Atmospheric neutrino fluxes at high energies depending on hadronic models

T.S. Sinegovskaya [1], A.D. Morozova [2], S.I. Sinegovsky [2,3]

[1] Irkutsk State Railway University, 664074 Irkutsk, Russia
[2] Physics Faculty, Irkutsk State University, 664003 Irkutsk, Russia
[3] Institute of Applied Physics, Irkutsk State University, 664003 Irkutsk, Russia
sinegovsky@api.isu.ru

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Abstract [T.S.Sinegovskaya et al., arXiv:1407.3591v1; 1306.5907v2]

High-energy neutrinos from decays of mesons, produced in collisions of cosmic ray particles with air nuclei, form the background for astrophysical neutrinos. More precise calculations of the high-energy neutrino spectrum are required since measurements in the IceCube experiment reach the energy region where the atmospheric neutrinos and astrophysical ones are entangled. Basing on the known hadronic models QGSJET II-03 and the SIBYLL 2.1, we calculate energy spectra of the muon and electron atmospheric neutrinos using parameterizations of cosmic ray spectra including the knee region. The neutrino flavor ratio, $\phi_{\nu_\mu}/\phi_{\nu_e}$, is calculated taking into acccount the diffuse flux of astrophysical neutrinos related to the high-energy events detected in the IceCube experiment [Science 342, 1242856 (2013); arXiv:1405.5303v2.]. Astrophysical neutrinos added to the atmospheric flux result in the flavor ratio decrease at the energy close to 10 TeV. The conclusion is consistent with a rough approximation for the flavor ratio extracted from IceCube data.

Sources of the atmospheric neutrinos

conventional ν's

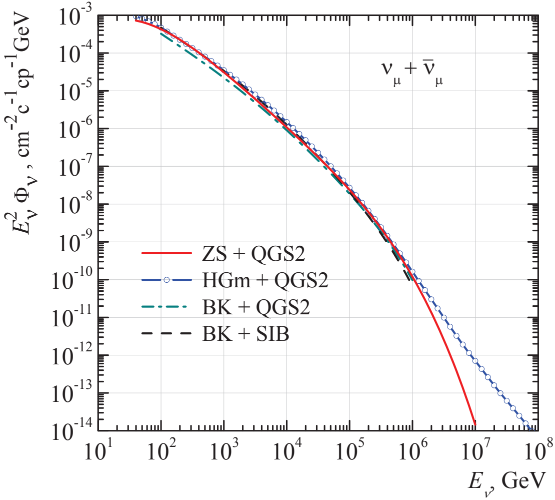
	Decay modes	Fraction
$\mu^\pm$	$e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$	$\backsimeq 100\,\%$
$\pi^\pm$	$\mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	$\backsimeq 100\,\%$
$K^\pm$	$\mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ $\pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ $\pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$ $\pi^\pm + \pi^0$	63.44 % 3.32 % 5.07 % 20.92 %
K_L^0	$\pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu)$ $\pi^\pm + e^\mp + \bar{\nu}_e(\nu_e)$	27.02 % 40.55 %
K_S^0	$\pi^+ + \pi^-$ $\pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu)$	69.20 % $4.66 \cdot 10^{-4}$

prompt ν's

	Decay modes	Fraction
$D^\pm$	$\mu^\pm + \nu_\mu(\bar{\nu}_\mu) + X$	17.2 %
$D^0, \bar{D}^0$	$\mu^\pm + \nu_\mu(\bar{\nu}_\mu) + X$	7.31 %
$D_s^\pm$	$e^\pm + X$	6.5 %
Λ_c^+	$\Lambda + \mu^+ + \nu_\mu$ $\Lambda + e^+ + \nu_e$	$2.0 \pm 0.7\,\%$ $2.1 \pm 0.6\,\%$

Influence of CR spectra on the $\nu_\mu + \bar{\nu}_\mu$ flux

Comparison of $\nu_\mu + \bar{\nu}_\mu$ flux calculations for 3 models of cosmic ray spectra involving the knee

