First Interaction of Air Shower and Monte Carlo Performance of ASHRA

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Motivation

High resolution fluorescence imaging of air shower could resolve the fundamental interaction, weak interaction, heavy quark production etc., those has been usually ignored or averaged in air shower modeling. The first interaction of air shower is studied using PYTHIA Monte Carlo. Background for VHE neutrino detection is discussed.

Results are very preliminary.
VHE neutrino detection

Detection Method (Basic scenario)
- Deeply penetrated AS (X_{1st}(X_{max}))
- Double-Bang signature for \( \nu_\tau \)
- “Earth-Skimming event” for \( \nu_\tau \) (Feng et al.)

Background Source
- \( X_{1st} \) fluctuation of hadron interaction
- \( X_{max} \) fluctuation of hadron shower
- Double-Bang signature due to shower fluctuation

Study using PYTHIA
PYTHIA Monte Carlo

- Version 6.125
- Widely used in particle physics community for more than 20 years

This study:
- No shower simulation
- No nuclear effect
- Calculation based on QCD high Pt process
- Typically $E = 10^{18}\ eV$
Air Shower MC

The study is made using CORSIKA. The simulation:
- for proton-air interaction.
- Hard collision simulated by PYTHIA.

Our simulation:
- \( X_{1st} = 83.1(E/GeV)^{-0.052} \text{ g/cm}^2 \) for proton-air interaction.
- Hard collision simulated by PYTHIA.

“Late starting” event ratio (4/200) is almost consistent with our simulation (0.064) for \( E=10^{14}\text{eV} \).
CR events should be suppressed by a factor of 1/R for neutrino detection

* Assume $E^{-3}(E^{-2})$ dependence for CR (neutrino) flux

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Flux Ratio</th>
<th>Cross Section Ratio</th>
<th>Event Rate Ratio (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{20}$</td>
<td>1</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>$10^2$</td>
<td>$6 \times 10^6$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>$10^4$</td>
<td>$3 \times 10^8$</td>
<td>$10^{15}$</td>
</tr>
</tbody>
</table>

* Aperture not take into account.
First Interaction Depth ( $X_{1st}$)

Suppression factor by $X_{1st}$ cut

<table>
<thead>
<tr>
<th>$X_{1st} (g/cm^2)$</th>
<th>300</th>
<th>700</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (eV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{20}$</td>
<td>$3 \times 10^{-5}$*</td>
<td>$5 \times 10^{-13}$</td>
<td>$7 \times 10^{-19}$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>$7 \times 10^{-4}$*</td>
<td>$5 \times 10^{-10}$*</td>
<td>$1 \times 10^{-14}$</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>$9 \times 10^{-3}$*</td>
<td>$1 \times 10^{-7}$*</td>
<td>$3 \times 10^{-11}$*</td>
</tr>
</tbody>
</table>

* Need more suppression factor

Actual cut on $X_{\text{max}}$ is affected by the shower fluctuation ($X_{\text{max}} + \sigma_{\text{max}}$)
Double-bang signature for $\nu_\tau$

Our simulation:
- For $\nu_\tau$, $X_{2nd} = ct\gamma$.
- Each leading baryon forms independent shower cluster starting at $X_{2nd}$.

$L_\tau \sim 5$km @ $E_\nu = 10^{17}$ eV
Energy fraction

Energy fraction carried away by leptons (tau)

Energy fraction carried away by most energetic baryons

\[ \nu p \]

\[ p p \]

Tau lepton tends to carry more than half energy.
Neutrino detection

• Enough suppression is obtained by $X_{1st}$ cut for $E = 10^{18-20}$ eV:

$$X_{1st} > 700(1000)\text{g/cm}^2 \text{ for } E=10^{20}(10^{18}) \text{ eV}$$

• We could gain the acceptance by relaxing $X_{1st}$ for higher energy neutrinos.

For tau neutrino:
• Leading baryon is main background source for double-bang signature.
• Additional suppression is made by $X_{2nd}$ cut and $E_2/E$ cut.

$$\sim 10^{-3}(10^{-4}) \text{ if } X_{2nd} > 600 \text{g/cm}^2 \text{ (and } E_2/E>0.5) \text{ @} E=10^{18}\text{eV}$$

• Enough suppression is obtained for $E > 10^{17}$ eV.
$P_T$ distribution

$P_T$ is well contained within $10\text{GeV/c}$. Pointing resolution of ASHRA, 1 arcmin, is not spoiled by $P_T$.

High Pt tail due to heavy quark production
Transverse Momentum of Tau (Leptons)

$W$-exchange process produces large transverse momentum of leptons above $s > m_W^2$.

100 GeV/c
Recoil hadron Pt for CC interaction

Hadron Pt distribution measured at HERA, the ep scattering at $\sqrt{s} = 320 GeV$.

PYTHIA reproduces this distribution.

H1 Collaboration, proc. 30th ICHEP (Osaka) (2000)
Heavy quark production

Heavy quark production is main background source for large Pt (V-shower) signature.

The suppression is made by F.L. -P_T cut.

