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# A new method to reconstruct the energy and mass of primary cosmic ray particles by EAS measurements

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**Abstract.**
A method is described to determine the energy and mass of primary cosmic rays by measuring the shower size $N_e$ for each shower at detection level and after an additional absorber of e.g. 100 g/cm$^2$. The method is interpreted in terms of the atmospheric depth of the first interaction. The simulations have been performed with the CORSIKA program.

## 1 Introduction

The measurement of the energy and mass of the primary cosmic ray particles in the energy range accessible to extensive air shower experiments is known to be notoriously difficult, due to the statistical nature of an air shower and the resulting fluctuations. Main contributions to these fluctuations in the number of particles $N_e$ measured at detection level (for a specific primary mass and energy) are due to the fluctuations of the atmospheric depth $Z_0$ of the first interaction and of the number of particles produced in the first (first few) interactions. The fluctuations observed at detection level are especially large for primary protons as compared to iron nuclei (Boos and Madigozhin , 1998).

Methods and observables which are sensitive to the longitudinal shower development in the atmosphere and which are partially able to compensate for the fluctuations measured at detection level, are very promising. This has been shown e. g. by the measurement of the Cherenkov light emitted from the electro-magnetic shower component in the atmosphere which allows to infer details on the longitudinal shower development i.e. the height of the shower maximum or correspondingly its penetration depth (Lindner , 1998).

Here a new method is presented to infer information on the longitudinal shower development by measuring the shower-size ($N_e$) at two different stages of the shower development e.g. at detection level $Z_1$ and below an absorber of i.e. 100 g/cm$^2$ at $Z_2$ (Fig. 2). This can be achieved by scintillators or similar devices separated e.g. by concrete or iron.

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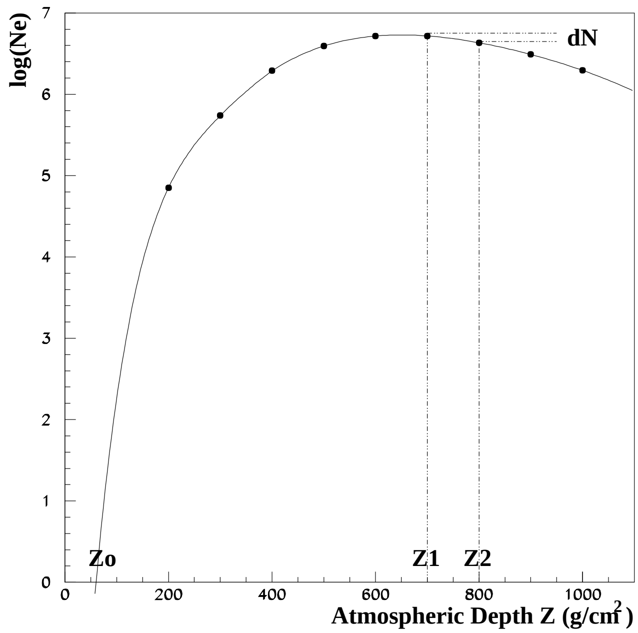


**Fig. 1.** Number of electrons log($N_e$) versus atmospheric depth Z (g/cm$^2$) for protons of $10^{16}$ eV (cascade curve). The Figure shows the notation used in the text: $Z_o$ is the penetration depth of the first interaction of the primary in the atmosphere, Z1 and Z2 denote the two observation levels and dN = log$N_e(Z_1)$-log$N_e(Z_2)$ the difference also called slope of the cascade curve.

The two measurements of $N_e$ correspond to a measurement of the shower size $N_e$ and the slope d$N_e$/dZ of the longitudinal shower development at detection level. The actually quantities used in this study are log$N_e$ and dN=log$N_e(Z_1)$-log$N_e(Z_2)$.

