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Search for Neutrino-Induced Double Tracks as an Exotic Physics Signature in IceCube

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Physics theories beyond the Standard Model, like Supersymmetry and models with extra dimensions, often invoke $\mathbb{Z}_2$-symmetries in order to avoid new couplings that lead to unobserved new physics, like unnaturally fast proton decay. This gives rise to the possibility of heavy new particles being produced in pairs with the lightest of them being (meta-)stable. Thus, under favorable conditions, neutrinos in the PeV range - like those observed by IceCube - can produce pairs of exotic, charged particles that can be seen in a km^3-sized detector as two parallel, muon-like tracks with a track separation of a few hundred meters. We discuss the methods of reconstructing double tracks and how to separate them from other air shower or neutrino-induced (coincident) muon events in a model independent way.
The first search for such events with the IceCube detector in its 79-string configuration resulted in no candidate events. This result can be used to derive limits that can be applied to explicit exotic models.

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1. Physics Beyond the Standard Model

With the observation of the Higgs boson [1], the last of the particles predicted by the Standard Model (SM) has been found. Yet there are some problems that lead to the conclusion that the SM can not be a fundamental description of nature: firstly, gravity is not part of the model and its apparent extreme weakness compared to the weak force gives rise to the *hierarchy problem* when trying to extend the Standard Model to the energy scale where gravity becomes important; secondly, experimental observations like a non-zero neutrino mass [2] and the existence of *dark matter* are direct evidence of physics not included in the Standard Model. Many models of new physics trying to explain these facts predict new particles at the TeV scale.

Pair Production of long-lived, exotic particles

Additionally, theories beyond the Standard Model like *Supersymmetry* or the assumption of *additional compact dimensions* are generally required to have a $\mathbb{Z}_2$-symmetry within the theory (like R-parity in Supersymmetry) in order not to spoil precision electroweak observations. This discrete symmetry leads to two important phenomenological aspects: most new particles can only be produced in pairs and the lightest of them will be stable - making it an excellent dark matter candidate. Unless the $\mathbb{Z}_2$-symmetry is (slightly) violated this particle has to be neutral but the next-lightest particle can possibly be both charged and long-lived. The latter is usually the result of the lightest exotic particle interacting only extremely weakly like in the case of *gravitinos* for Supersymmetry or Kaluza-Klein excitations of right-handed neutrinos in models with extra dimensions. Long-lived, $\underline{\text{cha}}$rged and $\underline{\text{m}}$assive $\underline{\text{p}}$articles like this are often called *CHAMPs*.

Mass Suppression of Energy-Losses

An interesting aspect of CHAMPs is how their mass influences their radiative energy losses in matter. Bremsstrahlung is naturally suppressed by mass and becomes sub-dominant for any heavy particle, but photonuclear and pair production processes can also be shown to be similarly affected [3]. In particular particles that mostly behave like *heavy leptons* exhibit a suppression of energy losses. The scaling for very heavy particles goes inversely with mass [3, 4]. The radiative energy losses of a CHAMP with $m_{\text{CHAMP}} > 100$ GeV are at least three orders of magnitude lower when compared to a muon - the most penetrating charged SM particle [5]. While even muons at the highest energies produced in air showers only have ranges of tens of kilometers, such a CHAMP can potentially traverse the whole Earth. On a smaller scale $\mathscr{O}(1\text{ km})$ they will mostly look like comparatively lower energy ($\approx$ few hundred GeV) muons. Ideal detectors for particles like this are cubic-kilometer neutrino telescopes like IceCube.

Neutrino-Induced Double Tracks

Production of pairs of exotic particles is possible directly in cosmic ray interactions in the atmosphere, but the observable flux is expected to be rather low (i.e. below ≈ 0.02 - $3\ \text{year}^{-1}\ \text{km}^{-2}$ [6]). A more prominent way to produce CHAMPs is neutrino interactions within the Earth [7]. For heavy, exotic particles to be produced these neutrinos need to be in the PeV range [8] or higher. The CHAMPs can be produced far from the detector site due to their long range and thus have an

