

Determination of the invisible energy of extensive air showers from the data collected at Pierre Auger Observatory

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Abstract. In order to get the primary energy of cosmic rays from their extensive air showers using the fluorescence detection technique, the invisible energy should be added to the measured calorimetric energy. The invisible energy is the energy carried away by particles that do not deposit all their energy in the atmosphere. It has traditionally been calculated using Monte Carlo simulations that are dependent on the assumed primary particle mass and on model predictions for neutrino and muon production.

In this work the invisible energy is obtained directly from events detected by the Pierre Auger Observatory. The method applied is based on the correlation of the measurements of the muon number at the ground with the invisible energy of the showers. By using it, the systematic uncertainties related to the unknown mass composition and to the high energy hadronic interaction models are significantly reduced, improving in this way the estimation of the energy scale of the Observatory.

1 Introduction

Above 10^{15} eV cosmic rays are detected indirectly through the extensive air showers (EAS) they produce in the atmosphere. Most of the cosmic ray energy is carried by electromagnetic particles of the EAS, which can be detected by their secondary electromagnetic signatures, e.g. radio, Cherenkov or fluorescence light. In the case of the fluorescence detection, the fluorescence radiation emitted by the nitrogen molecules of air excited by the charged particles of the EAS is produced in proportion to the energy dissipation, allowing a reconstruction of the longitudinal profile of the energy deposit (dE/dX) of the shower as a function of the atmospheric depth X . The atmosphere is used as a calorimeter and the integral $\int (dE/dX) dX$, called the calorimetric energy of the shower, E_{cal} , is measured.

E_{cal} underestimates the total shower energy (E_0) because neutrinos do not suffer electromagnetic interactions and high energy muons reach ground level after releasing only a portion of their energy into the atmosphere. Thus, an estimation of the primary energy E_0 with the fluorescence detection technique is obtained by adding to E_{cal} a correction to account for the *invisible* energy (E_{inv}) carried by the particles that do not dissipate all their energy in the atmosphere. E_{inv} amounts to about 10% - 20% of E_0 .

E_{inv} can be calculated directly from the energy deposited in the atmosphere by the different components of simulated air showers [1]. There are large differences in the values of the ratio of E_{inv} to E_0 as a function of E_{cal} for different hadronic models and primary masses, as could be

seen in Fig. 1. The estimation of E_{inv} is affected by the irreducible uncertainties associated with the models describing the hadronic interactions and also by the mass composition of cosmic rays.

The models to get E_{inv} can be improved further using the primary mass composition estimated with the fluorescence detectors [2] so that the spread between the predictions is significantly reduced for a given mass. However, the uncertainties associated with the hadronic interaction models are difficult to estimate and are ultimately unknown [3]. Even after the updates with LHC data, the models still fail to describe several properties of the shower development related to muons [15], and this can introduce unpredictable biases in the E_{inv} estimation.

Thus the strategy followed in this work is to estimate E_{inv} using the correlations that exist between E_{inv} and shower observables measured at the Pierre Auger Observatory [4], correlations that to a large extent are not sensitive to the hadronic interaction models and primary mass composition.

The Pierre Auger Observatory [4] is a *hybrid* observatory, because the measurements are done combining the data of a Surface Detector (SD) that is sensitive to the muon content of EAS and a Fluorescence Detector (FD). The SD consists of 1660 water-Cherenkov detectors (WCDs) arranged on a hexagonal grid of 1.5 km spacing extending over a total area of ~ 3000 km². The FD consists of 24 telescopes placed in four sites located along the perimeter of the Observatory that overlook the atmosphere above the surface array. The FD operates during clear and moonless nights with a duty cycle of about 14% [5].

