Probing the Cosmic-Ray Proton Fraction with Cosmogenic Multi-PeV Neutrinos and Gamma-rays Constraints

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The recent detection of a multi-PeV neutrino event by KM3NeT/ARCA opens a new window into the origin of ultra-high-energy cosmic rays (UHECRs). We revise the possibility of a cosmogenic origin of this neutrino by analysing the constraints induced by cascaded photons onto the isotropic gamma-ray background measured by the Fermi-LAT collaboration. We consider two scenarios: the first one, at low energies, with a primary proton population saturating the Pierre Auger Observatory data. The second one, the high-energy scenario, is a sub-population of protons contaminating the UHECR flux. Remarkably, the cascaded photons constrain the LE scenario which cannot explain the KM3-230213A event, if the cosmological evolution of the sources is too strong, because the corresponding gamma-ray spectrum would overshoot the corresponding measurements. By contrast, the high-energy scenario is allowed by current cosmic-rays, neutrinos and gamma-rays data and only future constraints on the UHECR composition will further constrain this scenario.

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1. Introduction

The KM3NeT collaboration has detected an astrophysical neutrino with an estimated reconstructed energy of 220^{+2380}_{-148} PeV (90% CL) [1]. Such an energetic neutrino might be a direct signature of Ultra-High-Energy Cosmic Rays (UHECRs) propagating through the Universe and producing the so-called cosmogenic neutrinos while interacting with the cosmic microwave background (CMB) and the extragalactic background light (EBL) [2]. For the first time, the observation of KM3-230213A allows us to probe the properties of cosmic rays at the highest energies through a messenger immune to magnetic deflection and absorption. In this regard, Ref. [3] has scrutinized the potential cosmogenic origin of KM3-230213A and points out that it requires UHECRs injected up to very high redshift or an unusual proton fraction at the highest energies of the UHECR flux. This latter scenario might already be a bit in tension with the results of the Pierre Auger Observatory (Auger), which suggest heavy and pure composition, with only a faint proton component [4, 5]. In this work, we critically examine the cosmogenic origin hypothesis of KM3-230213A, specifically with the aim of assessing the constraining power of cascaded cosmogenic photons. Indeed, when UHECRs interact with CMB and EBL also produce high-energy photons which get reprocessed at GeV energies because of photon pair production and inverse Compton processes [6], developing electromagnetic cascades. As a consequence, cascaded photons might strongly contribute to the isotropic gamma-ray background (IGRB) measured by the Fermi-LAT collaboration [7]. Our analysis is based on the propagation of UHE protons, whose spectrum is normalized to the Auger proton flux [4, 5], to compare the associated secondary particles produced during the propagation - cosmogenic neutrinos and cascaded photons - with IceCube [8] and Auger [9] upper limits, and KM3NeT [10] measurements, as well as with the constraints imposed by the Fermi-LAT diffuse gamma-ray background [7] data. We consider two scenarios for the UHECR proton components: the first one, at low energy (LE, energies below the ankle), where we normalize the UHECR flux to the proton component of the Auger spectrum inferred by multiplying the all-particle spectrum [11] with the proton fraction evaluated with Sybill2.3d [5]. The second one, at high energy (HE, above the ankle), considers a hard spectrum of protons contaminating the UHECR flux at the highest energies, still compatible with the composition measurements. Our results show that a multimessenger approach including both neutrinos and gamma rays could be used to constrain the cosmogenic origin of the KM3-230213A event.

