Establishing the astrophysical origin of a signal in a neutrino telescope

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Abstract

Recently the IceCube collaboration has reported the observation of 28 contained events with a visible energy in the interval between $6 \times 10^{13}$ eV and $1.5 \times 10^{15}$ eV, and has argued that this detection is evidence, with a statistical significance of more than four standard deviations, for the existence of an astrophysical neutrino flux that accounts for a large fraction of the events. In this work we analyze the arguments that allow to identify a component of astrophysical origin in the high energy neutrino flux separating it from atmospheric neutrinos. An astrophysical origin for a large fraction of the IceCube contained events is the simplest and most natural explanation of the data but, conservatively, an atmospheric origin cannot yet be entirely ruled out. This ambiguity should soon be resolved.

1 Introduction

Recently the IceCube detector has reported [1] the observation of 28 “contained events” where an energy larger than approximately 60 TeV (a minimum number of 6000 photo electrons) is visible in the detector. In the analysis the most external PMT’s of the telescope are used as a veto to select events where the energy deposition is confined to the inner part of the detector volume. The selection cuts determine a fiducial mass of approximately 400 Mton. The observation of the two highest energy events (with a deposited energy of $1.04 \pm 0.16$ and $1.14 \pm 0.17$ PeV) had been reported previously [2] from a search for contained events performed with a higher threshold.

The IceCube collaboration has estimated that the expected number of events (for the data taking period of 662 days) is $N_{\text{expected}} = 10.6^{+5.0}_{-3.6}$ in the absence of an astrophysical component. This estimate has a contribution
of $6.0 \pm 3.4$ events associated to down–going cosmic ray showers (this muon background was calculated extrapolating from data taken with a smaller fiducial volume and more stringent veto), and a contribution of $4.6 \pm 1.2$ events from standard atmospheric neutrinos (that is neutrinos created in the decay of charged pions and kaons). The contribution of neutrinos from charm decay is estimated as $1.5$ events, and this is included in the error for $N_{\text{expected}}$ and accounts for its asymmetry ($+5.0$ versus $-3.6$ events).

According to the IceCube analysis, the excess in the observed number of contained events can be explained assuming the existence of an isotropic flux of neutrinos that is approximately equal for the six neutrino types. This flux (for each flavor and summing over neutrinos and anti–neutrinos) has the form:

$$E^2 \phi_{\nu\alpha}(E) \simeq (1.2 \pm 0.4) \times 10^{-8} \text{ GeV}/(\text{cm}^2\text{s sr}) .$$

This flux cannot extend to energies larger than approximately $2 \text{ PeV}$, because of the non–detection of events with energy larger than $\simeq 1 \text{ PeV}$. The flux in equation (1) is not a unique solution, and softer spectra are also consistent with the data.

Note that most of the contained events are due to the charged current interactions of electron and tau (anti)–neutrinos. In the case of electron (anti)–neutrinos the visible energy is equal to the incident neutrino energy. For tau (anti)–neutrinos a fraction of the energy escapes the detector since the $\tau^\pm$ created in the interactions always decay into a neutrino. The observed rate of charged current interactions of muon (anti)–neutrino is suppressed because of the containment requirement. A smaller number of events is generated by neutral current interactions, where however a large fraction of the energy escapes with the final state neutrinos.

The detection of high energy astrophysical neutrinos has been a goal pursued for decades with telescopes of always increasing sensitivity, and is unquestionably a result of profound significance. Not surprisingly the IceCube results have immediately attracted considerable interest, and several authors have already commented on the possible implications of such an astrophysical neutrino flux.

In this work I take a very “conservative” attitude, and reanalyse the hypothesis that the data can be explained only with atmospheric neutrinos. This is motivated by the consideration that results of great importance must be analysed with great critical attention.

The problem of the identification of an astrophysical component in the observed fluxes of neutrinos has been already discussed extensively in the past. The obvious and unquestionable method to determine the astrophys-
cal origin of a set of neutrino events is the observation of a structure in their angular distribution in celestial coordinates. Any such anisotropy would be immediately unambiguous proof that at least a fraction of the observed neutrinos originates from astrophysical sources outside the solar system. It has however been predicted (see for example [3, 4]) that the first evidence for high energy astrophysical neutrinos could emerge in the form of an isotropic flux. This is the simple consequence of the fact that neutrinos can traverse the entire universe with negligible absorption, and the sum of all unresolved extragalactic sources (most of them faint and very distant) should form an isotropic flux that is likely to be largest contribution to the neutrino sky.

The signal observed by IceCube is consistent with such an isotropic angular distribution (even if the data shows some intriguing hints of anisotropy that have unavoidably generated speculations).

