Energy scale derived from Fluorescence Telescopes using Cherenkov Light and Shower Universality

Steffen Mueller* **for the Pierre Auger Collaboration**†

* *Karlsruhe Institute of Technology, Postfach 3640, 76021 Karlsruhe, Germany*
† *Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina*

***Abstract*. We describe a method to determine the energy scale of the fluorescence detection of air-showers based on the universal shape of longitudinal shower profiles. For this purpose, the ratio of scattered Cherenkov and fluorescence light is adopted as a free parameter while fitting the individual profiles of the longitudinal deposit of the energy to the universal shape. We demonstrate the validity of the method using a Monte Carlo study based on the detector simulation of the Pierre Auger Observatory and estimate systematic uncertainties due to the choice of high energy interaction model and atmospheric conditions.**

***Keywords*: Auger Fluorescence Energy**

I. Introduction

Knowing the absolute energy scale of cosmic ray detection is important for the interpretation of physics results such as flux, anisotropy, or composition. At the Pierre Auger Observatory, the energy measured with the fluorescence detector is used to calibrate that of the surface detector [1]. Previous experiments that consisted of a surface array used Monte Carlo simulations for their energy calibration.

In air shower detection with fluorescence telescopes, the atmosphere acts as a calorimeter. The amount of emitted fluorescence light is proportional to the energy deposit in the atmosphere. The light yield is measured in laboratory experiments with a precision that is at present typically 15% [2].

Here, we describe a method to obtain the overall normalization of the fluorescence yield directly from air shower measurements. This method makes use of the universality of the shape of the longitudinal shower profiles of the energy deposit in the atmosphere. It is also dependent on our ability to reliably calculate the Cherenkov light contribution (given the electron number and energy spectra). Only the *relative* fluorescence spectrum is needed, which is known with good precision from laboratory experiments.

As an air shower develops in the atmosphere, a beam of Cherenkov light builds up along the axis of the shower and undergoes Rayleigh and aerosol scattering. In general the scattered Cherenkov light which is observed from a certain point in the shower will have been originally emitted at an earlier stage of shower development. The result is a very different longitudinal light profile from that of the isotropically emitted fluorescence light. Therefore, the shape of the reconstructed longitudinal profile of the energy deposit depends on the assumed composition of the different contributions to the measured light. We modify the fluorescence light yield in the reconstruction of the longitudinal profile to change the light composition in such a way that the energy deposit profile matches the profile expected from universality.

II. Universality of Air Shower Profiles

The energy spectra of shower electrons and the differential energy deposit have been shown to be universal as a function of shower age, $s = 3X/(X + 2X_{\max})$ [3]–[9]. As a result, the shape of energy deposit profiles have been studied for universality when plotted as a function of age. It was found that the profile shape varied much less when plotted in terms of the depth relative to shower maximum, $\Delta X = X - X_{\max}$. Figure 1 shows many normalized energy deposit profiles in ΔX that were simulated with proton primaries using three different high-energy interaction models at 10^{19} eV. In ΔX, the majority of normalized profiles fall within a narrow band.

Consider the average of normalized energy deposit profiles $U_i(\Delta X)$ for a single interaction model and primary particle. Then figure 2 shows the absolute deviations $\delta_i(\Delta X)$ of each average profile from the mean $\langle U(\Delta X)\rangle$ of the average profiles

$$\begin{aligned} U_i(\Delta X) &= \left\langle \left(\frac{dE}{dX}\right) \Big/ \left(\frac{dE}{dX}\right)_{\max} \right\rangle (\Delta X) \\ \delta_i(\Delta X) &= U_i(\Delta X) - \langle U(\Delta X)\rangle \,. \end{aligned}$$

Nowhere does the total systematic difference rise above 3% from the mean and it stays below one percent after the shower maximum. The equivalent plot for shower age shows deviations of up to 5% from the mean both before and after the shower maximum. Due to the weak dependence on primary composition, interaction model and primary particle energy, the average profile $U(\Delta X)$ is henceforth referred to as the Universal Shower Profile (USP). The measurement of the energy scale of fluorescence detection with the method described below is most susceptible to systematic differences in the tail of the USPs for different parameters (cf. figure 3c).

