+\frac{1.1E_{\mu^+}\cos\theta}{850\ \mathrm{GeV}}}\right] \times \Big/ \left[\frac{(1-f_{\pi^+})}{1+\frac{1.1E_{\mu^-}\cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054(1-f_{K^+})}{1+\frac{1.1E_{\mu^-}\cos\theta}{850\ \mathrm{GeV}}}\right]$$

$$f_{\pi^+} = 0.55$$

$$f_{K^+} = 0.67$$

Problem: $f_{K^-} \neq 1 - f_{K^+}$ because p→ $K^+ \Lambda$ → μ^+ has no corresponding process for forward K^-

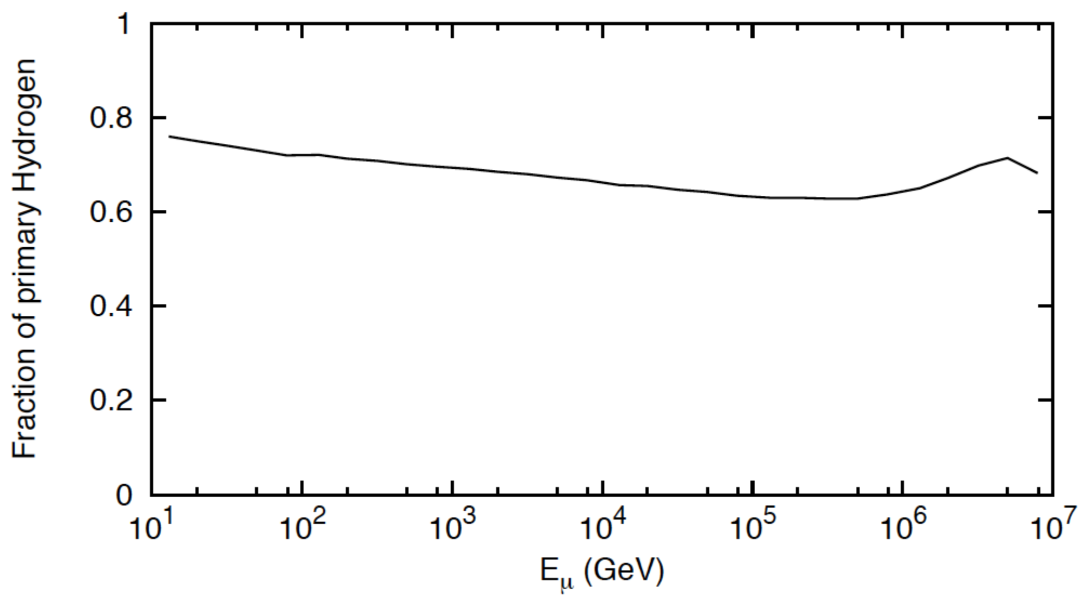
$$\phi_K(\mu^-) = \frac{Z_{NK^-}}{Z_{NK}} \frac{A_{NK}}{1 + B_{NK}\cos(\theta) E_\mu/\epsilon_K}$$

