On the capability of separating EAS events into mass groups on an event by event basis with the KASCADE-Grande experiment

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Abstract: The KASCADE-Grande experiment measures the total number of charged particles (N_{ch}) and the total number of muons (N_μ), at detection level (i.e. 110 m a.s.l.), in EAS originated by primaries in the $10^{16} - 10^{18} eV$ energy range. The two-dimensional (N_{ch} vs N_μ) spectrum is the basis for the cosmic-ray chemical composition studies. EAS and detection fluctuations prevent the measurement of the primary mass on an event by event basis, nevertheless the precision obtained by the KASCADE-Grande experiment allows to separate events into mass groups. In this contribution we discuss the purity obtained in the case of a two mass groups separation (light and heavy primaries), showing that it does not depend on experimental features and that it is constant with energy. As this separation relies on EAS and detector simulations we discuss the role played by the choice of the hadronic interaction models. Updated measurements of the energy spectra of the two mass groups are presented, showing that the detected spectral shapes are independent from the hadronic interaction models.

Keywords: KASCADE-Grande, air shower, chemical composition

1 Introduction

Chemical composition studies are one of the main tools to clarify the origin of the structures detected in the all particle cosmic ray primary spectrum. Above $\sim 10^{14} eV$ cosmic rays can only be studied by earth based EAS experiments, thus their characteristics can only be inferred indirectly. The EAS parameters that are mostly used to perform such measurements are[1]: the atmospheric depth of the shower maximum (available to fluorescence light detectors), the correlation between the muon and electron numbers at observation level (that can be detected in various ways, mainly by scintillation counters). The interpretation of these data is based on full EAS simulations that are necessarily based on hadronic interaction models founded on the extrapolation of the accelerator measurements, performed at lower energies. Data of the LHC experiments will cover the energies of the knee, thus in the near future (tuning the hadronic interaction models with these data) we can expect great improvements of the situation. Nevertheless shower development fluctuations almost prevent an event by event detection of the nature of the primary particle. Thus even high resolution experiments (such as KASCADE-Grande[2]) can only separate the events in groups of primary mass.

In this contribution we will discuss the performances of the KASCADE-Grande experiment in separating two mass groups (light and heavy primaries) on an event by event basis through the measurement of the ratio between the muon (N_μ) and charged particle (N_{ch}) numbers. In order to take into account the EAS development in the atmosphere, the N_{ch} and N_μ values measured at a zenith angle θ are converted to the respective values at a reference an-
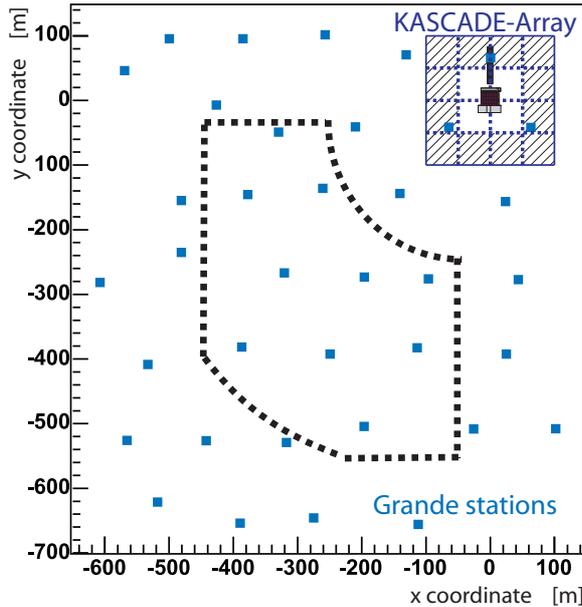
Figure 1: Layout of the KASCADE-Grande experiment. The KASCADE array and the distribution of the 37 stations of the Grande array are shown. The 192 muon detectors are placed in the outer 12 clusters of the KASCADE array (hatched area). The dotted line shows the fiducial area selected for this analysis.

gle ($\theta_{ref} = 22°$) using the constant intensity cut method. We will discuss how the results obtained by this technique are not influenced by the experimental resolution or by the hadronic interaction models used in the EAS simulation. Using this event by event separation into two mass groups the KASCADE-Grande experiment has evidenced structures in the spectra of both the light[3] (an hardening at E$\sim 1.2 \times 10^{17} eV$) and heavy[4] primaries mass groups (steepening at E$\sim 8 \times 10^{16} eV$).

