Implications of the Angular Spread of Shower Particles for the Fluorescence Technique

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[J. Alvarez-Muñiz *et al.* PRD 67, 101303 (2003)]

Air Light 2003, Bad Liebenzell, GERMANY

Idea

The "classic" method of determination of $N_e(X)$ is subject to a purely geometrical correction due to the lateral spread of shower particles.

$$N_\gamma^{\text{fluor}}(X) = g\, N_e(X)\, Y \Delta X \qquad (1)$$

$N_\gamma^{\text{fluor}}(X)$: Number of fluorescence γ emitted at depth X

$N_e(X)$: Shower Size at depth X

$Y \Delta X$: Number of fluorescence γ's emitted per e

Y: Fluorescence yield per e per meter of track $[\frac{\gamma}{m}]$

ΔX: Segment of shower along axis [m]

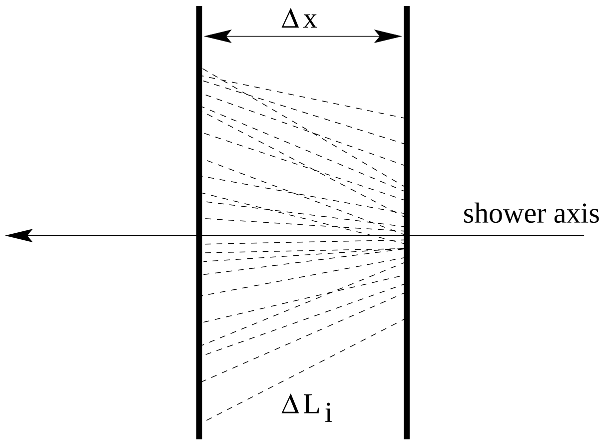
g: Corrects for:
- light attenuation
- mirror area

Idea

Point: Yield is measured per meter of track along the e's direction

The average number of fluorescence γ's per e $= Y \Delta L$

ΔL: Average track length of the e's in ΔX regardless of the e's direction



$$N_e^{\text{infer}} = \frac{N_\gamma^{\text{fluor}}(X)}{g\ Y \Delta X} \longrightarrow N_e^{\text{true}} = \frac{N_\gamma^{\text{fluor}}(X)}{g\ Y \Delta L} \qquad (2)$$

