Primary cosmic-ray spectra and composition in the energy range from $50 \text{ TeV}$ to $10^{16} \text{ eV}$ observed with the new Tibet hybrid experiment

J. Huang
for the Tibet ASγ Collaboration
huangjing@ihep.ac.cn
Institute of high energy physics, CAS, China, Beijing 100049
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• Knee of the spectrum
• New hybrid experiment (YAC+Tibet-III).
• Check interaction model dependence.
• Primary proton, helium spectra obtained by (YAC + Tibet-III).
• Summary
This hybrid experiment consists of low threshold Air shower core array (YAC) and Air Shower (AS) array and Muon Detector (MD).

Tibet-III (65700 m²) : Primary energy and incident direction.
YAC2 (500 m²): High energy AS core within several x 10m from the axis.
Tibet-MD (3400 m²): Number of muon.
Detector Calibration

1. PMT linearity, use of LED light source;

2. Linearity of PMT+scintillator,
   a. probe calibration;
   b. accelerator beam calibration.
- Full M.C. Simulation -

Hadronic interaction models

• CORSIKA (Ver. 7.5000)
  – EPOS LHC–
  – QGSJETII-04–
  – SIBYLL 2.3 –
  – SIBYLL 2.1 –

Primary composition models

- Helium poor model  [1]
- Helium rich model  [1]
- H4a model  [1]


= Air Shower simulation =

CORSIKA 7.5000 (EPOS –LHC, QGSJETII-04, SIBYLL2.3, SIBYLL2.1)

| ( 1 ) Primary energy: $E_0 > 1$ TeV |
| ( 2 ) All secondary particles are traced until their energies become 1 MeV in the atmosphere. |
| ( 3 ) Observation Site : Yangbajing (606 g/cm²) |

= Detector simulation =

(1) Geant 4 ( Ver. 9.5)

Simulated air-shower events are reconstructed with the same detector configuration and structure as the Tibet-III and YAC array.
Primary cosmic-ray composition spectrum assumed in MC

![Graph showing primary cosmic-ray composition spectrum](image)
Primary proton, helium spectra analysis
Primary proton, He spectra analysis

Identification of proton+helium events

ANN (a feed-forward artificial neural network) is used.

Input event features:

\[ N_e, \Sigma N_b, N_{b \text{ top}}, N_{\text{hit}}, <R_b>, <N_bR_b>, \theta \]

Classification: (proton+helium)/others

Primary (proton+helium) energy determination

\[ E_0 = f(N_e, s) \] based on (P+He)-like MC events
Core event selection
(Nb>200, \(N_{hit}\geq 4\), Nbtop \geq 1600, Ne>80000)

Statistics of core events in MC simulation and experiment
Live Time is 106.05 days.

<table>
<thead>
<tr>
<th>Selected core events</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EPOS-LHC+He-rich</td>
<td>680989</td>
</tr>
<tr>
<td>EPOS-LHC-He-poor</td>
<td>21726</td>
</tr>
<tr>
<td>QGSJETII-04+He-poor</td>
<td>21856</td>
</tr>
<tr>
<td>SIBYLL2.3+He-poor</td>
<td>10152</td>
</tr>
<tr>
<td>SIBYLL2.1+He-poor</td>
<td>19176</td>
</tr>
<tr>
<td>Expt.data</td>
<td>3416</td>
</tr>
</tbody>
</table>
Interaction model dependence in (YAC+Tibet-III) experiment
Primary \((P+He)\) separation by ANN for MC events

- **EPOS-LHC+He-poor**
  - Purity – 93.5%
  - Efficiency – 80.4%

- **QGSJETII-04+He-poor**
  - Purity – 93.7%
  - Efficiency – 83.0%

- **SIBYLL2.3+He-poor**
  - Purity – 94.3%
  - Efficiency – 82.3%

- **SIBYLL2.1+He-poor**
  - Purity – 93.0%
  - Efficiency – 80.0%
Comparison of the air-shower size \((N_e)\) between MC and Expt.data

(From this two figures, we can see that, the air-shower size \((N_e)\) has the shape very close to the MC prediction before and after ANN selection. Some other quantities have the same behavior as well.)

- **Before ANN (all events)**

- **After ANN \((T_{cut} \leq 0.3)\)**
  (Proton+He)-like events

Air shower size spectrum

J. Huang (ICRC2019, USA)
The primary energy ($E_0$) of each AS event is determined by the air-shower size ($N_{e}$) which is calculated by fitting the lateral particle density distribution to the modified NKG function.

**Modified NKG function**

\[
f(r) = \frac{1}{2\pi B(a(s, t) + 2, -b(s, t) - a(s, t) - 2)} \left(\frac{r}{r_m'}\right)^{a(s, t)} \left(1 + \frac{r}{r_m'}\right)^{b(s, t)} / r_m'^2
\]

\[t = \sec \theta - 1.\]
Air shower size to primary energy

\[ E_0 = \alpha N_e^{0.901} \]

\[ 1.0 \leq \sec \theta \leq 1.1 \]

25% @ 200 TeV

17% @ 1 PeV

J. Huang (ICRC2019, USA)
Check the systematic errors by ANN

The primary energy of (P+He)-like or P-like or Helium-like events is in a good agreement with the true primary energy spectrum.

J. Huang (ICRC2019, USA)
\[(S\Omega)_{\text{eff}} \text{ calculated by MC}\]
(YAC+Tibet-III) could measure protons and heliums spectra from 50 TeV to 200 TeV which is shown to be smoothly connected with direct observation data at lower energies. The results of the high energy above 200 TeV are under analysis.

J. Huang (ICRC2019, USA)
1. YAC shows the ability and sensitivity in checking the hadronic interaction models. High energy core events are very sensitive to the light components in CRs and the core parameters of $\text{sum Nb}$, $\text{Nb}_{\text{top}}$, $<R>$ and $<\text{Nb}*R>$ are very useful to separate the light components from all the observed events using a ANN technique.

2. (Tibet-III+YAC) could measure (P+He) spectra from 50TeV to 200TeV which is shown to be smoothly connected with direct observation data at lower energies. The results of the high energy above 200 TeV are under analysis.

3. The interaction models dependence in deriving the (P+He) spectra are found to be small (less than 20%), and the composition model dependence is less than 10% in absolute intensity, and various systematic errors are under study now!
Thank you for your attention!!