What can we know on hadron superhigh-energy interaction fragmentation range by XREC data?

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Abstract. Data on most energetic particles in EAS cores (γ-ray-hadron families) obtained with XRECs at superhigh energies in stratospheric and high-mountain experiments are discussed. Transverse size and alignment of most energetic subcores in γ-h families are considered. Lateral features of γ-ray families are shown to be dependent on \( p_t(x_{Lab}) \) at \( 0.05 \lesssim x_{Lab} \lesssim 0.20 \) in h-A interactions. Features of interactions at \( E_0 \gtrsim 10^{15} \) are formulated.

1. Introduction

All the ground-based astrophysical experiments exploit simulations of air cascade development at energies \( E_0 \gtrsim 10^{11} \) eV of particles of primary cosmic radiation (PCR). The best hadron-air nucleus (h-A) interaction model is not chosen yet. A number of models used by the CORSIKA package are tuned by using sea-level EAS data. High-mountain high-resolution X-ray emulsion chamber (XREC) results are not taken into account although the XREC techniques makes it possible to detect groups of EAS-core high-energy (\( E \gtrsim 4 \) TeV) hadrons, \( e^\pm \) and γ-rays (γ-h families) which seem to be very sensitive to model variations. Besides, the majority of γ-h families is produced by PCR protons that decreases uncertainties related to the PCR mass composition. Thus, γ-h families could be used to tune models at \( \sqrt{s} \approx 1 - 20 \) TeV (\( E_0 \approx 10^{15} - 5 \cdot 10^{17} \) eV) by comparing some experimental and simulated data.

2. γ-ray families at \( \sqrt{s} \lesssim 5 \) TeV

In [1] simulations of γ-ray families are made using PCR particles at \( E_0 \gtrsim 10^{15} \) eV. The following families at a depth of 600 g·cm\(^{-2}\) are selected: γ-ray multiplicity \( N_\gamma \geq 4 \), distance of particles with energy \( E_\gamma \geq 4 \) TeV from the event center \( R_\gamma \leq 15 \) cm; energy \( \sum E_\gamma = 100 - 400 \) TeV.

The transverse momentum, \( p_t \), is the most important factor influencing on lateral features of γ-ray families. However, their interrelation is implicate. Figure 1 (figure 2 in [1]) shows dependence of the average of mean radii of proton-initiated γ-ray families, \( \langle R_\gamma \rangle_p \), and charged-particle \( \langle p_t \rangle \) values at \( E_0 = 10^{16} \) eV for all the models under consideration (MC0 [2], FANSY 1.0/QGSJ and FANSY 1.01/QGSJ models [3, 4] as well as CORSIKA’s QGSJET 01, QGSJET II, SYBILL 2.1, EPOS 1.99 models). The scatter in \( \langle R_\gamma \rangle_p \) values is obviously much larger than that in \( \langle p_t \rangle \) values. No understandable correlation between \( \langle p_t \rangle \) and \( \langle R_\gamma \rangle_p \) is found.

Growth of inelastic cross section \( \sigma_{inel}^{p-air} \) or inelasticity coefficient \( \langle K_{inel}^{p-air} \rangle \) as well as softening of spectra of secondary particles could accelerate the cascade development and energy
As a result, energy of particles decreases on an average, and, consequently, \( \langle R_e \rangle \) increases at the same \( p_t \). However, analysis shows that some definite correlation between these factors and size of families is unobvious [1].

As the contribution of high-\( x_{\text{Lab}} \) particles (\( x_{\text{Lab}} = p_Z/p_{\text{tot}} \)) into the cascade transverse evolution at the initial stage is obviously higher than that of low-\( x_{\text{Lab}} \) particles, one can search for some effective \( x_{\text{Lab}} \) range [1]. Figure 2 (Figure 1 in [1]) shows a significant difference between \( p_t(x_{\text{Lab}}) \) dependencies realized by models in p-air interactions at \( E_0^{p-\text{air}} = 10^{16} \) eV. The FANSY 1.01 and 1.01 models differ only in behaviour of \( p_t(x_{\text{Lab}}) \) dependence at \( 0.01 \lesssim x_{\text{Lab}} \lesssim 0.5 \) and are identical in all other characteristics.

