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Investigating the UHECR characteristics from cosmogenic neutrino limits with the measurements of the Pierre Auger Observatory

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Cosmogenic neutrinos are expected to originate in the extragalactic propagation of ultra-high-energy cosmic rays (UHECRs), as a result of their interactions with background photons. Due to these reactions, the visible Universe in UHECRs is more limited than in neutrinos, which instead could reach us without interacting after traveling cosmological distances. In this contribution, we exploit a multimessenger approach by computing the expected energy spectrum and mass composition of UHECRs at Earth corresponding to combinations of spectral parameters and mass composition at their sources, as well as parameters related to the UHECR source distribution, and by determining, at the same time, the associated cosmogenic neutrino fluxes. By comparing the expected UHECR observables to the energy spectrum and mass composition measured at the Pierre Auger Observatory above $10^{17.8}$ eV and the expected neutrino fluxes to the most updated neutrino limits, we show the dependence of the neutrino fluxes on the characteristics of the properties of the potential sources of UHECRs, such as their cosmological evolution and maximum redshift. In addition, the fraction of protons compatible with the data is also investigated in terms of expected neutrino fluxes.

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1. Introduction

Cosmogenic neutrinos are expected to be produced during the extragalactic propagation of ultra-high-energy cosmic rays (UHECRs), as a consequence of their interactions with photon fields such as the cosmic microwave background (CMB) or the extragalactic background light (EBL), where the produced charged mesons subsequently decay, producing neutrinos. Due to these reactions, the visible Universe in UHECRs is much more limited than what can be seen in neutrinos, which can reach us without interacting in their extragalactic travel. Neutrinos can therefore bring information on parameters relevant for UHECR source classes which are connected with the cosmological distribution, as well as with the maximum redshift of the sources contributing to UHECRs.

In [1], a pure-proton scenario for UHECRs was used to constrain the source evolution and the maximum redshift of the UHECR source class, through the associated cosmogenic neutrinos. The aim of the present work is to take into account the most up-to-date upper limits from the Pierre Auger Observatory, shown in [2] and [3] with a pure-proton scenario for the UHECRs at the escape from the sources. In addition, here we also explore scenarios where the mass fractions and the spectral parameters at the emission from the sources are considered as free parameters, by taking into account the entire energy range across and above the ankle for the fit of the energy spectrum and the mass composition, as done in [4]. The outcome in cosmogenic neutrinos is thus exploited to possibly indicate the characteristics of UHECR source classes dominating different energy ranges. Being the UHECR propagation in the extragalactic space also subject to different computational treatments and approximations of the interactions, the outcome in neutrinos is affected by these details as well [5, 6], and the consequent source UHECR source parameters might reflect the use of different simulation codes, as discussed in the following.

The Pierre Auger Observatory [7] is currently the world largest array of detectors exploring the energy spectrum, arrival distributions and composition of cosmic rays above about 10^{17} eV. It is located in the *Pampa Amarilla*, in the Province of Mendoza, Argentina. The observatory is a giant hybrid detector combining water Cherenkov tanks known as the Surface Detector (SD) and fluorescence telescopes known as the Fluorescence Detector (FD). The original design consisted of an array of 1600 tanks separated by 1.5 km spread over an area of 3000 km^2 , overlooked by 24 fluorescence telescopes in four buildings at the edge of the array. The SD samples the lateral distribution of particles and the time of arrival of the shower front, while the FD records the longitudinal distribution profile of the extensive air shower (EAS). An extension deployed since then includes a denser infill array with 61 extra SD stations with 750 m spacing over a 27.5 km^2 area overlooked by 3 extra telescopes, designed to detect lower-energy showers down to 10^{17} eV. With the SD of the Pierre Auger Observatory we can detect neutrinos with energy between 10^{17} eV and 10^{20} eV from point-like sources across the sky. The identification is efficiently performed for neutrinos of all flavors interacting in the atmosphere at large zenith angles, as well as for Earth-skimming τ neutrinos with nearly tangential trajectories relative to the Earth. For more details on neutrino searches with Auger, see [1] and [3].

