

GeV–TeV Neutrino Spectra from Proton-Proton Interactions in Astrophysical Environments

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Neutrino astronomy has seen tremendous progress over recent years with the discovery of a diffuse flux of astrophysical neutrinos in the TeV–PeV energy range and the first compelling evidence of neutrino emission from gamma-ray blazars. Neutrinos are unique cosmic messengers that allow to discover and characterize the most energetic non-thermal sources in the Universe. We consider the possibility of observing transient neutrino sources in the GeV–TeV energy range, where neutrino telescopes are limited by atmospheric backgrounds. The production of these intermediate-energy neutrinos likely proceeds via proton interactions with ambient matter in the source and with the surrounding background gas. We study the production of GeV–TeV neutrinos based on GEANT4 simulations. We also investigate the impact of high-density environments on the development of particle cascades and secondary neutrino spectra.

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1. Introduction

Neutrino astronomy has reached two important landmarks: the discovery of TeV–PeV astrophysical neutrinos [1], by IceCube, and the identification of the first likely source of joint electromagnetic and neutrino emission, the blazar TXS 0506+056 [2]. Yet, the origin of the bulk of the IceCube high-energy neutrinos remains unknown. Finding their origin would reveal critical information about the most energetic non-thermal sources in the Universe [3, 4]. Figure 1 shows the wide range of neutrino spectra from different types of sources, including recent IceCube observations.

In astrophysical sources, high-energy neutrinos are expected to be produced in the interaction of high-energy protons and nuclei with ambient matter and photons. These interactions produce pions, that subsequently decay via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ and the charge-conjugated processes. Typically, a neutrino from this production channel receives about 5% of the energy from the initial cosmic ray nucleon. At the same time, cosmic-ray interactions also produce neutral pions that decay as $\pi^0 \rightarrow \gamma + \gamma$, where each gamma ray has, on average, 10% of the energy of the parent proton. Neutrinos are therefore tightly connected to other cosmic messengers and their sources need to be understood in the context of multi-messenger observations.

Traditionally, GeV–TeV astrophysical neutrinos have been less thoroughly explored than their high-energy counterparts, since at these energies the large background of atmospheric neutrinos makes their detection challenging. The level of the flux of atmospheric neutrinos is indicated as black and grey lines in Figure 1. Yet, existing and upcoming neutrino telescopes are well-positioned to discover them in coincidence with electromagnetic or gravitational-wave transients of short duration, during which the atmospheric background is negligible. This was demonstrated recently, when Super-Kamiokande [5], the Baksan Underground Scintillation Telescope [6], and IceCube [7] set upper limits on the GeV–TeV neutrino flux associated with the gravitational-wave event GW170817. KM3NeT/ORCA [8], currently under deployment in the Mediterranean Sea, and the IceCube upgrade [9], planned for 2022, should also be sensitive in this energy range.

To this end, we study GeV–TeV neutrino production via proton-proton collisions, from which we expect a significant contribution of neutrinos down to GeV energies. We do this by simulating proton-proton collisions in GEANT4 [10] and by tracking neutrino production in detail during the development of the ensuing particle showers. Our ultimate goal is to provide general-purpose, realistic spectra of astrophysical GeV–TeV neutrinos and anti-neutrinos of all flavors, for different source matter densities, that can be used in assessing discovery prospects. We present preliminary results towards achieving this goal.

