PHYSICAL REVIEW D **87,** 015018 (2013)

Indirect probes of supersymmetry breaking in the JEM-EUSO observatory

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(Received 26 September 2012; published 14 January 2013)

In this paper we propose indirect probes of the supersymmetry-breaking scale, through observations in the Extreme Universe Space Observatory onboard the Japanese Experiment Module (JEM-EUSO). We consider scenarios where the lightest supersymmetric particle is the gravitino, and the next-to-lightest supersymmetric particle (NLSP) is a long-lived slepton. We demonstrate that JEM-EUSO will be able to probe models where the NLSP decays, therefore probing supersymmetry-breaking scales below 5×10^6 GeV. The observatory field of view will be large enough to detect a few tens of events per year, depending on its energy threshold. This is complementary to a previous proposal [I. Albuquerque *et al.*, Phys. Rev. Lett. **92**, 221802 (2004)] where it was shown that 1 km^3 neutrino telescopes can directly probe this scale. NLSPs will be produced by the interaction of high-energy neutrinos in the Earth. Here we investigate scenarios where they subsequently decay, either in the atmosphere after escaping the Earth or right before leaving the Earth, producing taus. These can be detected by JEM-EUSO and have two distinctive signatures: one, they are produced in the Earth and go upwards in the atmosphere, which allows discrimination from atmospheric taus, and second, as NLSPs are always produced in pairs, coincident taus will be a strong signature for these events. Assuming that the neutrino flux is equivalent to the Waxman-Bahcall limit, we determine the rate of taus from NLSP decays reaching JEM-EUSO's field of view.

DOI: 10.1103/PhysRevD.87.015018 PACS numbers: 14.80.Ly, 12.60.Jv, 95.30.Cq

I. INTRODUCTION

Probes of the origin and stability of the weak scale and proposed solutions to the standard model hierarchy problem are now underway at the Large Hadron Collider (LHC). On the theoretical side, the supersymmetric model (SUSY) arises as a solution with no significant deviation from the standard model (SM) in relation to electroweak precision observables. It has been shown [1,2] that neutrino telescopes can probe the scale of supersymmetry breaking ($\sqrt{F}$) or of universal extra dimensions scenarios [3]. While R-parity symmetry ensures that the lightest supersymmetric particle (LSP) is stable, the identity of the LSP is determined by $\sqrt{F}$. If SUSY is broken at $\sqrt{F} > 10^{10}$ GeV the LSP is typically the neutralino; if $\sqrt{F} < 10^{10}$ GeV it is typically the gravitino.

There are many SUSY scenarios where $\sqrt{F}$ is low, such as gauge mediation SUSY-breaking models [4]. In these scenarios the next-to-lightest supersymmetric particle (NLSP) is a charged slepton, typically a right-handed stau, and its lifetime is given by [1]

$$c\tau = \left(\frac{\sqrt{F}}{10^7\text{GeV}}\right)^4 \left(\frac{100\text{ GeV}}{m_{\tilde{\tau}}}\right)^5 10\text{ km}, \quad (1)$$

where $m_{\tilde{\tau}}$ is the stau mass. It was shown [1,2] that km^3 neutrino telescopes can directly probe the SUSY-breaking scale, when one consider scenarios where $5 \times 10^6 < \sqrt{F} < 10^8$ GeV. In these scenarios, NLSPs produced in very high-energy collisions will travel very long distances before decaying. A detectable flux of NLSPs can be produced by the interaction of the diffuse flux of high-energy neutrinos with the Earth.

Here we consider [5] a complementary SUSY-breaking scale region, with $\sqrt{F} \lesssim 10^7$ GeV, which implies that the NLSP will decay after traveling a short distance. After being produced by neutrino interactions in the Earth, a good fraction of these particles will decay inside the Earth, or in the atmosphere after escaping the Earth. In this work we consider NLSPs that decay in the atmosphere (or right before reaching it). In a complementary investigation [5,6] we analyzed the $\sqrt{F}$ region where they decay inside the Earth and might be detected by multi-km^3 neutrino telescopes. Once the NLSPs decay, taus (τ's) will be produced and can be detected by fluorescence telescopes. We show that the Extreme Universe Space Observatory onboard the Japanese Experiment Module (JEM-EUSO) [7] can probe these scenarios where NLSP decays will yield a few tens of events per year, depending on its lower-energy threshold.

We also consider the regeneration process where τ's decay into τ neutrinos, which in turn will charge current interact inside the Earth, producing new τ's. However, these suffer large energy degradation, and only a small fraction of these events reach the detector with significant energy.

