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On the hadronic origin of the TeV radiation from GRB 190114C

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Abstract. The recently discovered TeV emission from Gamma-Ray Bursts (GRBs) has renewed the long-standing discussion about the hadronic versus leptonic origin of the observed GRB radiation. In this work, we investigate the possibility that the very high energy gamma rays observed by MAGIC from GRB 190114C (with energy from ~ 0.1 to ~ 0.8 TeV) are originated in a hadronic model. We developed a Monte Carlo (MC) simulation of the source internal state dynamics and of the photo-hadronic interactions at internal shock. We included in the simulation also the pair production process that the secondary gamma rays undergo in the GRB jet. We find upper limits on the internal shock model parameters by comparing our simulations to the sub-TeV observations of GRB 190114C. Neutrino flux predictions by the model are found to be consistent with experimental upper limits set by ANTARES and IceCube.

Keywords: gamma ray bursts theory, neutrino astronomy, absorption and radiation processes, cosmic ray theory

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1 Introduction

GRB 190114C is a long-duration GRB observed to emit gamma rays in the TeV band. MAGIC detected, from about one minute after the burst, high-energy gamma rays (~ 0.2 to ~ 0.8 TeV) with high statistical significance, at the transition between the prompt and afterglow phases of the GRB emission [4]. Several models have been proposed in order to reproduce the broadband emission observed in GRB 190114C, both hadronic [42, 49] and leptonic [20, 22, 26, 47, 48, 55]. Although, firm conclusions on the production mechanisms of GeV-TeV emission have not been reached so far, being also limited by the large number of parameters involved in GRB modelling.

In this paper, we consider the hypothesis that part of the emission at high energy from GRB 190114C could be caused by the presence of a hadronic component, with the subsequent production of high-energy neutrinos [24, 34, 35, 57].

The GRB 190114C light curve exhibits at the beginning irregular multi-peaks due to bunches of γ rays superimposed on a smoothly varying emission component that extends beyond the highly variable emission period. Therefore observations do not exclude that part of the high energy emission may be released during the prompt phase. We consider the possibility that a fraction of the Very High-Energy (VHE) emission of GRB 190114C may be due to photo-meson interactions within the internal shocks (IS) region. We consider the standard fireball model in which energy dissipation occurs at IS between shells in the relativistic outflow of the jet or through interactions with ambient matter [24, 34]. Thus, a substantial part of the bulk kinetic energy is converted into internal energy, which is then distributed between electrons, protons, and magnetic field. The internally accelerated electrons are presumably responsible for the keV–GeV photons observed in the GRB, which are emitted through synchrotron or inverse Compton processes. Accelerated protons may interact with these (\sim MeV) photons and produce both neutral and charged pions, which in turn decay into high-energy photons and neutrinos, respectively. However, MAGIC observations did not show any sign of significant spectral change or sharp flux variations from prompt phase to prolonged emission that are characteristic features of the prompt phase. Furthermore, recent LHAASO observations [37] provide a compelling evidence that the TeV emission can come from the afterglow, even if it overlaps in time with the prompt emission. MAGIC observations started in the early afterglow phase, therefore several authors have interpreted this emission as due to the external shock model [22, 49]. In this paper we consider the possibility that part of the TeV emission is due to the internal shocks. The comparison between MAGIC data and

the results of the Monte Carlo (MC) simulation developed for this work can set an upper limit on the contribution to very high energy photons due to the prompt phase. The results described in this paper have been obtained by a full Monte Carlo simulation that described in detail in a previous paper [25]. For this simulation each accelerated proton is generated according to a power law (E^{-2}) and is tracked into a radiation field until it interacts or escapes. The radiation field is generated according to the Fermi measurements [36] as described in section 3. Photo-mesons interactions are simulated for the production of charged and neutral pions. Photons and neutrinos are so obtained from mesons decays. For each photon from pion decay we evaluate the probability to escape from the source, if the photon interacts we evaluate the probability that a secondary photon can emerge from the source. This makes our simulation different from previous works i.e. [49]. The paper is structured as follows: in section 2, we describe spectral and temporal properties of GRB 190114C, assumed for the simulation. In section 3, we present our MC program, developed to simulate the photo-hadronic interactions occurring during the prompt phase. We also describe the result of the simulation of the electromagnetic cascades initiated by the interaction of high energy photons produced in π^0 decays. In section 4, we compare the photon flux resulting from our simulation to MAGIC data, deconvolved for the Extragalactic Background Light (EBL) interactions. From this comparison we obtain a set of best fit values for our model. We then predict a flux of high energy neutrinos and evaluate the expected number of events in present and future experiments. A discussion of our results is provided in section 5.

