TEV γ-RAY FLUXES FROM THE LONGER CAMPAIGNS ON MRK421 AS CONSTRAINTS ON THE EMISSION OF TEV-PEV NEUTRINOS AND UHECRS

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(Dated: November 27, 2014)

\textbf{ABSTRACT}

Longer TeV γ-ray campaigns have been carried out to study the spectrum, variability and duty cycle of the BL Lac object Markarian 421 (Mrk 421). The longer ones have given some evidence of the presence of protons in the jet: i) Its spectral energy distribution (SED) which shows two main peaks; one at low energies (<1 keV) and the other at high energies (hundreds of GeV), has been described by using synchrotron proton blazar (SPB) model. ii) The study of the variability at GeV γ-rays and X-rays has indicated no significant correlation. iii) Measurements of duty cycles at GeV-TeV γ-rays resulted higher than X-rays and iv) TeV γ-ray detections without activity in X-rays, called "orphan flares" have been observed in this object.

Recently, the Telescope Array (TA) experiment reported the arrival of 72 ultra-high-energy cosmic rays (UHECRs) with some of them possibly related to the direction of Mrk 421. In this paper, we consider the hadronic interactions and the γ-TeV/X-ray duty cycles to correlate the TeV longer campaigns with the number of UHECRs around Mrk 421. In addition, thanks to the Monte Carlo simulation of a Km\textsuperscript{3} detector in the southern hemisphere, we found that more than one decade of data taking is needed to observe a significant TeV-PeV neutrino signal above atmospheric neutrino background.

\textbf{Subject headings:} gamma rays: general – Galaxies: BL Lacertae objects individual (Mrk 421) — Physical data and processes: acceleration of particles — Physical data and processes: radiation mechanism: nonthermal

