Atmospheric Neutrinos

Emphasis on TeV and higher

Thanks for collaboration with Hans Dembinski, Anatoli Fedynitch, Felix Riehn, Ralph Engel, Todor Stanev

Outline

- Hadron production:
  - Accelerators: fixed beam energy
  - Cosmic-rays: integrate beam energy in cascade
- Phenomenology of atmospheric neutrinos
  - Importance of kaons for $E_\nu \geq$ TeV
  - Angular distributions
  - Neutrino/anti-neutrino ratio
  - An example from IceCube

Hadron production spectrum at depth X in the atmosphere

Schematic equation:

$$\frac{\mathrm{d}N_h(E_h,X)}{\mathrm{d}X} = -\frac{N_h(E_h,X)}{\lambda_h} + \int_{E_h}^{\infty} \frac{\mathrm{d}n_h(E_h,E_{\mathrm{beam}})}{\mathrm{d}E_h} \frac{\phi(E_{\mathrm{beam}},X)}{\lambda(E_{\mathrm{beam}})}$$

Boundary conditions at X = 0:

Air shower: $N_h(X=0) = \delta(E-E_0)\delta(h-A)$

Inclusive spectrum: $N_h(X=0) = \phi_N(E_N)\delta(h-N)$

Primary spectrum (cosmic-ray beam)

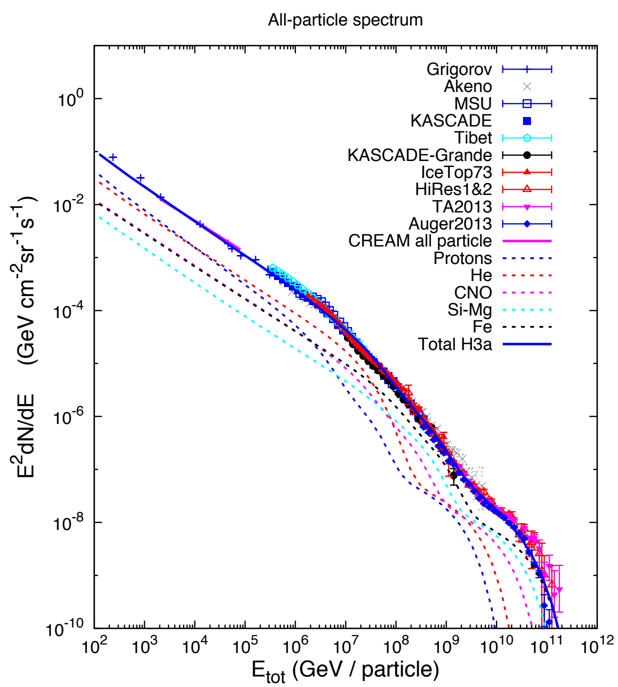


Fig. 12. All-particle spectrum showing' separately the contribution of five mass groups in a modified H3a model (see text).

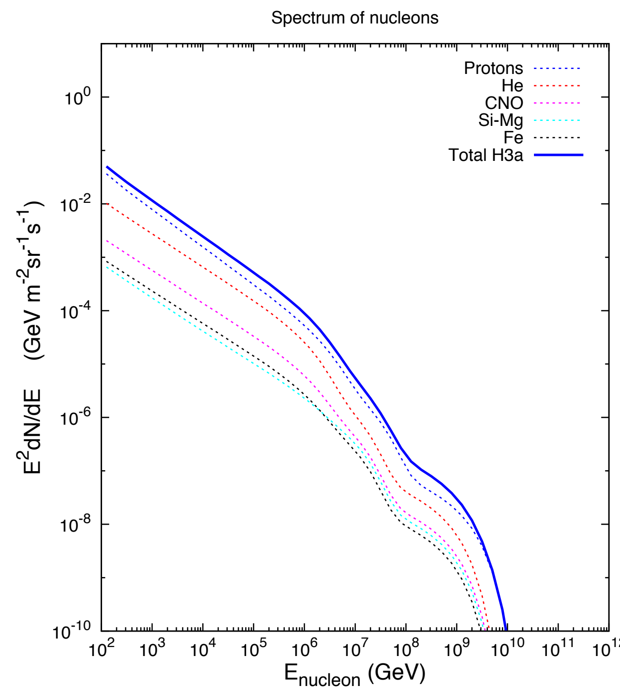


Fig. 13. Spectrum of nucleons corresponding to Fig. 12.

Need primary spectrum of nucleons to $E > E_{knee,1}$

Approximate solution to cascade equation for inclusive spectrum of atmospheric ν_μ

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \simeq \frac{N_0(E_\nu)}{1 - Z_{NN}} \left\{ \frac{Z_{N\pi}\, Z_{\pi\nu}}{1 + \mathcal{B}_{\pi\nu} \cos\theta\, E_\nu/\epsilon_\pi} + 0.635 \frac{Z_{NK}\, Z_{K\nu}}{1 + \mathcal{B}_{K\nu} \cos\theta\, E_\nu/\epsilon_K} + \sum_i B_{D_i} \frac{Z_{ND}\, Z_{D\nu}}{1 + \mathcal{B}_{D\nu} \cos\theta\, E_\nu/\epsilon_D} \right\}$$

Form for muons is same but different decay factors ($Z_{\pi\mu}$ >> $Z_{\pi\nu}$)
Contribution from muon decay not included here

Table 1. Critical energies, ϵ_i (GeV)

μ	$\pi^\pm$	$\mathrm{K}^\pm$	$\mathrm{D}^\pm$	D^0
1.	115.	850.	3.9×10^7	9.9×10^7

$$E_{\text{critical}} = \epsilon_h / \cos\theta^*$$

Spectrum weighted moments

Production: $Z_{Nh} = \int_0^1 (x_L)^\gamma \frac{\mathrm{d}n_h}{\mathrm{d}x_L} \mathrm{d}x_L$ $\gamma \approx 1.7$

$x_L \equiv E_h / E_{\mathrm{beam}}$

Decay (E > $\varepsilon_{critical}$) :

