Atmospheric Neutrinos

50 GeV to 100 TeV

Outline

- Phenomenology of atmospheric neutrinos
  - Solutions of cascade equation
  - Relation to muons
  - Importance of kaons
  - Angular distributions
  - Energy dependence
    - Primary spectrum
    - Hadronic models, scaling violation
- Muon charge ratio
  - Implications for neutrino/anti-neutrino ratio
  - Separate ν_μ and ν_μ fluxes
- Summary
  - Uncertainties

Cascade equation

Loss terms | Source terms

$$\frac{\mathrm{d}N_i(E_i,x,\theta)}{\mathrm{d}X} = -\frac{N_i(E_i,X,\theta)}{\lambda_i(E_i)} - \frac{N_i(E_i,X,\theta)}{d_i(E_i)} + \sum_{j=i}^{J}\int_{E_i}^{\infty}\left\{\frac{\mathrm{d}\sigma_{ji}(E_j,E_i)}{\sigma_j^{inel}(E_j)\,\lambda_j(E_j)} + \frac{R_{ji}}{d_j}\right\} N_j(E_j,X,\theta)\,\mathrm{d}E_j$$

Interaction | Decay | Interaction | Decay

Boundary conditions:

$$N_i(E_0,0,\theta) = \phi_N(E_0)\delta_{iN}$$ for inclusive flux

$$N_i(E_0,0,\theta) = \delta(E_0 - AE_N)\delta_{iA}$$ Air shower

Matrix Cascade Equation (MCEq)* starts with a nucleon of energy E_0 and integrates in steps of dX for each θ with a matrix of 65 particle types and 8 energy bins per decade.

*https://github.com/afedynitch/MCEq

Analytic Approximations (AA)

For a power law primary spectrum + scaling of production σ, solutions for low and high energy have the forms:

$$\frac{\mathrm{d}N_\ell}{\mathrm{d}E_\ell} = \int_0^{X_0/\cos\theta} P_{M\ell}(E_\ell, X)\,\mathrm{d}X\Bigg|_{E_\ell \ll \epsilon_M} \rightarrow \frac{N_0(E_\ell)}{1-Z_{NN}} A_{M\ell}$$

$$\frac{\mathrm{d}N_\ell}{\mathrm{d}E_\ell} = \int_0^{X_0/\cos\theta} P_{M\ell}(E_\ell, X)\,\mathrm{d}X\Bigg|_{E_\ell \gg \epsilon_M} \rightarrow \frac{N_0(E_\ell)}{1-Z_{NN}} \left(\frac{\epsilon_M}{\cos\theta\, E_\ell}\right) \frac{A_{M\ell}}{B_{M\ell}}$$

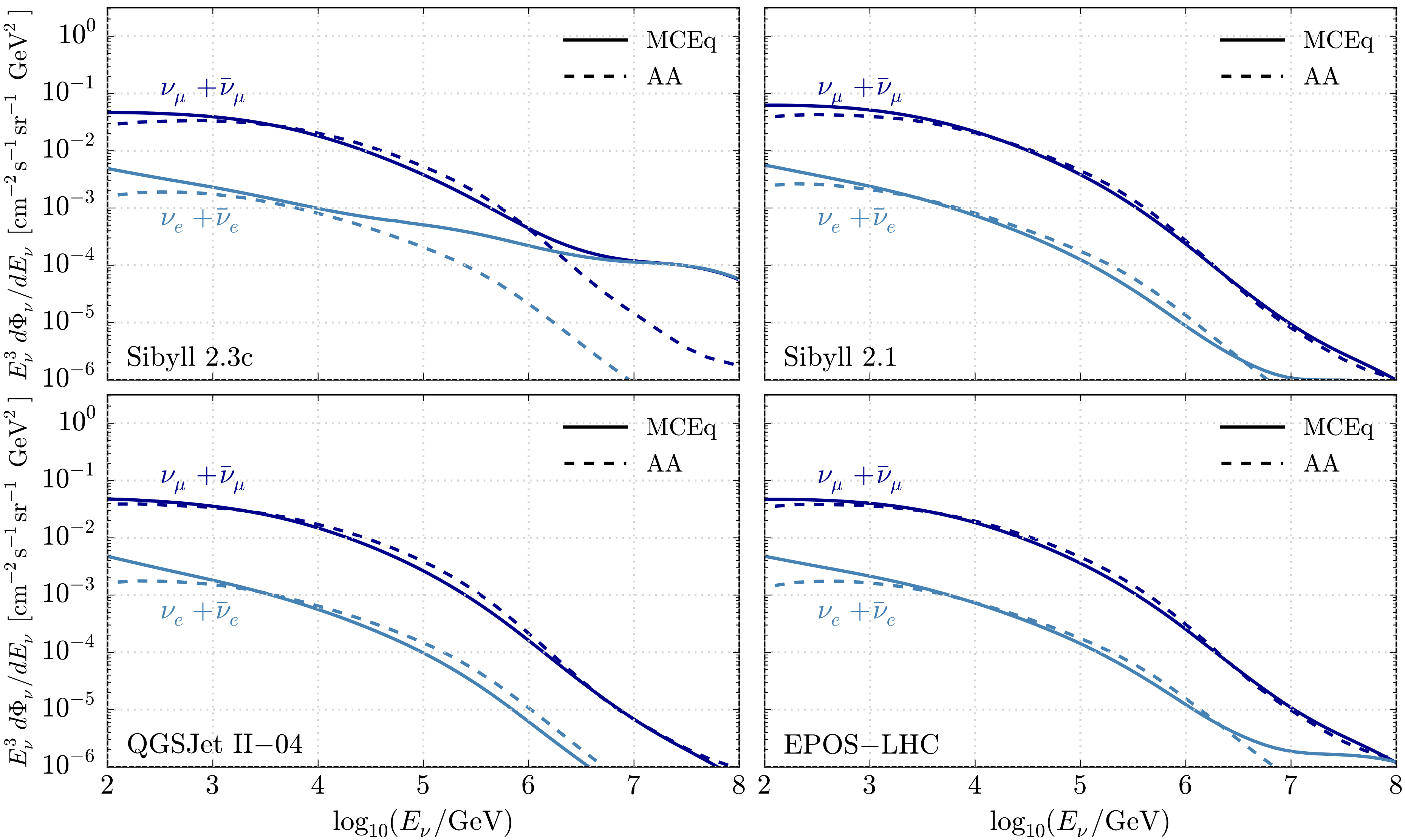
Combine low and high-energy forms in the approximation

$$\frac{\mathrm{d}N_\ell}{\mathrm{d}E_\ell} = \frac{N_0(E_\ell)}{1-Z_{NN}} \left\{ \frac{A_{\pi\ell}}{1+B_{\pi\ell}\cos\theta\, E_\ell/\epsilon_\pi} + \frac{A_{K\ell}}{1+B_{K\ell}\cos\theta\, E_\ell/\epsilon_K} \right\}$$

$$A_{M\ell} = R_{M\ell} Z_{NM} Z_{M\ell}(\gamma) \qquad B_{M\ell} = \frac{Z_{M\ell}(\gamma)}{Z_{M\ell}(\gamma+1)} \frac{\Lambda_M - \Lambda_N}{\Lambda_M \ln(\Lambda_M/\Lambda_N)}$$

Compare methods

TG, D. Soldin, A. Crossman, A. Fedynitch
ICRC 2019, arXiv:1910.08676



Two body decays of $\pi^{\pm}$ & $K^{\pm}$

For a power-law primary spectrum of nucleons with integral spectral index $\gamma \approx 1.7$

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

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

$$Z_{\pi\nu_\mu} << Z_{K\nu_\mu}$$

Critical energies and Z-factors

$$\epsilon_M = \frac{R\,T(X)}{M_{\rm mol}\,g}\,\frac{Mc^2}{c\,\tau_M}$$

For T = 220° K
$$\epsilon_\pi = 115\ \mathrm{GeV}$$
$$\epsilon_{K^\pm} = 857\ \mathrm{GeV}$$
$$\epsilon_{D^\pm} \approx 3.7\times 10^7\ \mathrm{GeV}$$

$$Z_{NM}(E) = \int_E^\infty \frac{N_0(E')}{N_0(E)}\,\frac{\sigma(E')}{\sigma(E)}\,\frac{\mathrm{d}n_{NM}(E',E)}{\mathrm{d}E}\mathrm{d}E' \rightarrow \int_0^1 x^\gamma\,\frac{\mathrm{d}n_{NM}(x)}{\mathrm{d}x}\,\mathrm{d}x$$

