Correlated neutrino and gamma-ray emission from Active Galactic Nuclei - an estimation

M Doert¹, J K Becker², F Halzen³, A O’Murchadha³, W Rhode¹

¹ Experimentelle Physik V, Technische Universität Dortmund, 44221 Dortmund, Germany,
² Theoretische Physik IV, Ruhr-Universität Bochum, 44780 Bochum, Germany,
³ Department of Physics, Phenomenology Institute, University of Wisconsin-Madison,
Madison, WI, USA

E-mail: marlene.doert@tu-dortmund.de

Abstract. Active galactic nuclei are among the candidates for sources which produce the extragalactic charged cosmic ray flux. However, the composition of their emission regions and the processes leading to their gamma-ray emission are still being investigated. A detection of neutrinos from these sources would prove the presence of hadrons in the emission region and thus establish AGN as sources of the charged cosmic rays. The search for neutrinos from astrophysical sources has been performed for many years now, employing e.g. the AMANDA and now the just-completed IceCube detector. However, the persistent absence of a detection suggests to venture an estimate on the neutrino flux which can be expected from AGN. The method presented here is based on bolometric considerations. We assume that the energy released through the different types of particles is related. On this basis the measured flux of gamma-rays from AGN can be utilized to estimate the possible output in neutrinos. We are aiming at an estimation of the expected neutrino flux, following basic assumptions. The resulting flux estimations show that a detection of single sources still appears to be out of reach. Still, the investigation of a stacked sample of AGN with additional constraints in time and energy seems promising.

1. Introduction

The search for neutrinos which originate from active galactic nuclei (AGN) could finally shed light on some of the most interesting matters of astroparticle physics. AGN constitute a class of extragalactic objects which produce an enormous output in photons, spanning nearly 20 orders of magnitude in energy. This leads to the supposition that the processes, which produce these highly energetic photons, have the ability to also provide an equally energetic output in charged particles. This particle output could substantially contribute to the measured flux in charged cosmic rays, whose origin is currently still under debate. But although AGN are already well-studied in the light of gamma-rays, the processes leading to the different parts of the electromagnetic spectrum are not completely understood. Amongst others, the question if leptons or hadrons are the main origin of the very high energy (VHE) gamma-ray emission is not fully solved. However, a detection of neutrinos from AGN would give more than a clue towards the composition of the emission region, as neutrino emission only takes place within a hadronically dominated acceleration scenario. Following this scenario, the flux of high energy gamma-rays and neutrinos must be closely linked. Thus, gamma-ray measurements, which are by now available for many sources and over a broad energy range, can yield information about
the possible correlated neutrino flux. In this study, we use the example of two AGN, which are classified as blazars.

2. AGN / blazar emission models

The spectral energy distributions (SED) of AGN or blazars in particular are characterized by a double bump structure consisting of one bump at lower energies and one bump at higher energies. For high-frequency peaked blazars (HBLs) the first bump appears at UV to X-ray energies and the second one at gamma-ray energies. The low energy bump is well-established to be originating from synchrotron emission of accelerated electrons. The origin of the second peak, however, is not yet completely pinned down. In a leptonic scenario, this emission is caused by the Inverse Compton effect. Lower energy photons are pushed to higher energies through interaction with fast electrons. There are several different specifications of this model type. Some assume the electron population, which causes the synchrotron emission, to interact with their own synchrotron field (SSC models, see e.g. [1]). Others presume an external field of photons to interact with the electrons, such as photons coming from the accretion disk of the AGN [2]. On all accounts, these models imply a simultaneous or at least correlated change in flux of the high energy bump in case the low energy bump shows a flare. In a hadronic emission scenario, where protons and possibly also heavier nuclei are present in the emission region, the second peak in the SED is thought to be produced mainly by a different process: If protons interact with the present photon field or with other protons, $\Delta^+$ resonances are produced which decay to neutral and charged pions:

$$p \gamma \rightarrow \Delta^+ \rightarrow \left\{ \begin{array}{l} p \pi^0, \ \text{fraction } \frac{2}{3} \\ n \pi^+, \ \text{fraction } \frac{1}{3} \end{array} \right.$$  