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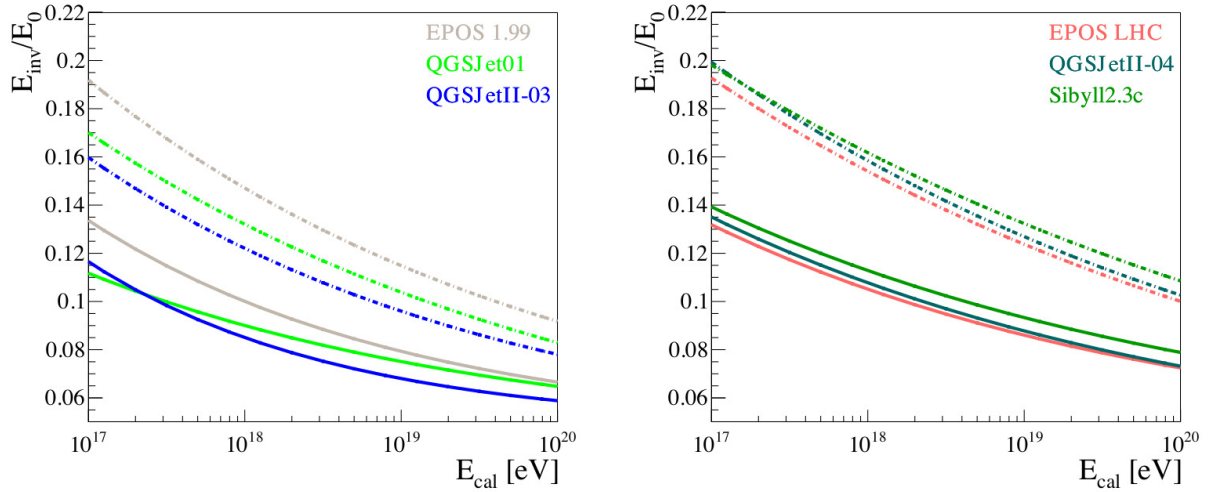


Figure 1. Average invisible energy fraction as a function of E_{cal} calculated with Monte Carlo simulations using the hadronic interaction models tuned with LHC data (right) and the models developed before the LHC data were available (left). The predictions for proton and iron primaries are shown with solid and dashed lines, respectively. The simulations were performed using the CORSIKA code for the models EPOS 1.99 and QGSJETII-03 [12, & references therein] and with the AIRES code for QGSJET01 [13, & references therein]. For the models tuned with the LHC data EPOS LHC, QGSJETII-04, and Sibyll2.3c we used the CONEX code [14, & references therein].

2 Phenomenology of the invisible energy

The Heitler model and its extension to hadronic cascades [9, 10] provide a qualitative description of EAS which is suitable enough to serve as a guiding thread in the next sections, where the starting points of the data-driven approaches to estimate E_{inv} will be inspired by some of the expressions outlined below.

In the model, only pions are produced in the hadronic interactions, all with the same energy and the same particle multiplicity (N). The neutral pions decay almost immediately into two photons, generating an electromagnetic cascade. Charged pions interact hadronically until the average energy of the charged pions is decreased to such a level that their time-dilated decay length becomes smaller than their hadronic interaction length. This energy is referred to as the pion critical energy:

$$\epsilon_c^\pi = \frac{E_0}{N^n}, \quad (1)$$

where E_0 is the primary particle energy and n is the number of interactions suffered by the charged pions.

One important feature of the model is that E_{inv} is proportional to the number of muons (N_μ) reaching ground level.

$$E_{\text{inv}} = \epsilon_c^\pi N_\mu, \quad (2)$$

This expression will be the guiding thread to estimate E_{inv} with a measurement of N_μ in inclined showers.

Another important feature of the model is the power law of E_{inv} :

$$E_{\text{inv}} = \epsilon_c^\pi \left(\frac{E_0}{\epsilon_c^\pi} \right)^\beta, \quad (3)$$

where $\beta = \ln(\frac{2}{3}N)/\ln N$. Air shower simulations predict values of β in the range from 0.88 to 0.92 [11]. β also fixes

the E_{inv} dependence on the mass number A of the primary. Neglecting collective effects in the first interactions so that the cascade is the superposition of A cascades initiated by primary protons of energy E_0/A one has:

$$E_{\text{inv}}^A = \epsilon_c^\pi \left(\frac{E_0}{\epsilon_c^\pi} \right)^\beta A^{1-\beta}. \quad (4)$$

This relationship will be the guiding thread to estimate E_{inv} from vertical showers measurements.

Monte Carlo simulations take into account all the complex phenomena occurring throughout the EAS development giving more quantitative predictions of E_{inv} , which is calculated following the method described in [1].

The correlation between E_{inv} and N_μ has been studied simulating showers with different primary masses and hadronic interactions models using the CORSIKA code [12, & references therein], as it is shown in Fig. 2. In spite of the very large spread in the predictions of N_μ and E_{inv} , the correlation is good and is similar for all models and primaries, suggesting that it is possible to obtain a robust estimation of E_{inv} from the measurements of N_μ .

