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Behaviour of the lateral shower age of cosmic ray extensive air showers

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Abstract. *Some simple arguments are introduced for a possible explanation of the behaviour of the lateral shower age of proton-initiated showers. The corresponding analytical treatment based on the proposed argument is then illustrated. Using the Monte Carlo simulation code CORSIKA, we have validated how the different characteristics associated with the lateral shower age predicted in the present analytical parameterization, can be understood. The lateral shower age of a proton-initiated shower and its correlations with the lateral shower ages of electron- and neutral pion-initiated showers supports the idea that the result of superposition of several electromagnetic sub-showers initiated by neutral pions might produce the lateral density distribution of electrons of a proton initiated shower. It is also noticed with the simulated data that the stated feature still persists even in the local shower age representation.*

1. INTRODUCTION

- In the EM cascade theory, every shower has to be assigned by an age, and it remains true for showers generated by hadrons or nuclei as well.
- Basically the trace of the shape/form of the lateral distribution of shower electrons is indicated by the shower age in the EM cascade theory for showers generated by electron/gamma-ray, and is fairly valid also for hadron/nuclei initiated showers.
- The lateral shower age is obtained by fitting the electron lateral density data (LDD) with the NKG type lateral density function.
- Experimentally it is observed that the lateral density function with a single *age* is insufficient to describe the LDD of EAS electrons properly at all distances, which implies that the lateral age changes with the radial distance.
- Under the above circumstances, the notion of *local shower age parameter* (LAP) had been introduced, which is in essence the lateral age at a point.
- With the help of a simple analytic approach, a more deeper physical insights on the concept of shower age parameter generated by p/nuclei is being investigated here.

2. ELEMENTS OF THE ANALYTIC METHOD

The superposition principle applied to electron-photon sub-cascades in a shower requiring the following equality,

$$N_e C(s) X^{s-2}(1+X)^{s-4.5} = \sum_i |N_{e_i} C(s_i) x^{s_i-2}(1+X)^{s_i-4.5}| \quad (1)$$

Dividing (1) by the LDF of an EM cascade initiated by an electron/gamma, i.e. $N_e C(\acute{s}) X^{\acute{s}-2}(1+X)^{\acute{s}-4.5}$, we have,

$$s \approx \acute{s} + \frac{ln \sum_i \alpha_i h^{\delta_i}}{ln(h)} \quad (2)$$

with $\alpha_i = \frac{N_{e_i}}{N_e}, h = X(1+X), X = \frac{r}{r_m}, \delta_i = s_i - \acute{s}$

and $C(s) \approx C(\acute{s}) \approx C(s_i)$ and if $s_1 \approx s_2 \ldots\ldots \approx s_i \ldots\ldots \approx \tilde{s}$, and also

$$\delta \approx \tilde{s} - \acute{s}, \quad s \approx 2\acute{s} - \tilde{s} \quad (3)$$

Again, $s_{local}^{Had}(i,j) = \frac{ln(F_{ij} X_{ij}^2 Y_{ij}^{4.5})}{ln(X_{ij} Y_{ij})}; F_{ij} = \frac{f(r_i)}{f(r_j)}, X_{ij} = \frac{r_i}{r_j}, Y_{ij} = \frac{(r_i + r_M)}{(r_j + r_M)}$

and, $s_{local}^{EM}(i,j) = \frac{ln(\acute{F}_{ij} \acute{X}_{ij}^2 \acute{Y}_{ij}^{4.5})}{ln(X_{ij} \acute{Y}_{ij})}$ and finally, $s_{local}^{Had}(i,j) \approx \frac{ln(\sum_k \widetilde{F_{ij,k}} \widetilde{X_{ij,k}^2} \widetilde{Y_{ij,k}^{4.5}})}{ln(\widetilde{X_{ij,k}} \widetilde{Y_{ij,k}})}$

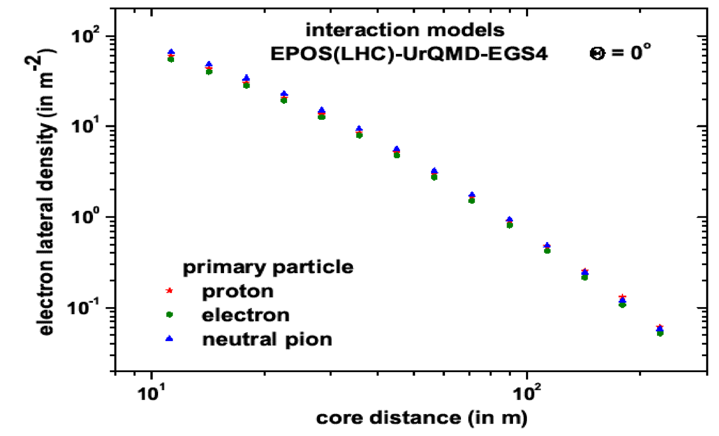
Like (3), we obtained, $\delta \approx s_{local}^{Had}(min) - s_{local}^{EM}(\acute{min}) \approx s_{local}^{EM}(min) - s_{local}\widetilde{(min)}$ (4)