Energy-dependent Z-factors

Gondolo, Ingelman, Thunman, Astropart. Phys. 5 (1996) 309

Scaling

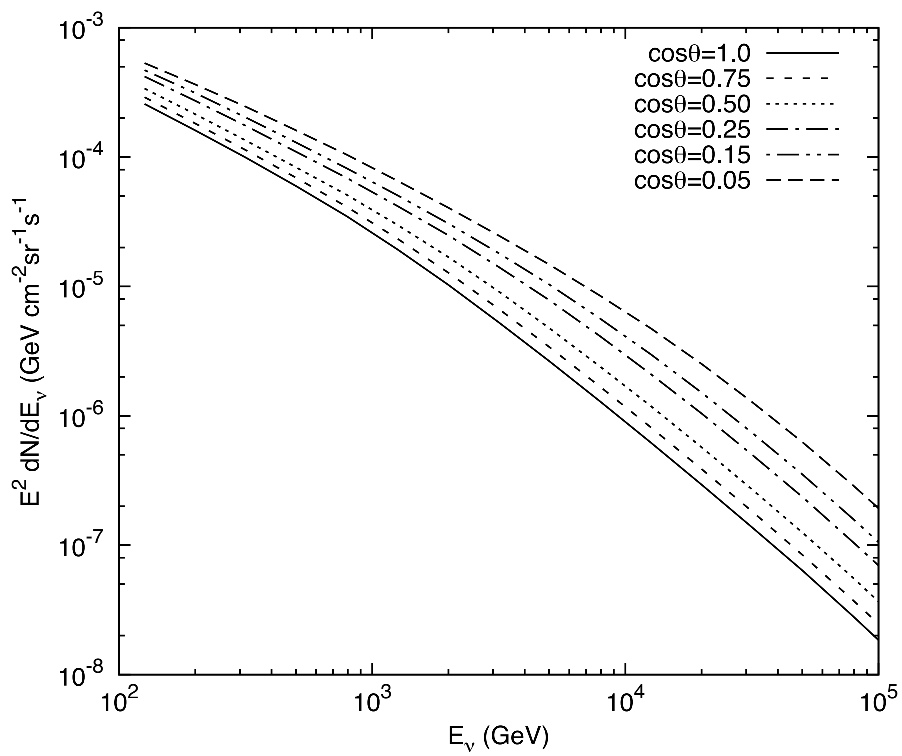
How the ν_μ spectrum steepens

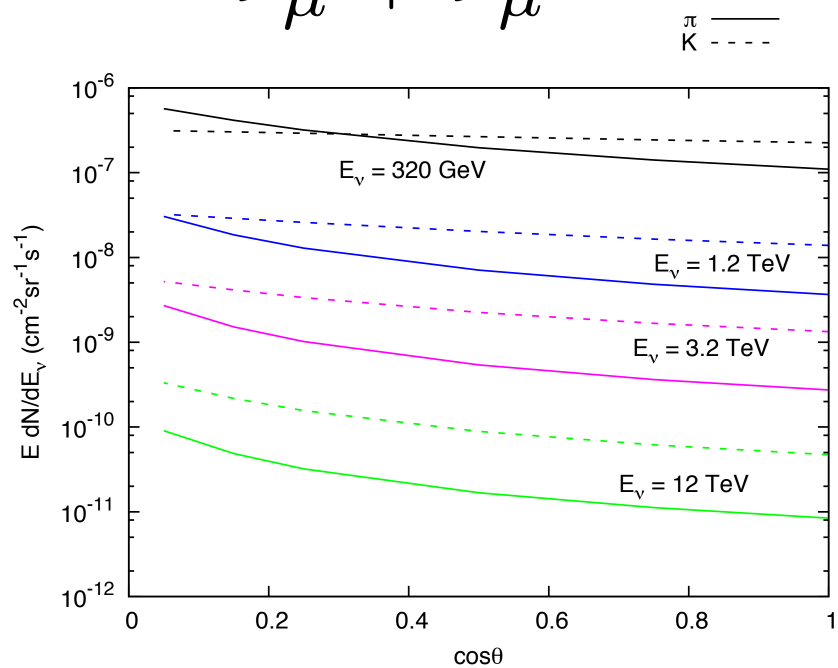
$$\frac{\mathrm{d}N_\ell}{\mathrm{d}E_\ell} = \frac{N_0(E_\ell)}{1 - Z_{NN}} \left\{ \frac{A_{\pi\ell}}{1 + B_{\pi\ell} \cos\theta \, E_\ell / \epsilon_\pi} + \frac{A_{K\ell}}{1 + B_{K\ell} \cos\theta \, E_\ell / \epsilon_K} \right\}$$

- Steepening first for $\pi^\pm$ component
  - Later for kaon component ($\varepsilon_\pi \ll \varepsilon_K$)
- Steepening first for near vertical
  - Later for more horizontal ($1/\cos\theta$)
- π to ν_μ suppressed
  - Muon carries most of energy in $\pi \rightarrow \mu + \nu_\mu$
- Kaon channel dominates for $E(\nu_\mu) > 100$ GeV

