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Supersymmetric and Kaluza-Klein particles multiple scattering in the Earth

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Neutrino telescopes with cubic kilometer volumes have the potential to discover new particles. Among them are next to lightest supersymmetric (NLSPs) and next to lightest Kaluza-Klein (NLKPs) particles. Two NLSPs or NLKPs will transverse the detector simultaneously producing parallel charged tracks. The track separation inside the detector can be a few hundred meters. As these particles might propagate a few thousand kilometers before reaching the detector, multiple scattering could enhance the pair separation at the detector. We find that the multiple scattering will alter the separation distribution enough to increase the number of NLKP pairs separated by more than 100 meters (a reasonable experimental cut) by up to 46% depending on the NLKP mass. Vertical upcoming NLSPs will have their separation increased by 24% due to multiple scattering.

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I. INTRODUCTION

One of the contemporary questions in particle physics regards extensions of the standard model at higher energy scales. New physics should appear around TeV energy scales. Large telescopes for high-energy astrophysical neutrinos can complement colliders in searching for signatures of extension models. In some models, their sensitivity can extend beyond the reach of the LHC. More specifically it was shown that neutrino telescopes can directly detect next to lightest supersymmetric particles (NLSP) [1,2] and next to lightest Kaluza-Klein (KK) particles (NLKP) [3]. In scenarios were the lightest supersymmetric (KK) particle is the gravitino (KK mode of the graviton), charged right-handed sleptons (KK lepton modes) will be the NLSP (NLKP). In the supersymmetric scenario, neutrino telescopes searches will complement collider searches in the determination of the supersymmetry breaking scale [1].

Searches for both NLSPs and NLKPs complement dark matter searches. The lightest particle in each of these scenarios are dark matter candidates. Both the gravitino and the KK mode of the graviton cannot be detected, at least with the current technologies. Therefore NLSP (NLKP) searches also probe dark matter, albeit indirectly. Other supersymmetry scenarios with charged leptons as NLSPs to be probed by neutrino telescopes were considered by [4]. These assume scenarios where either the neutralino or a super weakly massive interacting particle is the LSP.

High energy (above 10^5 GeV) neutrino interactions in the Earth may produce supersymmetric or KK particles. These will go through a decay chain [1,3] which will always lead to the production of two NLSPs or NLKPs. These next to lightest particles will propagate through the Earth, eventually reaching a neutrino telescope. Because of their heavy mass, their specific energy loss (dE/dx) as they propagate through the Earth is much smaller [2,5] than the loss by standard leptons. For this reason NLSPs and NLKPs may have a range of thousands of kilometers, while even the most energetic muons have a range of a few tens of kilometers. The smaller energy loss compensates the small NLSP and NLKP production cross sections.

One signature for these new particles is two charged tracks transversing the detector [2,3]. Here we investigate the NLSP and NLKP multiple scattering while propagating through the Earth. We consider the simulated distribution of their production point and energy loss as described in [2,3]. The separation distance between the two charged tracks in the detector will be a powerful discriminating observable. It is an excellent parameter to separate NSLPs or NLKPs from the main background, which consists of di-muon events. As a preview to our conclusion, we note that multiple scattering will increase the number of NKLP pairs separated by more than 100 meters up to 46% depending on its mass. Although the NLSP pair separation increase is smaller (3%) the multiple scatter increases the number of vertical upcoming NLSPs by 24%.

In the next section we describe how we account for multiple scattering and energy loss. Then we show our results, followed by a discussion on the detectability of these particle. Our conclusions follow in the last section.

II. MULTIPLE SCATTERING

The formulas for multiple scattering are well-known; the scattering is independent of the particle mass. The angular deviation by a singly charged relativistic particle with momentum p passing through a slab with thickness L made out of a material with radiation length X_0 in space (i.e., the total angular deviation, not that in a plane) is well described by a Gaussian distribution [6]. The scattering angle in a given plane θ_0 is defined as

$$\theta_0 = \frac{13.6\ \mathrm{MeV/c}}{p}\sqrt{\frac{L}{X_0}}. \tag{2.1}$$

The radiation length, X_0 is calculated using Dahl's fit given in Eq. 27.22 of [6] to the data:

$$X_0 = \frac{716.4\ \mathrm{g\,cm^{-2}}A}{Z(Z+1)\ln(287/\sqrt{Z})}, \tag{2.2}$$

where A and Z are the atomic mass and number of the target. This equation agrees with Tsai's [7] values for Earth targets to better than 2.5%.

