Atmospheric lepton fluxes

Outline

- Introduction
  - Calculating the flux of atmospheric μ and ν
- Muon charge ratio, K/π ratio, $\nu / \bar{\nu}$ ratio
- Primary spectrum
- Atmospheric neutrinos to PeV
  - Must account for knee in cosmic-ray spectrum
  - Prompt neutrinos from decay of charmed hadrons
- Atmospheric muon veto
- Atmospheric ν backgrounds in IceCube

Cascade equation for hadrons

$$\frac{\mathrm{d}N_i(E_i,X)}{\mathrm{d}X} = -\frac{N_i(E_i,X)}{\lambda_i} - \frac{N_i(E_i,X)}{d_i}$$
$$+\Sigma_{j=i}^{J}\int_{E}^{\infty}\frac{F_{ji}(E_i,E_j)}{E_i}\,\frac{N_j(E_j,X)}{\lambda_j}\,\mathrm{d}E_j$$

Production spectrum of muons (same form for ν)

$$\mathcal{P}_\mu(E_\mu,X) = \frac{\epsilon_\pi}{X\cos\theta(1-r_\pi)}\int_{E_\mu}^{E_\mu/r_\pi}\frac{\Pi(E,X)}{E}\frac{\mathrm{d}E}{E}$$
$$+\frac{0.635\,\epsilon_K}{X\cos\theta(1-r_K)}\int_{E_\mu}^{E_\mu/r_K}\frac{K(E,X)}{E}\frac{\mathrm{d}E}{E}$$

1961

SOVIET PHYSICS JETP VOLUME 12, NUMBER 6 JUNE, 1961

ANGULAR DISTRIBUTIONS OF HIGH-ENERGY MUONS IN THE ATMOSPHERE A THEIR PRODUCTION MECHANISM

G. T. ZATSEPIN and V. A. KUZ'MIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 10, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **39**, 1677-1685 (December, 1960)

The kinetic equation for μ mesons in the atmosphere in which the decay and energy los are taken into account is solved. The angular distributions of $10^{11}-10^{14}$ ev μ mesons the atmosphere are computed for two possible production mechanisms: $\pi \rightarrow \mu + \nu$ and $K \rightarrow \mu + \nu$ decays. The results indicate that in the energy range of $10^{11}-5 \times 10^{12}$ ev the μ-meson angular distributions depend significantly on the mechanism of their production.

K

SOVIET PHYSICS JETP VOLUME 14, NUMBER 6 JUNE,

Z

NEUTRINO PRODUCTION IN THE ATMOSPHERE

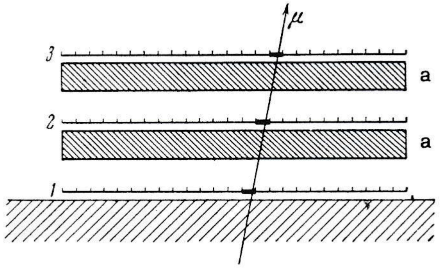
G. T. ZATSEPIN and V. A. KUZ'MIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 8, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1818-1827 (December, 1961)

The energy spectra and angular distribution of neutrinos produced in the atmosphere in the $\pi \rightarrow \mu + \nu$ and $\mu \rightarrow e + \nu + \bar{\nu}$ decays are calculated taking the μ-meson energy losses at neutrino energies $\varepsilon = 10^9-3 \times 10^{11}$ ev into account. It is shown that the neutrino flux from the $\mu \rightarrow e + \nu + \bar{\nu}$ decay is comparable with that from the $\pi \rightarrow \mu + \nu$ decay. μ-meson energy losses only weakly affect neutrino production. K mesons produce neutrinos more efficiently than do π mesons. An experimental arrangement for detecting high-energy cosmic ray neutrinos is proposed.



Scaling/power-law solutions for ν

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

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

ε_π = 115 GeV
ε_K = 850 GeV
$\varepsilon_{\mathrm{charm}}$ > 10 PeV

$$A_{i\nu} = \frac{Z_{Ni}\times BR_{i\nu}\times Z_{i\nu}}{1-Z_{NN}} \qquad Z_{pK^+} = \frac{1}{\sigma}\int x^\gamma \frac{\mathrm{d}\sigma(x)}{\mathrm{d}x}\mathrm{d}x$$

$$Z_{\pi\mu} = \frac{1-r_\pi^{\gamma+1}}{(\gamma+1)(1-r_\pi)} \text{ and } \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{1-r_\pi^{\gamma+2}}{(\gamma+2)(1-r_\pi)}$$

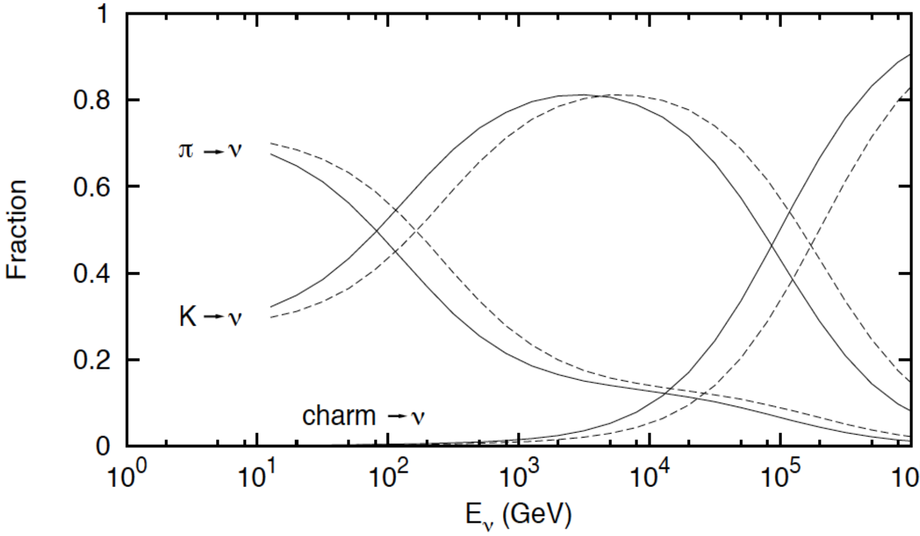
$$Z_{\pi\nu} = \frac{(1-r_\pi)^\gamma}{(\gamma+1)} \text{ and } \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{(1-r_\pi)^{(\gamma+1)}}{(\gamma+2)}$$

r_π = 0.573 but
r_K = 0.0458

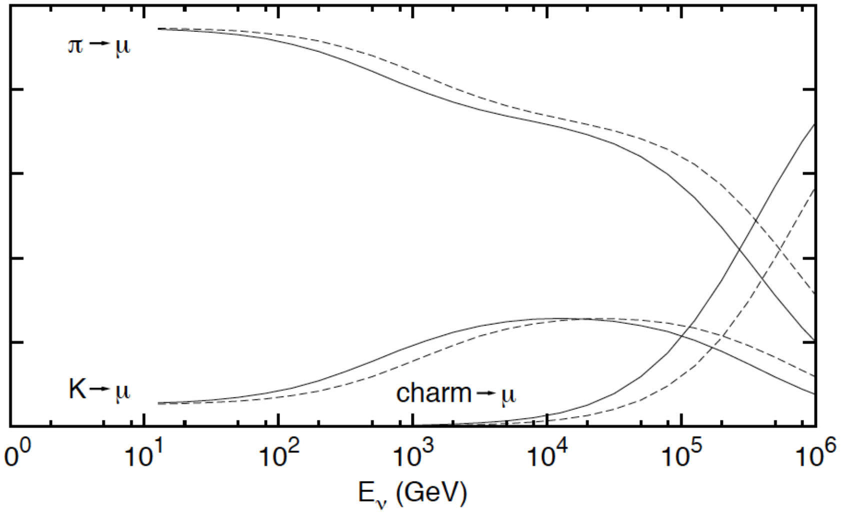
Importance of kaons for neutrinos

- Atmospheric ν_μ mainly from $K^{+/-}$
- TeV atmospheric ν_e from K_{e3} decays of K^0,$K^{+/-}$
- Associated production (p → $K^+\Lambda$) favors K^+
- Charm → μ, ν : small but potentially important at high E
  - contribution isotropic (compared to secant θ effect for >TeV leptons from decay of π and K)