As in Ref. [1], the crucial idea in probing $\sqrt{F}$ is that although the NLSP production cross section is much smaller than that for SM lepton production, the NLSP range in the Earth is much larger than for a standard lepton. As shown in Ref. [2], the NLSP energy loss is much

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smaller than that for muons or τ's. Here, when NLSP decays are considered, the NLSPs can be produced even further away from the detector, which implies that an extra decaying volume is gained. Also, as the NLSPs are always produced in pairs, a considerable fraction of the observable events will consist of a pair of τ's in the atmosphere. These coincident τ's will be a distinctive indirect signature of NLSPs. Another strong signature comes from the fact that these τ's emerge from the Earth and go upwards in the atmosphere, which discriminates them from descending atmospheric τ's.

In this paper we describe our analysis, where we develop a Monte Carlo simulation to investigate τ events generated from NLSP decays. The first steps, reviewed in the next section, reproduce the analysis done in Ref. [2], where NLSP production, propagation, and energy loss are described in detail. Subsequently, in Sec. III, we describe our simulation of NLSP decays and produced τ propagation. The signatures and rates of these events in the JEM-EUSO observatory are determined in Sec. IV, as well as their discrimination from the background. Finally, we discuss our results and state conclusions.

II. NLSP PRODUCTION

Here we consider NLSP production by a diffuse flux of high-energy neutrinos interacting in the Earth. The neutrino flux as well as the NLSP production cross section and propagation are determined as described in detail in Ref. [2], and are used as the first steps in our Monte Carlo simulation. In the next section we describe the original part of our work, where NLSP decays are included, and the produced τ rates in the JEM-EUSO observatory are determined.

Although the diffuse flux of high-energy neutrinos that reaches the Earth is yet unknown, there are several estimates of its upper limit. Waxman and Bahcall (WB) [8] determined such a limit based on the observed cosmic ray flux, since neutrinos are produced from pion decays, which in turn are produced from proton interactions. Considering optically "thin" sources, which would allow most of the protons to escape, they determine the neutrino spectrum as

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

where the allowed interval depends on the cosmological evolution of the sources. Here we adopt the upper value of the WB limit as the cosmological neutrino flux that reaches the Earth. Our results can be translated to other neutrino fluxes by properly rescaling the WB limit. The initial neutrino flux contains both muon and electron neutrinos, in a 2:1 ratio. However, we note that the initial neutrino flavor does not alter our results, since its interaction will always produce a left-handed slepton that will always immediately decay, having the right-handed slepton as a final product. For the same reason a large mixing of the cosmogenic neutrino flux does not modify our results.

Once the neutrino flux is defined, the NLSP production cross section should be determined. We follow the cross section calculation described in detail in Ref. [2] and reproduce their results. In short, the $\nu N \rightarrow \tilde{l}_L \tilde{q}$ process is analogous to the SM charged-current interaction with $\tilde{q}$ being an up or down type squark and, in the t-channel, the mediator is the chargino. The sub-dominant process with a neutralino exchange is also included in the cross section calculation. As a result of this interaction, an $\tilde{l}_L$ and a $\tilde{q}$ will be produced. These will immediately decay in a chain that will always end with the production of two NLSPs, typically the right-handed stau ($\tilde{\tau}$). We give our results considering the mass of the chargino and of the left-handed slepton, respectively, as $m_{\tilde{w}} = 250$ GeV and $m_{\tilde{l}_L} = 250$ GeV, of the NLSP as $m_{\tilde{\tau}} = 150$ GeV, and three possibilities for the squark mass: $m_{\tilde{q}} = 300$, 600, or 900 GeV. Note that the LHC constrains $m_{\tilde{q}}$ to larger values when considering specific scenarios that have the neutralino as the LSP [9], which is not our case. There are constraints on $m_{\tilde{\tau}}$ from big bang nucleosynthesis [10].

The probability of a neutrino interacting in the Earth, as well as the NLSP propagation through this medium, depend on the Earth density profile model. We use the model [11] described in detail in Ref. [12]. The lepton production cross section from neutrino-nucleon interaction is also determined in Ref. [12].

Once the NLSP is produced it will propagate through the Earth and lose energy. The main process for NLSP energy degradation is photo-nuclear interactions. However, as shown in Refs. [2,13], all radiative losses are suppressed due to the NLSPs heavier mass when compared to standard leptons.

NLSPs will always be produced in pairs and therefore, if one assumes the $\sqrt{F}$ region where they do not decay, they will have a very distinctive signature in neutrino telescopes. As a cross check of our simulation, we reproduced the NLSP rate and energy distribution in km^3 neutrino telescopes as determined in Refs. [1,2].

