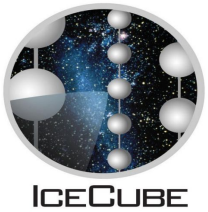
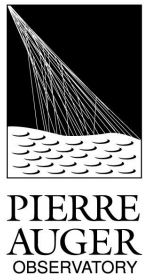


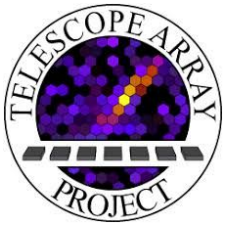
UHECR 2018

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

J. Aublin, A. Coleiro, A. Kouchner for the ANTARES Collaboration
I. Al Samarai, A. Barbano, T. Montaruli, L. Schumacher and C. Wiebuschfor for the IceCube Collaboration
L. Caccianiga, P.L. Ghia, U. Giaccari, G. Golup for the Pierre Auger Collaboration
H. Sagawa, P. Tinyakov for the Telescope Array Collaboration



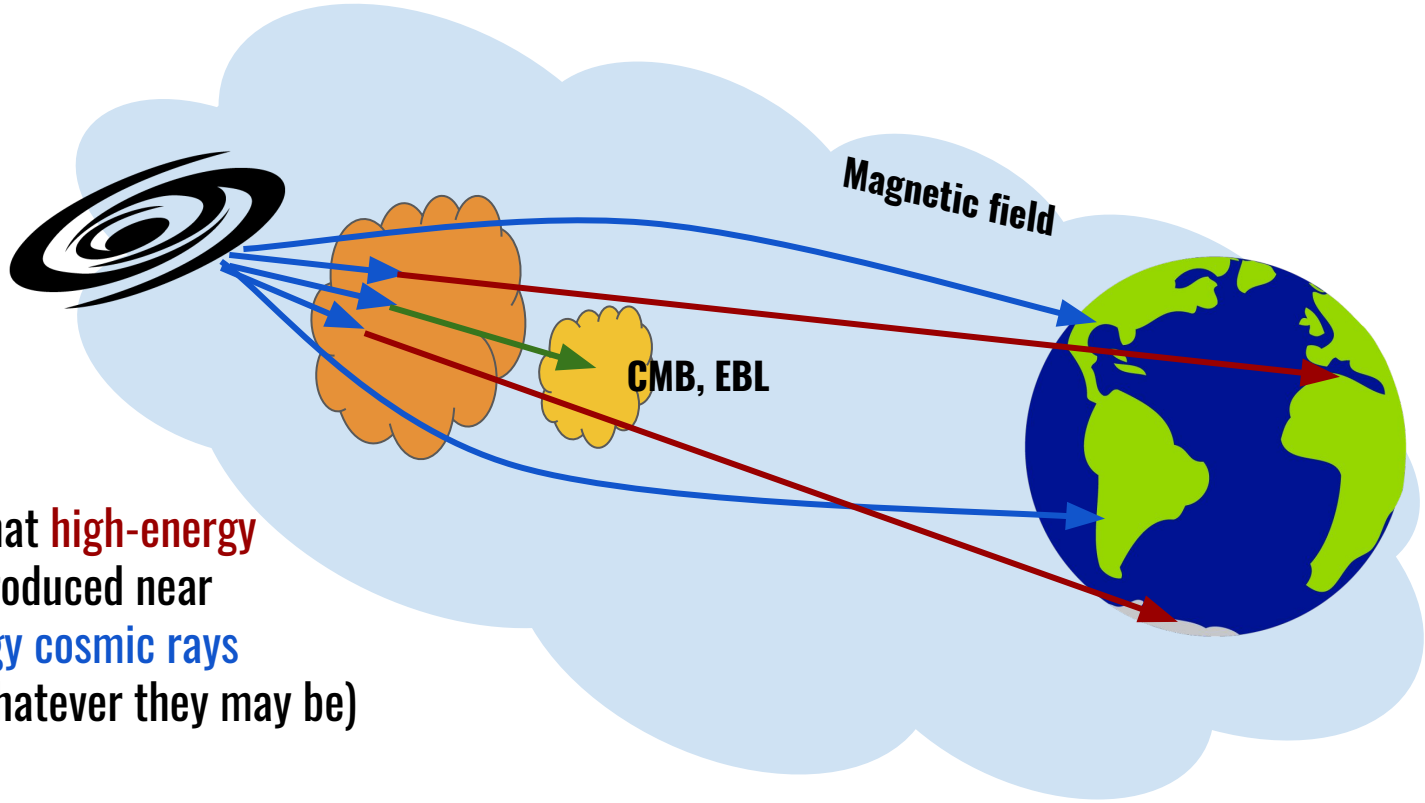
Paris, 10/10/2018



Motivation

$$p + \gamma/p \longrightarrow \pi^{+} + n \longrightarrow \mu^{+} + \nu_{\mu} + n \longrightarrow e^{+} + \overline{\nu}_{\mu} + \nu_{e} + \nu_{\mu} + n$$