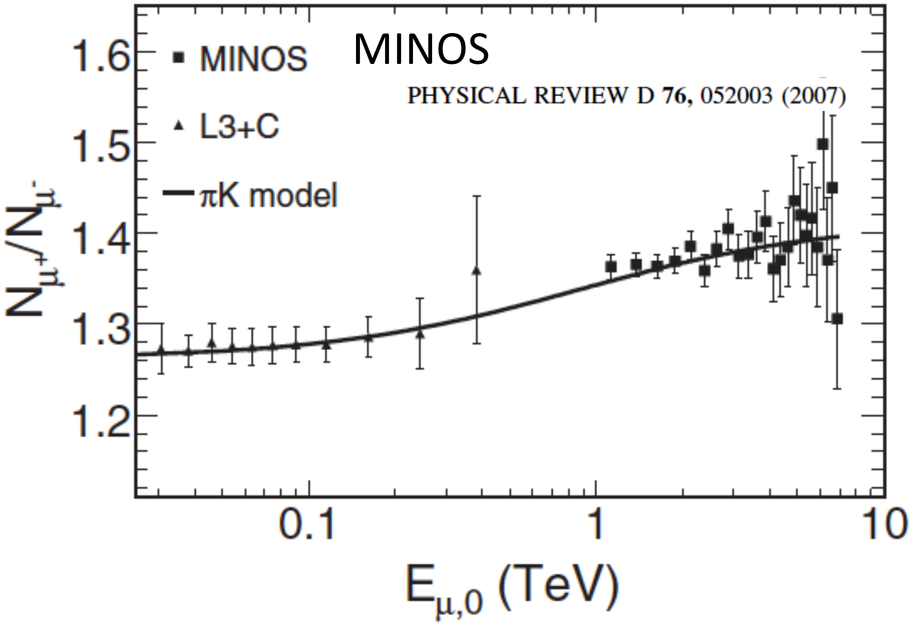
Neutrinos



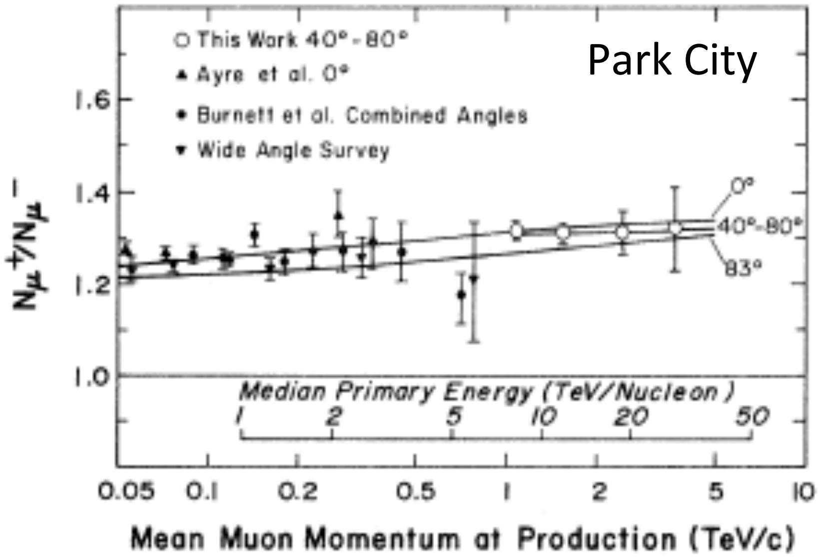
Muons



Muon charge ratio

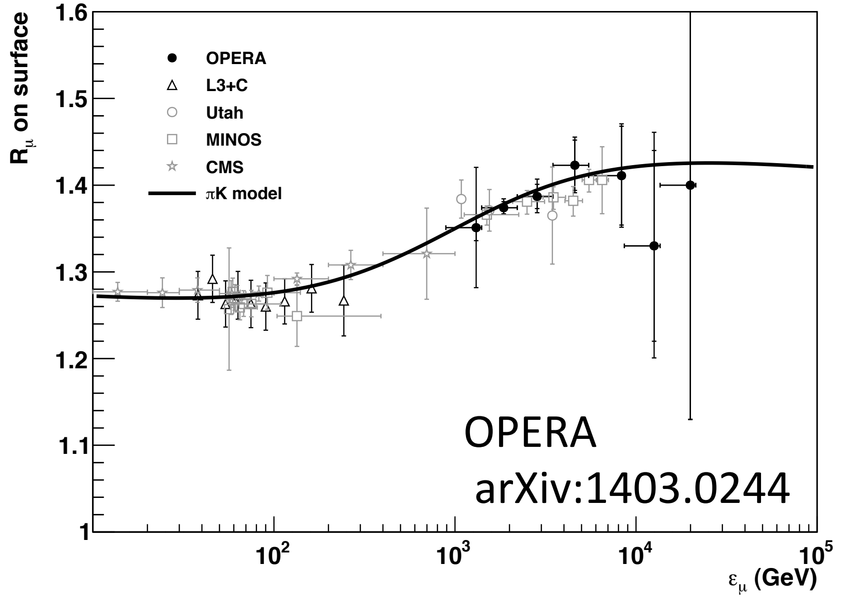

MINOS

PHYSICAL REVIEW D **76**, 052003 (2007)


Park City

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→ π^+ over p→ π^-
- Rise at TeV due to increased importance of Kaons (especially K^+)


OPERA

arXiv:1403.0244

Follow the charges

For the pion channel only (Frazer, 1972)

$$\frac{\mu^+}{\mu^-} = \frac{1 + \delta_0 \beta \alpha_\pi}{1 - \delta_0 \beta \alpha_\pi} = \frac{f_{\pi^+}}{1 - f_{\pi^+}}$$

$$\delta_0 = \frac{p(0) - n(0)}{p(0) + n(0)} \qquad \beta = \frac{1 - Z_{pp} - Z_{pn}}{1 - Zpp + Z_{pn}} \approx 0.909 \quad \alpha_\pi = \frac{Z_{p\pi^+} - Z_{p\pi^-}}{Z_{p\pi^+} + Z_{p\pi^-}} \approx 0.165$$

The result for pions uses the isospin relation $p \rightarrow n\,\pi^+ = n \rightarrow p\,\pi^-$

But $p \rightarrow n\,K^+ \neq n \rightarrow p\,K^-$ (for kaons an isospin analog is $p \rightarrow \Lambda\,K^+ = n \rightarrow \Lambda\,K^0$)

Muon charge ratio including kaons

$$\frac{\mu^+}{\mu^-} = \left[\frac{f_{\pi^+}}{1 + B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{\frac{1}{2}(1+\alpha_K\beta\delta_0)\,A_{K\mu}/A_{\pi\mu}}{1 + B^+_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right]$$
$$\times\left[\frac{(1-f_{\pi^+})}{1 + B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{(Z_{NK^-}/Z_{NK})\,A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right]^{-1}$$

where $\alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}}$ TG, Astropart. Phys. 35 (2012) 801

OPERA fit data as a function of cosθ and E with two free parameters.

They find $Z_{pK^+} = 0.0086 \pm 0.0004$ and $\delta_0 = 0.61$ at ~ 20 TeV/nucleon

(compared to 0.0079 and ~0.63 in Astropart. Phys. 35 (2012) 801)

Results for Z_{pK^+}

$$Z_{p\rightarrow K^+} = 0.0090$$

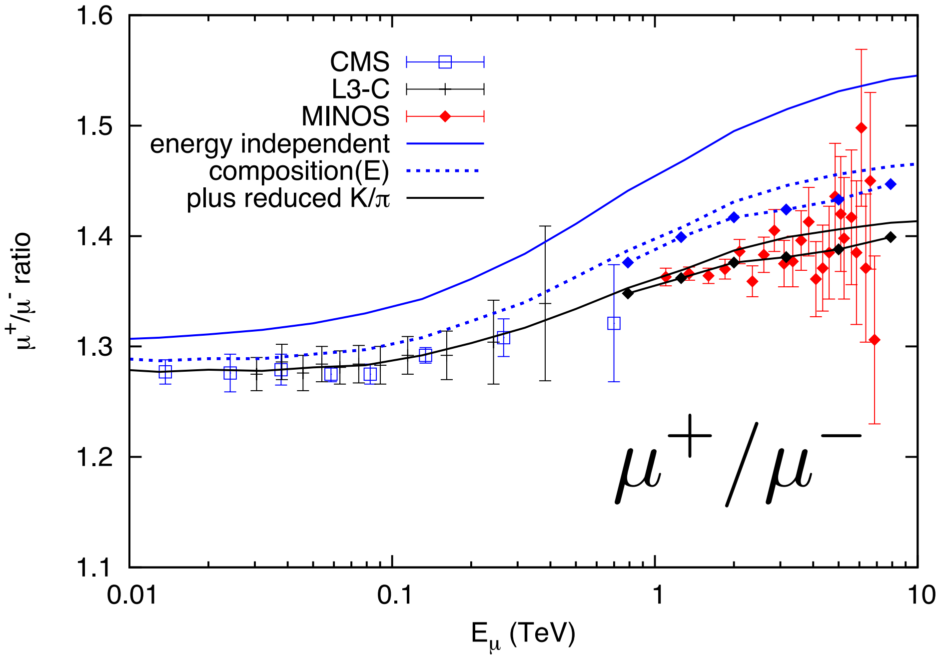
$$\rightarrow 0.0079$$

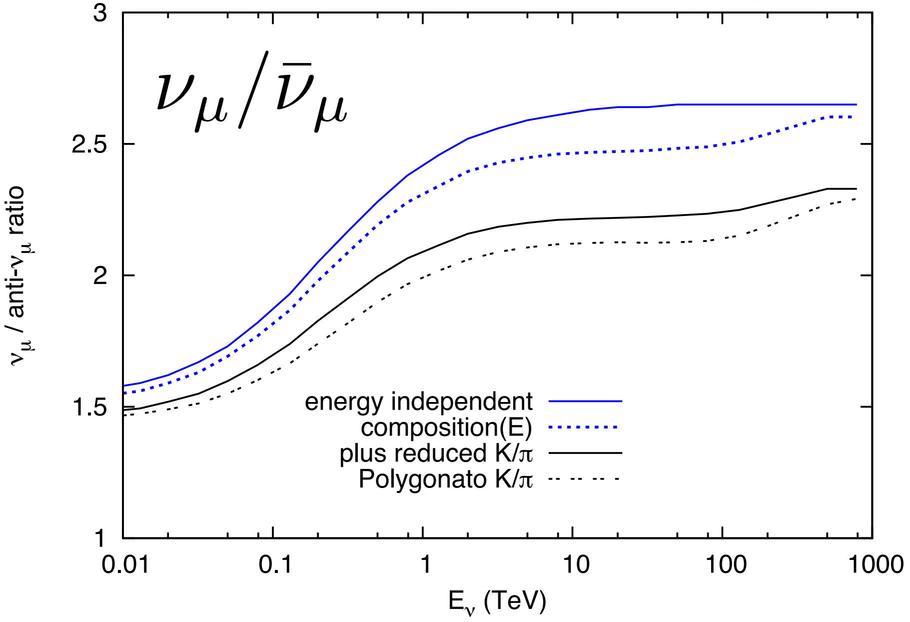
.0086

$$R_{K/\pi} \equiv \frac{Z_{p\rightarrow K^+} + Z_{p\rightarrow K^-}}{Z_{p\rightarrow \pi^+} + Z_{p\rightarrow \pi^-}} = 0.149$$

