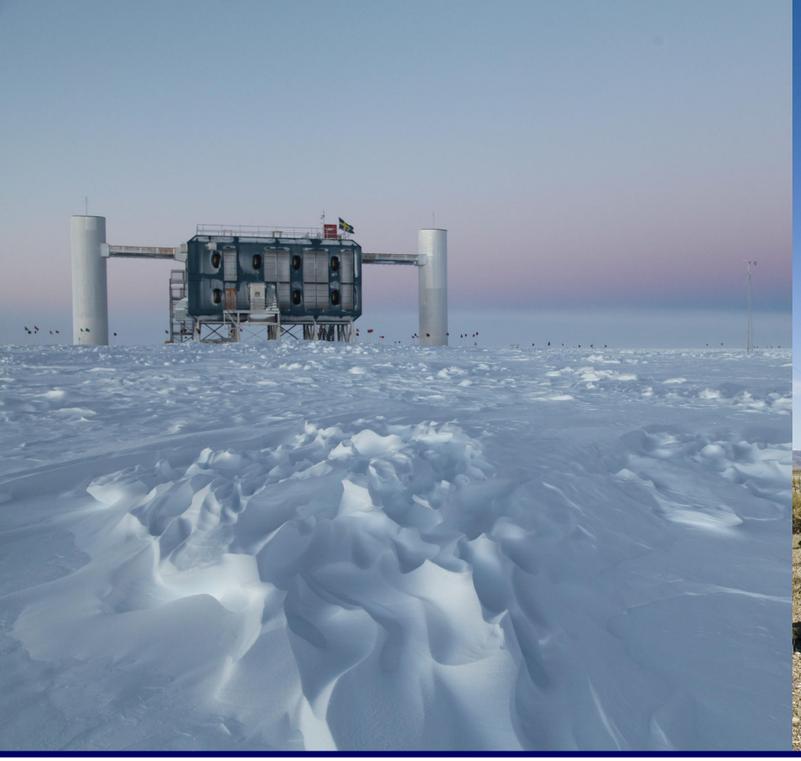


Search for a correlation between the UHECRs measured by the Pierre Auger Observatory and the Telescope Array and the neutrino candidate events from IceCube

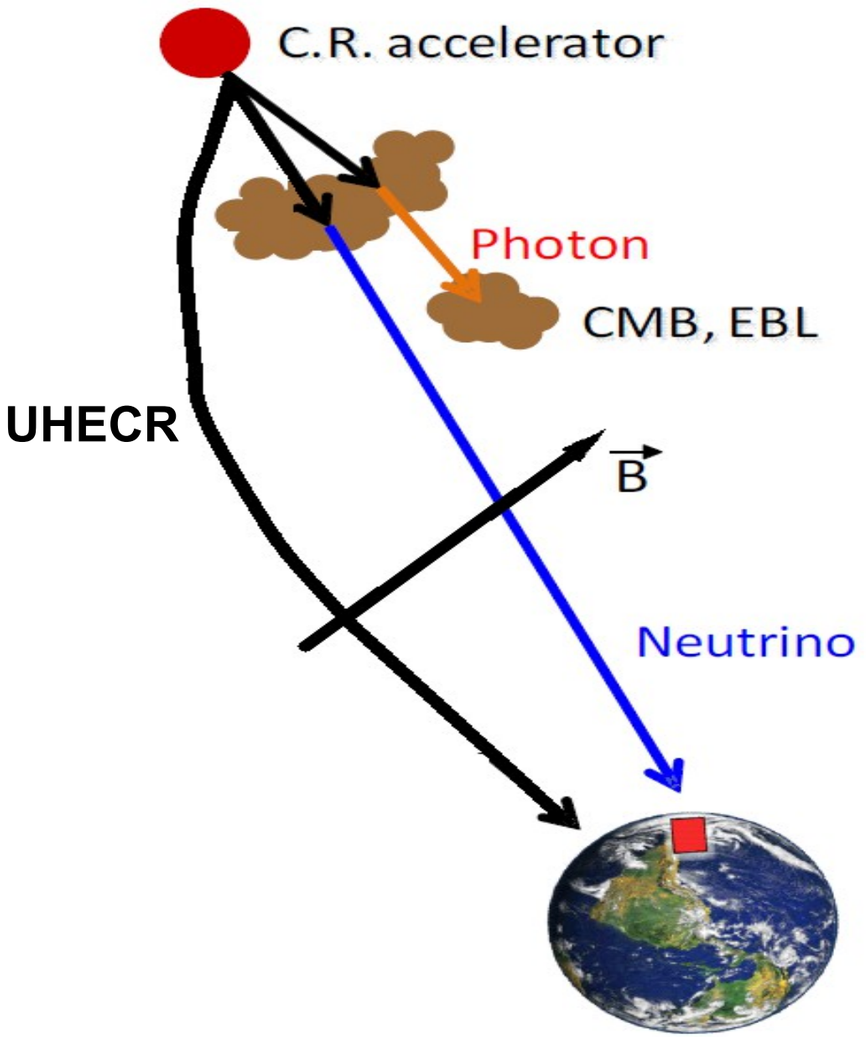
A. Christov, G. Golup, T. Montaruli, M. Rameez for the IceCube Collaboration; J. Aublin, L. Caccianiga, P.L. Ghia, E. Roulet, M. Unger for the Pierre Auger Collaboration; and H. Sagawa, P. Tinyakov for the Telescope Array Collaboration