I. INTRODUCTION

At a distance of 134.1 Mpc, the BL Lac object Mrk 421 (z=0.03) (Donnarumma et al.\textsuperscript{2009}) is one of the closest known and brightest sources in the extragalactic X-ray/TeV sky. In X-rays, this object has been imaged for more than 14 years, measuring fluxes ranging from few to hundreds mCrab (Isobe et al.\textsuperscript{2010}) (Donnarumma et al.\textsuperscript{2009}) Niinuma et al.\textsuperscript{2012}) (Krimm et al.\textsuperscript{2009}) Costa et al.\textsuperscript{2008}) Lichten et al.\textsuperscript{2006}) Balokovic et al.\textsuperscript{2013}) In particular the All-Sky Monitor (ASM) on board of the Rossi X-ray Timing Explorer (RXTE) was monitoring the X-ray sky from 1996 to 2011. This instrument observed continually the sky in four energy bands (1.5-3, 3-5, 5-12 and 1.5-12 keV) (Levine et al.\textsuperscript{1996}) The maximum X-ray flux measured was ~4.3 counts s\textsuperscript{-1} which corresponds to ~55.65 mCrab. Furthermore, Resconi et al.\textsuperscript{2009}) through RXTE/ASM data estimated the duty cycle of this source, founding a constant value of 18.1% for a standard deviation of 3 σ. In TeV energies, simultaneous observations have been carried out by different telescopes based on Imaging Atmospheric Cherenkov Techniques (IACT) (Punch et al.\textsuperscript{1992}) Gaidos et al.\textsuperscript{1996}) Acciari et al.\textsuperscript{& et al.\textsuperscript{2011}) (Krennrich et al.\textsuperscript{2002}) Albert et al.\textsuperscript{2007}) Aharonian et al.\textsuperscript{2005, 2002, 2003}) Carson et al.\textsuperscript{2007}) (The ARGO-YBJ Collaboration & et al.\textsuperscript{2011}) (Abdo et al.\textsuperscript{2014}) (Amenomori & et al.\textsuperscript{2007}) and air shower arrays (ASAs) (The ARGO-YBJ Collaboration & et al.\textsuperscript{2011}) (Abdo et al.\textsuperscript{2014}) (Amenomori & et al.\textsuperscript{2007}) (The ARGO-YBJ Collaboration & et al.\textsuperscript{2011}) (Abdo et al.\textsuperscript{2014}) (Amenomori & et al.\textsuperscript{2007}) Specially, Milagro experiment which was a large water-Cherenkov detector located in northern New Mexico, USA, observed this source consecutively for a period of 906 days with a significance of 7.1 standard deviations. During these almost 3 years of observations, Milagro measured an average flux for energies above 1 TeV equals (0.205 ± 0.090) \times 10^{-8} \text{cm}^{-2} \text{s}^{-1} for a spectral index of 2.3. With this observatory it was possible to estimate also the duty cycle for energies above 1 TeV for different baseline fluxes. At 3 standard deviations, the values of duty cycle reported were (0\pm 20\%) for 0.1 Crab and 0.33 Crab of luminosity, respectively (Abdo et al.\textsuperscript{2014}). For a period of 1.5 years (from 2008 August 5 to 2010 March 12), Mrk 421 was monitored by the Large Area Telescope (LAT) on board of the Fermi satellite. The γ-ray flux collected above 0.3 GeV was described by a power law with a photon index of 1.78 ± 0.02 and average flux of (7.23±0.16) \times 10^{-8} \text{ph cm}^{-2} \text{s}^{-1} (Abdo et al.\textsuperscript{2010}). The broadband SED with two peaks, one of low energy (≈0.5 keV), and the other of high energy (at hundreds of GeV) was described through leptonic and hadronic models. In the leptonic scenario, a one-zone synchrotron self-Compton (SSC) with three accelerated electron populations (through diffusive relativistic shocks with a randomly oriented magnetic field) has been used. In the hadronic scenario, the peak at low energies is explained by electron synchrotron radiation whereas the high-energy peak is explained evoking the SPB model (Mücke & Protheroe\textsuperscript{2001}) Mücke et al.\textsuperscript{2003}). In addition, (Abdo & et al.\textsuperscript{2010}) investigated the X-ray/GeV γ-ray correlation using RXTE/ASM and Fermi-LAT data, respectively. For RXTE/ASM, an energy range of 2-10 keV was used whereas for Fermi-LAT data two energy ranges 0.2 - 2 GeV and 2 - 300 GeV were analyzed. They observed that the variability in the Fermi fluxes above 2 GeV and below 2 GeV are shorter than the variability in X-rays, thus not finding any significant correlation in both energy ranges. From the above considerations, Mrk 421 may have the potential to emit high-energy neutrinos and to accelerate protons up to ultra-high energies (UHEs). Recently, IceCube collaboration reported the detection of 37 extraterrestrial neutrinos at 5.7σ above 30 TeV (IceCube Collaboration et al.\textsuperscript{2013a,b}) (Aartsen et al.\textsuperscript{2014}). The reconstructed neutrino events in the TeV - PeV energy range
range have been obtained during three consecutive years of data taking (2010 to 2013). In particular, nonevent-type track can be associated with Mrk 421. On the other hand, TA experiment detected 72 UHECRs above 57 EeV obtaining a statistical significance of 5.1σ within 5 years of operation. The field of view of this observatory covers the sky region above -10° of declination having a good sensitivity in the direction of Mrk421 (Abbasi & The Telescope Array Collaboration 2014). In fact, by considering the error reported for the reconstructed directions and the deviation due to extragalactic and galactic magnetic fields, a subset of few events might be linked to the position of Mrk421.

Taking into account the distance of Mrk 421, only 25% of a UHE proton fraction can come from this BL Lac (Kotera & Olinto 2011). Then, our starting point is to plot in a sky-map the neutrinos track–event detected by IceCube, the 72 UHECRs collected by TA experiment and the BL Lac Mrk 421. As shown in Fig. 1, a circular region of 5° around Mrk421 shows some UHECRs and no neutrino track event. In this work, we take into account the analysis and duty cycles reported by Resconi et al. (2009) and Milagro experiment (Abdo & et al. 2014), and introduce a hadronic model to link the TeV γ-ray fluxes reported by the longest campaigns as Milagro (Abdo & et al. 2014), ARGO YBJ (The ARGO-YBJ Collaboration & et al. 2011) and VERITAS (Acciari & et al. 2011) with the UHECRs observed in this region by the TA experiment (Abbasi & The Telescope Array Collaboration 2014). Additionally, we show the absence of neutrino tracks at the TeV - PeV energy range reported by IceCube (IceCube Collaboration et al. 2013a; Aartsen et al. 2014). For this work we required the parameters derived from the hadronic model able to describe reasonably well the broadband SED of this blazar (Abdo et al. 2011). The paper is arranged as follows. In Section 2 we show a brief summary is given in section 6. We hereafter use primes (unprimes) to define the quantities in a comoving (observer) frame, k=h=c=1 in natural units, and z=0.03± 0.

