Search for correlations of high-energy neutrinos and ultra-high energy cosmic rays

Anastasia Barbano*
for the IceCube, Pierre Auger, Telescope Array and ANTARES Collaborations
*DPNC, University of Geneva

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Outline

• Neutrinos as a probe of UHECR origin
• Detectors and data samples
• Strategy and results of three UHECR-neutrino correlation analyses
  ▶ UHECR-neutrino cross-correlation analysis
  ▶ Neutrino-stacking correlation analysis with UHECRs
  ▶ UHECR-stacking correlation analysis with neutrinos
• Summary and conclusions
Neutrinos as a probe of UHECR origin

- **Galactic accelerators** (as SNRs) most likely sources for cosmic rays (CRs) below $10^{15}$ eV [1]
- **Sources of UHECRs** ($E > 10^{18}$ eV) most probably of extra-galactic origin

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  - AGNs, γ-ray bursts, magnetized and fast-spinning neutron stars among most promising sources
  - Pierre Auger Observatory measured large-scale anisotropy above 8 EeV (significance > 5.2σ) \[2\]
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  \[
  \pi^0 \rightarrow \gamma + \gamma \quad \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu
  \]
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- **Neutrinos** are **excellent probes** to investigate the **origin of UHECRs** and acceleration mechanisms due to:
  - tiny interaction cross section
  - insensitivity to (inter-)-galactic magnetic fields
Neutrinos as a probe of UHECR origin

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• Neutrinos are excellent probes to investigate the origin of UHECRs and acceleration mechanisms due to:
  - tiny interaction cross section
  - insensitivity to (inter-)galactic magnetic fields

• Three analyses searching for a common origin of UHECRs and high-energy neutrinos will be presented

• Joint analyses by the IceCube, ANTARES, Pierre Auger and Telescope Array (TA) Collaborations
**Detectors**

**IceCube**
- Location: South Pole
- 86 string with 60 Digital Optical Modules each

**ANTARES**
- Location: Mediterranean Sea
- 12 strings anchored at sea floor
- 885 optical modules

**Telescope Array**
- Location: Utah desert
- Surface detector array (SD, 507 scintillator detectors)
- 3 fluorescence detector stations (FD, equipped with telescopes)
- Exposure: Northern hemisphere up to -15°

**Pierre Auger**
- Location: Argentina
- SD (1660 water-Cherenkov detectors) and FD arrays (27 telescopes at five peripheral buildings)
- Exposure: from -90° to +45° in declination

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A. Barbano

ICRC19
Data samples

**UHECRs:**

- **TA:** 143 events \((E > 57 \text{ EeV}, \text{ zenith angle} \leq 80^\circ)\), from May 2008 to May 2017 [1]
- **Auger:** 324 events \((E > 52 \text{ EeV}, \text{ zenith angle} \leq 80^\circ)\), recorded with the SD from Jan. 2004 to Apr. 2017 [2]
- Rescaling applied to event energies to match TA and Auger fluxes (-14% and 14% respectively) [3]

**Neutrinos:**

(Cross-correlation and Neutrino-Stacking Analyses)

- **IceCube:**
  (i) 7.5-year preliminary sample (6 years new reco, last 1.5 years old reco) of High-Energy Starting Events (tracks and cascades) [4]
  (ii) 9-year sample of Extremely High-Energy event alerts (tracks) [5]
  (iii) 7-year sample of through-going muons induced by charged-current interactions of \(\nu_\mu\) candidates from the Northern sky (tracks) [6]

  \(\rightarrow 81 \text{ tracks and 76 cascades in total}\)

- **ANTARES:** 9-year point-source sample (\(\rightarrow 3 \text{ tracks}\)) [7]

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Data samples

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![IceCube 7-yr point-source sample](image)

**Neutrinos:**

(UHECR-Stacking Analyses)

- **IceCube:**
  (i) 7-year neutrino point-source sample [4]
  (ii) latest 3.5 years of the gamma-ray follow-up sample [5]
  \[ \textbf{1.4M events in total, between 2008 and 2018} \]
- **ANTARES:** 11-year point-source sample including events until 2017 [6]