0.144

$$\rightarrow 0.135$$



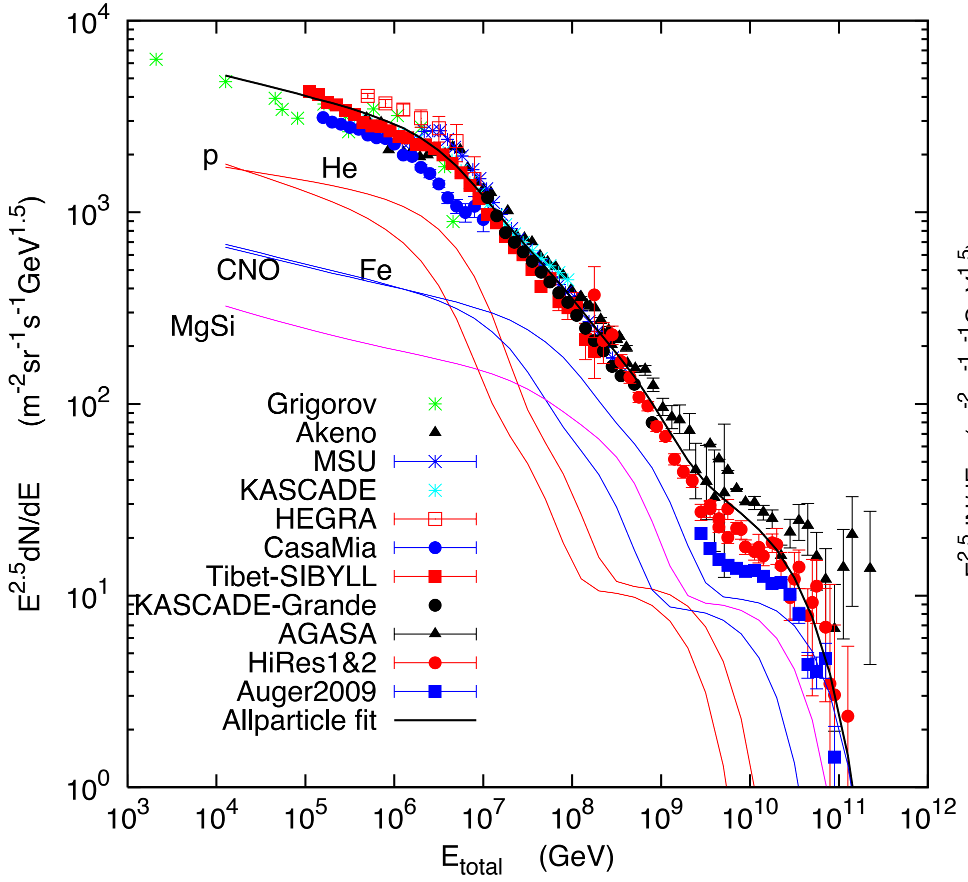


p → Λ K^+ is relatively more important for $\nu/\bar{\nu}$

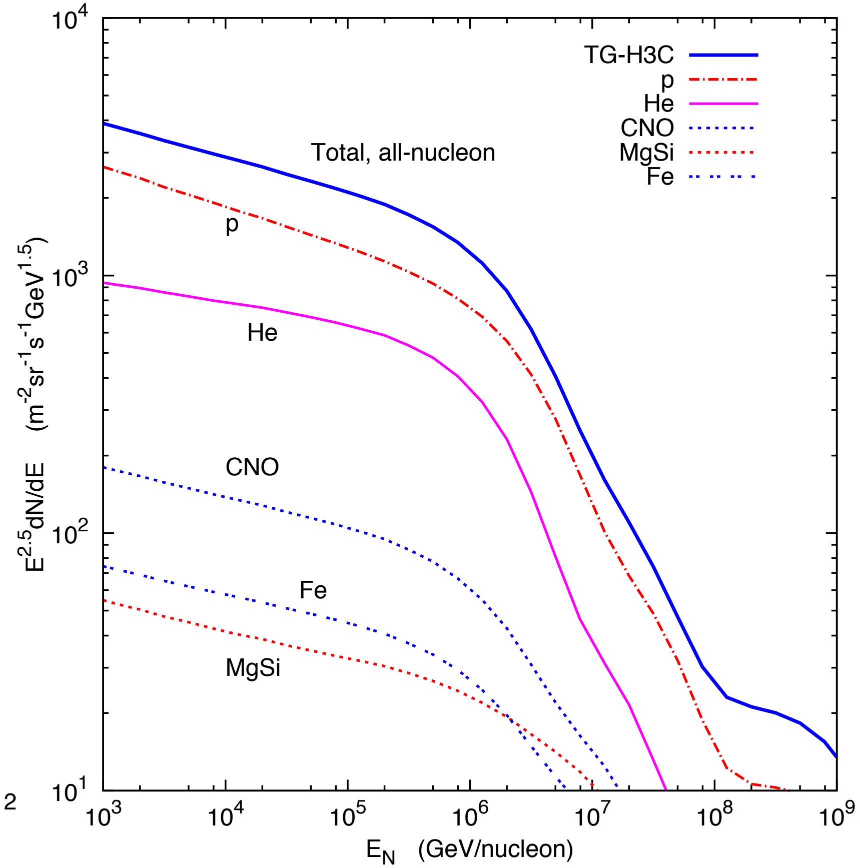
Primary spectrum

- 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 = Pc / Ze
  - 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: $\phi_{i,N}(E_N) \;=\; A \times \phi_i(A\, E_N)$
- Requirements
  - Consistency with air shower measurements of the all-particle spectrum
  - Anchor to composition from direct experiments below 100 TeV

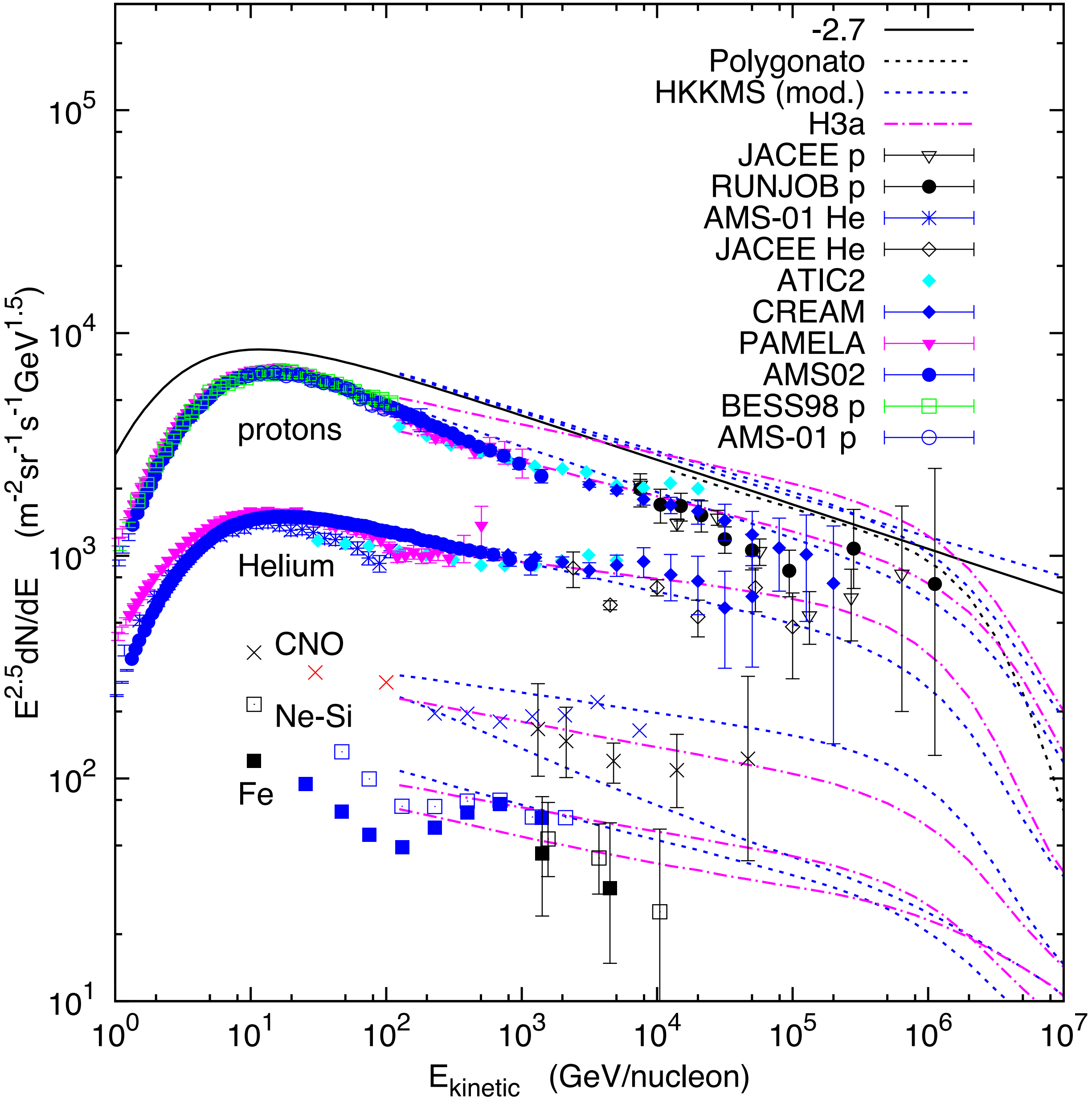
Spectrum of nucleons determines fluxes of atmospheric ν and μ



