Abstract: Cosmic rays reach the atmosphere with energies up to $10^{11}$ GeV and high energy neutrinos are expected to reach similar energy regions. The incident particle may interact with a nucleon within the atmosphere or inside the Earth to produce exotic particles, thereby probing physics beyond the Standard Model (SM). Attractive scenarios are, for example, supersymmetric extensions of the SM (SUSY) or Kaluza-Klein models. Under favorable conditions meta-stable, charged SUSY or Kaluza-Klein particles give rise to well-separated, parallel, minimum ionizing tracks in IceCube. Since background events from charm and bottom decays and Drell-Yan processes inside the air shower as well as coincident neutrino events could lead to similar signatures, these events are expected to form a relevant background. As the production of exotic particles is highly suppressed, the understanding of this di-muon background seems to be crucial for an analysis in IceCube.

Keywords: IceCube, Physics beyond the Standard Model, Supersymmetry, Simulation

1 Introduction

The cosmic ray spectrum is known up to energies of $10^{11}$ GeV [1] and recently IceCube reported the first observation of high-energy neutrinos in the PeV range [2]. These high-energy particles may interact with a nucleon within the atmosphere or inside the Earth to produce exotic particles, thereby probing physics beyond the Standard Model. Although large neutrino-telescopes like IceCube [3] are focused on the detection of single neutrino events, they are able to look for more exotic event signatures. One signature of great interest consists of two parallel tracks going upward through the detector, that could be produced by new physics.

Attractive scenarios are, for example, supersymmetric extensions of the SM where R-parity is conserved. Under favorable conditions parallel double-tracks can be produced when a neutrino interacts inside the Earth [4,5] or cosmic rays interact in the atmosphere [6,7], generating a pair of supersymmetric particles. These SUSY particles may then decay immediately into a pair of charged next-to-lightest supersymmetric particles (NLSPs), typically long-lived staus [1]. If these particles have a lifetime $\sim \mu$s, they can live long enough to travel large distances ($\sim 1000$ km) and enter the IceCube detector with track separations of several hundred meters. Other theories beyond the SM, e.g. Kaluza-Klein models (KK), could lead to similar predictions [8].

We expect a very low event rate of these particles, thus the understanding of background events is crucial. Previous studies have considered SM backgrounds from processes producing di-muons directly that can cause parallel double-tracks in the detector [4,9,10]. The decay of charmed/bottom hadrons, for example, as well as muons from Drell-Yan processes inside an air shower or coincident neutrino interactions could lead to similar signatures.

In this paper we show the signature of exotic double-track events in IceCube as well as the expected event rates for different benchmark SUSY ‘toy-models’ based on Monte Carlo simulations. We also discuss relevant background events and show their expected signatures based on simulations as well as recent results from our analysis of laterally separated muons in IceCube cosmic ray events [11].

2 Exotic signatures in IceCube

The spatial distribution of exotic double-track events depends on the underlying theory. In Supersymmetry, for example, the distributions depend on the given particle spectrum and SUSY breaking mechanism. To simulate exotic event signatures in IceCube we consider different SUSY models and use Monte Carlo simulations for the production, decay, propagation and detector simulation of supersymmetric particles.

We consider minimal supersymmetric models (MSSM) and use the benchmark models from [12] shown in Table 1, assuming different SUSY breaking mechanisms: Minimal supergravity (mSUGRA) and gauge-mediated symmetry breaking (GMSB). These mechanisms can be characterized by the sign of the SUSY Higgs mass parameter $\mu$ and four parameters: The scalar mass parameter $m_0$, the gauging mass parameter $m_{1/2}$, trilinear coupling $A_0$ and the ratio of the Higgs vacuum expectation values $\tan \beta$ in mSUGRA scenarios and the messenger mass $M_{mess}$, messenger index

1. The stau is the superpartner of the SM tau.
Table 1: SUSY models used for simulation [12].

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_{1/2}$</th>
<th>$m_0$</th>
<th>tan $\beta$</th>
<th>$\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>280 GeV</td>
<td>10 GeV</td>
<td>11</td>
<td>0 GeV</td>
</tr>
<tr>
<td>ε</td>
<td>440 GeV</td>
<td>20 GeV</td>
<td>15</td>
<td>-25 GeV</td>
</tr>
<tr>
<td>GMSB</td>
<td>$M_{sph}$</td>
<td>$\Lambda$</td>
<td>tan $\beta$</td>
<td>$N_{Mess}$</td>
</tr>
<tr>
<td>II</td>
<td>70 TeV</td>
<td>35 TeV</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>SPS 7</td>
<td>80 TeV</td>
<td>40 TeV</td>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>

$N_{Mess}$, the universal soft SUSY breaking mass scale $\Lambda$ as well as tan $\beta$ and sgn($\mu$) in GMSB scenarios respectively [13]. Although these models seem to be disfavored with respect to the squark mass limits of the LHC data and due to implications of the Higgs mass on supersymmetry breaking scenarios [14], we use these benchmark points to develop SUSY simulations, since inserting different models beyond the SM is straightforward.