UHECR-neutrino cross-correlation analysis

1° < δ < 30°, in 1° steps

- Two null-hypotheses investigated:
  i. isotropic distribution of UHECRs
  ii. isotropic distribution of neutrinos
- Angle that maximizes \( n_{\text{obs}} / n_{\text{exp}} \) provides local p-value
- Final global p-value obtained by trial correcting local p-value for the number of scanned angles
- Track- and shower-like events analyzed separately
  \( \rightarrow 4 \) p-values reported

Observable:

\[
\frac{n_{\text{obs}}}{\langle n_{\text{exp}} \rangle} - 1
\]

- \( n_{\text{obs}} = \) number of UHECR-neutrino pairs within angular distance \( \delta \)
- \( n_{\text{exp}} = \) number of UHECR-neutrino pairs within same distance, expected in the null-hypothesis scenario

U. Giaccari, G. Golup

A. Barbano

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Results: UHECR-neutrino cross-correlation analysis

Null hypothesis: isotropic CR distribution

![Graph 1: CR Isotropic Background](image1)

Preliminary

![Graph 2: CR Isotropic Background](image2)

Preliminary
Results: UHECR-neutrino cross-correlation analysis

Null hypothesis: isotropic CR distribution

- 303 pairs observed at 10°
- Post-trial p-value = 0.84

- 763 pairs observed at 16°
- Post-trial p-value = 0.18
Null hypothesis: isotropic neutrino distribution

- 582 pairs observed at 14°
- Post-trial p-value = 0.23

- 763 pairs observed at 16°
- Post-trial p-value = 0.15
Null hypothesis: isotropic neutrino distribution

- Result compatible with background
- Most significant result from previous publications [1]: post-trial p-value at 22° for cascades: $5.0 \times 10^{-4}$ (isotropic CR background)

[1] JCAP 1601 (2016) 01 037
Neutrino-stacking correlation analysis with UHECRs

- Method: stacked unbinned likelihood:

\[
\ln \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S_{\text{Auger}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B_{\text{Auger}}^i \right) + \sum_{i=1}^{N_{\text{TA}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S_{\text{TA}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B_{\text{TA}}^i \right),
\]

- \( n_s \) = number of UHECR signal event (free parameter)
- \( N_{\text{CR}} \) = total number of CR events

- Signal PDF:

\[
S^i_{\text{CR observatory}}(\vec{r}_i, E_i) = R_{\text{CR observatory}}(\delta_i) \sum_{j=1}^{N_{\text{src}}} S_j(\vec{r}_i, \sigma(E_i)) \]

Relative exposure at given event declination

\( N_{\text{src}} \): number of stacked sources

\( \sigma \) accounts for angular resolution of the CR observatory and magnetic deflection

- Background PDF: normalized exposure of the CR observatory

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\( S_{\text{CR experiment}}^i \) = signal PDF
\( B_{\text{CR experiment}}^i \) = background PDF

C. Alispach, A. Barbano, T. Montaruli
Neutrino-stacking correlation analysis with UHECRs

C. Alispach, A. Barbano, T. Montaruli

• Method: stacked unbinned likelihood:

\[
\ln \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S_{\text{Auger}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B_{\text{Auger}}^i \right) + \sum_{i=1}^{N_{\text{TA}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S_{\text{TA}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B_{\text{TA}}^i \right),
\]

- \( n_s \) = number of UHECR signal event (free parameter)
- \( N_{\text{CR}} \) = total number of CR events
- \( S_{\text{CR experiment}}^i \) = signal PDF
- \( B_{\text{CR experiment}}^i \) = background PDF

• Test statistic (TS) with one degree of freedom (\( n_s \)) is built:

\[ TS = -2 \ln \left( \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(n_s)} \right) \]

• Signal hypothesis: UHECRs events spatially correlated with neutrino events
• Background hypothesis: UHECR events distributed isotropically over the whole sky
Neutrino-stacking correlation analysis with UHECRs

- Different deflection values, for protons @ 100 EeV, in
  (i) Galactic North (b>0°), $D_0 = 2.4°$
  (ii) Galactic South (b<0°), $D_0 = 3.7°$

- Rescaled for CR energy and combined in one p-value:
  $$\sigma_{MD}(E) = D \times 100 \text{ EeV}/E$$

- Increased by factor 2 and 3 to account for heavier CR composition and/or larger magnetic fields
Results: Neutrino-stacking correlation analysis with UHECRs

