Estimate of the non-calorimetric energy of showers observed with the fluorescence and surface detectors of the Pierre Auger Observatory

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Abstract: The determination of the primary energy of extensive air showers using the fluorescence technique requires an estimation of the energy carried away by particles that do not deposit all of their energy in the atmosphere. This estimation is typically made using Monte Carlo simulations and thus depends on the assumed primary particle composition and model predictions for neutrino and muon production. In this contribution we introduce a new method to obtain the invisible energy directly from events measured simultaneously with the fluorescence and the surface detectors of the Pierre Auger Observatory. The robustness of the method, which is based on the correlation of the invisible energy with the muon number at ground, is demonstrated by applying it to different sets of Monte Carlo events. An event-by-event estimate of the invisible energy is given for the hybrid data set used for the energy calibration of the surface detector of the Pierre Auger Observatory.

Keywords: Pierre Auger Observatory, Ultra High Energy Cosmic Rays, Invisible Energy

1 Intoduction

When an ultra-high energy cosmic ray interacts in the atmosphere a cascade of particles is generated. In this cascade, an important fraction of the energy is deposited in the atmosphere as ionisation of the air molecules and atoms. A fraction of the deposited energy is then re-emitted during the de-excitation of the ionized molecules as fluorescence light that can be detected by fluorescence telescopes.

Since the fluorescence intensity is proportional to the deposited energy, the integral of the fluorescence profile yields an accurate measurement of the energy of the primary particle (E_0) that was deposited in the atmosphere by the charged particles due to electromagnetic energy losses. This is usually referred to as the calorimetric energy ($E_{\rm Cal}$).

The remaining energy, carried away mostly by neutrinos and high-energy muons that do not deposit all their energy in the atmosphere, is *a priori* unknown. An estimation of this "invisible" energy is required to derive the primary energy (E_0) from the measured $E_{\rm Cal}$. Historically, this non-calorimetric energy has been called "missing energy" [1]. However, we will use the name "invisible energy" ($E_{\rm Inv}$) deeming it more appropriate.

Generally, the invisible energy correction is parameterized as a function of $E_{\rm Cal}$ ($E_{\rm Inv}(E_{\rm Cal})$) and it is typically estimated using Monte Carlo simulations averaging over many showers. The average value depends on the high-energy hadronic interaction model and on the primary mass, ranging from 8.5 to 17% of the primary energy at 1 EeV and from 7 to 13.5 % at 10 EeV.

Selecting a particular interaction model when analysing real events could introduce a bias to the reconstruction of the primary energy that is ultimately unknowable. An accurate knowledge of the invisible energy is thus essential in experiments using the fluorescence technique if a reliable measurement of the primary energy of cosmic rays is to be obtained.

In a previous work [2] we have described a method that relies on the properties of shower universality and a simple model of extensive air showers to find a parameterization of $E_{\rm Inv}$. This method is robust to changes in the hadronic interaction models used in Monte Carlo simulations. In this work, the method has been updated to take into account the fact that the signal attenuation curve and the muon content measured in extensive air showers may not be properly described simultaneously by current Monte Carlo simulations.[3, 4, 5].

2 A simple model for the invisible energy

In the Heitler model extended to hadronic cascades by Matthews [6], the primary energy is distributed between the electromagnetic and muonic components of the air shower as

$$E_0 = \xi_c^e N_e^{\rm max} + \xi_c^\pi N_\mu, \quad (1)$$

where E_0 is the primary energy, $N_e^{\rm max}$ is the number of electrons at the shower maximum, and ξ_c^e is the critical energy for the electromagnetic particles. The second term is the energy transferred to the muonic component of the cascade and is considered to be proportional to the total number of muons (N_μ). The critical energy of the pion, ξ_c^π, is chosen as the proportionality factor to account for the fact that, in this model, the muons are considered to originate from pion decays with an associated muon neutrino (or muon antineutrino), transferring all of the energy into the non-calorimetric channel independently of how much energy goes to each muon. With these considerations, the second term of Eq.(1) can be identified directly with the invisible energy.

The model presented is clearly an oversimplification, as there are also muons being produced by other processes, the next in importance being kaon decay (roughly 10 times less frequent). Therefore, ξ_c^π should be considered as an "effective" critical energy, that averages the different contributions to the muonic component. If we pick cascades at the same stage of shower development at ground level, measured by the slant depth from shower maximum to ground level (DX), the number of high-energy muons is correlated with the number of muons at ground level.