### 2. HADRONIC MODEL

As has been pointed out by Mücke & Protheroe (2001), relativistic protons in the jet suggest that hadronic interactions must be taken into account for describing the broadband SED, as well as neutrino emission. Relativistic protons accelerated at the emission region and described through a power law by

\[
\frac{dN_p}{dE_p} = A_p \left( \frac{E_p}{\text{GeV}} \right)^{-\alpha},
\]

(1)
can interact with the target photon density given by

\[ n_\gamma \simeq \frac{d^2}{r_d^2} \frac{\nu F_\nu}{\epsilon_{\gamma, pk}}, \]

(2)
where \( \nu F_\nu \simeq L_\gamma / (4\pi d_d^2) \) is the photon flux, \( r_d \) is the emission radius and \( \epsilon_{\gamma, pk} \) is the peak energy of target photons. The charged (\( \pi^+ \)) and neutral (\( \pi^0 \)) pion production channels are

\[
p\gamma \rightarrow \begin{cases} n \pi^+ \text{ fraction } 1/3, \\ p \pi^0 \text{ fraction } 2/3, \end{cases}
\]

(3)
where neutral pions decay in photons \( \pi_0 \rightarrow \gamma \gamma \), and charged pions into electrons/positrons and neutrinos \( \pi^\pm \rightarrow \mu^\pm + \nu_\mu / \bar{\nu}_\mu \rightarrow e^\pm + \nu_\mu / \bar{\nu}_\mu + \bar{\nu}_\mu / \nu_\mu + \nu_e / \bar{\nu}_e \).

#### 2.1. \( \pi^0 \) decay products

From p\( \gamma \) interactions, photo-pions and neutrinos typically carry 10%\((\xi_{\pi^0}/2 = 0.1)\) and 5% of the proton’s energy \( E_p \), respectively. The energy lost rate due to pion production can be written through the pion cooling time (Waxman & Bahcall 1997)

\[
t_{\pi^0}^{-1} = \frac{1}{2 \gamma_p^2} \int dx \frac{d\epsilon}{d\epsilon} \frac{\pi^0}{x} \int dx x^{-2} \frac{d\epsilon}{d\epsilon} (\epsilon_\gamma = x),
\]

(4)
where \( \gamma_p \) is the proton Lorentz factor and \( \sigma_\pi(\epsilon) = \sigma_{peak} \approx 9 \times 10^{-28} \text{ cm}^2 \) is the cross section of pion production. Comparing the pion cooling and the dynamical time scale (photo pion efficiency),

\[
f_{\pi^0} = \frac{n_d}{n_{\pi^0}} \simeq \frac{3 L_\gamma \sigma_{peak} \Delta \epsilon_{peak} \xi_{\pi^0}}{4 \pi T^2 r_d \epsilon_{peak} \epsilon_{\gamma, pk} \frac{\epsilon_{\gamma, pk}^2}{\epsilon_{\gamma, pk}^2}},
\]

(5)
where \( \Delta \epsilon_{peak} \approx 0.2 \text{ GeV} \) and \( \epsilon_{peak} \approx 0.3 \text{ GeV} \), we can estimate the relation between the photo-pion and Fermi-accelerated proton fluxes as

\[
f_{\pi^0} E_p \left( \frac{dN}{dE} \right)_p dE_p = e_{\pi^0, \gamma} \left( \frac{dN}{dE} \right)_{\pi^0, \gamma} d\epsilon_{\pi^0, \gamma}.
\]

