Indirect searches for dark matter particles at Super-Kamiokande

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This work presents indirect searches for dark matter as WIMPs (Weakly Interacting Massive Particles) using atmospheric neutrino data of Super-Kamiokande-I, -II and III (1996-2008). The results of two analyses are discussed: (1) search for WIMP annihilations in the Sun and (2) search for WIMP-induced neutrinos from the Milky Way halo. We looked for an excess of WIMP-induced neutrino signal from the Sun/Milky Way as compared to the expected atmospheric neutrino background. No excess of the neutrino signal was observed in any of the analyses. Corresponding limit (1) on the spin-dependent WIMP-nucleon cross section $\sigma_{A N}$ and limit (2) on the WIMP self-annihilation cross section $\langle \sigma A V \rangle$ were derived as a function of the mass of relic particles.

1 Search for dark matter from the Sun

There is a compelling evidence that ordinary baryonic matter composes only 4% of the total mass-energy of the Universe which is dominated by dark energy (73%) and dark matter (23%) components of the unknown nature. Some well motivated candidates for the dark matter (DM) particle are provided by supersymmetric theories. They belong to a collective group of particles referred to as WIMPs (Weakly Interacting Massive Particles). WIMPs may be attempted to observe directly or indirectly through detection of the products of their annihilations.

It is expected that heavy celestial objects like the Sun can gravitationally bound WIMPs. Relic particles could accumulate in its core and effectively annihilate there. Neutrinos, as one of the annihilation products, can escape from dense matter region of the Sun’s core and could be detected using neutrino telescopes, like Super-Kamiokande (SK) detector.

In the following analysis, the Sun is assumed to be a point source of neutrinos and the search is conducted for the limited angular range around its position on the sky. We look for an excess of neutrino events from direction of the Sun as compared to the expected atmospheric neutrino background in the same angular range (Fig. 1). The data set used in this analysis consists of upward-going muons which are produced in $\nu_{\mu}/\bar{\nu}_{\mu}$ interactions below the SK detector. The upward-going muons are categorized into (1) through-going associated with showers or (2) non-showering or (3) muons which stops inside the detector. The search is sensitive to WIMP masses ($M_\chi$) in a range from 10 GeV/c$^2$ to 10 TeV/c$^2$.

Various half-cone angles around the Sun were examined and no excess of events was found above expected atmospheric background (Fig. 2). The size of the investigated cone-half angle was determined for each considered $M_\chi$ in a way that it should contain 90% of the flux of neutrinos from WIMP annihilations either into $b\bar{b}$ (soft channel) or into $W^+W^-$ (hard channel).
Based on the null contribution of DM-induced neutrinos from the Sun, the upper limit on the flux of upward-going muons induced by WIMPS was derived. It is often assumed in literature that capture rate of WIMPs in the Sun and their annihilation rate are in equilibrium. Therefore, the obtained limit on upward-going muon flux can be related to the limit on spin-dependent WIMP-nucleon cross section due to expected interactions of WIMPs on hydrogen in the Sun. Constrains on the spin-dependent cross section are presented in Fig. 3 for the soft and hard annihilation channels. Obtained limit can be compared against results of direct detection experiments. In particular, this constraint excludes DAMA allowed region.

2 Search for dark matter from the Galactic Halo

This analysis is focused on the search for a signal arising from a diffuse source of dark matter annihilation in the Milky Way halo. Maximum intensity of the signal is expected from the region of the Galactic Center (GC) according to the most common DM halo models. Therefore, the expected angular distribution of DM-induced neutrino events should be sharply peaked from the GC direction.

The energy spectrum of WIMP-induced neutrinos is model dependent. We consider various DM annihilation modes: direct WIMP annihilation into pair of neutrinos, , which lead to equal flux of neutrinos of every flavor; annihilations into and into . In soft and hard annihilation channels neutrinos are mainly created in decays of mesons produced during hadronization of primary quarks. In mode DM-induced neutrinos are monoenergetic and their energy equals the mass of the annihilating relic particles. DarkSUSY simulator package was used to obtain neutrino energy spectra for different DM annihilation modes. We take into account neutrino oscillations over galactic scales and simulated expected WIMP-induced neutrino signal in the detector. The data set of Super-Kamiokande-I, -II, -III was investigated for the presence of expected signal signatures. The data set corresponds to 2805.9 live-days for contained neutrino events and 3109.6 live-days for upward-going muons.

Figure 1: Angular distribution of upward-going muons with respect to the Sun (cos$\theta_{sun} = 1$ corresponds to direction of the Sun). Crosses indicate the observed data along with statistical uncertainties (livetime: 3109.6 days). Solid lines indicate atmospheric neutrino Monte Carlo normalized to the total number of data events in each category and after taking into account neutrino oscillations with $\sin^2 2\theta_{23} = 1$ and $\Delta m^2_{32} = 0.0025$ eV$^2$. See Tanaka et al.

Figure 2: The expanded view of the angular distribution of upward-going muons around the Sun. Here, 0 degrees corresponds to the direction of the Sun. All symbols are the same as in Fig. 1.
Figure 3: Upper 90% CL limits on the WIMP-proton spin-dependent cross section as a function of the WIMP mass (above lines is excluded). Limits from direct detection experiments: DAMA/LIBRA allowed region (dark red and light red filled, for with and without ion channeling, respectively), KIMS (light blue crosses), and PICASSO (grey dotted line). Limits from indirect detection experiments (neutrino telescopes): AMANDA (black line with triangles), IceCube (blue line with squares), and this analysis (red line with stars). The previous limit from Super-Kamiokande (green dashed line) is also shown.

Figure 4: Illustration of a signal from direct annihilation of DM particles of $M_x = 1.3 \text{ GeV/c}^2$ into pair of $\nu \bar{\nu}$. SK samples used in a fit are presented. SK data (black points with error), best fit atmospheric MC with and without oscillations (blue solid and black dotted lines, respectively) and DM signal (red dashed lines) are shown with respect to the direction of the Galactic Center ($\cos \theta_{\text{GC}} = 1$ corresponds to the direction of the Galactic Center) or using the distributions of lepton momentum. Equal flux of all neutrino flavors is expected for the DM-induced neutrinos. The signal contribution is shown before fit and its normalization is enhanced for the illustration purpose. In a fit, the angular distributions shown in the figure are also binned using the lepton momentum information and relative contribution of samples is conserved during $\chi^2$ minimization.
It is assumed that collected data could be described by two components: DM-induced neutrinos (signal) and atmospheric neutrinos (background). We try to find the best combination of signal and background that would fully explain the data. We allow to vary estimation of atmospheric neutrino background as well as the hypothetical contribution from simulated DM signal. Fit is based on momentum and angular information of all collected neutrino events. Angular distributions refer to cosine of the angle between reconstructed lepton direction and direction of the GC. The effect of 119 systematic uncertainty terms is included in the procedure. The signal was simulated for a wide range of DM particle masses and is simultaneously fitted in all neutrino flavors. The illustration of the samples used in a fit is shown in Fig. 4.

No significant signal contribution is allowed by the data in addition to the atmospheric neutrino oscillation effect as shown in Fig. 5. Therefore, corresponding limit on DM-induced diffuse neutrino flux and DM self-annihilation cross section \((\sigma_A V)\) were derived as a function of \(M_X\). The upper 90% CL limit on \((\sigma_A V)\) is shown in Fig. 6.

References