The number of muons is not measured directly at the Pierre Auger Observatory. We will use an observable that can be related to the muon content, namely the signal at 1000m from the core $S(1000)$. Based on universality studies [7, 8], the relationship between $S(1000)$ and the muon content of the shower is universal when expressed as a function of the stage of development of the cascade at ground level.

The primary energy E_0 can be parameterized as a power law of $S(1000)$

$$E_0 = \gamma_0(DX)\,[S(1000)]^{\gamma} \tag{2}$$

for a fixed zenith angle (S_{38°) [9], or for a fixed stage of shower development measured by DX. The value of $\gamma_0(DX)$ is closely related to the attenuation of $S(1000)$ with DX.

In the Heitler-Matthews model it is also inferred that the total number of muons follows a power law with the primary energy,

$$N_\mu = \beta_0 \left(\frac{E_0}{\xi_c^\pi}\right)^{\beta}. \tag{3}$$

Here β depends mildly on the pion multiplicity, on the inelasticity of the first interactions in the cascade, and on the energy partition between charged and neutral pions. β_0 is a muon scale factor introduced to account for these effects. This parameter can be considered to be independent of DX since the atmospheric depth of the maximum should have little influence on how many muons are generated in the shower.

Combining our correlation of $E_{\rm Inv}$ with the total number of muons and equations (3) and (2), we get a power law dependence of the invisible energy on $S(1000)$

$$E_{\rm Inv} = \xi_c^\pi N_\mu = \xi_c^\pi \beta_0 \left(\frac{\gamma_0(DX)\, S(1000)^{\gamma}}{\xi_c^\pi}\right)^{\beta}. \tag{4}$$

Based on these results, the invisible energy can be estimated as a function of $S(1000)$ and DX

$$\begin{aligned} \log(E_{\rm Inv}) &= A(DX) + B\log(S(1000)) \quad (5)\\ A(DX) &= (1-\beta)\log(\xi_c^\pi) + \\ &\quad \log(\beta_0) + \beta\log(\gamma_0(DX)) \\ B &= \beta\gamma. \end{aligned}$$

where $A(DX)$ and B can be determined from fits of $\log(E_{\rm Inv})$ vs $\log(S(1000))$ from full Monte Carlo simulations, in order to capture any further dependences with DX that are not described by this simplified model. To ensure a good reconstruction of $S(1000)$, only events in which the detector with the highest signal has all its 6 closest neighbours working at the time of the event (the 6T5 selection cut, see [10]) are used. This new parameterization of the invisible energy will be called $E_{\rm Inv}(S(1000),DX)$ from now on.

With current hadronic models, β is usually found to be within 10% of 0.9 [6] and γ is in the 1.06 - 1.09 range [11]. The constant B was fixed to 0.98 in this work, considering that the values of β and γ that best describes our QGSJET-II simulations are 0.925 and 1.0594 respectively. Other models will have slightly different values. However, the product $\beta\gamma$ is close to 0.98 for all the hadronic models considered, varying within 2% of this value. It is important to point out that this model for the invisible energy can be extended to include the effect of a primary nucleus using the superposition principle. The extended model gives a very good description of the change in the invisible energy associated with a change in the primary mass.

Differences in γ_0, β_0 and ξ_c^π for different hadronic models and masses tend to compensate each other to give a similar parameterizations of the $E_{\rm Inv}(S(1000),DX)$. However, this compensation is not complete and each hadronic model has a slightly different $A(DX)$. Since γ_0 and β_0 are the parameters that show greater variability between models, we will implement a correction to $A(DX)$ to compensate for the differences. This correction will be crucial when the method is applied to data, as it is known that the measured attenuation curve (closely related to γ_0) and the shower muon content (closely related to β_0) cannot be reproduced simultaneously [3, 4, 5] using the hadronic models currently available.

If we take the expression for $A(DX)$ for a reference model (in our case QGSJet-II [16] 50% proton/ 50% iron mixed composition) and we ignore the small variations in γ, β and ξ_c^π among the various models, the difference in $A(DX)$ from a different MC model is

$$\begin{aligned} A^{\rm MC}(DX) &= A^{\rm QII}(DX) + \quad (6)\\ &\quad \log_{10}\left(\left(\frac{\gamma_0^{\rm MC}(DX)}{\gamma_0^{\rm QII}(DX)}\right)^{\beta_{\rm QII}} \frac{\beta_0^{\rm MC}}{\beta_0^{\rm QII}}\right). \end{aligned}$$

The correction clearly has two separate contributions: one arising from the difference in the attenuation curve and another one from the difference in the muon normalization. The contributions tend to compensate each other, and the final correction is relatively small. The effect of this correction on the estimation of the invisible energy for each model is less than 15% in the most extreme case and is usually within 5%.

