Direct Detection of Physics Beyond the Standard Model

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Abstract

In supersymmetric theories where the lightest supersymmetric particle is the gravitino the next to lightest supersymmetric particle (NLSP) is typically a long lived charged slepton. These NLSPs can be produced by high energy neutrinos interactions with nucleons in the Earth and be detected by km$^3$ neutrino telescopes. The signal, consists of two parallel charged tracks separated by a few hundred meters. This is compared to the main background, coming from direct di-muon production. The distance between the background tracks is much smaller and allows for a clean separation from the NLSP signal. We conclude that neutrino telescopes will complement collider searches in the determination of the supersymmetry breaking scale, and may even provide the first evidence for supersymmetry at the weak scale.

Key words: neutrinos, supersymmetry, gravitino

PACS: 11.30.pb, 13.15+g, 12.60.jv, 95.30.Cq

1. Introduction

One of the most attractive candidate theory for the extension of the standard model of particle physics is weak scale supersymmetry (susy). The particle spectrum of this model is determined by the susy breaking mechanism ($\sqrt{F}$). When susy is broken at high scales such that $\sqrt{F} \gtrsim 10^{10}$GeV the LSP is typically the neutralino. If however susy is broken at lower scales, $\sqrt{F} \lesssim 10^{10}$GeV, the LSP tends to be the gravitino and the Next to Lightest Supersymmetric Particle (NLSP) is usually a charged slepton, typically the right-handed stau. Within these models, if $\sqrt{F}$ is much larger than a TeV the stau NLSP decay is suppressed [1] and its lifetime can be very large.

It was recently proposed [1] that the diffuse flux of high energy neutrinos colliding with the Earth can produce pairs of slepton NLSPs. The energy loss of these particles is very small and they travel for long distances before stopping. This compensates their small production cross section since they can be detected far away from their production point.

The NLSP production typically has a high boost and they will not decay inside the Earth provided the susy breaking scale is $\sqrt{F} > 10^7$GeV. Since the NLSP is charged, its upward going tracks can be detected in large ice or water Cerenkov detectors, such as IceCube.

We performed a Monte Carlo simulation of the NLSP production and propagation through the Earth and determined their signature in km$^3$ neutrino telescope [2].
The main background (di-muon events) was also simulated and compared to the NLSP signal.

2. NLSP Production and Propagation Through the Earth

The susy processes for NLSP production is analogous to the standard model (SM) charged current (CC) interaction and involves a t-channel production of a left-handed slepton ($\tilde{l}_L$) and a squark ($\tilde{q}$) through a gaugino exchange. In the dominant process the gaugino is a chargino and in the subdominant process a neutralino. The $\tilde{l}_L$ and $\tilde{q}$ prompt decay results in two lighter right-handed sleptons (NLSPs) plus SM particles. The NLSP will always be produced in pairs and is typically the stau ($\tilde{\tau}_R$).

The energy threshold for the NLSP production is given by the $\tilde{l}_L$ and $\tilde{q}$ masses. We take the typical values of 250 GeV for both chargino and $\tilde{l}_L$ masses, 150 GeV for the NLSP mass and set the $\tilde{q}$ mass to three values of 300, 600 and 900 GeV.

We compute the NLSP cross section including both dominant and subdominant processes. The susy cross section is about three orders of magnitude lower than the SM production cross section [2].

For the high energy neutrino flux reaching the Earth, we take the Waxman-Bahcall [3] limit

$$\left(\frac{d\phi_\nu}{dE}\right)_{WB} = (1 - 4) \times 10^{-8} \frac{E^2}{\text{GeV}} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}. \tag{1}$$

Since the NLSP production is independent of the neutrino flavor, the initial neutrino flux contains both $\nu_\mu$ and $\nu_e$ in a 2 : 1 ratio.

The NLSP propagation through the Earth depends on its energy loss which at high energies is dominated by radiative losses. The main processes are bremsstrahlung, pair production and photo-nuclear interactions [2,4]. As a result the NLSP will travel distances much greater than a muon which will compensate for the lower cross section.

3. Simulation of NLSP Production, Propagation and Detection

In order to analyze the NLSP production, propagation and detection we developed a Monte Carlo simulation. Assuming an isotropic incoming neutrino flux we generated 30K NLSP events for each $\tilde{q}$ mass. The neutrino incoming energy is distributed in steps ranging from the stau production threshold to $10^{11}$ GeV.

The survival probability ($P_S$) for a neutrino traveling through a path $dl$ is given by

$$P_S = \exp(\int n\sigma dl)$$

where $n$ is the Earth number density [5] and $\sigma$ is the interaction cross section. The probability of interaction is $1 - P_S$.

To simulate the NLSP production an interaction point is randomly chosen from an interaction probability distribution. If the interaction point falls within a distance from the detector that is smaller than the NLSP range the event is accepted. If this distance is greater than the NLSP range the event will only count for the normalization.

The center of mass (CM) angular distribution was chosen based on the differential cross section distribution. We assume that the CM angular distribution of the right-handed slepton pair (NLSPs) is the same as the CM angular distribution of the $\tilde{l}_L$ and $\tilde{q}$ which is a good approximation [2]. The 4-momentum of the NLSP pair is
Fig. 1. Energy distribution of $\tilde{\ell}_R$ pair events per km$^2$, per year, at the detector. Curves that do not reach y axis; from top to bottom: $m_{\tilde{q}} = 300, 600$ and 900 GeV. Here, $m_{\tilde{\ell}_R} = 150$ GeV and $m_{\tilde{\nu}} = 250$ GeV. Also shown are the neutrino flux at earth and the $\mu$ and the di-muon flux through the detector (curves that reach y axis; from top to bottom respectively). In all cases we make use of the WB limit for the neutrino flux.

determined in the CM from the angular distribution and boosted to the lab frame. The lab angular ($\Theta_{\text{lab}}$) distribution is determined from the lab 4-momentum.