<table>
<thead>
<tr>
<th>$D$</th>
<th>(2.4°, 3.7°)</th>
<th>(4.8°, 7.4°)</th>
<th>(7.2°, 11.1°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-values (tracks)</td>
<td>underfluctuation</td>
<td>underfluctuation</td>
<td>underfluctuation</td>
</tr>
<tr>
<td>p-values (cascades)</td>
<td>underfluctuation</td>
<td>0.41</td>
<td>0.29</td>
</tr>
</tbody>
</table>

- Result compatible with background
- Most significant result from previous publications [1]: post-trial p-value for cascades with $D = 6°$: $8 \times 10^{-4}$
- Right: stacked likelihood map of neutrino shower-like events and UHECR arrival directions

[1] JCAP 1601 (2016) 01 037
UHECR-stacking correlation analysis with neutrino directions

- Method: stacked unbinned likelihood:

\[
\ln \mathcal{L} = \sum_{S=1}^{N_{\text{CR}}} \left[ \sum_{i=1}^{N_{\nu}} \ln \left( \frac{n_s}{N_{\nu}} S_i(\gamma_s, \vec{x}_S) \right) + \left( 1 - \frac{n_s}{N_{\nu}} \right) B_i(\vec{x}_S) \right] - \frac{(\vec{x}_S - \vec{x}_{\text{CR},S})^2}{2\sigma(E_{\text{CR},S})^2}
\]

- Signal hypothesis: point-like neutrino sources spatially correlated with UHECR arrival directions
- Background hypothesis: neutrino events are distributed uniformly over the whole sky
UHECR-stacking correlation analysis with neutrino directions

- Method: stacked unbinned likelihood:

\[
\ln L = \sum_{i=1}^{N_{\text{UHECR}}} \left[ \left( \frac{n_S}{N_v} \right) S_i(\gamma_S, \bar{x}_S) + \left( 1 - \frac{n_S}{N_v} \right) B_i(\bar{x}_S) \right] - \frac{(\bar{x}_S - \bar{x}_{CR,S})^2}{2\sigma(E_{CR,S})^2}
\]

1. Fit neutrino signal parameters \((n_S, \gamma_S)\) on grid positions \(x_S \rightarrow\) TS skymap (standard point-source analysis)

- \(n_S\) = number of neutrino signal event (free parameter)
- \(N_v\) = total number of neutrino events
- \(x_S\) = position of neutrino source
- \(\gamma_S\) = spectrum index of neutrino source (free parameter)
- \(S_{CR\text{~experiment}}\) = signal PDF
- \(B_{CR\text{~experiment}}\) = background PDF
- \(x_{CR,S}, E_{CR,S}\) = position, energy of the CR source
- \(\sigma\) = deflection associated to the CR source

\[
\text{TS}(\bar{x}_S) = 2 \ln \left( \frac{L_{\text{step 1}}(\hat{n}_S, \hat{\gamma}_S)}{L_{\text{step 1}}(n_S = 0)} \right)
\]
UHECR-stacking correlation analysis with neutrino directions

- Method: stacked unbinned likelihood:

\[
\ln L = \sum_{S=1}^{N_{\text{CR}}} \left[ \sum_{i=1}^{N_{\nu}} \left( \frac{n_{S}}{N_{\nu}} S_{i}(\gamma_{S}, \vec{x}_{S}) + \left( 1 - \frac{n_{S}}{N_{\nu}} \right) B_{i}(\vec{x}_{S}) \right) \right] - \left( \frac{\overline{x}_{S} - \overline{x}_{\text{CR},S}}{2 \sigma(\overline{E}_{\text{CR},S})} \right) \]

1. \( n_{S} \) = number of neutrino signal event (free parameter)
2. \( N_{\nu} \) = total number of neutrino events
3. \( \vec{x}_{S} \) = position of neutrino source
4. \( \gamma_{S} \) = spectrum index of neutrino source (free parameter)

- Add the \( 2 \times \log(\text{CR}_{\text{space prior}}) \) to the TS map → selecting interesting region with prior window

- \( S_{\text{CR experiment}}^{i} \) = signal PDF
- \( B_{\text{CR experiment}}^{i} \) = background PDF
- \( \vec{x}_{\text{CR},S}, \overline{E}_{\text{CR},S} \) = position, energy of the CR source
- \( \sigma \) = deflection associated to the CR source
UHECR-stacking correlation analysis with neutrino directions