Atmospheric neutrinos produced in pion and kaon decay have a strong and characteristic zenith angle dependence due to the fact that the decay probability of the parent mesons is enhanced in inclined showers that develop higher in the atmosphere where the air density is lower. On the other hand prompt (that is generated in charm decay) neutrinos, in the energy range considered, are also to a very good approximation, isotropic.

In the absence of the unambiguous signature of a structure in the sky, the astrophysical origin of a component of the neutrino flux can however be obtained from a study of the flavor composition and energy spectrum of the neutrinos.

This work is organized as follows, in the the next section we make a few comments on the angular distribution of the neutrino fluxes and of the IceCube contained events. In section 3 we discuss the importance and sensitivity of neutrino induced muons. In section 4 we discuss the flavor composition of the fluxes. Sections 5 and 6 discuss the main uncertainties in the calculation of the atmospheric neutrino fluxes, namely the estimate of the primary cosmic ray (CR) nucleon flux, and the properties of the charm cross section, and discuss under which assumptions it possible to attribute the rate of contained events observed by IceCube to prompt atmospheric neutrinos. The last section gives a summary and an outlook.

2 Angular distribution

Of the 28 events reported in [1], 24 are down–going and only 4 are upgoing (with a ratio $N_{\text{down}}/N_{\text{up}} \simeq 6$).

The angular distribution of the observable neutrino flux is deformed
because of absorption in the Earth, and one expects a deficit for up–going neutrino events that have trajectories that traverse the Earth. Examples of the survival probability for $\nu_e$ and $\bar{\nu}_e$ as a function of zenith angle for different neutrino energy are shown in fig. 1. Integrating over the entire up–going and down–going hemisphere with the assumption of isotropic fluxes, one obtains the ratio shown in fig. 2.

If one assumes equal fluxes of $\nu_e$’s and $\bar{\nu}_e$’s and a spectral shape of form $\propto E^{-2}$, after integration in the energy range between 60 TeV–2 PeV, one estimates a ratio $N_{\text{down}}/N_{\text{up}} \simeq 1.84$. For softer spectra the ratio decreases, becoming 1.76 (1.70) for a power law spectrum of exponent 2.2 (2.4).

If the IceCube signal is entirely formed by isotropic astrophysical neutrinos, with a power law spectrum $\propto E^{-2}$, the probability to observe an up/down asymmetry as large or larger than the data is approximately 1.2%. On the other hand one should take into account the existence of the estimated background of 6 ± 3.4 events from atmospheric muons that is entirely down–going. The observed up/down asymmetry is therefore additional evidence for an important contribution of down–going events generated by atmospheric muons to the rate of contained events.

A possible explanation for the up/down asymmetry of the observations is that the hypothesis of isotropy of the astrophysical flux is incorrect. In fact if there is a significant contribution from sources located in the Milky Way one would expect an excess of down–going events, because from the South Pole most of the Galaxy (including the Galactic Center) is (always) above the horizon.

It is interesting to note that seven of the contained events have their origin in a $30^\circ \times 30^\circ$ region around the Galactic Center. The probability of having one such a fluctuation in the sky is of order 8%; nonetheless the Galactic Center is a very special location, and the result is certainly striking. The assumption that these events do indeed have their origin from a region around the Galactic Center implies that the neutrino emission from this region has a luminosity (in the 60 TeV–2 PeV energy band) of order $L_\nu \simeq 5 \times 10^{36}$ erg/s. For a comparison the observations of the Galactic Center with the HESS gamma–ray telescope measure a photon luminosity above $E_\gamma = 1$ TeV: $L_\gamma(E_\gamma > 1$ TeV) $\simeq 7 \times 10^{34}$ erg/s, that is approximately two order of magnitude smaller.

A Miky Way origin for a significant fraction of the IceCube signal would therefore have very surprising and exciting implications.
3 Neutrino Induced muons

The background due to down–going showers dominates the rate of contained events with an energy deposition below 60 TeV and, as discussed above, has a non negligible rate above the threshold. The IceCube data indicates that when the down–going background is sufficiently small to allow the detection of neutrino interactions as contained events, the neutrino flux is already dominated by an astrophysical component.

This situation is clearly not ideal, because there is not the possibility to “calibrate” the observations using the (relatively) well understood flux of atmospheric neutrinos at lower energy.

Extending the measurement of the contained events to lower energy one should be able to observe the transition from the standard atmospheric neutrino flux to the new component. The transition should manifest itself as an hardening of the energy spectrum and as a change in the angular distribution that evolves from the the characteristic “secant law” shape of atmospheric neutrinos with $E_\nu \gtrsim 1$ TeV to a shape determined by the distribution of the astrophysical sources (an isotropic distribution if extragalactic emission is dominant).

