

Search for the Kaluza-Klein Dark Matter with the AMANDA/IceCube Detectors

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Abstract. A viable WIMP candidate, the lightest Kaluza-Klein particle (LKP), is motivated by theories of universal extra dimensions. LKPs can scatter off nuclei in large celestial bodies, like the Sun, and become trapped within their deep gravitational wells, leading to high WIMP densities in the object's core. Pair-wise LKP annihilation could lead to a detectable high energy neutrino flux from the center of the Sun in the IceCube neutrino telescope.

We describe an ongoing search for Kaluza-Klein solar WIMPs with the AMANDA-II data for the years 2001-2003, and also present a UED dark matter sensitivity projected to 180 days from a study of data taken with the combined AMANDA II and IceCube detector in the year 2007. A competitive sensitivity, compared to existing direct and indirect search experiments, on the spin-dependent cross section of the LKP on protons is also presented.

Keywords: Kaluza-Klein, Dark Matter, IceCube

I. INTRODUCTION

Kaluza-Klein weakly interacting massive particles (WIMP) arising from theories with extra dimensions have come under increased scrutiny [1] alongside WIMP candidates from supersymmetric particle theories, e.g. the neutralino.

Several analyses [2], [3] performed on the data from the AMANDA-II and the IceCube detectors have already put limits on the neutralino induced muon flux from the Sun comparable to that of direct detection experiments. The first excitation of the Kaluza Klein (KK) photon, $B^{(1)}$, in the case of Universal Extra Dimensions (UED) with one extra dimension, annihilates to all standard model particles. This results in the production of a detectable flux of muon neutrinos in the IceCube detector. $B^{(1)}$ is often referred to as the LKP - lightest Kaluza-Klein Particle. KK-momentum conservation leads to the stability of the LKP, which makes it a viable dark matter candidate. Compared to neutralino WIMPs, LKPs come from a relatively simple extension of the Standard Model and, consequently, branching ratios (see Table I) and cross sections are calculated with fewer assumptions and parameter-dependences. This feature allows us to perform a combined channel analysis for an LKP particle. Another consequence of the simple UED model is that with the assumption of a compactified extra dimension

TABLE I
POSSIBLE CHANNELS FOR THE PAIR ANNIHILATION OF $B^{(1)}B^{(1)}$
AND BRANCHING RATIOS OF THE FINAL STATES. FIGURES TAKEN
FROM [20].

Annihilation Process	Branching ratio
$B^{(1)}B^{(1)} \rightarrow \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$	0.012
$\rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$	0.20
$\rightarrow u\bar{u}, c\bar{c}, t\bar{t}$	0.11
$\rightarrow d\bar{d}, s\bar{s}, b\bar{b}$	0.07

scale of around 1TeV, the particle takes a much narrower range of masses [1] from the relic density calculation - ranging from 600 GeV to 800 GeV and 500 GeV to 1500 GeV if coannihilations are accounted for [4]. Moreover, collider search limits rule out LKP masses below 300 GeV [5], [6].

In this paper we describe an ongoing solar WIMP analysis with the (2001) AMANDA data. Furthermore, we derive for the combined geometry of 22 IceCube strings (IC22) and AMANDA (to be referred to as the combined analysis in the rest of the paper) the projected sensitivity on the muon flux and spin-dependent (SD) cross section obtained for LKP WIMPs with data from the year 2007.

The AMANDA-II detector, a smaller predecessor of IceCube with 677 OMs on 19 strings, ordered in a 500m by 200m diameter cylindrical lattice, has been fully operational since 2001 [7]. The IceCube Detector, with its 59th string deployed this season, is much larger with increased spacing between the strings and will have a total instrumented volume of 1km³ [8]. The set-up in 2007 for the combined analysis consisted of 22 IceCube strings, and the 19 AMANDA strings, with a separate trigger and data acquisition system. The detector geometry for both AMANDA-II and IC22 is shown in Fig. 2a.