2. Production of GeV–TeV Neutrinos

In general, cosmic ray collisions with gas (pp) and radiation ($p\gamma$) can provide secondary neutrino spectra over a wide energy range, that is limited by the pion production threshold and the initial cosmic ray energy. The most relevant process for $p\gamma$ interactions are resonant collisions via the Δ^+ -resonance. For target photons with energy ε the corresponding resonant proton energy is given by $E_p \simeq \Gamma^2(m_\Delta^2 - m_p^2)/4\varepsilon$, where Γ is the bulk Lorentz factor of the environment where the target photon density is assumed to be isotropic. Efficient neutrino production in requires strong

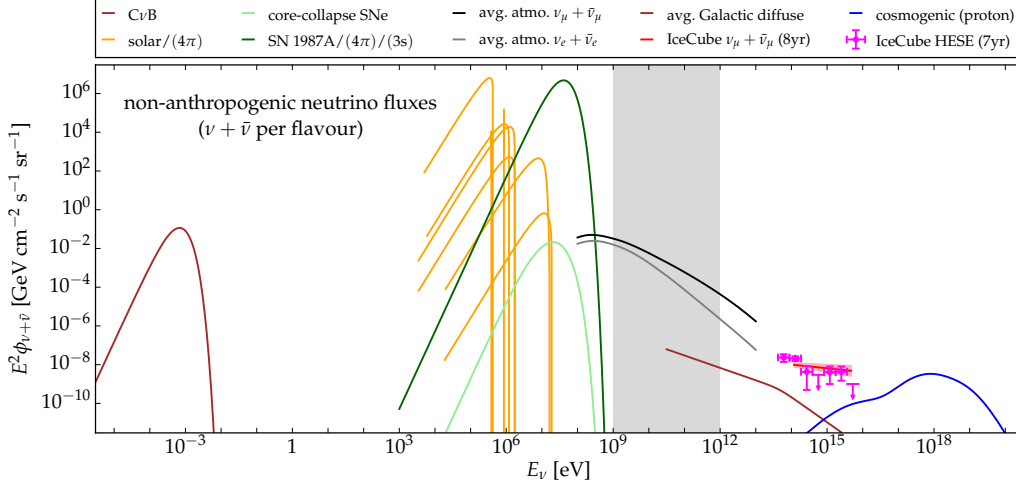


Figure 1: Cosmological, astrophysical and atmospheric neutrino spectra (predicted or detected). The GeV–TeV energy region – where the astrophysical flux is expected to be dominated by pp interactions – is grey-shaded. Note that the main contribution in this energy range comes from atmospheric neutrinos, limiting the sensitivity of neutrino observatories to diffuse astrophysical fluxes. This can be overcome in searches for transient astrophysical neutrino emission.

radiation backgrounds, which are typically associated with transient phenomena. This limits the photon energy to $\varepsilon/\Gamma < m_e$, above which the target photon density is expected to be diminished by e^+e^- pair production in photon-photon collision. Taking into account that a secondary neutrino takes on average 5% of the proton energy, we arrive at an effective lower bound on the secondary neutrino energy of $E_\nu \gtrsim 470(\Gamma/30)$ GeV.

In contrast, pp interactions are expected to produce neutrino emission that extend into the sub-TeV range eventually limited by the pion mass $E_\nu \gtrsim \Gamma m_{\pi^+}/4 \simeq 1(\Gamma/30)$ GeV. Therefore, transient neutrino emission in the GeV–TeV energy range is likely to be dominated by pp collisions. Transient neutrino emission via this mechanisms have been considered, *e.g.*, from neutron-proton collisions in expanding gamma-ray burst (GRB) fireballs [11] or choked jets in core-collapse supernovae [12].

Efficient production of GeV–TeV neutrinos in transient sources require sufficiently high densities ρ of target material. The inelastic pp cross section for cosmic ray energies of about 1 GeV is $\sigma_{pp} \simeq 3 \times 10^{-26} \text{cm}^2$ and somewhat increases towards higher energies. Astrophysical transients with durations T have a pp opacity $\tau_{pp} \simeq 0.5(T/0.1\text{s})(\rho/10^{-8} \text{g cm}^{-3})$. These extreme target densities can exist in early stages of GRB fireballs. One of the motivations of these proceedings is to study of development of particle cascades in very dense environments. In the following we study secondary production of neutrinos under these extreme conditions using the public simulation software GEANT4 [10].