(6)
Here $\Gamma$ is the bulk Lorentz factor, $\epsilon_{\gamma,\gamma,c} \simeq 0.25\Gamma^2 \xi_{\gamma,0} (m_{\pi}^2 - m_{\gamma}^2)/\epsilon_{\gamma, pk}$ is the break photo-pion energy and $m_{\Delta}$ is the resonance mass. Taking into account the proton spectrum (eq. [1]) and the energy fraction carried by photons, we can write the photo-pion spectrum as

$$\left(2 \frac{dN}{de}\right)_{\pi^0,\gamma} = A_\gamma \left\{ \begin{array}{ll} \left( \frac{\epsilon_{\pi,\gamma,c}}{\epsilon_{\gamma,0}} \right)^{-\alpha_3} & \epsilon_{\pi,\gamma} < \epsilon_{\pi,\gamma,c} \\ \left( \frac{\epsilon_{\pi,\gamma,c}}{\epsilon_{\gamma,0}} \right)^{-\alpha_2} & \epsilon_{\pi,\gamma,c} < \epsilon_{\pi,\gamma} \end{array} \right. \tag{7}$$

where $A_\gamma$ is obtained through the fit of each TeV spectrum and used to normalize the proton spectrum as

$$A_p \simeq f_{p,\gamma} A_\gamma \tag{8}$$

with the parameters of the jet given by

$$f_{p,\gamma} = \frac{\Gamma^2 \epsilon_{\text{peak}}}{6 \pi \eta_\gamma \epsilon_{\gamma,0}^2 \sigma_{\text{peak}} \Delta \epsilon_{\text{peak}}} \tag{9}$$

Here $\epsilon_{\gamma,0}$ is the normalization energy of the TeV $\gamma$-ray spectrum.

### 3. HIGH-ENERGY NEUTRINO FLUX

High-energy photons and neutrinos can be correlated through $p\gamma$ interactions (Fermi-accelerated protons with keV photon targets) (see, e.g. [Halzen 2007] and reference therein) as follows

$$\int \frac{dN_\nu}{dE_\nu} E_\nu dE_\nu = k_\nu \int \left( \frac{dN}{de} \right)_{\pi^0,\gamma} \tag{10}$$

where $k_\nu$ is 1/4. The integral term on the right represents the TeV $\gamma$-ray flux described by eq. [7] and the term on the left is the neutrino flux which can be described as a simple power law

$$\frac{dN_\nu}{dE_\nu} = A_\nu \left( \frac{E_\nu}{\epsilon_{\gamma,0}} \right)^{-\alpha_\nu} \tag{11}$$

Here we assume that spectral indices for neutrino and $\gamma$-ray spectra are similar $\alpha \simeq \alpha_\nu$ (Becker 2008). Solving the integrals in eq. [10], we found that the normalization factors, for neutrino and photon spectrum, are related by

$$A_\nu \simeq 2^{-\alpha} A_\gamma \tag{12}$$

With these considerations, we can write the expected number of reconstructed neutrino events in a hypothetical neutrino telescope ($> E_\nu^{\text{th}}$) as

$$N_{\nu} = T \rho_{\text{w,i}} N_A V_{\text{eff}} \int_{E_{\nu}^{\text{th}}}^{E_{\nu}} \sigma_{\nu N} \frac{dN_\nu}{dE_{\nu}} dE_{\nu} \tag{13}$$

where $T$ is the observation time, $N_A = 6.022 \times 10^{23}$ g$^{-1}$ is the Avogadro number, $\rho_{\text{w,i}}$ is the density of the water/ice, $\sigma_{\nu N} = 6.78 \times 10^{-35} \text{cm}^2 (E_{\nu}/\text{TeV})^{0.363}$ is the neutrino-nucleon cross section (Gandhi et al. 1998) and $V_{\text{eff}}$ is the $\nu_\mu + \bar{\nu}_\mu$ effective volume, obtained through Monte Carlo simulation for a point source emission at the position of Mrk 421. For a complete analysis, also atmospheric and diffuse neutrino “backgrounds” should also be introduced. The cosmic diffuse neutrino flux is obtained with the upper limit given as $E_\nu^2 d\Phi/dE_\nu < 2.0 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (Bahcall & Waxman 2001) and the atmospheric neutrino flux is described by the Bartol model (Barr et al. 2006, 2004).