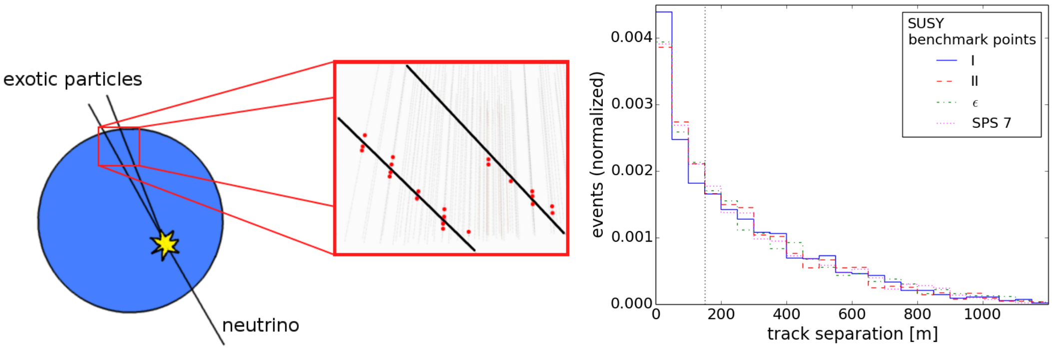

Figure 1: Scheme of a double track signal in a neutrino telescope like IceCube *(left)* and track distance distribution in SUSY models *(right)* (SUSY parameter points adopted from [10]) with a simplified energy loss behavior, not taking into account additional effects like multiple scattering [11]. The typical resolvable track separation in this analysis starts at about 150m.

increased effective volume for detection compared to muons. This can partially compensate for the low branching ratio to exotic particles compared to SM particles.

Due to CHAMPs mimicking the much more numerous muons, particle identification of a single CHAMP is a difficult. The CHAMPs will, however, always be produced in pairs and - at least generally - far from the detector. This results in a signature of *two parallel tracks* with a track separation of up to several hundred meters as seen in Figure 1. SM neutrino interactions producing di-muon tracks with a separation greater than 100 m are extremely rare [3, 9] and so an excess of well separated tracks is an excellent indicator for physics beyond the Standard Model. CHAMPs like this will also generally deposit less energy in the detector than other particles at the highest energies.

2. Search for Double Tracks in IceCube

The IceCube detector is installed in the ice at the geographic South Pole [12] between depths of 1450 m and 2450 m. Detector construction started in 2005 and finished in 2010. Reconstruction of the incoming event energy, position and direction relies on the optical detection of Cherenkov radiation emitted by charged particles in the surrounding ice. This search for double tracks is based on data collected between May 2010 and May 2011 in the 79 string configuration (IC79).

Reconstruction

The double track reconstruction is done in several steps. The reconstruction itself implicitly assumes parallel double track events and does not distinguish between signal (parallel tracks) and background (single or non-parallel tracks) events. Still, important cut variables can be derived from the reconstruction result. The start is the separation of photon pulses seen in the digital optical modules (DOMs) of IceCube and assigning them to one of the tracks based on geometric considerations. This is done in two ways, both of which effectively construct a plane that divides the detector. One way is to construct a *tensor of inertia* of the DOMs in an event by treating their

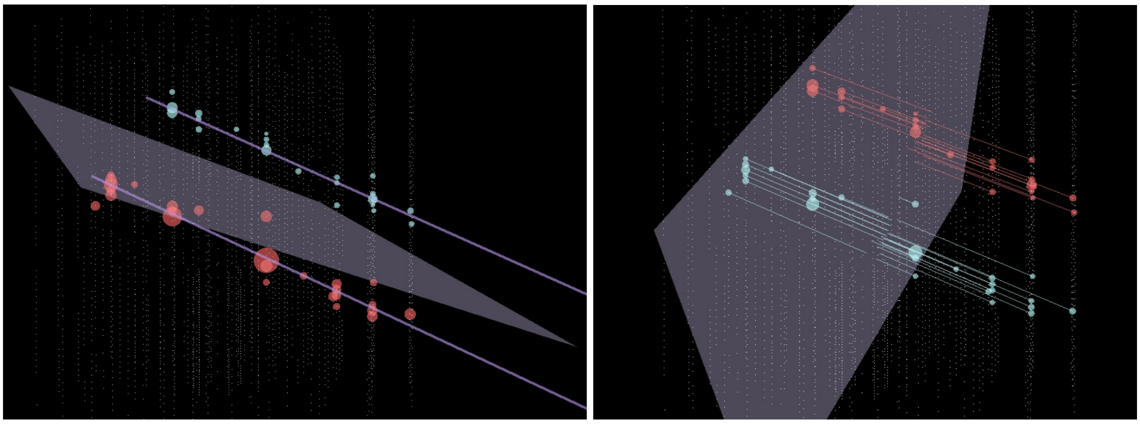

Figure 2: The geometric double track reconstruction - *left:* tensor of inertia based plane; *right:* combination of projection and k-means clustering

charge distribution like masses. The eigenvalues and eigenvectors are then related to the orientation of the parallel tracks within the detector and the correct choice of eigenvectors can be used to construct a dividing plane. The other way used is the application of a k-means clustering algorithm [13] to separate the pulses into two clusters. This is preceded by a projection of the DOM coordinates into a common plane that is perpendicular to the approximate direction of the tracks. This projection-vector is at first obtained via a *single track fit* on the whole event. The procedure minimizes the natural spread of pulses along their trajectory. Both types of reconstructions are illustrated in Figure 2.