Evolution of angular distribution

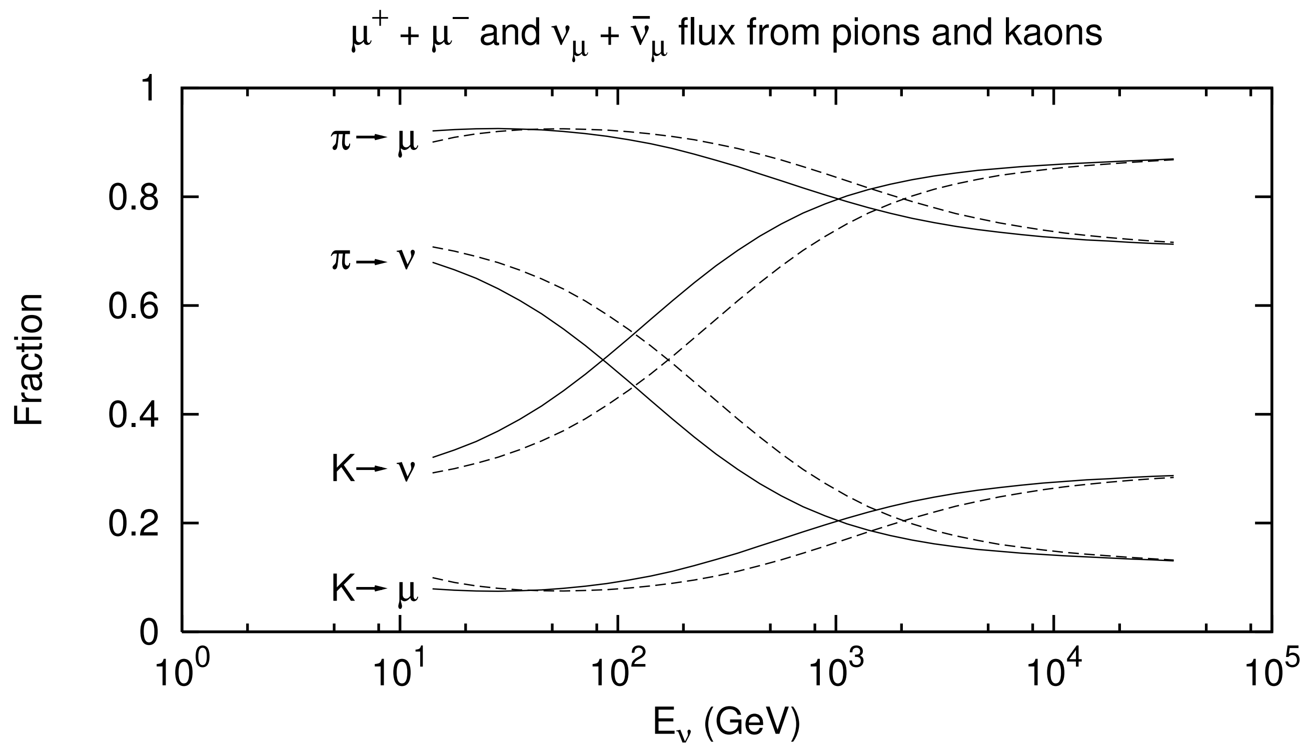
$\nu_\mu + \bar{\nu}_\mu$





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

Pion, kaon fractions vs. E for ν_μ & μ



Summary of μ^+/μ^- measurements

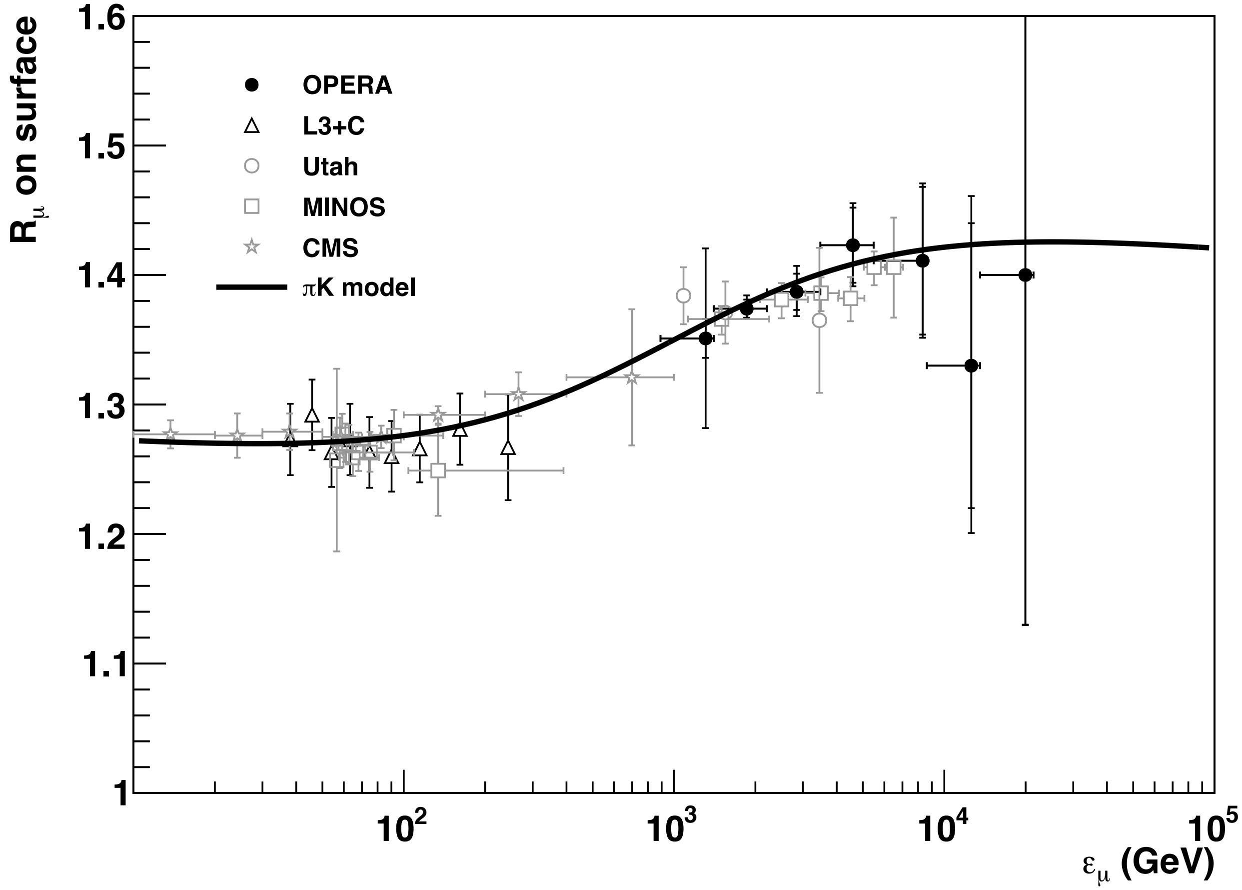


Figure from OPERA, N. Agafonova et al., Eur. Phys. J C74 (2014) 2933

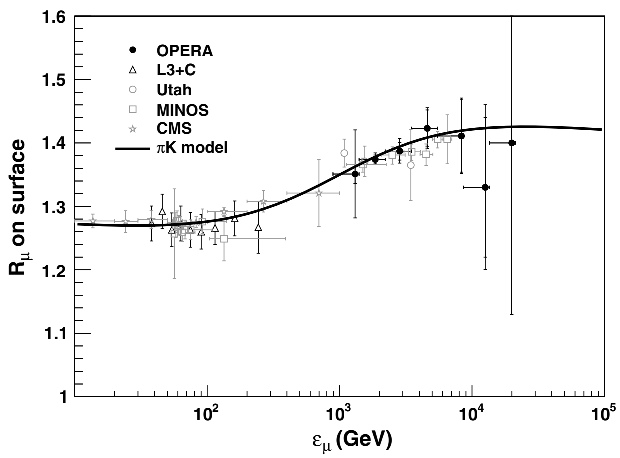
Muon charge ratio

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

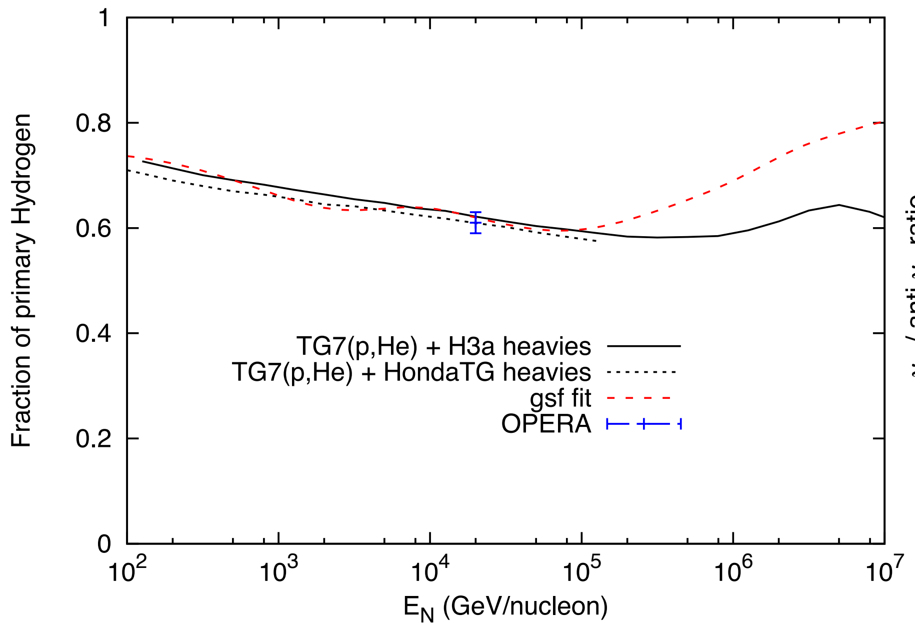
$$\frac{\mu^+}{\mu^-} = \left[\frac{f_{\pi^+}}{1 + B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{\frac{1}{2}(1 + \alpha_K\beta\delta_0)A_{K\mu}/A_{\pi\mu}}{1 + B^+_{K\mu}\cos(\theta)E_\mu/\epsilon_K}\right] \times \left[\frac{(1 - f_{\pi^+})}{1 + B_{\pi\mu}\cos(\theta)E_\mu/\epsilon_\pi} + \frac{(Z_{NK^-}/Z_{NK})A_{K\mu}/A_{\pi\mu}}{1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