$$\longrightarrow \pi^{0} + p \longrightarrow \gamma + \gamma + p$$



It is expected that high-energy neutrinos are produced near ultra-high energy cosmic rays accelerators (whatever they may be)

Introduction

- WG presented at UHECR 2014 originally with IceCube, Telescope Array and Auger
  - in 2017 ANTARES enters the WG.
- First results presented at ICRC 2015 and published in JCAP 1601 (2016) 01, 037.
- Updated at ICRC 2017 with new neutrino data from IceCube and 1 more year of TA data

Three analyses:

1) Cross-correlation method using the high-energy cascades and the high-energy tracks
-> updated results presented in this talk

2) Likelihood method stacking the high-energy cascades and the high-energy tracks
-> no update presented in this talk

3) Likelihood method stacking UHECRs and using the neutrino point source sample
-> update on the method presented in this talk

The datasets

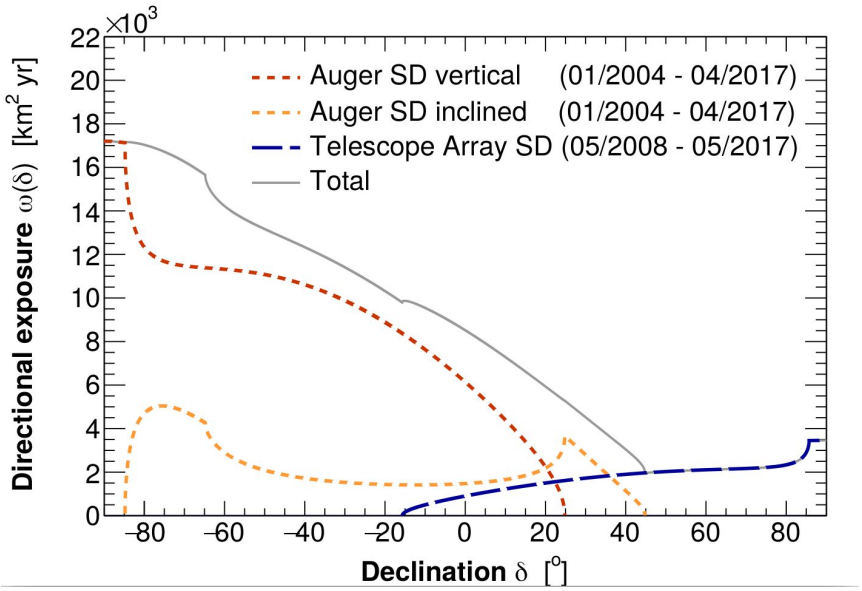
UHECR Datasets

Pierre Auger Observatory **(updated)**

- 324 events above 52 EeV recorded from 01/01/2004 to 30/04/2017 with zenith < 80°
  - +90 events with respect to ICRC 2017
- Angular resolution ~0.9°

Telescope Array **(updated)**

- 143 events above 57 EeV recorded from 11/05/2008 to 01/05/2017 with zenith < 55°
  - +34 events with respect to ICRC 2017
- Angular resolution ~1.5°