As will be shown below, these two quantities can be related to the depth $Z_0$ of the first interaction in a twofold way: First they allow for a given primary the determination of the energy *independent* of $Z_0$ (and therefore its fluctuations) and second, once the energy is known, $Z_0$ can be reconstructed

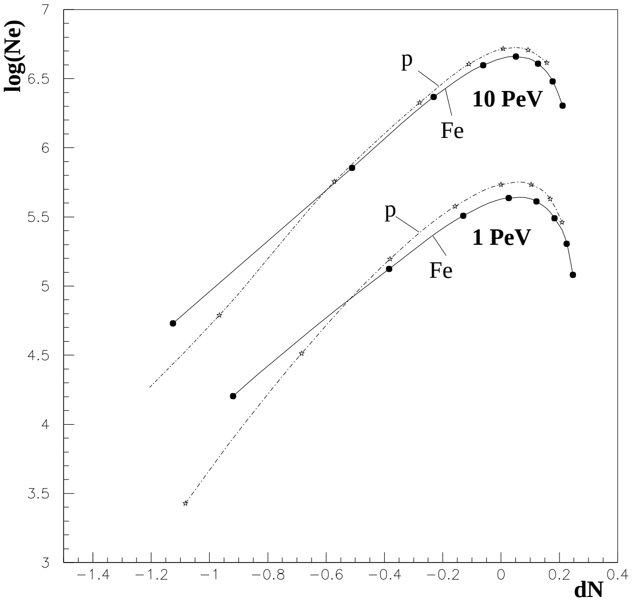


**Fig. 2.** Number of electrons $N_e$ versus the slope dN. Negative values of dN correspond to values before the shower maximum. For primary protons (stars, dash-dot line) and iron (points, solid line) at $10^{15}$ eV and $10^{16}$ eV. The points represent the mean of 100 simulated showers in each case.

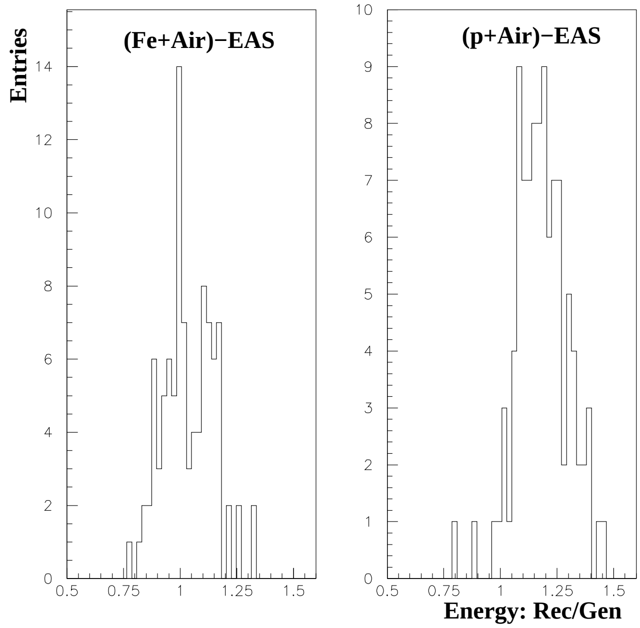


**Fig. 3.** Reconstructed energy normalized to the generated energy ($10^{16}$ eV) assuming the primaries to be iron nuclei. Left iron nuclei, right protons reconstructed with the iron hypothesis.

and used together with dN as an estimator for the primary mass. The estimation of the mass essentially is based on the fact that the longitudinal shower development (i.e. the position of the shower maximum) depends for a given $Z_0$ on the energy per nucleon E/A and therefore, for a given energy, on the primary particle mass A (Lindner , 1998).

In the following first the energy reconstruction is addressed and then the determination of the primary mass. The event samples used to demonstrate the methods consists of 100 showers of p, oxygen, sulfur and iron primaries each at $10^{15}$ eV and $10^{16}$ eV generated with the CORSIKA code (5.22) with the QGSJET/GEISHA option (Heck et al., 1998). During the simulation with Corsika the shower-sizes have been stored at fixed penetration depths in steps of 100 g/cm$^2$. No detector effects have been included yet. As material between the two detection level, for ease of calculation, air has still been assumed.