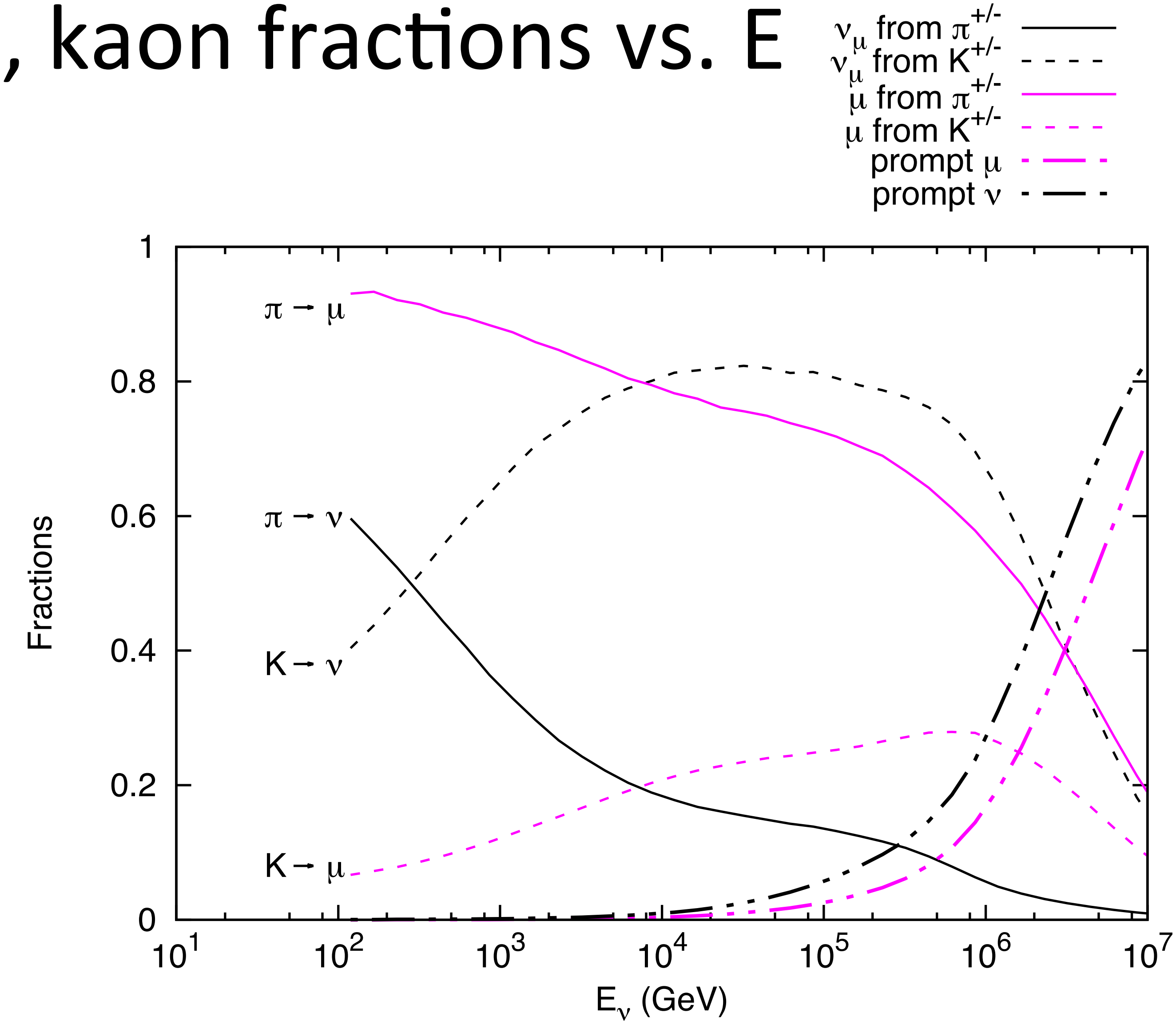
$$Z_{\pi\mu} = \frac{(1 - r_\pi^{\gamma+2})}{(\gamma+2)(1-r_\pi)} \quad \text{and} \quad Z_{\pi\nu_\mu} = \frac{(1-r_\pi)^{\gamma+2}}{(\gamma+2)(1-r_\pi)}$$

$$r_\pi = \frac{m_\mu^2}{m_\pi^2} \approx 0.573 \qquad r_K = \frac{m_\mu^2}{m_K^2} \approx 0.046$$

$$Z_{\pi\nu_\mu} << Z_{K\nu_\mu} \qquad Z_{\pi\mu} = 0.55 \quad Z_{K\mu} = 0.63$$