The transition from a flux dominated by standard atmospheric neutrinos to an astrophysical flux should also be observable using neutrino induced muons. A $\nu_\mu$ ($\bar{\nu}_\mu$) of energy $E_\nu$, interacting outside the detector generates a flux of $\mu^\mp$ with an energy spectrum that extends to the maximum energy $E_{\mu,\text{max}} \simeq E_\nu$. The study of neutrino indicated muon events has already allowed the measurement of the atmospheric muon neutrino flux for energies below 400 TeV using the IceCube–40 data (collected with the detector in construction), and has also allowed to set stringent limits on the size of a prompt or astrophysical contribution to the neutrino flux.

Some examples of the differential muon yield (that is the number of muons generated per (anti)–neutrino) are shown in fig. 3.

Convoluting the muon yield with the neutrino fluxes (and the survival probability in crossing the Earth) one can compute the observable flux of neutrino induced muons. In figure 4 we show the integral flux of muons calculated using three models for the neutrino flux. In the first one (motivated by the detection of the two events with PeV energy reported in [2]) we have assumed only the existence of a narrow “line” of neutrinos at $E_\nu \simeq 1$ PeV, normalized to produce two events (assuming equal fluxes for all six neutrino flavors).
trino types). In the second model we used the flux estimated by IceCube to explain the 28 events and given in equation (1), assuming its validity in the range 60 TeV–2 PeV. In the third model we extended the flux of equation (1) to a minimum energy of 100 GeV. The fluxes of neutrino induced muons integrated in angle over the entire up–going hemisphere and in energy for \( E_\mu \geq E_{\text{min}} \) are \{2.9, 5.9, 5.9\} events/(Km\(^2\)year) for a threshold \( E_{\text{min}} = 100 \) TeV. For the lower threshold of \( E_{\text{min}} = 10 \) TeV, the fluxes (in the same units) become \{6.5, 29, 37\}. Lowering the threshold to 1 TeV and to 10 GeV the fluxes are \{9.6, 51, 108\} and \{10, 60, 164\} respectively. These predicted fluxes should be observable with the existing IceCube data.

The fluxes of neutrino induced muons discussed above are also shown in differential form in fig. 5 together with a prediction of the muon flux generated by standard atmospheric neutrinos. The extra–component should become visible as an hardening of the muon spectrum at high energy. The hardening should also be associated to a change in the angular distribution of the flux. In fact the sensitivity to the existence of a hard component in the flux could be enhanced selecting a smaller vertical angular region. Such an angular cut should reduce more strongly the flux of standard atmospheric neutrinos that has a maximum for horizontal directions.

The detection of a new component of the neutrino flux using two independent, different methods (contained events and up–going muons) would strongly strengthen the confidence in the result.

4 Flavor composition

An often discussed method to identify the astrophysical origin of a neutrino signal is a measurement of its flavor composition. In general the flux of neutrinos of flavor \( \alpha \) can be expressed in the form

\[
\phi_{\nu_\alpha}(E, \Omega) = \sum_\beta \phi_{\nu_\beta}^{(0)}(E, \Omega) \langle P_{\nu_\beta \rightarrow \nu_\alpha}(E, \Omega) \rangle
\]

where the fluxes \( \phi_{\nu_\beta}^{(0)}(E, \Omega) \) are the expected fluxes in the absence of neutrino oscillations (determined by the flavor of the neutrinos at their creation point) and \( \langle P_{\nu_\beta \rightarrow \nu_\alpha}(E, \Omega) \rangle \) is the oscillation probability averaged over the distribution of distance of the neutrino production point.

In the energy range that we are considering here, flavor oscillations are negligible for atmospheric neutrinos since the shortest neutrino oscillation length (determined by the largest neutrino squared mass difference) is of order \( L_{\text{osc}} \simeq (160 R_{\oplus}) E_{\text{TeV}} \), much longer than the Earth diameter. On the
other hand for astrophysical neutrinos the range of distances of the sources is likely to be much larger than the oscillation lengths, so that averaging over distance in equation (2) one has:

\[ \langle P_{\nu_{\beta} \rightarrow \nu_{\alpha}}(E, \Omega) \rangle = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \]

with \( U_{\alpha j} \) the neutrino mixing matrix. This implies that for any flavor composition of the neutrino emission at the sources, one will observe at the Earth large fluxes for all three flavors, including a large flux of tau (anti–)neutrinos.

