A new method for determining the primary energy from the calorimetric energy of showers observed in hybrid mode on a shower-by-shower basis

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Abstract: The energy deposit integral can be used for determining the calorimetric energy of air showers observed with fluorescence telescopes. The invisible fraction of the primary energy, averaged over many showers, is typically estimated from Monte Carlo simulations and later added for the reconstruction of the total primary energy. In this contribution we derive a simple parameterization of the invisible energy correction that can be applied to individual events measured with both the fluorescence and the surface detectors. The obtained parameterization is robust with respect to a change of the high energy hadronic interaction model employed in the simulation and has only a very small primary mass dependence, reducing the associated systematic uncertainties of energy reconstruction.

Keywords: Ultra High Energy Extensive Air Showers, Missing Energy, Muons, Hadronic interactions

1 Introduction

When an ultra high energy cosmic ray interacts in the atmosphere a cascade of particles is generated. In the cascade, an important fraction of the energy is deposited in the atmosphere as ionization of the air molecules and atoms, and the remaining fraction is carried away by neutrinos and high energy muons that hit the ground.

A fraction of the total deposited energy is re-emitted during the de-excitation of the ionized molecules as fluorescence light that can be detected by fluorescence telescopes. The telescopes use the atmosphere as a calorimeter, making a direct measurement of the longitudinal shower development. The energy deposit integral can be used to determine the calorimetric energy (E_{Cal}) of air showers observed with fluorescence telescopes.

The fraction of energy carried away by neutrinos and high energy muons is *a priori* unknown, and corrections for this so-called missing energy ($E_{Missing}$) must be properly applied to the measured E_{Cal} to find the primary energy ($E_{Primary}$). Generally, the missing energy correction is parameterized as a function of E_{Cal} ($E_{Missing}(E_{Cal})$), which is estimated from Monte Carlo simulations averaging over many showers. The missing energy is about 10% of the primary energy depending on the high energy hadronic interaction model and on the primary mass, as shown in Figure 1. Since the primary mass cannot be determined on an event by event basis, an average mass composition must be assumed. This introduces a systematic uncertainty in the determination of the primary energy and possibly a bias, if the actual mass composition is different from the assumed average.

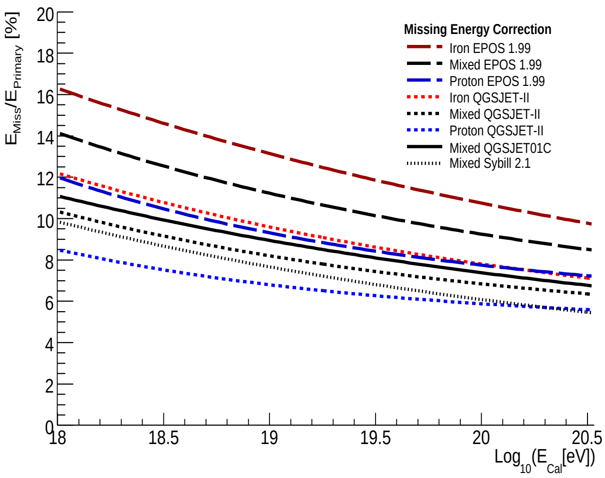

Figure 1: $E_{Missing}(E_{Cal})$ correction for fluorescence detectors.

The model dependence of the missing energy estimation as a function of E_{Cal} is a direct consequence of using a parameter that is not actually related to the missing energy, but to the electromagnetic energy. The lack of knowledge

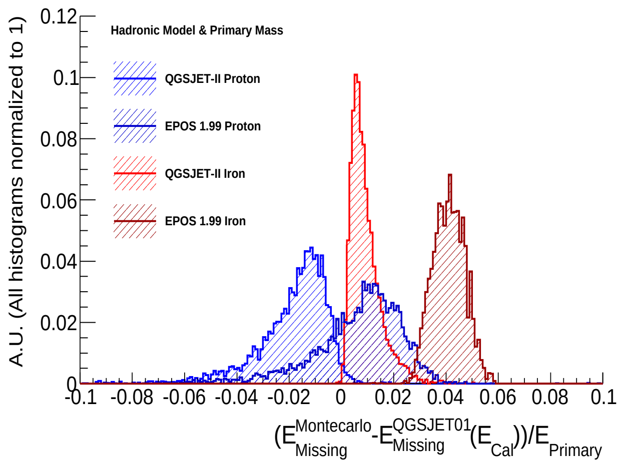

Figure 2: Difference between $E^{QGSJET01}_{Missing}(E_{Cal})$ and the missing energy from showers simulated with EPOS and QGSJETII, in units of the primary energy.

of the correct interaction model at high energies also introduces a systematic uncertainty and possibly a bias, that are ultimately not known. For example, a mis-reconstruction of the missing energy due to appearance of new physics in the hadronic interaction models could explain features of the cosmic ray energy spectrum like the knee without making any use of changes in the primary spectrum slope[1]. The event by event deviations with respect to a reference average value of the missing energy for QGSJET01 mixed mass composition($E^{QGSJET01}_{Missing}(E_{Cal})$) can be seen in Figure 2 . Looking at the spread caused by the mis-reconstruction of the missing energy, it is then desirable to have a missing energy parameterization as a function of shower observables that are less model dependent, and give a better estimation of the true missing energy on a shower-by-shower basis.