ICECUBE

PIERRE AUGER OBSERVATORY

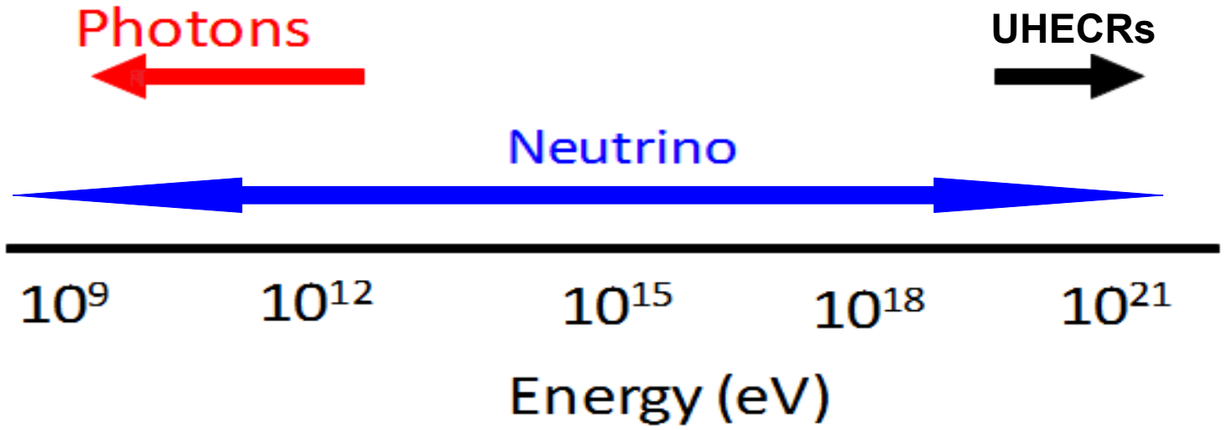
TELESCOPE ARRAY PROJECT

Multi-messenger astronomy

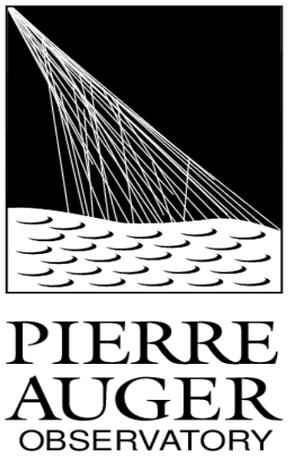


$$p + \gamma_{\text{or p...}} \rightarrow \pi^0 + p$$
$$\gamma + \gamma + p$$
$$\rightarrow \pi^+ + n$$
$$\rightarrow \mu^+ + \nu_\mu + n$$
$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n$$

Neutrinos

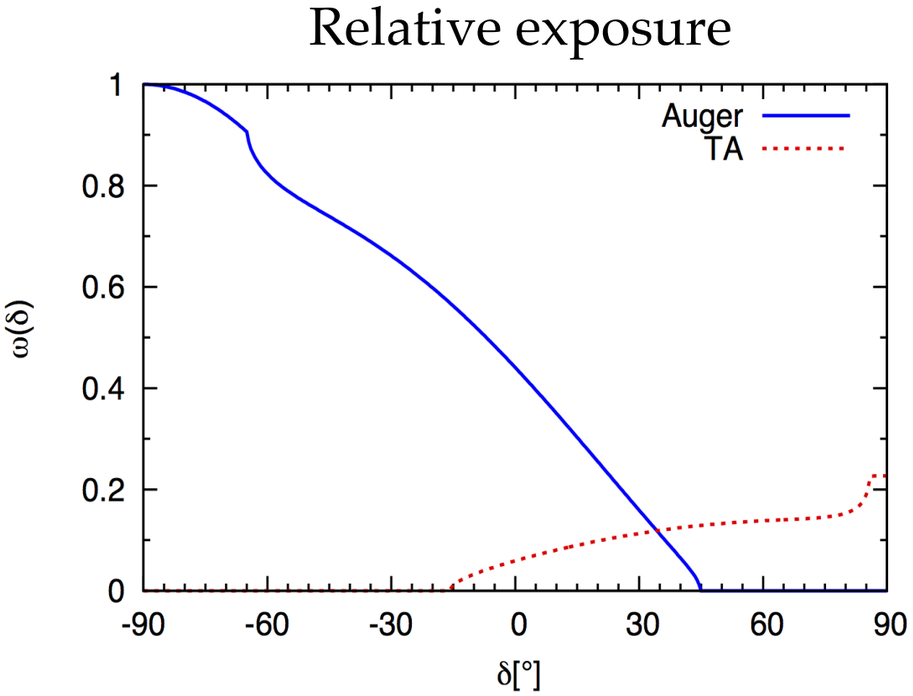


UHECR data set



- Period: 01/01/2004 to 31/03/2014
- 231 events above 52 EeV
- Maximum zenith angle = 80°
- Angular resolution: 0.9°

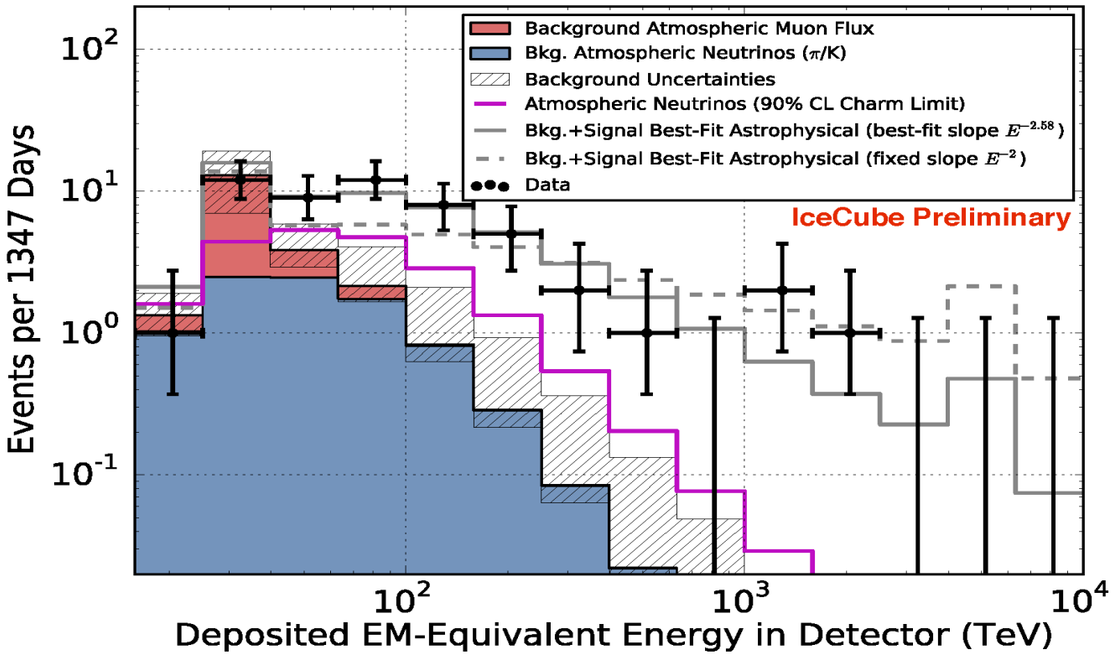
- Period: 11/05/2008 to 01/05/2014
- 87 events above 57 EeV
- Maximum zenith angle= 55°
- Angular resolution: 1.5°