- Method: stacked unbinned likelihood:

\[
\ln \mathcal{L} = \sum_{s=1}^{N_{\text{CR}}} \left( \sum_{i=1}^{N_{\nu}} \ln \left( \frac{n_s}{N_{\nu}} S_i(\gamma_s, \bar{x}_s) + \left( 1 - \frac{n_s}{N_{\nu}} \right) B_i(\bar{x}_s) \right) \right) - \frac{(\bar{x}_s - x_{\text{CR},s})^2}{2 \sigma^2(\text{E}_{\text{CR},s})^2}
\]

- Step 1: neutrino data, stacking
- Step 2: UHECR data

\[n_s = \text{number of neutrino signal event (free parameter)}\]
\[N_{\nu} = \text{total number of neutrino events}\]
\[x_s = \text{position of neutrino source}\]
\[\gamma_s = \text{spectrum index of neutrino source (free parameter)}\]
\[S_{\text{CR experiment}} = \text{signal PDF}\]
\[B_{\text{CR experiment}} = \text{background PDF}\]
\[x_{\text{CR},s}, E_{\text{CR},s} = \text{position, energy of the CR source}\]
\[\sigma = \text{deflection associated to the CR source}\]

3. Find hottest neutrino source “S” as counterpart for one particular CR \( \rightarrow \) TS(\(x_s\)) and repeat for all CRs
UHECR-stacking correlation analysis with neutrino directions

- Method: stacked unbinned likelihood: L. Schumacher, C. Wiebusch

\[
\ln L = \sum_{S=1}^{N_{\text{CR}}} \left[ \sum_{i=1}^{N_{\nu}} \ln \left( \frac{n_S}{N_{\nu}} S_i(\gamma_s, x_S^i) + \left( 1 - \frac{n_S}{N_{\nu}} \right) B_i(x_S^i) \right) \right] - \frac{(x_S^i - x_{\text{CR},S}^i)^2}{2\sigma(E_{\text{CR},S})^2}
\]

- \( n_s \) = number of neutrino signal event (free parameter)
- \( N_{\nu} \) = total number of neutrino events
- \( x_s \) = position of neutrino source
- \( \gamma_s \) = spectrum index of neutrino source (free parameter)

- All-sky uniform magnetic deflection value used:
  - 3° value for pure proton-like sample; also 6° tested to account for heavier composition
  - rescaled by CR energy

\[
\sigma_{\text{MD}}(E) = D \times 100 \text{ EeV}/E
\]

- Three different CR energy cuts: \( E_{\text{CR}} > 70, 85, 100 \text{ EeV} \)

- \( S^i_{\text{CR experiment}} \) = signal PDF
- \( B^i_{\text{CR experiment}} \) = background PDF
- \( x_{\text{CR},S}^i, E_{\text{CR},S}^i \) = position, energy of the CR source
- \( \sigma \) = deflection associated to the CR source

- Rescaled by CR energy

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- Protons @ 100 EeV
Results: UHECR-stacking correlation analysis with neutrino directions

<table>
<thead>
<tr>
<th>$D , [^\circ]$</th>
<th>3</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{CR} , [\text{EeV}] \geq$</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>p-value</td>
<td>0.27</td>
<td>0.46</td>
</tr>
</tbody>
</table>

- Result compatible with background
- Right: background TS from neutrino data randomized in right ascension (UHECR positions fixed) compared to experimental TS result

**0.16 post-trial**
Summary and conclusions

• The p-values from three different analyses, given our assumptions on CR composition and magnetic deflection, are compatible with background hypothesis.
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• This result does not imply absolute lack of correlations in the origin of the two messengers.
• Currently limiting factors:
  ▶ not yet conclusive understanding of UHECR composition
  ▶ large uncertainties in Galactic magnetic fields
Summary and conclusions

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• This result does not imply absolute lack of correlations in the origin of the two messengers.
• Currently limiting factors:
  ▶ not yet conclusive understanding of UHECR composition
  ▶ large uncertainties in Galactic magnetic fields
• Furthermore:
  ▶ despite neutrinos belong to different energy ranges than the UHECRs, lower energies may come from the same UHECR source spectrum
  ▶ only a small fraction of neutrinos origin within 10-100 Mpc (GZK horizon)
  → Only few percents of events in our samples may constitute correlated signal
Summary and conclusions