Extensive air showers created by ultra-high energy cosmic ray are measured with two complementary techniques at the Pierre Auger Observatory. The longitudinal shower development is recorded with the Fluorescence Detector (FD), while the muonic and electromagnetic components can be measured at ground by the Surface Detector (SD). The lateral distribution of the shower particles at ground is sampled with an array of more than 1600 water-Cherenkov detectors while the fluorescence light emission along the shower trajectory through the atmosphere is observed with a set of 24 telescopes [2].

In this article, a new approach for the determination of the missing energy in extensive air showers is presented. This approach takes advantage of the hybrid nature of the Pierre Auger Observatory, using the signal at 1000 m from the shower core ($S(1000)$) and the atmospheric slant depth of the shower maximum (X_{max}) to provide a robust estimation of the missing energy, reducing the systematic uncertainties that this correction introduces in the determination of the primary energy.

2 A Toy Model for the Missing Energy

In the Heitler model extended to hadronic cascades by Matthews [3], the primary energy is distributed between electromagnetic particles and muons.

$$E_0 = \xi_c^e N_{max} + \xi_c^\pi N_\mu \tag{1}$$

One can identify the second term directly as the missing energy:

$$E_{Missing} = \xi_c^\pi \, N_\mu \tag{2}$$

where ξ_c^e is the critical energy for the electromagnetic particles and ξ_c^π is the pion critical energy. Although the number of muons generated in the shower depends on the high energy hadronic interaction model, the pion critical energy is a well established quantity that depends primarily on the medium density where the first interactions take place, making this relationship robust to changes in the hadronic interaction model.

Nyklicek et al. [4] have shown using vertical showers that the model dependence is reduced if $E_{Missing}$ is estimated using its correlation with the total number of muons at ground above 1 GeV. In their work there is a linear relation to the number of muons (Eq. 2) and the proportionality factor obtained from Monte Carlo simulations is of the order of a critical energy $\xi_c^\pi \approx 10$ GeV which is in agreement with the predictions made using the extended toy model of Matthews [3].

An observable related to the muon content of the shower would be more suitable for the determination of the missing energy correction. However, the number of muons is not directly measured in the Pierre Auger Observatory. One of the simplest observables related to the muon content of the shower is $S(1000)$.

Based on universality studies [5, 6], the relationship between $S(1000)$ and the muon content should be universal when expressed as a function of the stage of development of the cascade at ground level measured by $DX = X_{ground} - X_{max}$ (distance measured in atmospheric depth from the ground to the point of maximum development of the shower). For a fixed DX, a change in the primary mass or the hadronic model that modifies the muon content of the shower (an thus, the missing energy) will change $S(1000)$ accordingly. This makes the combination of these parameters more robust for the determination of the missing energy, and less dependent of the details of the hadronic interactions or the primary mass composition. Even if the Heitler model is an oversimplification, it provides great insight on the phenomenology of shower cascades. The total number of muons follows a power law with the primary energy

$$N_\mu = \left(\frac{E_0}{\xi_c^\pi}\right)^\beta . \tag{3}$$

The primary energy E_0 is also a power law of $S(1000)$ for a fixed angle (S_{38°), or for a fixed stage of shower devel-

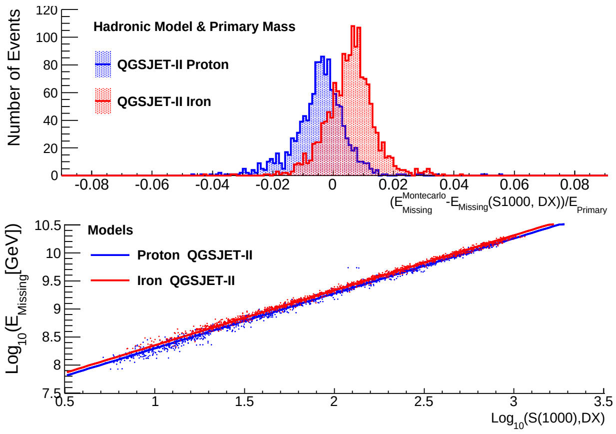

Figure 3: Fit of $\log(E_{Missing}[GeV])$ vs. $\log(S(1000)[VEM])$(bottom) and its residues(top) for fixed DX bin.