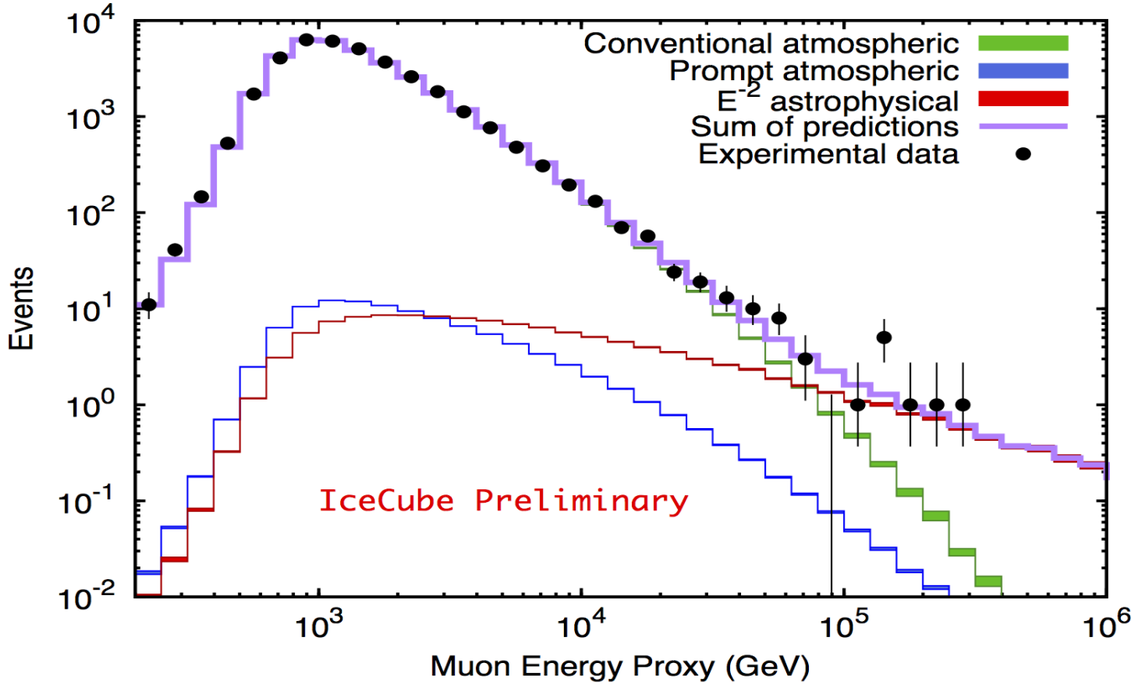
The Pierre Auger Collaboration, Astrophys. J. 804 (2015) 1 and PoS(ICRC2015)310.
The Telescope Array Collaboration, Astrophys. J. Lett. 790 (2014) L21.

Neutrino data sets

- High-energy cascades: 4-year HESE (High Energy Starting Events) cascades, 39 events (IC79+IC86-I+IC86-II+IC86-III) (see ICRC contribution # 1081)
- High-energy tracks: 7 of the HESE tracks plus 9 events with muon energy proxy > 100 TeV from diffuse up-going analysis (IC79+IC86-I)



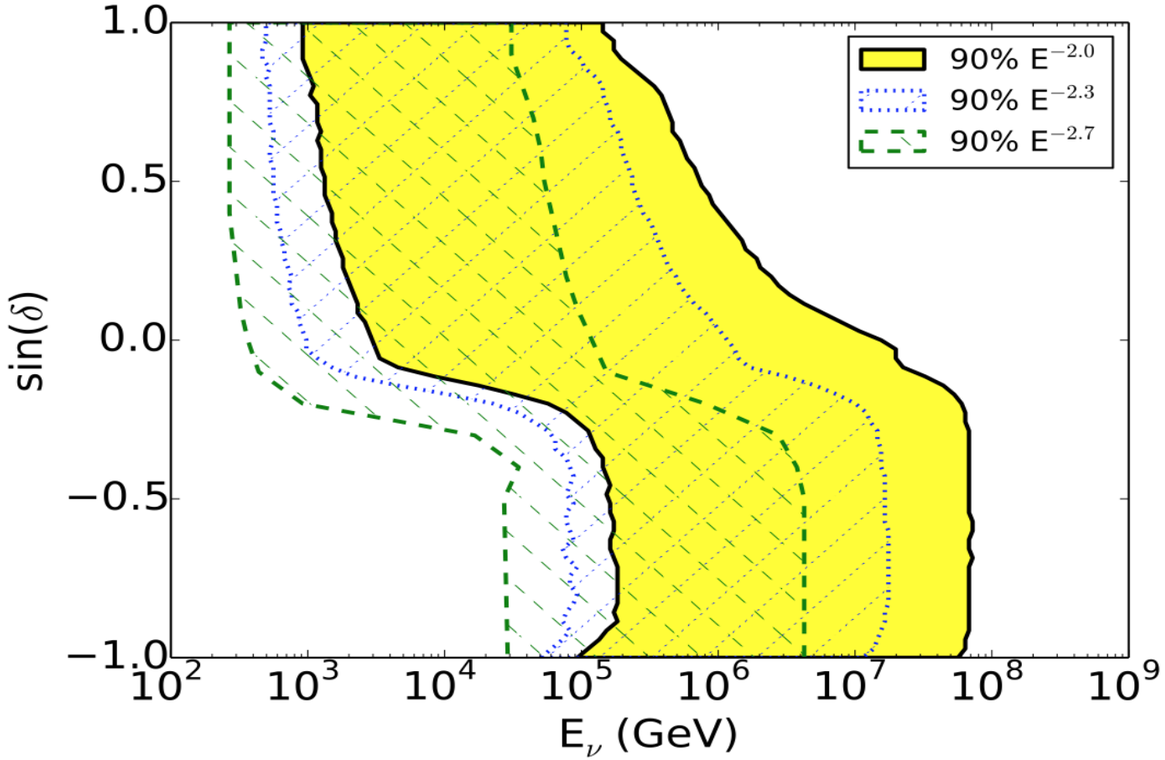
The IceCube Collaboration, PoS (ICRC2015) 1081.



