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Cosmic ray energy reconstruction from the S(500) observable recorded with the KASCADE-Grande air shower experiment

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Abstract

The energy reconstruction at KASCADE-Grande is based on a combination of the shower size and the total muon number, both estimated for each individual air-shower event. We present investigations by a second method to reconstruct the primary energy using S(500), the charged particle densities inferred with the KASCADE-Grande detector at 500 m distance from the shower axis. We account for the attenuation of inclined showers by applying the 'Constant Intensity Cut' method and we employ a simulation derived calibration to convert the recorded S(500) into primary energy. We observe a systematic shift of the S(500)-derived energy in relation to the earlier published results of the standard reconstruction technique. However, a comparison of the two methods on simulated and measured data shows that this shift appears only for measured data. Investigations show that this shift is mainly caused by the insufficient way simulations (QGSJet-II-2, EPOS-1.99) describe the shape of the lateral density distribution.

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Keywords: cosmic rays, primary energy, KASCADE-Grande, S (500), hadronic interaction models

1 1. Introduction

Cosmic rays experiments are mainly concerned with
 inferring the arrival direction, the energy spectrum and
 the elemental composition of the primary cosmic ra diation. The primary energy spectrum falls steeply

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and extends up to 10^{20} eV. Two features are immediately visible in the spectrum, in the form of two spectral index changes. These features produce a shape of the spectrum similar to a bent human leg hence their names: *knee* (steepening of the spectrum) and *ankle* (flattening). The two features are strongly correlated in the models describing their source (e.g. [1, 2]). It is generally accepted that towards the highest energies $(E_0 > 5 \times 10^{18} \text{ eV})$, the component above the ankle is most likely of extragalactic origin [3]. Towards lower energies (i.e. $E_0 \approx 4 \times 10^{15} \text{ eV})$, the knee is caused by a rigidity dependent extinction of the light component inthe galactic radiation.

The KASCADE-Grande [4] experiment has been de-19 signed to record air showers in the 1016-1018 eV en-20 ergy range to answer such questions regarding the tran-21 sition to the extragalactic radiation. Recent results at 22 KASCADE-Grande [7] show a flux of cosmic rays in 23 very good agreement with results of other experiments 24 (e.g. KASCADE [5], EAS-TOP [6]). The all-particle 25 energy spectrum reported by KASCADE-Grande ex-26 hibits a hardening of the spectrum at 2×10^{16} eV, a knee-27 like feature at around 8×10^{16} eV due to heavy primaries 28 and an ankle-like hardening at 10^{17.8} eV due to the light 29 component [7, 8, 9]. These results were provided by a 30 reconstruction technique based on a $N_{ch}-N_{\mu}$ correlation 31 (i.e. total shower size - muon size) used to infer the 32 primary energy from the data recorded by KASCADE-33 Grande. 34

In this paper we present a second approach to re-35 construct the primary energy with KASCADE-Grande. 36 This approach is applied independently from the stan-37 dard method and to the same shower sample leading 38 to subsequent cross-checks between results. The new 39 method is based on a specific primary energy estima-40 tor, the attenuation-corrected charged particle density at 41 500 m distance from the shower axis, S(500). 42

43 2. KASCADE-Grande

The studies in this paper are based on air shower ob-44 servations with the KASCADE-Grande [4] detector ar-45 ray, in particular on measurements of the lateral distri-46 bution of charged EAS particle densities. The array was 47 situated at the site of the Karlsruhe Institute of Tech-48 nology - KIT, Campus North, Germany (49° N, 8° E) 49 at 110 m a.s.l. It had a roughly rectangular shape with 50 a length of 700 m (Fig. 1). A complex multi-detector 51 system of various types of detectors enabled the regis-52 tration of different EAS observables. 53

Historically, the KASCADE-Grande detector array 54 was an extension of a smaller array, KASCADE [5], op-55 erated since 1996. KASCADE was designed to record 56 air showers initiated by primaries with energies in the 57 10^{14} - 10^{16} eV range (including the knee range whose 58 origin to clarify was one of the goals). The KASCADE 59 detector was a complex detector array providing infor-60 mation on a considerable number of observables asso-61 ciated with the electromagnetic, muonic and hadronic 62 63 component.

The extension of the original smaller but rather detailed KASCADE array was guided by the intention to extend the energy range for efficient EAS detection to



Figure 1: *Left*: schematic top-view of the KASCADE-Grande detector array (the Grande stations are shown as square dots and the fiducial area with line contour, see text) and the area covered by KASCADE (as shaded rectangle); *Right a*) simplified 3D view of the inside of a Grande station; *Right b*) inside view of a scintillator module.

the energy range of $10^{16} - 10^{18}$ eV. This energy range provides various interesting aspects: the expected transition from galactic to extragalactic origin of cosmic rays and, in particular the question whether there exists a further knee in the energy spectrum. The layout of the extension of KASCADE to KASCADE-Grande was governed by following basic considerations. Higher energy showers appear with smaller rate. Thus, in order to record enough events in a reasonable amount of time, a larger size of the array was necessary. The other aspect arose from the functionality of detectors themselves. High energy primaries generate particlerich showers that tend to saturate the detectors close to the shower core where the particle density is very high. Consequently for a small array, data recorded close to the shower core is not reliable and it appears necessary to extract data from the EAS at greater radial distances.