2. The procedure

We assume UHECRs to be injected in the extragalactic space with a power-law energy spectrum that depends on spectral index γ and rigidity cutoff R_{cut} . The injection spectrum for a cosmic ray of mass A follows

$$\frac{dN}{dE} \propto f_A \left(\frac{E}{10^{18} \text{ eV}} \right)^{-\gamma} \times (1+z)^m \times f_{\text{cut}}(E, Z_A R_{\text{cut}}) \quad (1)$$

where f_A is the CR primary mass fraction, z is the redshift of production, m is the evolution parameter and $f_{\text{cut}}(E, Z_A R_{\text{cut}})$ is the cutoff function of the energy spectrum at injection defined as

$$f_{\text{cut}}(E, Z_A R_{\text{cut}}) = \begin{cases} 1 & (E < Z_A R_{\text{cut}}) \\ \exp(1 - \frac{E}{Z_A R_{\text{cut}}}) & (E \geq Z_A R_{\text{cut}}) \end{cases} \quad (2)$$

where Z_A is the electric charge. We use *SimProp* [8] to simulate the propagation through the intergalactic medium and we consider Gilmore et al. 2012 fiducial (G12) [9] as EBL model. With the same software, we get the cosmogenic neutrino flux associated to the corresponding cosmic-ray flux. We note here that the neutrino flux computed with *SimProp* is a factor of 2 lower than what obtained with CRPropa [10] within the same initial assumptions (as shown in [6]), as due to details of the implementation of the photo-meson production. The total exposure ε_{tot} (reported in Fig. 1, for the time range Jan 04 - Dec 21 with solid lines and Jan 04 - Aug 18 with dashed lines) folded with a single-flavor flux of UHE neutrinos $\phi(E_\nu)$ per unit energy, area A , solid angle Ω and time, and integrated in energy gives the expected number of events for that flux:

$$N_{\text{evt}} = \int_{E_\nu} \varepsilon_{\text{tot}}(E_\nu) \phi(E_\nu) dE_\nu. \quad (3)$$

This number is then compared with the Feldman-Cousins factor [11] for a non-observation of events in the absence of an expected background accounting for systematic uncertainties [12], to the aim of evaluating the power of exclusion.

3. Results

In this section we report the indications for the UHECR source parameters related to the pure-proton and mixed composition scenarios, using the energy spectrum and mass composition data of ICRC 2019 reported in [13], and the cosmogenic neutrino limits from [3].

3.1 Pure-proton scenario with fixed parameters

In this first analysis, only a pure-proton scenario was considered in which the spectral index γ of the UHECR proton spectrum at the sources is fixed to 2.5, and the maximum energy is cut at $E_{\text{max}} = 6 \times 10^{20}$ eV. We performed a comprehensive scanning of the parameters z_{max} (in the range [1.0, 5.0] with steps of 0.1) and m (in the range [2.0, 5.0] with steps of 0.1) of the source evolution function: for each pair, the cosmogenic neutrino flux was obtained and, consequently, the expected number of neutrino events considering the Eq. 3. This is shown in Fig. 2 (top), corresponding to the exposure shown in Fig. 1 (solid line). We observe that the parameter space above the solid line can be excluded with a 90% confidence level (C.L.). When comparing these results to the ones

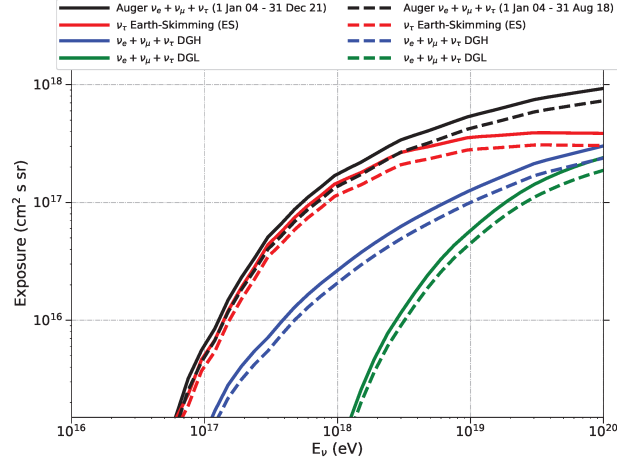


Figure 1: Exposure of the SD of the Pierre Auger Observatory to UHE neutrinos [2] as a function of neutrino energy for each neutrino flavor and for the sum of all flavors assuming a flavor mixture of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. The exposures to upward-going Earth-skimming ν_τ only and to the downward-going of all flavors including charged current and neutral current interactions are also shown. The exposures correspond to the time range Jan 04 - Dec 21 (solid lines) and Jan 04 - Aug 18 (dashed lines).

from [1], one should note that there are differences due to, apart from the updated neutrino limits, the updated energy spectrum and the shape of the cutoff function in Eq. 2 as well as the use of a different code for the simulation of the extragalactic propagation (CRPropa was used in [1]). In the bottom panel of Fig. 2, we report the exclusion plot re-scaling the exposure for the time range Jan 04 - Dec 35, showing the benefit of the extended running of the Observatory on the determination of UHECR characteristics, provided the fact that we do not observe neutrinos.