(1)

see also [3]. The resulting pions decay further, and therein produce highly energetic gamma-rays:

$$\pi^0 \rightarrow \gamma \gamma.$$  

(2)

While neutral pions produce the gamma-rays which can, according to this scenario, be found in the second peak of an AGN SED, the charged pions decay further to leptons, including the possibly illuminative neutrinos:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \overline{\nu}_\mu \nu_\mu.$$  

(3)

If this hadronic scenario applies to the processes leading to the strong electromagnetic emission seen by AGN, an accompanying neutrino flux should thus be present. This makes the detection of neutrinos from cosmic sources the “smoking gun” for determining the acceleration and emission processes within the source.

3. Search for neutrino sources with AMANDA and IceCube

The search for neutrinos from astrophysical sources is currently in full swing. Because of the neutrinos’ low interaction probability, large detector volumes are needed to search for neutrino signals from outside our solar system. The current state-of-the-art experiments exploit ice or sea water as their detection material. By installing photomultipliers and microphones on a grid within ice or water they utilize large volumes and can thereby largely enhance the detection probability for cosmic neutrinos. At the South Pole the neutrino telescope AMANDA has been replaced by the cubic kilometer scale detector IceCube. The building of IceCube has lately been finished and the detector is in full operation since 2011.

While the detector is in operation, the field of view comprises the whole sky. However, there
Figure 1. The spectral energy distribution for the blazar Mrk 501, ranging from radio to VHE gamma-rays (for details concerning the illustration see [4]). The typical double bump structure is visible: The first bump is superimposed by emission from the host galaxy, but is still clearly identifiable between $10^{19}$ and $10^{20}$ Hz. The second bump is depicted by the gamma-ray spectral points in the range between $10^{22}$ and $10^{28}$ Hz, showing both low state and high state measurements.

are important differences regarding events seen from above or below the horizon [5]. While for upgoing events, which have travelled through the Earth before they reach the detector, the main background consists of atmospheric neutrinos, the downgoing events are dominated by a background of atmospheric muons. Also the accessible energy range in neutrinos is different for events from above the horizon, because highly energetic neutrinos are absorbed by the Earth due to the increase of the neutrino-nucleus cross section with energy.

The directional reconstruction of incoming events is carried out in bins of about $1^\circ \times 1^\circ$ in size. This way, the analysis spreads over thousands of bins. Due to statistical inter-bin fluctuations an occurrence of several accumulations of events with a statistical significance of $3 - 5\sigma$ is expected within an all-sky analysis. This complicates the search for point sources, as a pile-up on the skymap of recorded events does not necessarily point to a real signal. So-called blind searches help to avoid this effect. The recorded events are scrambled w.r.t. their sky coordinates whilst the analysis is ongoing. This disarranging is carried out in a way which conserves the acceptance and the efficiency of the detector. The analyzer needs to define the sky coordinates, the analysis procedure and cuts for the expected signal before the data is finally “unblinded”. If an accumulation of events occurs for the full data sample at the predefined source positions investigated here, the presence of an actual signal is much more significant, as the trial factor for tried positions is much smaller. If a signal from one single location cannot be expected, a stacking analysis offers the possibility to detect a signal from a whole sample of sources of the same type [6],[7]. The detection probability for each source is stacked and a
conclusion can be drawn if the whole sample of investigated sources contains a signal or not. Furthermore spectral analyses can be performed on a stacked data sample, which could reveal the presence of cosmic neutrinos. As the atmospheric neutrino flux roughly follows a spectrum with a power-law index $\alpha_{\text{atm}} = -3.7$ and neutrinos originating from cosmic acceleration processes are expected to show a spectrum with about $\alpha_{\text{source}} = -2$, a flattening of the neutrino energy spectrum towards higher energies would point to a domination of the flux by neutrinos of non-atmospheric origin. Both the single source and the stacking analysis method imply the necessity to have a good guess about which sources might yield a possible neutrino signal. To get a notion of which sources to take into account, estimations on how many neutrinos can be expected from different sources or source types are essential.