2.1 Secondary Neutrino Spectra from GEANT4

Using the quark-gluon string model implemented in GEANT4, we simulate the interaction of protons of energy E_p in a medium made up of protons at rest, isotropic and of homogeneous

density ρ . We inject a mono-energetic proton flux of 100 GeV and 100 TeV into an environment with various densities. The simulation keeps track of individual particles during the development of the ensuing shower; particles may interact, lose energy, and decay while propagating. Neutrinos are made in the decay of pions, muons, kaons, and neutrons. The simulation outputs the energy, flavor, and parent particle of each neutrino. From this, we build the neutrino energy spectra as functions of $x \equiv E_\nu/E_p$, where E_ν is the energy of the daughter neutrino. In the following, we always consider the contributions of neutrinos and antineutrinos altogether, and the terms pions, muons and kaons refer to π^\pm, μ^\pm and K^\pm .

The production of neutrinos of different energies depends on the interplay of the energy loss and decay of their parent particles. The interplay is affected by the density of the medium: in a dense medium, the energy losses — especially of pions — are more significant, and so the neutrinos born from their decay have lower energies. We first focus on a high-opacity medium with a density of around $10^{-8} \text{ g cm}^{-3}$, that would allow the acceleration of cosmic rays to energies in the TeV range in transients of sub-second duration with maximal pion-production efficiency.

In the following, we will compare our simulation against the parametrization of the high-energy neutrino spectra from proton-proton interactions by Kelner, Aharonian & Bugayov (KAB) [13]. KAB compute the ν_e and ν_μ fluxes produced in the decay of pions and muons made in proton-proton interactions. In the KAB parametrization, only primary pions (and their direct daughter muons) produced in the proton-proton interaction are considered, not secondary pions and muons produced at later stages during shower development. Critically, the density of the surrounding medium is assumed to be low enough that these primary pions and muons decay into neutrinos before interacting and losing energy in the medium. The KAB parametrization is valid for $x \geq 10^{-3}$. Compared to SYBILL simulations of neutrino production in particle showers, the KAB parametrization is accurate to a few percent for $x > 0.5$, and to 20% close to $x = 10^{-3}$ [13].

Figure 2 shows the ν_μ spectrum coming from pion decays, as computed by our simulations, for a proton energy of 100 GeV (*left*) and 100 TeV (*right*). For the simulation of these distributions, we set the matter density at $10^{-8} \text{ g cm}^{-3}$, low enough that the energy loss of pions before their decay is negligible. We show separately the neutrino spectrum from the decay of primary pions only — those directly created in the proton-proton interaction — and the neutrino spectrum coming from the decay of all pions produced in the shower — including kaon decays, pion interactions, and secondary proton interactions.

For both $E_p = 100 \text{ GeV}$ (*left*) and $E_p = 100 \text{ TeV}$ (*right*), the simulated spectrum of ν_μ from primary pions agrees with the KAB spectrum to within 20%, *i.e.*, to within the uncertainty of the parametrization, in the announced range of validity (down to $x = 10^{-3}$). Therefore, we conclude that our simulation successfully reproduces the results of the KAB parametrization under the same assumptions, *i.e.*, down to $x = 10^{-3}$. Note that GeV neutrino production from 100 TeV protons imply values of x down to 10^{-5} , where production of neutrinos from secondaries is particularly important, and where the KAB parametrization is not designed to hold. At these low neutrino energies, the neutrino spectrum obtained with the simulation from the decay of all (primary and secondary) pions exhibits differences of up to about 40% with the KAB one.

Figure 3 shows the ν_μ and ν_e spectra coming from the decay of muons. For $E_p = 100 \text{ GeV}$, one can see that the spectra obtained from all (primary and secondary) muons in the simulation exhibit about 40% difference with the ones obtained with the KAB parametrization at $x = 10^{-3}$.

