Search for long-lived staus using neutrino telescopes

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We present a novel search strategy for long-lived charged particles with neutrino telescopes. Specifically, we consider long-lived staus produced in atmospheric air showers, which reach the IceCube Neutrino Observatory producing detectable track signatures. We show that their reconstructed energy peaks sharply at 700 GeV, making energy cuts an efficient technique for background reduction. Using one year of IceCube data from 2012, and conservative assumptions on the detection efficiency, we obtain the lower limit $m_\tilde{\tau} \geq 120$ GeV at the 95% C.L. assuming Drell-Yan production. For ten years of IceCube data, which have already been collected, we forecast a lower limit $m_\tilde{\tau} \geq 430$ GeV. We also comment on the prospects of improving the sensitivity to long-lived staus with future neutrino telescopes.

Introduction. - Various new physics models predict the existence of heavy long-lived charged particles. The archetypal example is the stau, the supersymmetric partner of the tau lepton. It is long-lived in scenarios where the gravitino is the lightest among all supersymmetric partners, and the stau is the next-to-lightest. In this case, and provided R-parity is conserved, the stau can only decay into a gravitino and a tau with a decay width suppressed by the scale of supersymmetry breaking (for a review, see [1]). As a result, the stau lifetime can be as long as several seconds, minutes or even years, depending on the parameters. More generically, a charged particle is long-lived if it is very weakly coupled to the other charged particles it can decay into, or when the phase space available for the decay is very small.

The most common search strategy for long-lived staus is direct production at the LHC via the Drell-Yan process or via cascade decays of other supersymmetric particles. Due to their longevity, the staus travel macroscopic distances before decaying. In particular, they traverse the ATLAS and CMS detectors, leaving a distinctive heavy ionizing track signature that cannot be mimicked by muons [2-4]. The non-observation of stau signatures in 36.1 fb$^{-1}$ of data collected by the ATLAS collaboration in proton-proton collisions at $\sqrt{s} = 13$ TeV leads to the lower limit $m_\tilde{\tau} \geq 430$ GeV at 95% C.L., assuming Drell-Yan production only [5]. A weaker limit, $m_\tilde{\tau} \geq 240$ GeV, had been set by the CMS collaboration using a smaller data sample, 2.5 fb$^{-1}$ [6].

An alternative search strategy uses cosmic rays, energetic particles from outer space, hitting the Earth’s atmosphere. This natural collider can also produce long-lived staus, albeit with a production rate much smaller than that of the LHC. On the other hand, the number of detected events can be enhanced if the detector is much larger than CMS or ATLAS. We will consider the possibility of detecting long-lived staus with the world’s largest optical Cherenkov detector: the IceCube neutrino observatory [7].

This possibility was first discussed in [8]. In that work, it was argued that cosmic neutrinos could interact with the rock in the Earth, producing pairs of long-lived staus. The signal then consists of two upgoing, almost parallel, charged tracks separated by about 100 m. Such a signal would have practically no background. This possibility was further investigated in [9-12]. Staus can also be produced by collisions of cosmic-rays with the Earth’s atmosphere, leading to two downgoing, also almost parallel, charged tracks. Similar signals are produced by atmospheric muons. However, as shown in [13], the atmospheric muon background is strongly suppressed for tracks separated by 50 m with horizontal arrival directions.

We propose a novel search strategy which exploits the fact that the staus deposit only a small fraction of their kinetic energy in the detector, which does not require the observation of parallel tracks in IceCube. We use cascade equation simulations to calculate the number of muon-induced and stau-induced tracks in IceCube and apply selection cuts to reduce the background from muon-induced track events. Specifically, we consider track events reaching the detector from zenith angles $\theta_{\text{zenith}} \geq 84^\circ$. At these angles, the muon background generated by cosmic rays is negligible and only receives contributions from collisions of high-energy neutrinos. Further, we reject very energetic tracks, since they are mostly induced by muons. Finally, we perform a stau search in the published one year IceCube data [14, 15]. We also comment on the prospects to increase the IceCube sensitivity to long-lived staus.

