Neutrino spectra and flavor composition on the Hillas plot

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Abstract. We describe energy-dependent neutrino fluxes and flavor ratios of neutrinos produced in cosmic accelerators over $20 \times 24$ orders of magnitude in $R$ and $B$, which are the parameters of the Hillas plot. For this approach, we use a self-consistent model where neutrinos are produced by photohadronic interactions between protons and synchrotron photons from co-accelerated electrons. We especially emphasize magnetic field and flavor effects in the neutrino production chains, including the most relevant neutrino production modes. We also illustrate how the energy-dependent flavor composition can be used to measure physics beyond the Standard Model, and we demonstrate what regions of the Hillas plane can be best probed by existing data, such as IC-40 or Auger.

1. Introduction
Neutrino telescopes [1, 2, 3, 4], such as IceCube or ANTARES, search for neutrinos from astrophysical sources. For example, in the $\Delta(1232)$ resonance approximation, one has for $p\gamma$ interactions

$$ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}. $$

(1)

The extraterrestrial neutrino flux then comes from decay chains such as

$$ \pi^+ \rightarrow \mu^+ + \nu_{\mu}, $$

$$ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu, $$

(2)

whereas the protons or neutrons may leave the source. Therefore, neutrino telescopes are an indirect method to search for the origin of the cosmic rays. Currently, the most stringent data come from the IceCube neutrino telescope, with a number of data releases, see e.g., Refs. [5, 6] for point source searches. However, so far no astrophysical neutrinos from cosmic accelerators have been found, which raises a number of questions: What does that mean? Are the models too optimistic? Which part of the parameter space does IceCube actually test? In this talk, we will address some of these questions.

First of all, we need a description of the parameter space. An often used approach is the so-called Hillas plot [7], where the sources are displayed as a function of $R$ (size of the acceleration region) and $B$ (typical magnetic field in the source), see Fig. 1, left panel. A model-independent,
necessary condition for the maximum energy can be obtained from the condition that the Larmor radius be smaller than the size of the acceleration region

\[ E_{\text{max}} = \eta Z e B R, \]  

(3)

where \( \eta \) is an acceleration efficiency typically \( \simeq 0.1 \ldots 1 \), and \( Z \) is the charge of the accelerated particle. In this talk, we use the Hillas plane \((R \times B)\) as parameter space.

2. Simulation of sources

As a starting point, consider first of all a model unbiased by cosmic ray and gamma-ray observations to test this parameter space. This model should be based on the minimal ingredients for neutrino production, in order to be as general as possible. Most models have in common that protons are injected with a power law with an index \( \sim 2 \). However, the assumptions for the target photons (or protons) strongly depend on the astrophysical source considered. Here we assume that the target photons are produced by synchrotron radiation of co-accelerated electrons (and positrons). This leads to a self-consistent picture depending on relatively few parameters only, the main ones being \( \alpha \) (injection index for protons and electrons), \( R \), and \( B \); see Ref. [8] for details. With the injection spectra defined, all secondaries spectra (pions, muons, and kaons) and the neutrino spectra are just a consequence.

For an accurate and efficient description of the photohadronic interactions, we use Ref. [9], based on the physics of SOPHIA [10]; the weak decays are described in Ref. [11]. An important feature is that direct (\( t \)-channel) pion production at low energies, higher resonances, and multipion production processes are included, which affect the spectral shape. Furthermore, the secondaries are not integrated out, which means that magnetic field effects can be taken into account. As a consequence, the corresponding spectra become loss-steepened above the critical energy

\[ E_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{70 e^4 B^2}}, \]  

(4)

where the synchrotron cooling and decay rates are equal. Obviously, \( E_c \) depends on particle physics parameters only (the mass \( m \) and the rest frame lifetime \( \tau_0 \)), and the magnetic field \( B \). Since \( E_c \) is different for pions, muons, and kaons, which will lead to different flavors of neutrinos after decay, the flavor composition at the source changes between the different critical energies. In addition, a “spectral split” of the shape will be introduced, with peaks at the critical energies. Note that any additional cooling processes mainly affecting the primaries will not affect the flavor composition, so perhaps the flavor composition is the most robust prediction one can make for a source. In addition, it may be the only direct way to measure the magnetic field.