### 4. PRODUCTION OF UHE COSMIC RAYS

It has been suggested that astrophysical objects accelerate cosmic rays up to UHEs, which might produce VHE $\gamma$-rays and neutrino fluxes through hadronic interactions. In our model we assume that the accelerated proton spectrum is extended up to $\sim 10^{20}$ eV energies and based on this assumption, we calculate the number of events expected in TA experiment.

#### 4.1. Mechanisms of UHECR acceleration

Cosmic rays can be accelerated up to UHEs depending on both the size ($R$) and the strength of the magnetic field ($B$) in the acceleration region. Therefore, the maximum energy required is $E_{\text{max}} = Z e B R \Gamma$ with $Z$ the atomic number (Hillas 1984). Additional limitations in this process could be mainly caused by the radiative losses or available time when particles go through the magnetized region. Close to the black hole (BH), this place is limited by the emitting region ($r_d$) and the strength of the magnetic field ($B$) in it. Then, the maximum energy achieved is (Abdo & et al. 2010; Sahu et al. 2012; Fraija 2014)

$$E_{\text{max}} = Z e B r_d \Gamma. \tag{14}$$

It is important to highlight that UHECRs traveling from source to Earth are randomly deviated by galactic ($B_G$) and extragalactic ($B_{EG}$) magnetic fields. By considering a quasi-constant and homogeneous magnetic field, the deflection angle due to the $B_G$ is

$$\theta_G \simeq 3.8^\circ \left( \frac{E_{p,\text{th}}}{57 \text{ EeV}} \right)^{-1} \int_0^{L_G} \left| \frac{dl}{\text{kpc}} \times \frac{B_G}{4 \mu \text{G}} \right|, \tag{15}$$
where $L_G$ corresponds to the distance of our Galaxy (20 kpc) and due to $B_{EG}$ can be written as

$$\theta_{EG} \sim 5^\circ \left(\frac{E_{p,th}}{57 \text{ EeV}}\right)^{-1} \left(\frac{B_{EG}}{1.25 \text{ nG}}\right) \left(\frac{L_{EG}}{100 \text{ Mpc}}\right)^{1/2} \left(\frac{l_c}{1 \text{ Mpc}}\right)^{1/2},$$  

(16)

where $l_c$ is the coherence length (Stanev 1997; Moharana & Gupta 2009). Here we use the same energy threshold ($E_{p,th} = 57 \text{ EeV}$) of the TA experiment.

### 4.2. Expected Number of UHECRs

TA experiment, located at 1.400 m above sea level in Millard Country (Utah), is made of three fluorescence detector (FD) stations and a scintillator surface detector (SD) array (Abu-Zayyad & et al. 2012). It was designed to observe cosmic rays that induce extensive air showers with energies above 1 EeV. This array has an area of ~700 km$^2$ and has been in operation since 2008. To estimate the number of UHECRs, we take into account the TA exposure, which for a point source is given by $\Xi t_{op} \omega(\delta_s)/\Omega$, where $\Xi t_{op} = (5) \times 10^2 \text{ km}^2 \text{ yr}$, $t_{op}$ is the total operational time (from 2008 May 11 to 2013 May 4), $\omega(\delta_s)$ is an exposure correction factor for the declination of Mrk 421 (Sommers 2001) and $\Omega \approx \pi$. The expected number of UHECRs above an energy $E_{p,th}$ yields

$$N_{UHECR} = F_r \left(\text{TA Expos.}\right) \times N_p,$$  

(17)

where $F_r$ is the fraction of propagating cosmic rays that survives over a distance $> D_s$ (Kotera & Olinto 2011) and $N_p$ is calculated from the proton spectrum (eq. (1)) extended to energies higher than $E_{p,th}$. Finally, the expected number can be written as

$$N_{UHECR} = F_r \frac{\Xi t_{op} \omega(\delta_s)}{\Omega (\alpha - 1)} f_{p,\gamma} A_\gamma \left(\frac{E_{p,th}}{\text{GeV}}\right)^{-\alpha+1} \text{ GeV},$$  

(18)

with $f_{p,\gamma}$ given by eq. (9). In addition, from eqs. (1) and (8) we can compute that the proton luminosity $L_p = 4\pi D_s^2 F_r \frac{\delta N_p}{dE_p}$ can be written as

$$L_p = 4\pi D_s^2 F_r f_{p,\gamma} A_\gamma \left(\frac{E_p}{\text{GeV}}\right)^{2-\alpha} \text{ GeV}^2.$$  

(19)

It is important to say that if $E_p = E_{p,th}$, then $L_p = L_{UHECR}$.

