PROCEEDINGS OF SCIENCE

Impact of the QCD dynamics on the determination of the high energy astrophysical neutrino flux

Victor P. Gonçalves,[a] **Diego R. Gratieri**[b,*] **and Alex S. C. Quadros**[a]

[a] *Instituto de Física e Matemática, Universidade Federal de Pelotas (UFPel), Caixa Postal 354, CEP 96010-090, Pelotas, RS, Brazil*

[b] *Escola de Engenharia Industrial Metalúrgica de Volta Redonda, Universidade Federal Fluminense (UFF), CEP 27255-125, Volta Redonda, RJ, Brazil*

E-mail: barros@ufpel.edu.br, drgratieri@id.uff.br, alexscq@gmail.com

The results presented here are based on the work [1], where we determine the impact of different assumptions in the description of the high-energy QCD interactions on the determination of the astrophysical neutrino flux, the normalization Φ_{Astro} and spectral index γ of. The energy distribution of neutrino events at the IceCube is estimated considering the DGLAP, BFKL, CGC and BBMT approaches, and the best estimates for the flux parameters are determined using a maximum likelihood fit comparing the predictions with the distribution of observed events at IceCube. We also investigate if the increase of the effective exposure time expected in IceCube - Gen2 will allow us to disentangle the QCD dynamical effects from the description of the astrophysical neutrino flux.

**** The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021) ****
**** 6–11 Sep 2021 ****
**** Cagliari, Italy ****

*Speaker

PoS(NuFact2021)091

1. Introduction

The study of the UHE events at the IceCube is expected to improve our understanding about the origin, propagation, and interaction of neutrinos. Indeed, the recent data has been used to constrain the energy behavior of the astrophysical neutrino flux as well as to constrain the neutrino - hadron cross-section. One has that variations in these quantities are expected to modify the flux and event rate at IceCube detector. Moreover, we assume that the number of events in IceCube is given by

$$dN_{events} \;=\; T\sum_{\nu+\bar{\nu}} N_{eff,\alpha}(E_\nu)\times\Phi_{\nu_\alpha}(E_\nu)\times\sigma_{\nu_\alpha}(E_\nu)\times d(E_{vis})\times S_\alpha(E_\nu)\times d\Omega, \qquad (1)$$

where $T = 2078$ days is the time of data taken, $N_{eff,\alpha}(E_\nu)$ is the effective number of scattering targets, Φ_{ν_α} is the astrophysical neutrino flux for a neutrino of flavor α, $\sigma_{\nu_\alpha}(E_\nu)$ is the neutrino - target cross-section for a given neutrino energy E_ν and $S_\alpha(E_\nu)$ is the absorption function, which takes into account the effects of the neutrino flux attenuation inside the Earth, and which is defined by [2]

$$S^j(E_\nu) = \int_{-1}^{0} d\cos(\theta_z)\exp\left\{-\kappa_j\,\sigma_{\nu j}(E_\nu)\int_0^{r(\theta_z)}\rho_j(r)dr\right\}\ , \qquad (2)$$

where θ_z is the zenith angle, $r(\theta_z) = -2\,R_{Earth}\cos\theta_z$ is the total distance travelled by neutrinos, $\rho_j(r)[g\ cm^{-3}]$ is the density profile of the Earth. Also, $\kappa_N = N_A$ and $\kappa_e = \langle Z/A\rangle\cdot N_A$. As shown in Ref. [3], $S^j(E_\nu)$ is strongly sensitive to the description of the neutrino - target cross-section and the amount of matter crossed by the neutrinos. We also assumed that the effective number of scattering targets is given by

$$N_{eff}(E_\nu) = N_A\times V_{eff}(E_\nu) = N_A\times M_{eff}(E_\nu)/\rho_{eff}. \qquad (3)$$

where the effective detector masses, $M_{eff,\alpha}$, are given in [4]. Furthermore, considering the astrophysical neutrino flux, one has that its origin is still a theme of intense debate. As usual in the literature, we will assume the same astrophysical neutrino flux for the three neutrino flavors, $\Phi_{\nu_e} = \Phi_{\nu_\mu} = \Phi_{\nu_\tau} = \Phi_0$, which from [5] is given by

$$\Phi_\nu(E_\nu) = \frac{\Phi_{astro}}{(E_\nu/100\,TeV)^\gamma}(f.u.), \qquad (4)$$

where γ is the power law index and $\Phi_{Astro} = 3\Phi_0$ defines the normalization and the flux unit is defined as $f.u. \equiv 10^{-18}GeV^{-1}s^{-1}sr^{-1}cm^{-2}$. The last ingredient that we must to specify is the neutrino-hadron cross-section. The standard framework to calculate the neutral and charged current cross-sections is the collinear DGLAP factorization, which predicts that $\sigma_{\nu h}$ increases with the neutrino energy due to the increase of the quark and gluon densities inside of hadrons at small - x. However, new dynamical effects can be present in the unexplored kinematical range probed by the neutrino telescopes, for example those associated with the BFKL dynamics or to the non-linear (saturation) corrections. Indeed, the fact that the growth of the parton distributions predicted by the DGLAP and BFKL equations is expected to saturate, forming a Color Glass Condensate (CGC), implies in a new regime where the physical process of recombination of partons becomes important in the parton cascade and the evolution is given by a non-linear evolution equation. Moreover, we