The IceCube Coll., accepted in Phys. Rev. Lett, arXiv:1507.04005.

Neutrino data sets

• Point source sample: 4 yr (IC40+IC59+IC79+IC86-I) sample of well reconstructed, through-going muons that could be associated with charged-current muon neutrino interactions (394,000 events)

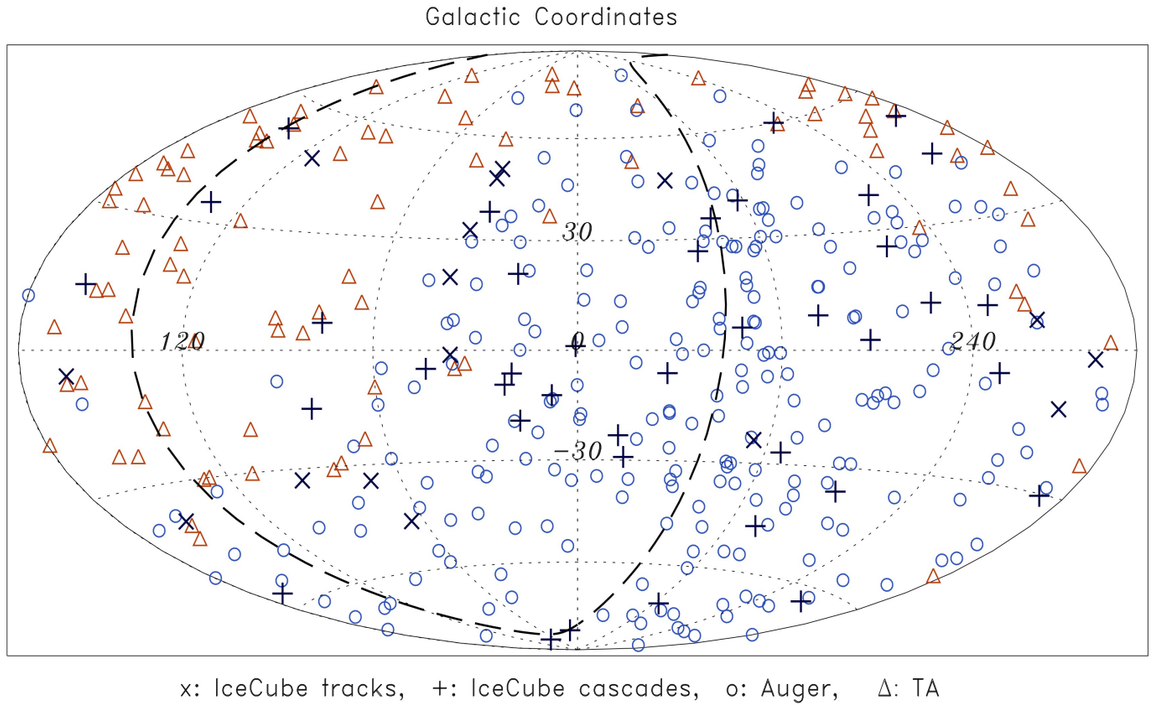


The IceCube Collaboration, Astrophys. J. 796 (2014) 109.

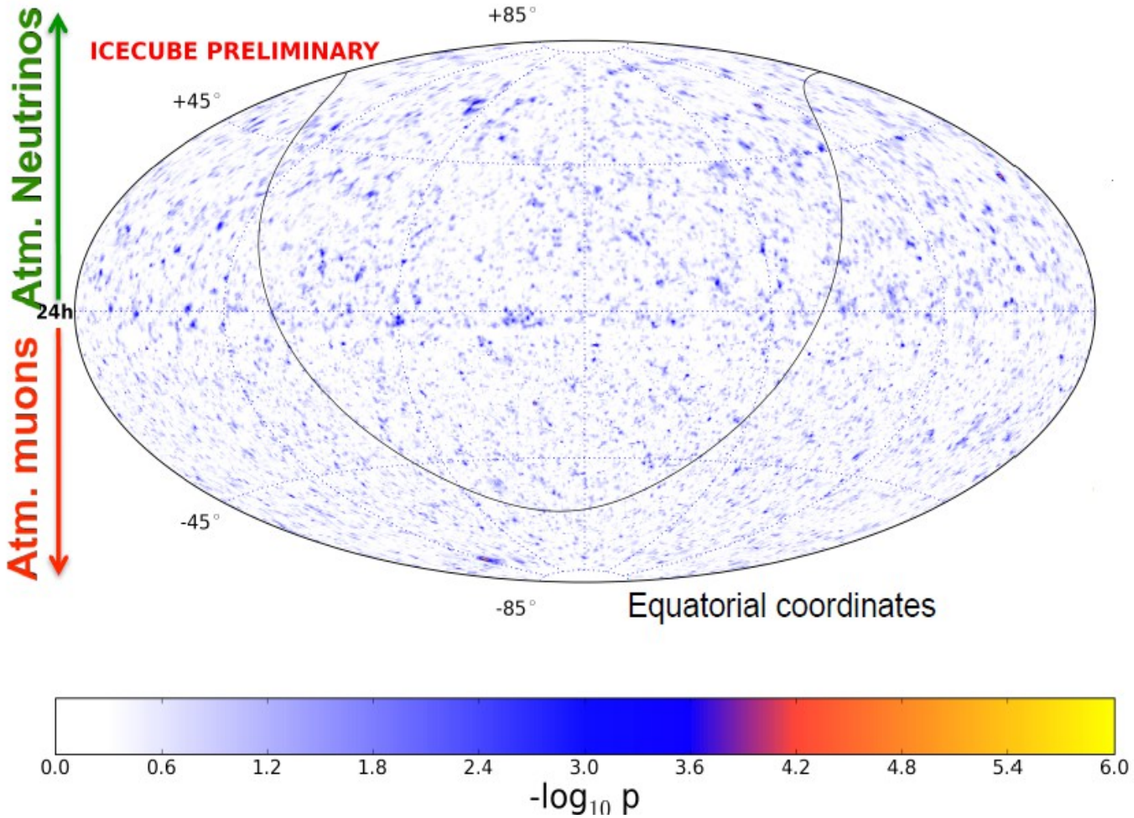
Analyses performed

1) Cross-correlation method using the high-energy cascades and the high-energy tracks
2) Likelihood method stacking the high-energy cascades and the high-energy tracks
3) Likelihood method stacking UHECRs and using the 4-year IceCube point source sample