### 5. ANALYSIS AND RESULTS

We have introduced a hadronic model based on the $p\gamma$ interactions to describe the VHE $\gamma$-ray flux observed from Mrk 421. First of all, we consider the longer campaigns performed for more than 5 years of observations, as shown in table 1. In this table we relate the main features of the campaigns performed by Milagro (Abdo & et al. 2014), VERITAS (Acciari & et al. 2011) and ARGO-YBJ (The ARGO-YBJ Collaboration & et al. 2011).

| Experiment      | Campaigning (Duration) | $T_{\text{live}}$ | significance ($\sigma$) | $A_{\gamma} \left(10^{-11}\right)$ (TeV cm$^2$ s$^{-1}$) | Photon index ($\alpha$) |
|-----------------|------------------------|------------------|-------------------------|----------------------------------------------------------|------------------------|
| Milagro         | 2005 - 2008 \(\approx\) 900 d | 7.1              | 2.67 \(\pm\) 0.39      | \(\approx\) 2.30                                            |                        |
| VERITAS (a)     | 2006 - 2008 \(\approx\) 7.83 s | 77.62            | 4.78 \(\pm\) 0.73      | \(\approx\) 2.29 \(\pm\) 0.11                              |                        |
| VERITAS (b)     | 2006 - 2008 \(\approx\) 16.3 h | 181.3            | 7.60 \(\pm\) 0.33      | \(\approx\) 2.28 \(\pm\) 0.035                              |                        |
| ARGO-YBJ        | 2007 - 2010 \(\approx\) 676 d | 10               | 8.68 \(\pm\) 0.49      | \(\approx\) 2.30 \(\pm\) 0.22                              |                        |

Table 1. Campaigns developed on Mrk 421 from 2005 to 2010. This table shows the main spectral characteristics of these observations.

The values of $A_{\gamma}$ and $\alpha$ reported in table 1 for ARGO-YBJ experiment were obtained as a result of fitting the spectra of the four groups with different flux levels collected from 2007 to 2010, as shown in fig. 2. Using the method of Chi-square $\chi^2$ minimization (Brun & Rademakers 1997) we fit these groups of spectra with a straight line $\alpha = [0] F t[1]$ (with $\alpha$ the spectral index and $F$ the flux) through the parameters $[0]$ and $[1]$ (see table 2). Taking into account the values of these parameters and the spectral index for longer campaigns $\alpha \approx 2.3$ (table 1) we obtain a flux equal to $(8.68 \pm 0.49) \times 10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$.

| Parameter | Value |
|-----------|-------|
| [0]       | 0.190 \(\pm\) 0.057 |
| [1]       | -2.610 \(\pm\) 0.184 |
| $\chi^2$/NDF | 0.3021/2 |