II. SIMULATIONS

A solar WIMP analysis can be thought of as using the Earth as its primary physical filter for data, as one only looks at data collected when the Sun is below the horizon at the South Pole, $\Theta_\odot \in [90^\circ, 113^\circ]$. Single¹, μ_{single} , and coincident², μ_{coin} , atmospheric muons that come from cosmic ray showers in a zenith angle

¹atmospheric muons from single CR showers

²atmospheric muons from coincident CR showers

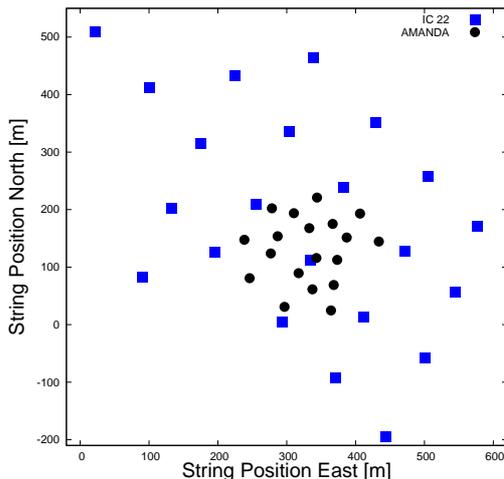


Fig. 1. Top view of the 2007 IceCube+AMANDA detector configuration. The IceCube-22 strings (squares) enclose the AMANDA strings (circles).

range Θ_μ of $[0^\circ, 90^\circ]$, constitute the majority of the background, whereas the near-isotropic distribution of atmospheric neutrinos, ν_{atm} , will form an irreducible background. The atmospheric muon backgrounds are generated using CORSIKA [9] with the Hörandel CR composition model [10]. For the atmospheric neutrino background, produced according to the Bartol model [11], ANIS [12] is used. For the combined analysis, the simulated μ_{single} background has a detector-lifetime of 1.2 days, μ_{coin} of 7.1 days and ν_{atm} of 9.8 years. WIMPSIM [13], [14] was used to generate the signal samples for LKP WIMPs, consisting of 2 million events per channel for WIMP masses varying from 250 GeV to 3000 GeV. Individual annihilation channels (three ν 's, τ , and t,b,c quarks), contributing to ν_μ 's at the detector, were generated for the combined analysis, as well as for the AMANDA only analysis (in the latter case for the energy range from 500 GeV to 1000 GeV). Muon and Čerenkov light propagation in Antarctic ice were simulated using IceCube/AMANDA software such as MMC [15], PTD and photonics [16]. Finally, AMASIM for AMANDA and ICESIM for the combined detector were used to simulate the detector response. The signal detection efficiency of the two detector configurations is given by the effective volume, V_{eff} , which is defined for a constant generation volume, V_{gen} , by

$$V_{eff} = V_{gen} \cdot \frac{N_{obs}}{N_{gen}}, \quad (1)$$

where N_{obs} is the number of observed LKP events and N_{gen} the number of generated LKP events, undergoing charged-current interaction within V_{gen} . V_{eff} is a good quantity to compare LKP detectability at trigger level for the two analyses, shown in Fig. 2a.

After deadtime correction, 142.5 days of data when the Sun was below the horizon were available in 2001 with a total number of $1.46 \cdot 10^9$ recorded events for the AMANDA analysis. The combined analysis is utilizing

a projected total livetime of 180 days of data for the calculated sensitivities in this paper.

The main purpose of the Monte Carlo (MC) simulations of the various background sources is to show that a good agreement with experiment is achieved, demonstrating a sufficient understanding of the detector. Thus, it is viable to assume that the LKP signal samples are simulated correctly within the AMANDA/IceCube simulation-chain and can be used to select the different cut parameters for the higher cut levels $L2$, $L3$ and $L4$, because their difference from background in different parameter distributions can be clearly identified. The actual cut value of each cut level is obtained by maximizing the efficiency function, or a figure-of-merit, for simulated LKP signals and the experimental background sample, which consists of data taken when the Sun was above the horizon and therefore contains no solar WIMP signal. Setting cut values based on experimental background datasets has the advantage that possible simulation flaws are minimized.