All-particle spectrum

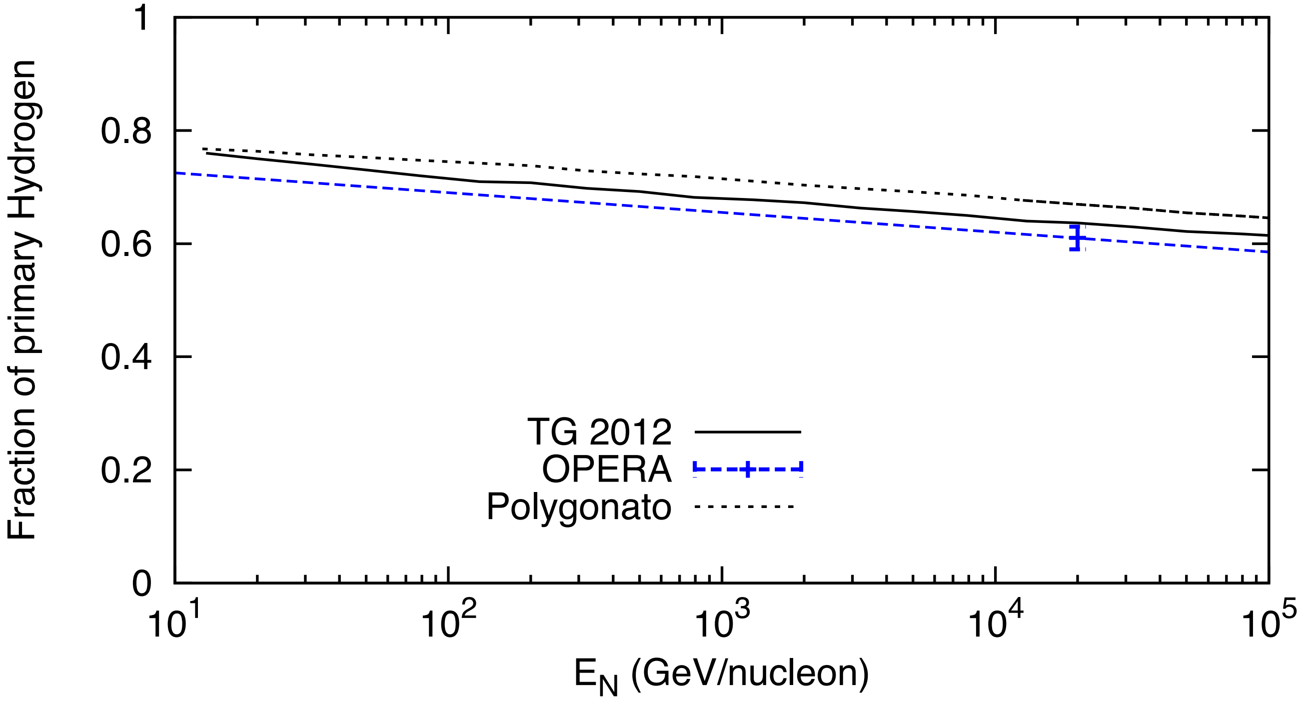


Spectrum of nucleons



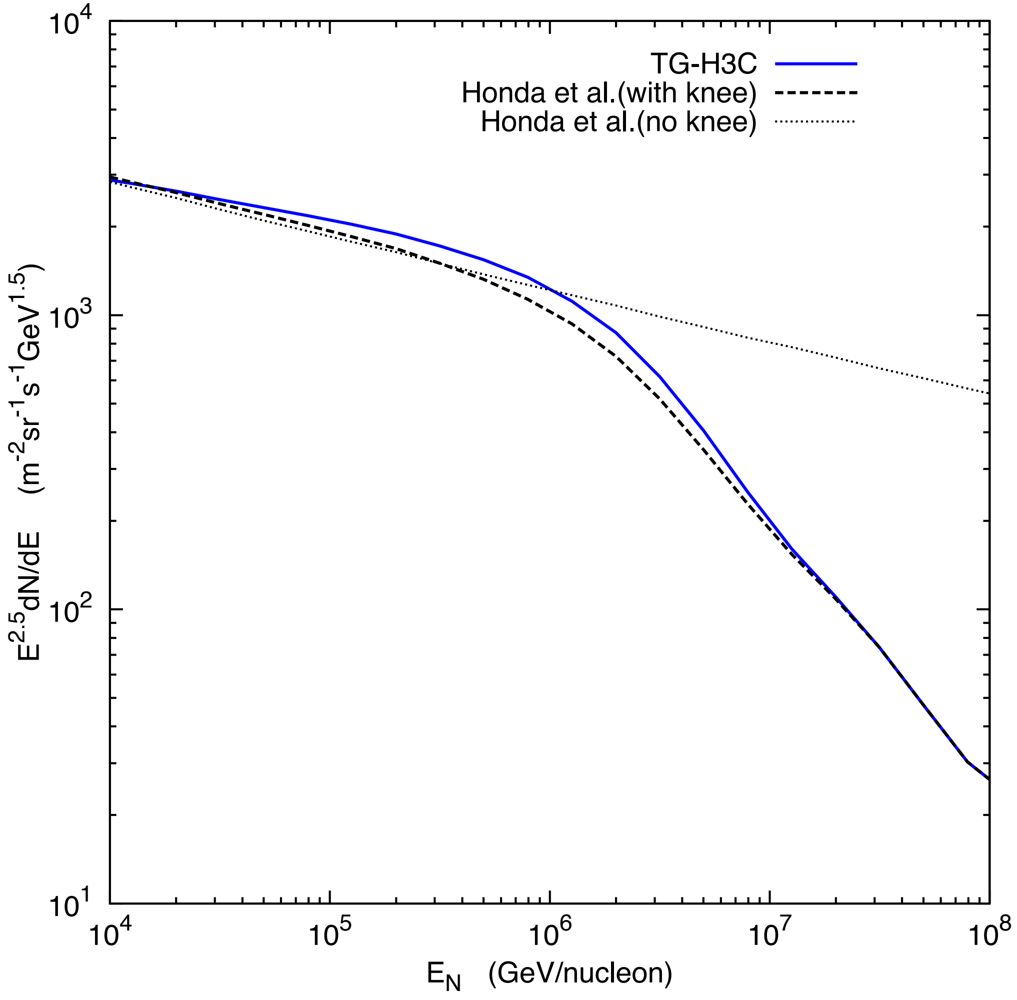
-2.7
Polygonato
HKKMS (mod.)
H3a
JACEE p
RUNJOB p
AMS-01 He
JACEE He
ATIC2
CREAM
PAMELA
AMS02
BESS98 p
AMS-01 p
protons
Helium
CNO
Ne-Si
Fe
$E^{2.5}dN/dE$ $(m^{-2}sr^{-1}s^{-1}GeV^{1.5})$
$E_{kinetic}$ (GeV/nucleon)
10^1
10^2
10^3
10^4
10^5
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

Proton excess in the Spectrum of primary nucleons



Decrease reflects increasing fraction of nuclei

Spectrum of nucleons



Challenge:

For the first time, we must account for the knee in the cosmic-ray spectrum to calculate atmospheric neutrinos

Also need to account for non-scaling behavior of meson production over wide energy range

How to account for the knee in $\phi_\nu(E_\nu)$

1. Calculate $\int_{E_\nu}^{\infty} \phi_n(E_0)\, Y(E_\nu, E_0)\, \mathrm{d}E_0$
    a. Use full Monte Carlo (problem with statistics)
    → b. Or use an approximation for the yield of neutrinos
2. Integrate the cascade equations
    a. Matrix method (see Anatoli Fedynitch's talk)
    → b. Or modify the scaling equations assuming changes in spectral index and scaling violations are smooth

$$Z_{i,j}(E) = \int_{E}^{\infty} \mathrm{d}E' \, \frac{\phi_N(E')}{\phi_N(E)} \, \frac{\mathrm{d}n_{i,j}(E', E)}{\mathrm{d}E}$$

Refs.: Thunman, Ingelman, Gondolo, Astropart. Phys. 5 (1996) 309.
Fedynitch, Becker Tjus, Desiati, PRD 86(2012) 114014
TG, arXiv:1303.1431

Details

$$Z_{ij}(\gamma) = \int_0^1 x^\gamma \frac{\mathrm{d}n_{ij}}{\mathrm{d}x}\,\mathrm{d}x \qquad \frac{\mathrm{d}n_{ij}}{\mathrm{d}x} = c_{ij}\frac{(1-x)^{p_{ij}}}{x}, \;\; x = \frac{E_j}{E_i}$$

Procedure:

1) start with a table of Z-factors as a function of E_{nucleon} from accelerator measurement and/or from an event generator
2) Find values of c and p for each channel by evaluating Z(1), Z(2)
3) Use simple forms for dn/dx to evaluate Z(E) for a non-power-law primary spectrum from

$$Z_{ij}(E) = \int_0^1 \frac{\mathrm{d}x}{x}\frac{\phi_N(E/x)}{\phi_N(E)}\frac{\mathrm{d}n_{ij}(E/x,E)}{\mathrm{d}x}$$

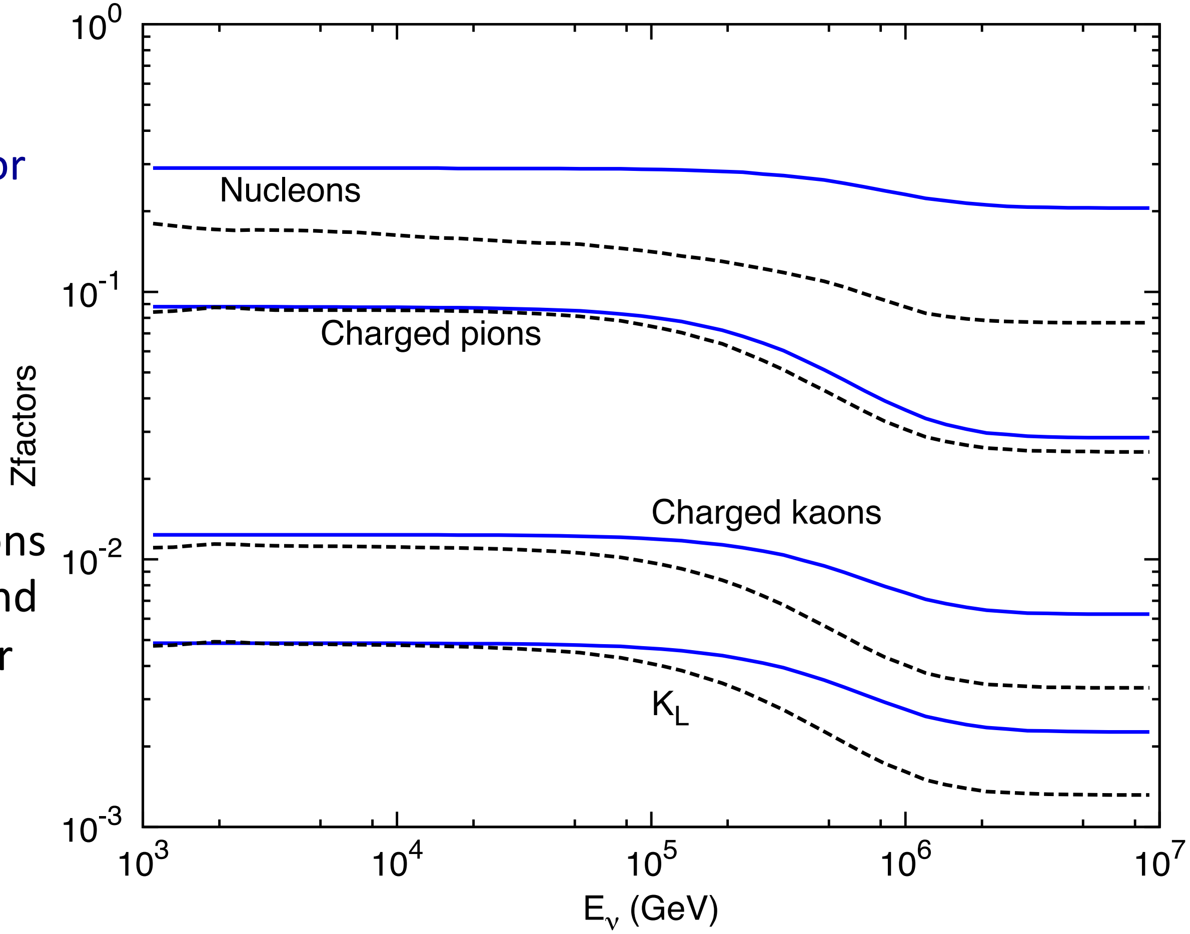
Interesting comparison is to Sinegovskaya & Sinegovsky – see poster at this meeting

Energy-dependent Z-factors

Acknowledgment:
thanks to M. Honda for providing extended table of Z-factors from PRD 75 (2007) 043006

Monte Carlo calculations of atmospheric ν extend only to 10 TeV (also for “Bartol” fluxes, 2004:
G. Barr et al. PRD 70, 023006

Z factors (solid: this calculation; dashed: extrapolation of Honda et al.)