4. How many neutrinos can be expected? - An estimation
To obtain an estimation of the possible neutrino flux from gamma-ray emitting sources, which is as unrestricted as possible, the method presented here is independent from elaborate acceleration and emission models. Instead, it is based on bolometric considerations only. The approach shown in this contribution has been discussed before in [8] and has recently been applied to gamma-ray burst studies [9]. As there is new instrumentation at hand which allows a more thorough investigation of both the gamma-ray emission and the neutrino emission, a revisit to this simple method promises to offer new insights also for AGN neutrino studies.

4.1. The method
As depicted above, the emission of highly energetic gamma-rays and neutrinos must be closely linked within the scope of a hadronic scenario, as they are both decay products of pions which are themselves produced with a fixed ratio in hadronic or photo-hadronic interactions. For the estimation given here we assume the interaction of protons with a photon field. This field could consist of synchrotron photons which are emitted by the accelerated particles themselves, in which case a correlation in time between the synchrotron photon flux, the gamma-ray emission and the flux in neutrinos is expected. Another possible source of low energy photons is given by the accretion disk of the AGN. At the moment no specific scenario is chosen, but a constant photon field is assumed.

We neglect, for now, the possibility that proton proton interactions could also cause the emission of high energy neutrinos, referring e.g. to [10] where it is noted that photon-hadronic interactions dominate in the scenario investigated there. A more detailed discussion of the optical depths for both processes is aimed at in a subsequent step of this study.

Making an assumption for the initial spectral shape of the interacting protons and hence for the pions which basically follow the distribution of the protons, the spectra of gamma-rays and the first neutrino can be gained from standard two-body decay kinematics [11],[12],[13]. The second neutrino results from the decay of the muon which emerges from pion decay (see eq. 3). This is described by a three-body decay of a particle resulting from two-body-decay and is determined following [13]. For explicit calculations see also [9]. The resulting spectra are normalized w.r.t. each other, but an absolute normalization of the fluxes is required, which can be provided by gamma-ray measurements. Ground-based gamma-ray telescopes have been measuring the VHE part of the gamma-ray spectrum ($\sim 50 \text{GeV} - 50 \text{TeV}$) for many years now. Since 2008 the satellite experiment Fermi complements these measurements by probing the energy range from 20 MeV to 300 GeV with its Large Area Telescope. These instruments thus provide measurements of more or less the entire second peak in the SED of AGN.

From their production to their measurement by Earth- or space-bound instruments, the gamma-rays undergo several interactions which leave them with an altered spectrum. An effect which has its main influence on distant sources is the interaction with the extragalactic background
light (EBL). Here the gamma particles interact with lower energy photons from former stars and galaxies and annihilate via $e^+e^-$ pair production. However, elaborate models describing the EBL density allow us to correct the measured gamma-ray spectra for this absorption effect in case the distance of the source is known (see e.g. [14]).

An effect which is more complex to reconstruct is the cascading of gamma-rays within the source. After their production in the emission region, the high energy gamma particles have to escape from this region. In general, they are surrounded by the synchrotron photon field. Thus an interaction of high energy and low energy photons is possible and can lead to a shift of the gamma-rays to lower energies. However, as the two bumps in the SED are distinctly separated, the assumption that the cascaded photons remain within the peak is a conservative one. Hence, the energy which has originally been emitted in gamma-rays should still be contained in the high energy bump, which is visible in the data. Thus, a normalization of the pion-induced gamma-ray flux is possible using energy conservation considerations:

$$\int_{E_{\text{min}}}^{E_{\text{max}}} E \frac{dN_{e^+e^- \rightarrow \gamma\gamma}}{dE} dE = \int_{E_{\text{min}}}^{E_{\text{max}}} E \frac{dN_{\text{meas}}}{dE} dE.$$  \hspace{1cm} \text{(4)}$$

