First analysis of inclined air-showers detected by Tunka-Rex

Tatjana Marshalkina, Dmitriy Kostunin for the Tunka-Rex Collaboration
June 14, 2018
Motivation

We consider inclined events as ones having $\theta > 60^\circ$ (e.g. $\cos \theta < 0.5$)

- Increasing aperture of array in more than two times
  $\Omega \times 2 + S \times n$: solid angle and area (larger footprints)
- CR studies for $E > 10^{18}$ eV
- Neutrino studies

First inclined events have been detected by Tunka-Rex in November, 2012
Dimensions of inclined event much larger than for vertical one

Amplitude suppression $\sim \frac{1}{D_{\text{max}}}$
Tunka-Rex antenna station sensitivity

- Short Aperiodic Loaded Loop Antenna\(^1\) is designed to suppress signals from below ⇒ reduced ground-related systematics
- \(\alpha \approx 90^\circ, 10^{18} \leq E_{pr} \leq 10^{19}\) eV for Tunka location/layout

\(^1\) P. Abreu et al. (Pierre Auger), JINST 7, P10011 (2012)
Configuration of the trigger
Reconstruction and quality cuts

Tunka-Grande triggered events from 2015-2017 (424 runs)

Reconstruction is similar to standard one, except few modifications:
- Signal window is extended from 200 to 500 ns (geometry reasons)
- All air-shower parameters are reconstructed by Tunka-Rex
- No cross-check with Tunka-Grande (radio standalone reconstruction)

Quality cut on number of antenna stations with signal

<table>
<thead>
<tr>
<th>Zenith angle (deg.)</th>
<th>$\min(N_{\text{ant.}})$</th>
<th>Detected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 – 70</td>
<td>21</td>
<td>28</td>
</tr>
<tr>
<td>70 – 80</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>80 – 90</td>
<td>10</td>
<td>5</td>
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<td></td>
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<td>52</td>
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</tbody>
</table>

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June 14, 2018
Example events (60 – 70 deg.)
Example events (70 – 80 deg.)
Example events (80 – 90 deg.)
Zenith distribution as expected

Supression of flux from North
Shadow from the mountains?

Mountain chain of height 1.5–2.5 km in 5-10 towards North
Comparison of signal properties

In average, pulse shapes of vertical and inclined events agree
Dimensions of the detector does not allow to resolve air-shower structure (Cherenkov bump, slope, axis core)

- NoLDF methods of reconstruction? (template fit, polarization, spectrum slope)
Rough energy estimation

Energy estimated as

\[ E = \kappa \times \left( \frac{D_{70^\circ}}{D_{50^\circ}} \right) \langle \mathcal{E} \rangle \]

+ 2 more very inclined (90°) events with estimated \( E > 10^{20} \) eV
Search for double burst events

Exotic or rare (arXiv:1111.0504) air-showers profiles with two bumps in $N(X)$, $X \gg 1000 \text{ g/cm}^2$

Structure can bee seen in radio (inclination + $c_{\text{radio}} < c_{\text{particles}}$)

Lag in pulses is described by relation $L(n - 1) = \tau c$, where lag $\tau$ corresponds to distance between bumps $L$

for $L \sim \text{km} : \tau \sim \text{ns}$

Challenging, but can be resolved for events with $\theta > 70^\circ$

Tunka-Rex is searching for such kind of events
Event with delayed signal (RFI?)

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June 14, 2018 16/18
Event with delayed signal (RFI?)

Inclination $\theta = 80^\circ$

Lag between signals $\approx \mu s$

Signals are prominent in $V \times V \times B$ polarization

Delayed signals are very similar to Tunka-Rex typical ones

More questions than answers
Summary

- Tunka-Rex with SALLA is sensitive to very inclined air-showers
- We probably see shadow from mountains ⇒ testbed for GRAND-like setups
- Singal properties show no exotics, influence of ground is under investigation
- It is hard to resolve shower geometry with Tunka-Rex dimensions
- Test of rare or exotic scenarios visible only in inclined cascades