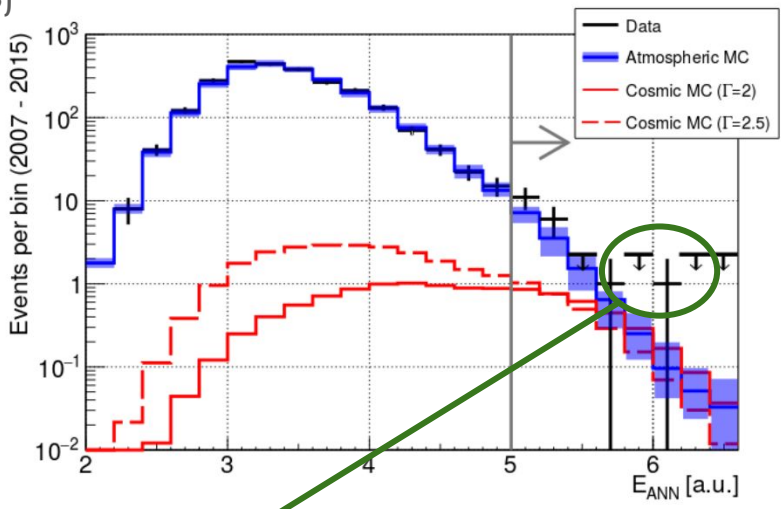


467 events with full sky coverage

Neutrino Datasets - High Energy samples

IceCube (same as in ICRC 2017) (atmospheric origin excluded at more than 5 σ)

- 58 High energy Cascades
  - HESE events
  - angular resolution ~15°
- 49 High energy Tracks
  - HESE + Diffuse ν_μ through up-going tracks
  - angular resolution ~ 1°



ANTARES (NEW) (hypothesis of a null cosmic flux excluded at 1.6 σ)

- Diffuse 9-yr sample A. Albert et al., ApJL 853, L7 (2018)
  - 2 track-like events with signalness > 0.4 (also in PS sample)
  - No cascade event passed selection
- Point source sample A. Albert et al., Phys. Rev. D 96, 082001 (2017)
  - +1 track-like event obtained applying the same signalness computed from the diffuse sample

$$S(E) = \frac{\Phi_{\mathrm{Astro}}(E)}{\Phi_{\mathrm{Astro}}(E) + \Phi_{\mathrm{Bkg}}(E)}$$

Neutrino Datasets - Point source samples

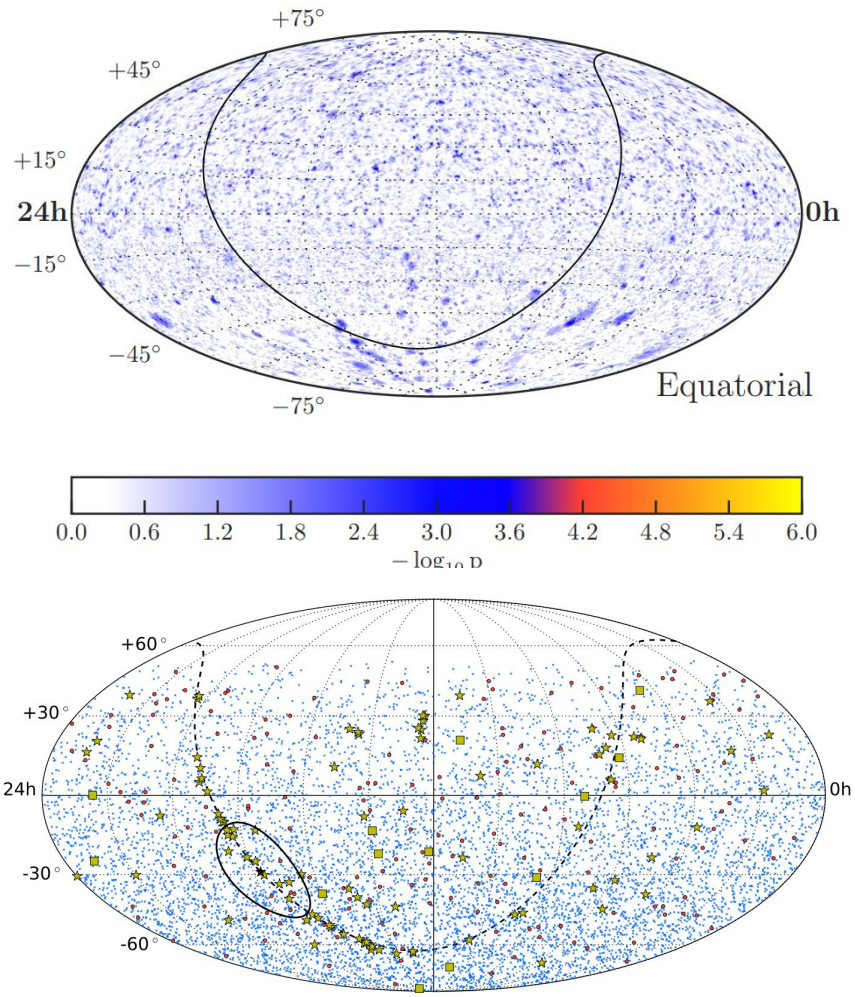
Updated point source samples are not used in the analyses so far

