Moon shadow and Sun shadow (not) seen by the experiment KASCADE & new energy calibration

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Content

The cosmic-ray experiment KASCADE

- Situated in Karlsruhe Institute of Technology, Campus North, Germany
- 1996 - 2003 only KASCADE, late 2003 KASCADE-Grande, stopped DAQ in 2012
- Computes muonic and electromagnetic components simultaneously and independently
- Piccolo = trigger for showers far from KASCADE array
- Parts in radio telescope and LOFAR and cosmic ray experiment Tunka

Why Moon (and Sun) shadow?

- Moon / Sun blocks trajectories of cosmic rays and geomagnetic field deflects them - the shift of Moon / Sun trajectory with respect to the true Moon position can be wrongly interpreted as systematic offset of event reconstruction
- Helps show angular resolution of data - KASCADE should have 0.1 degrees

Current dataset

Publicly available data from `https://kcdc.iap.kit.edu/` - data for the interested public, preselected datasets available, possible to request specific datasets, simulations with pre- and post-LHC hadronic interaction models

- Data from KASCADE run 877 – 4683, taken in 8. 5. 1998 – 20. 12. 2003
- Analysing energy range $10^{13} - 10^{19}$ eV = range where KASCADE is most sensitive + around knee
- Incoming events transformed into equatorial coordinates - implementation of libnova library - necessary to track Moon position
- Cut for declination: only looking at area close to the Moon trajectory: $(-12^{\circ}; 30^{\circ})$ (full range is $(-12^{\circ}; 90^{\circ})$)

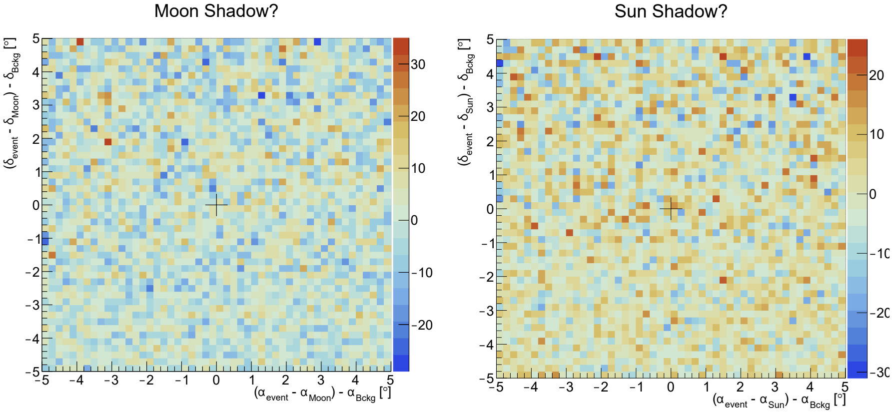

Fig. 1: Evident lack of Moon (left) and Sun (right) shadow on KASCADE data - most likely due to KASCADE zenith sensitivity; quality cuts put $\theta < 60^\circ$ for KASCADE, maximum Moon zenith angle is $\theta^{max}_{Moon} = 70^\circ$, maximum Sun zenith angle is $\theta^{max}_{Sun} = 65^\circ$.

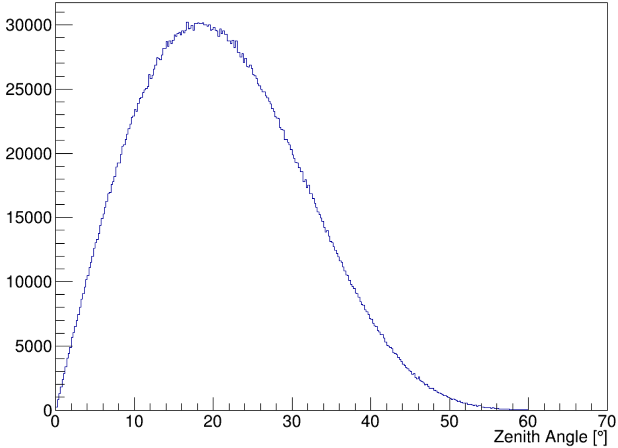

Fig. 2: Distribution of the zenith angle reconstructed by KASCADE. From `https://kcdc.iap.kit.edu/static/pdf/kcdc_mainpage/kcdc-Manual.pdf`.