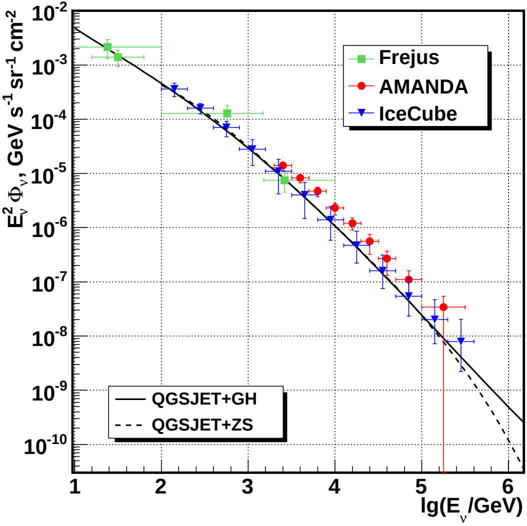


ZS: The model by Zatsepin & Sokolskaya (Astronomy & Astrophys. 458, 1 (2006));

BK: The modified multi-knee model by Bindig, Bleve and Kampert, 32 ICRC, Beijing, 2011, vol.1, p. 161;

HGm: The model of three classes of sources (A.M.Hillas astro-ph/0607109, T.K.Gaisser Astropart. Phys. 24, 801 (2012)).

The knee influence on the atmospheric $\nu_\mu + \bar{\nu}_\mu$ spectrum



The conventional (π/K) neutrino flux calculated with QGSJET II-03:

solid line: CR spectrum (beyond the knee) by Gaisser & Honda (GH) [ARNPS 52,153 (2002)]

dashed: CR spectrum by Zatsepin & Sokolskaya (ZS)

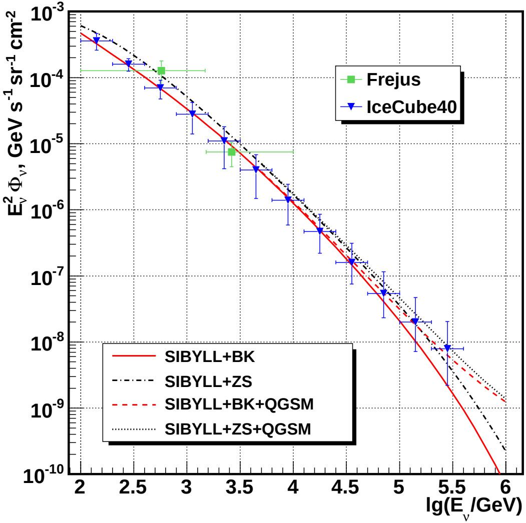
Flux ratio for different hadronic models

The comparison of atmospheric neutrino fluxes calculated with SIBYLL 2.1, QGSJET II-03 and KM for ZS and HGm cosmic ray spectra: 1 (4) – sib/qgs2; 2 (5) – km/qgs2; 3 (6) – sib/km.

E_ν, ТэВ	1	2	3	4	5	6
	ZS: $(\nu_\mu + \bar{\nu}_\mu)$			ZS: $(\nu_e + \bar{\nu}_e)$		
1	1.70	1.05	1.62	1.41	0.51	2.76
10	1.53	1.04	1.47	1.32	0.48	2.75
10^2	1.53	1.10	1.39	1.29	0.54	2.39
10^3	1.79	1.64	1.09	1.41	0.84	1.68
10^4	1.85	2.08	0.89	1.38	1.06	1.30
	HGm: $(\nu_\mu + \bar{\nu}_\mu)$			HGm: $(\nu_e + \bar{\nu}_e)$		
1	1.59	0.85	1.87	1.39	0.49	2.84
10	1.57	1.12	1.40	1.33	0.50	2.66
10^2	1.57	1.27	1.24	1.31	0.57	2.30
10^3	1.63	1.63	1.00	1.31	0.70	1.87
10^4	1.47	1.53	0.96	1.23	0.59	2.08

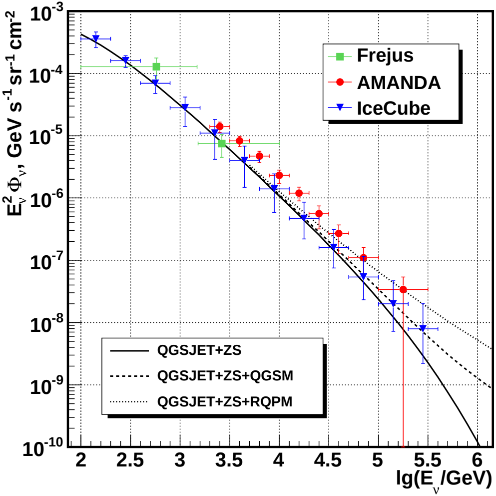
Muon neutrinos: SIBYLL 2.1 + ZS, BK

Fluxes of the conventional and prompt (QGSM) muon neutrinos ($\nu_\mu + \bar{\nu}_\mu$) calculated with SIBYLL 2.1.