There is a slight dependence of the shape of the energy deposit profile on the primary energy. This effect is relevant for this work only within the uncertainty

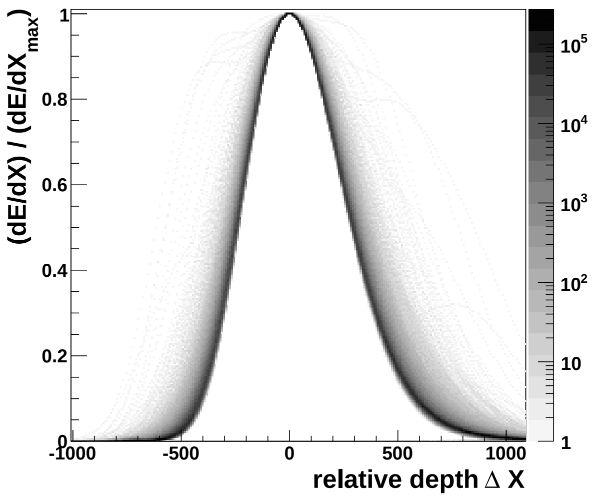


Fig. 1. Superposition of 30000 energy deposit profiles in ΔX. The CONEX [10] simulations are for proton primaries. Equal numbers of showers were generated with the QGSJet, QGSJetII.03, and Sibyll interaction models [11]–[13].

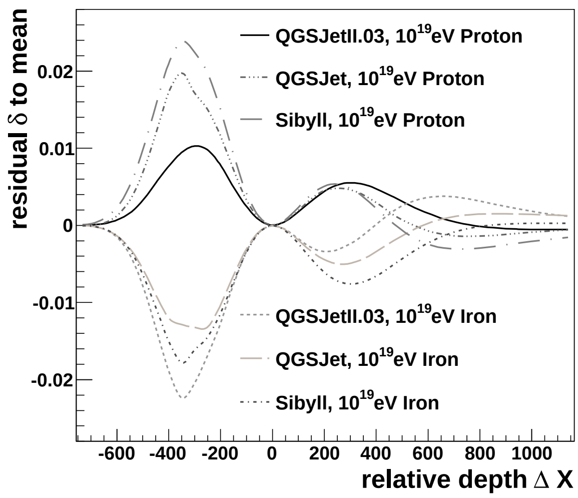


Fig. 2. Residuals $\delta\,(\Delta X)$ of universal shower profiles for various interaction models and primaries to the mean of the profiles.

of the reconstructed primary energy because the USP was recalculated for each event from simulations at the estimated energy. The dependence of the shape on the primary energy introduces a negligible systematic uncertainty (cf. table I).

III. Method

The longitudinal profile reconstruction [14] of the Offline software framework [15] was extended with an additional free parameter f so that the fluorescence yield becomes $Y^f = Y^f_{\rm lab}/f$ where $Y^f_{\rm lab}$ is the fluorescence yield currently used in the standard shower reconstruction by the Auger Collaboration [1]. This fluorescence yield is a parameterization of laboratory measurements, including the corresponding pressure dependence. Since Y^f is inversely related to f, a change in f corresponds to a proportional change in the reconstructed shower energy.

A set of showers is reconstructed many times while varying f. A low f corresponds to assuming a large fluorescence light yield and implies that fewer electrons are required in the shower to produce the observed fluorescence light. Since a smaller number of particles emits less Cherenkov light, the fraction of the measured light that is reconstructed as Cherenkov light is reduced accordingly.