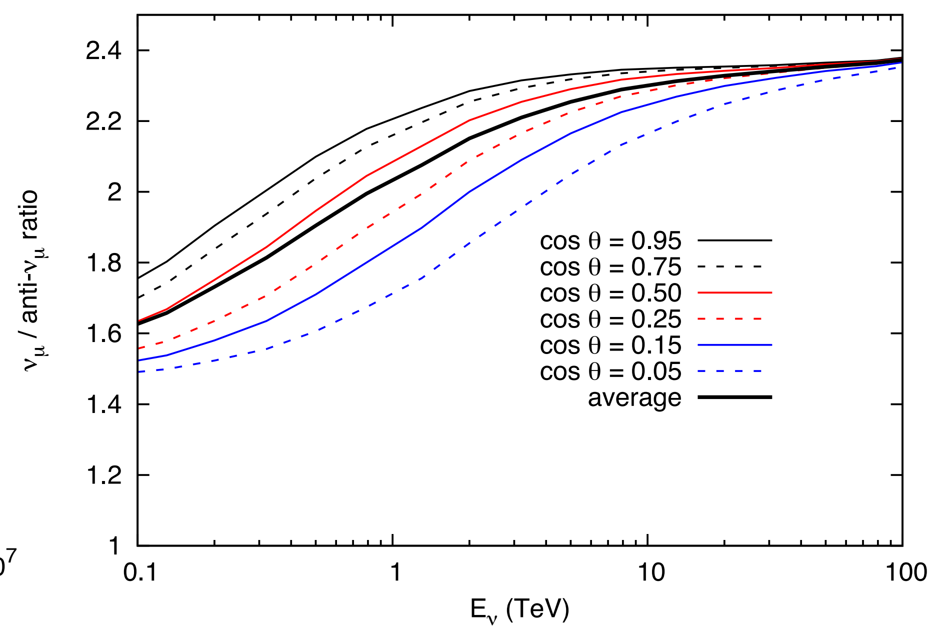
$$\alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}}$$

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^+

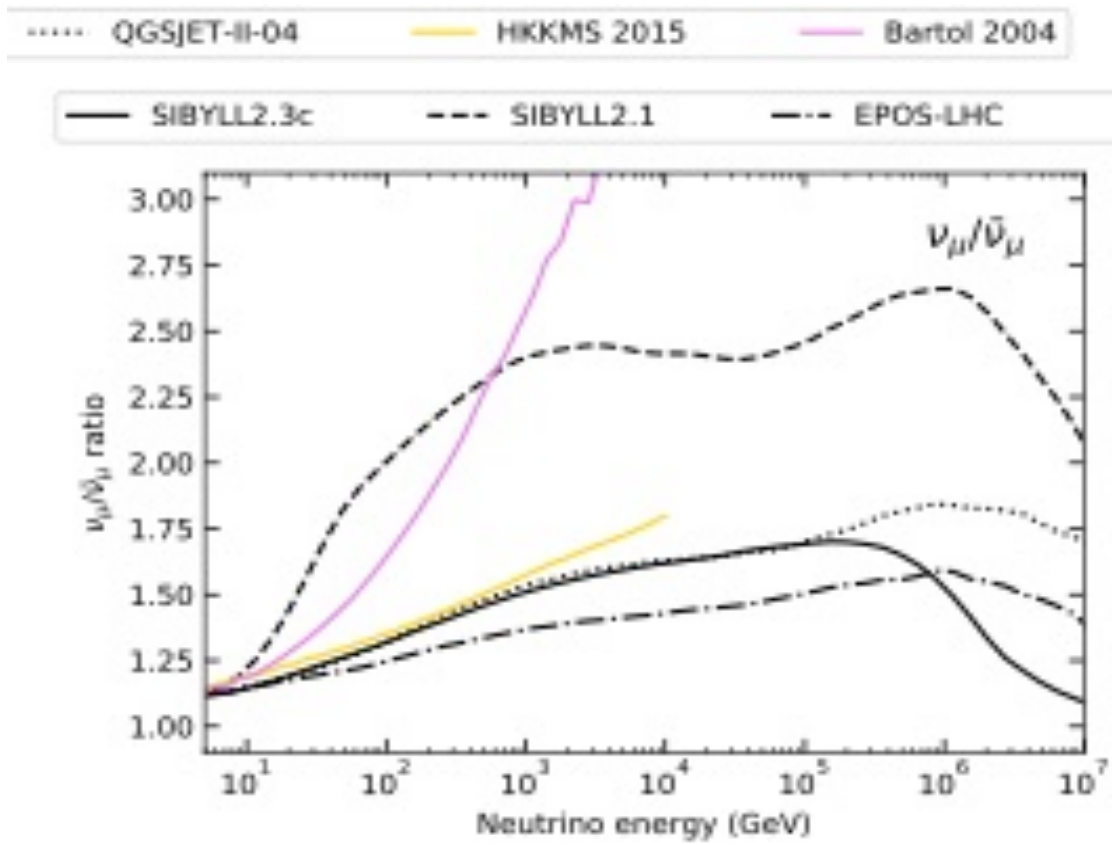
Use OPERA results to predict $\nu_\mu/\bar{\nu}_\mu$

$$\delta_0 = \frac{p-n}{p+n} = 0.61 \qquad \alpha_K = \frac{Z_{pK^+} - Z_{pK^-}}{Z_{pK^+} + Z_{pK^-}} = 0.51$$



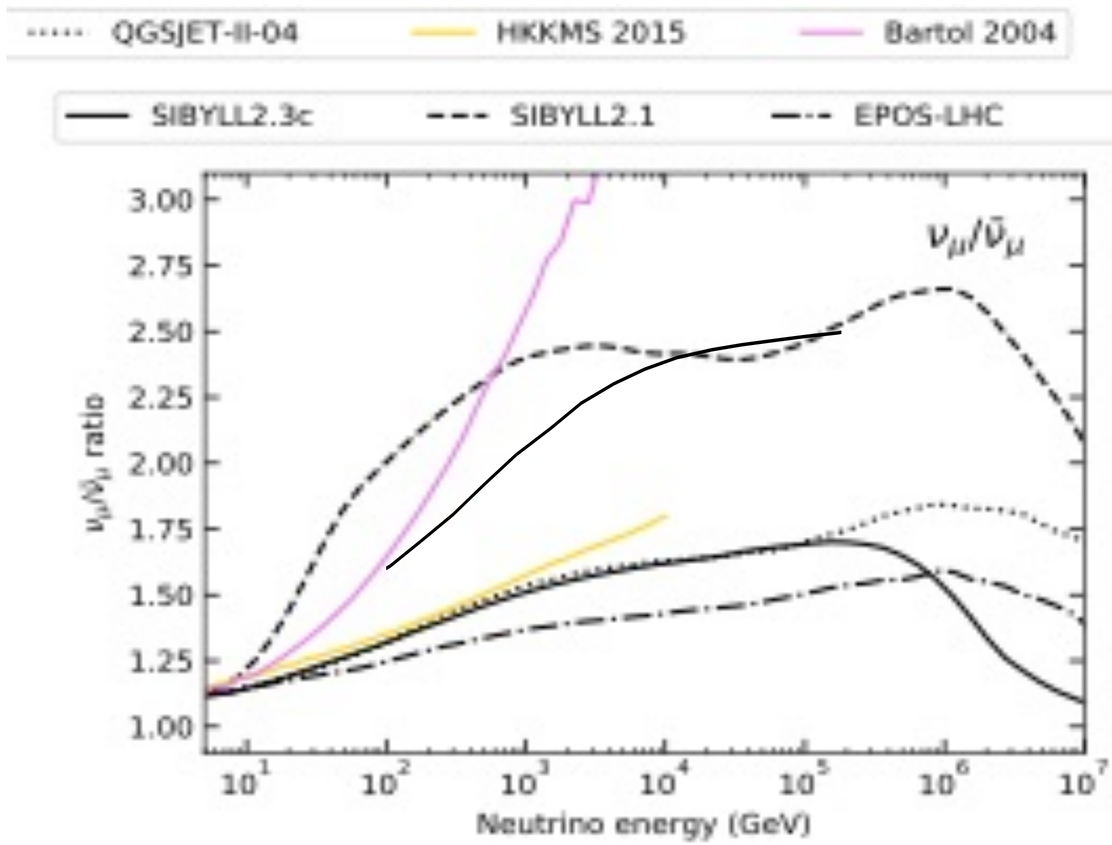


Muon neutrino/anti-neutrino ratio predicted in 6 hadronic interaction models



From Fedynitch et al., PRD 100 103018 (2019)

Muon neutrino/anti-neutrino ratio predicted in 6 hadronic interaction models



IceCube sterile neutrino analysis

PRL 125, 141801 (2020)