The two clusters of DOM pulses can then be used as a basis for a simple (i.e. assuming a plane wave) single track fit each. At least one of these four fits (two for each method) is usually a much more precise estimator for the direction of the double tracks than the initial guess. The clustering algorithm is repeated with a projection in each direction. The clustering attempt showing the smallest spread (i.e. squared mean deviation) of DOM positions around their cluster centers is assumed to be the best. The simple track fits on each of the *best* clusters then form the seed of two separate likelihood reconstructions [14]. The underlying assumptions of these fits are either two infinite tracks with arbitrary location and direction or two tracks that are assumed to be parallel. Whereas the non-parallel fit is done to slightly improve the reconstruction of the opening angle of the tracks, the likelihood parameter of the (more important) parallel fit is used directly in background suppression cuts.

Standard Model Backgrounds and Cuts

Most events in IceCube are muons directly produced in air showers. Since these come from *above* the horizon and exotic double tracks are mostly believed to come from *below* the horizon, simple cuts on the zenith angle of the observed tracks remove the bulk of cosmic ray muons. This leaves two general classes of track-like events: muon tracks related to neutrinos coming from below the detector and mis-reconstructed events actually coming from above.

Double tracks with low track separation are very hard to distinguish from single, up-going muon tracks. The typical horizontal spacing of DOMs in IceCube is 125 m and makes precise reconstruction of double tracks with separation below this challenging. Removing events with small and unresolvable track separation is done by setting a limit on the minimal reconstructed track separation (150 m). Additionally there is a cut on a variable that effectively works as a likelihood ratio test comparing a single track fit with a parallel double track fit. Only events that look much more like a double track than a single track in this variable are kept.

The most common background for mis-reconstructed events are coincident muons from independent air showers. Most cuts in the IceCube double track search are aimed at them. Note that the actual direction of the muons in these events does not play a large role influencing the mis-reconstructed direction. The misidentification comes from the first event causing a photon signal in DOMs that are - on average - located lower in the detector than the DOMs registering the second event. Simple reconstructions connect these separate events and treat them as a single, up-going, track. Figure 3 (left) shows a typical mis-reconstructed background event of this kind.

There are many ways to remove coincident events from the data. The most effective way is to cut on the (reduced) likelihood variable obtained in the likelihood reconstruction described earlier as can be seen in Figure 3 (right). Yet it is not feasible to do this for every event since the rate of air shower muons is very high and the likelihood reconstruction is computationally intensive. A series of variables for pre-cuts is needed to reduce the data volume to an acceptable level.

The time and geometric distance of the two sets of hits for each muon are not causally connected. Generally, there will be a geometric gap between the hits for coincident events *along the reconstructed track direction* and the hits will also not be very tightly clustered perpendicular to their apparent direction. The reconstructed speed of the tracks will also differ from the speed of light. Often the reconstructed tracks will not be very parallel as seen in their reconstructed opening angle.

If the coincident muons are produced in separate air showers - as is most often the case - their individual tracks will still be down-going. Ordering all DOM hits in time and assuming the two sub-events do not overlap, one gets an *average* downward pattern from one hit to the next apart from the very last hit of the first and the very first hit of the last track.

This is true for both muon tracks and the average pattern is usually retained even if there is some time overlap of both sub-events. Since the situation is reversed for an up-going signal double track this average pattern from one hit to the next is another useful cut. This does not work if one or both of the coincident events is an up-going muon caused by a neutrino interaction near the detector. Fortunately the situation of two (possibly up-going and somewhat parallel) coincident neutrino events is extremely rare (≈ 0.0008 per year) [9]. All these cuts - including the likelihood cut - were optimized to remove all air shower simulation corresponding to $\mathcal{O}(1\%)$ of a year's experimental IceCube data.