3.2 Pure-proton scenario with fitted parameters

In this section, we analyze again the case of a pure-proton scenario, but now the spectral index γ and the maximum energy of the protons $E_{\max}$ are not fixed. We performed a fit of the energy spectrum measured by the Pierre Auger Observatory at energies above 1.5×10^{18} eV. A minimization procedure is applied in the intervals $\gamma = [-2.0, 2.5]$ and $\log_{10}(R_{\text{cut}}/V) = [17.985, 19.985]$, while we scan over the parameters space $(z_{\max}, m)$ as in the previous section. The corresponding results are shown in Fig. 3. One can note a similar behaviour between the plot in the top panel of Fig. 2 and this plot, but the latter is the result of the fit of the spectrum in which the spectral parameters that characterize the flux are not fixed as in the previous case. The fact that the excluded region is smaller than the previous one, suggests that the fit procedure finds rigidity values much lower than in the previous case. The rigidity is strongly correlated to the spectral index and these small values of rigidity are thus reflected in the number of associated cosmogenic neutrinos.

3.3 Scaling of the proton component

We also want to explore the compatibility of our data with a proton component by reducing the expected spectrum chosen in Sec. 3.1, by a factor F_p . Such a proton component might have a limited effect on the observed spectrum, but would strongly alter the expected cosmogenic neutrino

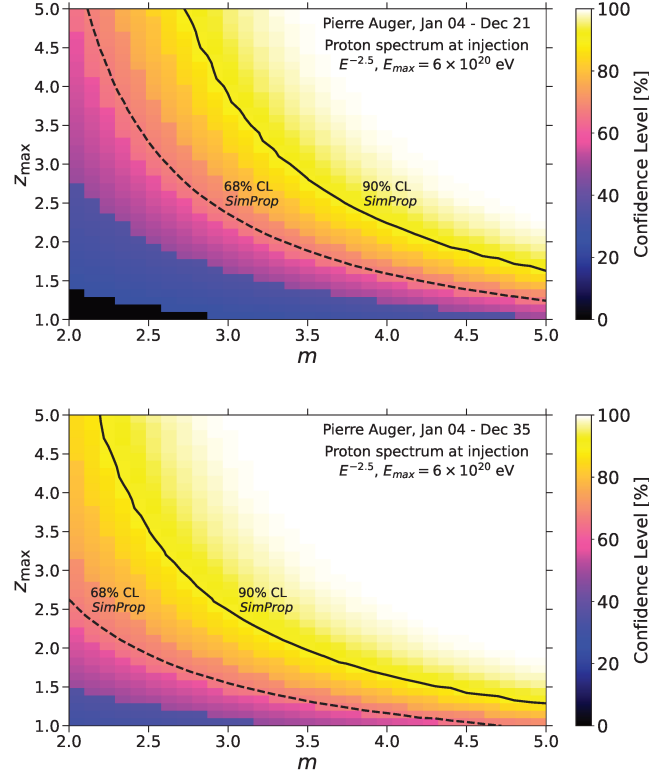


Figure 2: UHECR source evolution models parameterized as $\propto (1+z)^m$ for sources distributed homogeneously up to a maximum redshift $z_{\max}$ and emitting protons following a power-law $J(E) \propto E^{-2.5}$ up to $E_{\max} = 6 \times 10^{20}$ eV. The cosmogenic neutrino fluxes for each combination of m and $z_{\max}$ were obtained with *SimProp*. The color code shows different levels of C.L. exclusion reported on the z -axis. The solid and dashed lines represent the contours of 90% and 68% C.L. exclusion, respectively. Top panel: exposure from Jan 04 to Dec 21; Bottom panel: exposure from Jan 04 to Dec 35 (considering running of the observatory until Dec 35).

