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Search for Galactic disk and halo components in the arrival directions of high-energy astrophysical neutrinos

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Arrival directions of 40 neutrino events with energies $\gtrsim 100$ TeV, observed by the IceCube experiment, are studied. Their distribution in the Galactic latitude and in the angular distance to the Galactic Center allow to search for the Milky-Way disk and halo-related components, respectively. No statistically significant evidence for the disk component is found, though even 100 % disk origin of the flux is allowed at the 90 % confidence level. Contrary, the Galactic Center–Anticenter dipole anisotropy, specific for dark-matter decays (annihilation) or for interactions of cosmic rays with the extended halo of circumgalactic gas, is clearly favoured over the isotropic distribution (the probability of a fluctuation of the isotropic signal is ~ 2 %).

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The origin of high-energy astrophysical neutrinos, discovered recently by the IceCube experiment [1–4], is unknown. Large flux, relatively soft spectrum and lack of anisotropy in arrival directions make it difficult to explain the observed flux in terms of a single population of well-understood sources. It is even unknown, which fraction of the flux may come from Galactic sources. Some concentration of the high-energy starting events (HESE) with energies $E \gtrsim 60$ TeV towards the Galactic Center, visible in early skymaps, suggested a possible significant Galactic fraction. This may be related to a particular population of sources in the Milky Way, to interactions of cosmic rays with the interstellar matter, to the same process in the circumgalactic gas halo, or to decay or annihilation of dark-matter particles in the Galactic dark halo. The former two scenarios should reveal themselves via excess of events coming from the Galactic plane, while the latter two explanations imply the Galactic center-anticenter asymmetry due to the non-central position of the Solar System in the Galaxy. A recent study [5] claimed an evidence for the disk component in the distribution of arrival directions of 19 HESE neutrinos, observed by IceCube in four years, with estimated energies above 100 TeV, where the contribution of the atmospheric background events is minimal. The aim of the present study is to search for the Galactic component in the combined sample of these 19 events and of 21 high-energy muon-neutrino events (HEmu) in the similar energy range from the analysis of Ref. [4]. In what follows, I compare the observed distributions of arrival directions in the Galactic latitude b (test of the disk component) and in the angular distance to the Galactic Center Θ (test of the halo scenarios) with similar Monte-Carlo distributions combining the (known) background contribution with the assumed mixture of the Galactic and isotropic components in the signal.

Data. The data set studied here consists of two parts. The first is the 4-year HESE sample whose arrival directions are published in Refs. [3, 6]. From the list of 54 events, 19 neutrinos with estimated energies above 100 TeV were selected. The choice of the energy cut is rather arbitrary but is motivated by two facts. First, above this or similar energy, the contribution of background atmospheric neutrinos becomes small compared to the presumably astrophysical flux. Indeed, the mean expected number of background events is 2.26, as one may conclude from Fig. 3 of Ref. [6]. Second, arrival directions of events of these energies are published for the second sample, so the use of the energy threshold makes it possible to consider the largest sample of high-energy events jointly.

The second part is the sample of muon neutrino tracks from the Northern sky [4], whose arrival directions are published in a public data release of the IceCube collaboration [7]. There are 21 such events; their estimated energies, quoted in the catalog [7], are above 100 TeV. One of the events in the sample is present in the HESE sample as well; however, its reconstructed energy in the HESE analysis is below 100 TeV, so it is not counted twice. From Fig. 2 of Ref. [4], one concludes that the mean expected number of background events in the sample is a sum of 6.15 conventional atmospheric neutrinos and 0.86 prompt atmospheric neutrinos. Therefore,

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the data set used here contains 40 events with the mean expected background of 9.27 events.

Monte-Carlo set: background. For the HESE sample, the expected distribution of background events in the zenith angle is presented in Supplementary Fig. 5 of Ref. [3]. Note that for the South-Pole location of IceCube, the zenith angle is uniquely translated to declination, which allows to generate Monte-Carlo distribution of background events easily.

For the HEmu sample, one considers two components of the background separately. The contribution of prompt atmospheric neutrinos, not negligible at relevant high energies, is isotropic. To obtain the distribution of conventional atmospheric neutrinos in the zenith angle, I follow Refs. [8, 9]. Both distributions are convolved with the zenith-angle-dependent acceptance of the experiment which may be read from Fig. 3b of Ref. [10] (see also Fig. 6.2b of Ref. [11]). The acceptance for a sample of 0.1 % most energetic events is used; according to Table 6.1 of Ref. [11], this roughly corresponds to energies above ~ 120 TeV.

Monte-Carlo set: isotropic signal. The assumed isotropic signal is modified by the detector acceptance, which is described in the previous paragraph for the HEmu sample. For HESE, the simulated distribution of isotropic events in zenith angle at $E > 100$ TeV is also given in Supplementary Fig. 5 of Ref. [3].