What's the problem with the energy reconstruction? I

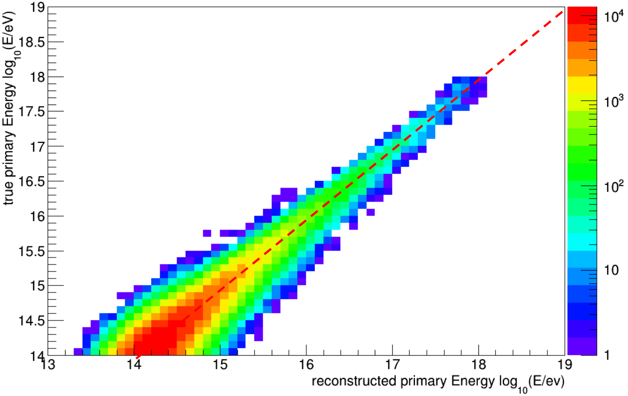

Fig. 3: True primary energy vs reconstructed primary energy for proton-induced showers. The dashed red line denotes the expected value. From `https://kcdc.iap.kit.edu/static/pdf/kcdc_mainpage/kcdc-Simulation-Manual.pdf`.

What's the problem with the energy reconstruction? II

Old energy reconstruction = only two parameters:

$$\begin{aligned}\log_{10} E = 1.93499 + 0.66704 \cdot \log_{10} N_\mu + 0.07507 \cdot \log_{10} N_\mathrm{e}^2 \\ + 0.25788 \cdot \log_{10} N_\mathrm{e} + 0.09277 \cdot \log_{10} N_\mu^2 \\ - 0.16131 \cdot \log_{10} N_\mathrm{e} \cdot \log_{10} N_\mu\end{aligned} \tag{1}$$

New energy reconstruction = takes zenith angle into account + lateral shape parameter / age of the shower:

$$\begin{aligned}\log_{10} E_\mathrm{inv} &= E_\mathrm{MC} - E_\mathrm{Cal} = C(\cos^2\theta) + \delta(\cos^2\theta) \cdot \log_{10} N_\mu \\ \log_{10} E_\mathrm{Cal} &= E_\mathrm{MC} - C(\cos^2\theta) + \delta(\cos^2\theta) \cdot \log_{10} N_\mu \\ &= D(s) + \omega(s) \cdot \log_{10} N_\mathrm{ch}(0^\circ), \\ N_\mathrm{ch}(0^\circ) &= N_\mathrm{e}(0^\circ) + N_\mu(0^\circ), \\ \Rightarrow E_\mathrm{MC} &= E_\mathrm{MC}(N_\mu, N_\mathrm{e}, \theta, s)\end{aligned} \tag{2}$$

What's the problem with the energy reconstruction? III

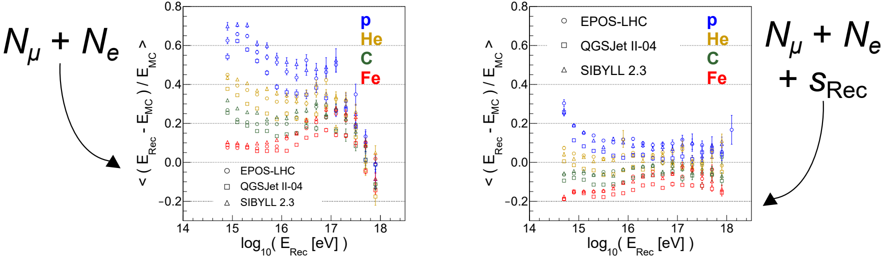

Fig. 4: Biases of the shower energy estimated using KASCADE formula (left) and using new energy calibration (right). From `https://pos.sissa.it/358/453/pdf`.