PoS(NuFact2021)091

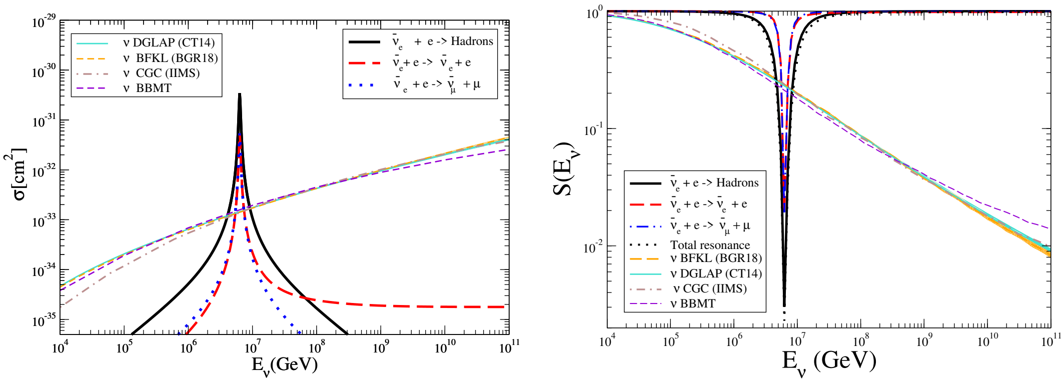

Figure 1: Left Panel Energy dependence of the neutrino-target cross-sections. **Right Panel** Neutrino absorption by the Earth as a function of neutrino energy for the different QCD models. For completeness, we also show the impact of the anti electron-neutrino interaction with electrons in the medium due to Glashow resonance.

will also consider the approach based on the assumption that the proton structure function saturates the Froissart bound at high energies, denoted BBMT hereafter. Please see [1] and the references therein for details on the different approaches to the neutrino-hadron cross-sections.

2. Results and outlook

Here present in Fig. 1 (a) our predictions for the energy dependence of the neutrino - target cross-section for the distinct approaches for the treatment of the QCD dynamics discussed in the previous Section. in Fig. 1 (b) we present our predictions for the absorption function $S(E_\nu)$. Moreover, to estimate the impact of the different QCD approaches on the IceCube data, we write the $\mathcal{X}^2$ function as

$$\mathcal{X}^2 \equiv 2\sum_{i=1}^{n}\left\{(E_i - O_i) + O_i\ ln\left(\frac{O_i}{E_i}\right)\right\} + \sum_{j=1}^{m}\left(\frac{\theta_j - \theta_j^*}{\sigma_j}\right)^2, \quad (5)$$

where prior information about the values for some parameters θ_j are included in the likelihood function. Gaussian penalties then reject solutions where the best fit value for the parameter θ_j^* is different from its prior value. To include the systematic errors we follow [6]. From Fig 2, we can see that for the four QCD models, we found that the values for the pull parameters associated with the best-fit point (B. F. P.) are consistent with each other and with the values reported by [6] in few percent level. In Table 1 we show the best fit points we obtained for the parameters γ and Φ_{astro} for the different interaction models we use. Furthermore, in Fig. 3 (a) we present our results for the energy dependence of the number of neutrino events considering the four different QCD dynamics. Finally, in Furthermore, in Fig. 3 (b) we consider the planned IceCube extension, IceCube-Gen2, and consider the impact of the higher number of events on the analysis.

In summary, we have investigated the impact of different assumptions for the QCD dynamics on the determination of the astrophysical flux parameters Φ_{astro} and γ. We have estimated the distribution of neutrino events at the IceCube considering the DGLAP, BFKL, and CGC approaches.

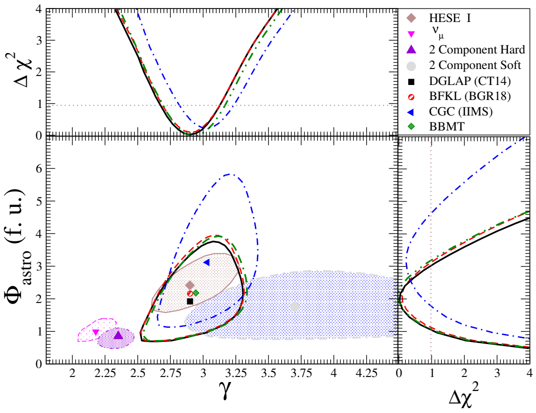

Figure 2: Our results for the *Likelihood* analysis for the High - Energy Starting Events (HESE) are compared with the different analyses performed by the IceCube Collaboration in Ref. [5]. In all cases points refer to the best fit and the allowed region at 68% of C. L. is also shown.