Study is in progress.
Earth-skimming tau neutrino


\[ L_\tau \sim 5\text{km} @ E_\nu = 10^{17} \text{eV} \]

After the competition among target mass, energy loss in the target and the decay length, observable Tau energy concentrate on energy around \( \sim 10^{17}\text{eV} \).

The acceptance study is done using FLUOS Monte Carlo.
FLUOS

FLUOS is Monte Carlo package developed for Telescope Array.

FLUOS package
• Gaisser-Hillas function for longitudinal development
• NKG function for lateral profile
• Air fluorescence spectrum
• Rayleigh scattering
• Mie scattering
• Telescope parameters: mirror reflectance, filter transmittance, quantum efficiency ...

The pointing resolution and the acceptance of ASHRA are studied using FLUOS.
Arrival direction measurement

ASHRA features highly precision measurement on arrival direction.

Method:
• Fitting on the Shower-Detector Plane (SPD fit)
• $\theta$ measurement using timing information
• Stereo measurement
• Event coincidence assuming a point source
Angular resolution by stereo reconstruction for $CC\nu_e$ events.

Accuracy of direction measurement

Angular Resolution [degree]

Number of Events

$E = 10^{19}$ eV

$E = 10^{20}$ eV

1 arcmin

0.03

18

Stereo Reconstruction

Log$_{10}$ (Kinetic Energy [eV])
Event coincidence

Sensitivity for neutrinos is maximized at single-station observation.

Deterioration of $\psi$ measurement due to mono reconstruction.

Arrival direction of neutrino could be measured in good resolution by making event coincidence: $\sigma \sim 0.01$. 
Neutrino flux
Neutrino acceptance

Acceptance from FLUOS MC

Earth-skimming tau neutrino

Deep penetrating tau neutrino

10^2

10^{17}

10^{17}
## Event rate for mono observation

<table>
<thead>
<tr>
<th>Source</th>
<th>$CC_{\nu_e}$</th>
<th>$CC_{\nu_\mu}$</th>
<th>$CC_{\nu_\tau}$</th>
<th>NC</th>
<th>ES$<em>{\nu</em>\tau}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greisen</td>
<td>0.26</td>
<td>0.13</td>
<td>0.18</td>
<td>0.16</td>
<td>1.16</td>
<td>1.90</td>
</tr>
<tr>
<td>AGN-jet</td>
<td>3.5</td>
<td>1.3</td>
<td>2.1</td>
<td>1.6</td>
<td>17.4</td>
<td>25.9</td>
</tr>
<tr>
<td>AGN-core</td>
<td>2.2</td>
<td>0.2</td>
<td>0.9</td>
<td>0.5</td>
<td>1.7</td>
<td>5.4</td>
</tr>
<tr>
<td>GRB</td>
<td>0.26</td>
<td>0.10</td>
<td>0.15</td>
<td>0.12</td>
<td>1.00</td>
<td>1.64</td>
</tr>
<tr>
<td>TD</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.11</td>
<td>0.28</td>
</tr>
<tr>
<td>Z-Bursts</td>
<td>0.32</td>
<td>0.21</td>
<td>0.20</td>
<td>0.22</td>
<td>0.32</td>
<td>1.27</td>
</tr>
</tbody>
</table>

*Assume 10% duty factor*
Event rate for stereo observation

<table>
<thead>
<tr>
<th></th>
<th>$CC_{\nu_e}$</th>
<th>$CC_{\nu_\mu}$</th>
<th>$CC_{\nu_\tau}$</th>
<th>NC</th>
<th>ES$<em>{\nu</em>\tau}$</th>
<th>ToTal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greisen</td>
<td>0.11</td>
<td>0.03</td>
<td>0.06</td>
<td>0.05</td>
<td>0.16</td>
<td>0.42</td>
</tr>
<tr>
<td>AGN-jet</td>
<td>0.9</td>
<td>0.2</td>
<td>0.4</td>
<td>0.3</td>
<td>1.2</td>
<td>3.0</td>
</tr>
<tr>
<td>AGN-core</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>GRB</td>
<td>0.07</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.09</td>
<td>0.25</td>
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<tr>
<td>TD</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.13</td>
</tr>
<tr>
<td>Z-Bursts</td>
<td>0.22</td>
<td>0.13</td>
<td>0.12</td>
<td>0.14</td>
<td>0.14</td>
<td>0.74</td>
</tr>
</tbody>
</table>

* Assume 10% duty factor
Conclusions

• First interaction study using PYTHIA Monte Carlo.
• VHE neutrino, $E>10^{18}\text{eV}$, would be detectable with background suppression by $X_{1st}$ cut.
• Clear tau neutrino signal would be obtained as double-bang signature for deeply penetrated air shower events for $E>10^{17}\text{eV}$ with $X_{2st}$ cut.
• High $P_T$ signature might be useful for lower energy neutrino detection.
• Earth-skimming tau neutrino is detectable by ASHRA.
• Arrival direction is measured in good resolution, $\sigma = 1\text{ arcmin}$, by stereo reconstruction and also event coincidence of mono reconstruction.
• ASHRA has excellent sensitivity to neutrino events.
• Need shower fluctuation study.