The Grande array consisted of 37 detector stations (formerly installed in the EAS TOP array [6]), arranged in a roughly hexagonal grid with a spacing of about 140 m. Each station housed plastic scintillation detectors organized in 16 units (Fig. 1a) with a total effective area of 10 m² per station. The station hut itself was made of metal and was placed on the ground. The scintillator plates ($80 \times 80 \times 4$ cm) were arranged in a 4 × 4 pattern inside each hut. Each plate was enclosed in a steel casing of pyramidal shape (Fig. 1b). The plate was viewed from below by a high gain photo-multiplier. Additionally, the 4 central modules were equipped also with low gain photomultipliers. KASCADE-Grande was in operation from 2003 until 2013, and is meanwhile dismantled.

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3. Reconstruction of S(500) 99

3.1. S(500) as energy estimator 100

Previous investigations have shown that the charged 101 particle density in air showers becomes independent of 102 the primary mass at a large but fixed distance from the 103 shower axis and that it can be used as an estimator for 104 the primary energy [10]. In a comparison between the 105 p and Fe initiated showers, the $e^{+/-}$ excess in p show-106 ers towards lower radial ranges diminishes with the in-107 crease of the distance to the shower axis as the electrons 108 get absorbed. At the same time the muon excess in the 109 Fe showers gradually becomes more important at larger 110 radial ranges. Following this trend, for a given radial 111 range this behaviour produces an overlap of the lateral 112 distributions (Fig. 2) and in that location the value of 113 the charged particle density becomes mass independent. 114 Such a distance is specific for a given experiment as it 115 depends on the observation level and on the detector 116 threshold and sensitivity to the charged particle com-117 ponent. Based on this property a method was derived 118 to reconstruct the primary energy from the particular 119 value of the charged particle density, observed at such 120 specific radial distances. While in the AGASA experi-121 ment the technique was applied for a distance of 600 m 122 to the shower axis [11], in the case of the KASCADE-123 Grande array detailed simulations [12] have shown that 124 the particular distance for which this effect takes place 125 is about 500 m (Fig. 2), hence the notation S(500) for 126 the charged particle density at 500 m distance from the 127 shower axis. The distance is measured in a plane nor-128 mal to the shower axis and containing the shower core. 129 The property of mass independence is visible also in 130 Fig. 3 showing the correlation between the energy es-131 timator S(500) and the primary energy for different pri-132 mary masses. 133

It must be stressed that the properties of the S(500)134 observable are predicted by simulation studies based on 135 the QGSJet-II-2 [14] hadronic interaction model and it 136 is entirely possible that simulations based on other inter-137 action models could predict different mass-independent 157 138 observables. 139

3.2. Event selection 140

Simulated showers are used for fine tuning the recon- 161 141 struction procedure and also for calibrating the observ-142 able of interest, S(500) with the primary energy. The 143 analysis is applied identically to simulated and experi-144 145 mental events using the same reconstruction procedure. Air showers are simulated using the CORSIKA [13] 146 Monte Carlo EAS simulation tool, with the QGSJet-II-2 147 [14] model embedded for high energy interactions. The 148



Figure 2: Averaged simulated lateral distributions for p and Fe primaries with energy in a narrow range



Figure 3: The dependence of the primary energy E_0 on the S(500) for p and Fe primaries (simulated showers in fairly equal proportions for the two masses); the boxes show the spread of data, the errors on the mean are represented with bars and are dot-sized.

set of simulated showers includes events simulated for 5 primaries (p, He, C, Si and Fe in fairly equal proportions) with continuous energy spectrum between 10^{15} – 3×10^{18} eV and with a spectral index $\gamma = -2$ harder than the measured data (this allows to faster increase the statistical accuracy at higher energies by not simulating as many showers at lower energies as in a $\gamma \approx -3$ sample). Since the spectral index of simulations is significantly different from the experimentally observed one, a weighting is applied to simulated events in most of the subsequent studies to emulate a softer energy spectrum $\gamma = -3$. About 3×10^5 events have been simulated for each primary. The arrival direction of showers is isotropical and the shower cores are spread randomly on an area larger than the Grande array. In addition, for comparisons a smaller set of showers has been simulated using the high energy hadronic interaction model EPOS v1.99 [15].

To select a high quality shower sample a set of quality cuts is applied identically to the simulated events and to

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the data. The main requirement is a good reconstruction 220 169 of S(500), triggering subsequent restrictions for shower 221 170 selection: a fiducial area (as shown in Fig. 1), EAS 222 171 zenith angle up to 30° and at least 24 triggered stations 223 172 in every event. These conditions are intended to mini-173 224 mize geometrical effects due to shower inclinations and 174 225 also to reduce the ratio of showers that have no infor-226 175 mation in the lateral density distribution at large radial 227 176 ranges. The fiducial area in Fig. 1 has been chosen to 228 177 be the same as in [7] in order to increase the similar- 229 178 ity of selected shower samples in different primary en- 230 179 ergy reconstruction approaches. The fiducial area is a 231 180 rectangle omitting the closest and farthest corners rel- 232 181 ative to the KASCADE array in order to minimize the 233 182 under- and overestimation on the muon number which 234 183 is relevant for the standard reconstruction approach in 235 184 [7]. The acceptance of the experiment under the above 236 185 mentioned assumption for fiducial area and zenith an- 237 186 gle is 1.28×10^5 m²sr. The total acquisition time for ²³⁸ 187 experimental data is 1503 days leading to an exposure 239 188 of 1.66×10^{13} m²s sr. Approximately 9.05×10^5 experi-189 mental events have passed all imposed selection cuts. 190

¹⁹¹ 3.3. The reconstruction of S(500)

The reconstruction procedure that is described in the following is applied without any change to both simu- ²⁴⁰ lated and experimental events [16].