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

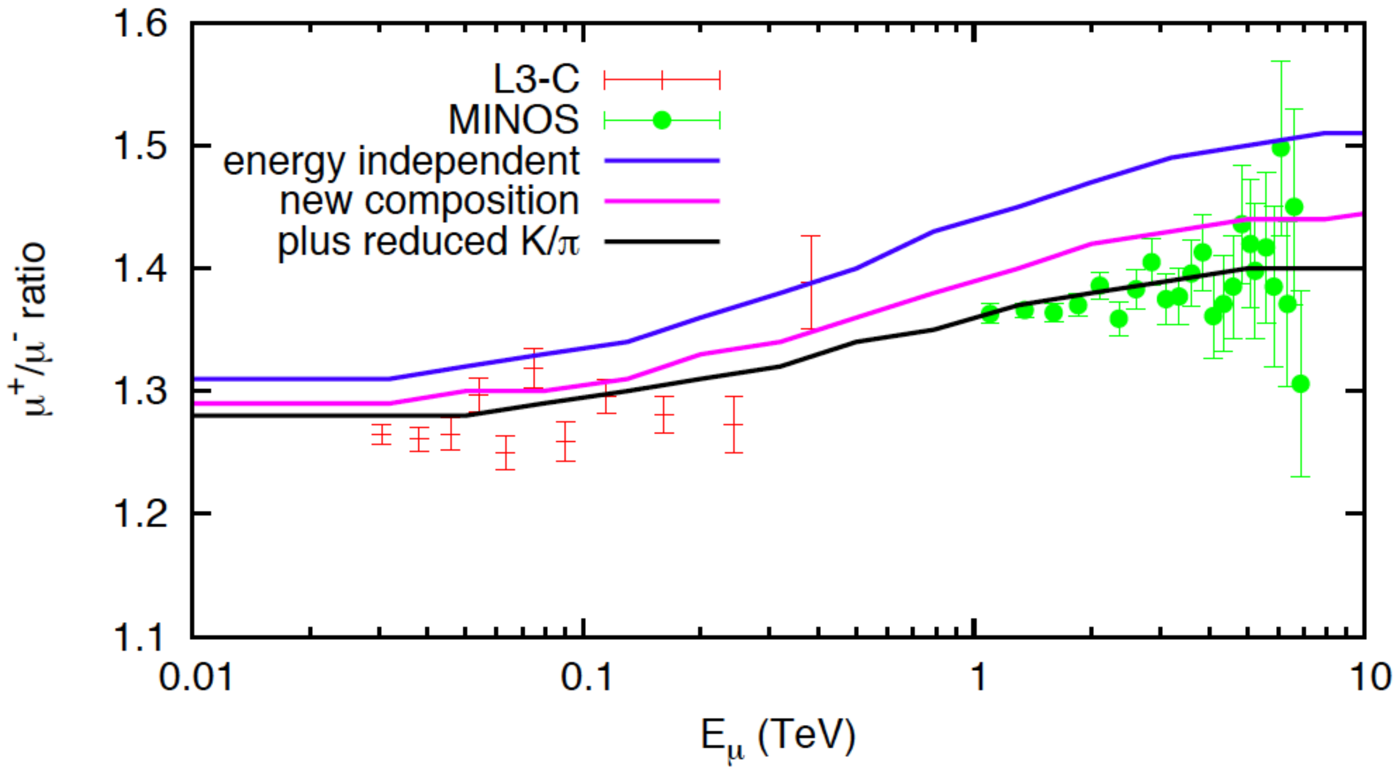
3 fits to μ^+/μ^- ratio:

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

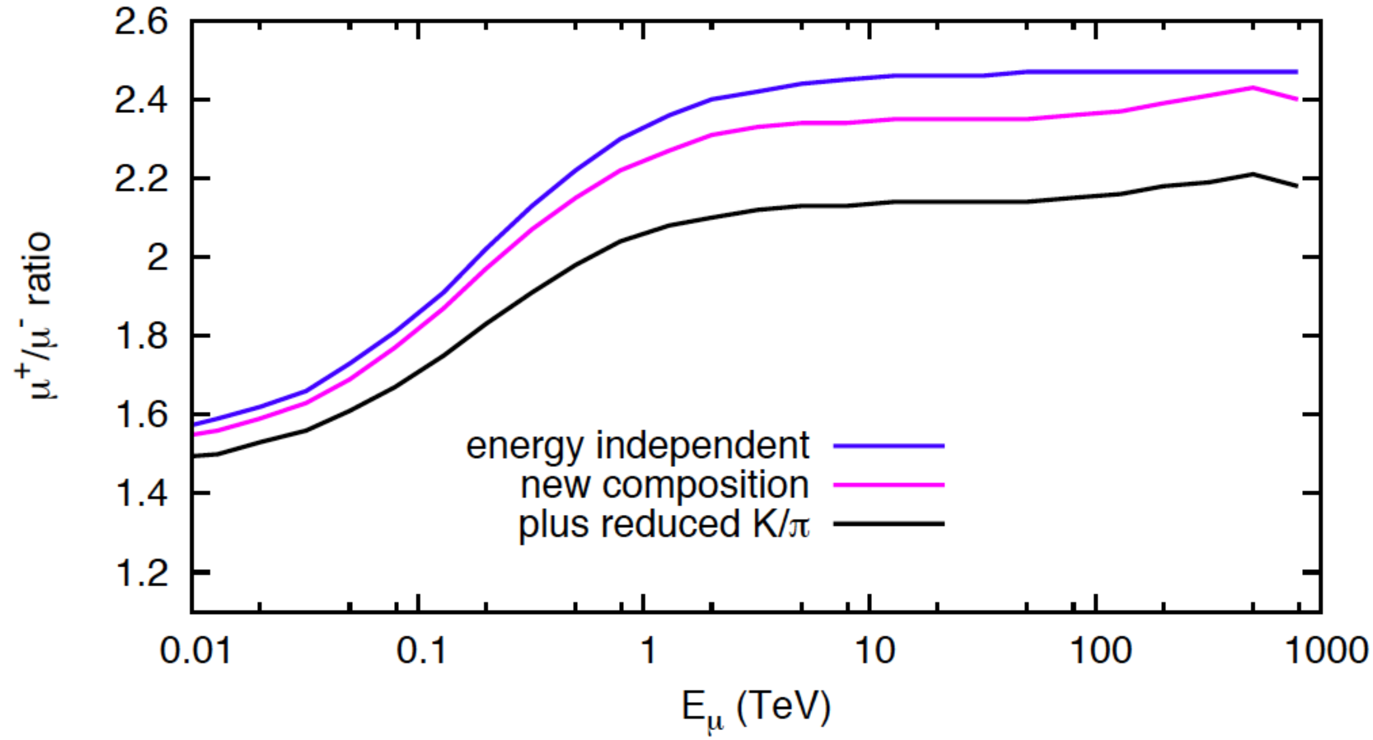
δ_0

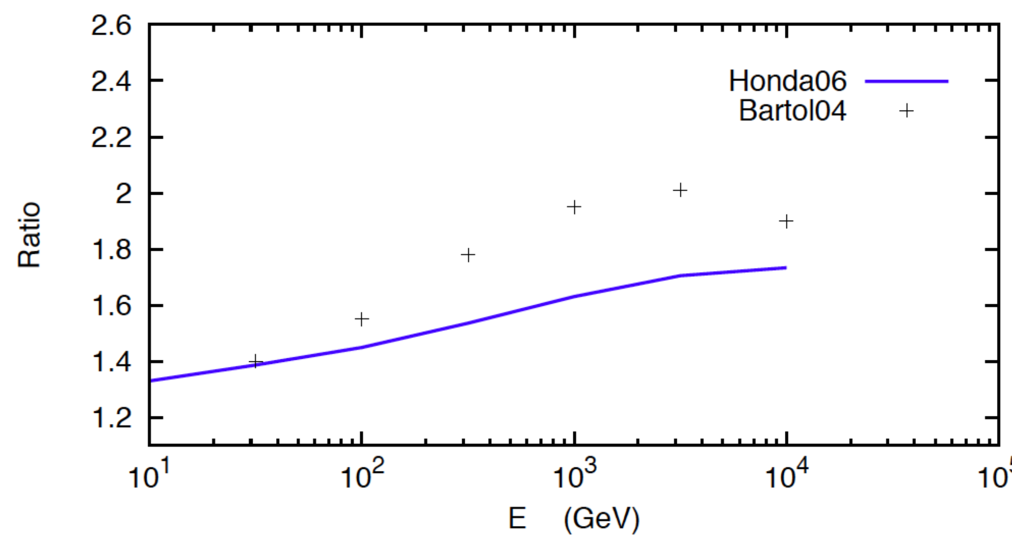


Fitting the μ^+/μ^- ratio



ν / anti-ν ratio





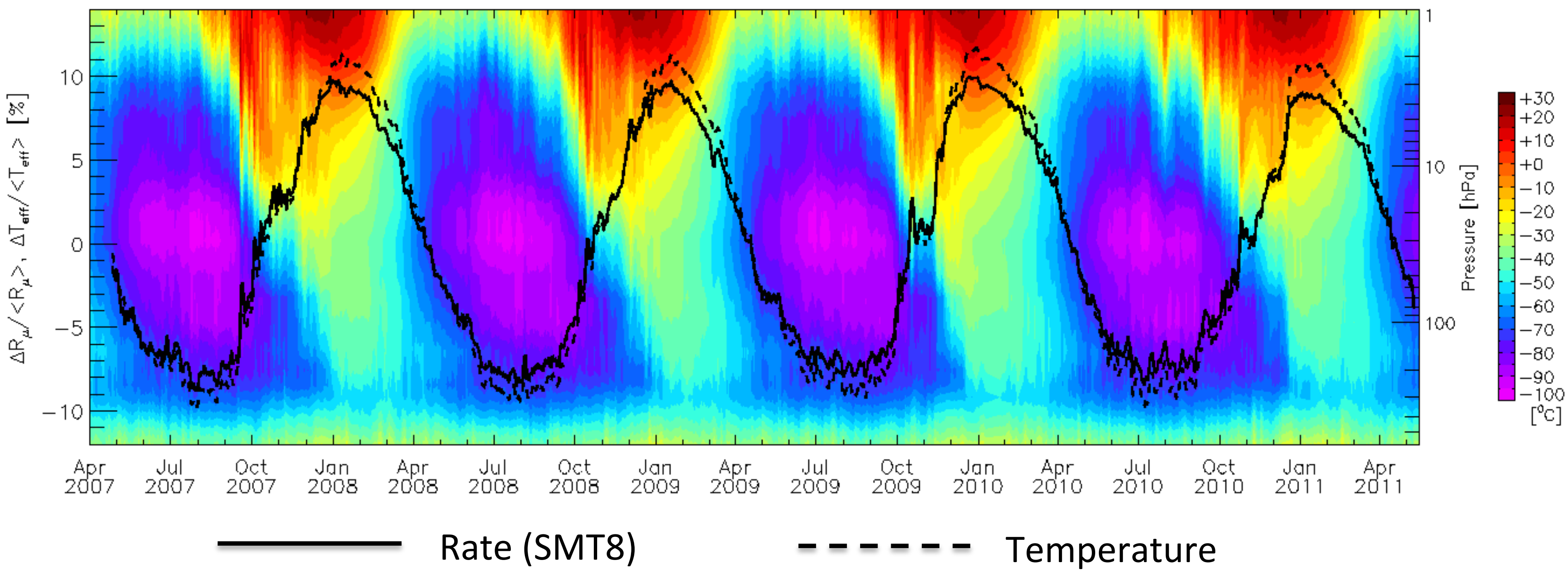