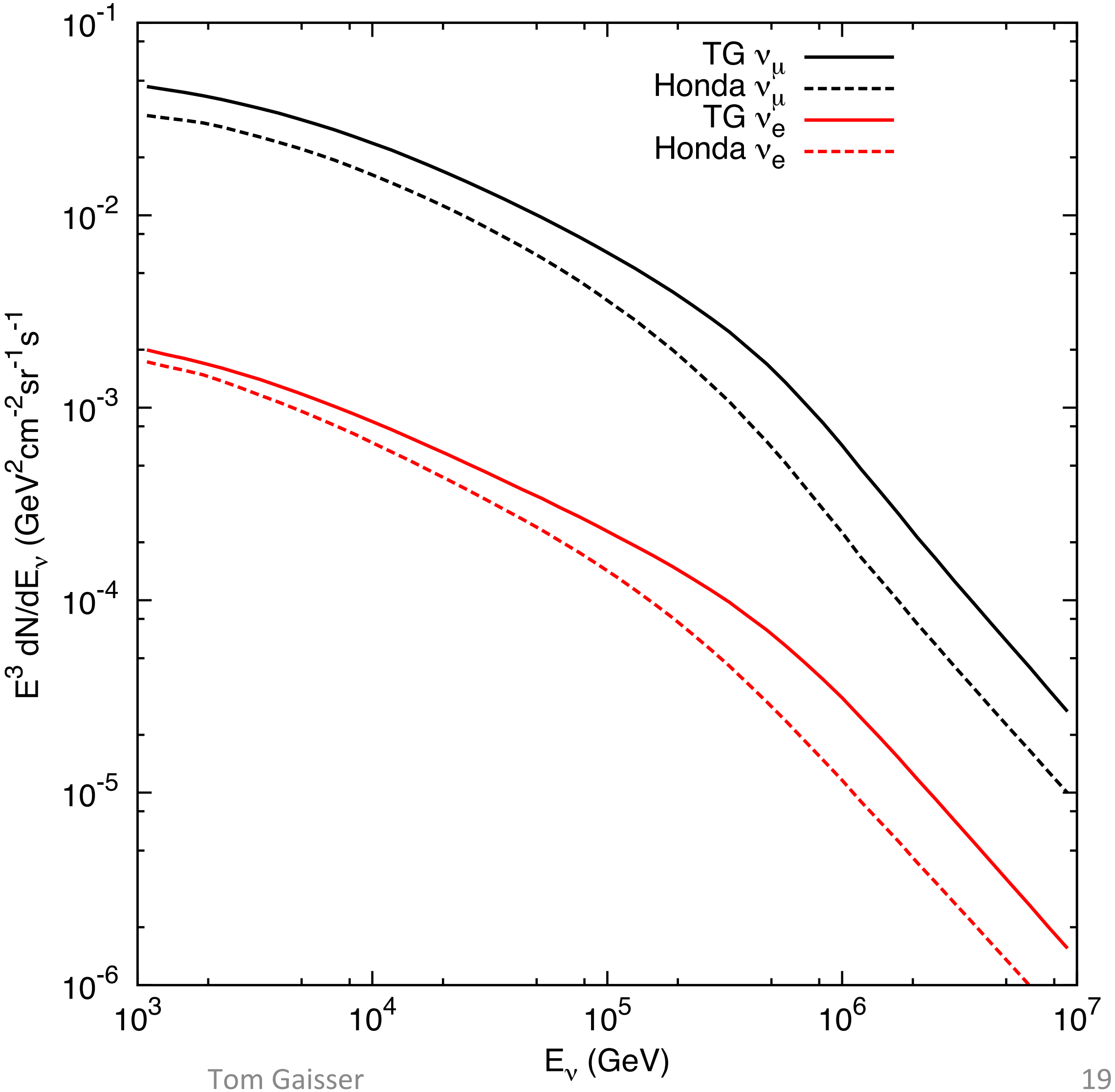


Compare with extrapolated Honda

Note: ν_e are from Ke3 decays, including $7 \cdot 10^{-4}$ K_S , which becomes important for E > $\varepsilon_{critical}$ ≈ 120 TeV.

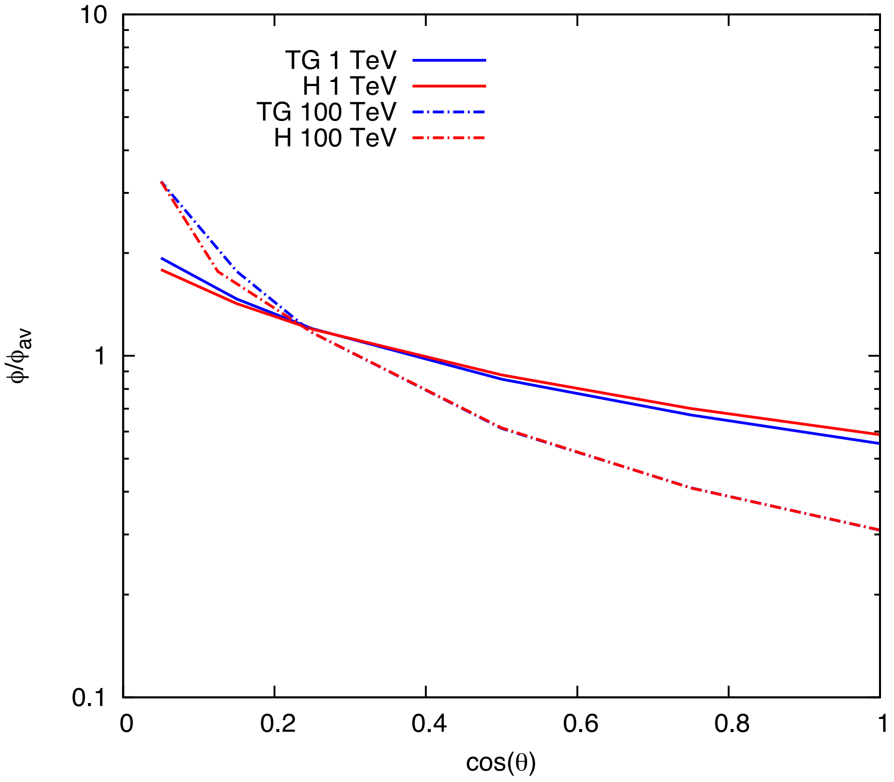
For E_ν > 120 TeV, the contribution from neutral kaons becomes greater than that from $K^\pm$ because of the extra neutral kaon channel.

At this energy the conventional atmospheric ν_e rate is too low to be a significant background.