The KASCADE-Grande detector stations record the 195 energy deposits of particles and the associated temporal 196 information (arrival times of particles) without disen-197 241 tangling the particle type (e.g. muons from electrons). 198 The temporal information is used to reconstruct the 242 199 zenith and azimuth angles of the shower axis [17]. The 200 244 recorded energy deposit is converted to particle densi-201 ties using appropriate Lateral Energy Correction Func-245 202 tions (LECF) [18] that take into account the arrival di-246 203 247 rection of the shower and the azimuthal position of each 204 248 station around the shower axis. 205

For both experimental and simulated events, the in-206 formation of particle density is usually given in the de-207 tector plane. The shower properties however are bet-208 ter revealed in the plane normal to shower axis. Par-209 ticle densities are therefore reconstructed in the plane 210 normal to the shower axis [19]. In order to map the 211 shower properties from the detector plane onto the nor-212 mal plane, special care was taken in order to avoid dis-213 torting the information. For an inclined shower, the par-214 ticle density around the shower core at a given radial 215 216 range can vary due to different particle absorption and scattering in the atmosphere. A relevant example is the 217 case of particles propagating directly below the shower 218 axis, as opposed to those directly above the shower axis 219

for an inclined shower. The particles below the axis will travel a shorter distance through atmosphere before reaching the detector level. If detectors are placed predominantly under the shower axis, the particle density would be overestimated (following that in the opposite case the density would be underestimated). Furthermore, the angle of incidence of particles in detectors will be different in the two cases because the particles have a transverse momentum and do not propagate parallel to each other or to the shower axis. The error in the density influences both the reconstructed shower size and the accuracy of shower core reconstruction. A procedure has therefore been introduced in order to compensate for the attenuation of inclined showers. In addition the dependence of energy deposits with the angle of incidence of particles is also taken into account.

To calculate the charged particle density at 500 m distance from the shower axis, the lateral density distribution is approximated with a 3-parameter Linsley function (eq. $1,2)[20]^4$:

$$\rho_{ch} = \frac{N}{r_0^2} \cdot C(\alpha, \eta) \cdot \left(\frac{r}{r_0}\right)^{-\alpha} \cdot \left(1 + \frac{r}{r_0}\right)^{-(\eta - \alpha)}$$
(1)

where

$$C(\alpha, \eta) = \Gamma(\eta - \alpha) \cdot \left[2\pi \cdot \Gamma(2 - \alpha) \cdot \Gamma(\eta - 2)\right]^{-1} \quad (2)$$

with

 ρ_{ch} (r) - charged particle density at distance r[m] from the shower core;

N - shower size (in this case the total number of charged particles);

 r_0 - Molière type radius [m];

r - radius [m];

 α , η - two shape parameters.

Fig. 4 shows that the ratio of successfully reconstructed S(500) in simulated events exceeds 95% at around $\log_{10}(E_0/\text{GeV}) = 7.5$. The fluctuations around the value 1 for energies $\log_{10}(E_0/\text{GeV}) > 7.5$ are due to the fluctuation of reconstructed shower cores inside or outside the fiducial area that is used for shower selection. In contrast to the S(500)-based method, the full efficiency of the standard reconstruction procedure [7] (based on $N_{ch} - N_{\mu}$) is reached at lower energies,

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⁴For applying an independent analysis also a different LDFfunction was chosen compared to the standard approach. However, investigations have shown that both functions work equally well in determining S(500).



Figure 4: Ratio between the number of simulated events for which S(500) was successfully reconstructed and the total number of simulated events as a dependence with the primary energy (the energies of the simulated events are distributed as a power law with spectral index γ =-2).

 $E_0 \approx 10^{16}$ eV. This is mainly due to the shower selection procedure (Section 3.2) that is employed to maximize the reconstruction quality of *S* (500). The recorded *S* (500) values can not be directly converted to primary energy without first accounting for

the different attenuation of inclined events in the atmosphere. This is achieved by applying the Constant Intensity Cut (CIC) method that corrects all recorded *S* (500) values as if the showers were coming from a fixed zenith angle (Appendix A). As the zenith angular distribution is peaked at $\approx 21^{\circ}$, this value was chosen for the CIC reference angle. The measured S(500) spectrum is

shown in Fig. 5 and the spectrum shows similar structures as reported in [7].



Figure 5: The measured S(500) spectrum after the CIC correction.

$_{272}$ 3.4. Energy reconstruction using S (500)

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A calibration is derived from simulated showers with ²⁸⁴ zenith angle around the CIC reference angle and with a ²⁸⁵ mass composition of 5 primaries in fairly equal proportions (Fig. 6). The calibration is a power law function as ²⁸⁷



Figure 6: E_0 - S(500) correlation; the dots are the profile of the scatter plot with box errors showing the spread of data while errors of the mean with simple line are dot sized; the continuous line is a power law fit with γ =0.915±0.002.