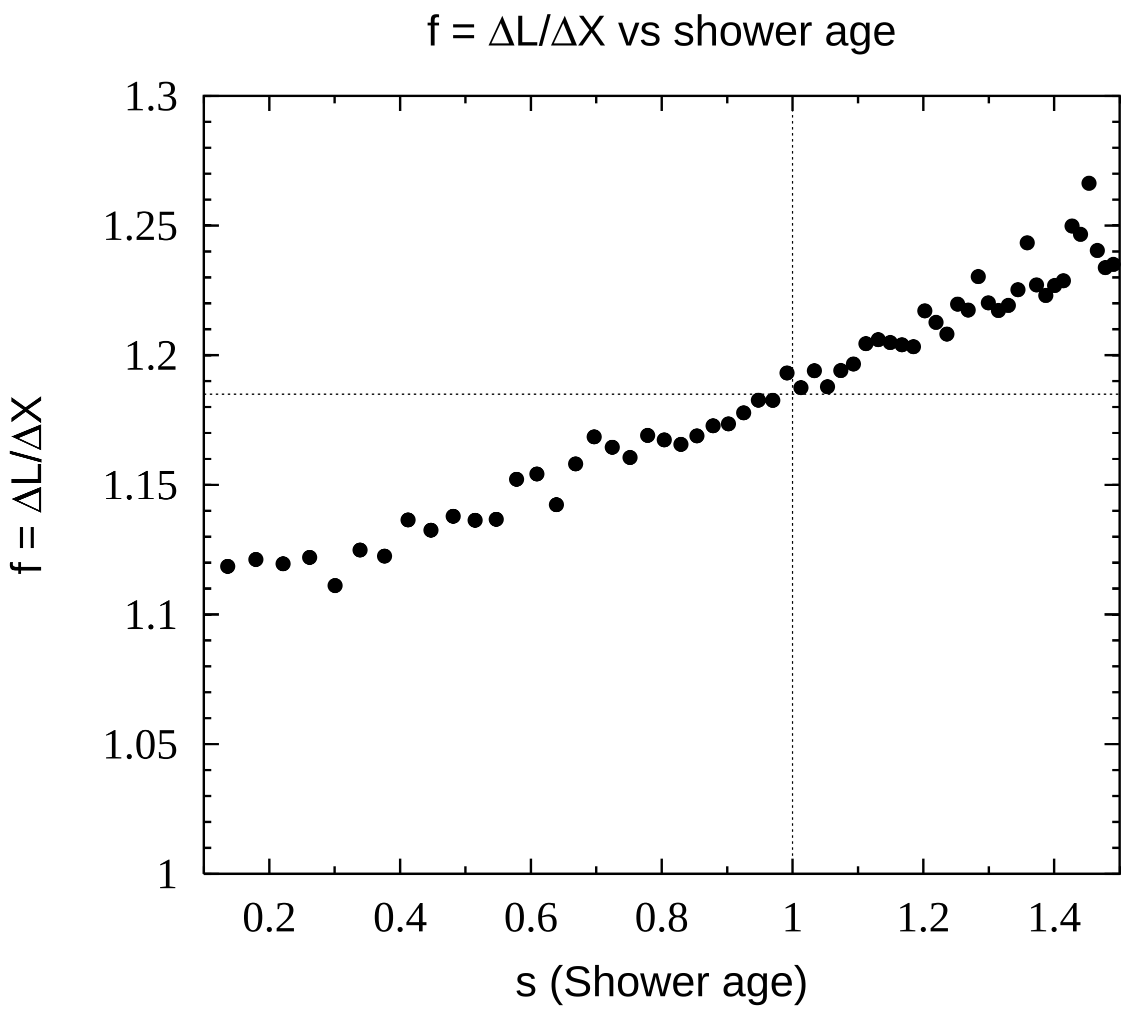
Expectation: $\Delta L > \Delta X \Rightarrow N_e^{\text{true}} < N_e^{\text{infer}}$

How big is the effect ($f = \frac{\Delta L}{\Delta X}$)?

Electromagnetic showers

GEANT 4 sims. in air: $E = 1$ TeV

$K^e_{\text{thresh}} = 10$ keV



$f = \frac{\Delta L}{\Delta X} \sim 1.18 - 1.19$ at s=1 shower max.

How big is the effect ($f = \frac{\Delta L}{\Delta X}$)?

Hadronic showers

Superposition of γ-induced showers ($\pi^0 \to 2\gamma$)

Approx: The lateral distribution corresponds to that of an electromagnetic shower with $s \sim 1$ in a broad range of X around X_{max}.

Expectation:

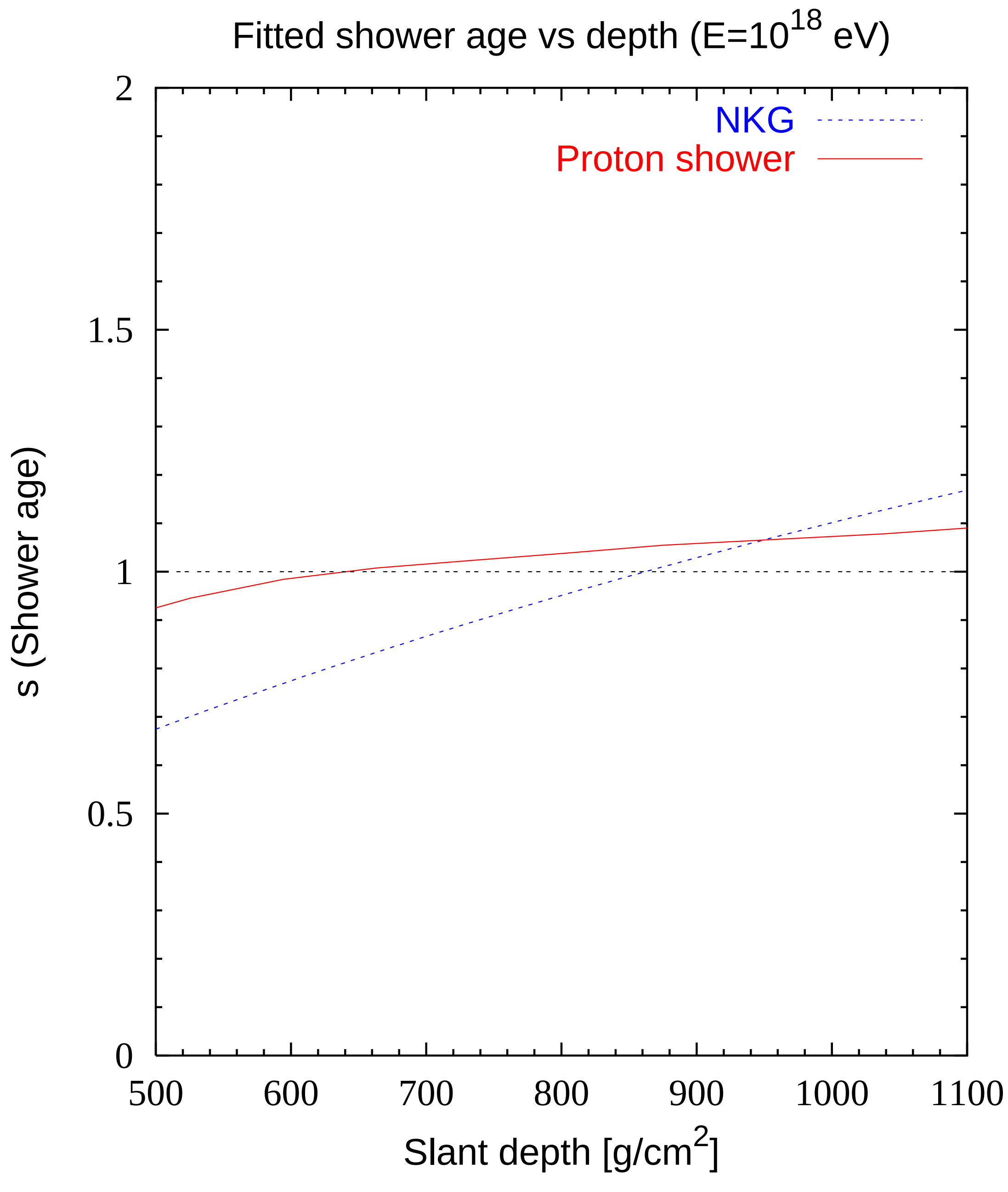
- $f = \frac{\Delta L}{\Delta X} \sim 1.18 - 1.19$ in a broad range of X around X_{max}.

- $f(X)$ flatter than in electromagnetic showers.

Simulations of hadronic showers in air needed.