With this procedure we can determine not only the rate of events at the detector as well as the two NLSP track separation in the detector. The separation is simply $\Theta_{\text{lab}}$ times the distance from the neutrino interaction point and the detector.

4. Background

Muons produced in the Earth could be a potential source of background for the NLSPs events. They can however be eliminated by requiring two charged tracks in the detector. The remaining important background is di-muon events originated from charm decay. Charm is produced from high energy neutrino interactions through the following process: $\nu N \rightarrow \mu^- H_c \rightarrow \mu^- \mu^+ H_x \nu$, where the charm hadron decays according to $H_c \rightarrow H_x \mu^+ \nu$ and $H_x$ can be a strange or non-strange quark.

We computed the charm production cross section $\sigma(\nu N \rightarrow cX)$ from a d or s quark [2]. Although this cross section is around an order of magnitude greater than the one for NLSP production [2], muons lose much more energy while traveling through the Earth and therefore have to be produced very close to the detector. For this reason their track separation in the detector will also be much smaller.

We performed a Monte Carlo simulation of the di-muon production, propagation and detection using the same procedure as for the NLSP.

5. Results

The energy distribution of NLSPs and di-muon background are shown in Figure 1. The number of events per km$^2$ per year is shown in Table 1 where not only a neutrino incoming rate equal to the WB limit is assumed but also one equal to the Mannheim, Protheroe and Rachen (MPR) limit [6].

Figure 1 and Table 1 show that km$^3$ neutrino telescopes are sensitive to NLSP detection. Although the number of di-muon events is larger than the NLSP rate there are many ways to reduce this background.
Table 1
Number of events per km$^2$ per year assuming the WB and MPR limits. The first column refers to di-muon events. The last three columns correspond to NLSP pair events, for three different choices of squark masses: 300 GeV, 600 GeV and 900 GeV. The number of di-muon events are given for energies above $10^3$ GeV and of NLSPs above threshold for production.

| Squark Mass (GeV) | Di-muon Events | NLSP (300) | NLSP (600) | NLSP (900) |
|------------------|----------------|------------|------------|------------|
| WB               | 30             | 6          | 1          | 0.3        |
| MPR              | 1412           | 21         | 3          | 1          |

Fig. 2. Arrival energy distribution of the $\tilde{\ell}_R$ at the detector and for $m_{\tilde{q}} = 300, 600$ and 900 GeV. Here, $m_{\tilde{\ell}_R} = 150$ GeV and $m_{\tilde{w}} = 250$ GeV. Also shown is the arrival distribution for the di-muon background. The energy deposited in the detector by a stau traveling the average track length of 800 m [7] is $E_{\tilde{\ell}_R}^{\text{dep}} = 150$ GeV, approximately the same for all the masses considered here.

First of all the lower integration limit to determine the number of events shown in Table 1 is different for the NLSP and the background. It is the NLSP production threshold energy for the number of NLSPs and $10^3$ GeV for the di-muon background. The reason for this is that as the NLSPs lose less energy than muons, they will look like lower energy muons in the detector. The NLSP energy deposition in the detector is 150 GeV (see figure in [2]). For the same reason, one can cut higher energy events removing events that deposit more than 300 GeV and reduce most of the dimuon background. Figure 2 shows the arrival energy at the detector for both NLSP and di-muon background where the efficiency of such a cut is clear.

Another powerful way for background reduction is the track separation between 2 NLSPs in the detector. This is shown in Figure 3. While a good fraction of the NLSP events are more than 50 m separated the dimuons are less than 50 m separated.

6. Conclusions

We conclude that Km$^3$ neutrino telescopes have the potential to discover the NLSP if susy models that predict the gravitino as the LSP and a charged slepton as the NLSP are correct. This will be an indirect determination of the dark matter.
Fig. 3. Top panel: Track separation distribution of $\tilde{\ell}_R$ pair events. Bottom panel: The track separation distribution of the di-muon background. The relative normalization corresponds to the relative number of events for signal and background. Note the different horizontal scales, as well as different binning between the two figures.

If the NLSP is observed it will constitute a direct probe of the susy breaking scale. This search is complementary to the LHC.

Acknowledgements I.F.M.A participation in the EPNT workshop was partially supported by the Brazilian National Counsel for Technological and Scientific Development (CNPq).

References
[1] I.F.M. Albuquerque, G. Burdman and Z. Chacko Phys. Rev. Lett. 92, 221802 (2004).
[2] I.F.M. Albuquerque, G. Burdman and Z. Chacko arXiv:hep-ph/0605120 (2006).
[3] E. Waxman and J. N. Bahcall, Phys. Rev. D 59, 023002 (1999); J. N. Bahcall and E. Waxman, Phys. Rev. D 64, 023002 (2001).
[4] M. H. Reno, I. Sarcevic and S. Su, Astropart. Phys. 24, 107 (2005).
[5] R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. 5, 81 (1996).
[6] K. Mannheim, R. J. Protheroe and J. P. Rachen, Phys. Rev. D 63, 023003 (2001).
[7] I.F.M. Albuquerque, J. Lamoureux and G. F. Smoot, Astrophys. J. Suppl. 141, 195 (2002).