Monte-Carlo set: Galactic-disk signal. The notion of the Galactic-disk signal is ambiguous, since various populations of potential sources follow different distributions. Since the neutrino emission is accompanied by gamma rays in most scenarios, the distribution of the Galactic diffuse gamma-ray flux is often used as a template for the disk neutrino flux, see, e.g., Refs. [12, 13]. Here, we use the FERMI–LAT template of Ref. [14], for the HI contribution at gamma-ray energies 0.2–1.6 GeV (the dependence on details of the template chosen is beyond the overall precision of the analysis). The distribution of arrival directions in this and further cases is corrected for the detector acceptance, as described above, for the HESE and HEmu samples separately.

Monte-Carlo set: dark-matter signal. To emulate the anisotropy pattern of the neutrino signal from dark-matter decays, we use explicit expressions of Ref. [15] and assume the Burkert [16] distribution of dark matter. This allows one to obtain the distribution of arrival directions in the angular distance to the Galactic Center (see Ref. [17] for a study of early $E > 60$ TeV IceCube data). For the case of dark-matter annihilation, the density of dark matter n is replaced by n^2 in the same expressions.

Monte-Carlo set: outer-halo signal. Following Refs. [18–20], we consider the possibility that neutrinos are produced by cosmic-ray interactions with gas in the extended (up to ~ 200 kpc) outer halo of the Galaxy. For the target-gas distribution, we use that of Ref. [21],

$$n_{\text{gas}} \propto \left[1 + (r/r_c)^2\right]^{-3\beta/2},$$

with $\beta = 0.5$ and $r_c = 5$ kpc [21]. For the cosmic-ray distribution, we use $n_{\text{CR}} \propto 1/(1+r/r_1)$ with $r_1 = 20$ kpc to reproduce the asymptotic used in Ref. [18]. The product $n_{\text{gas}} n_{\text{CR}}$ replaces n in expressions of Ref. [15].

Results. Fig. 1 presents the distribution of simulated and observed events in the Galactic latitude. Composing the simulated data set of a known number of atmospheric background events, a fraction of ξ_d from the disk component and $1 - \xi_d$ from the isotropic distribution, it is easy to compare the distribution of observed and simulated events by means of the Kolmogorov–Smirnov test, which gives the probability P_{KS} that the observed distribution is a statistical fluctuation of the simulated one, see Fig. 2. The isotropic distribution is perfectly consistent with data ($P_{\text{KS}} \approx 0.57$). However, as one can see from Fig. 2, all values, $0 \le \xi_d \le 1$, are allowed with $P_{\text{KS}} > 0.1$, that is at least at the 90 % confidence level (CL).

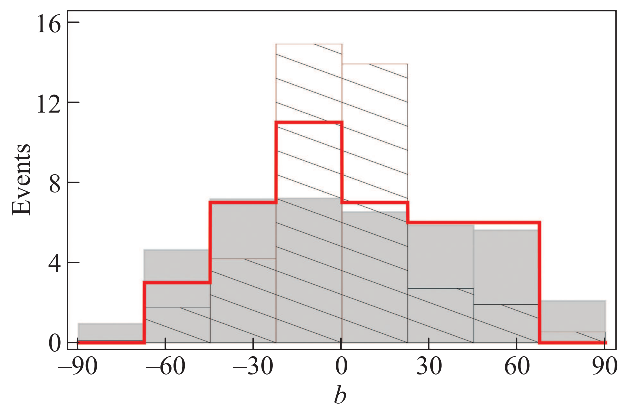

Fig. 1. (Color online) Distribution of arrival directions in galactic latitude b. Full line (red online) – data; shaded histogram – background plus isotropic signal; hatched histogram – background plus Galactic disk signal

For the halo scenarios, a similar analysis was performed in terms of the angular distance Θ between the arrival direction and the Galactic Center. The distributions of data and simulated event sets in Θ are shown in Figs. 3 and 4. The data favours the dipole anisotropy, either in the dark-matter decay or in the circumgalactic gas halo scenario, over isotropy (see Fig. 5). For the isotropic distribution, $P_{\text{KS}} \approx 0.02$, while $P_{\text{KS}} > 0.5$ for all three pure halo scenarios.

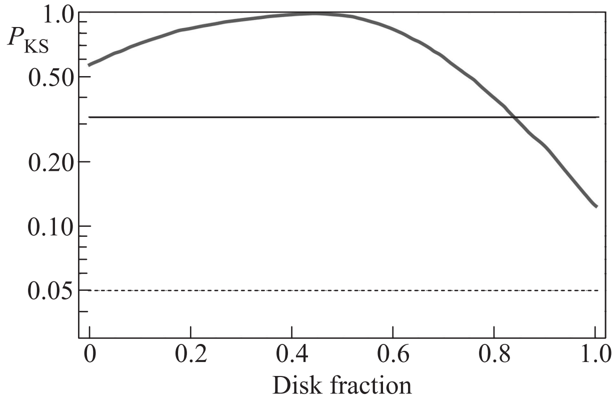

Fig. 2. The Kolmogorov–Smirnov probability P_{KS} that the observed distribution of events in the Galactic latitude b is a fluctuation of a model distribution in which the signal is a mixture of the disk fraction ξ_d and the isotropic fraction $1-\xi_d$, as a function of ξ_d (the full grey curve). Horizontal lines indicate $1-P_{KS}=0.68$ (full) and 0.95 (dotted): the values of ξ_d for which the curve is below the lines are excluded at the 68 % and 95 % CL, respectively