III. NLSP DECAY

The NLSP survival probability

$$P_s(x) = \exp(-m_{\tilde{\tau}} x / E_{\tilde{\tau}} c\tau) \tag{3}$$

is shown in Fig. 1 as a function of the traveled distance x, for different neutrino energies E_ν and $\sqrt{F} = 10^6$ GeV, where the initial NLSP energy is typically $E_\nu/6$ [2]. The NLSP production-energy threshold is $\sim 10^6$ GeV, and is defined by the $\tilde{q}$ and the left-handed $\tilde{l}_L$. At these energies, the distance $\gamma c\tau$ is determined by Eq. (1), and NLSPs decay when $\sqrt{F} \lesssim 5\times 10^6$ GeV. This feature is shown in Fig. 2. The decay channel is $\tilde{\tau} \rightarrow \tau + \tilde{G}$, where $\tilde{G}$ is the gravitino and its mass is much smaller than the τ mass.

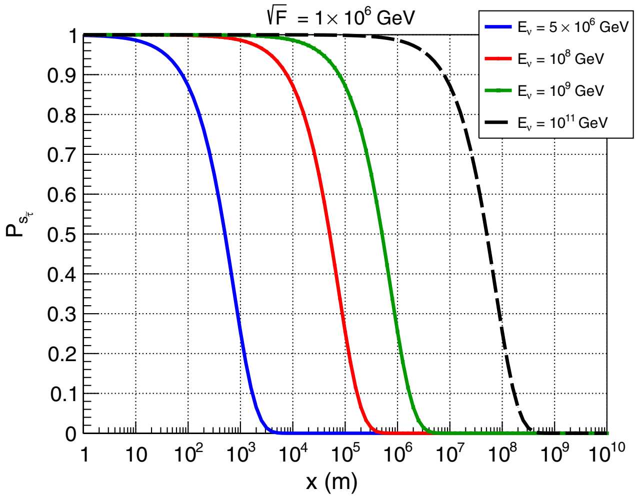

FIG. 1 (color online). NLSP survival probability as a function of traveled distance, for different neutrino energies (as labeled) and $\sqrt{F} = 10^6$ GeV. Top to bottom labels correspond to the leftmost to rightmost curves.

We developed a Monte Carlo simulation in which $\vartheta(10^5)$ events where generated corresponding to neutrinos reaching the Earth, isotropically distributed both in energy and impinging direction. These events are normalized by the WB limit. The NLSP production, propagation, and energy loss were simulated, reproducing the analysis shown in Ref. [2] (see Sec. II).

The NLSP decay point is chosen from the decay probability distribution (essentially, $1 - P_s$), and the generated τ center-of-mass isotropic angular distribution is boosted into the laboratory frame. To a good approximation, it will follow the same direction as its parent NLSP. As NLSPs are always generated in pairs, two τ's will be produced. A fraction of these τ's subsequently decay, always generating a ν_τ, which can charge current interact that produce a new τ. We determine the fraction of the τ energy carried by the ν_τ as in Refs. [14,15]. This regeneration process can happen a few times depending on the τ energy degradation. As mentioned before, this process will degrade the τ energy and most of the particles will not be detectable.

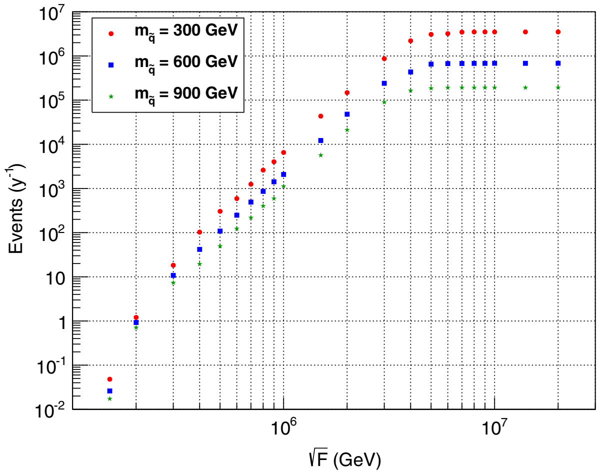

FIG. 2 (color online). Fraction of NLSP events in JEM-EUSO's FOV versus $\sqrt{F}$ for $m_{\tilde{q}}$ reference values. NLSPs decay for $\sqrt{F} \lesssim 5 \times 10^6$ GeV.