IceCube

- current results (JCAP 2016) based on the 4-yrs PS sample
  - ~400k events
- new (7-yrs PS+ 2.5 yrs GFU) sample sample available
  - >1M events

ANTARES

- 9 yrs PS sample
  A. Albert et al., Phys. Rev. D 96, 082001 (2017)
  - Track channel: 7622 events
  - Cascade channel: 180 events



Datasets evolution

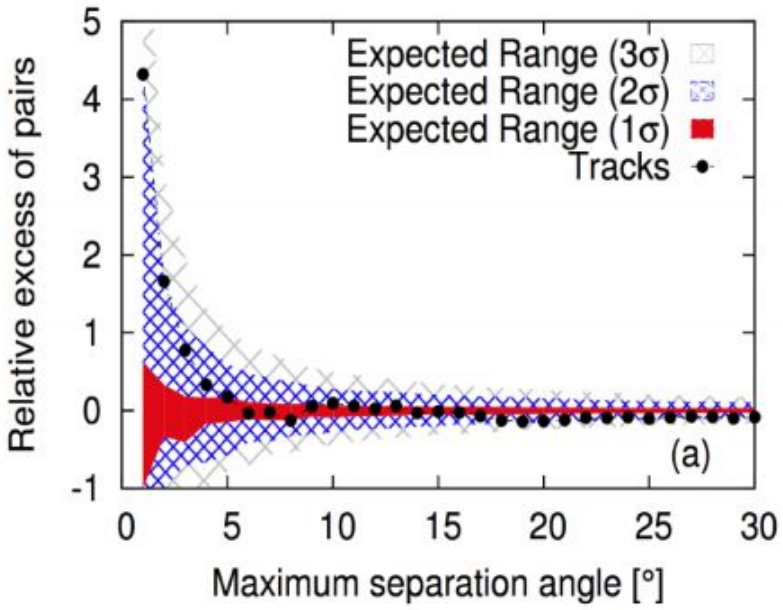
	JCAP 2016	ICRC 2017	UHECR 2018 (This work)
Auger UHECR	231 events 1/1/2004 -> 31/3/2014		324 events 1/1/2004 -> 30/4/2017
Telescope Array UHECR	87 events 11/5/2008 -> 1/5/2014	109 events 11/5/2008 -> 1/5/2015	143 events 11/5/2008 -> 1/5/2017
IceCube HE neutrinos	39 cascades 16 tracks (4 yrs HESE + diffuse up-going)	58 cascades 49 tracks	
ANTARES HE neutrinos	-		3 tracks (9-years diffuse + point source samples)