In what is by far the most plausible scenario, where the astrophysical neutrinos are created in the chain decay of charged pions and kaons, one expects that the fluxes of the three different flavors are in good approximation equal. The ratio neutrino/anti–neutrino is then determined by the relative importance of \( \pi^+ \) and \( \pi^- \) (and \( K^+ \) and \( K^- \)) production at the source.

5 The nucleon flux

Two elements enter the calculation of the atmospheric neutrino fluxes, the first is the description of the primary cosmic ray fluxes, the second is the modeling of the development of their showers in the atmosphere. For the purpose of calculating the neutrino fluxes, in good approximation, it is sufficient to have a good knowledge of the cosmic ray “all nucleon” flux \( \phi_N(E_0) \) that includes the contributions of all free (protons) and bound nucleons with energy per nucleon \( E_0 \). The nucleon flux can be calculated summing the contributions of all nuclear species present in the primary CR flux:

\[ \phi_N(E_0) = \sum_A A^2 \phi_A(E_0, A) . \]

The weight factor \( A^2 \) takes into account the number of nucleons in a primary particle and the Jacobian factor between the energy per nucleon \( E_0 \) and the total energy of the nucleus \( E_{\text{tot}} = A E_0 \). When the primary spectra are power laws with approximately equal exponents \( \langle \phi_A(E) \simeq K_A E^{-\alpha} \rangle \), the nucleon flux is also a power law with the same exponent, and the contribution of nucleus \( A \) is proportional to \( K_A A^{-\alpha+2} \). Since \( \alpha > 2 \), the contribution of bound nucleons is suppressed, and free protons are the dominant component of the nucleon flux.

Because of the steepness of the cosmic ray energy spectrum, neutrinos of energy \( E_{\nu} \) are mostly produced by primary nucleons with energy \( E_0 \) in a relatively narrow range above \( E_\nu \). Atmospheric neutrinos near 1 PeV are
therefore mostly produced in the showers of primary nucleons with energy
just above the “knee”, a prominent softening feature in the CR spectrum at
\( E_{\text{tot}} \approx 3 \) PeV, where the differential slope of the particle spectrum increases
from 2.7 to approximately 3.

The knee in the CR spectrum has been known for many decades, but its
origin remains controversial and poorly understood. Because of the small-
ness of the flux, cosmic rays in this energy range can only be measured in
Extensive Air Shower (EAS) experiments, that are able to determine the
mass number \( A \) of the primary particle with very poor resolution and large
systematic errors. EAS experiments can obtain a better measurement of
the total energy of a CR shower (that depend only weakly from the mass
number) and therefore usually only estimate an all particle flux (as a func-
tion of the total energy of the particle) that sums over all nuclear types. To
infer the nucleon flux one has then the problem to model the composition
of primary flux via equation (4).

Fig. 6 and 7 show a subset of the available measurements of the CR all
particle spectrum at high energy obtained in EAS experiments. The data
are shown in the form of the product \( \phi(E)E^3 \) versus \( E \) (with \( E \) the particle
energy) to enhance the spectral features. The \( y \)-axis scale is logarithmic in
fig. 6 and linear in fig. 7. The thin solid line is the model H3a of the CR
spectrum by Gaisser, Stanev and Tilav (GST) [10]. These authors discuss
also a composition model of the CR spectrum that is decomposed into the
sum of 5 groups of nuclei (free protons, Helium, CNO, Mg–Si and Fe). The
(free) proton spectrum of the model is shown in fig. 6 and 7 as the dot–
dashed line, while the thick line represents the all nucleon flux. The dashed
line in the figures is a “toy model” that we have constructed in the present
work to describe a possible (albeit speculative) larger free proton flux.

This is not the place for a full critical discussion of the data and possible
models of CR at the knee. The main point that we would like to make here
is that the data allow for an all nucleon flux at the knee energy that is as
much as three or four times larger than the “best fit” as estimated in works
such as GST without saturating the constraint that the nucleon flux must
be smaller than the particle flux.

This remark is not intended as a criticism of the work of Gaisser, Stanev
and Tilav, who in fact carefully construct what, on the basis of our present
understanding, can be considered as a very reasonable “best fit” of high
energy cosmic rays. The point is that we still have a poor understanding of
what is the origin of the knee, and of the mechanisms that are responsible
for its shape, and it is possible that the nucleon flux is significantly larger
that “baseline” expectations.
The estimate of the number of events in the energy range 60 TeV to 2 PeV for standard atmospheric neutrinos discussed by IceCube \cite{I} is $(4.6 \pm 1.2$ events) and has an uncertainty of order only 26\%. Allowing more freedom for the composition of the CR primary flux the uncertainty estimate could very well be significantly larger.