2 GRB 190114C: spectral and temporal properties

The first detection of GRB 190114C is due to Swift [31], further observations have followed by GBM [36] and LAT [40] onboard the *Fermi* satellite (up to 22.9 GeV), AGILE/MCAL [51], Integral/SPI-ACS [43] and Konus-Wind [29]. The combination of a rapid follow-up by MAGIC [44] with the close distance of the source (confirmed from its optical counterpart to be at redshift $z = 0.4245$ [19, 50]) allowed to unveil the presence of an extremely energetic radiation component in GRBs, as already expected by theory (e.g. [21]). The prompt phase of GRB 190114C, as observed by *Fermi*-GBM, appears as a multi-peak emission lasting $T_{90} \simeq 116$ s (50-300 keV). The time-averaged spectrum in the first ~ 40 s can be described by a Band function with low and high-energy slopes equal to $\alpha = 1.058$ and $\beta = 3.18$ respectively, a break energy value $E_b \simeq 1.1$ MeV in the observed frame [36], and a gamma-ray fluence $F_\gamma = 3.99 \times 10^{-4}$ erg cm $^{-2}$ (10-1000 keV). As such, the isotropic energy release in the source frame amounts to $E_{\text{iso}} \simeq 3 \times 10^{53}$ erg, indicating a fairly energetic GRB. The MAGIC detection, with a significance above 50σ , occurred 68 s after the *Fermi*-GBM trigger. The VHE emission lasted for ~ 40 minutes, with the highest observed photon energy $E_{\text{max}} = 0.852$ TeV [4]. Within this temporal window, the time-dependent analysis of VHE data showed a systematic decrease in flux normalization, as well as a steepening trend over time. The high-energy photon spectrum reported by MAGIC, for the time interval 68-110 s, entirely overlaps with the T_{90} estimated by *Fermi*-GBM for the prompt emission. During this time interval, the intrinsic burst spectrum in the 0.2-1 TeV band is characterised by a pure power-law ($\propto E^{-\xi}$) with $\xi = 2.16^{+0.29}_{-0.31}$ [5]. The photon spectral slope at the source has been derived deconvolving, from the observed spectrum the severe attenuation of the gamma ray flux due to its propagation to the Earth within the EBL [5], according to the Dominguez et al. model [23]. We hence consider such an intrinsic spectrum and compare it to the prediction of the gamma-ray flux emerging from our simulation of phenomena happening

in the IS region. Additionally, we investigated the effects of adopting a different EBL model, e.g. the one from Franceschini et al. [27, 28], finding results consistent with the Dominguez et al. model within the statistical uncertainty of the MAGIC measurements. The temporal overlap between the MAGIC observations and T_{90} is not sufficient to definitely attribute the high-energy photons measured by MAGIC to the prompt or to the afterglow phase of the GRB emission. In this paper we assume the hadronic scenario and we compare the MAGIC observation with the radiation emerging from photo-meson interactions where accelerated protons interact with the Band-like target radiation field in the prompt phase. The two main features of the hadronic scenario are the bulk Lorentz factor Γ of the relativistic jet, and the amount of energy channeled into relativistic protons $E_{\text{iso,p}}$. This last quantity can be expressed with the baryon loading $f_p = E_{\text{iso,p}}/E_{\text{iso}}$. Both the values of Γ and f_p can be constrained to reproduce the VHE MAGIC observed spectrum.

3 Monte Carlo simulation

Modeling the physical processes occurring inside the IS region of the expanding GRB fireball requires characterization of the site where particles propagation and interactions take place. Here we consider a simplified stationary one-zone scenario [13, 38, 46] in which mildly relativistic shells of plasma collide at a typical radius [17]

$$R_{\text{IS}} = \frac{2\Gamma^2 ct_{\text{var}}}{(1+z)} \simeq 4 \times 10^{12} \left(\frac{\Gamma}{100} \right)^2 \left(\frac{t_{\text{var}}}{0.01 \text{ s}} \right) \left(\frac{1.4}{1+z} \right) \text{ cm} \quad (3.1)$$

where all the GRB energy is released. As variability timescale, we assume the value $t_{\text{var}} = 6$ ms as suggested by observations during the prompt phase of GRB 190114C [12]. The bulk Lorentz factor Γ is treated as a free parameter of the model, and it will be fixed as the one that best reproduces MAGIC data.

The MC calculation is performed in the IS frame, assuming a spherical geometry [16] and a shell width $\Delta R_{\text{IS}} = \Gamma ct_{\text{var}}/(1+z)$. We simulate a flux of accelerated protons with energies ranging from 1 GeV to 10^9 GeV, according to $dN_p/dE_p \propto E_p^{-2}$, consistently with a Fermi I-order acceleration process. Such a large energy range has been selected in order to avoid biases in the results. The target photon energy distribution $dn_\gamma/d\epsilon_\gamma$ in the IS frame is assumed to reproduce the Band function observed by *Fermi*-GBM [36] in the prompt phase. In order to allow the particle Δ^+ resonance¹ production with the entire spectrum of accelerated protons, the Band function has been extended to high energy following the trend of the higher part of the spectrum. Each generated proton can either interact with ambient photons, if the center of mass energy is above the interaction threshold condition, or it propagates further in the shell. The average interaction length $\lambda_{p\gamma}(s) = [n_\gamma \sigma_{p\gamma}(s)]^{-1}$ is evaluated, depending on the $p\gamma$ center of mass energy and on the density of photons in the IS frame $n_\gamma(\epsilon_{\text{th},\Delta}^{\text{IS}})$, requiring a center of mass energy above the Δ^+ production threshold: $\epsilon_{\text{th},\Delta}^{\text{IS}} = (m_\Delta^2 - m_p^2)c^4/(4E_p^{\text{IS}})$, m_Δ and m_p being respectively the Δ^+ and proton masses.

According to the average interaction length $\lambda_{p\gamma}(s)$ we extracted the proton path before the interaction x_p . If $x_p < R_{\text{IS}}$ and if the threshold condition for the Δ^+ production is satisfied, the photo-meson interaction occurs. The energies of protons (E_p^{IS}) and target photons ($\epsilon_{\text{ph}}^{\text{IS}}$) that satisfy the photo-meson production condition are shown in figure 1.

Multi-pion generation beyond resonant Δ^+ production is also simulated and secondary particles like photons, muons, and neutrinos originated by decays are followed. Secondary

¹Mass $m_\Delta = 1232 \text{ MeV}/c^2$, spin $S = 0$, isospin $I = 3/2$, total angular momentum $J = 3/2$, parity $P = +$.