In order to estimate the rate of production of SUSY particles due to high-energy neutrino interactions with a nucleon $N$ inside the Earth, we assume an $E^{-2}$ primary neutrino flux normalized to current experimental limits [2]:

$$\frac{d\Phi_{\nu}}{dE} \approx 10^{-8} \frac{E^{-2}}{\text{GeV}} \frac{\text{cm}^2 \text{s sr}}{\text{GeV}}$$

(1)

To generate the event and handle fragmentation and decay of the involved particles into the NLSP we use PYTHIA [15] in connection with Madgraph [16].

To simulate SUSY events from cosmic ray interactions (hadronic interactions) the flux of primary nucleons can be approximated by

$$\frac{d\Phi_{N}}{dE} \approx 1.8 \frac{E^{-\gamma}}{\text{nucleons cm}^2 \text{s sr GeV}},$$

(2)

where $E$ is given in GeV. At $E \approx 10^6$ GeV the spectral index changes from $\gamma = 2.7$ to $\gamma = 3$ [1]. We assume that the interaction typically takes place at a height $H \approx 25 \text{ km}$. The production of SUSY particles is simulated using PYTHIA and the further shower development of the SM particles is simulated with CORSIKA [17]. We assume energy losses in the atmosphere to be negligible for SUSY particles.

Figure 1 shows the distinctive double-track signature of a simulated SUSY event (SPS 7) from a $\nu N$ interaction in the IceCube. As expected, we observe two well-separated, parallel, minimum ionizing tracks. The track separation distributions from $\nu N$ interactions for different SUSY models are shown in Figure 2. We expect track separations of roughly $150 \text{ m} < d < 1000 \text{ m}$ to be resolvable in IceCube thus making a direct detection of supersymmetric double-tracks feasible.

3 SUSY event rates

Using cross sections obtained from PYTHIA and the incoming fluxes mentioned in section 2 we estimate the SUSY event rates at the detector. We assume that every event triggers, which corresponds to an effective area of $\approx 1 \text{ km}^2$. We also assume that every SUSY particle decays into the NLSP, which does not decay on the way to the detector. Thereby we over-estimate the SUSY rates in IceCube. For the hadronic case we assume a uniformly distributed stau flux up to zenith angles of $115^\circ$. The expected event rates under these assumptions are shown in Table 2.

Since in several cases these rates are below the order of 1 event/year, consistent with [12], finding a signal will be - at best - very challenging. Current LHC data shows that the simplest SUSY models are disfavored. As one moves away from minimal SUSY models (e.g. MSSM), the phase space expands and there may be many more models that produce exotic double-track signatures in IceCube.

The propagation of SUSY particles in the antarctic ice is done using the Muon Monte Carlo simulation package [18], where we treat staus like SM taus, but replacing the masses accordingly and switching off the decay. The light propagation, detector response, and trigger are simulated with IceCube software in both cases.

Figure 2 shows the distribution of track separation at the detector obtained from simulations of double-tracks for all MSSM models shown in Table 1.

2. Due to the cubic detector volume of $\approx 1 \text{ km}^3$ and the horizontal string spacing of 125 m.
<table>
<thead>
<tr>
<th>Model</th>
<th>vN interactions</th>
<th>hadronic interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.7</td>
<td>$1.5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>II</td>
<td>0.82</td>
<td>$6.3 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>SPS 7</td>
<td>0.5</td>
<td>$2.9 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 2: Estimated SUSY event rates in IceCube given in events/year.

4 Backgrounds

Previous studies have considered charm production in SM processes as a major background in exotic double-track searches [3]. In [9] it was shown that other SM processes could produce double-track signatures as well. We consider the following SM background processes.

4.1 Charm/Bottom hadrons

If a neutrino interacts with a nucleon inside the Earth, a charmed hadron may be produced, which can produce dimuons via

$$\nu N \rightarrow \mu^- H_c \rightarrow \mu^- \mu^+ H_c \nu,$$

where $H_c$ is the charmed hadron that decays to another hadron $H_i$ [5]. These background events are simulated using the same method as described in section 2, with processes that produce charmed hadrons, instead of SUSY particles. In our simulations, we do not observe double-tracks from neutrino interactions with separations above 100 m; this is different from [4] and [8]. Since we are able to resolve track separations above $\sim$ 150 m, these events would be reconstructed as single tracks and therefore do not form a relevant background in double-track analyses.

The decay of heavy hadrons, mostly from charmed decays, in air showers can also produce laterally separated, high-energy muons (LS muons) with high transversal momentum. These muons, together with the associated muon bundle traveling along the core direction, may produce a double-track signature in IceCube. The muon $p_T$ is related to the muon separation from the shower core by

$$p_T \simeq \frac{d \cdot H}{E_{\mu} \cos(\theta)},$$

where $d$ is the perpendicular separation of the muon from the shower core, $E_{\mu}$ its energy at generation, $H$ the interaction height, and $\theta$ the zenith angle of the shower direction. The transition from soft interactions with $p_T < 2$ GeV, that are not describable in pQCD (perturbative Quantum Chromodynamics), to hard interactions is visible as a spectral change in the $p_T$ spectrum. This spectral change should be visible in lateral separation distributions [11].