This approach is not the only one followed by the KASCADE-Grande collaboration to study the primary chemical composition. In a different analysis the unfolding algorithm[5] has been applied to the two dimensional N_{ch} vs N_μ spectrum of vertical events ($\theta < 18°$). With this approach we are able to separate five mass groups enhancing different spectral characteristic (such as an evaluation of the elemental fluxes) but the results heavily depends on the hadronic interaction model used in the EAS simulation. The two results are thus complementary, being sensible to different features of the spectra and being affected by different systematic errors.

2   Analysis Technique

A full description of the experiment can be found in[2], in this contribution we briefly remind how we determine the number of muons (N_μ) and of charged particles (N_{ch}). A sketch of the array layout is shown in figure 1. N_{ch} is determined fitting, with a NKG-like lateral distribution function, the number of particles sampled by the Grande stations (37 plastic scintillation detectors, separated by $\sim 130m$ and covering an area of 0.5 km^2). While N_μ is evaluated with the event geometry estimated by the Grande detectors and the number of muons ($E_\mu > 230MeV$) measured by the
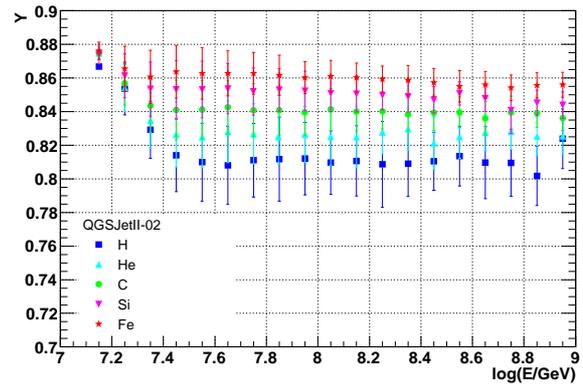
Figure 2: Mean values of the Y ratio obtained by a full EAS and detector simulation for five different primaries and using the QGSJetII-02 hadronic interaction model. Error bars represent the RMS of the distributions.
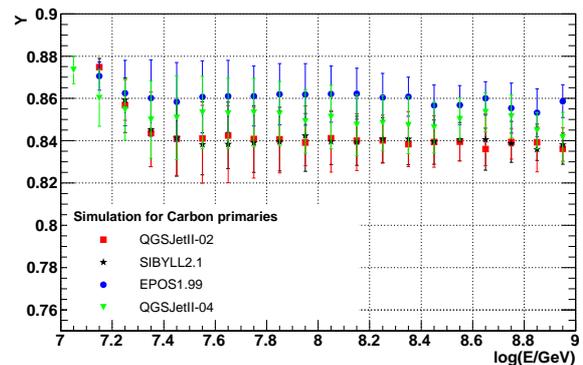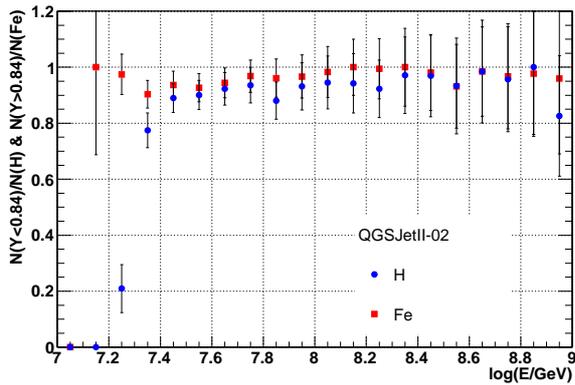

Figure 3: Mean values of the Y ratio obtained by a full EAS and detector simulation for C primaries and different hadronic interaction models.