2. Propagating UHECRs and Cosmogenic Photons and Neutrinos

Our theoretical framework follows the formalism of Ref. [12]. The intensity of UHE protons at Earth (i.e., $z = 0$) reads

$$I_p(E) = \frac{c}{4\pi} \int_0^{z_{\max}} dz_g \left| \frac{dt}{dz_g} \right| \mathbf{Q}_p(E_g(E, 0, z_g), z_g) \frac{dE_g}{dE}(E, 0, z_g), \quad (1)$$

where $E_g(E, 0, z_g)$ is the energy of the proton at the generation, as a function of the energy at Earth and of the redshift at the generation and $\frac{dt}{dz_g}$ takes into account the standard ΛCDM cosmology [13]. $\mathbf{Q}_p(E, z)$ represents the comoving injected spectrum of protons [12], properly normalized to the comoving sources' emissivity $\mathbf{L}$ in UHE protons above a reference energy $E_0 = 10^{17}$ eV:

$$\mathbf{Q}_p(E,z) = \frac{\mathbf{L}}{\int_{E_0}^{\infty} dE'\, E' \left(\frac{E'}{E_0}\right)^{-\gamma} \exp\left(-\frac{E'}{E_{\max}}\right)} \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_{\max}}\right) (1+z)^m. \tag{2}$$

Here, we have assumed that the injection of protons follows a power-law with index γ up to a maximum energy $E_{\max}$, and the factor $(1+z)^m$ accounts for the sources' evolution with redshift. The adopted values for each of the tested cases are reported in Table 1. The cosmogenic neutrino intensity at Earth is calculated in the same way [12], accounting only for adiabatic (cosmological) energy losses, as neutrinos propagate essentially unabsorbed:

$$I_\nu(E) = \frac{1}{3}\frac{c}{4\pi}\int_0^{z_{\max}} dz_g \left|\frac{dt}{dz_g}\right| \mathbf{Q}_\nu(E(1+z_g), z_g)(1+z_g), \tag{3}$$

where $\mathbf{Q}_\nu(E,z)$ is the comoving injected spectrum of neutrinos, which depends on the equilibrium density of protons at any redshift and on the differential production rate of each neutrino flavour. The former is calculated with the same method of Eq. 1 [12], while the latter is calculated accordingly to the parametrization of the photopion differential cross-section described in Ref. [14]. The factor $1/3$ accounts for neutrino flavor oscillations during propagation. We consider the EBL model described in Ref. [15].

For gamma rays, following Refs. [6, 12], we assume high-energy photons and electrons/positrons produced by UHE protons are immediately reprocessed at lower energies, and the photon fields can be approximated as monochromatic fields with characteristic energies $\epsilon_{\rm CMB}(z) = k_B T(z)$ and $\epsilon_{\rm EBL}(z) = 0.68$ eV. Therefore, the cascaded gamma-ray injection rate is

$$\mathbf{Q}_\gamma(E,z) = \frac{\omega_{\rm casc}(z)}{\epsilon_X^2[2+\ln(\epsilon_C/\epsilon_X)]}\begin{cases}(E/\epsilon_X)^{-3/2} & \text{if } E \lesssim \epsilon_X\,,\\ (E/\epsilon_X)^{-2} & \text{if } E \gtrsim \epsilon_X\,,\end{cases} \tag{4}$$

where ϵ_X and ϵ_C are the characteristic break and cutoff energy, respectively, for cascade development. The total cascade energy injection rate $\omega_{\rm casc}(z)$ is the sum of the energy injected into e^+/e^- pairs through pair production, $\omega_{\rm casc}^{ee}$, and the energy injected into leptons and photons through photopion production, $\omega_{\rm casc}^{\pi}$. The latter is calculated using the same parametrization of the photopion cross-section as for neutrinos [14], while the former is directly calculated from the proton energy-loss rate $\beta(E_p, z)$, since all the energy lost by protons goes into e^+/e^- pairs [16]:

$$\begin{aligned}\omega_{\rm casc}^{\pi}(z) &= \int dE\, E\left[\mathbf{Q}_{e^-}^{\pi}(E,z) + \mathbf{Q}_{e^+}^{\pi}(E,z) + \mathbf{Q}_{\gamma}^{\pi}(E,z)\right],\\ \omega_{\rm casc}^{ee}(z) &= \int dE_p\, E_p^2\, \mathbf{n}_p(E_p,z)\,\beta(E_p,z),\end{aligned} \tag{5}$$

where $\mathbf{n}_p(E_p, z)$ is the equilibrium proton density at any redshift.