Seasonal variations of μ in IceCube and K/π ratio

Draft paper almost ready for distribution

Paolo Desiati, TG, Takao Kuwabara

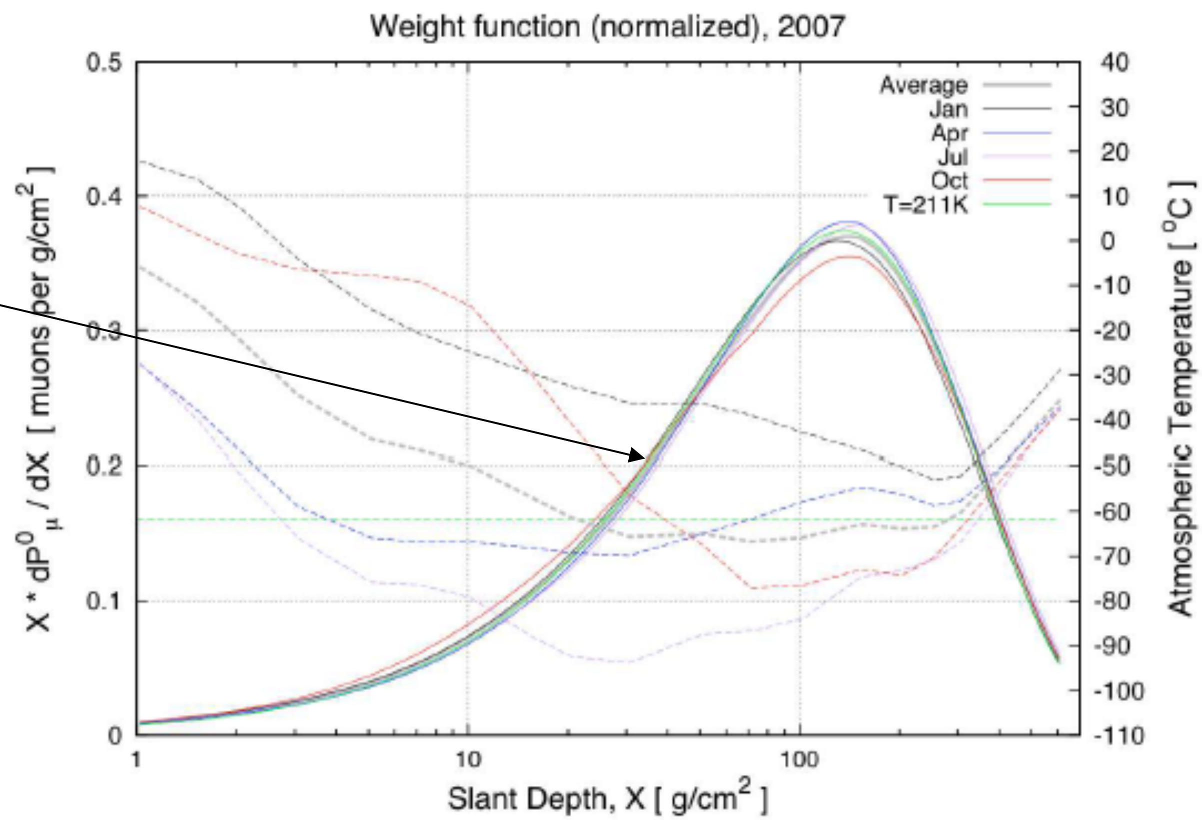
Correlation coefficient relates Rate & T