Since the Earth is inhomogeneous, we use the density profile described in [8]. This profile divides the Earth in ten layers. The Earth structure, mean atomic number $\langle Z\rangle$, mass $\langle A\rangle$ of each layer depend on if it belongs to the crust, the mantle or the core of the Earth. These together with the mean density $\langle \rho\rangle$ and the radiation length X_0 are given in Table I.

We calculate NLSP/NLKP energy loss following [2,3], and assume that it is smooth. The stochastic nature of the energy loss might broaden the distributions slightly, but should not be a significant factor here.

We calculate the NLSP/NLKP divergence from the original neutrino trajectory. The deviation due to the opening angle of the particle pair has been previously considered. Here, we consider the additional deviation due to the multiple scattering of the NLSP pairs.

For each layer, the mean scattering angle is calculated from Eq. (2.1), and, from that angle, the deviation from the neutrino trajectory is projected to a surface detector. The average deviation from the neutrino trajectory by a NLSP/NKLP particle due to scattering in layer i is $d_i = \sqrt{2}D\theta_0$, where D is the distance from the middle of the layer to the surface; the $\sqrt{2}$ accounts for scattering in the $\vec{x}$ and $\vec{y}$ directions perpendicular to the direction of travel.

TABLE I. Earth structure, mean atomic number $\langle Z\rangle$, mass $\langle A\rangle$, density $\langle \rho\rangle$ and radiation length for each of the Earth's layers. The layers are as in the density profile given in [8]. The height corresponds to the distance from the center of the Earth to the beginning of the layer. Layer 1 starts at the center of the Earth. The top of the 10th layer is at the surface of the Earth (6378 km). The values for the crust, mantle and core are given, respectively, in [9–11].

Layer #	Structure	Height (km)	$\langle Z\rangle$	$\langle A\rangle$	$\langle \rho\rangle$ (g/cm^3)	X_0 (cm)
1	Core	0	25.6	54.8	12.93	1.10
2	Core	1221.5	25.6	54.8	11.03	1.29
3	Mantle	3480	27	55	4.97	2.56
4	Mantle	5701	27	55	3.98	3.21
5	Mantle	5771	27	55	3.85	3.33
6	Mantle	5971	27	55	3.49	3.67
7	Mantle	6151	27	55	3.37	3.80
8	Crust	6346.6	12	24	2.90	8.66
9	Crust	6356	12	24	2.60	9.66
10	Crust	6368	12	24	1.02	24.63

As in Ref. [2], we integrate over different production points in the Earth.

The deviation in each layer is treated independently. Since the angles are independent, the deviations are added in quadrature. As we neglect the small initial energy difference between the two particles, and as they scatter independently, their deviations are also added in quadrature and determine the total separation due to multiple scattering. This separation is then added in quadrature (because the angles are uncorrelated) with the separation due to the initial opening angle.

Three factors affect the contribution to the multiple scattering from each layer. The inner layers are the densest, and also have the longest lever arm, increasing their contribution. However, the NLSP also have the higher energies while they are near the production point, decreasing the scattering. Overall, the inner layers still make the largest contribution to the scattering—the lever arm wins out.

We also considered the effect of magnetic fields on the separation; since the two NLSP have opposite charges, they are bent in opposite directions by the Earth's magnetic field. However, even after accounting for the increased field strength deep in the Earth [12], this does not contribute significantly to the scattering.

III. RESULTS

The analysis of NLKP detection by neutrino observatories [3] considered three mass values of 300, 600, and 900 GeV. The two NLKP track separation in the detector is the only discriminating parameter for the highest mass considered although not the only one for NLKP masses below 600 GeV. The background consists of di-muon events, mostly from charm decay.