Fitted shower age vs depth

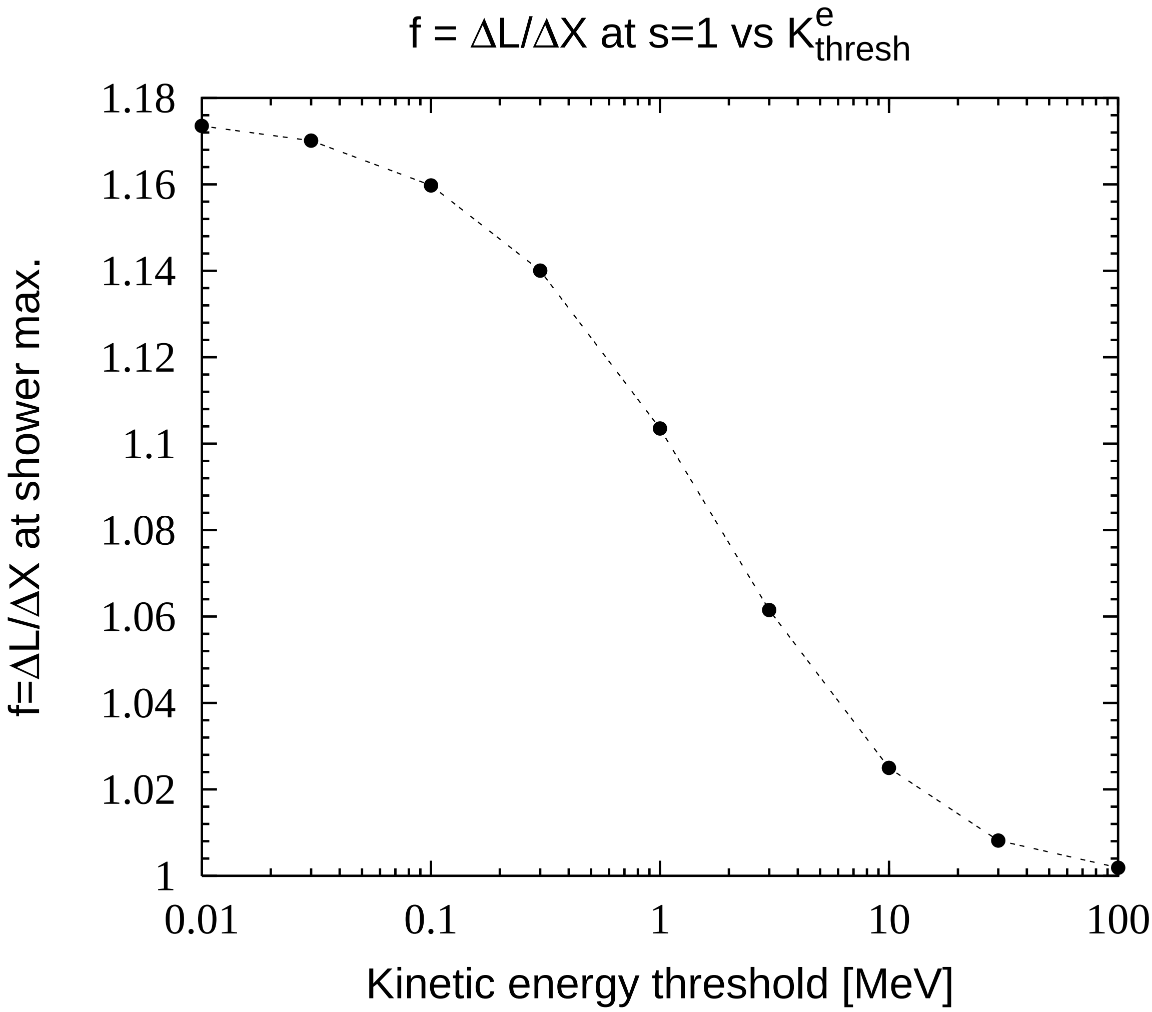
(Adapted from M.T. Dova *et al.* Astropart. Phys. 18 (2003) 351-365)



Why is the effect not seen in Č-telescopes ?

In a Cherenkov telescope the image of a shower in the focal plane of the camera is basically determined by the Cherenkov angle, i.e. there is no distortion due to the lateral spread of shower particles. Why?