Matter-enhanced resonance for near vertically upward anti-ν_μ

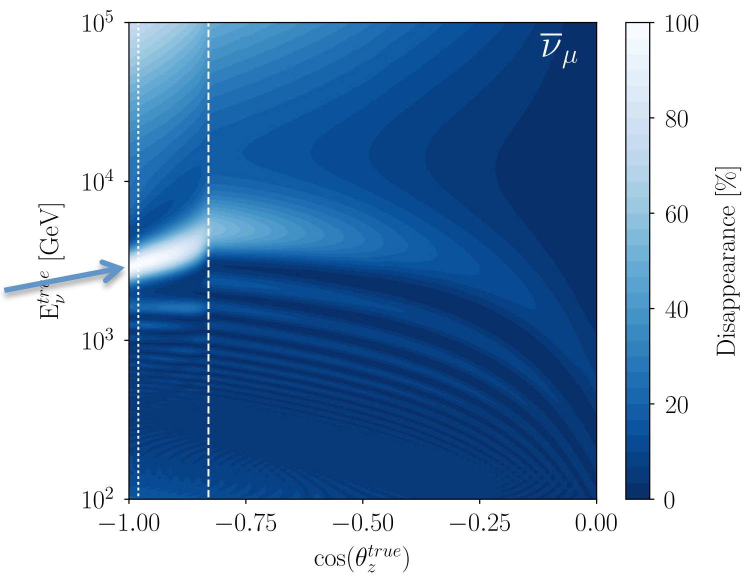
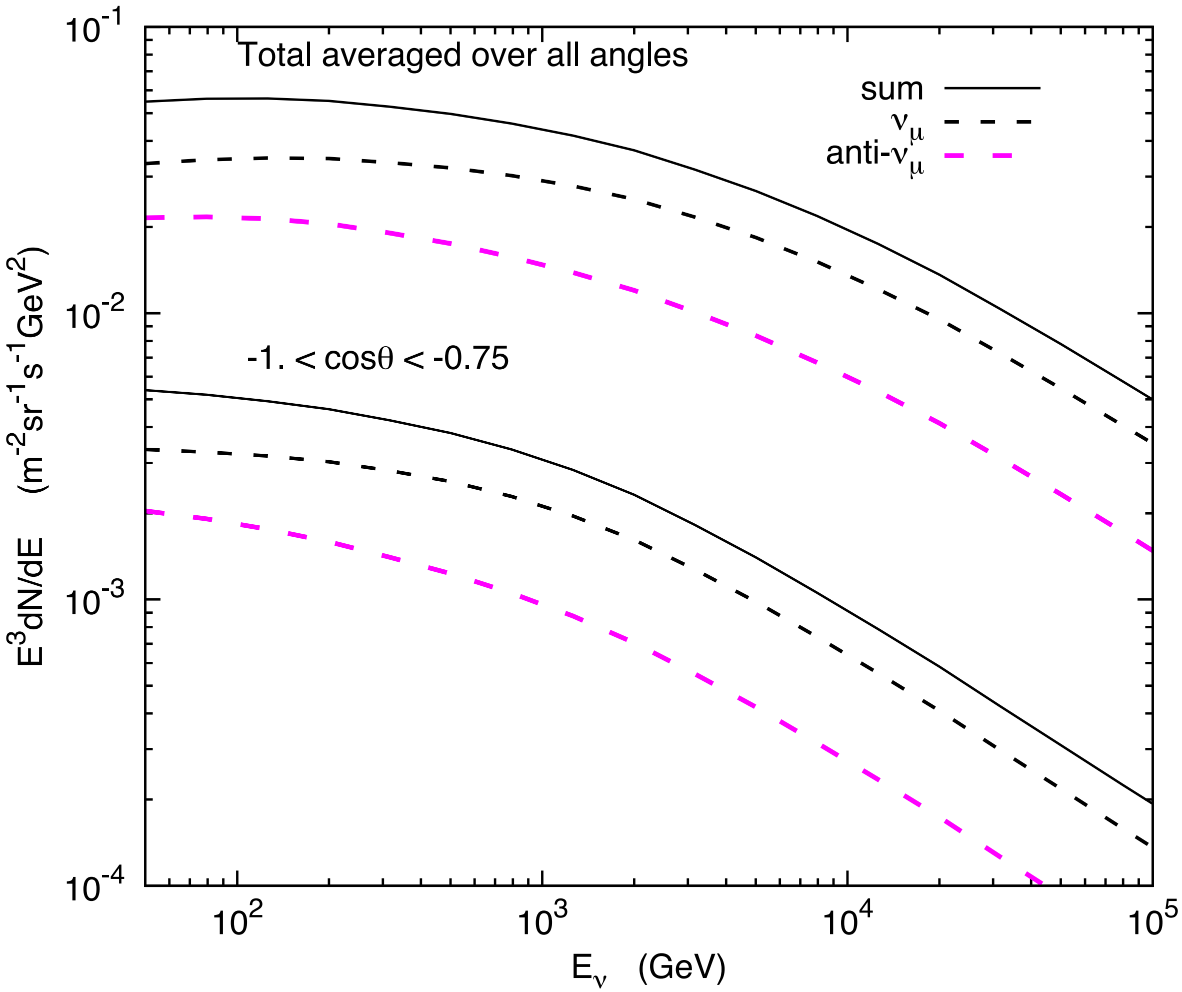


FIG. 1. Muon-antineutrino oscillogram. Atmospheric $\bar{\nu}_\mu$ disappearance probability vs true energy and cosine zenith at the globally preferred sterile neutrino hypothesis of Ref. [11] [$\Delta m^2_{41} = 1.3$ eV^2, $\sin^2(2\theta_{24}) = 0.07$, $\sin^2(2\theta_{34}) = 0.0$]. Effects include a matter-enhanced resonance at TeV energies, neutrino absorption at high energy and small zenith, and vacuumlike oscillation at low energies. The matter-enhanced resonance appears only in the antineutrino flux for the case of small angles and $\Delta m^2_{41} > 0$. Vertical white lines indicate transitions between inner to outer core [$\cos(\theta_\nu^{\rm true}) = -0.98$] and outer core to mantle [$\cos(\theta_z^{\rm true}) = -0.83$].