opment using universality in DX

$$N_\mu = \left(\frac{\alpha(DX) S(1000)^\gamma}{\xi_c^\pi} \right)^\beta \tag{4}$$

where the function $\alpha(DX)$ takes into account the attenuation with DX. Based on this toy model, one can estimate the missing energy using $S(1000)$ and DX

$$\begin{aligned} \log(E_{Missing}) &= A(DX) + B\ \log(S(1000)) \quad (5) \\ A(DX) &= \log(\xi_c^\pi) + \beta \log\left(\frac{\alpha(DX)}{\xi_c^\pi}\right) \\ B &= \beta\gamma. \end{aligned}$$

$A(DX)$ and B will have to be determined with fits to Monte Carlo simulations. As we will see in section 3, the B parameter can be set to a fixed value close to unity. This is easy to understand if we consider that in this simple model β depends on the inelasticity and multiplicity of pion interactions and is usually within 10% of 0.9 [3] and γ is in the 1.06 - 1.09 range [7]. Once the values of A and B are known, we will be able to estimate the missing energy of any event where $S(1000)$ and X_{max} are measured. We will call this new parameterization of the missing energy $E_{Missing}(S(1000), DX)$.

3 Results and conclusions

Showers simulated with CORSIKA[8] were subsequently used as input in the detector simulation code, and reconstructed using the official Offline reconstruction framework of the Pierre Auger Observatory [9]. The generated data sample contains approximately $4{\times}10^4$ showers simulated using the hadronic interaction model QGSJETII(03)[10]. This library consists of proton and iron initiated showers following a power law primary energy spectrum (E^{-1}) in the energy range $\log(E/eV)$ = 18.5 - 20.0 and uniformly distributed in $\cos^2\theta$ in zenith angle range $\theta = 0 - 65°$. The EPOS 1.99 [11] generated data sample contains also approximately $4{\times}10^4$ showers but discrete values of energy and zenith angle.

The X_{max} value for Monte Carlo simulations was taken from the Gaisser Hillas fit of the longitudinal energy deposit profile and the missing energy of the simulated event was calculated following [12]. Since the simulations in the library are not hybrid, the FD reconstruction accuracy was factored in by introducing a 20% Gaussian smearing of the Monte Carlo calorimetric energy, a 2° Gaussian smearing of the primary zenith angle and a 25 $\mathrm{g\,cm^{-2}}$ Gaussian smearing of X_{max}. These values are rather conservative for hybrid events and the results presented in this work are insensitive to the value of these parameters, as long as they are kept within a reasonable range.

The shower library generated with the QGSJETII hadronic interaction model was used to parameterize the missing energy as a function of $S(1000)$ and DX. The surface detector events had to satisfy quality cuts for good $S(1000)$ reconstruction[13]. The showers were divided in 13 equidistant bins of DX, ranging from 175 to 1100 $\mathrm{g\,cm^{-2}}$. For each bin of DX, the missing energy is fitted using equation (5). A representative example of these fits and the corresponding residues are shown in figure 3. The variation of the parameter A with DX was then parameterized with a third degree polynomial

$$\begin{aligned} A(DX) = 7.347 - 3.41\,10^{-4} DX + 1.58\,10^{-6} DX^2 \\ -7.88\,10^{-10} DX^3 \end{aligned} \tag{6}$$

the parameter B was fixed to 0.98 and the A parameter dependence with DX for QGSJETII showers. The difference between $E_{Missing}(S(1000), DX)$ and the actual missing energy of the QGSJETII showers as a function of E_{Cal} is presented in Figure 4 (left). Filled circles represent the values obtained using $E_{Missing}(S(1000), DX)$ and empty circles represent Monte Carlo true values, which are slightly shifted to the left to aid clarity. There is a good agreement with a small bias of less than 1 % of the primary energy depending on the mass composition and its value decreases with primary energy. The set of EPOS simulations was used to test how $E_{Missing}(S(1000), DX)$ performed with a change in the hadronic model. EPOS is significantly different from QGSJETII and is known to generate more muons than other models, and consequently more missing energy. The difference between $E_{Missing}(S(1000), DX)$ and the actual missing energy of the EPOS showers is presented in Figure 4(right). It is important to emphasise that we are using a parameterization obtained from QGSJETII showers to describe the missing energy given by a significantly different hadronic model like EPOS, without introducing important biases or loosing too much accuracy. As we mentioned in the introduction, this is possible because we are estimating the missing energy using observables closely related to the muonic component of the shower at a given shower development