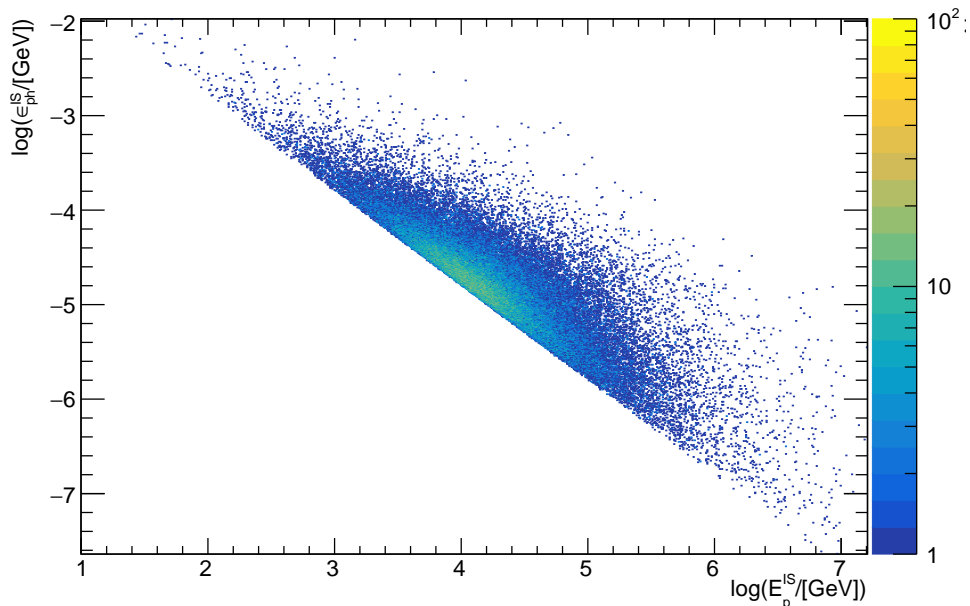


Figure 1. Target photon energy $\epsilon_{\text{ph}}^{\text{IS}}$ vs proton energy E_{p}^{IS} for events above the Δ^+ production threshold. Energies are given in the IS frame ($\Gamma = 800$ and $t_{\text{var}} = 6$ ms). The colour code indicates the number of simulated events.

protons, from Δ^+ decay, are tracked until they leave the IS region to account for possible re-interactions along their path.

To account for proton energy losses during the propagation inside the IS region, we compare the proton acceleration timescale $t_{\text{acc}}(E_{\text{p}}^{\text{IS}}) = r_{\text{L}}(E_{\text{p}}^{\text{IS}})/c$ (r_{L} being the particle Larmor radius), to the average Δ^+ production collision timescale $t_{p\gamma}(E_{\text{p}}^{\text{IS}}) = [n_{\gamma}(\epsilon_{\text{th},\Delta}^{\text{IS}})c\sigma_{p\gamma}^{\Delta}K_{p\gamma}]^{-1}$. In the previous expression, $K_{p\gamma} = 0.13$ and $\sigma_{p\gamma}^{\Delta} = 5 \times 10^{-28}$ cm² are respectively the inelasticity coefficient and the cross section for the interaction at the threshold [14].

Charged particles may be affected by synchrotron losses, therefore, in order to evaluate these effects, we calculate the magnetic field value at IS by equating the magnetic energy density $U_{\text{B}} = B^2/(8\pi)$ to the kinetic energy density of the accelerated electrons. Naming ϵ_{B} and ϵ_{e} respectively the fraction of jet energy converted into magnetic field and carried by electrons, we assume $\epsilon_{\text{e}} = \epsilon_{\text{B}} = 0.1$ [15]. Proton synchrotron losses are relevant for energy above $E_{\text{p,cut}}^{\text{IS}} \simeq 45, 65, 100, 400$ PeV assuming $\Gamma = 300, 500, 800, 1000$ and $t_{\text{var}} = 6$ ms. These evaluations confirm our choice to simulate the proton energy up to 10^9 GeV. Pion and muon propagations into magnetic field are also affected by synchrotron energy losses. We have compared the particles lifetime with the synchrotron timescale, $t_{\text{syn}}(E^{\text{IS}}) = 3m_x^4c^3/4\sigma_T m_e^2 \epsilon_{\pi} U_{\text{B}}$, [32], where m_x is the mass of the particle which we are taking into account. We found $E_{\mu^{\pm},\text{cut}}^{\text{IS}} \simeq 0.5, 2.6, 10, 20$ TeV and $E_{\pi^{\pm},\text{cut}}^{\text{IS}} \simeq 10, 50, 200, 400$ TeV ($\Gamma = 300, 500, 800, 1000$, $t_{\text{var}} = 6$ ms).

The MC simulation of $p\gamma$ interactions follows the methods described in [25]. The energy particle distribution for interacting protons, charged pions, muons and neutrinos assuming $\Gamma = 800$ and $t_{\text{var}} = 6$ ms is shown in figure 2.