What's the problem with the energy reconstruction? IV

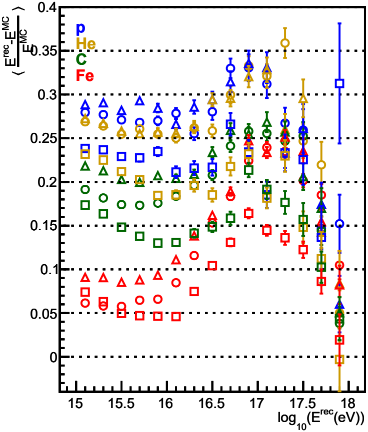

Fig. 5: Biases of the shower energy estimated using KASCADE formula using data available from `https://kcdc.iap.kit.edu/simul/simkas/`.

New plan for energy reconstruction I

- Additional showers using CORSIKA 7.64 (KASCADE data center did not save longitudinal profile of the showers necessary for MC calorimetric energy)
- 60 000 showers, three hadronic interaction models (EPOS LHC, QGSJet-II 04, Sibyll 2.3c), four primaries (p, He, N, Fe), ten fixed values of zenith angle for even distribution for $\cos^2\theta$ (0° - 40°), fourteen bins for s (0.6 - 1.3), five fixed energies (10^{15} eV - 10^{17} eV)
- New energy calibration applied on simulations from `https://kcdc.iap.kit.edu/simul/simkas/` for three hadronic interaction models (EPOS LHC, QGSJet-II 04, Sibyll 2.3d), four primaries (p, He, C, Fe), energy range of 10^{15} eV - 10^{18} eV & checked, how the biases changed

New plan for energy reconstruction II

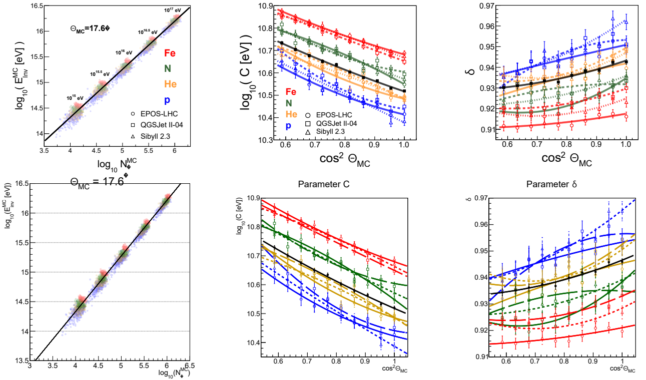

Fig. 6: Dependance of the invisible energy on number of muons. From `https://pos.sissa.it/358/453/pdf` (top), reproduced (bottom). Zenith dependancies are due to the attenuation of number of muons.

New plan for energy reconstruction III

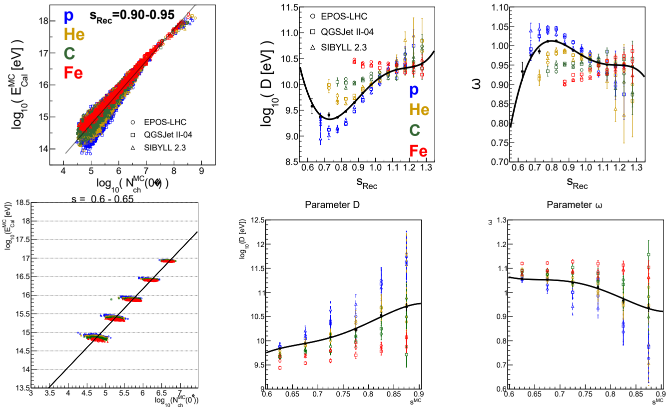

Fig. 7: Dependance of the calorimetric energy on number of charged particles at zero zenith angle. From `https://pos.sissa.it/358/453/pdf` (top), reproduced with polynomial of lesser order (bottom).

What is left to do

- Transform number of muons and number of electrons at ground to zero zenith angle
- Apply correction of calorimetric energy due to the evolution of the age / lateral shape parameter
- Put together the obtained parametrization of invisible energy and calorimetric energy for new energy reconstruction method
- Check the resulting energy biases
- If possible, investigate the Moon and Sun shadow further - experiments with the Moon / Sun outside of optimal range capable of seeing shadow