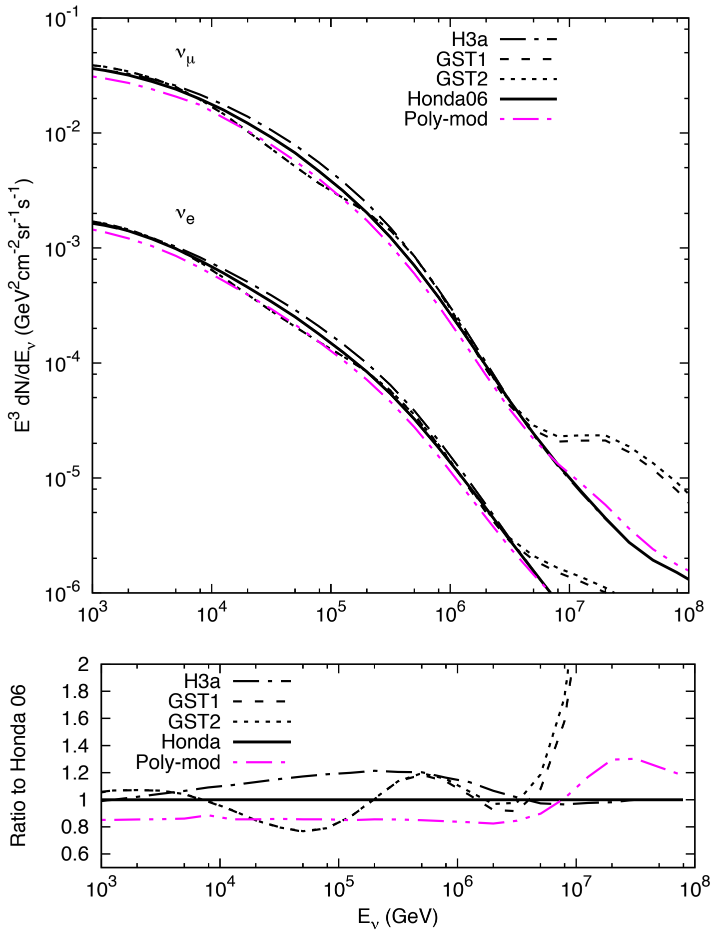
Separate ν_μ & $\bar{\nu}_\mu$ fluxes



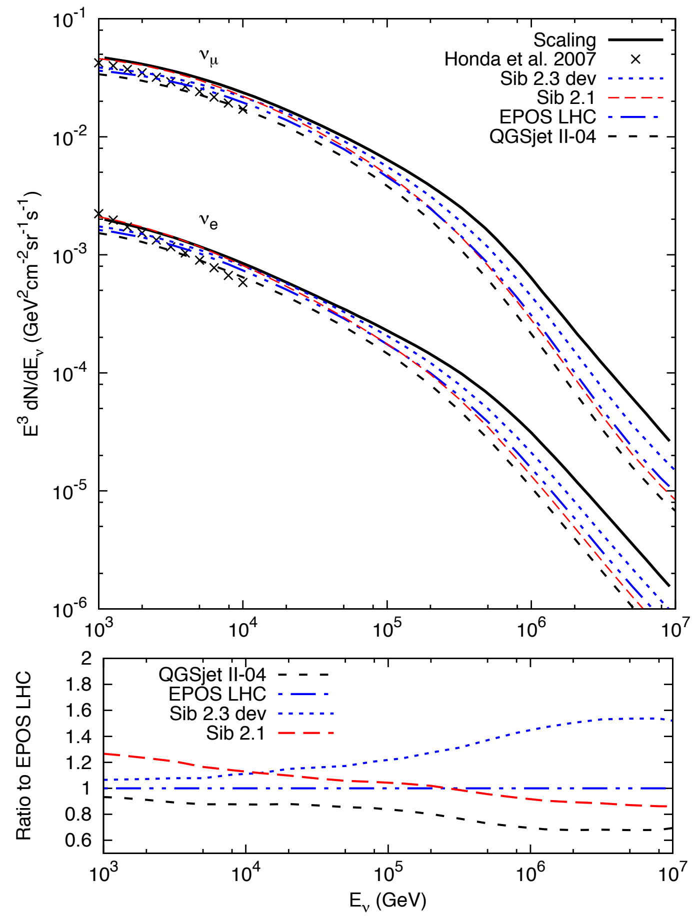
Uncertainties in conventional ν fluxes:

TG: 1605.03073

Different primary spectra

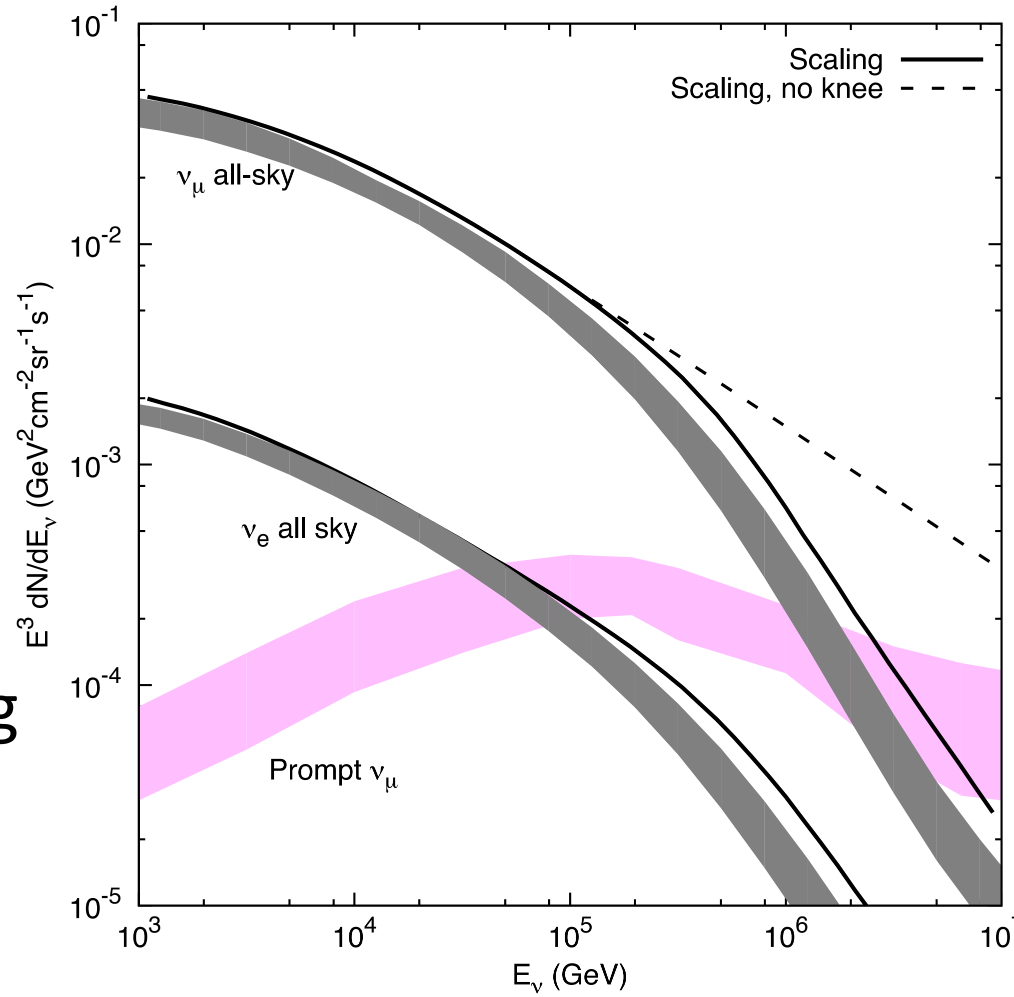


Different hadronic interaction models



Summary:

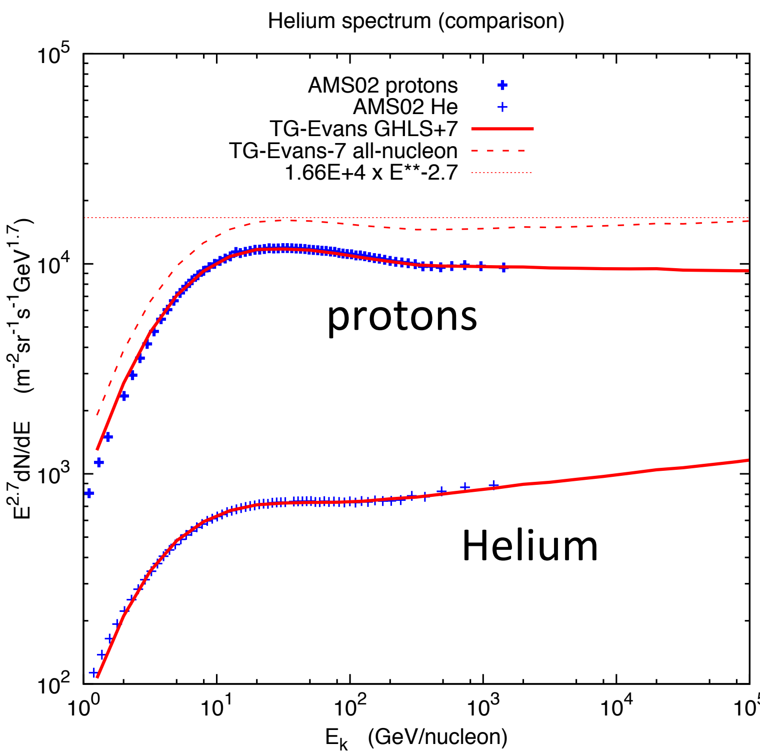
- Hadronic models
  - Gentle non-scaling
- Energy spectrum
  - Gradual steepening
  - Not a sharp break
- Prompt
  - Negligible for ν_μ below 100 TeV