3. MONTE CARLO DATA SAMPLE AND KCDC DATA

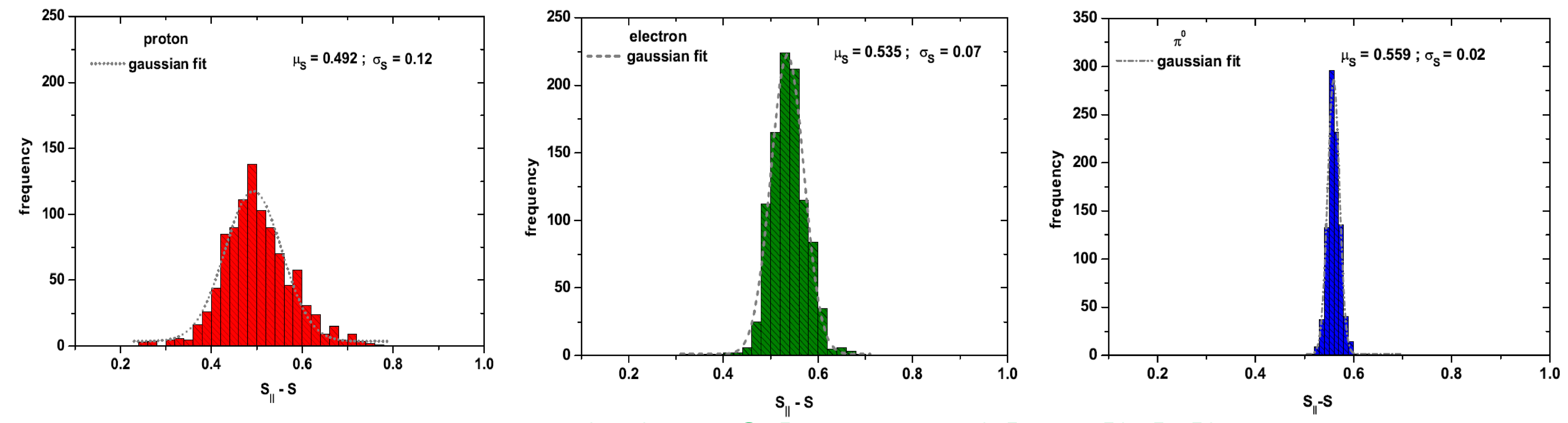
- CORSIKA Monte Carlo program version 7.7401
  - High-energy model: EPOS-LHC
  - Low energy model: UrQMD
  - Electromagnetic Interaction model: EGS4
- Location: KASCADE (Karlsruhe)
  - Energy: 2×10^{15} eV; M C Events: 3000

4. RESULTS

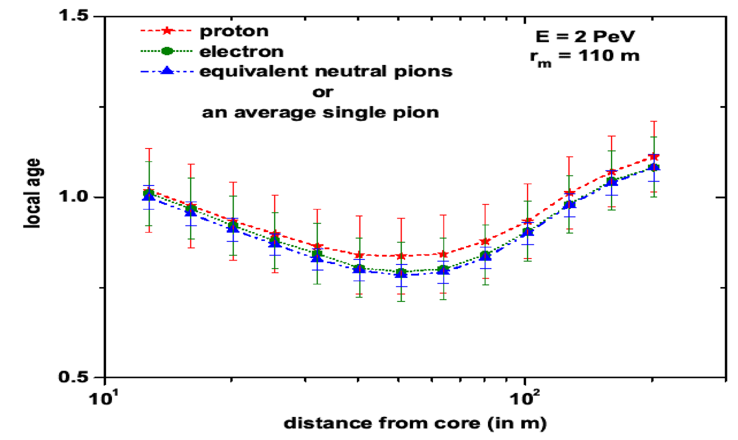
4.1. Lateral density distribution of electrons for p, e^-, π^0- initiated showers



4.2. Correlation between the lateral and longitudinal shower ages



4.3. Variation of the LAP with radial distance



t in gcm^{-2}	s	$\acute{s}$	$\tilde{s}$
850	0.8744 ± 0.052	0.8139 ± 0.014	0.7946
900	0.8844 ± 0.065	0.8248 ± 0.027	0.8081
950	0.8988 ± 0.071	0.8350 ± 0.035	0.8128
1022	0.9079 ± 0.081	0.8547 ± 0.044	0.8105

dt in gcm^{-2}	ds	$d\acute{s}$	$d\tilde{s}$
50	0.0100	0.0109	0.0135
50	0.0144	0.0102	0.0047
72	0.0091	0.0197	−0.0023

Left: Average lateral shower ages associated with p, e^-, π^0- initiated showers at different atmospheric depths at the KASCADE site; **Right** : The change of lateral shower ages with atmospheric depths.

5. CONCLUSIONS

1. The simulated electron LDDs of p, e^-, π^0- initiated showers equivocally support the idea, explained in the adopted simple analytical argument.
2. The difference in the numerical values between the lateral and longitudinal shower ages can be explained as the result of superposition of several EM sub-showers initiated by π^0-s mostly from a predetermined atmospheric level at the KASCADE site.
3. The radial variation of the local age has reiterated the fact that a single value of s is inadequate to describe the LDD of electrons accurately by a LDF (NKG) in the entire radial distance from the EAS core. The nature of variation of the LAP for p, e^-, π^0-initiated showers are portrayed as a generic feature of the LDDs of electrons in showers.
4. The numerical value of the difference $\delta \approx s - \acute{s} \approx 0.053$, indicates that the radial dependence of s is different than that of $\acute{s}$, because of the 2nd term in eq. (2). This result reveals the fact that for pure EM cascade the LDD is steeper than that of the hadronic cascade. Moreover, π^0-initiated sub-shower is steeper than that of a pure EM shower.
5. The conclusion drawn in (4) is valid in terms of local shower ages as well.

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