Tracks and cascades will be analyzed separately.



x: IceCube tracks, +: IceCube cascades, o: Auger, Δ: TA

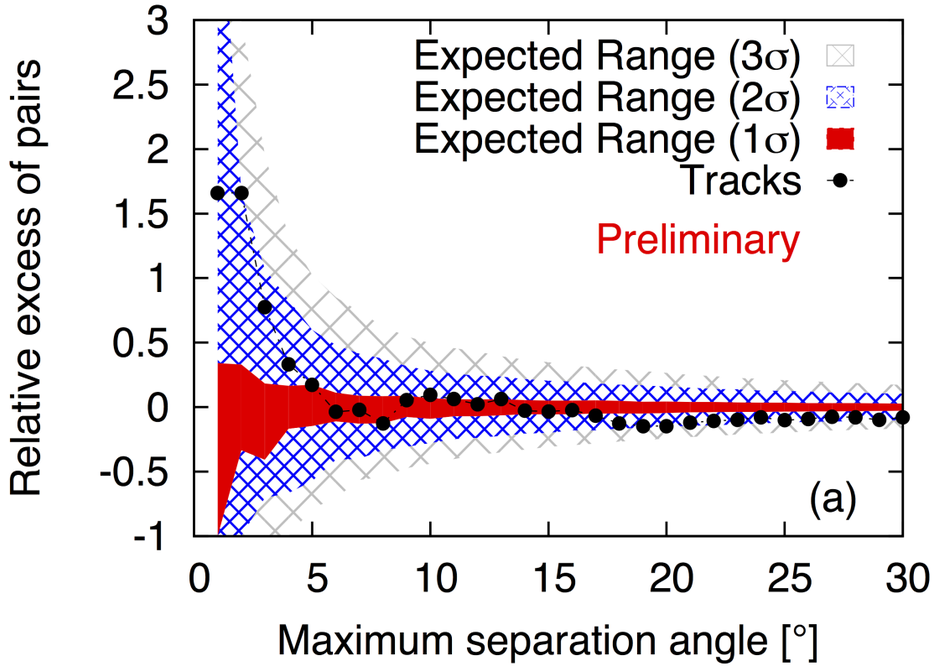


The IceCube Collaboration, Astrophys. J. 796 (2014) 109.

Cross-correlation analysis

Compute the number of UHECR-neutrino pairs as a function of the angular separation in the data and we compare it with expectations from an isotropic distribution of UHECRs.

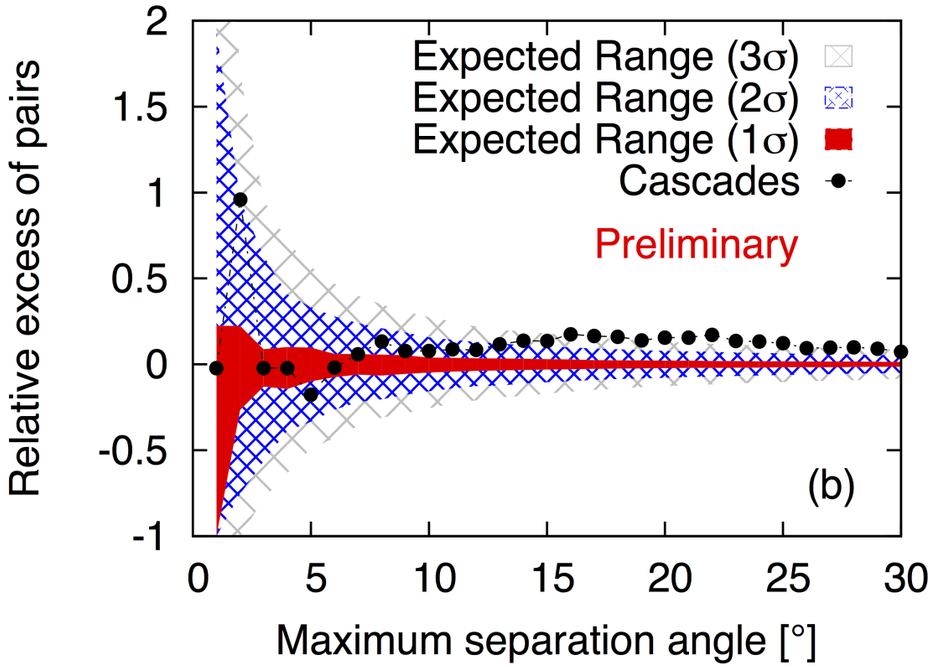
Relative excess of pairs: $[n_p(\alpha)/\langle n_p^{iso}(\alpha)\rangle] - 1$



Tracks: minimum at 2^0, n_p=4, $\langle n_p^{iso}\rangle$= 1.5,

post-trial p-value=0.34

with respect to an isotropic flux of CRs.



Cascades: min at 22^0, n_p=575, $\langle n_p^{iso}\rangle$= 490.3,

post-trial p-value=5 x 10^{-4}

with respect to an isotropic flux of CRs.