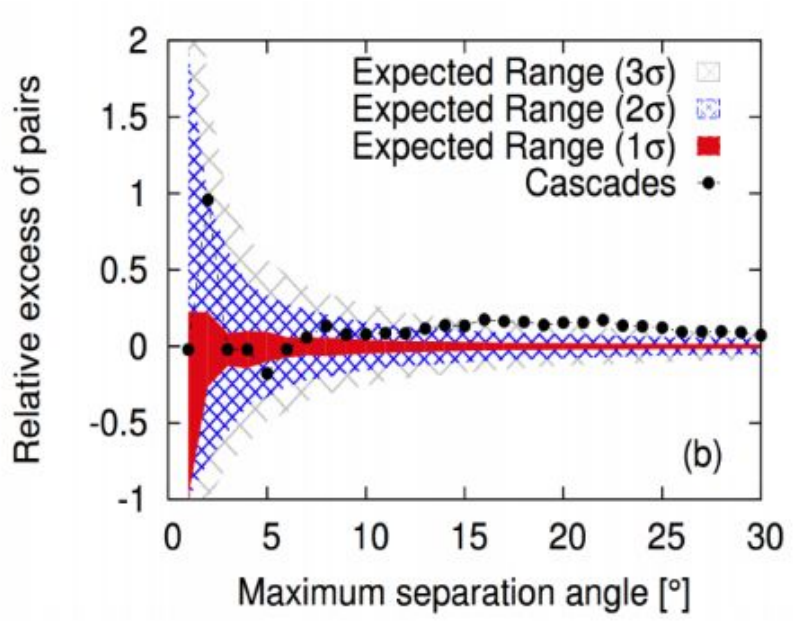
The analyses and previous results

Analysis method 1: cross-correlation

- Compute the number of pairs (n_p) UHECR-neutrino separated by less than a certain angle α
- Compare n_p with the expectations from the null hypotheses:
  - Null hypothesis 1: isotropic distribution of UHECR (neutrino directions are fixed)
  - Null hypothesis 2: isotropic distribution of neutrinos (UHECR directions are fixed)
- Scan on α from 1° to 30° in 1° steps to find for maximum departure from isotropy
- Analyse independently cascades and tracks neutrino samples
  - Final result: 4 p-values (2 null hypothesis for each sample)
- This analysis makes no assumption on the deflection of cosmic rays

Cross-correlation results - JCAP 2016





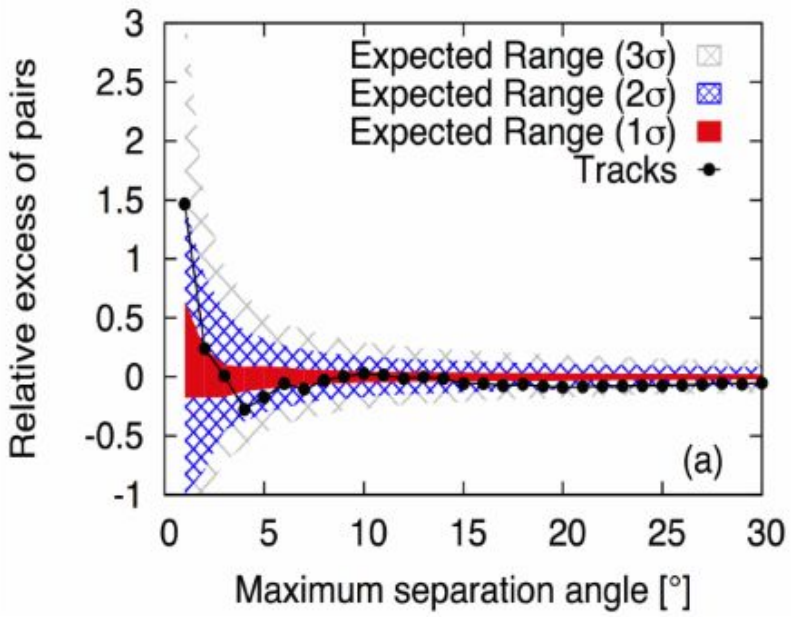
Tracks: minimum at 1°
post-trial p-value=0.28
with respect to an
isotropic flux of CRs.

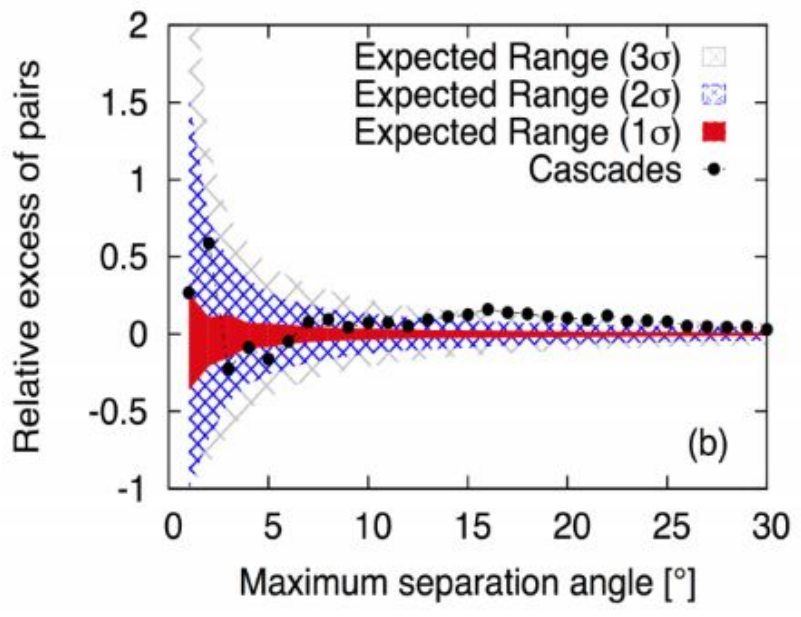
Cascades: min at 22°, np=575,
post-trial p-value=5×10^{-4}
with respect to an
isotropic flux of CRs

post-trial p-value= 8.5×10^{-3}
with respect to an
isotropic flux of neutrinos.