The majority of detected fluorescence photons has not been scattered in the atmosphere before reaching the detector. Therefore, the point on the shower axis from which fluorescence light is observed is also the point at which it was emitted. Showers with significant contributions of direct Cherenkov light are not selected for this analysis (see below). Thus, the bulk of the observed Cherenkov light has propagated along the shower axis before being scattered towards the detector on molecules or aerosols. This means that the detected Cherenkov light carries information from a different stage of shower development than the fluorescence light observed from the same direction. This gives us a handle to change the shape of the reconstructed longitudinal profile of the energy deposit for a given observed light profile by modifying the fluorescence yield scale factor f.

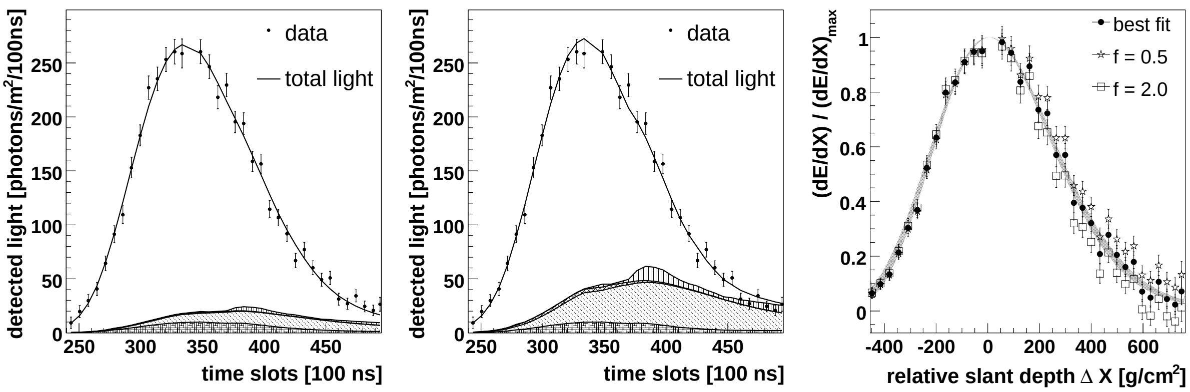
The effect of a modified f parameter on the reconstructed light composition is demonstrated with an example in figure 3a and 3b. The measured light profile is unchanged. But with higher fluorescence yield in 3a, the contribution of Cherenkov light is suppressed. Conversely, it is increased due to the reduced fluorescence yield in 3b.

At the same time, a modified f changes the shape of the reconstructed energy deposit profile as shown in figure 3c. Since the shape is known from universality considerations, a χ^2 minimization can be used to fit each profile to the universal shape in dependence of f.

Each event is assigned an uncertainty that is a combination of the uncertainty from the χ^2 minimization and several propagated uncertainties. These include the uncertainties on the direction of the shower axis, the spread of the showers that make up the Universal Shower Profile, and the uncertainty on the aerosol attenuation lengths. The fit is repeated twice for each of these parameters: once after increasing and once after decreasing each parameter by one standard deviation. The resulting difference to the default result is the propagated uncertainty.

IV. Results

To test the method, a set of showers that roughly corresponds to five years of Auger data was simulated with energies between 10^{18} and 10^{20}eV. The simulation setup follows that used for the Auger fluorescence detector exposure calculation [16]. Basic quality cuts such



(a) $f = 0.5$ (b) $f = 2.0$ (c)

Fig. 3. Example event (Los Morados detector, run 1392, event 2886). (a)/(b) Measured light profile with reconstructed light components for two modified yield scale factors. Fluorescence light, Cherenkov light (direct, Mie scattered, Rayleigh scattered), multiply scattered light; (c) Normalized, reconstructed energy deposit profiles. Grey band: Universal shower profile with uncertainty band. Graphs: energy deposit profiles for different values of the yield scale factor

as requiring an energy resolution better than 20% and an $X_{\rm max}$ resolution better than $40\mathrm{g/cm}^2$ were applied. Additionally, since the forward peaked nature of direct Cherenkov light introduces a strong susceptibility to the uncertainties of geometry reconstruction, showers with a significant contribution of direct Cherenkov light were not used for the analysis. This was implemented by selecting showers with a minimum viewing angle in excess of $20°$. The minimum viewing angle is the minimum angle between the shower axis and any vector between a point in the observed profile and the fluorescence detector.