In [11] we obtained the lateral distribution of muons produced in cosmic ray events from data taken with IceCube in its 59-string configuration. Figure 3 shows the separation distribution of LS muons where, after applying all selection criteria, 34,754 events remain in the data. The expectation from simulated data, as well as coincident double showers estimated from off-time data are also shown.

The simulated di-muons seem to be in good agreement with the data and a linear fit to the ratios of simulation to data did not show any statistically significant difference in the slopes. But we have also shown that the zenith angle distributions are in significant disagreement between simulation and data. We observe that QGSJET [21] and Sibyll [19] overpredict the event rate at high zenith angles and underpredict the rate for more vertical events, while DPMJET [20] shows a better match to data, but underpredicts the rate for more vertical showers. Note that none of these interaction models include bottom quark production and DPMJET is the only model that includes a hard component of charmed particles. It was previously shown that the hard components of charm and bottom quarks, as well as hard muons from Drell-Yan processes become relevant in double-track searches in neutrino telescopes, especially when including events from horizontal directions [9]. Therefore future simulations with more sophisticated $p_T$ modeling, such as a modified 'heavy-quark' CORSIKA version proposed in [22], may reduce the disagreement in simulations.

4.2 Drell-Yan processes in air showers

In [10] it was shown that Drell-Yan processes in air showers could contribute to the background in double-track searches. As far as we know there is no interaction model available including Drell-Yan processes in air showers. We simulate these processes using the method shown in section 2. Unfortunately, PYTHIA does not produce Drell-Yan pairs below 2 GeV invariant mass, since this region can not be described in pQCD. The obtained lateral separation of muons in air showers including Drell-Yan processes is shown in Figure 5, where we assumed a cosmic ray spectrum from Eq. 9 with primary energies in the range of $10^5$ GeV < $E_{\text{Prim}}$ < $10^9$ GeV up to zenith angles of 89.99°. Although rate calculations are not representative of the actual physics, the events with track separations up to $\sim$ 400 m and above could form a relevant background. Moreover we think that these processes are an interesting topic by itself and may be considered in future analyses.
4.3 Double-neutrino events

Another possible source of background events arises from two muons from a pair of neutrino interactions, produced in the same cosmic ray air shower. These muons will be nearly parallel and thus mimic a double-track signature in IceCube. In [23] we estimate the event rates using CORSIKA simulations where DPMJET and QGSJET interaction models and the cosmic ray spectrum in Eq. 2 are used. All the neutrinos in each event are paired with all of the other neutrinos in each event and the separation distance is computed. The neutrino detection probability \( P(E_\nu) \) depends on the neutrino interaction probability and the probability of observing the produced muon, and is given by [24]

\[
P(E_\nu) = \begin{cases} 
1.3 \cdot 10^{-6} E_\nu^{1.2} & \text{if } E_\nu \leq 1 \text{ TeV} \\
1.3 \cdot 10^{-6} E_\nu^{1.8} & \text{if } E_\nu > 1 \text{ TeV} \\
0 & \text{if } d > d_{\max}
\end{cases}
\]

where \( d \) is the track separation and \( d_{\max} \approx 1 \text{ km} \) the maximal resolvable track distance in IceCube and \( E_\nu \) in units of TeV. Table 3 shows the overall atmospheric neutrino rates from cosmic ray interactions in events/year under two extreme assumptions of the cosmic ray composition, for all-proton and all-iron. The expected event rate to observe two upward-going neutrinos from the same air shower is about one in 14 years, thus being a highly suppressed background and negligible in IceCube SUSY analyses.

5 Conclusions

We studied signatures from supersymmetric models in IceCube proposed in [5,6] using the simulation methods shown in section 2. The simulated MSSM track separations are in agreement with those obtained in [4]. The expected event rates are of the order of less than 1 event/year for currently allowed SUSY. By moving away from minimal SUSY models the phase space expands and there may be many more models that produce exotic signatures in IceCube. Other theories beyond the SM (e.g. Kaluza-Klein models) can lead to double-track signatures in IceCube that may produce more events per year [8]. Hence, this could be a signal of new physics. Therefore we studied any possible SM background events. Decays from heavy quarks produced in neutrino interactions or air showers, as well as muons produced in Drell-Yan processes inside the shower can produce double-tracks in IceCube with similar track separation distributions. Comparison between experimental data and simulations of laterally separated muons from cosmic rays shows a disagreement in the zenith angle distributions. When improved simulations become available future analyses could improve the understanding of these events and estimate the muon ratios, as well as measure the transverse momentum spectrum in air showers. Furthermore the understanding of background events may make it possible to find an excess of double-tracks which would be a signature of physics beyond the Standard Model.

### References


<table>
<thead>
<tr>
<th></th>
<th>QGSJET</th>
<th>DPMJET</th>
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<tr>
<td>Protons</td>
<td>0.068</td>
<td>0.070</td>
</tr>
<tr>
<td>Iron</td>
<td>0.065</td>
<td>0.056</td>
</tr>
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</table>

Table 3: Calculated double atmospheric neutrino event rates in IceCube given in events/year.