IV. SIGNATURES AND EVENT RATES IN THE JEM-EUSO OBSERVATORY

In order to determine the feasibility of NLSP indirect detection, where τ's originating in NLSP decays would be probed by a large fluorescence telescope, we have to consider basic detector features. The JEM-EUSO telescope [7] will observe fluorescent light emitted from an extensive air shower created by the interaction of a high-energy particle in the atmosphere. It will orbit the Earth at an altitude of about 430 km, yielding a detection area of $\sim 2 \times 10^5$ km^2 with a 250 km circular radius at the Earth's surface. It is scheduled to be launched in 2016.

At these energies, τ's produced by NLSPs can be observed by JEM-EUSO, mainly through the shower created once they decay. Direct detection of NLSPs is hard, since the energy of their emitted fluorescent light is much less than the detector threshold, which is projected to be around 10^{19} eV.

In order to determine the rate of observable events, we approximate the JEM-EUSO detection volume as a frustum of a cone, which represents the detector field of view. This is shown in Fig. 3. The frustum's height corresponds to the atmosphere altitude, which is taken as 40 km.

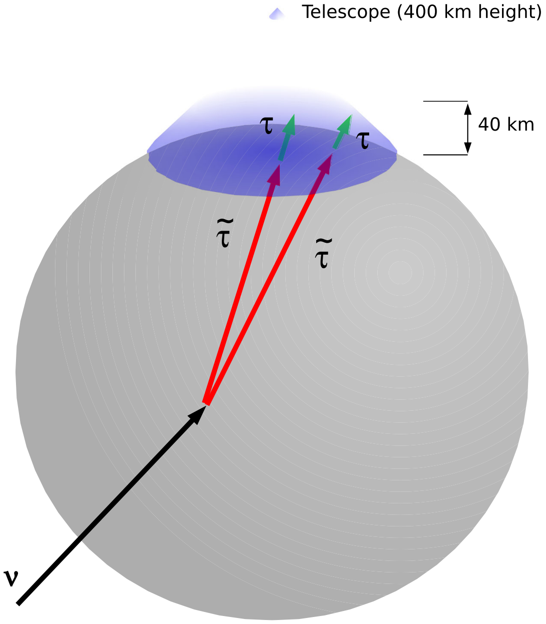

FIG. 3 (color online). Representation of the JEM-EUSO detection volume as a frustum of a cone, with a height of 40 km, corresponding to the atmosphere altitude. NLSPs originating from neutrino interactions will decay in the atmosphere, producing observable τ's.

As described in the previous section, we simulate NLSP production from neutrino interactions in the Earth, their propagation and energy loss, and finally their decay. The neutrino energy ranges from $\sim 10^6$ to $\sim 10^{12}$ GeV, where the lower limit corresponds to the NLSP production threshold. As the NLSPs are always produced in pairs, two τ's will be produced from their decay. Although the pair of NLSPs travel in parallel, they can decay at different times, and each τ can be produced at different positions. Each production point is independently chosen from the decay probability distribution.

The τ energy loss considers both ionization and radiation processes, where the latter includes loss due to bremsstrahlung, pair production, and photo-nuclear interactions [2,9]. We also follow the NLSPs which do not decay inside the Earth and reach the atmosphere, computing their energy and flux. The NLSP energy loss to the atmosphere is negligible.

In summary, we compute the τ production point and initial-energy distribution, as well as its decay point and energy distribution. These yield the number of τ's which decay in or propagate through the detector's field of view (FOV) and the corresponding energy distributions. We also compute the number of coincident τ decays in the FOV. All results are normalized by the WB neutrino flux.

Our results are presented as a function of $\sqrt{F}$. Figure 4 shows the number of coincident NLSP decays per year in the JEM-EUSO's FOV, while Fig. 5 shows the average decay energy of the NLSPs. As can be seen, the number of events is maximized for $\sqrt{F} = 3 \times 10^6$ GeV for both 300 and 600 GeV squark masses and 2×10^6 GeV for $m_{\tilde{q}} = 900$ GeV, due to its higher production-energy threshold. However, at these values of $\sqrt{F}$ the average decay energy of the NLSPs is lower than the detection threshold, and increases for lower $\sqrt{F}$ values. We will discuss this issue further.

