Hadronic interactions and EAS muon multiplicity investigated with the new Tibet hybrid experimental muon data

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(The Tibet AS\gamma Collaboration)
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The new Tibet hybrid experiment (Tibet-AS+MD)

The new Tibet ASγ experiment

- Tibet-AS array:
  - 597 plastic scintillation detectors
  - 65700 m² (Cover area)

- Tibet-MD array:
  - 64 water-Cherenkov-type detectors
  - 2.4 m underground
  - 3400 m² (Effective area)
Monte Carlo simulation

Air Shower Simulation  CORSIKA

- Hadronic interaction model: QGSJET01c, SIBYLL2.1 and EPOS-LHC
- Low-Energy hadronic Interaction model: GHEISHA
- Primary composition model: He-poor and He-rich
- Primary CRs energy: \( E_0 \geq 50 \text{ TeV} \)
- Zenith angle \( (\theta) \): \( 0 \sim 60^0 \)
- Energy of secondary particles trace: \( E_i \geq 1 \text{ MeV} \)
- Observation Site: Yangbajing (606 g/cm\(^2\))

Detector Simulation  Geant4

- Dropping Area:
  
  \[ 200 \text{ m} \times 200 \text{ m}, 100 \text{ m away from the Tibet-AS array center} \]

The detector performance, the trigger efficiency of detectors and the effective area are adequately taken into account based on the experimental conditions.
Comparison of Number of muon between GHEISHA and FLUKA for the Tibet-AS+MD array

The Tibet-MD array is located at 2.4 m underground beneath the Tibet-AS array, the mass thickness of the soil is equivalent to 19 radiation lengths, and the energy threshold for muons to penetrate the soil is approximately 1 GeV.

The Comparison of Number of secondary Muon in CORSIKA output with use of the low-energy hadronic interaction models GHEISHA and FLUKA as shown in the left figure, the shapes of the $N_\mu$ are almost the same, there are less than $\approx 5\%$ differences between them.

The results in this work are based on the GHEISHA model for low-energy hadronic interaction model in the CORSIKA.

ZhaoYang Feng, Ph.D. Theses, 2010.
The Primary Cosmic-ray Composition models

The proton spectrum of two models is fitted to the direct measurement at the low energy and consistent with the spectrum obtained from the Tibet-EC experiment at the high energy.

The Helium spectrum of He-poor model coincides with the results from RUNJOB and ATIC1, while the He spectrum of He-rich model coincides with the results from JACEE, ATIC2 and CREAM3.
The Data-select Condition

Data selection
- Number of the AS detectors hit $\geq 10$
- Number of particles per AS detector $\geq 1.6$
- Air shower Size (Ne) $\geq 10^5$
- The core position should be inside the inner most $135 \text{ m} \times 135 \text{ m}$ of area


<table>
<thead>
<tr>
<th>MC Expt. data</th>
<th>Number of Events selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSJET01c+He-poor</td>
<td>360574</td>
</tr>
<tr>
<td>SIBYLL2.1+He-poor</td>
<td>461655</td>
</tr>
<tr>
<td>EPOS-LHC+He-rich</td>
<td>786738</td>
</tr>
<tr>
<td>Expt.data</td>
<td>6287316</td>
</tr>
</tbody>
</table>

The cores distribution of events selected as shown in the *grey area* in the Up figure.
Comparison of Air Shower Size between MC and Expt. data

The Air Shower Size \( (N_e) \)

The distribution of air shower size \( (N_e) \) as shown in left figure, under the different zenith angles.