The NLKP energy loss depends on its mass. The larger the mass the less its energy will degrade while the particle propagates through the Earth. This means that heavier NLKPs can be produced farther from the detector. On one hand this enhances the multiple scattering, since the particle will have a longer lever arm. However on the other hand the NLKP enters each layer with larger energy, reducing the scattering.

Figures 1 and 2 show the effect of multiple scattering on the NLKP pair separation in a detector positioned at the same depth in the Earth as the IceCube detector (centered at 1950 m deep); the reduced scattering in the lower-Z ice is neglected. The separation is shown for three values of the NLKP mass. The separation distributions are based on 30 000 simulated events. The separation due to the initial opening angle is described in [3]. The multiple scatter enhancement to the separation is described in the previous section.

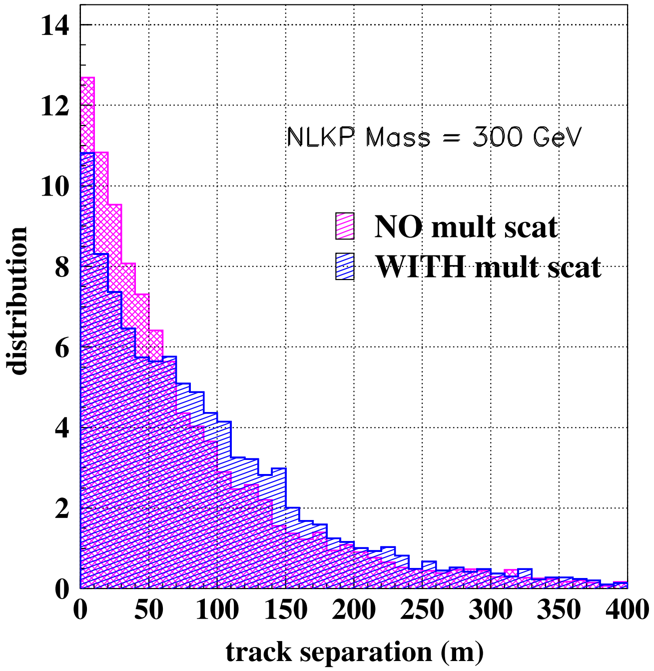

FIG. 1 (color online). Distribution of 300 GeV NLKP track separation distance in the detector. The separation is shown with and without multiple scattering as labeled and both cases have the same number of events.

Multiple scattering has the largest effect on the separation distance for NLKPs with a 300 GeV mass. The number of events per km^2 per year, at a depth equivalent to the IceCube detector with more than 100 m separation, rises from 137 to 200 events when multiple scattering is included, a 46% increase. For 600 and 900 GeV NLKPs, the corresponding increases are 30% and of 21%, respectively. The background will be separated at most by 100 meters, as can be seen in Fig. 7 of [2]. As described in the next section, 100 m is the average detectable separation in km^3 telescopes.

NLSPs are produced from neutrino interactions in the Earth. This interaction produces a charged left-handed slepton and a squark as described in Refs. [1,2]. These particles decay immediately producing the two 150 GeV NLSPs. In our calculations, we considered squark masses of 300 GeV, 600 GeV and 900 GeV. As all three scenarios led to very similar effects from multiple scattering; we present the 300 GeV results here.

Figure 3 shows the track separation between two NLSPs going through the detector. The distributions show the separation due to the initial opening angle of the pair with and without multiple scattering. The separation distance between the two NLSP is the main observable to discriminate it from the di-muon background.

The separation distributions shown in Fig. 3 are based on 30 000 simulated events as described in Ref. [2]. The darker (blue) histogram represents the separation without multiple scattering while the lighter (pink) the separation with multiple scattering.