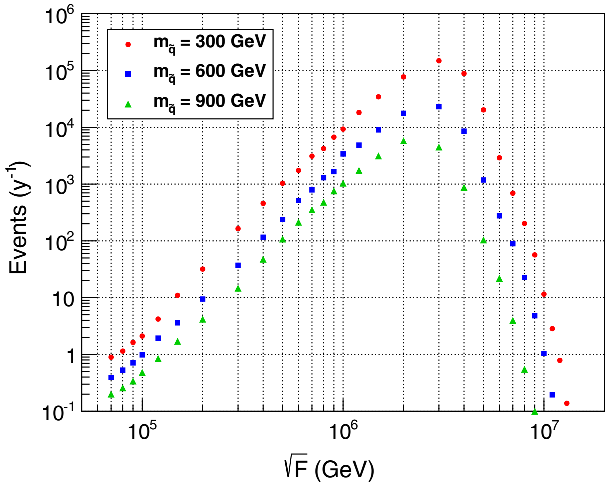

FIG. 4 (color online). NLSP coincident decays in the JEM-EUSO FOV as a function of $\sqrt{F}$.

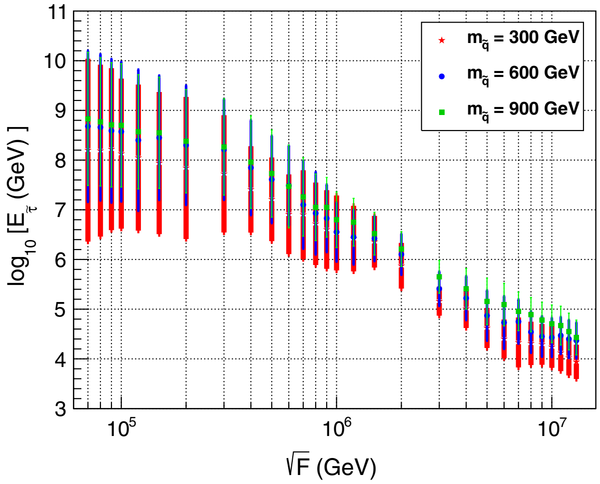

FIG. 5 (color online). Average energy of events shown in Fig. 4. Error bars represent the standard deviation of each energy distribution.

Figure 6 shows the number of events per year in the JEM-EUSO's FOV as a function of the parent neutrino energy for $\sqrt{F} = 5 \times 10^6$ GeV, which maximizes the number of events. It shows the NLSPs ($\tilde{\tau}$) and τ's that decay, the ones that go through the FOV without decaying, and those in which both NLSPs are produced as a pair or both τ's decay coincidently in the FOV. As a reference, the

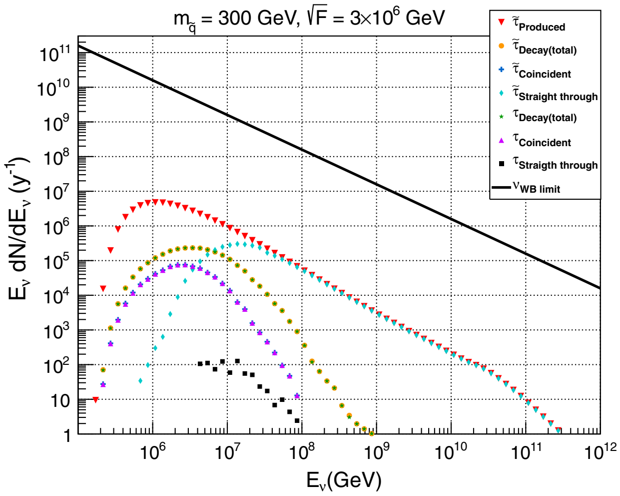

FIG. 6 (color online). Events per year in JEM-EUSO's FOV. Here, $m_{\tilde{q}} = 300$ GeV and $\sqrt{F} = 3 \times 10^6$ GeV, such that the number of events is maximized. The circles correspond to NLSPs (represented as $\tilde{\tau}$) and triangles to τ's. The NLSPs (τ) that decay are in yellow (green), the ones that go through the FOV without decaying are in light blue (black), and the events in which both NLSPs produced as a pair (or both τ's) decay in the FOV are in blue (purple). As a reference the total number of NLSPs that are produced in the direction of the FOV are shown in red, and the WB limit is shown as a black line. Other values of $m_{\tilde{q}}$ will have similar curves but with less events. Lighter colors correspond to NLSPs while darker colors to taus.

TABLE I. Number of NLSP events per year in JEM-EUSO's FOV, where $\sqrt{F} = 3(2) \times 10^6$ GeV for $m_{\tilde{q}} = 300$, 60 0 (900) GeV. For $m_{\tilde{q}} = 300$ GeV these events correspond to the ones shown in Fig. 6. "Total" is the total number of NLSPs produced in the direction of the FOV, "Straight Through" refers to the NLSPs that go through the FOV, "Decay " to those which decay in the FOV, and "Pair Decay" to the ones where the NLSP pair decays in coincidence in the atmosphere.

