PROCEEDINGS OF SCIENCE

Measurement of the spectrum of cosmic rays above $10^{16.5}$ eV with Cherenkov–dominated events at the Pierre Auger Observatory

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We present a profile constrained geometry fit (PCGF) method for shower geometry reconstruction implemented in the Pierre Auger Observatory analysis chain. It is used to reconstruct low–energy extensive air showers (3×10^{15} eV $< E < 10^{18}$ eV) detected by the high elevation Auger telescopes (HEAT). The method is proven to be particularly important for events with signal dominated by Cherenkov light. The precision of the reconstruction is evaluated using full Monte Carlo simulations of the showers and telescopes. Simulations are compared to the data, and the results are discussed. A preliminary measurement of the energy spectrum in the second knee region is presented.

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1. Introduction

The Pierre Auger Observatory [1] is primarily designed to measure the highest energy cosmic rays at energies above 10^{18} eV. This is achieved with an array of water–Cherenkov surface detectors (SD) with a 1500 m spacing and 24 telescopes of the fluorescence detector (FD) looking at an elevation of 1.51° above the horizon with a field of view of 30° × 30°. The FD is situated at four sites called Los Leones, Los Morados, Loma Amarilla and Coihueco.

Besides the instruments dedicated to the highest energies, two low–energy extensions are present at the Observatory, i.e. the SD array with 750 m spacing, and three high elevation Auger telescopes (HEAT). HEAT covers an elevation range up to 60° and is able to work in hybrid mode together with the 750 m array down to energies around 10^{17} eV. The 750 m array itself also delivers results down to 10^{17} eV [2].

The standard hybrid detection, commonly used by the Pierre Auger Observatory, is not suitable to address lower energies. This is caused by the weakness of the fluorescence light produced by air showers of lower energy. In this contribution, we utilize the showers approaching FD telescopes along their telescope axes. Such events have a lower detection threshold caused by the air–Cherenkov light emission from the charged particles in the shower. To solidly reconstruct Cherenkov–dominated events, we utilize the profile constrained geometry fit (PCGF). It was invented at the HiRes experiment [3] for fluorescence–dominated events and is currently used by TALE [4] for Cherenkov–dominated data.

2. Method

The PCGF is a method of shower geometry reconstruction that works for a monocular view of an extensive air shower. It is favoured over the simple monocular time fit because the time fit suffers from correlations between shower axis parameters described below. If the shower is assumed to propagate with a velocity equal to the speed of light c, then the shower axis is determined by R_p, t_0 and χ_0 inside the shower–detector plane (SDP), see [5] for parameter definitions. The parameters are connected by the formula

$$t_i = t_0 + \frac{R_\mathrm{p}}{c} \tan\left(\frac{\chi_0 - \chi_i}{2}\right), \tag{2.1}$$

where t_i is the time when the light from the shower is detected at a viewing angle χ_i inside the SDP. Because the field of view of the FD telescope is limited, the range of χ_i available for the fit is also limited. For events with a short angular track length, we see a correlation between two of the three parameters.

Within the PCGF approach, the above mentioned correlation is removed by an additional requirement on the energy deposit profile in the atmosphere. We require that the energy deposit profile calculated for a given geometry is compatible with the Gaisser–Hillas (GH) function [6],

$$\frac{\mathrm{d}E}{\mathrm{d}X}(X) = \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{max}} \left(\frac{X - X_0}{X_{\mathrm{max}} - X_0}\right)^{\frac{X_{\mathrm{max}} - X_0}{\lambda}} \exp\left(\frac{X_{\mathrm{max}} - X}{\lambda}\right), \tag{2.2}$$

where X_0 and λ are GH shape parameters, X_{max} is the depth of the shower maximum, and $\left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{max}}$ is the maximum of energy deposit.

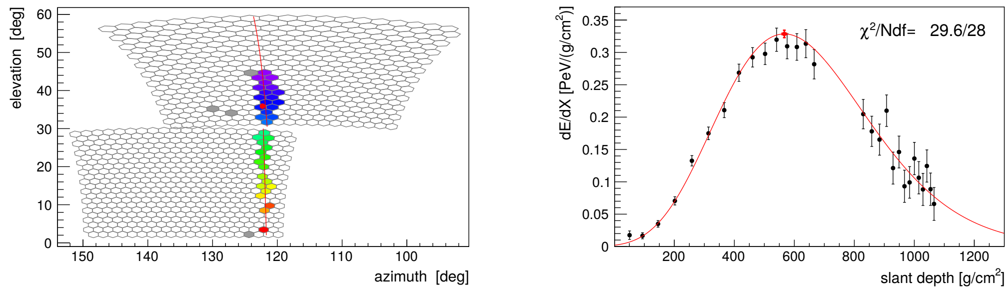

Figure 1: Reconstruction of event 6/1990/13000. The camera view (left panel) together with the reconstructed energy deposit profile (right panel) are shown. The reconstructed calorimetric energy is 2.1×10^{17} eV. The gap in the profile corresponds to the crossing between two telescopes.