3 Estimation of E_{inv} using Auger data

Two different reconstruction techniques are used for the SD events: one for the so-called vertical showers with zenith angles $\theta < 60^\circ$ [18], and one for the inclined showers with $\theta > 60^\circ$ [6]. WCDs are sensitive to the electromagnetic and hadronic components of a shower.

The most straightforward way to estimate E_{inv} is to use inclined showers, in which the electromagnetic component of the shower is largely absorbed and it is possible to measure the total number of muons arriving at ground level which is an observable expected to be proportional to E_{inv} ,

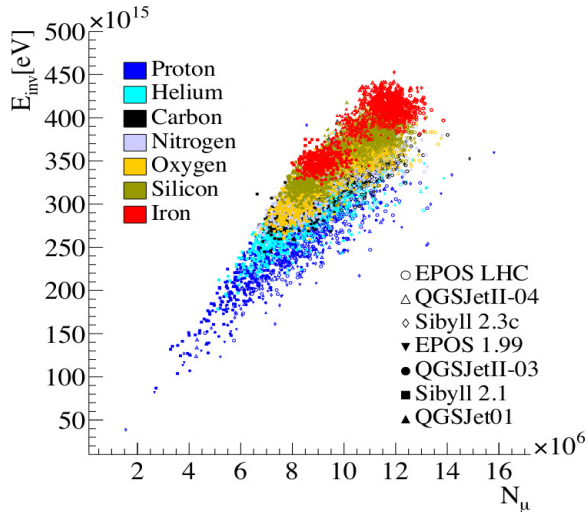


Figure 2. Correlation between E_{inv} and the number of muons reaching ground with energy greater than 100 MeV for different hadronic interaction models and primaries simulated with energy of 3×10^{18} eV arriving at 60° at the altitude of the observatory.

as seen in Sec. 2 (Eq. (2)). The muon number cannot be directly measured for vertical events. However, E_{inv} can be obtained from the energy estimator using the power law relationship between E_{inv} and E_0 (see Eq. (4)).

3.1 E_{inv} from inclined showers

The reconstruction of inclined events [6] is based on the fact that the muon number distribution at ground level can be described by a density scaling factor that depends on E_0 and primary mass, and by a lateral shape that, for a given arrival direction (θ, ϕ) of the shower, is consistently reproduced by different hadronic interaction models and depends only weakly on E_0 and primary mass.

The muon number density as a function of the position at ground \vec{r} is then parameterised with

$$\rho_\mu(\vec{r}) = N_{19} \rho_{\mu,19}(\vec{r}, \theta, \phi), \quad (5)$$

where $\rho_{\mu,19}(\vec{r}, \theta, \phi)$ is a reference distribution conventionally calculated for primary protons at 10^{19} eV using the hadronic interaction model QGSJETII-03, and the scale factor N_{19} represents the shower size relative to the normalization of the reference distribution.

The performance of the reconstruction is validated on simulated events. The reconstructed value of N_{19} is compared with its true value R_μ^{MC} for each simulated event. R_μ^{MC} is defined as the ratio of the total number of muons at ground level to the total number of muons in the reference model. The relative deviation of N_{19} from R_μ^{MC} is within 5% for several hadronic interaction models and primaries [16]. A bias correction is then applied to N_{19} in order to reduce the residuals to within 3% of the most recent models tuned with LHC data. In this way, the corrected value of N_{19} , which in the following is called R_μ , represents an unbiased estimator of the total number of muons at ground level.

The correlation between E_{inv} and the total number of muons at ground level is studied with two data sets: one simulated with CORSIKA using the hadronic interaction models EPOS LHC and QGSJET II-04 [12, & references therein] and the other with AIRES using the model QGSJET01 [13, & references therein].

For each simulated event, we calculate the values of E_{inv} and of the muon number at ground level R_μ^{MC} .

For all the samples of simulated events, the correlation between E_{inv} and R_μ^{MC} is well described by a power-law

$$E_{\text{inv}} = C \left(R_\mu^{\text{MC}} \right)^\delta, \quad (6)$$

where the values of the parameters C and δ are obtained from a fit to the events. Examples of the correlation between E_{inv} and R_μ^{MC} are shown for in Fig. 3 (left), where the lines show the fitted power law relationships.