$m_{\tilde{q}}$	Total	Straight through	Decay	Pair decay
300	1×10^7	8.7×10^5	5.2×10^5	1.5×10^5
600	1.3×10^6	2.4×10^5	9.6×10^4	2.2×10^4
900	2.8×10^5	2.0×10^4	1.9×10^4	5.8×10^3

figure also shows the total number of NLSPs that are produced in the direction of the FOV and the WB limit. This figure shows results assuming $m_{\tilde{q}} = 300$ GeV, where for the other $m_{\tilde{q}}$ values the shapes of the curves are very similar but contain less events. The total rate of events in the JEM-EUSO per year for our nominal value of the maximum atmosphere height of 40 km, for the three values of $m_{\tilde{q}}$, are shown in Table I.

As seen in this table, a huge amount of the NLSPs should either go through or decay in the JEM-EUSO's FOV. As the NLSPs are not detectable due to the low amount of fluorescence emitted while they traverse the atmosphere, the hope of probing these events relies on the τ's produced in their decay. However, although more than 10^5 τ's will traverse the atmosphere or decay in the JEM-EUSO's FOV, most of these events have energies below the detector threshold ($\sim 10^{19}$ eV) and will not be observed unless this threshold is lowered.

In order to determine the event rate that can be observed with an energy threshold around that currently projected by JEM-EUSO, we selected events above arbitrary lower-energy values of 10^8, 10^9, and 5×10^9 GeV. These are shown in Fig. 7, and the integrated number of events, maximized as a function of $\sqrt{F}$, are shown in Table II.

As can be seen from Table II, there is still a reasonable amount of events for a maximized $\sqrt{F}$ around JEM-EUSO's energy threshold. Above 10^{18} eV, 39 (15, 7) τ's can be detected per year, for a 300 (600, 900) GeV squark mass. From these, 4 (2, 1) τ pairs decay in coincidence in the atmosphere, which provides an excellent discriminating signature. For a threshold of 5×10^{18} eV, a bit below the nominal projected threshold, 0.5 (0.2, 0.1) events per year can be observed by JEM-EUSO.

In Fig. 8 we show the total number of τ decays as a function of the maximum atmosphere height, for different values of the required minimal τ energy. This allows one to rescale our results when considering different FOV heights. Although this figure is shown only for $m_{\tilde{q}} = 300$ GeV, the rescaling for other masses is about the same.