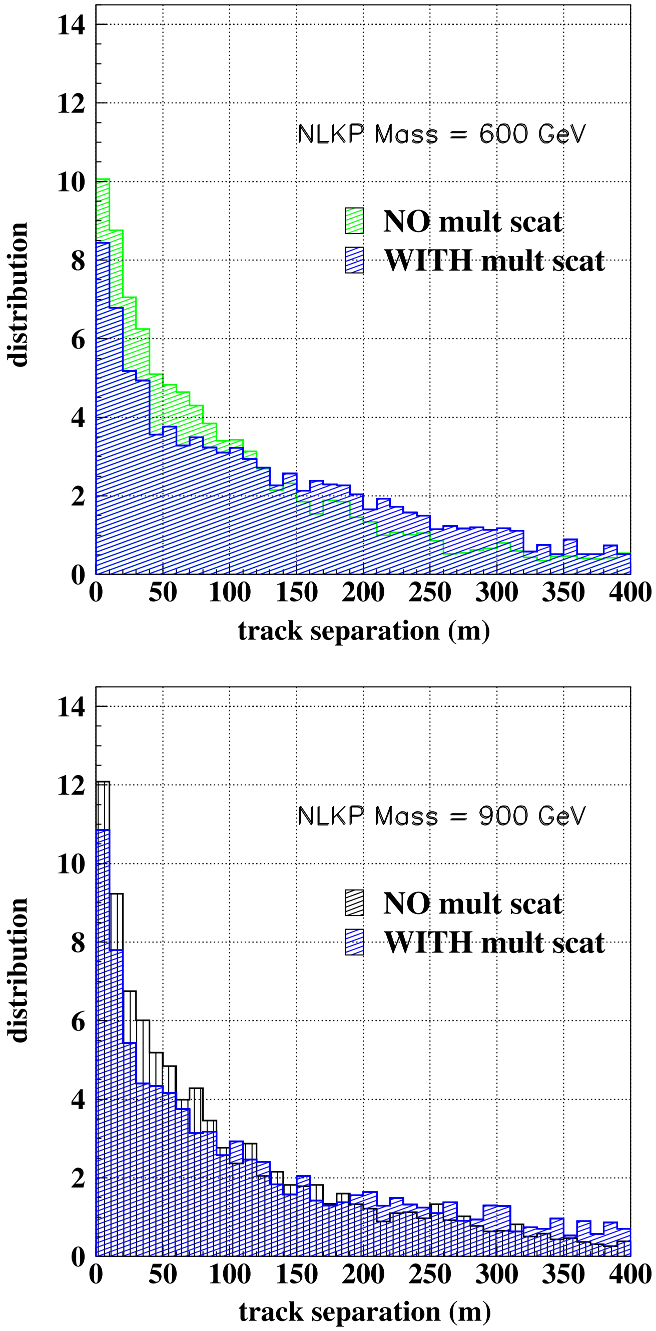

FIG. 2 (color online). Same as Fig. 1 but for 600 and 900 GeV NLKPs.

The multiple scatter effect in this case is weaker than for NLKPs. As the NLSP assumed in these scenarios is significantly lighter than the assumed masses for the NLKP, their energy range is also much shorter [1,3]. This reduces both the lever arm for multiple scattering, and the average density of the material traversed. Both these effects makes the multiple scattering effect stronger for NLKPs.

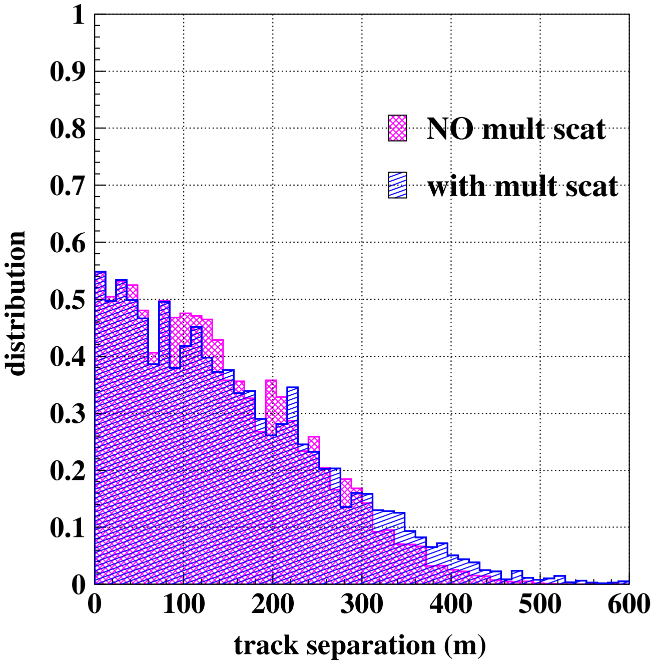

FIG. 3 (color online). Track separation distance for NLSP pair events, in scenarios with a 300 GeV/c^2 squark mass, with and without multiple scattering. The two curves have the same number of events. The multiple scattering enhancement on the separation distance is about the same for 600 and 900 GeV/c^2 squark masses.