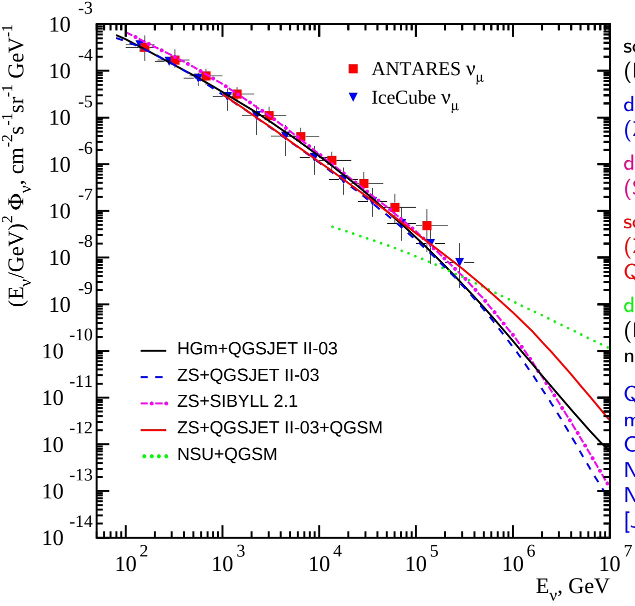


$\nu_\mu + \bar{\nu}_\mu$: QGSJET II-03 + ZS

The conventional (QGSJET II-03) and prompt (QGSM, RQPM) neutrino fluxes calculated for ZS spectrum. Symbols: the experimental data of Frejus, AMANDA, IceCube40.



$\nu_\mu + \bar{\nu}_\mu$: IceCube vs. ANTARES



solid black:
(HGm + QGSJET II)-π/K flux

dashed blue:
(ZS + QGSJET II)-π/K flux

dash-dotted:
(SIBYLL + ZS)- π/K flux

solid red:
(ZS + QGSJET II + QGSM)-total atmospheric flux

dotted green:
(NSU + QGSM)-prompt neutrino flux

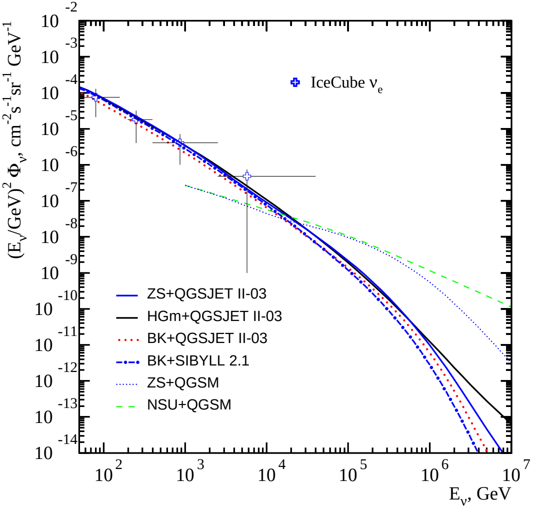
QGSM: quark-qluon string model [E.V.Bugaev et al., Nuovo Cim. C 12, 41 (1989)];
NSU: cosmic ray spectrum by Nikolsky, Stamenov, Ushev [JETP 60, 10 (1984)]