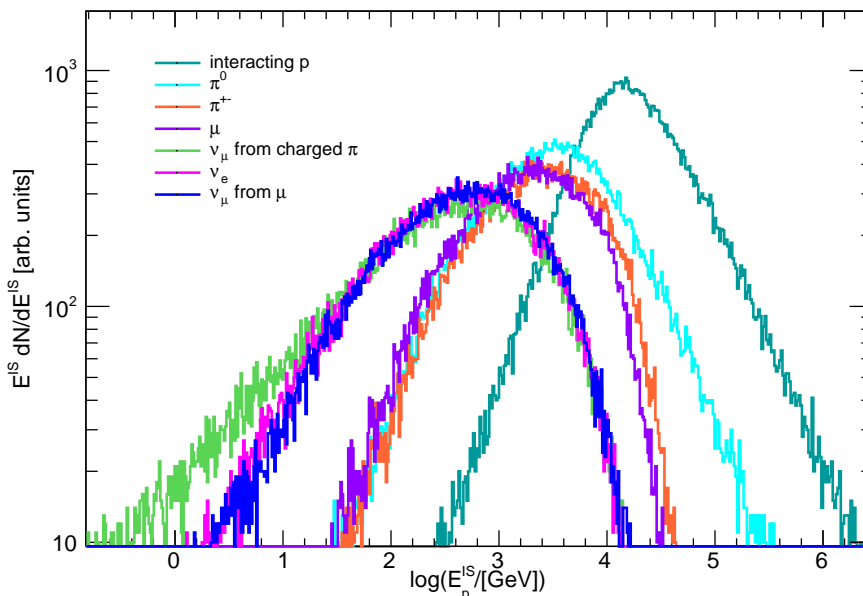


Figure 2. Particle spectra resulting from $p\gamma$ interactions, obtained in the IS frame from the simulation with $\Gamma = 800$ and $t_{\text{var}} = 6$ ms.

Concerning the neutral pion production and decay, we consider the possibility that each originated gamma ray might escape from the IS region, or interact with target photons, via e^\pm pair production. The average radiation length for this process is evaluated following [56] as

$$\lambda_{\gamma\gamma}^{-1}(E_\gamma^{\text{IS}}) = \frac{1}{2}\sigma_{\gamma\gamma} \int d\cos\theta(1 - \cos\theta) \int_{\epsilon_{th}}^{\infty} U_\gamma(\epsilon_\gamma) \frac{1}{2} \frac{dn_\gamma}{d\epsilon_\gamma} d\epsilon_\gamma \quad (3.2)$$

with the condition $\epsilon_{th} E_\gamma^{\text{IS}}(1 - \cos\theta) > 2(m_e c^2)^2$, being $0 < \theta < \pi$ the angle between the photons in the center of mass reference frame, and $\sigma_{\gamma\gamma}$ the e^\pm pair production cross section [53]. For the target photons we assumed the spectral energy distribution $dn_\gamma/d\epsilon_\gamma$ approximated by a Band function as described in section 2. For each π^0 -originated photon with energy E_γ^{IS} , we extract its free path x_γ according to the average radiation length $\lambda_{\gamma\gamma}$ in eq. (3.2). If $x_\gamma > R_{\text{IS}}$ the photon escapes the IS region and will eventually be observed in the laboratory frame with energy $E_{\text{obs}} = \Gamma E_{\text{IS}}/(1 + z)$. Most of the photons originated by π^0 decays are absorbed and initiate an electromagnetic cascade. We track the products of the interactions, until their energy can be included within the MAGIC observed energy range.

The contribution of photons from electromagnetic cascades to the MAGIC observed spectrum depends on the bulk Lorentz factor value used in the simulation: for a given π^0 energy this contribution from cascades is larger for lower values of Γ . The flux of escaping photons can be directly compared with the intrinsic spectral energy density evaluated on the basis of MAGIC published results [5]. The contribution of photons from electromagnetic cascades has been considered previously for GRBs [54] and other astrophysical sources (i.e. blazars [18]). For our work, instead of the semi-analytical treatment described in [39], we have developed a full MC simulation and applied it to GRB190114C.

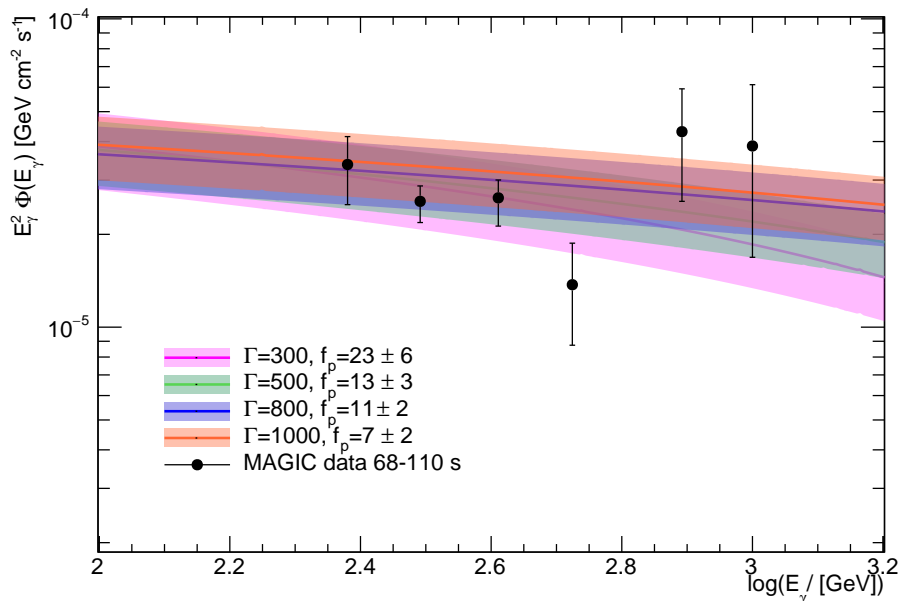


Figure 3. IS simulation: comparison between the EBL-deconvolved flux of GRB 190114C, as provided by MAGIC in the temporal interval 68-110 s [5] and the MC results. Photon fluxes are due to π^0 -decays and to electromagnetic showers following internal gamma-ray absorption on the IS for different parameters of the model.