## 2 Energy Reconstruction

Since the mass is not known at this stage and the method slightly depends on the mass, a primary mass has to be assumed. This will be iron in the following consideration (after the mass has been determined this step can be iterated). Note that the mass dependence is introduced by the fact that the longitudinal cascade curve, which enters in this analysis, depends on the energy per nucleon E/A rather than on the energy E alone.

### 2.1 Method

The energy reconstruction method is based on the relation between the shower size $N_e$ and and the slope dN which corresponds for a fixed energy $E_0$ and mass A to a specific curve e. g. in Fig. 2. Using Monte Carlo data these curves are fitted with a polynomial taking the energy $E_0$ as a parameter. This yields a function $\log N_e(dN, E_0)$ i.e $\log N_e$ as function of dN and $E_0$.

The energy $E_0$ is determined from this function by varying $E_0$ and minimizing the difference between the measured $\log(N_e)$ value and the function $\log N_e(dN, E_0)$ at the measured dN.

Note that the uncertainty of $Z_0$ does not enter (since also the observation level $Z_1$ does not enter explicitly). This is most easily seen taking as an example a measurement with dN =0 i.e. in the shower maximum. The described method then requires to find the curve (with the parameter E) for which $\log N_e$ in the shower maximum (at dN=0) describes best the measured value $\log N_e$. Neither $Z_0$ nor $Z_1$ enters in this way and the energy resolution is not hurt by the fluctuations of the depth of the first interaction. In other words the measured values $N_e$ and dN are compared to a mean expectation curve with fixed $Z_0$. Taking the depth of the observation level into account the depth of the primary interaction can be determined which will be used in section 3.

### 2.2 Results

For a test sample of iron nuclei with an energy of $10^{16}$ eV an energy resolution $\sigma$ of 11% is achieved (Fig. 3). For protons (assuming the iron nuclei hypothesis) the energy shows

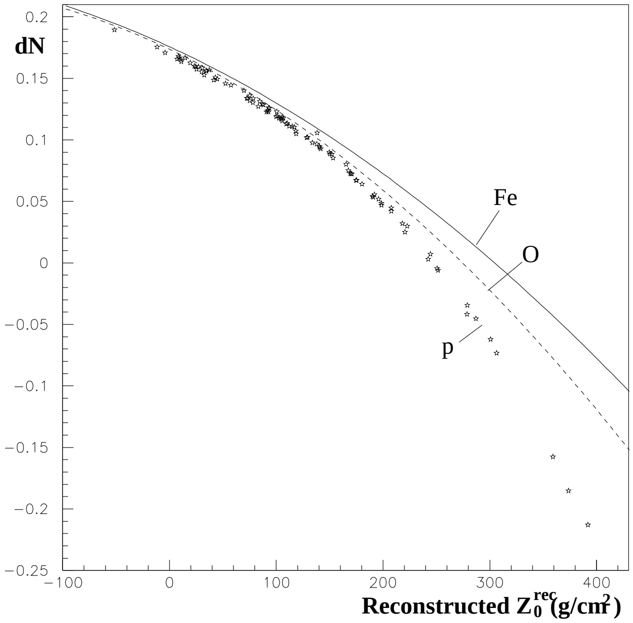


**Fig. 4.** The slope dN versus the reconstructed $Z_0$ for iron (line), oxygen (broken line) and protons (stars) at $10^{16}$ eV. The values dN correspond to the atmospheric depth of the detection level.