The number of NLSP pairs with more than 100 m separation will increase by 3%. However multiple scattering enhances the detection of vertical upcoming events as discussed in the next section.

IV. DETECTION

Next generation neutrino telescopes, like IceCube [13] and km3net [14] will be able to detect these pairs of upward-going charged tracks. The NLSPs/NLKPs production was determined always assuming they will be produced below the horizon in relation to the detector. This avoids the large background of multiple muons produced in cosmic-ray air showers. High p_T muons in air showers could mimic widely separated pairs. Isolated downgoing muons have been observed as far as 400 m from a shower core [15].

The minimum detectable separation for charged pairs is an experimental question. However, a reasonable guess is that the minimum separation for nearly vertical pairs is comparable to the string spacing, 125 m in IceCube. For pairs that are more horizontal, the smaller separations may be visible, since, in the vertical direction, optical modules are spaced every 17 m, providing finer pixilation. Here, we will assume that the average minimum separation distance is 100 m. In km3net, the spacing is unknown, but this is still a reasonable figure.

A detectable separation of 100 m would eliminate almost completely the di-muon background. This can be seen in Fig. 7 of Ref. [2]. Multiple scattering will however enhance NLSP/NLKP detection since it enhances the separation of events near the 100 m threshold for detecting two tracks.

As described in the last section, with the 100 m minimum distance, multiple scattering increases the number of visible 300 GeV (600 and 900 GeV) NLKPs by 46% (30 and 21%). NLSPs will have their number increased by 3%. Another feature to be accounted for is the detection dependence on the zenith angle.

The pair separation also depends on the charged particle arrival direction. Vertical upcoming particles can be produced farther from the detector. Therefore they have larger separation distances in the detector and also the multiple scattering effect is larger when compared to horizontal events.

Multiple scattering increases the number of near vertical upcoming NLSPs pairs separated by more than 100 meters by 24%. Here, near vertical (horizontal) is defined as pairs within a 5 degrees of vertical (horizontal) direction. For the near horizontal events multiple scattering has an insignificant effect the increase in the number of NLSPs separated by more then 100 meters is only 1.8%. Although vertical upgoing NLSPs are a tiny fraction of the event rate, we show the enhancement effect to highlight the fact that multiple scattering effect increases with increasing zenith angle. In this way, the far from horizontal events will be more affected by multiple scattering.

For NLKP pairs multiple scattering is also less effective for near vertical events when compared to near horizontal events. As an example, 300 GeV near vertical pairs will have an 67% increase in the number of events with more than 100 m separation when multiple scattering is included while near horizontal events will have a correspondent 16% increase.

V. CONCLUSIONS

We have determined the multiple scattering effect on NLKP and NLSP particles transversing the Earth. We have shown that multiple scattering will enhance the separation between NLKP pairs and between far from horizontal NLSPs.

The pair separation in the detector is a clear signature both for NLKPs as for NLSPs. As discussed in Sec. IV, 100 meters separation is an average lower limit on the experimental separation detectability. Although this separation by itself gets rid of most of the di-muon background, it will still enhance the detectability of the next to lightest particles.

We find a 46% increase on the number of 300 GeV NLKPs separated by more than 100 meters and 30 and 21% for 600 and 900 GeV NLKPs when multiple scattering is taken into account.

The effect is less significant for NLSPs. The number of pairs separated by more than 100 meters has a 3% increase when multiple scattering is taken into account. Scattering can, however, enhance the number of NLSPs that are produced far from the horizontal direction.

In conclusion, NLKP multiple scattering through the Earth is an important effect to be considered. This importance of scattering increases for pairs that are closer to vertical.

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