Figure 7: Energy resolution - the box errors show the spread of data while the error of the mean with bar is dot sized; the plot shows the case of p and Fe primaries and a similar behaviour is noted for other primaries too.

in eq. 3 and is used to convert all attenuation-corrected S(500) values to the corresponding primary energy.

$$E_0 = C \cdot S (500)^{\gamma} \tag{3}$$

with C - a constant; and γ - the slope index of the power law dependency.

Under the assumptions of the QGSJet-II-2 model the energy calibration is found to be composition independent. In order to test the method's ability to reproduce the primary energy values we calculate the energy resolution. For the simulated shower sample we show the relative difference between the reconstructed primary energy and the true energy as a function of the primary energy (Fig. 7). We then record the RMS of the distribution (i.e. energy resolution) for each primary energy bin. The energy resolution improves with the increase of the energy due to the decrease of shower to shower statistical fluctuations at higher energies. Fig. 7 shows also that there is a slight ($\approx 5\%$)

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underestimation of the primary energy, more so towards 288 lower energies, but still below 10% (this appears in 289 the case of small showers where the lateral particle 290 density has little or no data towards r = 500 m causing 291 the Linsley fit to better describe the range closer to 292 the shower core which is much steeper hence lead-293 ing to an underestimation of the density value at 500 m). 294 295

3.5. Comparison between results 296

In order to ensure that the method based on S(500)297 is working correctly we evaluate the energy reconstruc-298 tion by this and the standard method [7] on an event-by-299 event basis first for simulations and then for data. 300

Figure 8 shows the comparison between the recon-301 structed energy spectra in the two methods and the true 302 energy for the same shower sample (in this plot we rep-303 resent the result of each method relative to the true en-304 ergy distribution that is used in simulations). We con-305 clude that for simulated showers both reconstruction 306 methods function similarly as the results of each one 307 agrees reasonably well with the other. 308

In the following a similar test is performed for



Figure 8: Bin by bin ratio between the reconstructed energy distribution (number of events in each energy bin) and the true energy distribution when reconstructing CORSIKA simulated showers in the two approaches; the continuous lines show the estimated systematic uncertainty for the S(500)-derived distribution (see Appendix C).

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experimentally recorded data. In Fig. 9 we plot the ra-310 tio between the reconstructed primary energy from the described approach $(E_0^{S(500)})$ and from the standard re-311 330 312 construction $(E_0^{N_{ch}-N_{\mu}})$, for an experimental shower sample that has been reconstructed by both methods. We 313 331 314 332 note that unlike the case of simulations (Fig. 8), for data $\frac{1}{333}$ 315 $E_0^{S(500)}$ have systematically higher values (up to 30%) 316 334 than $E_0^{N_{ch}-N_{\mu}}$. The difference is not constant over the entire accessible energy range and seems to diminish at the highest energies above $\log_{10}[E_0^{N_{ch}-N_{\mu}}/\text{GeV}] \approx 8.4$. 317 335 318 336 337 319



Figure 9: Ratio between the energy from S(500), $E_0^{S(500)}$ and the re-constructed energy in the standard approach, $E_0^{N_{ch},N_{\mu}}$; the plot is a profile with box errors showing the spread of data and the bar errors the error of the mean.



Figure 10: The correlation between the NKG-derived shower size N_{ch}^{NKG} in the standard approach and the S(500) for p and Fe simulated events and for experimental data.

Applying a correction to the estimated resolution by a response matrix (unfolding), the energy spectrum based on the S(500) observable could be determined. But, as we observe a systematic shift in the estimated energy compared to the standard method applied to the KASCADE-Grande detected events, we focus on the investigation of the source of this shift. The unfolding procedure, the determination of the spectrum, as well as the discussion of the uncertainties are described in Appendix B and Appendix C.

4. Discussion

Considering that we are using the same procedure for the reconstruction of both simulated and experimental data, the disagreement between experimental results without a corresponding one found in simulated results might indicate that certain features of the EAS are not described accurately by simulations (such as the shape of the lateral distribution, the shower size, the position

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Figure 11: Averaged lateral charged particle density distributions for simulations (CORSIKA/QGSJet-II p and Fe showers) and experimental data, for events with $\log_{10}[S(500)/m^{-2}] \in [-1, -0.8](above)$ and $\log_{10}[S(500)/m^{-2}] \in [-0.2, 0.0]$ (below); we show only events inclined at $\approx 21^{\circ}$ to avoid effects induced by attenuation in the atmosphere; the 370 continuous lines are of a Linsley-type function.

of the shower maximum or the attenuation of the par-338 ticle number in the atmosphere). As a test we com-339 pare the shower size (N_{ch}) for p and Fe simulations 340 and for the experimental data, when selecting show-341 ers in the same narrow energy range (selected by same 342 S(500)). For showers detected by KASCADE-Grande 343 in the $10^{16} - 10^{18}$ eV energy range we expect that for a 344 given S(500) (i.e. fixed energy) the observed N_{ch} will 345 be in a range delimited by p and Fe assumptions [1, 2]. 346 We use the value of N_{ch} as inferred on an event by event 347 basis from a modified NKG fit [22] of the lateral distri-348 bution as in the standard approach [7] (Fig. 10). For var-349 ious S(500) ranges in Fig. 10 we observe that the data 350 does not satisfy the expectations and indicates a mass 351 composition heavier than Fe. This is in agreement with 352 Fig. 11 where we compare averaged lateral density dis-353 tributions for simulated showers (p and Fe primaries) 354 and data. The experimental lateral distribution is out-355 side the p and Fe predictions towards elements heavier 356 357 than Fe.