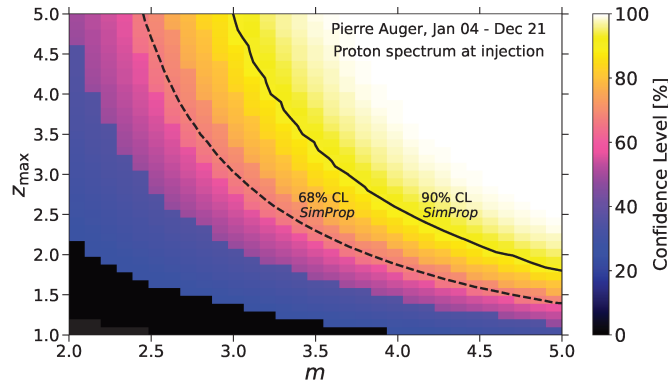


Figure 3: UHECR source evolution models as in Fig. 2 with exposure for the time range Jan 04 - Dec 21. Each $(z_{\max}, m)$ combination corresponds to the best (γ, R_{cut}) combination which fits the energy spectrum above 1.5×10^{18} eV.

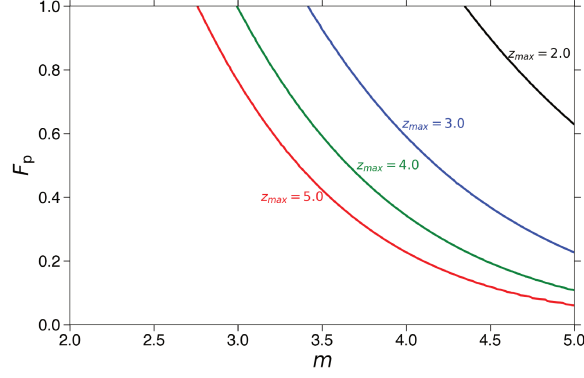


Figure 4: Exclusion plot for the source evolution model parameter m and the variable $F_p \leq 1$. The regions above the colored lines corresponding to several values of $z_{\max}$ are excluded at 90% C.L. from the lack of neutrino candidates in Auger data. We consider the same scenario as in Sec. 3.1.

flux. This is because protons produce significantly more neutrinos when propagating through the Universe than heavier nuclei of the same total energy, particularly if the latter were not accelerated significantly beyond the GZK energy threshold. The parameters describing the UHECR spectrum in Eq. 1 are fixed as in Sec. 3.1 and the expected spectrum is re-scaled by the value F_p (a scan of F_p from 0.0 up to 1.0 with steps of width 0.01). Fig. 4 shows the F_p as a function of the evolution parameter m and the lines correspond to the 90% C.L. for different values of $z_{\max}$. It is evident that as the value of $z_{\max}$ increases, the capability to exclude a region of the parameters space increases. For instance, corresponding to the energy of the ankle, a fraction of protons at Earth is found to be around 20% [14]; this analysis allows then to exclude the source classes with $z_{\max} = 5.0$ and $m > 4.0$.

3.4 Mixed composition scenario

In this section, we analyze more realistic scenarios by taking into account both the energy spectrum and mass composition measured by the Pierre Auger Observatory. We assume a model consisting of two populations of extragalactic sources, one dominating at energies above the ankle (high energy, HE), and another dominating at low energies (LE) as in [4]. The *SimProp* simulations are made taking into account the PSB (Puget, Stecker and Bredekamp) model [15] for photo-disintegration cross-section. We have adopted EPOS-LHC [16] as hadronic interaction model for estimating the mass distributions in each energy bin. For the HE component, the minimization procedure is applied in the intervals $\gamma_{\text{HE}} = [-4.0, 2.0]$ and $\log_{10}(R_{\text{cut,HE}}/V) = [17.0, 20.0]$, while for the LE component the intervals $\gamma_{\text{LE}} = [0.0, 4.0]$ and $\log_{10}(R_{\text{cut,LE}}/V) = [19.0, 22.0]$ were chosen. In this case, also the mass fractions are not chosen a priori, but they result from the fits of $X_{\max}$ distributions measured by the Pierre Auger Observatory [4]. A scan over each combination of $(z_{\max}, m)$ parameter space is performed for both the HE component and the LE component, with both $z_{\max}$ and m from 3.0 up to 5.0 with a step width of 0.2. The quality of the fit is evaluated by minimizing the deviance D defined as a generalised χ^2 , where the sum of the contributions of the energy spectrum and mass composition are taken into account, as in [4]. Fig. 5 shows the deviance as a function of the cosmological evolution of the two populations. For each population