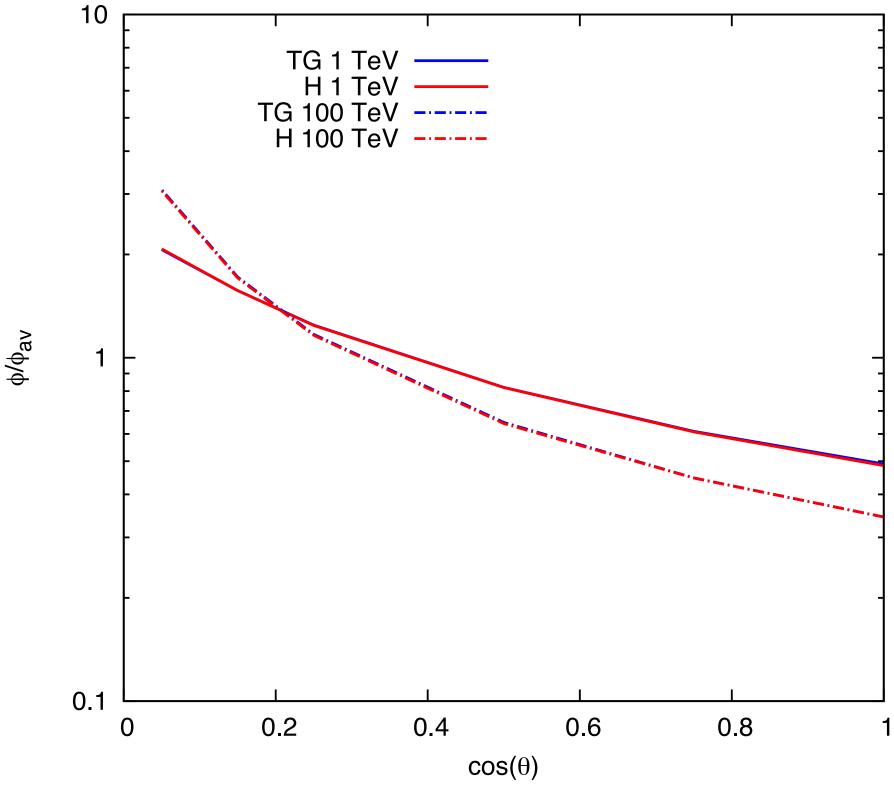


Angular distributions

angular-numu

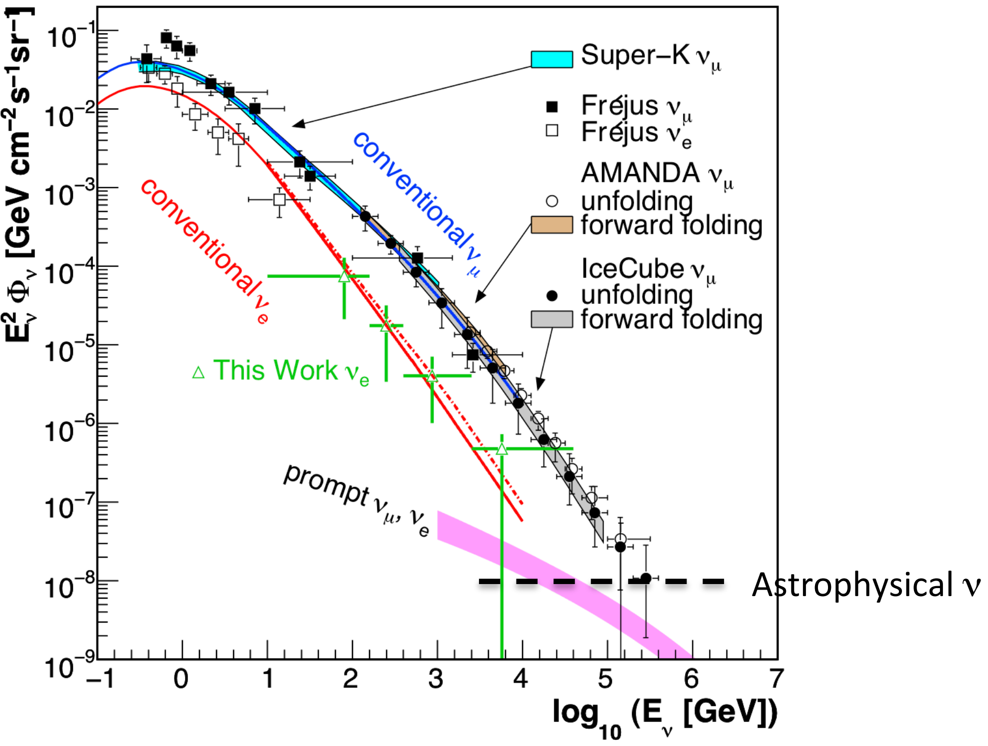


angular-nue

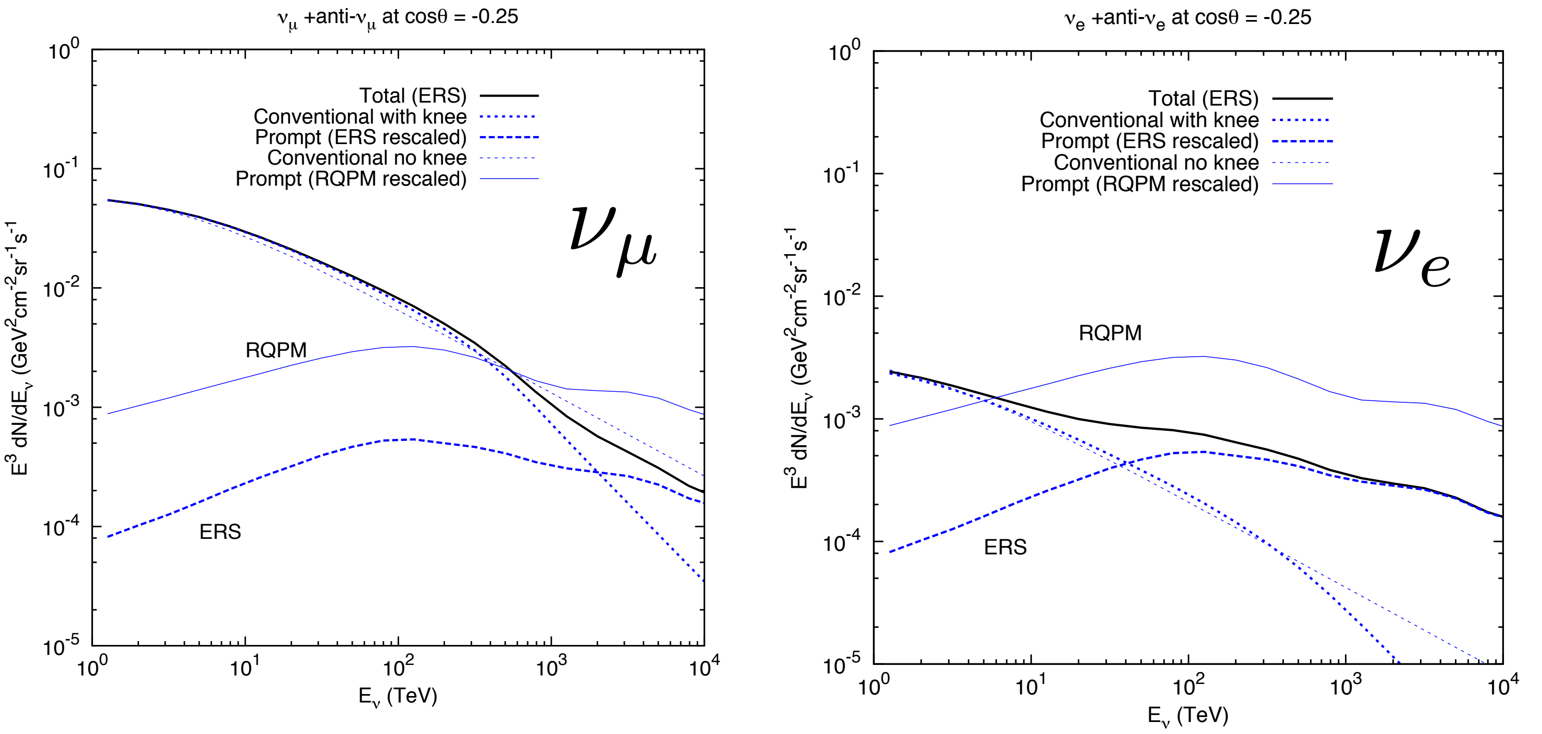


Importance of charm

- Critical energy $\varepsilon_{\mathrm{charm}} \approx 10^7$ GeV
- So spectrum of ν from charm follows primary spectrum
- Conventional ν one power steeper
- Crossover of prompt/conventional competes with the transition to astrophysical neutrinos
- Is there a charm analog of $p \rightarrow K^+\Lambda$?



Compare ν_μ and ν_e fluxes

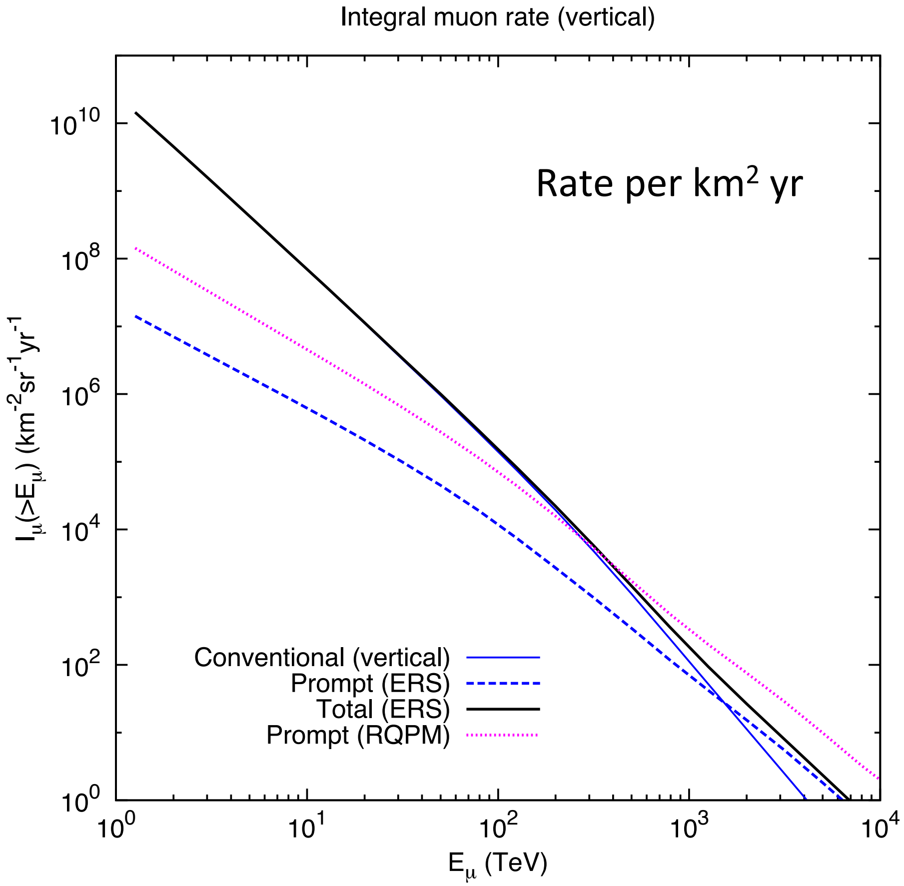


- Prompt crossover occurs at lower energy for ν_e
- Prompt component should be easier to see in cascade events

Compare two charm models:
QCD model: ERS = Enberg, Reno, Sarcevic, PRD 78 (2008) 043005
RQPM includes intrinsic charm: Bugaev et al., N.C. C12 (1989) 41, PRD 58 (1998) 054001

Can we identify prompt component with atmospheric muons?

- Advantages:
    - No astro component
    - High rate
    - Angular dependence
        - Isotropic for prompt
        - sec(θ) for conventional
    - Seasonal variation*
        - Strong for conventional
        - Absent for prompt
- Problems in practice
    - Crossover at high energy
    - Energy resolution



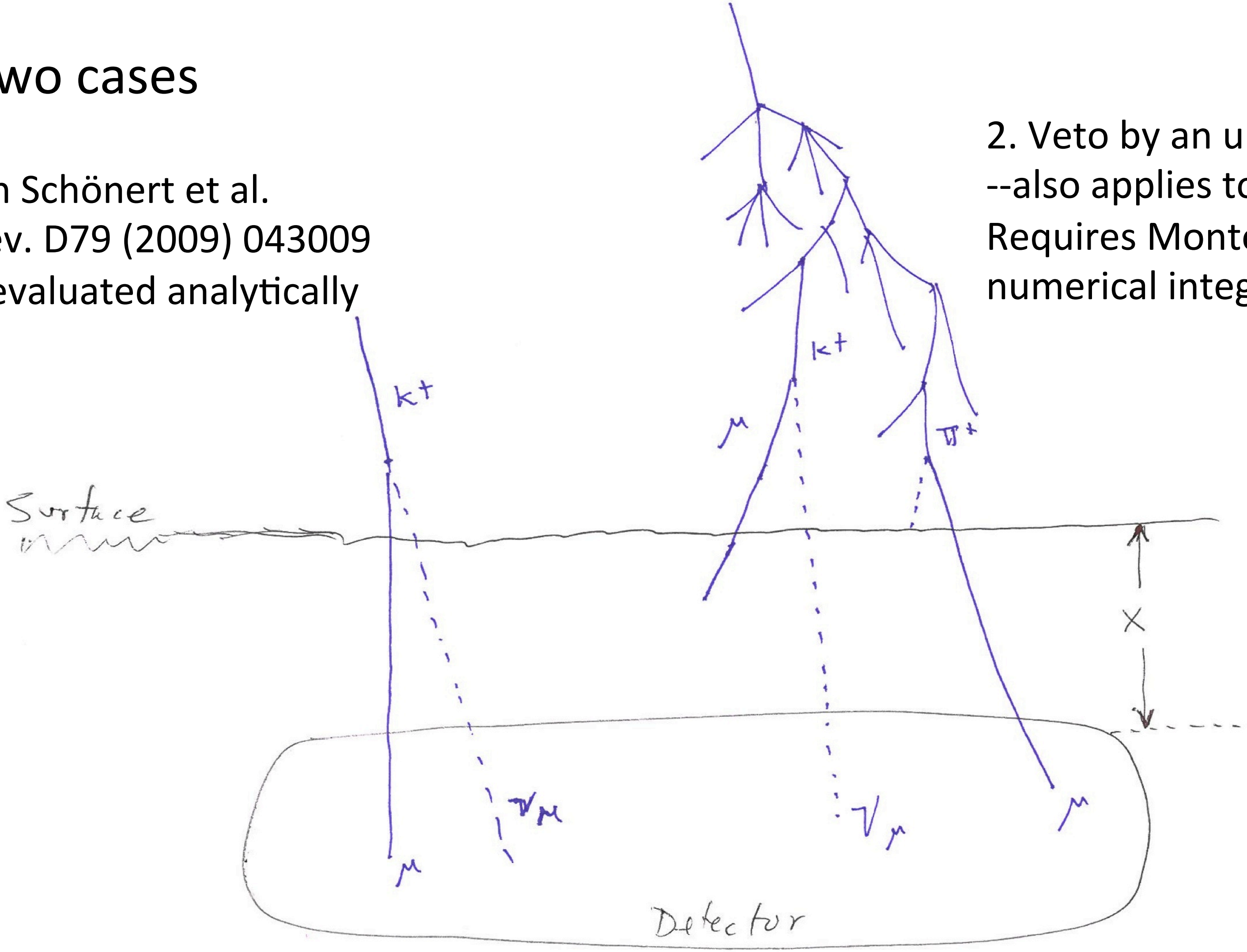
*Paolo Desiati's talk this afternoon

Atmospheric neutrino self veto

Two cases

1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

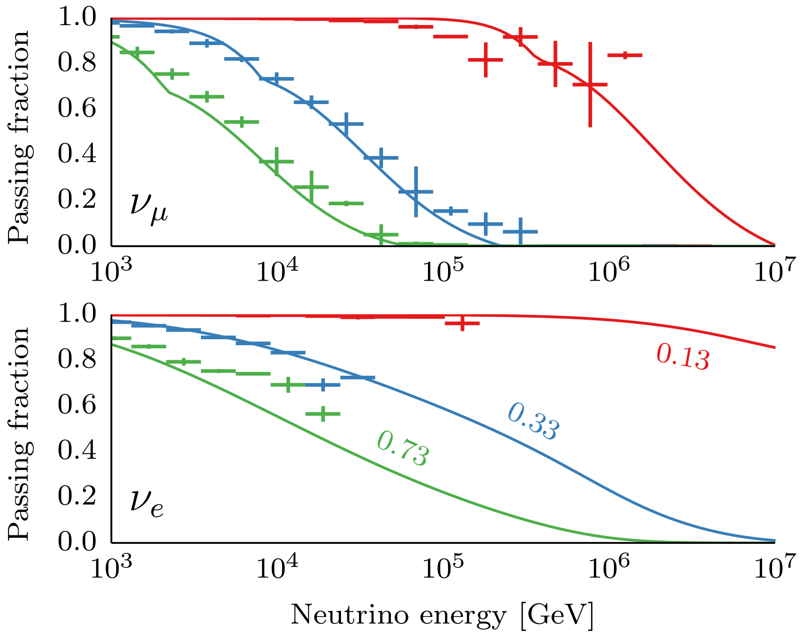
2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or numerical integration