The fundamental idea that underlies the CR models of GST, and that is in fact present in most of the works that interpret the cosmic ray spectra, is that the propagation and acceleration of cosmic rays is controlled by the particle rigidity (where the rigidity is the ratio $R = p/q$ with $p$ the momentum and $q = Ze$ the electric charge of the particle), because particles with equal rigidity have identical trajectories in a magnetic field. From this assumption it follows that features present in the proton spectrum should also be visible in the spectra of other nuclear species. A softening in the spectrum of (ultra-relativistic) protons at energy $E_p$ therefore implies a similar softening of the helium flux at energy $2E_p$, and more in general a softening at energy $Z E_p$ for the flux of nuclei with electric charge $Ze$. This idea, first discussed by Peters \cite{P} suggests that the knee observed in the CR all particle spectrum should be understood as a sequence of softenings of the different nuclear species present in the CR flux. This implies that the average mass of cosmic rays should increases with energy. Simultaneous measurements of different components of the CR showers at ground level, in particular of the electromagnetic and muon components, give information about the mass number of the primary particles. This composition analysis depends on the modeling of hadronic interactions, but the results of Kascade \cite{K} and other experiments have given clear indications that indeed the CR mass composition becomes heavier above the knee in a way that is consistent with the idea of a Peters sequence of softenings. A detailed quantitative measurement of the evolution of the composition is however not available.

It should be also noted that the idea that acceleration and propagation are determined by the particle rigidity seems to imply that the slopes of the cosmic ray spectra of all particles types should be identical. On the other hand there are clear indication that this is not the case, in particular that the helium spectrum is harder than the proton spectrum, so that the helium flux overtakes the proton spectrum well below the knee (at $E_{\text{tot}} \approx 20-50$ TeV).

The difference in the slopes of the proton and Helium fluxes has crucial importance for the extrapolation of the CR fluxes from the region of direct measurements to the region of EAS.

A careful inspection of fig. 6 and 7 shows that the shape of the energy spectrum around the knee is not well represented by a simple smooth softening. In fact, it appears that the knee is formed by a broad feature in the
energy range $E \simeq 2-7$ PeV, where the CR flux softens gradually, followed by a sharper hardening at $E \simeq 15$ PeV, that has been clearly seen by Kascade–Grande. These features are not well captured by the hypothesis of a simple superposition of cutoffs in the spectra of the individual components, and could be the indication of the need of a different type of description.

6 Neutrinos from charm decay

Most of the atmospheric neutrinos are produced in the weak decays of charged pions and kaons (and at low energy also in the chain decay of the muons produced in association with the muon (anti)–neutrinos). Charged pions and kaons have long lifetimes, and their decay becomes strongly suppressed at high energy, when their decay length becomes longer than the interaction length. Their decay probability decreases approximately $\propto E^{-1}$ because of relativistic effects.

Charmed particles have much shorter lifetimes, and decay rapidly with probability close to unity up to very high energy ($E \sim 100$ PeV). For this reason, neutrinos from charm decay become the dominant source of the atmospheric fluxes at a sufficiently large energy. A question that remains unanswered is if the transition energy $E_{\text{charm}}$ where the standard and charm decay contributions are equal is lower or higher than the energy $E_{\text{astro}}$ where the flux of astrophysical neutrinos overtakes the atmospheric one.

The component of the atmospheric neutrino fluxes due to charm decay has properties in angular distribution, flavor composition and energy spectrum that in principle allow its identification.

For $E_\nu \lesssim 30$ PeV the neutrino flux from charm decay is to a good approximation isotropic, reflecting the fact that nearly all charmed particles decay. In the case of neutrinos from pion and kaon decay the angular distribution has a strong and characteristic dependence on the zenith angle, because inclined showers develop higher in the atmosphere, where the air density is lower and decay is more likely.

Charm decay generates nearly identical fluxes of electron and muon (anti)–neutrinos, and a much smaller fraction of tau (anti)–neutrinos. This is the simple consequence of the fact that in charm decay, (with the exception of the 2–body leptonic decays of $D_s^\pm$ mesons) there is no dynamical suppression for decays into light charged leptons, and the mass difference between $\mu^\pm$ and $e^\pm$ results only in a small phase space suppression for muon neutrinos. The $D_s^\pm$’s (bound states $c\bar{s}$ and $s\bar{c}$) have a two body decay mode $\tau^\pm \nu_\tau$ and $\tau^- \bar{\nu}_\tau$, that, together with the chain decay of the $\tau^\pm$, are the
source of a smaller flux of tau (anti)–neutrinos. The ratio $\tau/\nu$ is determined by the relative importance of the mechanisms $D\bar{D}$ and $\Lambda_c\bar{D}$ in the charm production cross section. In the $D\bar{D}$ mode the $c$ and $\bar{c}$ charm (anti)–quarks are contained in two mesons, in the $\Lambda_c\bar{D}$ mode the $c$ quark is contained in a charmed baryon. If the $D\bar{D}$ mode dominates, the ratio $\nu/\bar{\nu}$ is approximately unity, while if the production of charmed baryon is not negligible the ratio (that also depends on the shape of inclusive spectra of the charmed particles) can be different from unity. If the charmed baryons have an average energy significantly larger than the anti–charmed mesons, it is possible to have a ratio $\nu/\bar{\nu}$ much larger than unity.