III. FILTERING

LKP signals are point sources with very distinct directional limitations (zenith angle theta, $\Theta_{zen} = 90^\circ \pm 23^\circ$). Hence, the general strategy of filtering for both analyses is to apply strict directional cuts in early filter levels. $L0$ and $L1$ consist of calibration, reconstruction and making a simple angular cut of $\Theta_{zen} > 70^\circ$ on the first-guess reconstructed track. This leads to a passing efficiency of around 0.7 for all LKP signal samples, and reduction of around 0.002 for both, data and muon background. All events passing the $L0 + L1$ level are reconstructed using log-likelihood methods (llh). $L2$ is a two dimensional cut on the reconstructed llh-fit zenith angle ($\Theta_{zen, llh}$) within Θ_\odot and the estimated angular uncertainty of the llh track. $L3$ picks reconstructed tracks, which are nearly horizontal and pass the detector, to further minimize vertical tracks associated with background events. The multivariate filter level, $L4$, consists of two different multivariate analysis routines from the TMVA [17] toolkit, namely a support vector machine (SVM) together with a Gaussian fit-function and a neural network (NN). The input variables for the two algorithms are obtained by choosing parameters with low correlation but high discrimination power between background and signal. The individual output parameters are combined in one multivariate cut parameter $Q_{NN} \cdot Q_{SVM}$.

IV. SENSITIVITY

After the $L4$ cut³, the muon background reduction is better than a factor $1.16 \cdot 10^{-7}$, which implies that the final sample is dominated by ν_{atm} background. The solar

³starting with $L4$, only the combined analysis is discussed

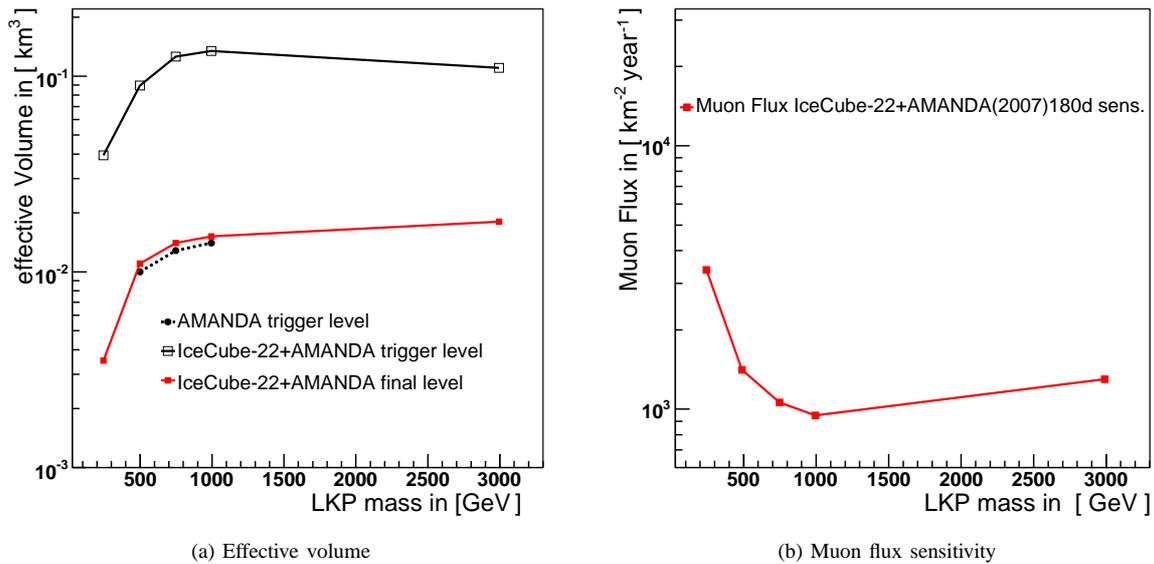


Fig. 2. Fig.2a shows the effective volume as a function of LKP mass at trigger level and final cut level for the IceCube-22+AMANDA analysis and at trigger level only for the AMANDA analysis. Fig.2b demonstrates the projected sensitivity to 180 days of livetime on the muon flux from LKP annihilations in the Sun as a function of LKP mass for the IceCube-22+AMANDA detector configuration.

search looks for an excess in neutrino events over the expected background in a specifically determined search cone towards the direction of the Sun with an opening angle Ψ . Events with a reconstructed track direction pointing back towards the Sun within an angle Ψ are kept, where Ψ is optimized to discriminate between the ν_{atm} background and a sum of all seven LKP channels, weighted with the expected branching ratios as listed in Table I.