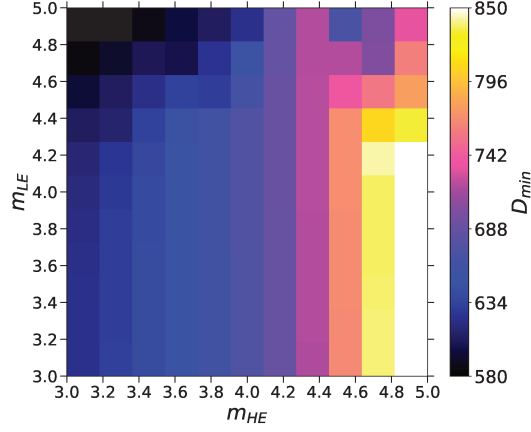


Figure 5: Deviance of the fit of the energy spectrum and mass composition as a function of the cosmological evolution of the two populations.

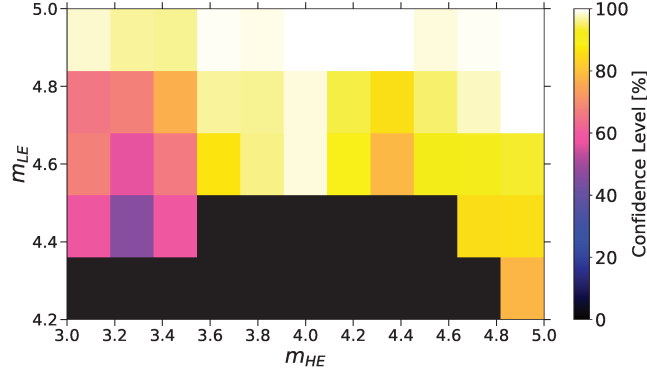


Figure 6: Confidence level as a function of the cosmological evolution of the two populations of UHECR sources dominating the LE and HE regions.

the free fit parameters are the spectral index γ , the rigidity cutoff R_{cut} and the $n - 1$ mass fractions f_A (where the n nuclear species are ^1H , ^4He , ^{14}N , ^{28}Si and ^{56}Fe). Thus, corresponding to each combination $(m_{\text{HE}}, m_{\text{LE}})$, all the parameters which are not shown are the ones that minimize the deviance. One can note how the deviance increases for high values of m_{HE} , as anticipated in [4]. Finally, we compute the corresponding neutrino flux associated to each combination of parameters for the HE and LE populations. In Fig. 6, we report the confidence level associated to the number of cosmogenic neutrinos as a function of the cosmological evolution of the two populations. In this case, the parameter space excluded at 90% C.L. corresponds to a region centered around $m_{\text{HE}} = 4.0$ and $m_{\text{LE}} \geq 4.6$. We observe that in this region the spectral parameters that minimize the deviance correspond to very high rigidity for the LE population which strongly contributes to the neutrino flux. In conclusion, while the strong evolution of the HE population is disfavored due to the quality of the fit of the spectrum and the mass composition, the white region in Fig. 6 can be excluded due to the associated neutrino flux.

4. Conclusions

In this contribution, we exploited a multimessenger approach by using the expected energy spectrum and mass composition of UHECRs at Earth to determine the associated cosmogenic neutrino fluxes for different scenarios. We showed that it is possible to indicate what UHECR source parameters give origin to a cosmogenic neutrino flux not exceeding the most up-to-date upper limits. Uncertainties in these indications include details of the implementation of the interactions producing cosmogenic neutrinos in the simulation codes used, as for instance the differences with respect to what obtained in [1] for the case of pure-proton composition. As a novelty with respect to [1], here we also explored scenarios where the mass fractions and the spectral parameters at the emission from the sources are considered as free parameters, by taking into account the entire energy range across and above the ankle for the fit of the energy spectrum and the mass composition. We put together the information coming from the quality of the fit and the outcome in terms of the flux of cosmogenic neutrinos and with this procedure we were able to indicate the characteristics of UHECR source classes. We found out that the strong evolution of HE population is disfavored due to the quality of the fit of the spectrum and the mass composition while a strong evolution of the LE population can be excluded with 90% C.L. thanks to the associated neutrino flux.

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