$$Z_{\pi\nu} = 0.027 \quad Z_{K\nu} = 0.53$$

Pion, kaon fractions vs. E



Energy-dependent Z-factors

Ref: P Gondolo, G. Ingelman, M Thunman, Astropart. Phys. 5 (1996) 309

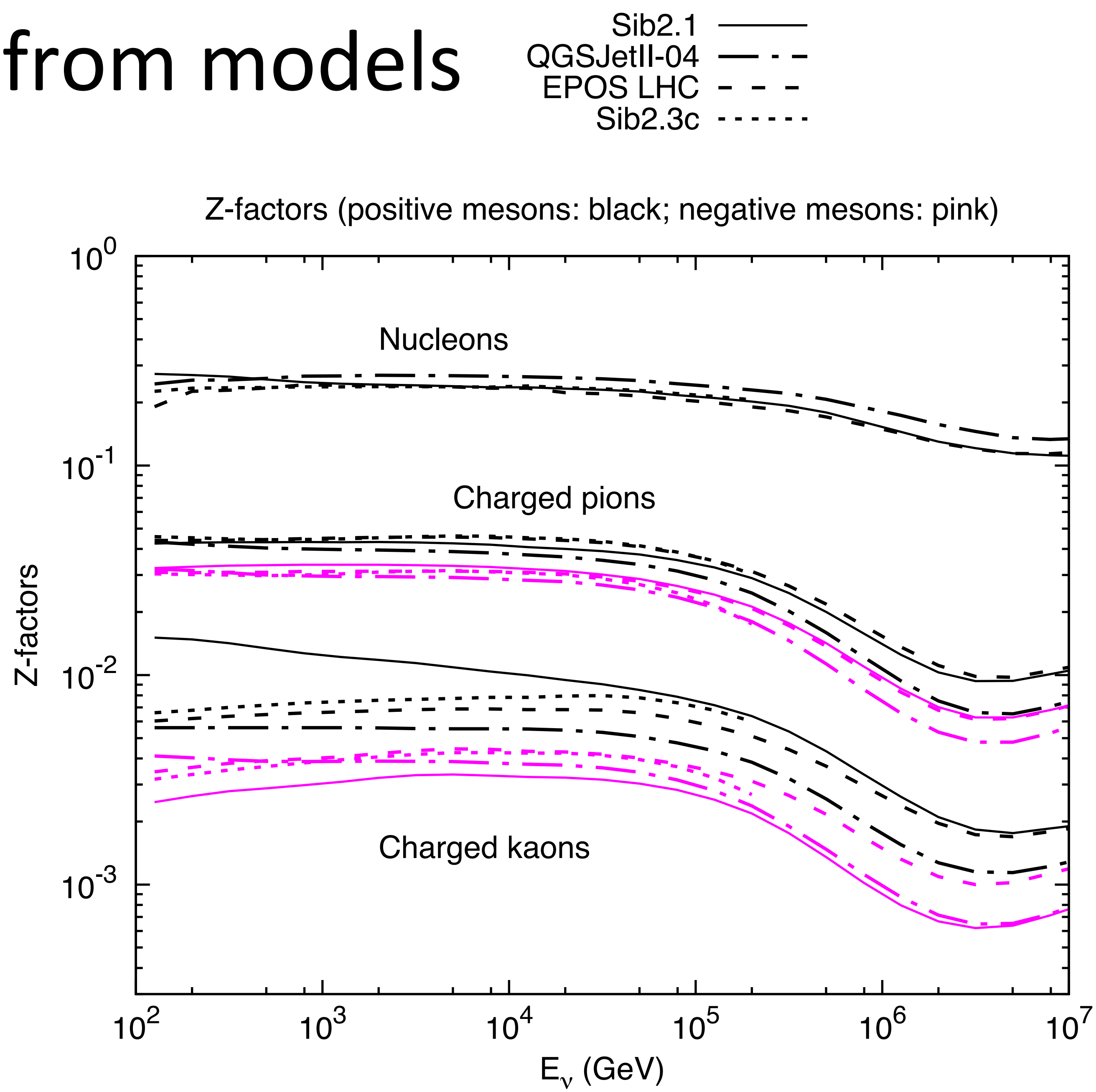
Example: p + A → K⁺ + X

$$Z_{pK^+} = \int_0^1 x^\gamma \frac{\mathrm{d}n_{K^+}(x)}{\mathrm{d}x}$$

becomes

$$Z_{NK^+}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{K^+}(E',E)}{\mathrm{d}E}$$

Z's from models

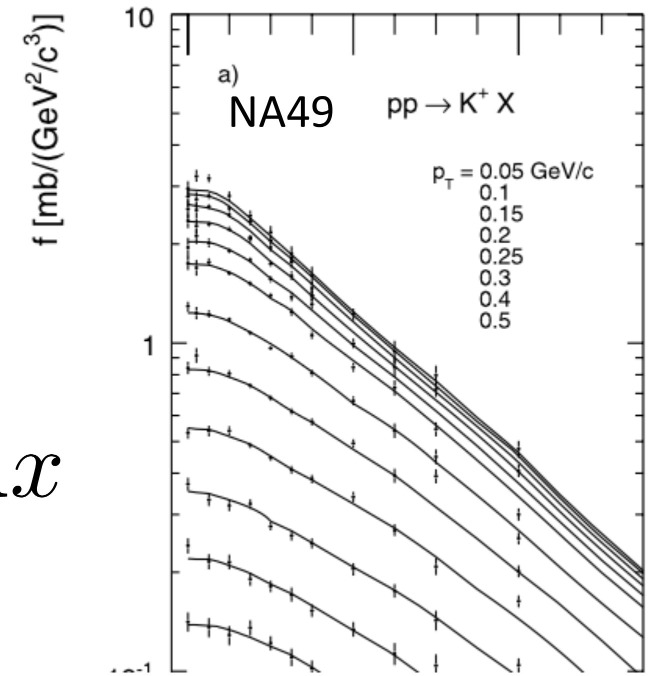


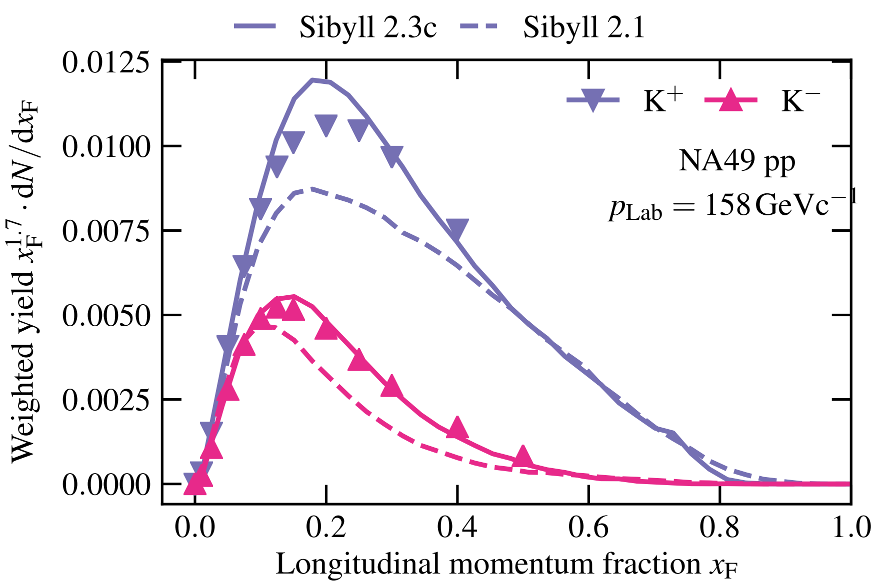
Largest uncertainty comes from charged kaons

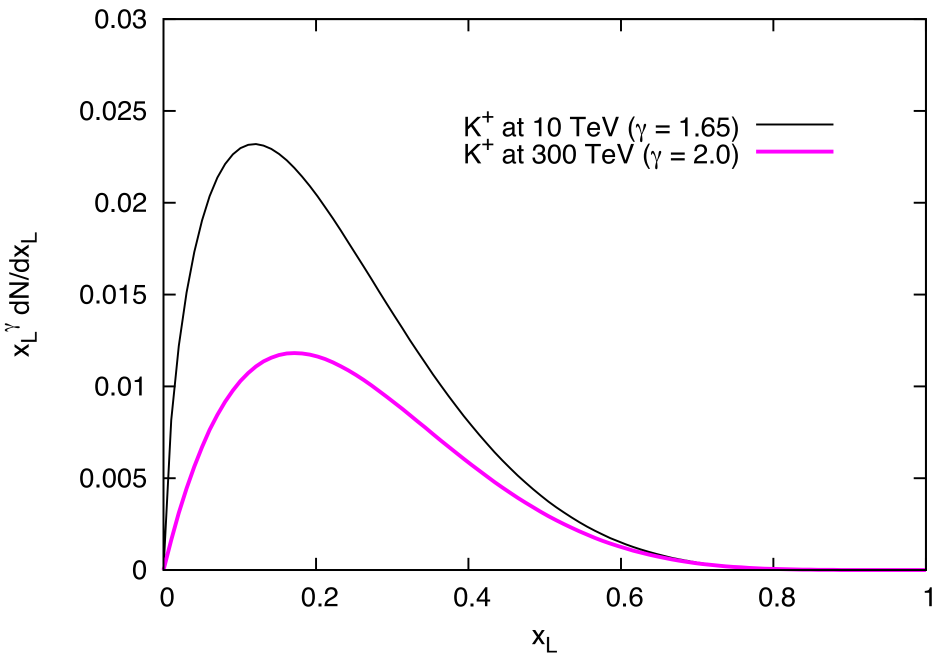
Phase space

Steep spectrum favors forward *x*

$$Z_{pK^+} = \int_0^1 \underbrace{x^\gamma \, \frac{\mathrm{d}n_{K^+}(x)}{\mathrm{d}x}} \, \mathrm{d}x$$