• The p-values from three different analyses, given our **assumptions on CR composition and magnetic deflection**, are **compatible with background hypothesis**
• This result **does not imply absolute lack of correlations** in the origin of the two messengers
• Currently limiting factors:
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• Furthermore:
  ▶ despite neutrinos belong to different energy ranges than the UHECRs, lower energies may come from the same UHECR source spectrum
  ▶ only a small fraction of neutrinos origin within $10-100$ Mpc (GZK horizon)
    → **Only few percents of events** in our samples **may constitute** correlated **signal**
• Work ongoing to define physical hypotheses for upper limit calculations
• Paper in preparation
Backup
CR composition above $10^{17.2}$ eV

- Auger mass fraction fits using parameterization of the expected $X_{\text{max}}$ distributions with different hadronic interaction models (PoS ICRC2017 (2018) 506)
TA and Auger flux rescaling

Neutrino-stacking correlation analysis with UHECRs

\[
\ln \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S_{\text{Auger}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B_{\text{Auger}}^i \right) + \sum_{i=1}^{N_{\text{TA}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S_{\text{TA}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B_{\text{TA}}^i \right),
\]

\(n_s\) = number of signal event (free parameter)

\(N_{\text{CR}}\) = total number of CR events

\(S_{\text{CR experiment}}^i\) = signal PDF

\(B_{\text{CR experiment}}^i\) = background PDF

Signal PDF:

\[
S_{\text{CR observatory}}^i(\vec{r}_i, E_i) = R_{\text{CR observatory}}(\delta_i) \sum_{j=1}^{N_{\text{src}}} S_j(\vec{r}_i, \sigma(E_i))
\]

Relative exposure at given event declination

\(N_{\text{src}}\): number of stacked sources

value of the normalized directional likelihood map for the \(j\)-th source (i.e. neutrino) taken at \(r_i\) and smeared with a Gaussian with standard deviation \(\sigma(E_i)\):

\[
\sigma(E_i) = \sqrt{\sigma_{\text{CR observatory}}^2 + \sigma_{\text{MD}}^2}
\]

- \(\sigma_{\text{CR observatory}}\): angular resolution of the CR observatory (0.9° for Auger and 1.5° for TA)
- \(\sigma_{\text{MD}} = D \times 100 \text{ EeV}/E_{\text{CR}}\) (for a pure proton composition with an energy \(E_{\text{CR}} = 100 \text{ EeV}\)
Neutrino-stacking correlation analysis with UHECRs

\[
\ln \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S^i_{\text{Auger}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B^i_{\text{Auger}} \right) + \sum_{i=1}^{N_{\text{TA}}} \ln \left( \frac{n_s}{N_{\text{CR}}} S^i_{\text{TA}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B^i_{\text{TA}} \right),
\]

- \( n_s \) = number of signal event (free parameter)
- \( N_{\text{CR}} \) = total number of CR events
- \( S^i_{\text{CR experiment}} \) = signal PDF
- \( B^i_{\text{CR experiment}} \) = signal PDF

Background PDF:

the experiments exposures, assuming isotropic cosmic ray flux
IceCube and ANTARES point-source sample combination

Likelihood as a function of the total number of fitted events $n_s$:

$$\ln \mathcal{L} = \sum_{j=1}^{N_{\text{sample}}} \left( \sum_{i=1}^{N_j} \ln \left( f^j \frac{n_s}{N^j} S_i + \left( 1 - f^j \frac{n_s}{N^j} \right) B_i \right) \right)$$

where:

$$n^j_s = n_s \cdot f^j (\delta, \frac{d\Phi}{dE})$$

number of signal events in the $j^{\text{th}}$ sample

$$f^j (\delta, \frac{d\Phi}{dE}) = \frac{N^j_s (\delta, \frac{d\Phi}{dE})}{\sum_j N^j_s (\delta, \frac{d\Phi}{dE})}$$

Relative number of expected source events in the $j^{\text{th}}$ sample

$$N^j_s (\delta, \frac{d\Phi}{dE}) = \int dt \ dE_{\nu} A^j_{\text{eff}} (E_{\nu}, \delta) \frac{d\Phi}{dE_{\nu}}$$