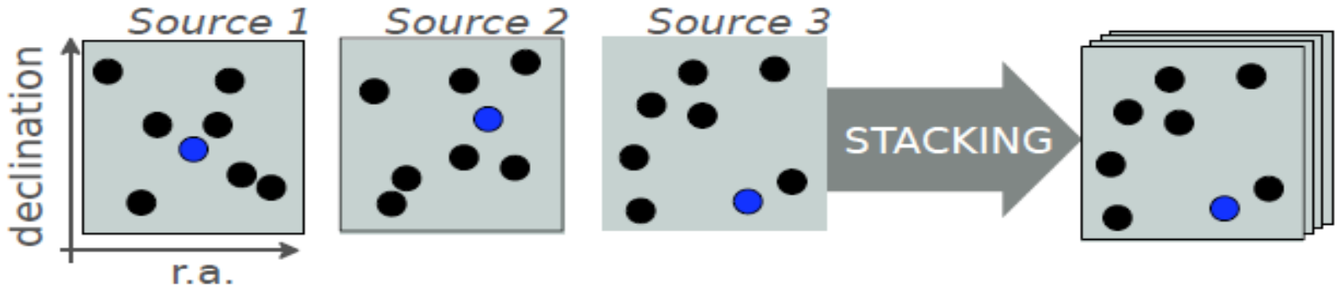
Cross-correlation analysis

The excess of pairs in the case of the cascades is due to the fact that there are cascades in regions with large densities of UHECRs, i.e. near the Super-Galactic plane and at the TA “hot spot”.

Doing a posteriori cross-correlation test, separating the data of Auger and TA, it is observed that both results have a minimum at 22^0, with post-trial p-values of 9.3×10^{-4} for TA and 4.1×10^{-2} for Auger. Hence, both results reinforce each other when considering the entire UHECR data set.

We also evaluated the significance under the hypothesis of an isotropic distribution of neutrinos (note that this alternative hypothesis preserves the degree of anisotropy in the arrival directions of CRs that is suggested by the TA hot spot or the excess around Cen A). The obtained value for the analysis with the cascades is: post-trial p-value= 8.5×10^{-3}, which is potentially interesting and will be monitored in the future.

Likelihood method stacking the high-energy cascades and high-energy tracks



The neutrino positions will be the "stacked sources", and we will compare the result to an isotropic distribution of CRs.

Unbinned Maximum Likelihood: one parameter: number of signal events n_{sCR}

$$\ln \mathcal{L} = \sum_{i=1}^{N_{\mathrm{Auger}}} \ln \left(\frac{n_{s_{CR}}}{N_{\mathrm{tot}}} S_i^{\mathrm{Auger}} + \frac{N_{\mathrm{tot}} - n_{s_{CR}}}{N_{\mathrm{tot}}} B_i^{\mathrm{Auger}} \right) + \sum_{i=1}^{N_{\mathrm{TA}}} \ln \left(\frac{n_{s_{CR}}}{N_{\mathrm{tot}}} S_i^{\mathrm{TA}} + \frac{N_{\mathrm{tot}} - n_{s_{CR}}}{N_{\mathrm{tot}}} B_i^{\mathrm{TA}} \right)$$

Background PDF: geometric exposure

Signal PDF: the magnetic deflection plus the neutrino spatial PDFs have to be accounted for:

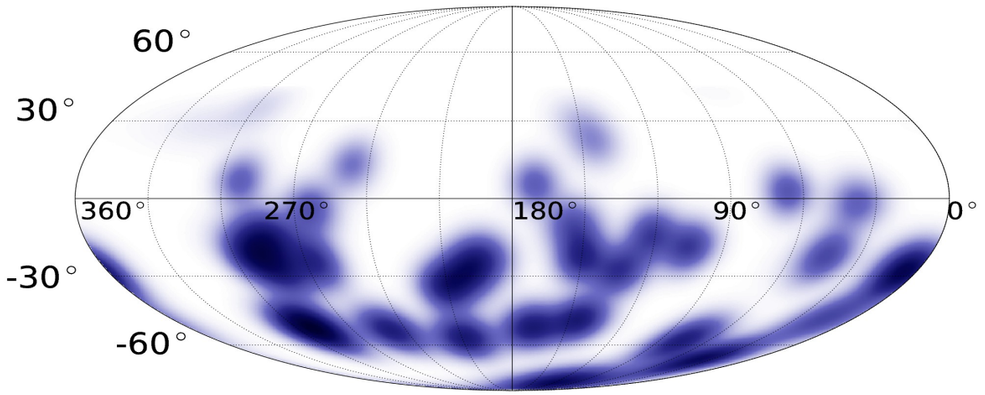
$$N_{\mathrm{tot}} = N_{\mathrm{Auger}} + N_{\mathrm{TA}}$$

$$S_i = \sum_{j=1}^{N_\nu} \omega(\delta_i) S_i^j(ra_i, \delta_i, \sigma_{MD}(E_i))$$

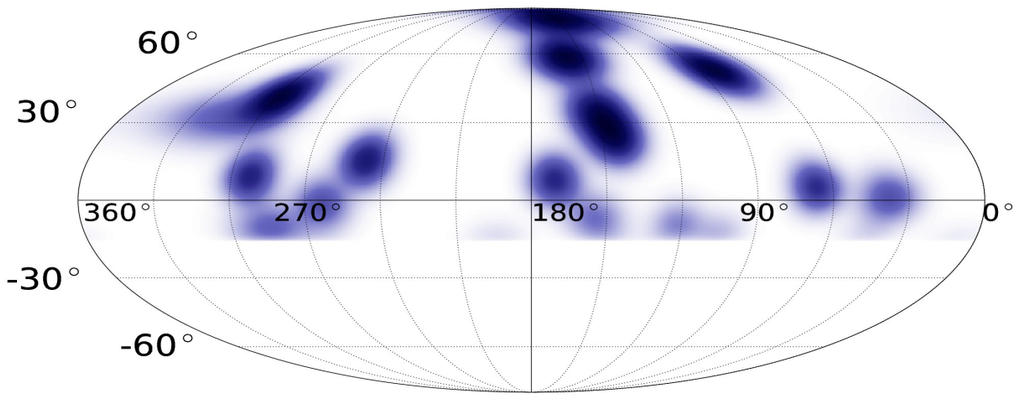
A PDF for a single CR and a single neutrino: takes into account the neutrino map and the magnetic deflection