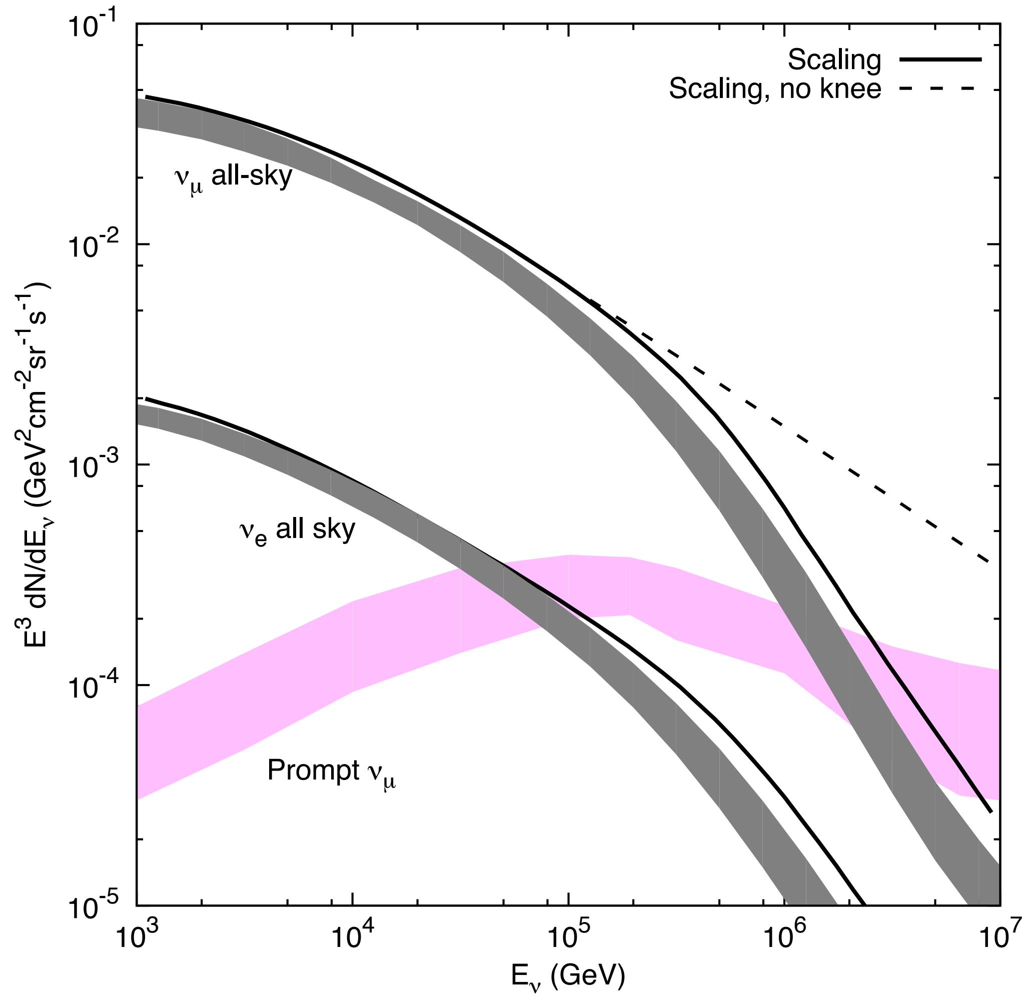






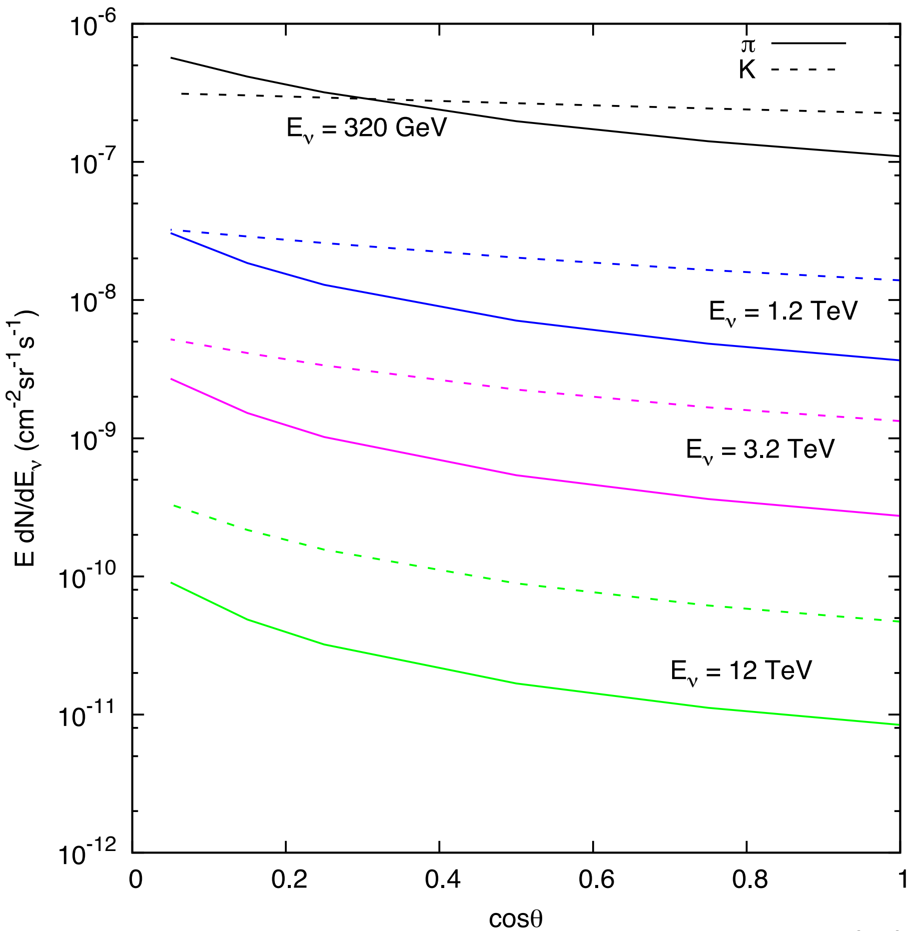
Fedynitch et al., arXiv:1806.04140

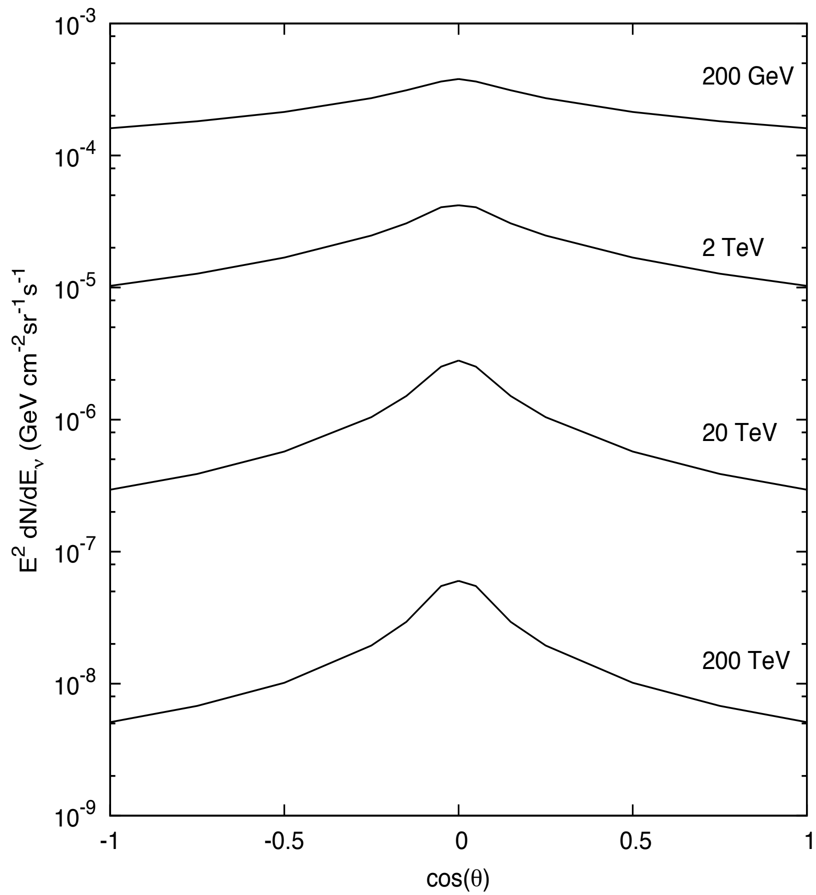
Largest contribution to the uncertainty is from models of hadro-production, especially kaons



Shaded bands for conventional span Sib2.3, Epos LHC, QGSjet II-04, prompt: PROSA, Sib2.3, GRRST, BERSS