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



T_{eff}

Production profile of muons (and ν_μ)



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

Theoretical α depends on K/π

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

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

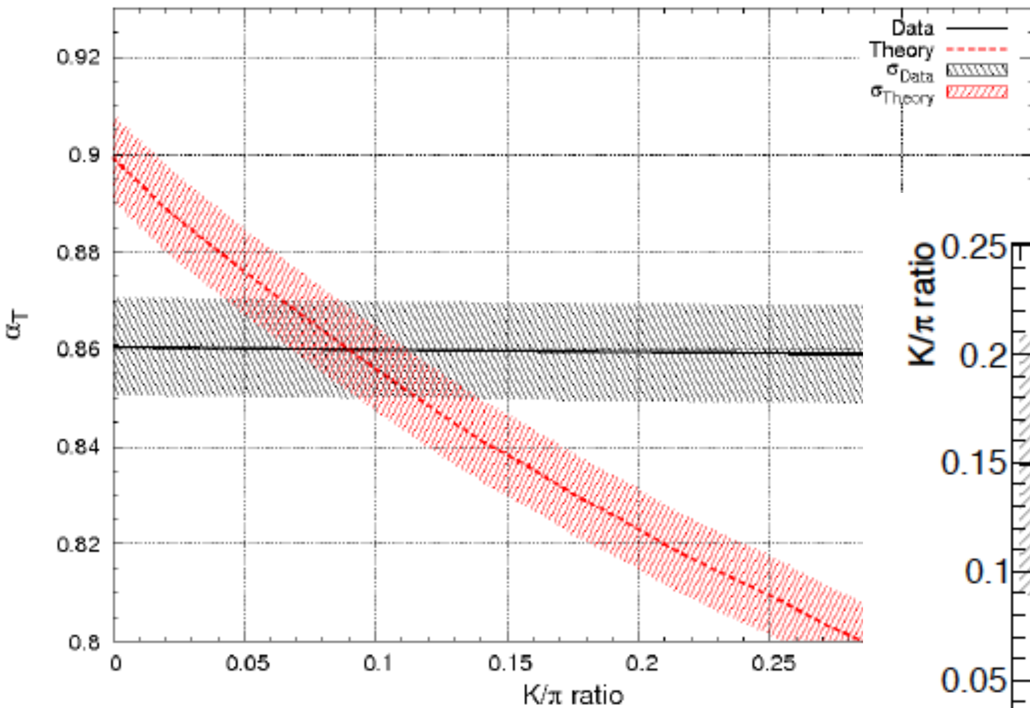
$$\alpha_\mu(E_\mu,\theta) = T \frac{1}{\phi_\mu(E_\mu,\theta)} \frac{\mathrm{d}\phi_\mu(E\mu,\theta)}{\mathrm{d}T}$$

See Desiati & TKG
PRL **105**, 121102 (2010)