Technically, a scan in χ_0 is performed, and for each fixed χ_0 the two remaining parameters, R_p and t_0, are calculated by linear regression of Eq. (2.1). For the geometry fixed in this way, a fit of the GH function Eq. (2.2) to the energy deposit profile is done as follows. The X_0, X_max, λ and $\left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_\mathrm{max}$ are varied, and for each of the combinations, the light flux that would be measured in the FD telescopes is predicted and compared to the measured flux. In the end, the likelihood that is used to quantify the level of agreement between the particular χ_0–defined geometry and our assumptions is then composed of parts corresponding to the time fit Eq. (2.1), constraints on GH parameters, and the observed light flux in the telescopes. Finally, the most likely geometry is selected, and for this geometry the resulting energy deposit profile is fine–tuned in later reconstruction steps.

Besides the implementation of the basic method described above, the PCGF reconstruction module is able to deal with telescopes placed at different positions. It allows us to use the HEAT telescopes together with Coihueco site telescopes[1], effectively working in a partial stereo observation regime for showers seen by both detectors. An example of a shower detected simultaneously by HEAT and Coihueco telescopes that was reconstructed by a PCGF is shown in Fig. 1.

3. Accuracy and precision of reconstruction

To evaluate the accuracy and precision of the PCGF reconstruction, a set of Monte Carlo (MC) simulations was produced. The air showers were generated with the CONEX program [7], and the light simulation together with the full FD response were calculated within the Offline framework [8]. Sibyll 2.3c [9] was used as the high–energy interaction model. The range of simulated energies was 10^{15}–$10^{18.2}$ eV for both protons and iron nuclei as primary particles.

Although the PCGF also works in principle for fluorescence–dominated events, our interest is restricted to the Cherenkov–dominated data only. The first reason is due to a better accuracy of the geometry reconstruction which is connected to the strong collimation of the Cherenkov beam produced by showers. It improves the sensitivity of the reconstruction to small changes in the mutual telescope–shower axis position. The second reason is the fact that low–energy showers are detectable thanks to the Cherenkov radiation, and fluorescence is mostly absent. In this contribu-

[1] Coihueco and HEAT sites are placed ca. 170 m apart.

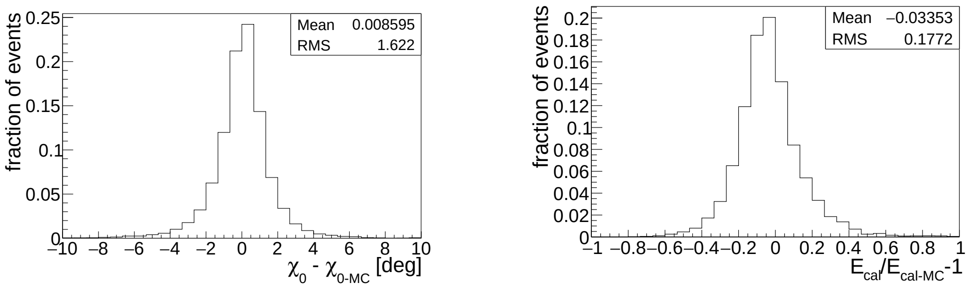

Figure 2: Resolution of the χ_0 shower axis parameter (left panel) and the calorimetric energy (right panel) reconstructed by the PCGF at calorimetric energies between $10^{15.5} - 10^{18}$ eV. The energy spectrum in simulations was re–weighted to $E^{-2.8}$.

tion, we are interested in the low–energy part of the cosmic–ray spectrum and the high–energy part is better analysed by hybrid measurements.