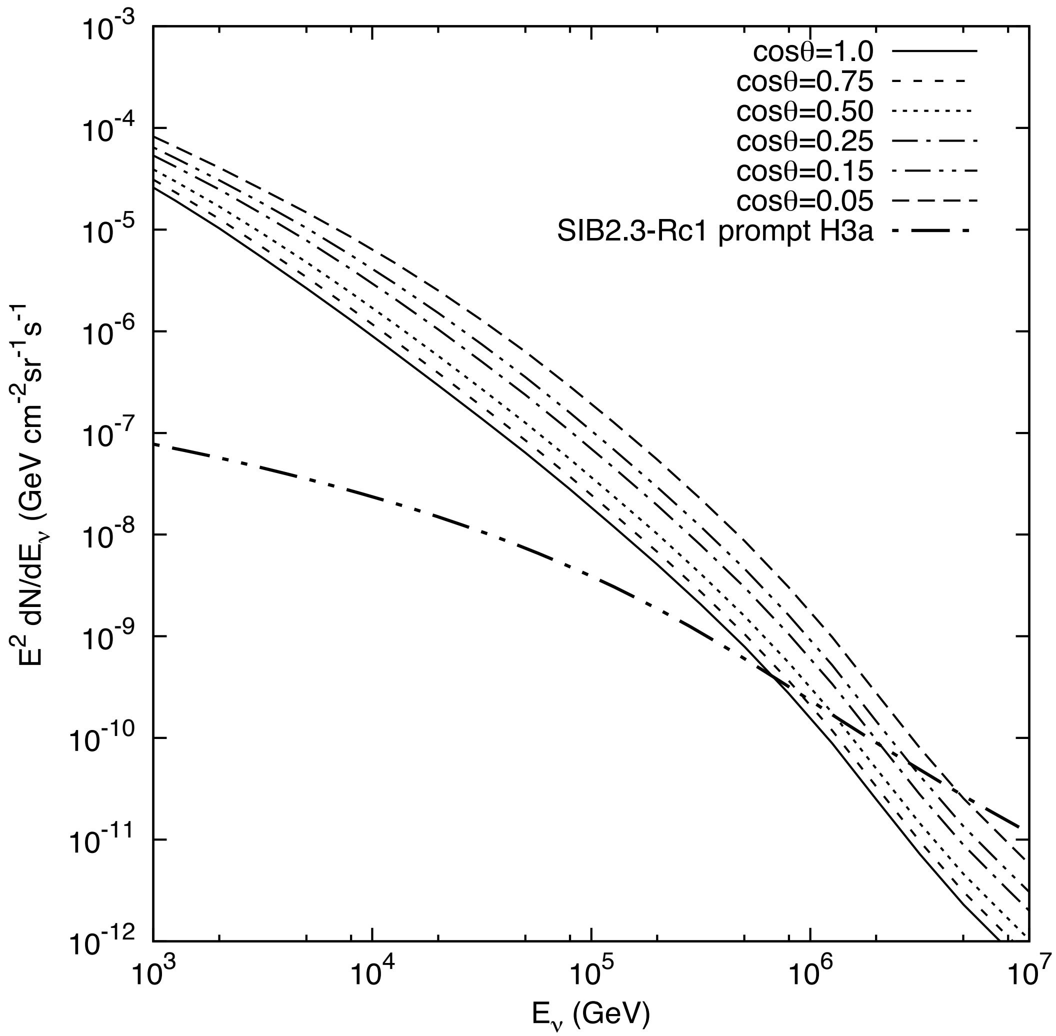
Evolution of angular distribution





For E ≈ TeV, pion component ≈ sec(θ), but kaon still almost isotropic

Flux of atmospheric ν_μ vs angle



Note harder spectrum and higher flux at large zenith angles

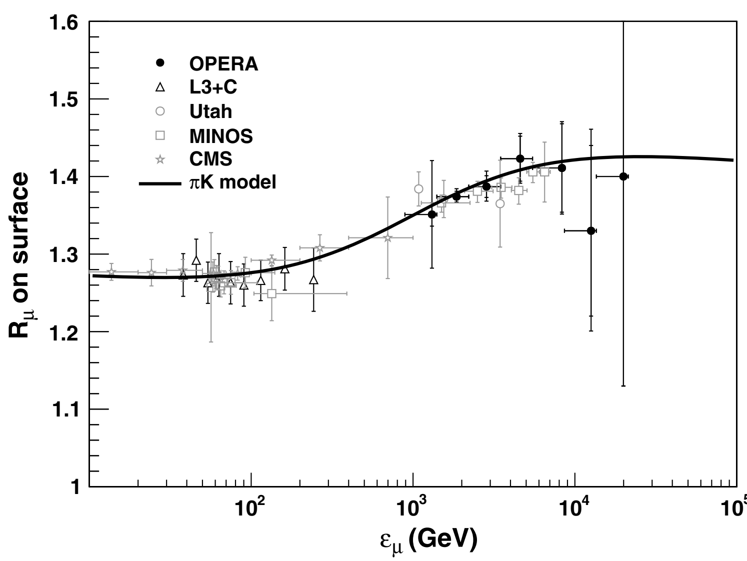
Muon charge ratio

Pions only (Frazer et al., PR D 5 (1972) 1653

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

$$\beta = \frac{1-Z_{pp}-Z_{pn}}{1-Z_{pp}+Z_{pn}} \approx 0.909;$$

$$\alpha_\pi = \frac{Z_{p\pi^+}-Z_{p\pi^-}}{Z_{p\pi^+}+Z_{p\pi^-}} \approx 0.165$$



Include K → μ + ν_μ

TG Astropart. Phys. 35 (2012) 801

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

$$\alpha_K = \frac{Z_{pK^+}-Z_{pK^-}}{Z_{pK^+}+Z_{pK^-}} \approx 0.51$$

Rise in muon charge ratio reflects higher asymmetry in the charged kaon channel, which becomes more important when $E_\mu > \varepsilon_K \approx 850$ GeV.

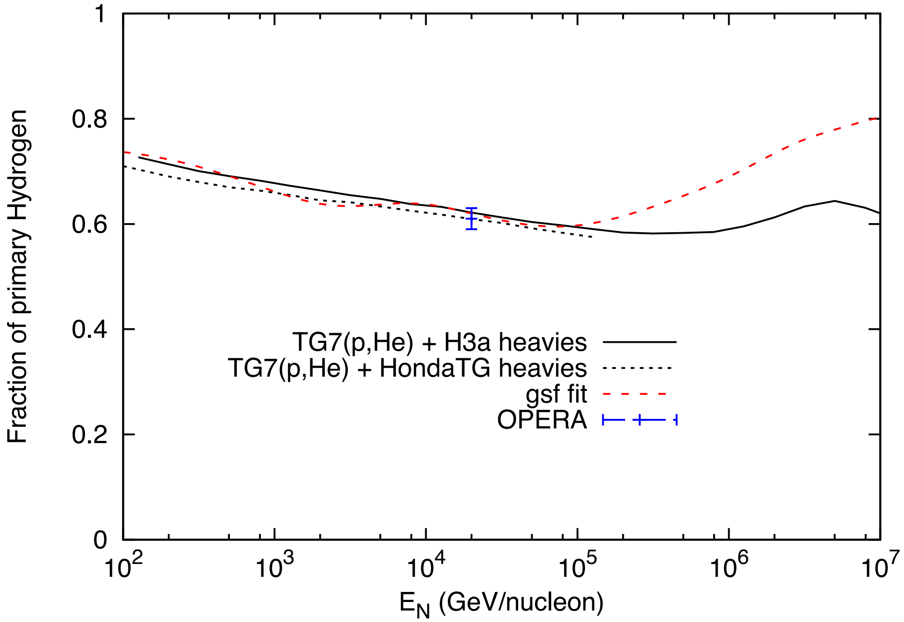
The key parameter is $\alpha_K > \alpha_\pi$ due to associated production: p → ΛK^+

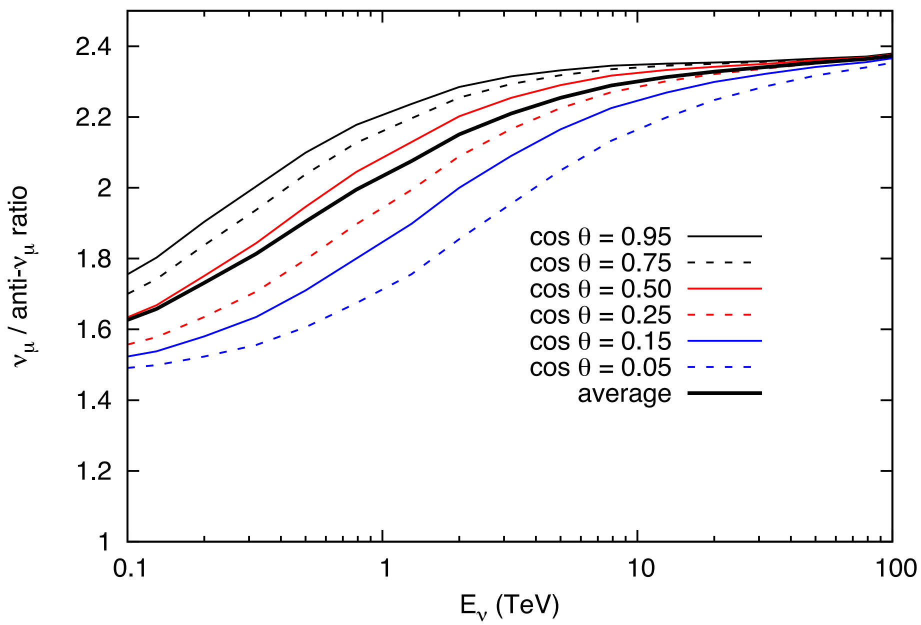
Implication: $\nu_\mu / \bar{\nu}_\mu$ rises to ≈ 2.5 @ 10 TeV