KASCADE array stations (192 plastic scintillation detectors, separated by 13 m, covering a 0.04 km^2 area, located in one corner of the Grande array). The experimental resolution has been evaluated in[2], being (above 100% detection efficiency) < 15% for N_{ch} and < 20% for N_μ.

The measured values of the $Y = lnN_\mu(\theta_{ref})/lnN_{ch}(\theta_{ref})$ ratio are compared with those obtained by a full EAS and detector simulation, based on the CORSIKA code[6]. Events are generated using different high energy hadronic interaction models (QGSJetII-02[7], Sibyll2.1[8], EPOS1.99[9] and QGSJetII-04[10]), while the low energy interactions are always simulated by means of the FLUKA code[11]. Montecarlo events have been generated on a E^{-2} energy spectrum, that is then weighted to E^{-3} to better take into account the EAS development fluctuations.

3   Results

In figure 2 the mean values of the Y ratio obtained, in the case of the QGSJetII-02 hadronic interaction model, for five different primaries are shown versus the reconstructed primary energy[12], the error bars represent the RMS of the distributions. As expected lighter elements induce EAS

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Figure 4: Fraction of H (Fe) generated events classified in the light (heavy) mass group by means of the Y ratio.

Figure 5: Fraction of H (Fe) generated events classified in the light (heavy) mass group versus the distance from KASCADE center (i.e. mean distance from the muon detectors).

with a lower Y value with respect to heavier ones. For all elements the mean values of the Y distributions are constant above the energy of 100% detection efficiency, corresponding, in the conditions defined for this analysis, to $logE/GeV = 7.6$. Thus defining a threshold value Y_{thr} we separate the events in two groups: $Y > Y_{thr}$ (heavy primaries) and $Y < Y_{thr}$ (light primaries).

The effect of the hadronic interaction model used in the simulation can be estimated comparing the mean Y values obtained in simulations performed for the same element with the four different hadronic interaction models included in the CORSIKA code. The results are shown in figure 3 for carbon generated events, we can see that the Y behavior is always constant with energy, but the actual value depends on the hadronic interaction model. We can observe that the Y values increase when we use hadronic interaction models generating EAS with an higher number of muons (i.e. EPOS1.99 and QGSJetII-04).

Thus fixing Y_{thr} we choose a primary element (for a particular interaction model) or an hadronic interaction model (for fixed primary element). The Y ratio increases for: heavier elements, hadronic interaction models generating EAS with more muons (for fixed primary energy and mass).

Selecting as threshold value the mean Y corresponding to the C primaries ($Y_{thr} = 0.84$ in the case of the QGSJetII-02 hadronic interaction model) we evaluate the fraction of H (Fe) events, having the core location reconstructed inside a fiducial area (see figure 1) and having zenith angle $\theta < 40°$, that are classified as $Y < Y_{thr}$ ($Y > Y_{thr}$). Figure 4 shows that the percentage of events correctly classified is above 90% ($logE/Gev > 7.6$) and, more important, it does not depend on the primary energy, allowing us to conclude that this event selection will not introduce artificial spectral features in the data.

The spectra of the event samples selected by this technique cannot be used to measure the fluxes of elemental spectra, but their shapes reflect real structures.

Being the muon detectors located in a corner of the KASCADE-Grande experiment, N_μ is evaluated sampling the muon density in a well defined range of core distances, the effects of this feature have been extensively studied and discussed[2] and its impact on the N_μ reconstruction is well understood. Nevertheless to check possible effects on this analysis we have evaluated the fraction of H (Fe) events ($logE/GeV > 7.6$) correctly classified as a function
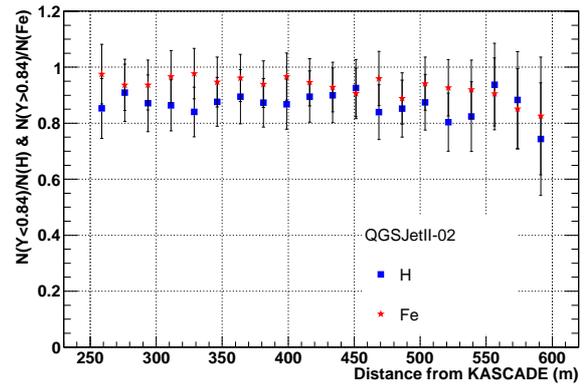
of the core distance from the KASCADE center (mean position of the muon detectors). The results are shown in figure 5: the percentage of events classified as heavy (or light) does not depend on this parameter.