It is important to note that the flux of muon neutrinos generated by charm decay is accompanied by an approximately equal (but slightly smaller) flux of $\mu^\pm$. The muon flux is smaller because in the decay $c \rightarrow s\mu^+\nu_\mu$ (or $\bar{c} \rightarrow \bar{s}\mu^-\bar{\nu}_\mu$) the neutrino has a harder spectrum than the charged lepton because of the structure of the weak matrix element. For the same reason in muon decay ($\mu^- \rightarrow \nu_\mu e^-\bar{\nu}_e$) the electron has a harder energy spectrum than the $\bar{\nu}_e$. This effect (that is neglected in several works, including Enberg et al. [18]) amounts to a relative suppression of order 15–20% of the muon with respect to the muon–neutrino flux. The muon flux can be in principle measured to constrain the size of the neutrino fluxes from charm decay.

The energy spectrum of high energy neutrinos from pion and kaon decay with energy $E_\nu \gtrsim 10$ TeV is a steep power law $\phi_\nu(E) \propto E^{-\alpha}$ with $\alpha \simeq \alpha_0 + 1$, where $\alpha_0$ is the exponent of the primary nucleon flux. This power law behaviour follows from the fact that the decay probability of pions and kaons is to a good approximation $\propto E^{-1}$ and that the inclusive spectra of particles in the forward region is approximately scaling (see for example Gaisser [25] or [26]). In the case of neutrinos from charm decay the decay probability suppression is absent, and the spectrum is harder. The detailed shape of the spectrum, as well as its normalization, are however model dependent. The important elements that enter the calculation (together with the nucleon flux) are the energy dependence of the charm production cross section $\sigma_{c\bar{c}}(s)$ and the inclusive spectra (and composition) of the charmed particles in the final state of hadronic interactions.

Discussing the results on contained events, the IceCube collaboration [1] has argued that it is not possible to explain the data as the effect of neutrinos from charm decay, because a sufficiently large prompt neutrino flux is excluded by the data of IceCube–59 [9]. This argument is constructed on the assumption that the shape of the energy spectrum of the prompt component of the neutrino flux is well determined, and that it is possible to change the normalization of this flux, leaving its spectral shape constant.
We will argue in the following that this assumption is too restrictive, and
that it is possible that the prompt neutrino flux is significantly harder than
what has been estimated by IceCube.

In this work we do not attempt a critical discussion of the theoretical
uncertainties in the calculation of the fluxes of neutrinos and muons from
the decay of charmed particles, and we do not review the different calculations
that are available in the literature (for this purpose see for example
Gaisser [24]). We also do not attempt to construct a “best fit” prompt neu-
trino flux on the basis of a detailed model of the charm production cross
section. A recent example of such a calculation, performed in a perturba-
tive QCD framework, is the work of Enberg et al. [18] that has been used
as a reference by the IceCube collaboration. Rather we argue that it can-
not be excluded that the charm production cross section receives important
contributions from (poorly understood) non–perturbative mechanisms, re-
sulting in a spectrum with a different shape and normalization. Using this
purely phenomenological approach it could be possible to explain the rate of
contained event measured by IceCube as the consequence of a large flux of
prompt atmospheric neutrinos without violating known physical principles
and without entering in conflict with existing data. Such a flux of prompt
neutrinos is larger and harder than the best motivated calculations, but it
remains as a logical possibility. It is clearly desirable to falsify this possibility
experimentally.

To illustrate this point one can consider a very simple toy model that
takes into account charm production only in the first interaction of a pri-
mary nucleon. The model is defined by the cross section \( \sigma_{c\bar{c}}(s) \), and by the
inclusive energy spectra of the final state charmed particles.