Cherenkov threshold in air: $K^e_{\text{thresh}} \sim 21$ MeV

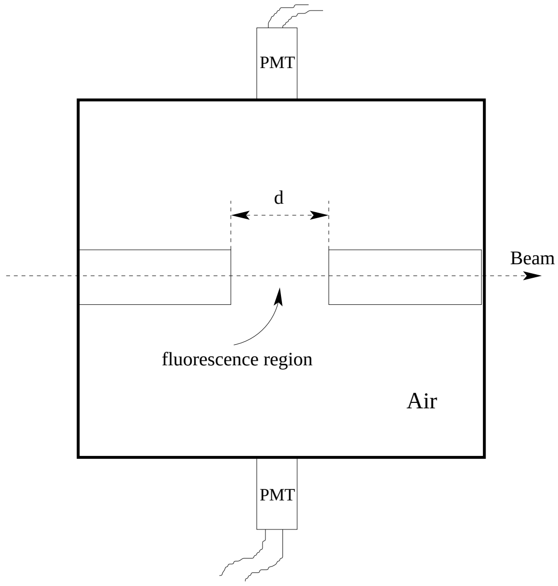


$$f = \frac{\Delta L}{\Delta X} \sim 1.01 \quad \text{for } K^e_{\text{thresh}} = 21 \text{ MeV}$$

⇒ No distortion of Č-image due to the lateral spread of shower particles.

Experimental consequences

Beam experiments measuring the fluorescence yield



$$Y_{\text{exp}}^{\text{infer}} = \frac{N_\gamma^{\text{fluor}}}{g\ d} \rightarrow Y_{\text{exp}}^{\text{true}} = \frac{N_\gamma^{\text{fluor}}}{g\ \Delta L} \qquad (3)$$

N_γ^{fluor} = Number of observed γ's in the PMTs.

g = PMT quantum efficiency, solid angle, etc...

d = Visible portion of the beam axis.

ΔL = Average electron track in d.

GEANT 4 sims, K^e=1.4 MeV, K^e_{thresh} =10 keV, d = 10 cm

$\rightarrow \Delta L/d \sim 1.02 \Rightarrow Y_{\text{exp}}^{\text{infer}} = 1.02\ Y_{\text{exp}}^{\text{true}}$

Experimental consequences

EAS Energy determination in fluorescence detectors

$$N_e^{\text{infer}} = \frac{\Delta L}{\Delta X} N_e^{\text{true}} = f(X)\; N_e^{\text{true}} \qquad (4)$$

$f(X) > 1 \;\Rightarrow$ Shower size overestimated

$$E_{\text{electrom.}} = \alpha_{\text{eff}} \int_0^\infty N_e^{\text{true}}(X)\; dX \qquad (5)$$

(α_{eff} [MeV/g cm^{-2}] obtained in MC simulations)

There are two ways of calculating α_{eff} in MC simulations:

$$\alpha_{\text{eff}}{}^{TTL} = \frac{E_{\text{electrom.}}}{TTL} = \frac{E_{\text{electrom.}}}{\sum_i \Delta L} \qquad (6)$$

or

$$\alpha_{\text{eff}}{}^{PTL} = \frac{E_{\text{electrom.}}}{PTL} = \frac{E_{\text{electrom.}}}{\sum_i \Delta X} \qquad (7)$$