The shapes of the \( N_e \) are almost the same between the Expt. data and MC data.
The hadronic interactions and EAS muon multiplicity are investigated by comparing the following parameters reconstructed with the new Tibet ASγ hybrid experiment (Tibet-AS +MD):

- **Mean energy-flow spread (Tibet-AS array)**
  
  The mean energy-flow spread, \( <R_{AS}> = \sum N_i \cdot r_i / \sum N_i \)

- **\( \sum N_\mu \) (Tibet-MD array)**
  
  The Number of **total** muon of all fired MD detector units

- **Mean Lateral spread (Tibet-MD array)**
  
  The mean lateral spread, \( <R_{MD}> = \sum r_i / N_{hit} \)
Two data sets for Hadronic interactions and EAS muon multiplicity investigated

**Data-set-I (150 TeV)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy (TeV)</th>
<th>(P+He)/All (%)</th>
<th>(P+He)/All (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSJET01c+He-poor</td>
<td>~150 TeV</td>
<td>62.5 ± 0.5</td>
<td>68.0 ± 0.7</td>
</tr>
<tr>
<td>SIBYLL2.1+He-poor</td>
<td></td>
<td>62.0 ± 0.4</td>
<td>67.6 ± 0.6</td>
</tr>
<tr>
<td>EPOS-LHC+He-rich</td>
<td></td>
<td>76.6 ± 0.3</td>
<td>79.2 ± 0.4</td>
</tr>
</tbody>
</table>

**Data-set-II (1 PeV)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy (PeV)</th>
<th>(P+He)/All (%)</th>
<th>(P+He)/All (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSJET01c+He-poor</td>
<td>~1 PeV</td>
<td>39.2 ± 1.8</td>
<td>42.5 ± 2.4</td>
</tr>
<tr>
<td>SIBYLL2.1+He-poor</td>
<td></td>
<td>39.4 ± 1.6</td>
<td>42.1 ± 2.0</td>
</tr>
<tr>
<td>EPOS-LHC+He-rich</td>
<td></td>
<td>51.7 ± 1.1</td>
<td>54.9 ± 1.4</td>
</tr>
</tbody>
</table>
Comparison of Mean energy-flow spread obtained by Tibet-AS

Mean Energy-flow spread $<R_{AS}>$

- $\sim 150$ TeV
- $1.2 < \sec(\theta) \leq 1.4$

Mean Energy-flow spread $<R_{AS}>$

- $\sim 150$ TeV
- $1.0 < \sec(\theta) \leq 1.1$

Mean Energy-flow spread $<R_{AS}>$

- $\sim 1$ PeV
- $1.2 < \sec(\theta) \leq 1.4$

Mean Energy-flow spread $<R_{AS}>$

- $\sim 1$ PeV
- $1.0 < \sec(\theta) \leq 1.1$
Comparison of $\Sigma N_\mu$ obtained by Tibet-MD

$\sim 150$ TeV

$1.0 < \sec(\theta) \leq 1.1$

$\sim 1$ PeV

$1.0 < \sec(\theta) \leq 1.1$

$\sim 150$ TeV

$1.2 < \sec(\theta) \leq 1.4$

$1.0 < \sec(\theta) \leq 1.1$

$\sim 1$ PeV

$1.2 < \sec(\theta) \leq 1.4$
Comparison of Mean Lateral spread obtained by Tibet-MD

~150 TeV

1.0<sec(θ) ≤ 1.1

~1 PeV

1.0<sec(θ) ≤ 1.1

1.2<sec(θ) ≤ 1.4

1.2<sec(θ) ≤ 1.4
Summary

1. We check three hadronic interaction models (QGSJETI01c, SIBYLL2.1 and EPOS-LHC) and investigate the Number of total muon with use of the data of (Tibet-AS+MD) array, by comparing the distribution of some parameters (Ne, Nµ, mean lateral spread, etc.) between MC and Expt. data in different zenith angles and different energy regions, and we found that the SIBYLL2.1 and EPOS-LHC models could reproduce the Expt. data well, while there are some differences in the distribution of $\sum N_\mu$ between the QGSJET01c model and Expt. data.

2. The checking of hadronic interaction models and muon multiplicity mentioned in this work are under the all-particle data-sets, which are the mix components, the more detailed work will be discussed in the near future.

Thank you for your attention!