Recently, measurements of the charm production cross section in \( pp \) in-
teractions at high energy have been obtained at \( \sqrt{s} = 200 \text{ GeV} \) by the
PHENIX [20] and STAR [21] collaborations and at \( \sqrt{s} = 2.76 \text{ and 7 TeV} \) by
the ALICE collaboration [22, 23] at LHC. Lower energy measurements are
reviewed in [19]. At \( \sqrt{s} = 200 \text{ GeV} \) (that corresponds to a lab. frame energy
\( E_0 \approx 20 \text{ TeV} \)) the PHENIX collaboration estimates the charm production
cross section as

\[
\sigma_{c\bar{c}} = 551 \pm 57 \text{ (stat.)} \pm 193 \text{ (sys.) } \mu b \quad (5)
\]

while the STAR collaboration measures:

\[
\sigma_{c\bar{c}} = 797 \pm 210 \text{ (stat.)} +^{208}_{-295} \text{ (sys.) } \mu b \quad (6)
\]

At LHC energies ALICE measures:

\[
\sigma_{c\bar{c}}(2.76 \text{ TeV}) = 4.5 \pm 0.8 \text{ (stat.)} +^{1.0}_{-1.3} \text{ (sys.) } +^{2.6}_{-0.4} \text{ (extrapolation) } \mu b \quad (7)
\]
and
\[ \sigma_{cc}(7 \text{ TeV}) = 8.5 \pm 0.5 \text{ (stat)} \pm^{1.0}_{-2.4} \text{ (sys.)} \pm^{5.0}_{-0.4} \text{ (extrapolation)} \text{ mb} \quad (8) \]

This corresponds to a power law growth of the charm production cross section \( \sigma_{cc}(s) \sim s^{p} \) with \( p \approx 0.6 - 0.8 \). It should however be stressed that the experiments measure the cross section in a limited region of phase space (for ALICE the rapidity region \( |y| < 0.5 \)), that accounts for only a small fraction of the cross section (of order 0.2 at 200 GeV and 0.1 at LHC) and then extrapolate to the entire phase space on the basis of theoretical models. From a purely phenomenological point of view there is therefore considerable freedom in the description of the charm cross section in the kinematical forward region.

To explore the possibility that a flux as large as the one indicated by the IceCube collaboration in equation (1) could due to neutrinos from charm decay, we have performed some calculations with very simple “toy” models. Four examples of such calculations are shown in fig. 8. Two calculations (shown as the solid lines labeled a and b) were performed using the nucleon flux of the model H3a of GST [10], while in the other two (shown as the dashed lines labeled a' and b’) we have added to the GST flux the extra component of free protons shown in fig. 6 and 7. For the calculation a and a’ the charm cross section in pp interactions was assumed to be \( \sigma_{cc}(E_0) \approx 0.7 \left[ \sqrt{s}/(200 \text{ GeV}) \right]^{0.7} \text{ mb} \), with a scaling inclusive cross section for the charmed particles \( \propto (1 - |x_F|)^2 \) (with \( x_F \) the Feynman x variable). For the calculations of lines labeled b and b’ the charm cross section was \( \sigma_{cc}(E_0) \approx 0.08 \left[ \sqrt{s}/(200 \text{ GeV}) \right]^{1.2} \text{ mb} \), and a scaling inclusive cross section \( \propto (1 - |x_F|) \). Note that this cross section is smaller than the detected one, and therefore must be understood as only a fraction of the charm cross section that corresponds to the production of charmed particles in the fragmentation region. All these particles were treated as \( \Lambda_c \)’s. For simplicity we have only taken into account charmed particles produced in the first interaction.

The toy models that we have just discussed are of course very naive and speculative, but indicate that it seems possible to obtain a prompt neutrino flux as large as the one needed to explain the IceCube contained events with neutrinos from charm decay. This requires assumptions on the dynamics of charm production that do not correspond to the presently favored theoretical models, but are not manifestly impossible.
7 Outlook

The announcement of the detection of two contained events with PeV energy by IceCube, and more recently of a larger set of contained events with visible energy in the range between 60 TeV and 1 PeV has understandably been met with great interest. Several authors have immediately started the discussion on the implications of these results when interpreted as the manifestation of a flux of astrophysical neutrinos.

An astrophysical origin for a large fraction of the contained events is probably the simplest and most natural explanation of the data, but (conservatively) an instrumental or atmospheric origin cannot be entirely ruled out.

From a purely experimental point of view the most important limitation of the IceCube result is that, because of the background of down–going showers, the detection of contained neutrino events has been possible only at very high energy ($E_{\text{vis}} \geq 60$ TeV) where the event rate seems to be already dominated by an astrophysical flux. This does not allow the direct observation of the required transition from a neutrino flux dominated by atmospheric neutrinos to the harder flux generated by astrophysical sources.

The direct observation of this transition is clearly very desirable and should be possible studying the flux of neutrino induced muons that enter the detector with up–going trajectories [8, 9].