$^3$ Labels (a) and (b) correspond to two different campaigns.
Milagro experiment had a ~2 sr field of view and a > 90% duty cycle that allowed continuous monitoring of the entire overhead sky in \( \gamma \)-rays between 100 GeV and 100 TeV \cite{Abdo_2008b}. This observation occurred for almost three years of the blazar Mrk 421 with a statistical significance of 7.1 standard deviations and estimated duty cycles above 1 TeV of ~ 40% and ~ 27% for 0.1 Crab and 0.33 Crab of luminosities, respectively. On the other hand, Resconi et al. \cite{Resconi_2009} analyzing more than 10 years of RXTE/ASM data from Mrk 421 estimated a constant value of ~18.1% in the X-ray duty cycle. In leptonic scenario, TeV \( \gamma \)-ray and X-ray fluxes are usually interpreted in the context of one-zone SSC emission, X-ray radiation is described through electron synchrotron radiation while TeV \( \gamma \)-ray emission is explained by means of the up-scatter of synchrotron photons. In this approach \( \gamma \)-ray activity is supposed to be correlated with X-ray activity and any extra contribution to the TeV \( \gamma \)-ray flux (without a counterpart at X-ray) comes from alternative emission processes, i.e., hadronic models, etc. Taking the difference of duty cycles between VHE \( \gamma \)-rays and X-rays, we can estimate the TeV \( \gamma \)-ray duty cycle that might be associated to hadronic processes. Then, the fractions of this \( \gamma \)-ray duty cycles related to accelerated proton density are ~ 21.9% and ~ 8.9% for luminosities of 0.1 Crab and 0.33 Crab, respectively. Although the analysis of TeV duty cycle was done for three years of observations (2005 - 2008), we extrapolate this quantity in the campaigns performed by ARGO-YBJ which corresponds from 2007 to 2010. Also, it is important to mention that though the analysis of the duty cycle was performed regarding flaring states, we extend it to the longer TeV-\( \gamma \)-ray campaigns considered in this work.

Due to extragalactic (eq. \ref{eq:16}) and galactic (eq. \ref{eq:15}) magnetic fields, UHECRs are deflected between the arrival direction and the original position of source. Regarding these considerations, the total deflexion angle may be as large as the mean value of \(< \theta_T > 15^\circ \) \cite{Ryu_2010}. Therefore, it is reasonable to associate UHECRs within a \( \gamma \) \( ^{\circ} \approx 5 \) \ref{eq:16} centered at Mrk 421. By considering the target photon flux at \( \nu F_\nu = 0.5 \text{ keV} \simeq 4 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) \cite{Abdo_2011} and from eq. \ref{eq:2}, it is possible to obtain a photon density equals to \( n_{\nu} \simeq 8.95 \times 10^{12} \text{ cm}^{-3} \). As one can see the amount of photons is copious, therefore \( p_{\gamma} \) interactions become an effective process. Assuming the values of an emission region \( r_d = 4 \times 10^{14} \text{ cm} \), a bulk Lorentz factor \( \Gamma = 10 \) and a magnetic field \( B = 50 \text{ Gauss} \) \cite{Abdo_2011}, we compute, through \( p_{\gamma} \) interactions, the neutrino flux (eq. \ref{eq:12}), the number of UHECRs (eq. \ref{eq:18}) and the proton luminosity (eq. \ref{eq:19}) associated to the VHE \( \gamma \)-ray fluxes reported by Milagro, VERITAS and ARGO-YBJ. By assuming that the BH jet has the potential to accelerate particles up to UHEs, we can see that from eq. \ref{eq:14} protons at the emitting region can achieve a maximum energy of \( 2.37 \times 10^{20} \text{ eV} \). Then, considering that proton spectrum is extended up to this energy. Additionally, by considering the VHE \( \gamma \)-ray duty cycles of 21.9% and 8.9% associated to hadronic components \cite{Abdo_2014}, we compute the neutrino and UHECR events. The number of UHECRs expected

| Experiment | Campaining (Duration) | \( \text{N}_{\text{UHECR}} \) | Duty Cycle |
|------------|----------------------|---------------------------------|-------------|
|            |                      | Without                        | 0.1 Crab    | 0.33 Crab |
| Milagro    | 2005 - 2008          | 1.83                           | 0.40        | 0.16      |
| VERITAS (a)| 2006 - 2008          | 4.13                           | 0.91        | 0.37      |
| VERITAS (b)| 2006 - 2008          | 7.38                           | 1.62        | 0.66      |
| ARGO-YBJ   | 2007 - 2010          | 5.90                           | 1.30        | 0.53      |

Table 3. The UHE protons estimated with our model.