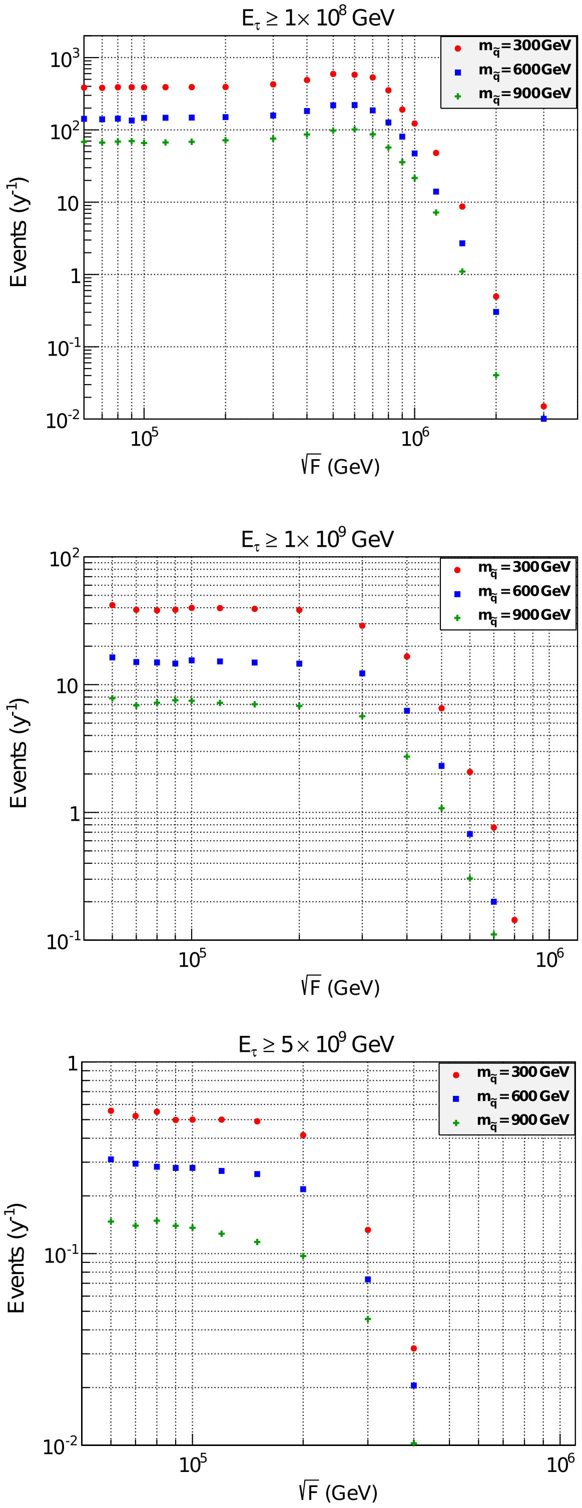

FIG. 7 (color online). Total number of τ decays in JEM-EUSO's FOV, requiring a minimal energy of 10^8 GeV (top plot), 10^9 GeV (middle plot), and 5×10^9 GeV (bottom plot).

A. Backgrounds

Under the scenarios we are considering, NLSP decays will have a very distinctive signature. Since the NLSPs are produced inside the Earth and decay into τ's that go

TABLE II. Number of τ events per year in JEM-EUSO's FOV after requiring a minimum τ energy E_τ. $\sqrt{F}$ is such that it maximizes the number of events. The line corresponding to $\sqrt{F} = 3 \times 10^6$ GeV is shown for reference and has no energy requirement.

$\sqrt{F}$ (GeV)	E_τ (GeV)	$\tau_{\mathrm{Decay(total)}}$	$\tau_{\mathrm{Coincident}}$
	$m_{\tilde{q}} = 300$ GeV		
3.0×10^6		5.5×10^5	1.5×10^5
6.0×10^5	$\geq 10^8$	5.8×10^2	1.0×10^2
1.5×10^5	$\geq 10^9$	3.9×10^1	4.2×10^0
1.2×10^5	$\geq 5 \times 10^9$	5.0×10^{-1}	1.0×10^{-2}
	$m_{\tilde{q}} = 600$ GeV		
3×10^6		9.8×10^4	2.2×10^4
6×10^5	$\geq 10^8$	2.2×10^2	3.8×10^1
1.2×10^5	$\geq 10^9$	1.5×10^1	1.6×10^0
2×10^5	$\geq 5 \times 10^9$	2.0×10^{-1}	1.0×10^{-2}
	$m_{\tilde{q}} = 900$ GeV		
2×10^6		2.0×10^4	5.8×10^3
6×10^5	$\geq 10^8$	1.0×10^2	1.8×10^1
1.2×10^5	$\geq 10^9$	7.2×10^0	8.0×10^{-1}
1.2×10^5	$\geq 5 \times 10^9$	1.3×10^{-1}	6.0×10^{-3}

upwards in the atmosphere, they can be discriminated from the more abundant descending cascades produced by normal ultra high-energy cosmic rays.

A considerable fraction of the NLSP pairs decay in coincidence in the atmosphere as well. Figure 9 shows the distribution of the time delay between two τ decays in the atmosphere. These are shown for different values of $\sqrt{F}$ and energy lower-limit requirements. It shows results for a 300 GeV squark mass, which do not vary significantly for larger values. The time delay spread as a function of $\sqrt{F}$ is small, and is distributed around 10^{-4} s. Considering that an atmospheric shower takes about 0.3 seconds, and that the detector resolution is about 2.5 μs, it is possible to determine the coincidence of these decays.

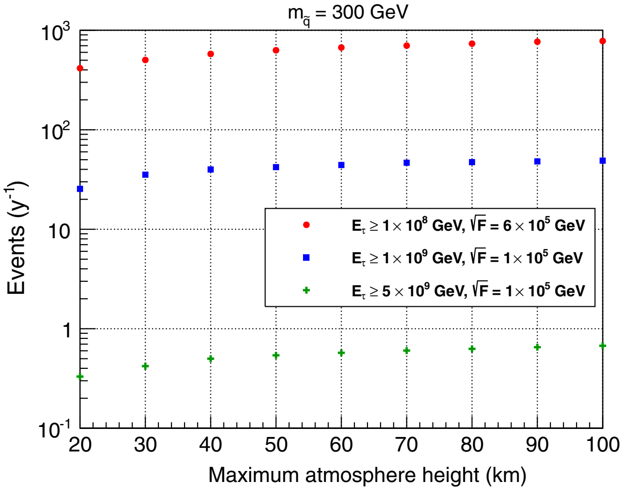

FIG. 8 (color online). Number of τ decays as a function of the maximum atmosphere height, for different values of the required minimal τ energy.