4 Results: gamma rays and neutrinos from photo-hadronic interactions

We perform MC simulation for different values of t_{var} and Γ , obtaining spectra of high-energy gamma rays and neutrinos emerging from the interaction region. We then convert these spectra into expected fluxes on Earth by taking into account the cosmological nature of GRBs. We evaluate the quantity $E_\gamma^2 \phi(E_\gamma)$ on Earth rescaling the IS energy spectrum according to: i) the luminosity distance d_L , ii) the first time interval of MAGIC observations $\Delta t = 42$ s, and iii) the energy conversion factor from the IS to the observed frame, as:

$$E_\gamma^2 \phi(E_\gamma) = f_p \Gamma \frac{(1+z)}{4\pi d_L^2 \Delta t} \left(E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \right)_{\text{IS}}. \quad (4.1)$$

For each simulated Γ and t_{var} , the baryon loading value f_p has been assumed in the interval 1 – 30 to find the best agreement between the EBL-deconvolved MAGIC data, in the 68-110 s time interval [5] and the simulated fluxes, through a χ^2 statistical test. For the assumed values of $\Gamma = 300, 500, 800, 1000$ we obtain $f_p = 23 \pm 6, 13 \pm 3, 11 \pm 2, 7 \pm 2$ as best-fit parameters. These values are well consistent with the expectations [45].

For each Γ value, we evaluated the expected flux on Earth $E_\gamma^2 \Phi(E_\gamma)$. This result is shown in figure 3 where the shaded area represents the 1σ statistical uncertainty on f_p . For the assumed values of Γ , we found that the majority of photons emerging from the source is originated in the electromagnetic cascades due to interactions of photons from π^0 .

A direct proof of the hadronic origin of the observed TeV radiation might come from coincident neutrino observations. Because of the transient nature of GRBs, the detection of a single neutrino event would allow identifying these sources as extreme hadronic accelerators.

Detector	Declination band	N_{events}
ANTARES	$-45^\circ < \delta < 0^\circ$	1×10^{-3}
IceCube	$-30^\circ < \delta < 0^\circ$	3×10^{-2}
KM3NeT/ARCA	Average	1×10^{-1}

Table 1. Number of neutrino induced events expected by the GRB Internal Shock MC simulation for different neutrino telescopes, as due to ν_μ and $\bar{\nu}_\mu$ interactions during the [68;100] s time interval of the prompt emission of GRB 190114C, for the model with $t_{\text{var}} = 6$ ms, $\Gamma = 800$ and $f_p = 11$.

To evaluate the neutrino energy flux on Earth for muon neutrinos and antineutrinos we assume $\Gamma = 800$, we use the energy conversion factor described in eq. (4.1), and we take into account neutrino oscillations, assuming normal ordering and the standard three-flavor scenario [41]. To check whether present and future neutrino detectors might be able to find a signal from an astrophysical source similar to a GRB 190114C, we have evaluated the expected neutrino, plus antineutrino, fluence $dN_{\nu_\mu+\bar{\nu}_\mu}/dE_{\nu_\mu+\bar{\nu}_\mu}dS$. We can then compute the expected number of track-like events with the

$$N_{\text{events}}(\delta) = \int A_{\text{eff}}^{\nu_\mu}(E_\nu, \delta) \left(\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}dS} \right)_{\text{Earth}} dE_{\nu_\mu}, \quad (4.2)$$

where $A_{\text{eff}}^{\nu_\mu}(E_{\nu_\mu}, \delta)$ is the Neutrino Telescope effective area, given as a function of the neutrino energy and of the source declination δ . Public effective areas of ANTARES [6] and IceCube [1] are evaluated at analysis level and for the declination band that includes the position of GRB 190114C. For KM3NeT/ARCA the effective area is evaluated at trigger level and averaged throughout the sky [7]. In figure 4 we report the number of muon neutrino and antineutrino expected events for the three neutrino detectors as a function of the neutrino energy. In table 1, we provide the total number of neutrino-induced events expected in the three detectors, obtained by the simulation with $t_{\text{var}} = 6$ ms, $\Gamma = 800$ and $f_p = 11$. Both the ANTARES and IceCube Collaborations have unsuccessfully searched for coincident neutrino-induced signals from the direction of GRB 190114C. In the case of ANTARES, the derived 90% confidence level integrated upper limit amounts to 1.6 GeV/cm^2 . For IceCube the same limit amount to 0.44 GeV/cm^2 [9, 52]. In both cases, the constraints are limited to the muon neutrino component reaching Earth. In fact, because angular precision is a crucial feature in reducing the atmospheric background entering the search cone angle, muon neutrino charged-current interactions constitute the better astronomical channel, as muons emerging from these can be identified in neutrino telescopes as long tracks. The non-detection of current instruments is compatible with the hadronic model expectations for the values of f_p and Γ that better reproduce the sub-TeV gamma-ray MAGIC data [3].

Since the coincident background rate expected from atmospheric neutrinos is by orders of magnitude lower than the signal rate expected from GRB 190114C, a detection from a single GRB appears to be very difficult. This result suggests that stacking several GRBs of the same kind could be a viable solution for a significant detection. Despite the experimental efforts, no clear signal has emerged so far in data from the ANTARES and IceCube telescopes [1, 6] when searching for spatial and temporal coincidences with the prompt emission of a sample of stacked GRBs. This leads to a constraint on the possible contribution of standard GRBs to less than 10% of the diffuse cosmic neutrino flux [2, 8, 10, 11]. Furthermore, it is still unclear whether TeV-emitting GRBs behave as the standard GRB population.