Three types of (1) \( x_{\text{Lab}} \)-independent, (2) \( x_{\text{Lab}} \)-dependent and (3) \( x_{\text{Lab}}^2 \)-dependent \( p_t \)-dependent parameters for \( N \) particles generated in “truncated” kinematic ranges, \( x_{\text{min}} \leq x_{\text{Lab}} \leq x_{\text{max}} \) are defined [1]:

\[
\langle p_t \rangle_{x_{\text{min}}-x_{\text{max}}} = \sum_{i=1}^{N} p_{ti}/N \quad (1),
\]

\[
\langle p_t \rangle_{x_{\text{min}}-x_{\text{max}}} = \sum_{i=1}^{N} p_{ti}x_{\text{Lab}i}/\sum_{i=1}^{N} x_{\text{Lab}i} \quad (2),
\]

\[
\langle p_t \rangle_{x_{\text{min}}-x_{\text{max}}} = \sum_{i=1}^{N} p_{ti}x_{\text{Lab}i}^2/\sum_{i=1}^{N} x_{\text{Lab}i}^2 \quad (3),
\]

Parameters (1) – (3) are calculated at \( x_{\text{min}} = 0 \), \( 0.07 \) and \( x_{\text{max}} = 0.2 \) – 1.0. Non-zero \( x_{\text{min}} \) and non-unity \( x_{\text{max}} \) values are used to exclude lowest-energy particles (which do not influence the real cascade development) and fluctuating contribution of the most energetic particle. Correlations between \( \langle R_e \rangle^{p} \) and parameters (1) – (3) are searched in the form \( Y = m \cdot X + \text{const} \) [1]. Here \( m \) is found by the OLS Method for relative variables \( X \) and \( Y \) defined for any parameter \( P \) calculated with using one of Eqs. (1) – (3) for any model as

\[
X = P_{\text{model}}/P_{\text{FANSY 1.01}}, \quad Y = \langle R_e \rangle_{p,\text{model}}^{\gamma}/\langle R_e \rangle_{\text{FANSY 1.01}}^{\gamma}.
\]

The determinancy coefficient, \( r^2 \), is additionally calculated. Results are perfect at \( m = r^2 = 1 \) [1].

Analysis of “truncated” parameters for different \( x_{\text{min}} \) and \( x_{\text{max}} \) show that the general trend is a growth of correlation with approaching of \( x_{\text{min}} \) to \( \sim 0.05 \) and \( x_{\text{max}} \) to \( \sim 0.20 \) for all the models excluding QGSJET II which deviates from this trend. The last requires a special analysis. So, \( m \) is calculated below for all the models, excluding QGSJET II, and denoted \( m_{p_t} \). An example of the real correlation is given in figure 3, which shows strong correlation of \( \langle R_e \rangle^{p} \) with \( \langle p_t \rangle_{x \sim 0.07-0.20} \) (\( m_{p_t} = 1.14 \pm 0.09, \quad r^2 = 0.97 \)).

To compare model and experimental data, it is necessary to account for PCR composition as well as the XREC response and measurement procedures, which result in some increase of \( \langle R_e \rangle \) by a factor of \( 1.14 \pm 0.04 \) [6]. Figure 4 shows dependence of model \( \langle R_e \rangle^{\text{all}} \) values on \( \langle p_t \rangle_{x \sim 0.05-0.50} \) found for all-nuclei-initiated \( \gamma \)-ray families with \( \sum E_\gamma = 100 \) – 400 TeV. The Pamir’s value [7] is shown by shadowed area including statistical errors. Only FANSY 1.01 gives a little lower \( \langle R_e \rangle^{\text{all}} \).
value as compared with experimental value. Other model points (MC0, EPOS 1.99, QGSJET 01, QGSJET II, SYBILL 2.1 and especially FANSY 1.0) are higher than the experimental value. Thus, the most reliable model must be characterized by $x_{\text{Lab}}$-weighted transverse momentum being as large as $\sim 0.55 - 0.60$ GeV/c at $x_{\text{Lab}} \approx 0.05 - 0.30$ and $E_0^{\text{p-air}} = 10^{16}$ eV.

3. $\gamma$-ray families at $\sqrt{s} \gtrsim 6$ TeV

3.1. Coplanarity phenomenon

Some tendency for a coplanarity of most energetic cores of $\gamma$-ray–hadron families has been first found by the Pamir Collaboration in XREC experiments [8, 9, 10, 11, 12] and confirmed later in Mt.Canbala experiment [13] as well as in the Strana and JF2af2 stratospheric events [14, 15, 16]. While assuming this effect to be produced by known elementary particles, it is related to hadron-nucleus interactions at $E_0 \gtrsim 10^{16}$ eV [17], i.e., $\sqrt{s} \gtrsim 6$ TeV, and can be characterized by large transverse momenta (up to $\sim n \cdot 10$ GeV/c) [18].