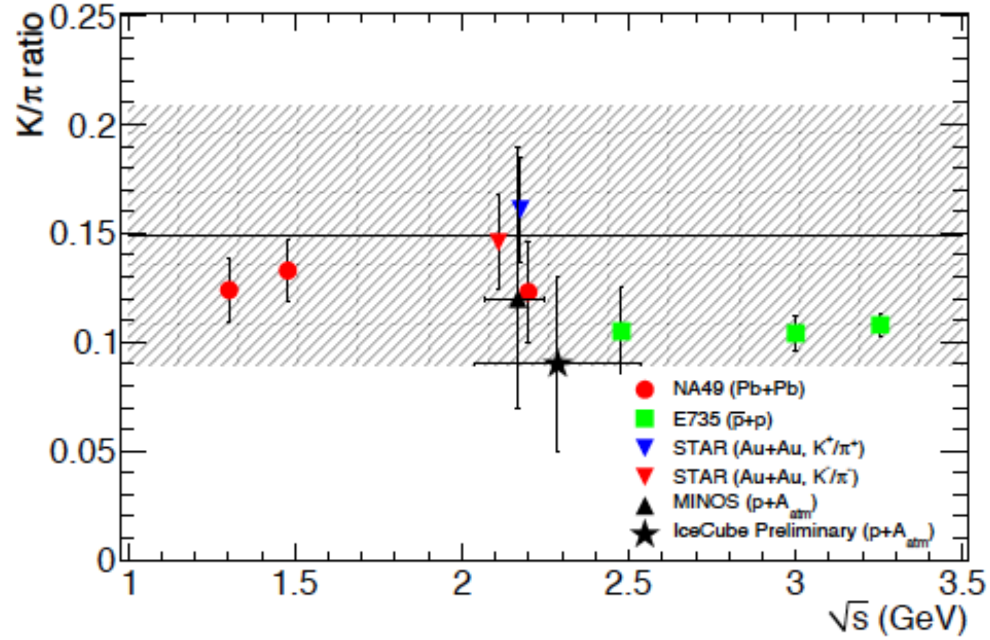
$$T\frac{\mathrm{d}}{\mathrm{d}T}\frac{A_{\pi\mu}}{1 + B_{\pi\mu}\cos\theta E_\mu/\epsilon_\pi} = \frac{A_{\pi\mu}B_{\pi\mu}\cos\theta E_\mu/\epsilon_\pi}{(1 + B_{\pi\mu}\cos\theta E_\mu/\epsilon_\pi)^2}$$

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

K/π ratio

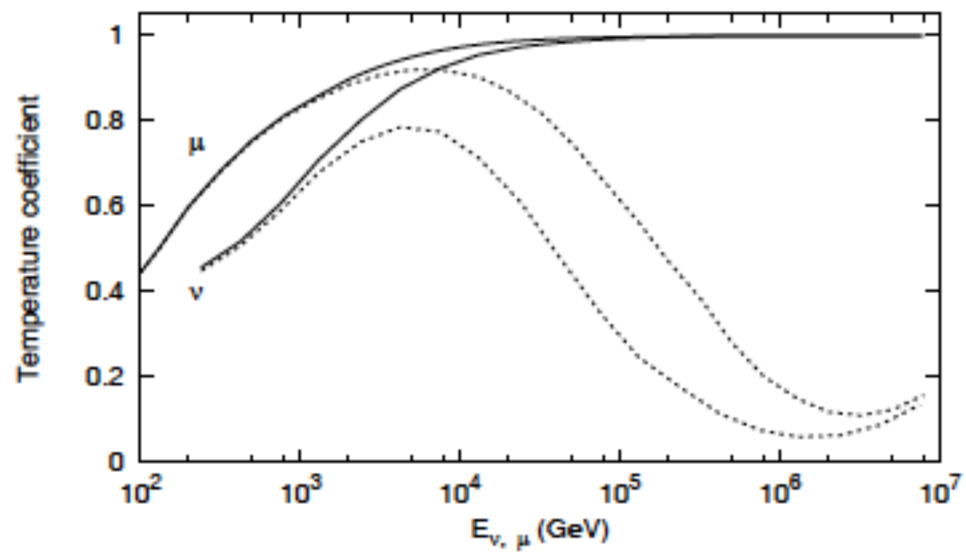


IceCube preliminary



For the future

- Measure muon energy spectrum to PeV
  - Patrick Berghaus is using μ-brems to get ϕ_μ
- Look for charm as temperature-independent component



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