The relationship of Eq. (6) is used to estimate E_{inv} in the data from the measurement of R_μ that, as seen before, is the unbiased estimator of R_μ^{MC} . Since the mass composition of the data is not precisely known, the estimation of E_{inv} is obtained using the parameterisation of E_{inv} as a function of R_μ for a mixture of 50% protons and 50% iron. This is done taking the average of the two E_{inv} estimations in Fig. 3 (left) obtained for proton and iron primaries using the EPOS LHC hadronic interaction model.

The performance of the analysis is studied on fully simulated events¹. For each event, we compute E_{inv} from R_μ using the estimation for the mixed proton and iron composition, and we compare it with the true value of E_{inv} . The average values of the residuals as a function of the true value of E_{inv} are shown in Fig. 3 (right) for proton and iron primaries for EPOS LHC, QGSJET II-04 and QGSJET01 hadronic interaction models. The residuals are within $\pm 10\%$ which is an indication of the overall systematic uncertainty in E_{inv} estimation, which is dominated by the model and mass dependence of the values of C and δ .

3.2 E_{inv} from vertical showers

As seen in Sec. 2, E_{inv} is a power law function of E_0

$$E_{\text{inv}} = \epsilon_c \beta_0 \left(\frac{E_0}{\epsilon_c} \right)^\beta. \quad (7)$$

β_0 , equal to $A^{1-\beta}$ in the extended Heitler model [10] (see Eq. (4)), is a parameter introduced in order to account for the large variations in the predictions of the number of muons that are obtained using different hadronic interaction models once E_0 and primary mass are fixed.

In the reconstruction of vertical events, E_0 is estimated from $S(1000)$, the signal at 1000 m from the core [4], by correcting for the shower attenuation using the constant intensity cut method [17]. To estimate E_{inv} from $S(1000)$, we use the functional form

$$E_0 = \gamma_0(\Delta X) [S(1000)]^\gamma, \quad (8)$$

¹ events simulated with the detector response and R_μ reconstructed with the same algorithm used for the data

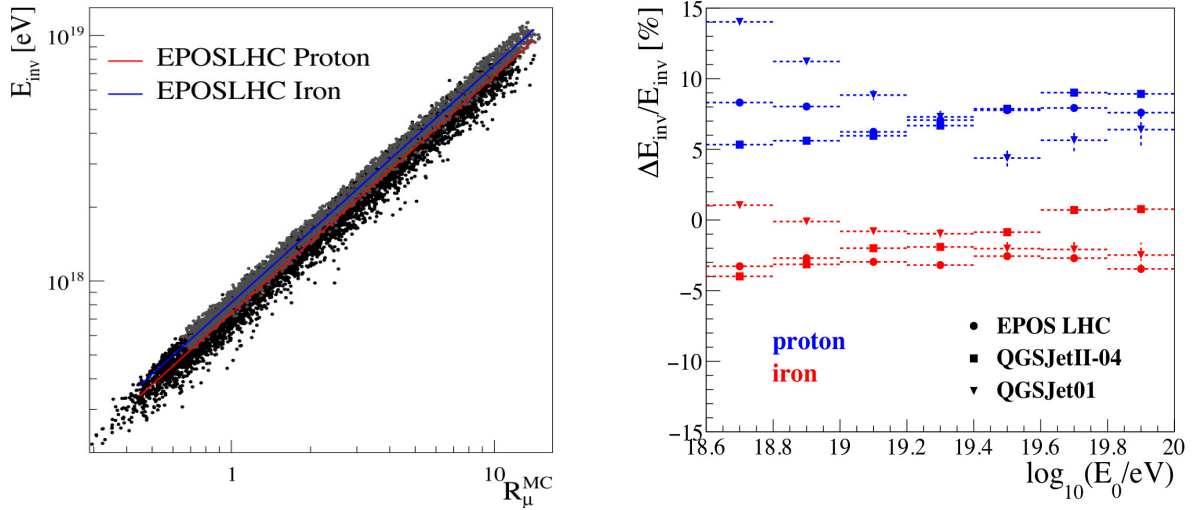


Figure 3. Left: Correlation between E_{inv} and R_{μ}^{MC} for the proton (black dots) and iron (grey dots) showers simulated with EPOS LHC. Right: Average value of the relative difference between the true value of E_{inv} and the value E_{inv} reconstructed using the EPOS LHC parameterisation for a mixture of 50% protons and 50% iron.