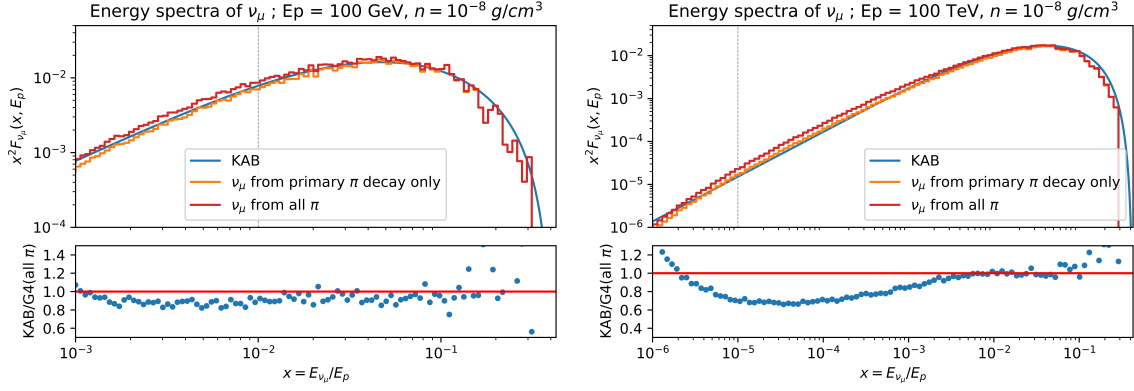


Figure 2: Spectrum of ν_μ from the decay of pions produced in proton-proton interactions, as a function of $x \equiv E_\nu/E_p$, as output by our simulation. For comparison, we show the spectrum of ν_μ computed using the KAB parametrization, which is valid for $x \equiv E_\nu/E_p \geq 10^{-3}$. Mono-energetic protons are injected with energy $E_p = 100$ GeV (*left*) or 100 TeV (*right*) in a medium of fixed matter density 10^{-8} g cm $^{-3}$. We show separately the simulated spectra of neutrinos coming from the decay of primary pions only and from the decay of all the pions produced during shower development. The vertical dashed grey line indicates on both plots a neutrino energy $E_\nu = 1$ GeV. In the right panel the horizontal range is extended. The bottom panels show the ratio of the KAB neutrino spectrum to the simulated spectrum from all pions. See the main text for details.

For $E_p = 100$ TeV, this difference can reach 60% for small values of $x \sim 10^{-5}$. These differences can again be ascribed to the contribution of neutrino production from secondaries, which is not accounted for in the KAB parametrization.

In summary, our preliminary results show a high level of agreement with the parametrization introduced by KAB [13] within its validity domain, *i.e.* down to neutrino energy fractions of $x \simeq 10^{-3}$. Presently, we are working on building a parametrization of the neutrino spectra that holds also in the range $x \lesssim 10^{-3}$, relevant for sub-TeV neutrino production by high-energy cosmic rays. We are also considering a comparison with a more recent parametrization [14], built to study the production of gamma rays.

2.2 Effect of the Source Matter Density

Finally, we investigate the effect of extremely dense target background with opacity $\tau_{pp} \gg 1$. Note that cosmic ray acceleration to high energies under these conditions is unfeasible and therefore production of secondary neutrino emission unlikely (unless one assumes that the cosmic rays have been accelerated prior to their entrance and propagation in the extremely high-density medium). Nevertheless, it is illustrative to see the effect of high-density environments on the production of secondary neutrino spectra.