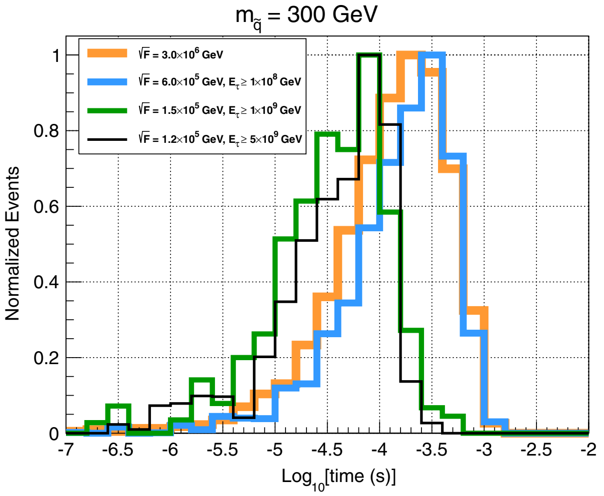

FIG. 9 (color online). Time delay between two coincident τ decays in the atmosphere, shown for arbitrary $\sqrt{F}$ and lower NLSP energy requirements. The squark mass is 300 GeV, but it does not vary considerably for larger values.

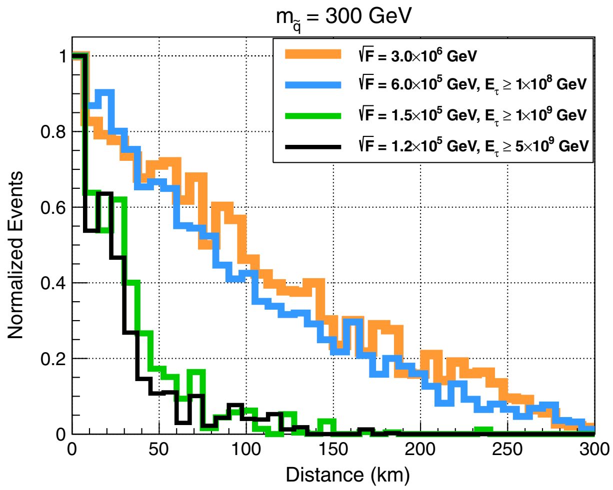

FIG. 10 (color online). Distance between two τ decays in the atmosphere, assuming same parameters as in the previous figure.

Figure 10 shows the distance between the coincidence showers, considering the same parameters as for the previous figure. Given that the detector's spacial resolution is about 0.75 km, it is clear that the majority of the coincident showers can be well-distinguished.

V. DISCUSSION AND CONCLUSIONS

In order to understand the effect of the experimental energy threshold, we have shown our results for arbitrary lower-energy cuts. As shown in Table II, the lower threshold has a significant effect on how well large fluorescence telescopes can probe the supersymmetry-breaking scale.

While an experimental energy threshold of 10^{18} eV allows JEM-EUSO to discover τ's produced by NLSPs, and to consequently probe a significant $\sqrt{F}$ region, an energy threshold 10^{19} eV allows one to set limits in the production and $\sqrt{F}$ parameters. Table II shows that, for a maximum value of $\sqrt{F}$, $\vartheta(10^5)$ of detectable events will go through JEM-EUSO's FOV. From these, hundreds of events per year can be seen if the energy threshold is set to 10^{17} eV, while tens of events per year can be seen for a threshold of 10^{18} eV, and more than a year is needed to detect events for 10^{19} eV. Although these numbers are for a maximized value of $\sqrt{F}$, one can see from Fig. 7 that there is a significant range—in which $10^5 \lesssim \sqrt{F} \lesssim 10^6$ GeV—that can be probed with the same order of events.

We have shown that large fluorescence telescopes such as JEM-EUSO have the potential to indirectly detect NLSPs, which are modeled in various supersymmetry-breaking scenarios. Scenarios where the supersymmetry-breaking scale $\sqrt{F}$ is such that the NLSP will decay close to or in the atmosphere can be probed by JEM-EUSO. Depending on the experimental energy threshold, scenarios with $10^5 \lesssim \sqrt{F} \lesssim 10^6$ can be probed, and NLSPs can be searched for indirectly.

This work complements the direct probe for long-lived NLSPs [1,2], where scenarios with $5 \times 10^6 \lesssim \sqrt{F} \lesssim 5 \times 10^8$ can be directly probed by neutrino telescopes. It is also complementary to searches for NLSP decays at the LHC.

ACKNOWLEDGMENTS

I. A. was partially funded by the Brazilian National Counsel for Scientific Research (CNPq), and J. C. S. was funded by the State of São Paulo Research Foundation (FAPESP).

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