Long-lived staus from cosmic rays. - Cosmic particles are constantly bombarding the Earth’s atmosphere producing energetic air showers. The probability of hadrons in these showers producing staus can be approximated by [13]

$$P_{\tilde{\tau}}^h(E) \approx \frac{A_{\tilde{\tau}}^{h, \text{nucleon}}}{A_{\text{total}}}.$$

(1)
Here, \( \sigma_{h, \text{nucleon}} \) denotes the total stau production cross-section from the collisions of a hadron \( h \) with a nucleon, \( \sigma_{h, \text{air}} \) is the total cross-section of \( h \) with air, and \( A = 14.6 \) is the average number of nucleons in a nucleus of air.

To simulate atmospheric particle cascades, we use MCEq [16], which pursues a cascade equation approach. The particle interactions are modeled with Sibyll 2.3c [17], EPOS-LHC [18], QGSJET-II [19] and DPMJET-III [20]. For the cosmic ray models we use the Gaisser-Hillas models H3a and H4a [21] and Gaisser-Stanev-Tilav Gen 3 and 4 [22]. The resulting differences are used as an estimate of the uncertainties in our calculation. We found these to be negligible compared to other uncertainties in our analysis that will be discussed later on. We use the NRLMSISE-00 [23] [24] model to simulate the atmosphere.

For stau production we assume the Drell-Yan process, which we simulate using MadGraph [25] [26] and the built in MSSM model. We furthermore adopt the parton distribution functions (PDF) from LHAPDF6 [27]. Concretely, we use the CT10nlo [28] PDF as well as the NNPDF30_nnlo_nf_5_pdf as from the NNPDF 3.0 [29] PDF set. This allows us to include the uncertainties due to different PDF parametrizations. For the interactions of other hadrons with air, we scale the \( p-p \) cross-sections according to [13].

Muons are the primary background for the long-lived stau search. The muon background is generated by hadron or by neutrino interactions with nuclei in the atmosphere and ice. The former is negligible for muons from zenith angles \( \theta_{\text{zenith}} > 84^\circ \) [15], as seen in Figure 1, and accordingly can be practically removed by imposing this angular cut in the track arrival direction. The latter is determined using the cross-sections from [20] and the primary sources for high-energy neutrinos, air showers and diffuse astrophysical neutrinos. We adopt MCEq for the calculation of the atmospheric neutrino flux, and use a single power-law for the astrophysical neutrino flux [31]:

\[
\frac{d\phi}{dE} = 1.66^{+0.25}_{-0.27} \left( \frac{E}{100 \, \text{TeV}} \right)^{-2.53 \pm 0.07}.
\]  

To calculate the contribution of neutrino-induced muons, we fold the 2D effective area, as a function of energy and declination, from [15] with the neutrino fluxes. The neutrino energy to muon energy mapping is approximated using the normalized 3D effective areas given in [32].

To make predictions for the stau component, we require a detector response to staus. We use the same approach as before and divide the convolution by the total neutrino cross-section. The resulting efficiency includes effects of muon propagation in the ice. These we compensate by gauging the results, so that 25% of the 600 GeV stau events are kept. This corresponds to a detection efficiency of 50% for 1 TeV muons, a conservative estimate.

In Figure 1 we show the expected event count at the detector for a 100 GeV stau, alongside with the expected muon background. We find that in this scenario the long-lived staus give a contribution to the total number of track events at angles \( \theta_{\text{zenith}} \in [82^\circ, 88^\circ] \) of \( \mathcal{O}(10\%) \); for larger stau masses this contribution quickly drops, to \( \mathcal{O}(1\%) \) for 200 GeV and to \( \mathcal{O}(0.1\%) \) for 300 GeV. Therefore, with sufficiently high statistics and with additional selection cuts, one may expect that the stau signal could be disentangled from the muon background.

To further reduce the muon background we impose a second selection cut on the track events, which exploits the fact that during the passage through the ice the rate of energy loss is much smaller for staus than for muons. The muon mean energy loss per column density, \( X \), can be approximated by

\[
- \frac{dE}{dX} = a_\mu(E) + b_\mu(E)E ,
\]  

where \( a_\mu(E) \) accounts for ionization losses, whereas \( b_\mu(E) \) accounts for energy loss by pair production, hadronic interactions, and bremsstrahlung. In our analysis we will adopt for these parameters the PDG values [33] [34]. The stau rate of energy loss is described by this equation as well, with the appropriate replacement of coefficients. Since ionization effects are similar for muons and for staus, one can approximate \( a_\tau(E) \approx a_\mu(E) \). In contrast, the other effects relevant for energy loss depend on the particle speed, therefore, one can approximate \( b_\tau(E) \approx b_\mu(E)m_\mu/m_\tau \) [13].