We evaluate this disagreement in a bit more detail. 358 Based on Fig. 10 we impose a change on an event 359 by event basis on the measured S(500) by decreas-360



Figure 12: Ratio between the reconstructed energy from S(500), $E_0^{S(500)}$ and $E_0^{N_{ch},N_{\mu}}$, where the recorded S(500) is corrected to be in agreement with the QGSJet-II Fe prediction. The box errors show the spread of data and the bar errors the error of the mean.

ing the reconstructed S(500) values with a value of $\Delta[\log_{10}S(500)/m^{-2}] = -0.1$. The value -0.1 for this correction is the minimum one must introduce in order to satisfy the QGSJet-II-2 (p,Fe) range prediction over the entire energy range accessible to KASCADE-Grande (see Fig. 10). Using the modified experimental S(500) values the differences in the energy determination vanishes at lower energies (Fig. 12) (and also the resulting spectrum is comparable to the published one within the range of the systematics uncertainties, see Appendix C).

We therefore conclude that the systematic shift between the two KASCADE-Grande results is mainly due to the simulations that do not accurately describe the shape of the lateral density distributions as they appear too steep at large radial ranges in comparison to the data. Since the S(500)-based method samples most of its information from a reduced radial range at 500 m from the shower axis, it is likely that this method is more sensitive to inaccuracies in the shape of the simulated lateral distribution than the standard approach which samples data from the entire radial range of the lateral density distribution. This is equivalent to saying that a significant (according to Fig. 10 approximately 30% less density) disagreement in shape at 500 m from the shower axis may have significantly less influence on the integrated value N_{ch} . This picture seems to change at higher energies, where S(500) is already in the steeper part of the lateral distribution. But as statistics is low, it cannot be decided if 500 m distance is still the appropriate value for an unbiased energy determination.

We discuss in the following two physics possibilities to explain a different lateral shape of charged particles in EAS by simulations and data:

• A shallower lateral density distribution as desired

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Figure 13: Averaged lateral charged particle density distributions similar to the ones in Fig. 11, but here the simulations are using the EPOS model.



Figure 14: This plot is similar to the one in Fig. 9 but here the S(500)derived energy for KASCADE-Grande is inferred using a calibration based on simulations with EPOS.

at large radial ranges is consistent with older show-396 ers starting higher in the atmosphere which trans-397 lates into larger cross section for the primary. This 39 solution however seems to contradict the latest re-399 sults at LHC⁵ [23, 24] that do not encourage fur-400 ther increase of the cross sections in most models. 401 Therefore an even larger cross section for the pri-402 mary does not seem to be the solution for improv-403 ing the agreement between data and simulations. 404

In a second approach to the matter it seems likely 405 that a higher muon multiplicity resulting in larger 406 number of muons in the shower could increase the 454 407 curvature of the lateral distribution, given that in 455 408 the lateral distribution the ratio N_{μ}/N_{ch} is not con-409 stant over the entire radial range. At large radial 457 410 ranges the electron component is practically ex- 458 411 tinct and the charge component at such ranges is 412

dominated by muons. An increase in muon multiplicity should therefore have a stronger effect at large radial ranges and produce the desired effect of further *bending* the lateral distribution. We test this hypothesis using a set of CORSIKA simulations based on the EPOS 1.99 hadronic interaction model. One of the differences between EPOS 1.99 and QGSJet-II-2 for a given primary is that on average the EPOS simulated showers will contain more muons (a feature which of course would affect both rconstruction methods at KASCADE-Grande). Fig. 13 shows the averaged lateral density distributions like in Fig. 11 but for simulations based on the EPOS model. With EPOS there seems to be better agreement between data and simulations although experimental data is still not inside the (p, Fe) expected range and the shape is still flatter than for the simulated ones. When deriving the primary energy from S(500) with a calibration based on EPOS simulations there is indeed a 10% systematic decrease of the primary energy when compared to the case of the QGSJet-II calibration, which reduces the observed difference (Fig. 14), but not vanishes the discrepancies.

In the S(500)-based method the simulation-derived calibration is very sensitive to the shape of the simulated lateral distribution and even small deviations in the shape of the distributions can have significant effects in the resulting energy spectrum. The same is true when talking about the fluctuations of the S(500) observable itself. The detected charge particle density at 500 m distance from the shower core can be accompanied by significant fluctuations due to the small number of particles per station or to the fact that in some cases there is no data close to 500 m due to the array size. However, the sensitivity of this method to the shape of the lateral distribution can be turned into a positive feature in evaluating the simulation quality. In contrast to the S(500)-based approach, the method based on the N_{ch} - N_{μ} correlation infers the primary energy from the whole range of the lateral distribution and is less affected by small deviations in the shape, local fluctuations or the lack of information in the lateral distribution. In this respect, the reconstruction of the primary energy from the charged particle and muon numbers (shower sizes) is more robust.