The observable diffuse gamma-ray intensity at Earth is then:

$$I_\gamma(E) = \frac{c}{4\pi}\int_0^{z_{\max}} dz_g \left|\frac{dt}{dz_g}\right| \mathbf{Q}_\gamma\left(E(1+z_g), z_g\right)(1+z_g). \tag{6}$$

The corresponding total energy density in cascade photons, $\Omega_{\rm tot} \approx \frac{4\pi}{c}E^2 I_\gamma(E)$, is reported separately for the pair production and photopion production, for each of the tested cases, in Table 1.

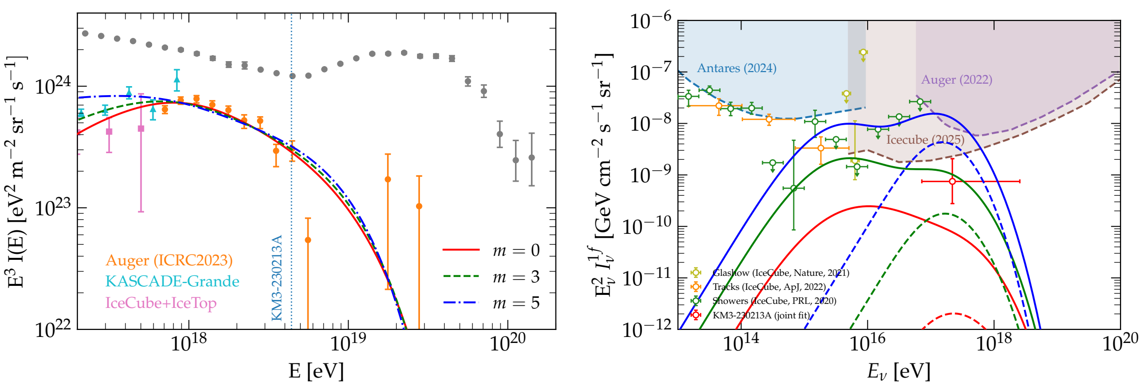

Figure 1: *Left:* UHECR fluxes, multiplied by E^3. Colored lines represent the expected proton fluxes obtained using the parameter set in Tab. 1. The grey and orange (circles) points indicate, respectively, the Auger all-particle spectrum [11] and the Auger proton spectrum as inferred with Sybill2.3d [5]. For comparison, the cyan (triangles) and purple (squares) points display the proton spectra measured by KASCADE-Grande [17] and IceCube/IceTop [18], both inferred using the same hadronic model. The vertical blue (dotted) line marks the proton energy corresponding to the KM3NeT neutrino event. *Right:* Single-flavour neutrino fluxes, multiplied by E^2, corresponding to the proton fluxes shown in the left panel and using the same color scheme. Solid lines indicate the total contribution from CMB and EBL, while dashed lines show the CMB-only contribution. Data points correspond to various IceCube measurements [19–21]; the red point marks the joint flux measured by KM3NeT, Auger, and IceCube associated with the KM3-230213A event [10]. Shaded regions correspond to upper limits from ANTARES (95% CL [22]), Auger (90% CL [9]) and IC-EHE (90% CL [8]).

3. Results and Discussion

We explore the parameter space by considering various choices for the sources' evolution with redshift, fixing the maximum redshift to be $z_{\max} = 5$. Figs. 1 and 2 report the UHE proton spectrum and associated cosmogenic neutrino flux for the LE and HE scenarios, respectively.

For the LE case, the maximum energy allowed by the Auger proton fraction [4, 5] lies below the energy threshold for photopion interaction on the CMB. In fact, the neutrino production is dominated by the EBL. The associated cosmogenic neutrino flux is compatible with the joint fit of the KM3-230213A event reported by [10] for $m = 3$, while it is in tension with IceCube [8] and Auger [9] upper limits for a stronger evolution.