The smaller rate of energy loss for the staus compared to the muons implies a smaller energy deposit in the de-
m_{\tilde{\tau}} \geq 180 \text{ GeV}, due to an excess of events compared to the expectation from the simulation. We chose to quote a conservative lower mass bound, since conservatively the stau component should not overshoot the data. More work towards understanding the data excess is necessary before a best-fit can be reported with confidence. Possible explanations are energy misreconstruction, misidentification of cascade events, or systematic errors in the primary and interaction models.

Our limits are worse than those derived from searches at the LHC. On the other hand, in this work we have merely presented a proof of concept of a new search strategy, and our assumptions have been very conservative. For example, we have assumed a stau detection efficiency of 25\%, however in a dedicated IceCube analysis the efficiency will grow and could realistically be close to 100\%, except for small regions in the detector with abnormally high dust concentrations. Assuming 100\% efficiency we would set a m_{\tilde{\tau}} \geq 220 \text{ GeV} limit with the one year IceCube data, and an expected limit m_{\tilde{\tau}} \geq 280 \text{ GeV}, also at 95\% C.L. A more refined search strategy, e.g. exploiting the fact that the stau signal is much sharper than the muon background, could lead to an even stronger limit. Yet, the search is limited by the “luminosity” of the collider. We estimate that for m_{\tilde{\tau}} \geq 500 \text{ GeV}, the number of events in IceCube over one year is smaller than one, and therefore detection would become challenging even if the background could be fully suppressed.

The sensitivity of the search increases with a larger statistical sample. With ten years of IceCube data, already recorded, and assuming no improvements to the reconstruction, simulation or energy resolution, the expected limit becomes m_{\tilde{\tau}} \geq 430 \text{ GeV}, which is comparable to the

FIG. 2. Reconstructed energy distribution of muon (orange) and stau events with arrival direction $\theta_{\text{zenith}} \in [84^\circ, 86^\circ]$, for $m_{\tilde{\tau}} = 100$ (lighter blue), 200 (darker blue) and 300 GeV (violet). We also show for comparison as dashed lines the true energy distribution.

FIG. 3. Same as Fig. 1 after imposing the energy cut $E \in [100 \text{ GeV}, 1 \text{ TeV}]$, for $\theta_{\text{zenith}} > 84^\circ$. We also show in the plot the measured number of track events in IceCube. The plot was generated using QGSJET and H3a as the interaction and primary models respectively.
current ATLAS limit. We summarize in Figure 4 the expected limit on the mass of the long-lived stau with IceCube, as a function of the time, for different values of the signal efficiency. For the plot we have assumed production via Drell-Yan, however long-lived staus could also be produced via cascade decay of squarks and gluinos, improving the prospects for discovery. Let us also note that squarks and gluinos could be too heavy to be produced at the LHC, but still be produced in significant amounts in atmospheric showers. In this class of scenarios, IceCube may detect signals of new physics which are not accessible to the LHC.

**Summary and outlook.** - New particles could be produced in cosmic ray showers and detected in neutrino telescopes. We have proposed a new search strategy for long-lived staus in IceCube, which combines angular cuts and energy cuts. Using conservative assumptions on the detection efficiency and one year of public IceCube data from 2012 we obtain the lower limit $m_{\tilde{\tau}} \geq 120$ GeV, assuming Drell-Yan production. For the ten years of IceCube data, which are already collected, we forecast the lower limit $m_{\tilde{\tau}} \geq 430$ GeV, comparable to the current ATLAS limit. Future improvements in the track reconstruction and in the energy resolution, together with the design of optimized selection cuts, will increase the sensitivity of IceCube to long-lived staus. Future neutrino telescopes, such as P-ONE [37], KM3NET [38], GVD [39] and IceCube-Gen2 [40], will increase the total detection volume, also leading to a more sensitive search for long-lived staus. To summarize, water- and ice-based Cherenkov telescopes can be very powerful instruments to search for long-lived charged particles, and can provide sensitivities competitive to those from the LHC detectors.

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