Atmosperic and diffuse $\nu_\mu + \bar{\nu}_\mu$ fluxes

Model	$E_\nu^2 \phi_\nu$, GeV (cm^2 s sr)$^{-1}$
conventional (angle averaged):	400 TeV - 1 PeV
ZS + SIBYLL 2.1	$(2.21 - 0.214) \times 10^{-9}$
ZS + QGSJET II	$(1.32 - 0.149) \times 10^{-9}$
HGm+QGSJET II	$(1.45 - 0.163) \times 10^{-9}$
prompt $\nu_\mu + \bar{\nu}_\mu$:	400 TeV - 1 PeV
NSU + QGSM	$(2.86 - 1.15) \times 10^{-9}$
HGm + QGSM	$(2.2 - 0.54) \times 10^{-9}$
$174 E_N^{-3}$ + DM	$(1.87 - 0.85) \times 10^{-9}$
total atmospheric $\nu_\mu + \bar{\nu}_\mu$**:**	$E_\nu = 1$ PeV
HGm+QGSJET II + QGSM	0.70×10^{-9}
HGm+QGSJET II + DM	1.01×10^{-9}
diffuse flux $(\nu_\mu + \bar{\nu}_\mu)$:	
IC59 limit (34.5 TeV – 36.6 PeV)	1.44×10^{-8}
ANTARES limit (45 TeV - 10 PeV)	4.8×10^{-8}
IC59 best fit,	0.25×10^{-8}
Phys.Rev. D89, 062007 (2014)	
per-flavor astrophysical flux $\nu + \bar{\nu}$:	
IceCube best fit (60 TeV - 3 PeV),	$(0.95 \pm 0.3) \times 10^{-8}$
arXiv:1405.5303v2	

Atmospheric $\nu_e + \bar{\nu}_e$ flux

$\nu_e + \bar{\nu}_e$: IceCube data and the calculations with QGSJET II-03, SIBYLL 2.1 for the three models of the cosmic ray spectrum, ZS, BK and HGm



IceCube ν_e: Phys. Rev. Lett. 110 (2013) 151105;

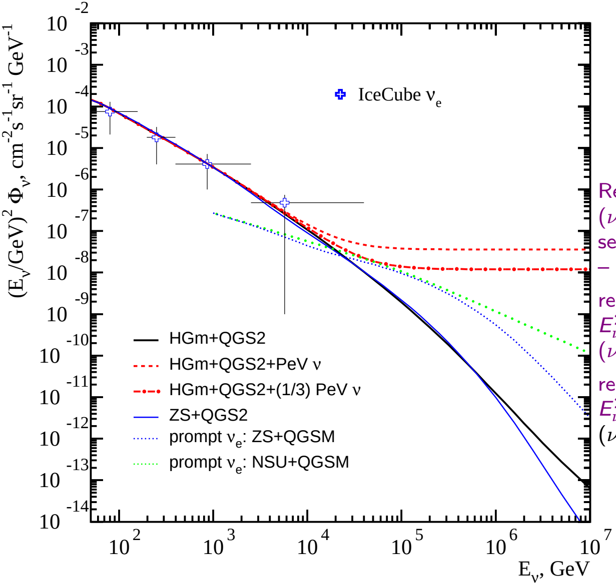
(ZS) V.I.Zatsepin, N.V.Sokolskaya, A & A. 458 (2006) 1.

(BK) D.Bindig, C.Bleve, K.-H.Kampert, 32 ICRC, Beijing, 2011, vol.1, p. 161;

(HGm) T.Gaisser, Astropart. Phys. 24 (2012) 801, arXiv:1303.1431.

The prompt neutrino fluxes: are calculated with QGSM [Nuovo Cim. C 12 (1989) 41] both for ZS (blue dots) and primary spectrum by Nikolsky, Stamenov, Ushev (NSU) [JETP 60 (1984) 10] (green dash

Atmospheric and astrophysical $\nu_e + \bar{\nu}_e$ fluxes

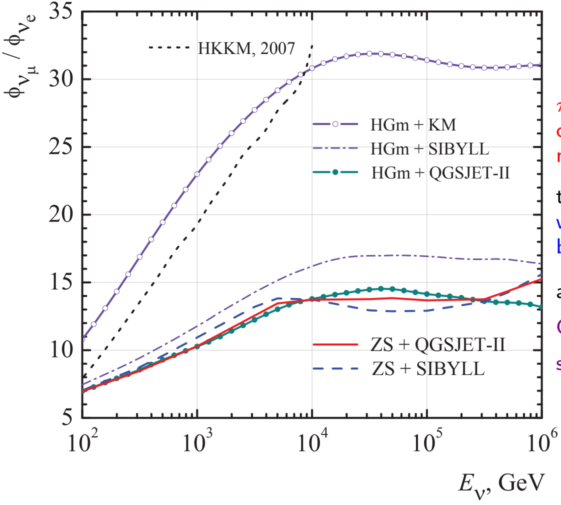


Red lines: sum of the conventional $(\nu_e + \bar{\nu}_e)$ flux and diffuse one observed in IceCube [arXiv:1304.5356] –