To reduce the number of badly reconstructed events, quality cuts were applied. In line with the preceding paragraph, only events with a total Cherenkov light fraction above 50% were used. Due to the limited FD electronics readout, the fast Cherenkov–dominated events are in general poorly sampled in time. Because of that, we applied a cut on the minimum number of points in the detected light flux to be at least 5, which corresponds to 250 ns and 500 ns durations in HEAT and Coihueco telescopes, respectively, due to different electronics. This cut[2] allows reasonable fits of the GH function to the energy deposit profile, see Fig. 1.

The overall precision of the reconstruction of the shower geometry can be quantified by the resolution and bias of the χ_0 parameter. The distribution of differences between the reconstructed and simulated χ_0 is shown in the left panel of Fig. 2. It corresponds to a simulated range of $10^{15.5} - 10^{18}$ eV in calorimetric energy (E_{cal}), and simulations were re–weighted according to the energy spectrum of $E^{-2.8}$, which also holds for all further plots. An almost unbiased estimation of χ_0 is achieved together with a resolution of about 1.6°.

The most critical observable for studies of cosmic rays is the energy of the incident air shower. Utilizing the full MC simulations, an energy response was calculated and is depicted in the right panel of Fig. 2. The obtained reconstruction resolution of calorimetric energy is 18%, and on average the energies are slightly underestimated. This result takes into account all the machinery of the shower reconstruction, i.e. the bias is not solely due to the discrepancy in the reconstructed shower axis[3]. The effects that are related to uncorrelated systematic uncertainties are not included in the reported energy resolution and will be evaluated in the future.

It is worth noting that the energy that is estimated is the calorimetric energy. The Cherenkov radiation reflects the integrated track length of charged particles above the Cherenkov energy threshold, which may not follow the energy deposit profile exactly. Such effects are taken into account in our simulations, and in the reconstruction, an average energy deposit per charged particle is used [10]. The fluctuations of energy deposit per charged particle at the CONEX level are still present, and the Cherenkov energy threshold is controlled by the model of light emission as described in

[2]We also use a reduced $\chi^2 < 3$ cut on the energy deposit profile.

[3]Actually, an energy bias of a similar value is also found for a MC–fixed shower axis. Nevertheless, in that case, the resolution is much better.

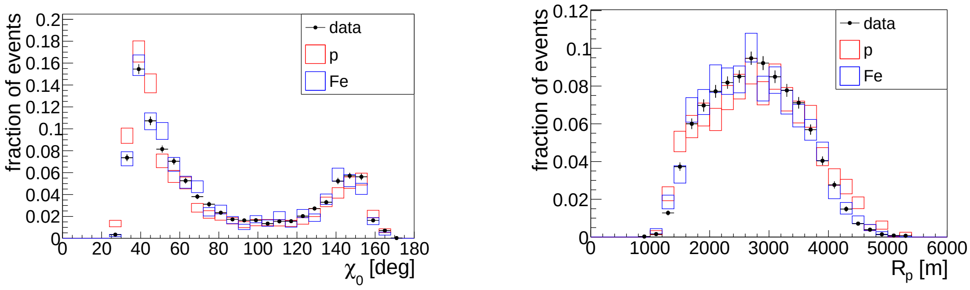

Figure 3: Distributions of reconstructed χ_0 (left panel) and R_p (right panel) in the energy bin of $10^{16.9}$ – $10^{17.1}$ eV for the data (black). Simulations of protons and iron nuclei are shown by red and blue boxes, respectively.

[11].

Besides the precision of the PCGF reconstruction itself, it is necessary to check the agreement between the simulated MC sample and the data. For this purpose, we present the distributions of shower axis parameters χ_0 and R_p in the calorimetric energy range of $10^{16.9}$ – $10^{17.1}$ eV. The distributions are shown in Fig. 3 for χ_0 and R_p in the left and right panel, respectively; the data are depicted by black points. Colored boxes correspond to simulations, and their length represents the statistical uncertainty of the MC.

4. Towards an energy spectrum

Data processed by the PCGF give rise to the possibility of an energy spectrum measurement at energies below the hybrid detection limit. However, the new measurement technique is complicated by several sources of systematic uncertainty. Besides the invisible energy correction and composition systematics described below, we also investigated other uncertainties related to the determination of the energy spectrum. The energy scale systematics of the FD [12], common to all Auger measurements, is the most important source of systematic uncertainty. It also affects the exposure through its dependence on the number of detected photoelectrons; the effect is ca. 15% on the flux at 10^{17} eV. The systematic uncertainty in energy due to the Cherenkov emission model used [13] is estimated to be 5%, and the uncertainty in the energy reconstruction procedure is below 6%.