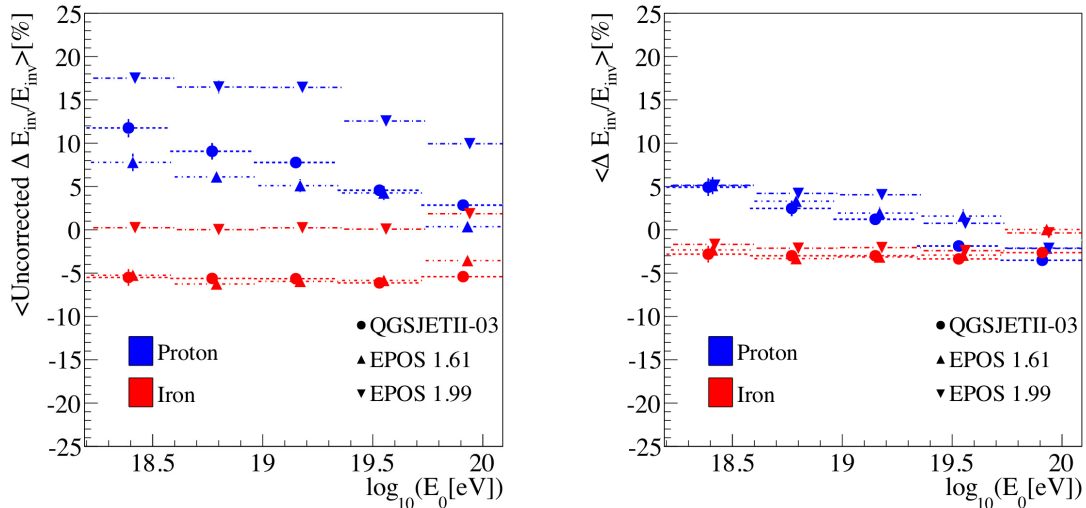


Figure 4. Average value of the relative difference between the true value of E_{inv} and the value of E_{inv} reconstructed from $S(1000)$ and X_{max} using Eq. (10) before (right) and after (left) applying the correction due to the difference among the simulations in the predictions of the number of muons and in the attenuation function, using Eq.(13).

where $\Delta X = X - X_{max}$ is the atmospheric slant depth between ground level at the Auger site and the depth of the shower maximum development, and $\gamma_0(\Delta X)$ is related to the attenuation of $S(1000)$ with ΔX .

Combining Eq. (7) and (8) one obtains

$$E_{inv} = \epsilon_c^\pi \beta_0 \left(\frac{\gamma_0(\Delta X) S(1000)^\gamma}{\epsilon_c^\pi} \right)^\beta \quad (9)$$

$$= A(\Delta X) [S(1000)]^B, \quad (10)$$

where

$$A(\Delta X) = (\epsilon_c^\pi)^{1-\beta} \beta_0 [\gamma_0(\Delta X)]^\beta, \quad (11)$$

$$B = \gamma\beta. \quad (12)$$

The parameter B and those defining the function $A(\Delta X)$ are determined using Monte Carlo simulations. Using the QGSJETII-03 hadronic interaction model, we find $\beta = 0.925$ and $\gamma = 1.0594$, so that their product is $B = 0.98$. Different interaction models yield the same value of B to within 2%. This value will be used from now on, so that with Eq. (10) and the measurements of $S(1000)$ and ΔX one can obtain an event-by-event estimate of E_{inv} . The function $A(\Delta X)$ is calculated using events simulated with the QGSJETII-03 hadronic interaction model for a mixed composition of 50% protons and 50% iron. $A(\Delta X)$ is parameterised with the fourth-degree polynomial.

The performance of the analysis is tested with proton and iron events simulated with the hadronic interaction