The expected upper limit, or sensitivity, for an expected number of background events n_{Bg} is

$$\bar{\mu}_s^{90\%}(n_{Bg}) = \sum_{n_{obs}=0}^{\infty} \mu_s^{90\%}(n_{obs}) \frac{(n_{Bg})^{n_{obs}}}{(n_{obs})!} e^{-n_{Bg}}, \quad (2)$$

where $\mu_s^{90\%}(n_{obs})$ is the Feldman-Cousins upper limit for the number of observed events, n_{obs} [18]. The model rejection factor [19]

$$MRF = \frac{\bar{\mu}_s^{90\%}}{n_s}, \quad (3)$$

is used to determine the optimum opening angle Ψ of the solar search cone. Here, n_s is the number of surviving LKP events within Ψ .

Under the assumption of no signal detection, it is possible to derive the Feldman-Cousins sensitivity discussed above for the combined detector with a total projected livetime of $T_{live} = 180$ days. The expected number of events after cut level $L4$ are estimated from a processed subset of observational data with a detector livetime of 5.61 days. The results are then extrapolated to the total livetime T_{live} , yielding an expectation of 7140 events. The corresponding expectation from the simulated background samples, $n_{Bg,MC}$, normalized

to the data at filter level $L1$ and extrapolated to T_{live} , is $633(\mu_{coin}) + 1038(\mu_{single}) + 5340(\nu_{atm}) = 7011(n_{Bg,MC})$.

The expected sensitivity on the neutrino-to-muon conversion rate $\bar{\Gamma}_{\nu \rightarrow \mu}^{90\%}$ is given by

$$\bar{\Gamma}_{\nu \rightarrow \mu}^{90\%} = \frac{\bar{\mu}_s^{90\%}}{V_{eff} \cdot T_{live}}, \quad (4)$$

where the effective volume V_{eff} is given by eq. 1. For each annihilation channel, one can separately calculate the V_{eff} within the solar search cone, determined by the combined signal p.d.f., $f_S^{all}(x|\Psi)$, and thereby determine a $\bar{\Gamma}_{\nu \rightarrow \mu}^{90\%}$ for each channel. Additionally, the combined effective volume, $V_{eff,LKP}$, for the expected ν_{LKP} spectrum is given by the sum of the individual V_{eff} per channel, weighted with the respective branching ratio of each channel. For the neutrino-to-muon conversion rate per single channel, the expected limit on the annihilation rate in the core of the Sun per second is given by,

$$\bar{\Gamma}_A^{90\%} = (c_1(ch, m_{B(1)}))^{-1} \cdot \bar{\Gamma}_{\nu \rightarrow \mu}^{90\%}, \quad (5)$$

where $c_1(ch, m_{B(1)})$ is an LKP annihilation channel (ch) and energy dependent constant. The sensitivity to the muon flux at a plane at the combined detector is derived via the calculation chain $\bar{\Gamma}_{\nu \rightarrow \mu}^{90\%} \rightarrow \bar{\Gamma}_A^{90\%} \rightarrow \Phi_{\mu}^{90\%}$ and is performed using the code described in [13], [14]. The results for the final V_{eff} and the predicted sensitivity to a muon flux resulting from LKP induced annihilations in the Sun for the combined IC22 and AMANDA detector 2007 with a total livetime of 180 days are presented in figures 2a and 2b. From the derived ν -to- μ conversion rate, $\bar{\Gamma}_{\nu \rightarrow \mu, LKP}^{90\%}$, we can calculate the sensitivity for the annihilation rate in the Sun per second, $\bar{\Gamma}_{A, LKP}^{90\%}$.