red dash:
$E_\nu^2 \phi_\nu = 3.6 \cdot 10^{-8}$ (cm^2 s sr)$^{-1}$ GeV
$(\nu_e : \nu_\mu : \mu_\tau = 1 : 0 : 0)$

red dash-dot:
$E_\nu^2 \phi_\nu = 1.2 \cdot 10^{-8}$ (cm^2 s sr)$^{-1}$ GeV
$(\nu_e : \nu_\mu : \mu_\tau = 1 : 1 : 1)$

Calculation of the flavor ratio R_{ν_μ/ν_e}

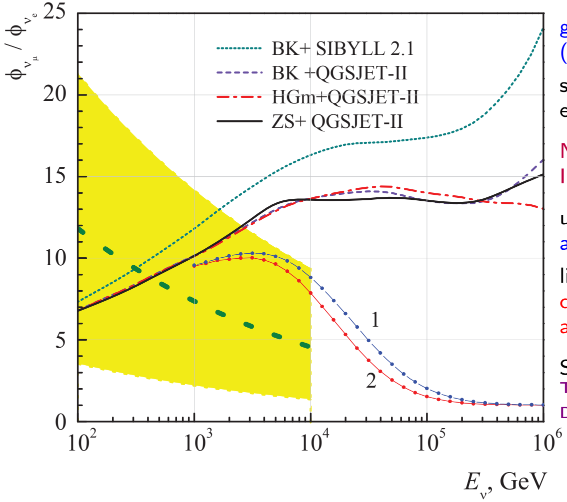


π/K neutrino flavor ratio R_{ν_μ/ν_e} calculated with different hadronic models

two top curves: this work calculation with KM and, for comparison, the result by HKKMS (2007) with DPMJET-III;.

at the bottom: calculations with QGSJET II-03 and SIBYLL 2.1 for CR spectra with knee, ZS и HGm.

The flavor ratio $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$



IceCube data:

green dashed line: mean of the $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ ratio;

solid lines: a rough estimate of the data errors.

Neutrino flux calculations with QGSJET II-03 and SIBYLL 2.1:

upper curves: the conventional atmospheric neutrino ratio;

lines 1, 2: the total neutrino flavor ratio comprising the conventional, prompt and astrophysical neutrinos.

See also:
T.Sinegovskaya, 1306.5907v2, 1407.3591v1;
D.Fargion, 1310.3543v4, 1404.5914v3.

Summary

- Considerable flux differences (up to 85%) originate from HE hadronic interaction models: the major factor of the discrepancy is the kaon production in nucleon-nucleus collisions.
- A dependence of atmospheric neutrino fluxes on the cosmic ray spectra and elemental composition becomes apparent at eneries $E_\nu > 300\,TeV$.
- The flux of astrophysical neutrinos related to the high-energy neutrino events in the IceCube experiment leads to the noticeable decrease of the flavor ratio R_{ν_μ/ν_e} in the atmosphere at energies 10 TeV - 30 TeV, even for astrophysical neutrino flavor rtaio $1:1:1$: diffuse ν_e flux dominate over atmosperic one above 10 ТэВ, if IcecCube the best fit $E^2\phi_\nu \sim 10^{-8}$ (ГэВ $\text{см}^{-2}\text{с}^{-1}\text{ср}^{-1}$) [M.G.Aartsen et al., arXiv:1405.5303v2] is valid below 30 ТэВ;
- An extrapolation of the diffuse PeV neutrino flux to $E_\nu < 30$ TeV shows the consistency of calculated neutrino flavor ratio and that of obtained from the IceCube data. This computation makes it clear that confirmation of astrophysical origin for high-energy neutrino events might be obtained from little progress in measurement of the ν_e spectrum above 10 TeV, where the flavor ratio, responsive to changes in the electron neutrino flux, allows to reveal a small fraction from astrophysical sources.

Acknowledgements

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