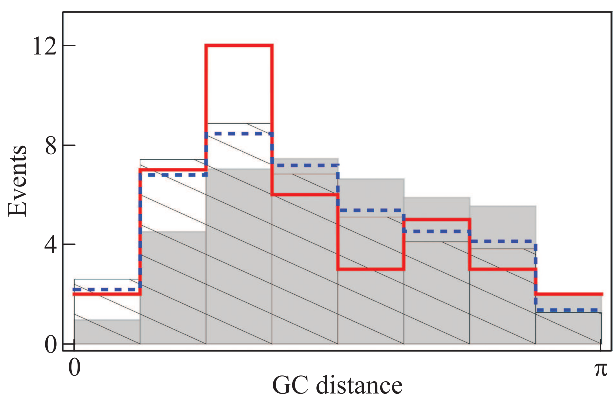

Fig. 3. (Color online) Distribution of arrival directions in the angular distance Θ to the Galactic Center. Full line (red online) – data; shaded histogram – background plus isotropic signal; hatched histogram – background plus signal from dark-matter annihilation in the Milky Way; dashed line (blue online) – background plus signal from dark-matter decays in the Milky Way

To summarize, the sample of 40 IceCube events with $E \gtrsim 100$ TeV, of which ~ 9 are background, neither shows a statistically significant evidence for, nor exclude, the Galactic disk component. The Galactic Center–Anticenter dipole, contrary, is favoured over isotropy at 98 % CL, which may be a signal of the Galactic halo component related either to dark-matter decays (annihilation) or to cosmic-ray interactions with circumgalactic gas. Further studies of high-energy neutrinos are mandatory to make stronger conclusions. In particular, more uniform full-sky statistics is important for global anisotropy studies, and will be provided in coming years with joint efforts of the South-Pole IceCube and Northern-hemisphere experiments: Baikal-GVD [22–24], whose first cluster is taking data since April 2015 and further ones are to be deployed next winter, and KM3NET [25] whose construction is expected to start.

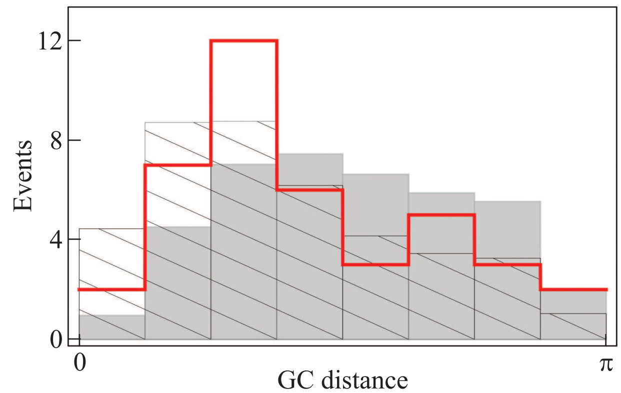

Fig. 4. (Color online) Distribution of arrival directions in the angular distance to the Galactic Center. Full line (red online) – data; shaded histogram – background plus isotropic signal; hatched histogram – background plus signal from cosmic-ray interactions with the halo of circumgalactic gas

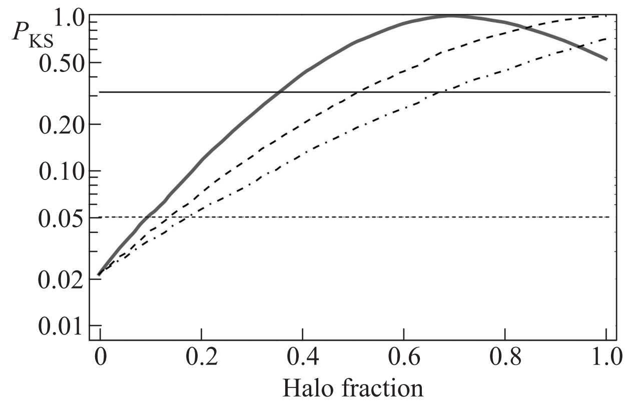

Fig. 5. The Kolmogorov–Smirnov probability P_{KS} that the observed distribution of events in the angular distance to the Galactic Center is a fluctuation of a model distribution in which the signal is a mixture of the fraction ξ_h coming from halo and the remaining fraction $1-\xi_h$ isotropic, as a function of ξ_h (full grey curve: cosmic-ray interactions with circumgalactic gas; dashed curve: dark-matter annihilation; dash-dotted curve: dark matter decays). Horizontal lines indicate $1-P_{KS}=0.68$ (full) and 0.95 (dotted): the values of ξ_h for which a curve is below the lines are excluded at the 68 % and 95 % confidence level, respectively

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