4.1 Invisible energy

To estimate the total energy (E_tot) of an air shower, a correction for the energy that was not deposited in the atmosphere, called the invisible energy (E_inv), has to be applied. For the purpose of the Cherenkov–dominated measurement, we estimate the invisible energy from IceTop data [14] with the use of the equation

$$E_\mathrm{inv} = \varepsilon_C^\pi N_\mu\,, \tag{4.1}$$

which comes from the extended Heitler model [15]. In this equation, N_μ is the number of muons in the extensive air shower reaching ground level, and ε_C^π is the pion critical energy. Justification of Eq. (4.1) is based on detailed MC simulations provided in [16].

polynomial	a	b	c
P	4.213	-0.463	0.013
P_{low}	3.838	-0.420	0.012
P_{up}	4.623	-0.509	0.015

Table 1: Parameters of the invisible energy model below 10^{17} eV. Above 10^{17} eV, the values reported in [16] are used.

A recalculation of muon densities at ground level reported by IceTop was done in [17], where the z quantity is defined by

$$z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu,\text{p}}^{\text{det}})}{\ln(N_{\mu,\text{Fe}}^{\text{det}}) - \ln(N_{\mu,\text{p}}^{\text{det}})}. \tag{4.2}$$

N_{μ}^{det} is the muon density estimate as seen in the detector, while $N_{\mu,\text{Fe}}^{\text{det}}$ and $N_{\mu,\text{p}}^{\text{det}}$ are the simulated muon density estimates for p and Fe induced showers after a full detector simulation. However, the simulated number of muons is dependent on the particular model of high–energy interactions. For the purpose of the invisible energy calculation, the QGSJetII-04 model [18] was chosen.

Utilizing Eqs. (4.1) and (4.2), the formula for the invisible energy is

$$E_{\text{inv}} = E_{\text{inv,p}} \left(\frac{E_{\text{inv,Fe}}}{E_{\text{inv,p}}} \right)^{z}, \tag{4.3}$$

where $E_{\text{inv,p}}$ and $E_{\text{inv,Fe}}$ are the invisible energies estimated by the chosen high–energy interaction model for protons and iron nuclei, respectively. Values of $E_{\text{inv,p}}$ and $E_{\text{inv,Fe}}$ are parametrized using CONEX simulations, and z is taken directly from [17]. The invisible energy is evaluated according to Eq. (4.3) and shown in Fig. 4 by green and orange points for 600 m and 800 m core distances, respectively.

To combine our estimates with those at higher energies [16], we performed a fit of the 2$^{\text{nd}}$ order polynomial P

$$E_{\text{inv}}/E_{\text{tot}} = a + b\log_{10} E_{\text{cal}}/\text{eV} + c\,(\log_{10} E_{\text{cal}}/\text{eV})^2, \tag{4.4}$$

to the data derived from IceTop in the energy range of $10^{15} - 10^{17}$ eV. The upper energy point at 10^{17} eV was fixed to the value reported in [16]. Systematic uncertainties were estimated combining the uncertainty reported in [16] and the one obtained by fitting the polynomials P_{low} and P_{up} to the IceTop lower and upper uncertainty bounds, respectively; for coefficients see Tab. 1.

4.2 Exposure

The exposure of HEAT and Coihueco telescopes to the Cherenkov–dominated events was estimated from detailed MC simulations introduced in Section 3. Protons and iron nuclei were used as primary particles to estimate the composition systematics. In the left panel of Fig. 5, the exposure in the time period of 06/2012–12/2015 is visualized under the condition that the invisible energy follows the model depicted in Fig. 4. In this way, only the systematic effects connected to the limited field of view of telescopes and different slant depth evolution of showers induced by

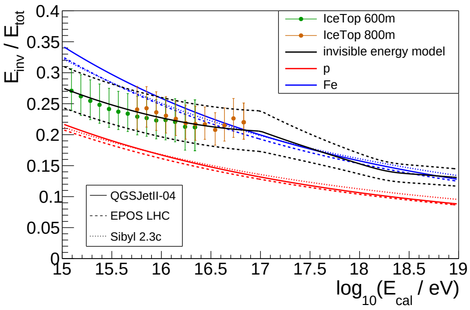

Figure 4: Invisible energy model (black line) estimated with the use of IceTop data [14] (points). The high–energy part above 10^{17} eV is fixed to the values reported in [16]. Dashed black lines show the systematic uncertainty. Red and blue lines correspond to the MC predictions for protons and iron nuclei, respectively.