Cross-correlation results - ICRC 2017

Results updated with new neutrino and TA (+1 yr) data





Tracks: minimum at 1°, np =3,
post-trial p-value=0.48
with respect to an isotropic flux of CRs
post-trial p-value= 0.52
with respect to an isotropic flux of ν.

Cascades:
min at 22°, np =843,
post-trial p-value=5.4×10^{-3}
with respect to an isotropic flux of CRs
(was 5×10^{-4} in JCAP)

min at 16°, np =465,
post-trial p-value= 1.0×10^{-2}
with respect to an isotropic flux of ν.
(was 8.5×10^{-3} in JCAP)

Analysis method 2: likelihood stacking neutrino sources

- No scan in angle, 1 Free parameter: number of signal events
- three standard deflections for UHECR based on magnetic field models (JF 2012, PT 2011) computed as $D \cdot 100\ \mathrm{EeV} / E_{\mathrm{UHECR}}$ with D= 3°,6° and 9° (no assumption on the charge of each event).
- Same two null hypotheses as before (isotropic distribution of UHECR/neutrinos)

JCAP 2016 results:

	High-energy tracks			High-energy cascades		
D	n_s	TS	pre-trial p-value	n_s	TS	pre-trial p-value
3°	4.26	0.6	0.22	53.7	8.21	2.1×10^{-3}
6°	0.5	2.9×10^{-3}	0.48	85.7	11.99	2.7×10^{-4}
9°	0	0	under-fluctuation	106.1	11.32	3.8×10^{-4}

Cascades D=6°:

post-trial p-value = 8×10^{-4} with respect to an isotropic flux of CRs, 1.3×10^{-3} wrt an isotropic flux of neutrinos.

ICRC 2017 update:

Cascades D=6° :

post-trial p-value 2.2×10^{-2}, with respect to an isotropic flux of CRs, 1.7×10^{-2} wrt an isotropic flux of neutrinos.

Analysis method 3: likelihood stacking UHECR sources

- Using the neutrino point source sample
- Same magnetic deflection approach as in method 2 (D = 9° not used)
- The UHECR positions will be the “stacked sources”.
- Two free parameters to maximize: the neutrino spectral index and the number of signal events
- Cut on UHECR energy not to cover the whole sky with stacked sources (Eth = 85 EeV defined a priori in a sensitivity study)

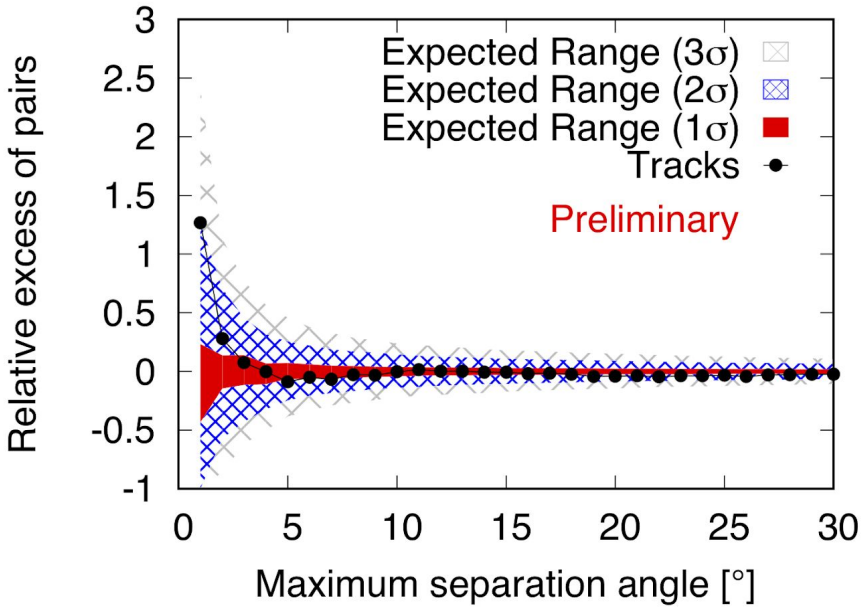
JCAP 2016 result:

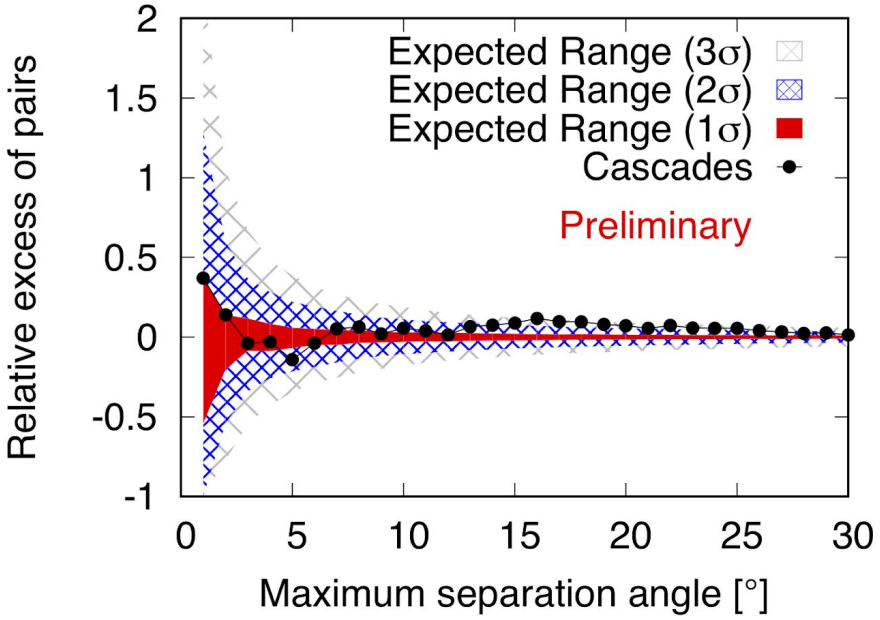
Post-trial p-value at minimum (D=3 deg 100 EeV/E): 25%

No update at ICRC 2017

Updated results for the cross-correlation analysis

Cross-Correlation analysis updated results





Tracks: minimum at 1°, np =4,
post-trial p-value=0.45
with respect to an isotropic flux of CRs
post-trial p-value= 0.49
with respect to an isotropic flux of ν.

Cascades: minimum at 16°, np =623,
post-trial p-value=2.7×10^{-2}
with respect to an isotropic flux of CRs (was 5.4×10^{-3} at ICRC 2017)
post-trial p-value= 2.6×10^{-2}
with respect to an isotropic flux of ν (was 1.0×10^{-2} in ICRC 2017)

Cross-Correlation results evolution

	JCAP 2016	ICRC 2017	UHECR 2018 (This work)
tracks wrt an isotropic flux of **UHECR**	0.28	0.48	0.45
tracks wrt an isotropic flux of **neutrinos**		0.52	0.49
cascades wrt an isotropic flux of **UHECR**	5×10^{-4}	5.4×10^{-3}	2.7×10^{-2}
cascades wrt an isotropic flux of **neutrinos**	8.5×10^{-3}	1.0×10^{-2}	2.6×10^{-2}

Summary and outlook

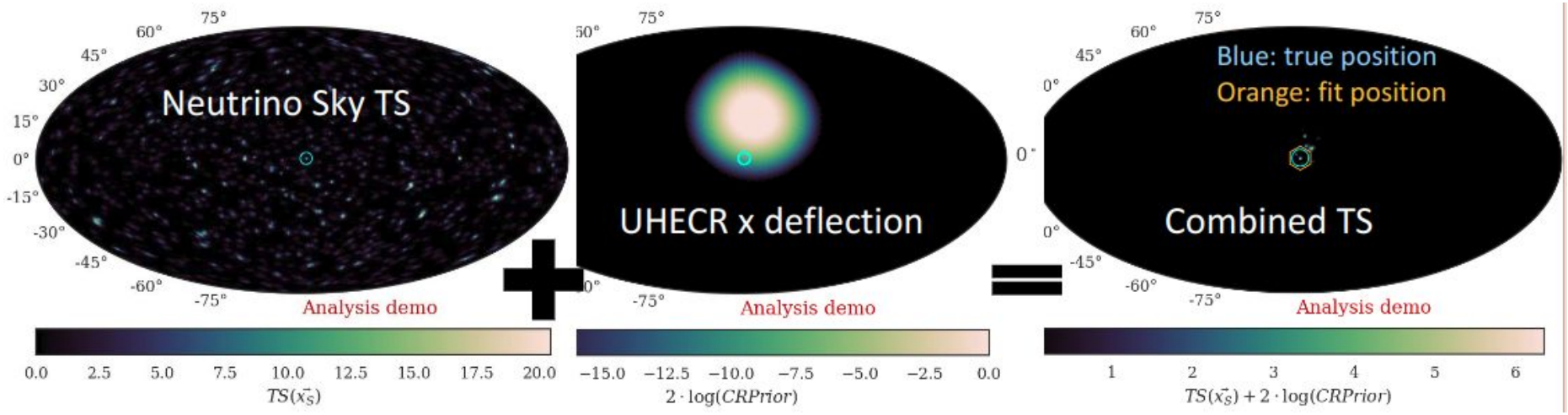
- Joint WG between IceCube, Pierre Auger and Telescope Array has been doing correlation analysis of the arrival directions of UHECRs and neutrino candidates since 2014. In 2017 ANTARES joined the WG.
- In the first publication, potentially interesting results were found in the analyses done between UHECR and high-energy cascades. These p-values have become larger with more statistics.
- Updated cross-correlation results was presented with new data from Auger, TA and data from ANTARES for the first time. The p-values for cascades have increased up to ~2.7×10^{-2}