Is this phenomenon caused by either cascade development fluctuations or new features of hadron interactions at super-high energies? In the latter case, some coplanarity process generates most energetic fragmentation-range ($x_{\text{Lab}} \gg 0.01$) particles with longitudinal momenta $p_z$ situated in some plane. One component ($p_x$, e.g.) of their transverse momenta is situated in this plane. Difference between $p_x$ values determined by the coplanar particle generation (CPG) can be very large. Values of $p_y$ components are assumed to be traditional.

3.2. Cascade fluctuations or hadron interactions?

Four versions of $pp$ and $pN$ interactions of the FANSY 1.0 model, namely, a traditional QGSJ version as well as very weak (feeble), moderate (weak), and extremist (strong) versions of CPG, are designed to study the coplanarity phenomenon [3, 4]. The versions differ in terms of transverse momentum and pseudorapidity only, for instance, in energy dependence of the coplanar transverse momentum distributions.

Second column in Table 1 shows probabilities to observe experimental coplanar family number $N_{\text{copl}}$ found in different experiments (first column) found with FANSY 1.0/QGSJ model. The total probability for these experimental results to be produced by fluctuations is estimated by multiplying single probabilities as low as $\sim 10^{-15}$ [4]. Thus, the explanation of the phenomenon with trivial fluctuations in the framework of traditional-type models seems to be improbable.

Third, forth and fifth columns show probabilities to observe experimental data on family coplanarity in the framework of feeble, weak, strong versions of FANSY 1.0 model. Obviously, the strong version gives results being most close to experimental data. However, figure 4

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**Figure 3.** Correlation between $\langle R_\gamma \rangle^p$ and $\langle p_t \rangle_{x=0.07-0.20}$.

**Figure 4.** Correlation between $\langle R_\gamma \rangle^{\text{all}}$ and $\langle p_t \rangle_{x=0.05-0.50}$.
Table 1. Probabilities $w_i$ to observe real (or larger) experimental number of coplanar families in accordance with FANSY 1.0 versions. Columns: 1. Experimental data set; 2 - 5. Probabilities $w_i$ calculated with $QGSJ$ (2), $feeble$ (3), $weak$ (4), $strong$ (5).

| Experimental data | QGSJ | feeble | weak | strong |
|-------------------|------|--------|------|--------|
| Pamir (Ph)        | $(11 \pm 7) \cdot 10^{-6}$ | $(7 \pm 4) \cdot 10^{-5}$ | $(5 \pm 2) \cdot 10^{-4}$ | 0.008 $\pm$ 0.003 |
| Pamir (C)         | 0.026 $\pm$ 0.010 | 0.050 $\pm$ 0.021 | 0.16 $\pm$ 0.04 | 0.62 $\pm$ 0.06 |
| Mt. Kabanal        | 0.012 $\pm$ 0.004 | 0.030 $\pm$ 0.007 | 0.045 $\pm$ 0.010 | 0.076 $\pm$ 0.013 |
| the Strana        | 0.0026 $\pm$ 0.0003 | 0.0046 $\pm$ 0.0004 | 0.017 $\pm$ 0.001 | 0.093 $\pm$ 0.002 |
| the JF2af2        | $(9 \pm 3) \cdot 10^{-4}$ | 0.0027 $\pm$ 0.0005 | 0.010 $\pm$ 0.001 | 0.030 $\pm$ 0.002 |

demonstrates that FANSY 1.0/QGSJ gives too wide $\gamma$-ray families due to too high $p_t$ values at $x_Lab \approx 0.05 - 0.50$ (figure 2). As a result, high CPG cross section is required by FANSY 1.0 to explain experimental data. FANSY 1.01 seems to be a more promising model, as it gives lower $p_t$ values in the same $x_Lab$ range and, as a result, requires a lower CPG cross section to get the same alignment of $\gamma$-$h$ families.

Conclusion
A preferable model of hadron-nucleus interactions must have the following features of the fragmentation range of secondary particles at $\sqrt{s} \approx 1 - 20$ TeV.

a) average transverse momentum $p_t$ is to be $\sim 0.45 - 0.50$ GeV/c (while $x_Lab$-weighted value is to be $\sim 0.55 - 0.60$ GeV/c) at $x_Lab \approx 0.05 - 0.30$ and $\sqrt{s} \approx 5$ TeV; b) coplanar particle generation at $\sqrt{s} \geq 6$ TeV could be described by a model like FANSY 1.01/weak. Such combination could pretend to describe XREC data on both transverse size and alignment of $\gamma$-$h$ families.

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