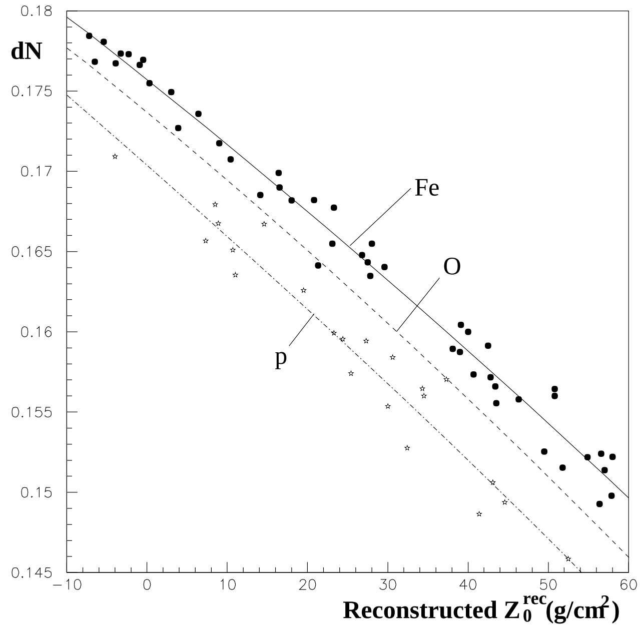


**Fig. 5.** Expanded view of the slope dN versus the reconstructed $Z_0$ for iron (line, points), oxygen (broken line) and protons (dash-dot line, stars). The lines are fits to the reconstructed Monte Carlo data using the iron hypothesis. The differences between the dN-$Z_0$ correlations for different primaries are caused by different longitudinal shower developments (depending mainly on E/A)

a systematic shift of 16% (Fig. 3) and for oxygen of 6%. This is expected due to the iron hypothesis.

## 3 Primary Particle Mass reconstruction

For the reconstruction of the primary mass the penetration depth $Z_0$ of the first interaction is reconstructed and then used in conjunction with dN as an estimator for the mass. As mentioned the dependence of the longitudinal shower development on E/A (at a fixed $Z_0$) enters in the measurement of dN and contributes in this way to the determination of the mass. The method can be divided up in the following two steps:

### 3.1 Estimation of $Z_0$

From Monte Carlo simulations (mean) longitudinal shower profiles $N_e(Z)$ are generated depending on the mass A and energy $N_e(Z) = N_e(Z, E_0, A)$ all starting at the same penetration depth e.g. Z=0. Then the profile corresponding to the energy determined above (and a mass hypothesis e.g. iron) is chosen and shifted in Z such that the measured $\log(N_e)$ and dN at observation level is reproduced. This shift in Z yields the penetration depth $Z_0^{rec}$ for the first interaction. Due to the fluctuation in the shower development also negative values (in the mathematical sense) are obtained.

### 3.2 Mass estimation

In order to use the reconstructed $Z_0^{rec}$ and dN for the mass esti mation first the correlation of $Z_0^{rec}$ versus dN (with energy E and mass A as parameter) are fitted by polynomials to reconstructed Monte Carlo data $Z_0$=$Z_0$(dN,E,A). In Fig 4 and Fig. 5 fits and Monte Carlo data are shown for E=$10^{16}$ eV.

Then the distance $\Delta$ of the reconstructed penetration depth $Z_0^{rec}$ to the expectation (for the reconstructed energy, the measured dN and the mass hypothesis A) is determined
$\Delta = Z_0^{rec} - Z_0(\mathrm{dN, E, A})$ and transformed into a probability. e.g. assuming the primary was an iron nucleus. The spread $\sigma$ used in the probability calculation is obtained from reconstructed Monte Carlo events, i.e. in this case the deviation of the Monte Carlo data for Fe+Air from the corresponding fit curve (Fig.5).

### 3.3 Results

The Figure 6 shows the result for the MC event samples of 100 events for proton, oxygen, and iron generated at $10^{16}$ eV and tested for the iron hypothesis. As can be seen, in the region where 68% of the primary iron events are reconstructed as iron only 11 (out of 100) oxygen events are found and no proton events. The highest probability amongst the proton events to be reconstructed as iron is 0.002.

Considering also the absolute values of the atmospheric depths $Z_0$ could further enhance the separation between different nuclei as e.g. protons penetrate much deeper into the atmosphere than heavy primaries.