There are also some other SM particle interactions that can directly lead to separated tracks. One such possibility is the production of a muon and a charmed hadron in a high energy neutrino interaction. The hadron can then decay into another muon and both muons can possibly show up as double tracks. These double tracks can not lead to high track separations (> 150 m) due to the more limited muon range and thus interaction vertices that are much closer to the detector. They are also much more likely to stop in the detector. They also can have a higher energy deposition and so can possibly be distinguished from exotic double tracks. However, in simulations of more than 10 years livetime such a di-muon background was not dominant at any analysis cut level and

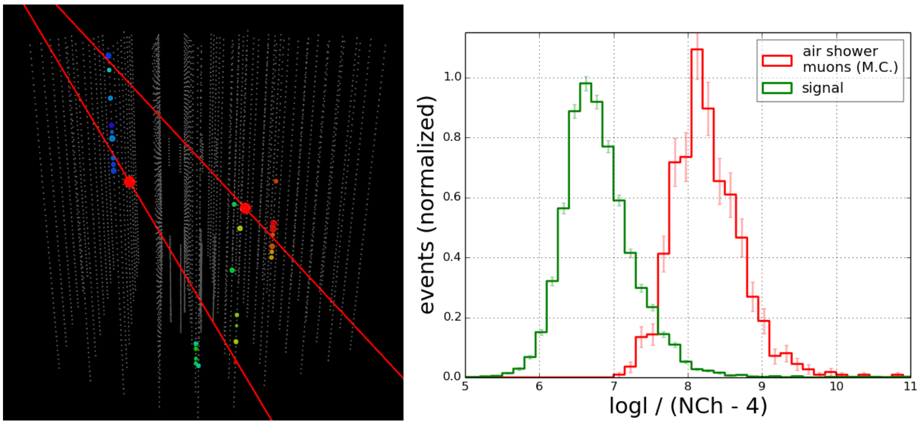

Figure 3: *Left:* A typical mis-reconstructed coincident air shower event - the dominant class of background. Note how the mis-reconstructed track directions do not coincide with the actual direction of the down-going muons. The rainbow palette illustrates the time structure of the DOM pulses (red: early, blue: late); *right:* Cut on a log-likelihood parameter removes most of the coincident air shower background. Distributions shown are at a late cut level.

eventually gets removed completely by cuts also removing single track muon events. This leaves one class of irreducible SM double track background. Two neutrinos produced *in the same* air shower, possibly at the other end of the Earth, are even more penetrating than any charged particle and will also generate parallel tracks with high separation if *both* interact near IceCube. Fortunately this kind of event is also very rare, with a rate ≈ 0.07 events/year [9].

Since the amount of available Monte Carlo data for low energy neutrino and (coincident) air shower muons was much lower than needed to fully characterize the background for the analyzed livetime, some additional cuts were introduced to remove low quality events that show up as either very short tracks or tracks with only a few associated higher quality DOM pulses (i.e. hits that have coincident hits on a nearby DOM). Low quality events that are only seen on very few (i.e. up to four) strings as well as events only clipping the bottom of the detector array are also removed.

3. Simplifications and Model Dependencies

There are many model dependencies that govern the parallel double track flux at the detector:

1. What is the mass of the exotic particles that can be produced in neutrino interactions?
2. What is the size and spectral shape of the neutrino flux most relevant to interactions?
3. How does the mass spectrum of the exotic model in question influence the decay cascade and ultimately the kinematics of the CHAMP?
4. What is the CHAMP's mass?
5. Does the weak interaction play a role in its energy losses?
6. How much does scattering on the way to IceCube change the track separation?
7. Can it decay on its way to the detector?

This renders simulating and analyzing each individual model impossible. On the other hand, the situation is quite easy for a given double track flux *near* the detector. The dependence of the