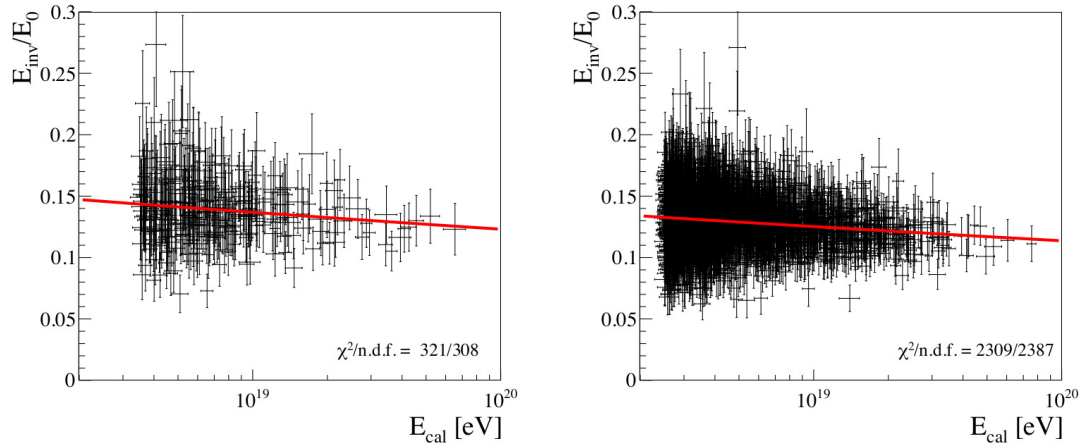


Figure 5. $\frac{E_{inv}}{E_0}$ as a function of E_{cal} from the inclined (left) and vertical (right) hybrid events. Fitted function shown with red line.

models QGSJETII-03, and EPOS 1.99. The average value of the residuals as a function of E_0 , shown in Fig. 4 (left), are between -5% and 20% . The spread in the residuals is mainly due to the difference in the predictions of the number of muons and of the attenuation function $\gamma_0(\Delta X)$ among the simulations used to parametrise $A(\Delta X)$, and the ones used to simulate the events. Note that the function $\gamma_0(\Delta X)$ includes the conversion factor needed to obtain E_0 from $S(1000)$ which is strongly model dependent.

A better estimation of E_{inv} can be obtained taking into account these differences using the following equation

$$E_{inv} = A(\Delta X) [S(1000)]^\beta \left(\frac{\tilde{\gamma}_0(\Delta X)}{\gamma_0(\Delta X)} \right)^\beta \frac{\tilde{\beta}_0}{\beta_0}, \quad (13)$$

where the quantities with and without the accent tilde are calculated for the data sample that we are analysing and for the one used to parametrise $A(\Delta X)$, respectively. β is fixed to 0.925. The functions γ_0 are obtained from Eq. (8) using E_0 and $S(1000)$. The ratio $\tilde{\beta}_0/\beta_0$ is estimated from the ratio of the number of muons at ground level for the two data sets, information that is available in the CORSIKA events. The residuals in E_{inv} using the improved parameterisation of Eq. (13) are shown in Fig. 4 (right). The true value of E_{inv} can be recovered within a few % for all models and primaries. Note also how we improve the estimation of E_{inv} for QGSJETII-03, despite the primary mass composition used to parametrise $A(\Delta X)$ being different to that of the simulated events used to test the analysis method.

3.3 Parameterisation of E_{inv} as a function of E_{cal}

The analysis methods described in Sec. 3.1 and 3.2 allow us to obtain an event-by-event estimation of E_{inv} from the data collected by the Pierre Auger Observatory.

The analysis is limited to events sufficiently energetic to ensure a full SD trigger efficiency. At energies lower than 4×10^{18} eV for the inclined [6] and 3×10^{18} eV for the vertical events [18], the trigger is biased towards events with a higher number of muons, and thus higher E_{inv} and consequently larger systematic uncertainties. In order to

get an estimation of E_{inv} useful for all FD events, including the ones with energies below the full SD trigger efficiency, the event-by-event estimation of E_{inv} is parameterised as a function of E_{cal} above the full trigger efficiency, with the function being extrapolated to lower energies.

Analysing hybrid events collected from 1 January 2004 to 31 December 2015, selected with the same cuts used for the energy calibration of the SD energy estimators [7] a parameterisation was obtained.

The correlation between E_{inv} and E_{cal} is well approximated by a power law relationship

$$E_{inv} = a \left(\frac{E_{cal}}{10^{18} \text{ eV}} \right)^b. \quad (14)$$

The data and the fitted function are shown in Fig. 5.

For a quantitative comparison of the two data-driven estimations of E_{inv} one has to take into account E_{inv} zenith angle dependence. Since the majority of the events are below 60° , the E_{inv} parameterisation from the inclined data set, that is on average 5% than the vertical one, has been corrected. The two data-driven E_{inv} estimations are compared in Fig. 6 (left) together with the theoretical predictions for post-LHC hadronic interaction models. They are still larger than the predictions for iron primaries, in contradiction with the mean mass obtained using X_{max} measurements [8]. This is due to the muon deficit [16] as models fail to describe the properties of shower development related to muons and therefore to E_{inv} .