- Update of analysis (3) method: use UHECR arrival directions and estimate their average deflection to construct "prior windows" in which to search for point-like neutrino hotspots
- The likelihood analysis done with the high-energy neutrino candidates (2) will be updated and as well as the likelihood analysis done with the IceCube and ANTARES point source samples (3).

Backup Slides

Analysis method 3: updated approach

- Recently presented at TeVPA 2018
- Use UHECR arrival directions and estimate their average deflection to construct “prior windows“ in which to search for point-like neutrino hotspots



-> to be applied to data soon

Magnetic field deflections

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

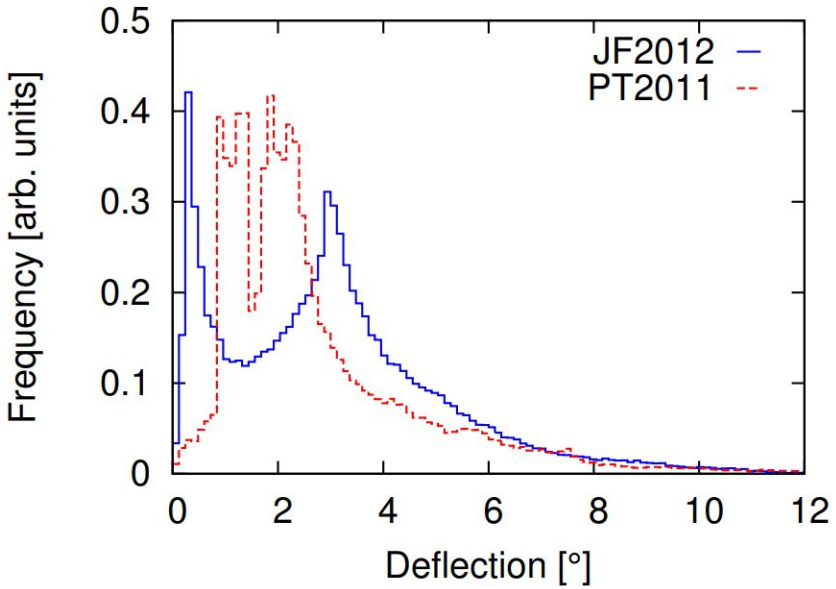


Figure 3. Distribution of UHECR deflections in two Galactic magnetic field models marked PT2011 [44] and JF2012 [45] for the regular component. The energies of actual UHECRs are renormalized to show the distributions for $E/Z = 100\,\mathrm{EeV}$. The double-peak structure is mostly due to the fact that UHECRs from different Galactic hemispheres undergo different deflections.

Analysis method 2: likelihood stacking neutrino sources

-

$$ln\mathcal{L} = \sum_{i=0}^{N_{\text{Auger}}} ln\left(\frac{n_{s_{CR}}}{N_{tot}} S_i^{\text{Auger}} + \frac{N_tot - n_{s_{CR}}}{N_{tot}} B_i^{\text{Auger}}\right) + \sum_{i=0}^{N_{\text{TA}}} ln\left(\frac{n_{s_{CR}}}{N_{tot}} S_i^{\text{TA}} + \frac{N_tot - n_{s_{CR}}}{N_{tot}} B_i^{\text{TA}}\right)$$