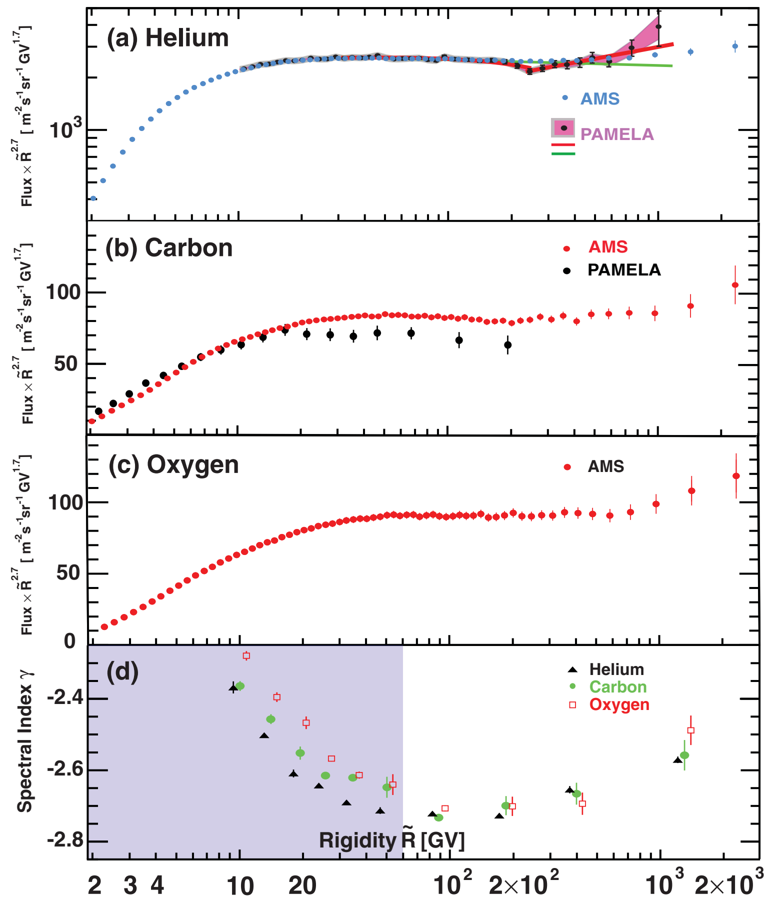
Shaded bands for conventional span Sib2.3, Epos LHC, QGSjet II-04, prompt: PROSA, Sib2.3, GRRST, BERSS