It is worth noting that the two estimates are partially correlated since they both use the measurement of N_μ . However, they are affected by different systematics.

The estimations of E_{inv} obtained above the energy of full SD trigger efficiency can be extrapolated to lower energies taking into account the change in the mean mass composition evolution with energy at $E_{cal}^A \simeq 2 \times 10^{18}$ eV measured by Auger [8, 20]. The function is obtained by extrapolating the parameterisation obtained from data down to E_{cal}^A and, below this energy, using a model inspired function that matches the parameterisation at E_{cal}^A . For the latter, we use the function of Eq. (4) in which the mean composition as a function of energy is taken from

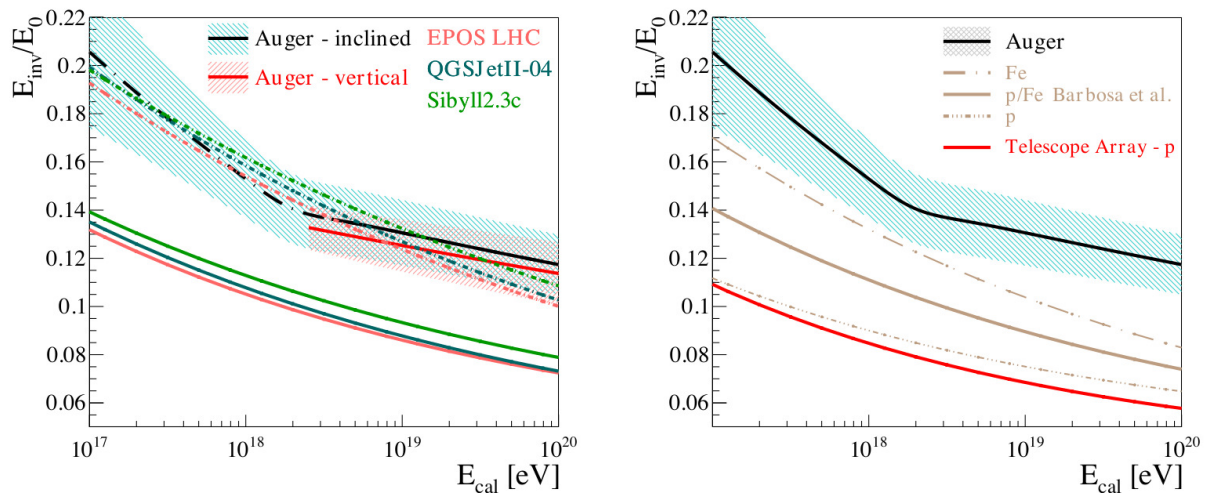


Figure 6. Left: E_{inv} for inclined and vertical events compared with predictions from simulations. Systematic uncertainty are shown with the shaded bands. The estimate for inclined events is extrapolated to low energies. Right: Auger data-driven estimation of E_{inv} compared with the parameterisations for protons, iron and mixed composition reported in [1] and the one in use by Telescope Array [22].

the Auger FD measurements [20] together with a value of $\beta = 0.9$ that reproduces the simulations at lower energies. The extrapolation of E_{inv} obtained from the inclined events, shown with the black dashed line in Fig. 6 (left), will be replaced in the near future with a more accurate estimation of E_{inv} using the data collected by the AMIGA muon detectors [21] installed at the Observatory and using the 750m-spacing sub-array of WCDs [4].

4 Conclusions

A data driven estimation of E_{inv} of cosmic ray showers detected by the Pierre Auger Observatory, was presented. Two analysis methods for inclined ($60^\circ < \theta < 80^\circ$) and vertical ($\theta < 60^\circ$) events were developed. E_{inv} has been parameterised as a function of E_{cal} and extrapolated to energies below the SD full trigger efficiency. The two estimations agree at a level well within the systematic uncertainties, that are estimated to be of the order of 10% – 15%.

E_{inv} results are considerably higher than the predictions given by simulations. This is a consequence of the muon deficit in models [16], a deficit due to the failure of the hadronic interaction models to describe the properties of shower development related to muons. Moreover, the results are consistent with the evolution of the mass with energy as measured by Auger [8, 20]. This is due to the sensitivity of N_μ to the primary mass and, at lower energy, due to the use of the mean mass composition to find the functional form that describes E_{inv} as a function of E_{cal} .

The measurement of N_μ makes the analysis of E_{inv} from inclined showers rather straightforward and intrinsically better than the analysis used for vertical events.

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