Figure 4 shows the effect of the source density on the fraction of pions that decay compared to the total number of pions produced by the proton-proton interactions, computed from the simulation. At high densities, the interaction length of the pions shortens. The density for which the interaction length equals the decay length can be estimated analytically (grey line) and is in good

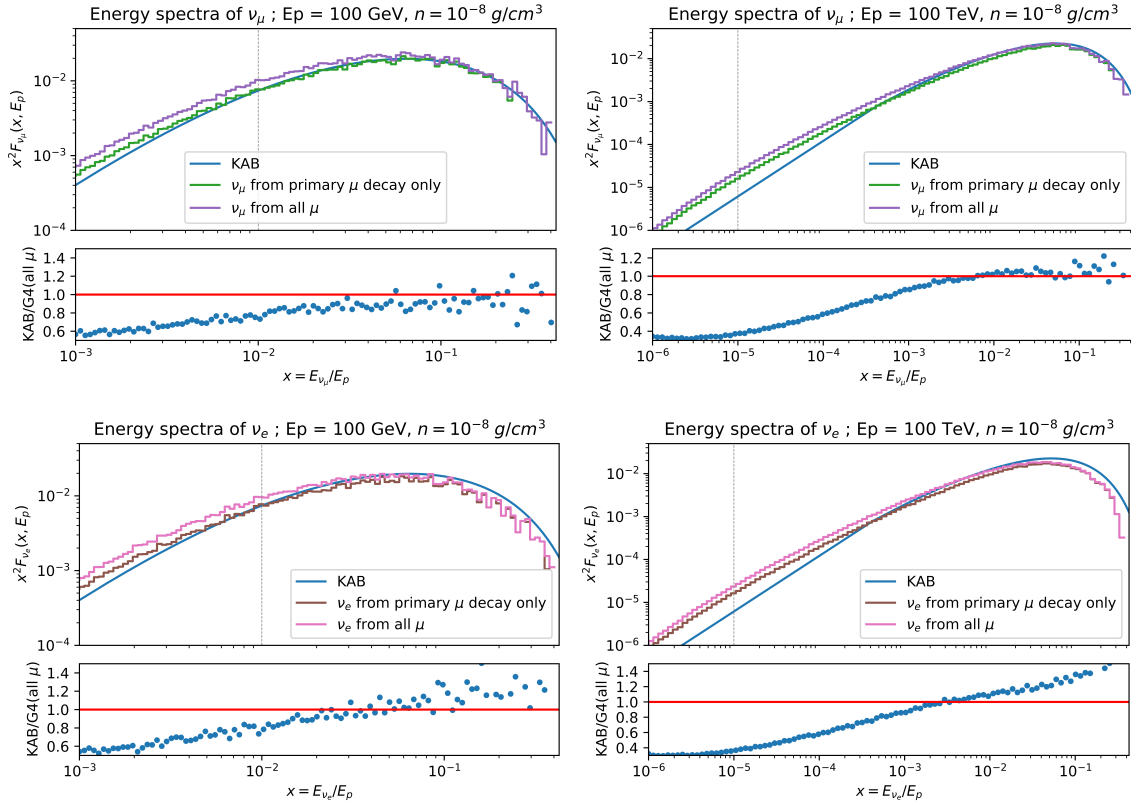


Figure 3: Same as Fig. 2, but showing the simulated spectra of muon (anti-)neutrinos (*top*) and electron (anti-)neutrinos (*bottom*) coming from the decay of primary muons only and from the decay of all the muons produced in the shower development.

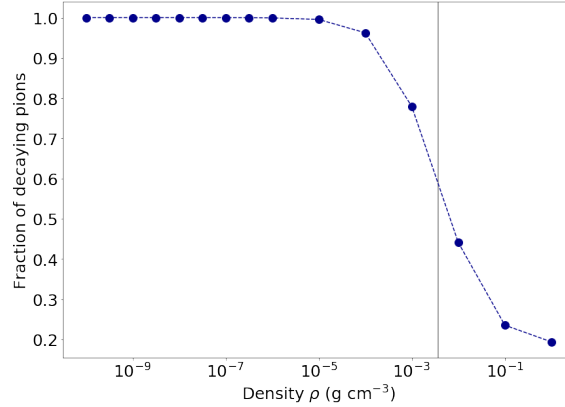


Figure 4: Fraction of pions produced in proton-proton interactions that decay, as a function of the density of protons of the medium, for incident protons with energy $E_p = 100$ GeV. For this plot, only the pions directly produced in the proton-proton interaction are counted. The grey line represents the analytical estimate of the density $\rho = 3.68 \times 10^{-3} \text{ g cm}^{-3}$ for which the pion interaction length equals the pion decay length.