For the HE case, we normalize the proton flux at 10% of the all-particle spectrum at approximately 3×10^{19} eV. The larger maximum energy allows for photopion production on the CMB; therefore, neutrinos are mostly produced on the CMB rather than the EBL. We obtain a cosmogenic neutrino spectrum consistent with the KM3-230213A flux for $m = 3$, also for this population. The degeneracy between these two scenarios can only be broken by considering the associated cascading gamma-rays.

Figure 3 displays the cascaded photon fluxes compared with the IGRB data [7] for the LE (left) and HE (right) scenarios. The contributions from photopion production and pair production are shown separately. For the LE population, the softer spectral index implies a larger contribution from pair production [6], which exceeds the one from photopion production by an order of magnitude. As a result, the expected contribution to the IGRB is clearly in tension with Fermi-LAT measurements

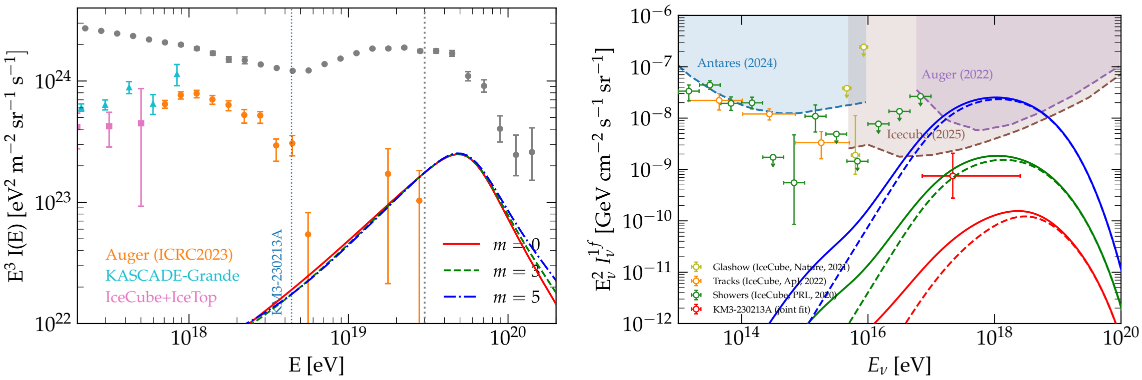

Figure 2: Same as Fig. 1, but for the high-energy (HE) population, with model parameters given in Tab. 1. Left: The grey line marks the reference energy where the model proton flux is normalized to 10% of the all-particle flux. Right: Corresponding single-flavour neutrino fluxes (multiplied by E^2) for the HE population, using the same color scheme and conventions as in Fig. 1.