Neutrino maps

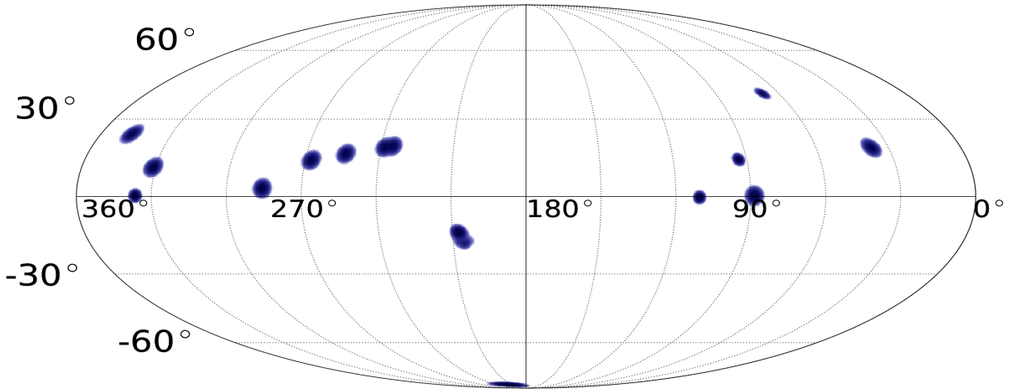
Auger exposure, high-energy cascades



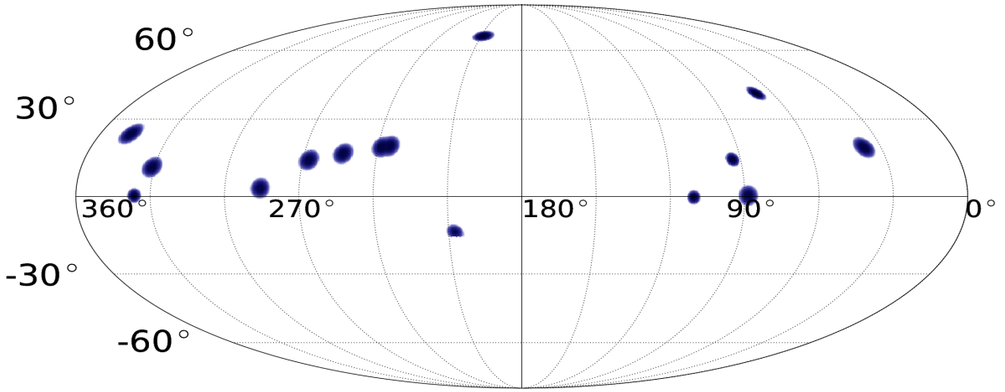
TA exposure, high-energy cascades



Auger exposure, high-energy tracks



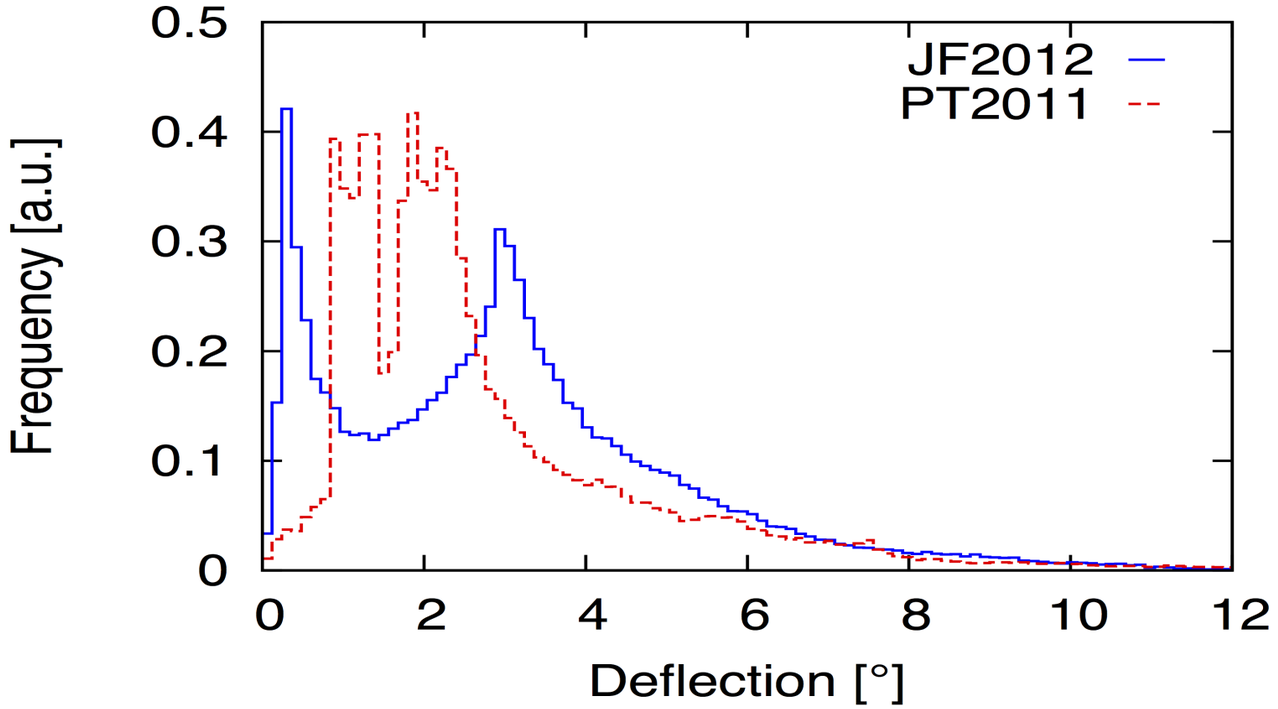
TA exposure, high-energy tracks



Signal PDFs taking into account the exposure of the CR observatories, in equatorial coordinates.

Magnetic deflections

Using the arrival directions of the UHECR data from Auger and TA and assuming E=100 EeV, Z=1, the deflections due to the regular component of the GMF in 2 different models are:



The median is for both models ~2.7° 100 EeV/E_{CR}. This does not include the turbulent component of the GMF.

PT2011: Pshirkov, Tinyakov, Kronberg, Newton-McGee, Astrophys. J. 738 (2011) 192.
JF 2012: Jansson, Farrar, Astrophys. J. 757 (2012) 14.

We will assume the following values for the deflection:

$$\sigma_{MD} = D \times 100\ \text{EeV}/E_{CR},\ D=3°,6°,(9°).$$

These may also account for cosmic rays heavier than protons or stronger magnetic fields.