To illustrate the performance of the correction we plot in Fig. 1 the reconstruction of the average $E_{\rm Inv}$ done with the QGSJET-II reference parameterization on events generated with other hadronic models, namely EPOS 1.6 and 1.99 [15], using the corresponding correction for each hadronic model and primary mass. Note that the correction is capable of recovering the correct invisible energy even for simulations done with EPOS 1.6, a hadronic model that gives a significantly different number of muons with respect to QGSJET-II.

3 $E_{\rm Inv}(S(1000),DX)$ from observations

To make an estimation of the invisible energy using experimental data, we use high-quality hybrid events that trigger the surface detector (SD) and the fluorescence detector (FD) of the Pierre Auger Observatory independently. These are known as "golden hybrid" events.

The correction due to the difference in the attenuation curve between data and Monte Carlo simulations can be measured at the Pierre Auger Observatory simply by making the corresponding fits of E_0 vs $S(1000)$ in bins of DX. From these fits, $\gamma_0^{\rm data}(DX)$ can be obtained. As there are still insufficient events to make reliable fits of Eq. (2) be-

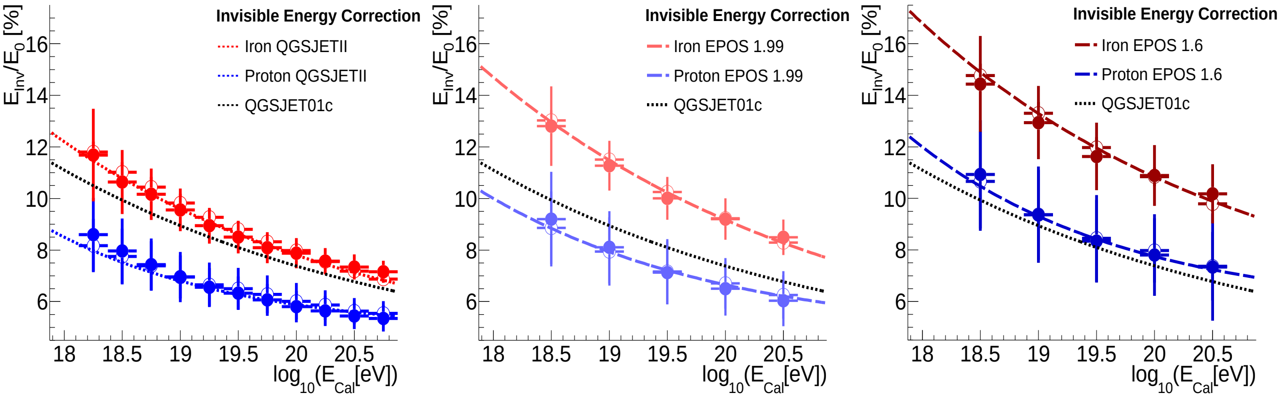

Figure 1: Average invisible energy as a function of the calorimetric energy. Open symbols represent the average invisible energy for a given energy bin, as obtained from Monte Carlo simulations performed with CORSIKA [13]. Filled symbols represent the average invisible energy for a given energy bin, obtained using $E_{\rm Inv}(S(1000), DX)$ with $A(DX)$ given by Eq. (5) for fits to QGSjet-II events and corrected by Eq. (7) (see text). The $E_{\rm Inv}(E_{\rm Cal})$ parameterization for QGSJet01c [14] 50% proton 50% iron from [1] is shown for reference in each of the plots.

low DX=200 g/cm^2 and above DX=900 g/cm^2 for sufficiently small bins of DX, the applicability of our method is presently limited to this range.

The factor $\beta_0^{\rm data}/\beta_0^{\rm MC}$ can be estimated using the N_{19} muon scale factor obtained in [12]. In that article, an estimation of the number of muons on inclined events with respect to a reference Monte Carlo is used to make a power law fit equivalent to Eq. (3). To estimate $\beta_0^{\rm data}/\beta_0^{\rm MC}$ we use the multiplicative constant of the power law in Eq. (3) of [12] (1.81, that represents the number of muons at 10 EeV with respect to QGSJET-II simulations for proton primaries) and re-scale it to our reference 50% proton/ 50% iron mixture. The obtained value is 1.56.