Conversely, the showers were required to have significant contributions of Rayleigh scattered Cherenkov light, and a long profile that includes both regions in slant depth where fluorescence light and regions where Cherenkov light dominate the measured light flux.

This requirement was implemented as a two-dimensional cut on the profile length after the shower maximum and a quantity R

$$R = \rho(X_{\rm up}) \cdot \left(1 + \cos^2\psi\right) .$$

It is the product of atmospheric density ρ in the deepest visible part of the shower track $X_{\rm up}$ and the angular dependence of Rayleigh scattering given the viewing angle ψ. Thus R is a measure for the amount of Cherenkov light scattered from the end of the profile towards the telescope.

The Monte Carlo simulation was carried out for three different fluorescence yields:

- The laboratory measurement $Y^f_{\rm default} = Y^f_{\rm lab}$ (corresponding to $f_{\rm true} = 1.0$),
- an increased fluorescence yield $Y^f_{\rm high} = Y^f_{\rm lab}/0.8$ ($f_{\rm true} = 0.8$),
- and a lowered fluorescence yield $Y^f_{\rm low} = Y^f_{\rm lab}/1.2$ ($f_{\rm true} = 1.2$).

In the shower reconstruction, the fluorescence yield was $Y^f_{\rm lab}/\tilde{f}$ with the fit parameter $\tilde{f}$.

For the selected set of simulated showers, the resulting, reconstructed fluorescence yield scale factors $\tilde{f}$ are weighted with their respective uncertainties. The distribution of these weighted scale factors is shown in figure 4 for three different input values of $f_{\rm true}$. As can be seen, we are able to recover the true yield with good accuracy. This shows that the method is sensitive to a true fluorescence yield which differs from the assumed yield $Y^f_{\rm lab}$ because the reconstructed scale factor $\tilde{f}$ has no bias relating to the input parameter $f_{\rm true}$. The width of the distributions, however, shows that a large number of suitable showers is required for the analysis.

The systematic uncertainties (table I) from various sources were taken into account by repeating the full procedure with various input parameters modified by their respective systematic uncertainties. For the systematics of the method, aerosols play a particularly important role. Both aerosol attenuation and scattering of Cherenkov light on aerosols are non-trivial effects that change the shape of the reconstructed energy deposit profile. The largest contribution is due to the uncertainties of the vertical aerosol optical depth (VAOD) profile. Since the available uncertainty bounds include both statistical and systematic effects, we estimate an upper limit for the systematics on f of about $\pm 7\%$. Another significant systematic uncertainty is introduced by the parameters of the aerosol phase function (APF) which describes the angular dependence of scattering on aerosols [17]. Its parameter g is a measure for the asymmetry of scattering, whereas the APF parameter f determines the relative strength of forward and backwards scattering. The contribution from the exponent γ describing the wavelength dependence of light attenuation due to aerosols is small. Likewise, the slight energy dependence of the shape of the universal shower profile leads to an uncertainty of less than one percent. Using various models or compositions for calculating the universal shower profile yields another contribution to the total of $\pm 1\%$ and $\pm 3\%$ respectively. Two different

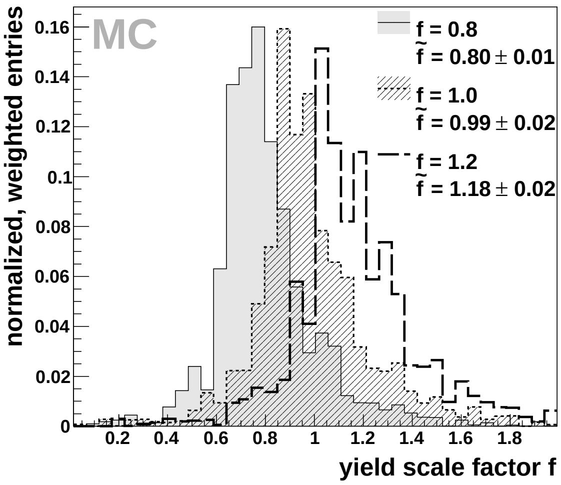


Fig. 4. Reconstructed, weighted yield scale factor distributions for three different input values of the scale factor f