$\gamma \pm \delta\gamma$	$\Phi_{astro} \pm \delta\Phi_{astro}$(f.u.)	χ^2_{min}
	DGLAP (CT14)	
$2.90^{+0.23}_{-0.22}$	$1.92^{+0.33}_{-0.28}$	10.81
	BFKL (BGR18)	
$2.94^{+0.19}_{-0.26}$	$2.16^{+0.44}_{-0.20}$	10.90
	CGC (IIMS)	
$3.03^{+0.20}_{-0.18}$	$3.12^{+0.48}_{-0.47}$	11.02
	BBMT	
$2.94^{+0.26}_{-0.25}$	$2.16^{+0.33}_{-0.40}$	10.76

Table 1: Best fit values for the extra-galactic neutrino flux derived assuming the different QCD approaches previously mentioned.

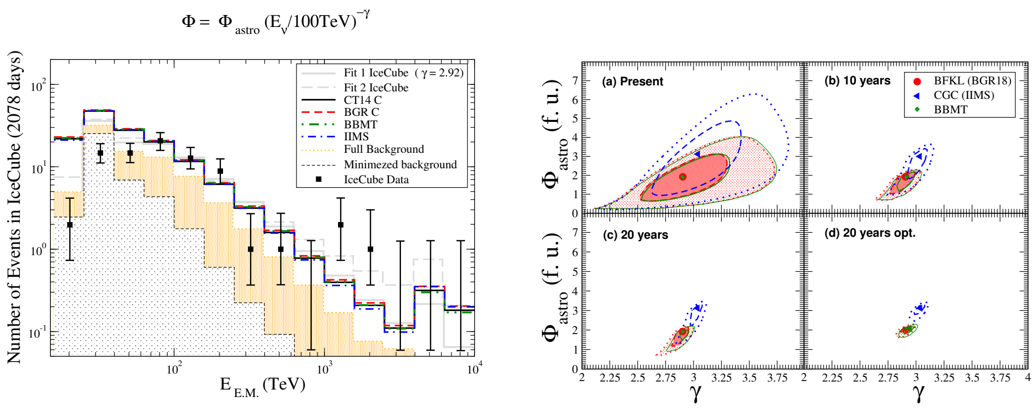

Figure 3: Left Panel : The number of neutrino events is compared with our results for the energy distribution of events for the respective B. F. P. values for the extragalactic neutrino flux shown in Table 1. **Right Panel:** Effects in the allowed region of parameters due to increments in the IceCube exposition as shown in the plots, where we assume the DGLAP (CT14) prediction as the observed number of events.

Also, using a maximum likelihood fit comparing the different predictions with the distribution of observed events at IceCube. Our results indicated that concerning the data description, the modifications in the normalization and energy dependence of the neutrino- nucleon cross-section due to the different dynamical approaches can be compensated by different values for the parameters neutrino flux normalization, Φ_{astro}, and the power index γ, in such a way that all the models can describe de data successfully and cannot be disregarded even at 68% of C. L.. As a consequence of the different QCD models, the resulting B.F. values for the flux parameters can be considerably distinct. For instance, the difference in the predictions for Φ_{astro} from CT14 and IIMS models is of order of 60%. Moreover, we also investigated if the increase in the effective exposure time expected in IceCube - Gen2 will allow us to disentangle the QCD dynamical effects from the description of the astrophysical neutrino flux. For this case, our results pointed out that the increase of the detection exposure is not enough to allow us to fully discriminate between the models studied and, consequently, to constrain the description of the QCD dynamics using only the data for the energy dependence of the number of events observed in neutrino telescopes.

Acknowledgments

This work was partially financed by the Brazilian funding agencies CNPq, FAPERGS and INCT-FNA (process number 464898/2014-5).

References

[1] V. P. Gonçalves, D. R. Gratieri and A. S. C. Quadros. Eur. Phys. J. C 81, 496 (2021).

[2] R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. **5**, 81 (1996)

[3] V. P. Goncalves and D. R. Gratieri, Phys. Rev. D **92**, no.11, 113007 (2015)

[4] Nancy Wandkowsky for the IceCube Collaboration. TeVPA, (2017).

[5] M. G. Aartsen *et al.* [IceCube], [arXiv:1710.01191 [astro-ph.HE]].

[6] M. G. Aartsen *et al.* [IceCube Collaboration], Astrophys. J. **809**, no. 1, 98 (2015)