Finally, since there is no way to estimate ξ_c^π from hybrid events, we will continue to treat this parameter as a constant taken from the reference Monte Carlo. The uncertainty associated with the possibility of having a different ξ_c^π in data was estimated to be around 1%, assuming that ξ_c^π is consistent with any of the hadronic models used in this work.

In Fig. 2 the invisible energy is shown for a random sample of golden hybrid events that pass the quality cuts. The error bars indicate the statistical uncertainty arising from the uncertainty in the fit parameters, plus a propagation of the systematic uncertainty in the values $S(1000)$ and DX that are used as input for the parameterization. The small dotted lines identify the bands within which the average invisible energy can vary due to its systematic uncertainty.

The total uncertainty has been estimated by considering the uncertainty in the N_{19} measurement and the estimation of β_0, the uncertainty due to possible difference in ξ_c^π, the uncertainty due to a deviation from $\beta\gamma = 0.98$ and the uncertainty propagated from the measurement of $S(1000)$ and DX. The total systematic uncertainty on the average $E_{\rm Inv}/E_0$ is 5% at 10^{17} eV, 3% at 10^{18} eV and 2% at 10^{19} eV. No further systematic uncertainty should arise from a change in the energy scale of the observatory in the determination of $E_{\rm Inv}$. However, such a change will obviously affect the $E_{\rm Inv}/E_0$ ratio. As the origin of this systematic effect is not intrinsic to the determination of $E_{\rm Inv}$ but to the way of presenting the data, we do not include it here.

In Fig. 2 it is also shown the prediction from $E_{\rm Inv}^{QGSJet01}(E_{\rm Cal})$ 50% proton / 50% iron parameterization, in the event reconstruction procedures used previously. This parameterization underestimated the invisible energy of the primary energy on average by 4 % in units of the primary energy.

It is important to note that below the energy of full trigger efficiency of the Observatory, the trigger is biased towards events with higher number of muons, and thus higher invisible energy. At these low energies, the relative systematic uncertainty in the determination of $S(1000)$ is also higher, resulting in a higher systematic uncertainty in the determination of the invisible energy. To avoid these biases only data at energies above $10^{18.3}$eV were used in this work.

For events in which $S(1000)$ cannot be determined accurately, a parameterization of the average invisible energy as a function of $E_{\rm Cal}$ can be used. In the Heitler-Matthews model, it is also inferred that there exists a power law dependence between $E_{\rm Cal}$ and E_0

$$E_{\rm Cal} \approx g \xi_c^e k \left(E_0\right)^\alpha \tag{7}$$

where g is the ratio of the total number of electromagnetic particles to the number of electrons and k is a proportionality constant related to the units chosen for the energy.

Combining equations (3),(4) and (7) we get

$$\frac{E_{\rm Inv}}{1\rm EeV} = \frac{\beta_0 10^{9(\frac{\beta}{\alpha}-1)}}{(g\xi_c^{em}k)^{\frac{\beta}{\alpha}} \xi_c^\pi{}^{\beta-1}} \left(\frac{E_{\rm Cal}}{1\rm EeV}\right)^{\frac{\beta}{\alpha}} \tag{8}$$

If we use the values of $\beta = 0.925$, $\beta_0 = 0.4$, $\xi_c^\pi = 12$GeV, that approximately describe QGSJet-II (50% /proton 50% iron) simulations, α= 1.011 and $g\xi_c^{em}k$=0.68 GeV$^{1-\alpha}$ to describe data and, expressing the calorimetric energy in EeV, we get 0.117 for the multiplicative constant of the exponential, and 0.915 for the exponent. As the muon normalization for data (β_0) is a factor 1.56 higher than for QGSJet-II 50% proton /50% iron simulations, we expect the multiplicative constant for data to be close to 0.187.