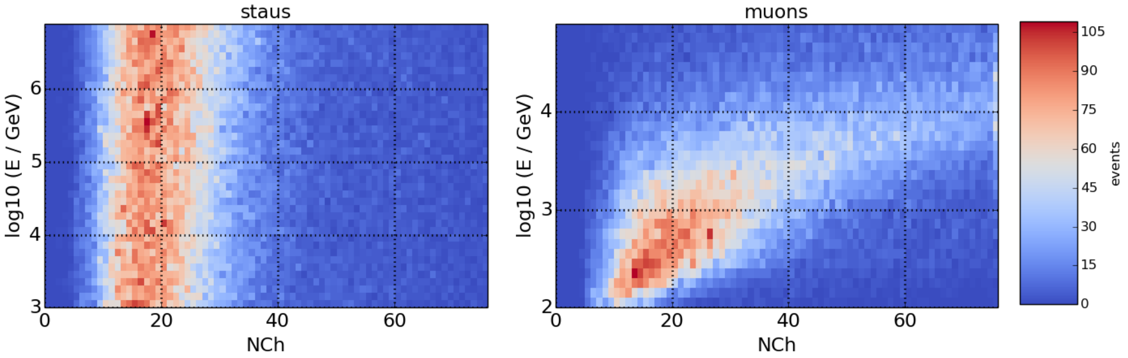

Figure 4: The number of DOM channels *NCh* showing a signal - a very simple energy estimator. For exotic particles like a *stau* in Supersymmetry *(left)* the event-to-event fluctuations dominate over many orders of magnitude in energy unlike for a SM signal like a muon track where the energy dependence is clearly visible *(right)*. Simulation done with the standard IceCube simulation using MMC (Muon Monte Carlo) [15]. Energies shown correspond to the situation when the particles are about to enter the detector volume.

detector signal on the CHAMP energy is extremely weak in many models and can almost be ignored (see Figure 4). The probability that particles with an extremely long range would be starting or stopping within the detector is also very small and can be ignored - it will later be part of the systematic uncertainties of the search. The only relevant parameters which influence the effective area for detection are the zenith angle and the track separation of the two particles.

After performing an analysis and setting a limit on double tracks at the detector one can use the result together with the effective area after all analysis cuts to constrain any specific model. This is done by convolution of the expected zenith and track separation distribution with the effective area. So even any future exotic model that has not been proposed yet can be easily tested this way after the analysis.

4. Results of the IC79 Analysis

None of of the final data sample was used to construct the background separation cuts. Only 1/10 of the data collected in the data taking season served as sample to ensure stable data to simulation rates and develop cuts but these runs are then discarded in the final analysis and the total remaining livetime is 279 days, 17 hours and 54 minutes. Even with an uncertain background rate due to limited Monte Carlo statistics, the data quality cuts proved to be sufficient in eliminating possible background events and there is *no event left* in the final data sample after all cuts. The safest way to interpret this null result is in a *background free pure upper limit* for double tracks at the detector. Exotic models can be easily tested by convolution of the predicted track separation at the detector (e.g. Figure 1) as well as zenith distributions with the limit seen in Figure 5. Since no background expectation was used to compute the limit, it only depends on the effective area after all analysis cuts, the livetime of the data sample and systematic uncertainties of the detector behavior (DOM efficiency, ice models, etc.). Any arbitrary double track model can be tested using this approach. This search is the first of its kind in IceCube and it shows the feasibility of the analysis technique. The analysis is inspired by certain exotic models (i.e. SUSY, UED) but was performed in a model-independent way, and testing any specific model could benefit from specifically tailored cut variables in order to improve the signal efficiency. Moreover, several years of detector data of the full 86 string IceCube array are still to be analyzed and the double track detection efficiency can be further enhanced with a more detailed background description with larger statistics. The current analysis is based on the IceCube *muon filter* data stream that has a preference for well reconstructed *single* tracks. So a dedicated double track filter is another option to increase the sensitivity.

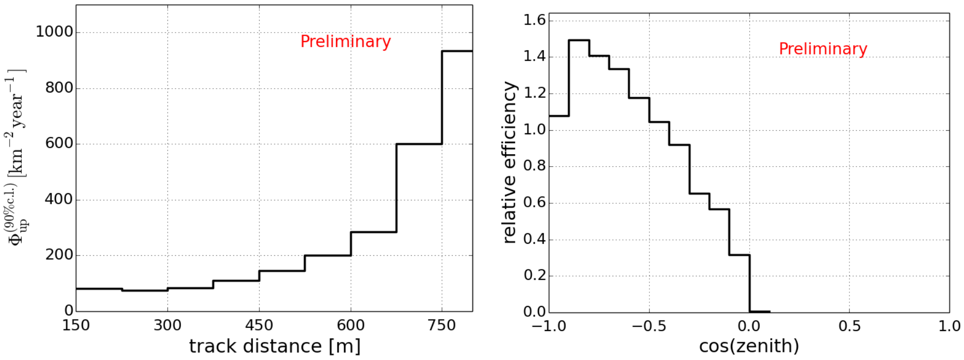

Figure 5: *Left:* The limit (90% confidence level) on up-going double tracks at the detector resulting from the livetime and the double track effective area distribution at the final cut level when assuming a uniform arrival direction from the lower hemisphere. *Right:* The relative efficiency of the analysis when moving from a uniform zenith distribution to a fixed arrival direction. The slightly reduced efficiency closer to the horizon is partially an effect of data quality cuts. There is no notable azimuth dependence.

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