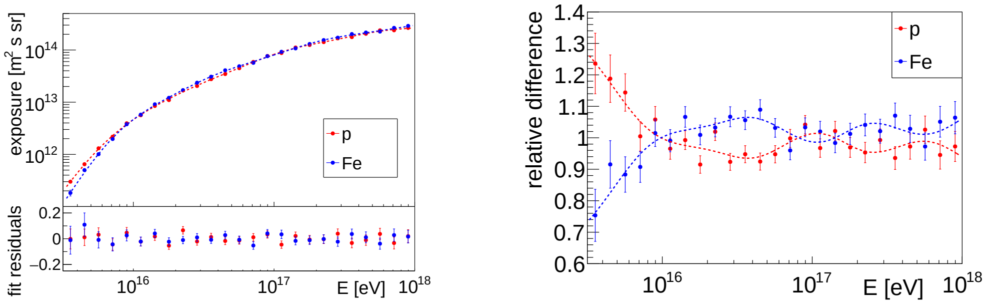

Figure 5: Left panel: Exposure to the Cherenkov–dominated events over the time period of 06/2012-12/2015 (top panel). Protons (red) and iron nuclei (blue) were used as primary particles. Residuals to the fitted functions (dashed lines) are shown in the bottom panel. Right panel: Relative difference between exposures inferred from pure primary beams and the 50% + 50% mix. Points depict the difference derived from the MC simulations directly, dashed lines correspond to the difference calculated with the use of exposure fits.

different primaries are estimated. The difference in the exposure to protons and iron nuclei with respect to the 50% + 50% mix is shown in the right panel of Fig. 5. The systematic uncertainty of the exposure connected to the uncertain composition is below 10% above 10^{16} eV.

Knowing the exposure, we calculate a preliminary energy spectrum. It is shown in Fig. 6 and restricted to energies above $10^{16.5}$ eV. Unfolding of the resolution and bias of the energy reconstruction is applied. Points correspond to the used composition assumption [19]. Magenta boxes show the acceptance systematics due to uncertain composition, and grey regions show the systematic uncertainties corresponding to other investigated effects.

5. Conclusions

The PCGF method of shower axis geometry reconstruction was successfully implemented in the Offline software used at the Pierre Auger Observatory. The resolution of the χ_0 reconstruction is 1.6°, and the calorimetric energy is reconstructed with a resolution of 18%. Correspondence between the measured data and full simulations of air showers and the FD is at a reasonable level.

A preliminary energy spectrum of cosmic rays in the energy region of $10^{16.5}$ – 10^{18} eV was estimated. Dominant systematic uncertainties are in the FD energy scale (14% in energy) and MC

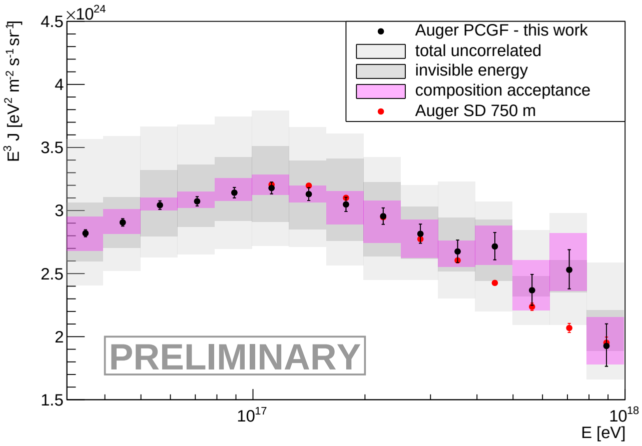

Figure 6: Preliminary energy spectrum derived from Cherenkov–dominated events detected by the HEAT and Coihueco telescopes (black). Light grey region corresponds to the total uncertainty uncorrelated with the Auger SD 750 m [2] measurement (red). It consists of uncertainties in the Cherenkov emission model, exposure and in the reconstruction procedure. Dark grey and magenta regions show the uncertainty due to the invisible energy model and different detector acceptance for different primaries, respectively.

simulations of the FD (15% in exposure). The reconstruction procedure and Cherenkov emission model contribute to the uncertainty in the Cherenkov energy scale by ca. 5% each. A presence of the second knee is robust against changes in the invisible energy even to the MC predictions for pure beams.

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