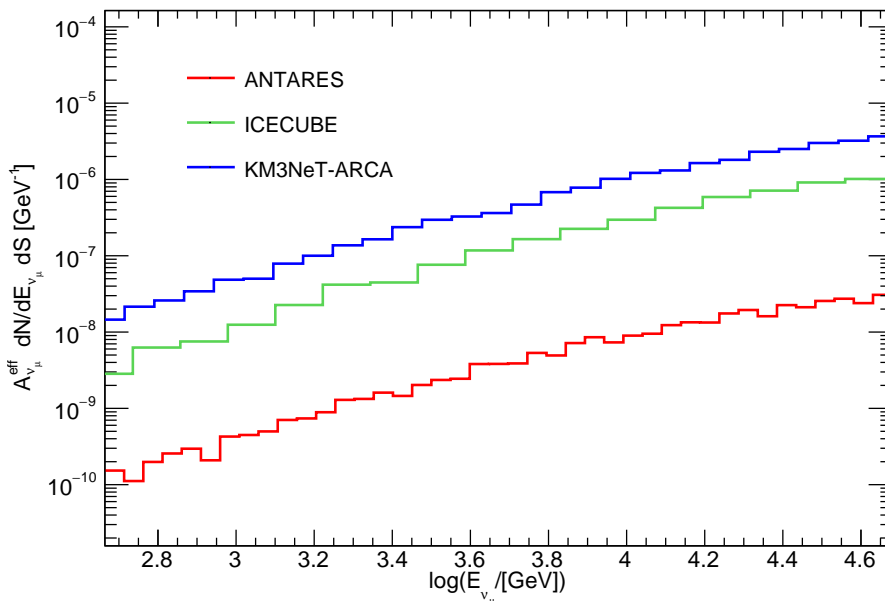


Figure 4. Number of expected muon neutrino and antineutrino events, for each energy bin, from GRB190114C for $\Gamma = 800$ and $t_{\text{var}} = 6$ ms, and $f_p = 11$: red for ANTARES [6], green for Icecube [1], blue for KM3NeT/ARCA [7].

5 Discussion and conclusions

The successful observation of radiation from GRBs extending up to the TeV domain has provided further evidence of the extreme nature of these sources. However, there is still poor understanding of the processes that characterize these TeV emissions that might witness the presence of effective hadronic acceleration in GRB jets, possibly already during the prompt phase of the emission or, more realistically, during the afterglow phase. This occurrence would establish the connection between GRBs and Ultra-High-Energy Cosmic Rays (UHECRs), which remains a long-standing paradigm still to be proven.

To test the hypothesis of the hadronic origin of TeV radiation, we developed a MC simulation of photo-meson interactions between high-energy protons and target photons distributed according to a Band-like spectrum, as indicated by Fermi-GBM observations, during the prompt phase. After computing the spectra of secondary particles emerging from these interactions, we additionally simulated the electromagnetic absorption that gamma rays undergo in the IS shell. The spectrum of escaping photons so obtained has been compared to the intrinsic source spectrum derived by the MAGIC observations of GRB 190114C. We obtained our results by developing a full MC simulation of the interactions of high energy accelerated protons with the IS radiation. High energy photons from π^0 , are followed until they interact in the IS region or escape. The total intrinsic flux of photons, directly from π^0 or from electromagnetic cascades, escaping from the interacting regions is then evaluated. This flux transported to Earth is compared with MAGIC observations deconvolved by EBL interaction. Several simulations have been performed, in the framework of both IS scenarios, assuming different values of the relevant model parameters, like the Lorentz factor Γ and the baryon loading f_p . From the comparison of the simulation results and the MAGIC data,

we extracted the parameter values that better reproduce the observations. In this paper we have considered the possibility that part of the TeV emission may be due to the IS model responsible of the prompt phase. We have found the best fit parameters for this model that can reproduce the maximum contribution due to the IS interactions.

The same MC code has been used to evaluate the flux of neutrino from charged pion decay arriving at Earth. Applying the same MC simulation to the entire sample of the observed TeV GRBs could provide insights on the physical mechanisms responsible for the TeV emission. A better knowledge of the high energy photon spectrum, that at present seems to be limited by the late response of imaging atmospheric Cherenkov telescopes in pointing, would help in the GRB characterization. Confirmation of the hadronic origin of sub-TeV radiation is expected from neutrino observations. However our simulation indicates that such a detection from individual astrophysical sources like GRB 190114C appears extremely unrealistic, as confirmed by the lack of spatial correlations in data reported by the ANTARES and IceCube neutrino telescopes.

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References

- [1] ICECUBE collaboration, *Searches for extended and point-like neutrino sources with four years of IceCube data*, *Astrophys. J.* **796** (2014) 109 [[arXiv:1406.6757](#)] [[INSPIRE](#)].
- [2] ICECUBE collaboration, *Extending the search for muon neutrinos coincident with gamma-ray bursts in IceCube data*, *Astrophys. J.* **843** (2017) 112 [[arXiv:1702.06868](#)] [[INSPIRE](#)].
- [3] ICECUBE collaboration, *Follow-up of astrophysical transients in real time with the IceCube neutrino observatory*, *Astrophys. J.* **910** (2021) 4 [[arXiv:2012.04577](#)] [[INSPIRE](#)].
- [4] MAGIC collaboration, *Teraelectronvolt emission from the γ -ray burst GRB 190114C*, *Nature* **575** (2019) 455 [[arXiv:2006.07249](#)] [[INSPIRE](#)].
- [5] MAGIC collaboration, *Observation of inverse Compton emission from a long γ -ray burst*, *Nature* **575** (2019) 459 [[arXiv:2006.07251](#)] [[INSPIRE](#)].
- [6] ANTARES collaboration, *Search for cosmic neutrino point sources with four year data of the ANTARES telescope*, *Astrophys. J.* **760** (2012) 53 [[arXiv:1207.3105](#)] [[INSPIRE](#)].
- [7] KM3NET collaboration, *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001 [[arXiv:1601.07459](#)] [[INSPIRE](#)].
- [8] ANTARES collaboration, *Search for muon neutrinos from γ -ray bursts with the ANTARES neutrino telescope using 2008 to 2011 data*, *Astron. Astrophys.* **559** (2013) A9 [[arXiv:1307.0304](#)] [[INSPIRE](#)].
- [9] ANTARES collaboration, *ANTARES upper limits on the multi-TeV neutrino emission from the GRBs detected by IACTs*, *JCAP* **03** (2021) 092 [[arXiv:2011.11411](#)] [[INSPIRE](#)].
- [10] A. Albert et al., *Search for high-energy neutrinos from bright GRBs with ANTARES*, *Mon. Not. Roy. Astron. Soc.* **469** (2017) 906 [[arXiv:1612.08589](#)] [[INSPIRE](#)].