5. Conclusions

The primary energy spectrum of cosmic rays in the range of 10¹⁶ - 10¹⁸ eV accessible by the KASCADE-

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⁵the particle energy of 900 GeV at the LHC translates in a primary energy of approximately 10¹⁶ eV of a proton impinging the atmosphere

Grande experiment has been determined based on a 509 462 correlation between the total number of charged parti-463 cles and the muon number. In this paper we presented 510 464 an approach to reconstruct the primary energy of indi-511 465 vidual measured air-showers based on another energy 466 512 estimator, the charged particle density at 500 m dis-467 513 tance from the shower axis similarly as used in exper-468 iments like Auger (S(1000) [25]), or AGASA (S(600)515 469 [26])⁶. According to the QGSJet-II-2 predictions the 516 470 S(500)-derived energy is composition independent as 517 471 the density of charged particles at 500 m distance to the 518 472 shower axis is mass-insensitive for the special case of 519 473 KASCADE-Grande. A study on simulated events pre- 520 474 ceded the study on experimental data in order to evalu-475 521 ate the reconstruction efficiency and quality and to de-476 522 rive a calibration curve E_0 - S(500). The analysis has 477 523 been applied identically to simulated and experimental 478 524 events. 479 525

526 The S(500)-derived primary energy shows a system-480 527 atic shift when compared to the result of the standard 481 528 reconstruction approach, but only in case of measured 482 data. In case of simulation both methods result in an 530 483 531 energy determination of similar good quality. We ex-484 532 plain the origin of this shift in the disagreement between 485 533 the shape of simulated lateral distributions and the ob-486 534 served distributions. The simulated lateral distributions 535 487 are too steep at large radial ranges in comparison with 488 the data. The effect seems to be much weaker at higher 489 538 energies. This might be due to the fact that KASCADE-490 539 Grande measures the particle densities up to 700 m core 540 491 distance only. This can lead to this observation as for 492 higher energies the muons dominate the lateral distri-493 543 butions at larger distances only. The inconsistency be-494 544 tween simulations and data is large enough to justify 545 495 546 most of the shift between the energy spectra from the 496 547 two methods. Methodical or detector effects are ex-497 548 cluded to be a major effect as several tests were per-549 550 formed like using different lateral distribution functions, 499 551 independent analysis codes, or the analysis of subsam-500 552 ples of the total shower sample. 501 553

We have discussed two possible solutions to improve the agreement between data and simulations. While one solution (higher cross sections) might be disfavored by recent results at the LHC, the possible solution of predicting a higher muon multiplicity seems to be more promising as are the results from preliminary tests based

on the EPOS 1.99 interaction model.

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⁶It should be noted that in case of the Auger Observatory the calibration of the value is based on calorimetric measurements by the fluorescence telescopes, whereas in case of AGASA or KASCADE-Grande simulations have to be used.

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Appendix A. The Constant Intensity Cut method 586

Some EAS observables at the detector level are 587 greatly influenced by the zenith angle of the shower 588 because, on average, the particles travel along paths 589 with different lengths in the atmosphere depending 590 on the zenith angle. Such is the case of the S(500)591 which on average can have different values for the same 592 primaries (E_0, A_0) arriving from different zenith angles. 593 One has to correct for this effect before performing an 594 analysis simultaneously on all recorded EAS events. 595 This is achieved by applying the Constant Intensity 596 Cut (CIC) method [27]. The method is based on the 597 assumption that for a given minimum primary energy 598 above the full efficiency threshold we should record the 599 same flux of primaries (i.e. air showers) from all zenith 600 angles. That is analogous to say that in the integral 601 spectra from different zenith angles equal intensity 602 corresponds to the same primary energy. 603

We perform several constant intensity cuts on the 604 integral S(500) spectra corresponding to different 605 zenith angles (Fig. A.15) and for each cut we establish 606 a correlation between the S(500) and the corresponding 607 zenith angle (Fig. A.16). To build the integral S(500)608 spectra we pick the zenith angular intervals in the range 609 $[0^{\circ}, 30^{\circ}]$ so that they subtend equal solid angles. We fit 610 all values in Fig. A.16 simultaneously with a functional 611 form derived from a second degree polynomial and use 627 612 this functional form as a correction function to account 613 for the attenuation of S(500). All reconstructed S(500) 628 614 values are corrected by bringing them to the value they 615 would have at a chosen reference angle. For the present 630 616 study the reference angle is considered to be 21°, since 631 617 618 the zenith angular distribution for the recorded EAS 632 sample peaks at this value. The CIC correction is thus 633 619 derived entirely from recorded experimental data and is 634 620 independent from simulated studies. 621

The attenuation length $\lambda_{S(500)}$ of S(500) is evaluated using a global fit of the attenuation curves assuming exponential attenuation (eq. A.1). The resulting value is $\lambda_{S(500)} = 402 \pm 7 \text{ g} \cdot \text{cm}^{-2}$.



Figure A.15: Integral S (500) spectra; the horizontal lines are constant intensity cuts at arbitrarily chosen intensities.