Expected source event number for a flux $E^{-2}$, given the effective area $A^j_{\text{eff}}$ of the $j^{\text{th}}$ sample
HESE 7.5 yr point-source searches

- Maximum observed TS = 12.24 (best-fit number of signal events $n_s = 5.1$ at $(\alpha, \delta) = (12.2^\circ, 5.1^\circ)$).
- Resulting p-value is 0.81.
UHECR-neutrino cross-correlation analysis: published results

[1] JCAP 1601 (2016) 01 037

- Isotropic CR background
- Post-trial p-value at 22°: 5.0 x 10^{-4}

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Post-trial p-value : evolution vs. time

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>tracks wrt an isotropic flux of UHECR</td>
<td>0.28</td>
<td>0.48</td>
<td>0.45</td>
</tr>
<tr>
<td>tracks wrt an isotropic flux of neutrinos</td>
<td></td>
<td>0.52</td>
<td>0.49</td>
</tr>
<tr>
<td>cascades wrt an isotropic flux of UHECR</td>
<td>5 x 10^{-4}</td>
<td>5.4 x 10^{-3}</td>
<td>2.7 x 10^{-2}</td>
</tr>
<tr>
<td>cascades wrt an isotropic flux of neutrinos</td>
<td></td>
<td>8.5 x 10^{-3}</td>
<td>1.0 x 10^{-2}</td>
</tr>
</tbody>
</table>

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Neutrino-stacking correlation analysis with UHECRs: published results

<table>
<thead>
<tr>
<th></th>
<th>High-energy tracks</th>
<th>High-energy cascades</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D^*$ $n_s$</td>
<td>pre-trial $p$-value</td>
</tr>
<tr>
<td>$3^\circ$</td>
<td>4.2</td>
<td>0.22</td>
</tr>
<tr>
<td>$6^\circ$</td>
<td>0.5</td>
<td>0.48</td>
</tr>
<tr>
<td>$9^\circ$</td>
<td>- underfluctuation</td>
<td></td>
</tr>
</tbody>
</table>

* In past analyses, a median all-sky value was used for $D^*$

**Post-trial: $8.0 \times 10^{-4}$**

<table>
<thead>
<tr>
<th></th>
<th>High-energy tracks</th>
<th>High-energy cascades</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D$ $n_s$</td>
<td>pre-trial $p$-value</td>
</tr>
<tr>
<td>$3^\circ$</td>
<td>0.9</td>
<td>0.44</td>
</tr>
<tr>
<td>$6^\circ$</td>
<td>- underfluctuation</td>
<td></td>
</tr>
<tr>
<td>$9^\circ$</td>
<td>- underfluctuation</td>
<td></td>
</tr>
</tbody>
</table>

**Post-trial: $2.2 \times 10^{-2}$**
UHECR-stacking correlation analysis with neutrino directions: published results

**Preliminary: Experimental Results**

- **$D = 3^\circ, E_{\text{cut}} = 70\text{EeV}$**
  - $p$-value = 0.66
  - Median
  - 3$\sigma$

- **$D = 6^\circ, E_{\text{cut}} = 70\text{EeV}$**
  - $p$-value = 0.44
  - Median
  - 3$\sigma$

- **$D = 3^\circ, E_{\text{cut}} = 85\text{EeV}$**
  - $p$-value = 0.39
  - Median
  - 3$\sigma$

- **$D = 6^\circ, E_{\text{cut}} = 85\text{EeV}$**
  - $p$-value = 0.32
  - Median
  - 3$\sigma$

- **$D = 3^\circ, E_{\text{cut}} = 100\text{EeV}$**
  - $p$-value = 0.72
  - Median
  - 3$\sigma$

- **$D = 6^\circ, E_{\text{cut}} = 100\text{EeV}$**
  - $p$-value = 0.55
  - Median
  - 3$\sigma$
IceCube event signatures

**Track-like events:**
- Charged-current (CC) interactions of muon neutrinos with nucleons (N): \( \nu_\mu + N \rightarrow \mu^- + X \)
- Good angular resolution: < 1° above few TeV
- Energy resolution: x2

**Cascade-like events:**
- neutral current (NC) \( \nu_\alpha + N \rightarrow \nu_\alpha + X \)
- charged current \( N \rightarrow \ell^-_\alpha + X \)
- Angular resolution: ~15° above 100 TeV
- Good energy resolution: ~15%