6. RESULTS AND CONCLUSIONS

We have introduced a hadronic model through \( p_{\gamma} \) interactions to correlate the longer campaigns of TeV \( \gamma \)-ray observations of the BL Lac Mrk421 (see table 1) with the expected HE neutrino flux and the proton spectrum. Taking into account that the maximum energy achieved by Fermi-accelerated protons at the emitting region is \( 2.7 \times 10^{20} \text{ eV} \), we assume that the proton spectrum is extended up to this energy. Additionally, by considering the VHE \( \gamma \)-ray duty cycles of 21.9% and 8.9% associated to hadronic components \cite{Abdo_2014}, we compute the neutrino and UHECR events.


in TA experiment is shown in table 3. For instance, considering the hadronic component related to the duty cycle of 8.9%, no events are expected whereas the component tied up to the duty cycle of 21.9%, only few events could come, thus describing those events detected by TA experiment around the Mrk 421 position. From our model we found that the proton luminosity required to describe the TeV γ-ray fluxes (reported in table 1) lies in the range $10^{43}$ erg/s $\leq L_p \leq 10^{45}$ erg/s and assuming that proton spectrum extends up to energies of $\sim 10^{20}$ eV, the UHE proton luminosity lies in the range $10^{42}$ erg/s $\leq L_p \leq 10^{43}$ erg/s as shown in fig. [3].

Correlating the TeV γ-ray and HE neutrino fluxes, we have estimated (through MC simulation) the expected events in a hypothetical km$^3$ Cherenkov telescope in the southern hemisphere. For the hadronic components associated to these duty cycles (21.9% and 8.9%), we found that more than a decade is required to obtain a neutrino track-event detection significantly correlated with Mrk 421. This result is consistent with the observations reported by IceCube collaboration.

After correlating the TeV γ-ray fluxes collected from Mrk 421 with the neutrino and UHECR fluxes by means of pγ interactions, we conclude that neutrino events can not be observed in some years but UHECR events might. The increasing statistics of IceCube and TA experiment will give more evidence of our model.

Requiring a good description of the UHECRs, we conclude that an hybrid lepto-hadronic model is needed to describe the broadband SED. Due to the low extragalactic background light (EBL) absorption for Mrk421 (Raue & Mazin 2008) the TeV γ-ray and HE neutrino fluxes, we have estimated (through MC simulation) the expected events in a hypothet-
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Requiring a good description of the UHECRs, we conclude that an hybrid lepto-hadronic model is needed to describe the broadband SED. Due to the low extragalactic background light (EBL) absorption for Mrk421 (Raue & Mazin 2008) the TeV γ-ray and HE neutrino fluxes, we have estimated (through MC simulation) the expected events in a hypothet-

ACKNOWLEDGEMENTS

We thank to Francis Halzen, Ignacio Taboada, Teresa Montarulli and William Lee for useful discussions. Also we thank to TOPCAT team for the useful sky-map tools. This work was supported by Luc Binette scholarship, Galilei postdoctoral grant and the projects IG1004141 and Conacyt 101958.

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Fig. 1.— Sky-map with the 8 VHE neutrino track-events detected by IceCube (blue circles), 72 UHECRs collected by TA experiments (red crosses) and the BL Lac Mrk 421 (black point).
Fig. 2.— ARGO YBJ experiment data of the four groups of spectra collected in the campaign 2007 - 2010. In this figure we plot the spectral indexes as a function of fluxes.
Proton luminosity as a function of its energy is plotted. The values of proton luminosity are normalized with the TeV γ-ray observations of Mrk421. In this figure we highlight two zones; the dotted line in blue color represents those protons responsible for the TeV γ production around $E_{p, pk} \approx 10$ TeV and the dotted line in green color represents those with energy collected in TA experiment. In the left-hand figure above we do not take into account the duty cycle whereas right-hand figure above and the above figure we take into account the duty cycle for 0.33 Crab and 0.1 Crab, respectively.
Fig. 4.— Mrk421 neutrino event rate as a function of neutrino energy is plotted. Here is reported the signal to noise ratio for a hypothetical Km$^3$ neutrino telescope in the south hemisphere considering the TeV $\gamma$-ray observations of Mrk421. The neutrino event rate from Mrk421 is reported in black while in red and blue we show respectively the atmospheric and the cosmic neutrino "background". In the left-hand figure above we do not take into account the duty cycle whereas right-hand figure above and the above figure we take into account the duty cycle for 0.33 Crab and 0.1 Crab, respectively.