Figure A.16: Variation of the S(500) observable with the angle of incidence; each set of points correspond to a constant intensity cut in Fig. A.15; the continuous lines show a global fit of all points.

$$S(500)_{\theta} = S(500)_{0^{\circ}} \exp\left[\frac{-h_{0^{\circ}}}{\lambda_{S(500)}}(\sec\theta - 1)\right]$$
 (A.1)

Appendix B. Unfolding based on a response matrix

If a given variable is characterized by intrinsic statistical fluctuations, when representing its spectrum as a histogram with given bin size, the fluctuations will cause the total value stored in each bin to deviate from the true (unknown) value due to events *leaking* to and from neighbouring bins. In effect, the reconstructed spectrum is obtained from the true spectrum of the given variable by folding in each bin the contributions from

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fluctuations in all neighbouring bins. This migration 636 depends on the bin size and on the amount of fluctua-637 tions and its effects can vary greatly depending on the 638 spectral shape. This is the case of the reconstructed en-639 ergy spectrum which is very steeply decreasing. Given 640 the steep decrease of the spectrum, it is expected that 641 contributions into neighbouring bins will have a greater 642 effect towards higher energies where the flux is much 643 lower. This affects the flux value and simultaneously 644 the spectral index and a correction should be applied in 645 order to compensate. Such a correction is derived us-646 ing simulated showers and is based on a response ma-647 trix in which we plot the probabilities $P(E_i^{rec}, E_i^{true})$ that 648 an energy E_i^{true} is reconstructed as energy E_j^{rec} (where 649 $E_i^{true}/eV \in [10^{16}, 10^{19.5}]$ thus covering the energy range 650 of interest where such effects are of importance). To un-651 fold the effects of fluctuations and infer the true energy 652 spectrum one has then to solve a system of equations as 653 eq. B.1. 654

$$N^{rec}(j) = \sum_{i=1}^{N_{bins}} P(E_j^{rec}, E_i^{true}) N^{true}(i)$$
(B.1)
(B.1)
(B.1)

where $\sum_{i=1}^{N_{bins}} P(E_i^{rec}, E_i^{true}) = 1$. 655

The system is solved iteratively by applying a method 656 based on the Gold algorithm [28] and then the result is 657 compared with the result of another approach based on 658 the Bayes algorithm [29] (applied also iteratively). For 659 a sufficiently large number of iterations the results of 660 the two methods converge (Fig. B.17). For each unfold-661 ing procedure, a smoothing was applied to the result of 662 each intermediate iteration in order to avoid fluctuations 663 amplifying from each iteration to the next. This smooth-664 ing was based on the 353HQ-twice algorithm [30]. Ad-665 ditionally, the simulation-derived response matrix has 666 been smoothed in order to reduce the effects induced by 667 the statistical fluctuations in the Monte Carlo sample. 668 To smooth the response matrix, the information in each 669 bin of true energy is fitted with a Gauss-Landau con-670 volution and the parameters of the convolution function 671 are then parametrized with the true energy. 672

The unfolding procedures based on the Gold and 673 Bayes algorithms were tested by comparing the mea-674 689 sured spectra with the forward folded ones and good 675 agreement was observed. 676 691

Appendix C. The energy spectrum based on *S*(500) 677 and its systematic uncertainties 678

The experimental energy spectrum as inferred from $_{696}$ the presented approach is shown as $E_0^{S(500)}$ in Fig. C.18 $_{697}$ 679 680



Figure B.17: Results of the Bayes and Gold unfolding algorithms.

along with the result of KASCADE [21] towards lower energies and with the result from the standard approach [7] as $E_0^{N_{ch}-N_{\mu}}$. It is important to note that the KAS-CADE spectrum is inferred from a procedure using the QGSJet-01 model for high energy interactions, with different specific systematics than the QGSJet-II-2 used to infer the two KASCADE-Grande spectra. The figure shows also the resulting spectrum obtained when using EPOS 1.99 as basis for the calibration.



Figure C.18: Primary energy spectra for KASCADE [21] and KASCADE-Grande [7]; the bands with continuous lines show the estimated systematic uncertainty. This plot is similar to the one in Fig. C.18 but here the S(500)-derived energy spectrum for KASCADE-Grande is inferred using a calibration based on simulations with EPOS.

The energy reconstruction procedure implies the use of complex mathematical procedures that rely on a considerable number of parameters. Certain such parameters can vary arbitrarily and lead to fluctuations of the obtained flux. In order to evaluate the fluctuation induced to the energy flux by each of these factors, they have been allowed to change and the resulting variation of energy flux in % was evaluated. We identify such

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free parameters and estimate their contribution to the 747 total fluctuation. 748

749 • The accuracy of the S(500) reconstruction. 700 750 The S(500) energy estimator is derived from a 751 701 Linsley LDF fit. The quality of this fit is signifi-752 702 cantly affected by the number of stations with good 703 753 signal and also by their position inside the lateral 704 density distribution. The fluctuations in the recon-754 705 structed S(500) act as a source of uncertainty and 755 706 amount to $\approx 16.5\%$ at $E_0 = 10^{17}$ eV, decreasing 756 707 with energy to $\approx 8\%$ at $E_0 = 10^{18}$ eV [31]. 757 708 758