Experimental consequences

EAS Energy determination in fluorescence detectors

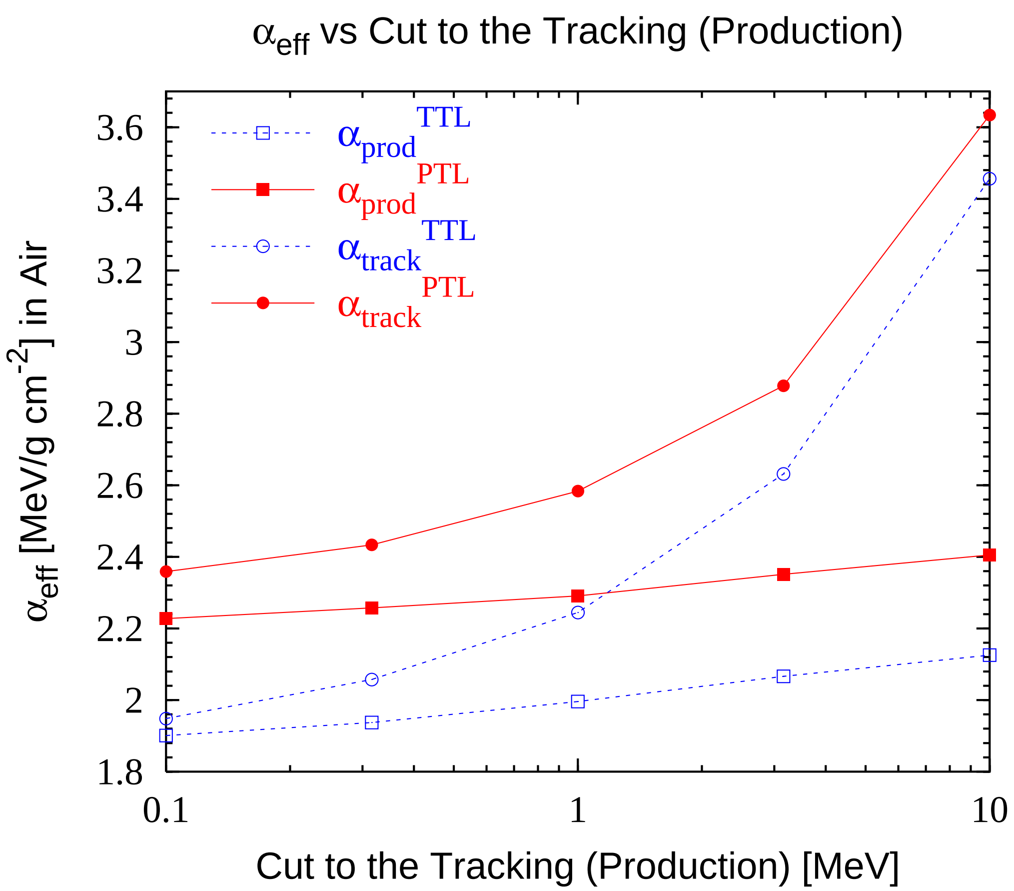
$$\int_0^\infty N_e^{\rm true}(X)\, dX \;=\; PTL \tag{8}$$

$$\Downarrow$$

$$E_{\rm electrom.} \;=\; \alpha_{\rm eff}^{PTL} \int_0^\infty N_e^{\rm true}(X)\, dX \tag{9}$$

Alternatively, we can use directly $TTL \;=\; \frac{N_\gamma^{fluor}}{Y}$

$$E_{\rm electrom.} \;=\; \alpha_{\rm eff}^{TTL} \frac{N_\gamma^{fluor}}{Y} \tag{10}$$



Experimental consequences

EAS Energy determination in fluorescence detectors

The values of α_{track} at 100 keV are

$$\alpha_{track}^{TTL} = 1.95$$
$$\alpha_{track}^{PTL} = 2.36$$

But the experiments are also sensitive to particles that have energies below 100 keV therefore we have to use the saturation values

$$\alpha_{track}^{TTL}(0) \simeq \alpha_{prod}^{TTL}(100keV) = 1.90$$
$$\alpha_{track}^{PTL}(0) \simeq \alpha_{prod}^{PTL}(100keV) = 2.23$$

