Oct. 21, 2014

Annex to the MoU on

Search for common sources of UHECRs detected by the Pierre Auger Observatory and the Telescope Array and neutrinos detected by the IceCube Observatory

The scope of this annex is to overview the data samples and the analysis methods that will be used in a joint paper on searches for common sources of ultra-high energy cosmic rays (UHECRs) and neutrinos. The paper will be published according to the regulations established by the MoU between the three experiments.

Three different analysis methods will be applied to the data samples in order to search for possible correlations between neutrinos and UHECRs that can indicate the **existence of common sources**. The analyses will be approved internally by experiments and by the dedicated UHECR-neutrino working group prior to publication.

Data Samples

The collaborations will share information on the following data samples:

IceCube samples:

- **HESE-3yr cascades and HESE-3yr tracks:** the high energy starting events (HESE) of 3 years of IceCube data are described in *`Observation of High-Energy Astrophysical Neutrinos in three years of IceCube data'*, arXiv:1405.5303. The HESE-3yr sample contains events selected by two criteria: a very high energy cut, and a veto that prevents any through-going track in the detector. The HESE sample is therefore a set of very high-energy events (tracks and cascades). Cascades have considerably lower angular accuracy compared to HESE tracks and the point-source IC40+IC59+IC79+IC86I-4yr sample. The amount of events in this sample is above the atmospheric background expectations indicating that it contains an astrophysical neutrino component. It is decided to use **3 tracks** (5: Dr. Strangepork, 13: Mr. Snuffleupagus, 23: Gonzo the Great) and **28 cascades** from this sample.
- **High-energy muon-neutrino induced tracks:** this events are from C. Weaver's analysis for a diffuse flux of upgoing muons. The **9 tracks** are selected from this sample since they are in the highest energy tail where the fit indicates departure from the atmospheric component. The paper is in preparation and a draft exists: *Evidence for Astrophysical Muon Neutrinos from the Northern Sky.*
- **IC40+IC59+IC79+IC86I-4yr sample:** the point/extended source sample of about 400'000 IceCube events is described in '*Searches for Extended and Point-like Neutrino Sources with Four Years of IceCube Data*' (approved for publication in ApJ. and arXiv:1406.6757). This sample is the result of a selection of only good quality reconstructed muon neutrino events with small angular uncertainty ($< 1^{o}$). Events are mostly high-energy single atmospheric neutrinos from the northern sky and high-energy atmospheric muons in the southern sky.

The Pierre Auger Observatory sample: 231 events with $E \geq 52$ EeV, collected between 1 January 2004 and 31 March 2014. The sample is described in detail in a forthcoming publication whose draft has been submitted to the Auger Publication Committee for internal review.

The above-described analyses are trained on the 69 events sample published in *'Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter'*, Astrop. Phys. 34 (2010) 314.

The Telescope Array sample: The sample of 72 events published in '*Indications of Intermediate-Scale Anisotropy of Cosmic Rays with Energy Greater Than 57 EeV in the Northern Sky Measured with the Surface Detector of the Telescope Array Experiment',* Astrop. J 790 (2014) L21 (**arXiv:1404.5890**) is updated to a total number of 87 events adding statistics to May 2014.

The following pieces of information per event are exchanged:

- Equatorial coordinates;
- Energy proxy.

Moreover, each experiment will provide the effective area and the exposure relative to the exchanged event sample.

Analyses

1) **Cross-correlation method**

Main author: Geraldina Golup.

Data samples. UHECRs samples. Neutrinos: HESE-3yr cascades + 3 HESE-3yr tracks and 9 high-energy muon-neutrino induced tracks.

Method. The cross-correlation method computes the number of UHECR-neutrino pairs as a function of the angular distance and it searches for the maximum departure from isotropic expectations. Tracks and cascades are analyzed separately given the difference in the angular uncertainty of their arrival direction.

Discovery potential. It is calculated as a function of the number of injected UHECRs. The neutrino arrival directions are kept fixed. UHECRs correlated with these positions are simulated and UHECRs with isotropic angular directions weighted for the Auger and TA event statistics are also included up to the total real statistics.

Result. The final result will **be two p-values**, one for tracks and one for cascades, to indicate the probability that an isotropic flux of UHECRs would produce a minimum correlation probability as the one observed.

2) **Stacking method with IceCube high-energy samples**

Main author: Asen Christov.

Data samples. UHECRs samples. Neutrinos: HESE-3yr cascades + 3 HESE-3yr tracks and 9 high-energy muon-neutrino induced tracks.

Method. This analysis uses a stacking unbinned likelihood method. The sources are assumed to be the neutrino directions. The magnetic deflection of UHECRs is taken to be inversely proportional to the energy for three different test values, namely 1, 3, and 6 degrees at 100 EeV

Discovery potential. For the purpose of calculating discovery potentials and sensitivities, the background events are assumed to be isotropic UHECRs injected considering the Pierre Auger and TA exposure region for extracting arrival directions and following the real event statistics. Signal events are injected from point-sources compatible with the neutrino directions. The average ratio of injected signal events for Auger and TA is defined by the ratio of the UHECRs

data samples. The total number of signal events and background events is equal to the number of events in the corresponding UHECRs data samples.

Result. The results will be **two p-values (for tracks and cascades separately) indicating the probability that an isotropic cosmic-ray flux can generate a fluctuation as large as the one observed in data**.

3) **Stacking method using the point-source sample.**
Main author: Mohammed Rameez
Data samples. UHECRs samples. Neutrinos: IC40+IC59+IC79+IC86I-4 yr.
Method. This analysis uses a stacking unbinned likelihood method to quantify the significance of an excess of events in the direction of the UHECRs above the atmospheric neutrino (northern hemisphere) and muon (southern hemisphere) background. The method and data sample is described in 'Searches for Extended and Point-like Neutrino Sources with Four Years of IceCube Data', arxiv:1406.6757.
The neutrino sources are the UHECR directions convolved with the directional uncertainty due to Galactic and inter-galactic magnetic field. Since the magnitude of these deflections is not well known, three median values (**D** = 1°, 3°, 6° at 100 EeV/E_{UHECR}) are scanned. Since stacking 318 sources, corresponding to the full set of UHECRs, would cover the entire sky approaching the domain of a diffuse analysis, only the highest energy UHECR events are retained. This number of events is chosen minimizing the discovery potential (flux per source) for each value of **D**.
Discovery potential. It is estimated injecting simulated neutrino events from the stacked sources defined above.
Result. The result will be **six p-values (for the Northern and Southern hemispheres and for each of the deflection hypotheses) indicating the probability that a flux of atmospheric neutrinos (muons) in the northern (southern) sky can generate a fluctuation as large as the one observed in data**.