• Uncertainties in the $E_0 - S(500)$ calibration. 709 759 The simulation-derived calibration curve is ob-710 760 tained by a fit procedure and each parameter is 761 711 characterized by an uncertainty. In order to evalu-712 762 ate the effects of these uncertainties in terms of sys-713 763 tematics of the energy flux, the fit parameters are 764 714 allowed to change according to their uncertainty 765 715 and the primary energy spectrum is reconstructed 716 766 in this particular new case. The contribution of 717 this source amounts for a systematic uncertainty of 767 718 $\approx 1\%$ at $E_0 = 10^{17}$ eV, increasing with energy to 768 719 $\approx 6\%$ at $E_0 = 10^{18}$ eV. 769 720 770

• The spectral index of the simulated event sample. 771 721 The simulated shower sample that was used 772 722 throughout this study was weighted on an event 773 723 by event basis to emulate a primary energy spec-724 774 trum with a spectral index $\gamma = -3$, close to the 775 725 natural index of the cosmic ray spectrum, but not 776 726 exactly the same. The reconstruction is repeated 777 72 for the cases $\gamma = -2.8$ and $\gamma = -3.2$ and the dif-728 ference between the fluxes obtained in these two 779 729 cases is considered as systematic uncertainty. This 780 730 source amounts for $\approx 2\%$ at $E_0 = 10^{17}$ eV, increas-781 731 ing slightly with energy to $\approx 4\%$ at $E_0 = 10^{18}$ eV 782 732

Influence of the Monte-Carlo statistics on the fit parameters.

The simulated shower sample used for energy cal-785 735 ibration is generated by a Monte Carlo algorithm 786 736 which introduces fluctuations differently for differ-787 737 ent energy ranges, since the energy spectrum is a 788 738 power law and at high energies there are much less 789 73 events available for analysis than at lower energies. 790 740 In order to estimate the effect of these fluctuations, 791 741 the energy range is divided into 3 sub-ranges and 792 742 743 the energy calibration is performed for every sub-793 range. The new parametrizations will vary slightly 794 744 from one case to the other due to Monte Carlo fluc-795 745 tuations. The reconstruction is being performed 796 746

for each particular parametrization and the results are compared. For every energy bin, the difference between the maximum reconstructed flux and the minimum value defines the systematic uncertainty from this source. It amount for $\approx 2\%$ at $E_0 = 10^{17}$ eV, increasing with energy to $\approx 8\%$ at $E_0 = 10^{18}$ eV

• The systematic error introduced by the CIC.

The CIC (Appendix A) method provides an attenuation-corrected S(500) with an associated uncertainty resulting from the CIC method itself. This acts as another source of systematic uncertainty, as the corrected S(500) is converted to energy. To evaluate the contribution of the CIC method to the overall systematics we allow the corrected S(500) value of each event to change according to the CIC-specific uncertainty. The contribution to the resulting energy flux is rather small, below 1% over the entire energy range.

• Choosing a specific reference angle for which to perform the S(500) correction of attenuation. When correcting the S(500) for attenuation, a certain reference angle is chosen. Since the experimental zenith angular distribution is peaked at 21°, the reference angle was chosen to be 21° in order to have the CIC method significantly affecting as few showers as possible. However it is possible to choose another angle as well without changing the relevance of the end result, but the correction would affect each shower differently depending on our choice for a reference angle. We are choosing as reference angles the extreme cases 0° and 30° and we compare the resulting spectra after applying CIC for these reference angles. The difference between these spectra define the contribution of this uncertainty source and it is $\approx 6\%$ at $E_0 = 10^{17}$ eV increasing to $\approx 14\%$ at $E_0 = 10^{18}$ eV.

• The response matrix correction

To account for the effect of the statistical fluctuations on the energy spectrum, the response matrix correction (see Appendix B) involves very complex mathematical operations that are repeatedly applied to the raw recorded energy spectrum. Such operations involve for example fits and smoothing. This is an additional source of systematics. To evaluate the contribution of this source we first generate a sample of test spectra. Each of the test spectra is derived by introducing random Poissonian noise in the raw un-corrected energy spectrum and then by unfolding it. We forward fold the test spectra (the inverse operation of the unfolding procedure) and then re-unfold them. We then calculate the average difference between the re-unfolded
spectra and the average of the test spectra. We use
this average difference to define the contribution of
the response matrix correction. It contributes with
about 4% over the entire energy range.

• Hadronic interaction model.

The combination of QGSJet-II-2 and FLUKA 805 models has been used for all studies on simulated 806 events and it is expected that the model itself intro-807 duces a systematic effect when describing certain 808 shower properties. To obtain a rough estimate of 809 this systematic a second calibration has been de-810 rived from simulations based on the EPOS 1.99 811 model and on average the energy variation with 812 the new calibration is systematically $\approx 10\%$ lower 813 than for QGSJet-II-2. Similarly, when we treat 814 the EPOS shower sample as experimental data and 815 reconstruct it using the calibration based on the 816 QGSJet-II model we obtain a systematic $\approx 10\%$ 817 overestimation of the energy. This contribution is 818 only evaluated here, but not included in the sys-819 tematic uncertainty band in Fig. C.18, Section 3.4. 820

The above sources (excluding the hadronic interaction models) introduce a combined systematic uncertainty of $\approx 32\%$ in the energy flux at $E_0 = 10^{17}$ eV increasing up to $\approx 45\%$ at $E_0 = 10^{18}$ eV.