Generalized ν self-veto

$$P_\nu(E_\nu,\theta) = \frac{\int \mathrm{d}E_N \phi_N(E_N) Y_\nu(E_\nu, E_N, \theta) \exp^{-N_\mu(E_N, E_{\mu,\min}(\theta))}}{\phi_\nu(E_\nu,\theta)}$$

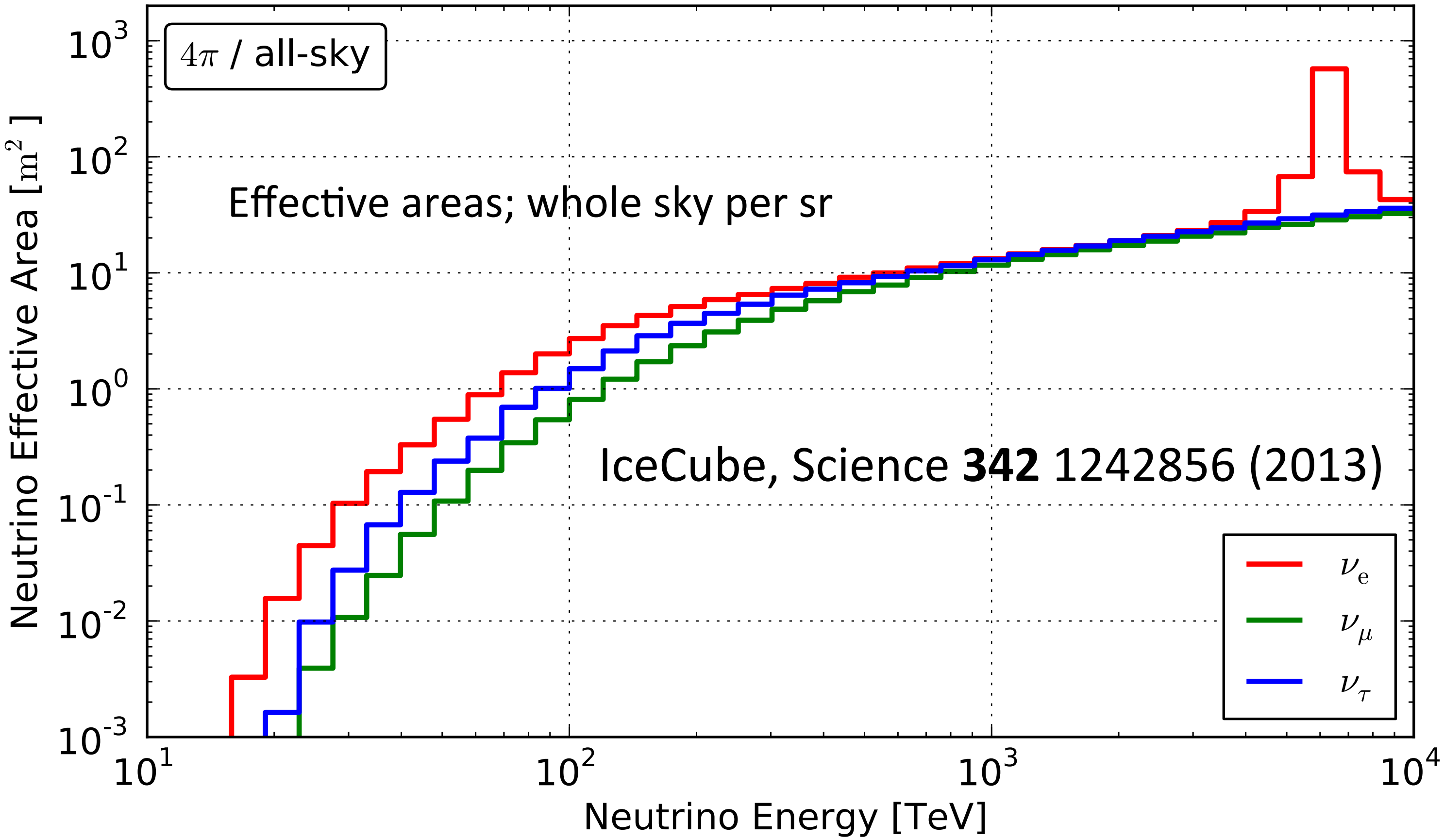
P = Passing fraction



- New parameterizations of yields of ν_μ, ν_e, and μ
- $E_{\mu,\min}(\theta)$ = energy for μ at θ to reach depth of detector
- Compare to full MC

TG, Jero, Karle & van Santen, arXiv:1405.0525

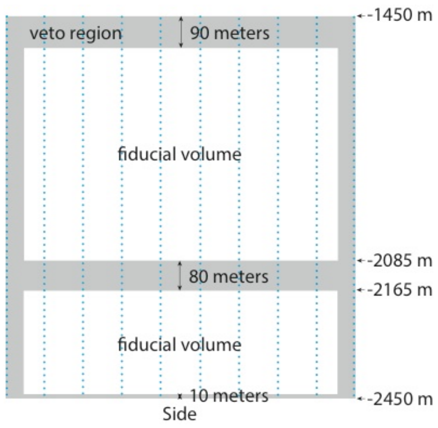
Fold fluxes with IceCube A_{eff} to get rates

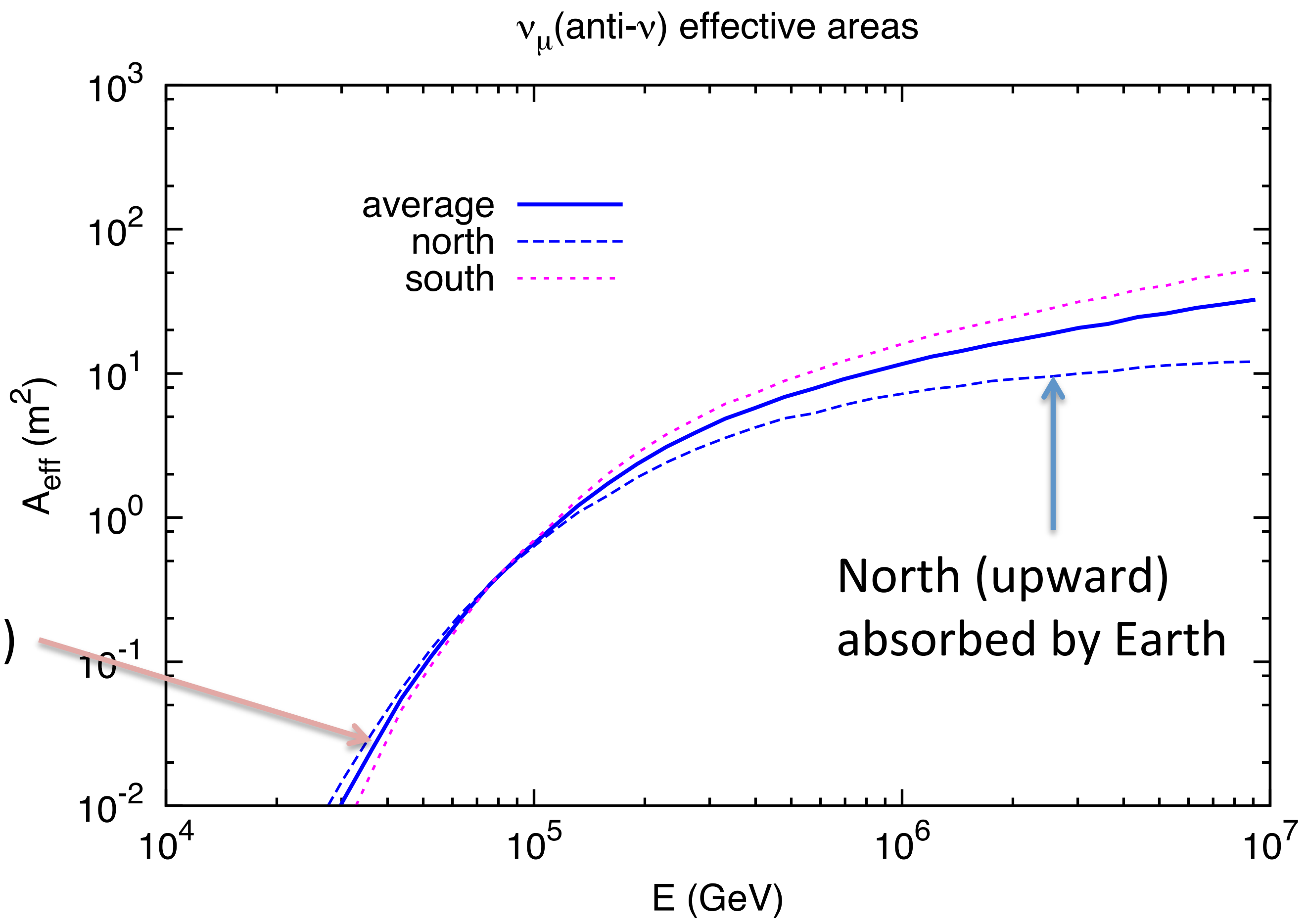


Visible energy threshold suppresses ν_τ and ν_μ relative to ν_e

IceCube ν_μ effective areas

separated by hemisphere





Veto tighter for South (downward) than for North

North (upward) absorbed by Earth

Application to IceCube

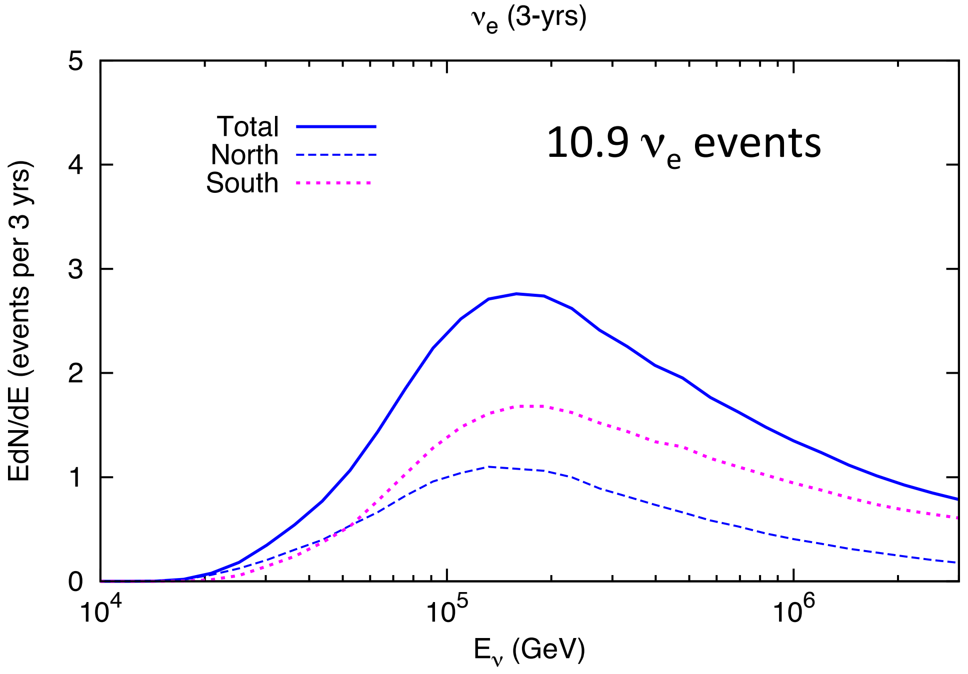
- IceCube 3 yr analysis suggests two fits for astrophysical component up to 3 PeV:

$$E_\nu^2\,\phi_\nu = 0.95\times10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 sr\,s}}\ \text{per flavor}$$

$$E_\nu^2\,\phi_\nu = 1.5\times10^{-8}\left(\frac{E}{100\mathrm{TeV}}\right)^{-0.3}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 sr\,s}}\ \text{per flavor}$$

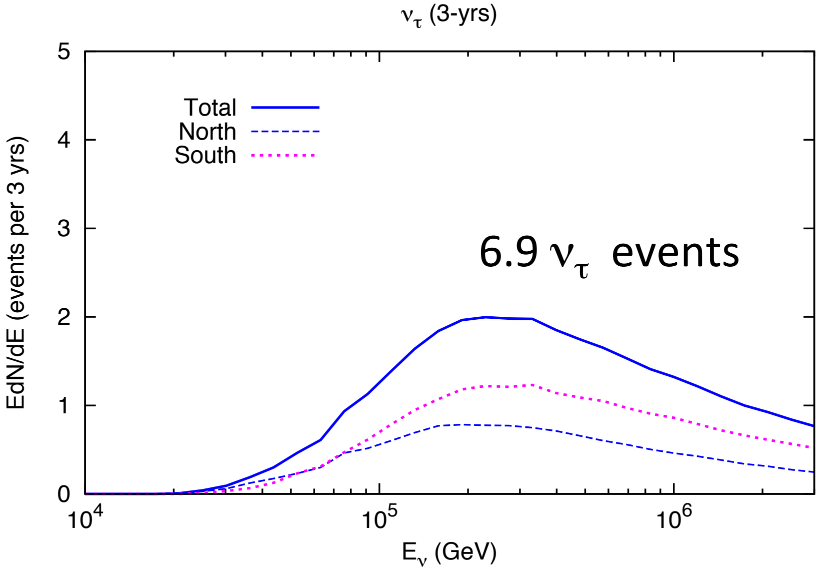
Astrophysical events for $E^{-2.3}$ fit

(Convolve astro spectrum with Aeff)

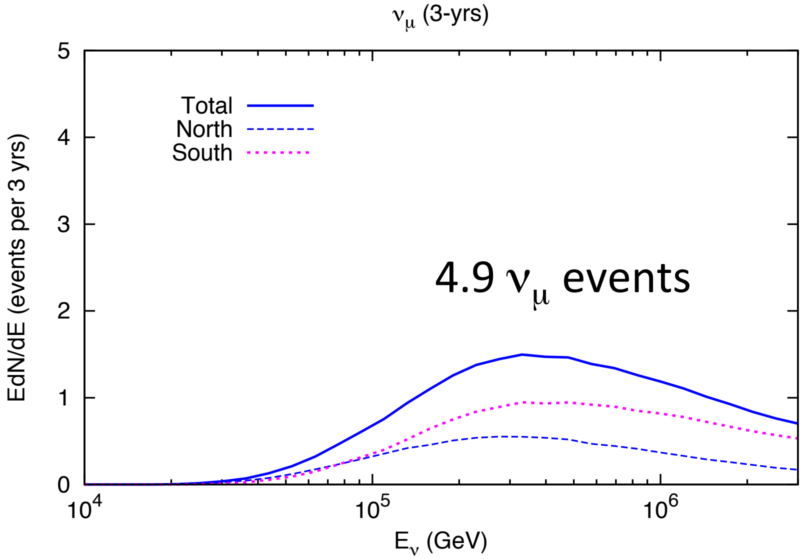


10.9 ν_e events

Note: Plots are vs ν energy (not E_{vis}) assuming $\phi_\nu \sim (E_\nu)^{-2}$

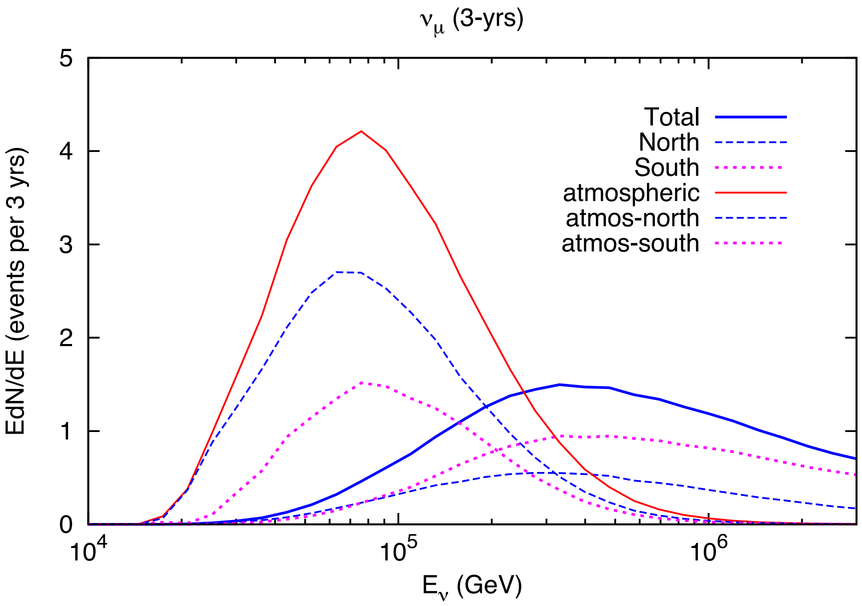


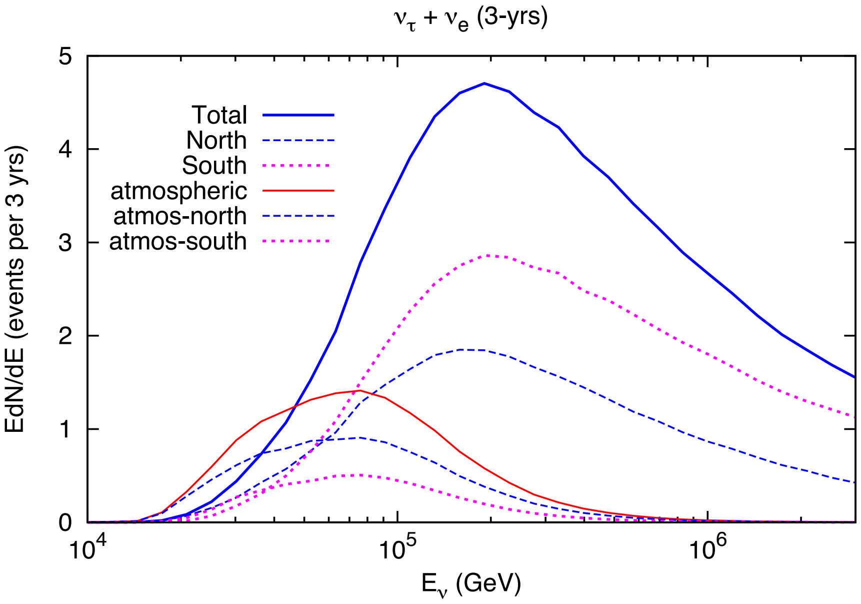
6.9 ν_τ events



4.9 ν_μ events

Signal/background





Note: plots are vs true neutrino energy, not $E_{visible}$

The distortion is biggest for ν_μ

37 events assuming $E^{-2.3}$ spectrum

TABLE III. Accounting for thirty-seven events ($E^{-2.3}$ spectrum)

	South	(before selfveto)	North	Total
Astro ν_e	6.94	N/A	3.94	10.88
Astro ν_τ	4.13	N/A	2.80	6.93
Astro ν_μ	3.04	N/A	1.83	4.87
Total Astro	14.1	N/A	8.6	22.7
Conventional ν_e	0.53	(0.69)	0.68	1.21
Conventional ν_μ	2.53	(4.58)	4.62	7.15
Charm (ERS) ν_e	0.36	(1.40)	1.12	1.48
Charm (ERS) ν_μ	0.10	(0.46)	0.37	0.47
Total atmospheric	3.52	(7.013)	6.79	10.3
Total neutrinos	17.6	(21.2)	15.4	33
Atmospheric μ (by subtraction)	≈ 4	N/A	0	≈ 4

	Cascades	Tracks
	18	5
	4	6
		4?
	22	15
Data:	28	9

Rates of atmospheric backgrounds

- Largest number is from interactions of ν_μ
  - These include neutral current events
- Charm contributions are model dependent
  - Here assume model of Enberg et al.
  - SELEX suggests some intrinsic charm
    - **Phys.Lett. B528 (2002) 49-57**
- Tension between expected flavor ratio and observed cascade/track ratio in IceCube
    - Mena, Palomares-Ruiz & Vincent, arXiv:1404.0017
    - Discrepancy is in low energy region with highly uncertain atmospheric muon background and rapidly changing Aeff(ν_μ)
    - Extending analysis to lower energy shows consistency with expected flavor ratios – see J. van Santen, previous talk

Summary comments

- Analytic/numerical evaluation of ν fluxes
  - Account for non-scaling, e.g. knee of spectrum
- Kaon channel dominates atmospheric ν
  - Increase of μ^+/μ^- sets level of kaon production
- Level of charm production is still uncertain
  - Selex expt suggests some intrinsic charm
  - Hidden in IceCube ν by astrophysical component
  - Sibyll with charm – Felix Riehn's talk this afternoon
- ν self-veto reduces downward background
  - Cascade/track ratio depends on astro spectrum and on conversion from flavor ratio