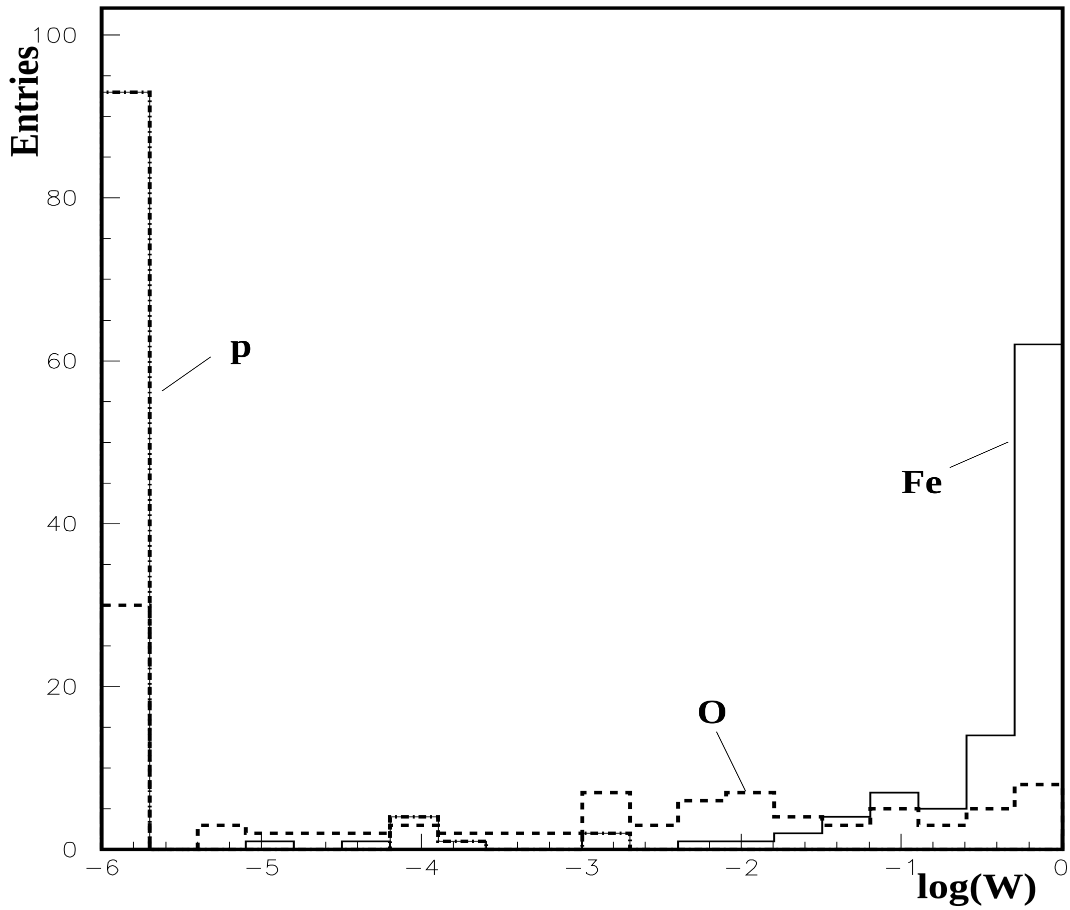


**Fig. 6.** The probability W that the primary particle is reconstructed as iron (i.e. iron hypothesis) for primary iron (solid line), oxygen (dashed line), and proton (dash-dot line) at $10^{16}$ eV.

## 4 Conclusion

A new method to reconstruct the energy and mass of cosmic ray primaries has been developed and applied to Monte Carlo test data at $10^{15}$ eV and $10^{16}$ eV. Detector effects have not yet been included. An energy resolution of 11% is obtained (for the correct mass hypothesis) and a good separation of different primary masses is achieved.

In general this method allows for a sensitive reconstruction of the longitudinal development of the electro magnetic part of the shower cascade. The results are very similar to analyses using the integral measurement of air Cherenkov light (as was realized for example with the AIROBICC installation within the HEGRA experiment). However in contrast to Cherenkov light measurements the method presented here is not restricted to data obtained in clear moon-less nights.

The method will be iterated and further studies are under way.

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