This technique can thus be applied to real data, the spectra obtained applying the same quality cuts described in previous papers (see [12]). The spectra of events with $Y > Y_{thr}$ obtained for different Y_{thr} values are shown in figure 6. All the spectra show a significant steepening at similar energies (in this plot the energy calibration is the one obtained by the QGSJetII-02 interaction model). The steepening is more pronounced in the spectra obtained selecting the events at higher Y_{thr} values, i.e. increasing the fraction of heavy (Fe) primaries in the sample.

4   Conclusions

We have shown that, with the resolution reached by the KASCADE-Grande experiment, the ratio between $lnN_\mu(\theta_{ref})$ and $lnN_{ch}(\theta_{ref})$ can be used to separate, on a event by event basis, two samples corresponding to heavy and light primaries.

The fraction of events correctly classified does not depend on primary energy, thus showing that spectral features eventually observed in the two samples correspond to real structures.

The actual value defined to separate the two mass groups correspond to a particular primary once we choose the hadronic interaction model; different models simply shift the value corresponding to the same element.

The spectra of the $Y > Y_{thr}$ samples, selected with different Y_{thr} values, show a steepening at similar energies, thus showing that this spectral feature, already published in[4], is not a feature introduced by the hadronic interaction model used in the EAS simulation.
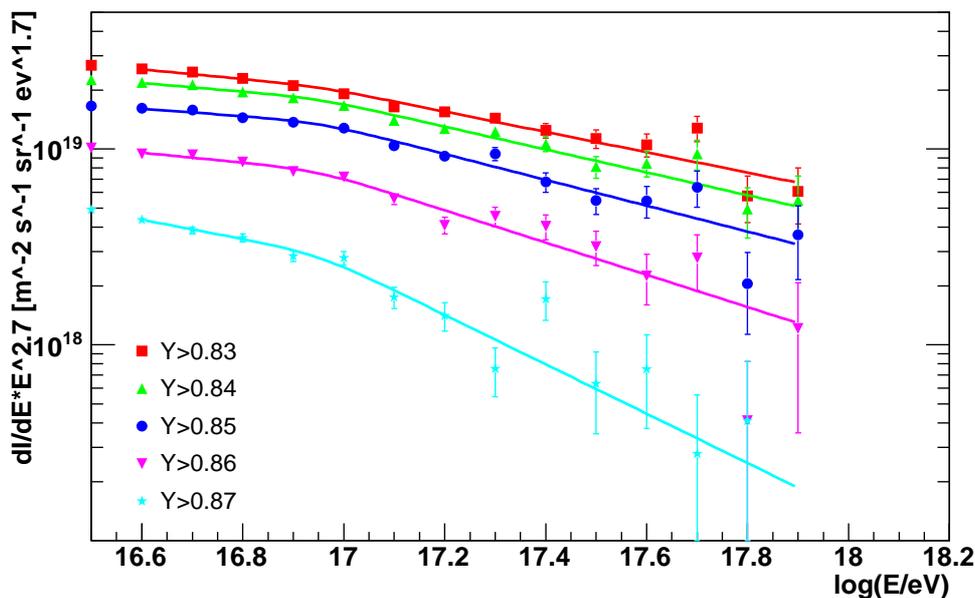
Figure 6: Energy spectra of the events with $Y > Y_{thr}$ shown for different threshold values.

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