Primary Energy Spectrum by the Data of EAS Cherenkov Light Arrays Tunka-133 and TAIGA-HiSCORE.

Vasily Prosin for the Tunka and TAIGA Collaborations

ISCRA 26.06.2019
175 optical detectors
EMI 9350 and
HAMAMATSU Ø 20 cm

Tunka-133

51° 48' 35" N
103° 04' 02" E
675 m a.s.l.
EXPERIMENTAL DATA

Tunka-133:

7 seasons, 350 nights, 2175 h, \( \sim 1.5 \times 10^7 \) single cluster events
100% effective registration:
\( \sim 375,000 \) events with \( E_0 > 6 \times 10^{15} \) eV,
\( \sim 4,200 \) events with \( E_0 > 10^{17} \) eV
Effective areas

Effective areas for

- 800 m - L
- 450 m - M
Tunka-133 single detector readout:
Fitting of the pulse and measuring of the parameters: \( Q = c \cdot S_{\text{pulse}}, A_{\text{max}}, t_i, \tau_{\text{eff}} = S/A/1.24 \)

Time step = 5 ns

anode:

dynode:
EAS parameters reconstruction

CORSIKA: Fitting functions – LDF and ADF

ADF: \[ A(R) = A(400) \cdot \left(\frac{R}{400} + 1\right)/2\] steepness: \( b_A \)

LDF: \[ Q(R) = Q(300) \cdot \left(\frac{R}{300} + 1\right)/2\] steepness: \( b_Q \)

\( b_A > b_Q \)
An Example of Tunka-133 event reconstruction

\[ Q_{200} \]
EAS parameters reconstruction by Cherenkov light flux density $Q_{200}$

Fitting of pulse amplitudes ($A_i$) with ADF.
Getting of $X_0$, $Y_0$ and ADF steepness ($b_A$).
Getting $Q_{200}$ with LDF

\[ E_0 = C_1 \cdot Q_{200}^{0.94}, \quad E_0 < 10^8 \text{ GeV} \]

\[ E_0 = C_2 \cdot Q_{200}^{0.95}, \quad E_0 > 10^8 \text{ GeV} \]

Simulated composition:
- $p – 50\%$, Fe – 50\%, $E_0 < 10^9 \text{ GeV}$
- $p – 100\%$, $E_0 = 10^9 \text{ GeV}$
Relative accuracy of EAS parameters reconstruction
Energy Spectrum

2010 – 2017
352 nights
2200 h
~ 140,000 – \( E_0 > 10^{16} \) eV
4224 – \( E_0 > 10^{17} \) eV
24 – \( E_0 > 10^{18} \) eV

\[ l^3 E^3 = \text{m}^{-2} \text{sec}^{-1} \text{ster}^{-1} \text{eV}^2 \]

\[ \log(E_0/\text{eV}) \]

- Tunka-133, 7 yrs
- Tunka-25
## TAIGA - collaboration

<table>
<thead>
<tr>
<th>Germany</th>
<th>Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamburg University (Hamburg)</td>
<td>SINP MSU (Moscow)</td>
</tr>
<tr>
<td>DESY (Zeuthen)</td>
<td>API ISU (Irkutsk)</td>
</tr>
<tr>
<td>MPI (Munich)</td>
<td>INR RAS (Moscow)</td>
</tr>
<tr>
<td><strong>Italy</strong></td>
<td>JINR (Dubna)</td>
</tr>
<tr>
<td>Torino University (Torino)</td>
<td>MEPHI (Moscow)</td>
</tr>
<tr>
<td><strong>Romania</strong></td>
<td>IZMIRAN (Moscow)</td>
</tr>
<tr>
<td>ISS (Bucharest)</td>
<td>NSU (Novosibirsk)</td>
</tr>
<tr>
<td></td>
<td>BINR SB RAS (Novosibirsk)</td>
</tr>
</tbody>
</table>
Low threshold wide angle station

Digitized with DRS-4.
Step = 0.5 ns
Synchronization and data taking via optical cable

Winston cone and PMT with 20 cm photocathode diameter

\[ S_{tot} = 0.5 \text{ m}^2 \]
Stations layout 2018 - 2019
Azimuth angle

Zenith angle

Field of view

Crab trajectory

Azimuth angle

Zenith angle
HiSCORE station sum record 2017-2019

anode:

dynode:

synchronisation:
EXPERIMENTAL DATA

TAIGA-HiSCORE:

season 2017-2018, 1\textsuperscript{st} cluster – 28 stations, 2\textsuperscript{nd} cluster – 13 stations
35 nights, 180 h, \sim3 \cdot 10^8 single station events
100\% effective registration:
\begin{align*}
2 \cdot 10^{14} – 3 \cdot 10^{14} & \sim 29,000 \text{ (one night 28.10.2018, } Q_{70}) \\
3 \cdot 10^{14} – 10^{15} & \sim 700,000 \text{ (35 nights, } Q_{70}) \\
10^{15} – 10^{17} & \sim 170,000 \text{ (35 nights, } Q_{200})
\end{align*}

Season 2018-2019. 1\textsuperscript{st} cluster – 32 stations, 2\textsuperscript{nd} cluster – 22 stations
\sim 40 nights, \sim 250 h
Processing and analysis is in progress.
Amplitude – Distance Function (ADF)
An Example of TAIGA-HiSCORE event reconstruction
Gravity Center Reconstruction

\[ \lg\left(\frac{E_0}{\text{TeV}}\right) = 2.0585 \quad \theta = 32.94^\circ \]

DATE = 1411

\[ N_{\text{ev}} = 711892 \]
EAS parameters reconstruction by $Q_{70}$

For energy $E_0 < 10^{15}$ eV:

$X_0, Y_0$ is the gravity center of $A_i$ for 4 stations, closest to the core.

$Q_{gc}$ is mean value by these 4 stations

Minimal event configuration:

Experimental correlations, obtained for the energy range $10^{15} - 3 \cdot 10^{15}$ eV, are extrapolated to lower energy:

$$Q_{70} = Q_{gc} \cdot 1.1(\sec(\theta) - 1) :$$

$$E_0 = C \cdot Q_{70}^{0.88} :$$
HiSCORE spectrum 2018

G.c. method:
2017 – 2018
~180 h
~ $10^6$ events

ADF fitting:
2016 – 2018
~ 500 h
~ $10^5$ events
$E_0$ Distribution

$E_\gamma = E_c / 1.8$
Tunka Primary Energy Spectra with EAS Cerenkov Light

Tunka-133:
350 clean moonless nights
2175 h
~375,000 events
With ~100% efficiency
~4200 events with $E_0 > 10^{17}$ eV

TAIGA-HiSCORE:
35 clean moonless nights
180 h
~900,000 events
with ~100% efficiency
Energy spectrum: power law fitting

\[ \frac{d^3N}{dE dO dE_0} \propto E^{-\gamma} \]

\[ \begin{align*}
\gamma_1 &= -2.73 \pm 0.01 \\
\gamma_2 &= -2.99 \pm 0.01 \\
\gamma_3 &= -3.3 \pm 0.1 
\end{align*} \]
Energy spectrum comparison with intermediate energy experiments
United Primary Energy Spectrum
$10^{13} - 10^{20}$ eV
Conclusions

1. United primary energy spectrum, obtained by the same method of EAS Chernkov light flux measurement cover 4 orders of magnitude and let us confirm that the primary energy measurements are in good agreement from relatively low ($10^{13}$ eV) to extremely high energy ($10^{20}$ eV)
Thank you!