- [11] ANTARES collaboration, *Constraining the contribution of gamma-ray bursts to the high-energy diffuse neutrino flux with 10 yr of ANTARES data*, *Mon. Not. Roy. Astron. Soc.* **500** (2020) 5614 [[arXiv:2008.02127](#)] [[INSPIRE](#)].
- [12] M. Ajello et al., *Fermi and swift observations of GRB 190114C: tracing the evolution of high-energy emission from prompt to afterglow*, *Astrophys. J.* **890** (2020) 9 [[arXiv:1909.10605](#)] [[INSPIRE](#)].
- [13] K. Asano, S. Inoue and P. Meszaros, *Prompt high-energy emission from proton-dominated gamma-ray bursts*, *Astrophys. J.* **699** (2009) 953 [[arXiv:0807.0951](#)] [[INSPIRE](#)].
- [14] A. Atoyan and C.D. Dermer, *High-energy neutrinos from photomeson processes in blazars*, *Phys. Rev. Lett.* **87** (2001) 221102 [[astro-ph/0108053](#)] [[INSPIRE](#)].
- [15] E. Waxman, *Gamma-ray bursts: afterglow, high-energy cosmic rays, and neutrinos*, *Astrophys. J. Suppl.* **127** (2000) 519 [[INSPIRE](#)].
- [16] P. Baerwald, S. Hummer and W. Winter, *Systematics in the interpretation of aggregated neutrino flux limits and flavor ratios from gamma-ray bursts*, *Astropart. Phys.* **35** (2012) 508 [[arXiv:1107.5583](#)] [[INSPIRE](#)].
- [17] M. Bustamante, P. Baerwald, K. Murase and W. Winter, *Neutrino and cosmic-ray emission from multiple internal shocks in gamma-ray bursts*, *Nature Commun.* **6** (2015) 6783 [[arXiv:1409.2874](#)] [[INSPIRE](#)].
- [18] M. Böttcher, A. Reimer, K. Sweeney and A. Prakash, *Leptonic and hadronic modeling of Fermi-detected blazars*, *Astrophys. J.* **768** (2013) 54 [[arXiv:1304.0605](#)] [[INSPIRE](#)].
- [19] GTC collaboration, *GRB 190114C: refined redshift by the 10.4 m GTC*, *GCN* 23708 (2019).
- [20] V. Chand et al., *MAGICal GRB 190114C: implications of cutoff in the spectrum at sub-GeV energies*, *Astrophys. J.* **903** (2020) 9 [[arXiv:1905.11844](#)] [[INSPIRE](#)].
- [21] E.V. Derishev, V.V. Kocharovskiy and V.V. Kocharovskiy, *TeV photons from γ -ray bursts*, *Adv. Space Res.* **27** (2001) 813 [[INSPIRE](#)].
- [22] E. Derishev and T. Piran, *The physical conditions of the afterglow implied by MAGIC's sub-TeV observations of GRB 190114C*, *Astrophys. J. Lett.* **880** (2019) L27 [[arXiv:1905.08285](#)] [[INSPIRE](#)].
- [23] A. Dominguez et al., *Extragalactic background light inferred from AEGIS galaxy SED-type fractions*, *Mon. Not. Roy. Astron. Soc.* **410** (2011) 2556 [[arXiv:1007.1459](#)] [[INSPIRE](#)].
- [24] D. Eichler, D. Guetta and M. Pohl, *The high energy budget allocations in shocks and GRB*, *Astrophys. J.* **722** (2010) 543 [[arXiv:1007.3742](#)] [[INSPIRE](#)].
- [25] M. Fasano et al., *Estimating the neutrino flux from choked γ -ray bursts*, *JCAP* **09** (2021) 044 [[arXiv:2101.03502](#)] [[INSPIRE](#)].
- [26] N. Fraija, R.B. Duran, S. Dichiara and P. Beniamini, *Synchrotron self-Compton as a likely mechanism of photons beyond the synchrotron limit in GRB 190114C*, *Astrophys. J.* **883** (2019) 162 [[arXiv:1907.06675](#)] [[INSPIRE](#)].
- [27] A. Franceschini and G. Rodighiero, *The extragalactic background light revisited and the cosmic photon-photon opacity*, *Astron. Astrophys.* **603** (2017) A34 [[arXiv:1705.10256](#)] [[INSPIRE](#)].
- [28] A. Franceschini and G. Rodighiero, *The extragalactic background light revisited and the cosmic photon-photon opacity (corrigendum)*, *Astron. Astrophys.* **614** (2018) C1.
- [29] KONUS-WIND collaboration, *Konus-Wind observation of GRB 190114C*, *GCN* 23737 (2019).
- [30] J. Granot, T. Piran and R. Sari, *Synchrotron self absorption in GRB afterglow*, *Astrophys. J.* **527** (1999) 236 [[astro-ph/9808007](#)] [[INSPIRE](#)].