TABLE I
UNCERTAINTIES OF THE SCALE FACTOR (SEE TEXT)

Source	Uncertainty [%]
APF: g	$+5, -3$
APF: f	± 0.4
wavelength dependence γ	$+0.0, -0.2$
VAODs	$\approx \pm 7$
multiple scattering	± 0.5
energy reconstruction	$+0.4, -0.5$
USP had. int. model	± 1
USP composition	± 3

parameterizations for the multiple scattering of light in the atmosphere [18], [19] produce yield scale factors that differ by 1%. If added in quadrature, these effects add up to a total expected systematic uncertainty of $8-9\%$.

V. CONCLUSIONS

We introduced a new method of measuring the energy scale of fluorescence detectors using the universality of shape of the longitudinal shower profile. Its applicability and sensitivity was demonstrated using Monte Carlo simulations of air showers and the detector of the Pierre Auger Observatory. The measurement of the energy scale uses air shower data to determine the absolute fluorescence yield scale directly, and only requires a laboratory measurement of the relative fluorescence spectrum.

The simulated fluorescence yields were reproduced to very good accuracy. The systematic uncertainties of this method could potentially allow for a fluorescence yield determination with a precision better than 10%. The application of this method to Auger data is in progress.

REFERENCES

[1] C. Di Giulio *et al.* (Pierre Auger Collab.), Proc. of 31th Int. Cosmic Ray Conf., Lodz (2009) .
[2] F. Arqueros *et al.*, Nucl. Instrum. Meth. A597 (2008) 1–22 and arXiv:0807.3760 [astro-ph].
[3] A. M. Hillas, J. Phys. G8 (1982) 1461–1473.
[4] M. Giller *et al.*, J. Phys. G31 (2005) 947–958.
[5] F. Nerling *et al.*, Astropart. Phys. 24 (2006) 421–437 and astro-ph/0506729.
[6] D. Gora *et al.*, Astropart. Phys. 24 (2006) 484–494 and astro-ph/0505371.
[7] M. Giller *et al.*, Int. J. Mod. Phys. A20 (2005) 6821–6824.
[8] S. Lafebre *et al.*, Astropart. Phys. 31 (2009) 243–254 and arXiv:0902.0548 [astro-ph.HE].
[9] P. Lipari, Phys. Rev. D 79 (2009) 063001 and arXiv:0809.0190 [astro-ph].
[10] T. Bergmann *et al.*, Astropart. Phys. 26 (2007) 420–432 and astro-ph/0606564.
[11] N. N. Kalmykov and S. S. Ostapchenko, Phys. Atom. Nucl. 56 (1993) 346–353.
[12] S. Ostapchenko, Phys. Rev. D 74 (2006) 014026.
[13] R. Engel *et al.*, Proc. of 26th Int. Cosmic Ray Conf., Salt Lake City 1 (1999) 415.
[14] M. Unger *et al.*, Nucl. Instrum. Meth. A588 (2008) 433–441 and arXiv:0801.4309 [astro-ph].
[15] S. Argiro *et al.*, Nucl. Instrum. Meth. A580 (2007) 1485–1496 and arXiv:0707.1652 [astro-ph].
[16] F. Salamida (Pierre Auger Collab.), Proc. of 31th Int. Cosmic Ray Conf., Lodz (2009) .
[17] S. Y. BenZvi *et al.* (Pierre Auger Collab.), Proc. of 31th Int. Cosmic Ray Conf., Lodz (2009) .
[18] M. D. Roberts, J. Phys. G31 (2005) 1291–1301.
[19] J. Pekala *et al.*, arXiv:0904.3230 [astro-ph] to appear in Nucl. Instrum. Meth. A.