### 4.2. Application to gamma-ray data

In this paper the estimation of a possible neutrino flux is carried out for two example sources: the blazars Markarian (Mrk) 501 and 1ES 1959+650, which both belong to the class of HBLs. Although it has been noted ([15]) that this type of sources might be disfavored for the emission of high energy cosmic neutrinos, the availability of recent data which cover the entire SED and especially the high energy bump recommends these sources as objects for a first application of the method presented here. The available data comprise Fermi spectral points gained with the LAT and VHE spectra from the ground-based telescopes MAGIC and VERITAS, respectively. For Mrk 501 separate data for a low state [16],[17] and a high state [4] measurement have been used here. For 1ES 1959+650 no flux variations have been observed recently, thus measurements of a constant flux level have been used [16],[18]. The low state spectra have been corrected for EBL absorption, using the model from Kneiske and Dole [14]. The Mrk 501 high state data have been provided as an already absorption-corrected spectrum. Here the model by Franceschini et al. has been applied [19], while it is shown that for Mrk 501, with a redshift of $z = 0.034$, a good agreement between the different models can be seen [4].

Polynomial functions of fourth and second order, respectively, have been fitted to the data points in double-logarithmic representation.

The integration limits for the energy normalization are chosen as $E_{\text{min}} = 10^{-5}$ TeV and $E_{\text{max}} = 10^8$ TeV. The lower limit is given by the left flank of the high energy bump. The upper limit is suggested by the expected cut-off in the spectrum of protons coming from cosmic accelerators at an energy of $10^9$ TeV. By using these limits we extrapolate the fit suggested by the measurement, but as the main contribution is given by the well-measured part of the spectrum, this appears to be feasible.

The collected gamma-ray data and the corresponding fits used for the integration are shown on the left side of Fig. 2.

### 4.3. Results

The resulting neutrino spectra can be seen in Fig. 2 on the right. Plotted are estimations for three different initial pion spectra for the two sources (top and bottom). A comparison of the low and high state flux of Mrk 501 is shown in the central panel. IceCube 40-string configuration upper limits of the Feldman-Cousins 90% confidence intervals for an $E^{-2.8}$ flux in a livetime of 375.5 days are drawn according to [20]. The atmospheric neutrino flux is calculated according to [21].
The obtained neutrino signals span an energy range from the pion production threshold at tens to hundreds of MeV up to $10^8$ TeV, where they are cut off by the suppression of highly energetic protons. The energy range accessible to IceCube, which reaches from 100 GeV to $10^7$ TeV, covers a large fraction of the expected neutrino signal. Using a standard effective area of the IceCube 80-string detector, the number of neutrino events which are expected to be seen by the IceCube detector can be derived for the different flux predictions. In table 1 the expected number of events per year are shown for an initial $E^{-2.0}$ spectrum, together with the expected number of events from the atmospheric background. It has to be noted that giving the number of neutrino events corresponding to a source in high-state flux over a full year is not true to reality, but chosen here for comparability.

### Table 1. Predicted event numbers for the calculated neutrino flux from the examined blazars seen within one year with the IceCube 80-string detector.

| Source           | # events [year$^{-1}$] | # signal events | √# bg events |
|------------------|------------------------|-----------------|--------------|
| Mrk 501 low state| 0.878                  | 0.192           |              |
| Mrk 501 high state| 6.232               | 1.365           |              |
| 1ES 1959+650     | 0.778                  | 0.170           |              |
| Atmosph. background| 20.84               | -               |              |