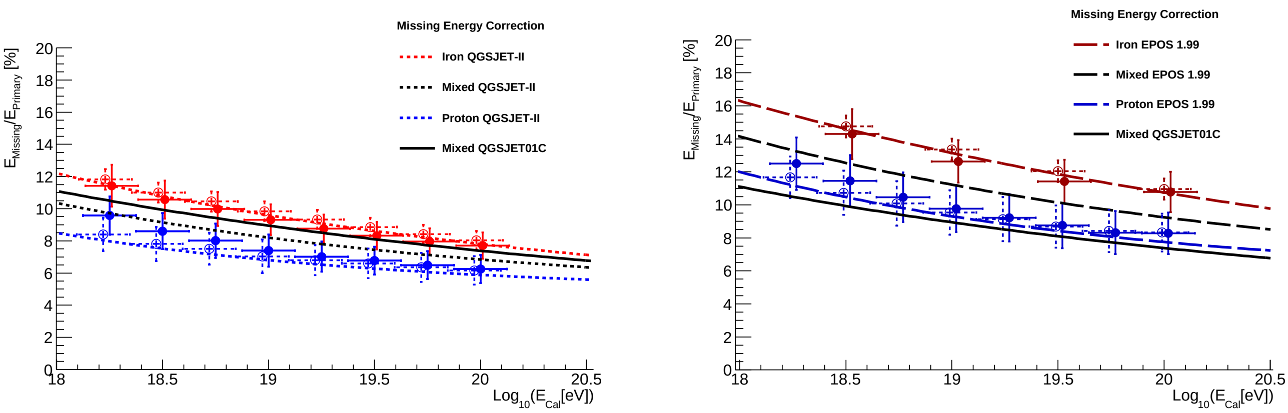

Figure 4: Average missing energy $E_{Missing}(S1000, DX)$ (filled circles) as a function of the calorimetric energy for QGSJETII (left) and for EPOS (right) using the $E_{Missing}(S1000, DX)$ from QGSJETII. Monte Carlo true values (empty circles) are slightly shifted to the left to aid clarity. Lines represent $E_{Missing}(E_{Cal})$ parameterizations.

stage, that are in turn tightly related to the origin of the missing energy.

To illustrate this point, in figures 2 and 5 we show the difference between the missing energy parameterizations and the simulation true values for each of the considered parameterizations. It can be seen in figure 5 how $E_{Missing}(S(1000), DX)$ gives a better estimation of the missing energy than $E^{QGSJET01}_{Missing}(E_{Cal})$, even if the hadronic model or the primary mass is changed. Using the presented missing energy estimator $E_{Missing}(S(1000), DX)$, the hadronic interaction model bias is removed while, at the same time, the bias due to the mass composition is reduced by a factor of two with respect to the previous $E^{QGSJET01}_{Missing}(E_{Cal})$ parameterization.

$E_{Missing}(S(1000), DX)$ enables us to estimate the missing energy of almost any event with a good reconstruction of $S(1000)$ and X_{max}, without making assumptions on the primary mass or the hadronic model. Future work will also include tests with other hadronic interaction models to strengthen the hypothesis of hadronic model independence, and an extension applicable to the reconstruction of very inclined showers.

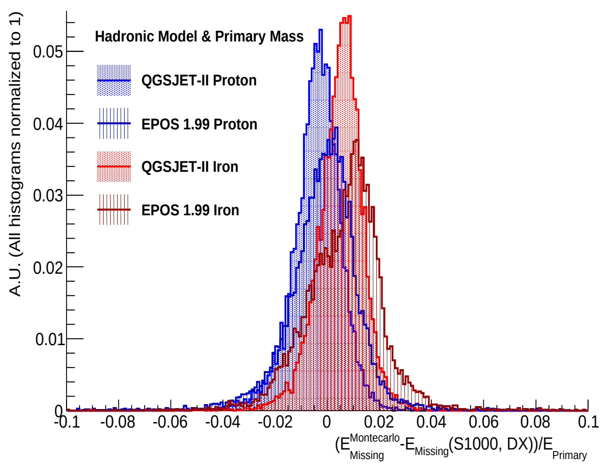

Figure 5: Difference between $E_{Missing}(S(1000), DX)$ and the missing energy from showers simulated with EPOS and QGSJETII, in units of the primary energy.

Hybrid events that trigger the surface detector array and the fluorescence telescopes separately are ideally suited to estimate the missing energy. The application of this method to determine the missing energy from a set of such hybrid events and a detailed study of the impact of this new missing energy correction on the surface detector calibration are in progress.

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