Results of the Likelihood method stacking the high-energy cascades and high-energy tracks

D	Tracks		Cascades	
	$n_{s_{CR}}$	pre-trial p-value	$n_{s_{CR}}$	pre-trial p-value
3°	4.3	0.22	53.7	2.1×10^{-3}
6°	0.5	0.48	85.7	2.7×10^{-4}
9°	-	under-fluctuation	106.1	3.8×10^{-4}

Cascades, D=6°:

post-trial p-value = 8 x 10^{-4}

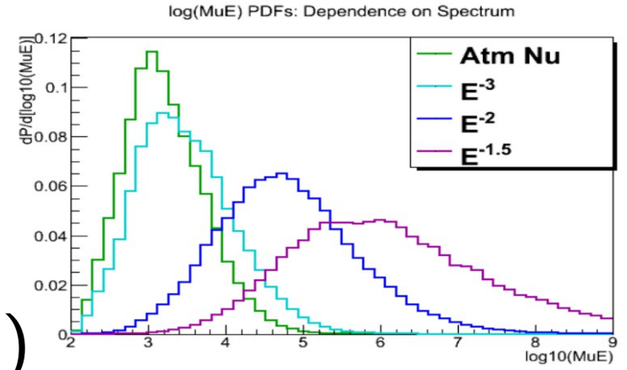
with respect to an isotropic flux of CRs.

Likelihood method stacking the UHECRs using the neutrino PS sample

The UHECR positions will be the “stacked sources”. Maximize: γ (the neutrino spectral index) and n_{sv} (number of signal events)

$$\mathcal{L}(n_{s_\nu}, \gamma) = \prod_{i=1}^{N_\nu} \left(\frac{n_{s_\nu}}{N_\nu} S_i(\gamma, E_i) + \left(1 - \frac{n_{s_\nu}}{N_\nu}\right) B_i \right)$$

$$B_i = B(\theta_i) P_{atm}(E_i)$$



Energy PDF

$$S_i = \sum_{j=1}^{N_{CR}} R_{\rm IC}(\delta_j, \gamma) S_i^j \Big/ \sum_{j=1}^{N_{CR}} R_{\rm IC}(\delta_j, \gamma)$$

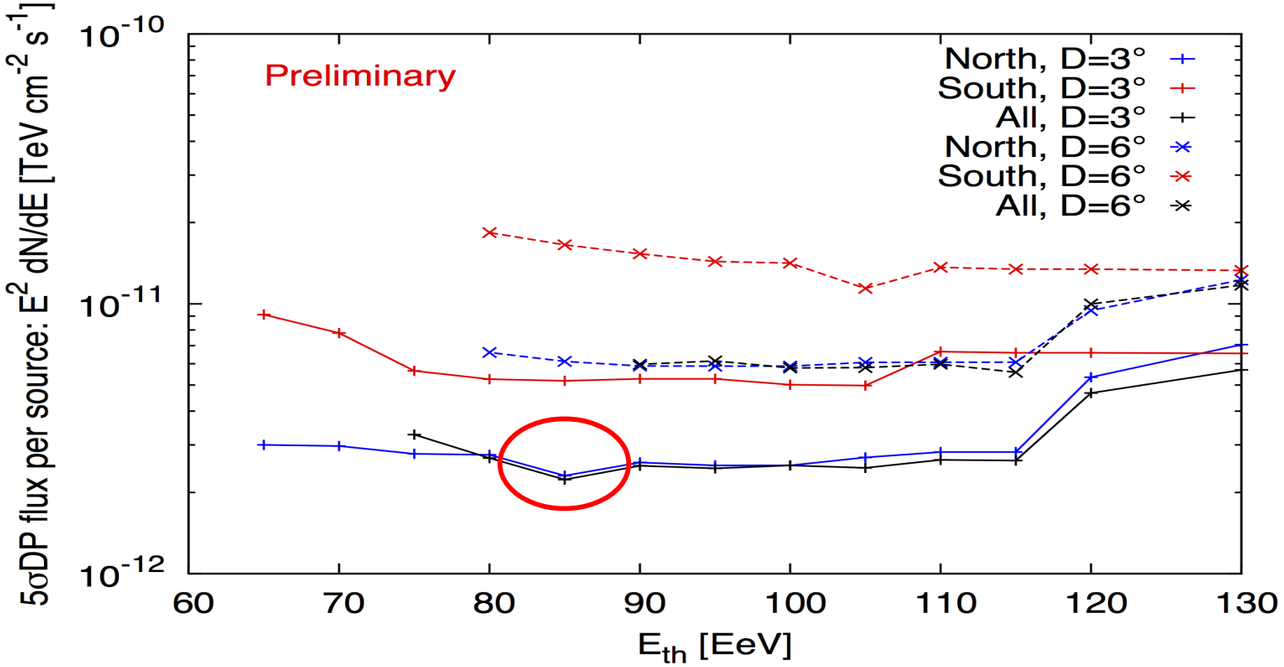
IceCube acceptance

$$S_i^j = \frac{1}{2\pi(\sigma_i^2 + \sigma_j^2)} e^{-r_{ij}^2/2(\sigma_i^2+\sigma_j^2)} P(E_i|\gamma)$$

$$\sigma_j = \sqrt{\sigma_{\rm MD}^2 + \sigma_{\rm exp}^2}$$

The 318 UHECRs smeared on few degrees would cover large fraction of the sky => to enhance sensitivity we select only those above a certain energy threshold (downscaling TA energies by 13%)

Likelihood method stacking the UHECRs using the neutrino PS sample



The discovery potential shows a minimum at E_{th} = 85 EeV considering the whole sky (N+S).

Results:

D	Fitted $n_{s\nu}$	Fitted γ	pre-trial p-value
3°	123.3	3.24	17.1%
6°	$\sim$0	-	$>$ 50%

Post-trial p-value=25%

Conclusions

• The first joint IceCube-Pierre Auger-Telescope Array correlation analysis was performed.
• All correlations found have less than 3.3 sigma significance.
• There is a potentially interesting result in the analyses with high-energy cascades - if we assume an isotropic flux of neutrinos (fixing the directions of the UHECRs) to assess the effect of the presence of anisotropies in the CR arrival directions (such as TA hot spot), the significance is ~2.4 sigma.
• These results were obtained with relatively few events and we will update these analyses in the future with more statistics.

Thank you!

Backup slides

Likelihood method stacking the high-energy cascades and high-energy tracks:

A posteriori scan in D for the stacking done on the neutrino positions