- [31] SWIFT collaboration, *GRB 190114C: Swift detection of a very bright burst with a bright optical counterpart*, [GCN 23688](#) (2019).
- [32] D. Guetta and J. Granot, *Neutrinos from gamma-ray bursts in pulsar wind bubbles: $\sim 10^{16}$ eV*, [Phys. Rev. Lett. **90** \(2003\) 201103](#) [[astro-ph/0212045](#)] [[INSPIRE](#)].
- [33] R. Sari, T. Piran and R. Narayan, *Spectra and light curves of γ -ray burst afterglows*, [Astrophys. J. Lett. **497** \(1998\) L17](#) [[astro-ph/9712005](#)] [[INSPIRE](#)].
- [34] D. Guetta, M. Spada and E. Waxman, *On the neutrino flux from γ -ray bursts*, [Astrophys. J. **559** \(2001\) 101](#) [[astro-ph/0102487](#)] [[INSPIRE](#)].
- [35] D. Guetta, *Neutrinos from gamma ray bursts in the IceCube and ARA era*, [JHEAp **7** \(2015\) 90](#) [[arXiv:1503.07146](#)] [[INSPIRE](#)].
- [36] FERMI-GBM collaboration, *GRB 190114C: Fermi GBM detection*, [GCN 23707](#) (2019).
- [37] LHAASO collaboration, *LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV*, [GCN 32677](#) (2022).
- [38] S. Hummer, P. Baerwald and W. Winter, *Neutrino emission from γ -ray burst fireballs, revised*, [Phys. Rev. Lett. **108** \(2012\) 231101](#) [[arXiv:1112.1076](#)] [[INSPIRE](#)].
- [39] S.R. Kelner and F.A. Aharonian, *Energy spectra of γ -rays, electrons and neutrinos produced at interactions of relativistic protons with low energy radiation*, [Phys. Rev. D **78** \(2008\) 034013](#) [[Erratum ibid. **82** \(2010\) 099901](#)] [[arXiv:0803.0688](#)] [[INSPIRE](#)].
- [40] FERMI-LAT collaboration, *GRB 190114C: Fermi-LAT detection*, [GCN 23709](#) (2019)
- [41] C. Mascaretti and F. Vissani, *On the relevance of prompt neutrinos for the interpretation of the IceCube signals*, [JCAP **08** \(2019\) 004](#) [[arXiv:1904.11938](#)] [[INSPIRE](#)].
- [42] A. Melandri et al., *The supernova of the MAGIC gamma-ray burst GRB 190114C*, [Astron. Astrophys. **659** \(2022\) A39](#) [[arXiv:2112.04759](#)] [[INSPIRE](#)].
- [43] P. Minaev and A. Pozanenko, *GRB 190114C: SPI-ACS/INTEGRAL extended emission detection*, [GCN 23714](#) (2019).
- [44] R. Mirzoyan et al., *First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C*, [Astron. Tel. **12390** \(2019\) 1](#).
- [45] K. Murase, *High energy neutrino early afterglows γ -ray bursts revisited*, [Phys. Rev. D **76** \(2007\) 123001](#) [[arXiv:0707.1140](#)] [[INSPIRE](#)].
- [46] K. Murase and S. Nagataki, *High energy neutrino emission and neutrino background from γ -ray bursts in the internal shock model*, [Phys. Rev. D **73** \(2006\) 063002](#) [[astro-ph/0512275](#)] [[INSPIRE](#)].
- [47] M.E. Ravasio et al., *GRB 190114C: from prompt to afterglow?*, [Astron. Astrophys. **626** \(2019\) A12](#) [[arXiv:1902.01861](#)] [[INSPIRE](#)].
- [48] J.A. Rueda et al., *Magnetic fields and afterglows of BdHNe: inferences from GRB 130427A, GRB 160509A, GRB 160625B, GRB 180728A and GRB 190114C*, [Astrophys. J. **893** \(2020\) 148](#) [[arXiv:1905.11339](#)] [[INSPIRE](#)].
- [49] S. Sahu and C.E. López Fortín, *Origin of sub-TeV afterglow emission from γ -ray bursts GRB 190114C and GRB 180720B*, [Astrophys. J. Lett. **895** \(2020\) L41](#) [[arXiv:2005.12383](#)] [[INSPIRE](#)].
- [50] NOT collaboration, *GRB 190114C: NOT optical counterpart and redshift*, [GCN 23695](#) (2019).
- [51] AGILE collaboration, *GRB 190114C: AGILE/MCAL detection*, [GCN 23712](#) (2019).
- [52] ICECUBE collaboration), *GRB 190114C: search for high-energy neutrinos with IceCube*, [Astron. Tel. **12395** \(2019\)](#).

- [53] S. Vernetto and P. Lipari, *Absorption of very high energy γ rays in the Milky Way*, *Phys. Rev. D* **94** (2016) 063009 [[arXiv:1608.01587](#)] [[INSPIRE](#)].
- [54] K. Wang, R.-Y. Liu, Z.-G. Dai and K. Asano, *Hadronic origin of prompt high-energy emission of γ -ray bursts revisited: in the case of a limited maximum proton energy*, *Astrophys. J.* **857** (2018) 24 [[arXiv:1803.04112](#)] [[INSPIRE](#)].
- [55] X.-Y. Wang et al., *Synchrotron self-Compton emission from external shocks as the origin of the sub-TeV emission in GRB 180720B and GRB 190114C*, *Astrophys. J.* **884** (2019) 117 [[arXiv:1905.11312](#)] [[INSPIRE](#)].
- [56] E. Waxman, *γ -ray bursts: the underlying model*, *Lect. Notes Phys.* **598** (2003) 393 [[astro-ph/0303517](#)] [[INSPIRE](#)].
- [57] L. Yacobi, D. Guetta and E. Behar, *Constraints on the hadronic content of γ ray bursts*, *Astrophys. J.* **793** (2014) 48 [[arXiv:1407.0155](#)] [[INSPIRE](#)].