In particle physics, the flavor composition at the source is typically described by a simplified picture: pion decays (followed by muon decays) leads to a flavor composition \( (\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0) \), cf., Eq. (2). If the muons lose energy before they decay, one has \( (0 : 1 : 0) \) from pion decay only, see, e.g., Ref. [12]. On the other hand, depending on the spectral shape, the cooled muons may pile up at lower energies [8], leading to \( (1 : 1 : 0) \). Finally, the neutrons produced by processes as in Eq. (1) decay into neutrinos with \( (1 : 0 : 0) \). Since in none of these scenarios \( \nu_\tau \) are produced at the source, it turns out to be useful to describe the flavor composition at the source by the flavor ratio between \( \nu_e \) and \( \nu_\mu \). In fact, these flavor ratios can be reproduced in a numerical simulation. However, in general, the flavor ratios are energy-dependent. In Fig. 1, right panel, a rough classification of the flavor ratios can be found. For low magnetic fields, the pion beam is found. For large \( B \), all charged species lose energy rapidly by synchrotron radiation, which means that a neutron beam is found. For values of \( B \) between these region, depending on the spectral shape, muon beam and muon damped flavor compositions can be identified, while sometimes different processes compete and no clear flavor ratio can be assigned. As a summary,
For $B < 100 \text{ G}$, it is safe to assume a pion beam. For larger magnetic fields, however, the flavor composition can be predicted in a self-consistent way.

3. Neutrino propagation and detection

In the Standard Model, the neutrino propagation from source to detector is assumed to be governed by flavor mixing. This implies that the magnetic field effects will correspondingly translate in the spectral shape and flavor ratio at the detector. As one observation, the neutrino telescopes are typically quite sensitive to the spectral shape, see discussion in Ref. [13]. A very good sensitivity can be obtained if one of the humps in the spectrum coincides with the minimum of the differential limit. Therefore, predicting the spectral shape is rather important to describe the instrument response. In addition, note that an $E^{-2}$ neutrino spectrum, as frequently used for astrophysical neutrino limits, is only found in rare cases in this model. As another observation, Auger is, at least in principle, more sensitive to the part of the parameter space where the sources of the highest energetic cosmic rays are suspected.

As far as the flavor composition at the detector is concerned, a useful observable is the ratio of muon tracks to cascades [14]

$$
\hat{R} = \frac{\Phi_{\mu}^{\text{Det}}}{\Phi_{e}^{\text{Det}} + \Phi_{\tau}^{\text{Det}}},
$$

where $\Phi_{\alpha}^{\text{Det}}$ is the flux of flavor $\nu_{\alpha}$ at the detector. Note that neutral current events will also produce cascades, which, in practice, have to be included as background. In Ref. [15], the most recent IceCube cascade analysis, the contribution of the different flavors for a $E^{-2}$ extragalactic test flux with equal contributions of all flavors at the Earth was given as: electron neutrinos 40%, tau neutrinos 45%, and muon neutrinos 15% (after all cuts). This implies that charged current cascades dominate and that electron and tau neutrinos are detected with comparable efficiencies, i.e., that Eq. (5) is a good first approximation to discuss flavor at a neutrino telescope. The benefit of this flavor ratio is that the normalization of the source drops out. Therefore, it may represent the experimental flavor measurement with the simplest possible assumptions.
One can show that the energy-dependent flavor ratios at the source directly translate into energy-dependent values of $\hat{R}$, where the mixing parameter uncertainties enter as an additional variable [8]. For reliable conclusions from this flavor ratio, at least the knowledge from the upcoming reactor experiments and T2K will be needed.

Another interesting aspect of $\hat{R}$ in the particle physics literature is the possible sensitivity to new physics effects in the neutrino propagation. If such an effect is energy-dependent, such as neutrino decay, the energy-dependent flavor ratio at the source and the energy-dependent new physics effect will have to be disentangled. However, if the flavor composition at the source can be predicted, its energy-dependence can help for the new physics effect identification, see Ref. [16] for a detailed discussion.

4. Summary and outlook

As a peculiarity of the neutrino fluxes, flavor and magnetic field effects (on the muons, pions, kaons) change the shape and flavor composition of astrophysical neutrino fluxes. In addition, the spectral shape is affected by additional multi-pion production processes at high center-of-mass energies because of the cross section being qualitatively different from the $\Delta$-resonance. Flavor ratios, although difficult to measure, are interesting because they may be the only way to directly measure $\hat{B}$ (astrophysics), they are useful for new physics searches (particle physics), and they are relatively robust with respect to the cooling and escape processes of the primaries (electrons and protons).

In the near future, the same techniques will be applied to gamma-ray bursts (GRBs), where the target photon spectrum is typically inferred from gamma-ray observations (compared to the self-consistent model discussed above). It is especially interesting that IceCube reaches already generic predictions from the conventional fireball model, see Ref. [17]. However, it has been demonstrated that magnetic field effects and additional production processes in the photohadronic interactions have a similar impact on GRBs, see, e.g., Refs. [11, 12, 18]. In addition, it has been shown that various sources of systematical errors have to be taken into account, such as from stacking a few bursts to infer on the quasi-diffuse flux [19, 20]. A re-computation of the conventional fireball model is in preparation [21].

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