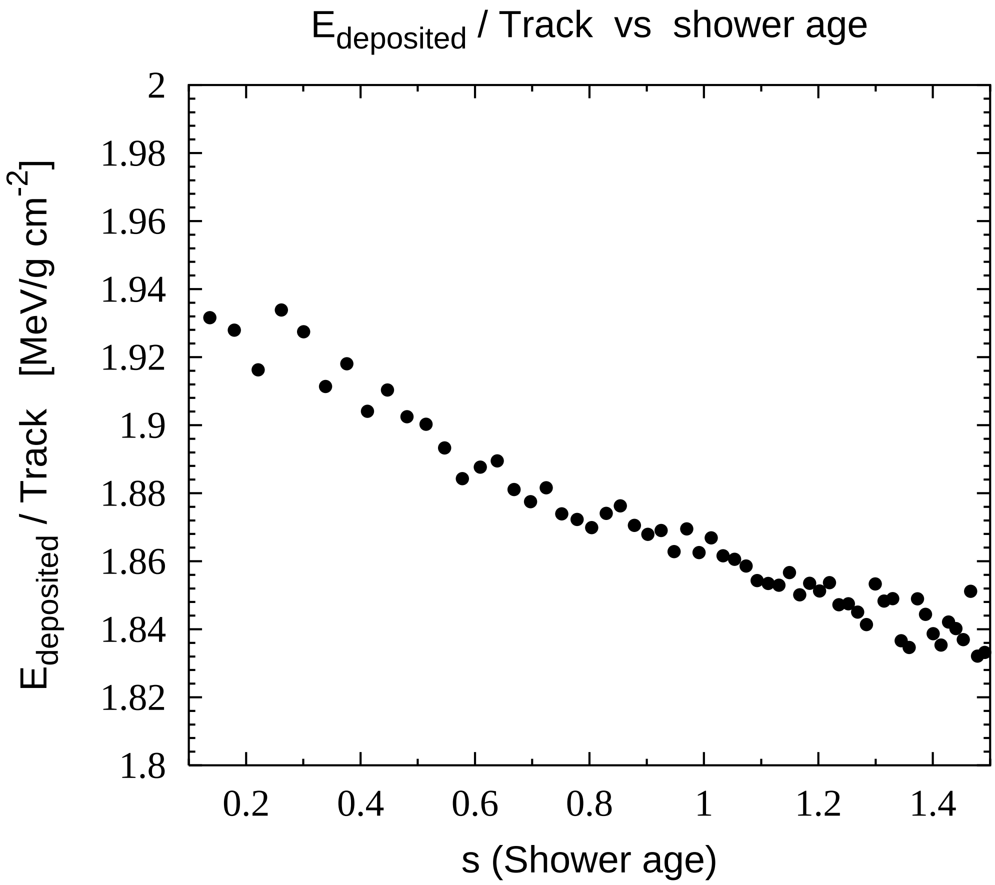
Our results seem to be pointing at an overestimate of E_{electrom} if $f(X)$ is not accounted for.

Discussion

"Classical" treatment of fluorescence emission:

- Based on the assumption: $N_\gamma^{\text{fluor}} \propto$ tracklength. However measurements (and theory) indicate: $N_\gamma^{\text{fluor}} \propto E_{\text{dep}}$ (energy deposited by ionization).

But in an EAS: Tracklength (X) $\neq K \times E_{\text{dep}}$ (X), due to the energy dependence of dE/dX and the change of the electron's energy spectrum with depth.



- Based on $N_e(X)$ and α_{eff}, "ill-defined" quantities in a MC simulation (depend on K_{thresh}, distance between planes,...).

Alternative

(J. Linsley, M. Risse *et al.*, B. Dawson)

(Being explored but still not applied to the data analysis).

$$E_{\text{electrom.}} = \int_0^\infty E_{\text{dep}}(X)dX, \qquad (11)$$

$$E_{\text{dep}}(X) = \frac{E_\gamma^{\text{fluor}}(X)}{\epsilon(X)} \qquad (12)$$

$E_\gamma^{\text{fluor}}(X) = E$ in fluor. γ's $= N_\gamma^{\text{fluor}}(X) \times \langle h\nu \rangle$

$\epsilon(X)$ = fluorescence efficiency

E_{dep}, the energy deposited locally in the medium is a "well-defined" MC quantity.

Conclusions

If we determine the energy of an EAS through

$$E_{\text{electrom.}} = \alpha_{\text{eff}} \int_0^\infty N_e(X)\, dX$$

we have to use

$$\alpha_{eff} = \alpha_{track}^{PTL}(0) \simeq \alpha_{prod}^{PTL}(100keV) = 2.23$$

and

$$N_e(X) = N_e^{\text{true}} = \frac{N_\gamma^{\text{fluor}}(X)}{g\ Y \Delta L}$$

if we use

$$N_e(X) = N_e^{\text{infer}} = \frac{N_\gamma^{\text{fluor}}(X)}{g\ Y \Delta X}$$

we are overestimating $N_e(X)$ and the energy of the shower.

All this is true in the assumption that $N_\gamma^{\text{fluor}} \propto$ tracklength.