Use OPERA results to predict $\nu_\mu/\bar{\nu}_\mu$

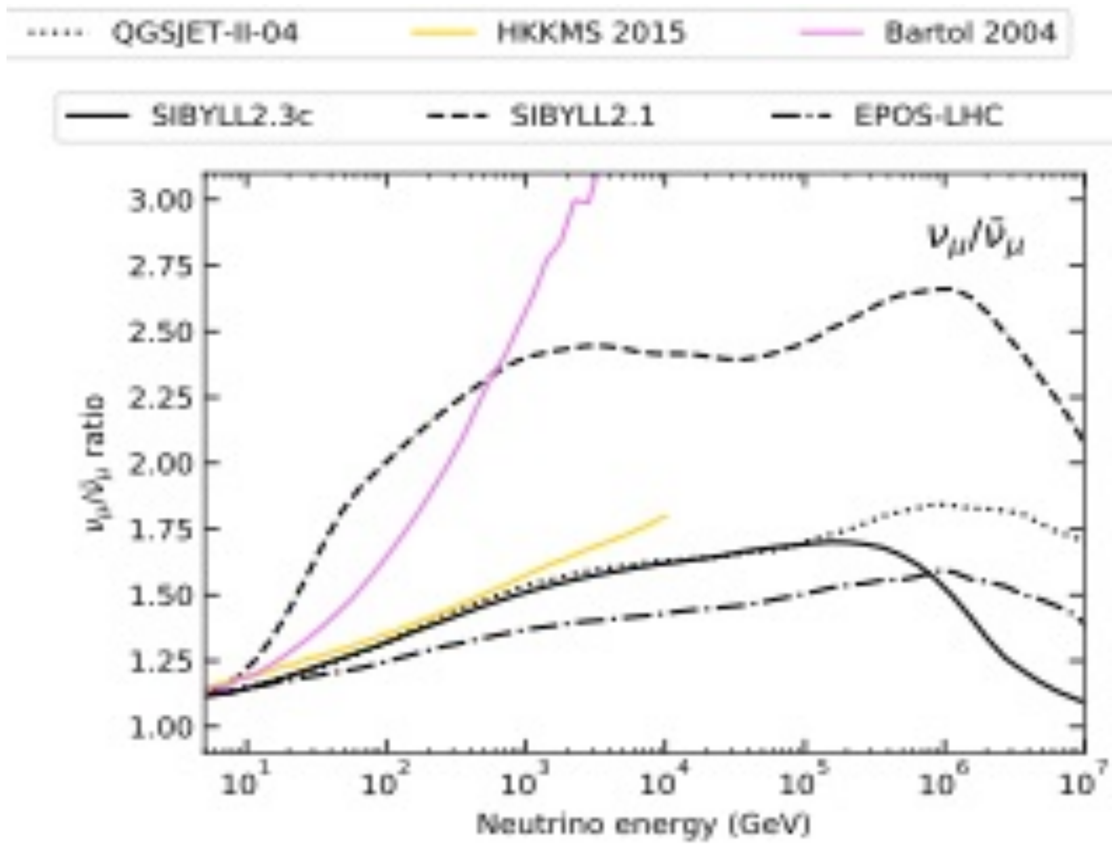
$$\delta_0 = \frac{p-n}{p+n} \approx \frac{H}{N}$$