Backup on primary spectrum and composition

AMS 02

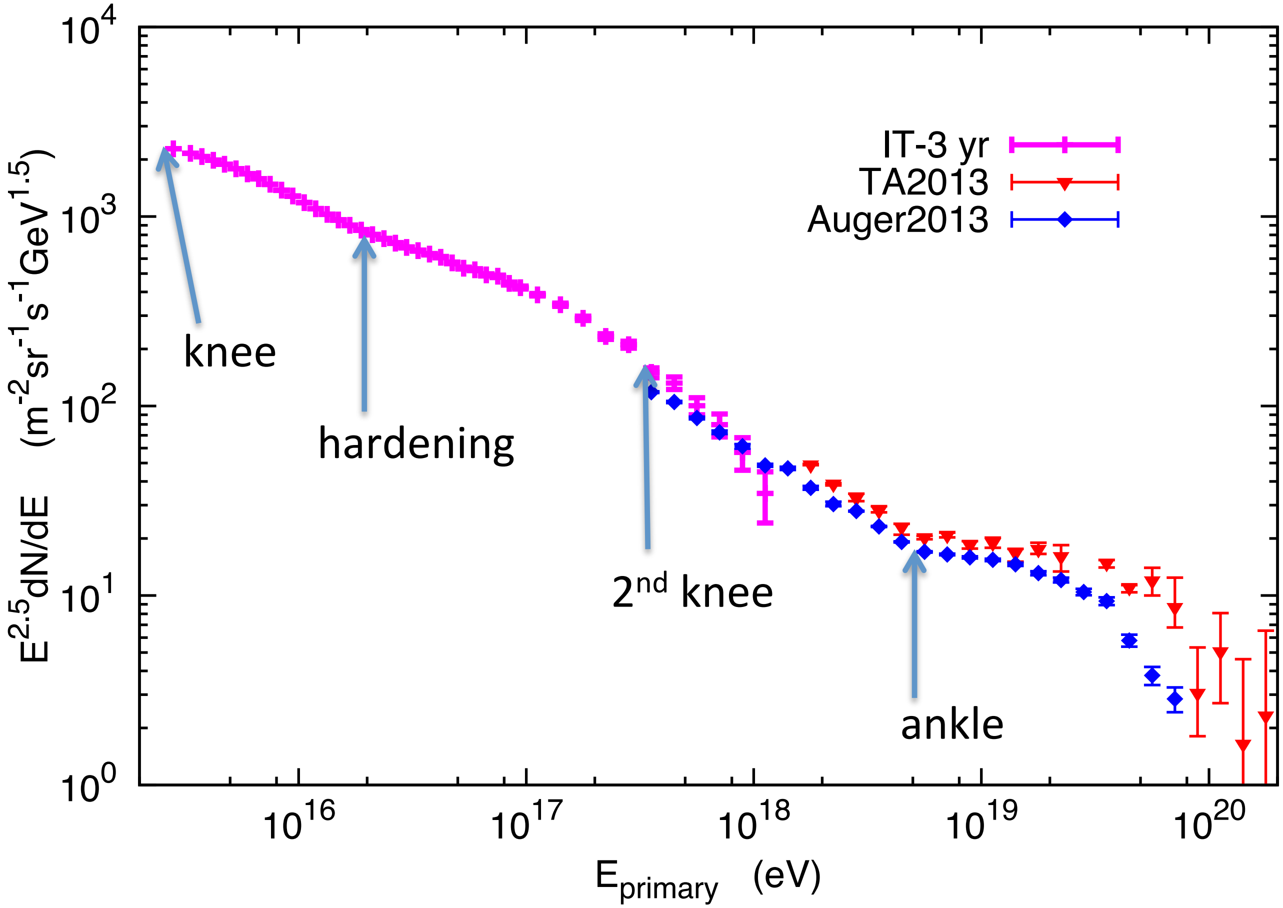


Rigidity dependent hardening



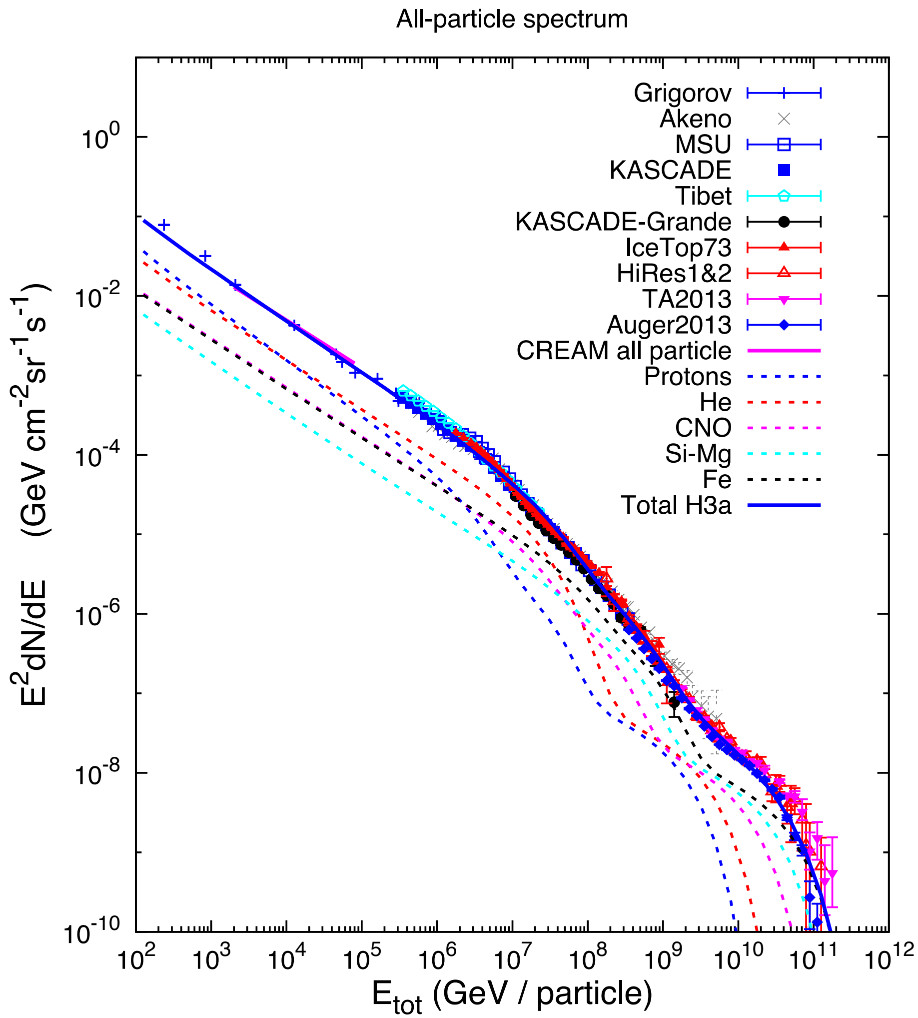
AMS02, PRL 119 (2017) 251101

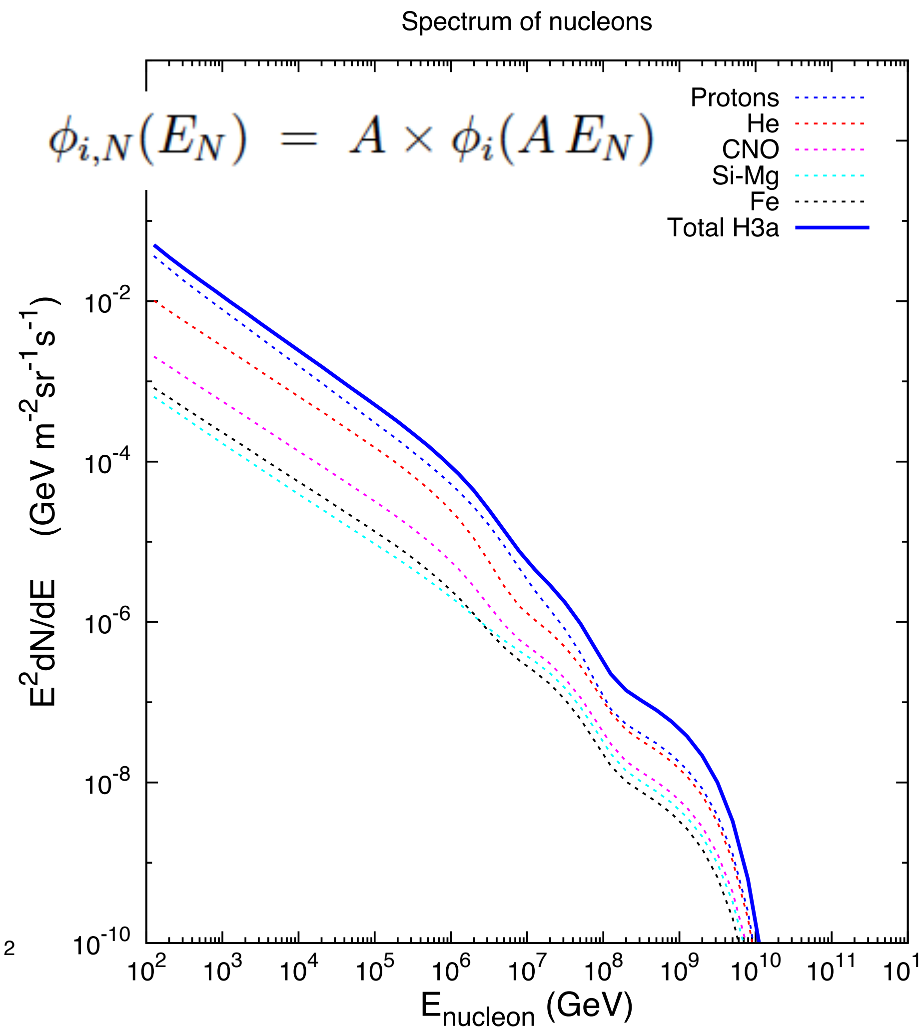
Features in all-particle spectrum



All-particle spectrum to nucleon spectrum

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





Three-population models

		p	He	CNO	Mg-Si	Fe
Galactic A	Pop. 1:	7860	3550	2200	1430	2120
	$R_c = 4$ PV	1.66 1	1.58	1.63	1.67	1.63
Galactic B	Pop. 2:	20	20	13.4	13.4	13.4
	$R_c = 30$ PV	1.4	1.4	1.4	1.4	1.4
Extragalactic: H3a →	Pop. 3:	1.7	1.7	1.14	1.14	1.14
	$R_c = 2$ EV	1.4	1.4	1.4	1.4	1.4
Extragalactic: H4a →	Pop. 3(*):	200	0.0	0.0	0.0	0.0
	$R_c = 60$ EV	1.6				

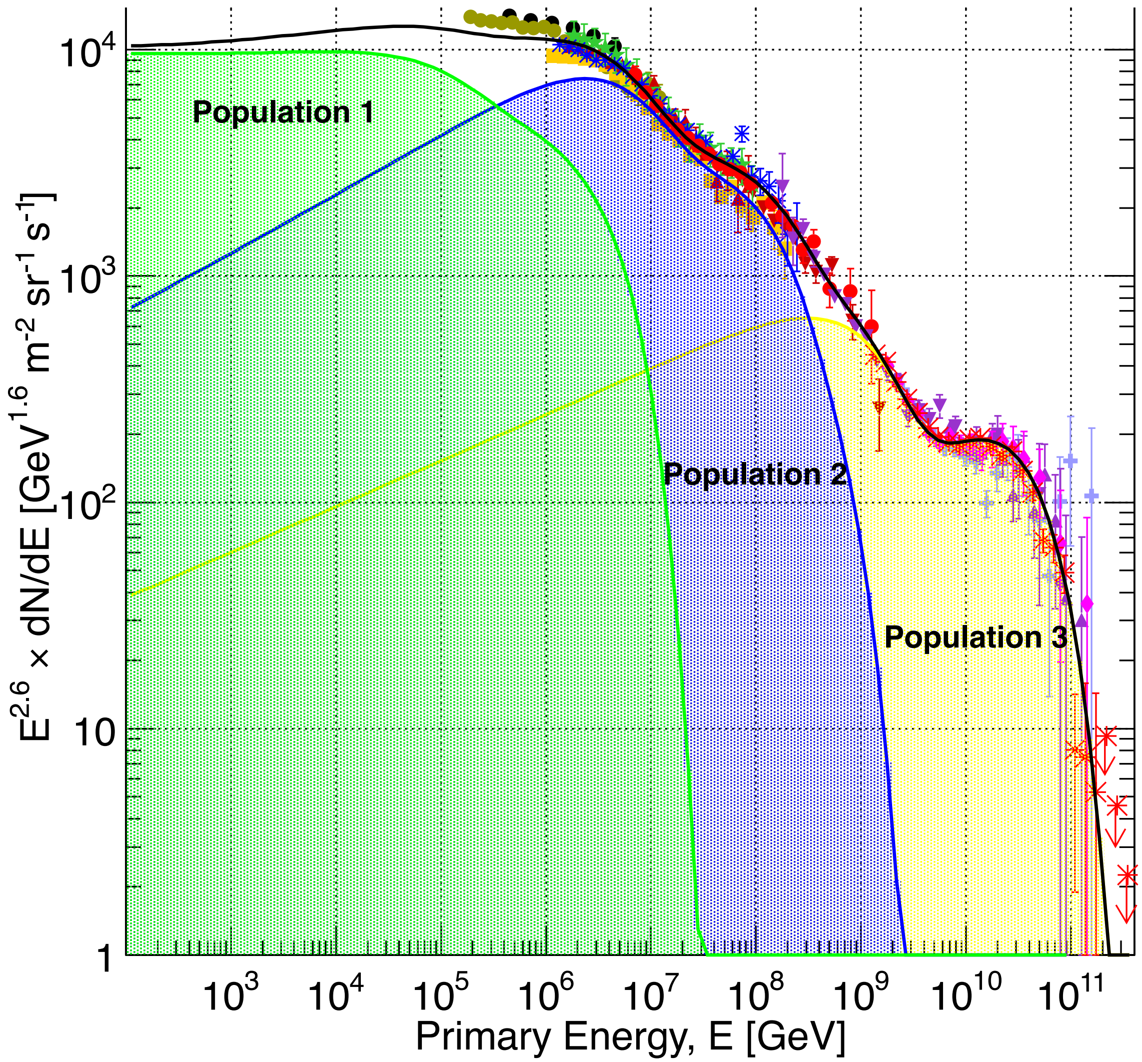
TG Astropart. Phys. 35 (2012) 801

GST

	p	He	C	O	Fe	$50 < Z < 56$	$78 < Z < 82$
Pop. 1:	7000	3200	100	130	60		
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3		
Pop. 2:	150	65	6	7	2.3	0.1	0.4
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3:	14				0.025		
$R_c = 1.3$ EV	1.4				1.2		

TG, Stanev, Tilav, Front. Phys. (Beijing) 8 (2013) 748 (arXiv:1303.3565

GST 3 population model



GSF (Global Spline Fit)

"Data-driven", no input model (H. Dembinski et al., 1711.11432)