The lack of a positive detection of a harder flux component in these studies is not in contradiction with the contained event analysis, but if the contained events are produced by real neutrino interactions a new harder component in the neutrino flux should soon be detected with in up–going muon events.

In this work we have also investigated the possibility that the contained events observed by IceCube are generated by atmospheric neutrinos. We have demonstrated that this requires assumptions that are not the simplest and most natural, but that are not impossible or in contradiction with existing data.

For atmospheric neutrinos with PeV energy (the crucial energy range investigated here), a large uncertainty is due to the fact that they are generated by primary particles at or just above the “knee” in the CR spectrum, a structure that remains poorly understood. Modifying the composition of the CR near the knee there is room to increase (or in fact also decrease) the neutrino flux by a large factor.

Very recently, our understanding of the charm production cross section has made great progress, but we are still lacking in data on the size and
properties of the cross section in the fragmentation region. If charm production in the forward region of the interaction kinematical space is larger than expected and grows with c.m. energy in an appropriate way, it could be possible to obtain the observed rate of contained events with neutrinos from charm decay.

The bottom line of this discussion is that it is clearly very desirable to exclude the speculative possibilities considered above not with theoretical arguments but experimentally. The detection of a large fraction of tau neutrinos in the flux would be unambiguous evidence for the presence of astrophysical neutrinos. This detection could be accomplished with the identification of tau decays inside the detector, but also with a careful comparison of the rates of shower and track contained events, or of the rate of contained events with the fluxes of neutrino induced muons. Also a comparison of the neutrino and (down–going) muon fluxes could give information on the size of the prompt neutrino component. This method however suffers from the problem of a possible contamination of muons generated in the decay of flavorless mesons [27].

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Figure 1: Absorption probability for $\nu_e$ (solid lines) and $\bar{\nu}_e$ (dashed lines) of different energies ($E_\nu = 10^4, 10^5, 10^6$ and $10^7$ GeV) plotted as a function of zenith angle. The calculation was performed using the neutrino cross section of Gandhi et al. [5].
Figure 2: Ratio upgoing/downgoing events for $\nu_e$ and $\bar{\nu}_e$, plotted as a function of the neutrino energy. The calculation assumes isotropic fluxes, and integrates over the entire up–going and down–going hemispheres.
Figure 3: Differential muon yield for $\nu_\mu$ (solid lines) and $\bar{\nu}_\mu$ (dashed lines) of different energies.
Figure 4: Neutrino induced muon flux integrated in solid angle in the up–going hemisphere and in energy for $E_\mu \geq E_{\text{min}}$. The flux is calculated assuming equal isotropic fluxes of $\nu_\mu$ and $\bar{\nu}_\mu$. The solid line corresponds to the neutrino flux $E_\nu^2 [\phi_{\nu_\mu}(E_\nu) + \phi_{\bar{\nu}_\mu}(E_\nu)] = 1.2 \times 10^{-8}$ GeV/(cm$^2$ s sr) between energies 60 TeV and 2 PeV. The dashed line is calculated extending the same functional form to a minimum energy 100 GeV. The dot–dashed line is calculated assuming that the neutrino spectrum is a narrow line at 1 PeV normalized to produce 1 contained event per year (with equal fluxes for all flavors).
Figure 5: Neutrino induced muon flux as in fig. 4 (with the same meaning for the different lines). The flux is shown in differential form. The thicker line describes atmospheric neutrinos.
Figure 6: The points are measurements [13, 14, 15, 16] of the CR all particle flux by the TIBET III detector (circles, the three sets of data are spectra estimated using different hadronic interaction models), Kascade Grande (diamonds), HiRes (squares) and Auger (triangles). The lines are the estimates of the all particle flux (thin, solid line) the proton flux (dot-dashed line) and the all nucleon flux (thick, solid line) of Gaisser, Stanev and Tilav [10]. The dashed line indicates a possible extra contribution to the all nucleon flux discussed in this work.
Figure 7: As in fig. 6 (but with a linear scale for the $y$ axis). The squares are a measurement of the CR flux performed by IceCube-40 [17].
Figure 8: The figure shows the result of calculations of the atmospheric prompt neutrino flux ($\nu_\mu + \bar{\nu}_\mu$ or $\nu_e + \bar{\nu}_e$) performed with four very simple toy models. For the solid lines labeled $a$ and $b$ the nucleon flux is the model H3a of GST [10]. The dashed lines are computed adding to the GST flux the extra component to the all nucleon flux shown in fig. 6 and 7. See the main text for a description of the models. The thin rectangular line gives the neutrino flux indicated by IceCube as a possible source of the contained events.