5. Conclusions and Outlook

From the numbers of neutrinos which are expected to be seen for AGN ground states, it is obvious that single sources are not close to being detectable by a standard point source analysis. With a complete IceCube detector, the performance will be doubled due to the doubled detection area compared to IC-40. Also, significance will improve roughly with the square root of time. Thus, the predicted flux may be detectable with a full IceCube detector after a few years of data taking. Still, the suppression of the atmospheric background is the key issue. In an all-data analysis, single sources do not seem to be seizable. Instead, the analysis of IceCube data which are correlated in time to gamma-ray high states of the sources could be more profitable, as a reduced time window reduces the atmospheric background substantially and the flux of expected neutrinos is higher in general. For studies on the time correlation of the optical, the gamma-ray and the neutrino signal see e.g. [22]. An additional optimization of the considered energy range can improve the signal-to-background-ratio further. Ultimately a stacking analysis of several promising gamma-ray sources - possibly during their high state periods - could yield a sensitivity which is high enough for a detection of neutrinos originating from these sources. The estimations performed here will be refined further by modeling the interactions of protons with protons and of protons with photon fields in more detail, following [23] and [24], in order to gain a more precise pion spectrum. Furthermore the cascading of VHE gamma-rays within the source will be looked into. Ultimately, the study will be extended to a larger catalog of sources. Additional to the HBLs considered here, the possibly more favorable LBL sources and the class of Flat Spectrum Radio Quasars (FSRQs) will be investigated with the method presented above. A forthcoming paper will incorporate the aspects mentioned above and aim at a prediction for a stacked neutrino detection from AGN.
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References
[1] Tavecchio, F. et al. 1998 *ApJ* 509 608
[2] Dermer, C. D. and Schlickeiser, R. 1993 *ApJ* 416 458
[3] Becker, J. K. 2008 *Phys. Rept.* 458 173-246
[4] Abdo, A. A. et al. 2011 *ApJ* 727 129A
[5] Abbasi, R. et al. 2009 *Phys. Rev. Letters* 103 Issue 22, id. 221102
[6] Achterberg, A. et al. 2006 *ApP* 26 Issue 4-5 282-300
[7] Becker, J. K. et al. 2007 *ApP* 28 98-118
[8] Halzen, F. and Zas, E. 1997 *ApJ* 488 669
[9] Becker, J. K. et al. 2010 *ApJ* 721 1891-1899
[10] Becker, J. K. and Biermann, P. L. 2009 *ApP* 31 Issue 2 138-148
[11] Stecker, F. 1971 *Mono Book Co.*
[12] Dermer, C. 1986, *ApJ* 307 47
[13] Gaisser, T. 1990 *Cambridge University Press*
[14] Kneiske, T. M. and Dole, H. 2010 *A&A* 515 id.A19
[15] Mücke, A. et al., 2002 *ApP* 18 Issue 6 503-613
[16] Abdo, A. A. et al., 2010 *ApJ* 716 30A
[17] Aleksić, J. et al., 2010 *A&A* 519 A32
[18] Tagliaferri, G. et al. 2008 *ApJ* 679 1029A
[19] Franceschini, A., Rodighiero, G. and Vaccari, M. 2008 *A&A* 487 Issue 3 837-852
[20] Abbasi, R. et al. 2011 *ApJ* 732 18
[21] Honda, M. et al. 2007 *Phys. Rev. D* 75 043006
[22] Eichmann, B. 2011 *JPCS* in prep.
[23] Kelner, S. R. and Aharonian, F. A. and Bugayov, V. V. 2006 *Phys. Rev. D* 74 Issue 3, id. 034018
[24] Kelner, S. R. and Aharonian, F. A. 2008 *Phys. Rev. D* 78 Issue 3, id. 034013
Figure 2.
Left side: Measured gamma-ray spectral points from Fermi and ground-based telescopes and the according fits to the high energy peak: Mrk 501 in low state (top panel) and high state (central panel) and 1ES 1959+650 (bottom panel). The data points for Mrk 501 have been obtained here: [16], [17] (low state); [4] (high state). For the spectral points of 1ES 1959+650 see [16] and [18].

Right side: Predicted neutrino spectra for the sources Mrk 501 and 1ES 1959+650. Top and bottom panel: Estimations for three different initial $\pi$-spectra for Mrk 501 in low state and 1ES 1959+650, respectively. Central panel: Estimations for $\alpha_\pi = -2.0$ spectrum of Mrk 501 in low and high state. IC 40 limits are drawn according to [20]. The atmospheric neutrino flux is determined according to [21].