The fit of a 2-parameter exponential function to the invisible energy on the golden hybrid events above $10^{18.3}$ eV, using a χ^2 function that takes into account the fluctuations of both $E_{\rm Cal}$ and $S(1000)$, is shown in Fig. 3. The result is

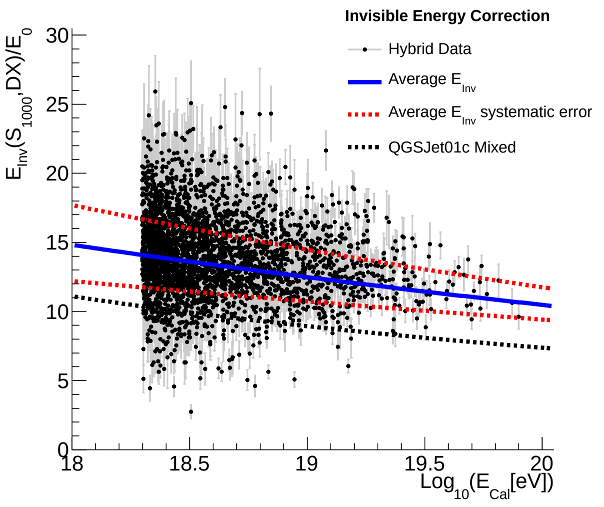

Figure 2: Estimation of the invisible energy in golden hybrid events using $E_{\mathrm{Inv}}(S(1000),DX)$, as proposed in this paper, superimposed on the $E_{Inv}^{QGSJet01c}(E_{\mathrm{Cal}})$ parameterization calculated in [1] for 50% proton 50% iron (dot dashed line). The red dotted line shows the bounds of the systematic uncertainty in the average. The error bars on the points represent uncertainties propagated from the systematic uncertainty in S_{1000} and DX plus the statistical uncertainty from the $A(DX)$ fit.

$$\frac{E_{\mathrm{Inv}}}{1\mathrm{EeV}} = 0.174\left(\frac{E_{\mathrm{Cal}}}{1\mathrm{EeV}}\right)^{0.914}. \quad (9)$$

The good agreement between the model and the fit gives us confidence in using the extrapolation of this fit for events with energies below $10^{18.3}$ eV. Using $E_{\mathrm{Inv}}(S(1000),DX)$ introduces a dependence of E_0 on $S(1000)$ that complicates the energy calibration of the surface detector of the Pierre Auger Observatory using golden hybrid events, as it correlates the fluctuations in the energy determined with the surface detector with the fluctuations in the energy determined with the fluorescence detector. To avoid these complications, the presented parameterization (9) is used for the determination of the invisible energy instead of $E_{\mathrm{Inv}}(S(1000),DX)$ over the whole energy range of the Observatory [17]. The statistical uncertainty of this fit is very small and its impact on the total energy is below 0.5%.

4 Conclusions

We have presented a method that allows us to make an unbiased and model-independent determination of the invisible energy. The method is based on a calibration of the invisible energy with $S(1000)$ and DX made with Monte Carlo simulations, that is then corrected with the measured N_{19} from horizontal events and the attenuation curve obtained from golden hybrid events.

The method was successfully applied to measure the average invisible energy of a set of golden hybrid events showing that the correction previously in use [1] underestimated the primary energy by approximately 4% on average, introducing a shift in the energy scale [17].

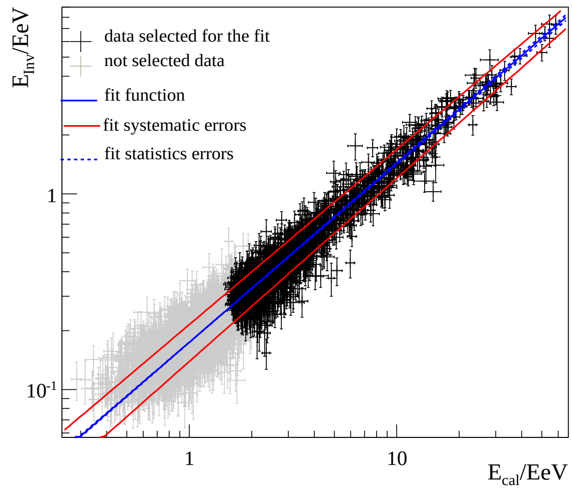

Figure 3: Fit of $E_{\mathrm{Inv}}(S(1000),DX)$ vs E_{Cal} presented in Eq. (9).

An expression of the invisible energy as a function of E_{Cal} was presented and used to parametrize the data at energies above $10^{18.3}$ eV. Good agreement between the model prediction and the parameters obtained was found. This function is used to calculate the invisible energy correction over the full energy range of the Pierre Auger Observatory.

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