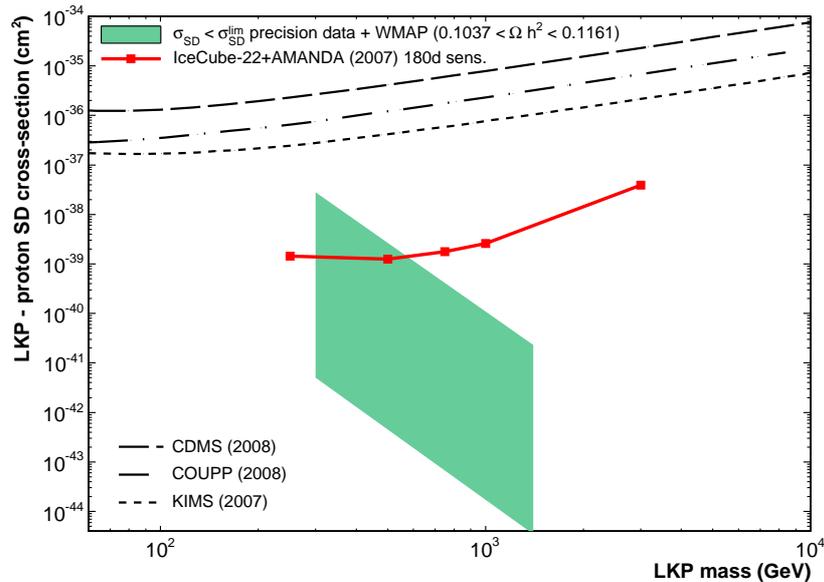


Fig. 3. Theoretically predicted spin-dependent $B^{(1)}$ -on-proton elastic scattering cross sections are indicated by the shaded area [22]. The cross-section prediction vary with the assumed mass of the first KK excitation of the quark, constrained by $0.01 \leq r = (m_{q^{(1)}} - m_{B^{(1)}})/m_{B^{(1)}} \leq 0.5$. The current ‘best’ limits, set by direct search experiments are plotted together with the sensitivity of the combined detector IceCube-22+AMANDA. The region below $m_{B^{(1)}} = 300$ GeV is excluded by collider experiments [5], [6] and $m_{B^{(1)}} > 1500$ GeV is strongly disfavored by WMAP observations [23].

In [20], it is shown that the equilibrium condition between $\Gamma_{A,LKP}$ and the capture rate C^\odot is met by LKPs within the probed mass range. Furthermore, the capture rate of LKPs in the Sun is entirely dominated by the spin-dependent component of the $B^{(1)}$ -on-proton elastic scattering [21]. Consequently, presuming an equilibrium of $\Gamma_{A,LKP} = C^\odot$, the sensitivity for the spin-dependent elastic scattering cross section⁴ of $B^{(1)}$ can be calculated as,

$$\sigma_{H,SD} \simeq 0.597 \cdot 10^{-24} \text{pb} \left(\frac{m_{B^{(1)}}}{1 \text{TeV}} \right)^2 \cdot \left(\frac{\bar{\Gamma}_{A,LKP}^{90\%}}{\text{s}^{-1}} \right). \quad (6)$$

The estimated sensitivity for the spin-dependent cross section for LKPs is displayed in figure 3, along with the most recently published limits from direct search experiments. The theoretical spin-dependent cross section predictions (shaded area) for LKPs are taken from [22] and are plotted for different predictions for the mass of the first KK-excitation of the quark.

V. CONCLUSION AND OUTLOOK

We showed that a competitive result on the spin-dependent cross-section of LKP-on-proton scattering can be obtained with the combined geometry of AMANDA-II and IceCube-22, which explores parts of the unrejected regions in the theoretically predicted LKP-region.

We also described the ongoing solar WIMP analysis

⁴The local density of DM in our galaxy is taken to match the mean density $\bar{\rho}_{DM} = 0.3 \text{ GeV}/c^2 \text{ cm}^3$, and the rms velocity is set to $\bar{v} = 270 \text{ km/s}$.

of the AMANDA-II data taken during 2001. This will be extended to include 2002 and 2003 data. Furthermore, as the energy signature of ν_μ 's induced by LKP annihilations in the Sun is very hard, the full-sized IceCube-80 detector will markedly improve the sensitivity and set strong limits on LKP WIMP theories.

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