$\alpha_K \cong 0.51$



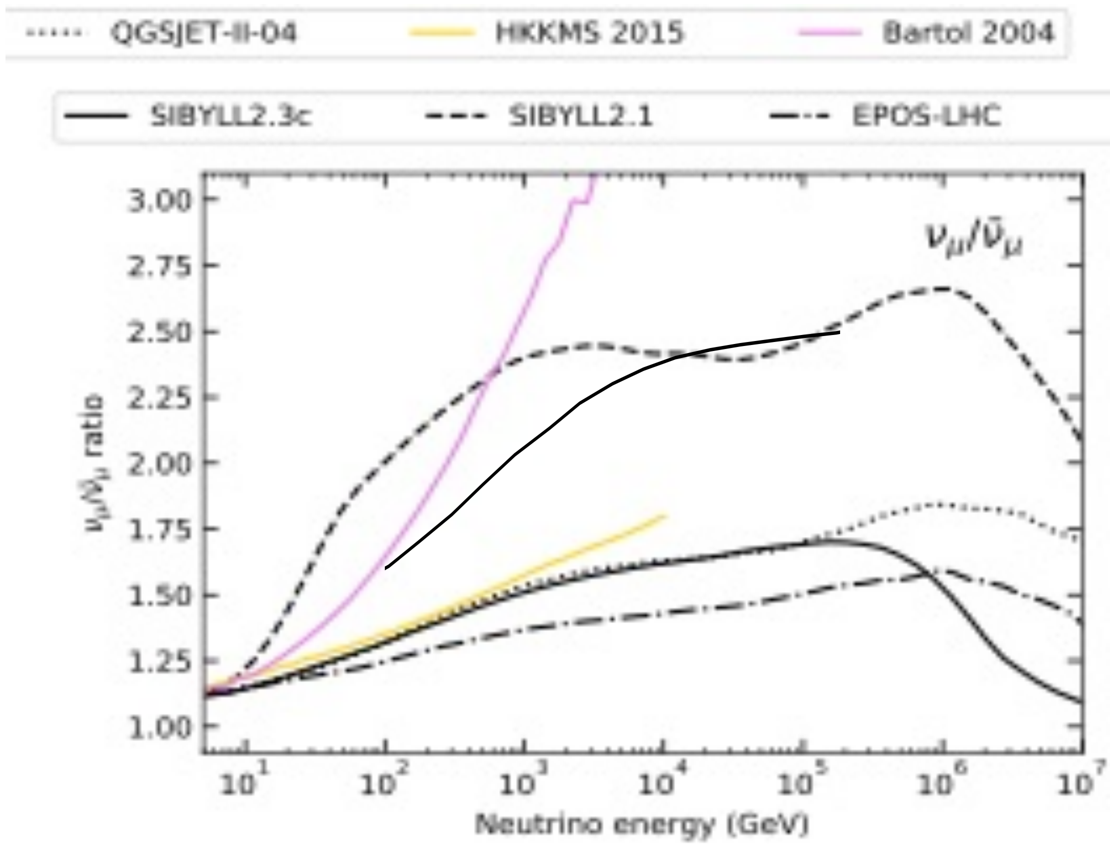


Muon neutrino/anti-neutrino ratio



From Fedynitch et al., http://arxiv.org/abs/arXiv:1806.04140

Muon neutrino/anti-neutrino ratio

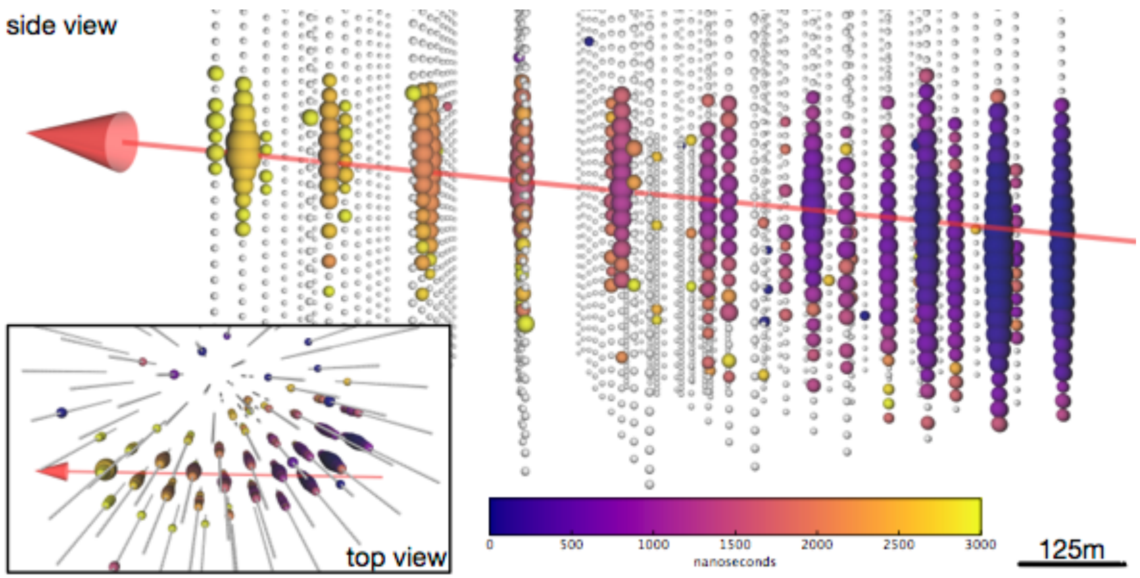


From Fedynitch et al., http://arxiv.org/abs/arXiv:1806.04140
with predicted value using OPERA parameters

Publication in *Science,* 13 July 2018

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†



The IceCube Collaboration et al., Science 361, eaat1378 (2018) 13 July 2018

Likelihood that alert is not an atmospheric event

From Bacodine <vxw@capella2.gsfc.nasa.gov>
Subject **[icecube-c] GCN/AMON_ICECUBE_EHE**
To nl_169_email_none@capella2.gsfc.nasa.gov

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;    265 DOY;    17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
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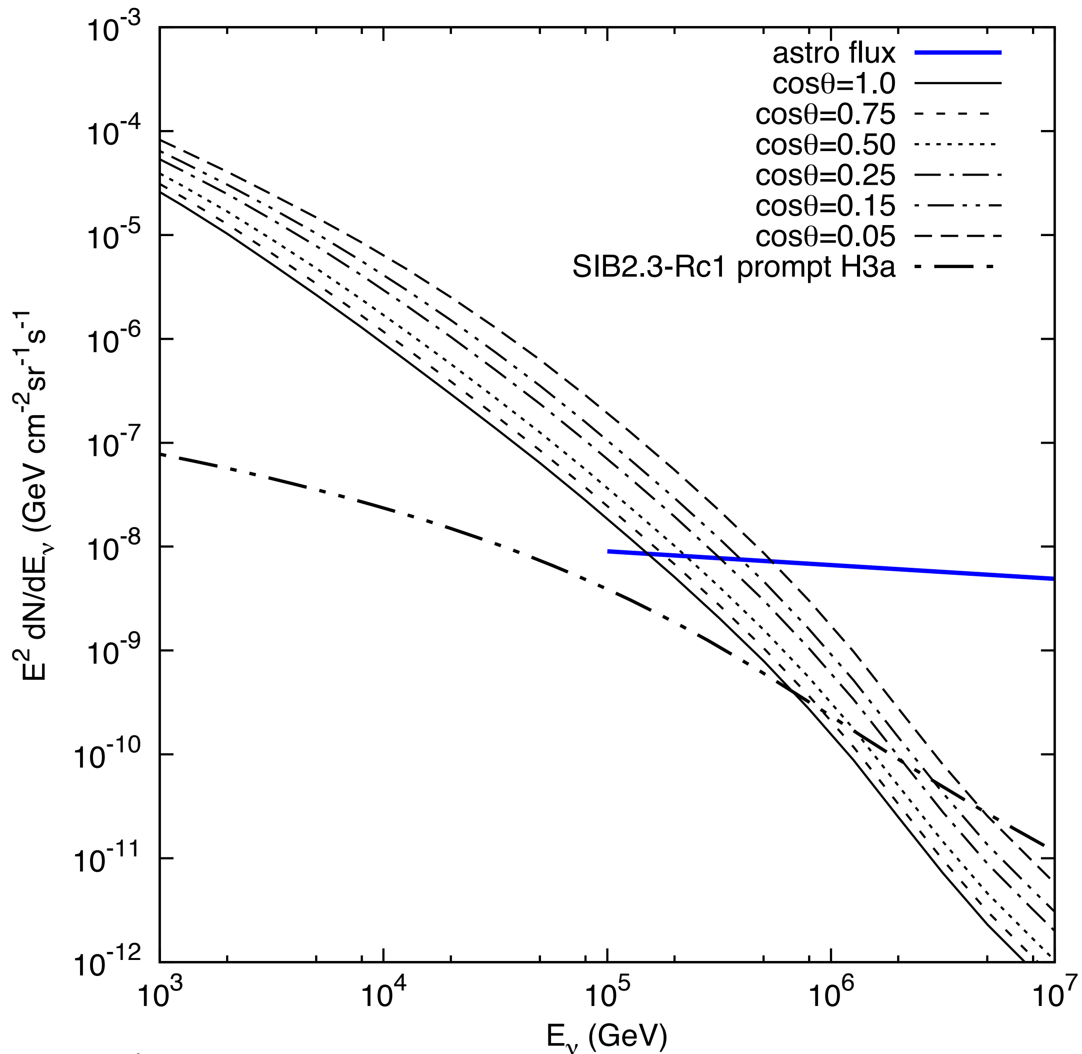
Signalness = 0.565

"Signalness" of 170922A

- Compare to the astrophysical spectrum of the upward ν_μ analysis (Ap.J. 833 (2016) 3):
  - At 100 TeV $E^2\phi_{\mathrm{astro}} \approx 0.9 \times 10^{-8}\, GeV\ cm^{-2}s^{-1}sr^{-1}$
  - Fitted differential spectral index = -2.13
- Compare to atmospheric flux accounting for direction of the event
  - Declination = 5.72$^{\mathrm{o}}$
  - Below horizon, so no atmospheric muons
  - Zenith angle = 95.72, cos(θ) ≈ -0.1, not absorbed by the Earth

Flux of atmospheric ν_μ vs angle



Note: actual evaluation of "signalness" compares ν_μ –induced muon spectra rather than neutrino spectra.

Summary comments

- Atmospheric neutrinos at high energy:
  - A beam for neutrino physics (not covered here)
  - Background for astrophysical neutrinos
- For $1 \leq E_\nu \leq 100$ TeV neutrinos are from kaons
  - Electron neutrinos from KL3 decays
  - Most muon neutrinos from $K^\pm$
- Measure kaon production at 7 TeV with SMOG