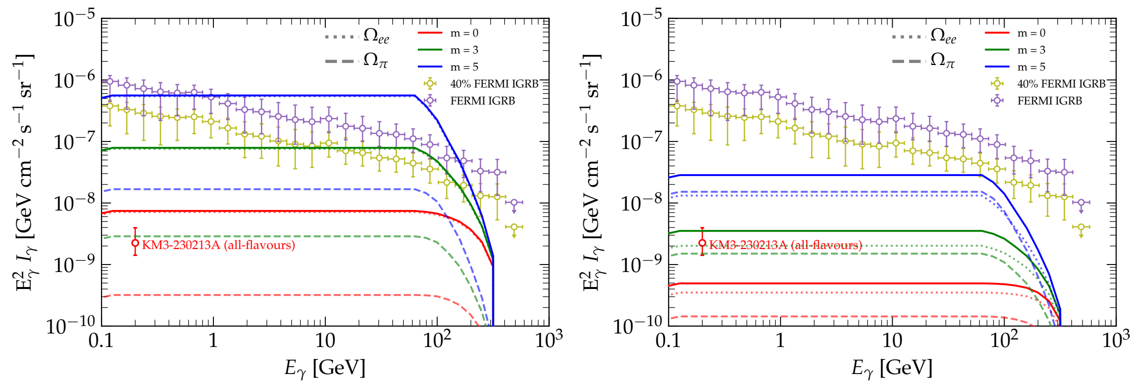

Figure 3: Gamma-ray fluxes multiplied by E^2, shown using the same color scheme as in Fig. 1. The left panel corresponds to the low-energy (LE) population, and the right panel to the high-energy (HE) population. Solid lines represent the total gamma-ray flux (from proton pair production plus photopion production), while dotted and dashed lines indicate the individual contributions from pair production and photopion production, respectively. Purple data points indicate the isotropic gamma-ray background (IGRB) measured by Fermi-LAT [7]. Yellow data points show the same Fermi-LAT measurements, rescaled by a factor of 0.4 to account for the expected contributions from unresolved source populations [23–27]. For visual comparison, the red point marks the neutrino flux level (multiplied by E^2) associated with the joint KM3-230213A event.

in the case $m = 3$. This tension is even larger if it is considered that a significant fraction (at least 60%) of the IGRB is already attributed to unresolved sources from various populations [23–27]. We also show the Fermi-LAT IGRB scaled by a factor of 0.4 as a comparison. For the HE scenario, instead, the expected gamma-ray flux is compatible with the Fermi-LAT IGRB. The harder spectral index suppresses the contribution from pair production, which in this case lies at the same level as the one from photopion production. Fig. 3 reports also the gamma-ray intensity expected from the energy redistribution in photopion interactions between charged and neutral pions [28], producing neutrinos and gamma-rays, respectively.

4. Conclusions

Our analysis shows that cascaded gamma-rays impose powerful constraints, disfavoring a strong redshift evolution of the sources in the LE scenario as the origin of the KM3-230213A event. Indeed, a low-energy primary proton population would overshoot or completely saturate the IGRB flux, leading to strong tension between the different datasets, if a source's evolution compatible with the KM3NeT flux is considered. By contrast, a high-energy proton population could account for the observed event. Improved composition measurements, predicted by AugerPrime [29], will be crucial to constrain the proton fraction at the highest energies and test the origin of the highest-energy neutrinos in the Universe.

Table 1: Parameter sets adopted for this analysis. From left to right, the columns report: the source redshift evolution parameter (m), spectral index (γ), maximum proton energy ($E_{\rm max}$), total proton emissivity ($\mathbf{L}$), and the integrated contributions to the electromagnetic cascade energy density from proton pair production ($\Omega^{ee}_{\rm tot}$) and photopion interactions ($\Omega^{\pi}_{\rm tot}$). The upper and lower sections correspond to the low-energy (LE) and high-energy (HE) source populations, respectively.

	m	γ	$E_{\rm max}$ [10^{18} eV]	$\mathbf{L}$ [$10^{45}\frac{\rm erg}{\rm Mpc^3 yr}$]	$\Omega^{ee}_{\rm tot}$ [$\frac{\rm eV}{\rm cm^3}$]	$\Omega^{\pi}_{\rm tot}$ [$\frac{\rm eV}{\rm cm^3}$]
LE	0	2.5	6.0	2.68	$2.90 \cdot 10^{-9}$	$1.31 \cdot 10^{-10}$
	3	2.01	5.0	17.3	$3.09 \cdot 10^{-8}$	$1.17 \cdot 10^{-9}$
	5	1.4	4.0	0.24	$2.22 \cdot 10^{-7}$	$6.85 \cdot 10^{-9}$
HE	0	1.3	10^2	$1.59 \cdot 10^{-2}$	$1.47 \cdot 10^{-10}$	$6.02 \cdot 10^{-11}$
	3	1.0	10^2	$9.86 \cdot 10^{-3}$	$8.46 \cdot 10^{-10}$	$6.30 \cdot 10^{-10}$
	5	0.7	10^2	$6.86 \cdot 10^{-3}$	$5.52 \cdot 10^{-9}$	$6.37 \cdot 10^{-9}$

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