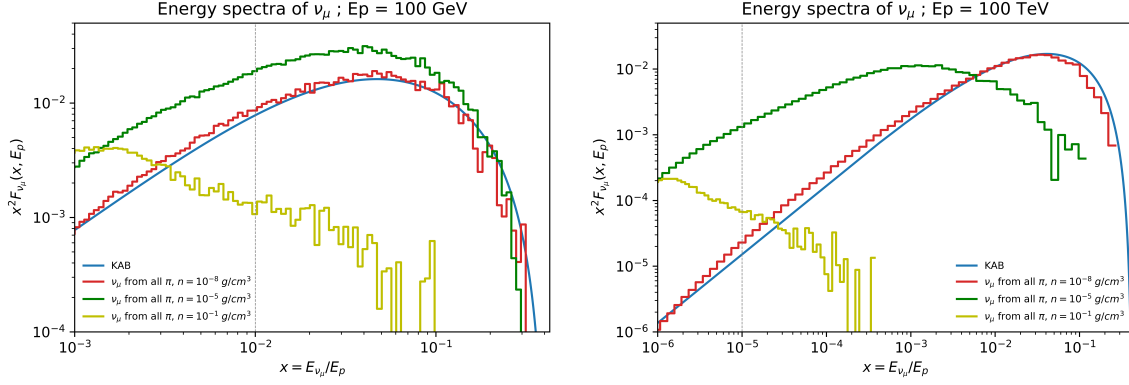


Figure 5: Effect of the density of the matter in the source on the neutrino spectrum produced by pion decays when assuming a mono-energetic injected proton spectrum of $E_p = 100$ GeV (*left*) and 100 TeV (*right*).

agreement with the simulation.

Figure 5 shows the effect of the matter density of the proton target at the source on the neutrino spectra from pion decays in our simulations. We select three benchmark values of the density ρ : 10^{-8} , 10^{-5} , and 10^{-1} g cm $^{-3}$, which correspond to different regimes in the fraction of decaying pions as shown in Fig. 4. At 10^{-8} g cm $^{-3}$, all the pions decay before interacting. At 10^{-5} g cm $^{-3}$, pion decays and interactions start to compete. At 10^{-1} g cm $^{-3}$, the pions predominantly interact instead of decaying.

3. Conclusions

In the search for the unknown astrophysical sources of the TeV–PeV neutrinos seen by Ice-Cube, detecting the associated GeV–TeV neutrinos from astrophysical transient events would provide important complementary information. We have presented preliminary results towards building a general-purpose, accurate parametrization of the spectrum of GeV–TeV neutrinos produced by proton-proton interactions in astrophysical sources.

Our studies are based on GEANT4 simulations of proton-proton interactions. We have explored the neutrino spectra resulting from the interaction of protons of different energies, in environments with different matter densities. To validate our simulations, we have confirmed that, at high energies, our neutrino spectra agree with the popular parametrization from proton-proton interactions by Kelner, Aharonian, & Bugayov [13].

Our simulations track the energy losses, interactions, and decays of secondary particles in the showers initiated by the proton-proton interactions. As a result, our simulations accurately produce the neutrino spectra at low energies, coming from the decay of secondaries that have lost considerable energy during shower development. In addition, our simulations allow us to study the influence of the matter density of the sources on the neutrino spectra.

We are working on a parametrization of secondary neutrino yields from cosmic ray interactions that extends to low neutrino energy fractions $x \equiv E_\nu/E_p$, necessary for the prediction of GeV–TeV neutrino signals from transient astrophysical sources.

Acknowledgments

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